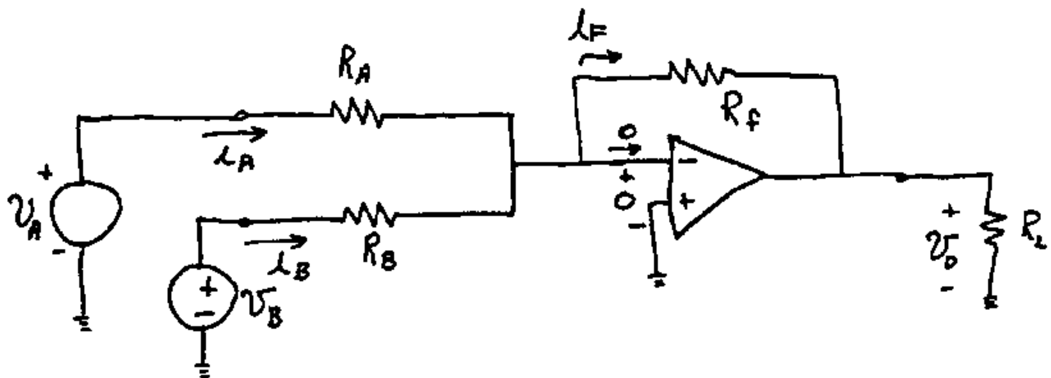
Chapter 2

Exercise 2.1



(a) $i_A = \frac{v_A}{R_A}$ $\quad i_B = \frac{v_B}{R_B}$ $\quad i_f = i_A + i_B = \frac{v_A}{R_A} + \frac{v_B}{R_B}$

$$v_o = -R_f i_f = -\left(\frac{R_f}{R_A} v_A + \frac{R_f}{R_B} v_B\right)$$

(b) For the v_A source:

$$R_{inA} = \frac{v_A}{i_A} = R_A$$

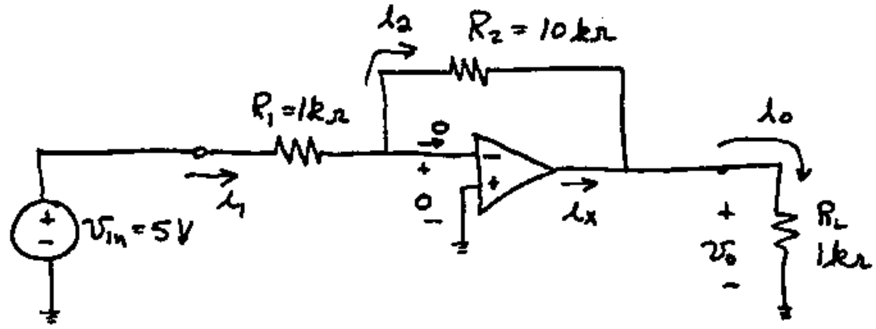
(c) for the v_B source:

$$R_{inB} = \frac{v_B}{i_B} = R_B$$

(d) Because v_o is independent of R_L, the output of the amplifier behaves as an ideal voltage source. Thus the output resistance is zero.

Exercise 2.2

(a)

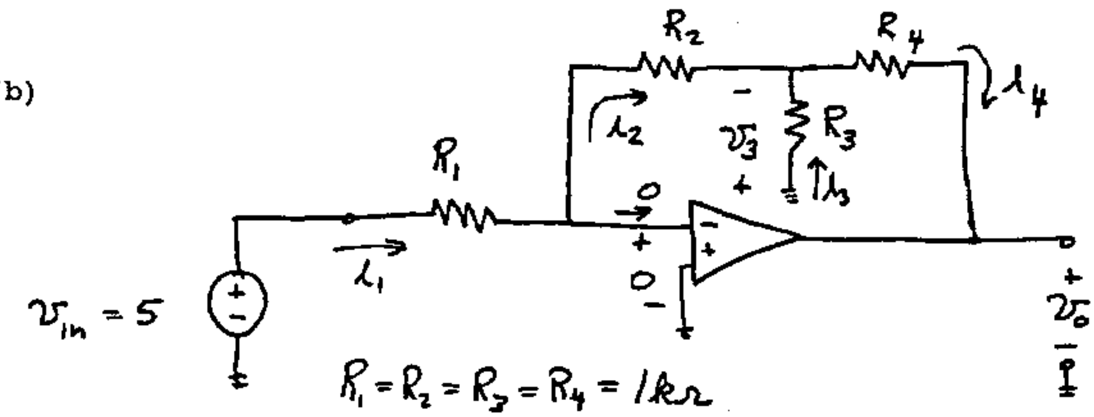


$$i_1 = \frac{v_{in}}{R_1} = 5 \text{ mA} \qquad i_2 = i_1 = 5 \text{ mA}$$

$$v_o = -R_2 i_2 = -50 \text{ V} \qquad i_o = \frac{v_o}{R_L} = -50 \text{ mA}$$

$$i_x = i_o - i_2 = -55 \text{ mA}$$

(b)

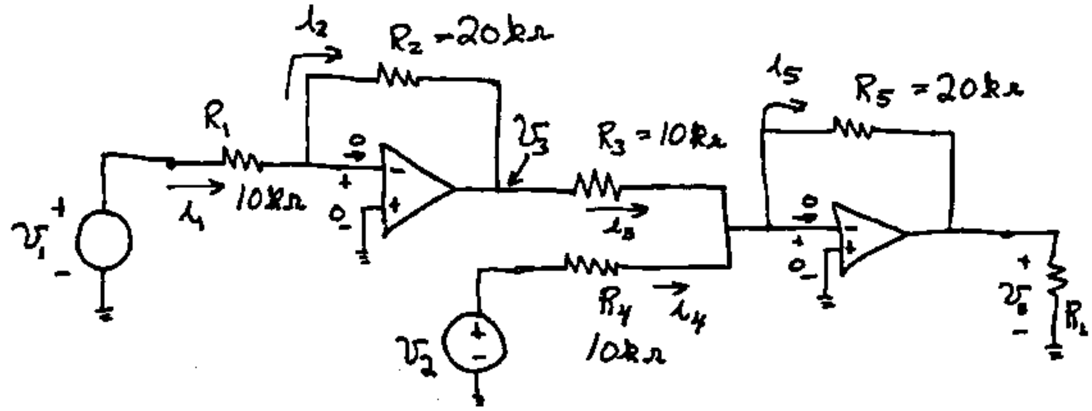


$$i_1 = \frac{v_{in}}{R_1} = 5 \text{ mA} \qquad i_2 = i_1 = 5 \text{ mA} \qquad v_3 = R_2 i_2 = 5 \text{ V}$$

$$i_3 = \frac{v_3}{R_3} = 5 \text{ mA} \qquad i_4 = i_2 + i_3 = 10 \text{ mA}$$

$$v_o = -R_4 i_4 - v_3 = -15 \text{ V}$$

Exercise 2.3



From the circuit we can write:

$$i_1 = \frac{v_1}{R_1} \qquad i_2 = i_1 \qquad v_3 = -R_2 i_2$$

The equations above yield: $v_3 = -\frac{R_2}{R_1} v_1 = -2v_1$

From the circuit we can write:

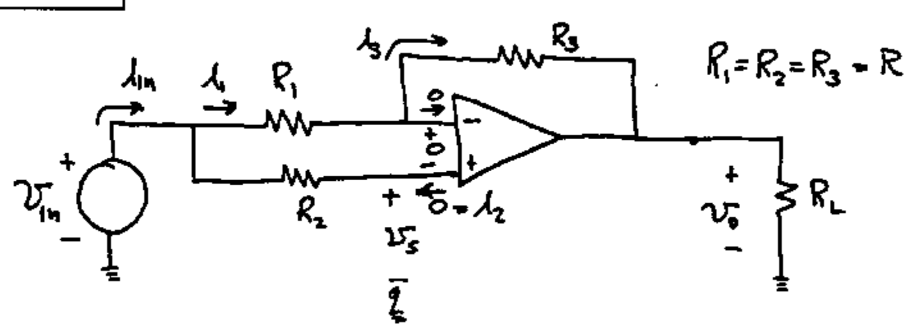
$$i_3 = \frac{v_3}{R_3} \qquad i_4 = \frac{v_2}{R_4} \qquad i_5 = i_3 + i_4 \qquad v_o = -R_5 i_5$$

The equations above yield:

$$v_o = -\frac{R_5}{R_4} v_2 + \frac{R_2 R_5}{R_1 R_3} v_1 = 4v_1 - 2v_2$$

Exercise 2.4

(a)



$v_s = R_2 i_2 + v_{in} = v_{in}$ (because $i_2 = 0$ by summing constraint)

$$i_1 = \frac{v_{in} - v_s}{R_1} = 0$$

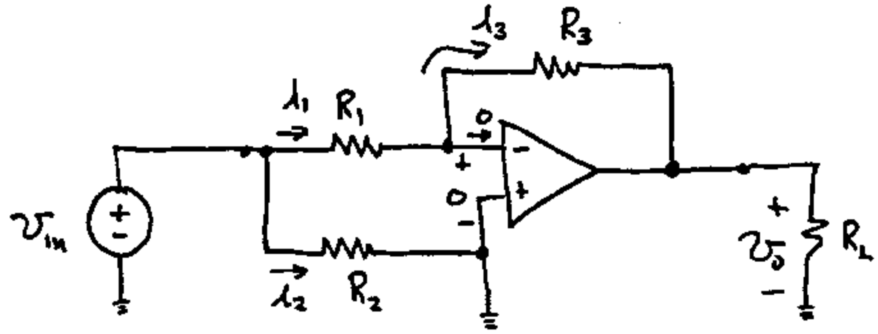
$$i_3 = i_1 = 0$$

$$v_o = -R_3 i_3 + v_s = 0 + v_{in}$$

Thus $v_o = v_{in}$ and $A_v = v_o/v_{in} = +1$

$$R_{in} = v_{in}/i_{in} = \infty$$

(b)



$$i_3 = i_1 = \frac{v_{in}}{R_1} \qquad v_o = -R_3 i_3$$

$$v_o = -\frac{R_3}{R_1} v_{in} \qquad A_v = -\frac{R_3}{R_1} = -1$$

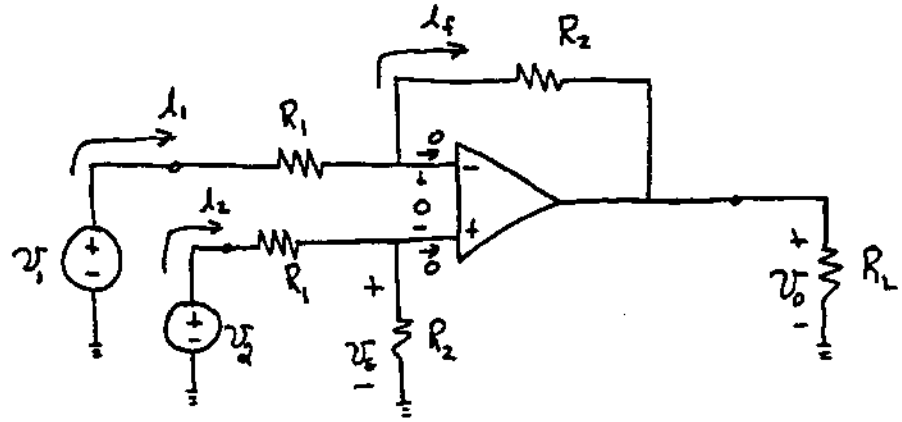
$$R_{in} = \frac{v_{in}}{i_{in}} = \frac{v_{in}}{i_1 + i_2}$$

$$= \frac{v_{in}}{v_{in}/R_1 + v_{in}/R_2}$$

$$= \frac{1}{1/R_1 + 1/R_2}$$

$$= \frac{R}{2}$$

Exercise 2.5



$$i_2 = \frac{v_2}{R_1 + R_2}$$

$$v_s = R_2 i_2 = \frac{R_2}{R_1 + R_2} v_2$$

$$i_1 = \frac{v_1 - v_s}{R_1} = i_f$$

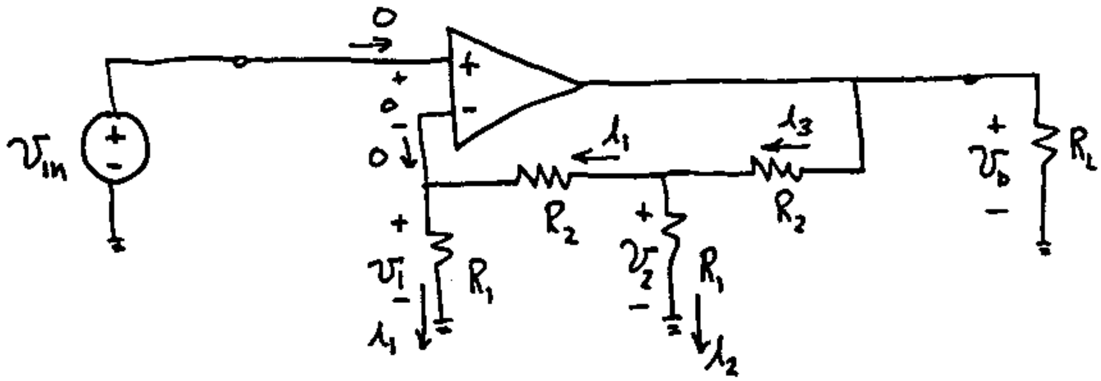
$$v_o = -R_2 i_f + v_s$$

$$= -R_2 \frac{v_1 - v_s}{R_1} + v_s = -\frac{R_2}{R_1} v_1 + \left(1 + \frac{R_2}{R_1}\right) v_s$$

$$= -\frac{R_2}{R_1} v_1 + \frac{R_1 + R_2}{R_1} \frac{R_2}{R_1 + R_2} v_2$$

$$v_o = \frac{R_2}{R_1} (v_2 - v_1)$$

Exercise 2.6



(a) $v_1 = v_{in} \quad i_1 = v_{in}/R_1 \quad v_2 = v_1 + R_2 i_1$

$$v_2 = v_{in} + \frac{R_2}{R_1} v_{in} = v_{in} \frac{R_1 + R_2}{R_1}$$

$$i_2 = \frac{v_2}{R_1} = v_{in} \frac{R_1 + R_2}{R_1^2}$$

$$i_3 = i_1 + i_2 = v_{in} \frac{1}{R_1} + v_{in} \frac{R_1 + R_2}{R_1^2}$$

$$i_3 = v_{in} \frac{2R_1 + R_2}{R_1^2}$$

$$v_o = R_2 i_3 + v_2 = v_{in} \frac{R_1^2 + R_2^2 + 3R_1R_2}{R_1^2}$$

$$A_v = \frac{v_o}{v_{in}} = 1 + 3 \frac{R_2}{R_1} + \left(\frac{R_2}{R_1}\right)^2$$

(b) $A_v = 131$

(c) $R_{in} = v_{in}/i_{in} = v_{in}/0 = \infty$

(d) v_o is independent of R_L, therefore $R_o = 0$.

Exercise 2.7

For a film resistor, we have

$$\frac{L}{W} = \frac{R}{R_{\square}} = \frac{6000}{300} = 20$$

If W = 10 μm, then we must have L = 200 μm and the area is

$$A = LW = 2000\ (\mu m)^2$$

Exercise 2.8

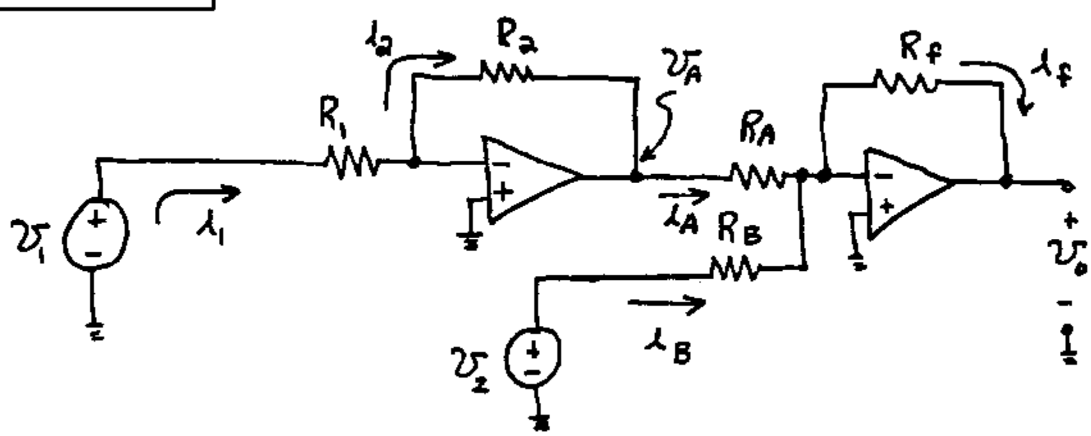
We have three rectangular sections with L/W = 5, 4, and 5 respectively. We count the corners as 0.56 square each and the end pads as 0.65 square each. Thus we have

$$\text{number of squares} = 2(0.65) + 2(0.56) + 5 + 4 + 5 = 16.42$$

Then the resistance is the number of squares times the sheet resistance.

$$R = 16.42 \times R_{\square} = 1642\ \Omega$$

Exercise 2.9



$$i_1 = i_2 = \frac{v_1}{R_1} \qquad v_A = -R_2 i_2 = -\frac{R_2}{R_1} v_1$$

$$i_A = \frac{v_A}{R_A} \qquad i_B = \frac{v_2}{R_B} \qquad i_f = i_A + i_B$$

$$v_o = -R_f i_f = -\frac{R_f}{R_A} v_A - \frac{R_f}{R_B} v_2$$

$$v_o = \frac{R_f R_2}{R_A R_1} v_1 - \frac{R_f}{R_B} v_2$$

Exercise 2.10

Use the circuit of Figure 2.11 with $R_2 = 3R_1$. Many resistance values would work. One example is $R_2 = 30$ kΩ and $R_1 = 10$ kΩ. The gain of the noninverting amplifier is given by

$$A_v = 1 + \frac{R_2}{R_1}$$

The minimum value of A_v occurs if R_2 is 5% lower than its nominal value and R_1 is 5% higher. Then the gain is

$$A_v = 1 + \frac{0.95\ R_2}{1.05\ R_1} = 1 + \frac{0.95}{1.05} \times 3 = 3.714$$

which is lower than the nominal value by

$$\frac{4 - 3.714}{4} \times 100\% = 7.14\%$$

Similarly the maximum value of A_v occurs if R_2 is 5% higher than its nominal value and R_1 is 5% lower. Then the gain is

$$A_v = 1 + \frac{1.05\ R_2}{0.95\ R_1} = 1 + \frac{1.05}{0.95} \times 3 = 4.316$$

which is higher than the nominal value by

$$\frac{4.316 - 4}{4} \times 100\% = 7.89\%$$

Exercise 2.11

(a) From Equation (2.39) in the text we have:

$$f_{BOL} = \frac{A_{0CL} f_{BCL}}{A_{0OL}} = \frac{10 \times 200 \times 10^3}{10^6} = 2 \text{ Hz}$$

(b)
$$f_{BCL} = \frac{A_{0OL} f_{BOL}}{A_{0CL}} = \frac{10^6 \times 2}{100} = 20 \text{ kHz}$$

Exercise 2.12

For $A_{0OL} = 10^6$ we have

$$A_{0CL} = \frac{A_{0OL}}{1 + \beta A_{0OL}} = \frac{10^6}{1 + 0.01 \times 10^6} = 99.9900$$

For $A_{0OL} = 0.9 \times 10^6$ we have

$$A_{0CL} = \frac{A_{0OL}}{1 + \beta A_{0OL}} = \frac{0.9 \times 10^6}{1 + 0.01 \times 0.9 \times 10^6} = 99.9889$$

The percentage change in gain is

$$\frac{99.9889 - 99.9900}{99.9900} = -1.1 \times 10^{-3}\%$$

Exercise 2.13

For $A_{0OL} = 10^6$ we have

$$A_{0CL} = \frac{A_{0OL}}{1 + \beta A_{0OL}} = \frac{10^6}{1 + 0.1 \times 10^6} = 9.99990$$

For $A_{0OL} = 0.9 \times 10^6$ we have

$$A_{0CL} = \frac{A_{00L}}{1 + \beta A_{00L}} = \frac{0.9 \times 10^6}{1 + 0.1 \times 0.9 \times 10^6} = 9.99989$$

The percentage change in gain is

$$\frac{9.99989 - 9.99990}{9.99990} = -0.111 \times 10^{-3}\%$$

Exercise 2.14

The circuit is shown in Figure 2.29 in the text. The op amp limits at output voltages of ±12 V and currents of ±20 mA. The gain of the circuit is 4. The output current of the op amp is

$$i_o = \frac{v_o}{R_1 + R_2} + \frac{v_o}{R_L} \qquad (1)$$

(a) For a load resistance R_L = 1 kΩ, clipping occurs for v_o = 12 V (or v_s = 3 V) because the current required for a 12-V output is 15 mA which is less than the current limit of the op amp.

