1.2 The operational amplifier

1.5 Given an op amp with $r_d \cong \infty$, $a = 10^4$ V/V, and $r_o \cong 0$, find (*a*) v_O if $v_P = 750.25$ mV and $v_N = 751.50$ mV, (*b*) v_N if $v_O = -5$ V and $v_P = 0$, (*c*) v_P if $v_N = v_O = 5$ V, and (*d*) v_N if $v_P = -v_O = 1$ V.

1.6 A 741 op amp drives a 1-kΩ load. Find the voltages across and the currents through r_d and r_o if $v_P = 1$ V and $v_O = 5$ V.

1.3 Basic op amp configurations

1.7 In the noninverting amplifier of Fig. 1.6*a*, let $R_1 = 100$ kΩ, $R_2 = 200$ kΩ, and $a = \infty$. (*a*) What is its closed-loop gain? How does its gain change if a third resistance $R_3 = 100$ kΩ is connected in series with R_1? In parallel with R_1? In series with R_2? In parallel with R_2? (*b*) Repeat (*a*) for the inverting amplifier of Fig. 1.10*a*.

1.8 (*a*) Design a noninverting amplifier whose gain is variable over the range 1 V/V $\le A \le$ 5 V/V by means of a 100-kΩ pot. (*b*) Repeat (*a*) for 0.5 V/V $\le A \le$ 2 V/V. *Hint:* To achieve $A \le 1$ V/V, you need an input voltage divider.

1.9 (*a*) A noninverting amplifier is implemented with two 10-kΩ resistances having 5% tolerance. What is the range of possible values for the gain A? How would you modify the circuit for the exact calibration of A? (*b*) Repeat, but for the inverting amplifier.

1.10 In the inverting amplifier of Fig. 1.10*a*, let $v_I = 0.1$ V, $R_1 = 10$ kΩ, and $R_2 = 100$ kΩ. Find v_O and v_N if (*a*) $a = 10^2$ V/V, (*b*) $a = 10^4$ V/V, (*c*) $a = 10^6$ V/V. Comment on your findings.

1.11 (*a*) Design an inverting amplifier whose gain is variable over the range -10 V/V $\le A \le 0$ by means of a 100-kΩ pot. (*b*) Repeat, but for -10 V/V $\le A \le -1$ V/V. *Hint:* To prevent A from reaching zero, you must use a suitable resistor in series with the pot.

1.12 (*a*) A source $v_S = 2$ V with $R_s = 10$ kΩ is to drive a gain-of-five inverting amplifier implemented with $R_1 = 20$ kΩ and $R_2 = 100$ kΩ. Find the amplifier output voltage and verify that because of loading its magnitude is *less* than $2 \times 5 = 10$ V. (*b*) Find the value to which R_2 must be changed if we want to compensate for loading and obtain a full output magnitude of 10 V.

1.13 (*a*) A source $v_S = 10$ V is fed to a voltage divider implemented with $R_A = 120$ kΩ and $R_B = 30$ kΩ, and the voltage across R_B is fed, in turn, to a gain-of-five noninverting amplifier having $R_1 = 30$ kΩ and $R_2 = 120$ kΩ. Sketch the circuit, and predict the amplifier output voltage v_O. (*b*) Repeat (*a*) for a gain-of-five inverting amplifier having $R_1 = 30$ kΩ and $R_2 = 150$ kΩ. Compare and comment on the differences.

1.14 An inverting amplifier is implemented with $R_1 = 10$ kΩ, $R_2 = 20$ kΩ and an op amp with $r_d \cong \infty$, $a = 1$ V/mV, and $r_o \cong 0$. Sketch and label v_I, v_O, and v_N versus time if v_I is a 1-kHz sine wave with ±5-V peak values.

1.4 Ideal op amp circuit analysis

– **1.15** Find v_N, v_P, and v_O in the circuit of Fig. P1.15, as well as the power released by the 4-V source; devise a method to check your results.

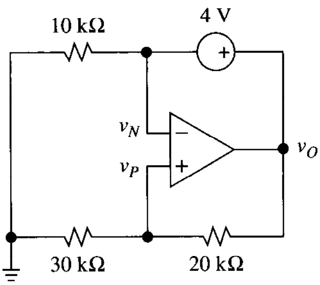

FIGURE P1.15

1.16 (*a*) Find v_N, v_P, and v_O in the circuit of Fig. P1.16. (*b*) Repeat (*a*) with a 5-kΩ resistance connected between A and B.

