1.2 The operational amplifier

1.5 Given an op amp with \( r_d \equiv \infty, a = 10^4 \) V/V, and \( r_o \equiv 0 \), 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-k\( \Omega \) 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. 1.6a, let \( R_1 = 100 \) k\( \Omega \), \( R_2 = 200 \) k\( \Omega \), and \( a = \infty \). (a) What is its closed-loop gain? How does its gain change if a third resistance \( R_3 = 100 \) k\( \Omega \) 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. 1.10a.

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

1.9 (a) A noninverting amplifier is implemented with two 10-k\( \Omega \) 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. 1.10a, let \( v_i = 0.1 \) V, \( R_1 = 10 \) k\( \Omega \), and \( R_2 = 100 \) k\( \Omega \). 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 \( \leq A \leq 0 \) by means of a 100-k\( \Omega \) pot. (b) Repeat, but for \(-10 \) V/V \( \leq A \leq -1 \) V/V. \text{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 \( R_s = 10 \) k\( \Omega \) is to drive a gain-of-five inverting amplifier implemented with \( R_1 = 20 \) k\( \Omega \) and \( R_2 = 100 \) k\( \Omega \). 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 \( R_A = 120 \) k\( \Omega \) and \( R_B = 30 \) k\( \Omega \), and the voltage across \( R_B \) is fed, in turn, to a gain-of-five noninverting amplifier having \( R_1 = 30 \) k\( \Omega \) and \( R_2 = 120 \) k\( \Omega \). Sketch the circuit, and predict the output voltage \( v_o \). (b) Repeat (a) for a gain-of-five inverting amplifier having \( R_1 = 30 \) k\( \Omega \) and \( R_2 = 150 \) k\( \Omega \). Compare and comment on the differences.

1.14 An inverting amplifier is implemented with \( R_1 = 10 \) k\( \Omega \), \( R_2 = 20 \) k\( \Omega \) and an op amp with \( r_d \equiv \infty, a = 1 \) V/mV, and \( r_o \equiv 0 \). Sketch and label \( v_f, v_o, \) and \( v_N \) versus time if \( v_f \) is a 1-kHz sine wave with \( \pm 5 \) 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.
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](image)

**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](image)

**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](image)

**FIGURE P1.22**

1.26 (a) Find \( f \) in the circuit.

1.27 (a) Find \( f \) in the circuit.

(b) Find \( m \) in the circuit.
1.23 Consider the following statements about the input resistance $R_i$ of the noninverting amplifier of Fig. 1.14a: 

(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 $-100 \leq V/V \leq A \leq 9$ by means of a 100-kΩ pot. Try minimizing the number of resistors you use.

![Figure P1.24](image)

**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, $v_L/v_i = -1$ 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](image)

**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) $v_o = -10(v_i + 1$ V); (b) $v_o = -v_i + v_o$, where $v_o$ is variable over the range $-5 \leq V_o \leq +5$ 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 \( v_1 = 3 \, \text{V} \), find \( v_2 \) for \( v_O = 10 \, \text{V} \). (b) If \( v_2 = 6 \, \text{V} \), find \( v_1 \) for \( v_O = 0 \, \text{V} \). (c) If \( v_1 = 1 \, \text{V} \), find the range of values for \( v_2 \) for which \(-10 \, \text{V} \leq v_O \leq +10 \, \text{V} \).

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 \( A_2 \leq A_1 + 1 \). Applications requiring \( A_2 \geq A_1 + 1 \) can be accommodated by connecting an additional resistance \( R_3 \) 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 \( R_2 = R_4 = 100 \, \text{k}\Omega \). Find \( v_O \) if \( v_1 = 10\cos 2\pi 60t - 0.5\cos 2\pi 10^2t \, \text{V} \), and \( v_2 = 10\cos 2\pi 60t + 0.5\cos 2\pi 10^2t \, \text{V} \). (b) Repeat if \( R_4 \) is changed to \( 101 \, \text{k}\Omega \). 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](image)

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) \( v_O = 10v_I + 5 \, \text{V} \); (b) \( v_O = 10(v_2 - v_1) - 5 \, \text{V} \).