(b) For a load resistance R_L = 200 Ω, clipping occurs for i_o = 20 mA. Using Equation (1), we find that this corresponds to an output voltage of v_o = 3.81 V or an input voltage of 0.952 V.

Exercise 2.15

(a) $f_{FP} = \frac{SR}{2\pi V_{omax}} = \frac{5 \times 10^6}{2\pi(4)} = 199$ kHz

(b) Clipping occurs when the output voltage limit occurs which is ±4 V.

(c) The output current is given by

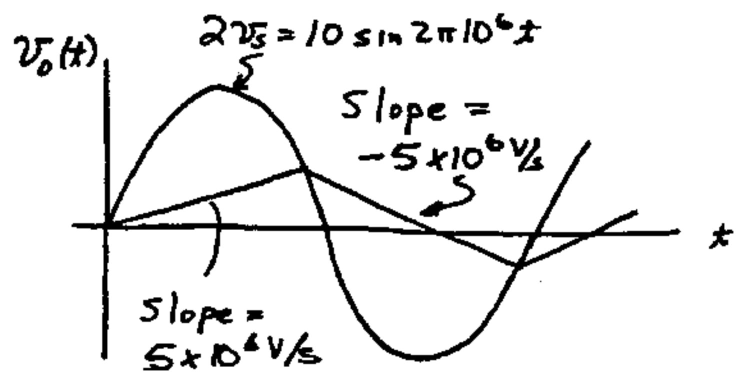
$$i_o = \frac{v_o}{R_1 + R_2} + \frac{v_o}{R_L}$$

Substituting i_o = 10 mA and the resistor values, we find v_{omax} = 0.9995 V.

(d) In this case the slew rate is the limitation.

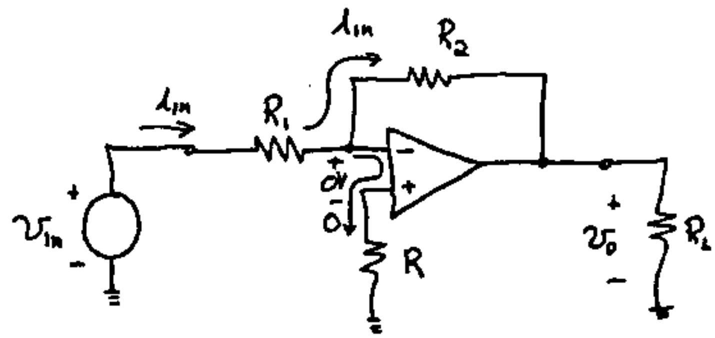
$$V_{omax} = \frac{SR}{2\pi f} = \frac{5 \times 10^6}{2\pi 10^6} = 0.796 \text{ V}$$

(e) The output is limited by the slew rate and is a triangular waveform. Its peak-to-peak amplitude is $V_{p-p} = SR \times T/2$ where $T = 1\ \mu s$ is the period of the waveform. Thus $V_{peak} = V_{p-p}/2 = 1.25$ V.



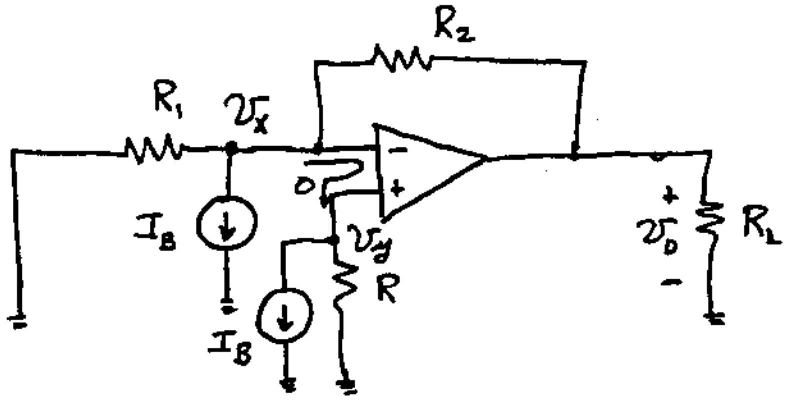
Exercise 2.16

(a)



$$i_{in} = \frac{v_{in}}{R_1} \qquad v_o = -R_2 i_{in} = -\frac{R_2}{R_1} v_{in} \qquad A_v = \frac{v_o}{v_{in}} = -\frac{R_2}{R_1}$$

(b)



The current equation at the inverting input is:

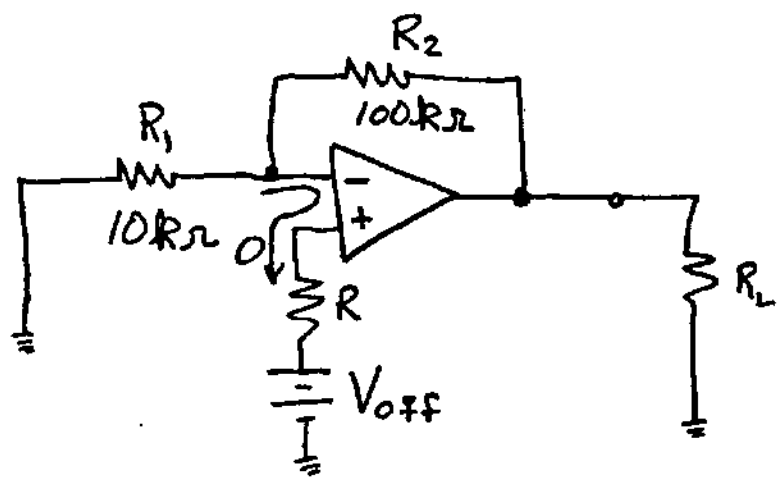
$$\frac{v_x}{R_1} + I_B + \frac{v_x - v_o}{R_2} = 0 \qquad (1)$$

Note that $v_y = -RI_B$. By the summing-point constraint we have $v_x = v_y = -RI_B$. Substituting for v_x in Equation (1) we have

$$\frac{-RI_B}{R_1} + I_B + \frac{-RI_B - v_o}{R_2} = 0$$

Then substituting $R = \frac{R_1 R_2}{R_1 + R_2}$ and solving for v_o, we find $v_o = 0$.

(c)

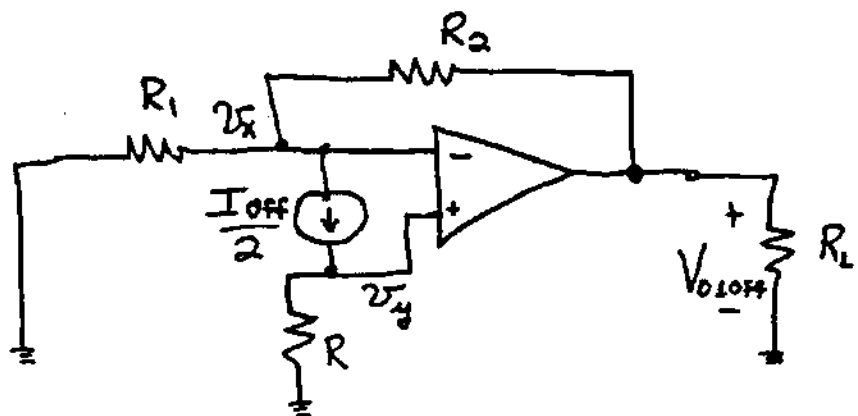


The voltage across R is zero. For the input V_{off} the circuit acts as the standard noninverting amplifier. Thus

$$V_{o,voff} = \left(1 + \frac{R_2}{R_1}\right) V_{off} = 11V_{off}$$

Thus $V_{o,off}$ ranges from -33 mV to +33 mV.

(d)



We have $v_y = RI_{off}/2$. Also because of the summing--point constraint we have $v_y = v_x$. Writing a current equation at the inverting input we have:

$$\frac{v_x}{R_1} + \frac{I_{off}}{2} + \frac{v_x - V_{o,ioff}}{R_2} = 0$$

Substituting $v_x = RI_{off}/2$ as well as $R = \frac{R_1R_2}{R_1 + R_2}$, and solving we find:

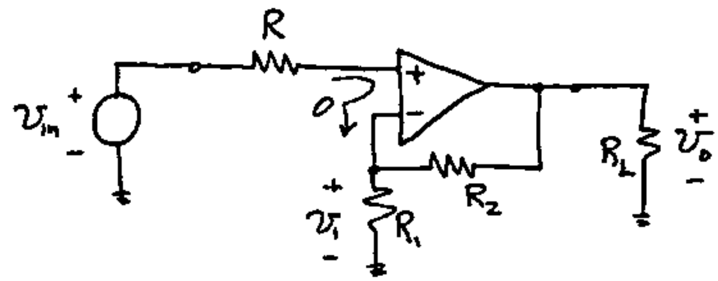
$$V_{o,ioff} = -R_2I_{off} = (100\ \text{k}\Omega) \times (\pm 40\ \text{nA}) = \pm 4\ \text{mV}$$

Thus $V_{o,ioff}$ ranges from -4 mV to + 4 mV.

(e) By superposition, the output ranges from -37 mV to +37 mV.

Exercise 2.17

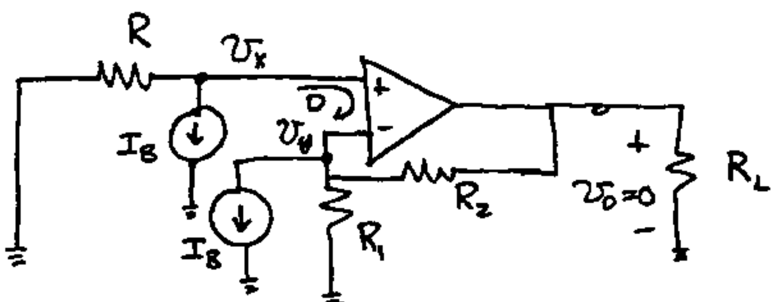
(a)



Because of the summing-point constraint, the voltage across R is zero. Thus R does not affect the gain.

$$v_{in} = v_1 = v_o \frac{R_1}{R_1 + R_2} \quad \Rightarrow \quad A_v = \frac{v_o}{v_{in}} = 1 + \frac{R_2}{R_1}$$

(b)



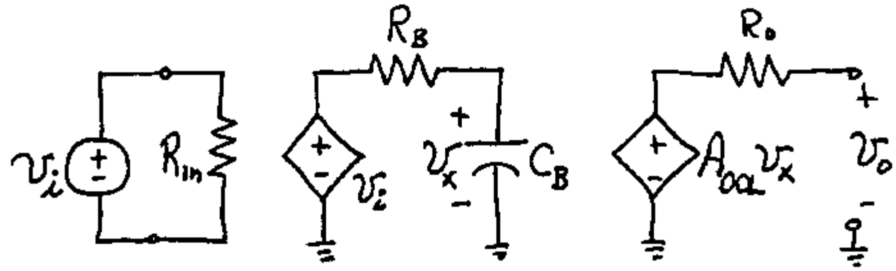
Note: With $v_o = 0$, R_2 appears to be in parallel with R_1.

$$v_x = -RI_B = v_y = -I_B \frac{R_1 R_2}{R_1 + R_2}$$

Thus we want $R = R_1 || R_2 = \frac{R_1 R_2}{R_1 + R_2}$

Exercise 2.18

The equivalent circuit is:



R_B and C_B act as a voltage divider and we have:

$$\mathbf{V}_x = \mathbf{V}_i \times \frac{1/(j2\pi f C_B)}{R_B + 1/(j2\pi f C_B)} = \frac{\mathbf{V}_i}{1 + j2\pi f R_B C_B} = \frac{\mathbf{V}_i}{1 + j(f/f_{BOL})}$$

With an open-circuit load the output voltage is

$$\mathbf{V}_o = A_{0OL}\mathbf{V}_x = \frac{A_{0OL}\mathbf{V}_i}{1 + j(f/f_{BOL})}$$

Thus the transfer function for the circuit is

$$\frac{\mathbf{V}_o}{\mathbf{V}_i} = \frac{A_{0OL}}{1 + j(f/f_{BOL})}$$

Exercise 2.19

See the solution of Exercise 2.18 for the circuit diagram in which we must have $R_{in} = 10\ \text{M}\Omega$ and $R_o = 100\ \Omega$. For an open-circuit dc voltage gain of 90 dB we have:

$$90 = 20\log A_{0OL} \quad \Rightarrow \quad A_{0OL} = 10^{90/20} = 31.6 \times 10^3$$

$$f_{0OL} = \frac{\text{Gain-Bandwidth}}{A_{0OL}} = \frac{15 \times 10^6}{31.6 \times 10^3} = 474.7\ \text{Hz}$$

$$C_B = \frac{1}{2\pi R_B f_{0OL}} = \frac{1}{2\pi(1000)474.7} = 0.3353\ \mu\text{F}$$

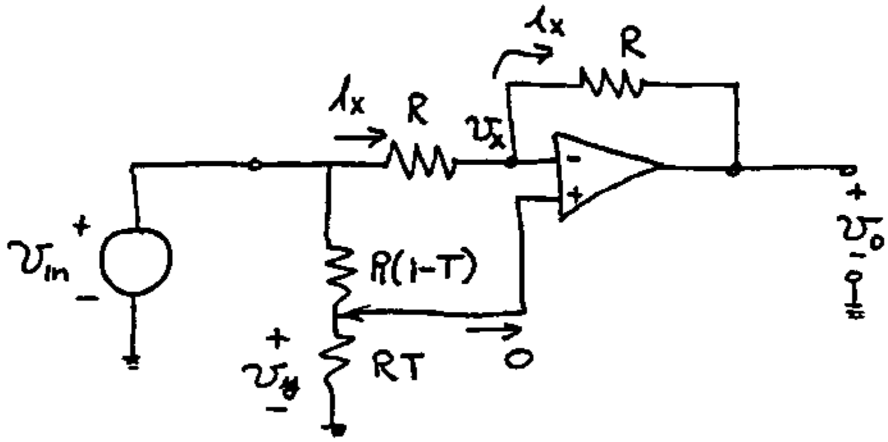
Exercise 2.20

The circuit file can be downloaded from the website for the text.

(a) From the SPICE results we find that $A_{0CL} = 1$, $f_{BCL} = 4$ MHz, and gain--bandwidth = 4 MHz.

(b) $|A_{0CL}| = 1$, $f_{BCL} = 2$ MHz, and gain--bandwidth = 2 MHz. Notice that the noninverting circuit performs best with respect to gain--bandwidth product.

Exercise 2.21



$$v_y = v_{in} \frac{RT}{R(1-T) + RT} = v_{in}T$$

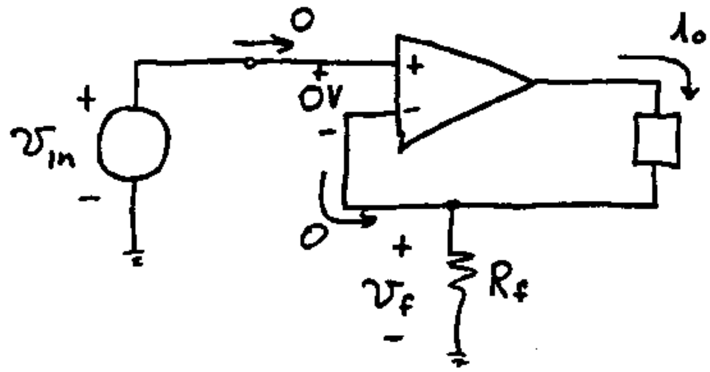
$$v_x = v_y \quad \text{(summing-point constraint)}$$

$$i_x = \frac{v_{in} - v_x}{R} = \frac{v_{in}}{R}(1-T)$$

$$v_o = -Ri_x + v_x = -v_{in}(1-T) + v_{in}T = v_{in}(2T - 1)$$

$$A_v = v_o/v_{in} = 2T - 1$$

Exercise 2.22

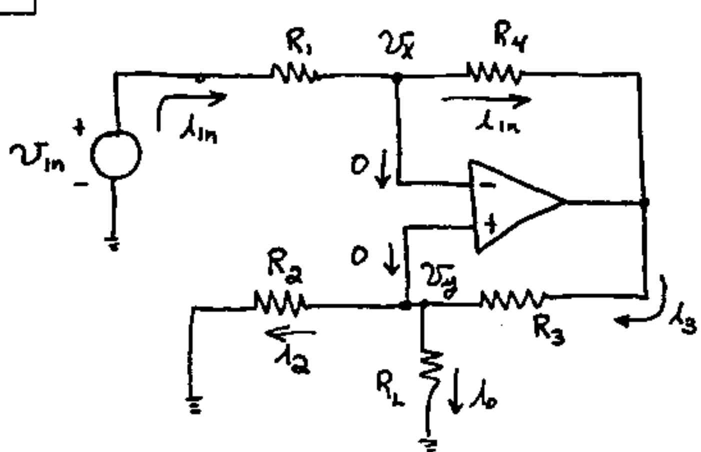


$v_f = v_{in}$ $\qquad i_f = \frac{v_f}{R_f} = \frac{v_{in}}{R_f}$ $\qquad i_o = i_f = \frac{v_{in}}{R_f}$

$R_{in} = \frac{v_{in}}{i_{in}} = \frac{v_{in}}{0} = \infty$

Because i_o is independent of the load, we conclude that $R_o = \infty$.

