

the same shape as the input. Clipping is generally undesirable, though there are situations in which it is exploited on purpose to achieve specific effects.

## PROBLEMS

### 1.1 Amplifier fundamentals

- 1.1 In the voltage amplifier circuit of Fig. 1.1, let  $v_S = 100$  mV,  $R_S = 100$  k $\Omega$ ,  $v_I = 75$  mV,  $R_L = 10$   $\Omega$ , and  $v_O = 2$  V. If connecting a 30- $\Omega$  resistance in parallel with  $R_L$  drops  $v_O$  to 1.8 V, find  $R_i$ ,  $A_{oc}$ , and  $R_o$ .
- 1.2 Sketch the transconductance and transresistance amplifiers; derive expressions for their source-to-load gains.
- 1.3 (a) A transresistance amplifier with  $R_i = 20$  k $\Omega$ ,  $A_{oc} = 1$  V/ma, and  $R_o = 300$   $\Omega$  is driven by a source  $i_S$  with parallel resistance  $R_S = 100$  k $\Omega$  and drives a load  $R_L = 600$   $\Omega$ . Find the transresistance gain  $v_L/i_S$  as well as the power gain  $p_L/p_S$ , where  $p_S$  is the power delivered by the source  $i_S$  and  $p_L$  that absorbed by the load  $R_L$ . (b) To what value must  $A_r$  be changed to achieve  $v_L/i_S = 1$  V/mA exactly? What is the corresponding power gain?
- 1.4 A transconductance amplifier is driven by a source with  $v_S = 30$  mV and  $R_S = 100$  k $\Omega$  and drives a load  $R_L$ . Digital multimeter (DMM) readings at the input and output ports yield  $v_I = 25$  mV,  $i_L = 0.9$  A for  $R_L = 20$   $\Omega$ , and  $i_L = 0.8$  A for  $R_L = 30$   $\Omega$ . Predict the DMM readings if the same amplifier is driven by a source with  $v_S = 33$  mV and  $R_S = 50$  k $\Omega$  and drives a load  $R_L = 40$   $\Omega$ .

## 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-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. *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. *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 amplifier 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  $r_d \cong \infty$ ,  $a = 1$  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  $\pm 5$ -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.

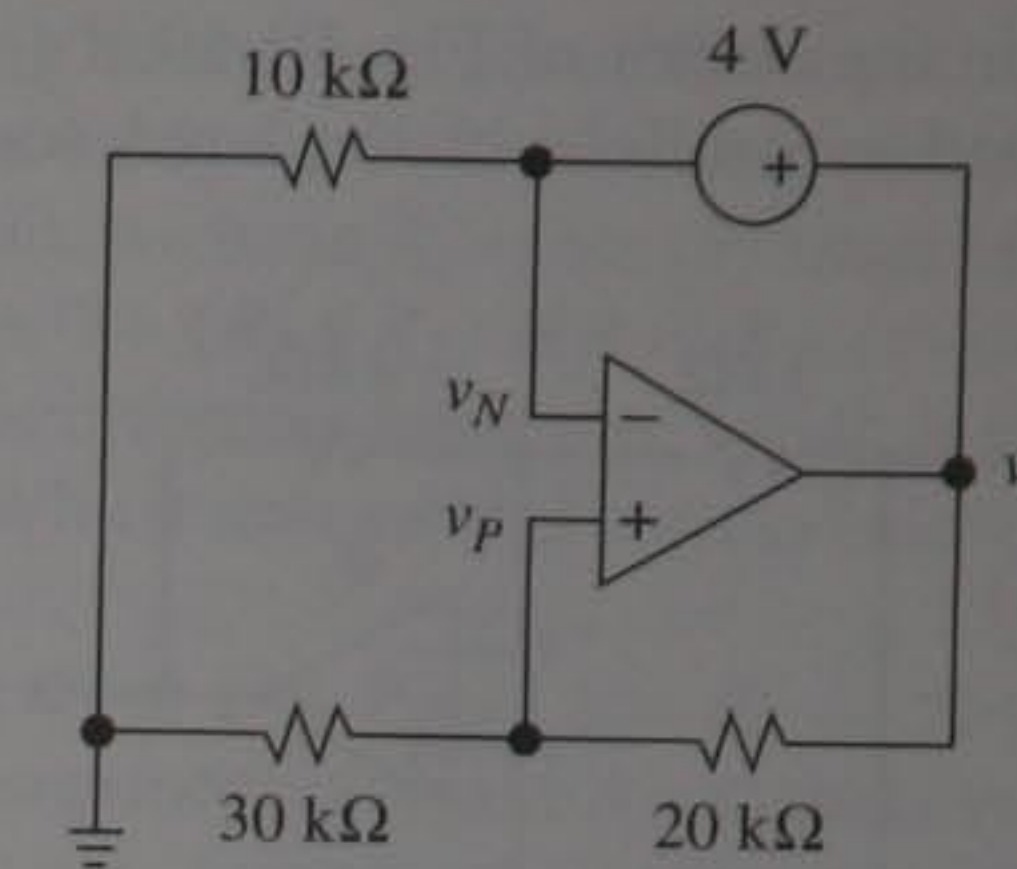


FIGURE P1.15

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

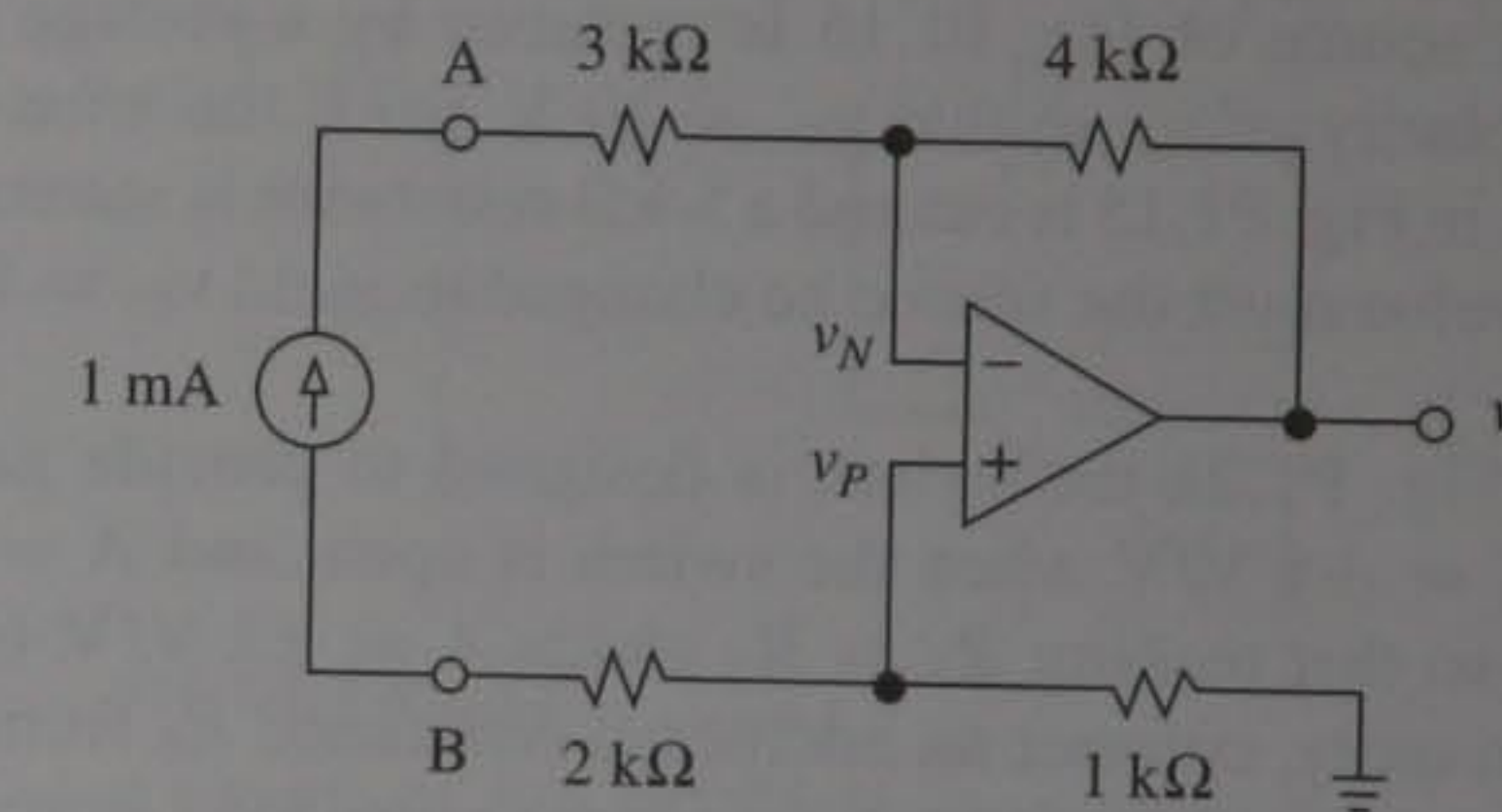


FIGURE P1.16

- 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.

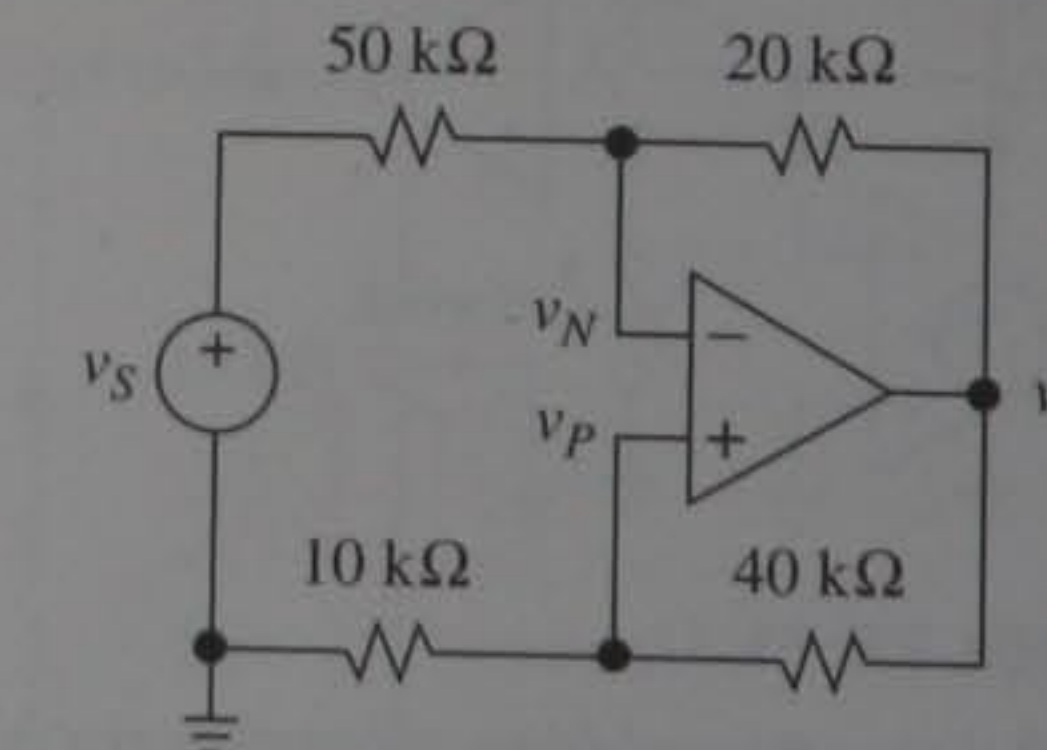


FIGURE P1.17

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

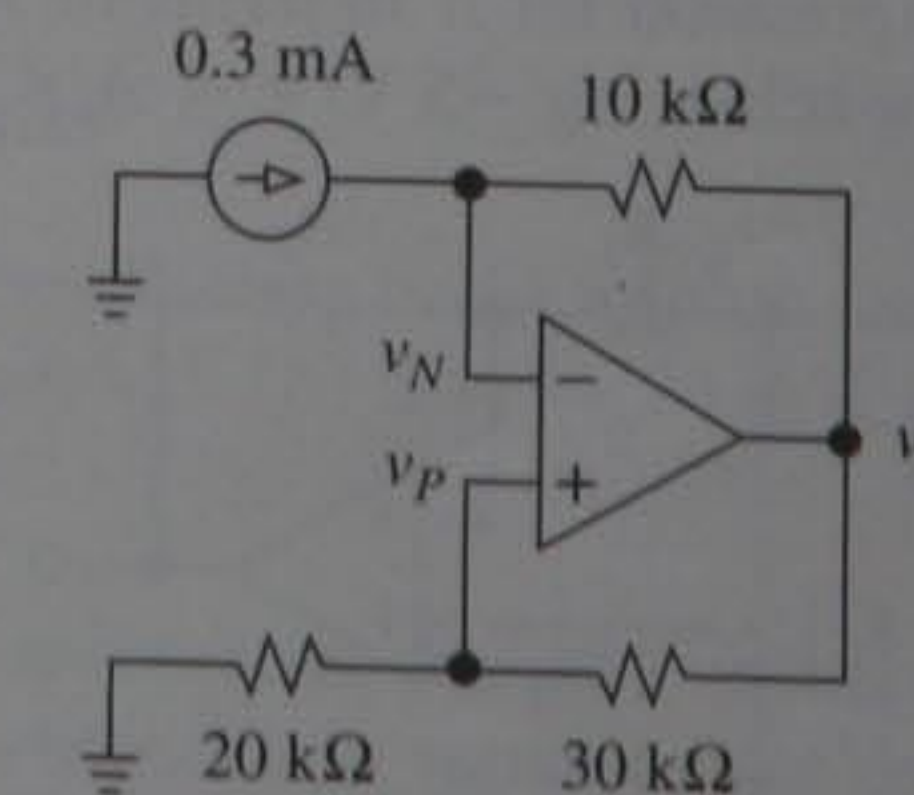


FIGURE P1.18

- 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).

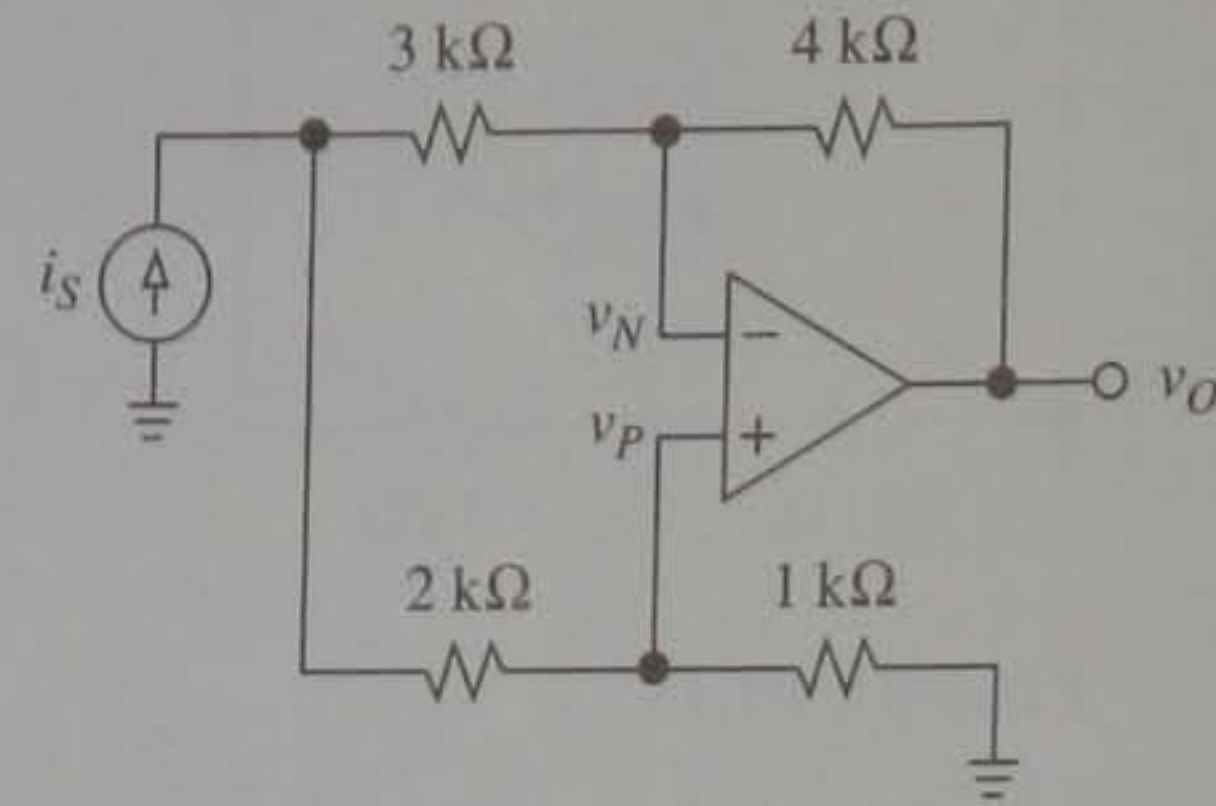


FIGURE P1.19

- 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.

