EE103 Lecture 4 Notes

Stavan Mehta

microphone ⇒ 1mV at max } This amplification is not done through BJT
speaker ⇒ 60V atleast

• Gain of BJT common emitter amp is:

$-g_m \frac{R_C}{R_L}$; $g_m = \frac{I_C}{V_T}$

inversion

• 4 types of Amplifiers:
a) voltage controlled voltage Amp
b) voltage controlled current Amp
c) current controlled voltage Amp
d) current controlled current Amp

$R_S = 10^6\,\Omega$ } microphone Resistance

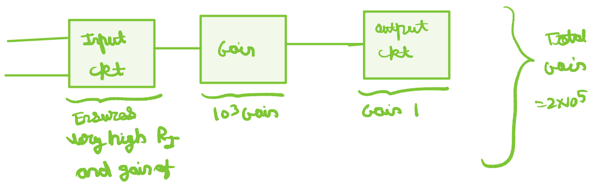
• voltage amp. ⇒ Input Resistance should be very high ($R_I \to \infty$)

• $V_I = \frac{V_S R_I}{R_I + R_S}$

$V_o = \frac{A_{V_o} V_I R_L}{R_o + R_L}$ → very small   8–32 Ω } speaker impedance

∴ R_o should be very small
└ output resistance

• op Amp has 3 blocks inside:



• Amplifiers ⇒ Power gain should be there
As compared to conventional voltage gain

• Direct-coupled ⇒ input directly to transistor, no capacitors involved in between

• we define one input to be common ground

Input	No common GND (No. of wires)	Common GND (No. of wires)
1	2	2
2	4	3
8	16 } very costly	9

} Amplifier symbol
Triangle symbolises unidirectional

Inverting ⇒ sin ωt (input-1), GND (input-2) ⇒ −sin(ωt) (output) } Inverted

GND (input-1), sin ωt (input-2) ⇒ sin ωt (output) } Non-inverting

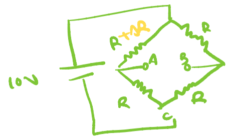
• Earlier all Amp were inverting, but not now. ∴ we coined the word 'Non-inverting'

• OP AMP amplifies difference btw input-1,2 } Differential voltage

• Differential mode ⇒ $V_2 - V_1$ → op amp
common mode ⇒ $\frac{V_2 + V_1}{2}$ ← strain gauge amplifiers

on strain R varies to R+ΔR

• A_c practically is 10^4



$V_{AC} = 5V$
$V_{BC} = 5V$
$V_{AB} = 0V$

on strain:
$V_A - V_B \approx 0$
$V_A - V_B$ = tiny AC } Amplified
we want that Amplified
and not $\frac{V_A + V_B}{2}$ } common mode

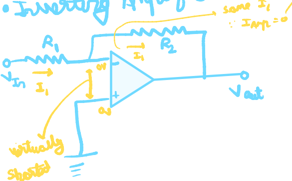
∴ A_c should be very small

• V_{out} depends on power supply ∵ Amp draws power from supply to amplify

$A_D = 10^6$ ⇒ $V_{out} = 12V$ at max
$V_1 - V_2 = 12\,\mu V$ ⇒ virtual short ; $I_{In} \approx 0$
≈0V

→ In reality its in nano/pico Amperes

• Inverting Amplifier:



$I_1 = \frac{V_{In}}{R_1} = \frac{-V_{out}}{R_2}$

∴ $V_{out} = -\frac{R_2}{R_1} V_{In}$

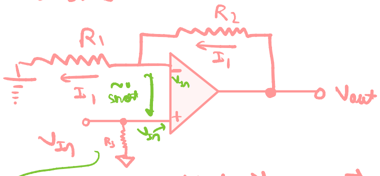
In our hands and not device property unlike in BJT Amps

• Linearity ⇒ f(a+b) = f(a) + f(b)

• $V_{out} = A(V_+ - V_-)$

If we inc. V_- ⇒ I_1 ↑ ⇒ V_- will ↓

• Since OP AMP has no Ground, we can amplify Bipolar signals



} Non-inverting amp

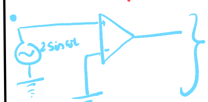
$I_1 = \frac{V_{In}}{R_1} = \frac{V_{out} - V_{In}}{R_2}$ ⇒ $\frac{V_{out}}{V_{In}} = 1 + \frac{R_2}{R_1}$ } No inversion

R_3 is put since in some cases like oscilloscope, we need R_I to be some value ∴ we can choose R_3

• Unity buffer ⇒ $A_V = 1$ but current gain is v. high and Power

• Differential Amp ⇒ both input has signals unlike inverting, non-inverting } where one is grounded

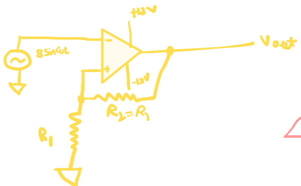
• OP AMP can't handle very high frequency
• we have special OPAMP for this



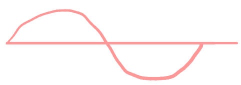
} compares 2sin ωt to 0

If we replace this with 1V battery ⇒ compares it with 1V

• If we add noise to it ⇒ output signal is completely corrupted.



$V_{out} = A(V_+ - V_-)$ $A = 10^5$



Noise has no effect here

Lecture 4: Op amp Circuits

EE 103

2023-24/I (Autumn)

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Problems of BJT based Amplifiers

- Voltage gain depends on the device parameters

  (which in turn depends on temperature and also vary from device to device)

- For example, the gain of a BJT Common-Emitter amplifier is:

  $-g_m R_C \| R_L$

- Solution:
  - Cascaded amplifiers

microphone ⇒ 1mV at max
speaker ⇒ 60V atleast } This amplification is not done through BJT

- Gain of BJT common emitter amp is:

$-g_m \dfrac{R_C}{R_L}$; $g_m = \dfrac{I_C}{V_T}$

Inversion

- 4 types of Amplifiers:
  a) voltage controlled voltage Amp
  b) voltage controlled current Amp
  c) current controlled voltage Amp
  d) current controlled current Amp

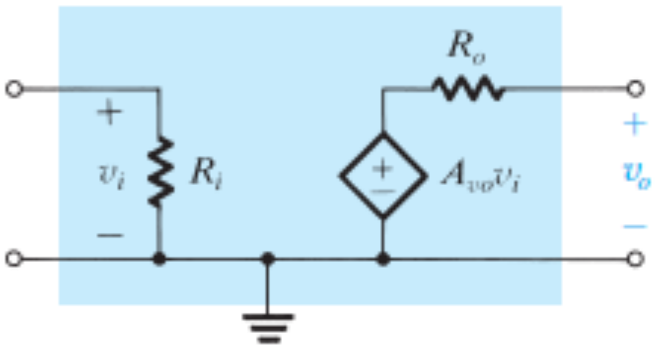
$R_S = 10^6\,\Omega$ } Microphone Resistance

Amplifier Requirements

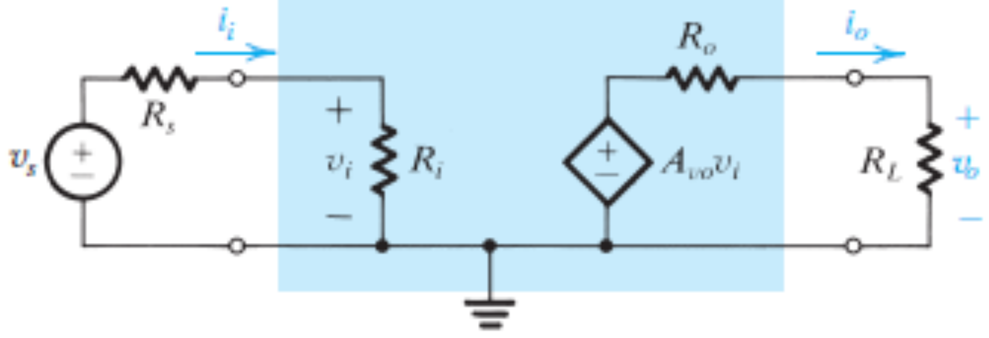
- voltage amp. ⇒ Input Resistance should be very high ($R_I \to \infty$)
- $V_I = \dfrac{V_S R_I}{R_I + R_S}$

$V_0 = \dfrac{A_{V_0} V_I R_L}{R_0 + R_L}$ → very small $\underline{\underline{8-32\,\Omega}}$ } speaker impedance

