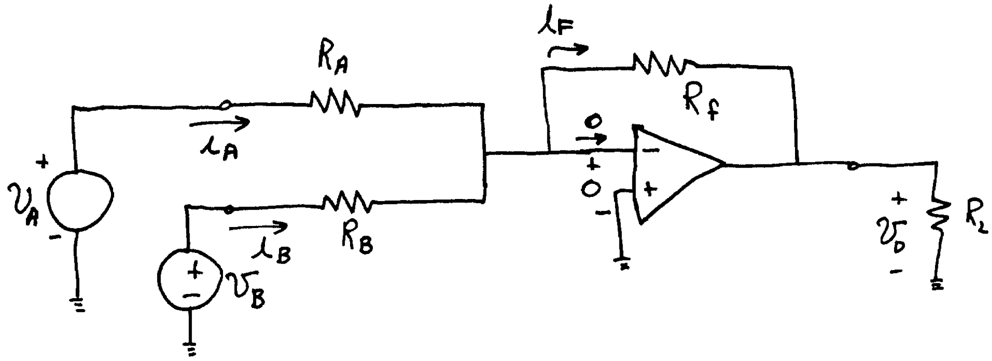
CHAPTER 14

Exercises

E14.1



(a) $i_A = \dfrac{v_A}{R_A} \qquad i_B = \dfrac{v_B}{R_B} \qquad i_F = i_A + i_B = \dfrac{v_A}{R_A} + \dfrac{v_B}{R_B}$

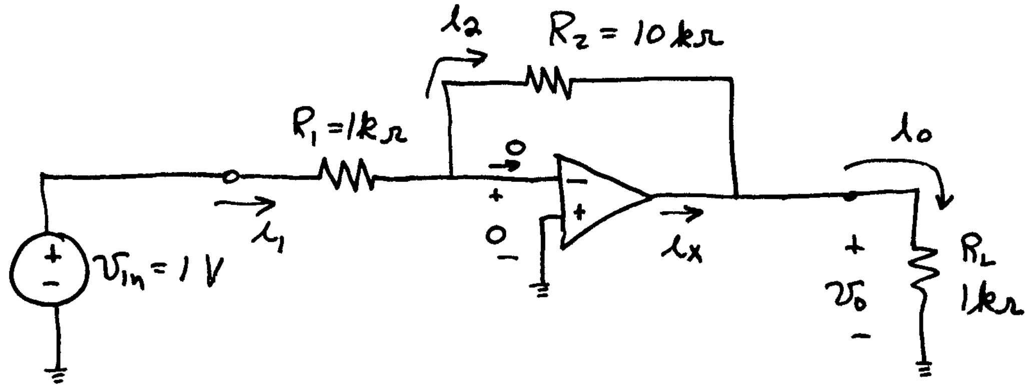
$$v_o = -R_F i_F = -R_F\left(\frac{v_A}{R_A} + \frac{v_B}{R_B}\right)$$

(b) For the v_A source, $R_{\text{in}A} = \dfrac{v_A}{i_A} = R_A$.

(c) Similarly $R_{\text{in}B} = R_B$.

(d) In part (a) we found that the output voltage is independent of the load resistance. Therefore, the output resistance is zero.

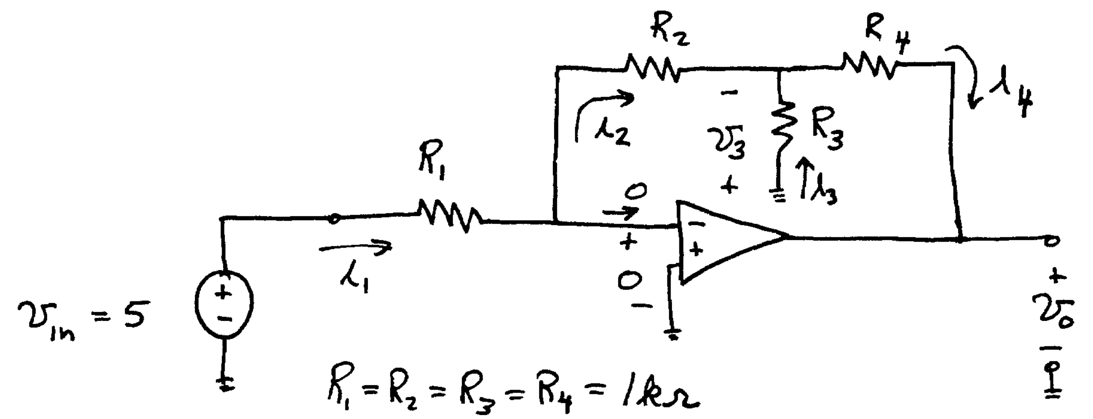
E14.2 (a)



$i_1 = \dfrac{v_{in}}{R_1} = 1\,\text{mA} \qquad i_2 = i_1 = 1\,\text{mA} \qquad v_o = -R_2 i_2 = -10\,\text{V}$

$i_o = \frac{v_o}{R_L} = -10 \text{ mA} \qquad i_x = i_o - i_2 = -11 \text{ mA}$

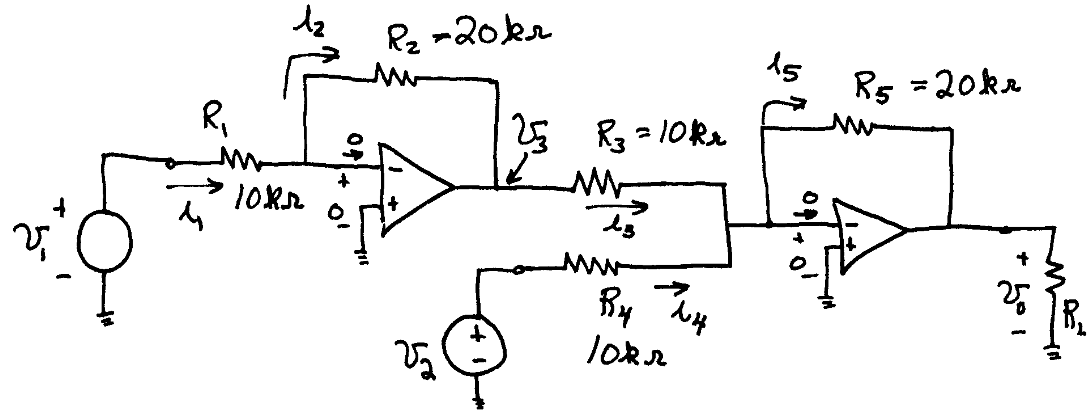
(b)



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

$i_3 = \frac{v_3}{R_3} = 5 \text{ mA} \qquad i_4 = i_2 + i_3 = 10 \text{ mA} \qquad v_o = -R_4 i_4 - R_2 i_2 = -15 \text{ V}$

E14.3



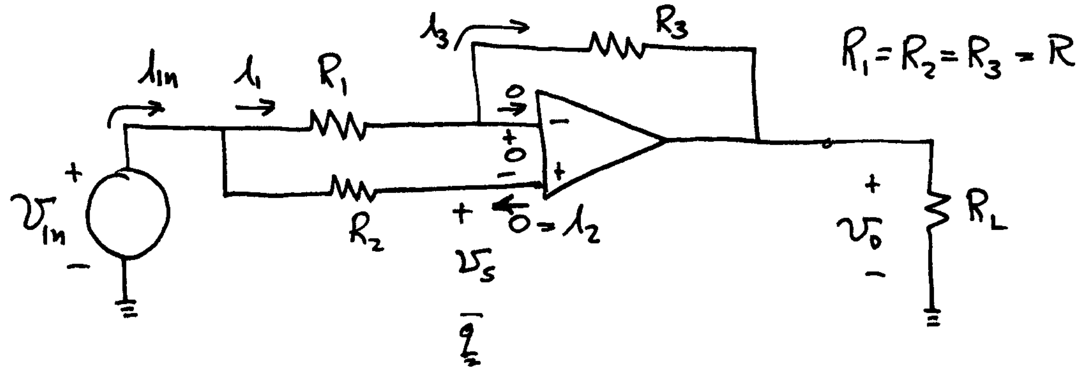
Direct application of circuit laws gives $i_1 = \frac{v_1}{R_1}$, $\quad i_2 = i_1$, and $v_3 = -R_2 i_2$.