1.34 Using just one op amp powered from \( \pm15\)-V supply voltages, design a circuit that accepts an ac input \( v_I \) and yields \( v_O = v_I + 5 \, \text{V} \), under the constraint that the resistance seen by the ac source be \( 100 \, \text{k}\Omega \).

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 \( v_I \) 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 \( v_I \) 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 \( C = 10 \text{ nF} \) and \( R = 100 \text{ k}\Omega \), 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 \( v_I \) versus time if \( v_I \) is (a) a sine wave; (b) a triangular wave.

1.39 In the integrator of Fig. 1.19 let \( R = 100 \text{ k}\Omega \) and \( C = 10 \text{ nF} \). Sketch and label \( v_I(t) \) and \( v_I(t) \) if (a) \( v_I = 5 \sin 2\pi 100t \text{ V} \) and \( v_I(0) = 0 \); (b) \( v_I = 5[u(t) - u(t - 2 \text{ ms})] \text{ V} \) and \( v_I(0) = 5 \text{ V} \), 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 \( R = 10 \text{ k}\Omega \) and \( C = 0.1 \text{ \mu F} \). Assuming that \( C \) is initially discharged, sketch and label \( v_I(t) \) for 0 \( \leq t \leq 10 \text{ ms} \) if \( v_I \) is a 1-V step.

(b) Repeat (a) with a 100-k\Omega \) resistance connected in parallel with \( C \).

1.41 If \( R_p \) 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-\text{nF} \) capacitance, specify suitable resistances for \( v_I(t) = v_I(0) - 10^3 \int_0^t v_I(t') dt' + 2 \times 10^4 v_I(t) dt' + 0.5 \times 10^3 v_I(t) dt' \).

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

− 1.43 Find an expression for \( R_t \) in Fig. P1.43; discuss its behavior as \( R \) is varied over the range 0 \( \leq R \leq 2R_t \).

**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 \( R_i = R_t/(1 - R_t/R_s) \). (b) Specify resistances suitable for achieving \( A = -10 \text{ V/V} \) with \( R_t = \infty \).

1.5 Negative feedback

1.45 A voltage amplifier has \( A = 10^3 \text{ V/V} \) and \( v_I = 10 \text{ mV} \). Find \( v_{2d}, v_{1d}, v_{o}, A, T \), and the percentage deviation of \( A \) from \( A_{ideal} \) for \( \beta = 10^{-3} \text{ V/V}, 10^{-2} \text{ V/V}, 10^{-1} \text{ V/V}, \) and 1 V/V. Compare the various cases and comment.
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 ±0.1%, or $A = 10^2$ V/V ± 0.1%. All you have available are amplifier stages with $a = 10^3$ V/V ± 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 $\beta$ of each stage?

1.48 The open-loop VTC of a certain amplifier can be approximated piecewise by five segments with symmetric breakpoints at $(V_D, V_O) = (±60 \mu V, 8 \, \text{V})$, $(±280 \mu V, 12 \, \text{V})$, and $(±530 \mu V, 13 \, \text{V})$. (a) Sketch the above VTC; calculate and sketch the closed-loop VTC when the amplifier is placed in a feedback loop with $\beta = 0.5 \, \text{V/V}$. (b) Sketch $V_I$, $V_O$, and $V_D$ versus time if $V_D$ is a triangular wave with ±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 $V_D$.

1.49 A crude BIT power amplifier of the class B (push-pull) type exhibits the VTC of Fig. P1.49a. The dead band occurring for $-0.7 \, \text{V} \leq V_I \leq +0.7 \, \text{V}$ 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 $\beta = 1 \, \text{V/V}$. (a) Sketch and label the closed-loop VTC if $a_1 = 10^2 \, \text{V/V}$. (b) Sketch $V_I$, $V_O$, and $V_D$ 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 $\beta$?

1.6 Feedback in op amp circuits

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