Exercise 2.23



$v_x = v_y = v_{in} - R_1 i_{in}$

$R_4 i_{in} + R_3 i_3 = 0 \qquad \Rightarrow \qquad i_3 = -\frac{R_4}{R_3} i_{in}$

$$i_o = i_3 - i_2 = -\frac{R_4}{R_3} i_{in} - \frac{v_y}{R_2} = -\frac{R_4}{R_3} i_{in} - \frac{v_{in} - R_1 i_{in}}{R_2}$$

Now if we have $R_4/R_3 = R_1/R_2$

$$i_o = -\frac{v_{in}}{R_2}$$

Exercise 2.24

(a) $$v_o(t) = -\frac{1}{RC}\int_0^t v_{in}(t)\,dt = -1000\int_0^t v_{in}(t)\,dt$$

$$v_o(t) = -1000\int_0^t 5\,dt = -5000\,t \qquad 0 < t < 1\text{ ms}$$

$$= -1000\int_0^{10^{-3}} 5\,dt - 1000\int_{10^{-3}}^t (-5)dt \qquad 1\text{ ms} < t < 3\text{ ms}$$

$$= -10 + 5000\,t \qquad 1\text{ ms} < t < 3\text{ ms}$$

etc.

The resulting waveform is shown in Figure 2.62 in the text.

(b) $$v_o(t) = -\frac{1}{RC}\int_0^t v_{in}(t)\,dt$$

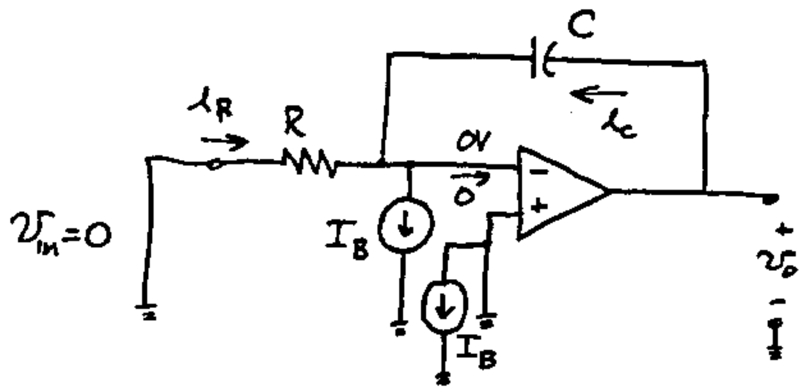
Notice that a peak-to-peak amplitude of 2 V implies a peak amplitude of 1 V. The negative peak amplitude occurs at t = 1 ms so we have:

$$V_{peak} = -1 = -\frac{1}{10^4 C}\int_0^{10^{-3}} 5\,dt$$

$$10^4 C = 5 \times 10^{-3}$$

$$C = 0.5\ \mu F$$

Exercise 2.25



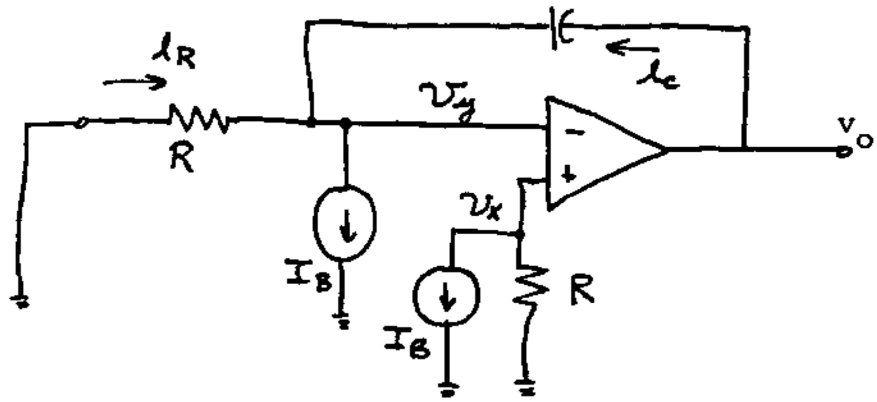
$i_R = 0/R = 0 \qquad i_C = I_B$

$$v_o = \frac{1}{C}\int_0^t i_C \, dt = \frac{1}{C}\int_0^t I_B \, dt = \frac{I_B}{C} t$$

(a) $v_o(t) = \dfrac{100 \times 10^{-9}}{10^{-8}} = 10t$

(b) $v_o(t) = \dfrac{100 \times 10^{-9}}{10^{-6}} = 0.1t$

Exercise 2.26

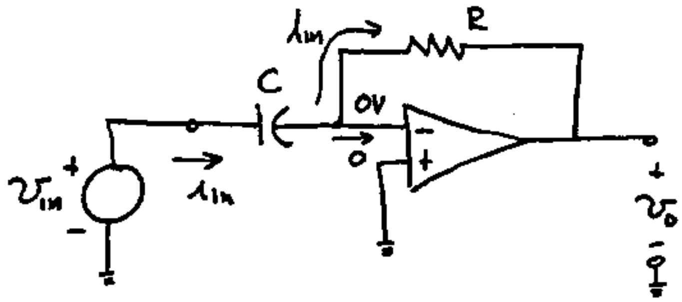


$v_y = v_x = -RI_B = -1$ mV $\qquad i_R = -v_y/R = I_B$

$$i_C = I_B - i_R = 0 \qquad v_C = \frac{1}{C}\int_0^t i_C\,dt = \frac{1}{C}\int_0^t 0\,dt = 0$$

$$v_o = v_y = -1 \text{ mV}$$

Exercise 2.27



$$i_{in} = C\frac{dv_{in}}{dt} \qquad v_o = -Ri_{in} = -RC\frac{dv_{in}}{dt}$$

Problem 2.1

Differential input voltage: $v_{id} = v_1 - v_2$

Common-mode input voltage: $v_{icm} = \frac{1}{2}(v_1 + v_2)$

Problem 2.2

$$v_{id} = v_1 - v_2 = 0.2\cos(20\pi t)$$

$$v_{icm} = \frac{1}{2}(v_1 + v_2) = 20\sin(120\pi t)$$

Problem 2.3

An ideal operational amplifier has the following characteristics:

- Infinite input impedance.
- Infinite open-loop gain A_{OL} for the differential signal.
- Zero gain for the common-mode signal.
- Zero output impedance.
- Infinite bandwidth.

Problem 2.4

Three pins are needed for each op amp: two input pins and an output pin. Thus we can have four op amps in a 14-pin package allowing two pins for power-supply connections common to all four op amps.

Problem 2.5

The summing-point constraint states that if negative feedback is present the op amp output will assume the value required to zero the differential input voltage and input currents. If positive feedback is present the summing-point constraint does not apply.

Problem 2.6

The steps in analyzing linear op-amp circuits are:

1. Verify that negative feedback is present. Usually this takes the form of a resistor network connected to the output terminal and to the inverting input terminal.

2. Assume that the differential input voltage and the input current of the op amp are forced to zero. (This is the summing-point constraint.)

3. Apply standard circuit analysis principles, such as Kirchhoff's laws and Ohm's law, to solve for the quantities of interest.

Problem 2.7

In a shower we use negative feedback to adjust water temperature. If it is too hot we increase the cold-water flow or reduce the hot-water flow. We adjust until the difference between actual temperature and desired temperature is driven to zero.

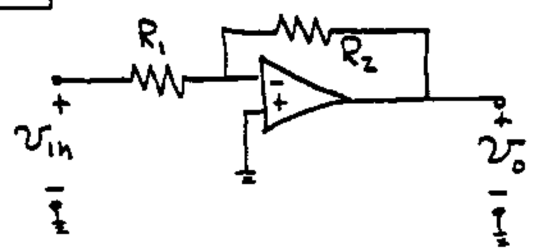
In driving an automobile on a two-lane highway in the United States we adjust the position of our vehicle to remain centered in the right-hand lane. If we are too close to the edge of the highway we steer toward the center, if we are too close to the center we steer to the right.

Problem 2.8

Positive feedback is a problem when we have a fire in a building. When a fire first starts heat is created which vaporizes additional fuel increasing the size of the fire. Usually positive feedback is self limiting. In the case of a building fire, the fire dies out when the building is totally consumed.

When our children behave well we give them positive feedback encouraging them to continue their good behavior.

Problem 2.9

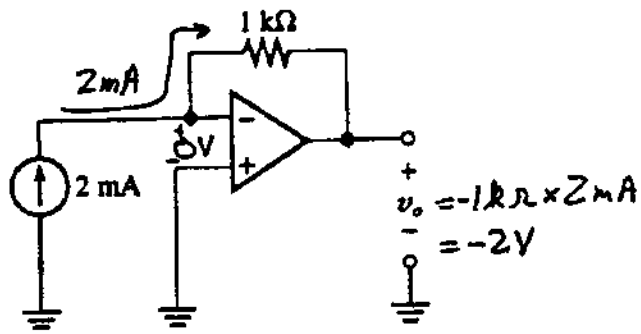


$$A_v = -\frac{R_2}{R_1}$$

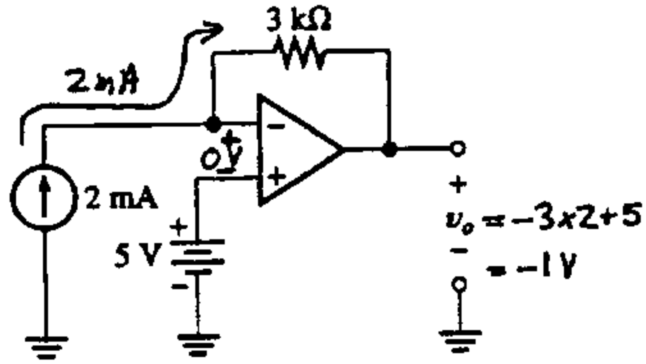
$$R_{in} = R_1$$

$$R_o = 0$$

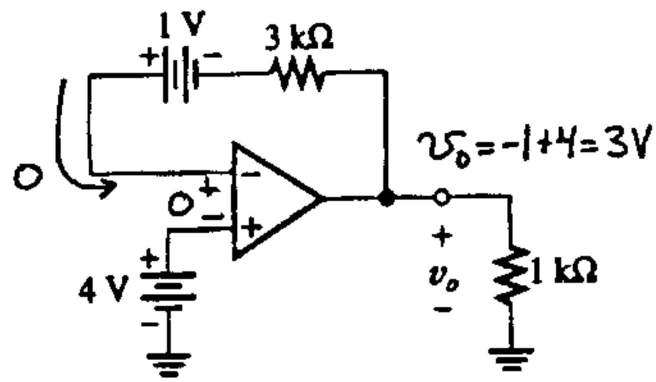
Problem 2.10



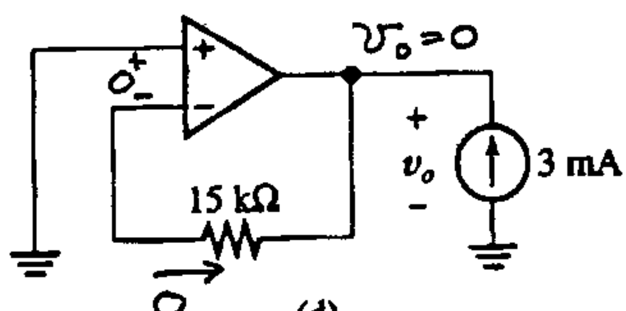
(a)


3 kΩ
2 mA
2 mA
0
5 V
$v_o = -3 \times 2 + 5$
$= -1$ V

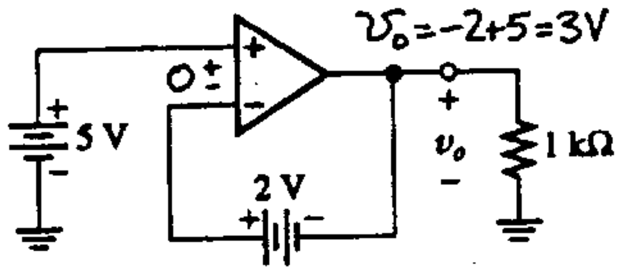
(b)


1 V
3 kΩ
0
0
4 V
$v_o = -1 + 4 = 3$V
v_o
1 kΩ

(c)

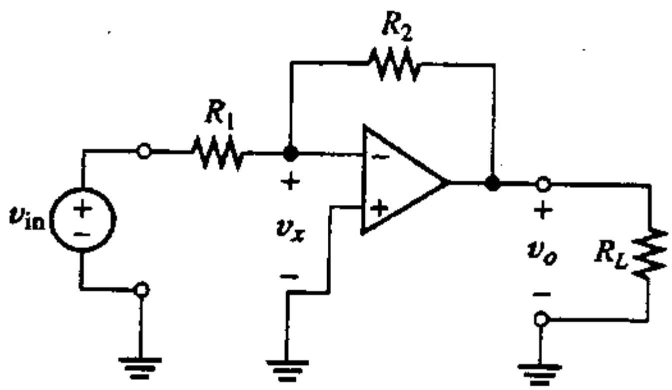

$v_o = 0$
0
v_o
3 mA
15 kΩ
0

(d)



(e)

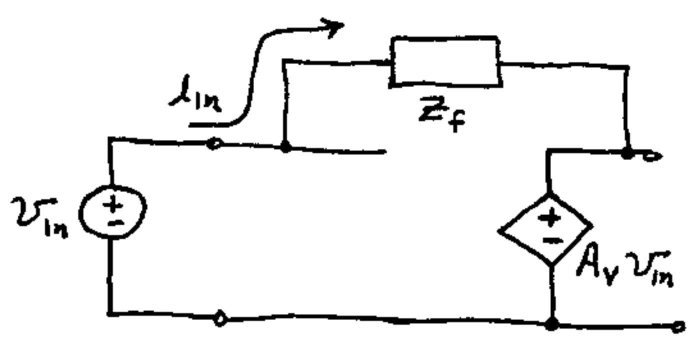
Problem 2.11



Notice that $A_v = -R_2/R_1 = -10$. For $v_o = 12$ V, we have $v_{in} = v_o/A_v = 12/(-10) = -1.2$ V and $v_x = v_o/(-A_{OL}) = 12/(-10^4) = -1.2$ mV. Thus v_x is 1000 times less than v_{in}, and v_x can be assumed to be zero with sufficient accuracy for most applications. Thus we are justified in using the summing-point constraint for this circuit.

Problem 2.12

(a)



$$I_{in} = \frac{V_{in} - A_v V_{in}}{Z_f} \quad \Rightarrow \quad Z_{in} = \frac{V_{in}}{I_{in}} = \frac{Z_f}{1 - A_v}$$

(b) $$Z_{in} = \frac{Z_f}{1 - A_v} = \frac{10^4}{1 - (-10^5)} \cong 0.10\ \Omega$$

The input impedance is very low. If an impedance were placed in series with v_{in} (as in an inverter) the input voltage to the op amp would be driven to zero as the op amp open-loop gain approaches infinity (just as we assume when we use the summing-point constraint).

(c) $$Z_{in} = \frac{Z_f}{1 - A_v} = \frac{10^4}{1 - 2} = -10\ \text{k}\Omega$$

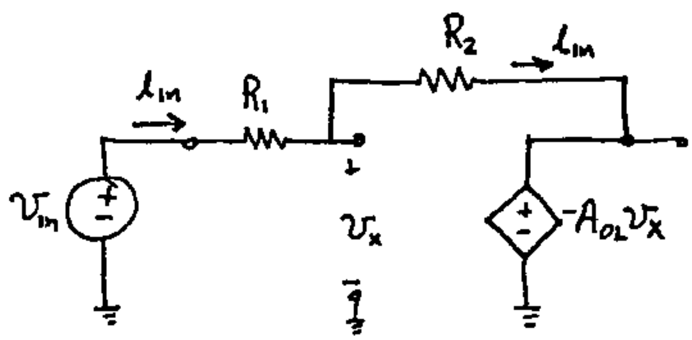
The input impedance is a negative resistance. This is a positive feedback situation.

(d) $$Z_{in} = \frac{Z_f}{1 - A_v} = \frac{\frac{1}{j\omega C}}{1 - (-100)} = \frac{1}{j\omega(99C)}$$

The input impedance is that of a 99-pF capacitance. This situation often occurs in amplifiers because of device capacitances and is a significant problem when extended high-frequency response is needed.

Problem 2.13

The equivalent circuit is:



$$V_{in} = (R_1 + R_2)I_{in} - A_{OL}V_x \tag{1}$$

$$v_x = v_{in} - R_1 I_{in} \tag{2}$$

Using Equation (2) to substitute for v_x in Equation (1) and solving for the input impedance, we find

$$Z_{in} = \frac{v_{in}}{I_{in}} = R_1 + \frac{R_2}{1 + A_{OL}}$$

Evaluating for $R_1 = 1\ \text{k}\Omega$, $R_2 = 10\ \text{k}\Omega$, and $A_{OL} = 10^4$, we find

$$Z_{in} = 1001\ \Omega$$

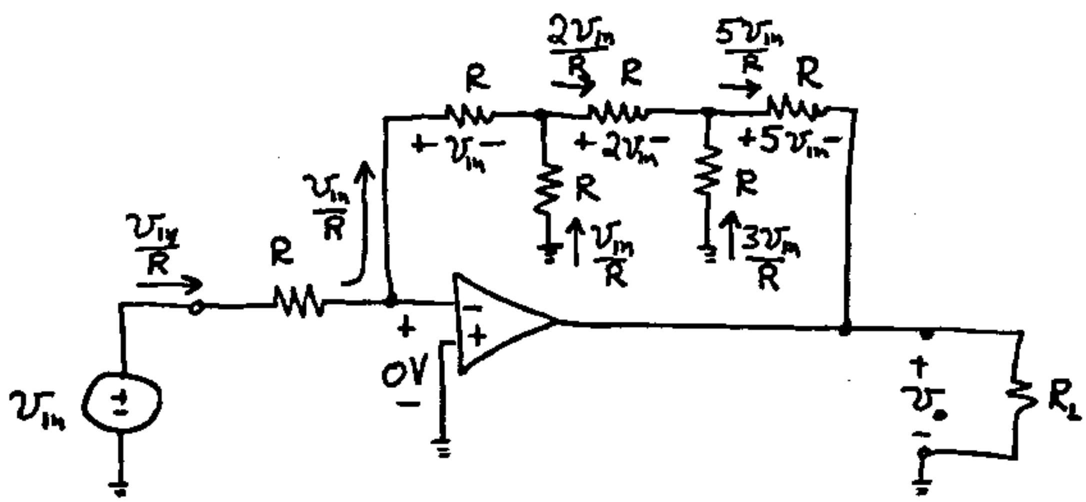
The input impedance assuming infinite A_{OL} is

$$Z_{in} = R_1 = 1000\ \Omega$$

The percentage difference between the two answers is 0.1%

Problem 2.14

Starting from the input and working toward the output we can determine the voltages and currents shown below:



Eventually we determine that $v_o = 8v_{in}$ so we have a closed loop voltage gain of 8.