From the previous three equations, we obtain $v_3 = -\frac{R_2}{R_1} v_1 = -2v_1$. Then

applying circuit laws gives $i_3 = \frac{v_3}{R_3}$, $i_4 = \frac{v_2}{R_4}$, $i_5 = i_3 + i_4$, and $v_o = -R_5 i_5$.

These equations yield $v_o = -\frac{R_5}{R_3}v_3 - \frac{R_5}{R_4}v_2$. Then substituting values and using the fact that $v_3 = -2v_1$, we find $v_o = 4v_1 - 2v_2$.

E14.4 (a)

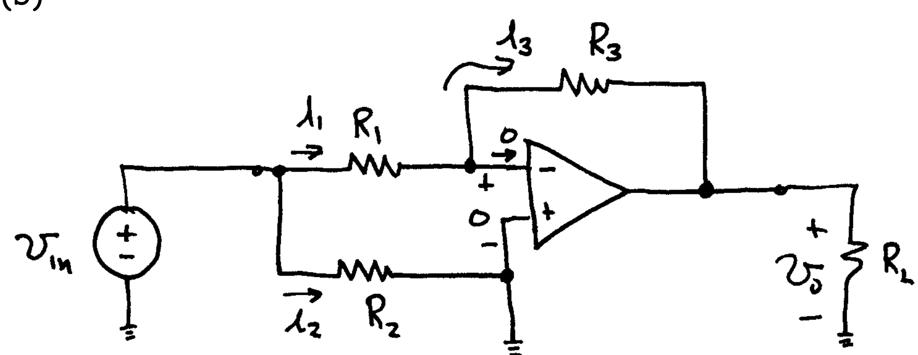


$v_s = v_{in} + R_2 i_2 = v_{in}$ (Because of the summing-point restraint, $i_2 = 0$.)

$i_1 = \frac{v_{in} - v_s}{R_1} = 0$ (Because $v_s = v_{in}$.) $\qquad i_{in} = i_1 - i_2 = 0$

$i_3 = i_1 = 0 \qquad v_o = R_3 i_3 + v_s = v_{in}$ Thus, $A_v = \frac{v_o}{v_{in}} = +1$ and $R_{in} = \frac{v_{in}}{i_{in}} = \infty$.

(b)

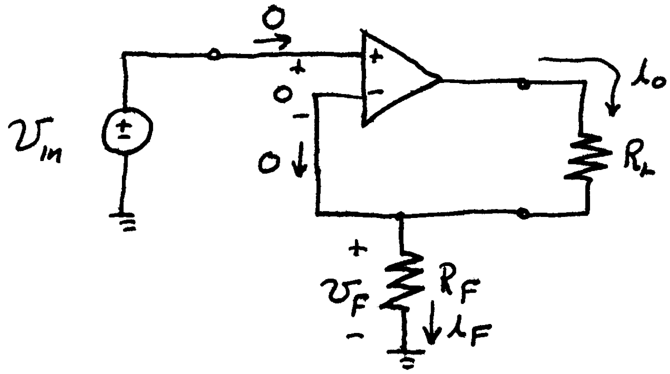


(Note: We assume that $R_1 = R_2 = R_3$.)

$i_1 = \frac{v_{in}}{R_1} = \frac{v_{in}}{R} \qquad i_2 = \frac{v_{in}}{R_2} = \frac{v_{in}}{R} \qquad i_{in} = i_1 + i_2 = \frac{2v_{in}}{R} \qquad R_{in} = \frac{R}{2}$

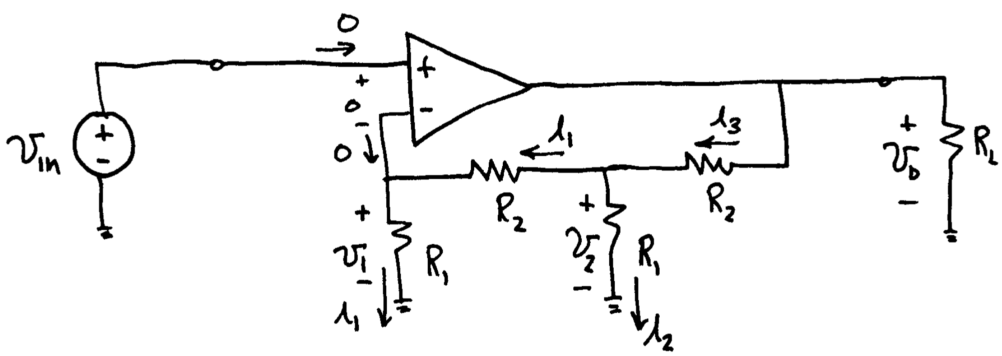
$i_3 = i_1 = \frac{v_{in}}{R_1} \qquad v_o = -R_3 i_3 = -\frac{R_3}{R_1}v_{in} = -v_{in} \qquad A_v = \frac{v_o}{v_{in}} = -1$

E14.5



From the circuit, we can write $v_F = v_{\text{in}}$, $i_F = \dfrac{v_F}{R_F}$, and $i_o = i_F$. From these equations, we find that $i_o = \dfrac{v_{\text{in}}}{R_F}$. Then because i_o is independent of R_L, we conclude that the output impedance of the amplifier is infinite. Also R_{in} is infinite because i_{in} is zero.

E14.6 (a)



$v_1 = v_{\text{in}}$ $\quad i_1 = \dfrac{v_1}{R_1}$ $\quad v_2 = R_2 i_1 + R_1 i_1$ $\quad i_2 = \dfrac{v_2}{R_1}$ $\quad i_3 = i_1 + i_2$ $\quad v_o = R_2 i_3 + v_2$

Using the above equations we eventually find that

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

(b) Substituting the values given, we find $A_v = 131$.

(c) Because $i_{\text{in}} = 0$, the input resistance is infinite.

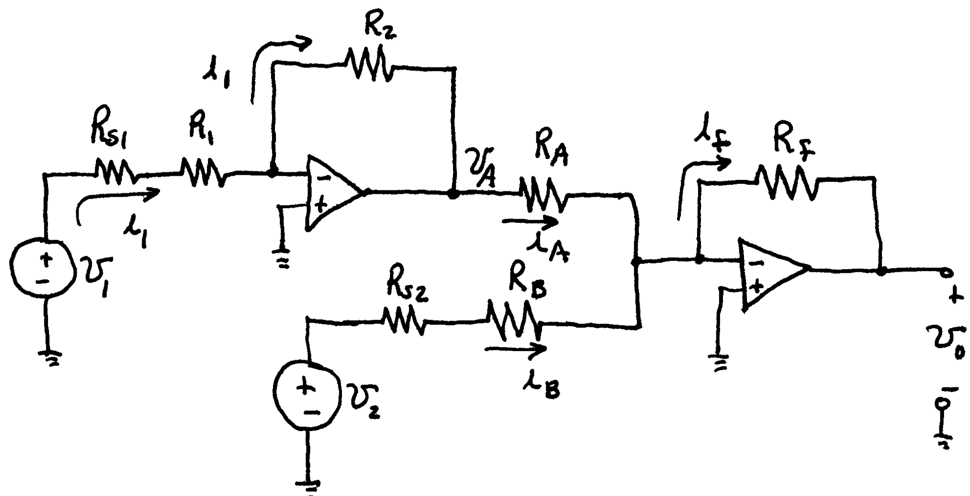
(d) Because $v_o = A_v v_{in}$ is independent of R_L, the output resistance is zero.

E14.7 We have $A_{vs} = -\dfrac{R_2}{R_s + R_1}$ from which we conclude that

$$A_{vs\max} = -\frac{R_{2\max}}{R_{s\min} + R_{1\min}} = -\frac{499 \times 1.01}{0 + 49.9 \times 0.99} = -10.20$$

$$A_{vs\min} = -\frac{R_{2\min}}{R_{s\max} + R_{1\max}} = -\frac{499 \times 0.99}{0.500 + 49.9 \times 1.01} = -9.706$$

E14.8



Applying basic circuit principles, we obtain:

$$i_1 = \frac{v_1}{R_1 + R_{s1}} \qquad v_A = -R_2 i_1 \qquad i_A = \frac{v_A}{R_A}$$

$$i_B = \frac{v_2}{R_B + R_{s2}} \qquad i_f = i_A + i_B \qquad v_o = -R_f i_f$$

From these equations, we eventually find

$$v_o = \frac{R_2}{R_{s1} + R_1}\frac{R_f}{R_A}v_1 - \frac{R_f}{R_{s2} + R_B}v_2$$

E14.9 Many correct answers exist. A good solution is the circuit of Figure 14.11 in the book with $R_2 \cong 19R_1$. We could use standard 1%-tolerance resistors with nominal values of $R_1 = 1\ \text{k}\Omega$ and $R_2 = 19.1\ \text{k}\Omega$.