∴ R_0 should be very small
↳ output resistance

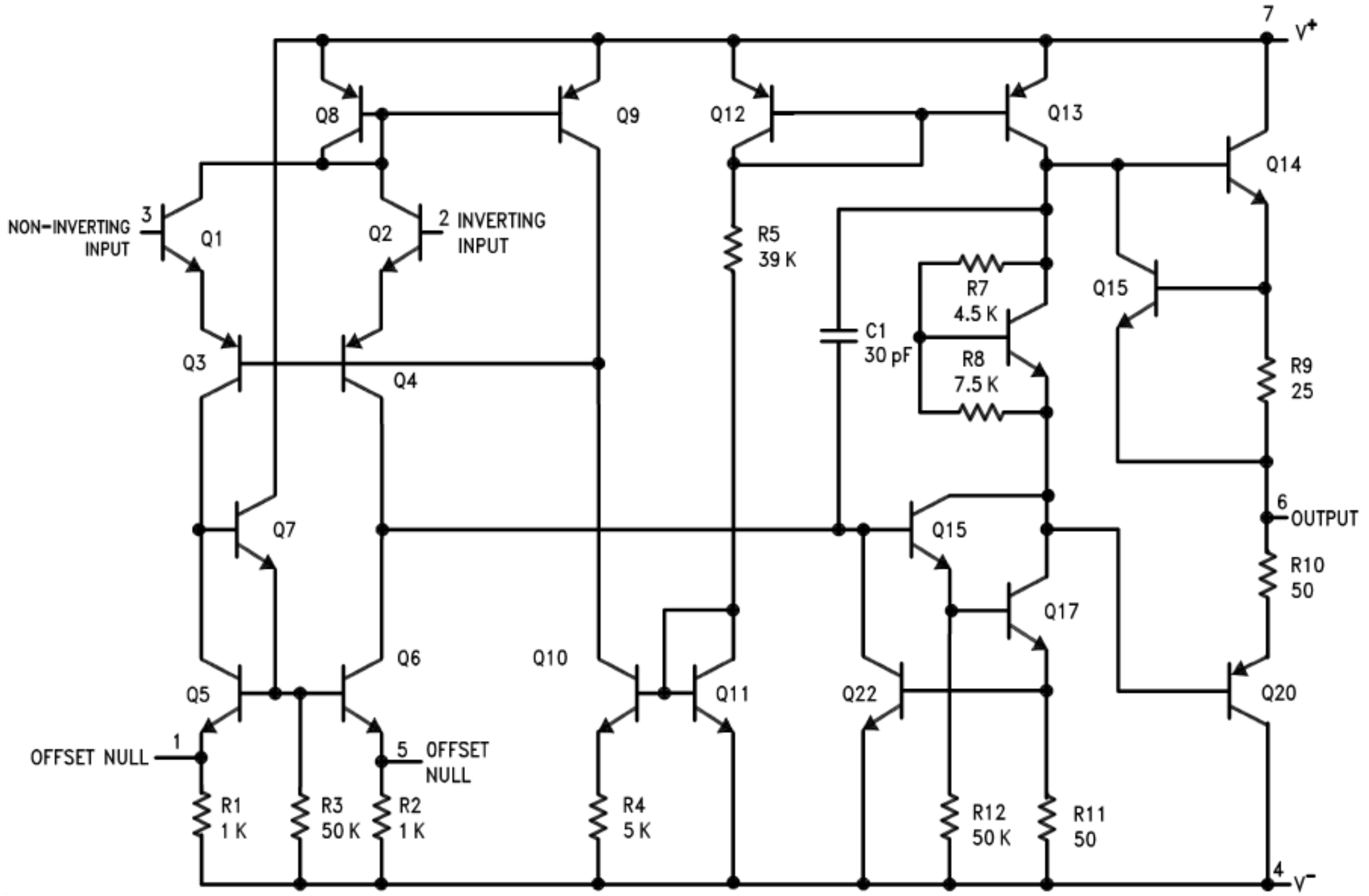


(a)



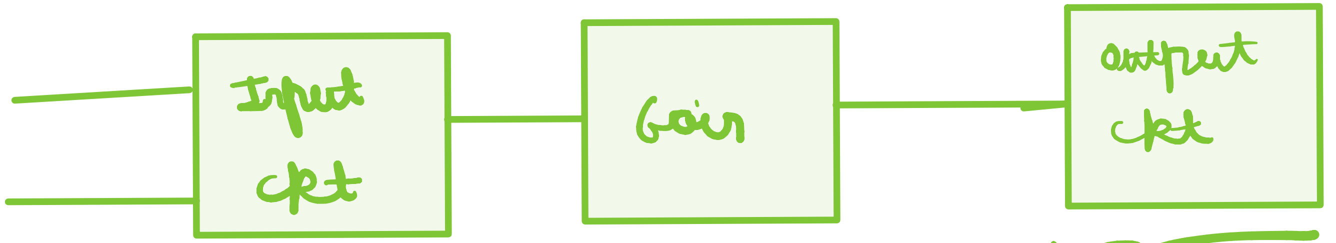
- Input side requirements
  - Input resistance (R_i) of the amplifier should be ideally infinite.
- Load requirements
  - Output resistance (R_o) of the amplifier should be ideally 0.

LM 741 Op amp



- **Three major blocks:**
  - Input block: gives very high input resistance and also a voltage gain of about 1000.
- A gain clock:
  - gives a voltage gain of about 1000.
- Output stage:
  - Unity voltage gain but very high current gain; also provides short-circuit protection to the output

• Op Amp has 3 blocks inside.



Ensures very high R_I and gain of voltage $= 10^3$

10^3 Gain

Gain 1

Total Gain $= 2 \times 10^5$

• Amplifier → Power gain should be there

As compared to conventional Voltage gain

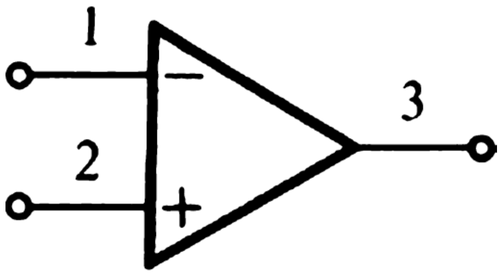
3. Operational Amplifier

Operational amplifier (op amp)

Direct-coupled (dc) high-gain amplifier with differential voltage input & single-ended voltage output.

- Developed for mathematical operations on signal waveforms. It is an electronic circuit with several internal passive & active devices, available as a single-chip device, several op amps on a single chip, or op amps with other circuits on the same chip.
- Main objective: Circuit performance parameters decided by passive components & nearly independent of electronic device parameters.

Op amp circuit symbol (simplified)



- Input terminals: 1, 2. Output terminal: 3.
- 3 single-ended ports with the circuit ground (Gnd) as the common terminal (implied, not shown in the symbol).
- Inverting input v_{i-}: 1-Gnd. Non-inverting input v_{i+}: 2-Gnd. Output v_o: 3-Gnd.

• Direct-coupled ⇒ input directly to transistor; no capacitors involved in between

• We define one input to be common ground

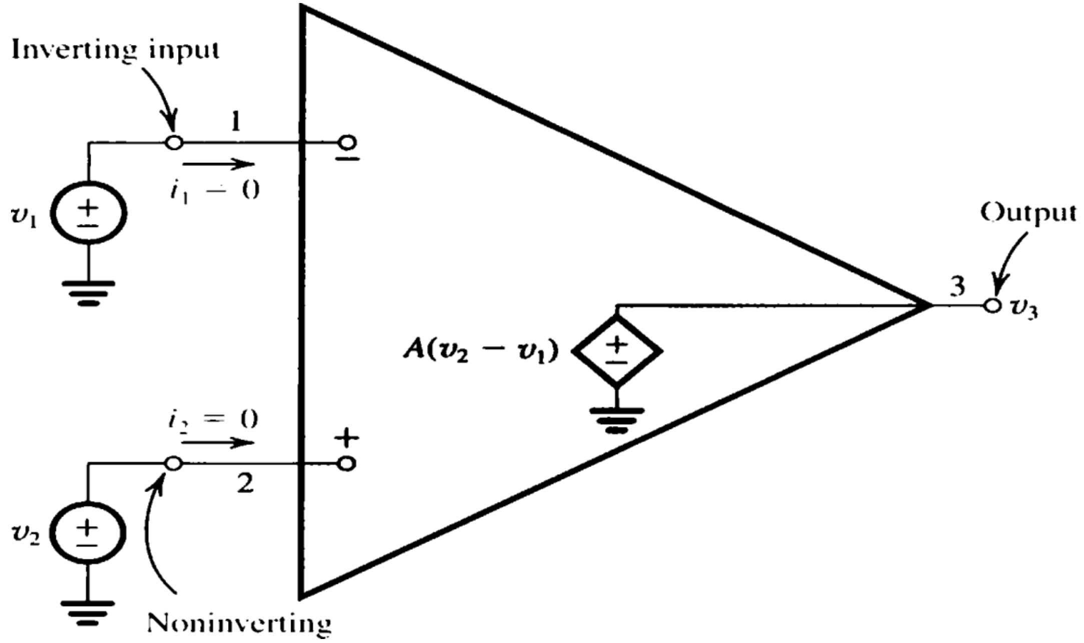
Input	No common GND (No. of wires)	common GND (No. of wires)
1	2	2
2	4	3
8	16 } very costly	9

} Amplifier symbol
Triangle symbolises unidirectional

Inverting ⇒ Sin ωt (input-1) GND (input-2) ⇒ −Sin(ωt) (output) } Inverted

GND (input-1) Sin ωt (input-2) ⇒ Sin ωt (output) } Non-inverting

Input-output relation



- Terminal voltage: voltage between the terminal & Gnd.
- Difference-mode (DM) input $v_{id} = v_2 - v_1$.
- Common-mode (CM) input $v_{ic} = (v_2 + v_1)/2$.
- Output voltage $v_3 = A_d v_{id} + A_c v_{ic}$.
- DM gain: A_d. CM gain: A_c.
- Common-mode rejection ratio (CMRR) $= A_d/A_c$.

Ideal op amp

→ Draws no current ∵ $R_I \to \infty$

- $A_d \to \infty$. $A_c \to 0$. $v_3 = A_d(v_2 - v_1)$

DM input amplification with no effect of CM input. Finite output voltage obtained with zero DM input.

i.e. $v_{in} = 0$ v_{out} = Finite

CMRR $= A_d/A_c \to \infty$.

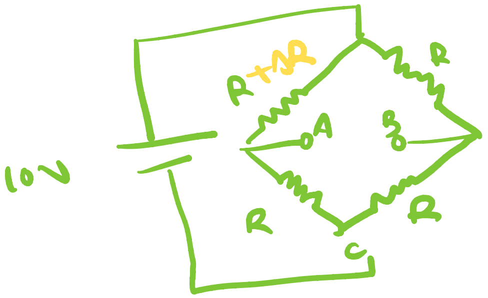
- Infinite input resistances for the two inputs (zero input currents) .
- Zero output resistance (output voltage independent of the load current).

we coined the word "Non-inverting"

- Earlier all Amp were inverting, but not now ∴
- OP AMP amplifies difference btw input-1, 2 } Differential voltage
- Differential mode ⇒ $V_2 - V_1$ → OP AMP
  common mode ⇒ $\frac{V_2+V_1}{2}$ ← strain gauge amplifiers

- A_c practically is 10^4

On strain R varies to R+∂R



$V_{AC} = 5V$
$V_{BC} = 5V$
$V_{AB} = 0V$

on ∂R change
$V_A - V_B \neq 0$
$V_A - V_B$ = tiny AC
we want that amplified
and not $\frac{V_A+V_B}{2}$ } common mode

∴ A_c should be very small

Op amp in linear operation

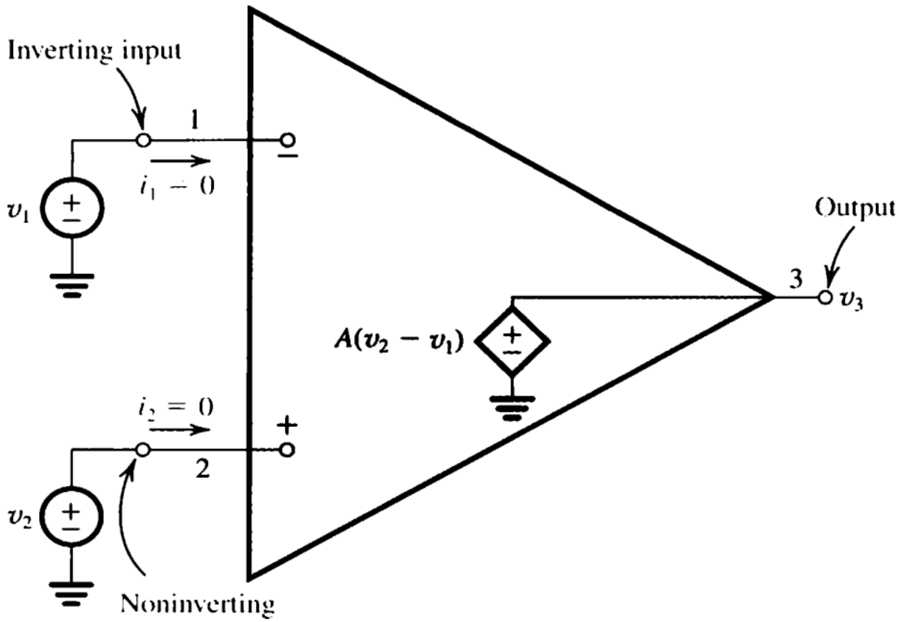
- $v_3 = A_d v_{id}$

For finite output v_3 and $A_d \to \infty$, DM input $v_{id} = v_3/A_d \to 0$.

