L04
Operational Amplifiers Applications 3

Chapter 9
Ideal Operational Amplifiers and Op-Amp Circuits

Donald A. Neamen *(2009).* **Microelectronics**: Circuit Analysis and Design*,*

4th Edition, Mc-Graw-Hill

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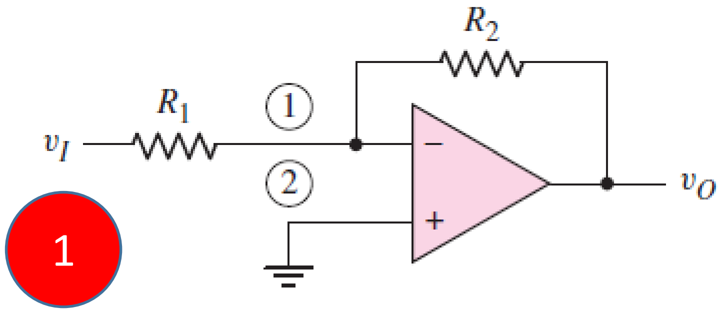
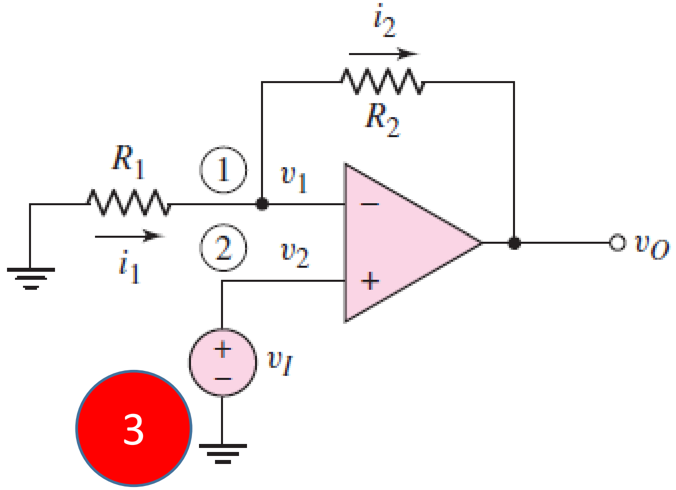
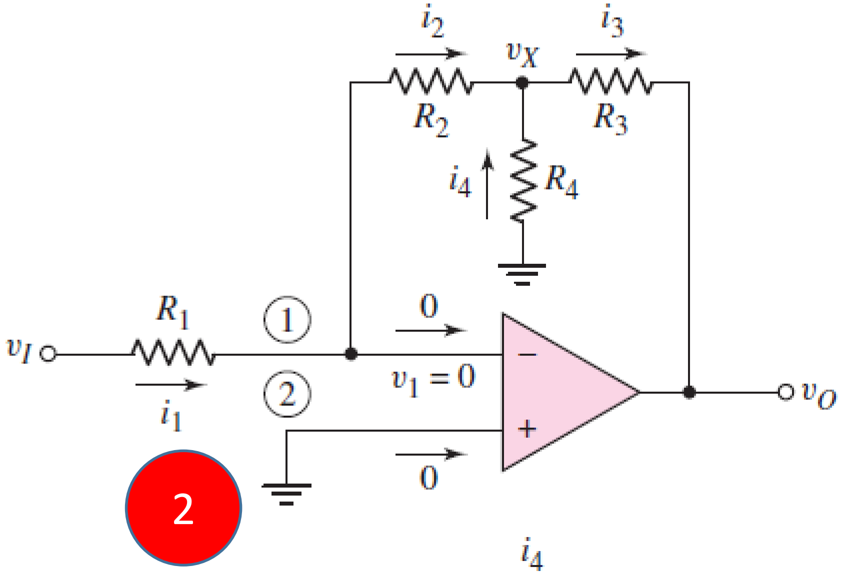
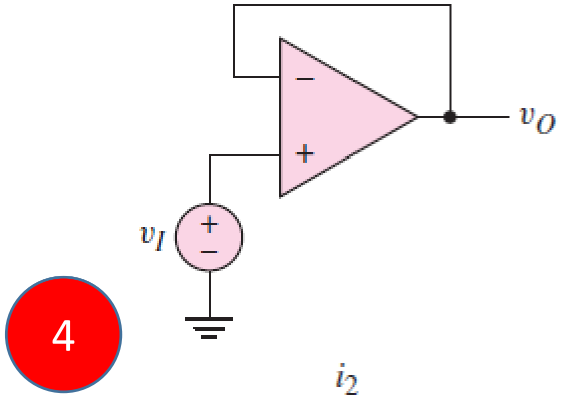
Op-Amp Applications

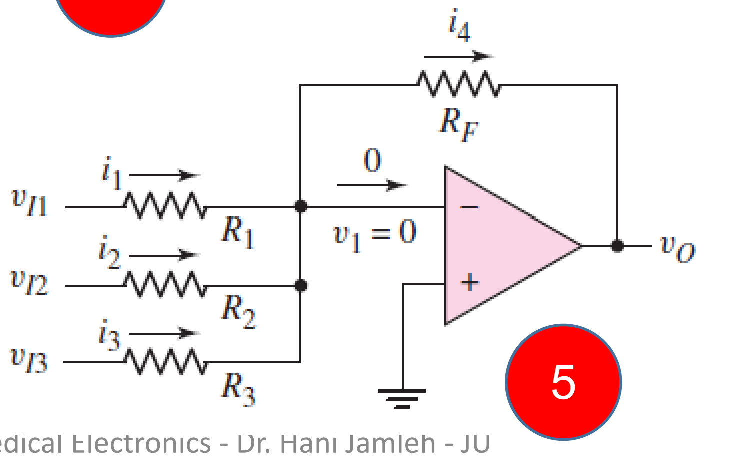
1. Inverting Amplifier
2. Amplifier with T-Network
3. Non-Inverting Amplifier
4. Voltage Follower (Buffer)
5. Summing Amplifier
6. Current to Voltage Converter

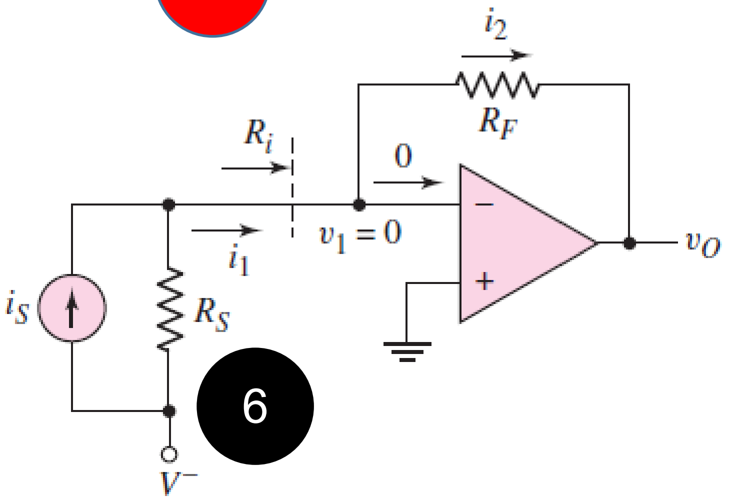






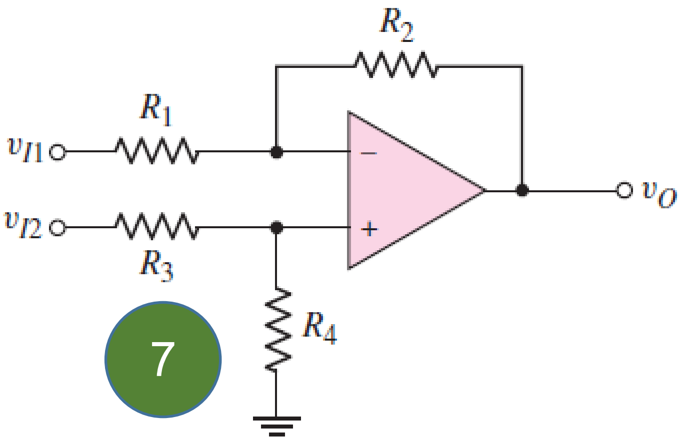


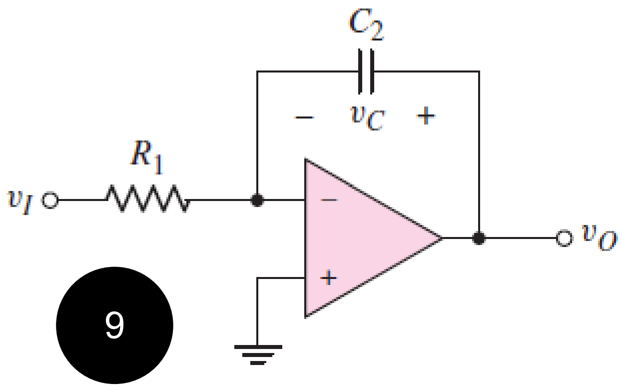


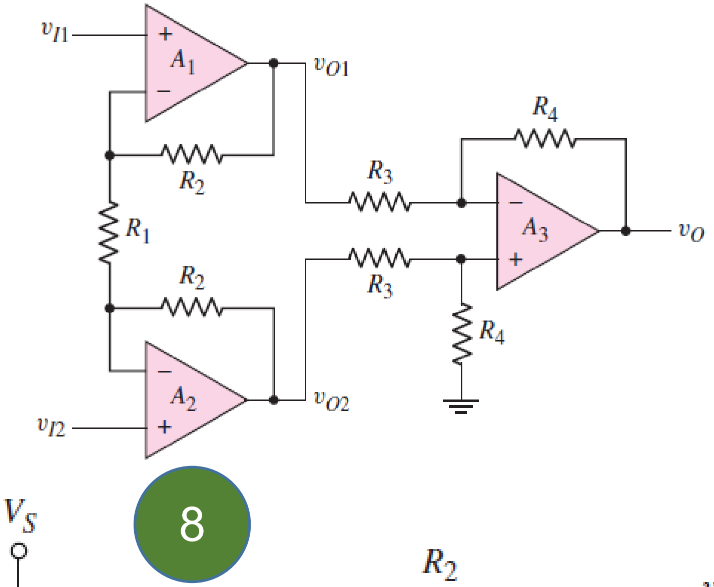


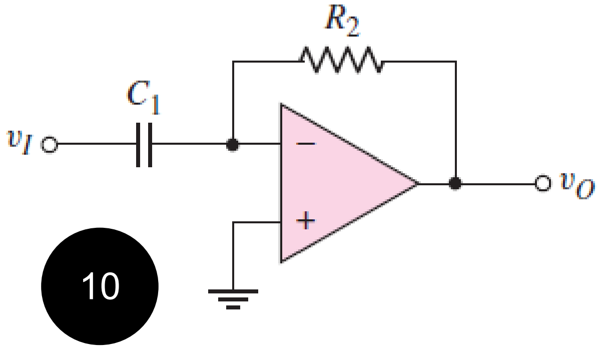
Op-Amp Applications

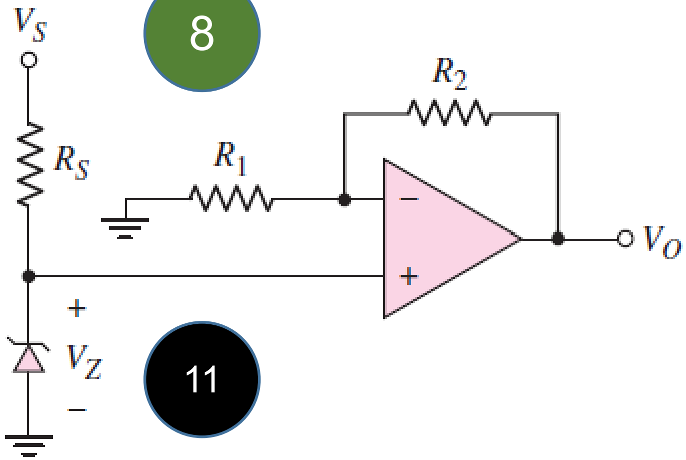
7. Difference Amplifier
8. Instrumentation Amplifier
9. Integrator
10. Differentiator
11. Reference Voltage Source Design
12. Precision Half-wave Rectifier

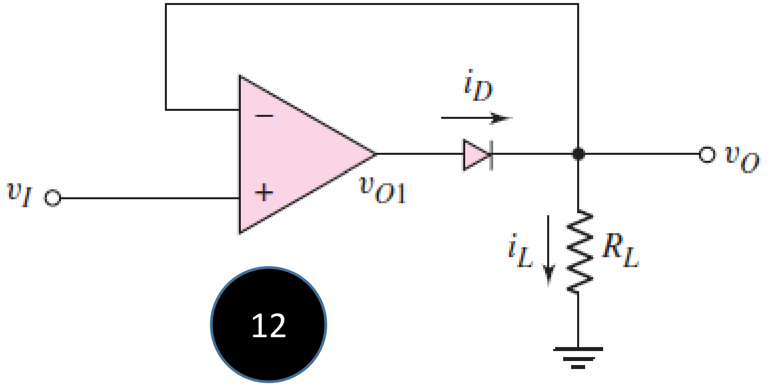












9.5.3 Difference Amplifier

- An ideal **difference amplifier** amplifies only the difference between two signals
  - It rejects any common signals to the two input terminals.
  - For example, a microphone system amplifies an audio signal applied to one terminal of a difference amplifier, and rejects any $60\ Hz$ noise signal or “hum” existing on both terminals.
- We would like to make a difference amplifier, in which:
  - The output is a function of the ratio of resistors, as we had for the inverting and noninverting amplifiers.

