Ve215 Electric Circuits

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Chapter 5

Operational Amplifiers

5.1 Introduction

- The *operational amplifier*, or *op amp*, is an electronic device that behaves like a voltage-controlled voltage source. An op amp circuit can perform mathematical operations of addition, subtraction, multiplication, division, differentiation, and integration.

Vacuum Tube Op Amp

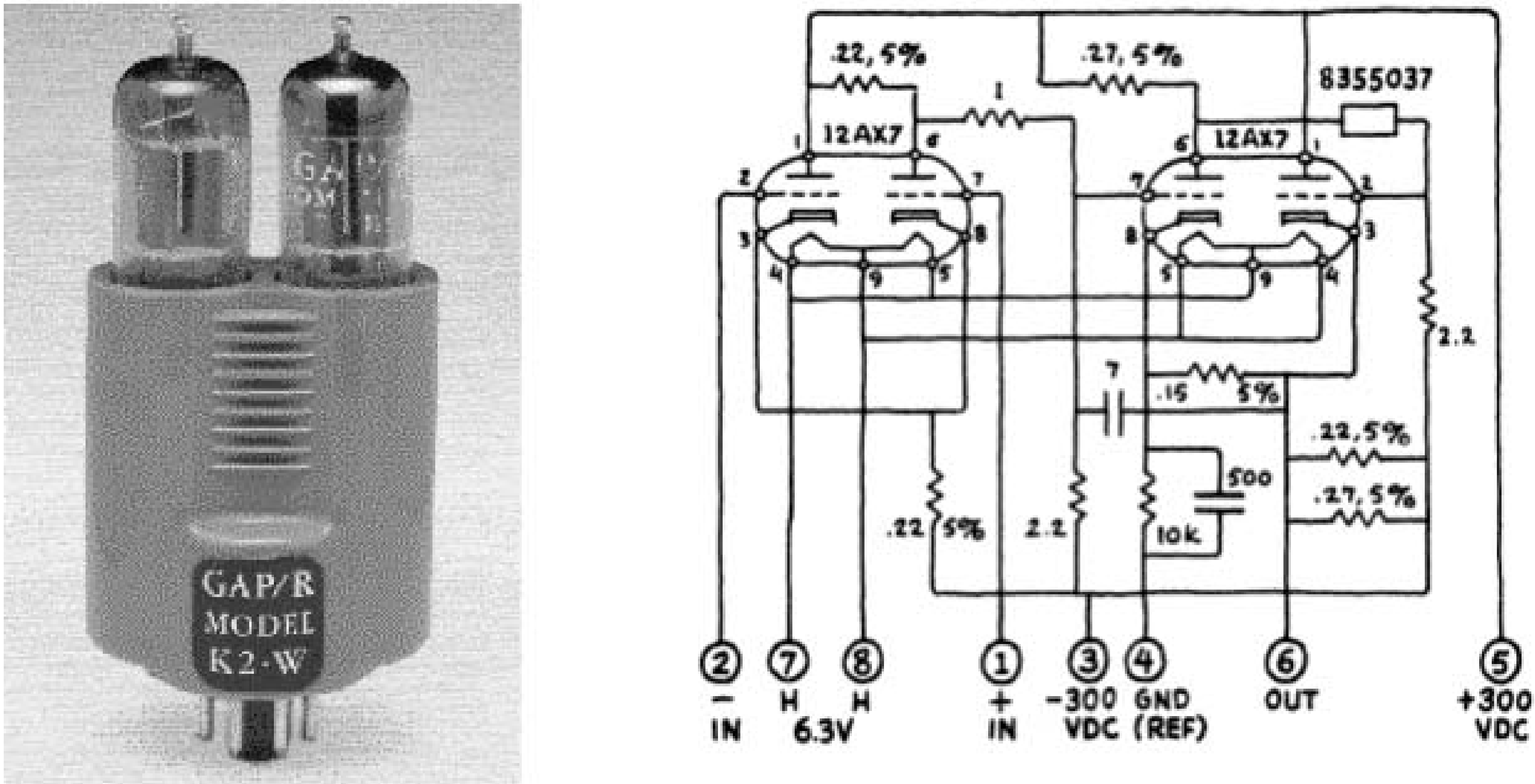


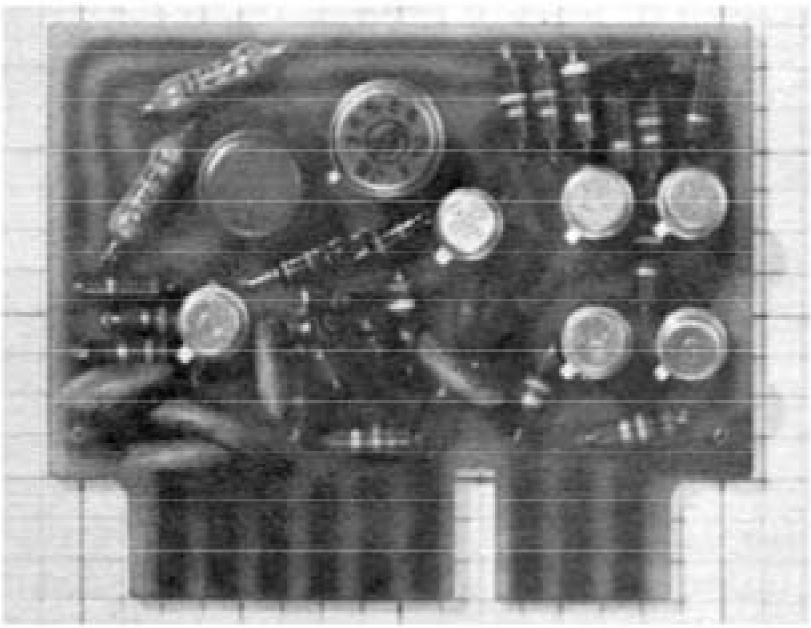
Figure H-5: *The GAP/R K2-W op amp, photo and schematic diagram (courtesy of GAP/R alumnus Dan Sheingold - schematic values in megohms and pF.)*

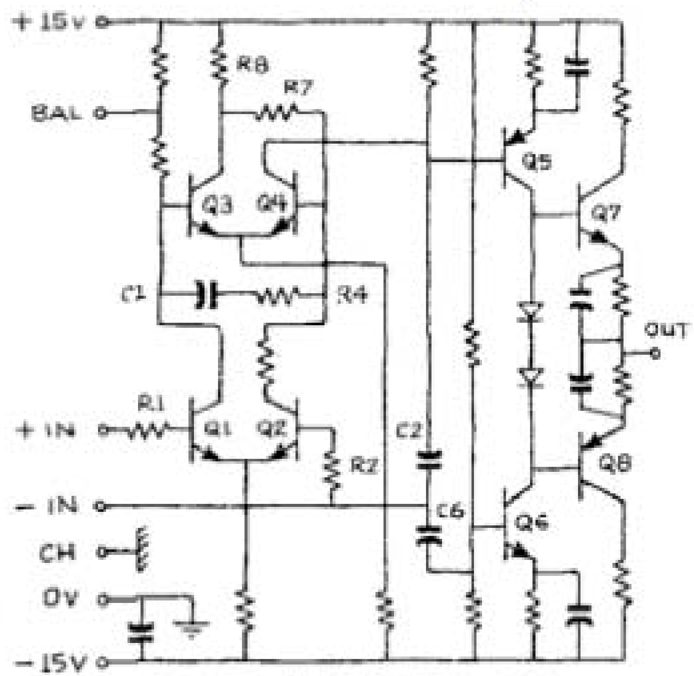
Taken from the book "Op Amp Applications" by Walter Jung, www.analog.com

Generation 1: Vacuum Tube Op Amp

- George A. Philbrick formed a company bearing his name George A. Philbrick Researches Inc., in 1946 (GAP/R)
- GAP/R introduced the world’s first commercially available op amp, known as K2-W, which was developed in 1952 and appeared in Jan. 1953.
- K2-W operated on $\pm$300V
- $20/each

Solid State Op Amp





CIRCUIT of P45 AMPLIFIER

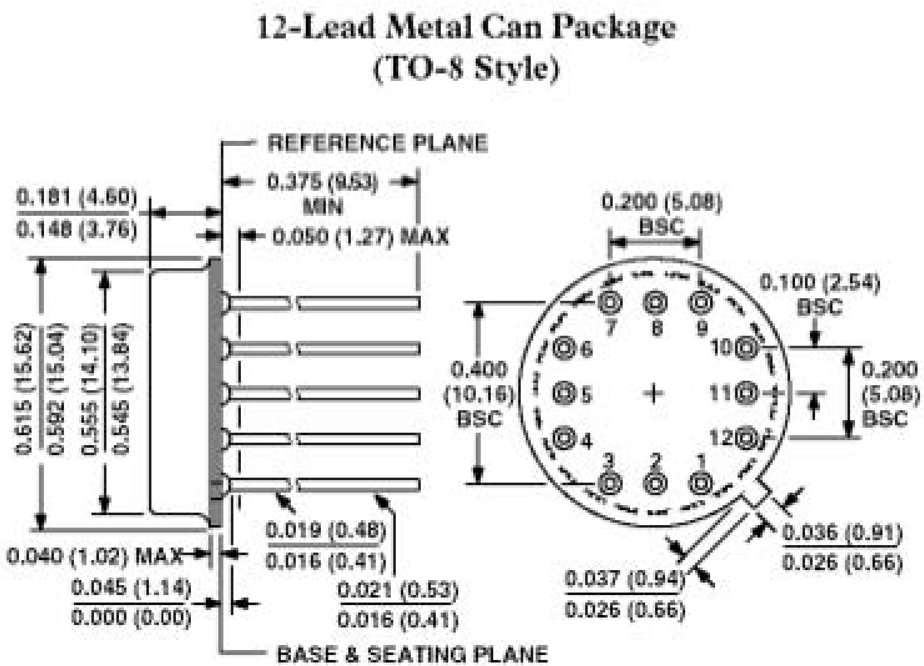
Figure H-8: *The GAP/R model P45 solid-state op amp*

Taken from the book "Op Amp Applications" by Walter Jung, www.analog.com

Generation 2: Solid State Op Amp

- GAP/R introduced a solid-state op amp P45 in 1963
- Faster AC response; better stability
- One of the most outstanding specification: gain-bandwidth product of 100MHz
- P45 ran on ±15V (Intended for output ranges of ±10V)
- $118/each (quantities 1-4)

Hybrid IC Op Amp



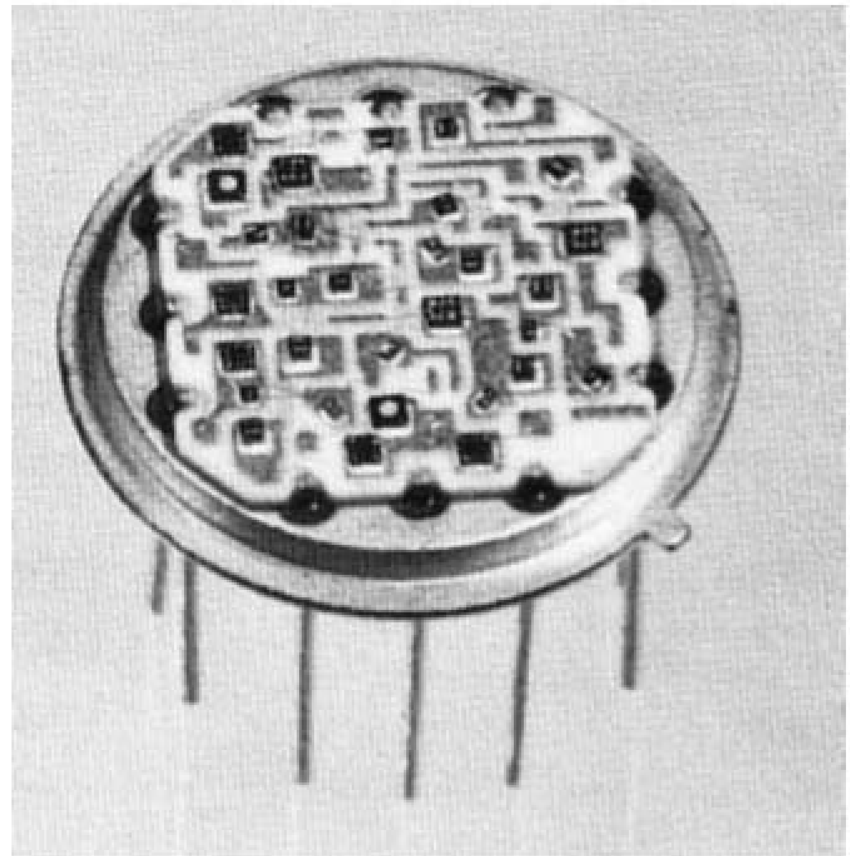
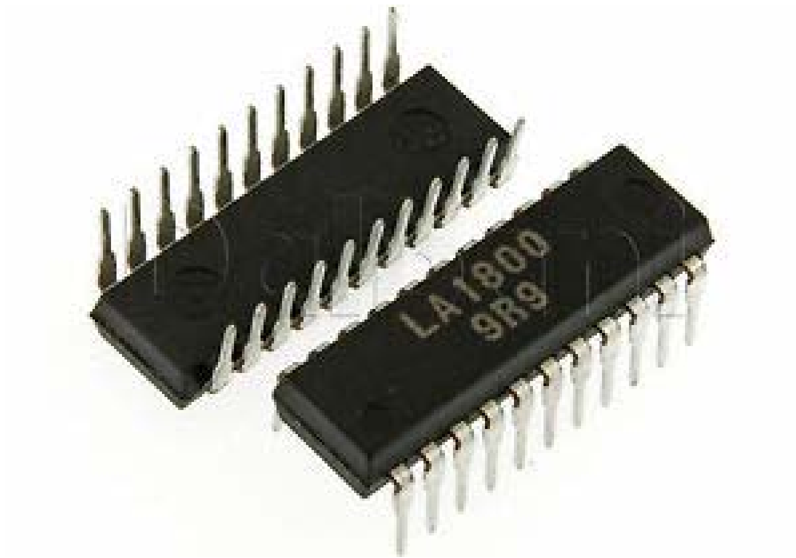


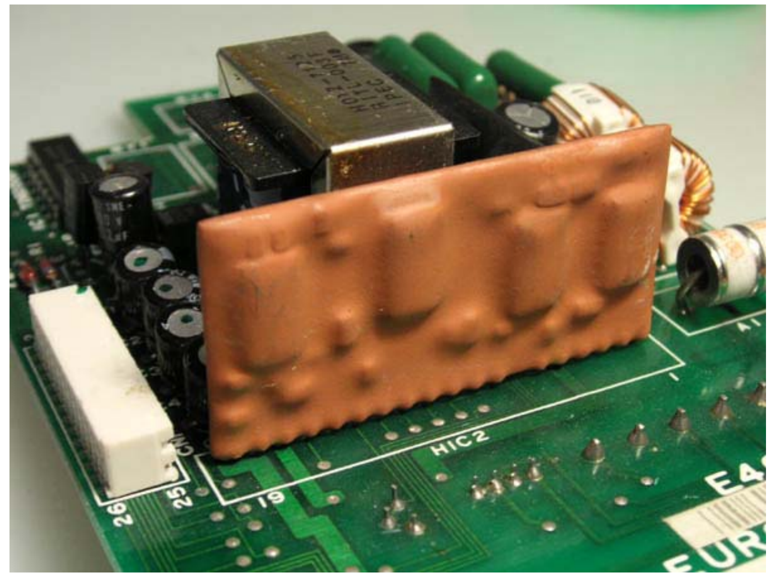
Figure H-14: *The ADI HOS-050 high speed hybrid IC op amp*

Taken from the book "Op Amp Applications" by Walter Jung, www.analog.com

Monolithic IC



Hybrid IC

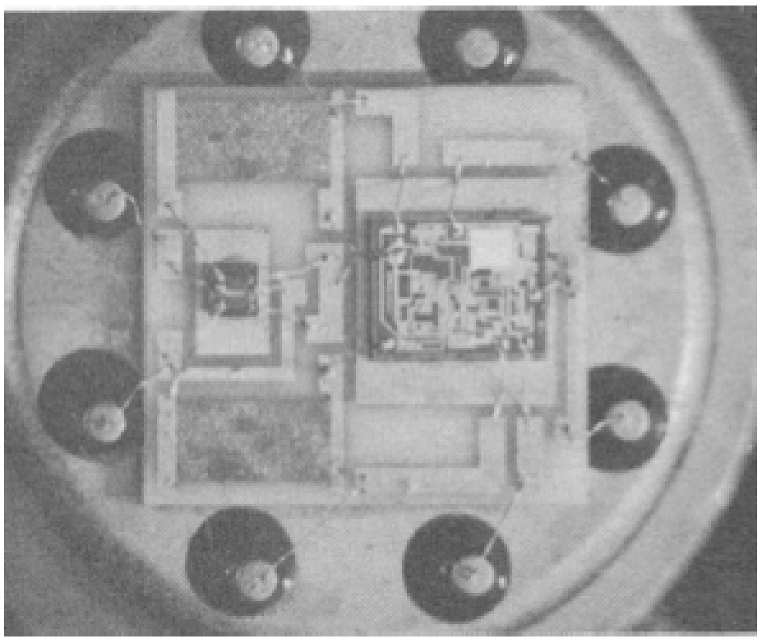


Constructed of individual devices
- Semiconductor devices
- Passive components

Generation 3-1: Hybrid IC Op Amp

- HOS-050 manufactured by ADI in 1970’s and 1980’s
- The most dense form of circuit packaging available at that time
- Hybrid op amp lifetimes were relatively short (Reason: sophisticated but hard to produce)

Hybrid IC Op Amp



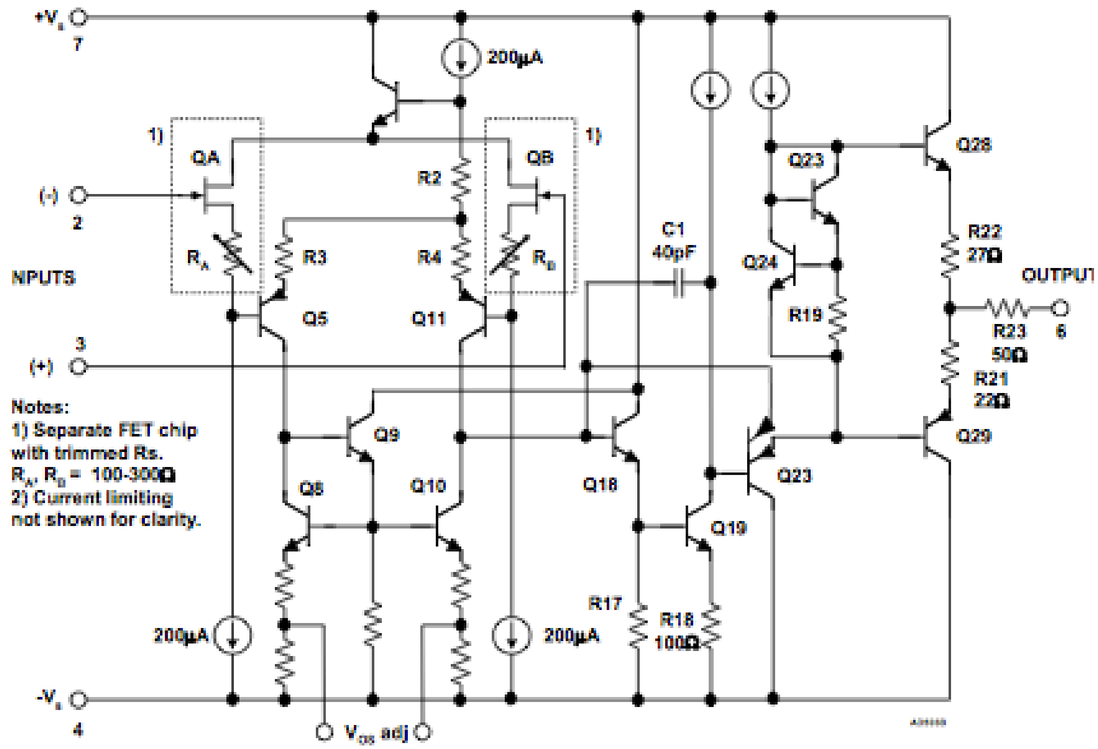


Figure H-25: *The AD503 and AD506 two-chip hybrid IC op amps*

Taken from the book "Op Amp Applications" by Walter Jung, www.analog.com

Generation 3-2: Hybrid IC Op Amp

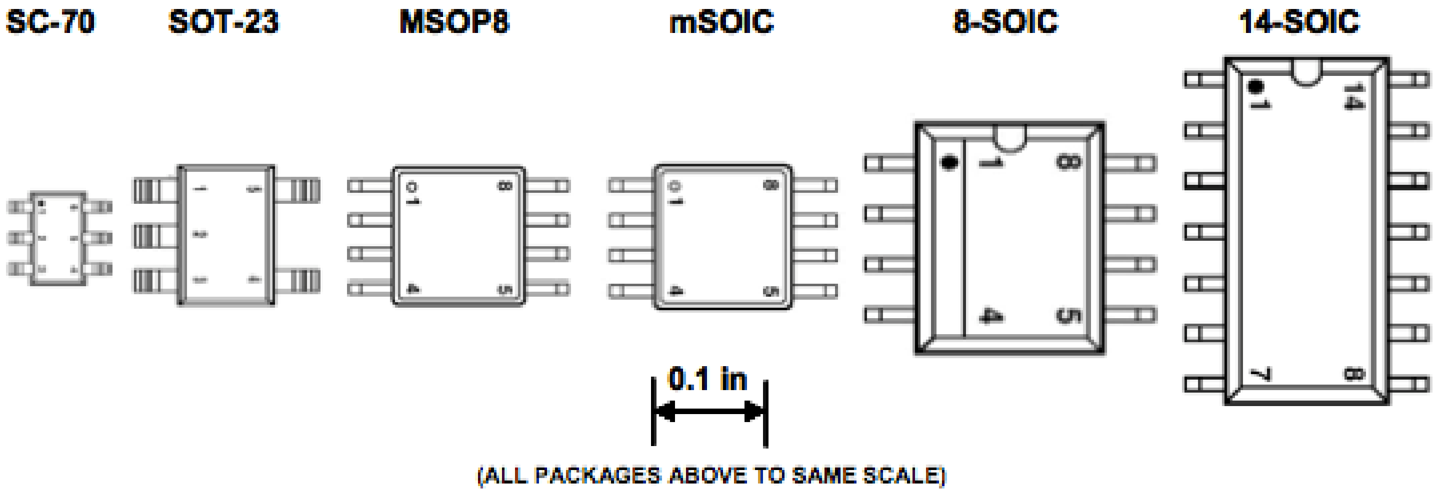
- The ADI amplifier, known as the AD503 and AD506, was released in 1970.
- Two chips used
- Excellent common-mode rejection (CMR) specifications