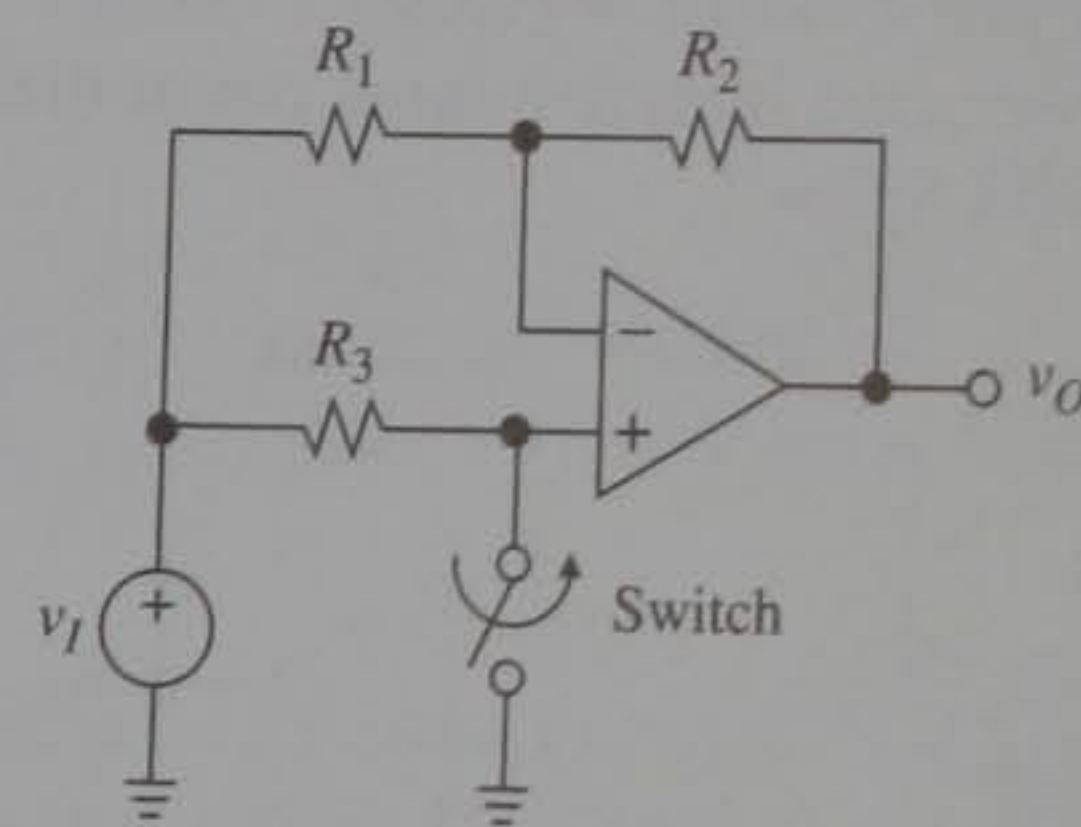


FIGURE P1.21

- 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.

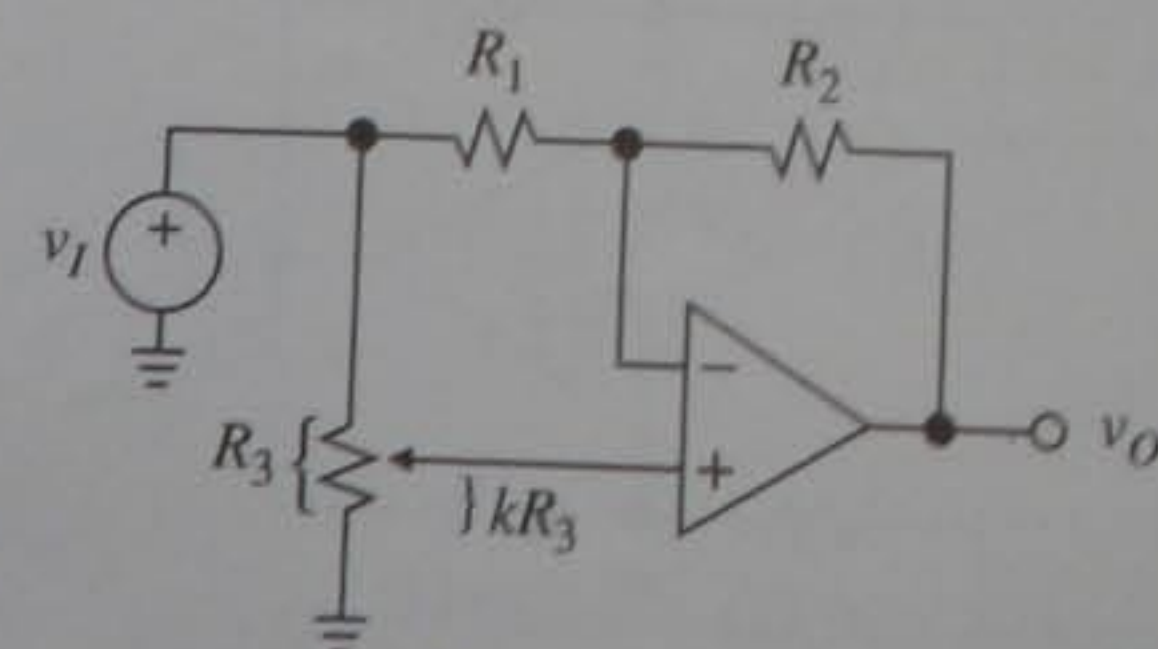


FIGURE P1.22

- 1.23 Consider the following statements about the input resistance  $R_i$  of the noninverting amplifier of Fig. 1.14a: (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  $-100$  V/V  $\leq A \leq 0$  by means of a 100-kΩ pot. Try minimizing the number of resistors you use.

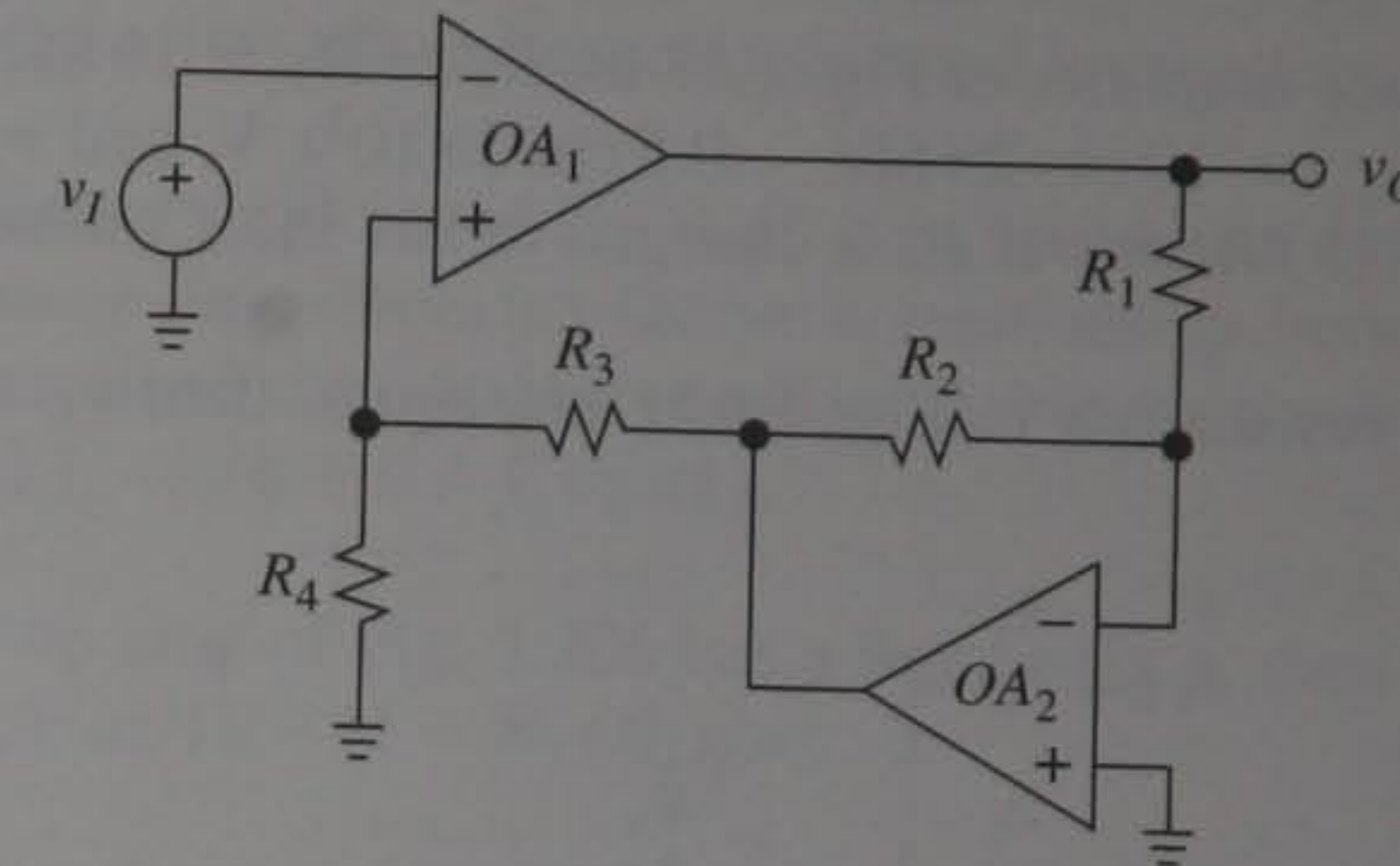


FIGURE P1.24

- 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.

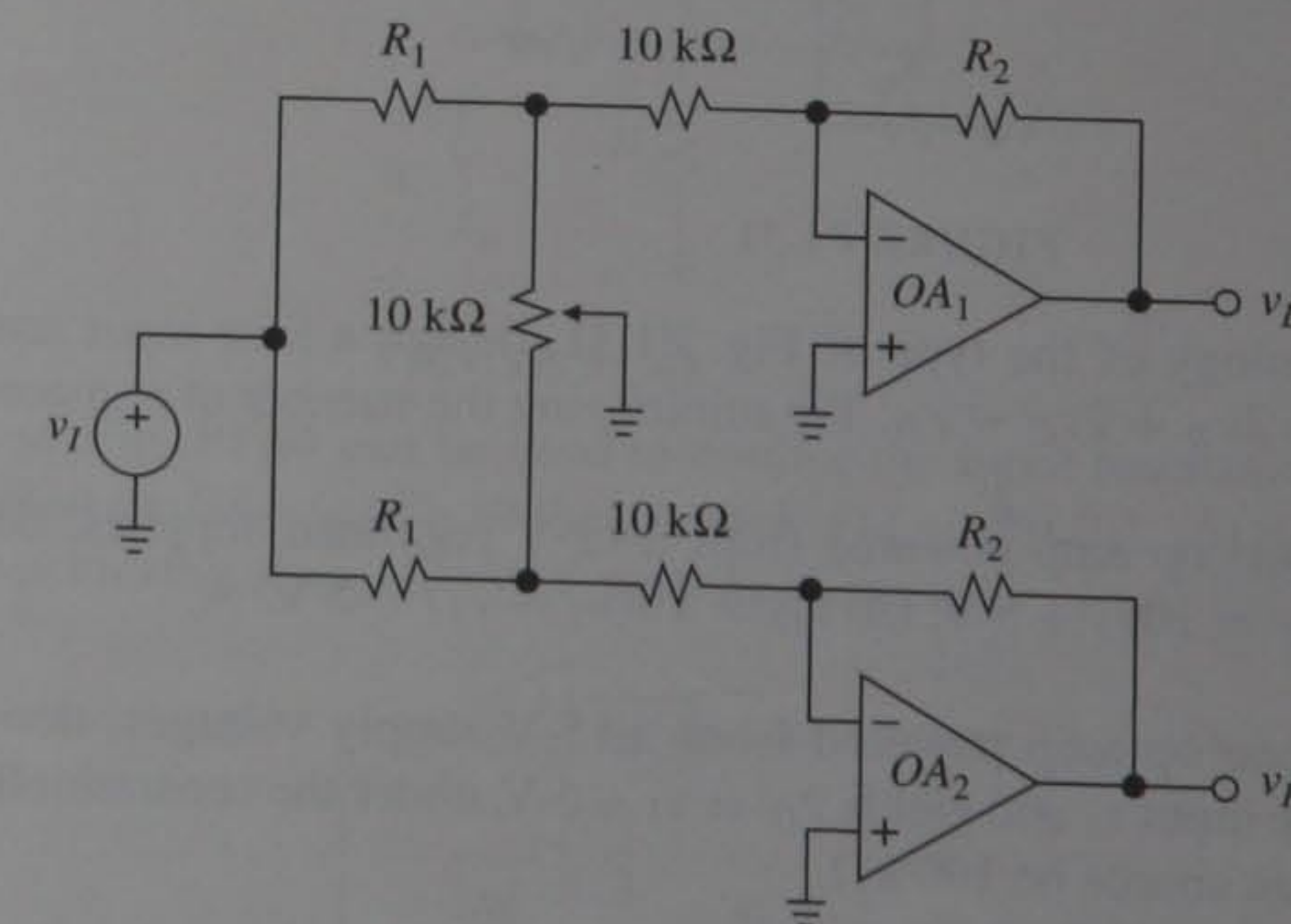


FIGURE P1.25

- 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)  $v_O = -10(v_I + 1$  V); (b)  $v_O = -v_I + V_O$ , where  $V_O$  is variable over the range  $-5$  V  $\leq V_O \leq +5$  V by means of a 100-kΩ pot. Hint: Connect the pot between the  $\pm 15$ -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  $v_O = A_2 v_2 - A_1 v_1$  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  $R_5$  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  $R_2 = R_4 = 100 \text{ k}\Omega$ . Find  $v_O$  if  $v_1 = 10 \cos 2\pi 60t - 0.5 \cos 2\pi 10^3 t \text{ V}$ , and  $v_2 = 10 \cos 2\pi 60t + 0.5 \cos 2\pi 10^3 t \text{ V}$ . (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  $v_O = v_2 + v_4 + v_6 - v_1 - v_3 - v_5$ .

