L02
Operational Amplifiers Applications 1

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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9.1.3 Analysis Method
Feedback

- Usually, an op-amp is not used in the open-loop configuration shown in Figure 9.2.
  - **Feedback** is added to close the loop between the output and the input.
  - **Negative feedback:**
    - The output is connected to the **inverting terminal**.
    - This configuration produces stable circuits.
  - **Positive feedback**:
    - The output is connected to the **noninverting terminal**.
    - This configuration can be used to produce oscillators.

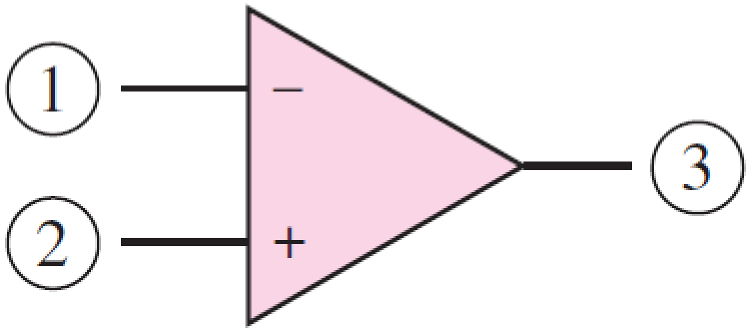


Figure 9.1(a)

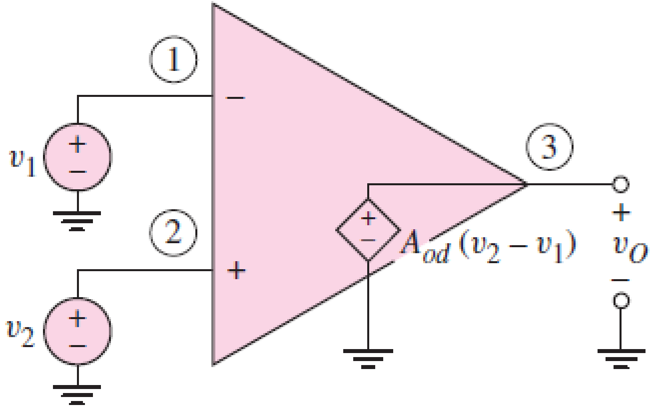


Figure 9.2

9.1.3 Analysis Method
Two Port Network Voltage Amplifier

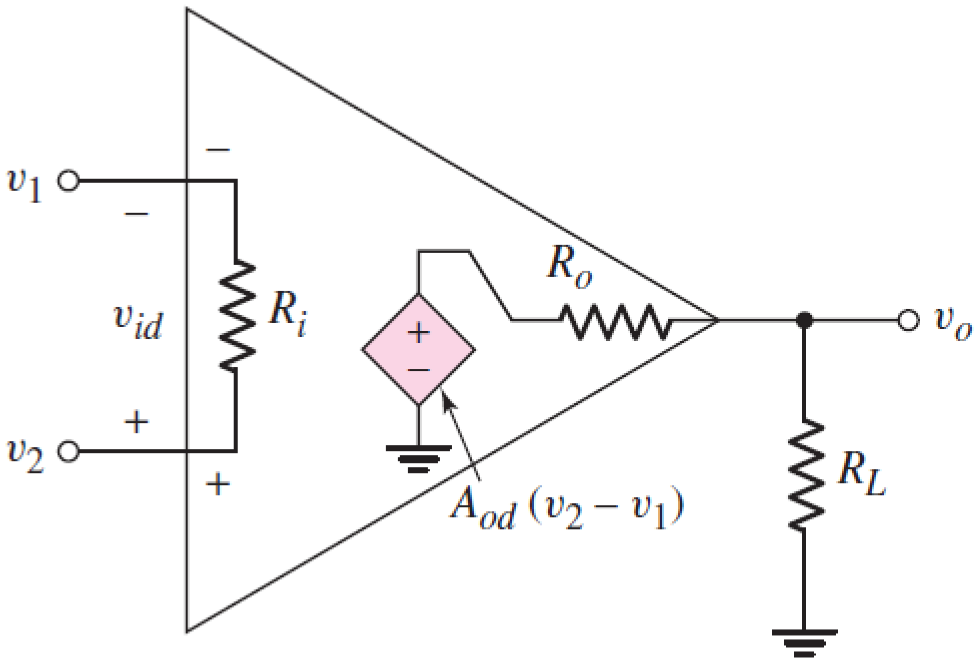
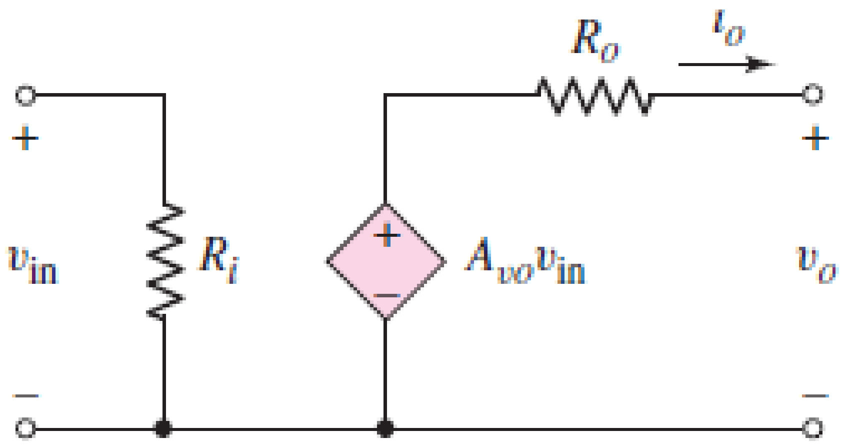


Figure 9.7(a)



9.1.3 Analysis Method

Ideally

$A_{od} \to \infty$ $R_i \to \infty$ $R_o \to 0$

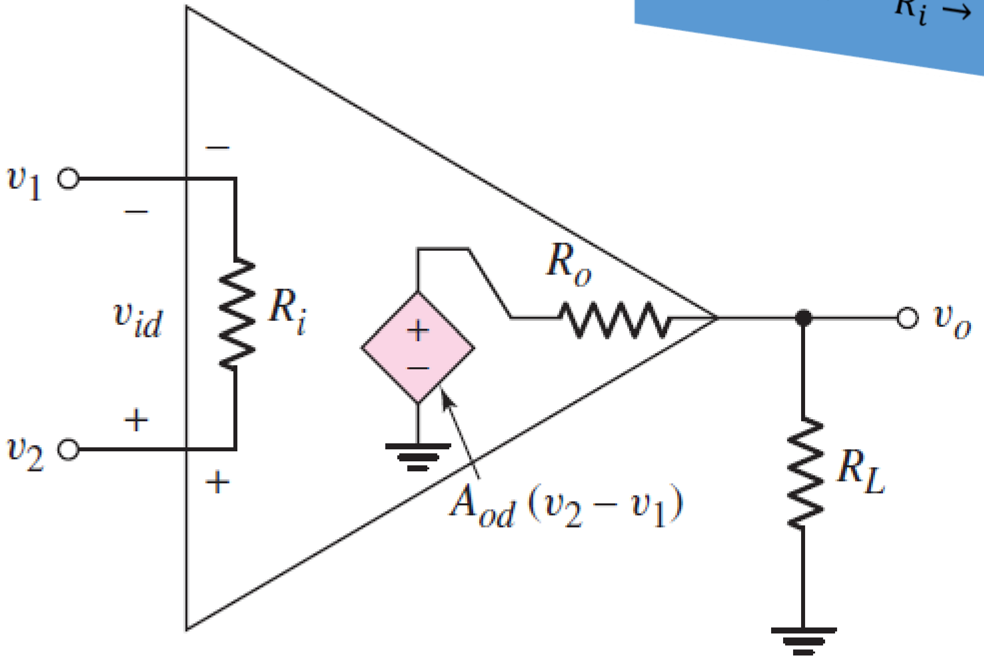


Figure 9.7(a)

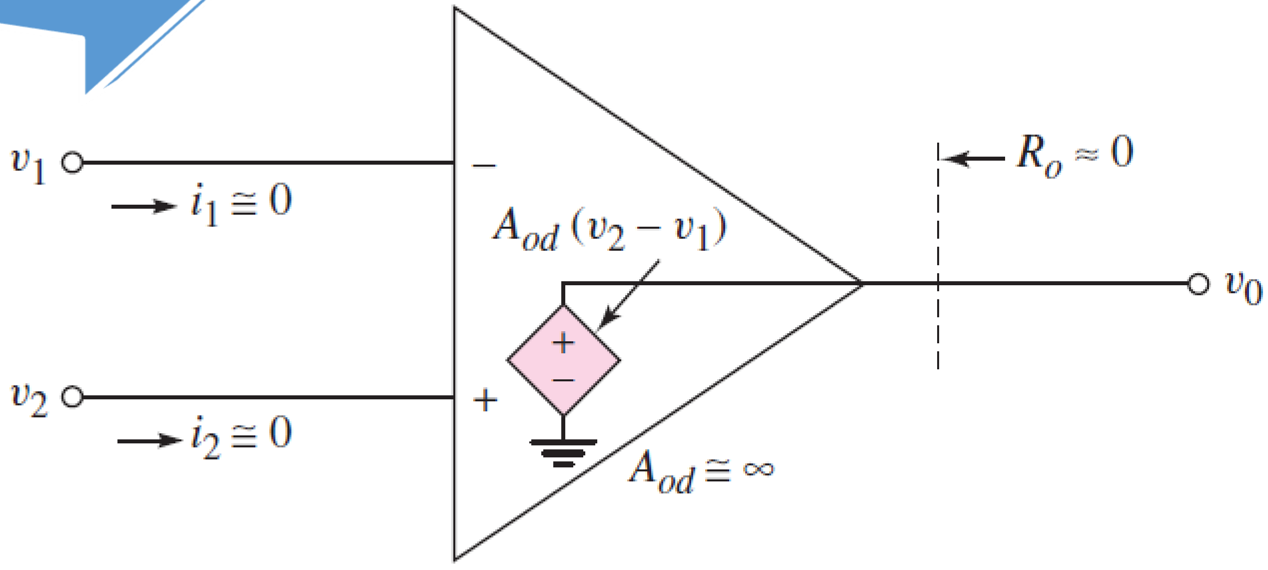


Figure 9.6

9.1.3 Analysis Method
Ideal op-amp characteristics

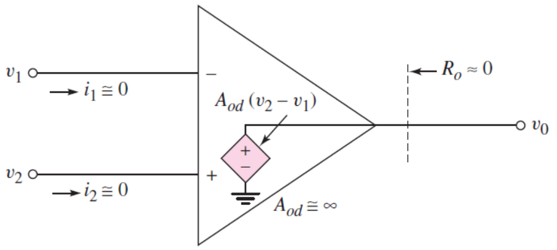


Figure 9.6

- The **ideal op-amp** characteristics resulting from our negative feedback analysis are shown in Figure 9.6 and summarized below.
  1. The internal differential gain A_{od} is considered to be $infinite$.
  2. The differential input voltage $(v_2 - v_1)$ is assumed to be $zero$.
  - If A_{od} is very large and if the output voltage v_O is $finite$, then the two input voltages must be nearly equal.

$$v_o = A_v(v_2 - v_1) \rightarrow (v_2 - v_1) = \frac{v_o}{A_v} \rightarrow (v_2 - v_1) = \frac{v_o}{\infty} = 0 \rightarrow \boxed{v_2 = v_1}$$

  3. The effective input resistance R_i to the op-amp is assumed to be $infinite$, so the two input currents, $\boxed{i_1 = i_2 = 0}$.
  4. The output resistance R_o is assumed to be $zero$, so the output voltage:
     1. is connected directly to the dependent voltage source, and
     2. is independent of any load connected to the output.

9.1.4 Practical Specifications

- Practical op-amps are not ideal.
  - Although their characteristics approach those of an ideal op-amp.
- Figure 9.7(a) is a more accurate equivalent circuit of an op-amp.
- A load resistance R_L is connected to the output terminal.
  - R_L may actually represent another op-amp circuit.