Differential amplifier

Ideal $V_o = A_d(V_+ - V_-)$

Real $V_o = A_d(V_+ - V_-) + \frac{1}{2}A_{cm}(V_+ + V_-),$

Integrated Op Amp



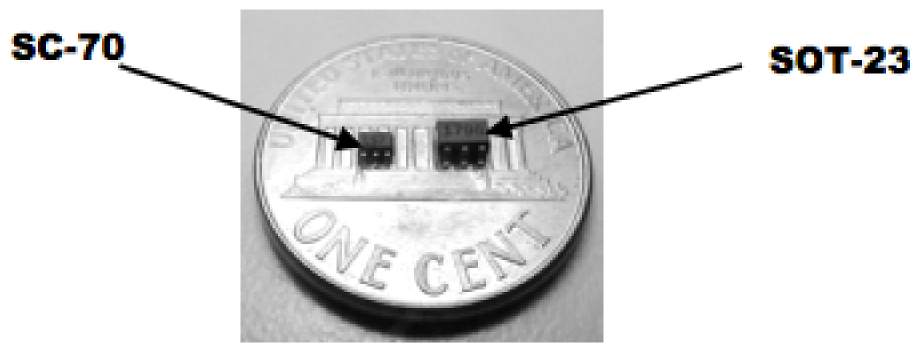


Figure H-24: *The relative scale of some modern IC op amp packages*

Taken from the book "Op Amp Applications" by Walter Jung, www.analog.com

Generation 4: Integrated Op Amp

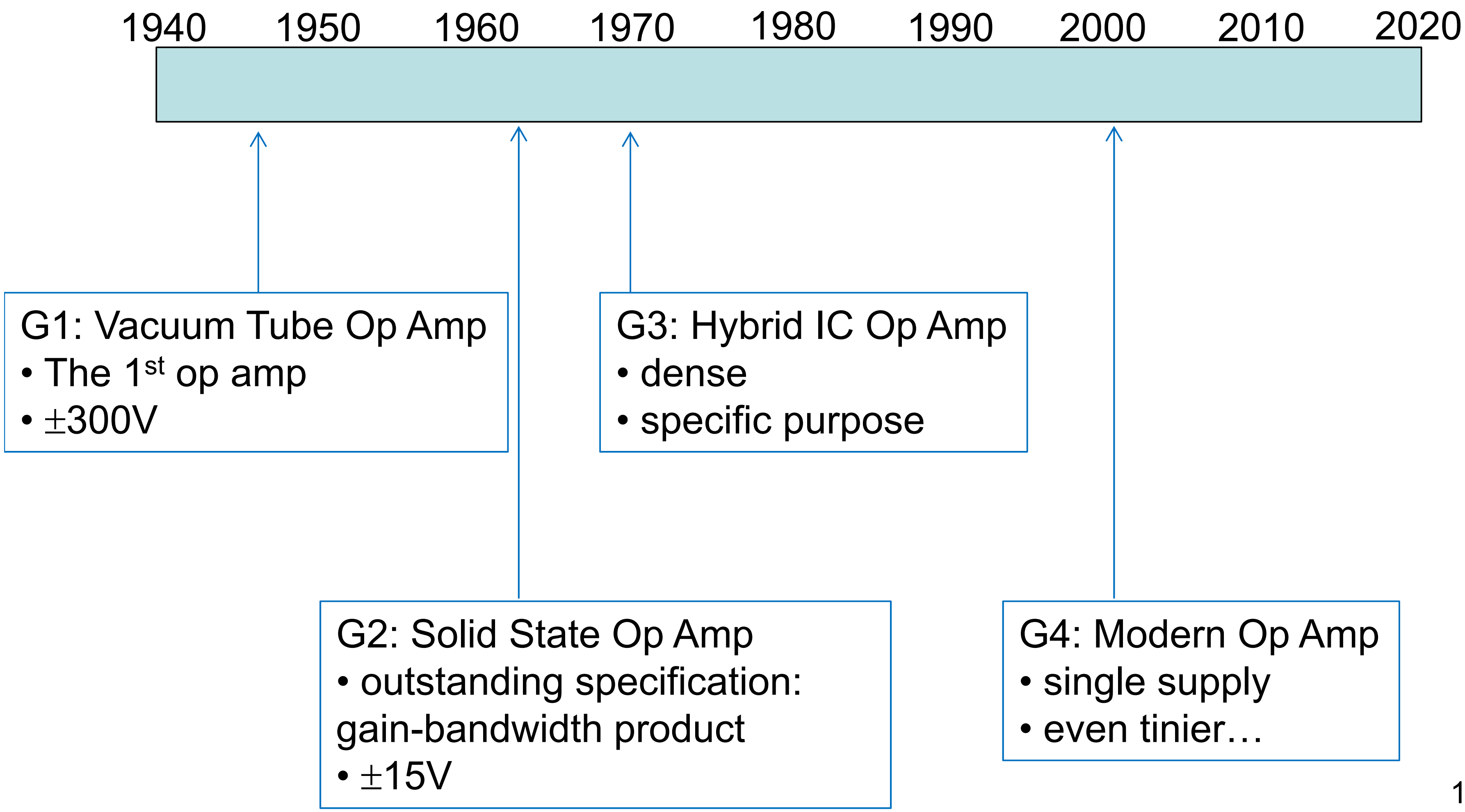
- While the high precision is still often sought, amplifier versions with single-supply capability are now in demand, as are tiny and even tinier packages
- Examples:

  op777 series released in 2000

  op1177 series released in 2001

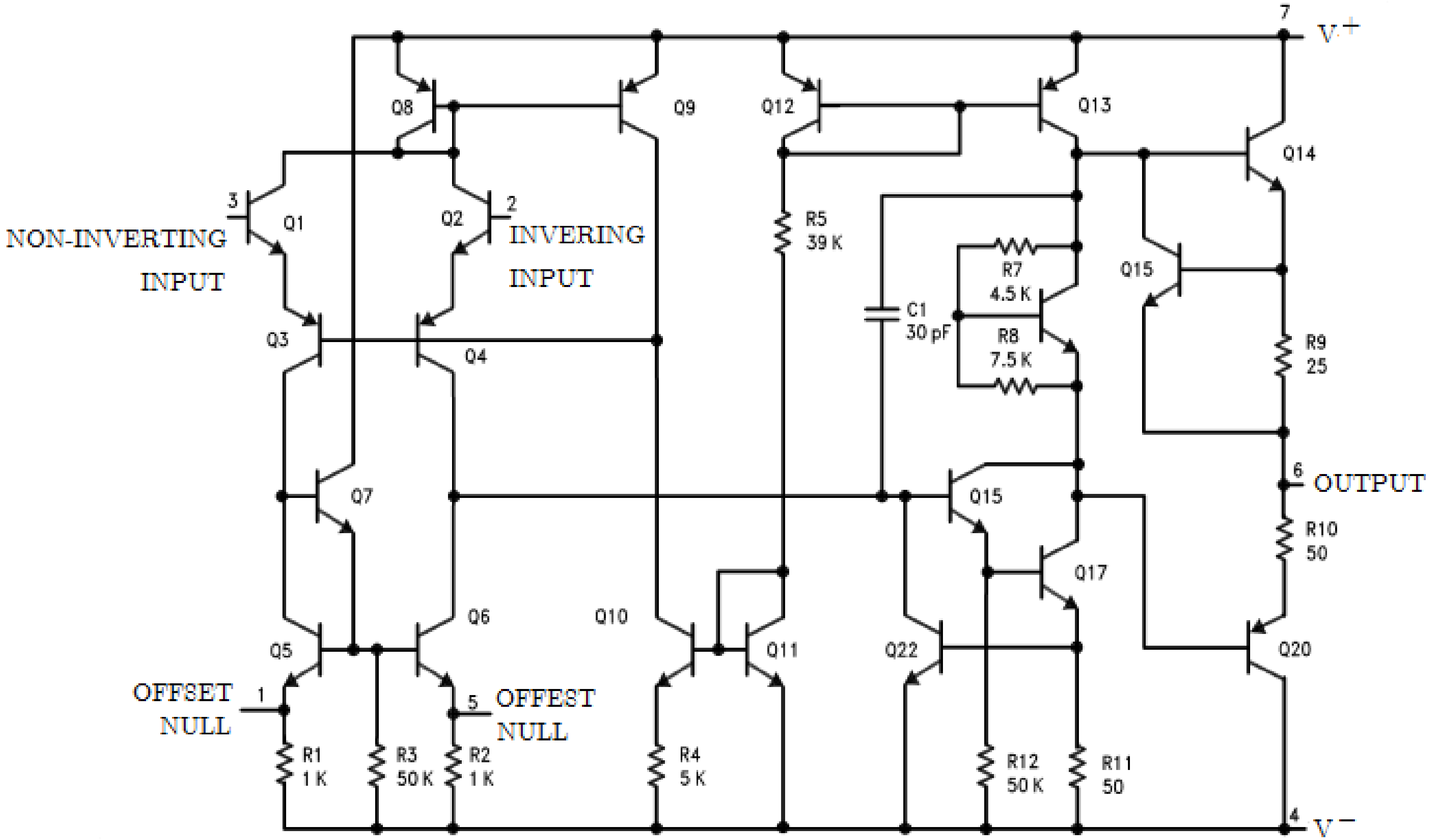
  (designed by Derek Bowers)

Summary


1940
1950
1960
1970
1980
1990
2000
2010
2020
G1: Vacuum Tube Op Amp
• The 1st op amp
• ±300V
G3: Hybrid IC Op Amp
• dense
• specific purpose
G2: Solid State Op Amp
• outstanding specification: gain-bandwidth product
• ±15V
G4: Modern Op Amp
• single supply
• even tinier…

5.2 Operational Amplifiers

- As shown on the next page, an op amp consists of a complex arrangement of resistors, transistors, capacitors, and diodes. A full discussion of what is inside the op amp is in Ve311.
- In Ve215, we treat the op amp as a circuit building block and simply study what takes place at its terminals.



Schematic diagram for LM741 op amp.

- Op amps are commercially available in integrated circuit packages in several forms. Figure 5.2(a) shows the pin configuration of a typical op amp. The circuit symbol for the op amp is the triangle in Fig. 5.2(b).

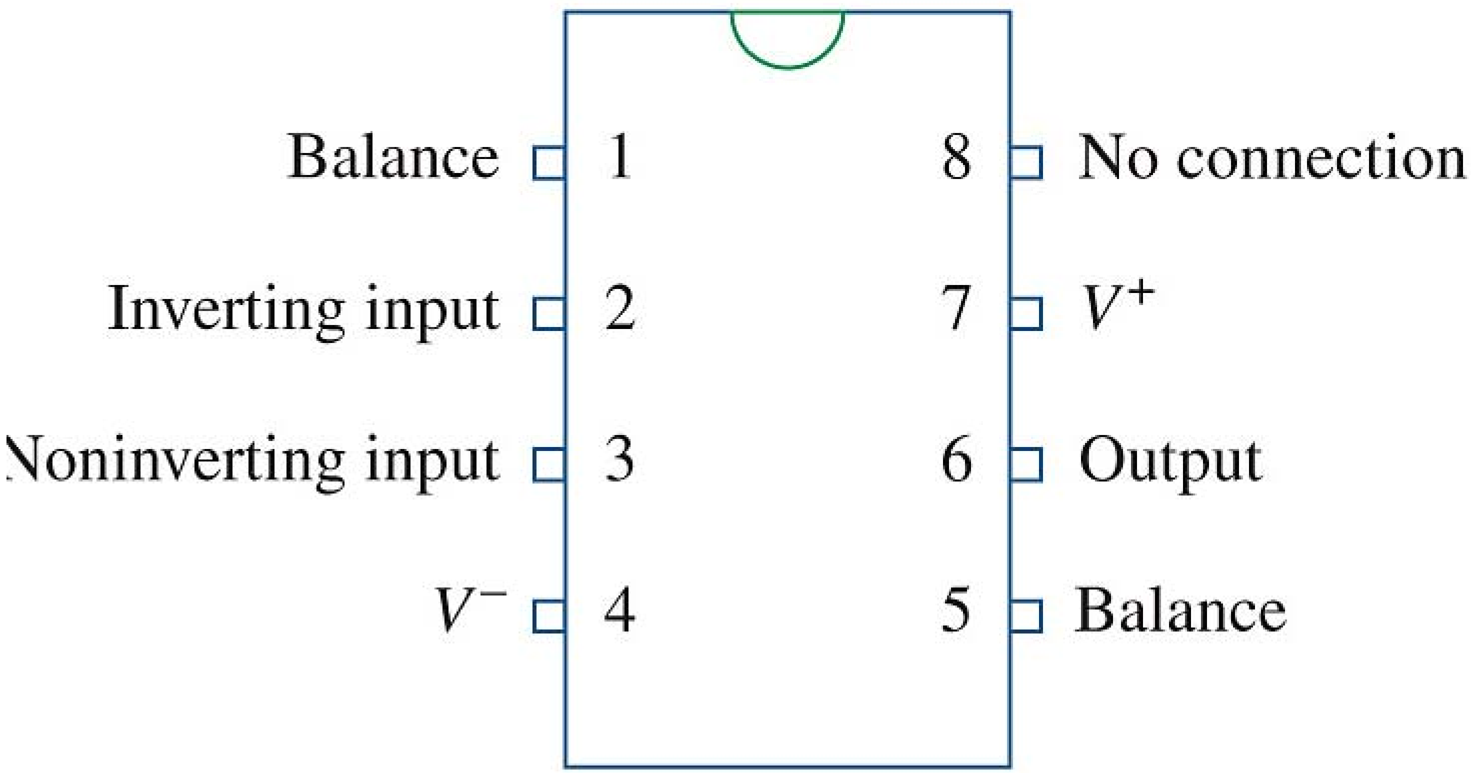


Figure 5.2(a) A typical op amp: pin configuration.

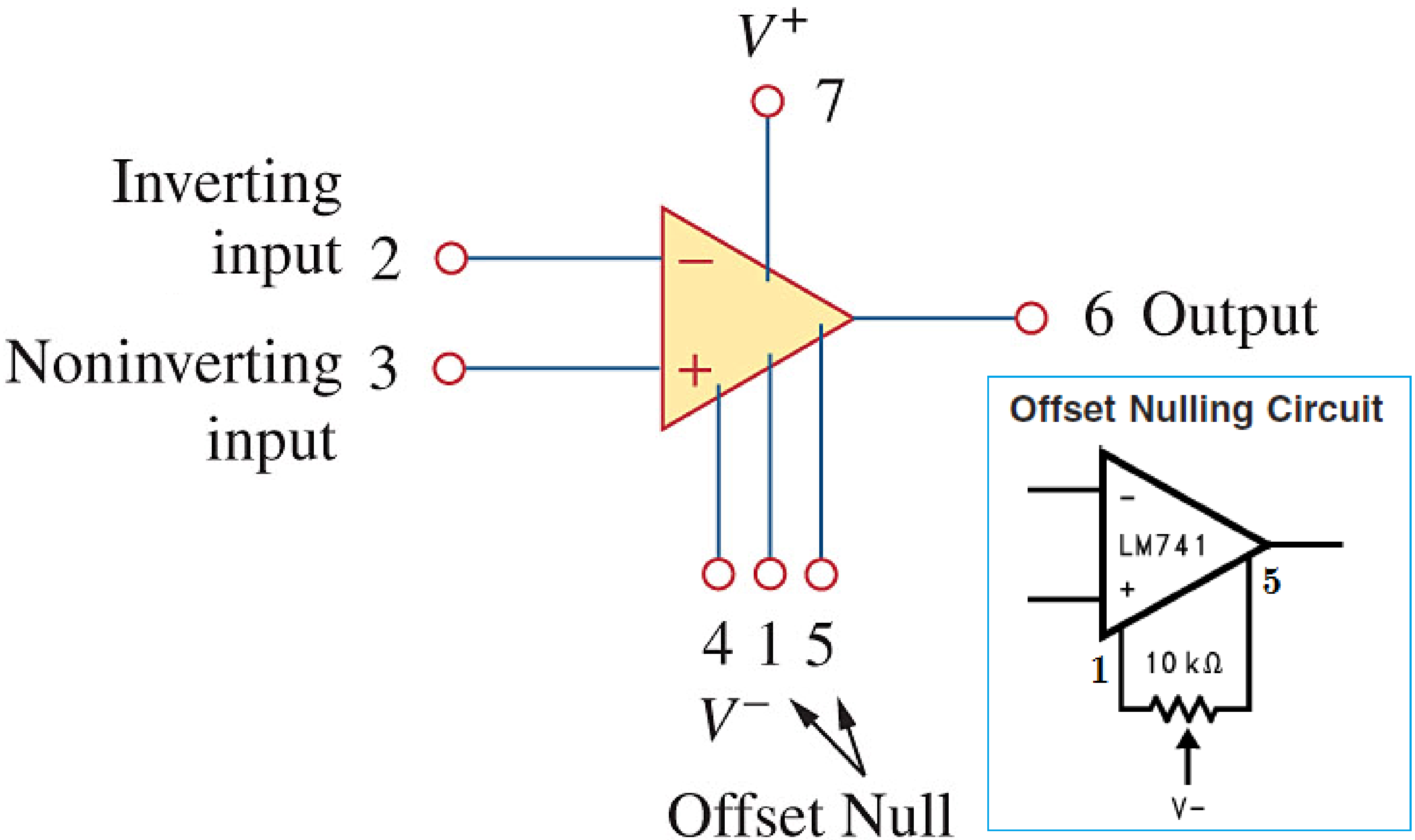


Figure 5.2(b) A typical op amp: circuit symbol.

About Offset null

- By adjusting the pot we can null any offset error.
- Offset error
  - when the inputs are exactly equal but the output isn't exactly zero
  - Due to random variation in manufacturing
  - Can be safely ignored in AC applications (since it's just a DC offset), but can be an issue in DC applications

    $v_O = Av_I + V_{os}$

    If $v_I = \sin(\omega t)$, then $v_O = A\sin(\omega t) + V_{os}$

    AC signal, $A\sin(\omega t)$, is still preserved

- As an active element, the op amp must be powered by one or two voltage supplies as typically shown in Fig. 5.3.

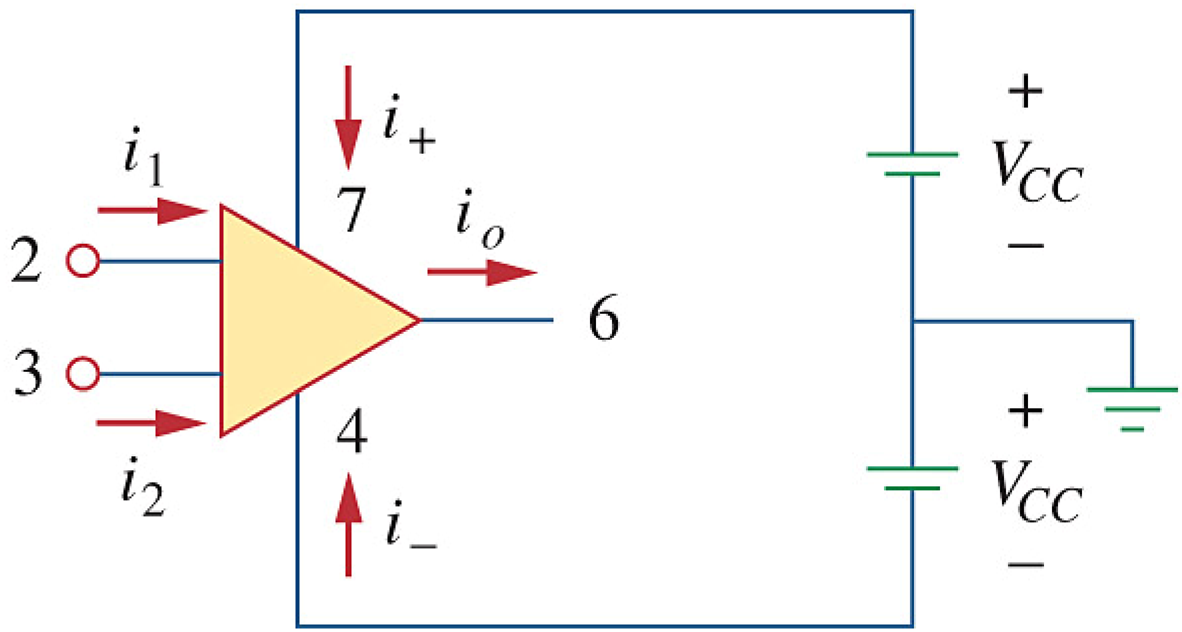
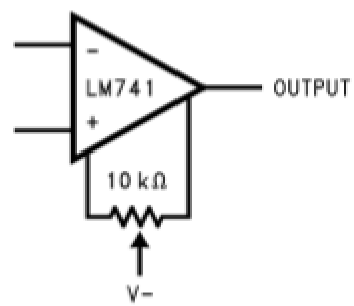


Figure 5.3 Powering the op amp.