Problem 2.15

The circuit diagram for the inverting amplifier is shown in Figure 2.5 in the text. The gain of an inverting amplifier is $A_v = -R_2/R_1$. The largest gain magnitude occurs if R_2 is 1% high and R_1 is 1% low in which case we have

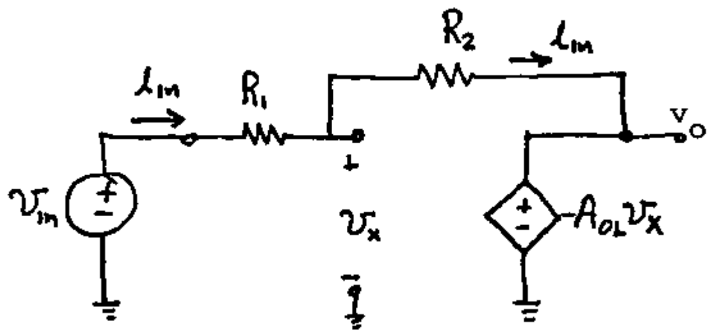
$$A_v = -\frac{1.01R_{2nom}}{0.99R_{1nom}} = 1.020\ A_{vnom}$$

in which R_{1nom} is the nominal value of R_1, R_{2nom} is the nominal value of R_2 and A_{vnom} is the nominal gain.

Similarly, for the opposite extreme we obtain $A_v = 0.980A_{vnom}$. Thus the tolerance of the closed-loop gain is ±2%.

Problem 2.16

The equivalent circuit is:



$$\frac{v_x - v_{in}}{R_1} + \frac{v_x - v_o}{R_2} = 0 \qquad (1)$$

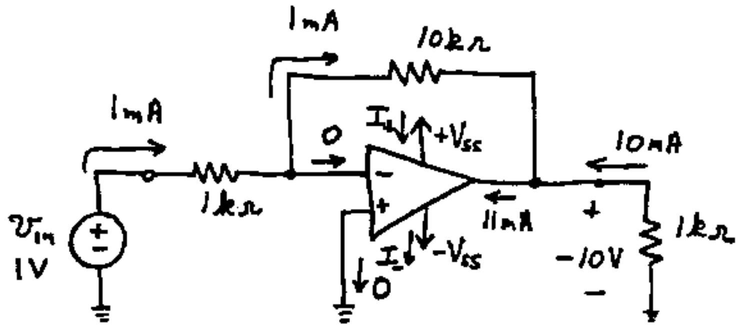
$$v_o = -A_{OL}v_x \qquad (2)$$

Solving Equation (2) for v_x, substituting into Equation (1), and applying algebra yields

$$A_v = \frac{-R_2A_{OL}}{R_2 + R_1 + A_{OL}R_1}$$

For R_1 = 1 kΩ, R_2 = 10 kΩ and $A_{OL} = 10^4$ we obtain A_v -9.989. For $A_{OL} = 10^5$, we obtain A_v = -9.998. As A_{OL} approaches infinity, A_v approaches $-R_2/R_1$ = 10.

Problem 2.17

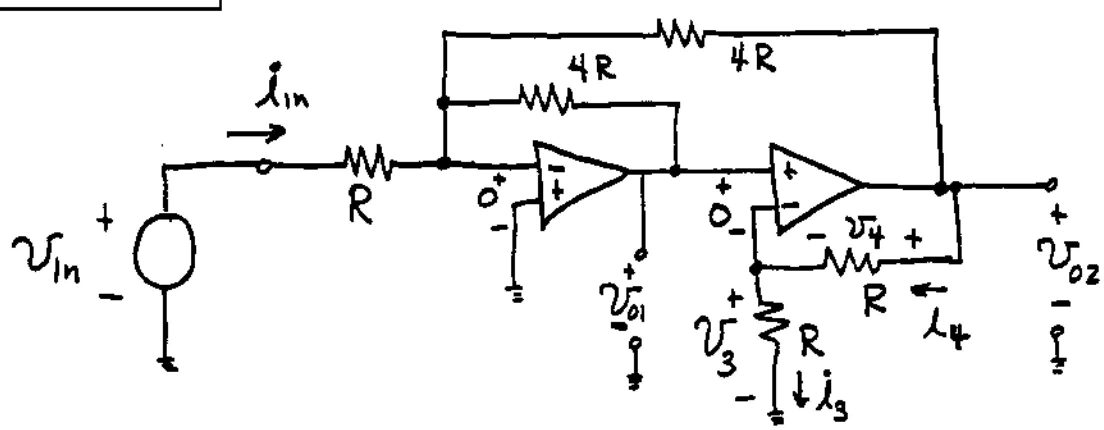


Kirchhoff's current law may not seem to be satisfied for the op-amp terminals if we do not consider the power-supply terminals. However if we considered the power-supply currents, the equation

$$I_+ + 11\text{ mA} = I_-$$

would be satisfied. Not enough information is given in the problem to determine the power-supply currents.

Problem 2.18



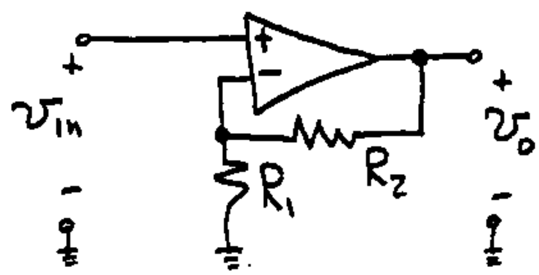
$v_{o1} = v_3$ $\qquad$ $i_{in} = \dfrac{v_{in}}{R}$ $\qquad$ $i_4 = i_3 = v_{o1}/R$

$v_{o2} = v_3 + v_4 = 2v_{o1}$ $\qquad$ $i_{in} + \frac{v_{o1}}{4R} + \frac{v_{o2}}{4R} = 0$

$$\frac{v_{in}}{R} + \frac{v_{o1}}{4R} + \frac{2v_{o1}}{4R} = 0 \quad \Rightarrow \quad A_1 = \frac{v_{o1}}{v_{in}} = -\frac{4}{3}$$

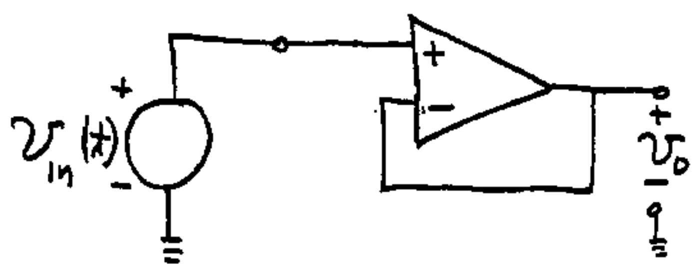
$$A_2 = \frac{v_{o2}}{v_{in}} = \frac{2v_{o1}}{v_{in}} = 2A_1 = -\frac{8}{3}$$

Problem 2.19



$A_v = 1 + R_2/R_1$ $\qquad$ $R_{in} = \infty$ $\qquad$ $R_o = 0$

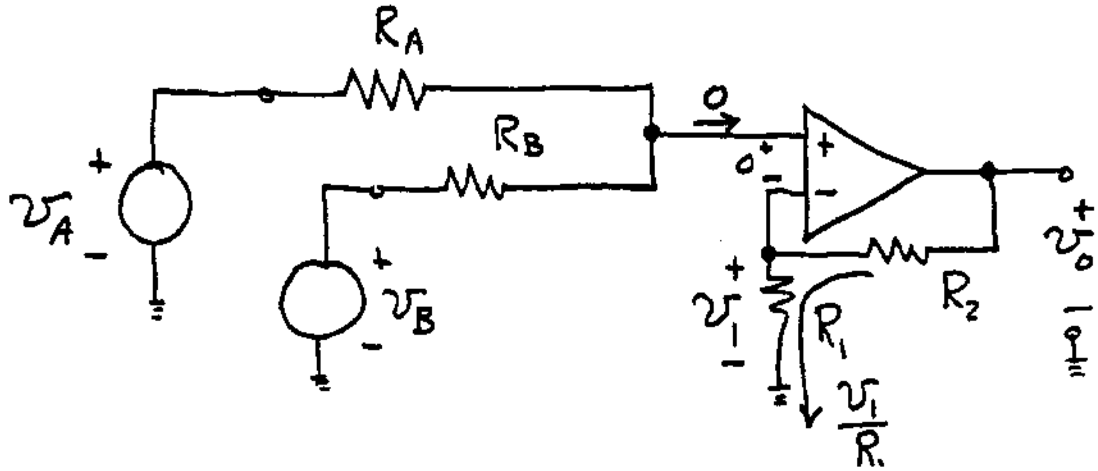
Problem 2.20



Problem 2.21

The voltage follower has a very large input impedance (ideally infinite) and a very low output impedance (ideally 0). If the source impedance is much larger than the load impedance and the load is connected directly to the source, the load voltage is much less than the open-circuit source voltage. By using the voltage follower, the load voltage can be nearly equal to the open-circuit source voltage.

Problem 2.22



$$\frac{v_1 - v_A}{R_A} + \frac{v_1 - v_B}{R_B} = 0 \qquad \Rightarrow \qquad v_1 = \frac{v_A R_B + v_B R_A}{R_A + R_B}$$

$$v_o = v_1 + R_2 \frac{v_1}{R_1} = \frac{R_1 + R_2}{R_1} v_1$$

$$v_o = \frac{R_1 + R_2}{R_1} \times \frac{v_A R_B + v_B R_A}{R_A + R_B}$$

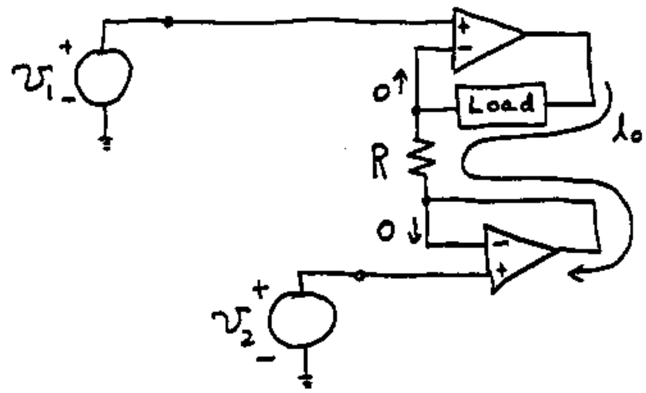
$$v_o = A_A v_A + A_B v_B$$

$$\text{where } A_A = \frac{R_1 + R_2}{R_1} \times \frac{R_B}{R_A + R_B}$$

$$\text{and } A_B = \frac{R_1 + R_2}{R_1} \times \frac{R_A}{R_A + R_B}$$

Problem 2.23

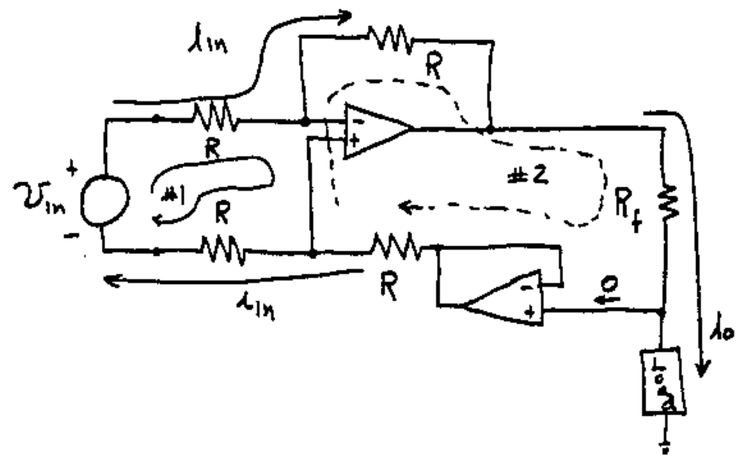
(a)



$$v_1 = 0 + Ri_o + 0 + v_2 \quad \Rightarrow \quad i_o = \frac{v_1 - v_2}{R}$$

Because i_o is independent of the load we conclude that the output impedance is infinite.

(b)



Loop 1: $v_{in} = Ri_{in} + 0 + Ri_{in}$

Loop 2: $Ri_{in} + R_f i_o + Ri_{in} = 0$

Solving: $i_o = -v_{in}/R_f$

Because i_o is independent of the load, we conclude that the output impedance is infinite.

Problem 2.24

(a) $A_v = \frac{V_o}{V_{in}} = -\frac{R_2}{R_1}$ $\quad P_{in} = \frac{V_s^2}{R_1}$ $\quad P_o = \frac{V_o^2}{R_L} = \frac{R_2^2 V_s^2}{R_1^2 R_L}$

$$G = \frac{P_o}{P_{in}} = \frac{R_2^2}{R_1 R_L}$$

(b) $P_{in} = 0$ because $I_{in} = 0$. Therefore $G = P_o/P_{in} = \infty$. Thus the noninverting amplifier has the higher power gain.

Problem 2.25

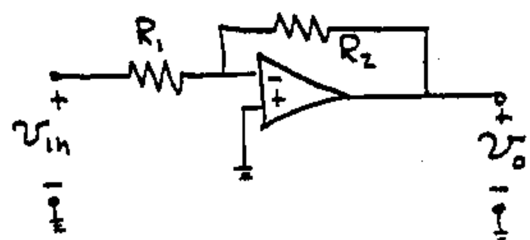
(a) $v_o = -R_f i_{in}$

(b) Because v_o is independent of R_L, the output behaves as an ideal voltage source and the output resistance is zero.

(c) The input voltage is zero because of the summing-point constraint. Therefore $R_{in} = 0$.

(d) This is an ideal transresistance amplifier.

Problem 2.26



Because $A_v = -R_2/R_1$, we select the nominal resistances such that $R_{2nom} = 2R_{1nom}$. Given 5%-tolerances we have

$$R_{1min} = 0.95R_{1nom} \qquad R_{1max} = 1.05R_{1nom}$$

$$R_{2min} = 0.95R_{2nom} \qquad R_{2max} = 1.05R_{2nom}$$

Then the minimum gain magnitude is

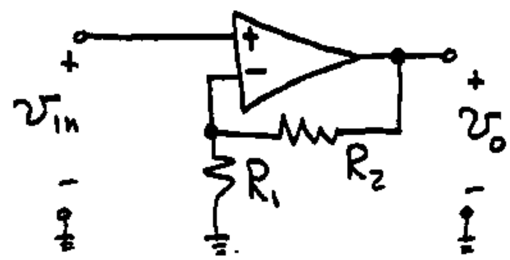
$$|A_v|_{min} = \frac{R_{2min}}{R_{1max}} = \frac{0.95R_{2nom}}{1.05R_{1nom}} = 1.81$$

Similarly

$$|A_v|_{max} = \frac{R_{2max}}{R_{1min}} = \frac{1.05R_{2nom}}{0.95R_{1nom}} = 2.21$$

The tolerances of the gain magnitude are -9.5% and +10.5%.

Problem 2.27



Because $A_v = 1 + R_2/R_1$, we select the nominal resistances such that $R_{2nom} = R_{1nom}$. Given 5%-tolerances we have

$$R_{1min} = 0.95R_{1nom} \qquad R_{1max} = 1.05R_{1nom}$$

$$R_{2min} = 0.95R_{2nom} \qquad R_{2max} = 1.05R_{2nom}$$

Then the maximum gain magnitude is

$$|A_v|_{min} = 1 + \frac{R_{2min}}{R_{1max}} = 1 + \frac{0.95R_{2nom}}{1.05R_{1nom}} = 1.905$$

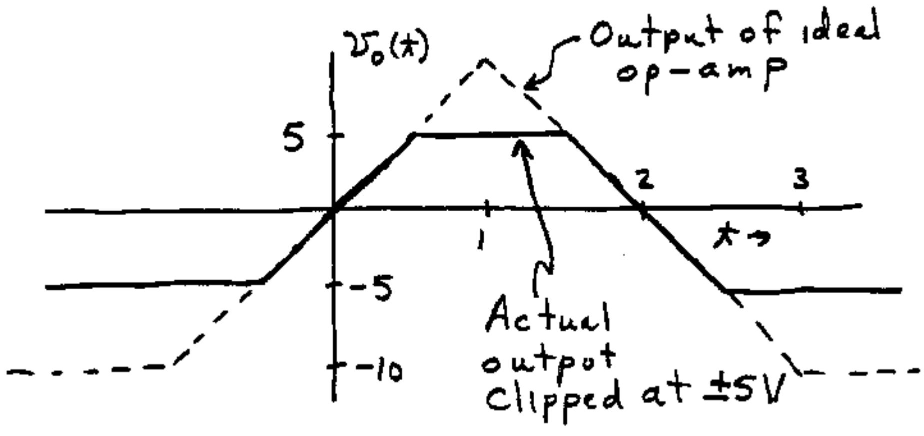
Similarly

$$|A_v|_{max} = 1 + \frac{R_{2max}}{R_{1min}} = 1 + \frac{1.05R_{2nom}}{0.95R_{1nom}} = 2.105$$

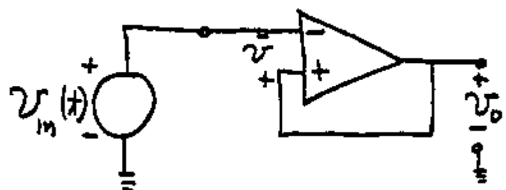
The tolerances of the gain magnitude are -4.75% and +5.25%.

Problem 2.28

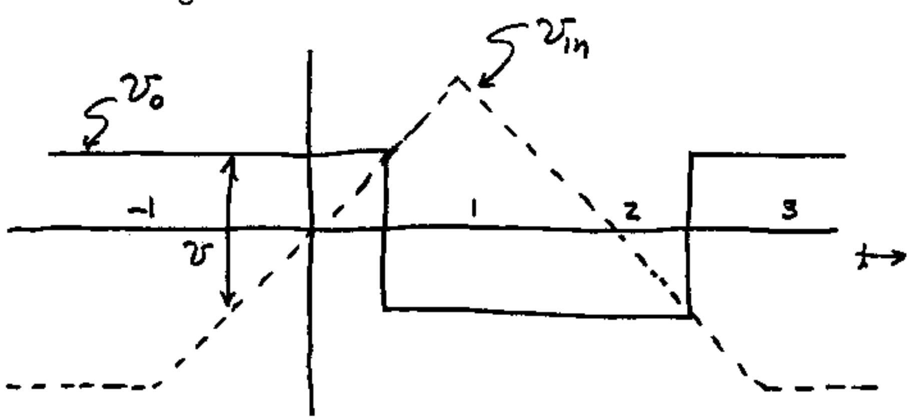
(a) This circuit has negative feedback. For an ideal op amp we have $v_o(t) = v_{in}(t)$.