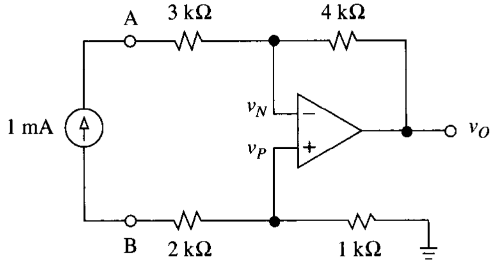

FIGURE P1.16

1.17 (*a*) Find v_N, v_P, and v_O in the circuit of Fig. P1.17 if $v_S = 9$ V. (*b*) Find the resistance *R* that, if connected between the inverting-input pin of the op amp and ground, causes v_O to double. Verify with PSpice.

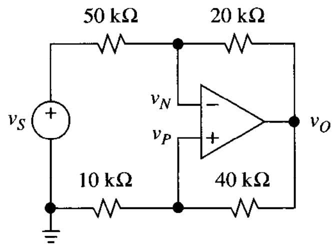

FIGURE P1.17

1.18 (*a*) Find v_N, v_P, and v_O in the circuit of Fig. P1.18. (*b*) Repeat (*a*) with a 40-kΩ resistance in parallel with the 0.3-mA source.

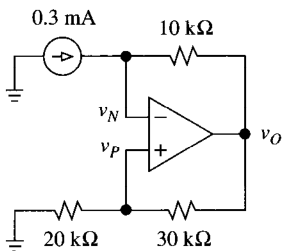

FIGURE P1.18

1.19 (a) Find v_N, v_P, and v_O in the circuit of Fig. P1.19 if $i_S = 1$ mA. (b) Find a resistance R that when connected in parallel with the 1-mA source will cause v_O to drop to half the value found in (a).

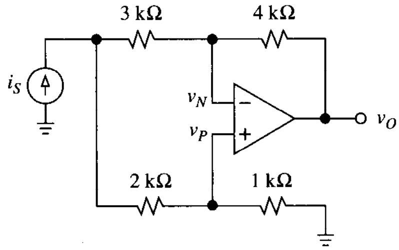

FIGURE P1.19

1.20 (a) If the current source of Fig. P1.16 is replaced by a voltage source v_S, find the magnitude and polarity of v_S so that $v_O = 10$ V. (b) If the wire connecting the 4-V source to node v_O in Fig. P1.15 is cut and a 5-kΩ resistance is inserted in series between the two, to what value must the source be changed to yield $v_O = 10$ V?

1.21 In the circuit of Fig. P1.21 the switch is designed to provide gain-polarity control. (a) Verify that $A = +1$ V/V when the switch is open, and $A = -R_2/R_1$ when the switch is closed, so that making $R_1 = R_2$ yields $A = \pm 1$ V/V. (b) To accommodate gains greater than unity, connect an additional resistance R_4 from the inverting-input pin of the op amp to ground. Derive separate expressions for A in terms of R_1 through R_4 with the switch open and with the switch closed. (c) Specify resistance values suitable for achieving $A = \pm 2$ V/V.

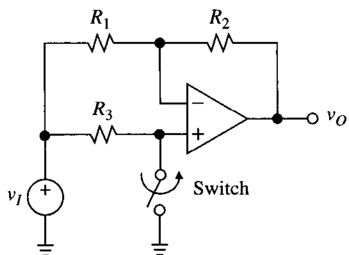

FIGURE P1.21

1.22 In the circuit of Fig. P1.22 the pot is used to control gain magnitude as well as polarity. (a) Letting k denote the fraction of R_3 between the wiper and ground, show that varying the wiper from bottom to top varies the gain over the range $-R_2/R_1 \leq A \leq 1$ V/V, so that making $R_1 = R_2$ yields -1 V/V $\leq A \leq +1$ V/V. (b) To accommodate gains greater than unity, connect an additional resistance R_4 from the op amp's inverting-input pin to ground. Derive an expression for A in terms of R_1, R_2, R_4, and k. (c) Specify resistance values suitable for achieving -5 V/V $\leq A \leq +5$ V/V.

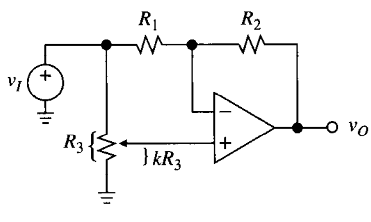

FIGURE P1.22

1.23 Consider the following statements about the input resistance R_i of the noninverting amplifier of Fig. 1.14*a*: (*a*) Since we are looking straight into the noninverting-input pin, which is an open circuit, we have $R_i = \infty$; (*b*) since the input pins are virtually shorted together, we have $R_i = 0 + (R_1 \parallel R_2) = R_1 \parallel R_2$; (*c*) since the noninverting-input pin is virtually shorted to the inverting-input pin, which is in turn a virtual-ground node, we have $R_i = 0 + 0 = 0$. Which statement is correct? How would you refute the other two?