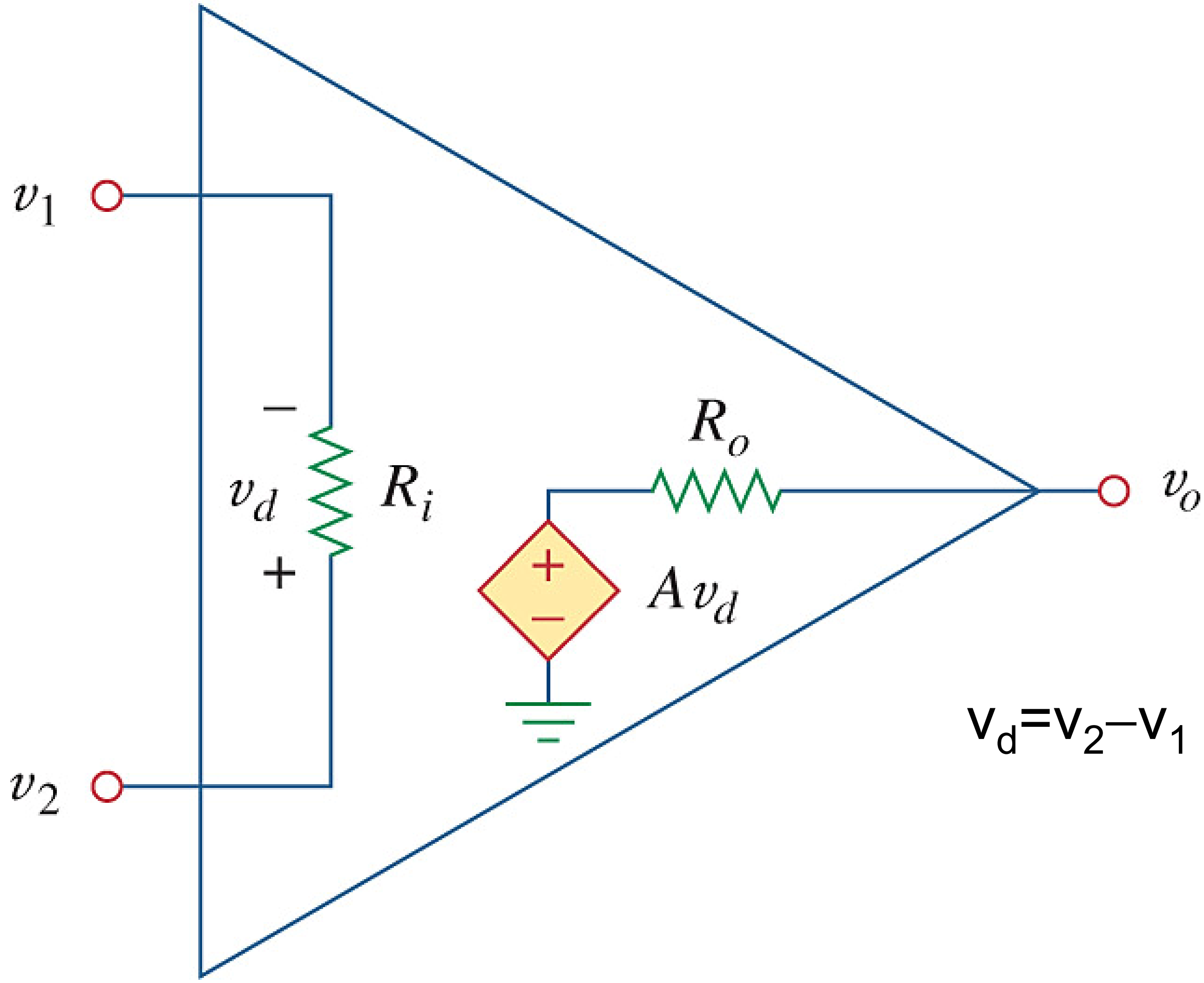
Although the power supplies are often ignored in op amp circuit diagrams for the sake of simplicity, the power supply currents must not be overlooked. By KCL,

$$i_o = i_1 + i_2 + i_+ + i_-$$

(This formula is valid even if pins 1 and 5 are used)



The equivalent circuit model of an op amp is shown in Fig. 5.4. $v_d = v_2 - v_1$ is called the differential input voltage and A is the *open-loop voltage gain.*



$v_d = v_2 - v_1$

Figure 5.4 The equivalent circuit of the nonideal op amp.

TABLE 5.1 Typical ranges for op amp parameters

Parameter	*Typical range*	*Ideal values*
Open-loop gain, A	10^5 to 10^8	∞
Input resistance, R_i	10^5 to 10^{13} Ω	∞
Output resistance, R_o	10 to 100 Ω	0
Supply voltage, V_{CC}	5 to 24 V	NA

A practical limitation of the op amp is that the magnitude of its output voltage cannot exceed $|V_{CC}|$. Figure 5.5 illustrates that the op amp can operate in three modes: (1) positive saturation, (2) linear region, (3) negative saturation.

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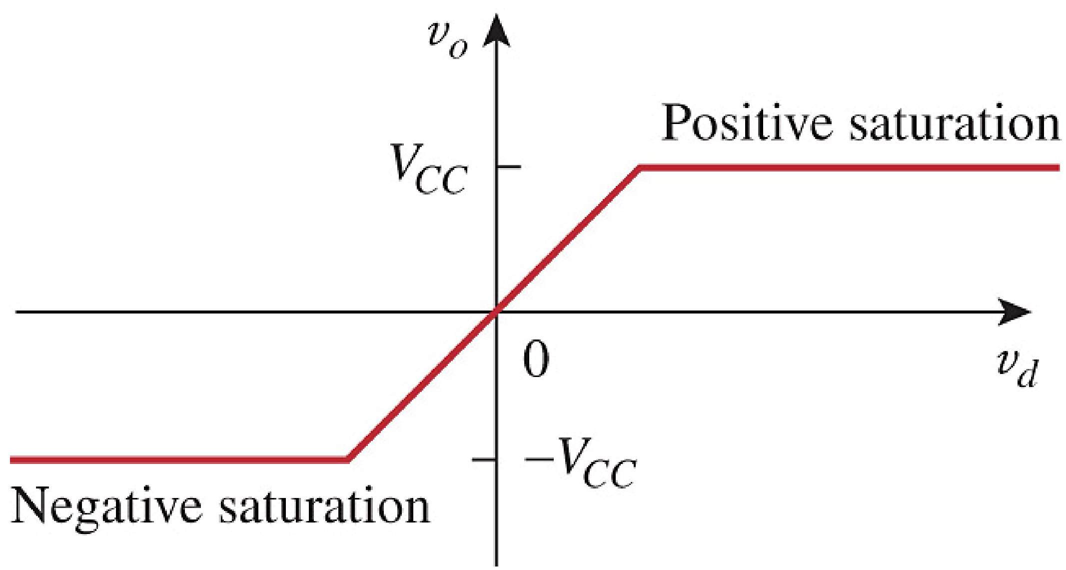


5.3 Ideal Op Amp

An op amp is ideal if it has the following characteristics:

1. Infinite open-loop gain, $A = \infty$.
2. Infinite input resistance, $R_i = \infty$.
3. Zero output resistance, $R_o = 0$.

For circuit analysis, an ideal op amp is illustrated in Fig. 5.8.

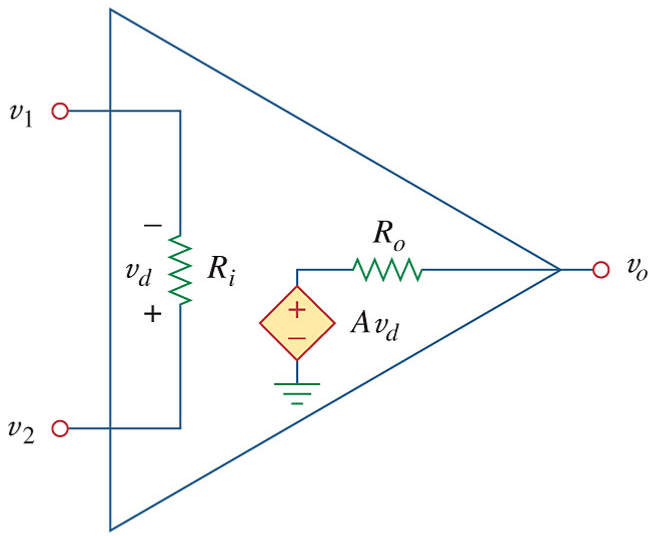
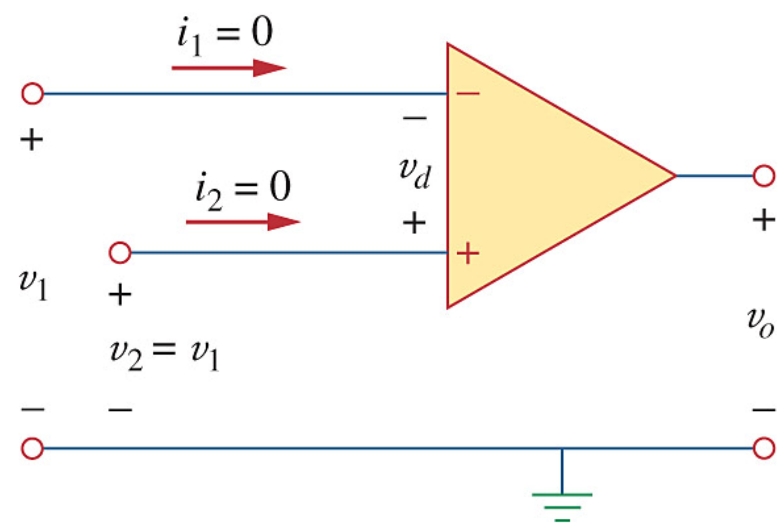
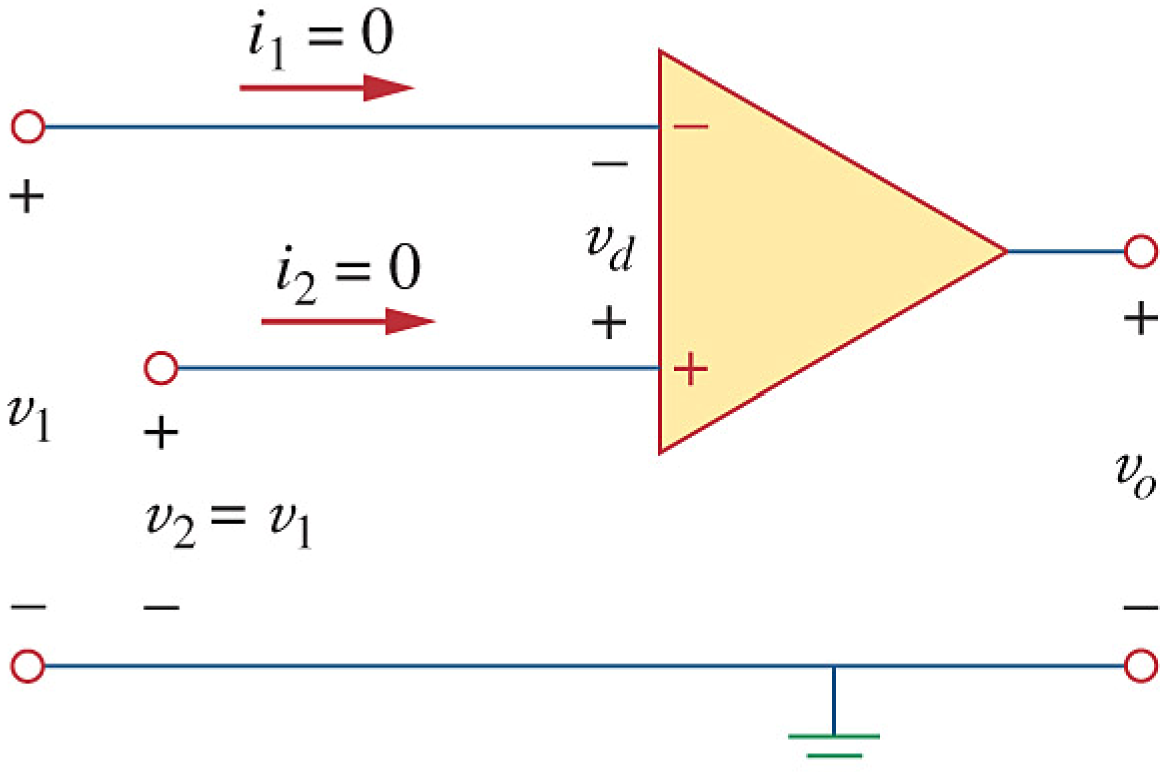


Figure 5.4 The equivalent circuit of the nonideal op amp.



A=∞
R_i=∞
R_o=0



$i_1 = 0$
$i_2 = 0$
v_d
v_1
$v_2 = v_1$
v_o

Two important characteristics of the ideal op amp are

1. The current into both input terminals are zero due to $R_i = \infty$:

$i_1 = 0$ and $i_2 = 0$ (virtual open-circuit)

Proof :

$$v_d = v_2 - v_1 = i_2 R_i < \infty \Rightarrow i_2 = 0 \Rightarrow$$
$$i_1 = -i_2 = 0$$

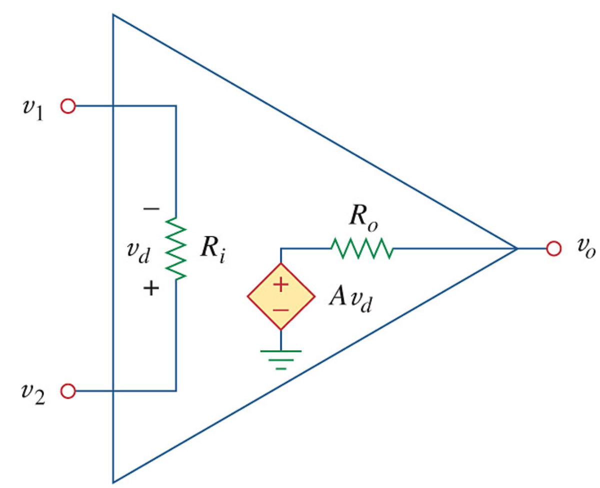


Figure 5.4 The equivalent circuit of the nonideal op amp.

2. When the op amp operates in the linear region, the voltage across the input terminals are zero due to $A = \infty$ and $R_o = 0$:

$v_d = v_2 - v_1 = 0$ (virtual short-circuit)

or $v_1 = v_2$

Proof :

$v_o = Av_d < \infty \Rightarrow v_d = 0$

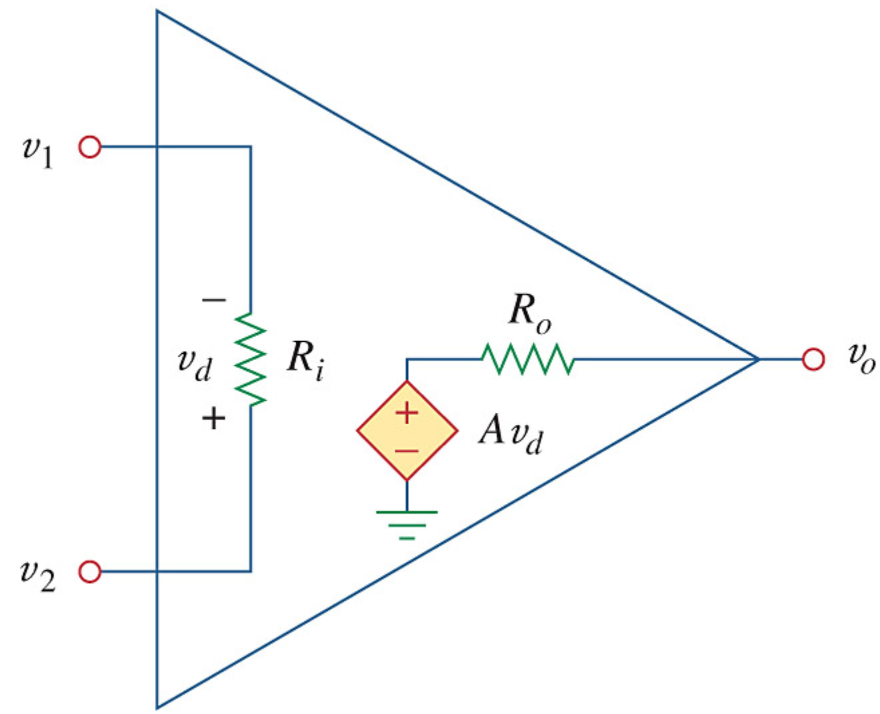
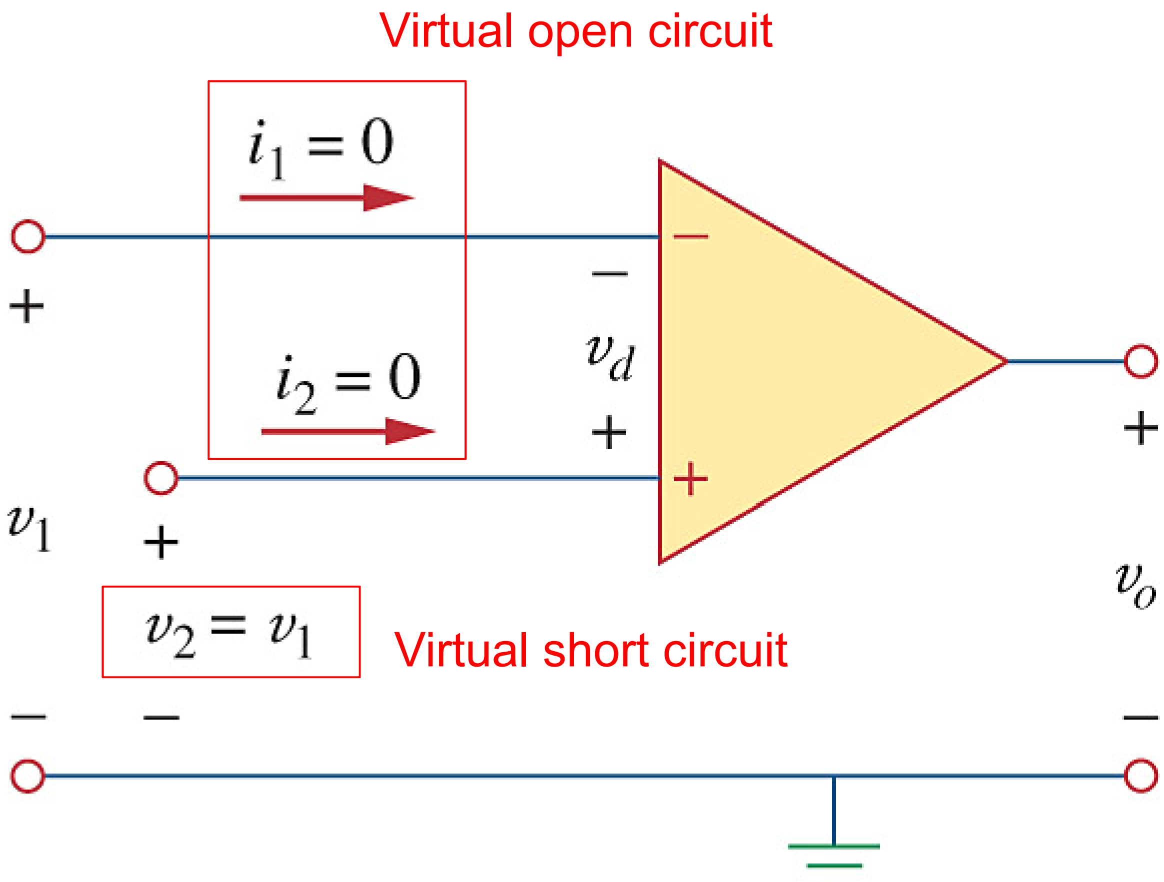


Figure 5.4 The equivalent circuit of the nonideal op amp.


Virtual open circuit
$i_1 = 0$
$i_2 = 0$
$-$
v_d
$+$
$+$
v_1
$+$
$-$
$-$
$+$
v_o
$-$
$v_2 = v_1$
Virtual short circuit

5.4 Inverting Amplifier (Inverter)

An inverting amplifier reverses the polarity of the input signal while amplifying it.