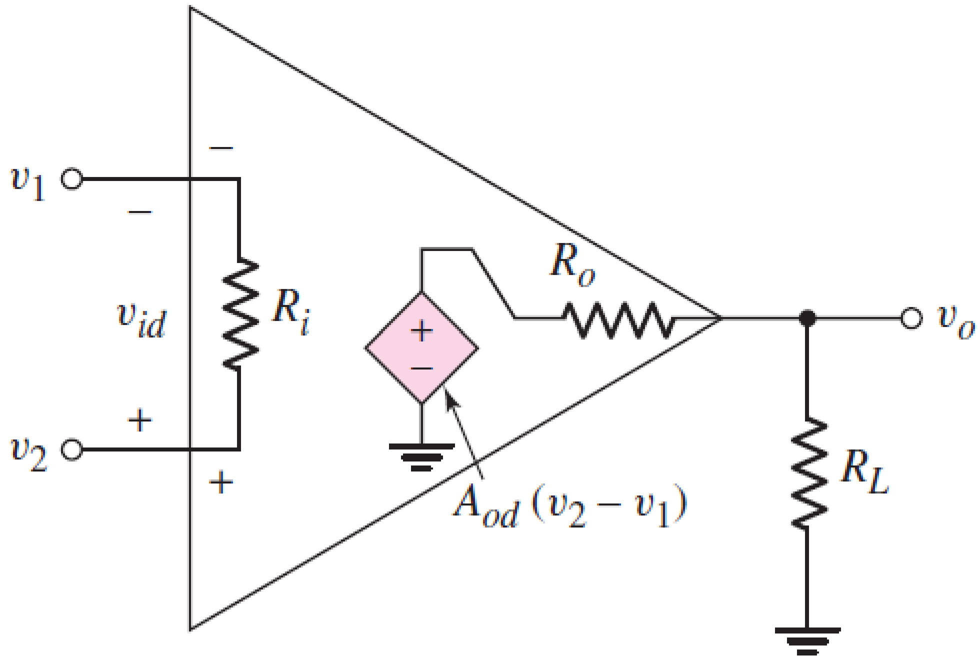


Figure 9.7(a)

9.1.4 Practical Specifications

Output Voltage Swing

- Since the op-amp is composed of transistors biased in the active region by the DC input voltages V^+ and V^-, the output voltage is limited.
  - When $v_O \to V^+$, it will saturate at a value nearly equal to V^+.
  - When $v_O \to V^-$, it will saturate at a value nearly equal to V^-.
  - v_O cannot go above the V^+ or below the V^-.
- The output voltage is limited to:

$$V^- + \Delta V < v_O < V^+ - \Delta V$$

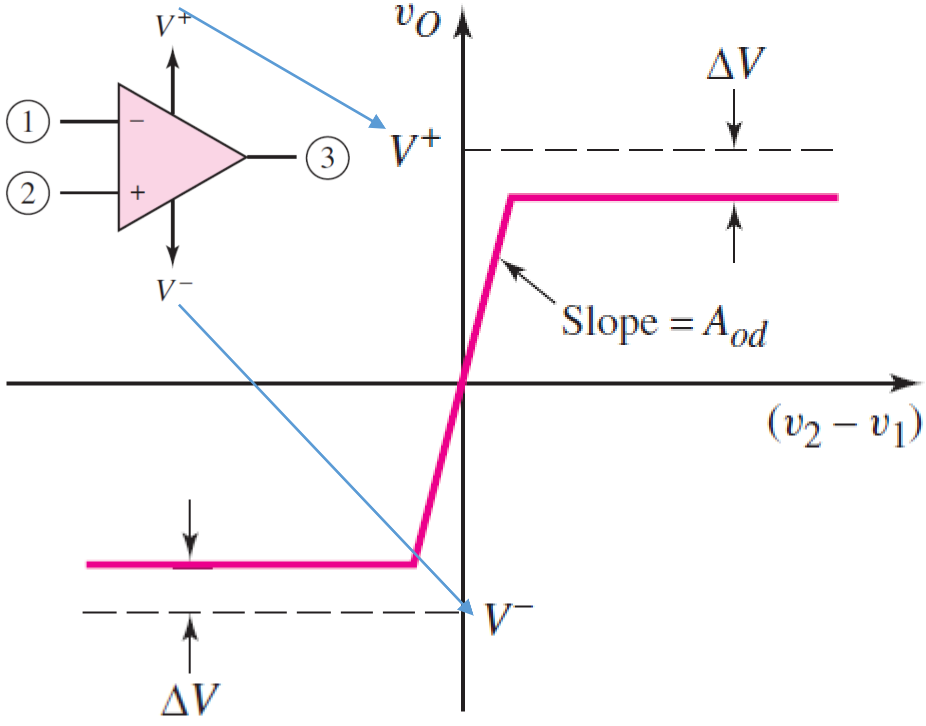


Figure 9.7(b)

9.1.4 Practical Specifications

Output Voltage Swing

- Figure 9.7(b) is a simplified voltage transfer characteristic for the op-amp, showing the saturation effect.
- In older op-amp designs, such as the 741, the value of ΔV is between 1 and $2V$.
    - Example: If $V^+ = 15V$ and $V^- = -15V$, let $\Delta V = 2V$ then:

$$-13 < v_O < 13$$

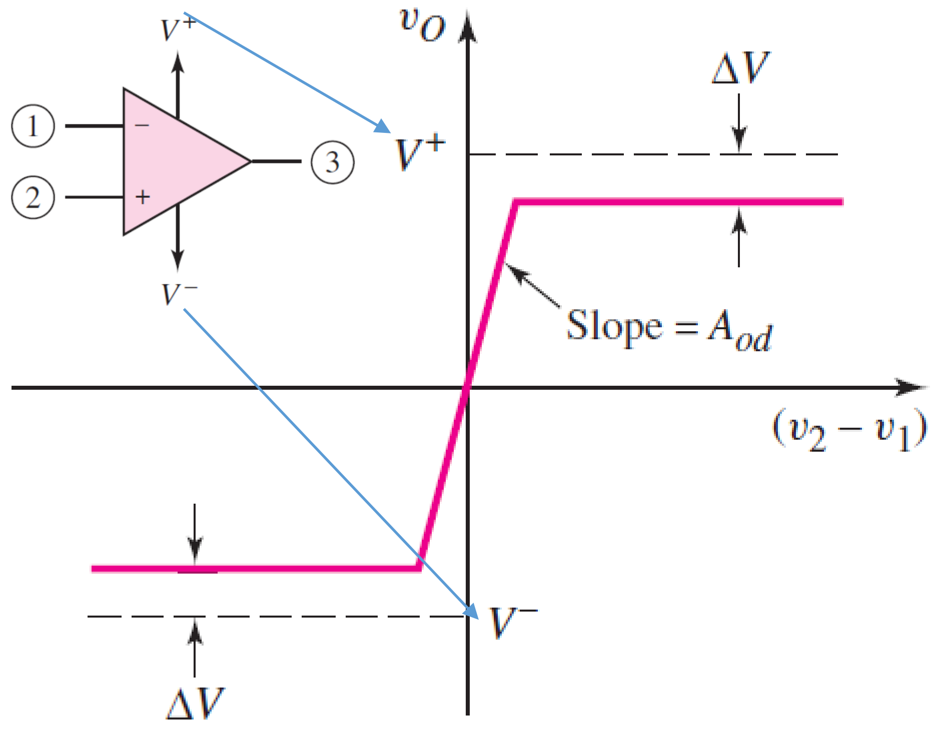


Figure 9.7(b)

9.1.4 Practical Specifications
Output Currents

- As we can see from Figure 9.7(a):
  - If the output voltage is positive, the load current is supplied by the output of the op-amp.
  - If the output voltage is negative, then the output of the op-amp sinks the load current.
- A limitation of practical op-amps is the maximum current that an op-amp can supply or sink.
- A typical value of the maximum current is on the order of $\pm 20mA$ for a general-purpose op-amp.

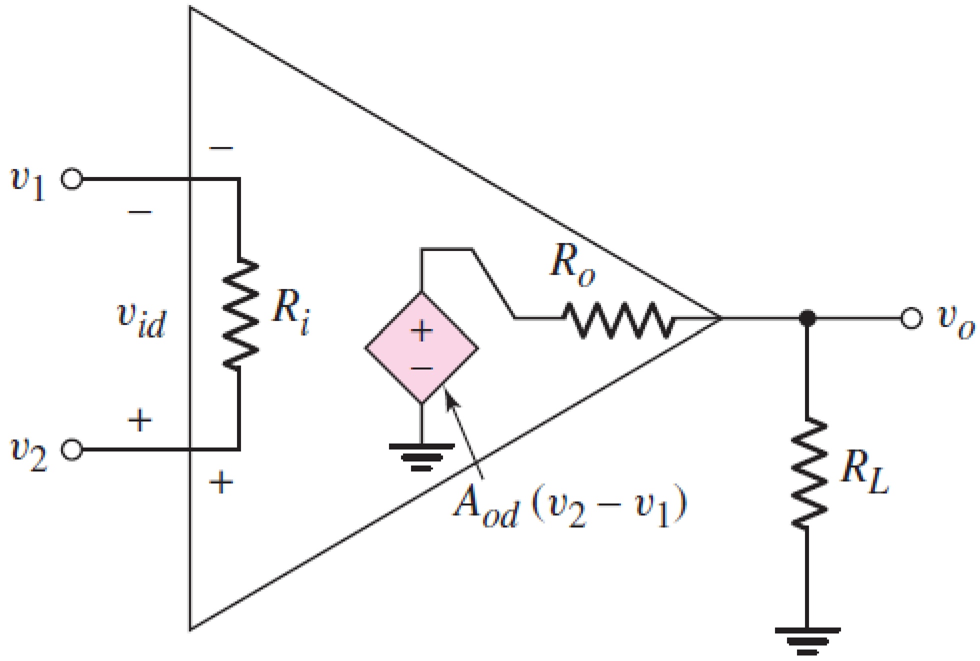
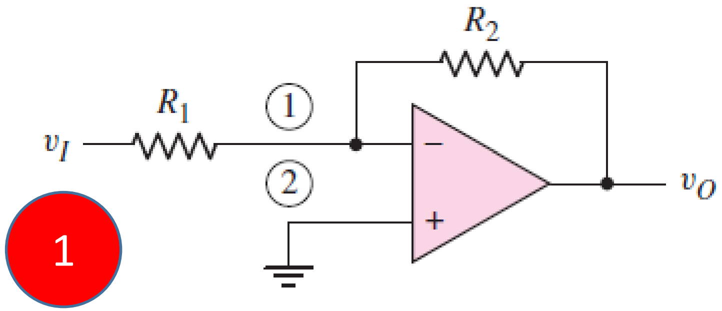
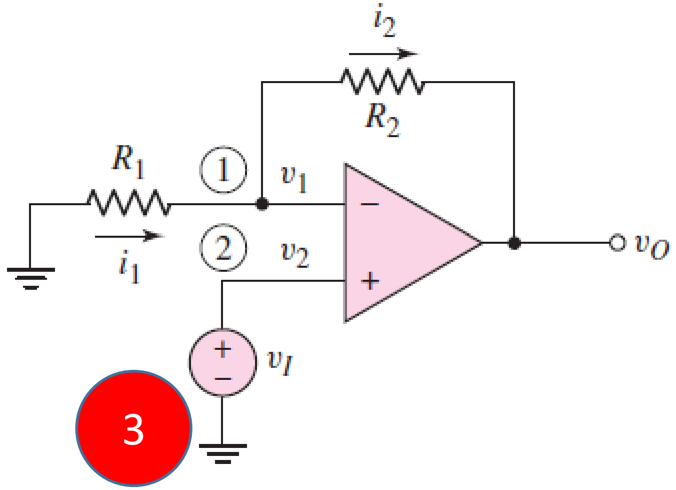


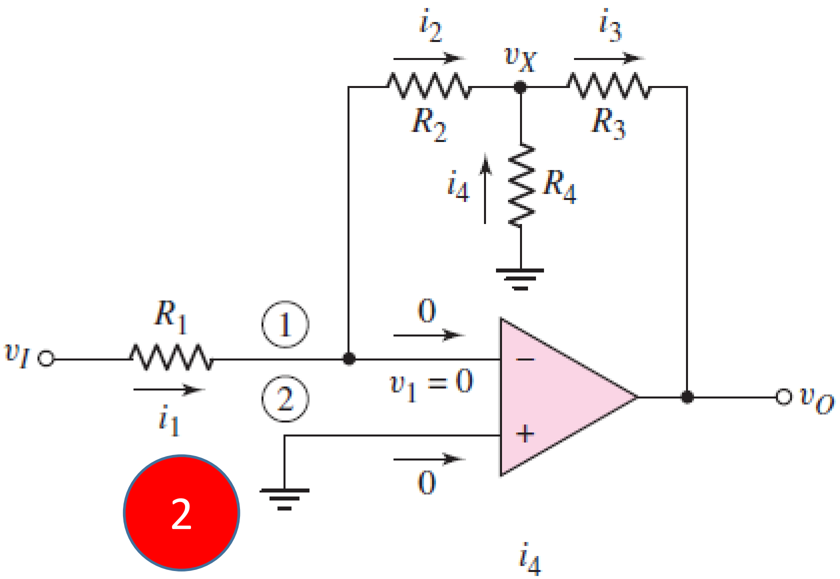
Figure 9.7(a)

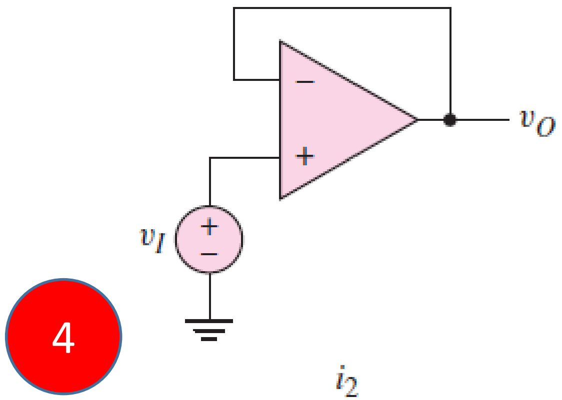
Op-Amp Applications

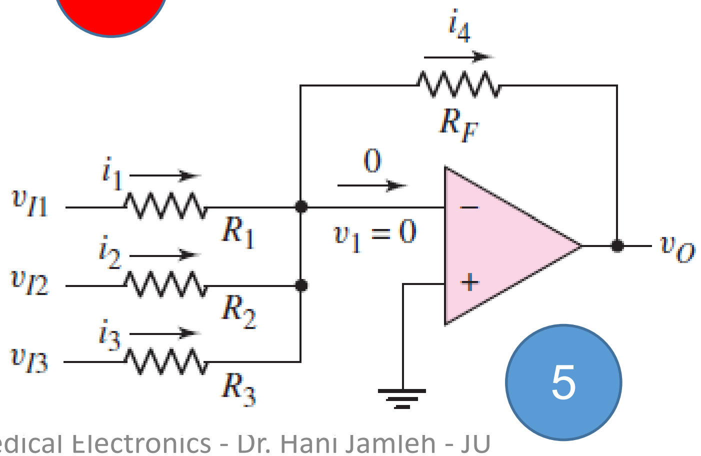
1. Inverting Amplifier
    2. Amplifier with T-Network
3. Non-Inverting Amplifier
    4. Voltage Follower (Buffer)
5. Summing Amplifier
6. Current to Voltage Converter