9.5.3 Difference Amplifier

- Consider the circuit shown in Figure 9.24(a), with inputs v_{I1} and v_{I2}.
- To analyze the circuit, we will use:
  1. Superposition and
  2. The virtual short concept.
- Figure 9.24(b) shows the circuit with input $v_{I2} = 0$.
  - There are no currents in R_3 and R_4; therefore, $v_{2a} = 0$.
- The resulting circuit is the inverting amplifier previously considered, for which:

$$v_{O1} = -\frac{R_2}{R_1} v_{I1}$$

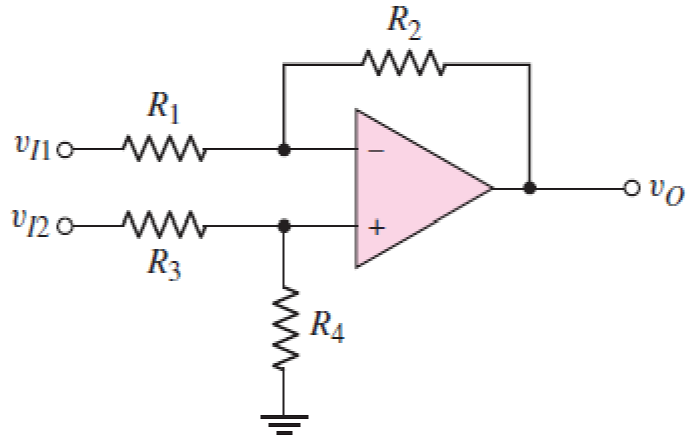


Figure 9.24(a)

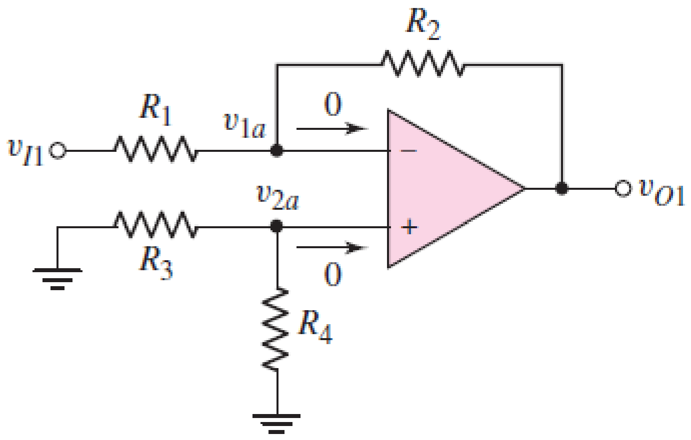


Figure 9.24(b)

9.5.3 Difference Amplifier

- Figure 9.24(c) shows the circuit with $v_{I1} = 0$.
- Since the current into the op-amp is $zero$, R_3 and R_4 form a voltage divider.

$$v_{2b} = \frac{R_4}{(R_3 + R_4)} v_{I2}$$

- From the virtual short concept, $v_{1b} = v_{2b}$ and the circuit becomes a noninverting amplifier:

$$v_{O2} = \left(1 + \frac{R_2}{R_1}\right) v_{1b} = \left(1 + \frac{R_2}{R_1}\right) v_{2b}$$

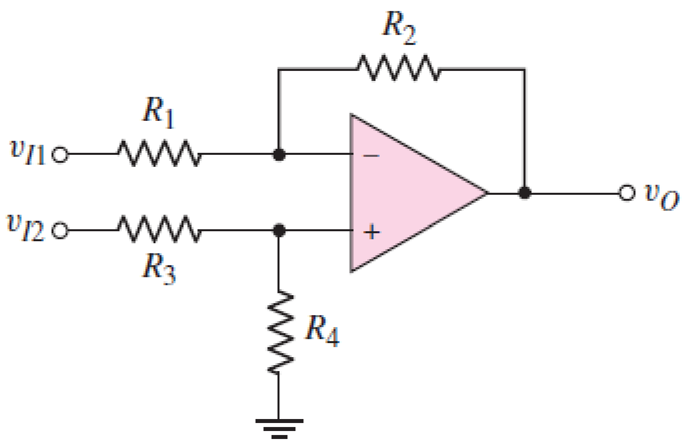


Figure 9.24(a)

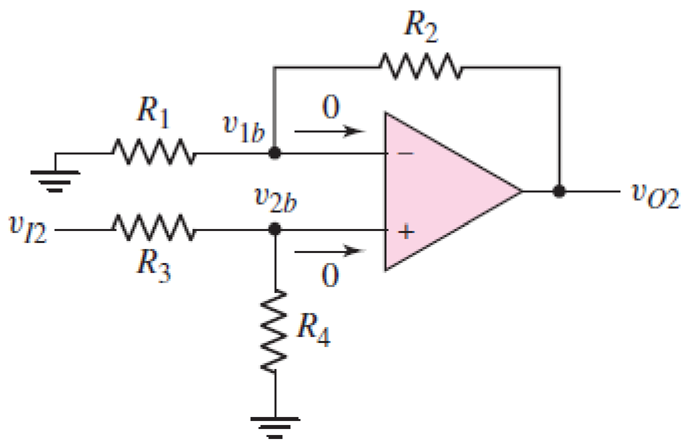


Figure 9.24(c)

9.5.3 Difference Amplifier

- Substituting:

$$v_{2b} = \frac{R_4}{(R_3+R_4)} v_{I2}$$

- Into:

$$v_{O2} = \left(1 + \frac{R_2}{R_1}\right) v_{2b}$$

- we obtain:

$$v_{O2} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4}{R_3 + R_4}\right) v_{I2}$$

which can be rearranged as follows:

$$v_{O2} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4/R_3}{1 + R_4/R_3}\right) v_{I2}$$

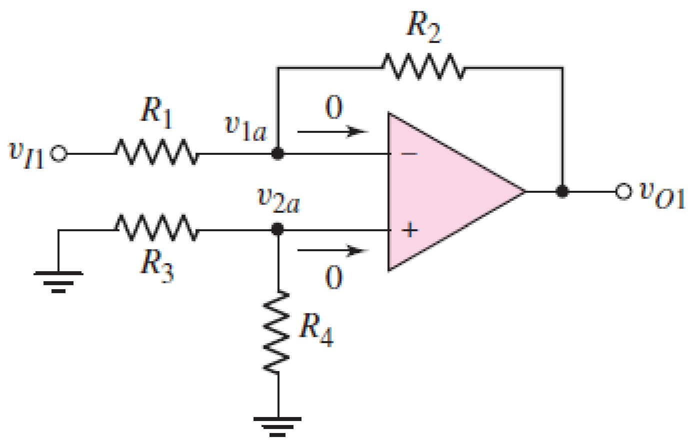


Figure 9.24(b)

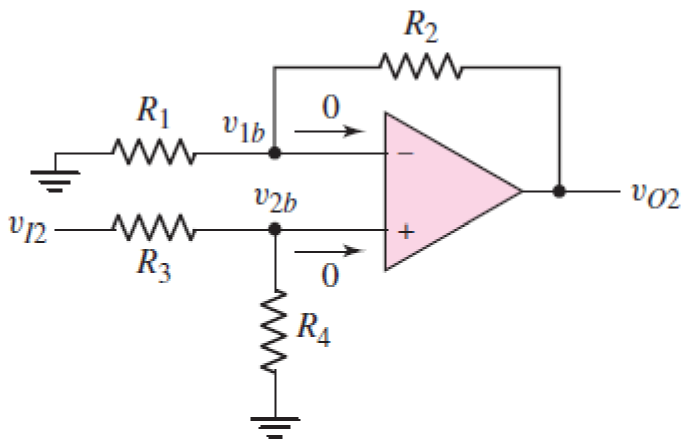


Figure 9.24(c)

9.5.3 Difference Amplifier

$$v_{O1} = -\left(\frac{R_2}{R_1}\right) v_{I1}$$

$$v_{O2} = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4/R_3}{1 + R_4/R_3}\right) v_{I2}$$

- By superposition, the net output voltage is the sum of the individual terms, we have:

$$v_O = v_{O1} + v_{O2}$$

$$v_O = -\left(\frac{R_2}{R_1}\right) v_{I1} + \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4/R_3}{1 + R_4/R_3}\right) v_{I2}$$

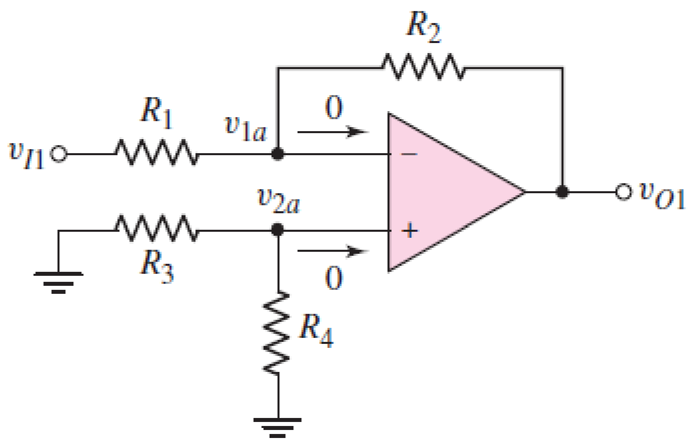


Figure 9.24(b)

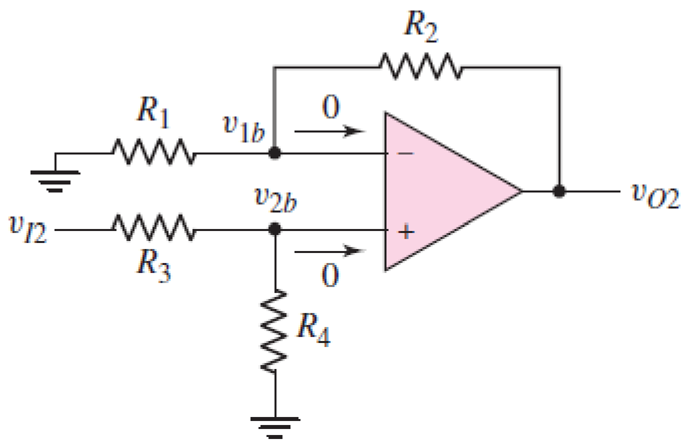


Figure 9.24(c)

9.5.3 Difference Amplifier

$$v_O = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4/R_3}{1 + R_4/R_3}\right) v_{I2} - \left(\frac{R_2}{R_1}\right) v_{I1}$$

- A property of the ideal difference amplifier is that:
  - The output voltage is $zero$ when $v_{I1} = v_{I2}$.
- An inspection of Equation above shows that this condition is met if:

$$\frac{R_4}{R_3} = \frac{R_2}{R_1}$$

- The output voltage is then:

$$v_O = \frac{R_2}{R_1}(v_{I2} - v_{I1})$$

  - Which indicates that this amplifier has a differential gain of:

$$A_d = R_2/R_1$$

  - This factor is a closed-loop differential gain, rather than the open-loop differential gain A_{od} of the op-amp itself.