(b) This circuit has positive feedback. The summing-point constraint does not apply. Instead either $v_o = +5$ V or $v_o = -5$ V.

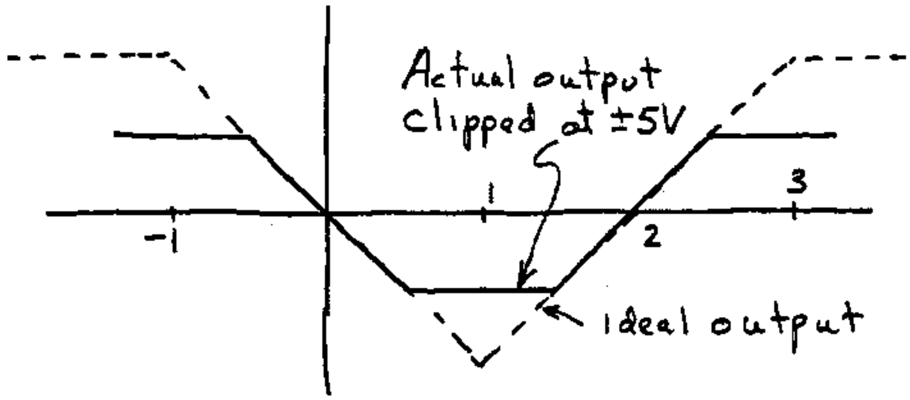


Notice that $v = v_o - v_{in}$. If $v > 0$, $v_o = +5$ V. On the other hand if $v < 0$, $v_o = -5$ V.

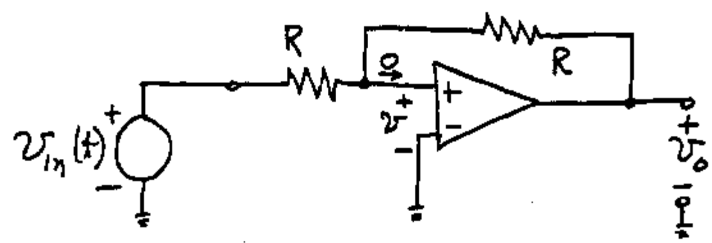


Problem 2.29

(a) This circuit has negative feedback. For an ideal op amp we have $v_o(t) = -v_{in}(t)$.



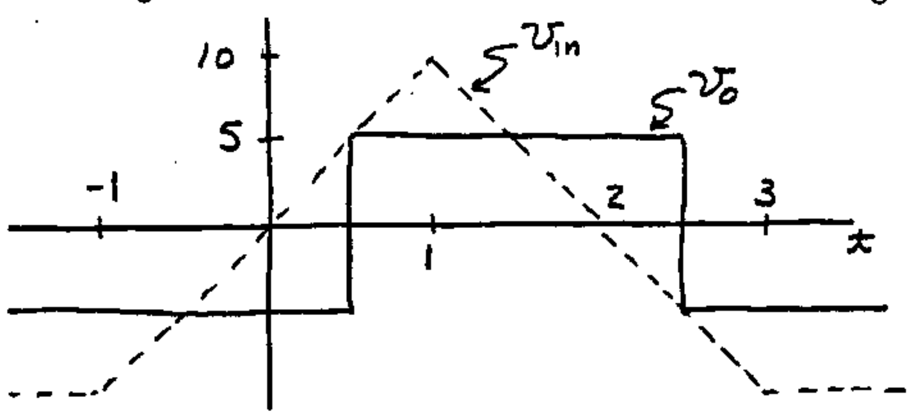
(b)



This circuit has positive feedback and the summing-point constraint does not apply. Writing a current equation at the noninverting input of the op amp yields

$$\frac{v - v_{in}}{R} + \frac{v - v_o}{R} = 0 \quad \Rightarrow \quad v = \frac{v_o + v_{in}}{2}$$

If $v > 0$ then $v_o = +5$ V. On the other hand if $v < 0$, $v_o = -5$.



Problem 2.30

The sheet resistances of the various layers are commonly optimized for purposes, such as the base regions of BJTs, other than fabricating resistors. Adding more steps to the process to create layers optimized for resistors would reduce yield and increase cost.

Problem 2.31

Very small resistances imply large currents and high power dissipation. Very large resistances are subject to stray coupling of undesired signals. Furthermore, resistances of either extreme are likely to require excessive chip area because $R = R_{\square} L/W$ and we need to have $L \cong W$ for minimum area.

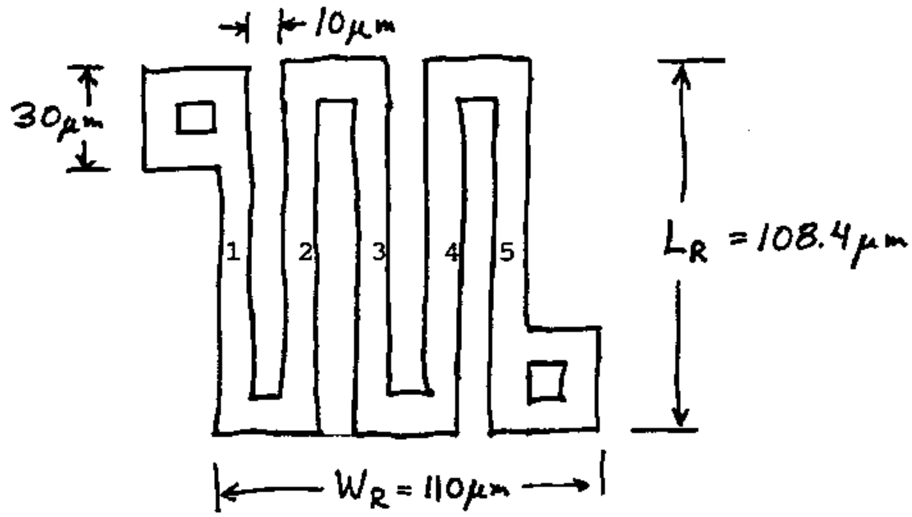
Problem 2.32

Doubling the thickness of the layer creates a second identical resistor above or below the original resistor. The resistors are electrically in parallel. Thus the resistance is reduced by a factor of 2. If we double the thickness of a 200-Ω layer, the sheet resistance $R_{\square}$ is reduced to 100 Ω.

Problem 2.33

We should choose the width of the conductors to be $W = 10\ \mu m$ to minimize the area consumed. For a resistor composed of a single straight conductor, we would have $L = WR/R_{\square} = 10(10^4/200) = 500\ \mu m$. Including the guard strips the area consumed is $(20\ \mu m) \times L = 10^4\ \mu m^2$.

Because we want the resistor to occupy an approximately square area, we need $W_R = L_R \cong \sqrt{A} = 100\ \mu m$. Thus, we need $W_R/(20\ \mu m) = 5$ or 6 conductors. We propose the layout composed of 5 conductors:



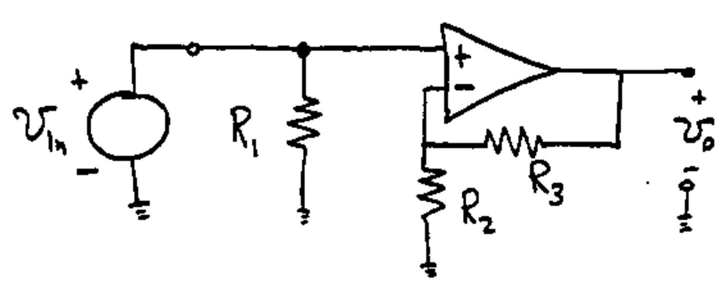
For this layout, the resistance is the sum of:

two end pads:	$2 \times 0.65 \times 200$	$= 260\ \Omega$
eight corners:	$8 \times 0.56 \times 200$	$= 896\ \Omega$
four ends:	4×200	$= 800\ \Omega$
Conductors 1 and 5:	$2 \times [(L_R - 40)/10] \times 200$	$= 40L_R - 1600$
Conductors 2, 3, and 4:	$3 \times [(L_R - 20)/10] \times 200$	$= 60L_R - 1200$
Total		$100L_R - 844$

Thus we need $10^4\ \Omega = 100L_R - 844$ which yields $L_R = 108.4\ \mu m$

Problem 2.34

Here is one solution:



$R_{in} = R_1 = 10\ k\Omega \quad R_2 = 20\ k\Omega \quad R_3 = 180\ k\Omega$

Problem 2.35

A simple answer is the standard inverter shown in Figure 2.5 in the text with R_1 = 1 kΩ and R_2 = 100 kΩ for a total resistance of 101 kΩ.

A better answer is the circuit shown in Figure 2.6 in the text with $R_1 = R_3$ = 1 kΩ and $R_2 = R_4$ = 9.05 kΩ for a total resistance of 20.1 kΩ. (See the analysis of this circuit in Example 2.1 in the text.)

Very likely still better answers exist.

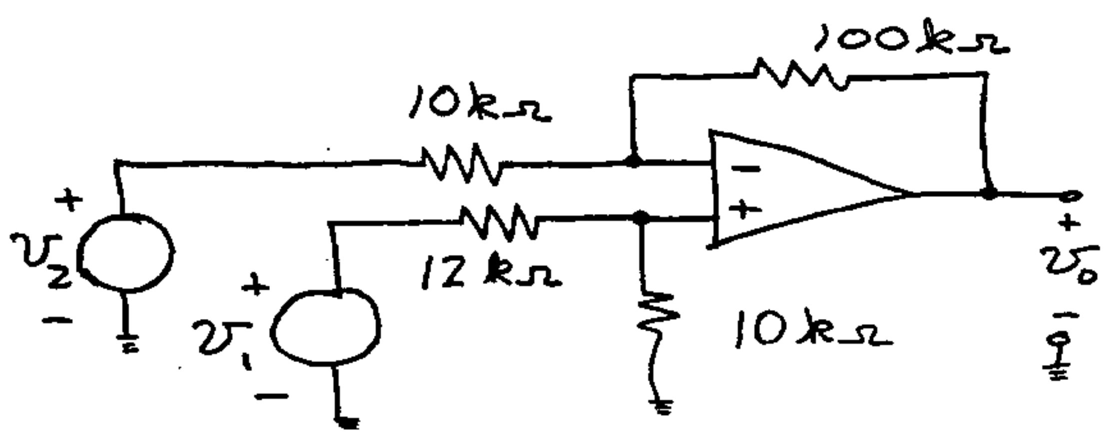
Problem 2.36

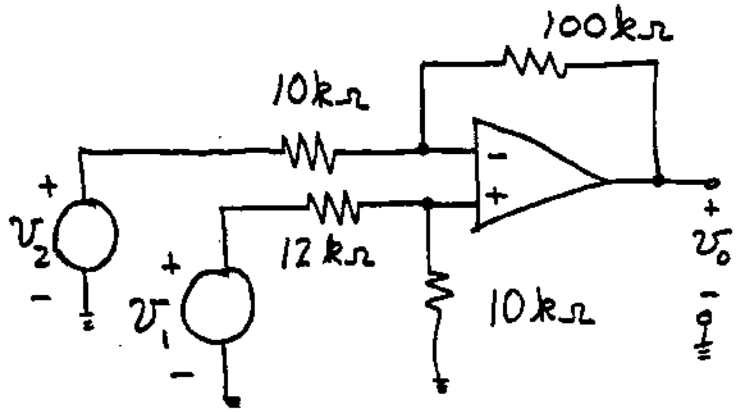
A good answer is to cascade two noninverting amplifiers like the one shown in Figure 2.11 in the text. Each amplifier should have R_1 = 1 kΩ and R_2 = 9 kΩ. The total resistance is 20 kΩ and two op amps are used. The total area consumed is that of 4 op amps. (We assume that area is proportional to resistance.)

Another good answer is the circuit of Figure 2.15 analyzed in Exercise 2.6 with R_1 = 1 kΩ and R_2 = 8.56 kΩ for a total area equal to nearly 3 op amps.

Problem 2.37

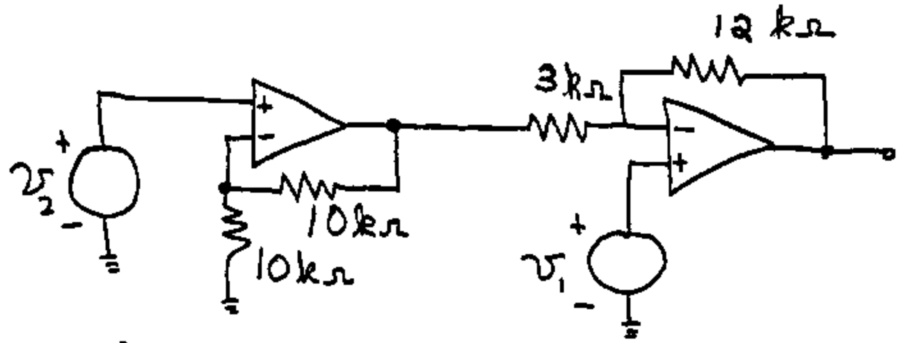
Here are two answers:





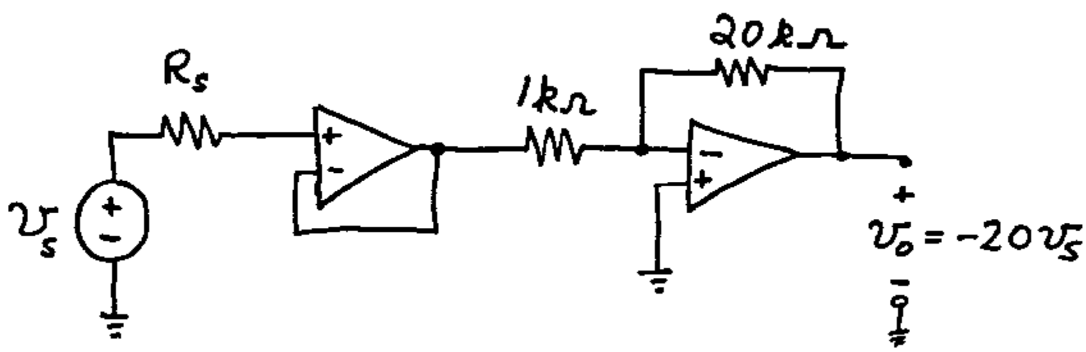
Problem 2.38

Two possibilities are to place unity-gain voltage followers between the sources and the inputs of the circuits designed for Problem 2.37. A better answer that uses fewer op amps is:



Problem 2.39

Here is one answer:



Problem 2.40

Op amp imperfections in the linear range of operation include:

- finite input impedance
- nonzero output impedance
- finite open-loop gain
- finite bandwidth
- nonzero common-mode gain

Problem 2.41

For the noninverting amplifier with a given op amp, the product of dc gain and closed-loop bandwidth is constant as the dc gain is changed.

Problem 2.42

(a) Refer to Figure P2.42 in the text.

$$v_s = R_{in}i_s + R_o i_s + A_{OL}(R_{in}i_s)$$

$$v_o = R_o i_s + A_{OL}(R_{in}i_s)$$

$$A_{vs} = \frac{v_o}{v_s} = \frac{R_o + A_{OL}R_{in}}{R_{in} + R_o + A_{OL}R_{in}}$$

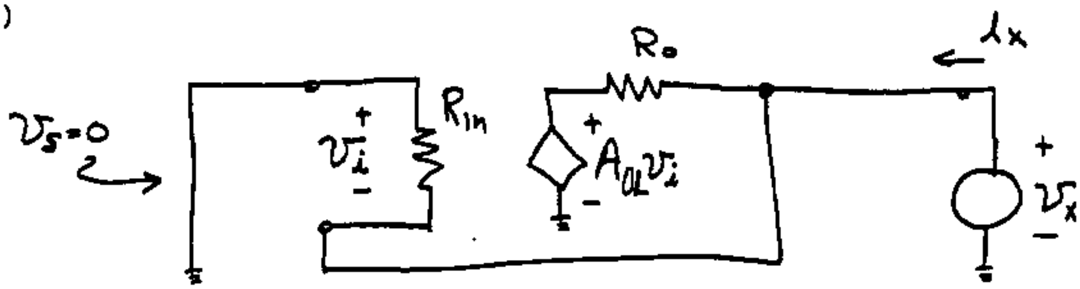
$$A_{vs} = \frac{25 + 10^5 \times 10^6}{10^6 + 25 + 10^5 \times 10^6} = 0.99999$$

The gain would be 1.00000 for an ideal op amp.

(b) $Z_{in} = \frac{v_s}{i_s} = R_{in} + R_o + A_{OL}R_{in} = 10^{11}\ \Omega$

In comparison, we would have $Z_{in} = \infty$ for an ideal op amp.

(c)



$v_i = -v_x$ $\qquad i_x = \dfrac{v_x}{R_{in}} + \dfrac{v_x - A_{OL}v_i}{R_o} \qquad Z_o = \dfrac{v_x}{i_x} = \dfrac{1}{\dfrac{1}{R_{in}} + \dfrac{1 + A_{OL}}{R_o}}$

Evaluating we find $Z_o = 2.5 \times 10^{-4}\ \Omega$ compared to $Z_o = 0$ for an ideal op amp.

Problem 2.43

(a) Refer to Figure P2.43 in the text. Writing current equations at the input terminal of the op amp and at the output terminal we have:

$$\frac{v_s + v_i}{R_1} + \frac{v_o + v_i}{R_2} + \frac{v_i}{R_{in}} = 0 \tag{1}$$

$$\frac{v_o + v_i}{R_2} + \frac{v_o - A_{OL}v_i}{R_o} = 0 \tag{2}$$

Now we solve Equation (1) for v_i, substitute into Equation (2), and use algebra to obtain:

$$A_{vs} = \frac{v_o}{v_s} = \frac{-R_2}{R_1\left[1 + \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_{in}}\right)\frac{R_oR_2 + R_2^2}{A_{OL}R_2 - R_o}\right]}$$

Evaluating we find $A_{vs} = -9.9989$ compared to $A_{vs} = -10$ for an ideal op amp.

(b) From the circuit we can write:

$$v_s = R_1 i_s - v_i \tag{3}$$

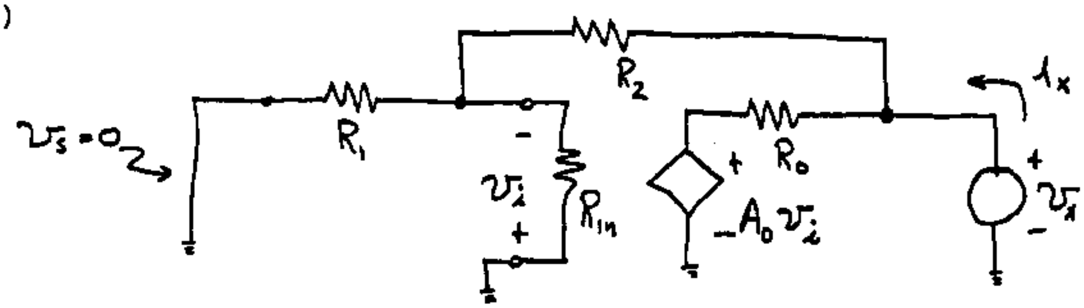
$$v_i + (R_1 + R_o)\left[\frac{v_i}{R_{in}} + i_s\right] + A_{OL} v_i = 0 \tag{4}$$

Now we solve Equation (3) for v_i, substitute into Equation (4), and use algebra to obtain:

$$Z_{in} = \frac{v_s}{i_s} = R_1 + \frac{R_2 + R_o}{1 + A_{OL} + \dfrac{R_2 + R_o}{R_{in}}}$$

Evaluating we find Z_{in} = 1.0001 kΩ compared to Z_{in} = 1.0000 kΩ for an ideal op amp.