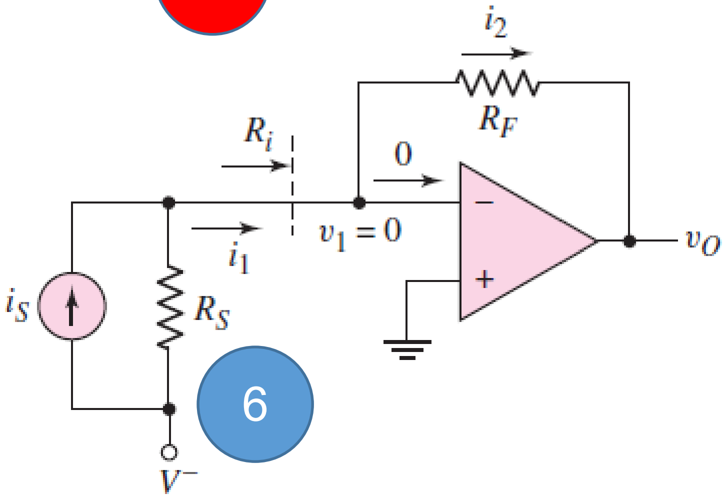






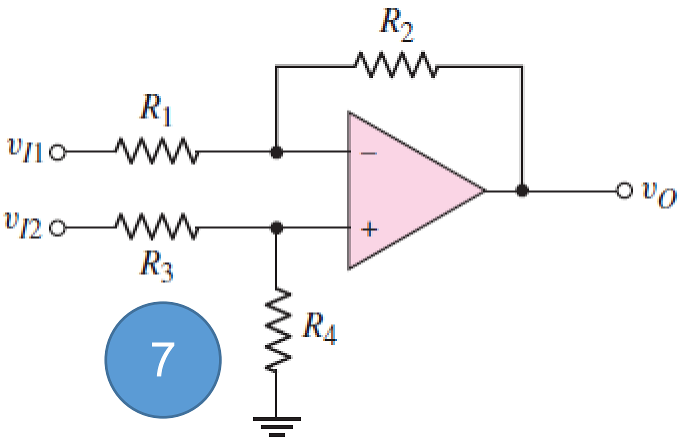


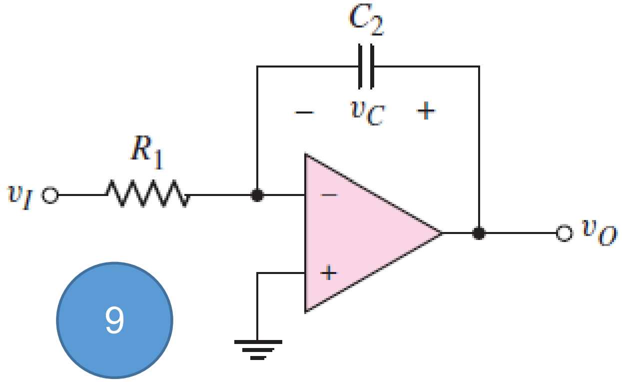


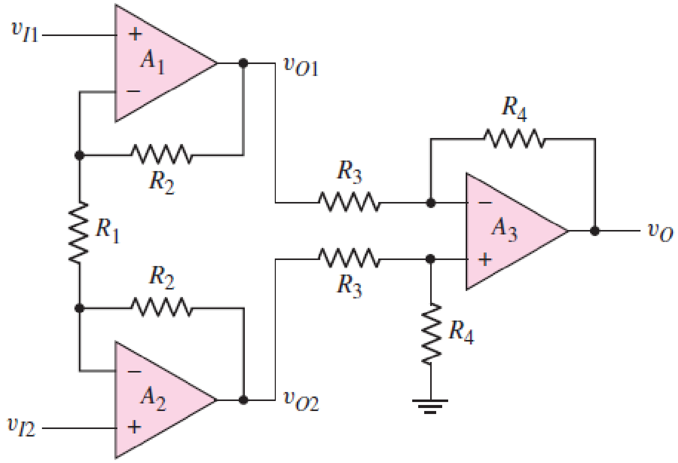


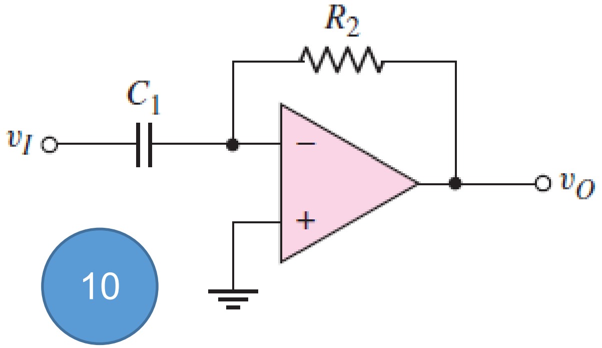
Op-Amp Applications

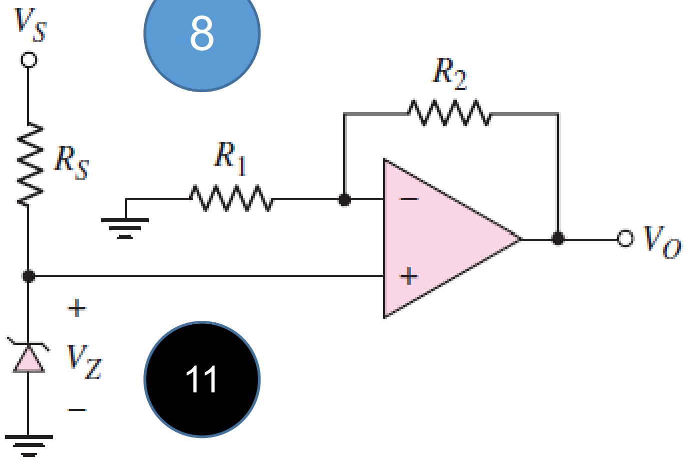
7. Difference Amplifier
8. **Instrumentation Amplifier**
9. Integrator
10. Differentiator
11. Reference Voltage Source Design
12. Precision Half-wave Rectifier

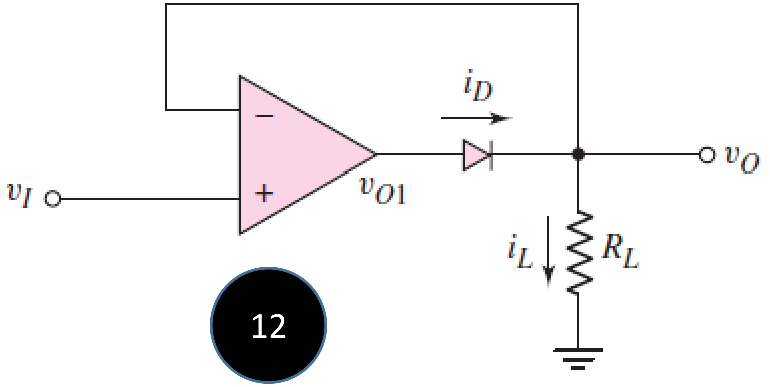












9.2 Inverting Amplifier

- One of the most widely used op-amp circuits is the **inverting amplifier.**
- Figure 9.8 shows the closed-loop configuration of this circuit.
- **Note**, we must keep in mind that:
  - The op-amp is biased with DC voltages as an active device.

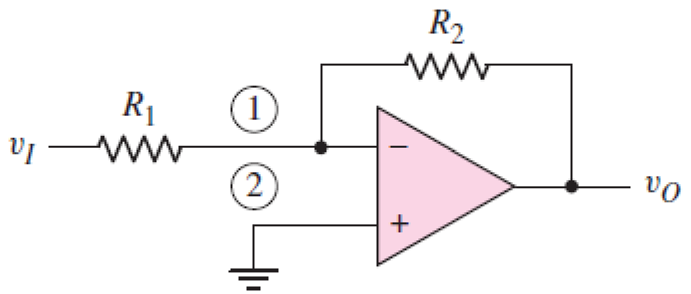


Figure 9.8

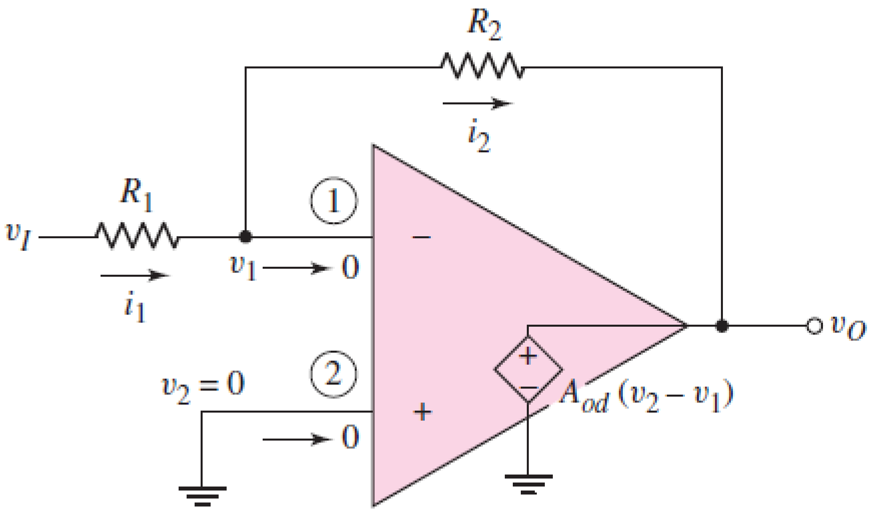


Figure 9.9

9.2.1 Basic Amplifier-Inverting Amplifier

- We analyze the circuit in Figure 9.8 by considering the ideal equivalent circuit shown in Figure 9.9.
- The **closed-loop voltage gain,** or simply the voltage gain, is defined as:

$$A_v = \frac{v_O}{v_I}$$

- We stated that if the open-loop gain A_{od} is very large, then the two inputs v_1 and v_2 must be nearly equal.
- ***Proof:***

$$v_O = A_{od}(v_2 - v_1)$$

$$\frac{v_O}{A_{od}} = (v_2 - v_1)$$

$$A_{od} \rightarrow \infty$$

$$v_2 = v_1$$

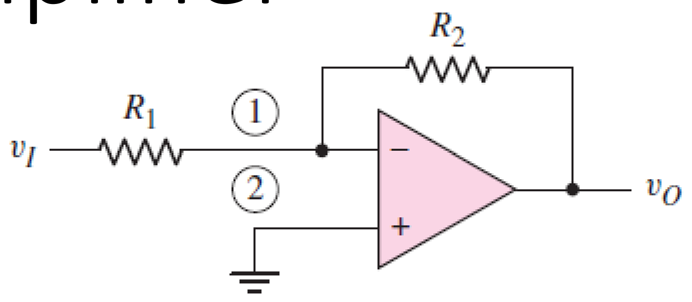


Figure 9.8

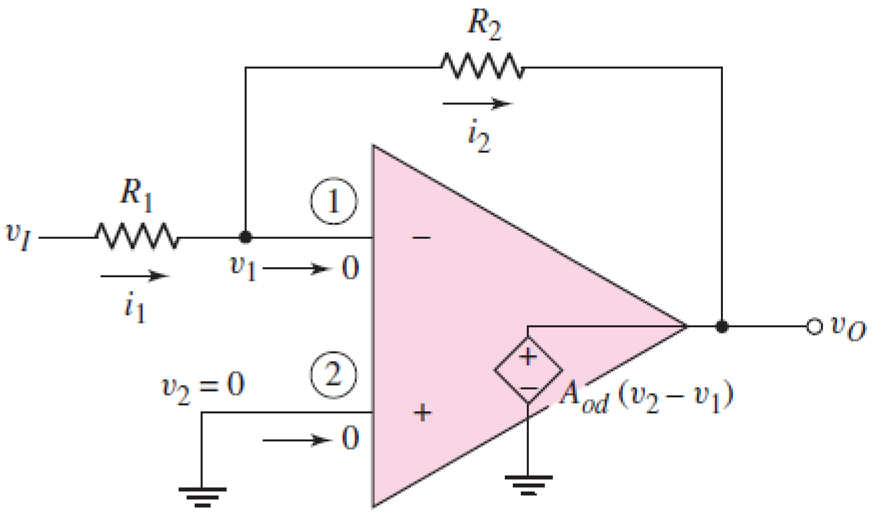


Figure 9.9

9.2.1 Basic Amplifier-Inverting Amplifier

$$v_2 = v_1$$

- Since v_2 is at ground potential, voltage v_1 must also be approximately $zero$ volts.
  - Having v_1 be essentially at ground potential does not imply that terminal (1) is grounded.
  - Terminal (1) is said to be at **virtual ground**:
    - It is essentially $zero$ volts, but it does not provide a current path to ground → means that terminal 1 is essentially at $zero$ volts, but is not connected to ground potential.