1.24 (*a*) Show that the circuit of Fig. P1.24 has $R_i = \infty$ and $A = -(1 + R_3/R_4)R_1/R_2$. (*b*) Specify suitable components to make A variable over the range $-100\ \text{V/V} \le A \le 0$ by means of a 100-kΩ pot. Try minimizing the number of resistors you use.

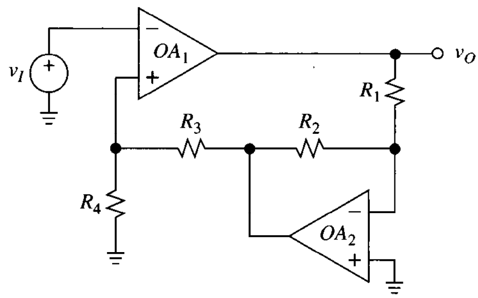

FIGURE P1.24

1.25 The audio panpot circuit of Fig. P1.25 is used to continuously vary the position of signal v_I between the left and the right stereo channels. (*a*) Discuss circuit operation. (*b*) Specify R_1 and R_2 so that $v_L/v_I = -1$ V/V when the wiper is fully down, $v_R/v_I = -1$ V/V when the wiper is fully up, and $v_L/v_I = v_R/v_I = -1/\sqrt{2}$ when the wiper is halfway.

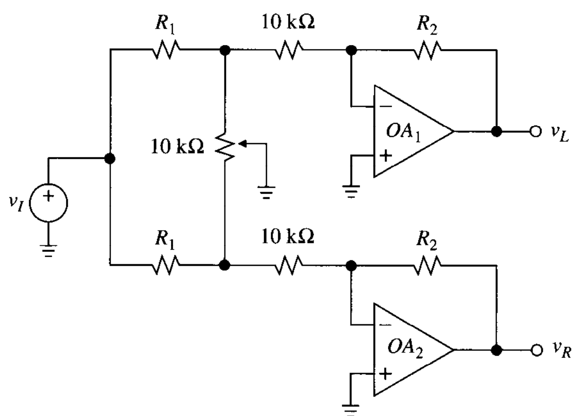

FIGURE P1.25

1.26 (*a*) Using standard 5% resistances in the kilohm range, design a circuit to yield $v_O = -100(4v_1 + 3v_2 + 2v_3 + v_4)$. (*b*) If $v_1 = 20$ mV, $v_2 = -50$ mV, and $v_4 = 100$ mV, find v_3 for $v_O = 0$ V.

1.27 (*a*) Using standard 5% resistances, design a circuit to give (*a*) $v_O = -10(v_I + 1\ \text{V})$; (*b*) $v_O = -v_I + V_O$, where V_O is variable over the range $-5\ \text{V} \le V_O \le +5\ \text{V}$ by means of a 100-kΩ pot. *Hint:* Connect the pot between the ±15-V supplies and use the wiper voltage as one of the inputs to your circuit.

1.28 In the circuit of Fig. 1.17 let $R_1 = R_3 = R_4 = 10\,\text{k}\Omega$ and $R_2 = 30\,\text{k}\Omega$. (*a*) If $v_1 = 3$ V, find v_2 for $v_O = 10$ V. (*b*) If $v_2 = 6$ V, find v_1 for $v_O = 0$ V. (*c*) If $v_1 = 1$ V, find the range of values for v_2 for which $-10\text{ V} \le v_O \le +10\text{ V}$.

1.29 You can readily verify that if we put the output in the form $v_O = A_2v_2 - A_1v_1$ in the circuit of Fig. 1.17, then $A_2 \le A_1 + 1$. Applications requiring $A_2 \ge A_1 + 1$ can be accommodated by connecting an additional resistance R_5 from the node common to R_1 and R_2 to ground. (*a*) Sketch the modified circuit and derive a relationship between its output and inputs. (*b*) Specify standard resistances to achieve $v_O = 5(2v_2 - v_1)$. Try minimizing the number of resistors you use.