- Input resistances $R_{i1}, R_{i2} \to \infty \Rightarrow$ zero input currents.

- Zero voltage across the input terminals with zero input currents is known as "virtual short" across the input terminals.

- Virtual short condition is very useful in analyzing linear op amp circuits.



- Virtual short is applicable only during linear operation, & the conditions for it have to be satisfied by external circuit & input voltages. Input currents may increase and output may be distorted during nonlinear operation. Input and output voltage limits for linear operation:

CM input: $V_{CC+} > V_{ICH} > [v_1, v_2] > V_{ICL} > V_{CC-}$.
Output: $V_{CC+} > V_{OH} > v_3 > V_{OL} > V_{CC-}$.

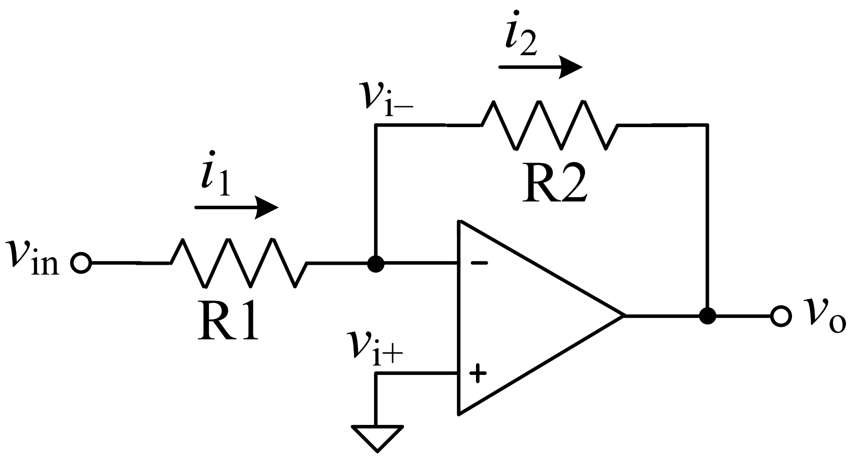
• V_{out} depends on power supply ∵ Amp draws power from supply to amplify

$A_D = 10^6 \Rightarrow V_{out} = 12V$ at max

$v_1 - v_2 = 12\,\mu V \Rightarrow$ virtual short ; $I_{in} \sim 0$
$\sim 0V$

4. Linear Circuits

4.1. Inverting Amplifier Circuit



$v_{i+} = 0.$
Virtual short: $v_{i-} = v_{i+} = 0.$ $i_1 = i_2.$
$i_2 = i_1 = (v_{in} - v_{i-})/R_1 = v_{in}/R_1$
$v_o = v_{i-} - R_2\, i_2 = -(R_2/R_1)\, v_{in}$
Voltage gain: $A_v = v_o / v_{in} = -R_2/R_1.$
Input resistance: $R_{in} = v_{in} / i_1 = R_1.$

Circuit operation basis: Negative feedback (visited later), which opposes disturbance. Check the circuit operation with virtual short assumption and a disturbance at the −ve input. If v_{i-} increases, v_o decreases, i_2 increases, v_{i-} decreases, leading to virtual short restoration. If the op-amp input terminals are interchanged, an increase in v_{i+} will cause further increase leading to virtual short violation.

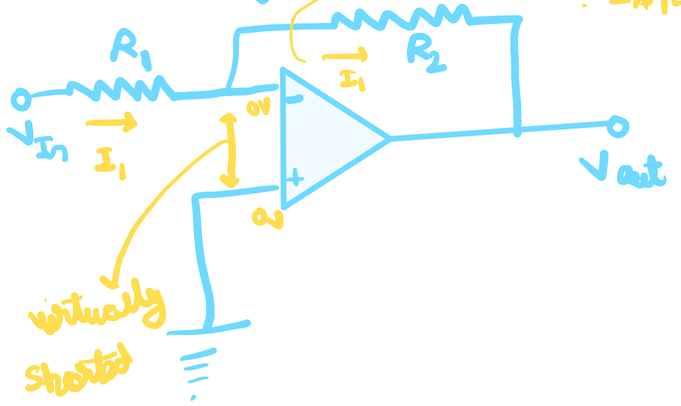
Current & power gains depend on load resistance (not shown). R_{in} can be decreased by connecting a resistor between input and ground.

Application: Precise inverting gain with low to moderate R_{in}.

Example: $R_1 = 10$ kΩ, $R_2 = 100$ kΩ. $R_L = 1$ kΩ. $A_v = -10$, $R_{in} = 10$ kΩ .

- Inverting Amplifier :

same I_1 $\because I_{Amp} = 0$ → In reality its in nano/pico Amperes

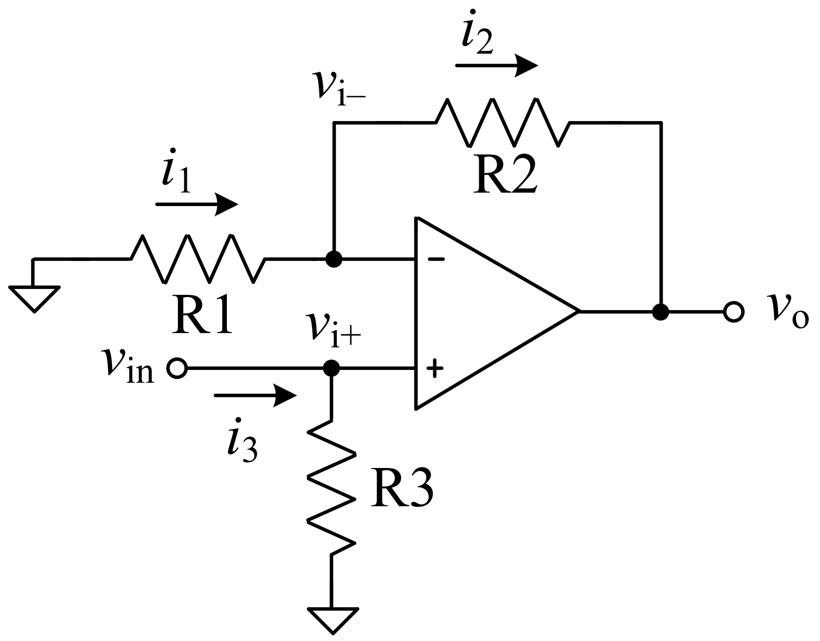


$$I_1 = \frac{V_{in}}{R_1} = \frac{-V_{out}}{R_2}$$

$$\boxed{\therefore V_{out} = \underbrace{\frac{-R_2}{R_1}}_{\text{In our hands and not device property unlike in BJT Amps}} V_{in}}$$

- Linearity → $f(a+b) = f(a) + f(b)$

4.2. Non-inverting Amplifier Circuit



$v_{i+} = v_{in}$

Virtual short assumption: $v_{i-} = v_{i+}$ & $i_1 = i_2$

$i_1 = (0 - v_{i-})/R_1 = -v_{in}/R_1$

$v_o = v_{i+} - R_2\, i_2 = (1+R_2/R_1)\, v_{in}$

Voltage gain: $A_v = v_o/\ v_{in} = 1+R_2/R_1$

Input resistance: $R_{in} = v_{in}/i_3 = R_3$

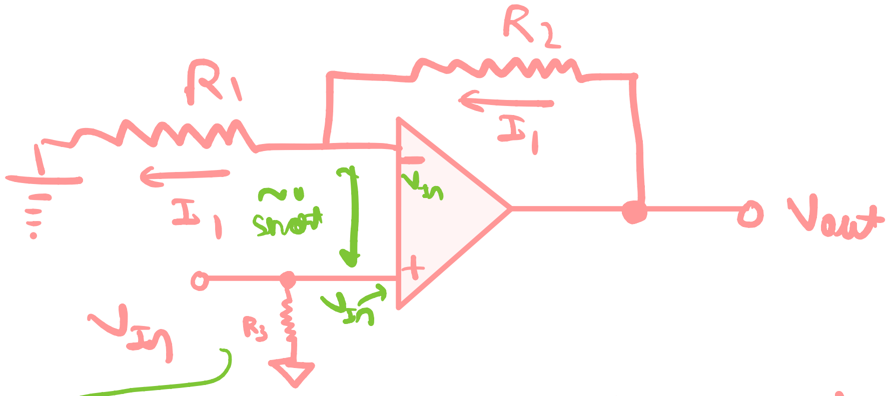
R3 is optional & can be selected for the desired R_{in}.

Basis for circuit operation: Negative feedback. Check the circuit operation, with virtual short assumption & a disturbance at the −ve input. If v_{i-} increases, v_o decreases, i_2 increases, v_{i-} decreases, leading to virtual short restoration. Next check with the op-amp input terminals interchanged.

Application: Precise non-inverting gain with high, moderate, or low R_{in}.

Example: $R_1 = 10$ kΩ, $R_2 = 100$ kΩ, $R_3 = 1$ MΩ, $A_v = 11$, $R_{in} = 1$ MΩ .