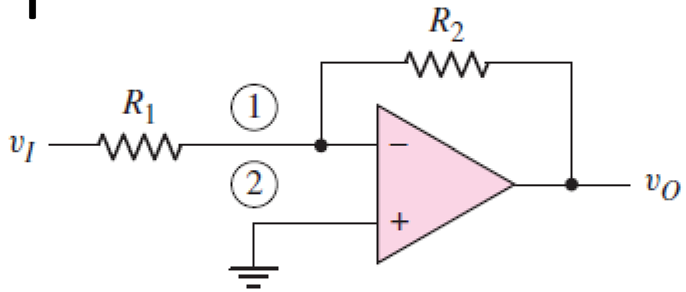


Figure 9.8

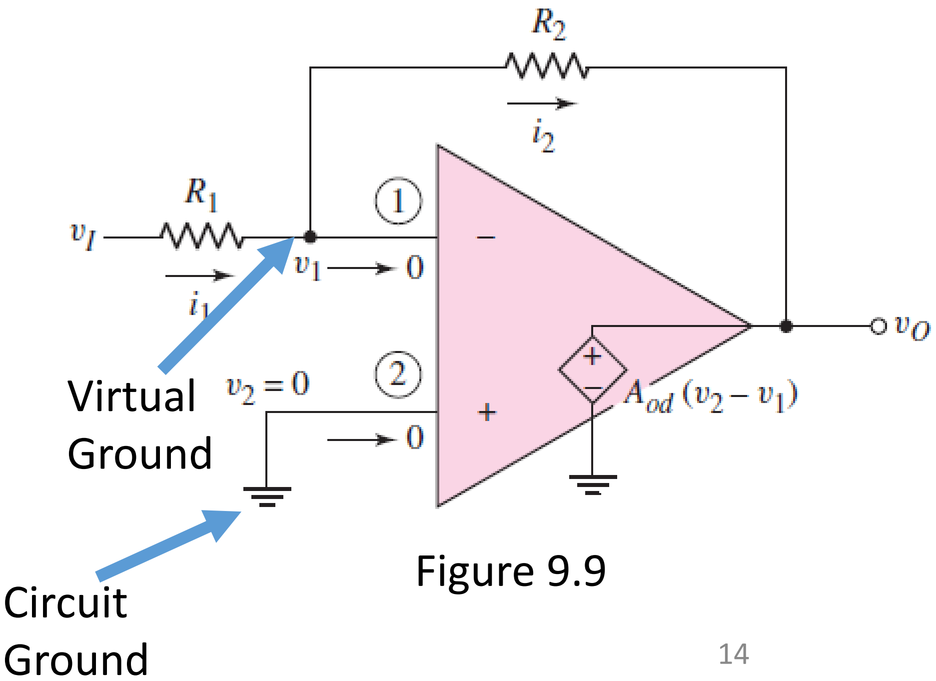


Figure 9.9

9.2.1 Basic Amplifier-Inverting Amplifier

- From Figure 9.9, we can write:

$$i_1 = \frac{v_I - v_1}{R_1} = \frac{v_I - 0}{R_1} = \frac{v_I}{R_1}$$

- Since the current into the op-amp is assumed to be *zero*, current i_1 must flow through resistor R_2 to the output terminal, which means that $i_2 = i_1$.
- The output voltage is given by (KVL):

$$v_O = v_1 - i_2 R_2 = 0 - \left(\frac{v_I}{R_1}\right) R_2$$

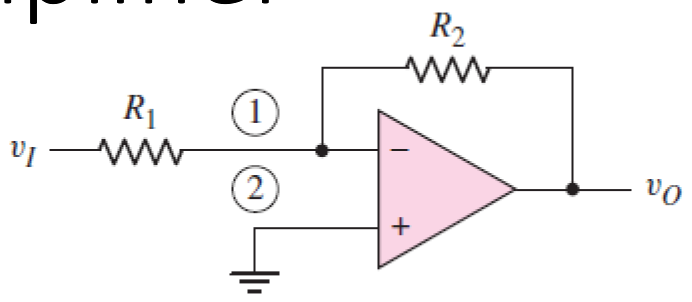


Figure 9.8

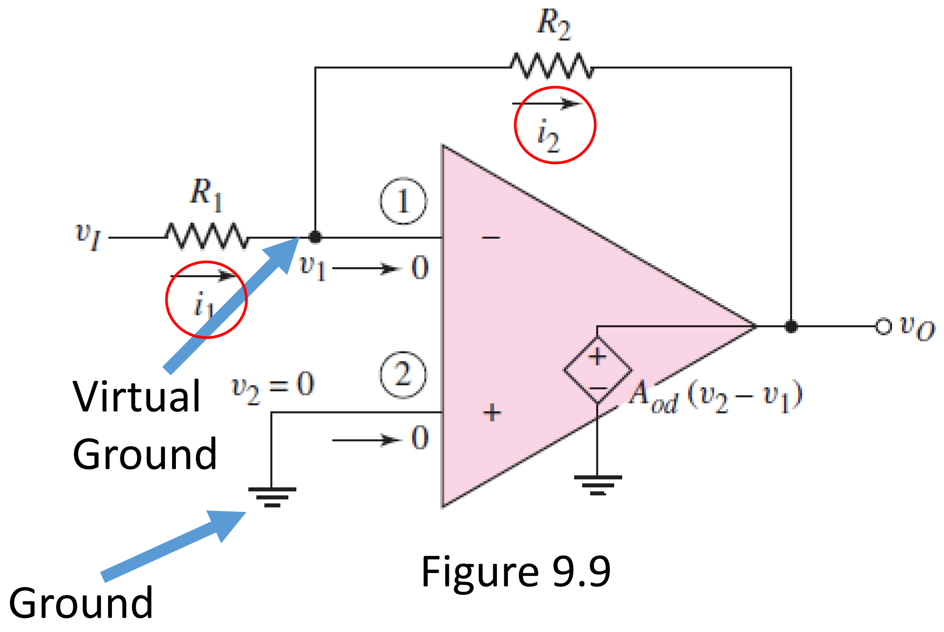


Figure 9.9

9.2.1 Basic Amplifier-Inverting Amplifier

$$v_O = v_1 - i_2 R_2 = 0 - \left(\frac{v_I}{R_1}\right) R_2$$

- Therefore, the closed-loop voltage gain is:

$$A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1}$$

- For the ideal op-amp, the closed-loop voltage gain A_v is a function of the ratio of two resistors;
    - **Note:** It is not a function of the transistor parameters within the op-amp circuit.
- The minus sign implies a phase reversal → 180^0 phase shift.

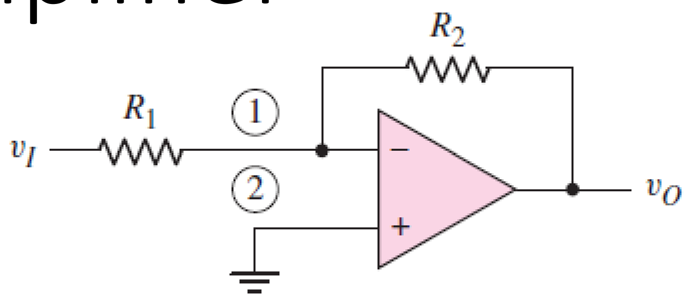


Figure 9.8

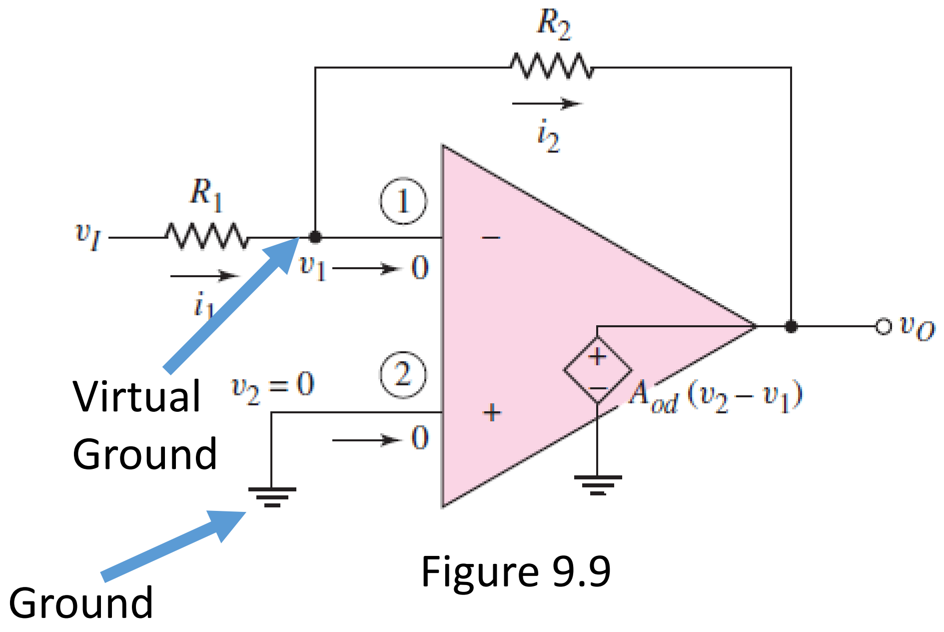


Figure 9.9

9.2.1 Basic Amplifier-Inverting Amplifier

- We can also determine the **input resistance** seen by the voltage source v_I.
- Because of the virtual ground, we have:

$$i_1 = \frac{v_I - v_1}{R_1} = \frac{v_I - 0}{R_1} = \frac{v_I}{R_1}$$

$$i_1 = \frac{v_I}{R_1}$$

- The **input resistance** is then defined as:

$$R_i = \frac{v_I}{i_1} = R_1$$

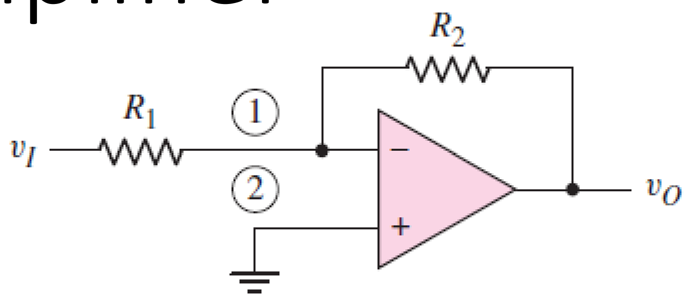


Figure 9.8

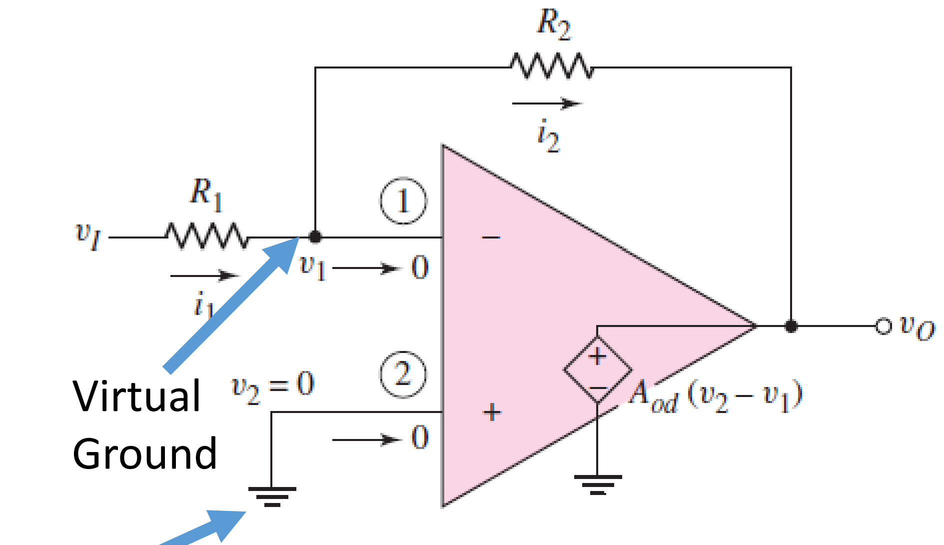


Figure 9.9

9.2.1 Basic Amplifier-Inverting Amplifier

$$R_i = \frac{v_I}{i_1} = R_1$$

- This shows that:
  - The input resistance seen by the source is a function of R_1 only, and is a result of the “virtual ground” concept.
- Figure 9.10 summarizes our analysis of the inverting amplifier circuit.
- Since there are no coupling capacitors in the op-amp circuit, the input and output voltages, as well as the currents in the resistors, can be DC signals.
  - The inverting op-amp can then amplify DC voltages.

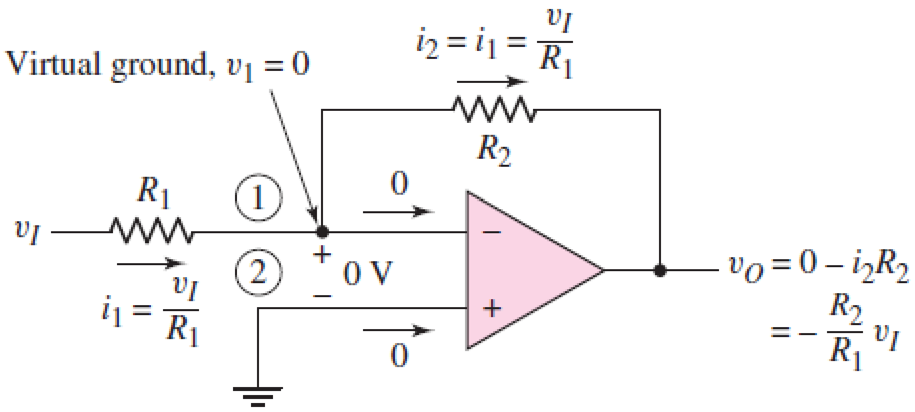


Figure 9.10

DESIGN EXAMPLE 9.1

- **Specifications**: The circuit configuration to be designed is shown in Figure 9.10.
- Design the circuit such that the voltage gain is $A_v = -5$.
- Assume the op-amp is driven by an ideal sinusoidal source:

$$v_s = 0.1\sin\omega t\ (V)$$

that can supply a maximum current of $5\mu A$.

- Note: Assume that frequency ω is low so that any frequency effects can be neglected.
- **Design Pointer**: If the sinusoidal input signal source has a nonzero output resistance, the op-amp must be redesigned to provide the specified voltage gain.