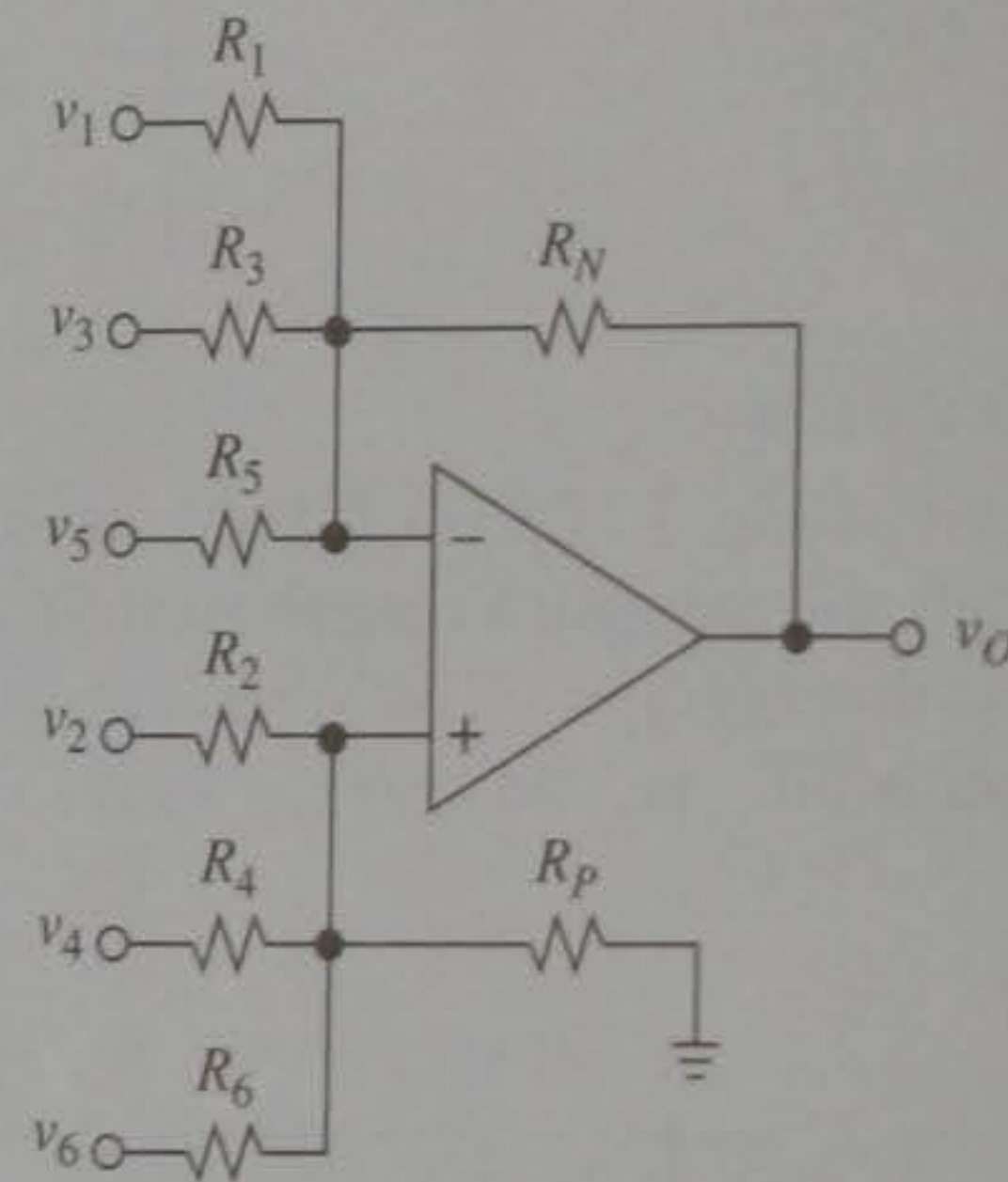


FIGURE P1.31

- 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  $\pm 12\text{-V}$  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  $\pm 15\text{-V}$  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  $R_i$  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  $C = 10 \text{ nF}$  and  $R = 100 \text{ k}\Omega$ , and let  $v_I$  be a periodic signal alternating between  $0 \text{ V}$  and  $2 \text{ V}$  with a frequency of  $100 \text{ Hz}$ . 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  $R = 100 \text{ k}\Omega$  and  $C = 10 \text{ nF}$ . Sketch and label  $v_I(t)$  and  $v_O(t)$  if (a)  $v_I = 5 \sin 2\pi 100t \text{ V}$  and  $v_O(0) = 0$ ; (b)  $v_I = 5[u(t) - u(t - 2 \text{ ms})] \text{ V}$  and  $v_O(0) = 5 \text{ V}$ , 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  $C = 0.1 \mu\text{F}$ . Assuming that  $C$  is initially discharged, sketch and label  $v_O(t)$  for  $0 \leq t \leq 10 \text{ ms}$  if  $v_I$  is a  $1\text{-V}$  step. (b) Repeat (a) with a  $100\text{-k}\Omega$  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  $10\text{-nF}$  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. 1.20b has a finite gain  $a$ , then  $R_{\text{eq}} = (-R_1 R / R_2) \times [1 + (1 + R_2 / R_1) / a] / [1 - (1 + R_1 / R_2) / a]$ .
- 1.43 Find an expression for  $R_i$  in Fig. P1.43; discuss its behavior as  $R$  is varied over the range  $0 \leq R \leq 2R_1$ .

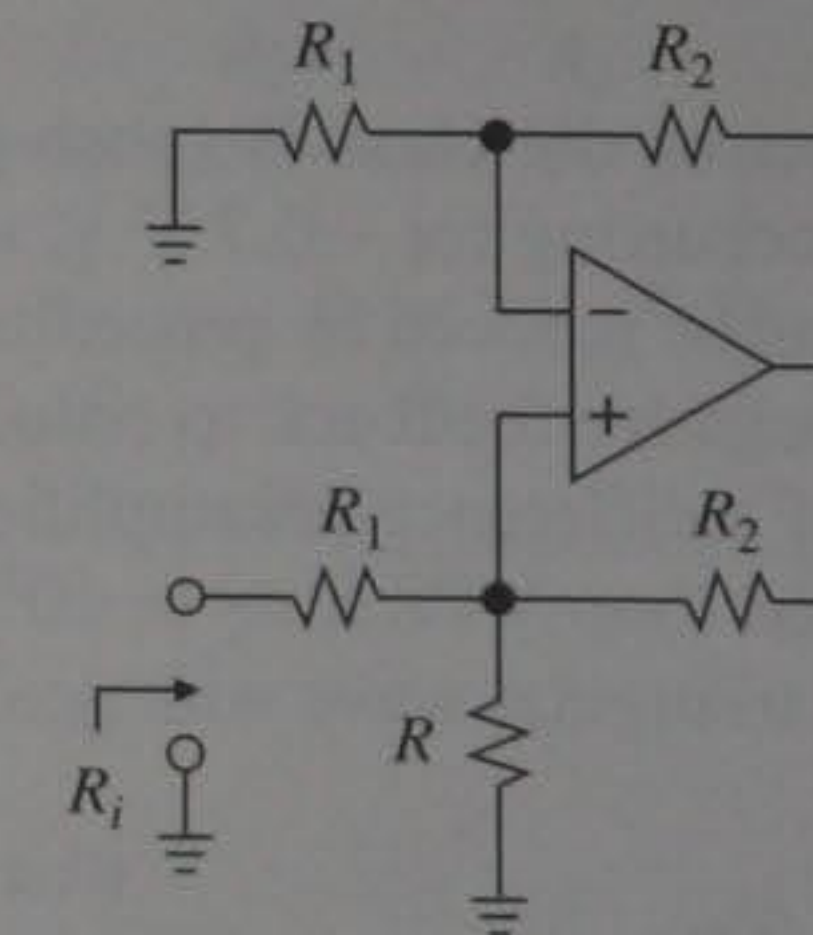


FIGURE P1.43

- 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  $A = -10 \text{ V/V}$  with  $R_i = \infty$ .

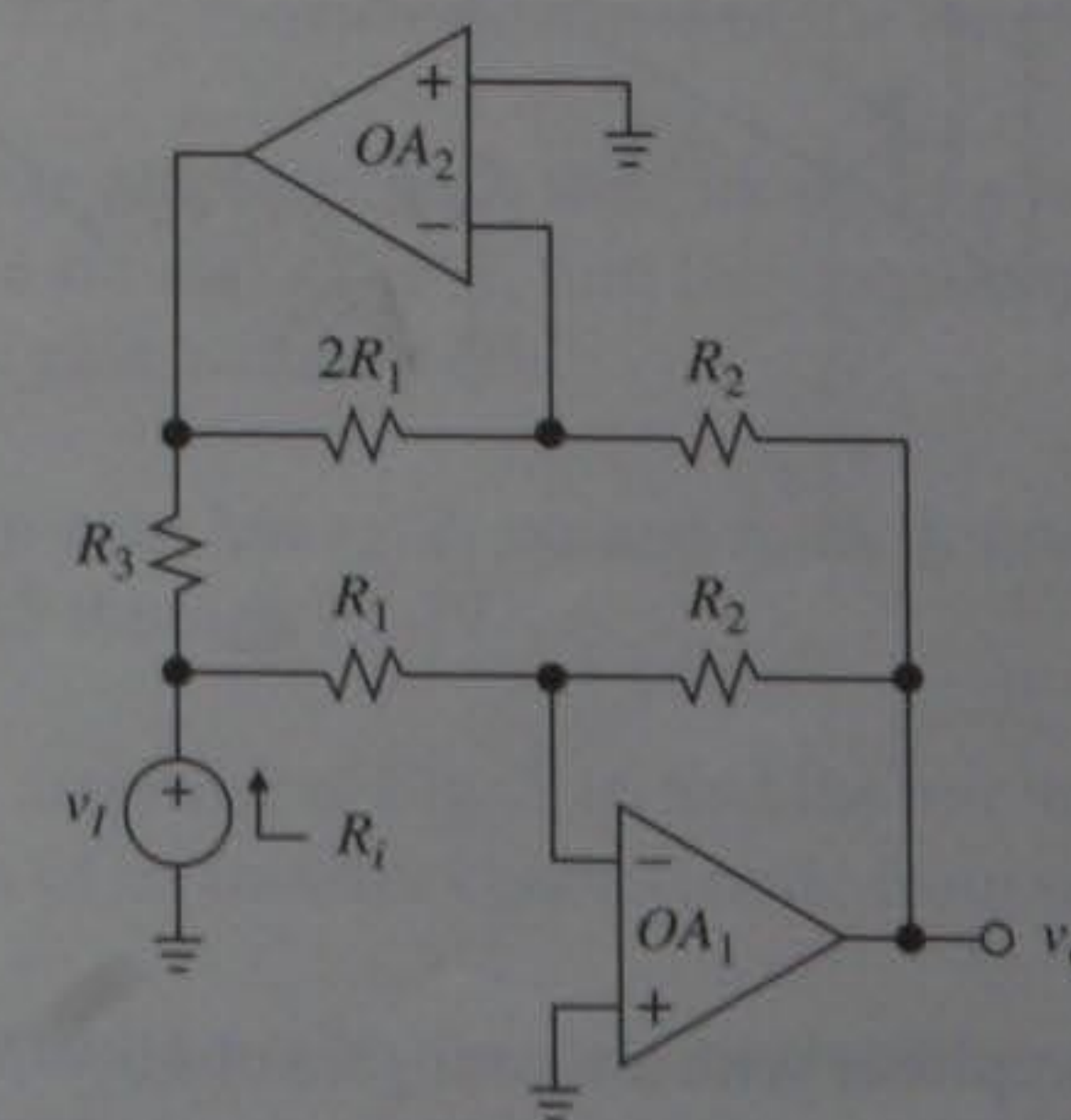


FIGURE P1.44

## 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.
- 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  $\beta$  of each stage?
- 1.48 The open-loop VTC of a certain amplifier can be approximated piecewise by five segments with symmetric breakpoints at  $(v_D, v_O) = (\pm 80 \mu\text{V}, 8 \text{ V})$ ,  $(\pm 280 \mu\text{V}, 12 \text{ V})$ , 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  $-0.7 \text{ V} \leq v_i \leq +0.7 \text{ V}$  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  $\beta = 1$  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  $\pm 1$  V.

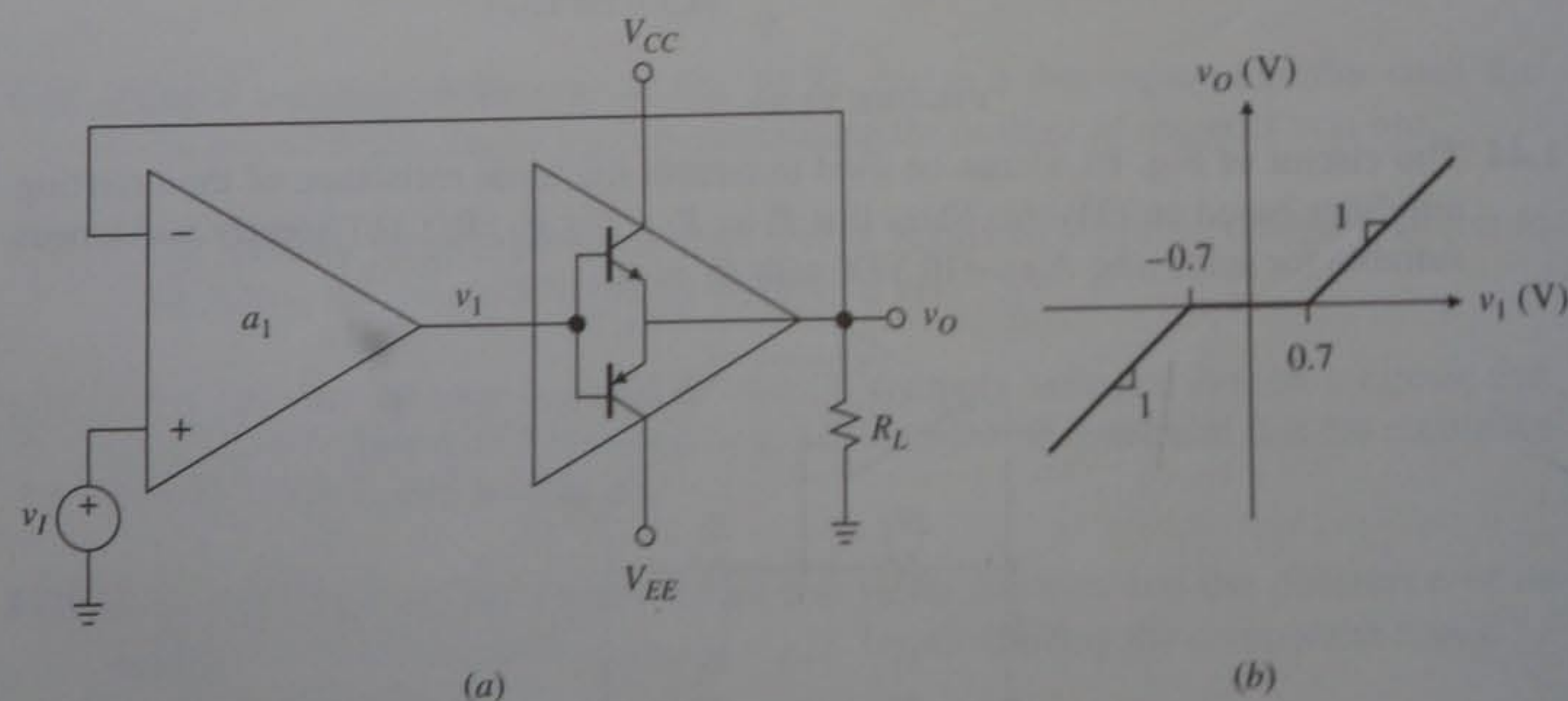


FIGURE P1.49

- 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  $r_d = 1 \text{ M}\Omega$ ,  $a = 1 \text{ V/mV}$ , 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.
- 1.52 An inverting amplifier is implemented with two precision resistors  $R_1 = 100 \text{ k}\Omega$  and  $R_2 = 200 \text{ k}\Omega$  and drives a 2-k $\Omega$  load. Assuming an op amp with  $r_d = 1 \text{ M}\Omega$  and  $r_o = 100 \Omega$ , find the minimum gain  $a$  needed to contain the deviation of  $A$  from the ideal within (a) 1%, (b) 0.001%.
- 1.53 Let a voltage follower be implemented with an op amp having  $r_d = 1 \text{ k}\Omega$ ,  $r_o = 20 \text{ k}\Omega$ , and  $a = 10^6$  V/V (poor resistances, but excellent gain). Find  $A$ ,  $R_i$ , and  $R_o$ , and comment on your findings.

## 1.7 The loop gain

- 1.54 (a) Find  $A_{ideal}$  in the circuit of Fig. P1.54 if all resistances are equal. (b) Assuming  $r_d \cong \infty$  and  $r_o \cong 0$ , find  $a_{min}$  such that the deviation of  $A$  from  $A_{ideal}$  is less than 0.1%.