(c)



$$v_i = \frac{R_{in} || R_1}{R_2 + R_{in} || R_1} v_x$$

$$i_x = \frac{v_x}{R_2 + R_{in} || R_1} + \frac{v_x - A_{OL} v_i}{R_o}$$

$$Z_o = \frac{v_x}{i_x} = \frac{1}{\dfrac{1}{R_2 + R_{in}||R_1} + \dfrac{1}{R_o}\left[1 + \dfrac{A_{OL}(R_{in}||R_1)}{R_2 + R_{in}||R_1}\right]}$$

Evaluating we find Z_o = 2.75 mΩ compared to Z_o = 0 for an ideal op amp.

Problem 2.44

Equation 2.39 states:

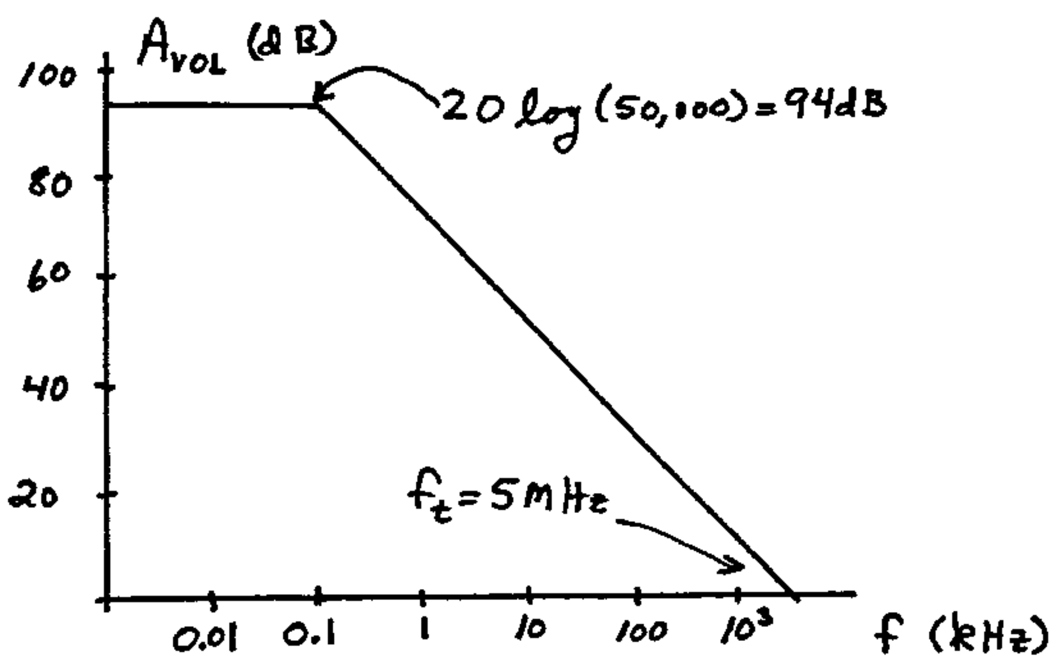
$$f_t = A_{OCL} f_{BCL} = A_{OOL} f_{BOL}$$

Solving for f_{BCL} we have

$$f_{BCL} = \frac{f_t}{A_{OCL}}$$

For A_{OCL} = 10 we find f_{BCL} = 1.5 MHz. For A_{OCL} = 100, we have f_{BCL} = 150 kHz.

Problem 2.45



Problem 2.46

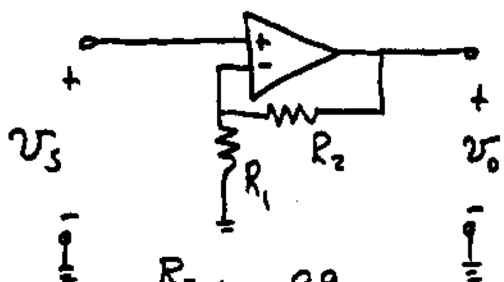
$$A_{OL}(f) = \frac{A_{0OL}}{1 + j(f/f_{BOL})} = \frac{2 \times 10^5}{1 + j(f/5)}$$

Evaluating we find:

Frequency	$\lvert A_{OL} \rvert$	Phase
100	9988	-87.14°
1 kHz	1000	-89.71°
1 MHz	1	-90.00°

Problem 2.47

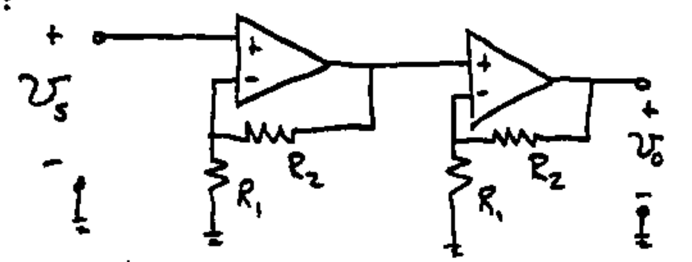
Alternative 1:



$R_2/R_1 = 99$

The half-power bandwidth is $f_{BCL} = f_t/A_{0CL} = 10^6/100 = 10$ kHz

Alternative 2:



$R_2/R_1 = 9$

For each stage we have $f_{BCL} = f_t/A_{0CL} = 10^6/10 = 100$ kHz

$$A_{CL}(f) = \frac{A_{0CL}}{1 + j(f/f_{BCL})} = \frac{10}{1 + j(f/10^5)}$$

The overall gain is

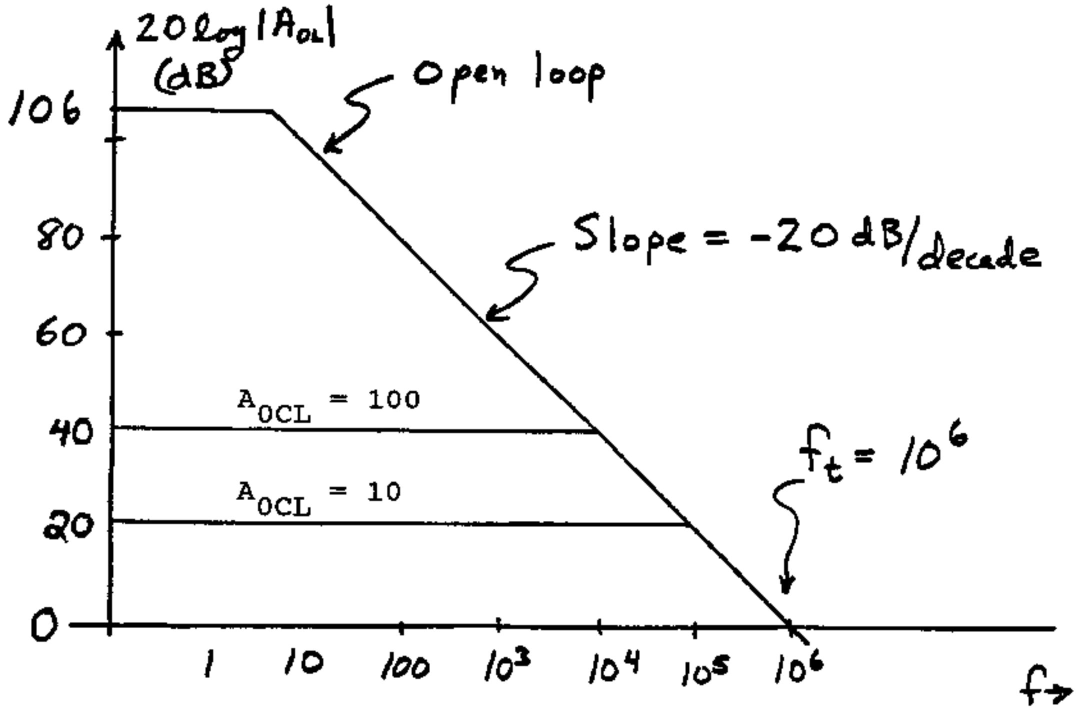
$$A(f) = \left[\frac{10}{1 + j(f/10^5)} \right]^2$$

At the half-power frequency f_H we have:

$$\frac{100}{\sqrt{2}} = \frac{100}{1 + (f_H/10^5)^2}$$

Solving we find f_H = 64.4 kHz compared with 10 kHz for the single stage amplifier.

Problem 2.48



Problem 2.49

The slew-rate limitation is the maximum rate at which the op-amp output can increase or decrease.

Full-power bandwidth is the maximum frequency for which a full-amplitude sine wave output does not experience slew-rate limiting.

Problem 2.50

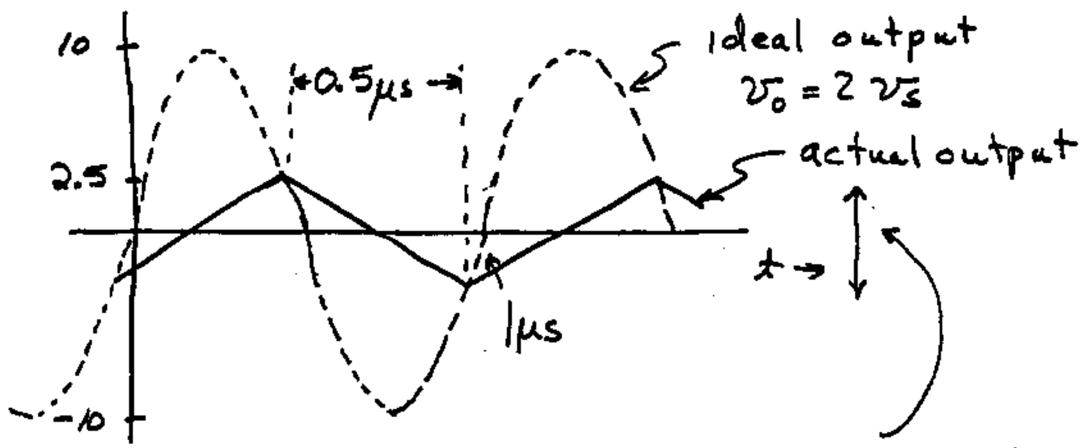
(a) $f_{FP} = \frac{SR}{2\pi V_{om}} = \frac{10^7}{2\pi 10}$

$= 159$ kHz

(b) 10 V (Amplitude limitation of the op amp.)

(c) $V_{om} = 20$ mA $\times$ 100 Ω = 2 V (Limited by current capability of the op amp.)

(d) $V_{om} = \frac{SR}{2\pi f} = \frac{10^7}{2\pi 10^6} = 1.59$ V



peak-to-peak amplitude = $0.5\mu s \times 10^7$ V/s
= 5 V

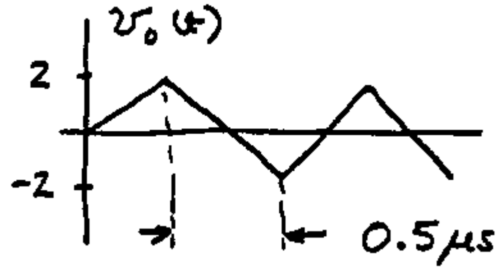
Problem 2.51

$SR = 2\pi f V_{om}$

$= 2\pi 10^5 \times 5$

$= 3.14 \times 10^6 = 3.14$ V/μs

Problem 2.52



$$SR = \frac{4\ V}{0.5\ \mu s} = 8\ V/\mu s$$

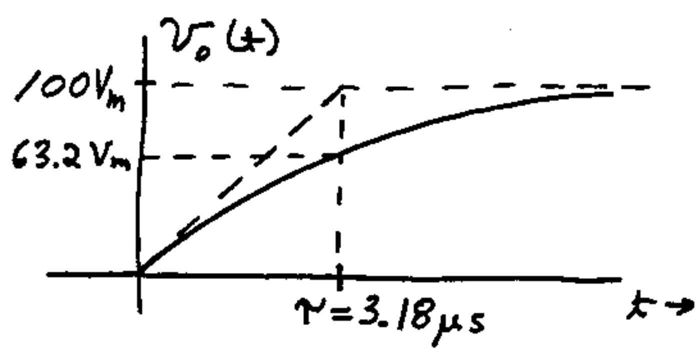
Problem 2.53

$$f_{0CL} = \frac{f_t}{A_{0CL}} = \frac{5 \times 10^6}{100} = 50\ kHz$$

$$A_{CL}(s) = \frac{A_{0CL}}{1 + s/(2\pi f_{BCL})} = \frac{100}{\frac{s}{10^5\pi} + 1}$$

$$V_o(s) = A_{CL}(s)V_{in}(s) = \frac{100}{\frac{s}{10^5\pi} + 1} \times \frac{V_m}{s}$$

$$v_o(t) = 100V_m - 100V_m\exp(-\pi 10^5 t)$$



$$\frac{dv_o(t)}{dt} = 100V_m(\pi 10^5)\exp(-\pi 10^5 t)$$

$$\left|\frac{dv_o(t)}{dt}\right|_{max} = \pi 10^7 V_m \qquad \text{(at } t = 0\text{)}$$

$$\pi 10^7 V_m = SR = 10^6 \qquad \Rightarrow \qquad V_m = 31.8 \text{ mV}$$

Problem 2.54

The circuit shown in Figure P2.54 is an inverting amplifier with a closed loop dc gain of -10.

(a) $f_{FP} = \dfrac{SR}{2\pi V_{om}} = \dfrac{10^6}{2\pi 10} = 15.9$ kHz

(b) Notice that the output of the op amp must supply current to R_2 as well as to R_L. Thus we have:

$$V_{om} = (25 \text{ mA}) \times R_L || R_2 = 2.498 \text{ V}$$

(c) $V_{om} = 10$ V (limited by maximum range of output voltage)

(d) $V_{om} = \dfrac{SR}{2\pi f} = \dfrac{10^6}{2\pi 10^5} = 1.59$ V (limited by slew rate)

Problem 2.55

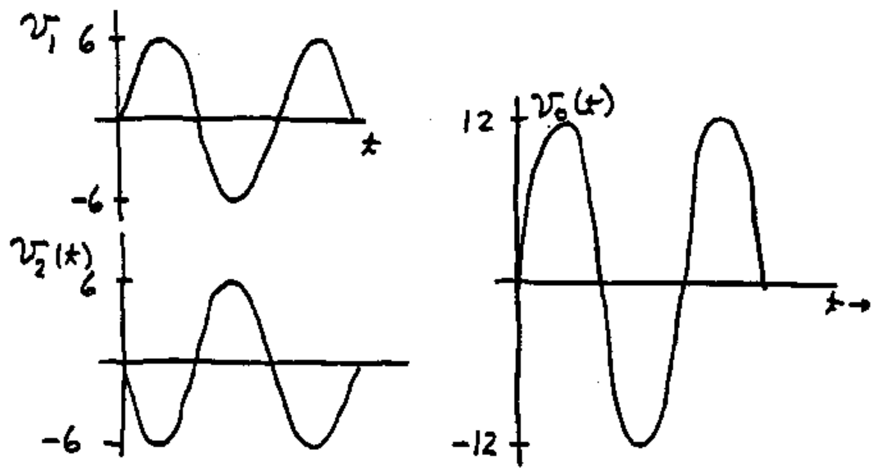
(a) Refer to the circuit shown in Figure P2.55 in the text. Notice that the upper op amp is configured as a noninverting amplifier with a gain of 2. The lower op amp is configured as an inverting amplifier with a gain of -2. Thus we have

$$v_2(t) = -2v_s(t)$$

$$v_1(t) = 2v_s(t)$$

$$v_o(t) = v_1(t) - v_2(t) = 4v_s(t) \qquad \Rightarrow \qquad A_{vs} = \frac{v_o}{v_s} = 4$$

(b)



(c) $v_o(t)$ is clipped when it reaches amplitudes of ±28 V.

Problem 2.56

See Figure 2.33 in the text.

Problem 2.57

Lower bias and offset currents are the main advantages of a FET-input op amp compared to a BJT-input op amp.

Problem 2.58

Following the approach of Example 2.10 in the text, we obtain:

Offset voltage: $V_o = (1 + R_2/R_1) \times (\pm 4 \text{ mV})$

$= \pm 44 \text{ mV}$

Bias current: $V_o = R_2 I_B = 20 \text{ mV}$

Offset current: $V_o = R_2 I_{off}/2 = \pm 2.5 \text{ mV}$

Total: V_o ranges from -26.5 mV to +66.5 mV

Problem 2.59

The problem with the circuit shown in Figure P2.59 is that the bias current of the op amp must flow through the coupling capacitor. The voltage across the capacitor ramps up (or down) until the op amp reaches its maximum output. A solution is to connect a large resistance from the noninverting input to ground to provide a path for the bias current. To minimize the effect of the bias current, the resistance should be 50 kΩ. However, this may make the input impedance too small, depending on the application.