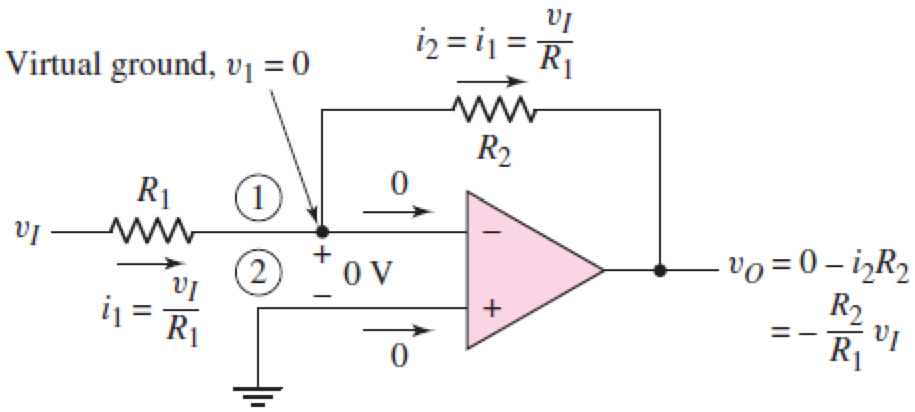


Figure 9.10

DESIGN EXAMPLE 9.1

- **Initial Solution**: The input current is given by:

$$i_1 = \frac{v_I}{R_1} = \frac{v_s}{R_1}$$

- If $i_1(\text{max}) = 5\ \mu A$, then we can write:

$$R_1 = \frac{v_s(\text{max})}{i_1(\text{max})} = \frac{0.1}{5 \times 10^{-6}} \Rightarrow\ 20\ k\Omega$$

- The closed-loop gain is given by:

$$A_v = -\frac{R_2}{R_1} = -5$$

- We then have:

$$R_2 = 5R_1 = 5(20k\Omega) = 100\ k\Omega$$

- **Comment**: The output resistance of the signal source R_s must be included in the design of the op-amp to provide a specified voltage gain.

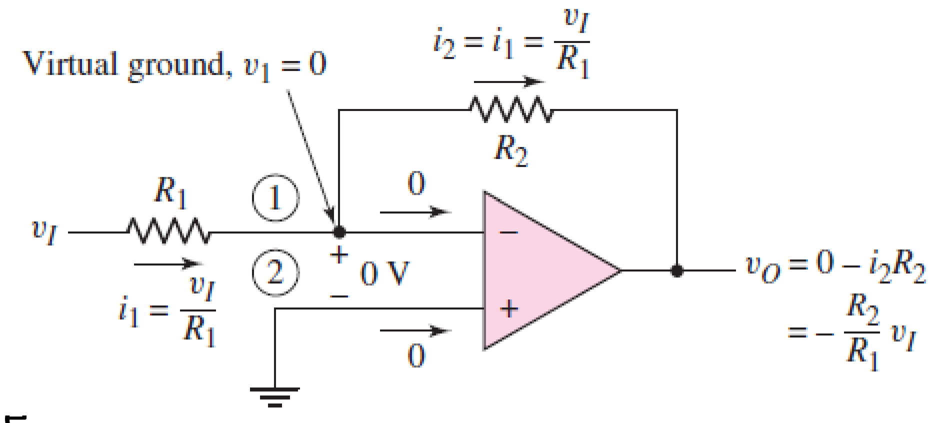


Figure 9.10

Problem-Solving Technique: Ideal Op-Amp Circuits

1. If the noninverting terminal of the op-amp is at ground potential, then the inverting terminal v_1 is at virtual ground.
   - Sum currents at this node, assuming $zero$ current enters the op-amp itself.
2. If the noninverting terminal of the op-amp is not at ground potential, then the inverting terminal voltage v_1 is equal to that at the noninverting terminal voltage v_2.
   - Sum currents at the inverting terminal node, assuming $zero$ current enters the op-amp itself.
3. For the ideal op-amp circuit, the output voltage is determined from either step 1 or step 2 above and is independent of any load connected to the output terminal.

9.2.2 Amplifier with a T-Network

- Assume that an inverting amplifier is to be designed having a closed-loop voltage gain of $A_v = -100$ and an input resistance of $R_i = R_1 = 50\ k\Omega$.
- The feedback resistor R_2 would then have to be $R_2 = |A_v| \cdot R_1 = 100 \cdot 50k\Omega = 5M!$
  - However this resistance value is too large for most practical circuits.
  - Practically, for IC design, always avoid resistance values larger than $50k\Omega$!
- What is the solution?

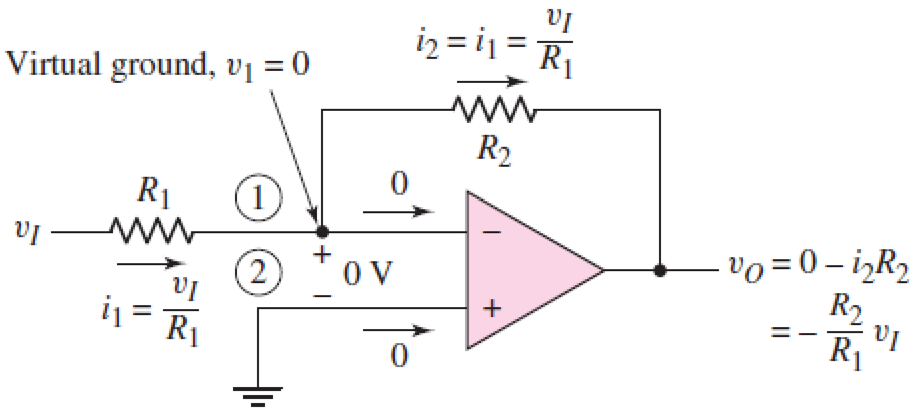


Figure 9.10

9.2.2 Amplifier with a T-Network

- Consider the op-amp circuit shown in Figure 9.12 with a T-network in the feedback loop.
- The analysis of this circuit is similar to that of the inverting op-amp circuit of Figure 9.10. At the input, we have:

$$i_1 = \frac{v_I}{R_1} = i_2$$

- We can also write that:

$$v_X = 0 - i_2 R_2 = -v_I \left(\frac{R_2}{R_1}\right)$$

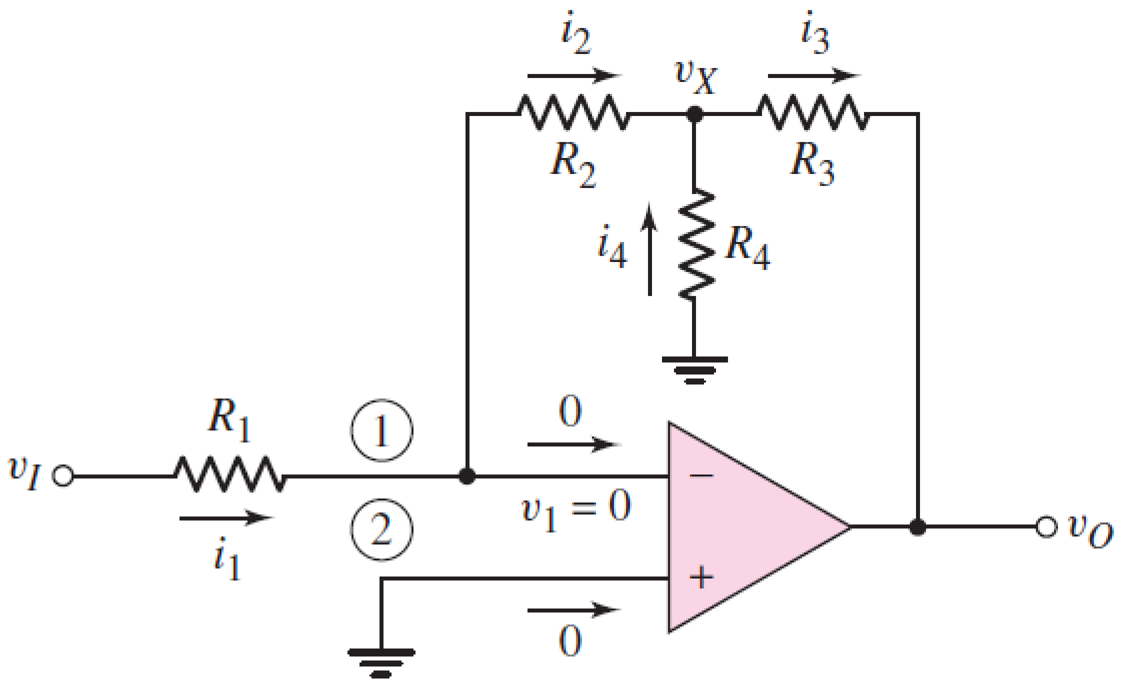


Figure 9.12

9.2.2 Amplifier with a T-Network

$$v_X = 0 - i_2 R_2 = -v_I \left(\frac{R_2}{R_1}\right)$$

- If we sum the currents at the node v_X, we have (i.e. KCL at node v_X):

$$i_2 + i_4 = i_3$$

- which can be written:

$$-\frac{v_X}{R_2} - \frac{v_X}{R_4} = \frac{v_X - v_O}{R_3}$$

$$v_X\left(\frac{1}{R_2} + \frac{1}{R_4} + \frac{1}{R_3}\right) = \frac{v_O}{R_3}$$

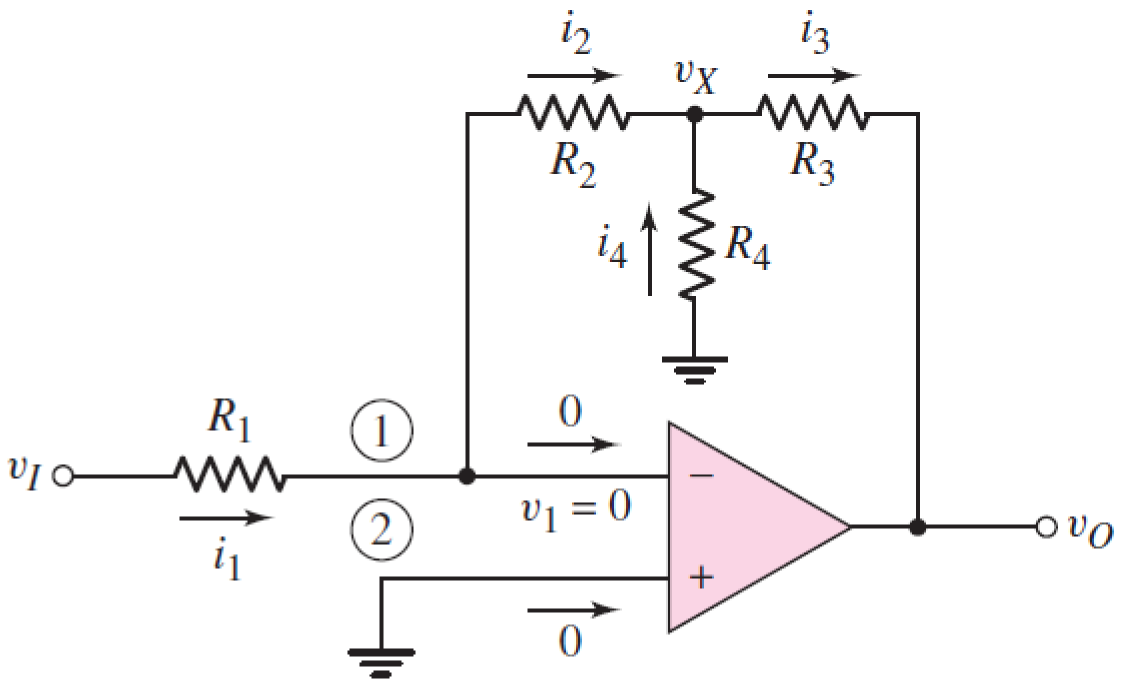


Figure 9.12

9.2.2 Amplifier with a T-Network

$$v_X = 0 - i_2 R_2 = -v_I\left(\frac{R_2}{R_1}\right)$$

$$v_X\left(\frac{1}{R_2} + \frac{1}{R_4} + \frac{1}{R_3}\right) = \frac{v_O}{R_3}$$

- Substituting the expression for v_X we obtain:

$$-v_I\left(\frac{R_2}{R_1}\right)\left(\frac{1}{R_2} + \frac{1}{R_4} + \frac{1}{R_3}\right) = \frac{v_O}{R_3}$$

- The closed-loop voltage gain is therefore:

$$A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4} + \frac{R_3}{R_2}\right)$$

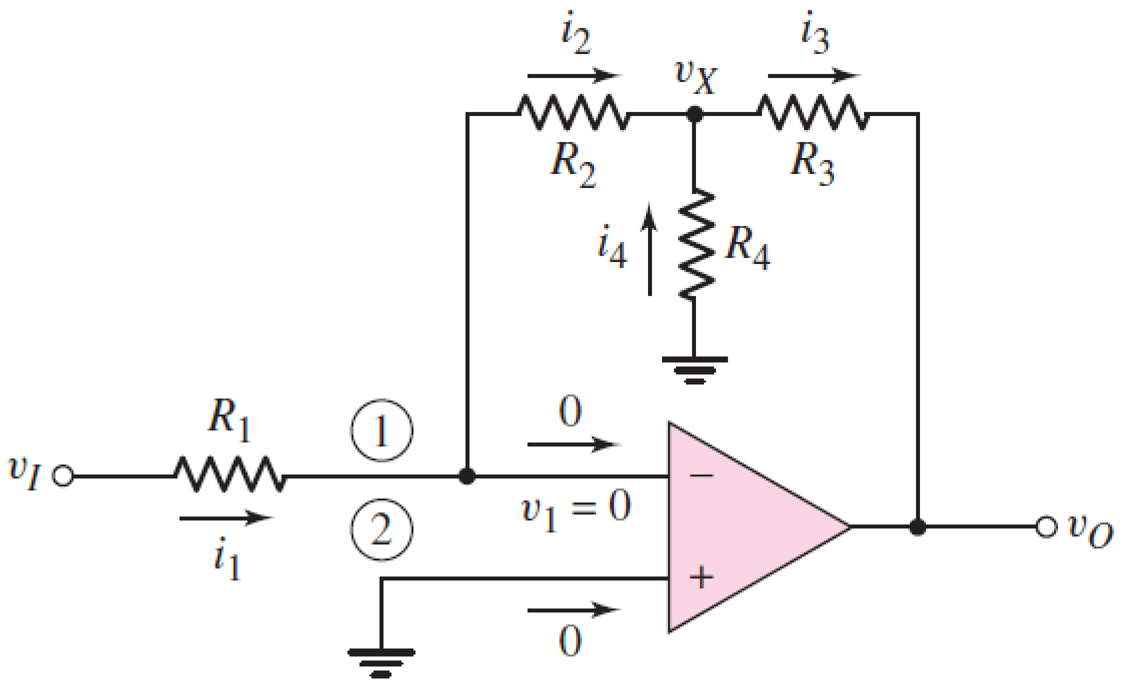


Figure 9.12

DESIGN EXAMPLE 9.2

- **Objective**: An op-amp with a T-network is to be designed as a microphone preamplifier.
- **Specifications**: The circuit configuration to be designed is shown in Figure 9.12.
- The maximum microphone output voltage is $12mV\ (rms)$ and the microphone has an output resistance of $R_S = 1k\Omega$.
- The op-amp circuit is to be designed such that the maximum output voltage is $1.2V\ (rms)$.
- The input amplifier resistance should be fairly large, but all resistance values should be less that $500k\Omega$.