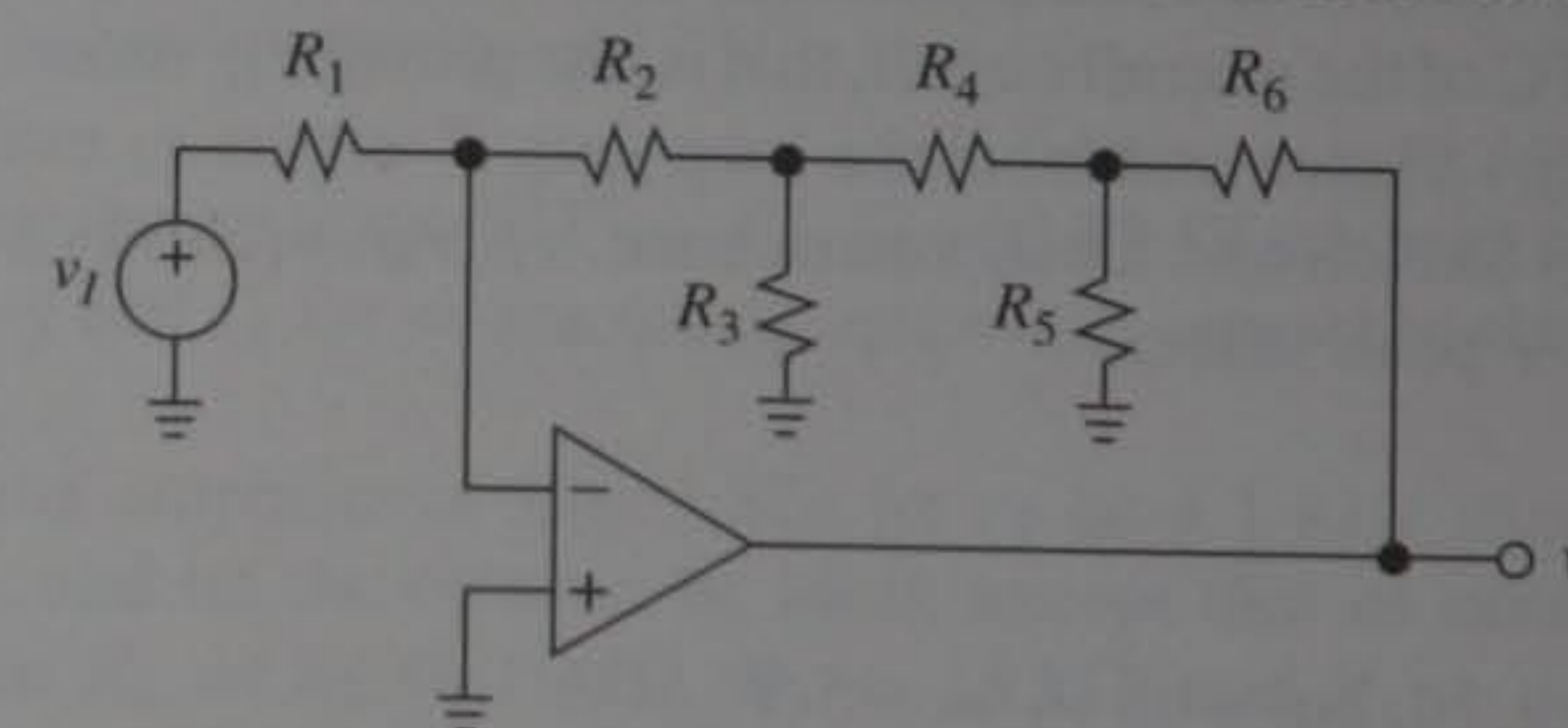


FIGURE P1.54

- 1.55 (a) Assuming that  $R_3$  in Fig. 1.32a is a potentiometer connected as a variable resistance over the range  $0 \leq R_3 \leq 1 \text{ M}\Omega$ , specify suitable components for an input resistance of 500 k $\Omega$  and a continuously variable gain over the range  $-10^3 \text{ V/V} \leq A_{ideal} \leq -0.5 \text{ V/V}$ . (b) If  $r_d = 1 \text{ M}\Omega$ ,  $a = 10^5 \text{ V/V}$ ,  $r_o = 100 \Omega$ , and  $R_L = 2 \text{ k}\Omega$ , estimate the gain departure from the ideal at the two extremes of the range.
- 1.56 (a) Design a difference amplifier such that, ideally,  $v_O = 100(v_2 - v_1)$ . (b) Assuming an op amp with  $r_d \cong \infty$  and  $r_o \cong 0$ , find the open-loop gain needed to approximate the ideal closed-loop gain within 0.1%.
- 1.57 Assuming that the op amp has  $r_d \cong \infty$  and  $r_o \cong 0$ , find the feedback factor  $\beta$  in the circuits of Figs. P1.15 through P1.19.
- 1.58 For the dc-offsetting amplifier of Fig. 1.16 find the minimum open-loop gain needed to contain the deviation of its transfer characteristic from the ideal within 1%.
- 1.59 Using a single op amp, along with the ideas expressed in Problem 1.29, design a circuit that accepts two inputs  $v_1$  and  $v_2$  and yields  $v_O = 100(3v_2 - 2v_1)$ . Hence, assuming

$r_d = \infty$  and  $r_o = 0$ , find the minimum open-loop gain  $a$  needed to contain the transfer characteristic's deviation from ideality within 0.1%.

- 1.60 Assuming the op amp of Fig. P1.60 has  $a = 3000$  V/V,  $r_d = \infty$ , and  $r_o = 0$ , find the loop gain  $T$ .

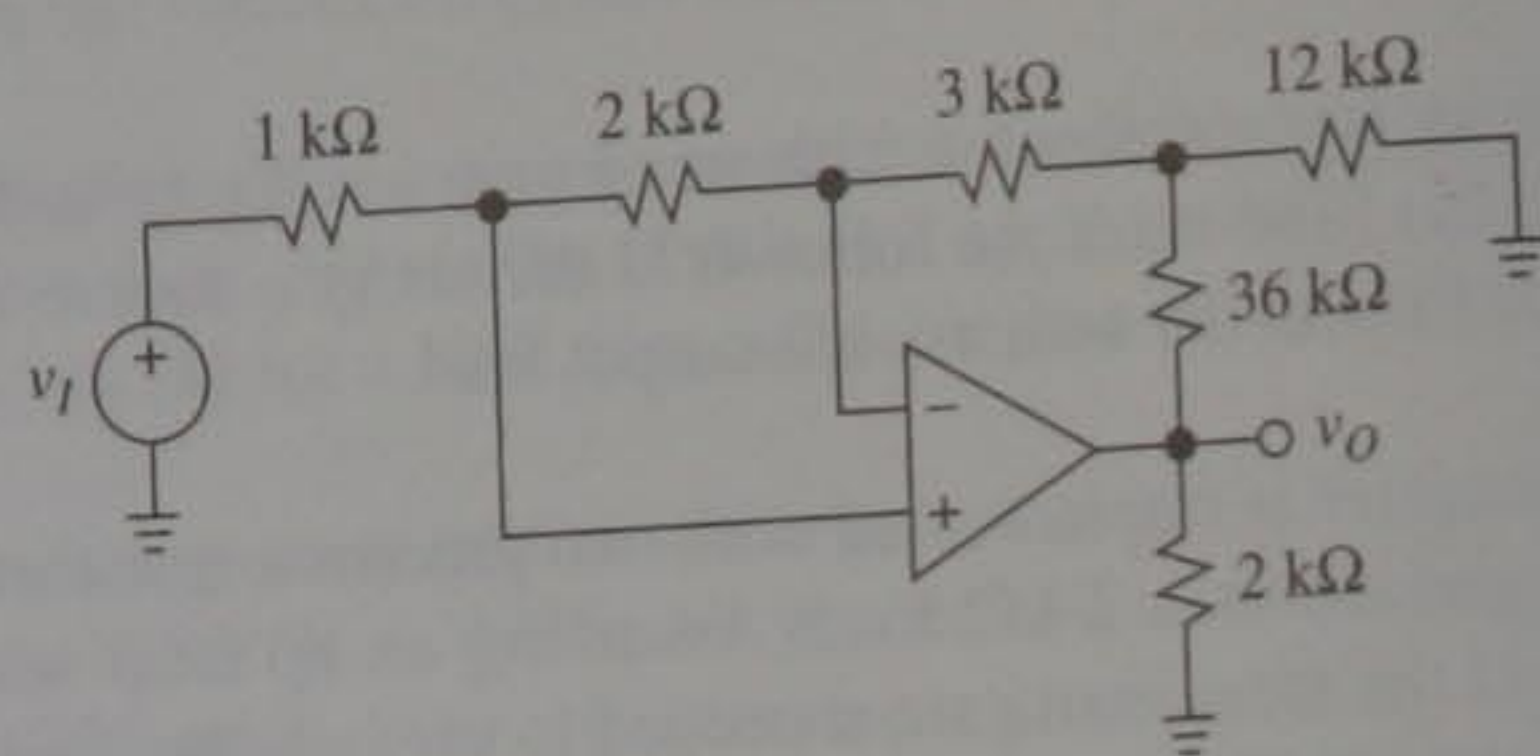


FIGURE P1.60

- 1.61 (a) Assuming the op amp of Fig. P1.16 has  $r_d = \infty$  and  $r_o = 0$ , find  $\beta_N$ ,  $\beta_P$ , and  $\beta$ .  
(b) Repeat, but with the current source replaced by a voltage source.
- 1.62 Repeat Problem 1.61, but for the circuit of Fig. P1.19.
- 1.63 In the circuit of Fig. P1.49a let  $a_1 = 3000$  V/V and  $R_L = 2$  k $\Omega$ , and suppose an additional 10-k $\Omega$  resistor is connected from node  $v_1$  to node  $v_O$ . (a) Sketch and label the open-loop VTC of the overall circuit, that is, the plot of  $v_O$  versus the input difference  $v_D = v_P - v_N$ . (b) Sketch and label the loop gain  $T$  versus  $v_I$  over the range  $-0.3$  V  $\leq v_I \leq 0.3$  V. (c) Sketch and label, versus time,  $v_I$ ,  $v_O$ ,  $v_1$ , and  $v_D$  if  $v_I$  is a triangular wave with  $\pm 0.3$ -V peak values.

## 1.8 Op amp powering

- 1.64 Repeat Example 1.14, but with  $v_I = -5$  V.

- 1.65 Assuming that  $I_Q = 1.5$  mA in the circuit of Fig. P1.65, calculate all currents and voltages, as well as the power dissipated inside the op amp, if (a)  $v_I = +2$  V; (b)  $v_I = -2$  V.

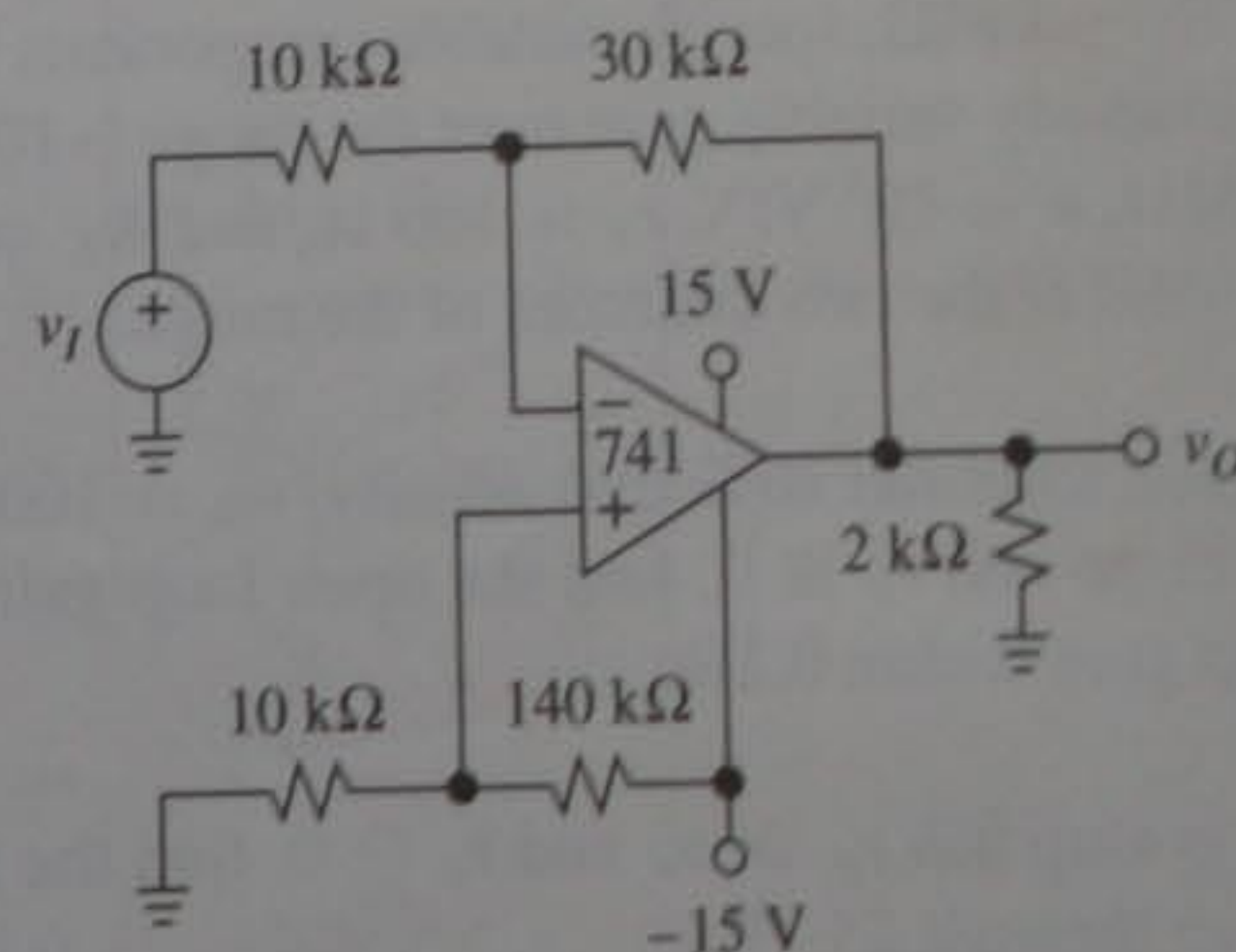


FIGURE P1.65

- 1.66 Using a 741 op amp powered from  $\pm 12$ -V supplies, design a noninverting amplifier with a gain of 6 V/V. Sketch and label  $v_I$ ,  $v_O$ , and  $v_N$  versus time if  $v_I$  is a sine wave with  $\pm 3$ -V peak values.

- 1.67 (a) Assuming  $\pm 15$ -V power supplies, design a variable voltage source over the range  $0$  V  $\leq v_S \leq 10$  V. (b) Assuming a 1-k $\Omega$  grounded load and  $I_Q = 1.5$  mA, find the maximum internal power dissipation of your op amp.
- 1.68 Assuming a 741 op amp in the dc-offsetting amplifier of Fig. 1.16, find: (a)  $v_I$  and  $v_N$  if  $v_O = 5$  V; (b) find  $v_N$  and  $v_O$  if  $v_I = 3$  V.
- 1.69 The noninverting amplifier of Fig. 1.14a is implemented with  $R_1 = 10$  k $\Omega$  and  $R_2 = 15$  k $\Omega$ , and a 741 op amp powered from  $\pm 12$ -V supplies. If the circuit includes also a third 30-k $\Omega$  resistor connected between the inverting input and the 12-V supply, find  $v_O$  and  $v_N$  if (a)  $v_I = 4$  V, and (b)  $v_I = -2$  V.
- 1.70 (a) Assuming  $I_Q = 50$   $\mu$ A and a grounded load of 100 k $\Omega$  at the output of the dc-offsetting amplifier of Fig. 1.16, find the values of  $v_I$  for which the op amp dissipates the maximum power. Show all corresponding voltages and currents. (b) Assuming  $\pm V_{\text{sat}} = \pm 12$  V, find the range of values of  $v_I$  for which the op amp still operates within the linear region.
- 1.71 In the amplifier of Fig. 1.17 let  $R_1 = 30$  k $\Omega$ ,  $R_2 = 120$  k $\Omega$ ,  $R_3 = 20$  k $\Omega$ , and  $R_4 = 30$  k $\Omega$ , and let the op amp be a 741-type powered from  $\pm 15$  V. (a) If  $v_2 = 2 \sin \omega t$  V, find the range of values of  $v_1$  for which the amplifier still operates in the linear region. (b) If  $v_1 = V_m \sin \omega t$  and  $v_2 = -1$  V, find the maximum value of  $V_m$  for which the op amp still operates in the linear region. (c) Repeat (a) and (b) for the case in which the power supplies are lowered to  $\pm 12$  V.
- 1.72 Assuming that the op amps of Figs. P1.17 and P1.19 saturate at  $\pm 10$  V, find the range of values of  $v_S$  and  $i_S$  for which the op amps still operate in the linear region.
- 1.73 In the inverting amplifier of Fig. 1.32a let  $v_I$  be a 1-kHz triangular wave with peak values  $\pm V_{im}$ , and let the op amp be ideal, except that its output saturates at  $\pm 10$  V. Assuming that  $R_1 = R_2 = 1$  M $\Omega$ ,  $R_3 = 18$  k $\Omega$ , and  $R_4 = R_L = 2$  k $\Omega$ , sketch and label  $v_I$ ,  $v_N$ ,  $v_1$ , and  $v_O$  versus time if (a)  $V_{im} = 0.5$  V; (b)  $V_{im} = 2$  V.
- 1.74 The circuit of Fig. P1.74, called a *bridge amplifier*, allows one to double the linear output range as compared with a single op amp. (a) Show that if the resistances are in the ratios shown, then  $v_O/v_I = 2A$ . (b) If the individual op amps saturate at  $\pm 13$  V, what is the maximum peak-to-peak output voltage that the circuit can provide without distortion?