The *closed - loop gain* of the inverting amplifier is

$$A_v = \frac{v_o}{v_i} = -\frac{R_f}{R_i}$$

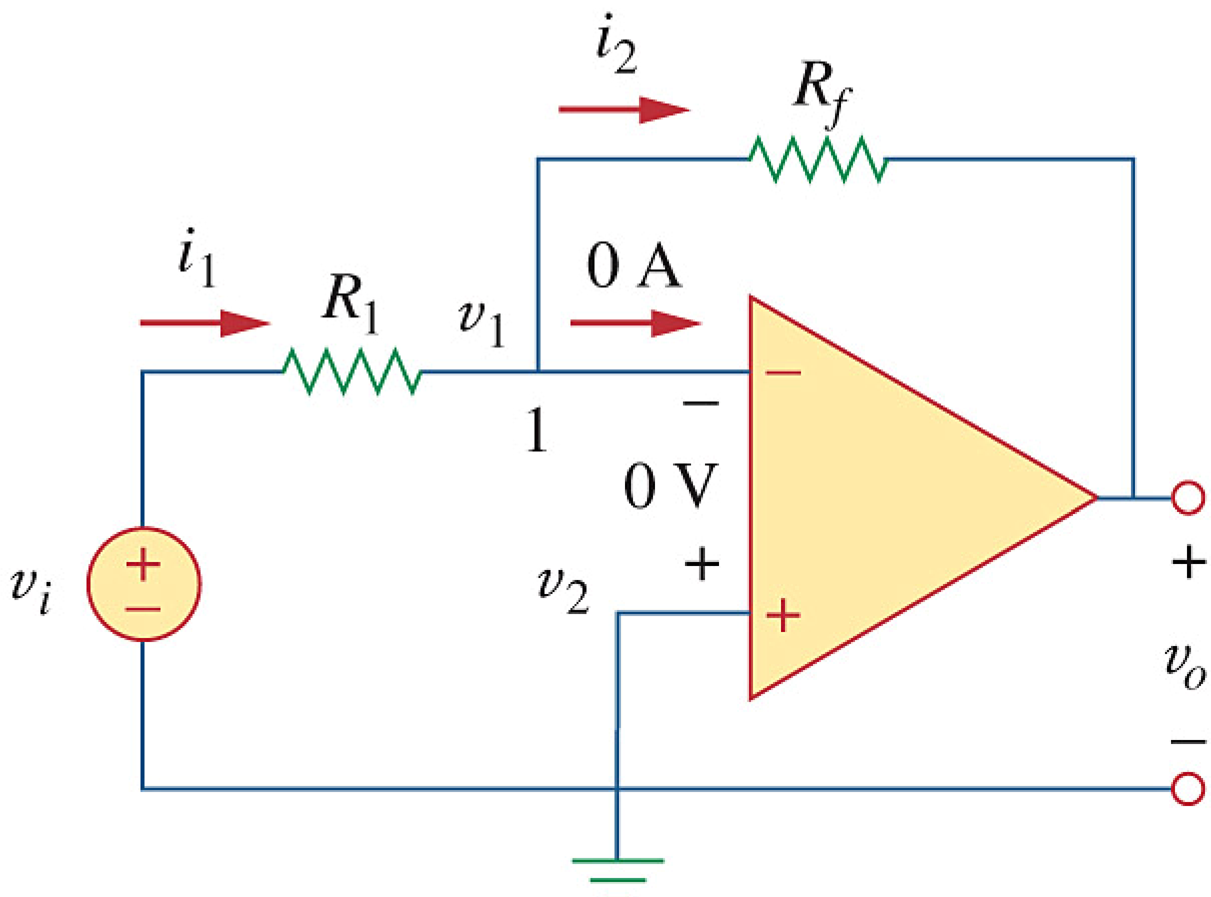


Figure 5.10 the inverting amplifier.

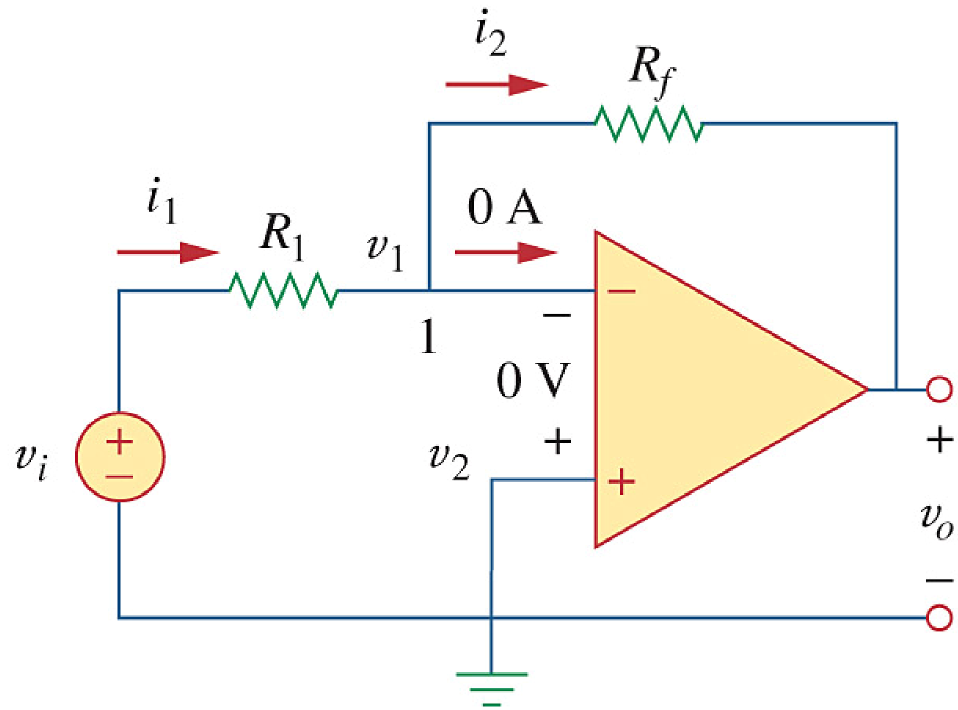


Figure 5.10 the inverting amplifier.

Proof :

$$i_1 = i_2 \Rightarrow \frac{v_i - v_1}{R_1} = \frac{v_1 - v_o}{R_f}$$

$$v_1 = v_2 = 0$$

$$\frac{v_i}{R_1} = -\frac{v_o}{R_f} \Rightarrow v_o = -\frac{R_f}{R_1} v_i \Rightarrow A_v = \frac{v_o}{v_i} = -\frac{R_f}{R_1}$$

An equivalent circuit for the inverting amplifier is shown in Fig. 5.11.

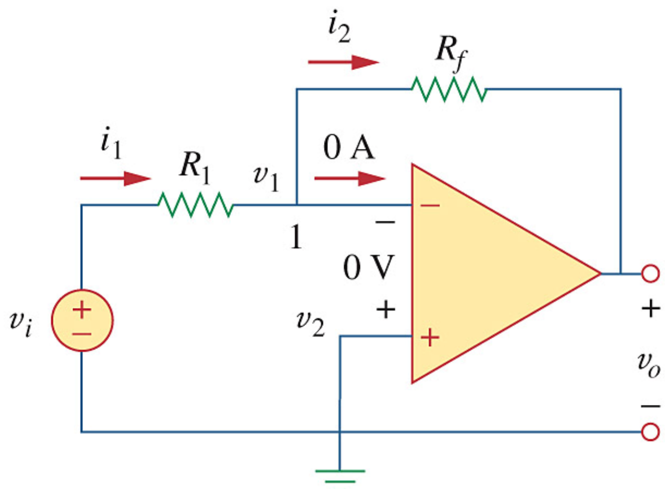


Figure 5.10 the inverting amplifier.

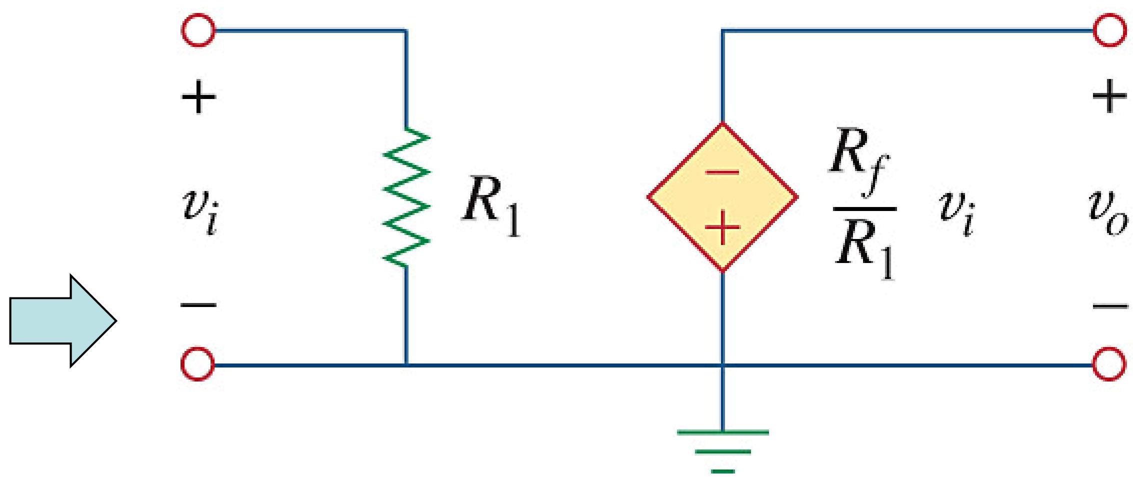


Figure 5.11 An equivalent circuit for the inverter in Fig. 5.10.

The concept of *feedback* is crucial to our understanding of op amp circuits. A *negative feedback* is achieved when the output is fed back to the inverting terminal of the op amp. As a result of the negative feedback, the op amp operates in the linear region.

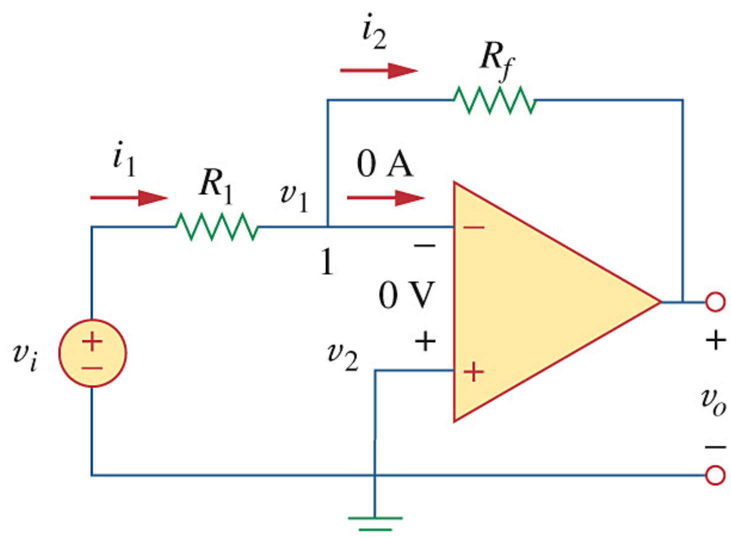


Figure 5.10 the inverting amplifier.

Example 5.3 Refer to the circuit in Fig. 5.12. If $v_i = 0.5$ V, calculate (a) the output voltage v_o, and (b) the current in the 10-kΩ resistor.

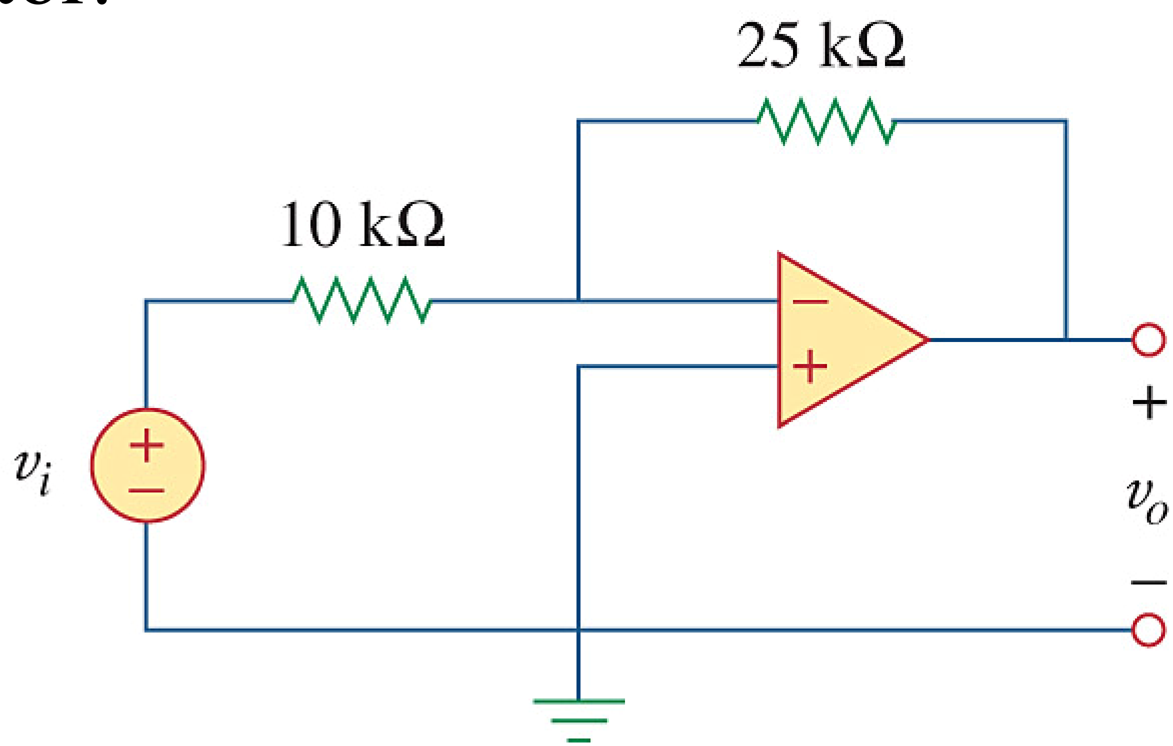


Figure 5.12

Solution :

$$v_o = -\frac{R_f}{R_1} v_i = -\frac{25}{10} \times 0.5 = -1.25 \text{ (V)}$$

$$i = \frac{v_i}{R_1} = \frac{0.5}{10 \times 10^3} = 5 \times 10^{-5} \text{ (A)} = 50\ \mu\text{A}$$

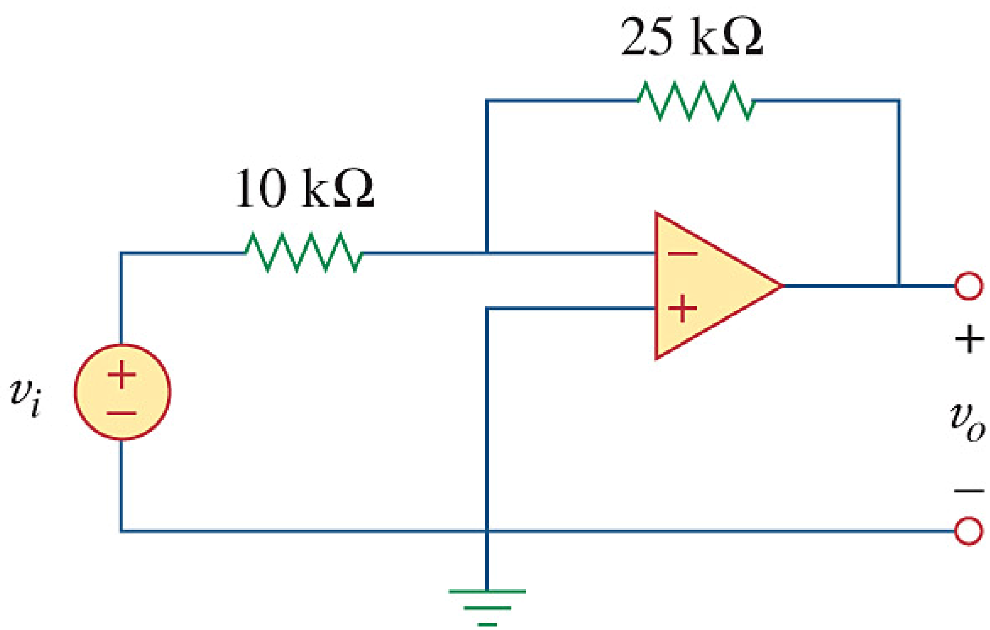


Figure 5.12

Example 5.4 Two kinds of current-to-voltage converters (also known as transresistance amplifier) are shown in Fig. 5.15.

(a) Show that for the converter in Fig. 5.15(a),

$v_o / i_s = -R$

(b) Show that for the converter in Fig. 5.15(b),

$v_o / i_s = -R_1(1 + R_3 / R_2 + R_3 / R_1)$

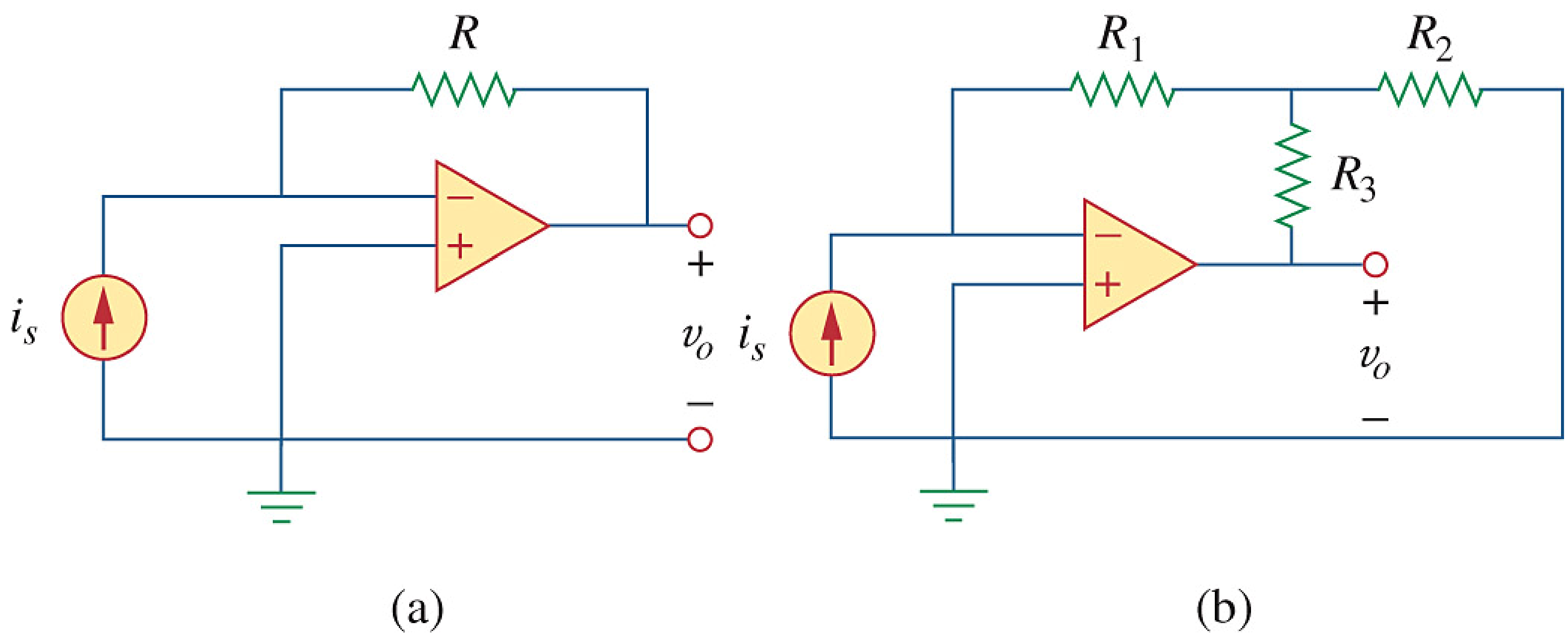
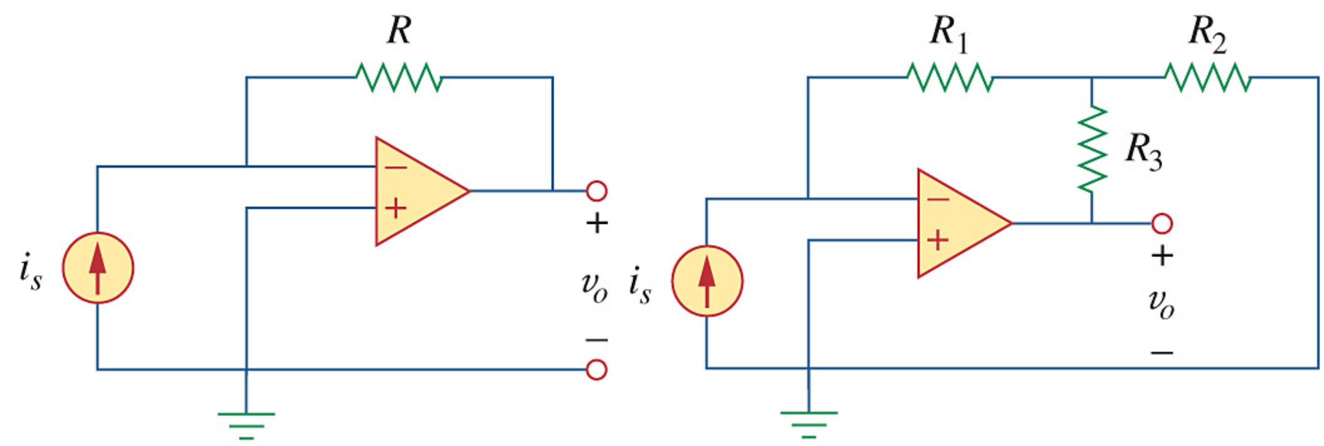


Figure 5.15

Proof :

(a)



(a) (b)