• Since OP AMP has no Ground, we can amplify Bipolar signals

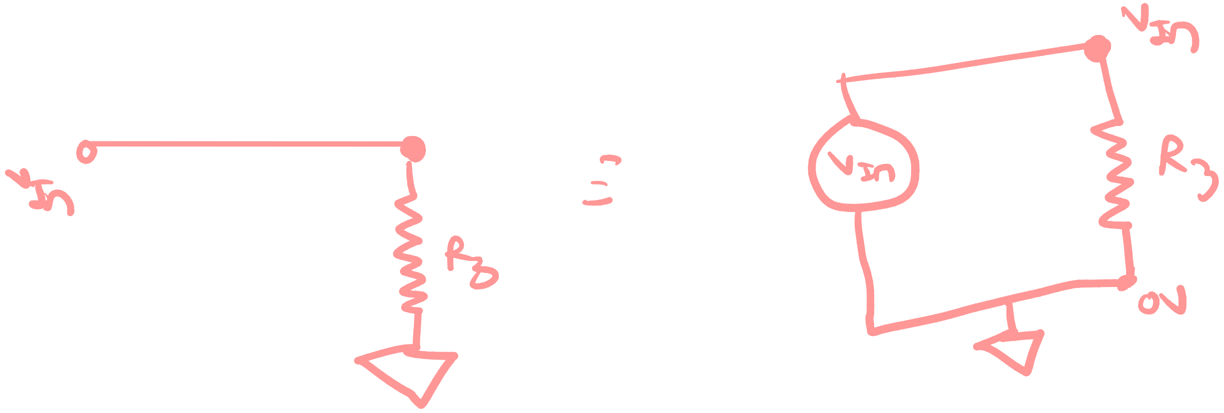


Non-inverting amp

$$I_1 = \frac{V_{in}}{R_1} = \frac{V_{out} - V_{in}}{R_2} \Rightarrow \frac{V_{out}}{V_{in}} = 1 + \frac{R_2}{R_1}$$

No inversion

R_3 is put since in some cases like oscilloscope, we need R_I to be some value ∴ we can choose R_3

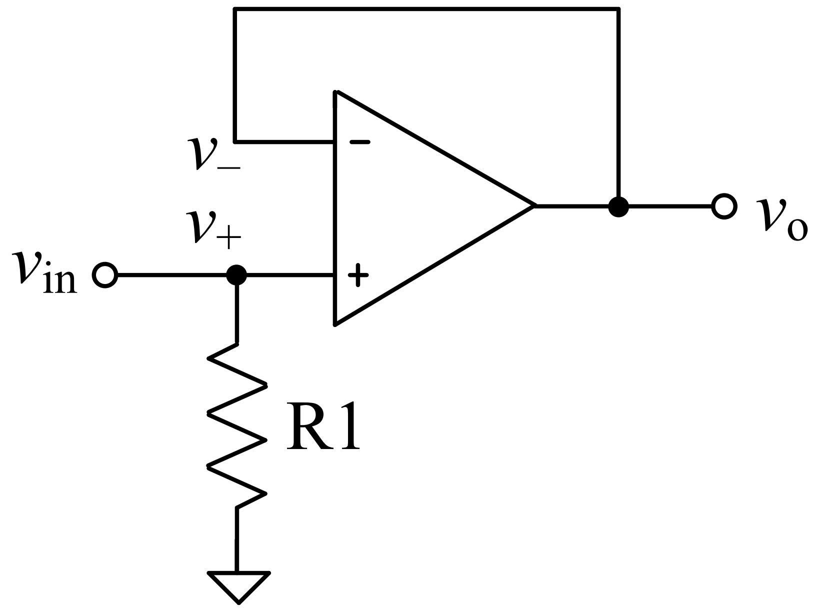


4.3. Non-inverting Unity Follower Circuit (Unity Buffer)

It is a special case of non-inverting amplifier with unity voltage gain.

Voltage gain: $A_v = 1$
Input resistance: $R_{in} = R_1$

Application: Buffer amplifier with very high R_{in} and very low R_o. It is used for connecting a source with high source resistance to a relatively low value load resistance without causing voltage attenuation. It provides unity voltage gain and large current gain.



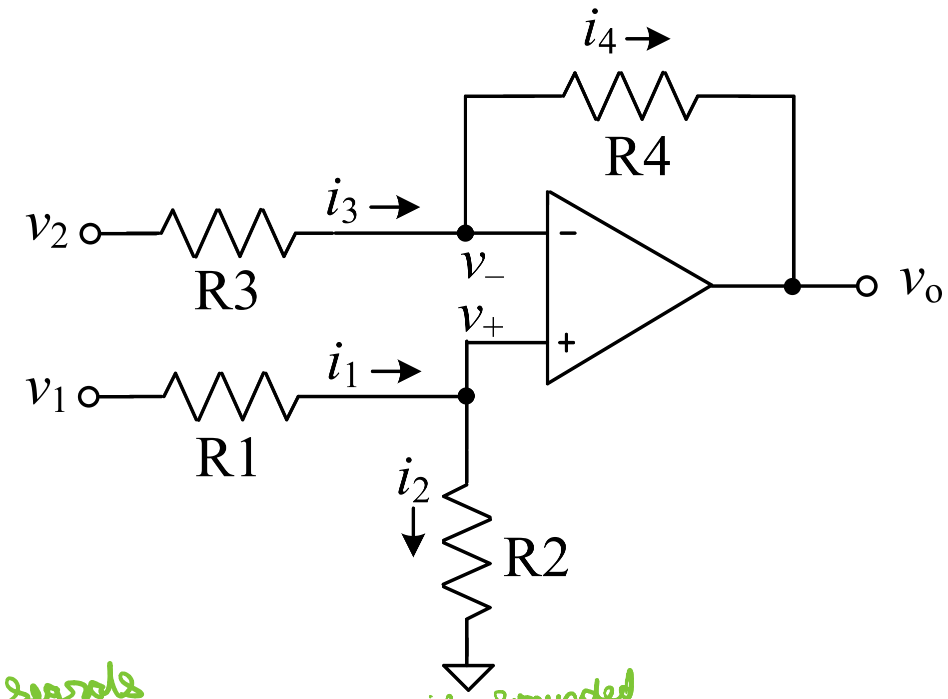
- Unity buffer ⇒ $A_v = 1$ but current gain is V.High and Power

4.4. Difference Amplifier Circuit

Select $R_2/R_1 = R_4/R_3 = \alpha$.

Virtual short assumption: $i_1 = i_2$ & $i_3 = i_4$.

Circuit function: (i) inverting amplifier for v_2, (ii) attenuator & non-inverting amplifier for v_1.



$$v_o = v_1 [R_2/(R_1+R_2)] [1+R_4/R_3] - v_2 [R_4/R_3]$$

$$= v_1 [\alpha/(1+\alpha)][1+\alpha] - v_2 [\alpha] = \alpha (v_1 - v_2)$$

DM gain $A_d = \alpha$.

CM gain $A_c = 0$

$R_{in1} = R_1 + R_2$, $R_{in2} = R_3$.

• Differential Amp → both input has signals unlike inverting, non-inverting } where one is grounded

• op Amp can't handle very high frequency

• we have special OPAMPs for this

• Precise differential gain. Resistance matching needed. Difficult gain control. Unequal input resistances.

• A voltage (DC bias) v_3 can be added to the output by connecting R2 to this voltage in place of ground.

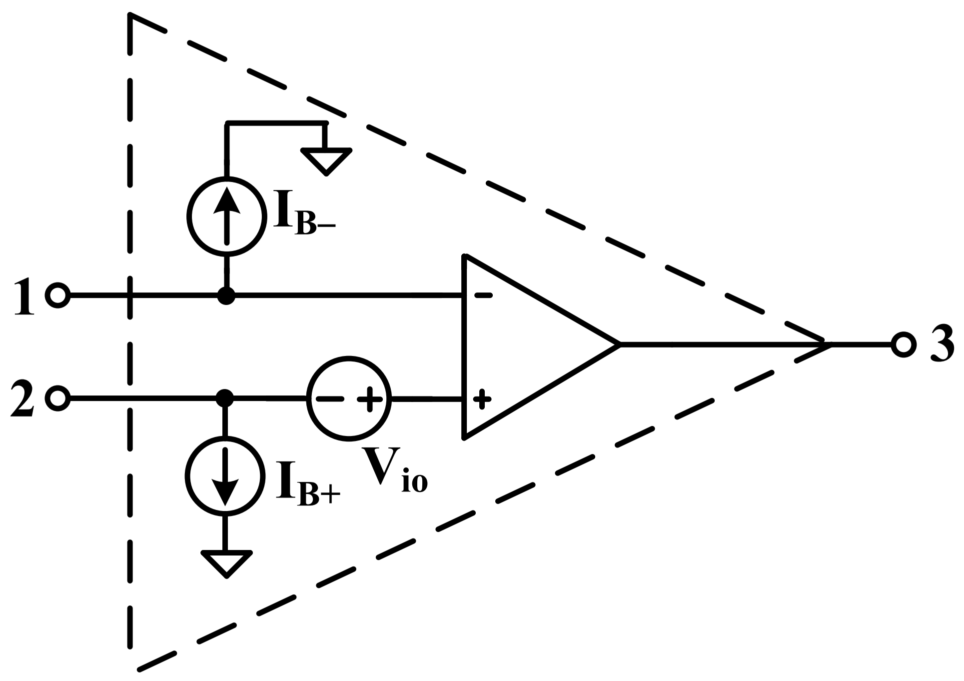
$$v_o = \alpha (v_1 - v_2) + v_3[1/(1+\alpha)] /(1+\alpha)] = \alpha (v_1 - v_2) + v_3$$

4.9. Practical Op Amp

• Op-amp linear operation has limits for CM input voltage, output voltage, & output current (due to DC supplies & internal circuit)

• DC imperfections
- Input offset voltage (internal error voltage: 1—5 mV) causing output saturation in high-gain circuits.
- Input bias currents: Small DC input currents (10 pA to 100 nA). These must be permitted by external circuit for proper operation.

• Finite input & output resistances.



Op-amp DC error model

• Finite diff. gain (typically > 10^5 at dc, decreasing with frequency), finite CMRR. Another limitation for large amplitude AC signals is "slew rate", the maximum rate of change of output voltage (typically 1 V/μs).