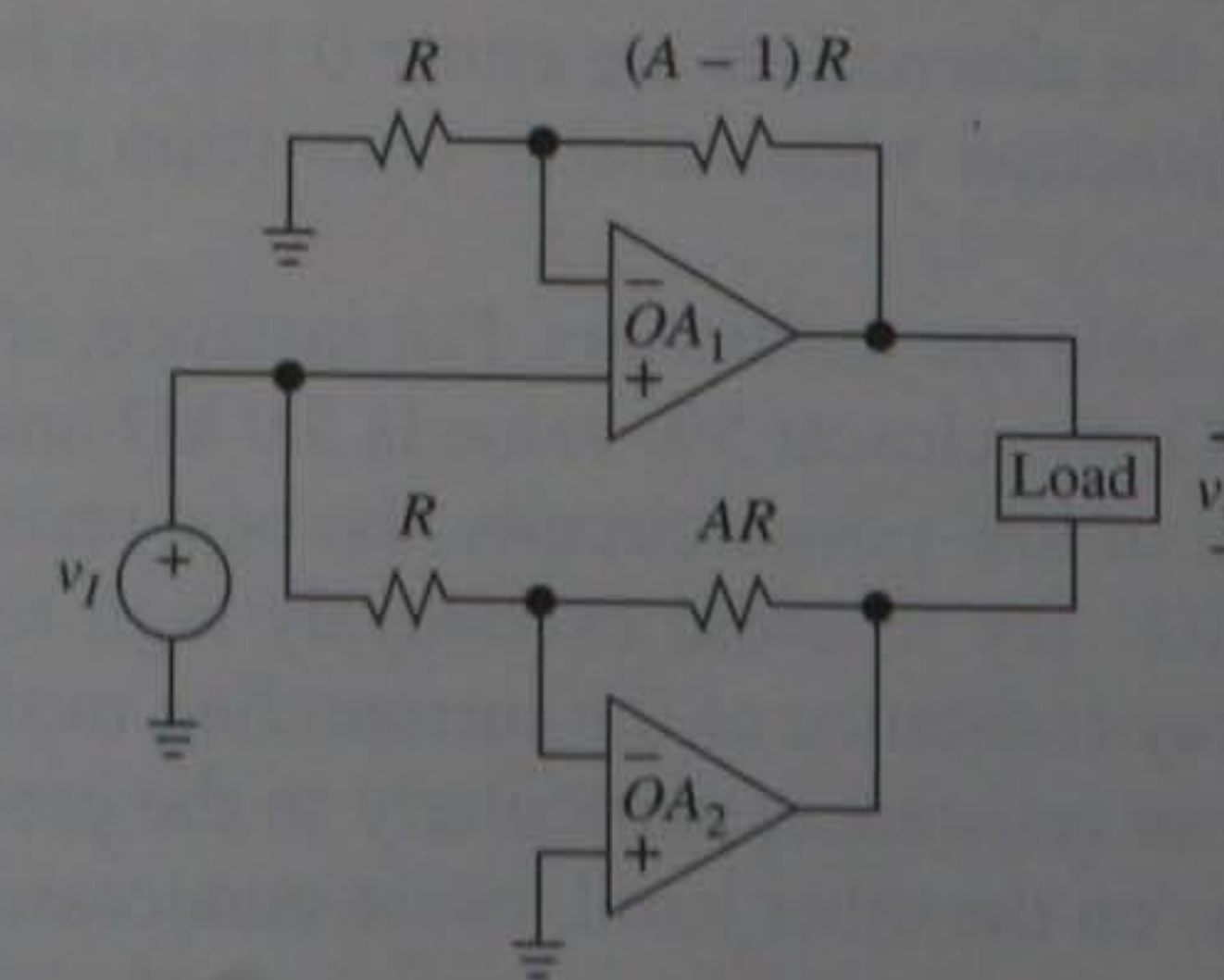


FIGURE P1.74

- 1.75 For the circuit of Fig. P1.65 sketch and label  $v_I$ ,  $v_N$ , and  $v_O$  versus time if  $v_I$  is a triangular wave with  $\pm 5$ -V peak values.
- 1.76 In the integrator of Fig. 1.19 let  $R = 100 \text{ k}\Omega$  and  $C = 10 \text{ nF}$ , and let the op amp be ideal, except that its output saturates at  $\pm 13 \text{ V}$ . Assuming that  $v_O(0) = 0 \text{ V}$ , sketch and label  $v_O$  and  $v_N$  versus time if (a)  $v_I = 1 \text{ V}$ ; (b)  $v_I = 1 \text{ mV}$ ; (c)  $v_I = -1 \text{ mV}$ .

## BIBLIOGRAPHY

- Dostál, J.: *Operational Amplifiers*, 2d ed., Butterworth-Heinemann, Stoneham, MA, 1993.
- Fredericksen, T. M.: *Intuitive IC Op Amps*, National Semiconductor Co., Santa Clara, CA, 1984.
- Graeme, J. G.: *Optimizing Op Amp Performance*, McGraw-Hill, New York, 1997.
- Graeme, J. G., G. E. Tobey, and L. P. Huelsman: *Operational Amplifiers: Design and Applications*, McGraw-Hill, New York, 1971.
- Horowitz, P., and W. Hill: *The Art of Electronics*, 2d ed., Cambridge University Press, Cambridge, U.K., 1989.
- Jung, W. G.: *IC Op Amp Cookbook*, 3d ed., Howard W. Sams, Carmel, IN, 1986.
- Kennedy, E. J.: *Operational Amplifier Circuits: Theory and Applications*, Holt, Rinehart and Winston, Orlando, FL, 1988.
- Pease, R. A.: *Troubleshooting Analog Circuits*, Butterworth-Heinemann, Stoneham, MA, 1991.
- Roberge, J. K.: *Operational Amplifiers: Theory and Practice*, John Wiley & Sons, New York, 1975.
- Rosenstark, S.: *Feedback Amplifier Principles*, Macmillan, New York, 1986.
- Williams, J.: *Analog Circuit Design: Art, Science, and Personalities*, Butterworth-Heinemann, Stoneham, MA, 1991.

APPENDIX 1A  
STANDARD RESISTOR VALUES

As a good work habit, always specify standard resistance values for the circuits you design (see Table 1A.1). In many applications 5% resistors are adequate; however, when higher precision is required, 1% resistors should be used. When even this tolerance is insufficient, the alternatives are either 0.1% (or better) resistors, or less precise resistors in conjunction with variable ones (trim pots) to allow for exact adjustments.

The numbers in the table are multipliers. For instance, if the calculations yield a resistance of  $3.1415 \text{ k}\Omega$ , the closest 5% value is  $3.0 \text{ k}\Omega$  and the closest 1% value is  $3.16 \text{ k}\Omega$ . In the design of low-power circuits, the best resistance range is usually between  $1 \text{ k}\Omega$  and  $1 \text{ M}\Omega$ . Try to avoid excessively high resistances (e.g., above  $10 \text{ M}\Omega$ ), because the stray resistance of the surrounding medium tends to decrease the effective value of your resistance, particularly in the presence of moisture and salinity. Low resistances, on the other hand, cause unnecessarily high-power dissipation.

TABLE 1A.1  
Standard resistance values

5% resistor values		1% resistor values		
10	100	178	316	562
11	102	182	324	576
12	105	187	332	590
13	107	191	340	604
15	110	196	348	619
16	113	200	357	634
18	115	205	365	649
20	118	210	374	665
22	121	215	383	681
24	124	221	392	698
27	127	226	402	715
30	130	232	412	732
33	133	237	422	750
36	137	243	432	768
39	140	249	442	787
43	143	255	453	806
47	147	261	464	825
51	150	267	475	845
56	154	274	487	866
62	158	280	499	887
68	162	287	511	909
75	165	294	523	931
82	169	301	536	953
91	174	309	549	976

## PROBLEMS

## 2.1 Current-to-voltage converters

- 2.1 Using two op amps, design a circuit that accepts two current sources  $i_1$  and  $i_2$  having parallel resistances  $R_1$  and  $R_2$  and yields  $v_O = (0.1 \text{ V}/\mu\text{A}) \times (i_1 - i_2)$  to a load  $R_L$  regardless of  $R_1$ ,  $R_2$ , and  $R_L$ . The reference directions of both sources are from ground into your circuit. Try minimizing the number of resistors you use.
- 2.2 Design a circuit to convert a 4-mA-to-20-mA input current to a 0-V-to-10-V output voltage. The reference direction of the input source is from ground into your circuit, and the circuit is powered from  $\pm 15\text{-V}$  regulated supplies.
- 2.3 Estimate the closed-loop parameters if the circuit of Example 2.2 is implemented with a 741 op amp.
- 2.4 (a) Using an op amp powered from  $\pm 15\text{-V}$  regulated supplies, design a photodetector amplifier such that as  $i_I$  changes from 0 to  $1 \mu\text{A}$ ,  $v_O$  changes from  $-5 \text{ V}$  to  $+5 \text{ V}$ .  
(b) What is the minimum open-loop gain for a deviation of the transfer characteristic from the ideal of less than 1%?

## 2.2 Voltage-to-current converters

- 2.5 (a) Show that the floating-load  $V-I$  converter of Fig. P2.5 yields  $i_O = v_I/(R_1/k)$ ,  $k = 1 + R_2/R_3$ . (b) Specify standard 5% resistances for a sensitivity of  $1 \text{ mA/V}$  and  $R_i = 1 \text{ M}\Omega$ , where  $R_i$  is the resistance seen by the input source. (c) If  $\pm V_{\text{sat}} = \pm 13 \text{ V}$ , what is the voltage compliance of your circuit?

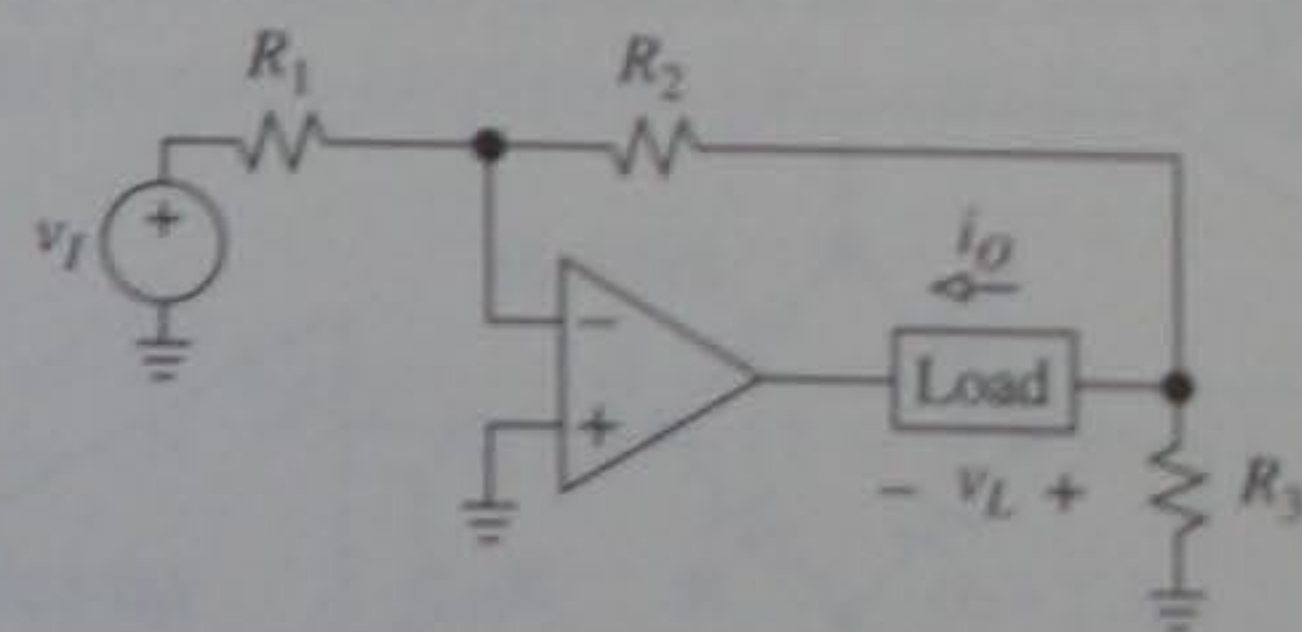


FIGURE P2.5

- 2.6 In the circuit of Fig. P2.5 let  $R_1 = 100 \text{ k}\Omega$ ,  $R_2 = 99 \text{ k}\Omega$ , and  $R_3 = 1 \text{ k}\Omega$ . If  $r_d \cong \infty$ ,  $a = 10^3 \text{ V/V}$ , and  $r_o \cong 0$ , estimate the resistance  $R_o$  seen by the load.
- 2.7 Consider the following statements about the resistance  $R_o$  seen by the load in the  $V-I$  converter of Fig. 2.4b, where the op amp is assumed ideal: (a) Looking toward the left, the load sees  $R \parallel r_d = R \parallel \infty = R$ , and looking to the right, it sees  $r_o = 0$ ; hence,  $R_o = R + 0 = R$ . (b) Looking toward the left, the load sees a virtual-ground node with zero resistance, and looking to the right, it sees  $r_o = 0$ ; hence,  $R_o = 0 + 0 = 0$ . (c)  $R_o = \infty$  because of negative feedback. Which statement is correct? How would you refute the other two?
- 2.8 Repeat Example 2.4 for the case of a 1.5-mA sink. Then find the currents through  $R_1$  and  $R_2$  if the load is (a) a 2-k $\Omega$  resistor; (b) a 6-k $\Omega$  resistor; (c) a 5-V Zener diode with the cathode at ground; (d) a short circuit; (e) a 10-k $\Omega$  resistor. In (e), is  $i_O$  still 1.5 mA? Explain.

- 2.9 Suppose in the Howland circuit of Fig. 2.6a we lift the left terminal of  $R_3$  off ground and simultaneously apply an input  $v_1$  via  $R_3$  and an input  $v_2$  via  $R_1$ . Show that the circuit is a difference  $V-I$  converter with  $i_O = (1/R_1)(v_2 - v_1) - (1/R_o)v_L$ , where  $R_o$  is given by Eq. (2.8).
- 2.10 Design a grounded-load  $V-I$  converter that converts a 0-V to 10-V input to a 4-mA to 20-mA output. The circuit is to be powered from  $\pm 15\text{-V}$  regulated supplies.
- 2.11 Design a grounded-load current generator meeting the following specifications:  $i_O$  is to be variable over the range  $-2 \text{ mA} \leq i_O \leq +2 \text{ mA}$  by means of a 100-k $\Omega$  pot; the voltage compliance must be 10 V; the circuit is to be powered from  $\pm 15\text{-V}$  regulated supplies.
- 2.12 (a) Prove Eq. (2.15). (b) Using a 741 op amp powered from  $\pm 15\text{-V}$  supplies, design an improved Howland circuit with a sensitivity of  $1 \text{ mA/V}$  for  $-10 \text{ V} \leq v_I \leq 10 \text{ V}$ . The voltage compliance of the circuit must also be 10 V.
- 2.13 Design an improved Howland circuit whose sensitivity is variable from  $0.1 \text{ mA/V}$  to  $1 \text{ mA/V}$  by means of a 10-k $\Omega$  pot.
- 2.14 (a) Given that the circuit of Fig. P2.14 yields  $i_O = A(v_2 - v_1) - (1/R_o)v_L$ , find expressions for  $A$  and  $R_o$ , as well as the condition among the resistances that yields  $R_o = \infty$ . (b) Discuss the effect of using 1% resistances.