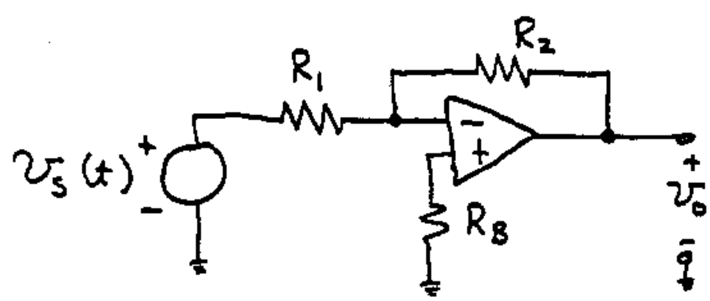
Problem 2.60

(a) $V_o = V_{off}(1 + R_2/R_1) \Rightarrow \pm 100 \text{ mV} = V_{off} \times 11 \Rightarrow$

$V_{off} = \pm 9.09 \text{ mV}$

(b) $V_o = I_B R_2 \Rightarrow I_B = (\pm 100 \text{ mV})/(100 \text{ k}\Omega) \Rightarrow I_B = \pm 1 \ \mu\text{A}$

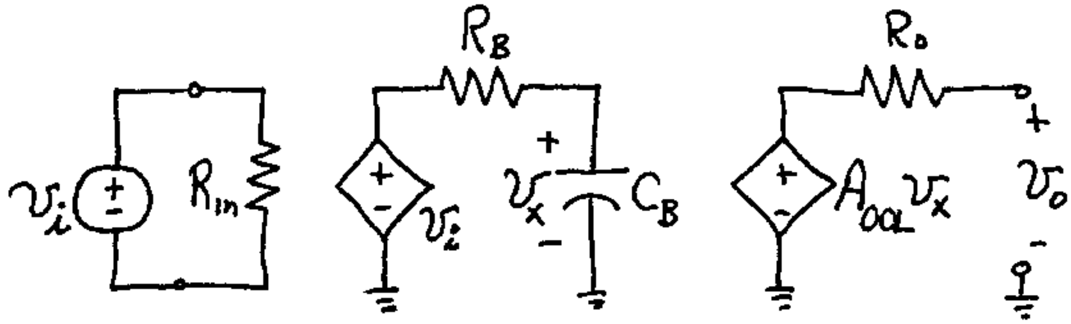
(c)



$R_B = R_1 || R_2 = 9.09 \text{ k}\Omega$

(d) $V_o = I_{off} R_2 \Rightarrow I_{off} = (\pm 100 \text{ mV})/R_2 = \pm 1 \ \mu\text{A}$

Problem 2.61



Problem 2.62

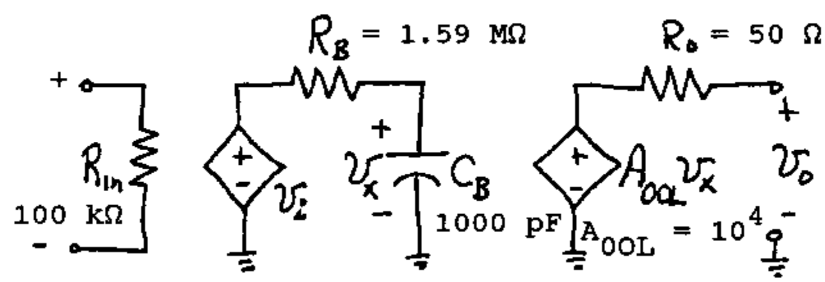
A macromodel is a relatively simple circuit that models the external behavior of an op amp. A macromodel usually does not resemble the actual internal circuit of the op amp. The advantage of a macromodel is that simulations run faster and require less memory than if the actual internal circuit was used in the simulation.

Problem 2.63

$80 = 20\log|A_{OOL}| \Rightarrow A_{OOL} = 10^{80/20} = 10^4$

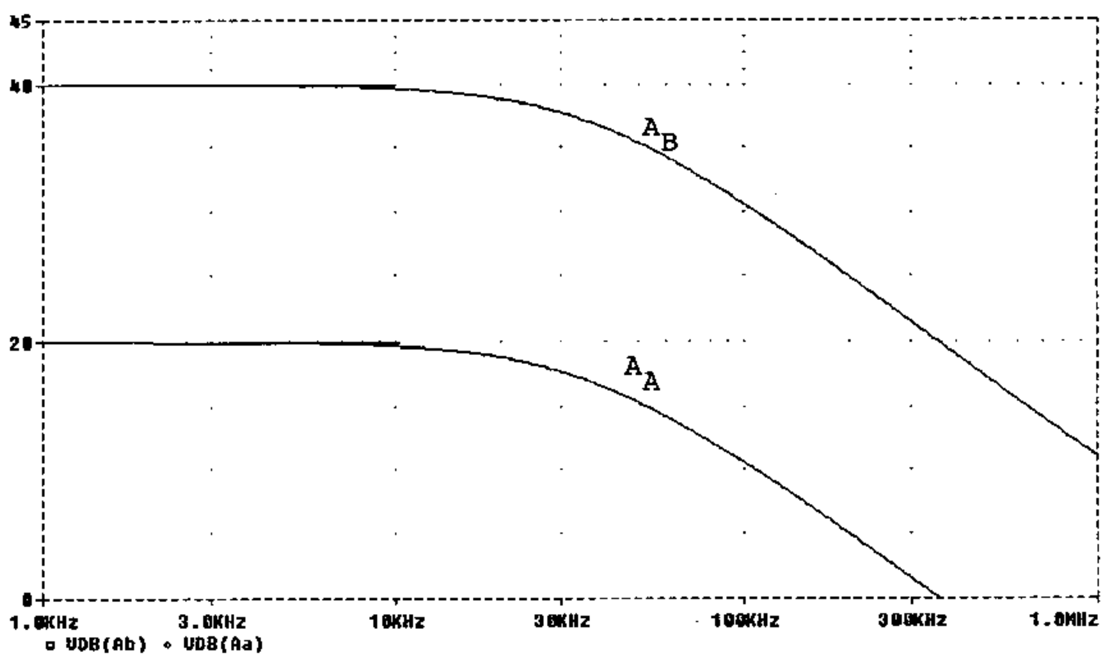
$f_{BOL} = f_t/A_{OOL} = 100$ Hz

We arbitrarily select $C_B = 1000$ pF. Then $R_B = 1/(2\pi f_{BOL}C_B)$ $= 1.59$ MΩ.



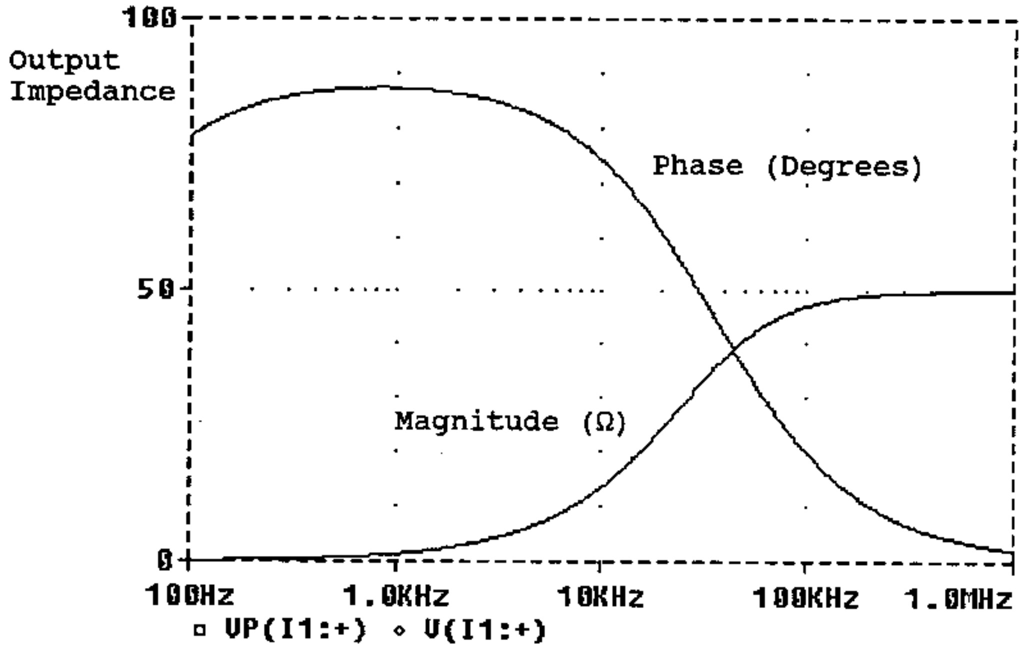
Problem 2.64

The schematic is stored in the file named P2_64. The low-frequency gain magnitude for A_A is 10 (20 dB), and the low-frequency gain magnitude for A_B is 100 (40 dB). The upper half-power frequency for both gains is approximately 36 kHz. Thus the gain-bandwidth product for A_A is 10×36 kHz = 360 kHz. For A_B it is 100×36 kHz = 3.6 MHz. Notice that the gain-bandwidth product is not the same for both gains. (The concept of constant gain-bandwidth product applies to the noninverting amplifier only.) The Bode plots for the gains are shown below.



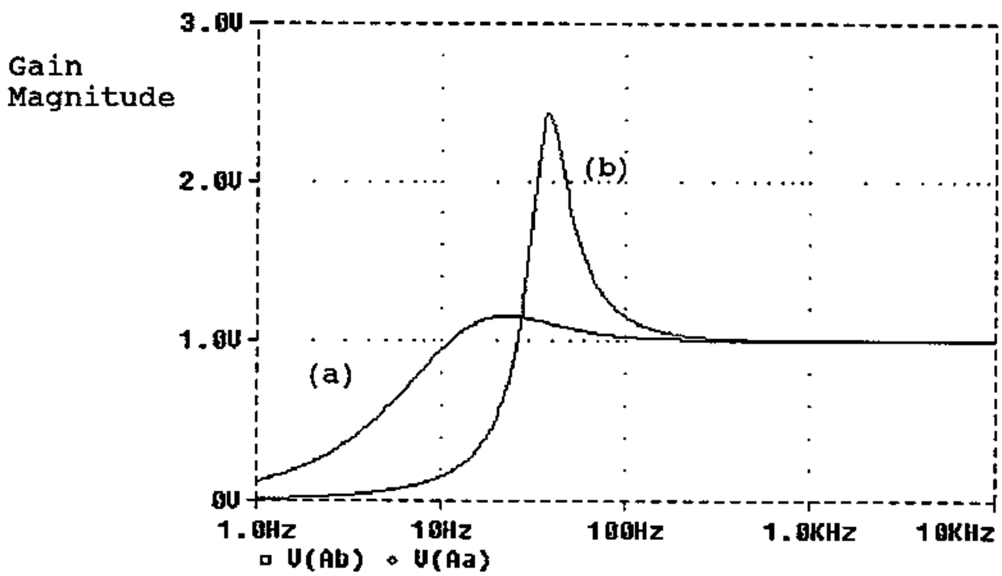
Problem 2.65

The schematic is stored in file P2_65. The magnitude and phase plots of the output impedance are shown on the next page. Because the phase angle of the output impedance is positive, we say that the output impedance is inductive. Notice that at higher frequencies the output impedance of the circuit approaches that of the op amp alone which is 50 Ω.



Problem 2.66

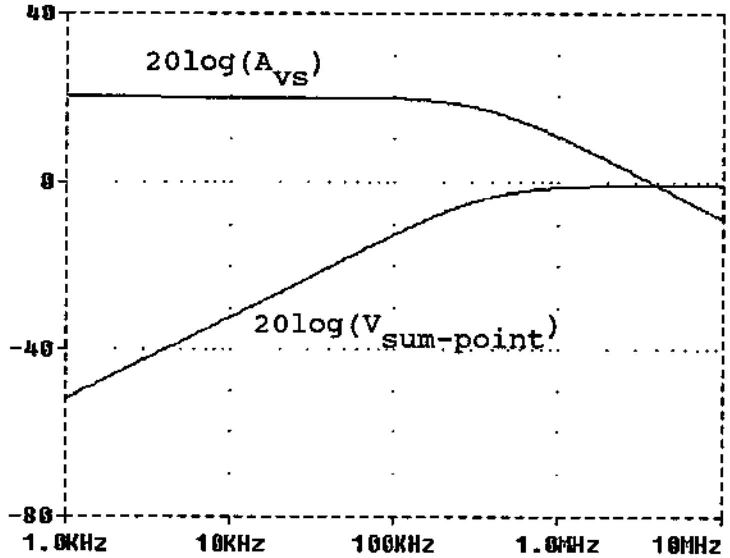
The schematic is stored in file P2_66. Plots of the gains versus frequency are:



Usually a gain curve that displays a high peak such as the curve for part b is not desirable. For example if these were amplifiers for audio signals, amplifier b would amplify the low notes out of proportion to higher notes.

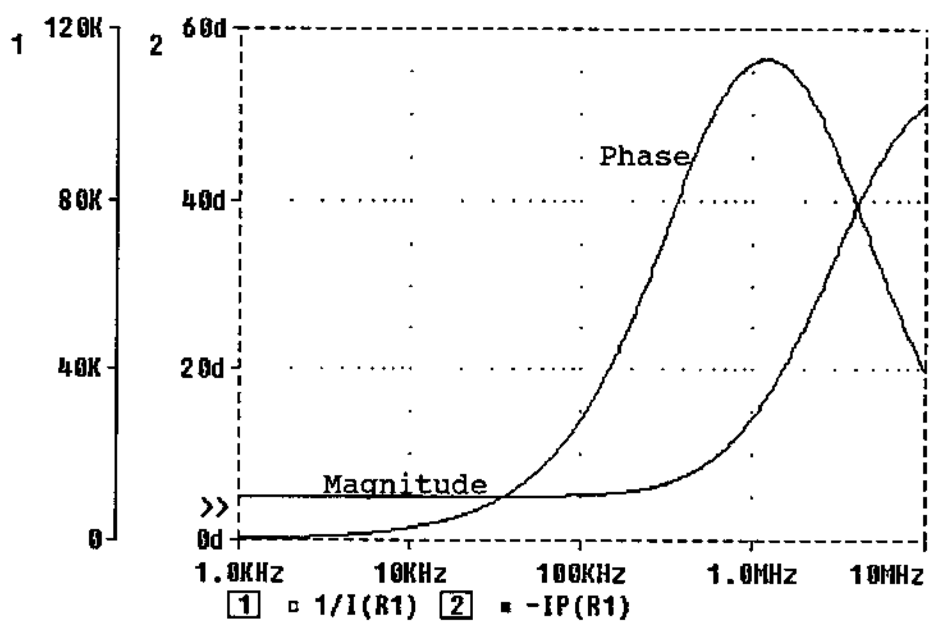
Problem 2.67

The simulation is stored in file P2_67. Plots of $20\log(A_{vs}) = 20\log(V_{out})$ and $20\log(V_{sum\text{-}point})$ are:



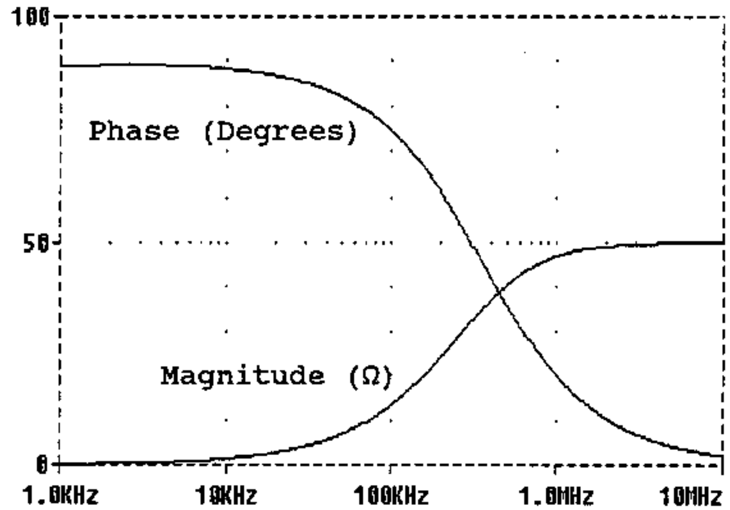
Because the source voltage is 1 V (0 dB) the voltage at the summing point must be -40 dB or less to be less than 1% of V_s. This is true for frequencies less than about 4 kHz.

Plots of the input impedance magnitude and phase are:



At low frequencies the input impedance is 10 kΩ resistive as predicted by the theory for an ideal op amp. However at higher frequencies the input impedance becomes capacitive and larger in magnitude.

Plots of the output impedance magnitude and phase are:



The ideal-op amp analysis predicts zero output impedance. The actual output impedance is very low at low frequencies but approaches 50 Ω resistive at high frequencies.

Problem 2.68

(a) A dc-coupled inverting amplifier is shown in Figure 2.47 in the text.

(b) An ac-coupled inverting amplifier is shown in Figure 2.48 in the text.

(c) A two-input summing amplifier is shown in Figure 2.49 in the text.

(d) A dc-coupled noninverting amplifier is shown in Figure 2.50 in the text.

(e) An ac-coupled noninverting amplifier is shown in Figure 2.51 in the text.

(f) A single-op-amp differential amplifier is shown in Figure 2.53 in the text.

(g) A voltage-to-current converter with floating load is shown in Figure 2.55 in the text.

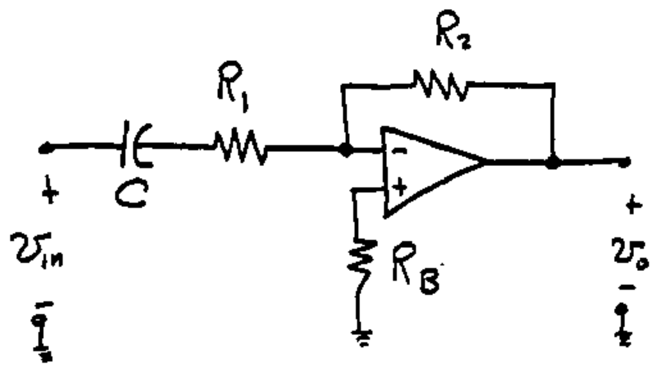
(h) A current-to-voltage converter is shown in Figure 2.57 in the text.

(i) A current amplifier is shown in Figure 2.58 in the text.

Problem 2.69

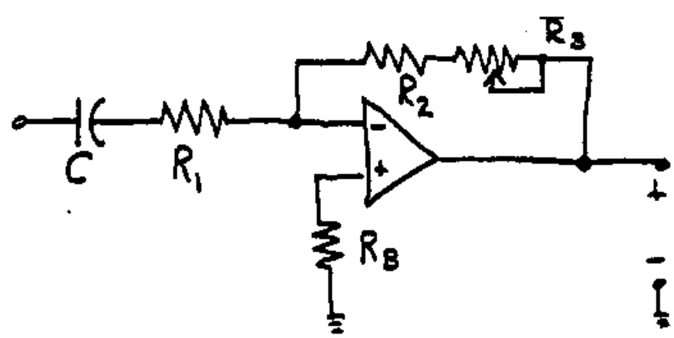
Many correct answers exist. Here are two solutions:

Solution 1



In this circuit use 1%-tolerance resistors. We need $R_2 = 10 R_1$, $R_B = R_2$, If we choose the capacitance such that $C > 1/(2\pi 100 R_1)$ we will find in the simulation that the gain is within 5% of the desired value at 1 kHz. One suitable choice of component values is R_1 = 20 kΩ, $R_2 = R_B$ = 200 kΩ, C = 0.1 μF, and the LF411 op amp.

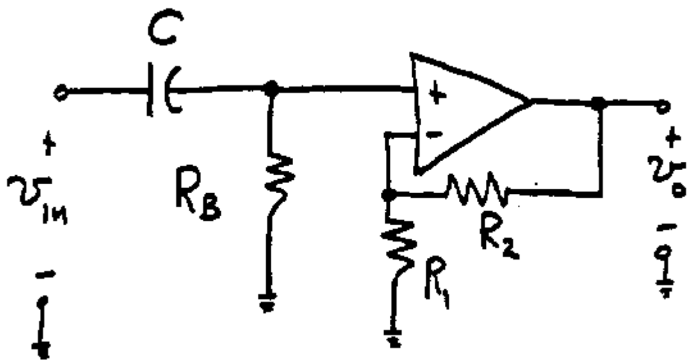
Solution 2



In this circuit use 5%-tolerance resistors and adjust the gain to within 5% by use of the potentiometer. Use the LF411 op amp, R_1 = 20 kΩ ± 5%, R_2 = 180 kΩ ± 5%, C = 0.1 μF, R_3 = 50 kΩ potentiometer, and R_B = 200 kΩ ±5%.