1.30 (*a*) In the difference amplifier of Fig. 1.17 let $R_1 = R_3 = 10\text{ k}\Omega$ and $R_2 = R_4 = 100$ kΩ. Find v_O if $v_1 = 10\cos 2\pi 60t - 0.5\cos 2\pi 10^3 t$ V, and $v_2 = 10\cos 2\pi 60t + 0.5\cos 2\pi 10^3 t$ V. (*b*) Repeat if R_4 is changed to 101 kΩ. Comment on your findings.

– **1.31** Show that if all resistances in Fig. P1.31 are equal, then $v_O = v_2 + v_4 + v_6 - v_1 - v_3 - v_5$.

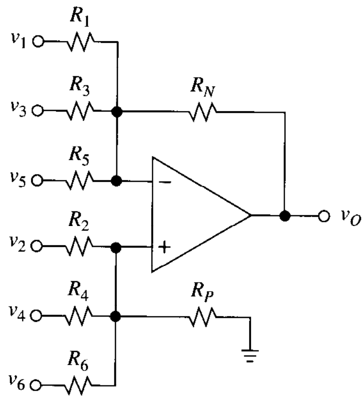

FIGURE P1.31

1.32 Using a topology of the type of Fig. P1.31, design a four-input amplifier such that $v_O = 4v_A - 3v_B + 2v_C - v_D$. Try minimizing the number of resistors you use.

1.33 Using just one op amp powered from ±12-V regulated supplies, design a circuit to yield: (*a*) $v_O = 10v_I + 5$ V; (*b*) $v_O = 10(v_2 - v_1) - 5$ V.

1.34 Using just one op amp powered from ±15-V supply voltages, design a circuit that accepts an ac input v_i and yields $v_O = v_i + 5$ V, under the constraint that the resistance seen by the ac source be 100 kΩ.

1.35 Design a two-input, two-output circuit that yields the sum and the difference of its inputs: $v_S = v_{I1} + v_{I2}$, and $v_D = v_{I1} - v_{I2}$. Try minimizing the component count.

1.36 Obtain a relationship between v_O and v_I if the differentiator of Fig. 1.18 includes also a resistance R_s in series with C. Discuss the extreme cases of v_I changing very slowly and very rapidly.

1.37 Obtain a relationship between v_O and v_I if the integrator of Fig. 1.19 includes also a resistance R_p in parallel with C. Discuss the extreme cases of v_I changing very rapidly and very slowly.

1.36 Obtain a relationship between v_O and v_I if the differentiator of Fig. 1.18 includes also a resistance R_s in series with C. Discuss the extreme cases of v_I changing very slowly and very rapidly.

1.37 Obtain a relationship between v_O and v_I if the integrator of Fig. 1.19 includes also a resistance R_p in parallel with C. Discuss the extreme cases of v_I changing very rapidly and very slowly.

1.38 In the differentiator of Fig. 1.18 let $C = 10$ nF and $R = 100$ kΩ, and let v_I be a periodic signal alternating between 0 V and 2 V with a frequency of 100 Hz. Sketch and label v_I and v_O versus time if v_I is (*a*) a sine wave; (*b*) a triangular wave.

1.39 In the integrator of Fig. 1.19 let $R = 100$ kΩ and $C = 10$ nF. Sketch and label $v_I(t)$ and $v_O(t)$ if (*a*) $v_I = 5 \sin 2\pi 100t$ V and $v_O(0) = 0$; (*b*) $v_I = 5[u(t) - u(t - 2 \text{ ms})]$ V and $v_O(0) = 5$ V, where $u(t - t_0)$ is the unit step function defined as $u = 0$ for $t < t_0$, and $u = 1$ for $t > t_0$.

1.40 (*a*) In the integrator of Fig. 1.19 let $R = 10$ kΩ and $C = 0.1$ μF. Assuming that C is initially discharged, sketch and label $v_O(t)$ for $0 \le t \le 10$ ms if v_I is a 1-V step. (*b*) Repeat (*a*) with a 100-kΩ resistance connected in parallel with C.

1.41 If R_F in the summing amplifier of Fig. 1.15 is replaced by a capacitance C, the circuit becomes a *summing integrator*. (*a*) Derive a relationship between its output and its inputs. (*b*) Using a 10-nF capacitance, specify suitable resistances for $v_O(t) = v_O(0) - 10^3(\int_0^t v_1\, d\xi + 2\int_0^t v_2\, d\xi + 0.5\int_0^t v_3\, d\xi)$.

1.42 Show that if the op amp of Fig. 1.20*b* has a finite gain a, then $R_{eq} = (-R_1R/R_2) \times [1 + (1 + R_2/R_1)/a]/[1 - (1 + R_1/R_2)/a]$.