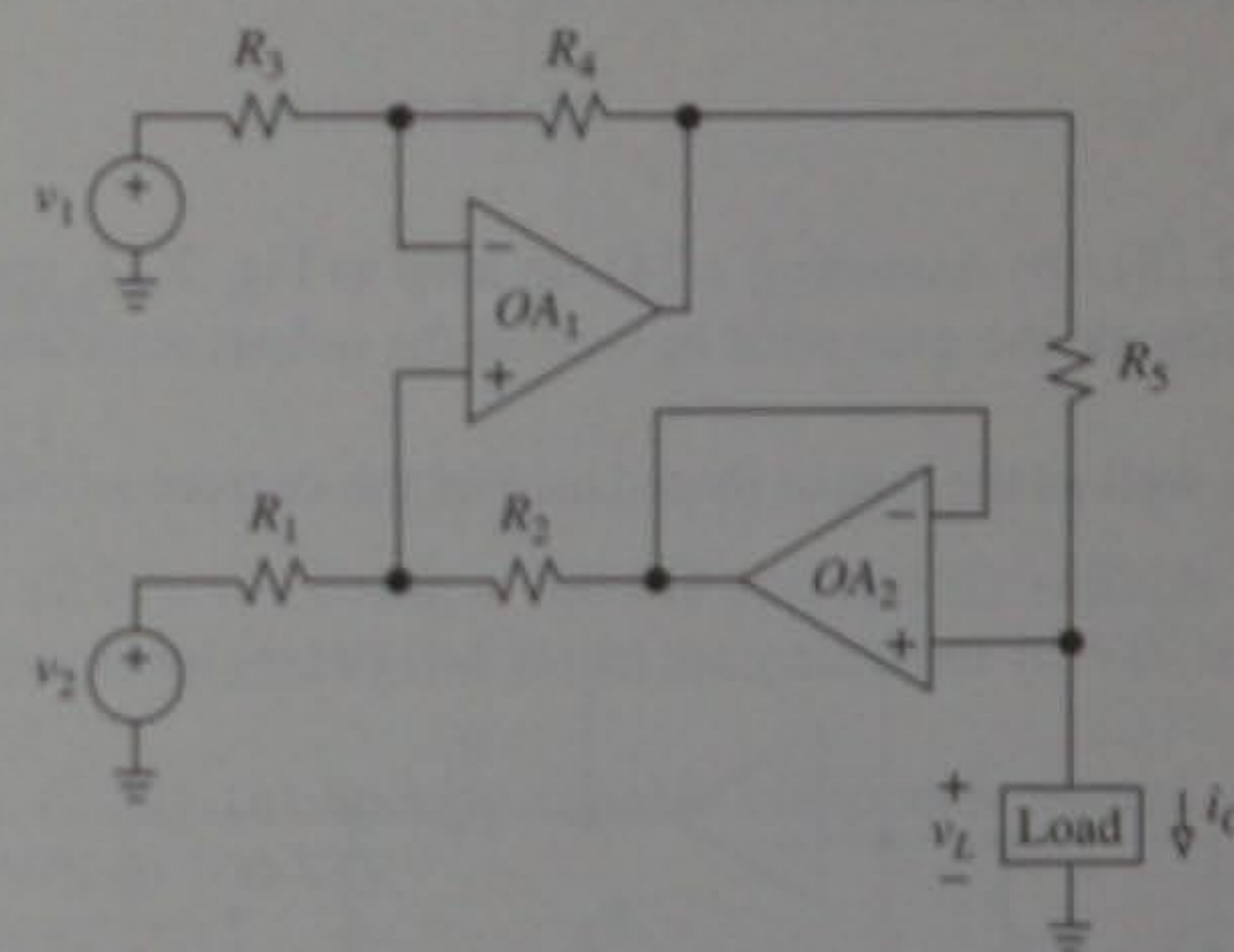


FIGURE P2.14

- 2.15 (a) Given that the circuit of Fig. P2.15 yields  $i_O = Av_I - (1/R_o)v_L$ , find expressions for  $A$  and  $R_o$ , as well as the condition among its resistances that yields  $R_o = \infty$ . (b) Discuss the effect of using 1% resistances.

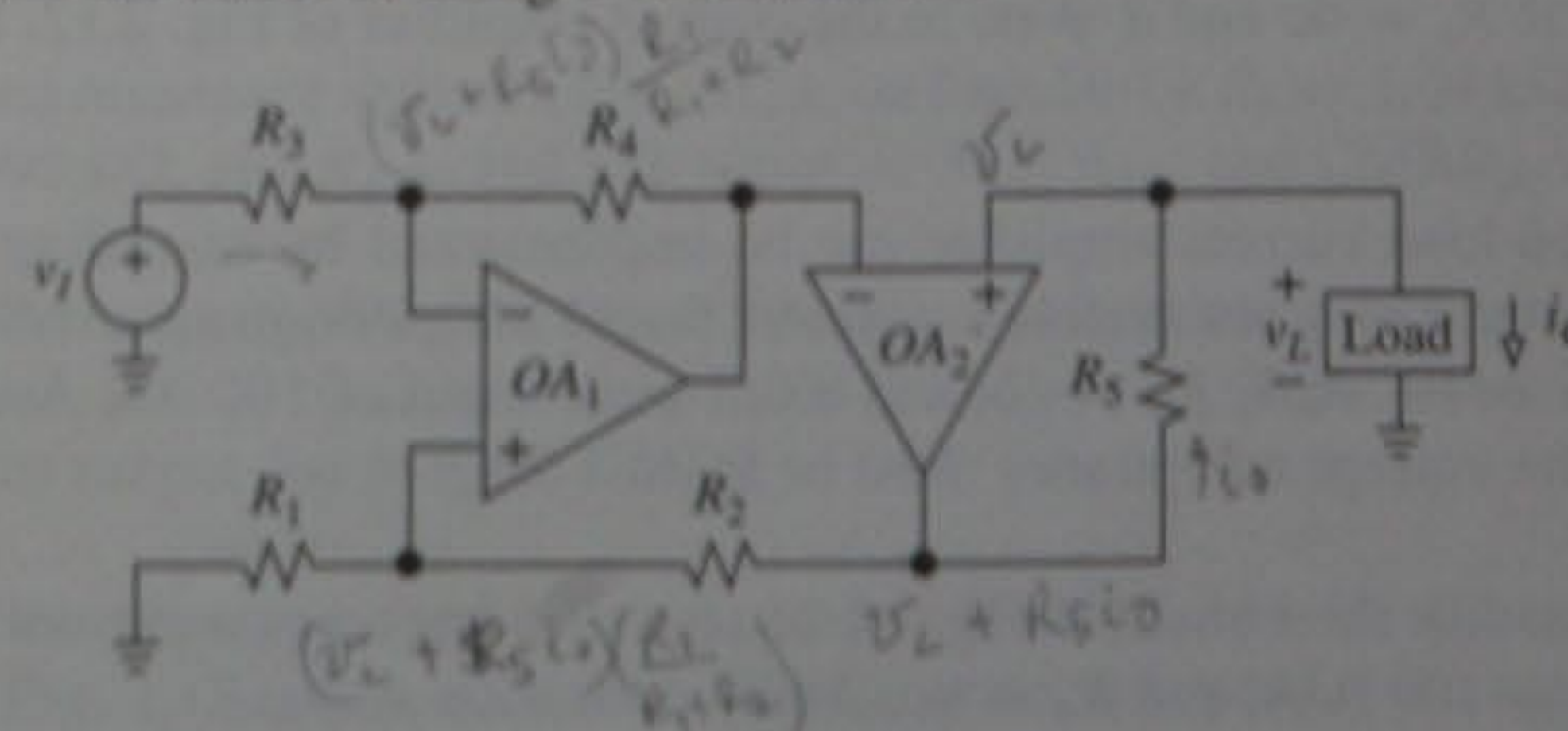


FIGURE P2.15

2.16 Repeat Problem 2.15 for the circuit of Fig. P2.16.

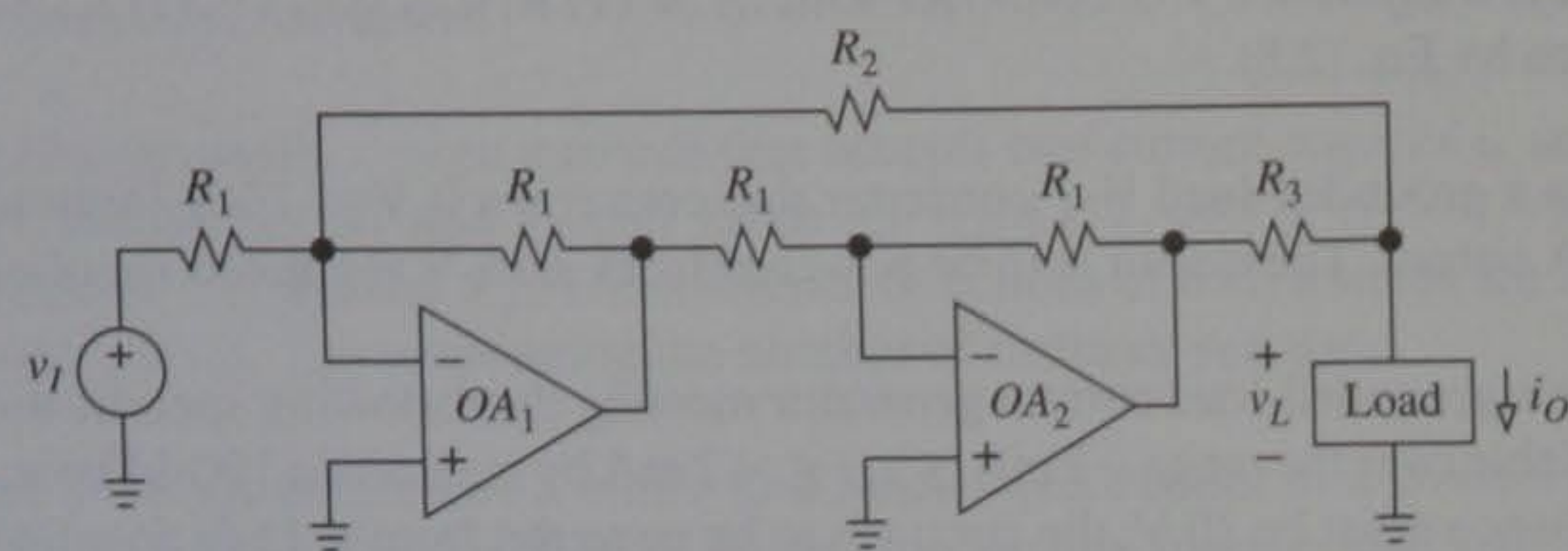


FIGURE P2.16

2.17 The current source of Example 2.4 drives a  $0.1\text{-}\mu\text{F}$  load. (a) Assuming that the capacitance is initially discharged, sketch and label  $v_O(t \geq 0)$ . (b) Find the time it takes for the op amp to enter the saturation region.

2.18 Repeat Problem 2.17 with  $R_4$  (a) decreased by 10%, and (b) increased by 10%.

2.19 Assuming an ideal op amp, find the input resistance  $R_i$  of a Howland current pump as a function of the load  $R_L$ . Comment.

### 2.3 Current amplifiers

2.20 (a) Prove Eq. (2.18). (b) Assuming a 741 op amp in Fig. 2.11, specify resistances for  $A = 10\text{ A/A}$ ; estimate the gain error as well as the output resistance of the circuit.

2.21 Find the gain as well as the output impedance of the current amplifier of Fig. P2.21.

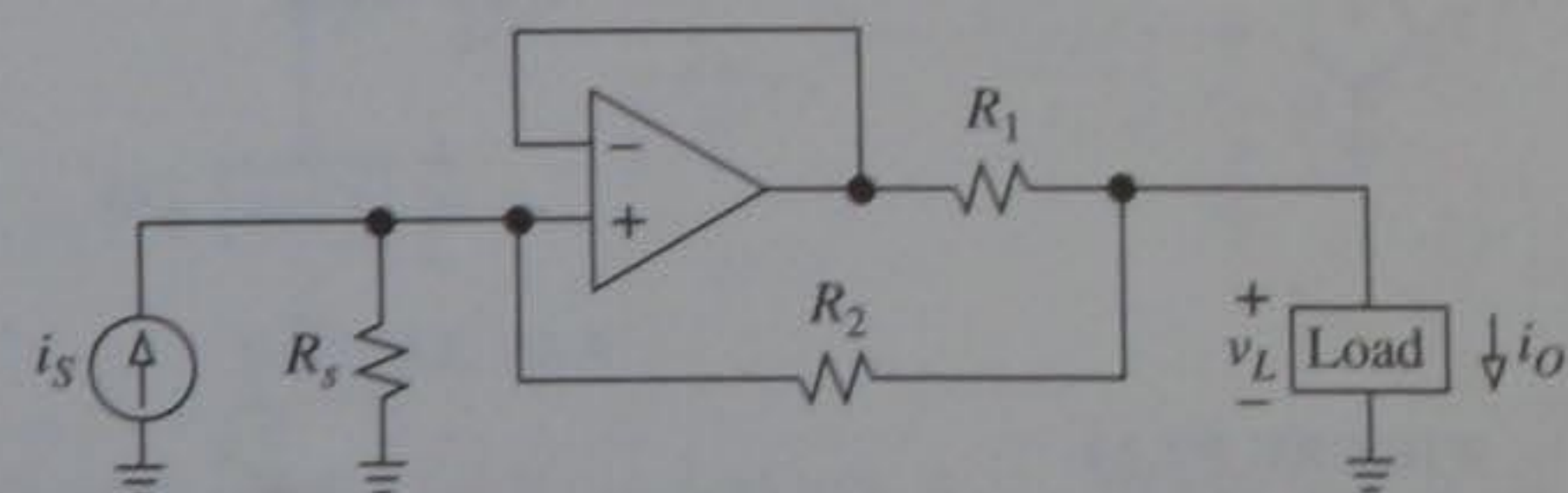


FIGURE P2.21

2.22 Show that if  $R_s = \infty$  and  $a \neq \infty$  in the current amplifier of Fig. 2.12, then Eq. (2.18) holds.

2.23 A grounded-load current amplifier can be implemented by cascading an  $I$ - $V$  and a  $V$ - $I$  converter. Using resistances no greater than  $1\text{ M}\Omega$ , design a current amplifier with  $R_i = 0$ ,  $A = 10^5\text{ A/A}$ ,  $R_o = \infty$ , and a full-scale input of  $100\text{ nA}$ . Assuming  $\pm 15\text{-V}$  supplies, the voltage compliance must be at least  $5\text{ V}$ .

2.24 Suitably modify the circuit of Fig. P2.16 so that it becomes a current amplifier with  $R_i = 0$ ,  $A = 100\text{ A/A}$ , and  $R_o = \infty$ . Assume ideal op amps.

2.25 In Fig. P2.25 the odd-numbered inputs are fed to  $OA_2$ 's summing junction directly, and the even-numbered inputs are fed via a current reverser. Obtain a relationship between  $v_O$  and the various inputs. What happens if any of the inputs is left floating? Will it affect the contribution from the other inputs? What is an important advantage of this circuit compared to that of Problem 1.31?