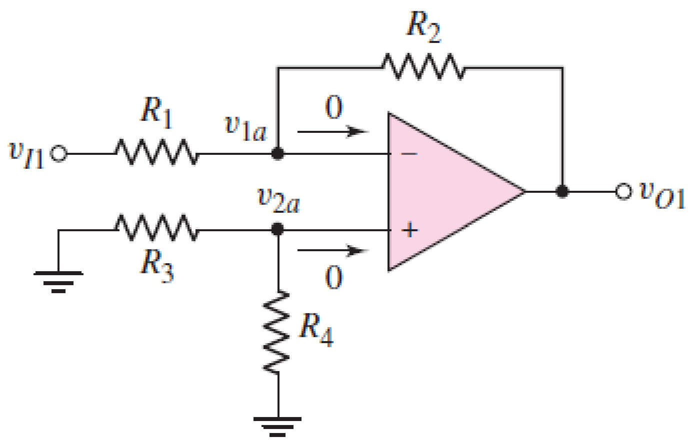


Figure 9.24(b)

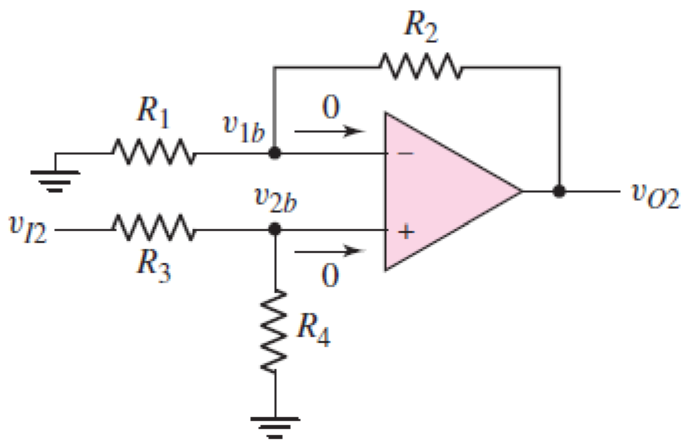


Figure 9.24(c)

9.5.3 Difference Amplifier

- Another important characteristic of electronic circuits is the input resistance.
- The **differential input resistance** can be determined by using the circuit shown in Figure 9.25.
- In the figure, we have imposed the condition given in Equation:

$$\frac{R_4}{R_3} = \frac{R_2}{R_1}$$

  - Set $R_1 = R_3$ and $R_2 = R_4$.
- The input resistance is then defined as:

$$R_i = \frac{v_I}{i}$$

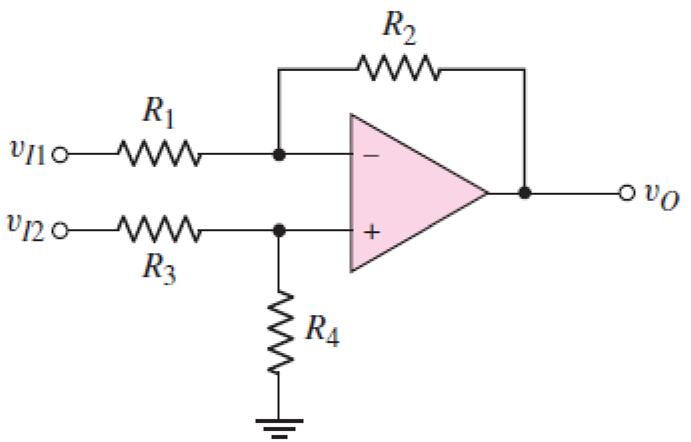


Figure 9.24(a)

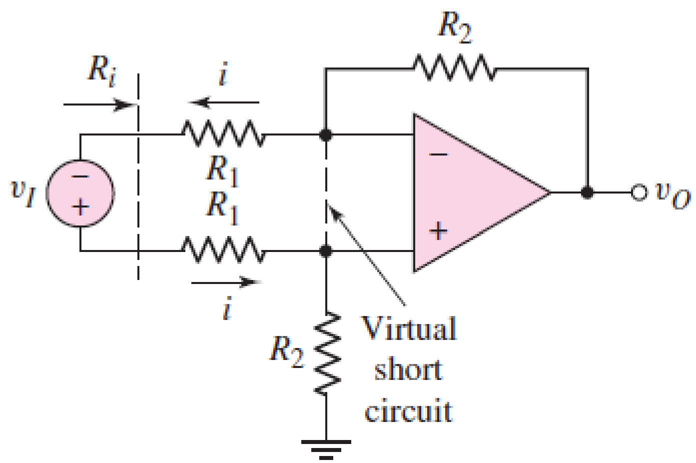


Figure 9.25

9.5.3 Difference Amplifier

$$R_i = \frac{v_I}{i}$$

- Taking into account the virtual short concept, we can write a loop equation, as follows:

$$v_I = i \cdot R_1 + i \cdot R_1 = i(2 \cdot R_1)$$

- The input resistance is:

$$R_i = 2R_1$$

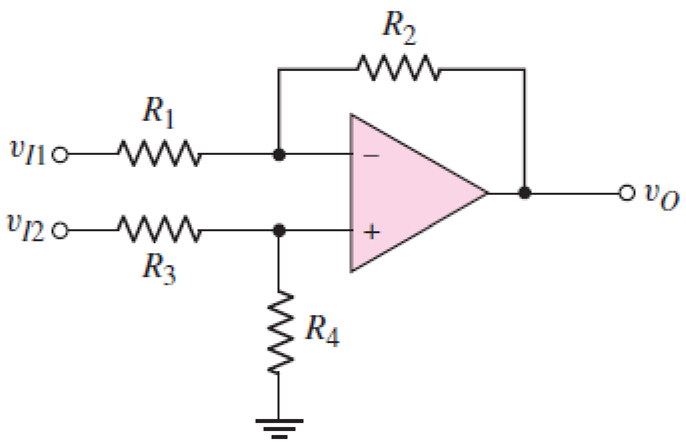


Figure 9.24(a)

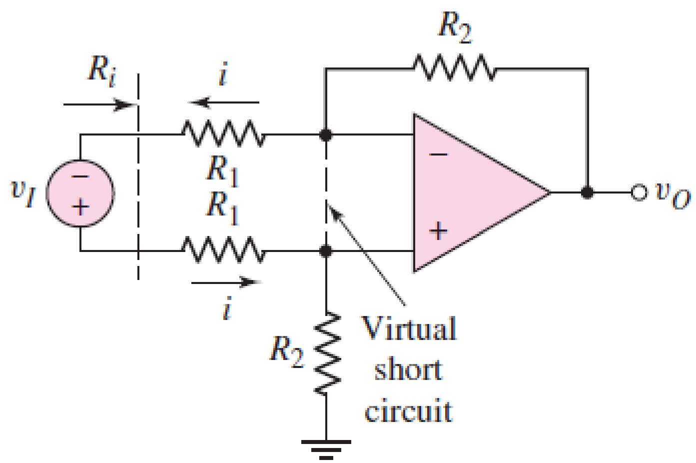


Figure 9.25

9.5.3 Difference Amplifier

common-mode input signal

- In the ideal difference amplifier, the output v_O is $zero$ when $v_{I1} = v_{I2}$.
- However, an inspection of Equation:

$$v_O = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4/R_3}{1 + R_4/R_3}\right) v_{I2} - \left(\frac{R_2}{R_1}\right) v_{I1}$$

shows that this condition is not satisfied if:

$$R_4/R_3 \neq R_2/R_1$$

- When $v_{I1} = v_{I2}$, the input is called a **common-mode input signal.**
- The common-mode input voltage is defined as:

$$v_{cm} = (v_{I1} + v_{I2})/2$$

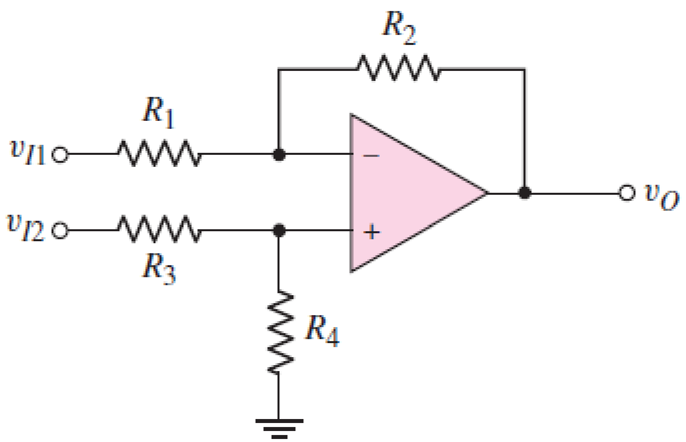


Figure 9.24(a)

9.5.3 Difference Amplifier
common-mode rejection ratio

$$v_{cm} = (v_{I1} + v_{I2})/2$$

- The common-mode gain is then defined as:

$$A_{cm} = \frac{v_O}{v_{cm}}$$

- Ideally, when a common-mode signal is applied, $v_O = 0$ and $A_{cm} = 0$.
- A $nonzero$ common-mode gain may be generated in actual op-amp circuits.
- A figure of merit for a difference amplifier is the **common-mode rejection ratio (CMRR),** which is defined as:
  - The magnitude of the ratio of differential gain to common-mode gain:

$$CMRR = \left|\frac{A_d}{A_{cm}}\right|$$

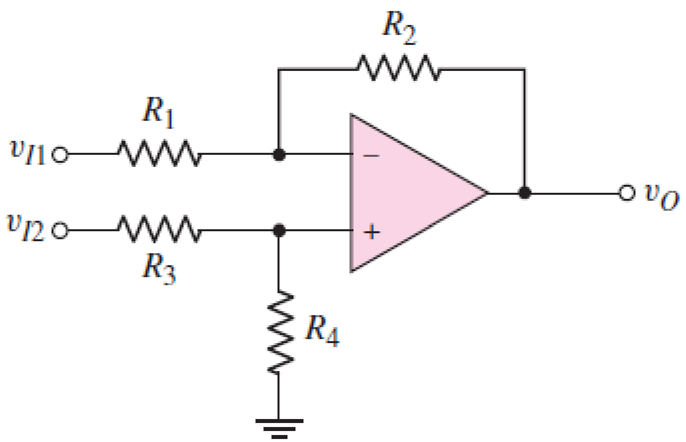


Figure 9.24(a)

9.5.3 Difference Amplifier

$$CMRR = \left|\frac{A_d}{A_{cm}}\right|$$

- Usually, the $CMRR$ is expressed in decibels:

$$CMRR(dB) = 20\log_{10}\left|\frac{A_d}{A_{cm}}\right|$$

  - Ideally, the common-mode rejection ratio is $infinite$.
  - In an actual differential amplifier, we would like the common-mode rejection ratio to be as large as possible.