E14.10 Many correct answers exist. A good solution is the circuit of Figure 14.18 in the book with $R_1 \geq 20R_s$ and $R_2 \cong 25(R_1 + R_s)$. We could use standard 1%-tolerance resistors with nominal values of $R_1 = 20\,\text{k}\Omega$ and $R_2 = 515\ \text{k}\Omega$.

E14.11 Many correct selections of component values can be found that meet the desired specifications. One possibility is the circuit of Figure 14.19 with:

$R_1 =$ a 453-kΩ fixed resistor in series with a 100-kΩ trimmer (nominal design value is 500 kΩ)

R_B is the same as R_1

$R_2 = 499\ \text{k}\Omega$

$R_A = 1.5\ \text{M}\Omega$

$R_f = 1.5\ \text{M}\Omega$

After constructing the circuit we could adjust the trimmers to achieve the desired gains.

E14.12 $f_{BCL} = \dfrac{f_t}{A_{0CL}} = \dfrac{A_{0OL} f_{BOL}}{A_{0CL}} = \dfrac{10^5 \times 40}{100} = 40\,\text{kHz}$ The corresponding Bode plot is shown in Figure 14.22 in the book.

E14.13 (a) $f_{FP} = \dfrac{SR}{2\pi V_{om}} = \dfrac{5 \times 10^6}{2\pi(4)} = 198.9\,\text{kHz}$

(b) The input frequency is less than f_{FP} and the current limit of the op amp is not exceeded, so the maximum output amplitude is 4 V.

(c) With a load of 100 Ω the current limit is reached when the output amplitude is 10 mA × 100 Ω = 1 V. Thus the maximum output amplitude without clipping is 1 V.

(d) In deriving the full-power bandwidth we obtained the equation:

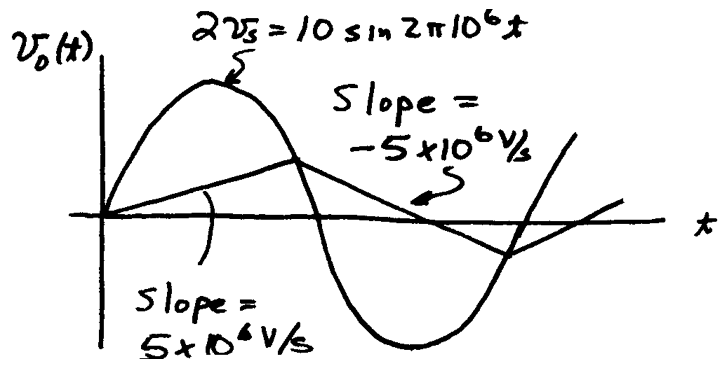
$$2\pi f V_{om} = SR$$

Solving for V_{om} and substituting values, we have

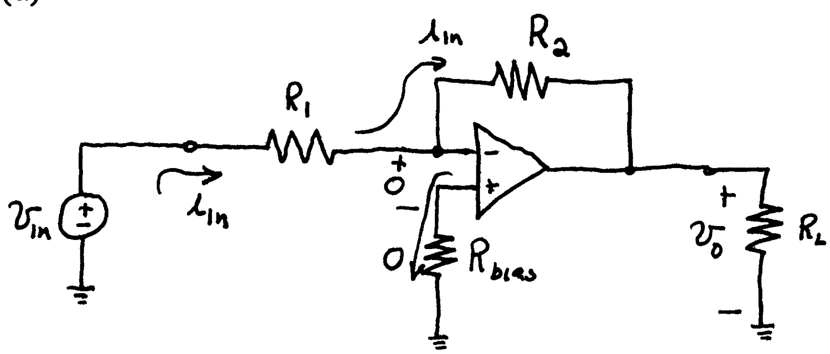
$$V_{om} = \frac{SR}{2\pi f} = \frac{5 \times 10^6}{2\pi 10^6} = 0.7958\ \text{V}$$

With this peak voltage and R_L = 1 kΩ, the current limit is not exceeded.

(e) Because the output, assuming an ideal op amp, has a rate of change exceeding the slew-rate limit, the op amp cannot follow the ideal output, which is $v_o(t) = 10\sin(2\pi 10^6 t)$. Instead, the output changes at the slew-rate limit and the output waveform eventually becomes a triangular waveform with a peak-to-peak amplitude of SR $\times$ (T/2) = 2.5 V.

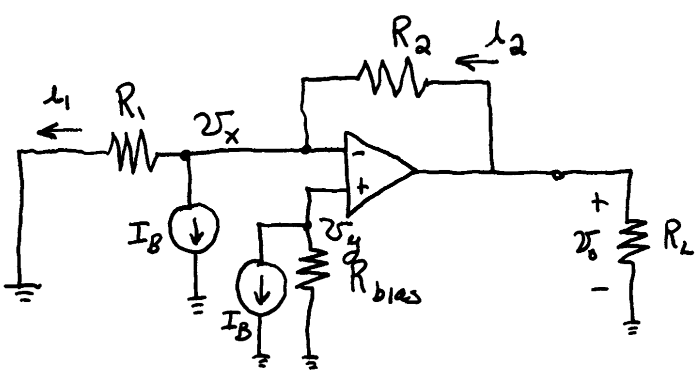


E14.14 (a)



Applying basic circuit laws, we have $i_{in} = \frac{v_{in}}{R_1}$ and $v_o = -R_2 i_{in}$. These equations yield $A_v = \frac{v_o}{v_{in}} = -\frac{R_2}{R_1}$.

(b)



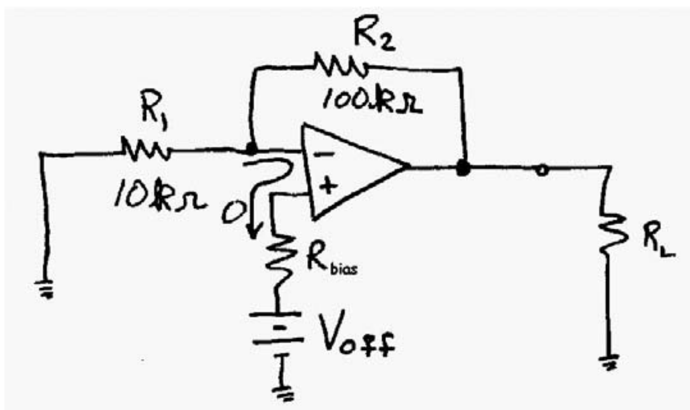
Applying basic circuit principles, algebra, and the summing-point restraint, we have

$$v_x = v_y = -R_{bias}I_B \qquad i_1 = \frac{v_x}{R_1} = -\frac{R_{bias}}{R_1}I_B = -\frac{R_2}{R_1+R_2}I_B$$

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

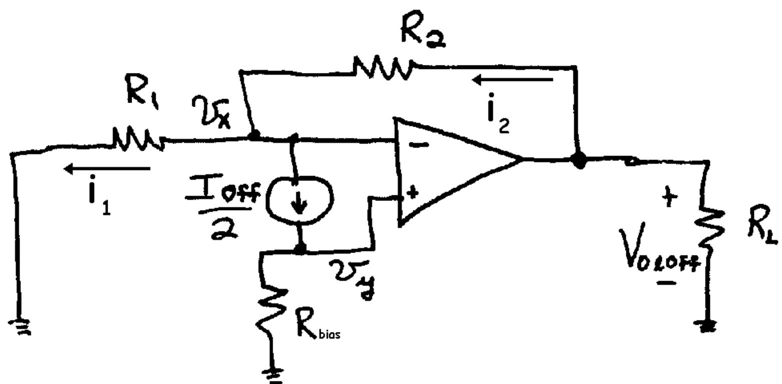
$$v_o = R_2 i_2 + v_x = R_2\frac{R_1}{R_1+R_2}I_B - R_{bias}I_B = 0$$

(c)



The drop across R_{bias} is zero because the current through it is zero. For the source V_{off} the circuit acts as a noninverting amplifier with a gain $A_v = 1 + \frac{R_2}{R_1} = 11$. Therefore, the extreme output voltages are given by $v_o = A_v V_{\text{off}} = \pm 33\,\text{mV}$.