– **1.43** Find an expression for R_i in Fig. P1.43; discuss its behavior as R is varied over the range $0 \le R \le 2R_1$.

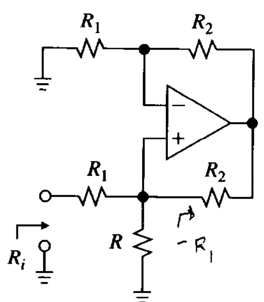

FIGURE P1.43

– **1.44** The circuit of Fig. P1.44 can be used to control the input resistance of the inverting amplifier based on OA_1. (*a*) Show that $R_i = R_1/(1 - R_1/R_3)$. (*b*) Specify resistances suitable for achieving $A = -10$ V/V with $R_i = \infty$.

1.5 Negative feedback

1.45 A voltage amplifier has $a = 10^5$ V/V and $v_i = 10$ mV. Find v_d, v_f, v_o, A, T, and the percentage deviation of A from A_{ideal} for $\beta = 10^{-3}$ V/V, 10^{-2} V/V, 10^{-1} V/V, and 1 V/V. Compare the various cases and comment.

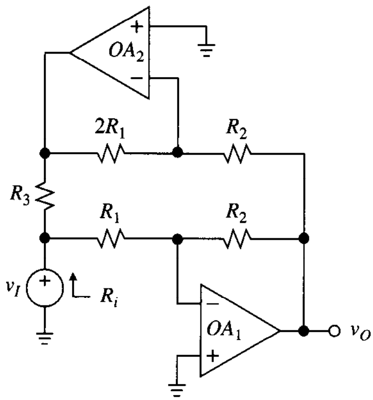

FIGURE P1.44

1.46 (a) Find the desensitivity factor of a negative-feedback system with $a = 10^3$ and $A = 10^2$. (b) Find A exactly via Eq. (1.40), and approximately via Eq. (1.49) if a drops by 10%. (c) Repeat (b) for a 50% drop in a; compare with (b) and comment.

1.47 You are asked to design an amplifier with a gain A of 10^2 V/V that is accurate to within $\pm 0.1\%$, or $A = 10^2$ V/V $\pm 0.1\%$. All you have available are amplifier stages with $a = 10^4$ V/V $\pm$ 25% each. Your amplifier can be implemented using a cascade of basic stages, each employing a suitable amount of negative feedback. What is the minimum number of stages required? What is the β of each stage?

1.48 The open-loop VTC of a certain amplifier can be approximated piecewise by five segments with symmetric breakpoints at $(v_D, v_O) = \pm(80\ \mu\text{V}, 8\ \text{V})$, $\pm(280\ \mu\text{V}, 12\ \text{V})$, and $\pm(530\ \mu\text{V}, 13\ \text{V})$. ($a$) Sketch the above VTC; calculate and sketch the closed-loop VTC when the amplifier is placed in a feedback loop with $\beta = 0.5$ V/V. (b) Sketch v_I, v_O, and v_D versus time if v_I is a triangular wave with $\pm$5-V peak values; comment on the waveform of v_D. *Hint:* $v_D(t)$ can be derived point by point from $v_O(t)$ using the open-loop VTC of (a).

1.49 A crude BJT power amplifier of the class B (push-pull) type exhibits the VTC of Fig. P1.49b. The dead band occurring for $-0.7\ \text{V} \le v_1 \le +0.7\ \text{V}$ causes a crossover distortion at the output that can be reduced by preceding the power stage with a preamplifier stage and then using negative feedback to reduce the dead band. This is shown in Fig. P1.49a for the case of a difference preamplifier with gain a_1 and $\beta = 1$ V/V. (a) Sketch and label the closed-loop VTC if $a_1 = 10^2$ V/V. (b) Sketch v_I, v_1, and v_O versus time if v_I is a 100-Hz triangular wave with peak values of ± 1 V.

1.50 A certain audio power amplifier with a signal gain of 10 V/V is found to produce a 2-V peak-to-peak 120-Hz hum. We wish to reduce the output hum to less than 1 mV without changing the signal gain. To this end, we precede the power stage with a preamplifier stage with gain a_1 and then apply negative feedback around the composite amplifier. What are the required values of a_1 and β?

1.6 Feedback in op amp circuits

1.51 A voltage follower is implemented with an op amp having $r_d = 1\ \text{M}\Omega$, $a = 1$ V/mV, and $r_o = 1\ \text{k}\Omega$. (a) Find v_O if the follower is driven by a source $v_S = 10.000$ V with $R_s = 2\ \text{M}\Omega$. (b) Repeat (a) with a 1-kΩ output load.