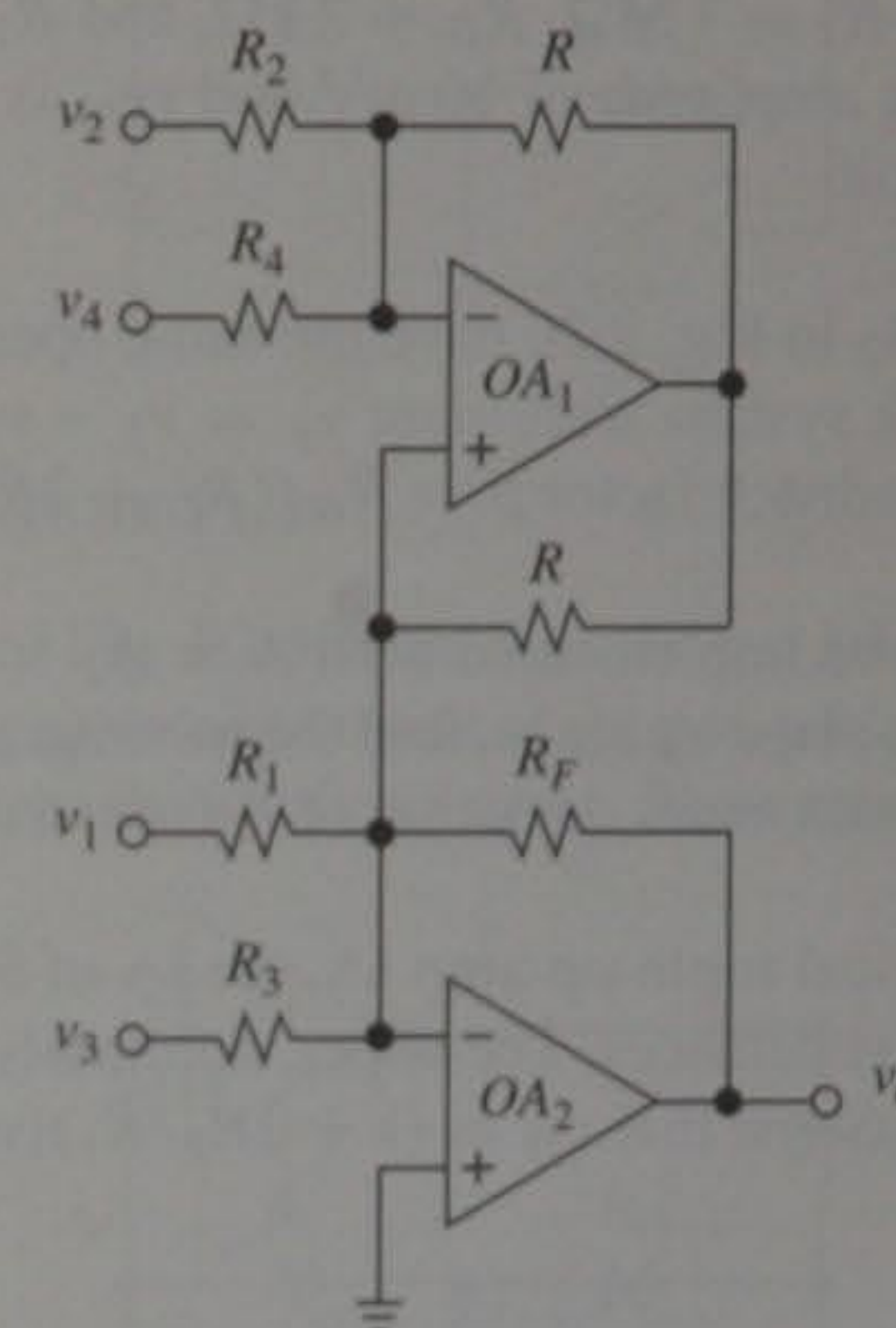


FIGURE P2.25

### 2.4 Difference amplifiers

2.26 Derive Eq. (2.23).

2.27 (a) Derive Eq. (2.27). (b) Using a  $100\text{-k}\Omega$  pot, specify suitable resistances such that varying the wiper from end to end varies the gain from  $10\text{ V/V}$  to  $100\text{ V/V}$ .

2.28 (a) Derive Eq. (2.28). (b) Specify suitable component values such that gain can be varied from  $1\text{ V/V}$  to  $100\text{ V/V}$ .

2.29 (a) A difference amplifier has  $v_1 = 10 \cos 2\pi 60t\text{ V} - 5 \cos 2\pi 10^3t\text{ mV}$ , and  $v_2 = 10 \cos 2\pi 60t\text{ V} + 5 \cos 2\pi 10^3t\text{ mV}$ . If  $v_O = 100 \cos 2\pi 60t\text{ mV} + 2 \cos 2\pi 10^3t\text{ V}$ , find  $A_{dm}$ ,  $A_{cm}$ , and  $\text{CMRR}_{dB}$ . (b) Repeat (a) with  $v_1 = 10.01 \cos 2\pi 60t\text{ V} - 5 \cos 2\pi 10^3t\text{ mV}$ ,  $v_2 = 10.00 \cos 2\pi 60t\text{ V} + 5 \cos 2\pi 10^3t\text{ mV}$ , and  $v_O = 0.5 \cos 2\pi 60t\text{ V} + 2.5 \cos 2\pi 10^3t\text{ V}$ .

2.30 If the actual resistance values in Fig. 2.13a are found to be  $R_1 = 1.01\text{ k}\Omega$ ,  $R_2 = 99.7\text{ k}\Omega$ ,  $R_3 = 0.995\text{ k}\Omega$ , and  $R_4 = 102\text{ k}\Omega$ , estimate  $A_{dm}$ ,  $A_{cm}$ , and  $\text{CMRR}_{dB}$ .

2.31 If the difference amplifier of Fig. 2.13a has a differential-mode gain of  $60\text{ dB}$  and  $\text{CMRR}_{dB} = 100\text{ dB}$ , find  $v_O$  if  $v_1 = 4.001\text{ V}$  and  $v_2 = 3.999\text{ V}$ . What is the percentage error of the output due to finite  $\text{CMRR}$ ?

2.32 If the resistance pairs are perfectly balanced and the op amp is ideal in the difference amplifier of Fig. 2.13a, then we have  $\text{CMRR}_{dB} = \infty$ . But what if the open-loop gain  $a$  is

finite, everything else being ideal? Is the CMRR still infinite? Justify your finding intuitively.

### 2.5 Instrumentation amplifiers

- 2.33 In the IA of Fig. 2.20 let  $R_3 = 1 \text{ M}\Omega$ ,  $R_G = 2 \text{ k}\Omega$ , and  $R_1 = R_2 = 100 \text{ k}\Omega$ . If  $v_{DM}$  is an ac voltage with a peak amplitude of 10 mV and  $v_{CM}$  is a dc voltage of 5 V, find all node voltages in the circuit.
- 2.34 Show that if  $OA_1$  and  $OA_2$  in Fig. 2.20 have the same open-loop gain  $a$ , together they form a negative-feedback system with input  $v_I = v_1 - v_2$ , output  $v_O = v_{O1} - v_{O2}$ , open-loop gain  $a$ , and feedback factor  $\beta = R_G / (R_G + 2R_3)$ .
- 2.35 A triple-op-amp IA is to be implemented with  $A = A_I \times A_{II} = 50 \times 20 = 10^3 \text{ V/V}$ . Assuming matched input-stage op amps, find the minimum open-loop gain required of each op amp for a 0.1% maximum deviation of  $A$  from the ideal.
- 2.36 Compared with the classical triple-op-amp IA, the IA of Fig. P2.36 (see *EDN*, Oct. 1, 1992, p. 115) uses fewer resistances. The wiper, nominally positioned halfway, is used to maximize the CMRR. Show that  $v_O = (1 + 2R_2/R_1)(v_2 - v_1)$ .

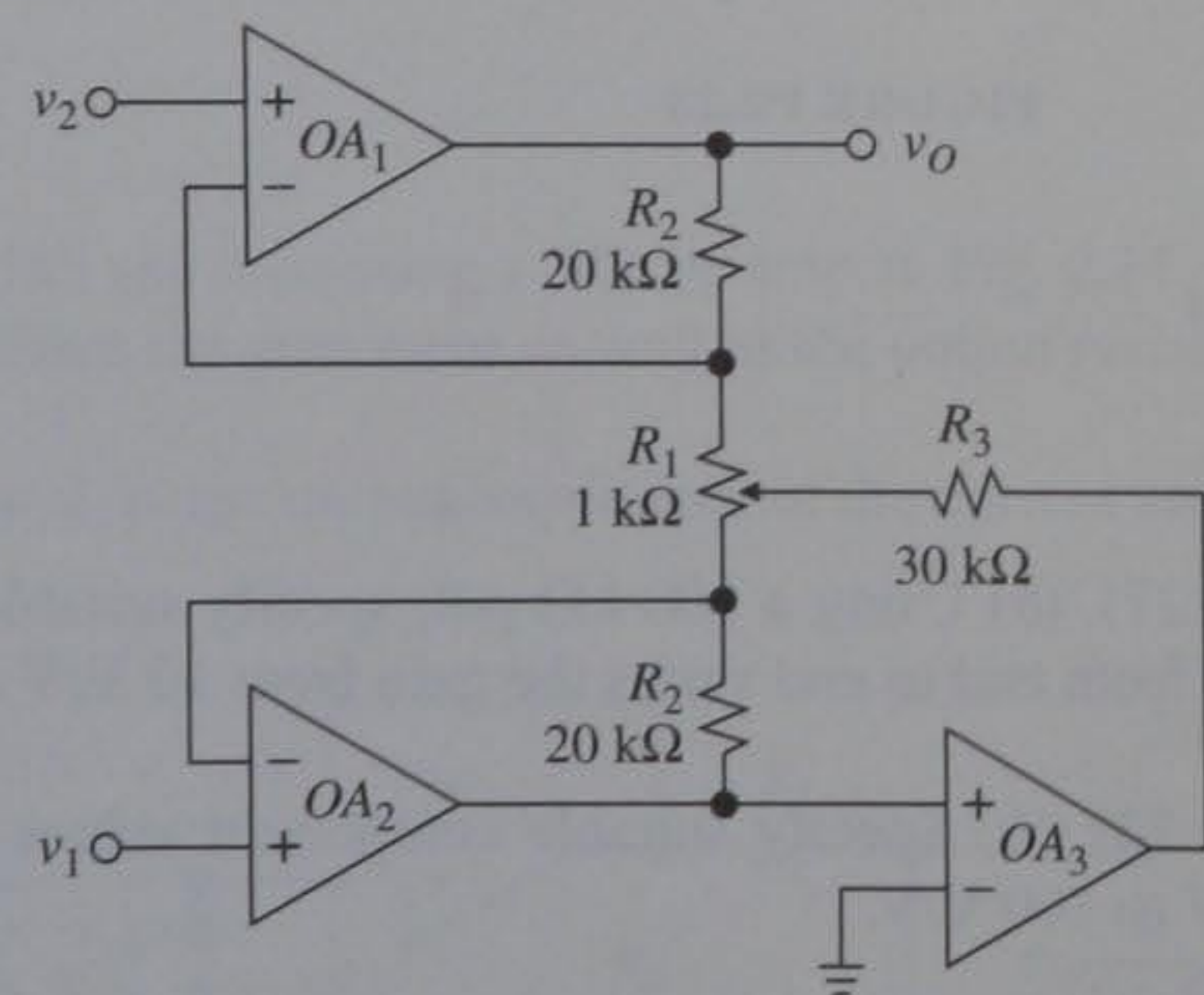


FIGURE P2.36

- 2.37 (a) To investigate the effect of mismatched resistances in the IA of Fig. 2.23, assume that  $R_3/R_4 = (R_1/R_2)(1 - \epsilon)$ . Show that  $v_O = A_{dm}v_{DM} + A_{cm}v_{CM}$ , where  $A_{dm} = 1 + R_2/R_1 - \epsilon/2$  and  $A_{cm} = \epsilon$ . (b) Discuss the implications of using 1% resistors without trimming for the case  $A = 10^2 \text{ V/V}$ .
- 2.38 (a) Derive Eq. (2.35). (b) Specify suitable components such that  $A$  can be varied over the range  $10 \text{ V/V} \leq A \leq 100 \text{ V/V}$  by means of a 10-k $\Omega$  pot.
- 2.39 The gain of the dual-op-amp IA of Fig. P2.39 (see *EDN*, Feb. 20, 1986, pp. 241–242) is adjustable by means of a single resistor  $R_G$ . (a) Show that  $v_O = 2(1 + R/R_G)(v_2 - v_1)$ . (b) Specify suitable components to make  $A$  variable from 10 V/V to 100 V/V by means of a 10-k $\Omega$  pot.

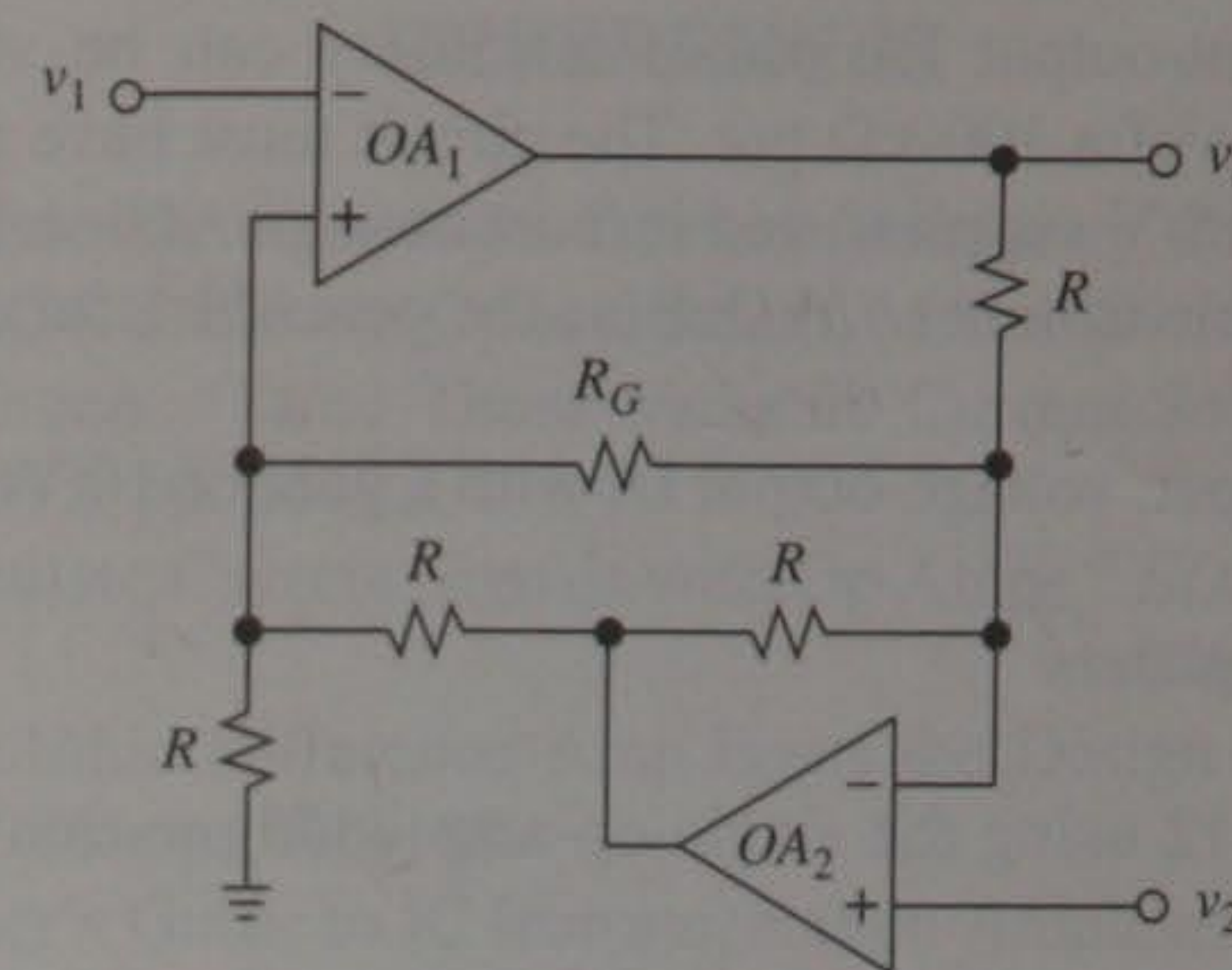


FIGURE P2.39

- 2.40 The dual-op-amp IA of Fig. P2.40 (see *Signals and Noise*, *EDN*, May 29, 1986) offers the advantage that by proper adjustment of the pot, a fairly high CMRR can be achieved and maintained well into the kilohertz range. Show that  $v_O = (1 + R_2/R_1)(v_2 - v_1)$ .