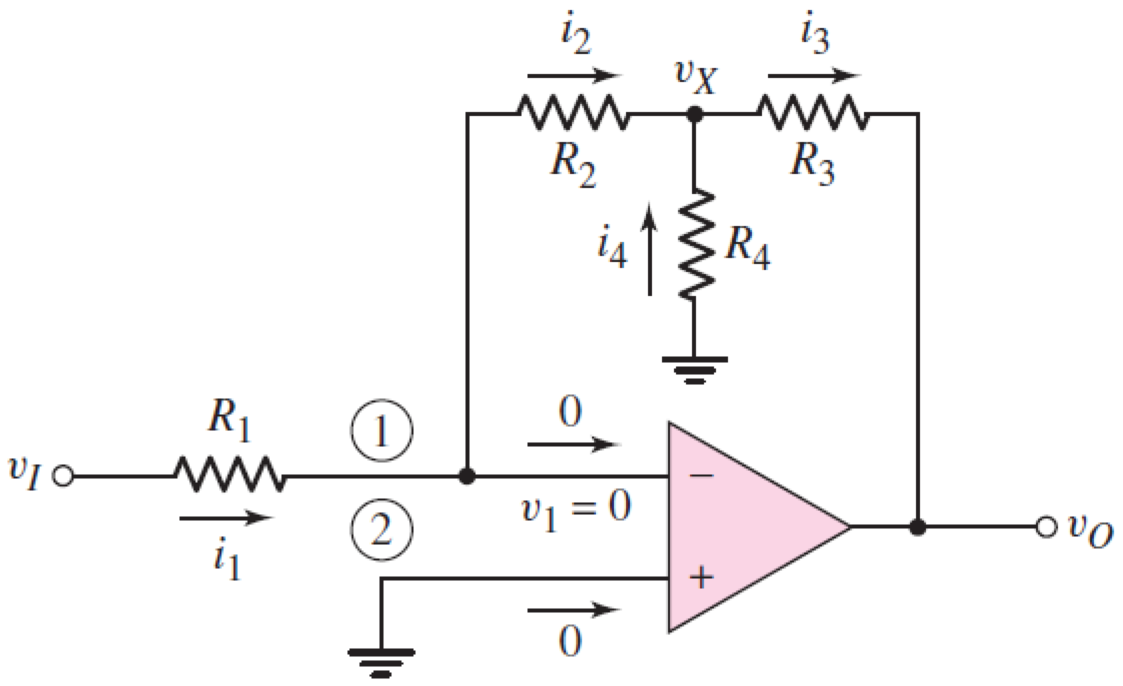


Figure 9.12

DESIGN EXAMPLE 9.2

- **Choices**:
  - The final design should use standard resistor values.
  - Standard resistors with tolerances of $\pm 2\ percent$ are to be considered.
- **Solution**: We need a voltage gain of
  $$|A_v| = 1.2/0.012 = 100$$
- The gain Equation for such a circuit can be written in the form:

$$A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4} + \frac{R_3}{R_2}\right)$$
$$= -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4}\right) - \frac{R_3}{R_1}$$

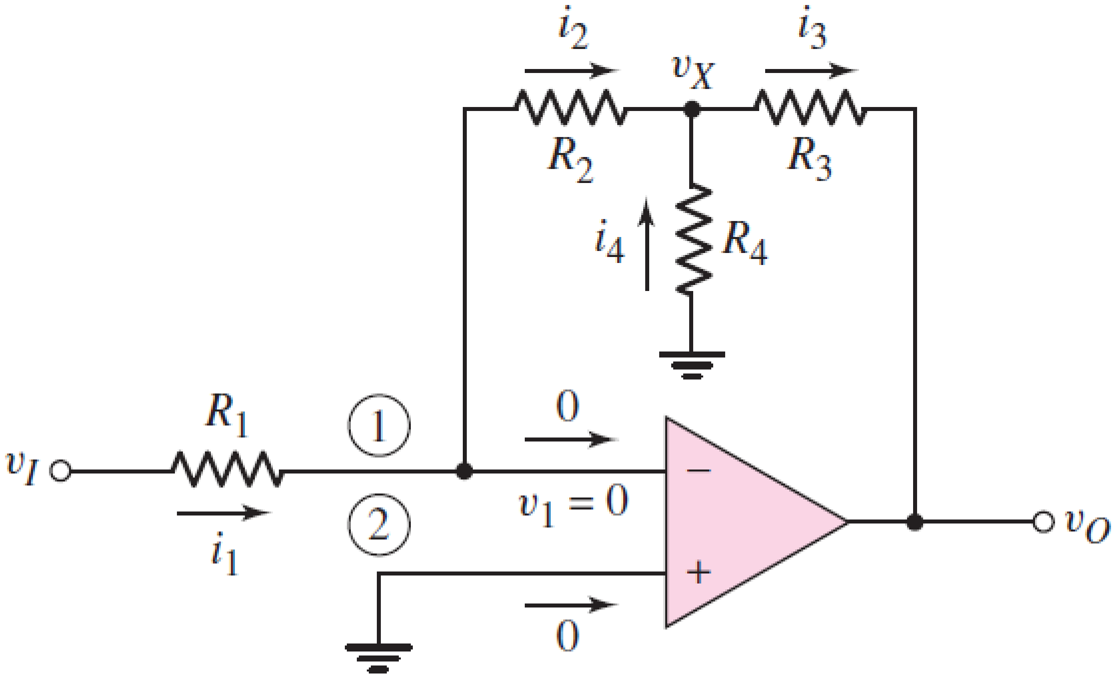


Figure 9.12

DESIGN EXAMPLE 9.2

$$A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1}\left(1 + \frac{R_3}{R_4}\right) - \frac{R_3}{R_1}$$

- As a designer, we arbitrarily choose:

$$R_2/R_1 = R_3/R_1 = 8$$

- Then:

$$-100 = -8(1 + \frac{R_3}{R_4}) - 8$$

- Which yields:

$$\frac{R_3}{R_4} = 10.5$$

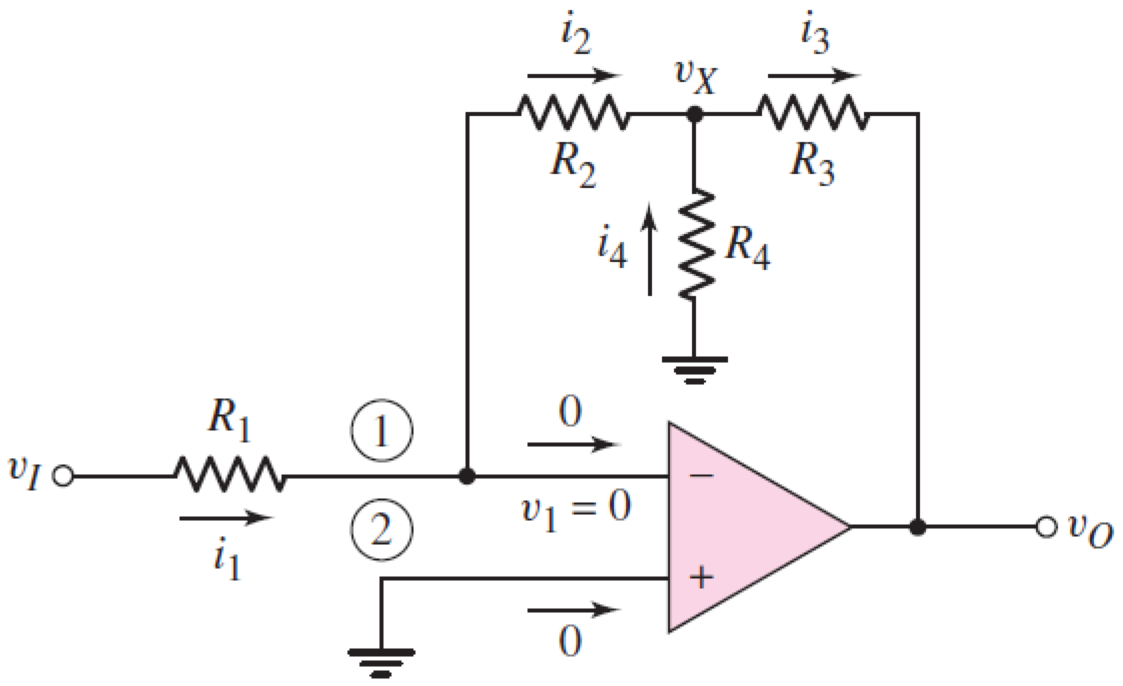


Figure 9.12

DESIGN EXAMPLE 9.2

- The effective R_1' must include the R_S resistance of the microphone.
- If we set $R_1 = 49\ k\Omega$ so that $R_1' = 50k\Omega$, then:

$$R_2 = R_3 = 400\ k\Omega$$

and:

$$R_4 = \frac{R_3}{10.5} = \frac{400k}{10.5} = 38.1k\Omega$$

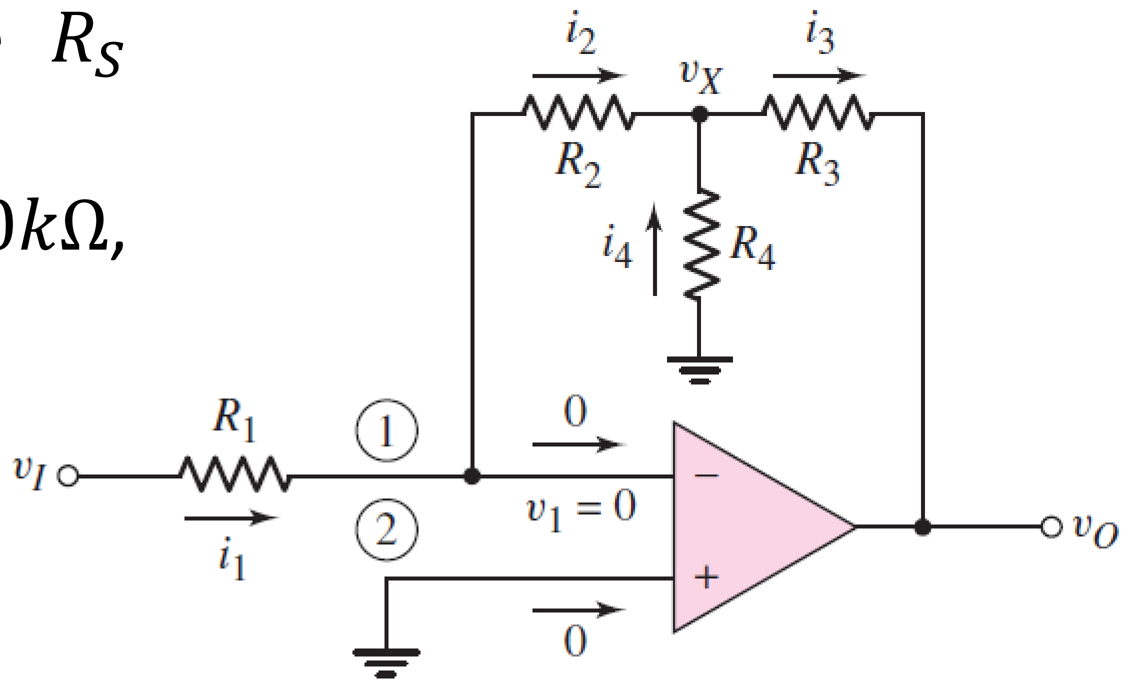


Figure 9.12

Choosing Standard Resistor Values (Appendix C)

Resistor	Calculated Value	Nearest Standard Value
R_1	$49\ k\Omega$	$51\ k\Omega$
R_2	$400\ k\Omega$	$390\ k\Omega$
R_3	$400\ k\Omega$	$390\ k\Omega$
R_4	$38.1\ k\Omega$	?