(d)



Applying basic circuit principles, algebra, and the summing-point restraint, we have

$$v_x = v_y = R_{bias}\frac{I_{\text{off}}}{2} \qquad i_1 = \frac{v_x}{R_1} = \frac{R_{bias}}{R_1}\frac{I_{\text{off}}}{2} = \frac{R_2}{R_1+R_2}\frac{I_{\text{off}}}{2}$$

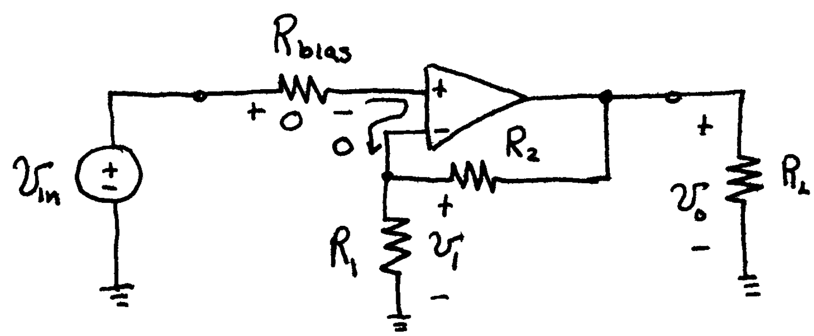
$$i_2 = \frac{I_{\text{off}}}{2} + i_1 = \left(1 + \frac{R_2}{R_1+R_2}\right)\frac{I_{\text{off}}}{2} = \frac{R_1+2R_2}{R_1+R_2}\frac{I_{\text{off}}}{2}$$

$$v_o = R_2 i_2 + v_x = R_2\frac{R_1+2R_2}{R_1+R_2}\frac{I_{\text{off}}}{2} + R_{bias}\frac{I_{\text{off}}}{2} = R_2 I_{off}$$

Thus the extreme values of v_o caused by I_{off} are $V_{o,\text{Ioff}} = \pm 4$ mV.

(e) The cumulative effect of the offset voltage and offset current is that V_o ranges from -37 to +37 mV.

E14.15 (a)



Because of the summing-point constraint, no current flows through R_{bias} so the voltage across it is zero. Because the currents through R_1 and R_2 are the same, we use the voltage division principle to write

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

Then using KVL we have

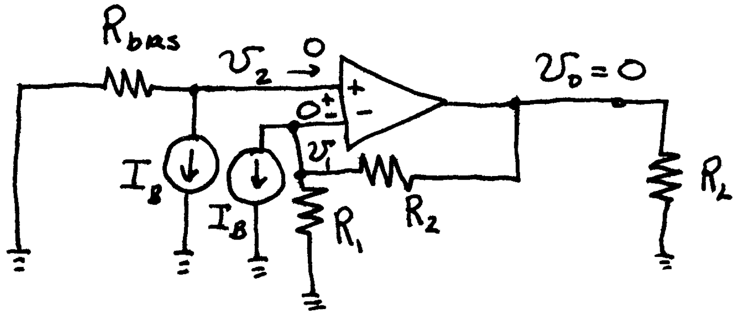
$$v_{\text{in}} = 0 + v_1$$

These equations yield

$$A_v = \frac{v_o}{v_{\text{in}}} = 1 + \frac{R_2}{R_1}$$

Assuming an ideal op amp, the resistor R_{bias} does not affect the gain since the voltage across it it zero.

(b) The circuit with the signal set to zero and including the bias current sources is shown.

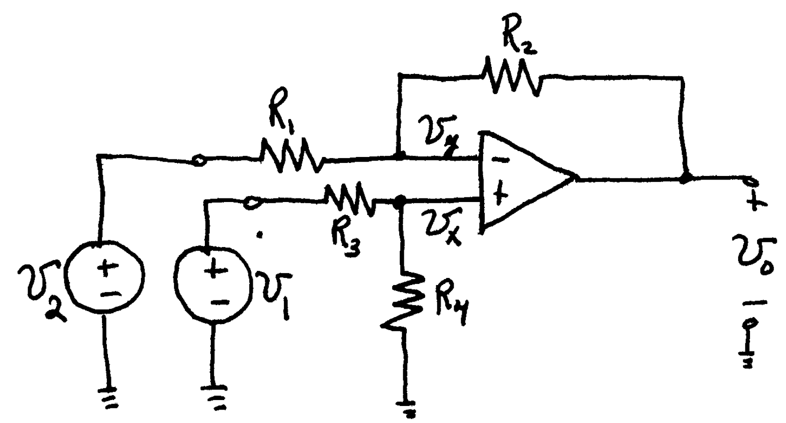


We want the output voltage to equal zero. Using Ohm's law, we can write $v_2 = -R_{\text{bias}} I_B$. Then writing a current equation at the inverting input, we have $I_B + \frac{v_1}{R_1} + \frac{v_1}{R_2} = 0$. Finally, because of the summing-point restraint, we have $v_2 = v_1$. These equations eventually yield

$$R_{\text{bias}} = \frac{1}{1/R_1 + 1/R_2}$$

as the condition for zero output due to the bias current sources.

E14.16



Because no current flows into the op-amp input terminals, we can use the voltage division principle to write

$$v_x = v_1 \frac{R_4}{R_3 + R_4}$$

Because of the summing-point restraint, we have

$$v_x = v_y = v_1 \frac{R_4}{R_3 + R_4}$$

Writing a KCL equation at the inverting input, we obtain

$$\frac{v_y - v_2}{R_1} + \frac{v_y - v_o}{R_2} = 0$$

Substituting for v_y and solving for the output voltage, we obtain

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

If we have $R_4 / R_3 = R_2 / R_1$, the equation for the output voltage reduces to

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

E14.17 (a) $v_o(t) = -\frac{1}{RC}\int_0^t v_{\text{in}}(t)dt = -1000\int_0^t v_{\text{in}}(t)dt$

$$= -1000\int_0^t 5dt = -5000t \quad \text{for } 0 \le t \le 1\,\text{ms}$$

$$= -1000\left(\int_0^{1\,\text{ms}} 5dt + \int_{1\,\text{ms}}^{t} -5dt\right) = -10 + 5000t \quad \text{for } 1\ \text{ms} \le t \le 3\,\text{ms}$$

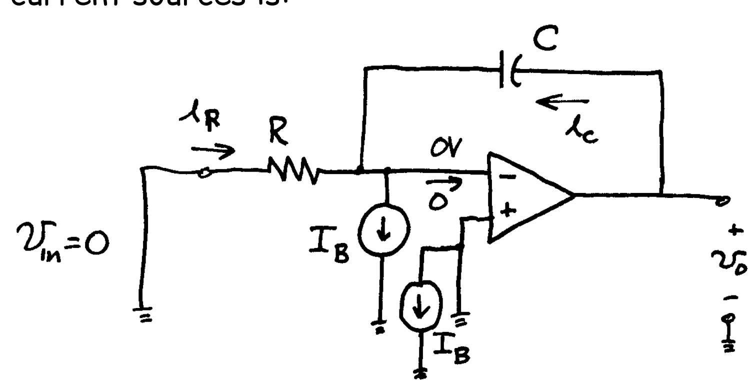
and so forth. A plot of $v_o(t)$ versus t is shown in Figure 14.37 in the book.

(b) A peak-to-peak amplitude of 2 V implies a peak amplitude of 1 V. The first (negative) peak amplitude occurs at $t = 1\,\text{ms}$. Thus we can write

$$-1 = -\frac{1}{RC}\int_0^{1\,\text{ms}} v_{\text{in}}dt = -\frac{1}{10^4 C}\int_0^{1\,\text{ms}} 5dt = -\frac{1}{10^4 C} \times 5 \times 10^{-3}$$

which yields $C = 0.5\ \mu\text{F}$.