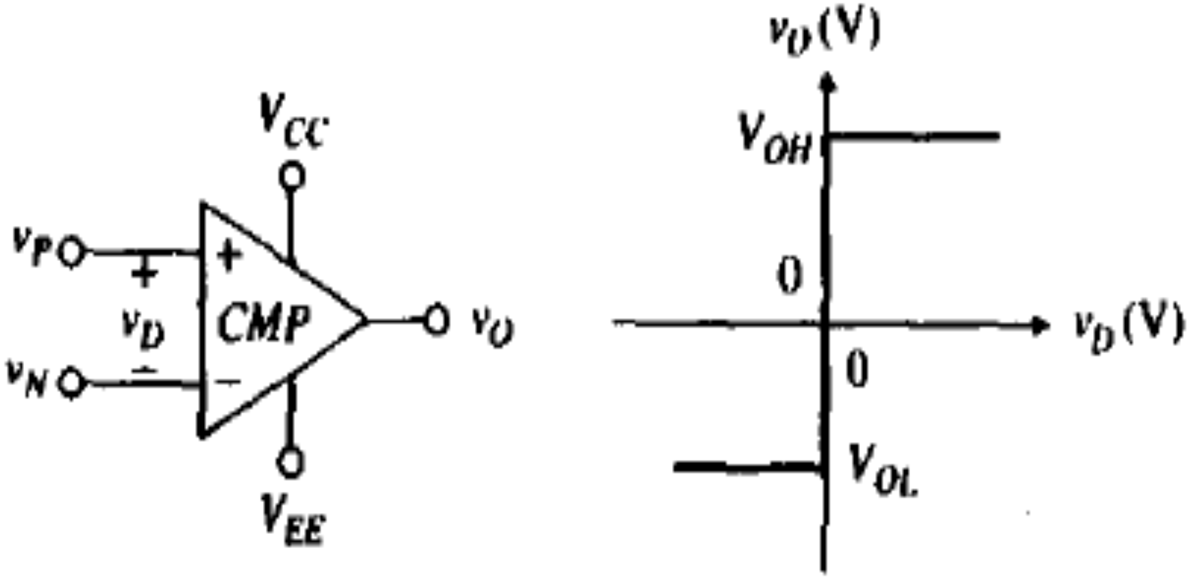
6. Nonlinear Circuits

Voltage Comparator

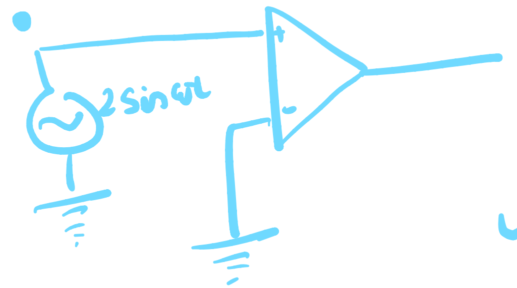
Op-amp like device for open-loop operation & precise binary output levels.

$v_p > v_n$: $v_o = V_{OH}$ (high-level voltage)

$v_p < v_n$: $v_o = V_{OL}$ (low-level voltage)



- Circuit symbol: same as op amp, with analog inputs, binary output. Transfer characteristic: Very high gain at $v_p = v_n$ with sharp transition between the two output levels.
- Input swing and output levels generally dependent on V_{CC+} and V_{EE-}.
- A comparator is designed for very low input currents despite large differential input voltage. It has buffers at each input before the differential high-gain. An op amp can also be used as a comparator with due consideration for finite differential input voltage.



compares $2\sin\omega t$ to 0

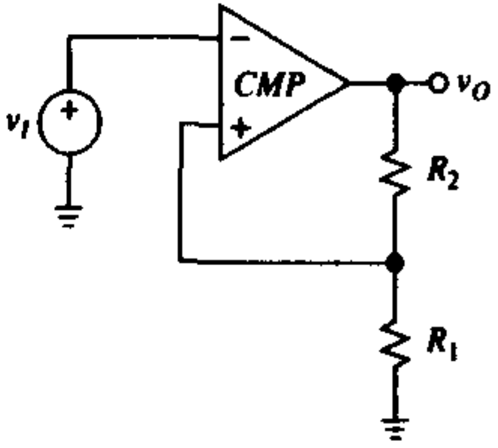
If we replace this with 1V battery $\Rightarrow$ compares it with 1V

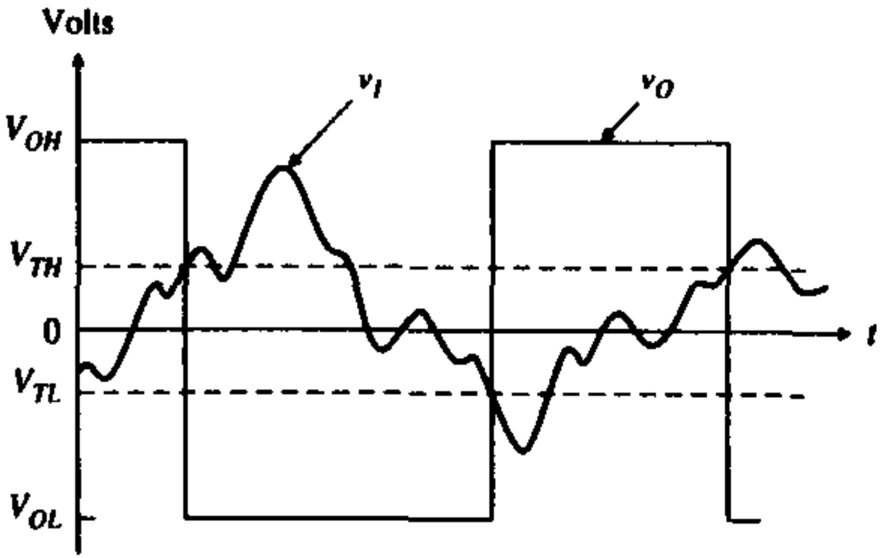
Schmitt Trigger

Comparator with hysteresis: high-gain differential amplifier with +ve feedback. Bistable circuit.

• Inverting Schmitt trigger: clockwise hysteresis.

• Non-inverting Schmitt trigger: counterclockwise hysteresis.





Applications: **Chatter elimination, waveform generation, signal processing.**

- If we add noise to it → output signal is completely corrupted.

Reference-1

CHAPTER 2

Operational Amplifiers

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IN THIS CHAPTER YOU WILL LEARN

1. The terminal characteristics of the ideal op amp.
2. How to analyze circuits containing op amps, resistors, and capacitors.
3. How to use op amps to design amplifiers having precise characteristics.
4. How to design more sophisticated op-amp circuits, including summing amplifiers, instrumentation amplifiers, integrators, and differentiators.
5. Important nonideal characteristics of op amps and how these limit the performance of basic op-amp circuits.

Introduction

Having learned basic amplifier concepts and terminology, we are now ready to undertake the study of a circuit building block of universal importance: the operational amplifier (op amp). Op amps have been in use for a long time, their initial applications being primarily in the areas of analog computation and sophisticated instrumentation. Early op amps were constructed from discrete components (vacuum tubes and then transistors, and resistors), and their cost was prohibitively high (tens of dollars). In the mid-1960s the first integrated-circuit (IC) op amp was produced. This unit (the μA 709) was made up of a relatively large number of transistors and resistors all on the same silicon chip. Although its characteristics were poor (by today's standards) and its price was still quite high, its appearance signaled a new era in electronic circuit design. Electronics engineers started using op amps in large quantities, which caused their price to drop dramatically. They also demanded better-quality op amps. Semiconductor manufacturers responded quickly, and within the span of a few years, high-quality op amps became available at extremely low prices (tens of cents) from a large number of suppliers.

One of the reasons for the popularity of the op amp is its versatility. As we will shortly see, one can do almost anything with op amps! Equally important is the fact that the IC op amp has characteristics that closely approach the assumed ideal. This implies that it is quite easy to design circuits using the IC op amp. Also, op-amp circuits work at performance levels that are quite close to those predicted theoretically. It is for this reason that we are studying op amps at this early stage. It is expected that by the end of this chapter the reader should be able to successfully design nontrivial circuits using op amps.

As already implied, an IC op amp is made up of a large number (about 20) of transistors together with resistors, and (usually) one capacitor connected in a rather complex circuit. Since we have not yet studied transistor circuits, the circuit inside the op amp will not be discussed in this chapter. Rather, we will treat the op amp as a circuit building block and study its terminal characteristics and its applications. This approach is quite satisfactory in many op-amp applications. Nevertheless, for the more difficult and demanding applications it is quite useful to know what is inside the op-amp package. This topic will be studied in Chapter 13. More advanced applications of op amps will appear in later chapters.

2.1 The Ideal Op Amp

2.1.1 The Op-Amp Terminals

From a signal point of view the op amp has three terminals: two input terminals and one output terminal. Figure 2.1 shows the symbol we shall use to represent the op amp. Terminals 1 and 2 are input terminals, and terminal 3 is the output terminal. As explained in Section 1.4, amplifiers require dc power to operate. Most IC op amps require two dc power supplies, as shown in Fig. 2.2. Two terminals, 4 and 5, are brought out of the op-amp package and connected to a positive voltage V_{CC} and a negative voltage $-V_{EE}$, respectively. In Fig. 2.2(b) we explicitly show the two dc power supplies as batteries with a common ground. It is interesting to note that the reference grounding point in op-amp circuits is just the common terminal of the two power supplies; that is, no terminal of the op-amp package is physically connected to ground. In what follows we will not, for simplicity, explicitly show the op-amp power supplies.

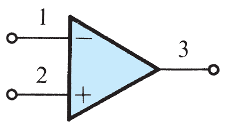


Figure 2.1 Circuit symbol for the op amp.

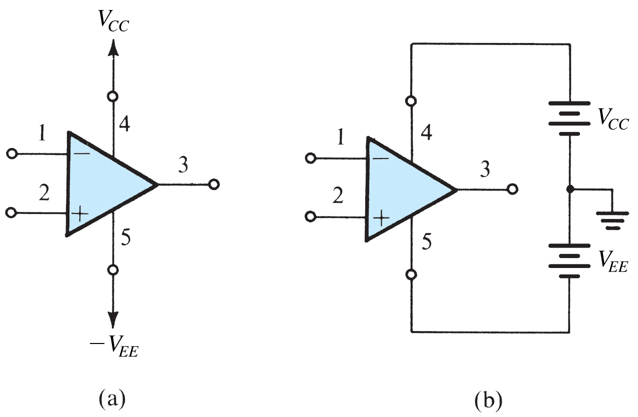


Figure 2.2 The op amp shown connected to dc power supplies.

In addition to the three signal terminals and the two power-supply terminals, an op amp may have other terminals for specific purposes. These other terminals can include terminals for frequency compensation and terminals for offset nulling; both functions will be explained in later sections.

EXERCISE

2.1 What is the minimum number of terminals required by a single op amp? What is the minimum number of terminals required on an integrated-circuit package containing four op amps (called a quad op amp)?
Ans. 5; 14 $\rightarrow$ $\underbrace{4\times 2}_{\text{input}} + \underbrace{4\times 1}_{\text{output}} + \underbrace{2}_{\text{Powers is}} = 14$ common to all 4 OP

2.1.2 Function and Characteristics of the Ideal Op Amp

We now consider the circuit function of the op amp. The op amp is designed to sense the difference between the voltage signals applied at its two input terminals (i.e., the quantity $v_2 - v_1$), multiply this by a number A, and cause the resulting voltage $A(v_2 - v_1)$ to appear at output terminal 3. Thus $v_3 = A(v_2 - v_1)$. Here it should be emphasized that when we talk about the voltage at a terminal we mean the voltage between that terminal and ground; thus v_1 means the voltage applied between terminal 1 and ground.