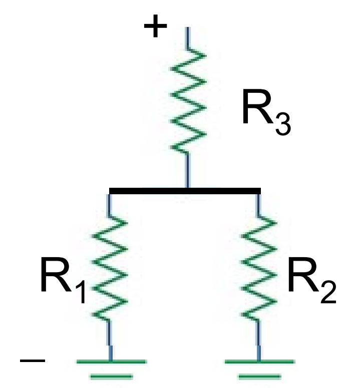
Figure 5.15

$$i_s = \frac{0 - v_o}{R} \Rightarrow \frac{v_o}{i_s} = -R$$

(b)

$$i_s = -\frac{R_2}{R_1 + R_2} \cdot \frac{v_o}{R_1 \parallel R_2 + R_3}$$

$$\frac{v_o}{i_s} = -\frac{R_1 + R_2}{R_2}\left(R_1 \parallel R_2 + R_3\right)$$



$$= -\frac{R_1 + R_2}{R_2}\left(\frac{R_1 R_2}{R_1 + R_2} + R_3\right)$$

$$= -\left(R_1 + \frac{R_1 + R_2}{R_2} R_3\right)$$

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

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

5.5 Noninverting Amplifier

The noninverting amplifier is a circuit designed to provide positive voltage gain. The closed-loop gain for the noninverting amplifier is

$$A_v = \frac{v_o}{v_i} = 1 + \frac{R_f}{R_1}$$

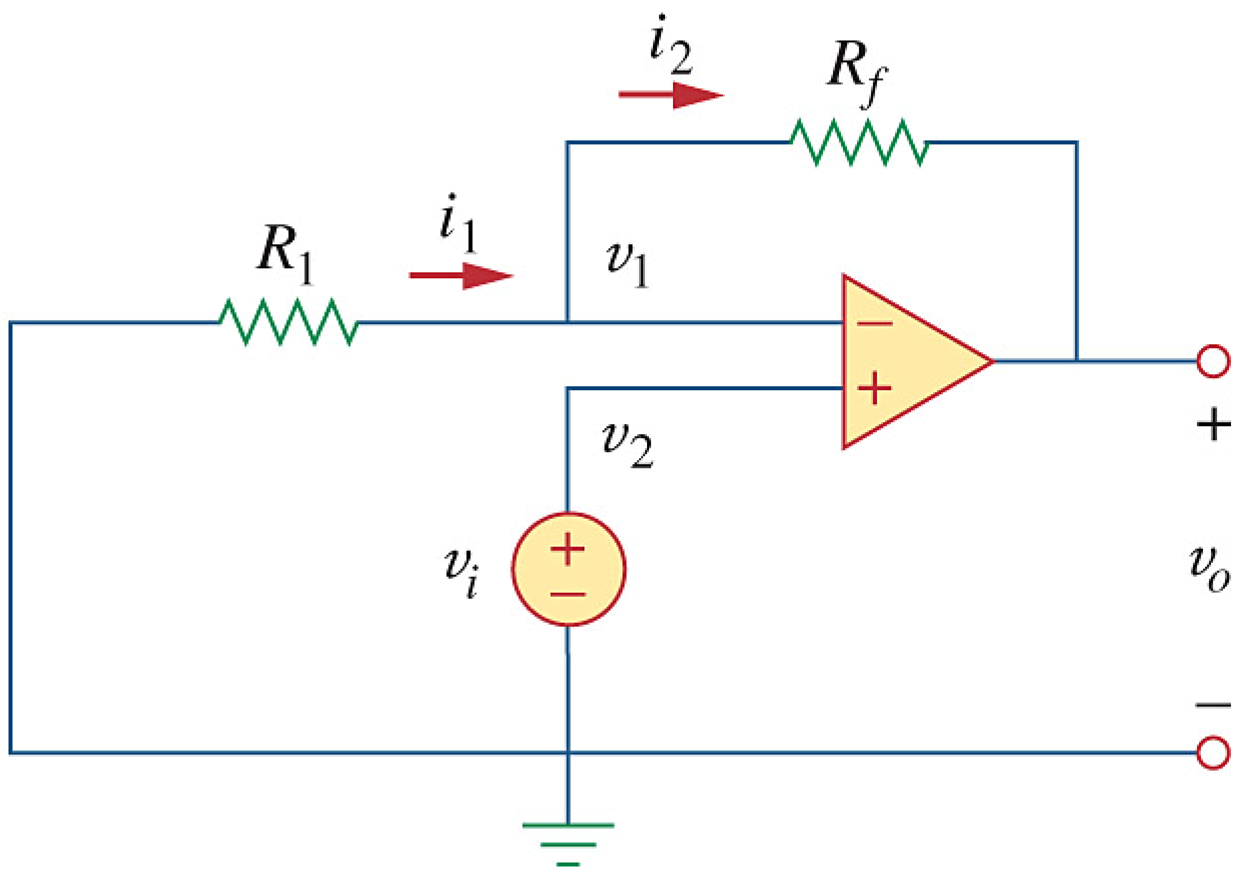


Figure 5.16 The noninverting amplifier.

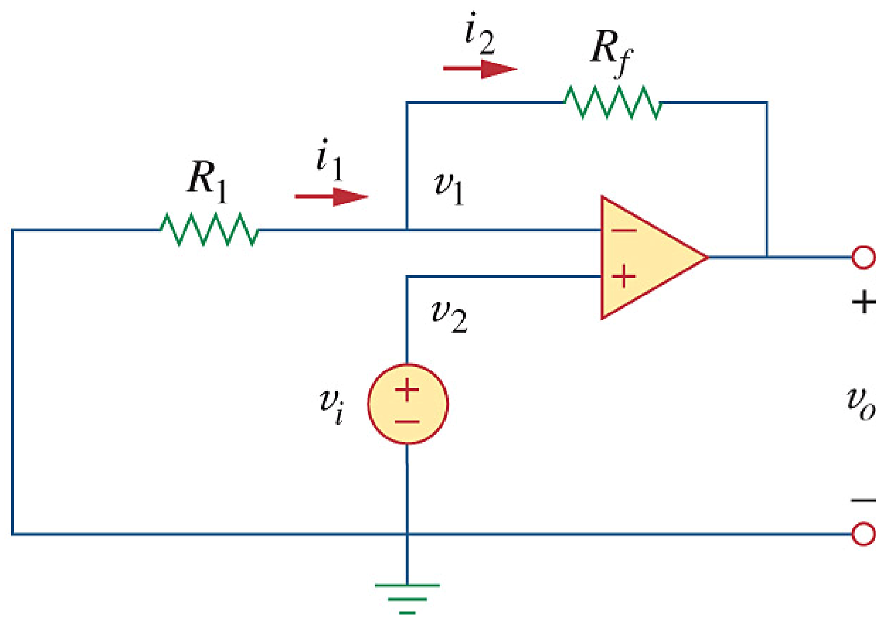


Figure 5.16 The noninverting amplifier.

Proof :

$$i_1 = i_2 \Rightarrow \frac{0 - v_1}{R_1} = \frac{v_1 - v_o}{R_f} \Rightarrow \frac{v_o}{v_1} = 1 + \frac{R_f}{R_1}$$

$$v_1 = v_2 = v_i$$

$$A_v = \frac{v_o}{v_i} = 1 + \frac{R_f}{R_1}$$

Notice that if $R_f = 0$ or $R_1 = \infty$ or both, $A_v = 1$. The circuit in Fig. 5.16 becomes a *voltage follower* (or unity gain amplifier) because the output follows the input, i.e.,

$$v_o = v_i$$

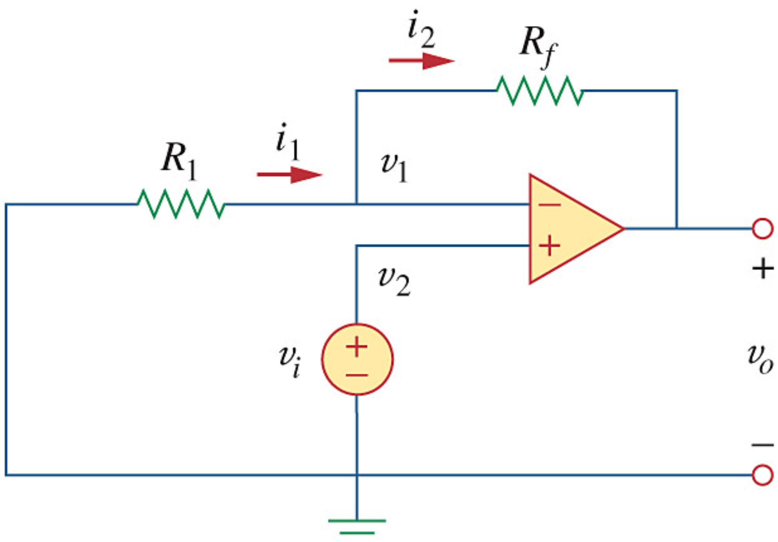


Figure 5.16 The noninverting amplifier.

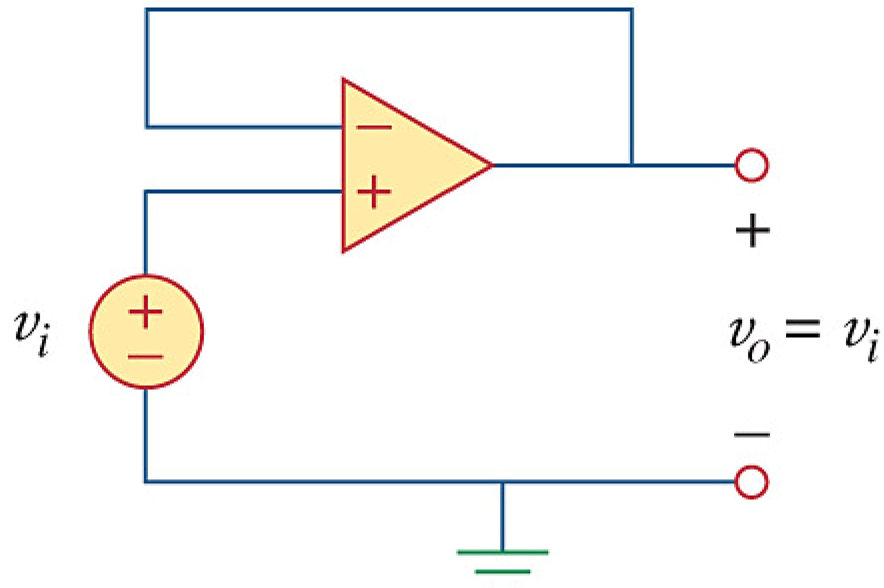


Figure 5.17 The voltage follower.

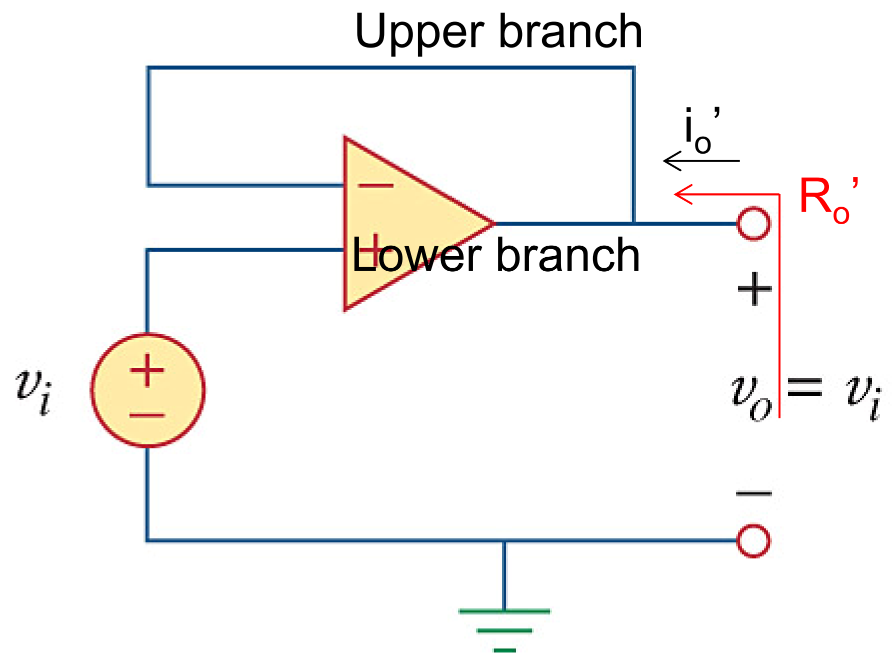


Figure 5.17 The voltage follower.

- very high input resistance: $R_{in} = v_i/i_+ = v_i/0 = \infty$
- very low output resistance:

  connect a test v_o and calculate i_o'

  Upper branch: $R_{upper} = v_o/i_- \rightarrow v_o/0 \rightarrow \infty$

  Lower branch: $R_o \rightarrow 0$

  $\Rightarrow R_o' = 0$

Such a circuit has a very high input resistance and a very low output resistance. It is therefore useful as an intermediate-stage (or buffer) to isolate two cascaded stages, as portrayed in Fig.5.18. The voltage follower minimizes interaction between the two stages and eliminates interstage loading.

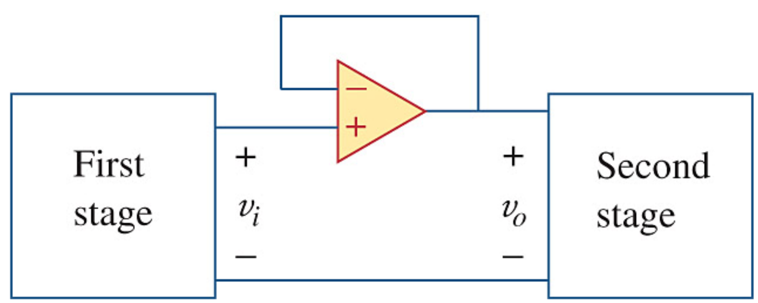


Figure 5.18 A voltage follower used to isolate two cascaded stages of a circuit.

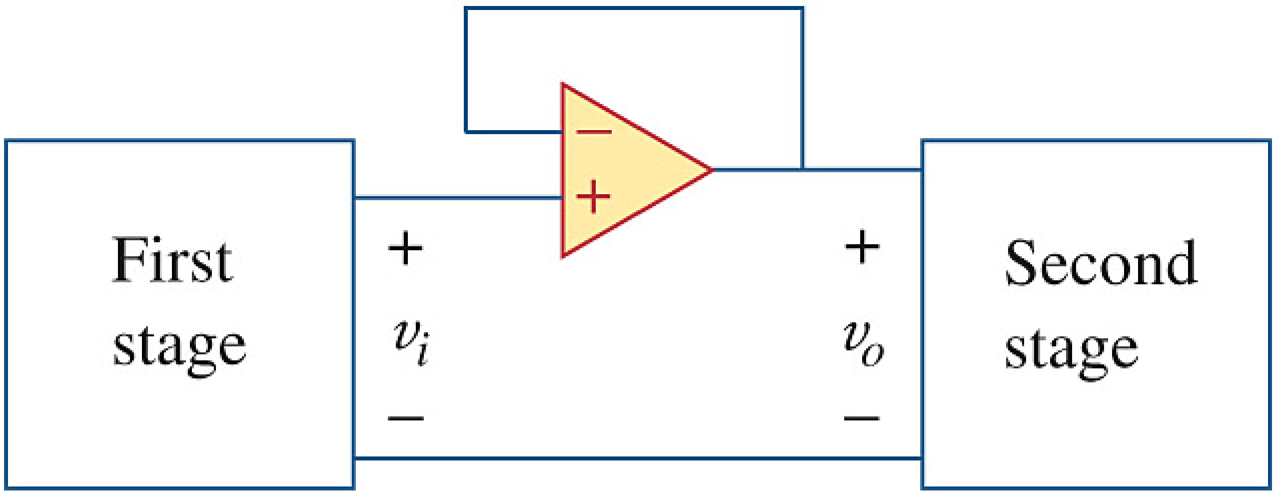


Figure 5.18 A voltage follower used to isolate two cascaded stages of a circuit.

5.6 Summing Amplifier (Adder)

A summing amplifier is an op amp circuit that combines more than one input and produces an output that is the weighted sum of the inputs, with all weights having the same sign. For example, in Fig. 5.21,

$$v_o = -\left(\frac{R_f}{R_1} v_1 + \frac{R_f}{R_2} v_2 + \frac{R_f}{R_3} v_3 \right)$$

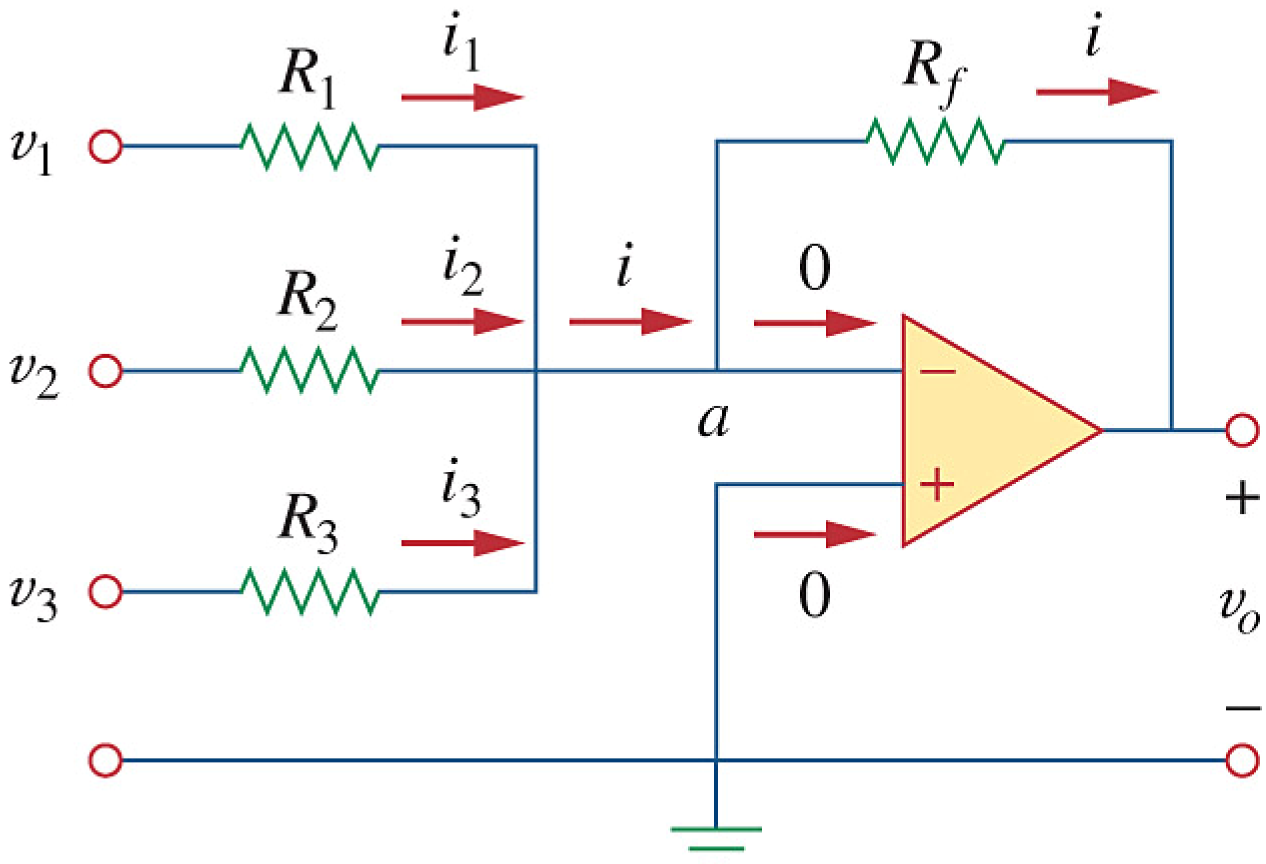


Figure 5.21 The summing amplifier.

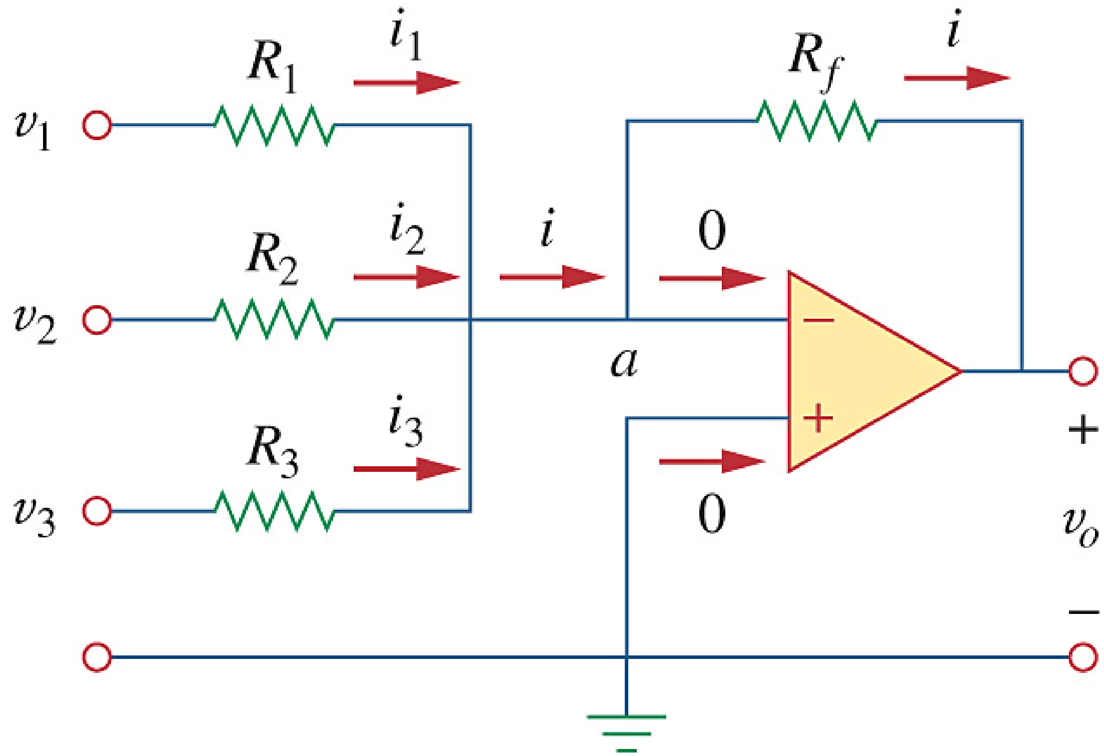


Figure 5.21 The summing amplifier.