E14.18 The circuit with the input source set to zero and including the bias current sources is:



Because the voltage across R is zero, we have $i_C = I_B$, and we can write

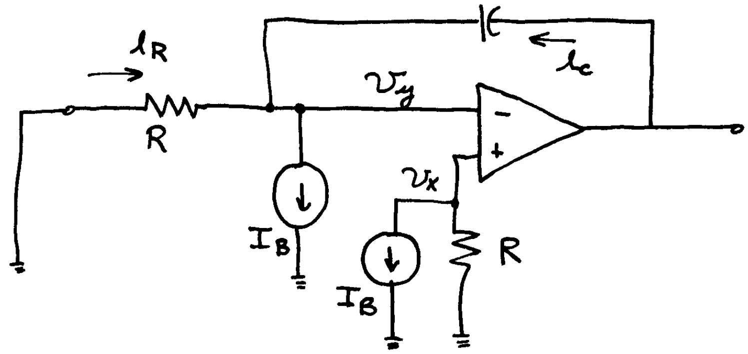
$$v_o = \frac{1}{C}\int_0^t i_C dt = \frac{1}{C}\int_0^t I_B dt = \frac{100\times 10^{-9} t}{C}$$

(a) For C = 0.01 μF we have $v_o(t) = 10t$ V.

(b) For C = 1 μF we have $v_o(t) = 0.1t$ V.

Notice that larger capacitances lead to smaller output voltages.

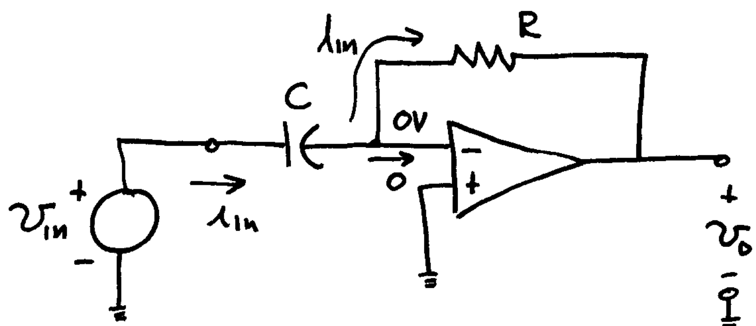
E14.19



$v_y = v_x = -I_B R_B \quad i_R = -v_y / R_B = I_B \quad i_C = i_R + I_B = 0$

Because $i_C = 0$, we have $v_C = 0$, and $v_o = v_y = -I_B R = 1$ mV.

E14.20



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

E14.21 The transfer function in decibels is

$$|H(f)|_{dB} = 20\log\left[\frac{H_0}{\sqrt{1+(f/f_B)^{2n}}}\right]$$

For $f >> f_B$, we have

$$|H(f)|_{dB} \cong 20\log\left[\frac{H_0}{\sqrt{(f/f_B)^{2n}}}\right] = 20\log|H_0| + 20n\log(f_B) - 20n\log(f)$$

This expression shows that the gain magnitude is reduced by $20n$ decibels for each decade increase in f.

E14.22 Three stages each like that of Figure 14.40 must be cascaded. From Table 14.1, we find that the gains of the stages should be 1.068, 1.586, and 2.483. Many combinations of component values will satisfy the requirements of the problem. A good choice for the capacitance value is 0.01 μF, for which we need $R = 1/(2\pi C f_B) = 3.183\ \text{k}\Omega$. Also $R_f = 10\ \text{k}\Omega$ is a good choice.

Answers for Selected Problems

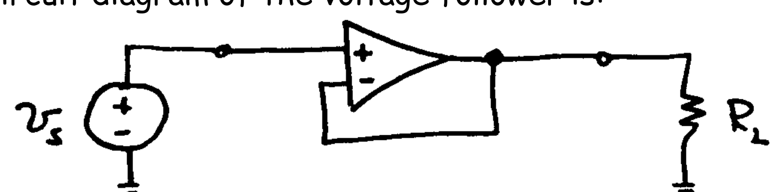
P14.4* $v_{id} = v_1 - v_2 = \cos(2000\pi t)$ $\qquad v_{icm} = \frac{1}{2}(v_1 + v_2) = 20\cos(120\pi t)$

P14.6* The steps in analysis of an amplifier containing an ideal op amp are:

1. Verify that negative feedback is present.
2. Assume that the differential input voltage and the input currents are zero.
3. Apply circuit analysis principles including Kirchhoff's and Ohm's laws to write circuit equations. Then solve for the quantities of interest.

P14.10* $A_v = -8$

P14.17* The circuit diagram of the voltage follower is:



Assuming an ideal op amp, the voltage gain is unity, the input impedance is infinite, and the output impedance is zero.

P14.18* If the source has non-zero series impedance, loading (reduction in voltage) will occur when the load is connected directly to the source. On the other hand, the input impedance of the voltage follower is very high (ideally infinite) and loading does not occur. If the source impedance is very high compared to the load impedance, the voltage follower will deliver a much larger voltage to the load than direct connection.

P14.21* $v_o = \left(\dfrac{R_1 + R_2}{R_1}\right)\dfrac{v_A R_B + v_B R_A}{R_A + R_B}$

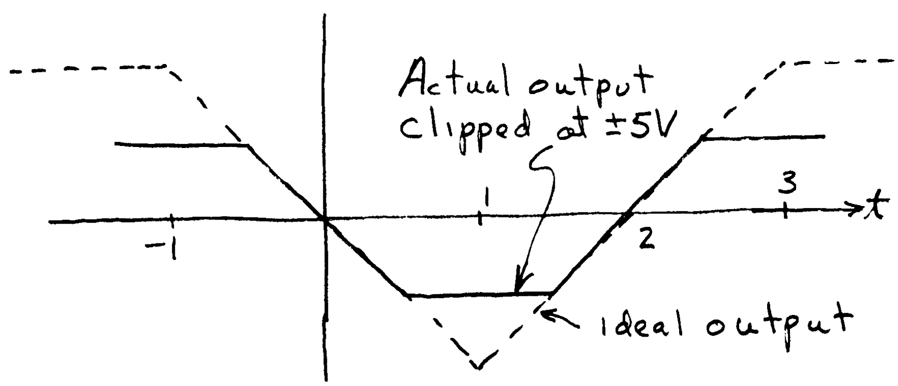
P14.24* (a) $v_o = -R_f i_{in}$

(b) Since v_o is independent of R_L, the output behaves as a perfect voltage source, and the output impedance is zero.

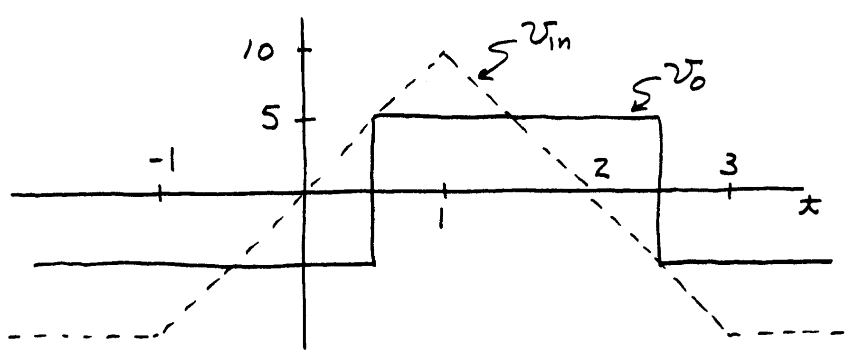
(c) The input voltage is zero because of the summing-point constraint, and the input impedance is zero.

(d) This is an ideal transresistance amplifier.

P14.28* (a)



(b)

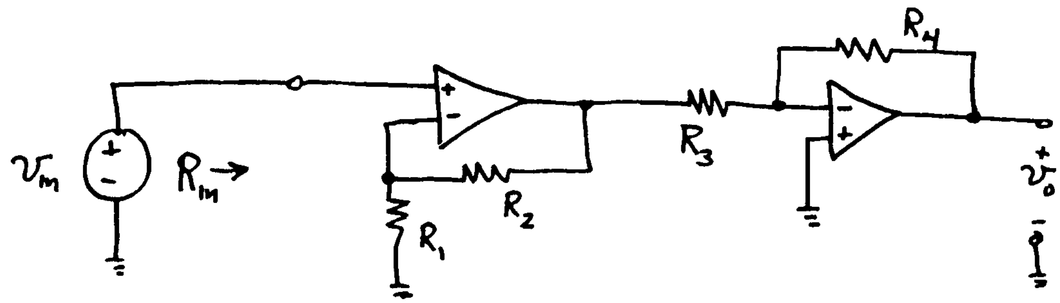


P14.32* $i_o = -\left(1 + \frac{R_1}{R_2}\right) i_{in}$

$R_{in} = 0$

The output impedance is infinite.