The ideal op amp is not supposed to draw any input current; that is, the signal current into terminal 1 and the signal current into terminal 2 are both zero. In other words, *the input impedance of an ideal op amp is supposed to be infinite.*

How about the output terminal 3? This terminal is supposed to act as the output terminal of an ideal voltage source. That is, the voltage between terminal 3 and ground will always be equal to $A(v_2 - v_1)$, independent of the current that may be drawn from terminal 3 into a load impedance. In other words, *the output impedance of an ideal op amp is supposed to be zero.*

Putting together all of the above, we arrive at the equivalent circuit model shown in Fig. 2.3. Note that the output is in phase with (has the same sign as) v_2 and is out of phase with (has the opposite sign of) v_1. For this reason, input terminal 1 is called the **inverting input terminal** and is distinguished by a "−" sign, while input terminal 2 is called the **noninverting input terminal** and is distinguished by a "+" sign.

As can be seen from the above description, the op amp responds only to the *difference* signal $v_2 - v_1$ and hence ignores any signal *common* to both inputs. That is, if $v_1 = v_2 = 1$ V, then the output will (ideally) be zero. We call this property **common-mode rejection**, and we conclude that an ideal op amp has zero common-mode gain or, equivalently, infinite common-mode rejection. We will have more to say about this point later. For the time being note that the op amp is a **differential-input, single-ended-output** amplifier, with the latter term referring to the fact that the output appears between terminal 3 and ground.[1]

[1]Some op amps are designed to have differential outputs. This topic will not be discussed in this book. Rather, we confine ourselves here to single-ended-output op amps, which constitute the vast majority of commercially available op amps.

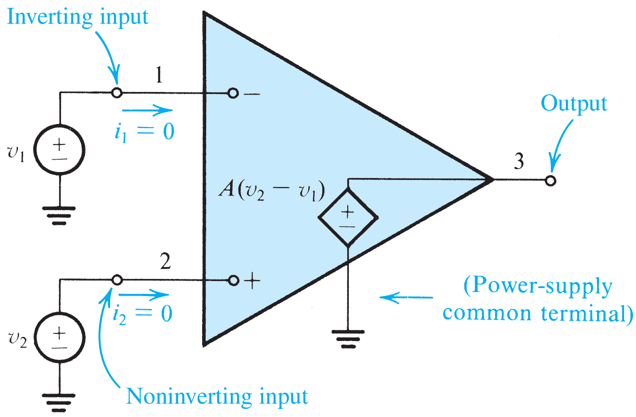


Figure 2.3 Equivalent circuit of the ideal op amp.

Furthermore, gain A is called the **differential gain**, for obvious reasons. Perhaps not so obvious is another name that we will attach to A: the **open-loop gain**. The reason for this name will become obvious later on when we "close the loop" around the op amp and define another gain, the closed-loop gain.

An important characteristic of op amps is that they are **direct-coupled** or **dc amplifiers**, where dc stands for direct-coupled (it could equally well stand for direct current, since a direct-coupled amplifier is one that amplifies signals whose frequency is as low as zero). The fact that op amps are direct-coupled devices will allow us to use them in many important applications. Unfortunately, though, the direct-coupling property can cause some serious practical problems, as will be discussed in a later section.

How about bandwidth? The ideal op amp has a gain A that remains constant down to zero frequency and up to infinite frequency. That is, ideal op amps will amplify signals of any frequency with equal gain, and are thus said to have *infinite bandwidth.*

We have discussed all of the properties of the ideal op amp except for one, which in fact is the most important. This has to do with the value of A. *The ideal op amp should have a gain A whose value is very large and ideally infinite.* One may justifiably ask: If the gain A is infinite, how are we going to use the op amp? The answer is very simple: In almost all applications the op amp will *not* be used alone in a so-called open-loop configuration. Rather, we will use other components to apply feedback to close the loop around the op amp, as will be illustrated in detail in Section 2.2.

For future reference, Table 2.1 lists the characteristics of the ideal op amp.

Table 2.1 Characteristics of the Ideal Op Amp

1. Infinite input impedance
2. Zero output impedance
3. Zero common-mode gain or, equivalently, infinite common-mode rejection
4. Infinite open-loop gain A
5. Infinite bandwidth

2.1.3 Differential and Common-Mode Signals

The differential input signal v_{Id} is simply the difference between the two input signals v_1 and v_2; that is,

$$v_{Id} = v_2 - v_1 \tag{2.1}$$

The common-mode input signal v_{Icm} is the average of the two input signals v_1 and v_2; namely,

$$v_{Icm} = \tfrac{1}{2}(v_1 + v_2) \tag{2.2}$$

Equations (2.1) and (2.2) can be used to express the input signals v_1 and v_2 in terms of their differential and common-mode components as follows:

$$v_1 = v_{Icm} - v_{Id}/2 \tag{2.3}$$

and

$$v_2 = v_{Icm} + v_{Id}/2 \tag{2.4}$$

These equations can in turn lead to the pictorial representation in Fig. 2.4.

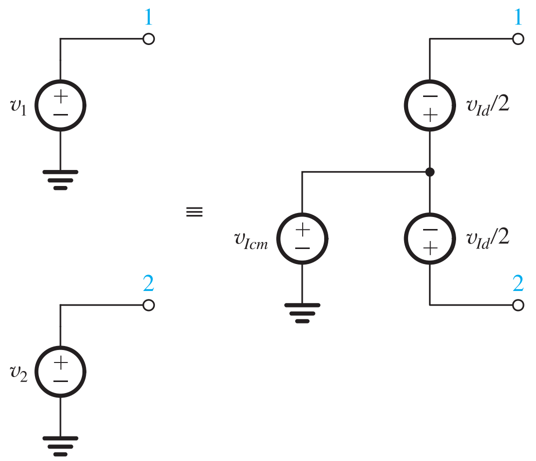


Figure 2.4 Representation of the signal sources v_1 and v_2 in terms of their differential and common-mode components.

EXERCISES

2.2 Consider an op amp that is ideal except that its open-loop gain $A = 10^3$. The op amp is used in a feedback circuit, and the voltages appearing at two of its three signal terminals are measured. In each of the following cases, use the measured values to find the expected value of the voltage at the third terminal. Also give the differential and common-mode input signals in each case. (a) $v_2 = 0$ V and $v_3 = 2$ V; (b) $v_2 = +5$ V and $v_3 = -10$ V; (c) $v_1 = 1.002$ V and $v_2 = 0.998$ V; (d) $v_1 = -3.6$ V and $v_3 = -3.6$ V.
Ans. (a) $v_1 = -0.002$ V, $v_{Id} = 2$ mV, $v_{Icm} = -1$ mV; (b) $v_1 = +5.01$ V, $v_{Id} = -10$ mV, $v_{Icm} = 5.005 \simeq 5$ V; (c) $v_3 = -4$ V, $v_{Id} = -4$ mV, $v_{Icm} = 1$ V; (d) $v_2 = -3.6036$ V, $v_{Id} = -3.6$ mV, $v_{Icm} \simeq -3.6$ V

2.3 The internal circuit of a particular op amp can be modeled by the circuit shown in Fig. E2.3. Express v_3 as a function of v_1 and v_2. For the case $G_m = 10$ mA/V, $R = 10$ kΩ, and $\mu = 100$, find the value of the open-loop gain A.

Ans. $v_3 = \mu G_m R(v_2 - v_1)$; $A = 10{,}000$ V/V or 80 dB

↳ Voltage gain (dB)
$= 20 \cdot \log\left(\frac{V_{out}}{V_{in}}\right)$
$= 20 \log(A)$

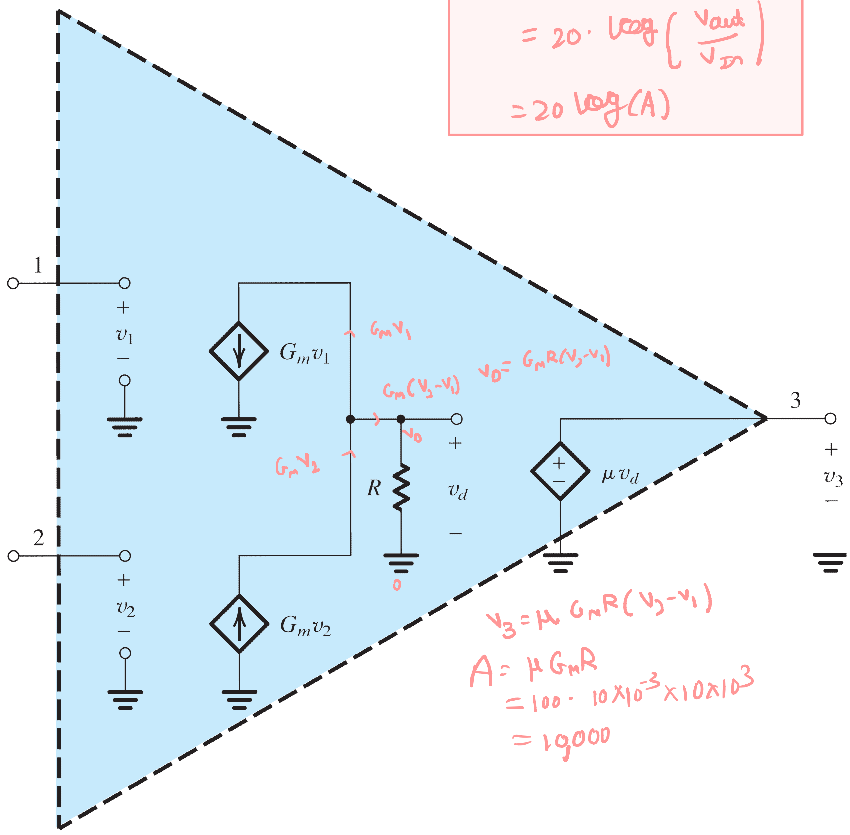


Figure E2.3

2.2 The Inverting Configuration

As mentioned above, op amps are not used alone; rather, the op amp is connected to passive components in a feedback circuit. There are two such basic circuit configurations employing an op amp and two resistors: the inverting configuration, which is studied in this section, and the noninverting configuration, which we shall study in the next section.