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**

DESIGN EXAMPLE 9.2

- **Design Pointer:** If we need to use standard resistance values in our design, then, using Appendix C, we can choose $R_1 = 51\ k\Omega$ so that $R_1' = 52k\Omega$, and we can choose $R_2 = R_3 = 390\ k\Omega$. Then, after recalculating for R_4 we have:

$$-100 = -\frac{R_2}{R_1'}\left(1 + \frac{R_3}{R_4}\right) - \frac{R_3}{R_1'}$$

$$-100 = -\frac{390k}{52k}\left(1 + \frac{390k}{R_4}\right) - \frac{390k}{52k}$$

- which yields $R_4 = 34.4\ k\Omega$. We may use a standard resistor of $R_4 = 33\ k\Omega$.
- This resistance value then produces a voltage gain of:

$$A_v = -\frac{R_2}{R_1'}\left(1 + \frac{R_3}{R_4}\right) - \frac{R_3}{R_1'} = -\frac{390}{52}\left(1 + \frac{390}{33}\right) - \frac{390}{52} = -103.6$$

DESIGN EXAMPLE 9.2

- **Trade-offs**: If we consider $\pm 2\,percent$ tolerances in the standard resistor values, the A_v can be written as:

$$A_v = -\frac{R_2(1 \pm 0.02)}{1k + R_1(1 \pm 0.02)}\left[1 + \frac{R_3(1 \pm 0.02)}{R_4(1 \pm 0.02)}\right] - \frac{R_3(1 \pm 0.02)}{1k + R_1(1 \pm 0.02)}$$

$$= -\frac{390k(1 \pm 0.02)}{1k + 51k(1 \pm 0.02)}\left[1 + \frac{390k(1 \pm 0.02)}{33k(1 \pm 0.02)}\right] - \frac{390k(1 \pm 0.02)}{1k + 51k(1 \pm 0.02)}$$

- Analyzing this equation, we find:
  - The maximum magnitude as $|A_v|_{\max} = 111.6$ or $+7.72\,percent$, and
  - The minimum magnitude as $|A_v|_{\min} = 96.3$ or $-7.05\,percent$.

DESIGN EXAMPLE 9.2

- **Comments**:
  1. All resistor values are less than $500\ k\Omega$.
  2. The resistance ratios in the voltage gain expression are approximately equal.
- As with most design problems, there is no unique solution.
- We must keep in mind that:
  - Because of resistor value tolerances, the actual gain of the amplifier will have a range of values.
- The amplifier with a T-network allows us to obtain a large gain using reasonably sized resistors.

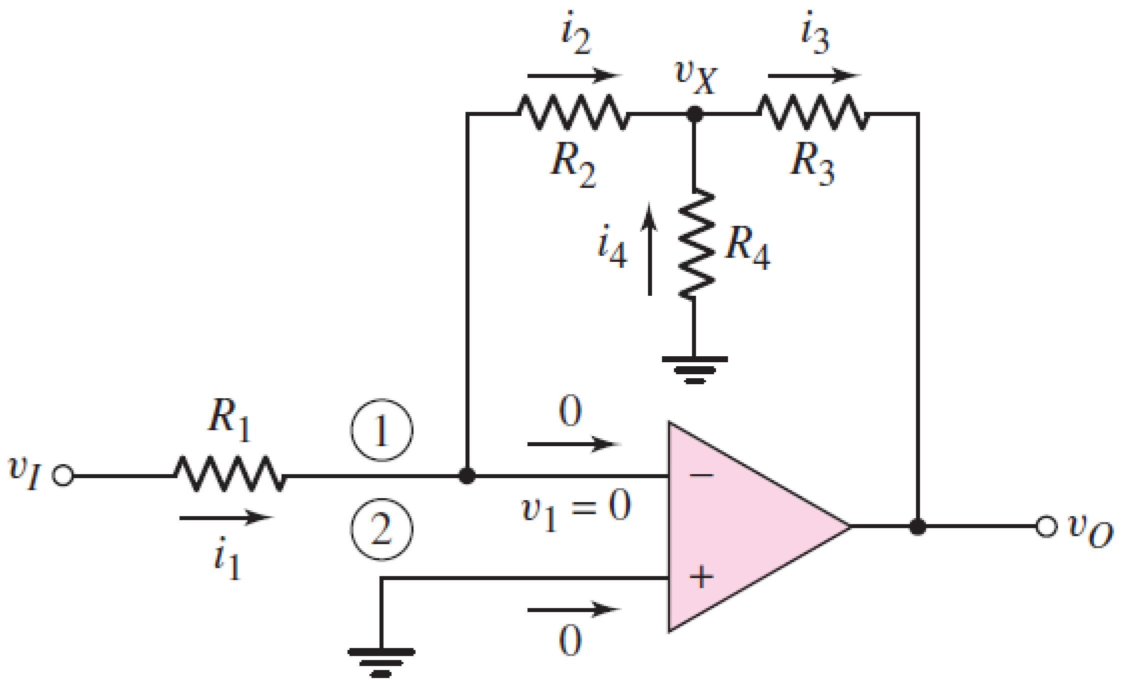


Figure 9.12

9.4.1 Basic Amplifier-Noninverting Amplifier

- Figure 9.15 shows the basic **noninverting amplifier.**
- The input signal v_I is applied directly to the noninverting terminal, while:
  - One side of resistor R_1 is connected to the inverting terminal and
  - The other side is at ground.

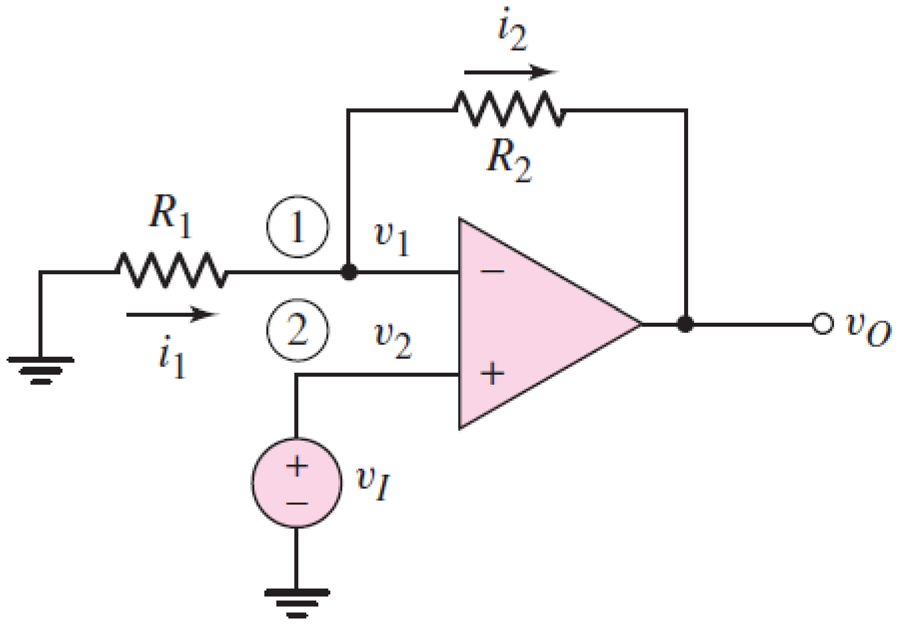


Figure 9.15

9.4.1 Basic Amplifier-Noninverting Amplifier

- The analysis of the noninverting amplifier is essentially the same as for the inverting amplifier.
- We assume that no current enters the input terminals.
- Since $v_1 = v_2$, then $v_1 = v_I$, and current i_1 is given by:

$$i_1 = -\frac{v_1}{R_1} = -\frac{v_I}{R_1}$$

- Current i_2 is given by:

$$i_2 = \frac{v_1 - v_O}{R_2} = \frac{v_2 - v_O}{R_2} = \frac{v_I - v_O}{R_2}$$

- As before, $i_1 = i_2$, so that:

$$-\frac{v_I}{R_1} = \frac{v_I - v_O}{R_2}$$

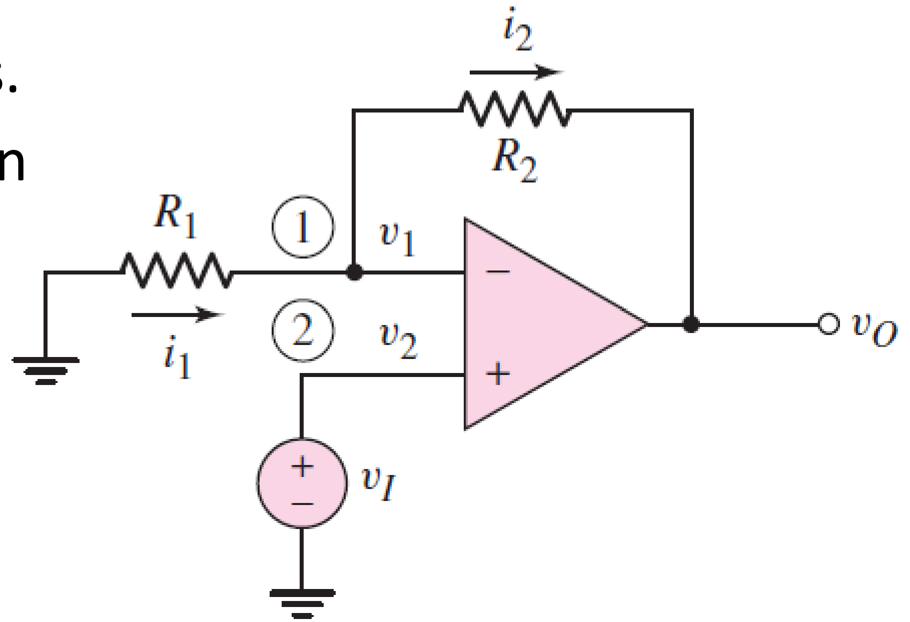


Figure 9.15

9.4.1 Basic Amplifier-Noninverting Amplifier

$$-\frac{v_I}{R_1} = \frac{v_I - v_O}{R_2}$$

- Solving for the closed-loop voltage gain, we find:

$$A_v = \frac{v_O}{v_I} = 1 + \frac{R_2}{R_1}$$

- From this equation, note that:
    1. The output is in phase with the input, as expected (i.e. it is a non-inverting amplifier).
    2. The gain is always greater than unity (i.e $A_v > 1$).

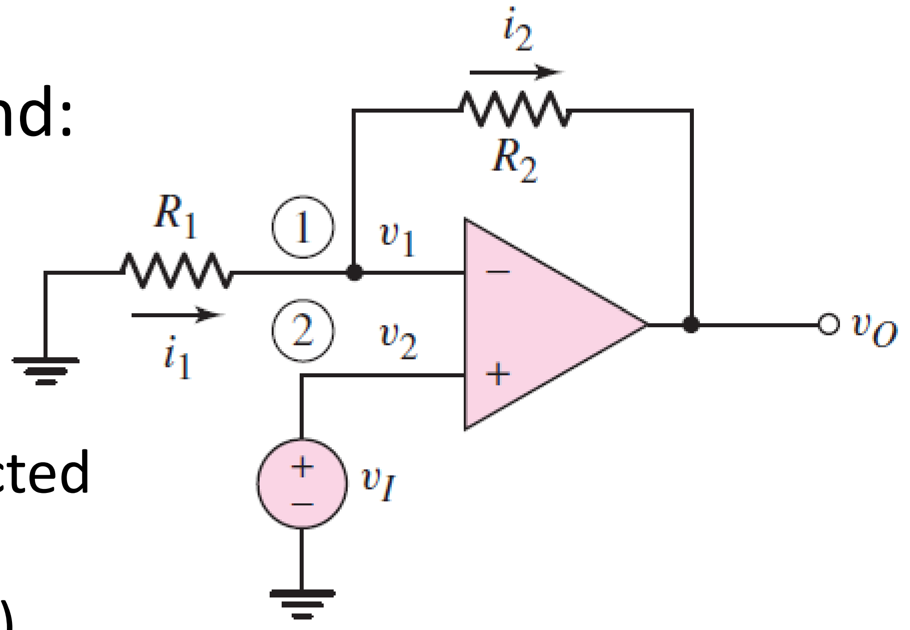
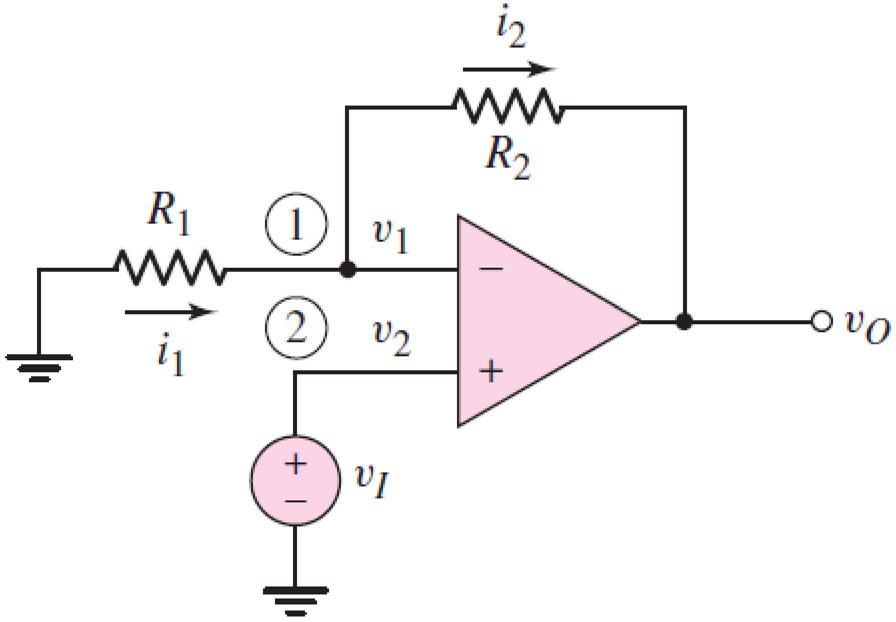


Figure 9.15

9.4.1 Basic Amplifier-Noninverting Amplifier

- The input signal v_I is connected directly to the noninverting terminal; therefore, since the input current is essentially $zero$, the input impedance R_i seen by the source is very large, ideally infinite.
- The ideal equivalent circuit of the noninverting op-amp is shown in Figure 9.16.