P14.36*



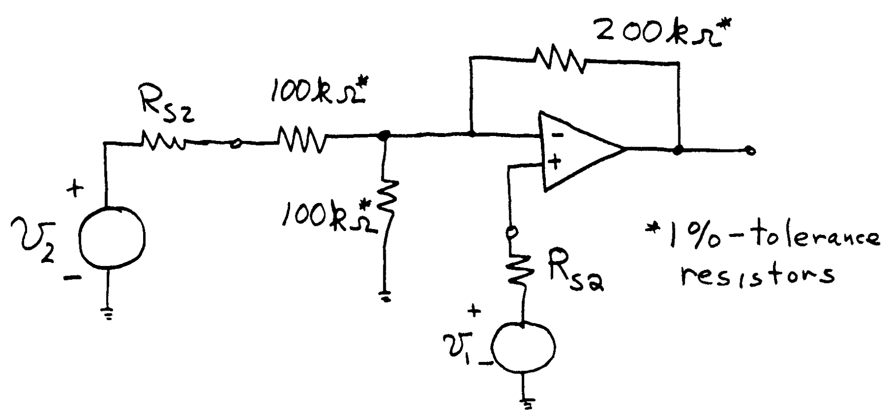
Many combinations of resistance values will achieve the given specifications. For example:

$R_1 = \infty$ and $R_2 = 0$. (Then the first stage becomes a voltage follower.) This is a particularly good choice because fewer resistors affect the overall gain, resulting in small overall gain variations.

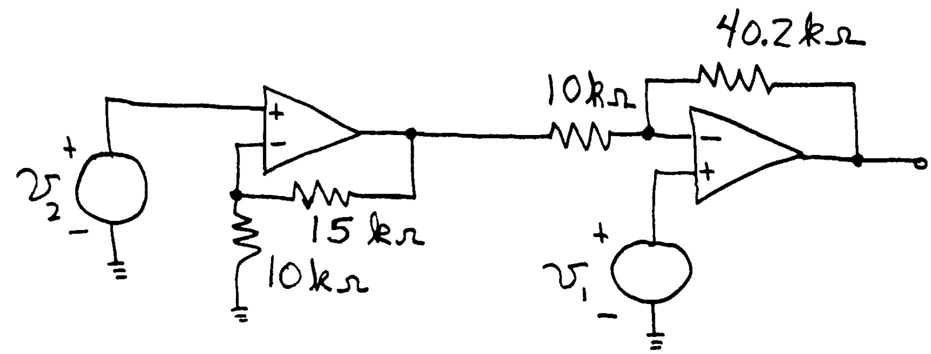
R_4 = 100 kΩ, 5% tolerance.

R_3 = 10 kΩ, 5% tolerance.

P14.37* A solution is:



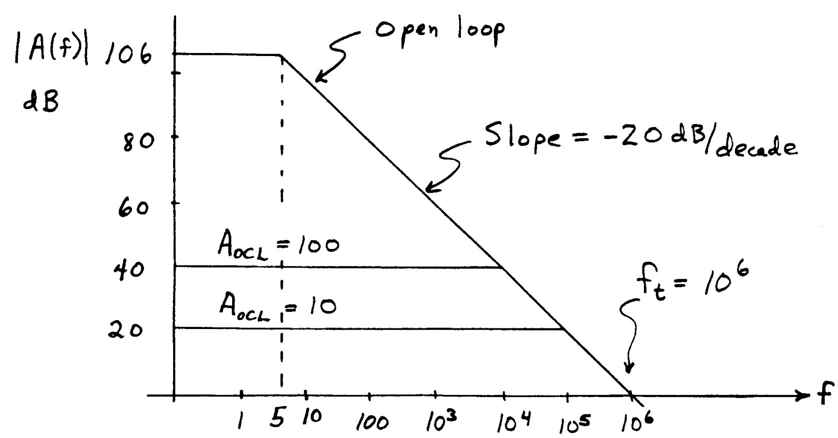
P14.41*



All resistors are $\pm 1\%$ tolerance.

P14.45* For $A_{0CL} = 10$, $f_{BCL} = 1.5\text{ MHz}$.
For $A_{0CL} = 100$, $f_{BCL} = 150\text{ kHz}$.

P14.52*



P14.57* (a) $$f_{FP} = \frac{SR}{2\pi V_{om}} = \frac{10^7}{2\pi 10} = 159\text{ kHz}$$

(b) $V_{om} = 10\text{ V}$. (It is limited by the maximum output voltage capability of the op amp.)

(c) In this case, the limit is due to the maximum current available from the op amp. Thus, the maximum output voltage is:

$$V_{om} = 20\text{ mA} \times 100\ \Omega = 2\text{ V}$$

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

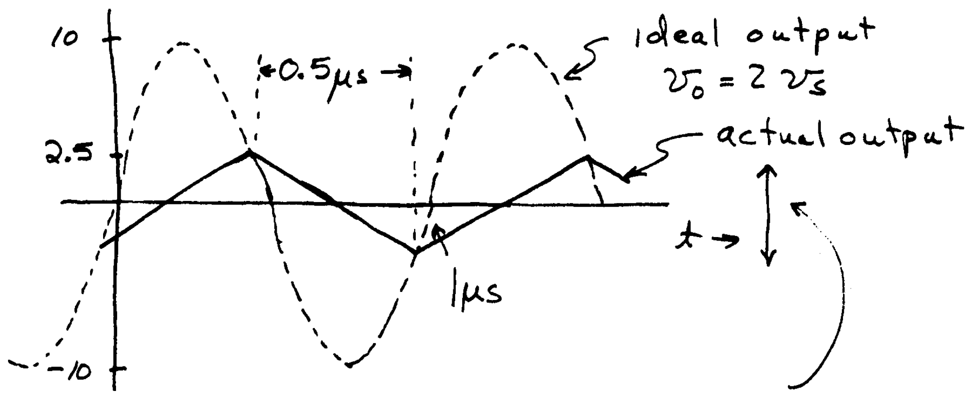
$$v_o(t) = V_{om}\sin(\omega t)$$

$$\frac{dv_o(t)}{dt} = \omega V_{om} \cos(\omega t)$$

$$\left|\frac{dv_o(t)}{dt}\right|_{\max} = \omega V_{om} = SR$$

$$V_{om} = \frac{SR}{\omega} = \frac{10^7}{2\pi 10^6} = 1.59 \text{ V}$$

(e)



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

P14.60* $SR = (4 \text{ V})/(0.5\ \mu\text{s}) = 8\ \text{V}/\mu\text{s}$

P14.63* See Figure 14.29 in the text.

P14.66* $V_{o,voff} = \pm 44 \text{ mV}$

$V_{o,bias} = 10 \text{ mV and } 20 \text{ mV}$

$V_{o,ioff} = \pm 2.5 \text{ mV}$

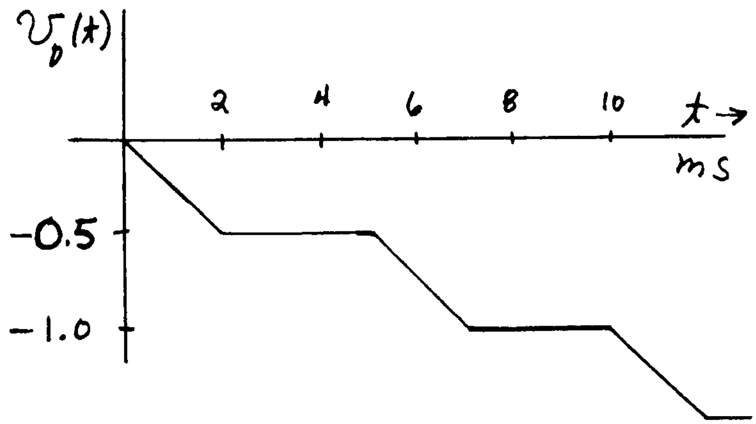
Due to all of the imperfections, the extreme output voltages are:

$$V_{o.\max} = 44 + 20 + 2.5 = 66.5 \text{ mV}$$

$$V_{o,\min} = -44 + 10 - 2.5 = -36.5 \text{ mV}$$

P14.70* The circuit diagram is shown in Figure 14.33 in the text. To achieve a nominal gain of 10, we need to have $R_2 = 10R_1$. Values of R_1 ranging from about 1 kΩ to 100 kΩ are practical. A good choice of values is R_1 = 10 kΩ and R_2 = 100 kΩ.