Proof :

$$i = i_1 + i_2 + i_3 \Rightarrow$$

$$\frac{0 - v_o}{R_f} = \frac{v_1 - 0}{R_1} + \frac{v_2 - 0}{R_2} + \frac{v_3 - 0}{R_3}$$

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$

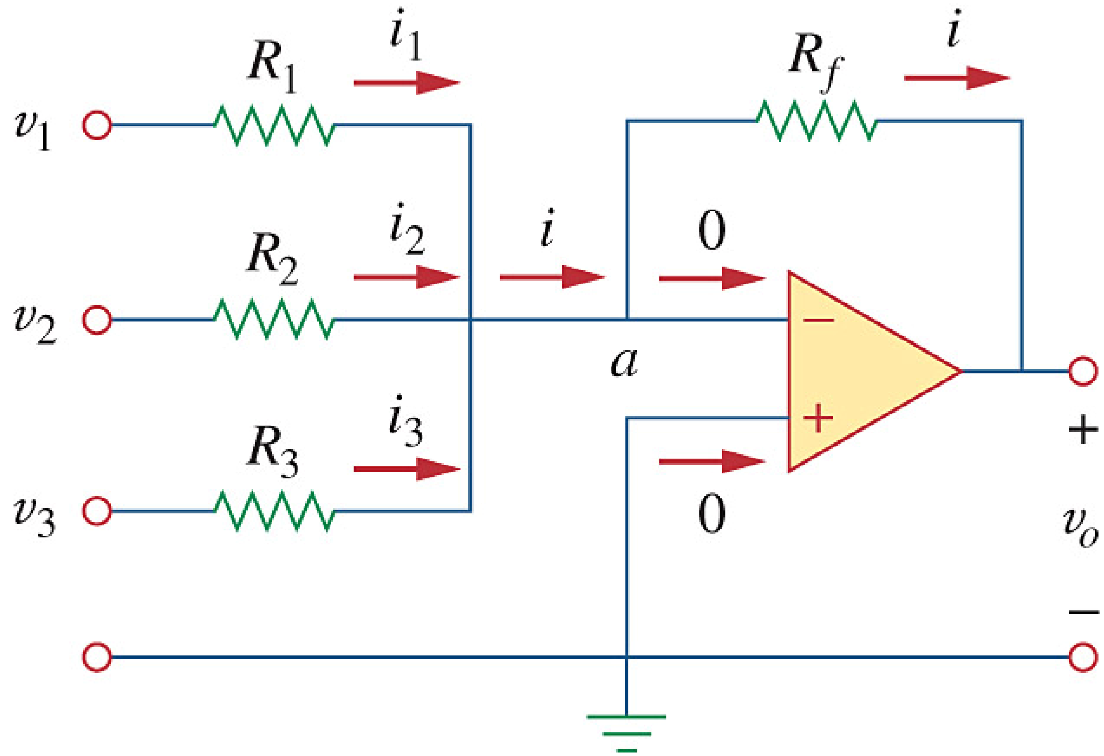


Figure 5.21 The summing amplifier.

If $R_3 = R_2 = R_1$, then

$$v_o = -\frac{R_f}{R_1}\left(v_1 + v_2 + v_3\right)$$

If $R_3 = R_2 = R_1 = R_f$, then

$$v_o = -\left(v_1 + v_2 + v_3\right)$$

Example 5.6 Calculate v_o and i_o in the op amp circuit in Fig. 5.22.

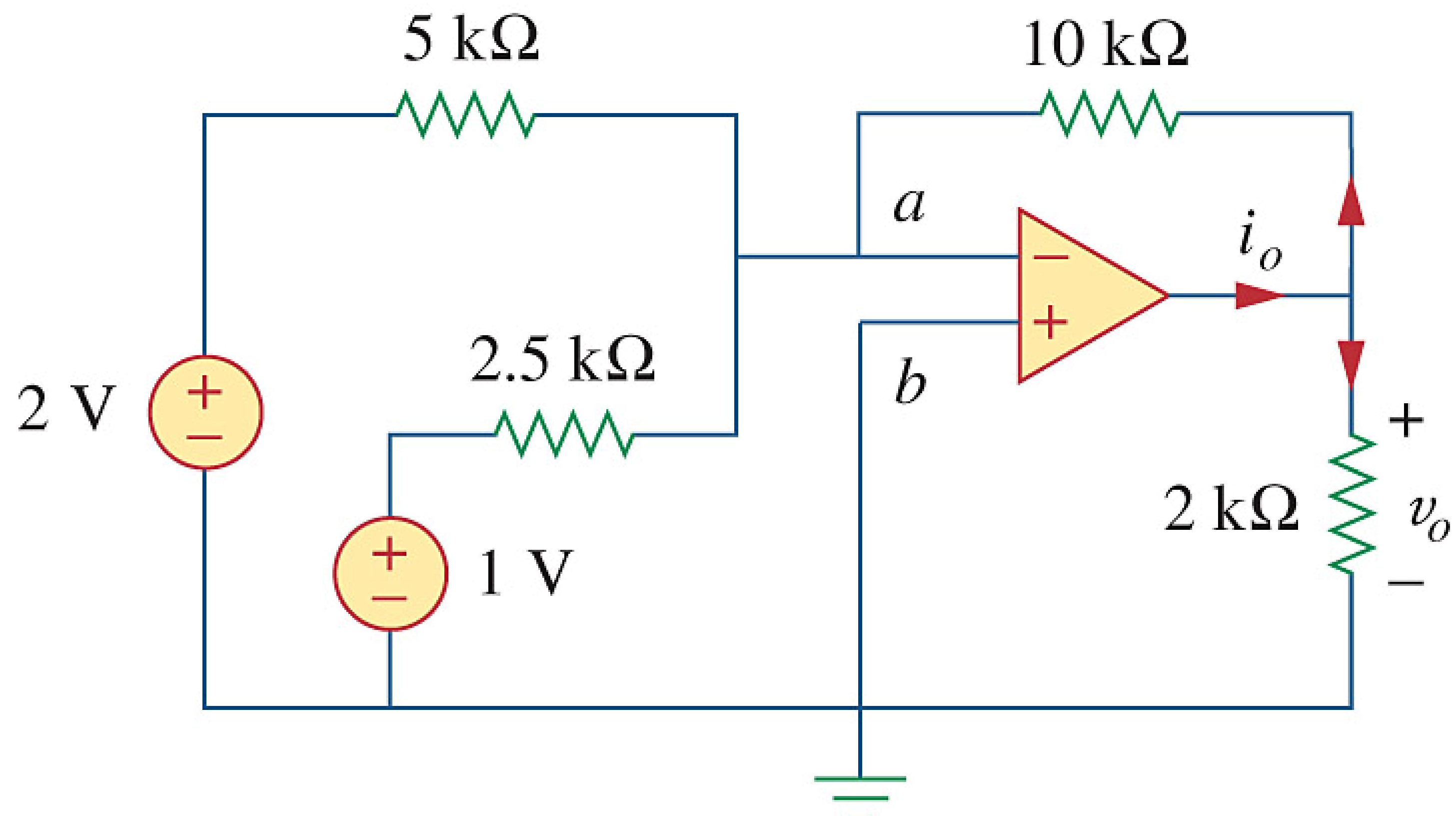


Figure 5.22

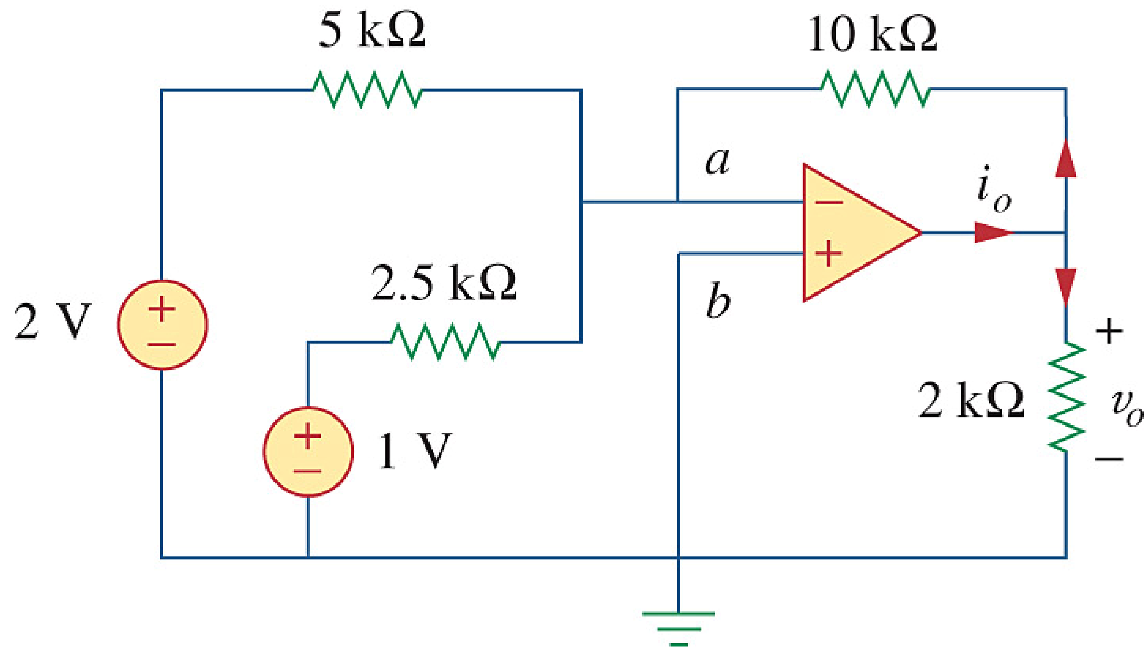


Figure 5.22

Solution :

$$v_o = -\left(\frac{R_f}{R_1} + \frac{R_f}{R_2}\right) = -\left(\frac{10}{5}\times 2 + \frac{10}{2.5}\times 1\right)$$

$$= -8 \text{ (V)}$$

$$i_o = \frac{v_o}{10 \parallel 2} = \frac{-8}{10\times 2/(10+2)} = -4.8 \text{ (mA)}$$

5.7 Difference Amplifier (Subtractor)

A difference (or differential) amplifier is an op amp circuit that combines two inputs and produces an output that is a weighted sum of the two inputs, with the two weights having different signs. For example, in Fig. 5.24,

$$v_o = \left(1 + R_2 / R_1\right) \frac{R_4 / R_3}{1 + R_4 / R_3} v_2 - \frac{R_2}{R_1} v_1$$

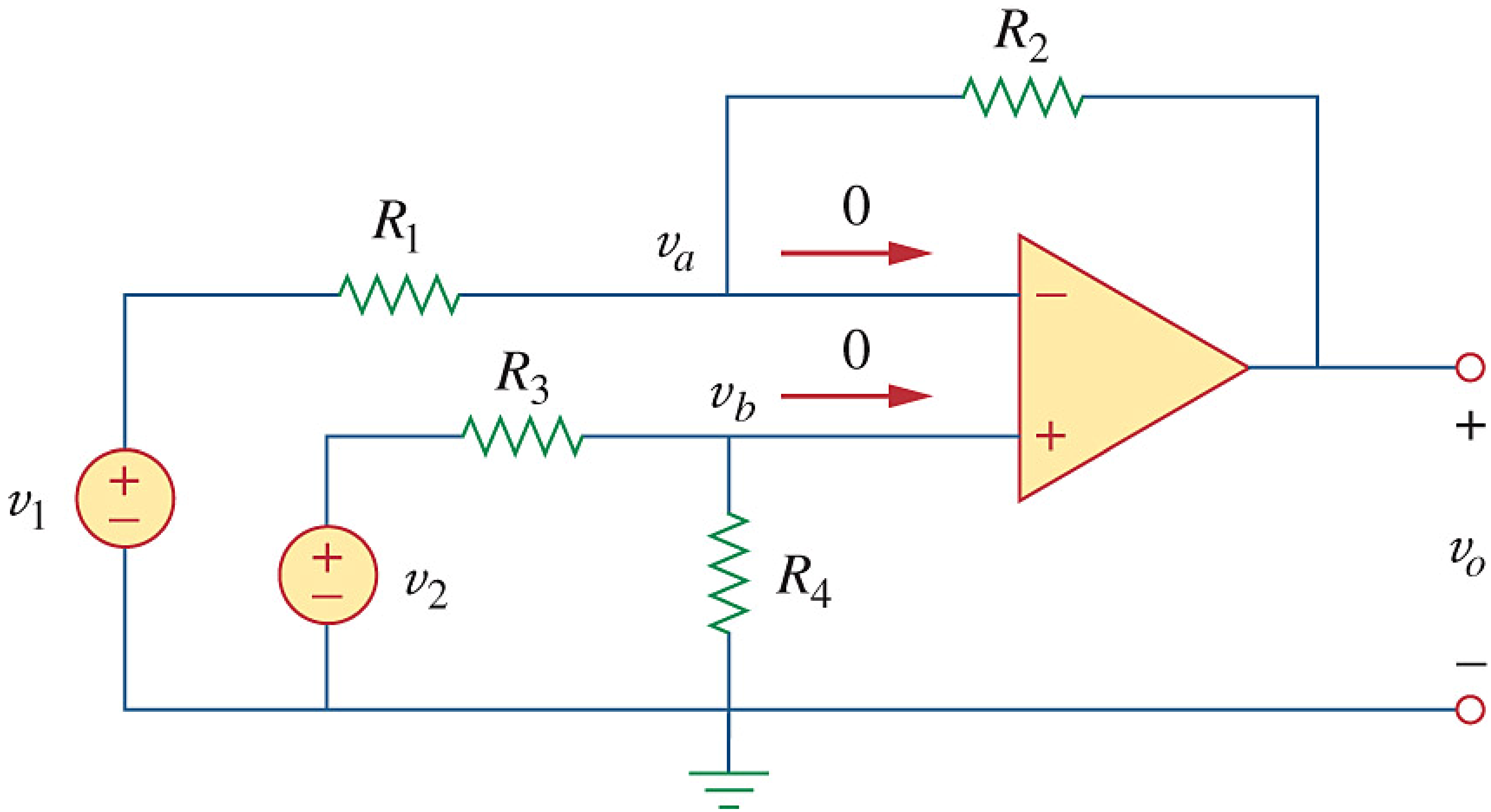


Figure 5.24 Difference amplifier.

Proof :

$$\frac{v_1 - v_a}{R_1} = \frac{v_a - v_o}{R_2} \Rightarrow v_o = \left(1 + \frac{R_2}{R_1}\right) v_a - \frac{R_2}{R_1} v_1$$

$$v_a = v_b = \frac{R_4}{R_3 + R_4} v_2$$

$$v_o = \left(1 + \frac{R_2}{R_1}\right) \frac{R_4}{R_3 + R_4} v_2 - \frac{R_2}{R_1} v_1$$

$$= \left(1 + R_2 / R_1\right) \frac{R_4 / R_3}{1 + R_4 / R_3} v_2 - \frac{R_2}{R_1} v_1$$

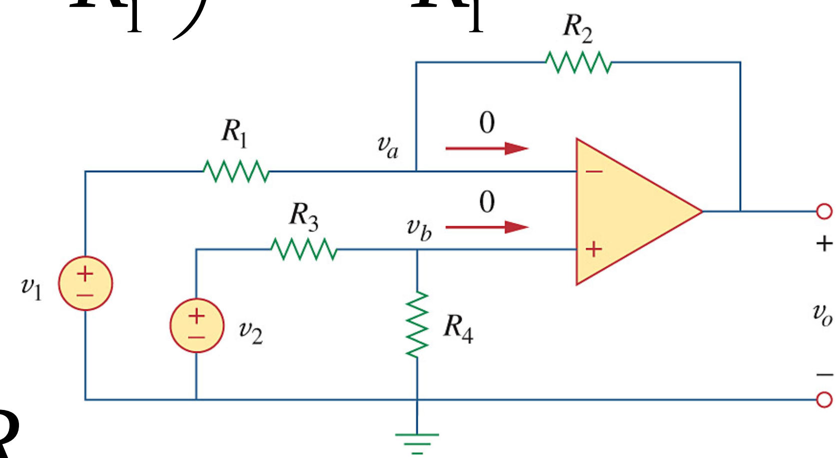


Figure 5.24 Difference amplifier.

$$\text{If } R_4 / R_3 = R_2 / R_1, \text{ then}$$

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

$$\text{If } R_2 = R_1 \text{ and } R_4 / R_3, \text{ then}$$

$$v_o = v_2 - v_1$$

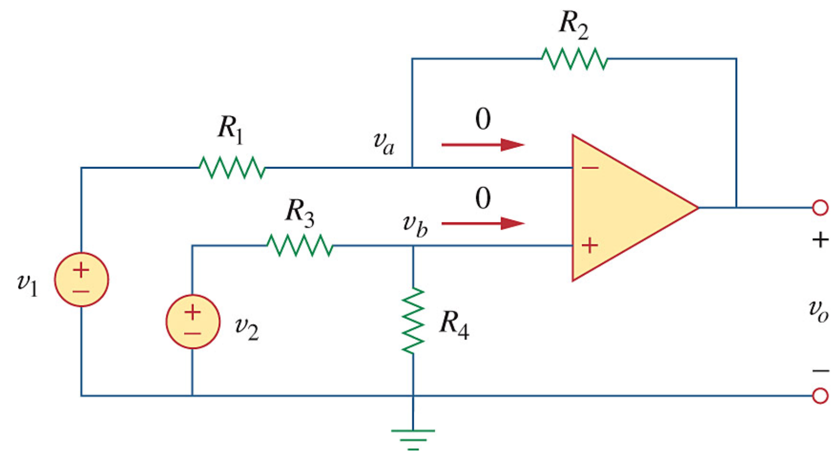


Figure 5.24 Difference amplifier.

5.8 Cascaded Op Amp Circuits

A cascade connection is a head-to-tail arrangement of two or more op amp circuits such that the output of one is the input of the next.

When op amp circuits are cascaded, each circuit in the string is called a *stage*.

Figure 4.28 displays the block diagram of a three-stage cascaded op amp circuits. The overall gain is the product of the gains of the individual stages:

$$A = \frac{v_o}{v_1} = \frac{v_2}{v_1} \cdot \frac{v_3}{v_2} \cdot \frac{v_o}{v_3} = A_1 A_2 A_3$$

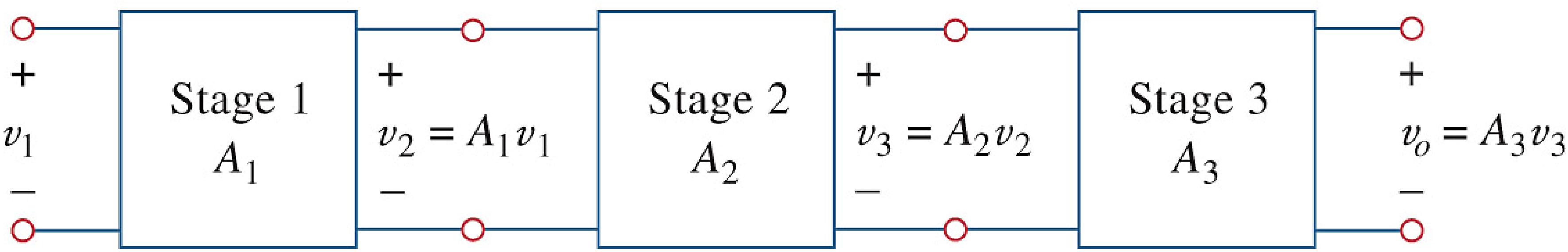


Figure 5.28 A three-stage cascaded connection.

Example 5.9 Find v_o and i_o in the circuit in Fig. 5.29.

