Problem 4.5 For the op-amp circuit shown in Fig. P4.5:

(a) Use the model given in Fig. 4-4 to develop an expression for the current gain $G_i = i_L/i_s$.

(b) Simplify the expression by applying the ideal op-amp model by (taking $A \to \infty$, $R_i \to \infty$, and $R_o \to 0$).

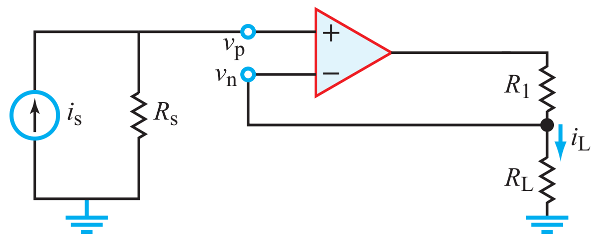
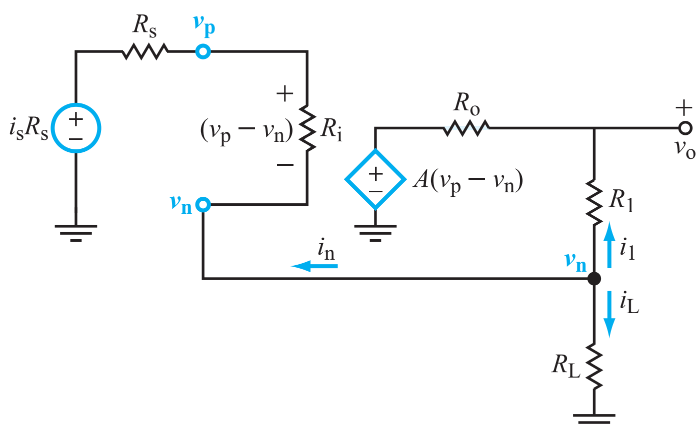


Figure P4.5: Circuit for Problem 4.5.

Solution: (a) We start by replacing the op amp in Fig. P4.5 with its equivalent model, and to simplify the analysis, we will convert the parallel combination of (i_s, R_s) into a voltage source $v_s = i_s R_s$ and a series resistor R_s.



At node v_n,

$$i_1 + i_L + i_n = 0 \tag{1}$$

$$i_1 = \frac{v_n - A(v_p - v_n)}{R_1 + R_o}$$

$$i_L = \frac{v_n}{R_L}$$

$$i_n = \frac{v_n - i_s R_s}{R_s + R_i}$$

Hence,

$$\frac{v_n - A(v_p - v_n)}{R_1 + R_o} + \frac{v_n}{R_L} + \frac{v_n - i_s R_s}{R_s + R_i} = 0 \tag{2}$$

Additionally,

$$v_p - v_n = -R_i i_n = -R_i \left(\frac{v_n - i_s R_s}{R_s + R_i} \right) \tag{3}$$

Using Eq. (3) in Eq. (2) and then solving for v_n leads to:

$$v_n = \frac{(AR_i + R_1 + R_o) i_s R_s R_L}{(R_s + R_i)(R_L + R_1 + R_o) + R_L (AR_i + R_1 + R_o)} \, .$$

$$i_L = \frac{v_n}{R_L} \, ,$$

and

$$G_i = \frac{i_L}{i_s} = \frac{v_n}{R_L i_s} = \frac{(AR_i + R_1 + R_o) R_s}{(R_s + R_i)(R_L + R_1 + R_o) + R_L (AR_i + R_1 + R_o)} \, .$$

(b) For the ideal op amp,

$$A \approx 10^6 \quad \text{and} \quad R_i \approx 10^6 \ \Omega,$$

so the product of the two is many orders of magnitude larger than all other products. Hence,

$$G_i \simeq \frac{AR_i R_s}{AR_i R_L} = \frac{R_s}{R_L} \, .$$

Problem 4.11 Determine the output voltage for the circuit in Fig. P4.11 and specify the linear range for v_s, given that $V_{cc} = 15$ V and $V_0 = 0$.

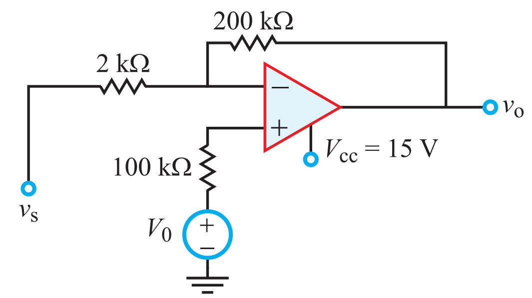
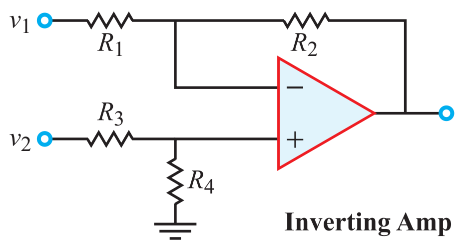


Figure P4.11: Circuit for Problem 4.11.



Solution: The given circuit is the same as the difference amplifier circuit of Table 4-3, with:

$$R_2 = 200 \text{ k}\Omega, \qquad R_1 = 2 \text{ k}\Omega, \qquad R_3 = 100 \text{ k}\Omega,$$
$$R_4 = \infty, \qquad v_1 = v_s, \qquad v_2 = V_0 = 0.$$

Applying the difference amplifier equation given by Eq. (4.41),

$$v_o = \left(\frac{R_4}{R_3 + R_4}\right)\left(\frac{R_1 + R_2}{R_1}\right) v_2 - \left(\frac{R_2}{R_1}\right) v_1$$
$$= -\left(\frac{200 \times 10^3}{2 \times 10^3}\right) v_s = -100 v_s.$$

Since $|(v_o)_{\max}| = 15$ V, the linear range of v_s is

$$|v_s| \le \frac{15}{100} = 150 \text{ mV},$$

or $-150 \text{ mV} \le v_s \le 150$ mV.