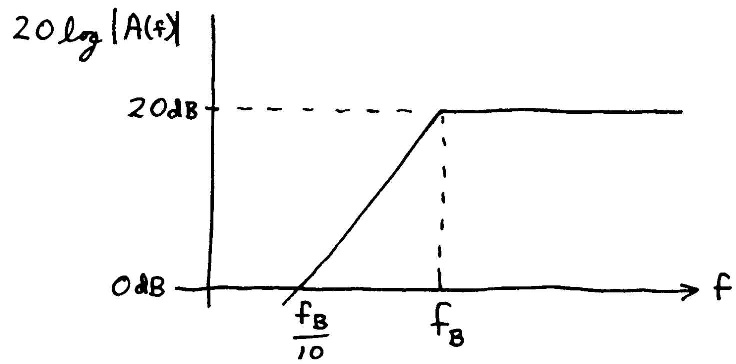
P14.74*



20 pulses are required to produce v_o = -10V.

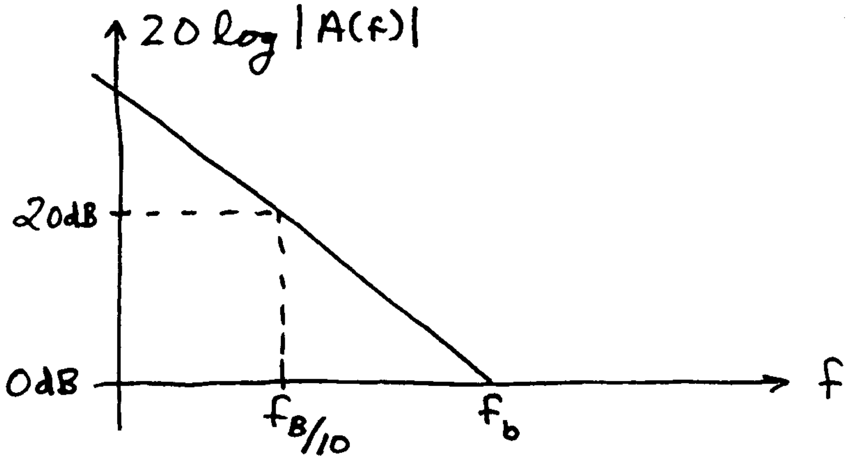
P14.78* (a) $$A(f) = \frac{-10}{1 - jf_B/f}$$

where $f_B = \dfrac{1}{2\pi RC}$



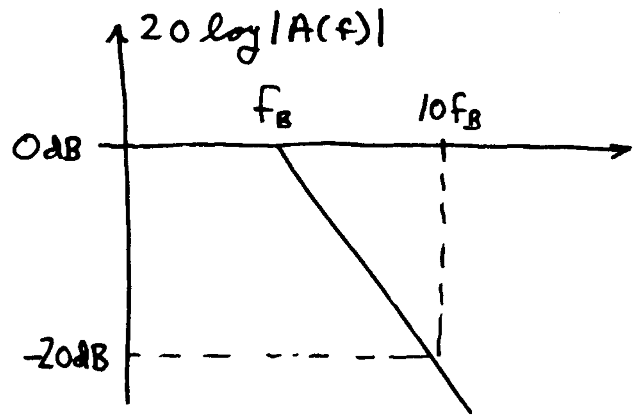
(b) $$A(f) = -\frac{R + 1/j\omega C}{R} = -\left(1 - j\frac{f_B}{f}\right)$$

where $f_B = \dfrac{1}{2\pi RC}$



(c) $A(f) = -\dfrac{\dfrac{1}{1/R + j\omega C}}{R} = -\dfrac{1}{1 + jf/f_B}$

where $f_B = \dfrac{1}{2\pi RC}$



Practice Test

T14.1 (a) The circuit diagram is shown in Figure 14.4 and the voltage gain is $A_v = -R_2/R_1$. Of course, you could use different resistance labels such as R_A and R_B so long as your equation for the gain is modified accordingly.

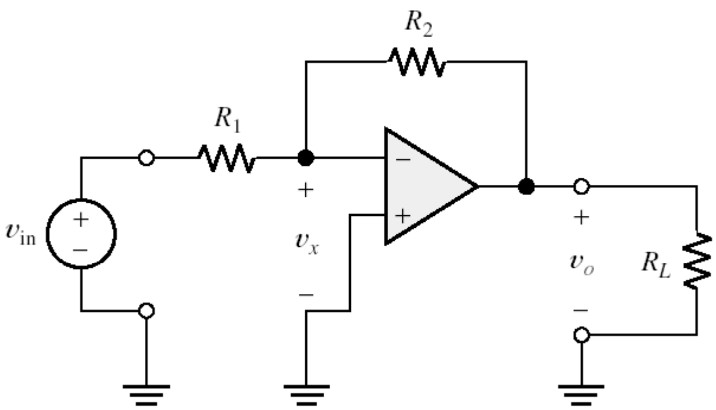


Figure 14.4 The inverting amplifier.

(b) The circuit diagram is shown in Figure 14.11 and the voltage gain is $A_v = 1 + R_2/R_1$.

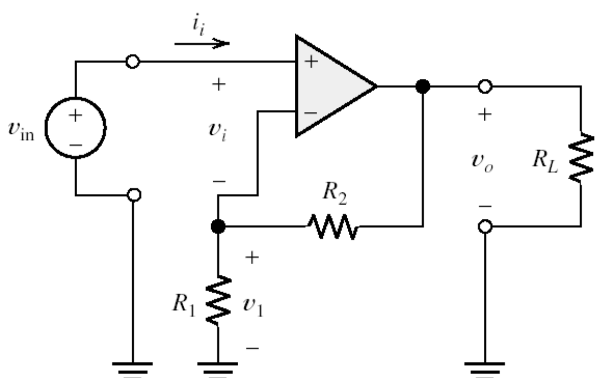
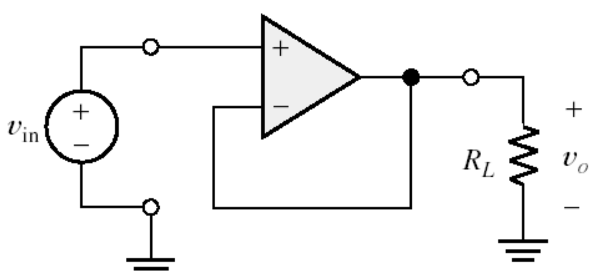


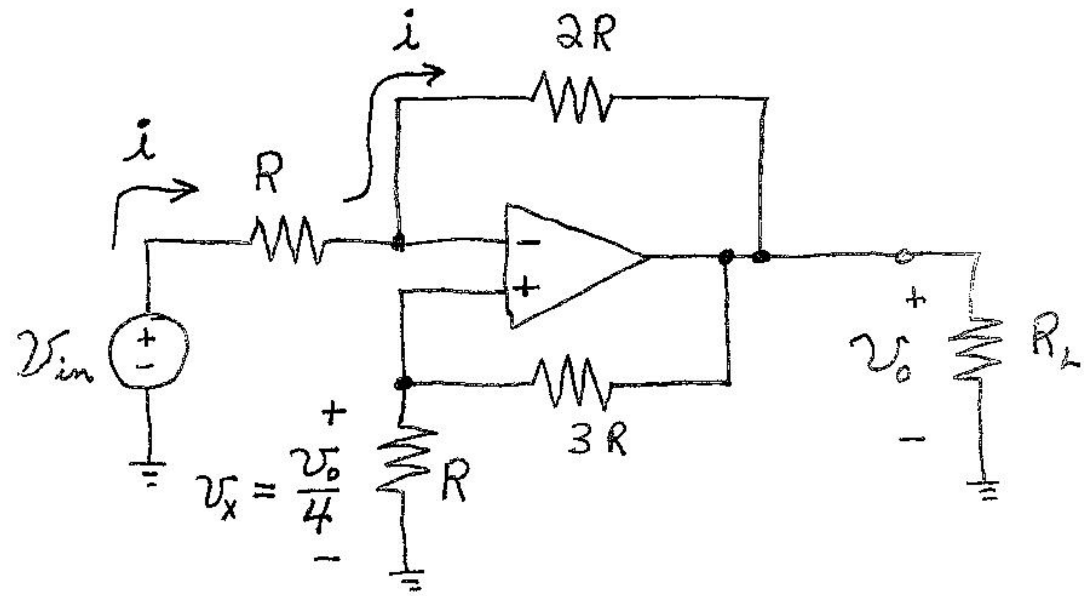
Figure 14.11 Noninverting amplifier.