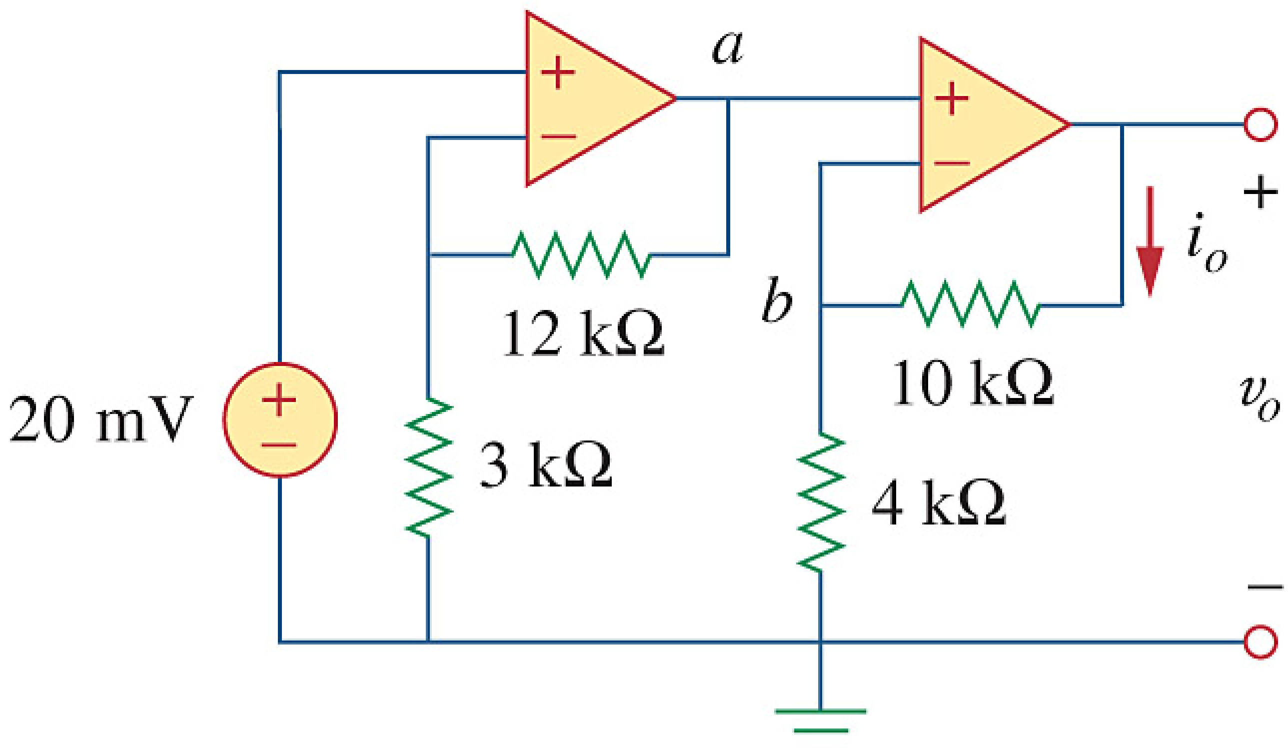


Figure 5.29

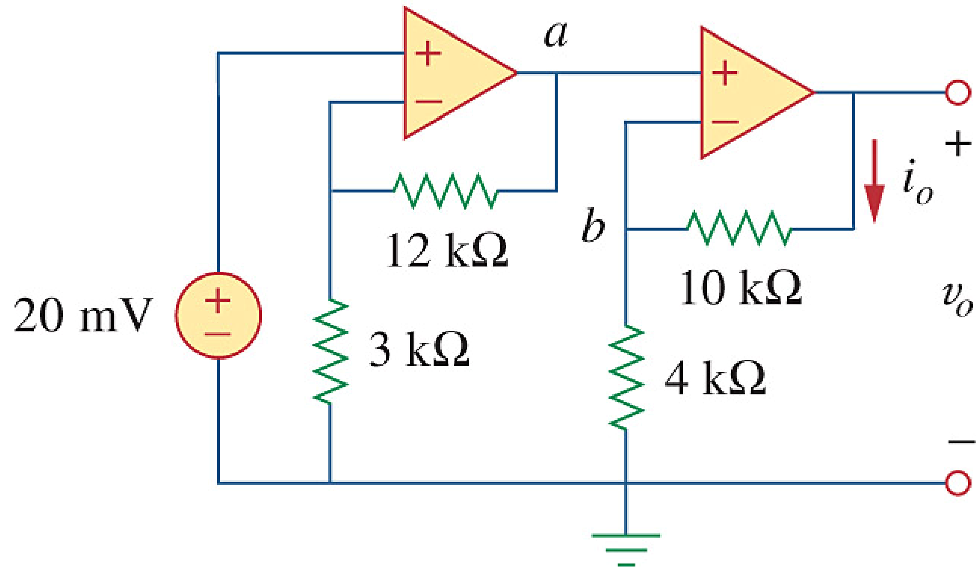


Figure 5.29

Solution :

$$v_a = \left(1 + \frac{12}{3}\right) \times 20 \times 10^{-3} = 0.1 \text{ (V)}$$

$$v_o = \left(1 + \frac{10}{4}\right) v_a = \left(1 + \frac{10}{4}\right) \times 0.1 = 0.35 \text{ (V)}$$

$$i_o = \frac{v_o}{10 + 4} = \frac{0.35}{14} = 0.025 \text{ (mA)} = 25\ \mu\text{A}$$

Example 5.10 If $v_1 = 1$ V and $v_2 = 2$ V, find v_o in the op amp circuit of Fig. 5.31.

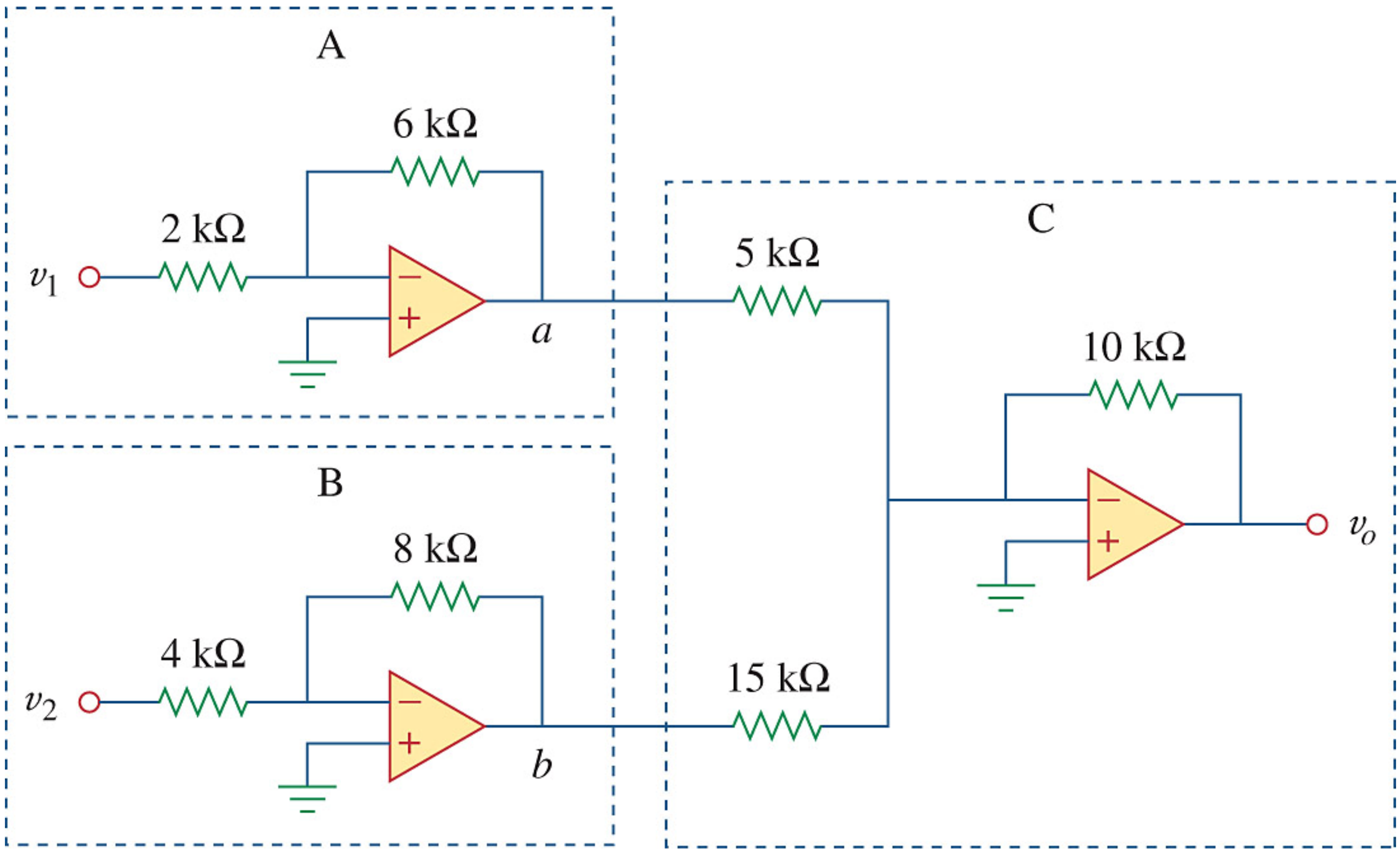


Figure 5.31

Solution :

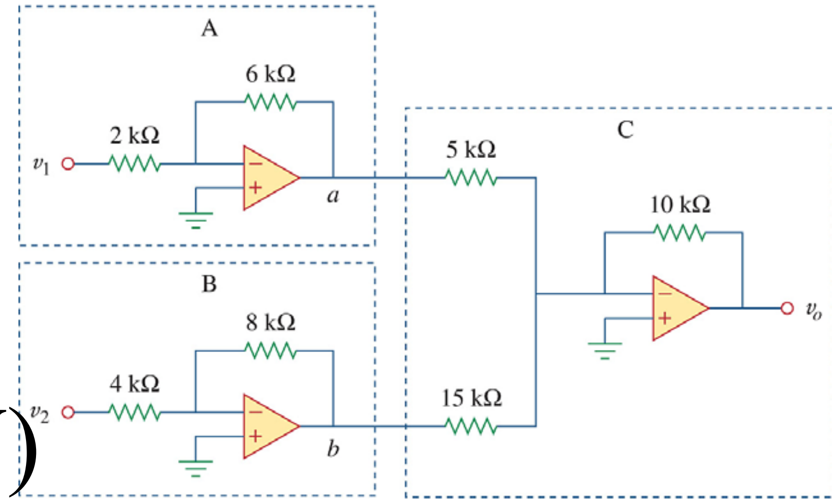


Figure 5.31

$$v_a = -\frac{6}{2} v_1 = -\frac{6}{2} \times 1 = -3 \text{ (V)}$$

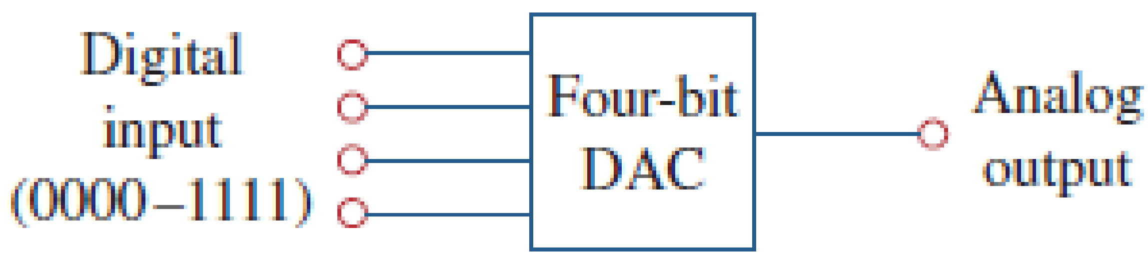
$$v_b = -\frac{8}{4} v_2 = -\frac{8}{4} \times 2 = -4 \text{ (V)}$$

$$v_o = -\left(\frac{10}{5} v_a + \frac{10}{15} v_b \right)$$

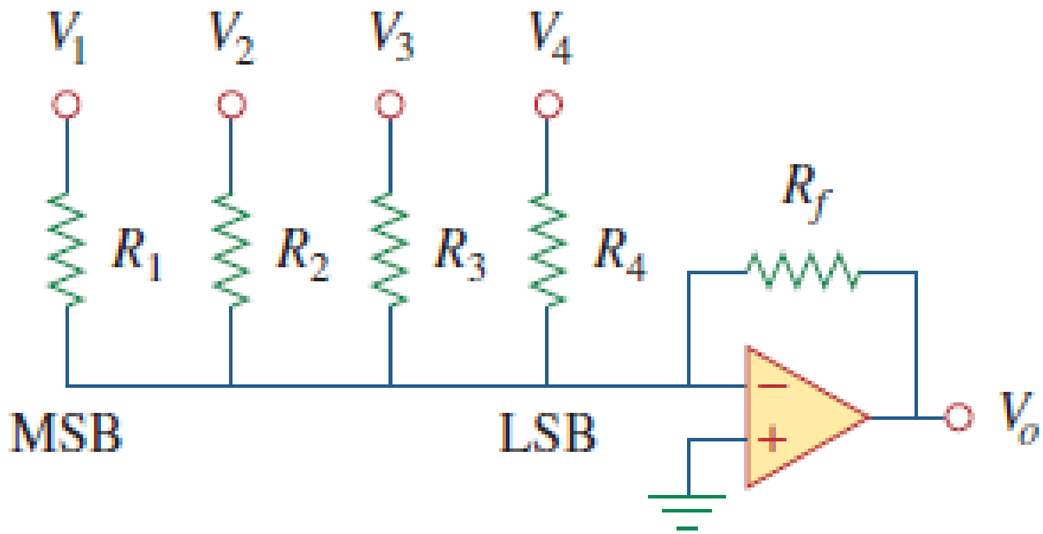
$$= -\left(\frac{10}{5} \times (-3) + \frac{10}{15} \times (-4) \right) = \frac{26}{3} \approx 8.67 \text{ (V)}$$

5.10.1 Digital-to-Analog Converter

- The digital-to-analog converter (DAC) transforms digital signals into analog form.
- Example: a four-bit DAC

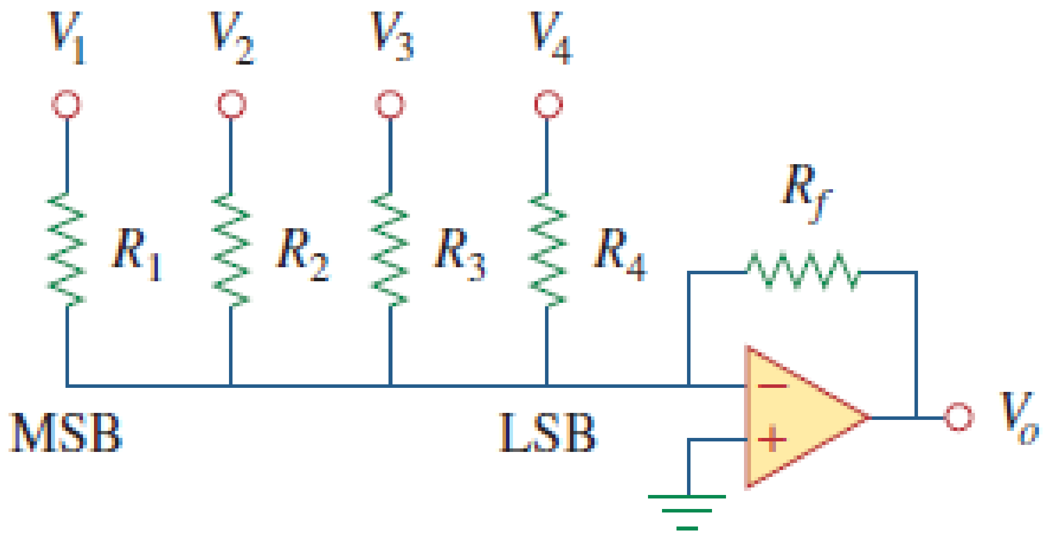


- Realization is the binary weighted ladder



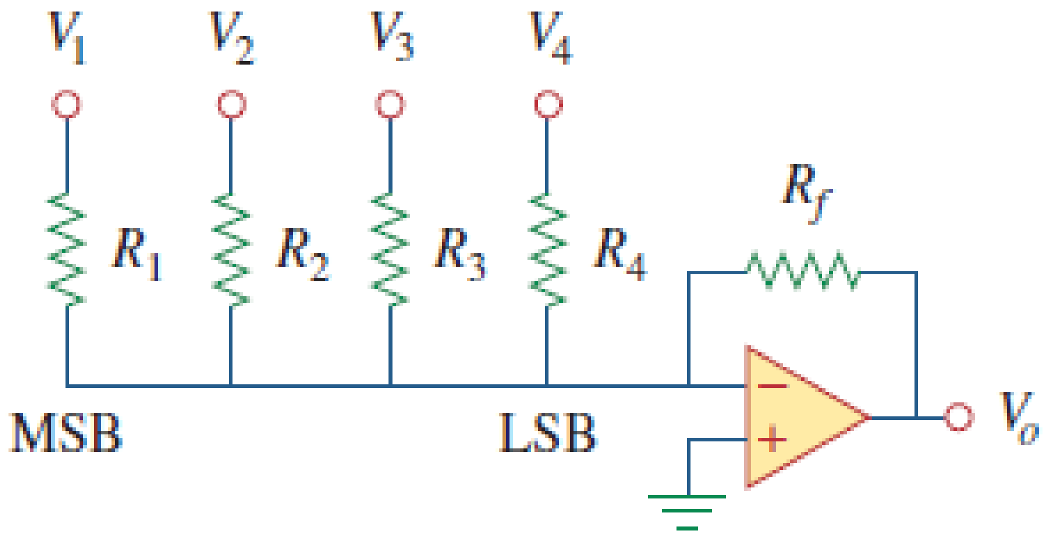
  - an inverting summing amplifier $-V_o = \frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + \frac{R_f}{R_4}V_4$
  - bits are weighted by descending value of R_f/R_n to produce 2 times difference for adjacent bits

- Realization is the binary weighted ladder



  - V_1: most significant bit (MSB)
    V_4: least significant bit (LSB)
  - Assume only two voltage levels for V_1 to V_4: 0 and 1V

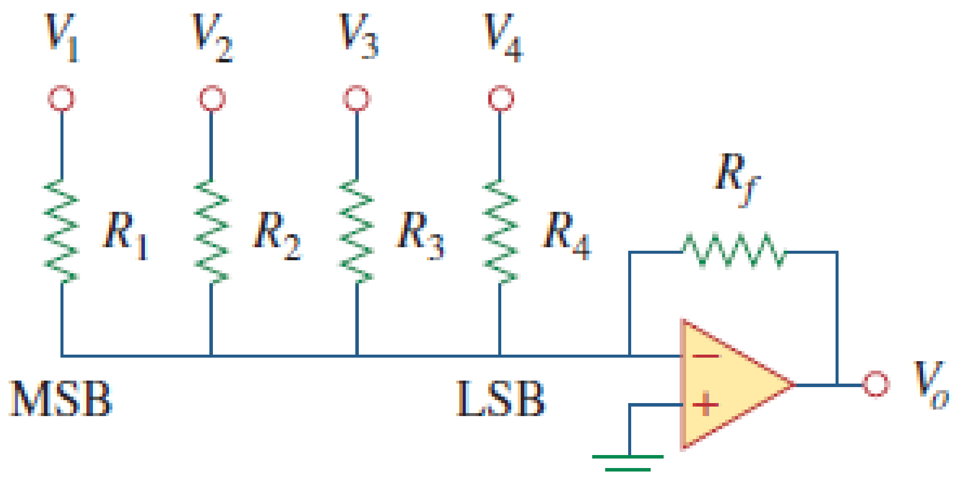
- Realization is the binary weighted ladder



$$-V_o = \frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + \frac{R_f}{R_4}V_4 \Rightarrow \boxed{-V_o=k(2^3V_1+2^2V_2+2^1V_3+2^0V_4)}$$

Example 5.12

In the op amp circuit of Fig. 5.36(b), let $R_f = 10\ \text{k}\Omega$, $R_1 = 10\ \text{k}\Omega$, $R_2 = 20\ \text{k}\Omega$, $R_3 = 40\ \text{k}\Omega$, and $R_4 = 80\ \text{k}\Omega$. Obtain the analog output for binary inputs [0000], [0001], [0010], . . . , [1111].



- 1. Output voltage V_o

$$-V_o = \frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + \frac{R_f}{R_4}V_4$$
$$= V_1 + 0.5V_2 + 0.25V_3 + 0.125V_4$$

- 2. digital input $[V_1V_2V_3V_4]$ = [0000] produces an analog output of $-V_o = 0$ V

  [0001] → $-V_o = -0.125$ V

TABLE 5.2

Input and output values of the four-bit DAC.

Binary input $[V_1V_2V_3V_4]$	Decimal value	Output $-V_o$
0000	0	0
0001	1	0.125
0010	2	0.25
0011	3	0.375
0100	4	0.5
0101	5	0.625
0110	6	0.75
0111	7	0.875
1000	8	1.0
1001	9	1.125
1010	10	1.25
1011	11	1.375
1100	12	1.5
1101	13	1.625
1110	14	1.75
1111	15	1.875

$\div$ 0.125

$\times$ 0.125

- Resolution: the smallest resolvable analog output
- **Question**: In practice, for 1V range, if you want to produce a resolution of 1mV, roughly how many bits do you need?

5.10.2 Instrumentation Amplifiers

- One of the most useful and versatile op amp circuits is the instrumentation amplifier (IA), so called because of its widespread use in measurement systems.
- The IA is an extension of the **difference amplifier** in that it amplifies the difference between its inputs.