Problem 4.17 Determine v_o across the 10-kΩ resistor in the circuit of Fig. P4.17.

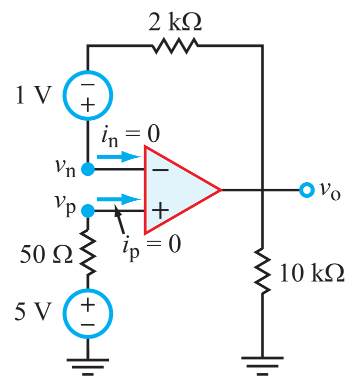


Figure P4.17: Circuit for Problem 4.17.

Solution: Since $i_p = 0$, there is no voltage drop across the 2-kΩ resistor. Hence,

$$v_o = (v_n - 1) \text{ V}.$$

Similarly, since $i_p = 0$,

$$v_p = 5 \text{ V}.$$

Moreover, $v_p = v_n$ (ideal op-amp constraint), leading to

$$v_o = 5 - 1 = 4 \text{ V}.$$

Problem 4.19 Repeat Problem 4.18 for $R_f = 0$.

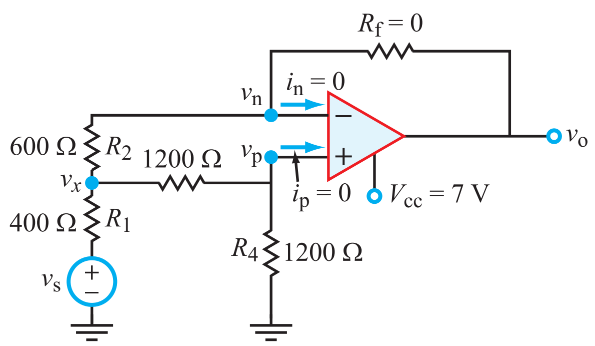


Figure P4.19: Circuit for Problem 4.19.

Solution: Since $R_f = 0$,

$$v_o = v_n.$$

At node v_x:

$$\frac{v_x - v_s}{R_1} + \frac{v_x - v_n}{R_2} + \frac{v_x}{R_3 + R_4} = 0$$

Voltage division:

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

Invoking $v_p = v_n$ leads to:

$$\frac{v_x - v_s}{R_1} + \frac{1}{R_2}\left(v_x - \frac{v_x R_4}{R_3 + R_4}\right) + \frac{v_x}{R_3 + R_4} = 0$$

Hence,

$$v_x = \frac{R_2(R_3 + R_4)v_s}{(R_1 + R_2)(R_3 + R_4) + R_1R_2 - R_4R_1}$$

$$v_o = v_n = \left(\frac{R_4}{R_3 + R_4}\right) v_x = \frac{R_2R_4v_s}{(R_1 + R_2)(R_3 + R_4) + R_1R_2 - R_4R_1}$$

$$G = \frac{v_o}{v_s} = \frac{600 \times 1200}{(400 + 600)(1200 + 1200) + 400 \times 600 - 1200 \times 400} = 0.33$$

Hence, the linear range of v_s is

$$-\frac{7}{0.33}\text{ V} \le v_s \le \frac{7}{0.33}\text{ V},$$

or -21 V $\le v_s \le 21$ V.

Problem 4.42 In the circuit of Fig. P4.42, Op Amp 1 receives feedback at its input from its own output as well as from the output of Op Amp 2. Relate v_o to v_s.

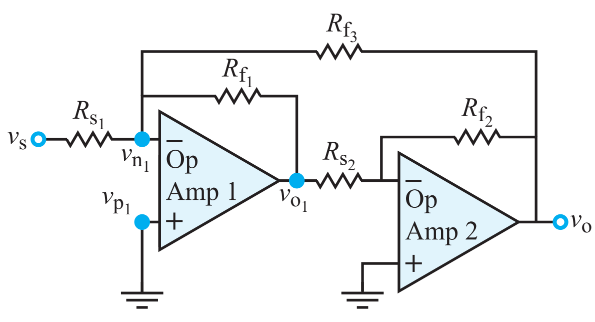


Figure P4.42: Circuit for Problem 4.42.

Solution: For the second op amp,

$$v_o = \left(-\frac{R_{f_2}}{R_{s_2}}\right) v_{o_1} \tag{1}$$

For the first op amp,

$$\frac{v_{n_1} - v_s}{R_{s_1}} + \frac{v_{n_1} - v_{o_1}}{R_{f_1}} + \frac{v_{n_1} - v_o}{R_{f_3}} = 0$$

Also,

$$v_{n_1} = v_{p_1} = 0.$$

Hence,

$$-\frac{v_s}{R_{s_1}} - \frac{v_{o_1}}{R_{f_1}} - \frac{v_o}{R_{f_3}} = 0 \tag{2}$$

Simultaneous solution of (1) and (2) leads to

$$v_o = \frac{v_s}{R_{s_1}} \left[\frac{R_{f_1} R_{f_2} R_{f_3}}{R_{f_3} R_{s_2} - R_{f_1} R_{f_2}}\right].$$