(c) The circuit diagram is shown in Figure 14.12 and the voltage gain is $A_v = 1$.



T14.2 Because the currents flowing into the op-amp input terminals are zero, we can apply the voltage-division principle to determine the voltage v_x at the noninverting input with respect to ground:

$$v_x = v_o \frac{R}{R + 3R} = \frac{v_o}{4}$$



This is also the voltage at the inverting input, because the voltage between the op-amp input terminals is zero. Thus, the current i is

$$i = \frac{v_{\text{in}} - v_o / 4}{R}$$

Then, we can write a voltage equation starting from the ground node, through v_o, through the $2R$ resistance, across the op-amp input terminals, and then through v_x to ground. This gives

$$-v_o - 2Ri + 0 + v_x = 0$$

Substituting for i and v_x gives:

$$-v_o - 2R\frac{v_{\text{in}} - v_o / 4}{R} + 0 + \frac{v_o}{4} = 0$$

which simplifies to $v_o = -8v_{\text{in}}$. Thus, the voltage gain is $A_v = -8$.

T14.3 (a) $f_{BCL} = \dfrac{f_t}{A_{0CL}} = \dfrac{A_{0OL} f_{BOL}}{A_{0CL}} = \dfrac{2 \times 10^5 \times 5}{100} = 10\ \text{kHz}$

(b) Equation 14.32 gives the closed-loop gain as a function of frequency:

$$A_{CL}(f) = \frac{A_{0CL}}{1 + j(f/f_{BCL})} = \frac{100}{1 + j(f/10^4)}$$

The input signal has a frequency of 10^5 Hz, and a phasor representation given by $\mathbf{V}_{in} = 0.05\angle 0^\circ$. The transfer function evaluated for the frequency of the input signal is

$$A_{CL}(10^5) = \frac{100}{1 + j(10^5/10^4)} = 9.95\angle -84.29^\circ$$

The phasor for the output signal is

$$\mathbf{V}_o = A_{CL}(10^5)\mathbf{V}_{in} = (9.95\angle -84.29^\circ) \times (0.05\angle 0^\circ) = 0.4975\angle -84.29^\circ$$

and the output voltage is $v_o(t) = 0.4975\cos(2\pi \times 10^5 t - 84.29^\circ)$.

T14.4 (a) $f_{FP} = \dfrac{SR}{2\pi V_{om}} = \dfrac{20 \times 10^6}{2\pi \times 4.5} = 707.4\ \text{kHz}$

(b) In this case, the limit is due to the maximum current available from the op amp. Thus, the maximum output voltage is:

$$V_{om} = 5\ \text{mA} \times 200\ \Omega = 1\ \text{V}$$

(The current through R_2 is negligible.)

(c) $V_{om} = 4.5\ \text{V}$. (It is limited by the maximum output voltage capability of the op amp.)

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

$$v_o(t) = V_{om}\sin(\omega t)$$

$$\frac{dv_o(t)}{dt} = \omega V_{om}\cos(\omega t)$$

$$\left|\frac{dv_o(t)}{dt}\right|_{\max} = \omega V_{om} = \text{SR}$$

$$V_{om} = \frac{SR}{\omega} = \frac{20 \times 10^6}{2\pi \times 5 \times 10^6} = 0.637\ \text{V}$$

T14.5 See Figure 14.29 for the circuit.

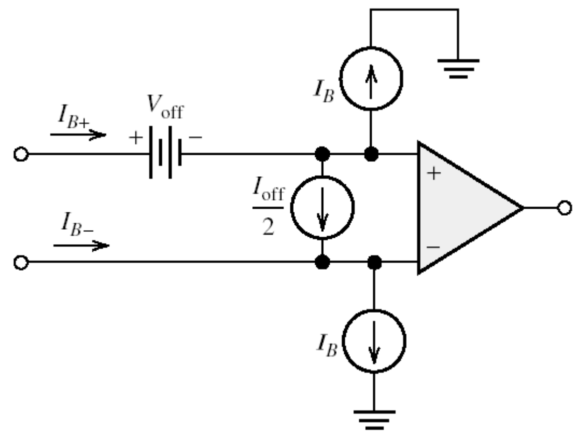


Figure 14.29 Three current sources and a voltage source model the dc imperfections of an op amp.

The effect on amplifiers of bias current, offset current, and offset voltage is to add a (usually undesirable) dc voltage to the intended output signal.

T14.6 See Figure 14.33 in the book.

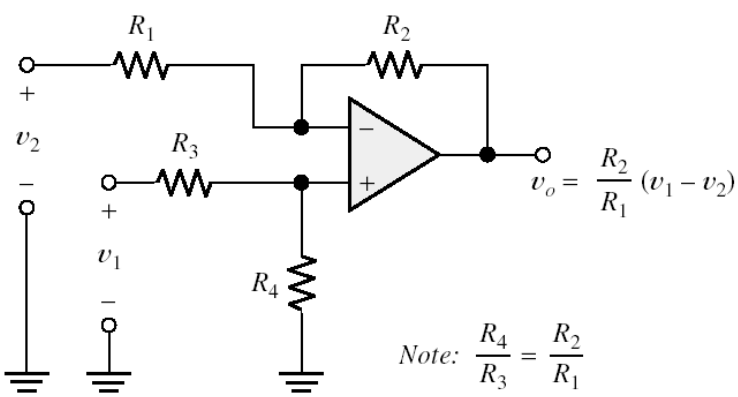


Figure 14.33 Differential amplifier.

Usually, we would have $R_1 = R_3$ and $R_2 = R_4$.

T14.7 See Figures 14.35 and 14.38 in the book:

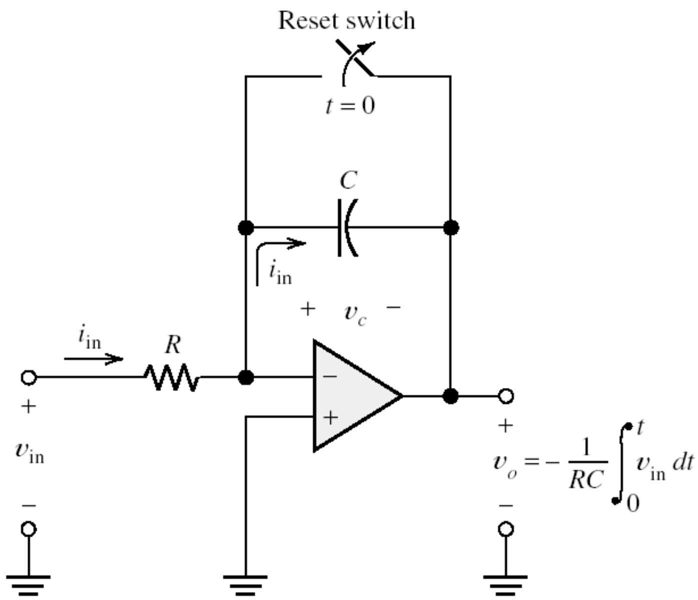


Figure 14.35 Integrator.

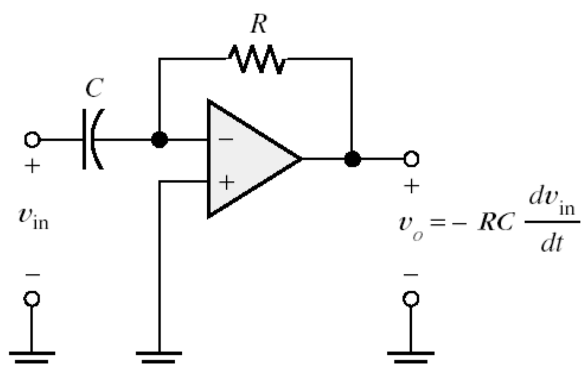


Figure 14.38 Differentiator.

T14.8 Filters are circuits designed to pass input components with frequencies in one range to the output and prevent input components with frequencies in other ranges from reaching the output.

An active filter is a filter composed of op amps, resistors, and capacitors.

Some applications for filters mentioned in the text are:

1. In an electrocardiograph, we need a filter that passes the heart signals, which have frequencies below about 100 Hz, and rejects higher frequency noise that can be created by contraction of other muscles.

2. Using a lowpass filter to remove noise from historical phonograph recordings.

3. In digital instrumentation systems, a low pass filter is often needed to remove noise and signal components that have frequencies higher than half of the sampling frequency to avoid a type of distortion, known as aliasing, during sampling and analog-to-digital conversion.