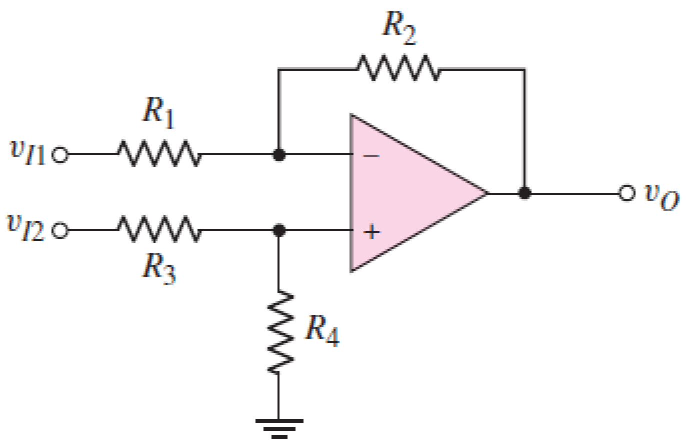


Figure 9.24(a)

EXAMPLE 9.7

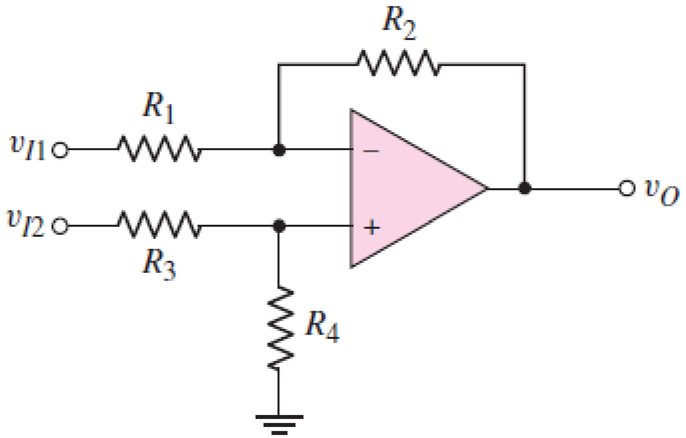


Figure 9.24(a)

- **Objective**: Calculate the common-mode rejection ratio of a difference amplifier.
- Consider the difference amplifier shown in Figure 9.24(a). Let $R_2/R_1 = 10$ and $R_4/R_3 = 11$.
- Determine $CMRR(dB)$.
- **Solution**: From Equation:

$$v_O = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{R_4/R_3}{1 + R_4/R_3}\right) v_{I2} - \left(\frac{R_2}{R_1}\right) v_{I1}$$

- we have:

$$v_O = (1 + 10)\left(\frac{11}{1 + 11}\right) v_{I2} - (10) v_{I1}$$

$$v_O = 10.0833 v_{I2} - 10 v_{I1}$$

EXAMPLE 9.7

$$v_O = 10.0833 v_{I2} - 10 v_{I1}$$

- The differential-mode input voltage is defined as:

$$v_d = v_{I2} - v_{I1}$$

and the common-mode input voltage is defined as:

$$v_{cm} = (v_{I1} + v_{I2})/2$$

- Combining these two equations produces:

$$v_{I1} = v_{cm} - \frac{v_d}{2}$$

$$v_{I2} = v_{cm} + \frac{v_d}{2}$$

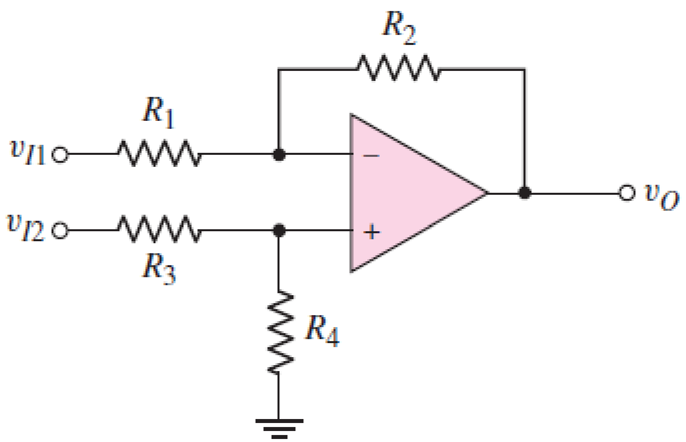


Figure 9.24(a)

EXAMPLE 9.7

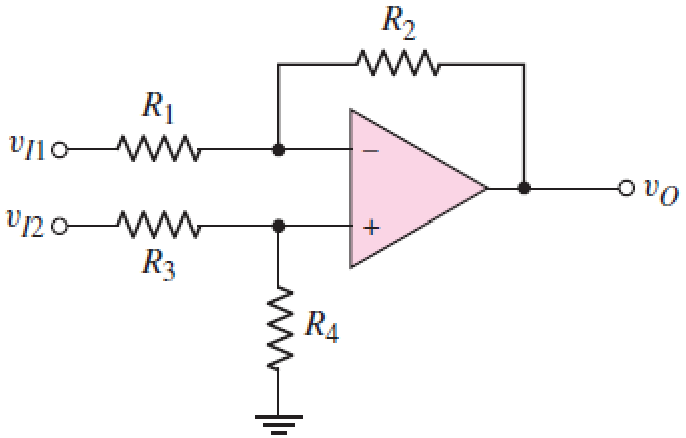


Figure 9.24(a)

- If we substitute Equations:

$$v_{I1} = v_{cm} - \frac{v_d}{2}$$

and

$$v_{I2} = v_{cm} + \frac{v_d}{2}$$

in Equation:

$$v_O = 10.0833 v_{I2} - 10 v_{I1}$$

we obtain:

$$v_O = (10.0833)\left(v_{cm} + \frac{v_d}{2}\right) - (10)\left(v_{cm} - \frac{v_d}{2}\right)$$

EXAMPLE 9.7

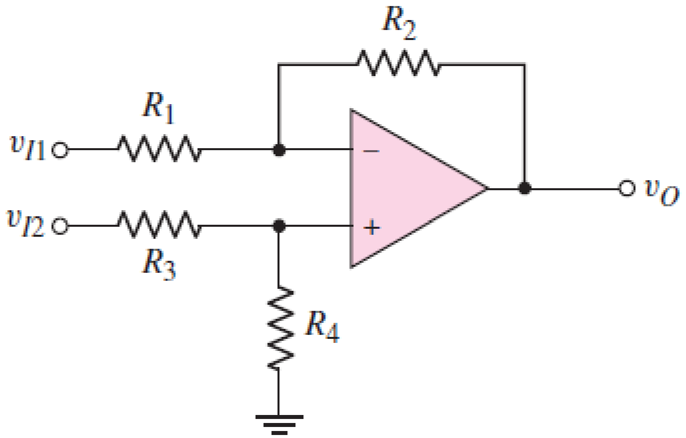


Figure 9.24(a)

$$v_O = (10.0833)\left(v_{cm} + \frac{v_d}{2}\right) - (10)\left(v_{cm} - \frac{v_d}{2}\right)$$

$$v_O = 10.042v_d + 0.0833v_{cm}$$

- The output voltage is also:

$$v_O = A_d v_d + A_{cm} v_{cm}$$

- If we compare the two Equations above, we get:

$$A_d = 10.042 \text{ and } A_{cm} = 0.0833$$

- Therefore the common-mode rejection ratio, is:

$$CMRR(dB) = 20\log_{10}\left|\frac{A_d}{A_{cm}}\right| = 20\log_{10}\left(\frac{10.042}{0.0833}\right) = 41.6dB$$

EXAMPLE 9.7

$$CMRR(dB) = 20\log_{10}\left(\frac{10.042}{0.0833}\right) = 41.6dB$$

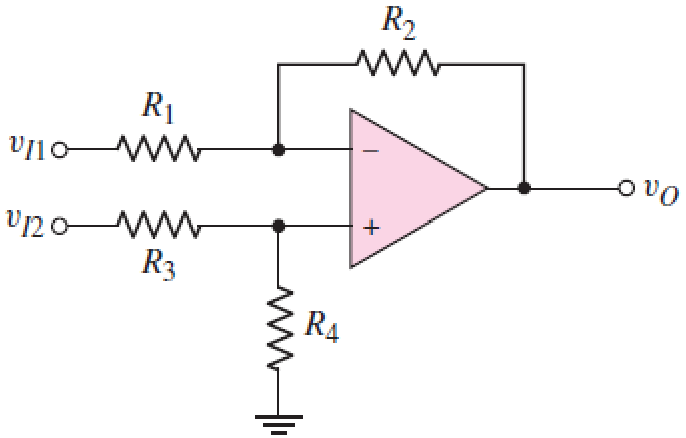
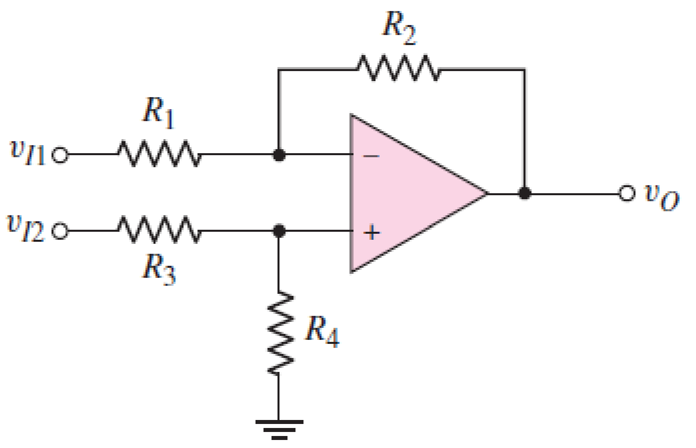


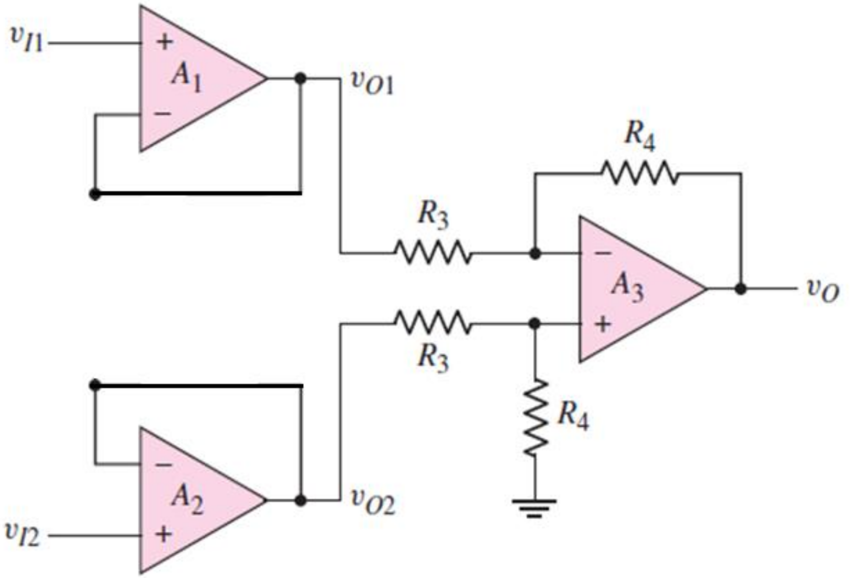
Figure 9.24(a)

- **Comment**: For good differential amplifiers, typical $CMRR$ values are in the range of $80{\sim}100$ dB.
- This example shows how close the ratios R_2/R_1 and R_4/R_3 must be in order to achieve a $CMRR$ value in that range.

9.5.4 Instrumentation Amplifier



- We saw that it is difficult to obtain:
  1. A high input impedance R_i and
  2. A high gain A_d in a difference amplifier
  - with reasonable resistor values.
- One solution is:
  - To insert a voltage follower between each source and the corresponding input.
- A disadvantage of this design is that:
  - The gain of the amplifier cannot easily be changed. In which we would need to change two resistance values and still maintain equal ratios between R_2/R_1 and R_4/R_3.



9.5.4 Instrumentation Amplifier

- Optimally, we would like to be able to change the gain by changing only a single resistance value.
- The circuit in Figure 9.26, called an instrumentation amplifier, allows this flexibility.
  - Two noninverting amplifiers, A_1 and A_2, are used as the input stage, and
  - A difference amplifier, A_3 is the amplifying stage.