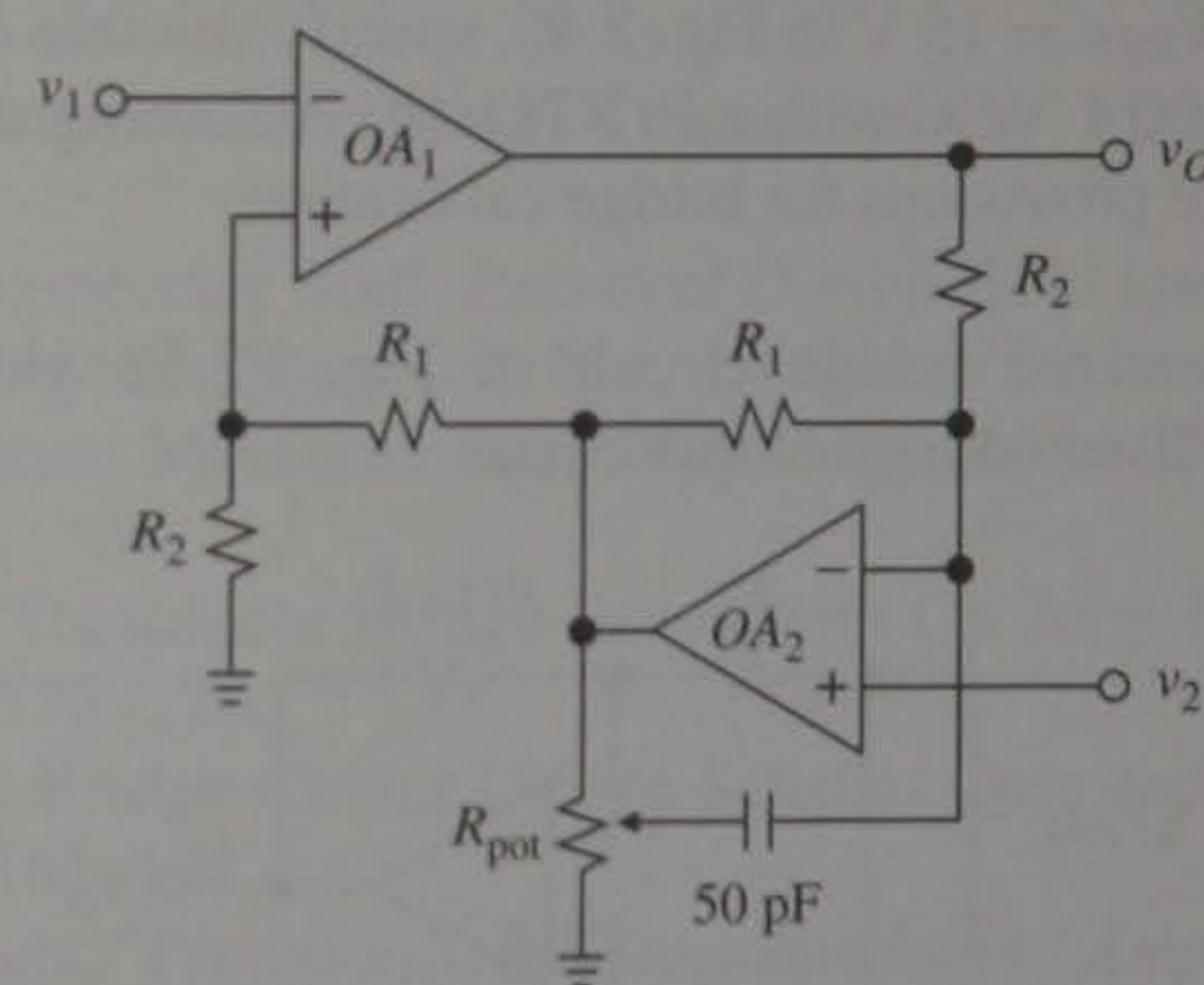


FIGURE P2.40

- 2.41 Assuming perfectly matched resistances as well as perfectly matched op amps in the dual-op-amp IA of Fig. 2.23, investigate the effect of finite open-loop op amp gain  $a$  upon the CMRR of the circuit (except for their finite gain, both op amps are ideal). Assuming  $a = 10^5 \text{ V/V}$ , find  $\text{CMRR}_{dB}$  if  $A = 10^3 \text{ V/V}$ . Repeat, but if  $A = 10 \text{ V/V}$ , and comment on your findings.
- ### 2.6 Instrumentation applications
- 2.42 Design a digitally programmable IA having an overall gain of 1 V/V, 10 V/V, 100 V/V, and 1000 V/V. Show the final design.
- 2.43 Assuming  $\pm 15\text{-V}$  regulated power supplies, design a programmable IA with two operating modes: in the first mode the gain is 100 V/V and the output offset is 0 V; in the second mode the gain is 200 V/V and the output offset is  $-5 \text{ V}$ .
- 2.44 (a) Derive Eq. (2.42). (b) In the current-output IA of Fig. 2.33 specify suitable components for a sensitivity of 1 mA/V. (c) Investigate the effect of using 0.1% resistances.
- 2.45 In the circuit of Fig. 2.33 let  $R_1 = R_4 = R_5 = 10 \text{ k}\Omega$ ,  $R_2 = 1 \text{ k}\Omega$ , and  $R_3 = 9 \text{ k}\Omega$ . If an additional resistance  $R_G$  is connected between the inverting input nodes of the two op amps, find the gain as a function of  $R_G$ .

**2.46** (a) Design a current-output IA whose sensitivity can be varied from 1 mA/V to 100 mA/V by means of a 100-k $\Omega$  pot. The circuit must have a voltage compliance of at least 5 V with  $\pm 15$ -V supplies, and it must have provision for CMRR optimization by means of a suitable trimmer. (b) Outline the procedure for calibrating the trimmer.

**2.47** Design a current-input, voltage-output IA with a gain of 10 V/mA.

### 2.7 Transducer bridge amplifiers

**2.48** Repeat Example 2.12 using the single-op-amp configuration of Fig. 2.38. Show the final circuit.

**2.49** (a) Derive Eqs. (2.52) and (2.53). (b) Derive Eq. (2.55).

**2.50** Assuming that  $V_{REF} = 2.5$  V in Fig. 2.39, specify suitable component values for an output sensitivity of 0.1 V/ $^{\circ}$ C with a Pt RTD.

**2.51** (a) Assuming that  $V_{REF} = 15$  V in Fig. 2.40, specify suitable component values for an output sensitivity of 0.1 V/ $^{\circ}$ C with a Pt RTD. (b) Assuming the same tolerances as in Example 2.13, make provisions for bridge calibration.

**2.52** Show that the linearized bridge circuit of Fig. P2.52 yields  $v_O = -RV_{REF}\delta / (R_1 + R)$ . Name a disadvantage of this circuit.

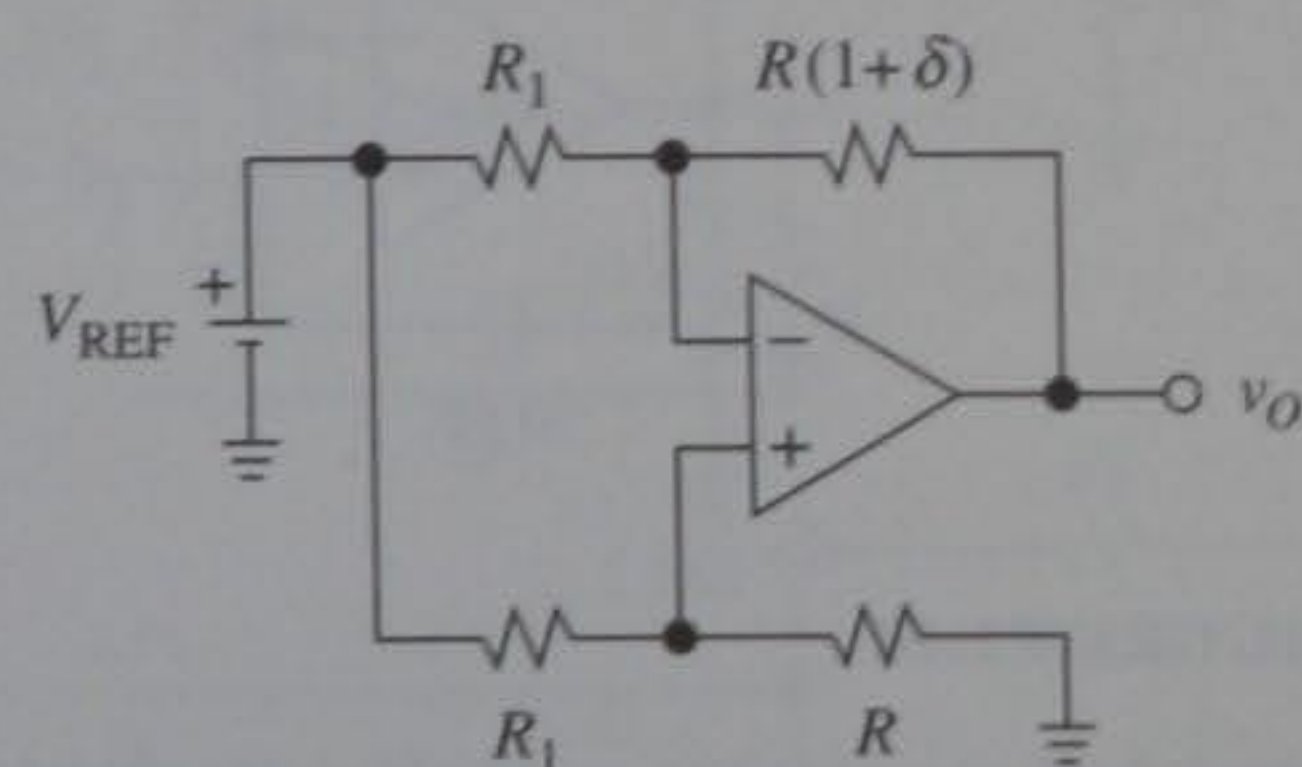


FIGURE P2.52

**2.53** Using the circuit of Fig. P2.52 with  $V_{REF} = 2.5$  V and an additional gain stage, design an RTD amplifier circuit with a sensitivity of 0.1 V/ $^{\circ}$ C. The circuit is to have provisions for bridge calibration. Outline the calibration procedure.

**2.54** Show that the linearized bridge circuit<sup>11</sup> of Fig. P2.54 (U.S. Patent 4,229,692) yields  $v_O = R_2 V_{REF} \delta / R_1$ . Discuss how you would make provisions for calibrating the circuit.

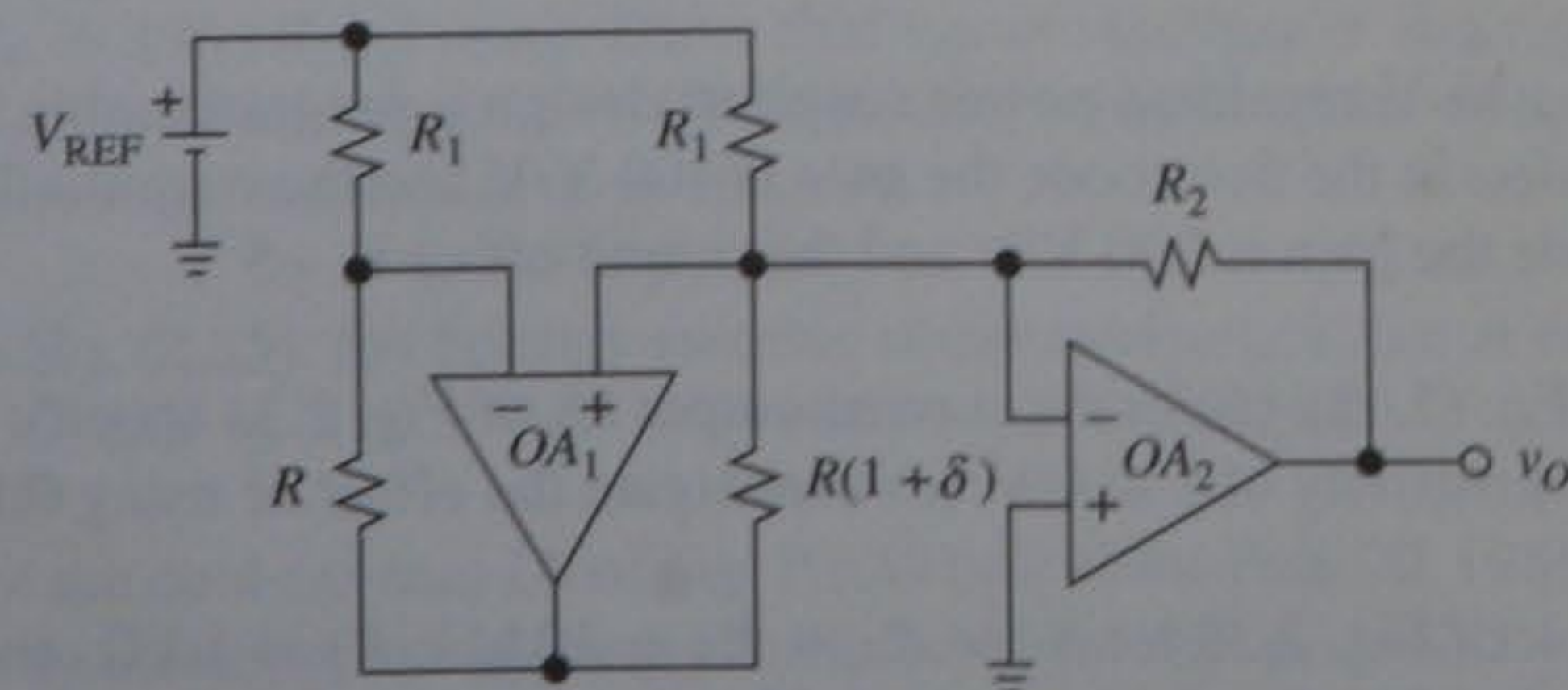


FIGURE P2.54

## REFERENCES

1. "Silicon Photovoltaic Detectors and Detector/Amplifier Combinations," Application Note D3011C-8, EG&G Electro-Optics, Salem, MA, 1984.
2. J. Steele and T. Green, "Tame Those Versatile Current-Source Circuits," *Electronic Design*, Oct. 15, 1992, pp. 61-72.
3. J. Graeme, "Manipulate Current Signals with Op Amps," *EDN*, Aug. 8, 1985, pp. 147-158.
4. R. M. Stitt, "Monolithic Difference Amp Eases the Design of a Variety of Circuits," *EDN*, March 20, 1986, pp. 181-188.
5. J. R. Riskin, "A User's Guide to IC Instrumentation Amplifiers," Application Note AN-244, *Applications Reference Manual*, Analog Devices, Norwood, MA, 1993.
6. J. Williams, "Applications for a Switched-Capacitor Instrumentation Building Block," Application Note AN-3, *Linear Applications Handbook*, vol. 1, Linear Technology, Milpitas, CA, 1990.
7. "Instrumentation Amplifiers: Versatile Differential Input Gain Blocks," Application Note AN-75, *Burr-Brown Handbook of Linear IC Applications*, Burr-Brown, Tucson, AZ, 1987.
8. J. Graeme, "Bootstrapped Amp Makes Current Source," *EDN*, Jan. 21, 1991, pp. 152-154.
9. Analog Devices Engineering Staff, *Practical Design Techniques for Sensor Signal Conditioning*, Analog Devices, Norwood, MA, 1999.
10. "Practical Temperature Measurements," Application Note 290, Hewlett-Packard, Palo Alto, CA, 1980.
11. J. Graeme, "Tame Transducer Bridge Errors with Op Amp Feedback Control," *EDN*, May 26, 1982, pp. 173-176.
12. J. Williams, "Good Bridge-Circuit Design Satisfies Gain and Balance Criteria," *EDN*, Oct. 25, 1990, pp. 161-174.
13. J. Wong and A. Garcia, "Precision Transducer Interfaces," *Amplifier Applications Guide*, Analog Devices, Norwood, MA, 1992.