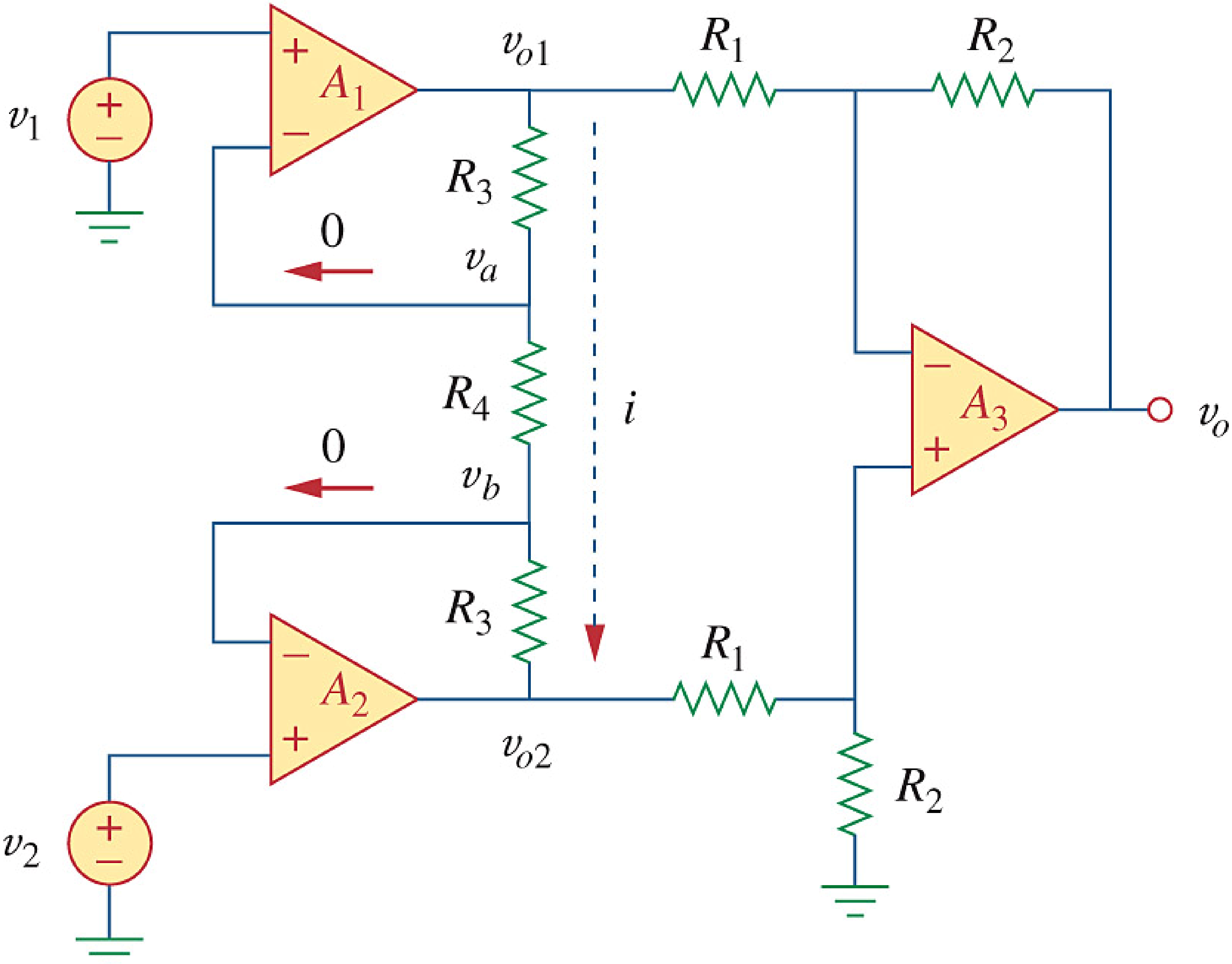


Figure 5.26 Instrumentation amplifier.

An IA circuit is shown in Fig. 5.26. Show that

$$v_o = \frac{R_2}{R_1}\left(1 + \frac{2R_3}{R_4}\right)(v_2 - v_1)$$

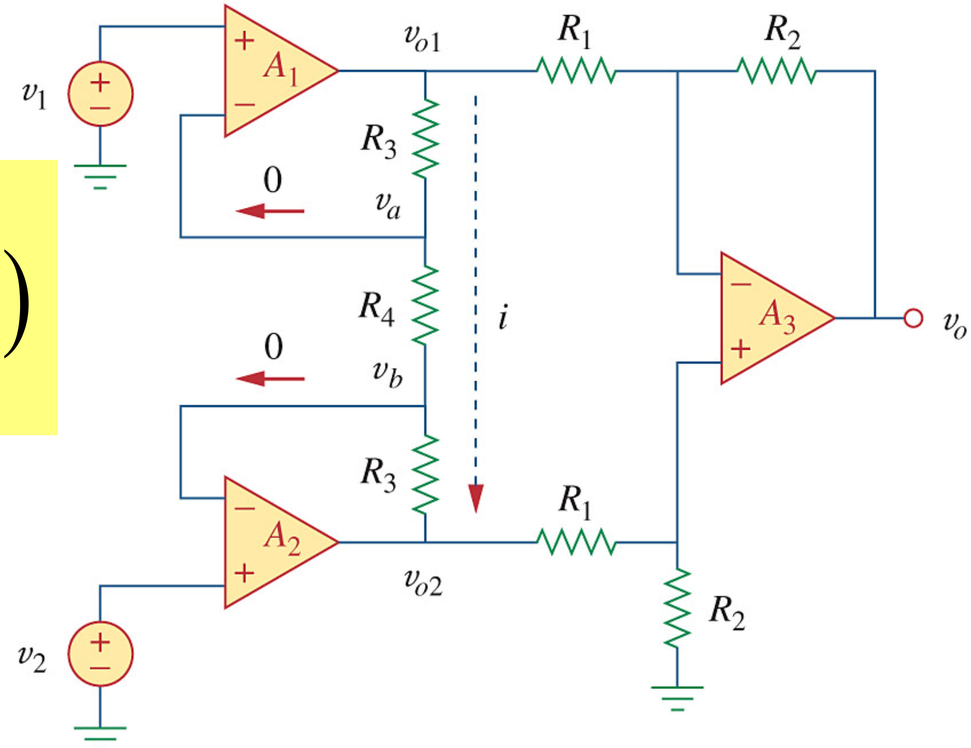


Figure 5.26 Instrumentation amplifier.

Proof :

$$\begin{cases} v_a = v_1,\ v_b = v_2 \\ i = \dfrac{v_a - v_b}{R_4} = \dfrac{v_{o1} - v_{o2}}{R_3 + R_4 + R_3} \end{cases}$$

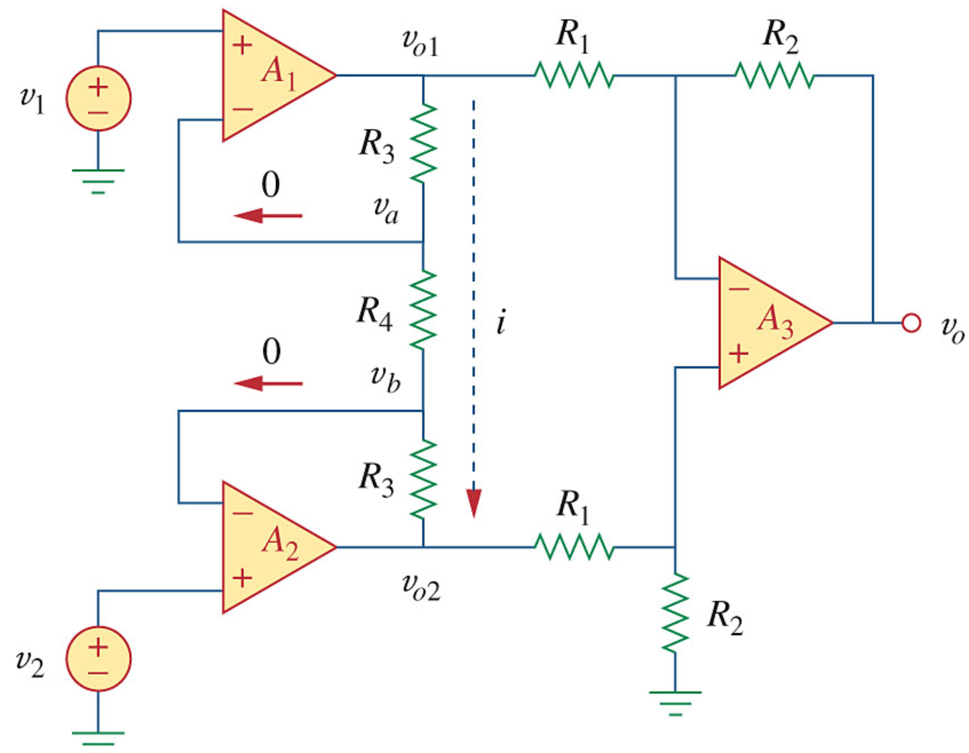


Figure 5.26 Instrumentation amplifier.

$$v_{o2} - v_{o1} = \left(1 + \frac{2R_3}{R_4}\right)\left(v_2 - v_1\right)$$

$$v_o = \frac{R_2}{R_1}\left(v_{o2} - v_{o1}\right) = \frac{R_2}{R_1}\left(1 + \frac{2R_3}{R_4}\right)\left(v_2 - v_1\right)$$

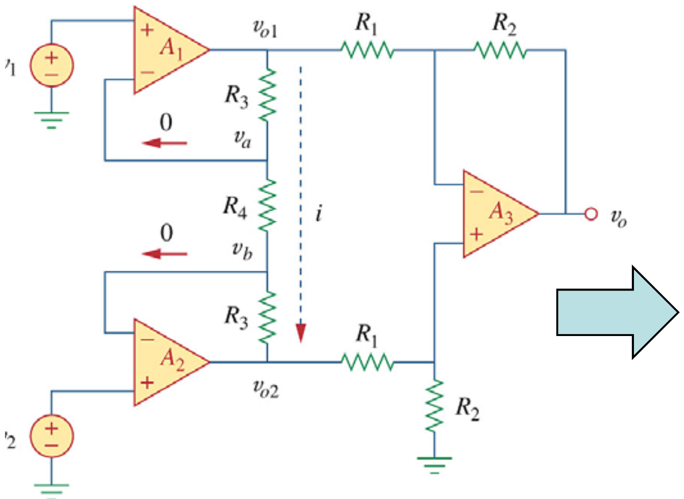


Figure 5.26 Instrumentation amplifier.

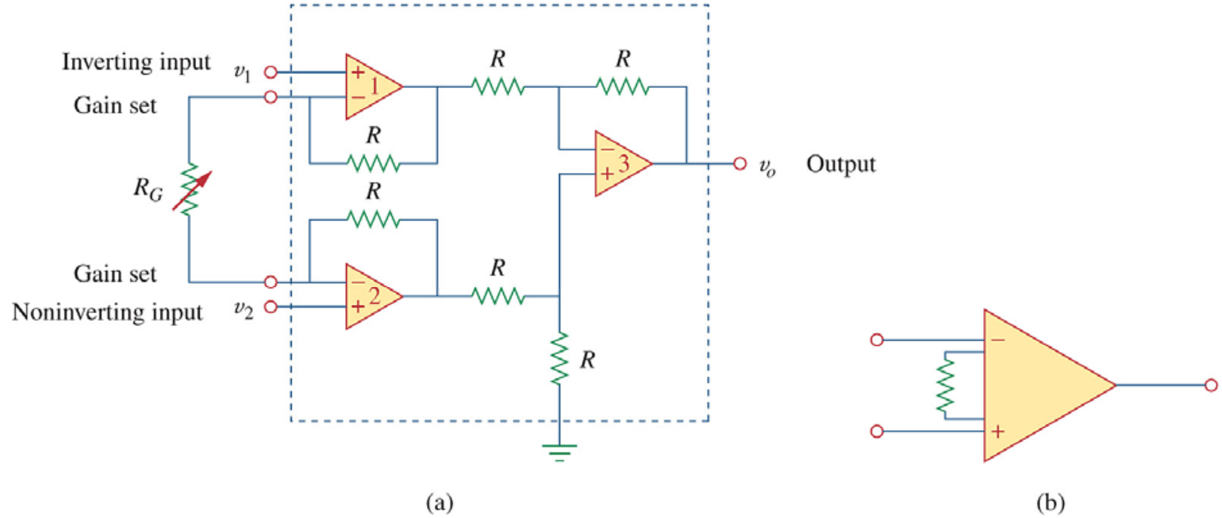


Figure 5.38 (a) The IA with an external resistance to adjust the gain, (b) schematic symbol.

In Fig. 5.38(a), $R_4 = R_G$, $R_3 = R_2 = R_1 = R$,

$$v_o = \frac{R_2}{R_1}\left(1 + \frac{2R_3}{R_4}\right)(v_2 - v_1)$$

$$= \left(1 + \frac{2R}{R_G}\right)(v_2 - v_1)$$

$$= A_v\,(v_2 - v_1)$$

The advantage over a difference amplifier:
Gain is adjustable by an external resistor

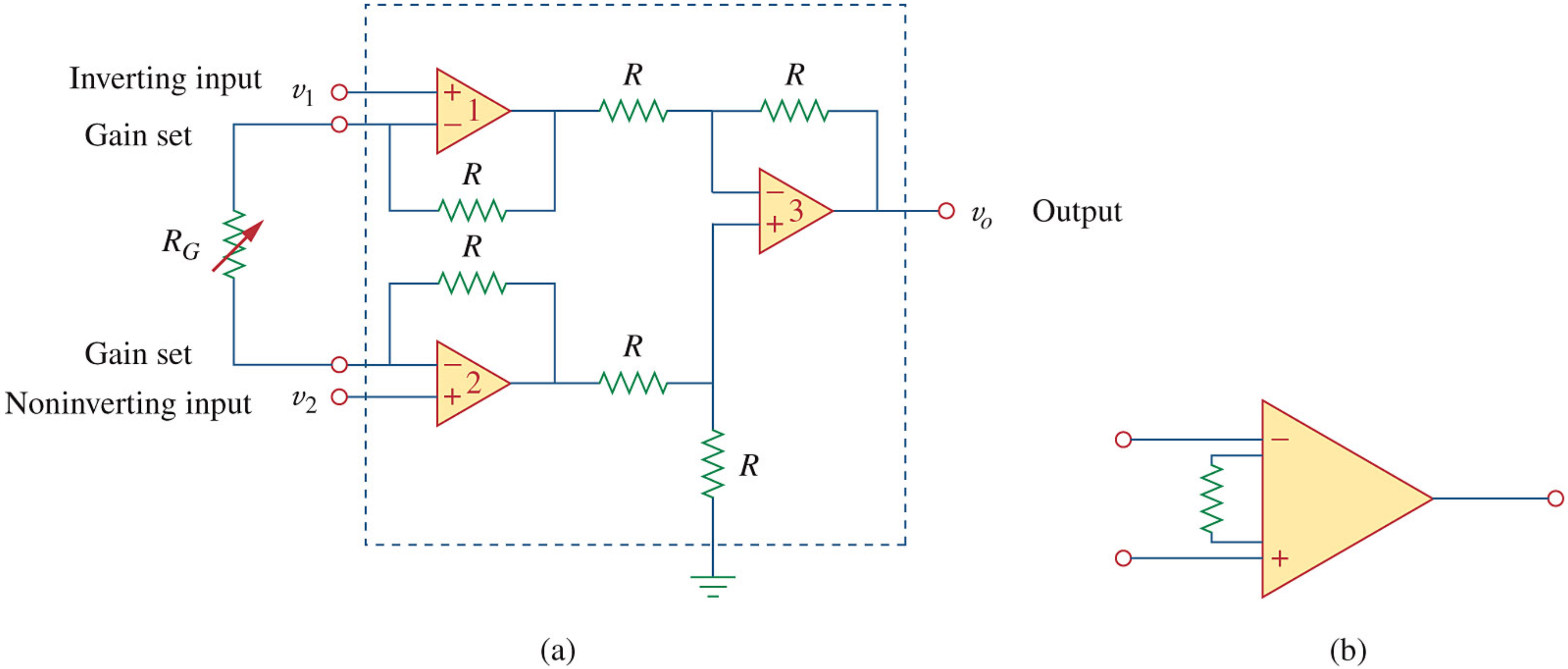


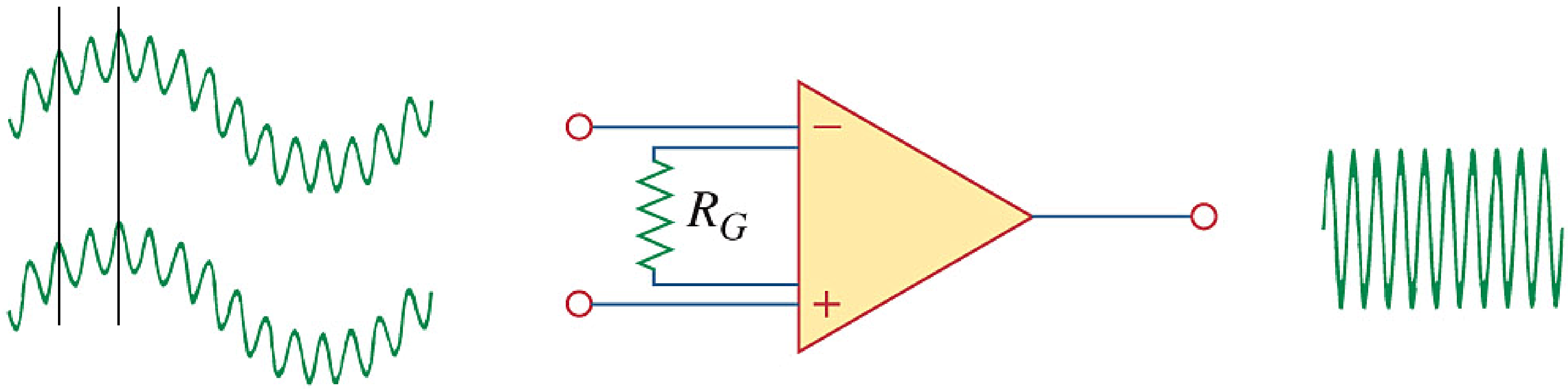
Figure 5.38 (a) The IA with an external resistance to adjust the gain, (b) schematic symbol.

As shown in Fig. 5.39, the IA amplifies small differential signals superimposed on larger common-mode signal.

$$\begin{cases} v_d = v_2 - v_1 \\ v_c = \dfrac{v_1 + v_2}{2} \end{cases} \Leftrightarrow \begin{cases} v_2 = \dfrac{v_d}{2} + v_c \\ v_1 = -\dfrac{v_d}{2} + v_c \end{cases}$$

$$v_o = A_v\left(v_2 - v_1\right) = A_v v_d$$

$\boxed{v_o \text{ is Independent of } v_c}$



Small differential signals riding on larger common-mode signals

Instrumentation amplifier

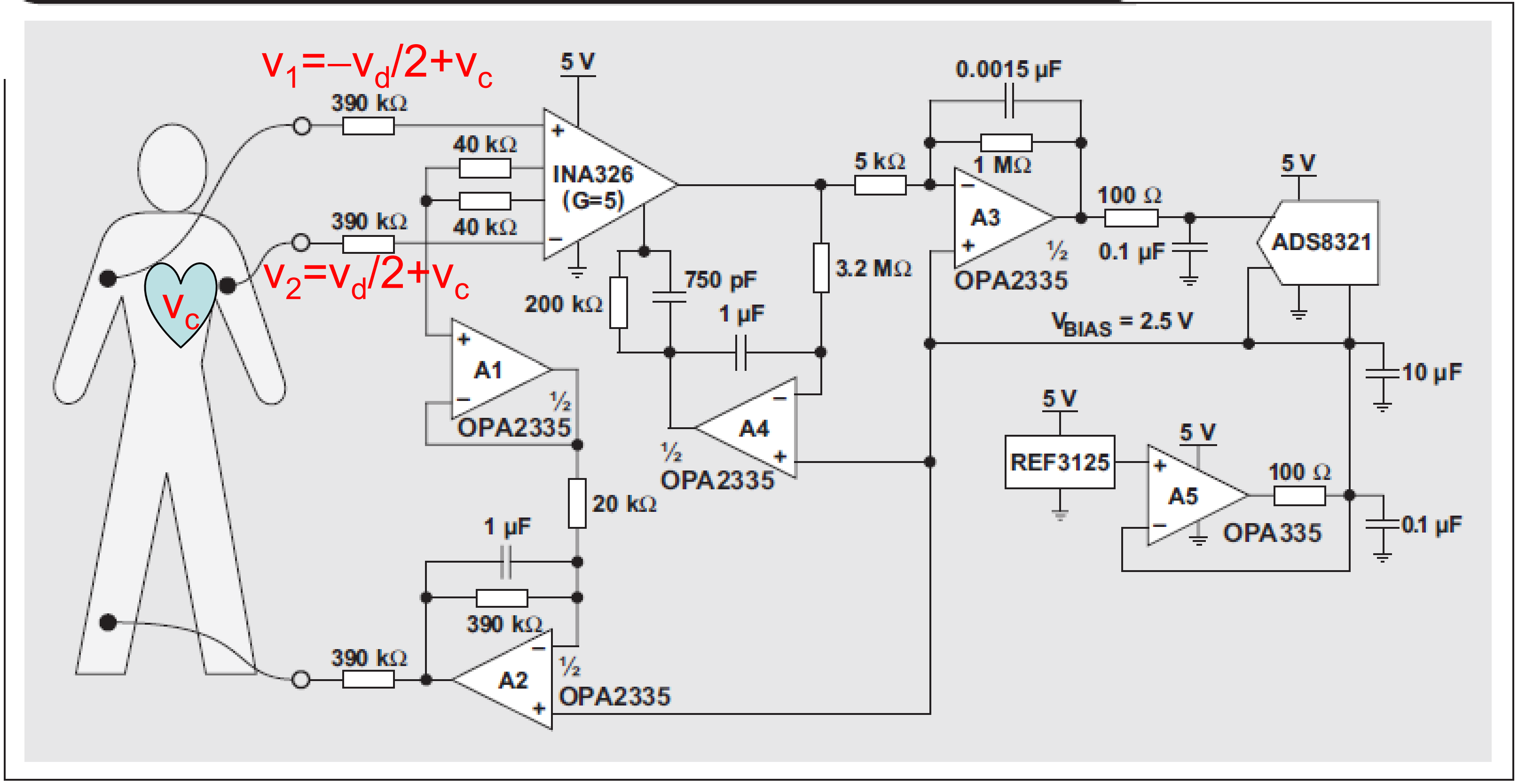
Amplified differential signal, No common-mode signal

Figure 5.39 The IA rejects common voltages but amplifies differential voltages.

The IA has three major characteristics:

1. The voltage gain is adjusted by one external resistor R_G.
2. The input resistance is very high and does not vary as the gain is adjusted.
3. The output v_o depends on v_d, not on v_c.

Figure 5. High-precision analog front end of a portable ECG application



• **Electrocardiography** is the recording of the electrical activity of the heart. It can measure:

- the rate and regularity of “heartbeats”
- the “size and position of the chambers”
- the presence of any “damage” to the heart
- the effects of drugs or devices used to regulate the heart (drug evaluation…) www.ti.com