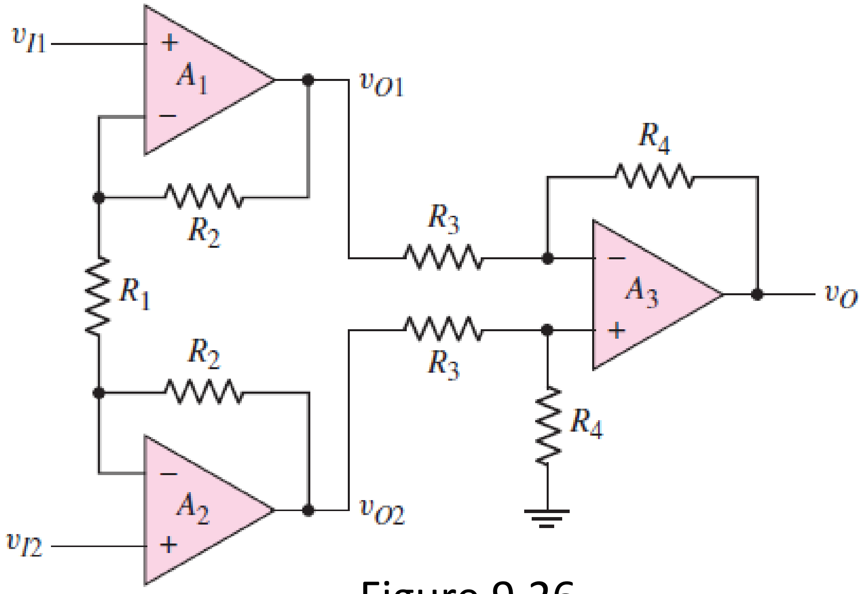


Figure 9.26

9.5.4 Instrumentation Amplifier

- We begin the analysis using the virtual short concept for the input stages.
- The currents and voltages in the amplifier are shown in Figure 9.27. The current in resistor R_1 is then:

$$i_1 = \frac{(v_{I1} - v_{I2})}{R_1}$$

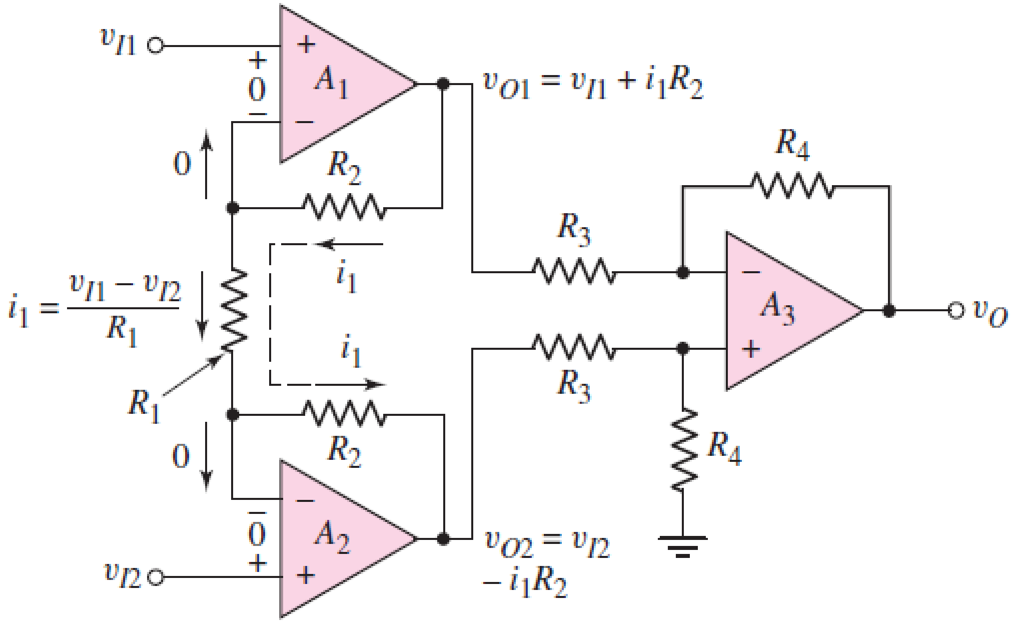


Figure 9.27

9.5.4 Instrumentation Amplifier

- The current in resistors R_2 is also i_1, and the output voltages of op-amps A_1 and A_2 are, respectively:

$$v_{O1} = v_{I1} + i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{I1} - \frac{R_2}{R_1} v_{I2}$$

$$v_{O2} = v_{I2} - i_1 R_2 = \left(1 + \frac{R_2}{R_1}\right) v_{I2} - \frac{R_2}{R_1} v_{I1}$$

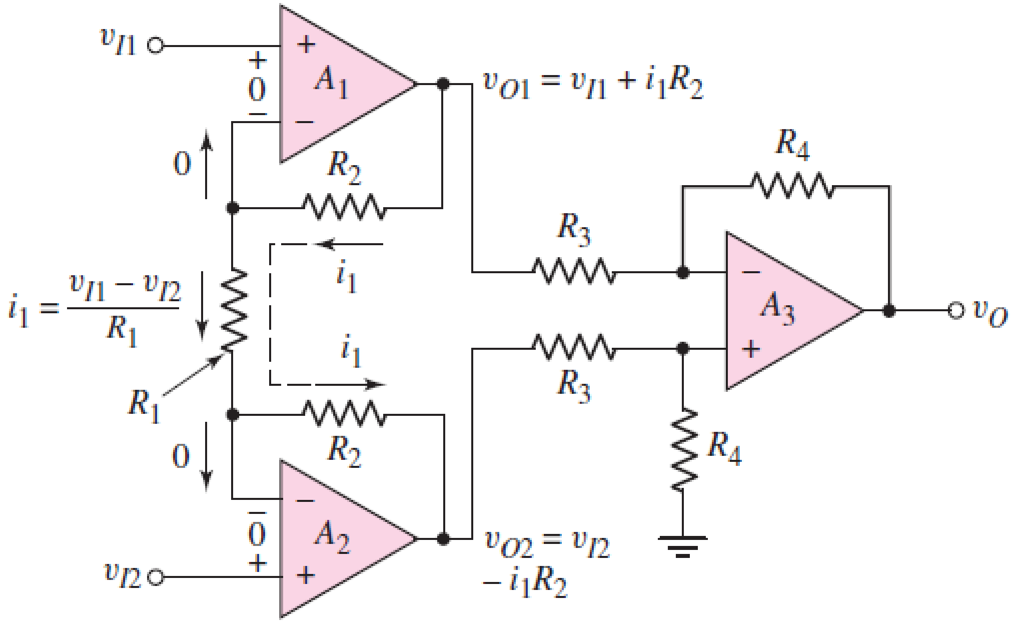


Figure 9.27

9.5.4 Instrumentation Amplifier

- From previous results, the output of the difference amplifier is given as:

$$v_O = \frac{R_4}{R_3}(v_{O2} - v_{O1})$$

- Substituting Equations of v_{O1} and v_{O2} into the Equation above:

$$v_O = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)(v_{I2} - v_{I1})$$

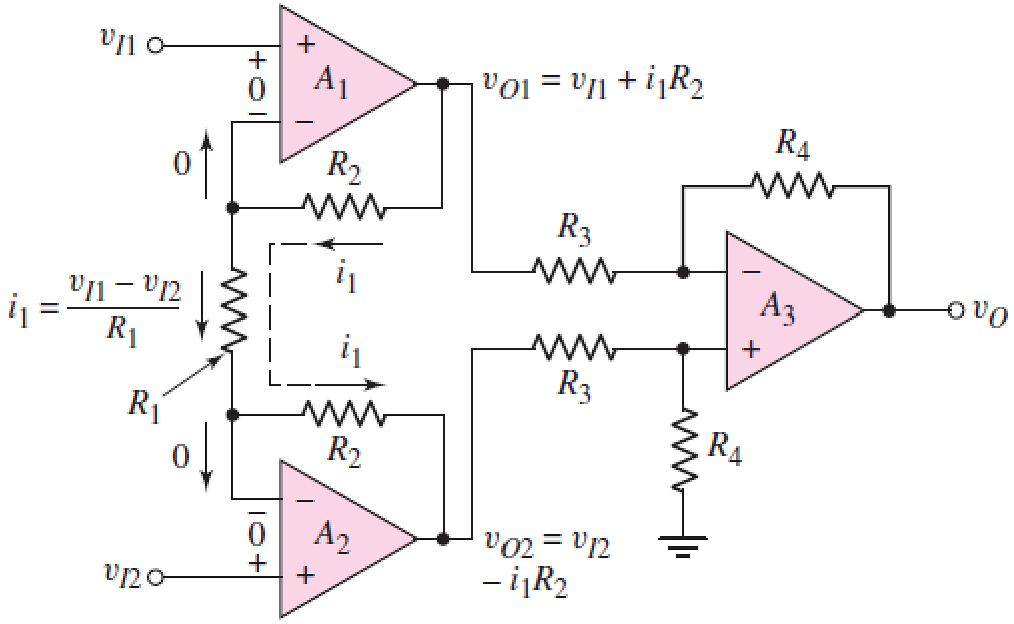


Figure 9.27

9.5.4 Instrumentation Amplifier

$$v_O = \frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)(v_{I2} - v_{I1})$$

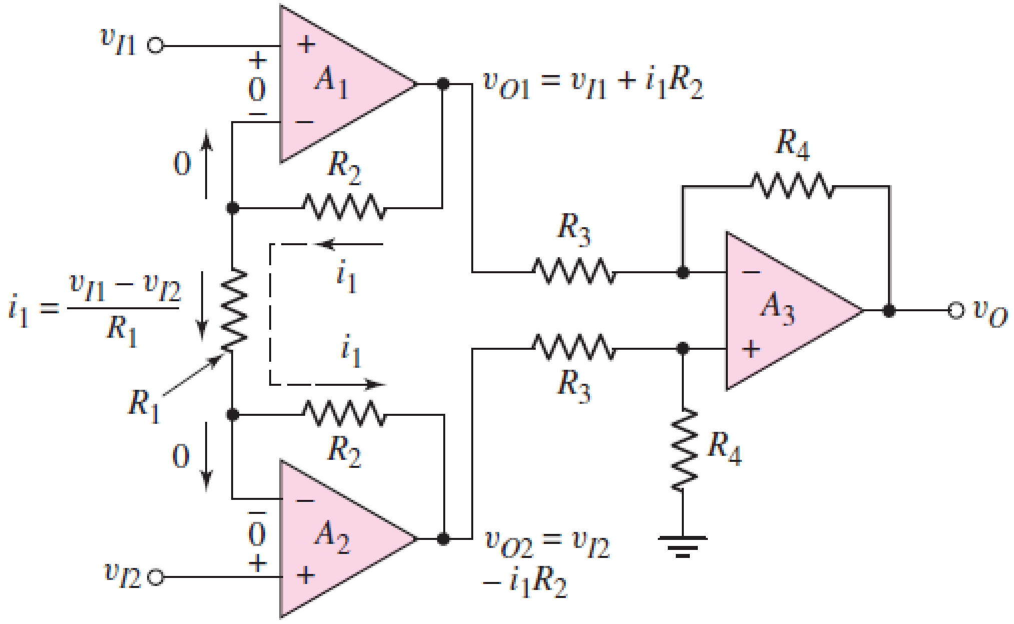


Figure 9.27

- Two advantages:

1. Since the input signal voltages are applied directly to the noninverting terminals of A_1 and A_2, the input impedance is **very large**, ideally infinite.
   - It is one desirable characteristic of the instrumentation amplifier.
2. The differential gain is a function of resistor R_1, which can easily be varied by using a potentiometer, thus providing a variable amplifier gain.

EXAMPLE 9.8

- **Objective**: Determine the range required for resistor R_1, to realize a differential gain adjustable from 5 to 500.
- For the instrumentation amplifier circuit shown in Figure 9.26.
- Assume that $R_4 = 2R_3$, so that the difference amplifier gain is 2.