Problem 2.70

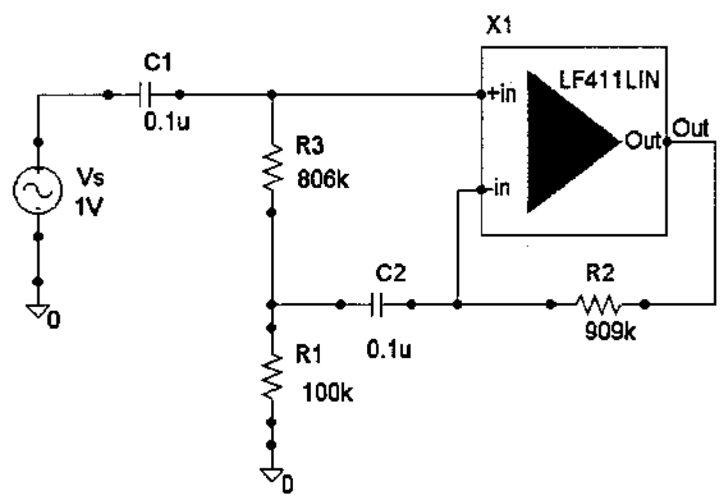
Many correct answers exist. Here is one of them:



To achieve the desired specifications, we need $R_2 = 9R_1$, $R_B = R_1||R_2$, and $C \geq 1/(2\pi 100 R_B)$. Any value of R_1 between 1 kΩ and 100 kΩ is suitable. Either use 1%-tolerance resistors or use 5%-tolerance resistors with a potentiometer to adjust the gain magnitude.

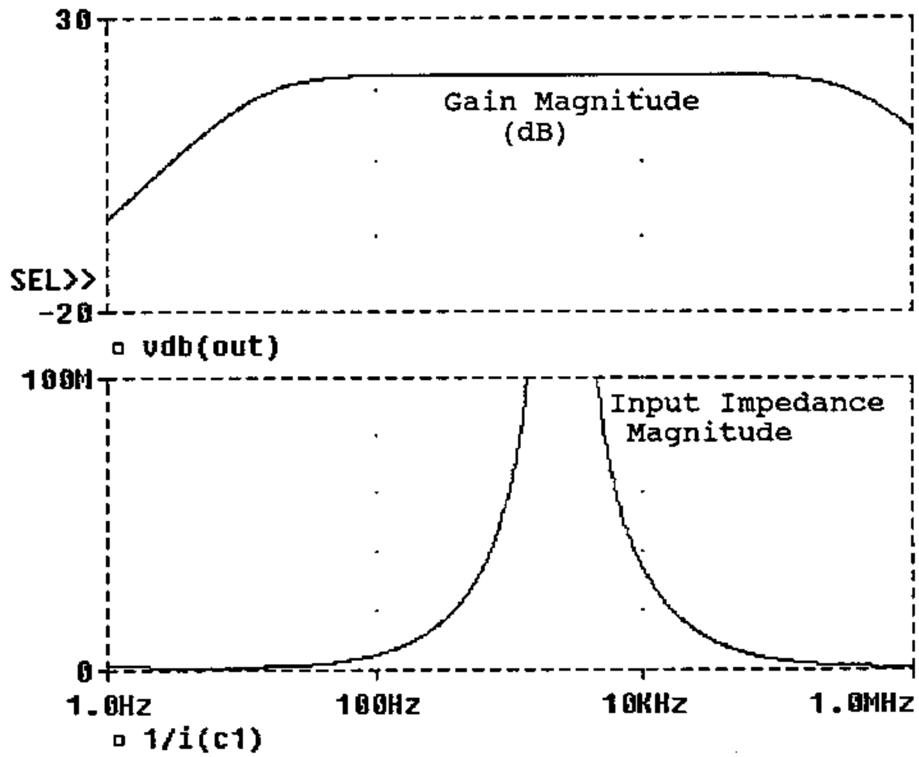
Problem 2.71

Resistors of 20 MΩ or more are usually impractical. Thus we need to select a circuit that makes a smaller resistance appear large. One approach is to use a circuit similar to Figure 2.52 in the text:



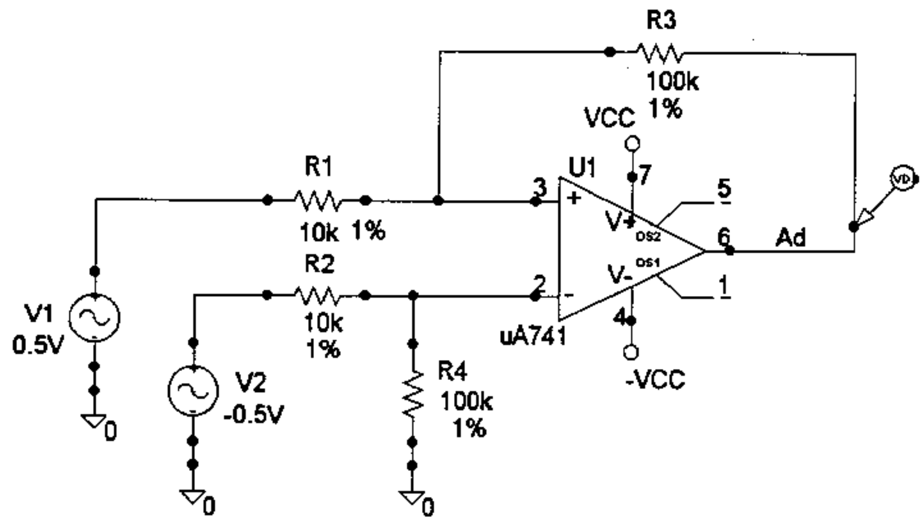
To attain a gain magnitude of 10 we need $R_2 = 9R_1$. To minimize the effect of bias current, we should choose $R_1 + R_3 = R_2$. To attain the desired gain-magnitude accuracy, 1%-tolerance resistors are used. A suitable set of component values is shown on the circuit diagram. (C_1 and C_2 were selected mainly by trial and err.)

The simulation for the circuit is stored in the file named P2_71. Plots of the input impedance magnitude and gain magnitude versus frequency are shown below:



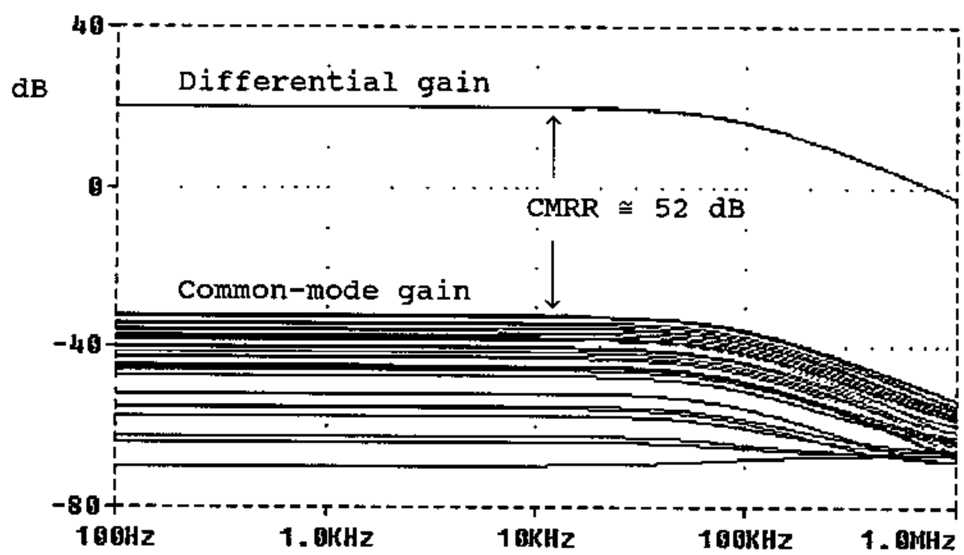
Problem 2.72

Here is the circuit and a suitable set of component values:



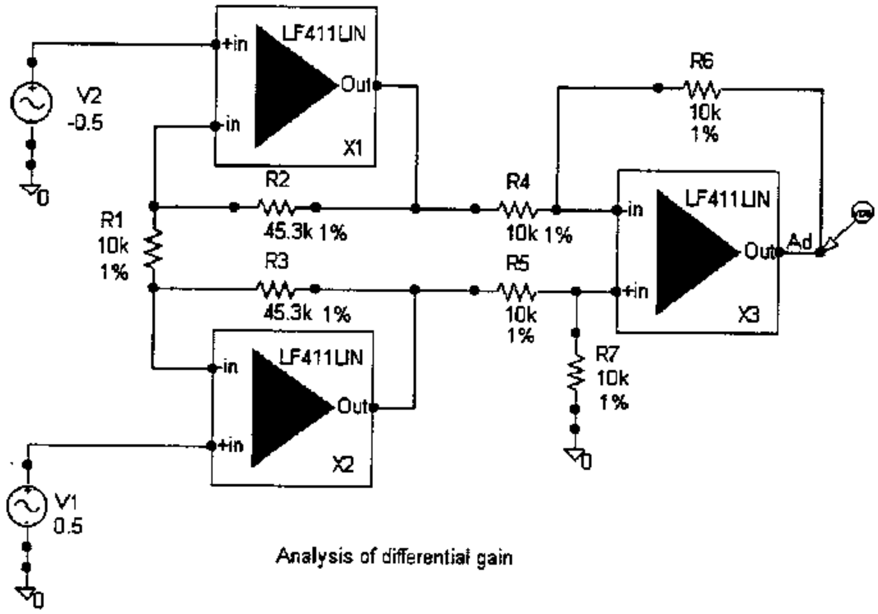
The schematic capture version of the simulation for 40 Monte Carlo runs is stored in the file named P2_72.

Plots of the differential and common-mode gains versus frequency are shown below:



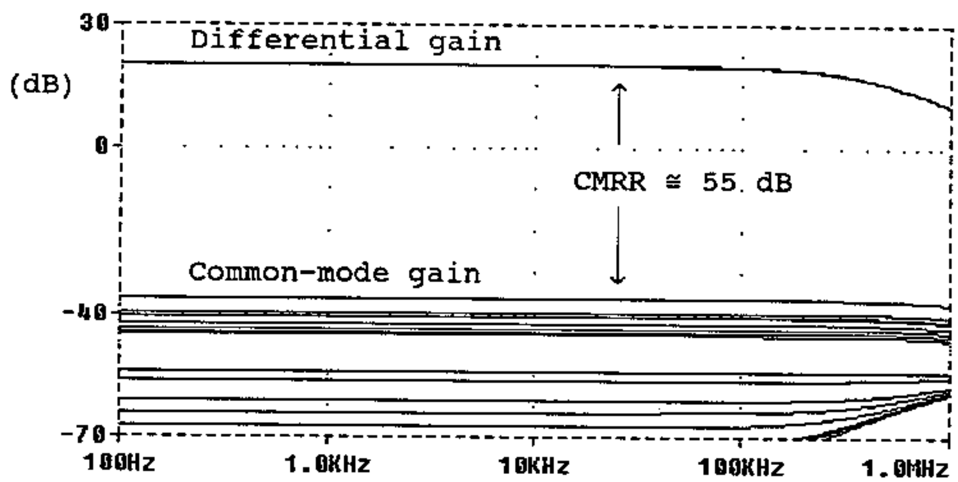
Problem 2.73

The circuit diagram is shown below. Choose R_1 in the range from 1 kΩ to 200 kΩ. To attain a gain of 10 we need $R_2 = R_3 = 4.5 \times R_1$. Then choose $R_4 = R_5 = R_6 = R_7$ in the range from about 1 kΩ to 1 MΩ.



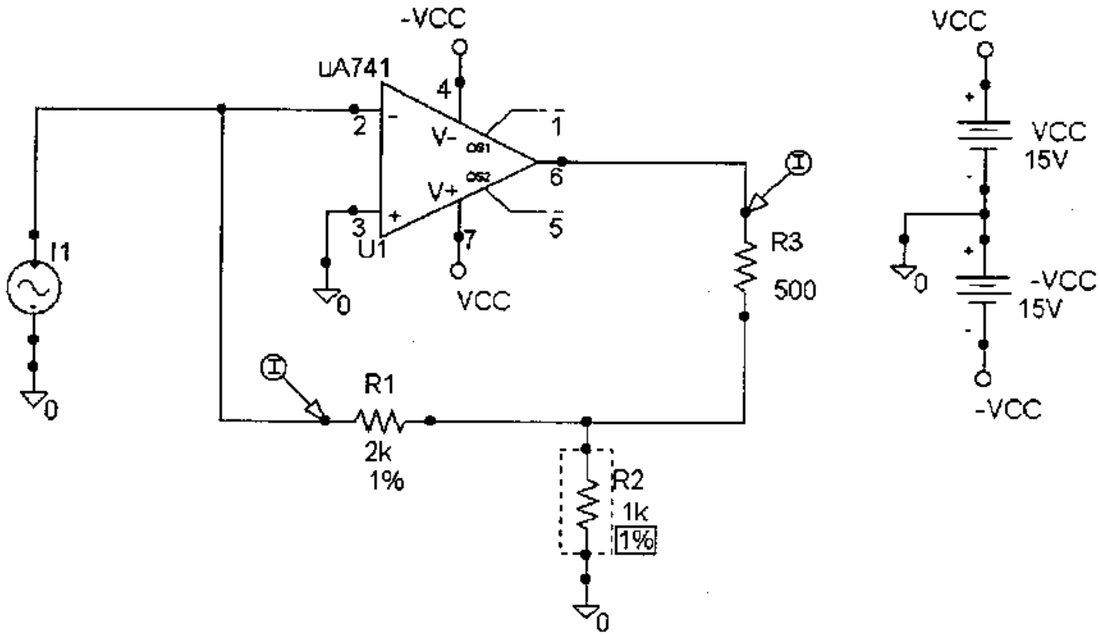
Analysis of differential gain

Plots of the differential and common-mode gains versus frequency are shown below:



Problem 2.74

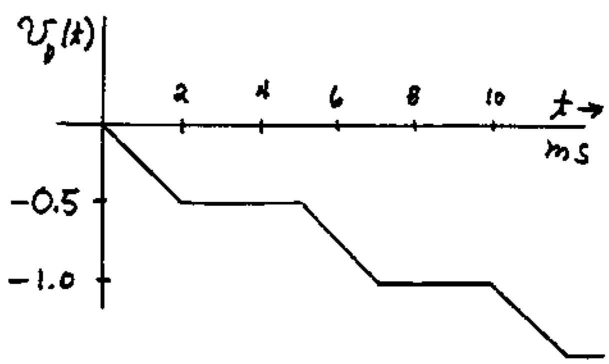
The circuit is shown below. The current gain is $A_i = -(1 + R_1/R_2)$. Thus for a current gain magnitude of 3 we need to choose $R_1 = 2R_2$. A good choice of values is $R_1 = 2\ k\Omega \pm 1\%$ and $R_2 = 1\ k\Omega \pm 1\%$. Another alternative would be to use 5%-tolerance resistors and a potentiometer to adjust the gain. The PSpice simulation is stored in the file named P2_74.



Problem 2.75

$$v_o(t) = -\frac{1}{RC}\int_0^t v_p(t)\,dt = -50\int_0^t v_p(t)\,dt$$

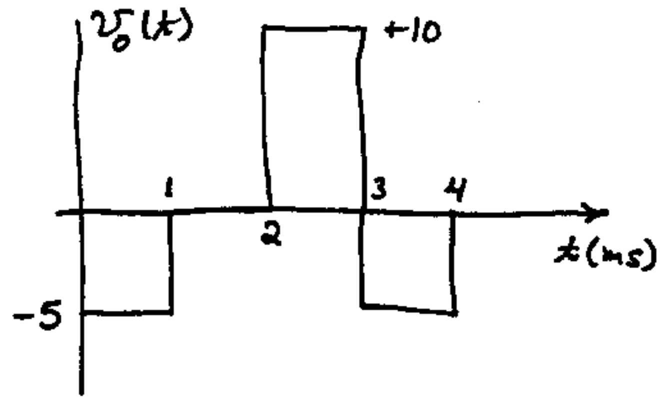
The plot of $v_o(t)$ versus t is shown on the next page.



Each input pulse reduces $v_o(t)$ by 0.5 V. Thus 20 pulses will result in $v_o(t)$ = -10 V.

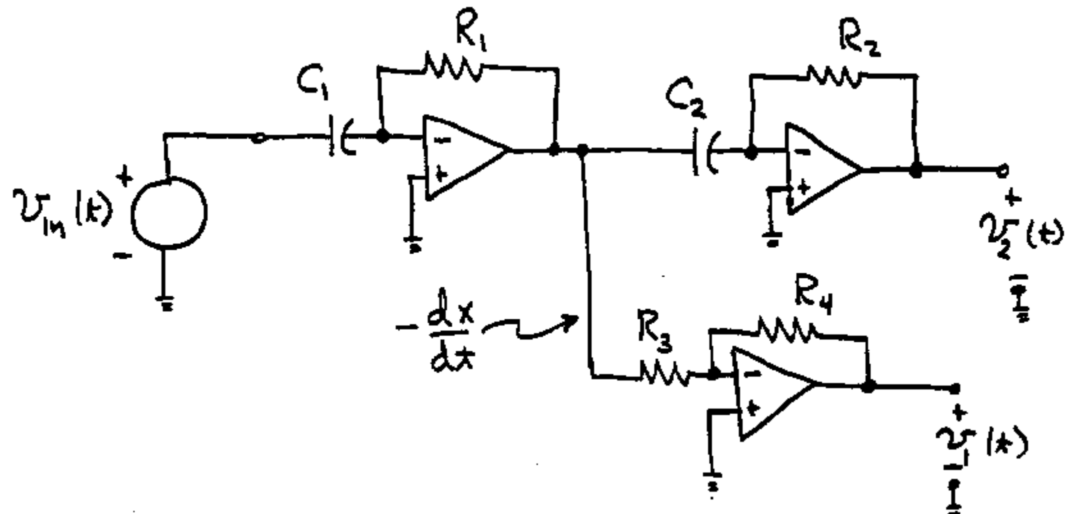
Problem 2.76

$$v_o(t) = -RC\frac{dv_{in}}{dt} = -10^{-3}\frac{dv_{in}}{dt}$$



Problem 2.77

Let x(t) = displacement in meters. Then $v_{in} = 10x(t)$, and we need $v_1(t) = dx/dt = 0.1dv_{in}/dt$ and $v_2(t) = d^2x/dt^2 = dv_1/dt$.



We need $R_1C_1 = 0.1$, $R_2C_2 = 1$ and $R_3 = R_4$. Suitable values are $R_1 = R_2 = 1$ MΩ, $C_1 = 0.1$ μF, $C_2 = 1.0$ μF, and $R_3 = R_4 = 10$ kΩ. LF411 op amps are a good choice because they have relatively small bias currents.