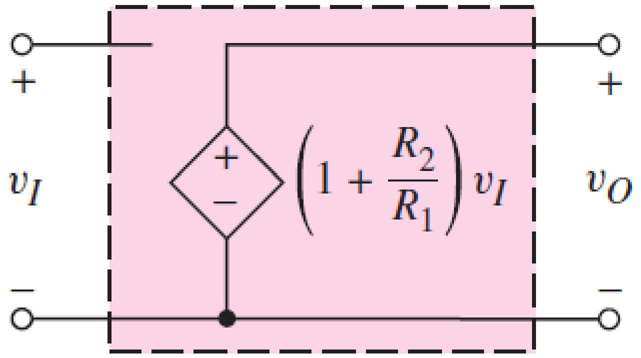


Figure 9.16

9.4.2 Voltage Follower-Noninverting Amplifier

$$A_v = \frac{v_O}{v_I} = 1 + \frac{R_2}{R_1}$$

- An interesting property of the noninverting op-amp occurs when:
  - $R_1 = \infty$, an open circuit, and
  - $R_2 = 0$, a short circuit.
- The closed-loop gain then becomes:

$$A_v = \frac{v_O}{v_I} = 1 + \frac{R_2}{R_1} = 1 + \frac{0}{\infty} = 1$$

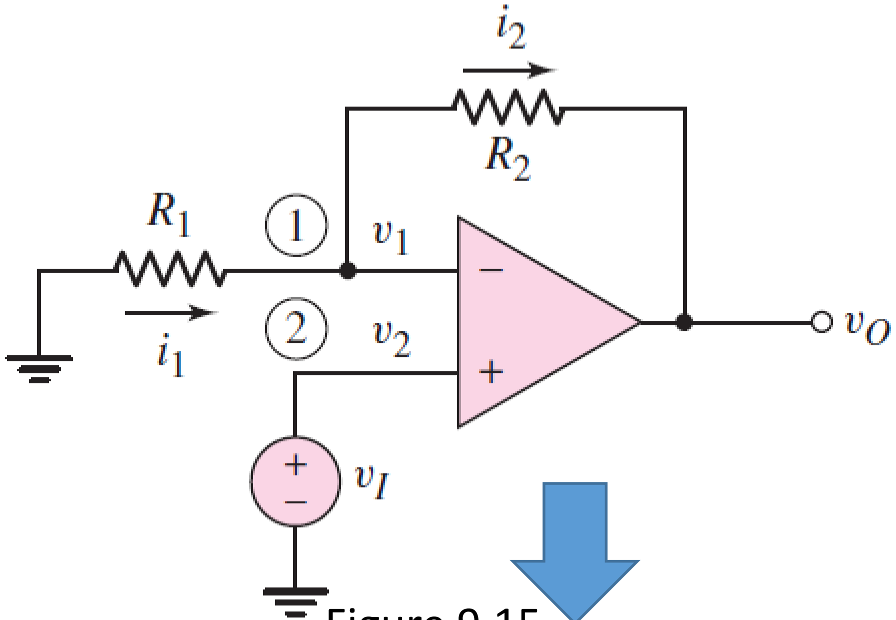


Figure 9.15

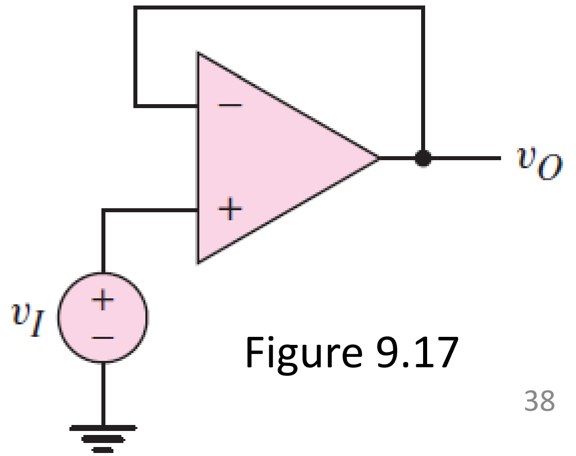


Figure 9.17

9.4.2 Voltage Follower-Noninverting Amplifier

$$A_v = \frac{v_O}{v_I} = 1 + \frac{R_2}{R_1} = 1 + \frac{0}{\infty} = 1$$

$$v_O = v_I$$

- Since the output voltage follows the input, this op-amp circuit is called a **voltage follower**.
- The closed-loop gain is independent of resistor R_2 (except when $R_2 = \infty$),
- So we can set $R_2 = 0\Omega$ to create a short circuit.

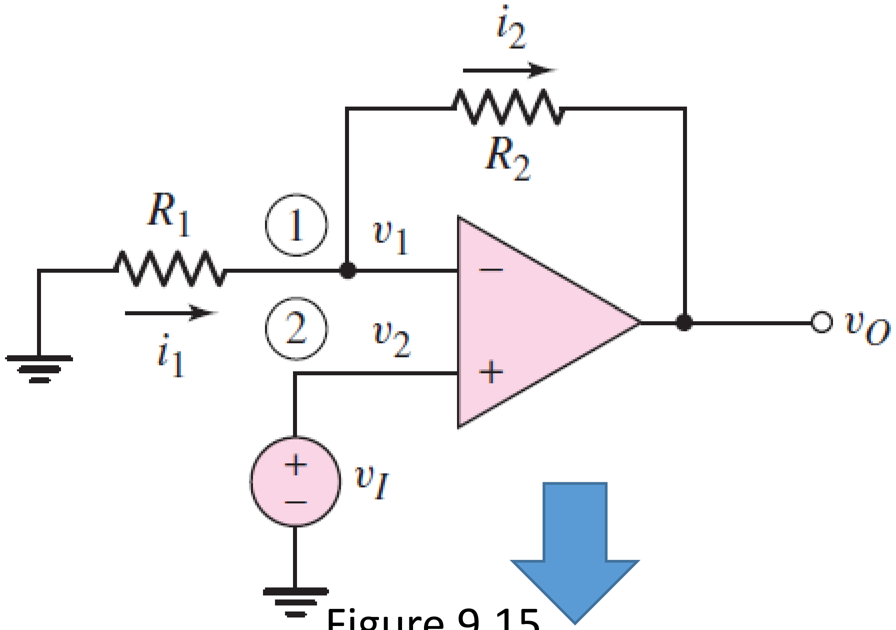


Figure 9.15

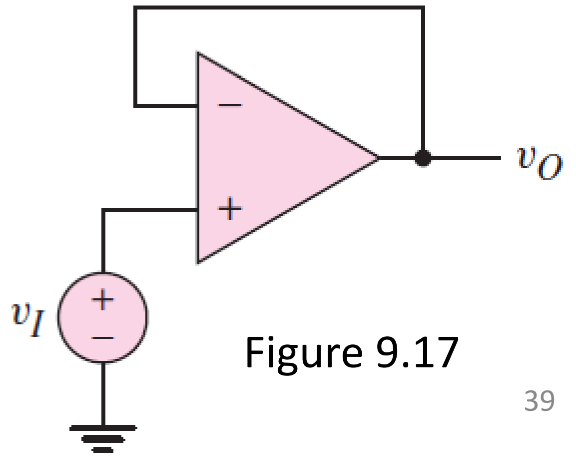


Figure 9.17

9.4.2 Voltage Follower-Noninverting Amplifier

- The **voltage-follower op-amp** circuit is shown in Figure 9.17.
- It might seem that this circuit, with unity voltage gain, would be of little value.
  - However, other terms used for the voltage follower are **impedance transformer** or **buffer**.
- The input impedance $R_i \to \infty$, and the output impedance $R_o \to 0$.
- If, for example, the output impedance of a signal source is large, a voltage follower inserted between the source and a load will prevent **loading effects**.
  - It will act as a **buffer** between the source and the load.

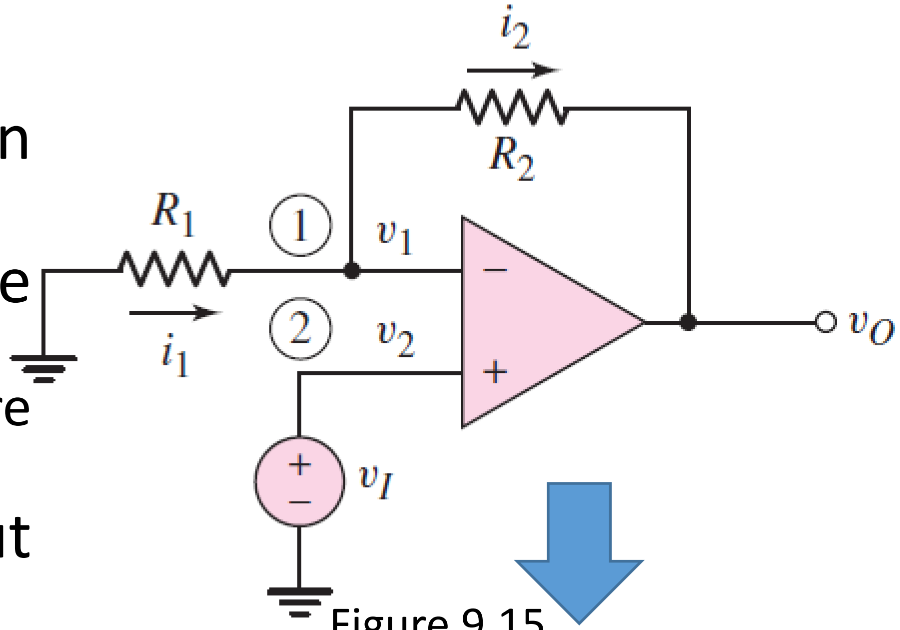


Figure 9.15

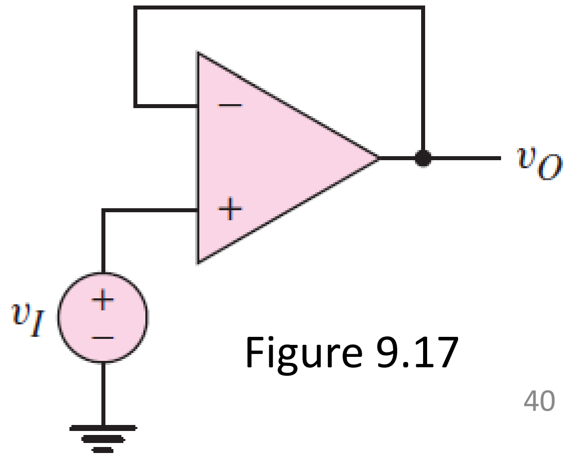


Figure 9.17

9.4.2 Voltage Follower-Noninverting Amplifier

- Compare between the following two circuits!

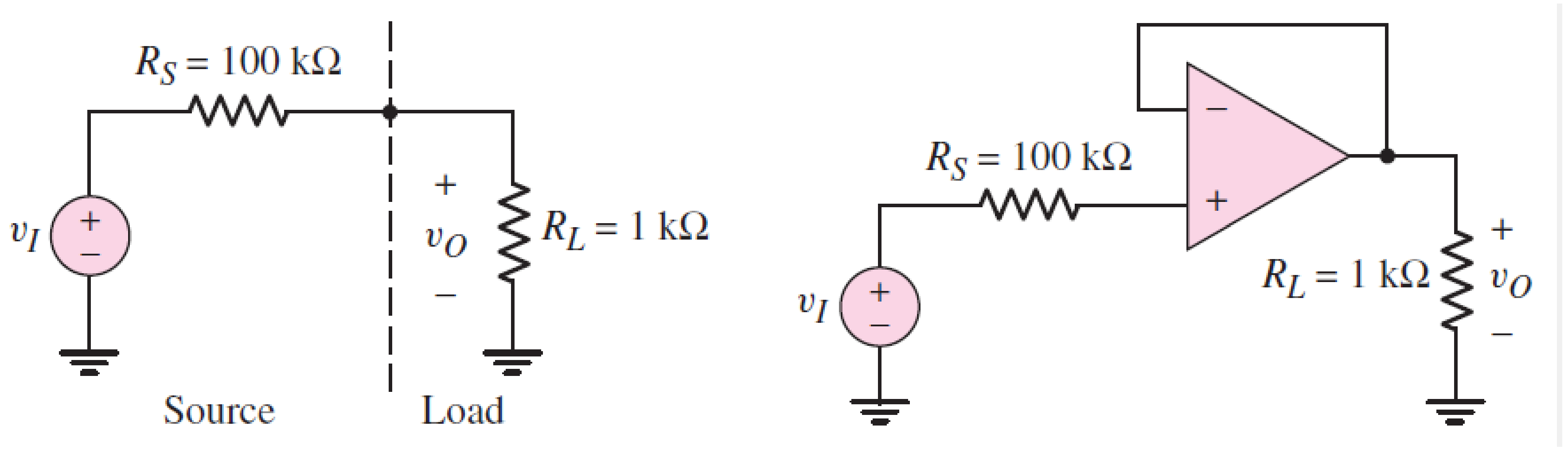


Figure 9.18