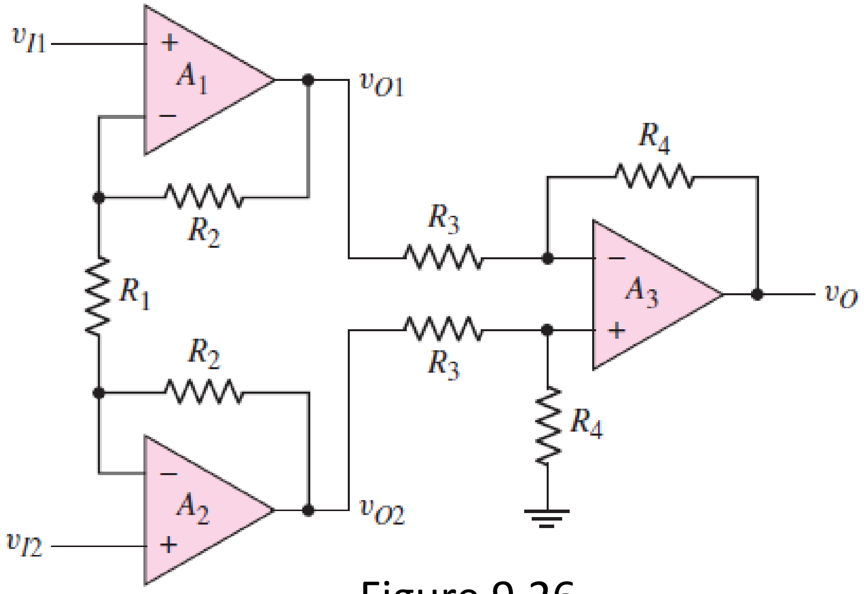


Figure 9.26

EXAMPLE 9.8

- **Solution**: Assume that resistance R_1 is a combination of a fixed resistance R_{1f} and a variable resistance R_{1v}, as shown in Figure 9.28.
- The fixed resistance ensures that:
  - The gain is limited to a maximum value, even if the variable resistance is set equal to $zero$.
- Assume the variable resistance is a potentiometer:

$$\mathrm{R}_{1\mathrm{v}} = 100\ k\Omega$$

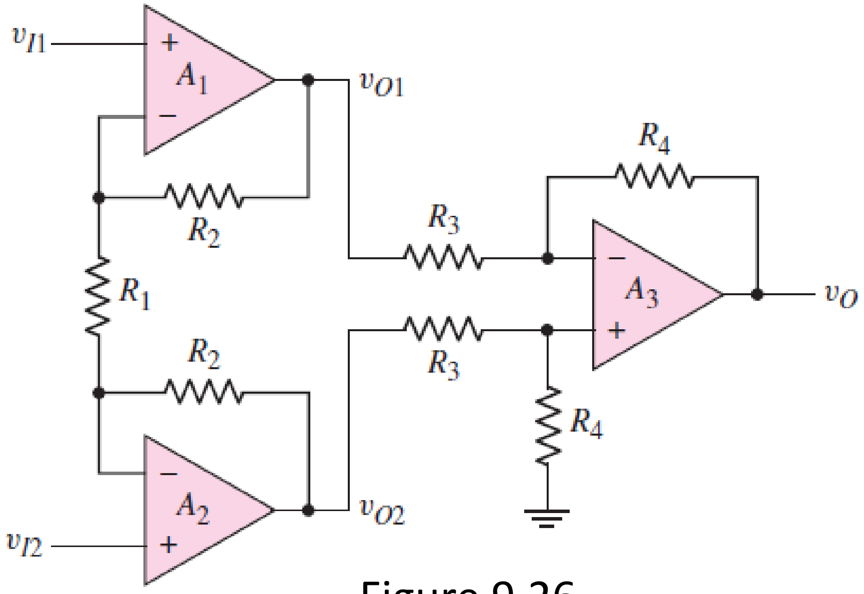


Figure 9.26

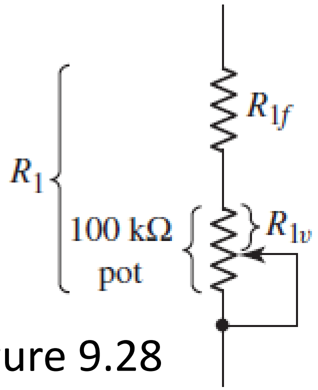


Figure 9.28

EXAMPLE 9.8

- From the Equation:

$$v_O = \frac{R_4}{R_3}\left(1\ + \frac{2R_2}{R_1}\right)(v_{I2} - v_{I1})$$

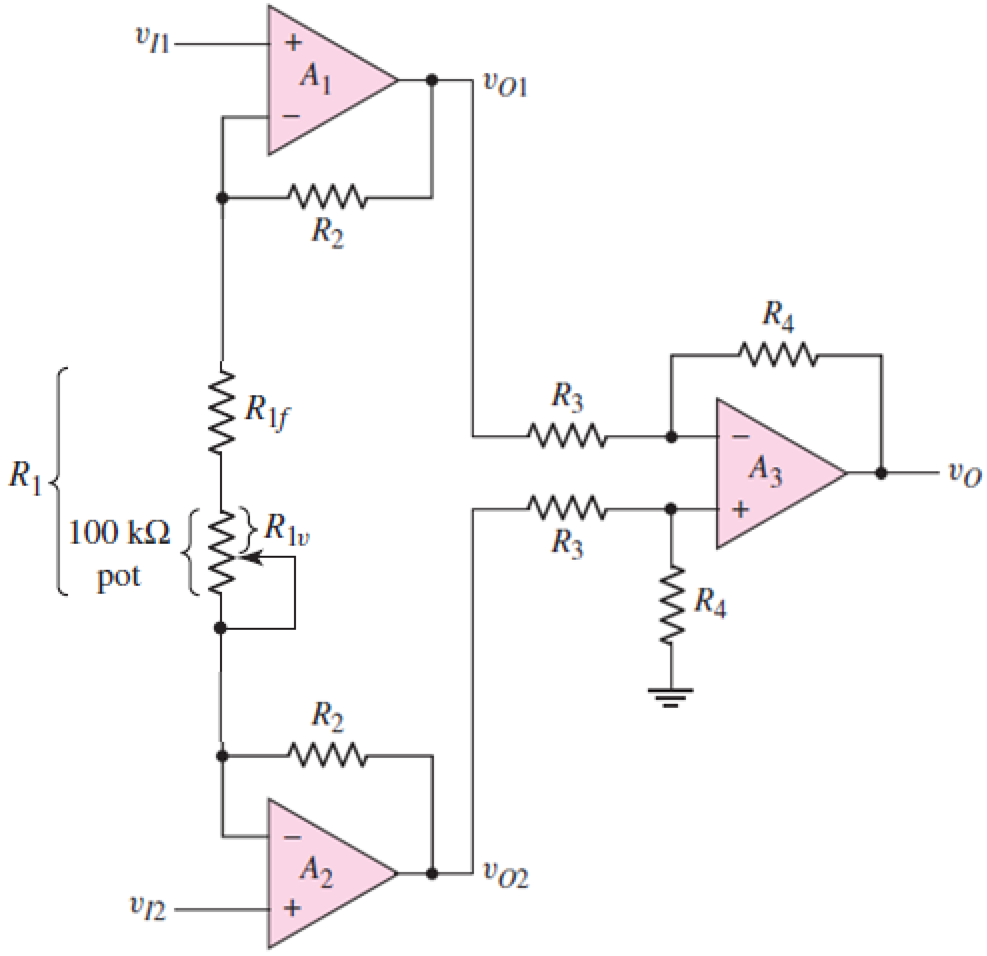
- The maximum differential gain is:

$$500 = 2\left(1 + \frac{2R_2}{R_{1f}}\right)$$

$$2R_2 = 249R_{1f}$$

- The minimum differential gain is:

$$5 = 2\left(1 + \frac{2R_2}{R_{1f} + 100k}\right)$$



EXAMPLE 9.8

- Let:

$$2R_2 = 249R_{1f}$$

- Into:

$$5 = 2\left(1 + \frac{2R_2}{R_{1f} + 100k}\right)$$

- We get:

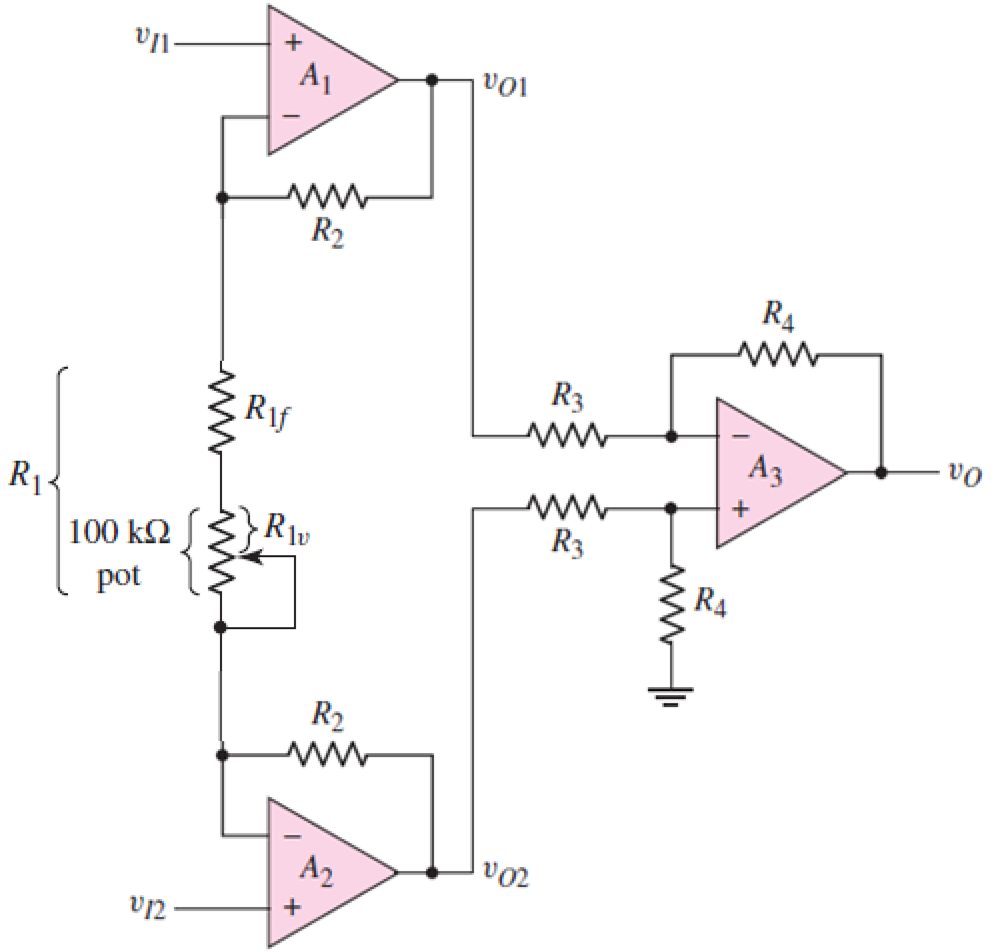
$$1.5 = \frac{249R_{1f}}{R_{1f} + 100}$$

- The resulting value of R_{1f} is:

$$R_{1f} = 0.606k\Omega = 606\Omega$$

- which yields:

$$R_2 = 75.5k\Omega$$



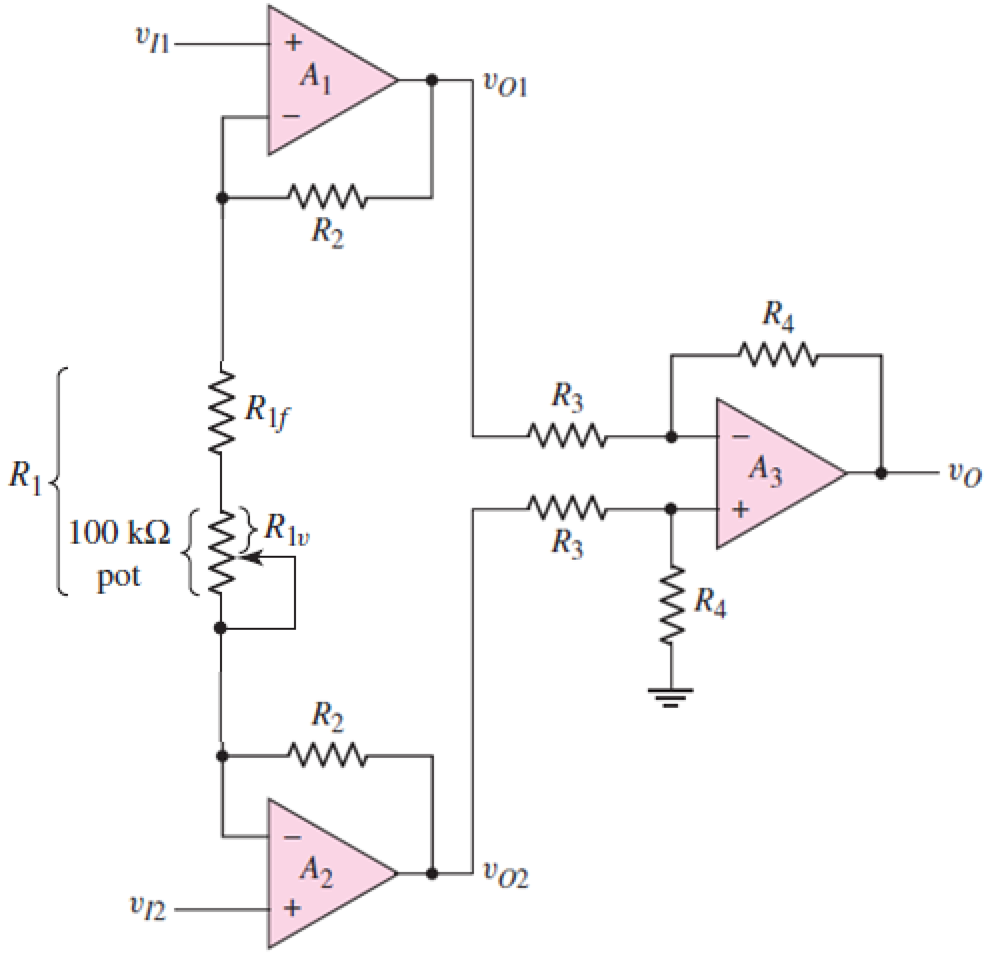
EXAMPLE 9.8

$$R_{1f} = 606\Omega, \text{ and } R_2 = 75.5k\Omega$$

- **Comment**: We can select standard resistance values that are close to the values calculated, and the range of the gain will be approximately in the desired range.