Figure 2.5 shows the inverting configuration. It consists of one op amp and two resistors R_1 and R_2. Resistor R_2 is connected from the output terminal of the op amp, terminal 3, *back* to the *inverting* or *negative* input terminal, terminal 1. We speak of R_2 as applying **negative feedback**; if R_2 were connected between terminals 3 and 2 we would have called this **positive feedback**. Note also that R_2 *closes the loop* around the op amp. In addition to adding R_2, we have grounded terminal 2 and connected a resistor R_1 between terminal 1 and an input signal source

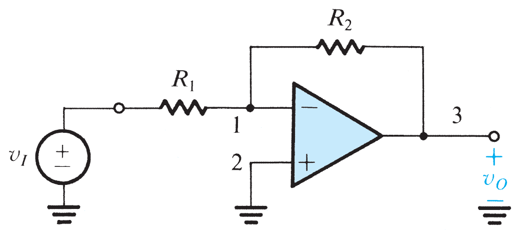


Figure 2.5 The inverting closed-loop configuration.

with a voltage v_I. The output of the overall circuit is taken at terminal 3 (i.e., between terminal 3 and ground). Terminal 3 is, of course, a convenient point from which to take the output, since the impedance level there is ideally zero. Thus the voltage v_O will not depend on the value of the current that might be supplied to a load impedance connected between terminal 3 and ground.

2.2.1 The Closed-Loop Gain

We now wish to analyze the circuit in Fig. 2.5 to determine the **closed-loop gain** G, defined as

$$G \equiv \frac{v_O}{v_I}$$

We will do so assuming the op amp to be ideal. Figure 2.6(a) shows the equivalent circuit, and the analysis proceeds as follows: The gain A is very large (ideally infinite). If we assume that the circuit is "working" and producing a finite output voltage at terminal 3, then the voltage between the op-amp input terminals should be negligibly small and ideally zero. Specifically, if we call the output voltage v_O, then, by definition,

$$v_2 - v_1 = \frac{v_O}{A} = 0$$

It follows that the voltage at the inverting input terminal (v_1) is given by $v_1 = v_2$. That is, because the gain A approaches infinity, the voltage v_1 approaches and ideally equals v_2. We speak of this as the two input terminals "tracking each other in potential." We also speak of a "virtual short circuit" that exists between the two input terminals. Here the word *virtual* should be emphasized, and one should *not* make the mistake of physically shorting terminals 1 and 2 together while analyzing a circuit. A **virtual short circuit** means that whatever voltage is at 2 will automatically appear at 1 because of the infinite gain A. But terminal 2 happens to be connected to ground; thus $v_2 = 0$ and $v_1 = 0$. We speak of terminal 1 as being a **virtual ground**—that is, having zero voltage but not physically connected to ground.

Now that we have determined v_1 we are in a position to apply Ohm's law and find the current i_1 through R_1 (see Fig. 2.6) as follows:

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

Where will this current go? It cannot go into the op amp, since the ideal op amp has an infinite input impedance and hence draws zero current. It follows that i_1 will have to flow through R_2 to the low-impedance terminal 3. We can then apply Ohm's law to R_2 and determine v_O; that is,

$$\begin{aligned} v_O &= v_1 - i_1 R_2 \\ &= 0 - \frac{v_I}{R_1} R_2 \end{aligned}$$

Thus,

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

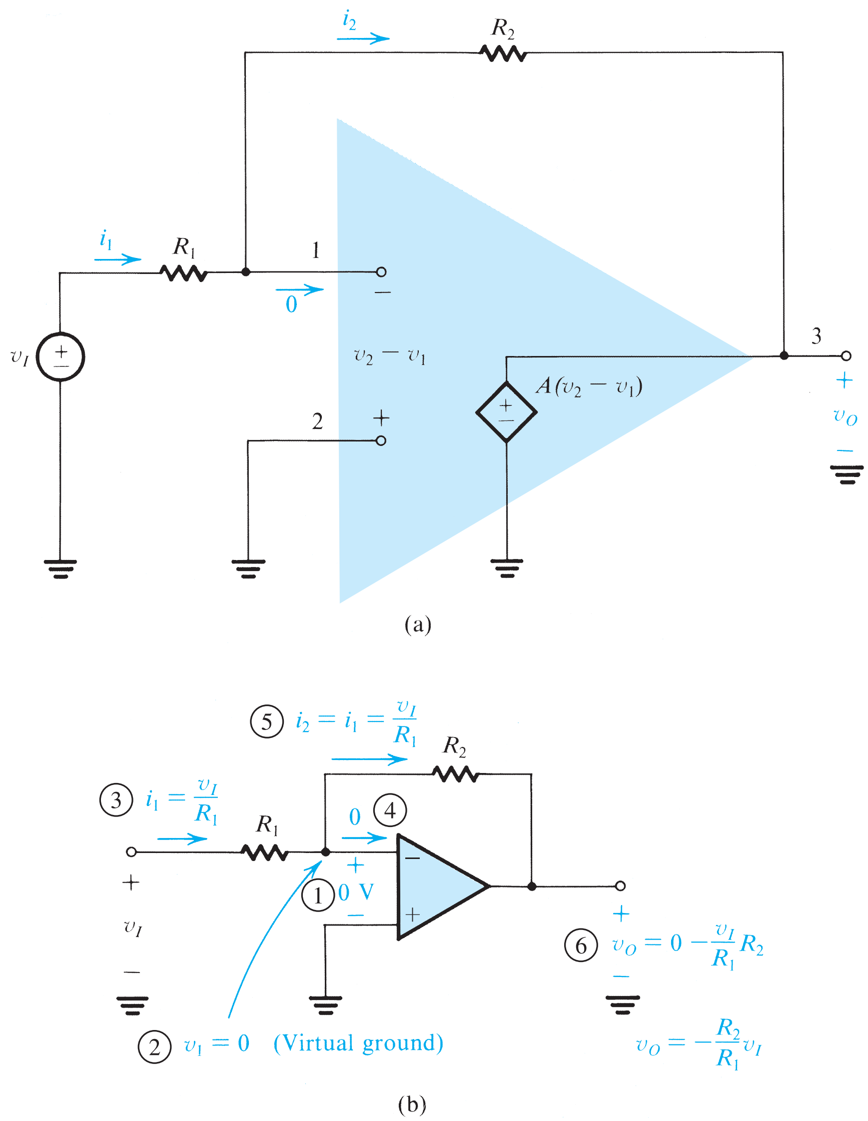


Figure 2.6 Analysis of the inverting configuration. The circled numbers indicate the order of the analysis steps.

which is the required closed-loop gain. Figure 2.6(b) illustrates these steps and indicates by the circled numbers the order in which the analysis is performed.

We thus see that the closed-loop gain is simply the ratio of the two resistances R_2 and R_1. The minus sign means that the closed-loop amplifier provides signal inversion. Thus if $R_2/R_1 = 10$ and we apply at the input (v_I) a sine-wave signal of 1 V peak-to-peak, then the output v_O will be a sine wave of 10 V peak-to-peak and phase-shifted 180° with respect to the input sine wave. Because of the minus sign associated with the closed-loop gain, this configuration is called the **inverting configuration**.

Reference-2

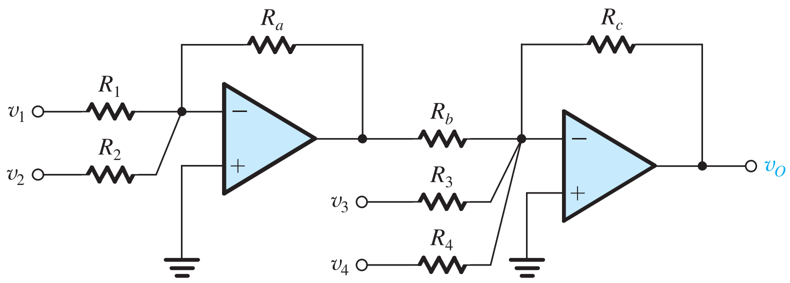


Figure 2.11 A weighted summer capable of implementing summing coefficients of both signs.

EXERCISES

D2.7 Design an inverting op-amp circuit to form the weighted sum v_O of two inputs v_1 and v_2. It is required that $v_O = -(v_1 + 5v_2)$. Choose values for R_1, R_2, and R_f so that for a maximum output voltage of 10 V the current in the feedback resistor will not exceed 1 mA.
Ans. A possible choice: $R_1 = 10\text{ k}\Omega, R_2 = 2\text{ k}\Omega$, and $R_f = 10\text{ k}\Omega$

D2.8 Use the idea presented in Fig. 2.11 to design a weighted summer that provides

$$v_O = 2v_1 + v_2 - 4v_3$$

Ans. A possible choice: $R_1 = 5\text{ k}\Omega$, $R_2 = 10\text{ k}\Omega$, $R_a = 10\text{ k}\Omega$, $R_b = 10\text{ k}\Omega$, $R_3 = 2.5\text{ k}\Omega$, $R_c = 10\text{ k}\Omega$

2.3 The Noninverting Configuration

The second closed-loop configuration we shall study is shown in Fig. 2.12. Here the input signal v_I is applied directly to the positive input terminal of the op amp while one terminal of R_1 is connected to ground.

2.3.1 The Closed-Loop Gain

Analysis of the noninverting circuit to determine its closed-loop gain (v_O/v_I) is illustrated in Fig. 2.13. Again the order of the steps in the analysis is indicated by circled numbers. Assuming that the op amp is ideal with infinite gain, a virtual short circuit exists between its two input terminals. Hence the difference input signal is

$$v_{Id} = \frac{v_O}{A} = 0 \qquad \text{for } A = \infty$$

Thus the voltage at the inverting input terminal will be equal to that at the noninverting input terminal, which is the applied voltage v_I. The current through R_1 can then be determined as v_I/R_1. Because of the infinite input impedance of the op amp, this current will flow through R_2, as shown in Fig. 2.13. Now the output voltage can be determined from

$$v_O = v_I + \left(\frac{v_I}{R_1}\right)R_2$$

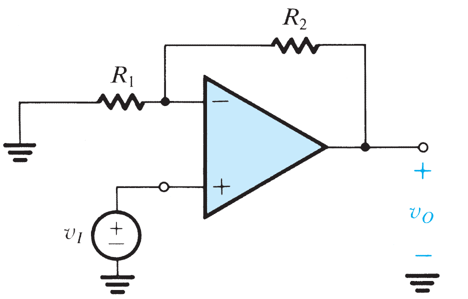


Figure 2.12 The noninverting configuration.