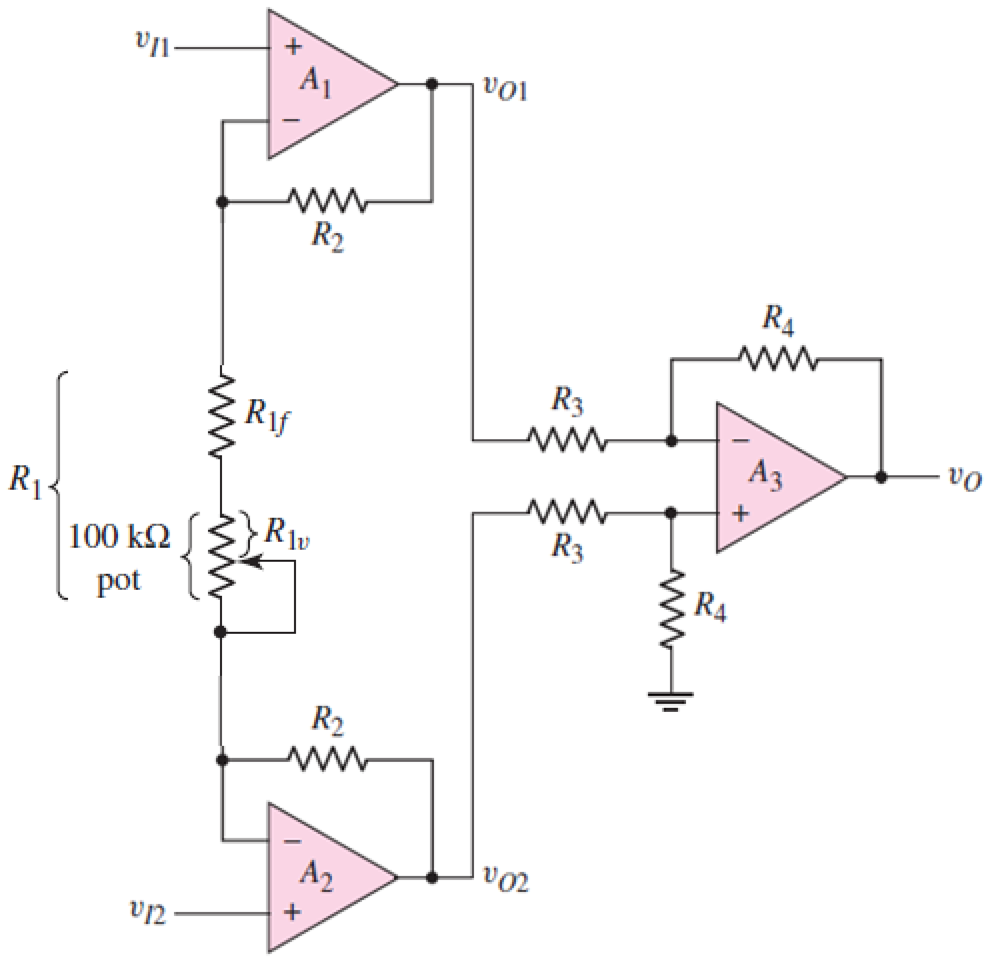
Table C.1		Standard resistance values ($\times 10^n$)		
10	16	**27**	43	**68**
11	**18**	30	**47**	75
12	20	**33**	51	**82**
13	**22**	36	**56**	91
15	24	**39**	62	**100**

- $R_{1f} = 606 \rightarrow 470 + 130 = 600\Omega$, and
- $R_2 = 75.5k\Omega \rightarrow 75\text{k}\Omega + 510\Omega = 75.51\ \text{k}\Omega$



EXAMPLE 9.8

- **Design Pointer**: An amplifier with a wide range of gain and designed with a potentiometer would normally not be used with standard integrated circuits in electronic systems.
- However, such a circuit might be very useful in specialized test equipment.



9.7.3 Difference Amplifier and Bridge Circuit Design

- A **transducer** is:
  - A device that transforms one form of energy into another form.
- One type of transducer uses nonelectrical inputs to produce electrical outputs.
- For example:
  - A **microphone** converts acoustical energy into electrical energy.
  - A **pressure transducer** is a device in which a resistance is a function of pressure, so that pressure can be converted to an electrical signal.
- Often, the output characteristics of these transducers are measured with a **bridge circuit**.

Wheatstone bridge [Wikipedia]

- A Wheatstone bridge is an electrical circuit used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, one leg of which includes the unknown component.
- The primary benefit of a Wheatstone bridge is:
  - Its ability to provide extremely accurate measurements (in contrast with something like a simple voltage divider).
- Its operation is similar to the original potentiometer.

9.7.3 Difference Amplifier and Bridge Circuit Design

- Figure 9.44 shows a bridge circuit.
  - Resistance R_3 represents the transducer, and
  - Parameter δ is the deviation of R_3 from R_2 due to the input response of the transducer.
  - The output voltage v_{O1} is now a measure of δ.
- Applying voltage divider concept:

$$v_{O1}^{+} = \frac{R_3}{R_3 + R_1} V^{+}$$

$$v_{O1}^{-} = \frac{R_2}{R_1 + R_2} V^{+}$$

- Therefore:

$$v_{O1} = v_{O1}^{+} - v_{O1}^{-}$$

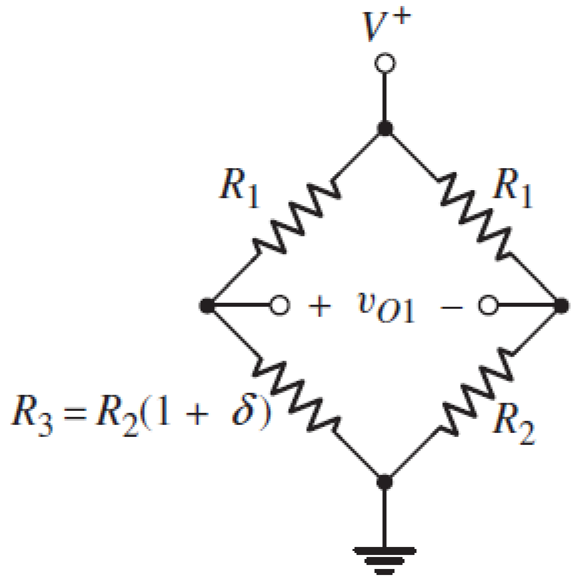


Figure 9.44

9.7.3 Difference Amplifier and Bridge Circuit Design

- If v_{O1} is an open-circuit voltage, then:

$$v_{O1} = v_{O1}^{+} - v_{O1}^{-}$$

$$v_{O1} = \left[\frac{R_2(1+\delta)}{R_2(1+\delta)+R_1} - \frac{R_2}{R_1+R_2}\right]V^{+}$$

$$v_{O1} = \frac{R_1R_2 + R_2^2 + \delta R_1R_2 + \delta R_2^2 - R_2^2 - \delta R_2^2 - R_1R_2}{\delta R_2(R_1+R_2)+(R_1+R_2)^2}V^{+}$$

$$v_{O1} = \frac{\delta R_1R_2}{\delta R_2(R_1+R_2)+(R_1+R_2)^2}V^{+}$$

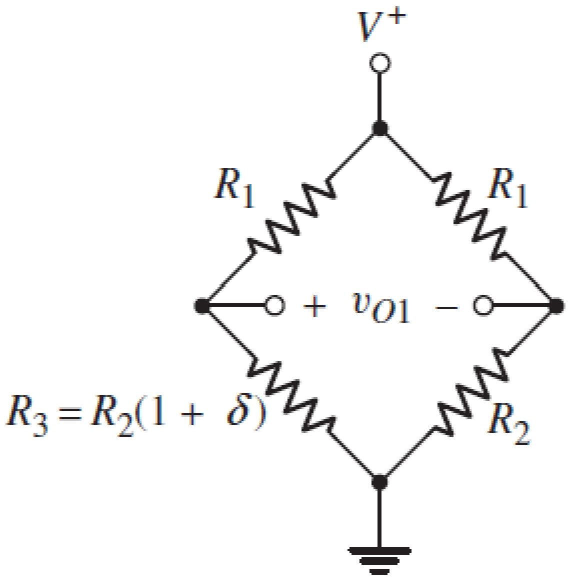


Figure 9.44

9.7.3 Difference Amplifier and Bridge Circuit Design

$$v_{O1} = \frac{\delta R_1 R_2}{\delta R_2 (R_1 + R_2) + (R_1 + R_2)^2} V^+$$

Reduces to:

$$v_{O1} = \delta \left(\frac{R_1 \parallel R_2}{R_1 + R_2} \right) V^+$$

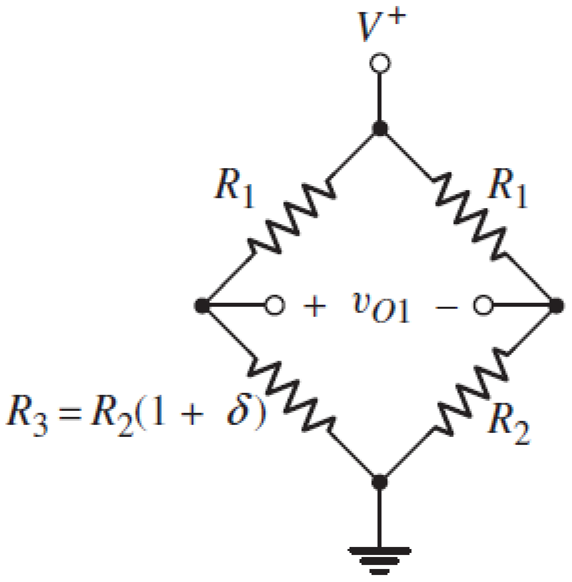


Figure 9.44

9.7.3 Difference Amplifier and Bridge Circuit Design

$$v_{O1} = \delta\left(\frac{R_1 \parallel R_2}{R_1 + R_2}\right)V^+$$

- Since neither side of voltage v_{O1} is at ground potential, we must connect v_{O1} to an instrumentation amplifier.
- In addition, v_{O1} is directly proportional to supply voltage V^+; therefore, this bias should be a well-defined voltage reference.

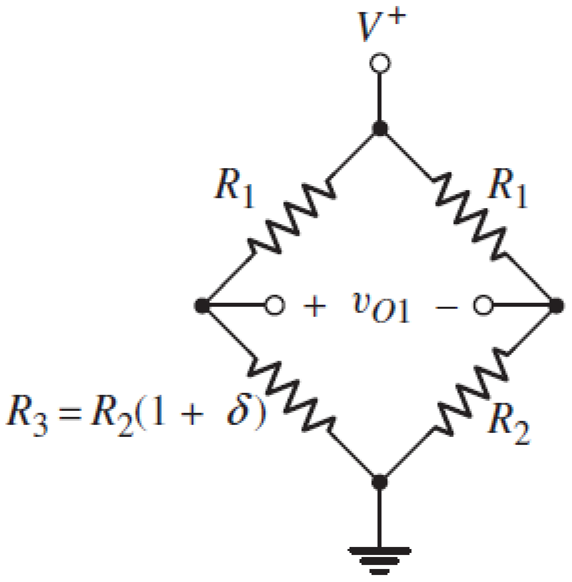


Figure 9.44

DESIGN EXAMPLE 9.12

- **Objective**: Design an amplifier system that will produce an output voltage of $\pm 5V$ when the resistance R_3 deviates by $\pm 1\%$ from the value of R_2.
- This would occur, for example, in a system where R_3 is a thermistor whose resistance is given by:

$$R_3 = 200\left[1 + \frac{(0.040)(T - 300)}{300}\right] k\Omega$$

  - Where T is the absolute temperature.
- For R_3 to vary by $\pm 1\%$ means the temperature is in the range:

$$225 \le T \le 375K \rightarrow -48 \le T \le 102^{o}C$$

- Consider biasing the bridge circuit at $V^{+} = 7.5V$ using a 5.6 V Zener diode.
- Assume $\pm 10V$ is available for biasing the op-amp and reference voltage source, and that $R_1 = R_2 = 200\ k\Omega$.

Home Work #1

- Simulate the circuit shown in Figure 9.45 using **Multisim**.
- See DESIGN EXAMPLE 9.12 in Microelectronics Book by Neamen 4th ed.

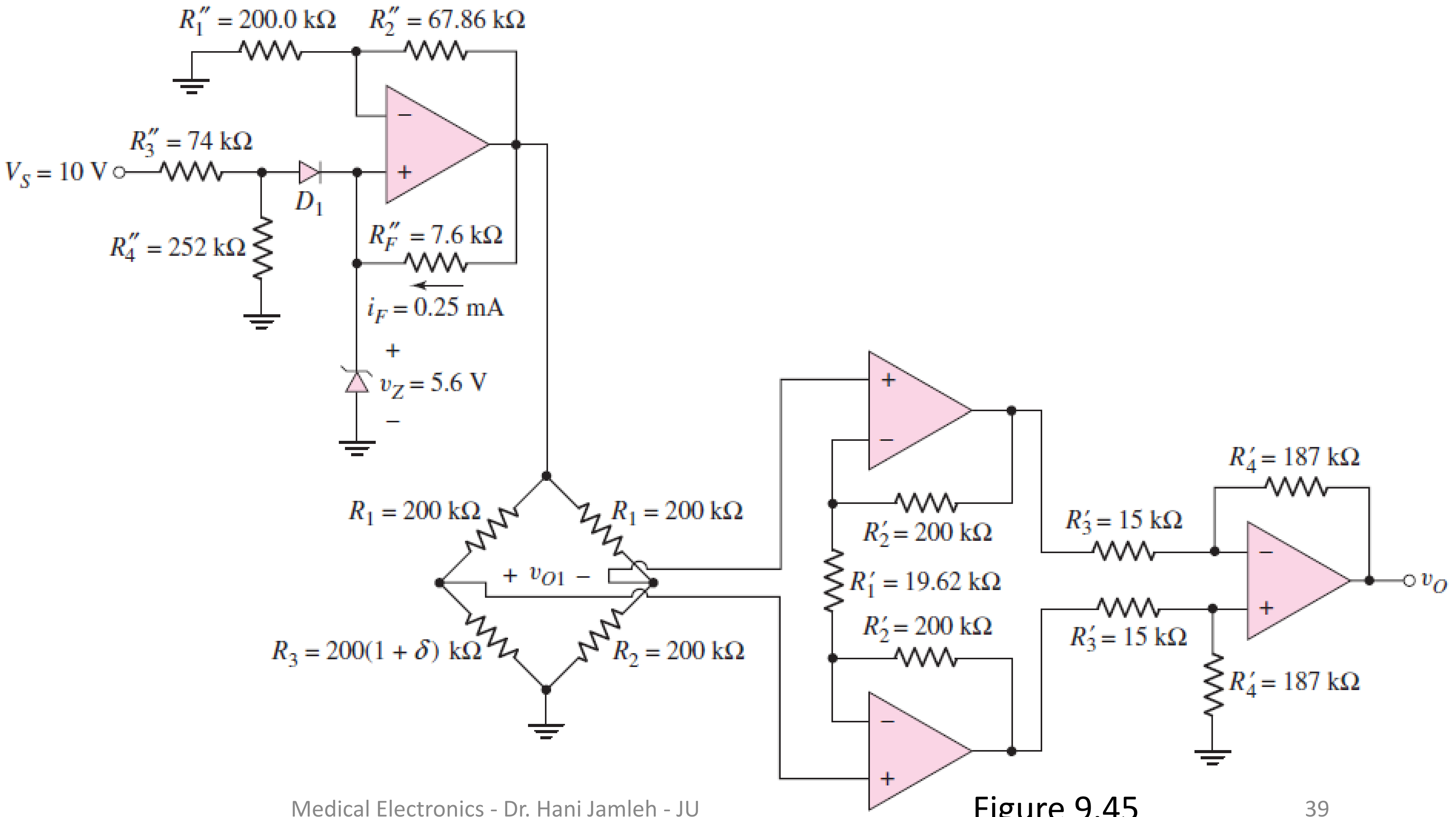


Figure 9.45

9.5.5 Integrator and Differentiator

- In the op-amp circuits previously considered, the elements exterior to the op-amp have been resistors.
  - Other elements can be used, with differing results.
- Figure 9.29 shows a generalized **inverting amplifier** for which the voltage transfer function has the same general form as before:

$$\frac{v_O}{v_I} = -\frac{Z_2}{Z_1}$$

- where Z_1 and Z_2 are generalized **impedances**.
- Two special circuits can be developed from this generalized inverting amplifier :
  - Integrator and
  - Differentiator.

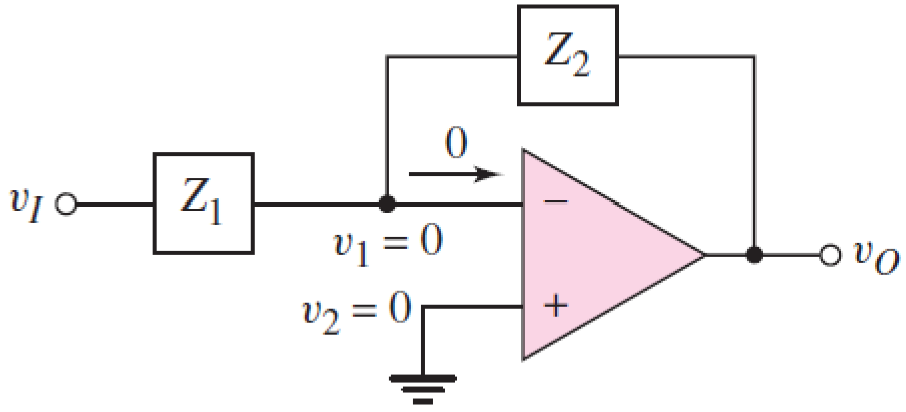


Figure 9.29

Op-amp integrator

- Low Pass Filter

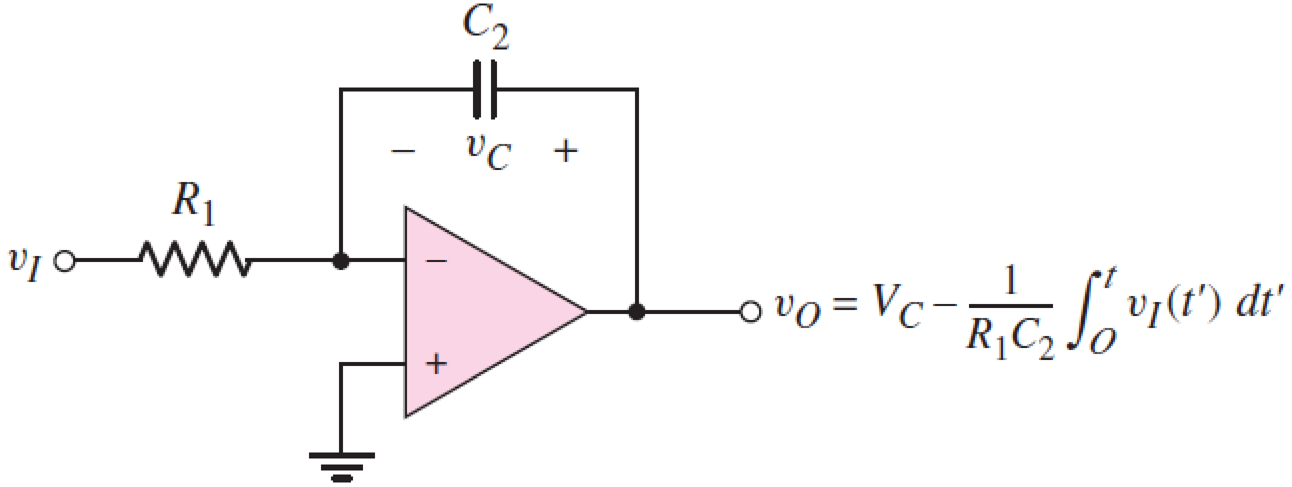
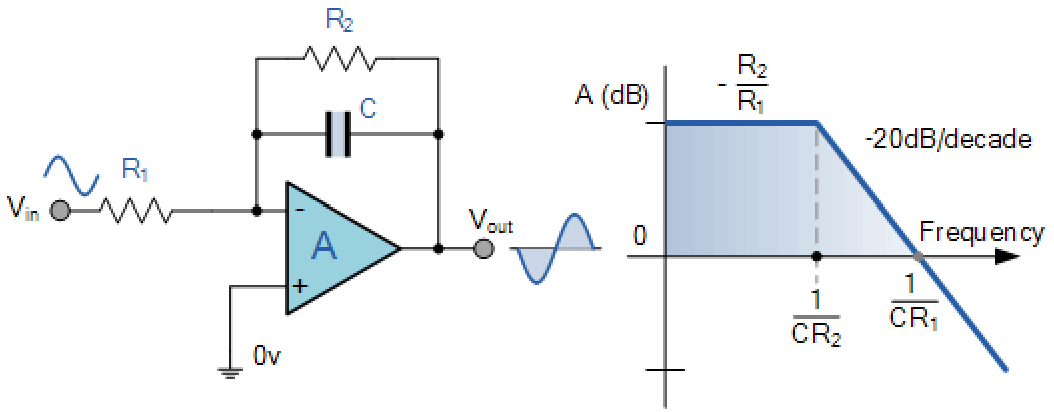


Figure 9.30



Op-amp differentiator

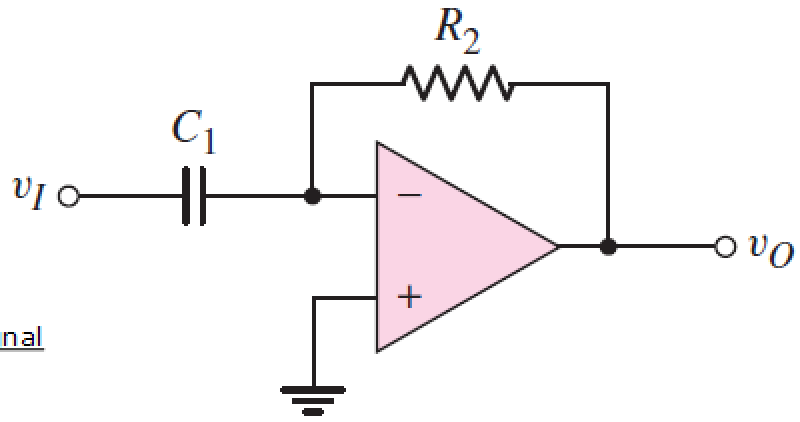


Figure 9.31

- High Pass Filter