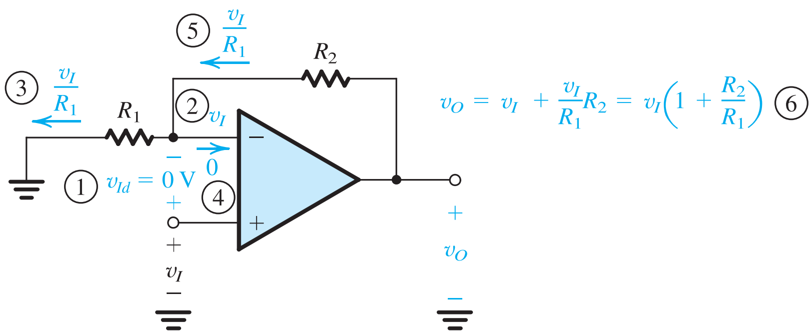


Figure 2.13 Analysis of the noninverting circuit. The sequence of the steps in the analysis is indicated by the circled numbers.

which yields

$$\frac{v_O}{v_I} = 1 + \frac{R_I}{R_2} \tag{2.9}$$

Further insight into the operation of the noninverting configuration can be obtained by considering the following: Since the current into the op-amp inverting input is zero, the circuit composed of R_1 and R_2 acts in effect as a voltage divider feeding a fraction of the output voltage back to the inverting input terminal of the op amp; that is,

$$v_1 = v_O\left(\frac{R_1}{R_1 + R_2}\right) \tag{2.10}$$

Then the infinite op-amp gain and the resulting virtual short circuit between the two input terminals of the op amp forces this voltage to be equal to that applied at the positive input terminal; thus,

$$v_O\left(\frac{R_1}{R_1 + R_2}\right) = v_I$$

which yields the gain expression given in Eq. (2.9).

This is an appropriate point to reflect further on the action of the negative feedback present in the noninverting circuit of Fig. 2.12. Let v_I increase. Such a change in v_I will cause v_{Id} to increase, and v_O will correspondingly increase as a result of the high (ideally infinite) gain of the op amp. However, a fraction of the increase in v_O will be fed back to the inverting input terminal of the op amp through the (R_1, R_2) voltage divider. The result of this feedback will be to counteract the increase in v_{Id}, driving v_{Id} back to zero, albeit at a higher value of v_O that corresponds to the increased value of v_I. This *degenerative* action of negative feedback gives it the alternative name **degenerative feedback**. Finally, note that the argument above applies equally well if v_I decreases. A formal and detailed study of feedback is presented in Chapter 11.

2.3.2 Effect of Finite Open-Loop Gain

As we have done for the inverting configuration, we now consider the effect of the finite op-amp open-loop gain A on the gain of the noninverting configuration. Assuming the op amp to be ideal except for having a finite open-loop gain A, it can be shown that the closed-loop gain of the noninverting amplifier circuit of Fig. 2.12 is given by

$$G \equiv \frac{v_O}{v_I} = \frac{1 + (R_2/R_1)}{1 + \dfrac{1 + (R_2/R_1)}{A}} \tag{2.11}$$

Observe that the denominator is identical to that for the case of the inverting configuration (Eq. 2.5). This is no coincidence; it is a result of the fact that both the inverting and the noninverting configurations have the same feedback loop, which can be readily seen if the input signal source is eliminated (i.e., short-circuited). The numerators, however, are different, for the numerator gives the ideal or nominal closed-loop gain ($-R_2/R_1$ for the inverting configuration, and $1 + R_2/R_1$ for the noninverting configuration). Finally, we note (with reassurance) that the gain expression in Eq. (2.11) reduces to the ideal value for $A = \infty$. In fact, it approximates the ideal value for

$$A \gg 1 + \frac{R_2}{R_1}$$

This is the same condition as in the inverting configuration, except that here the quantity on the right-hand side is the nominal closed-loop gain. The expressions for the actual and ideal values of the closed-loop gain G in Eqs. (2.11) and (2.9), respectively, can be used to determine the percentage error in G resulting from the finite op-amp gain A as

$$\text{Percent gain error } = -\frac{1 + (R_2/R_1)}{A + 1 + (R_2/R_1)} \times 100 \tag{2.12}$$

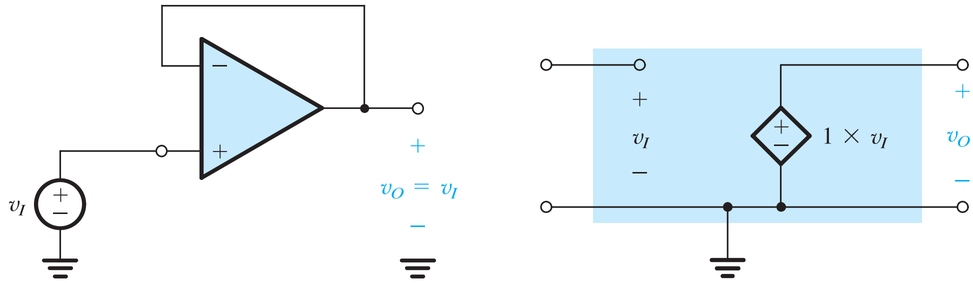
Thus, as an example, if an op amp with an open-loop gain of 1000 is used to design a noninverting amplifier with a nominal closed-loop gain of 10, we would expect the closed-loop gain to be about 1% below the nominal value.

2.3.3 Input and Output Resistance

The gain of the noninverting configuration is positive—hence the name *noninverting*. The input impedance of this closed-loop amplifier is ideally infinite, since no current flows into the positive input terminal of the op amp. The output of the noninverting amplifier is taken at the terminals of the ideal voltage source $A(v_2 - v_1)$ (see the op-amp equivalent circuit in Fig. 2.3), and thus the output resistance of the noninverting configuration is zero.

2.3.4 The Voltage Follower

The property of high input impedance is a very desirable feature of the noninverting configuration. It enables using this circuit as a buffer amplifier to connect a source with a high impedance to a low-impedance load. We discussed the need for buffer amplifiers in Section 1.5. In many applications the buffer amplifier is not required to provide any voltage gain; rather, it is used mainly as an impedance transformer or a power amplifier. In such cases we may make $R_2 = 0$ and $R_1 = \infty$ to obtain the **unity-gain amplifier** shown in Fig. 2.14(a). This circuit is commonly referred to as a **voltage follower**, since the output "follows" the input. In the ideal case, $v_O = v_I$, $R_{in} = \infty$, $R_{out} = 0$, and the follower has the equivalent circuit shown in Fig. 2.14(b).



(a) (b)

Figure 2.14 **(a)** The unity-gain buffer or follower amplifier. **(b)** Its equivalent circuit model.

Since in the voltage-follower circuit the entire output is fed back to the inverting input, the circuit is said to have 100% negative feedback. The infinite gain of the op amp then acts to make $v_{Id} = 0$ and hence $v_O = v_I$. Observe that the circuit is elegant in its simplicity!

Since the noninverting configuration has a gain greater than or equal to unity, depending on the choice of R_2/R_1, some prefer to call it "a follower with gain."

EXERCISES

2.9 Use the superposition principle to find the output voltage of the circuit shown in Fig. E2.9.
Ans. $v_O = 6v_1 + 4v_2$

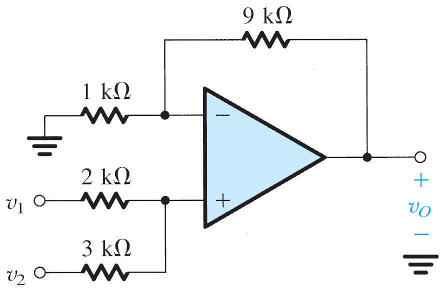


Figure E2.9

2.10 If in the circuit of Fig. E2.9 the 1-kΩ resistor is disconnected from ground and connected to a third signal source v_3, use superposition to determine v_O in terms of v_1, v_2, and v_3.
Ans. $v_O = 6v_1 + 4v_2 - 9v_3$

D2.11 Design a noninverting amplifier with a gain of 2. At the maximum output voltage of 10 V the current in the voltage divider is to be 10 μA.
Ans. $R_1 = R_2 = 0.5\ \text{M}\Omega$

2.12 (a) Show that if the op amp in the circuit of Fig. 2.12 has a finite open-loop gain A, then the closed-loop gain is given by Eq. (2.11). (b) For $R_1 = 1$ kΩ and $R_2 = 9$ kΩ find the percentage deviation ϵ of the closed-loop gain from the ideal value of $(1 + R_2/R_1)$ for the cases $A = 10^3, 10^4$, and 10^5. For $v_I = 1$ V, find in each case the voltage between the two input terminals of the op amp.
Ans. $\epsilon = -1\%, -0.1\%, -0.01\%$; $v_2 - v_1 = 9.9$ mV, 1 mV, 0.1 mV

2.13 For the circuit in Fig. E2.13 find the values of i_I, v_1, i_1, i_2, v_O, i_L, and i_O. Also find the voltage gain v_O/v_I, the current gain i_L/i_I, and the power gain P_L/P_I.
Ans. 0; 1 V; 1 mA; 1 mA; 10 V; 10 mA; 11 mA; 10 V/V (20 dB); ∞; ∞

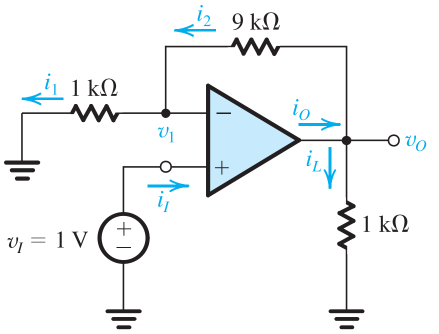


Figure E2.13

2.14 It is required to connect a transducer having an open-circuit voltage of 1 V and a source resistance of 1 MΩ to a load of 1-kΩ resistance. Find the load voltage if the connection is done (a) directly, and (b) through a unity-gain voltage follower.
Ans. (a) 1 mV; (b) 1 V

2.4 Difference Amplifiers

Having studied the two basic configurations of op-amp circuits together with some of their direct applications, we are now ready to consider a somewhat more involved but very important application. Specifically, we shall study the use of op amps to design difference or differential amplifiers.[2] A difference amplifier is one that responds to the difference between the two signals applied at its input and ideally rejects signals that are common to the two inputs. The representation of signals in terms of their differential and common-mode components was given in Fig. 2.4. It is repeated here in Fig. 2.15 with slightly different symbols to serve as the input signals for the difference amplifiers we are about to design. Although ideally the difference amplifier will amplify only the differential input signal v_{Id} and reject completely the common-mode input signal v_{Icm}, practical circuits will have an output voltage v_O given by

$$v_O = A_d v_{Id} + A_{cm} v_{Icm} \tag{2.13}$$

where A_d denotes the amplifier differential gain and A_{cm} denotes its common-mode gain (ideally zero). The efficacy of a differential amplifier is measured by the degree of its rejection of common-mode signals in preference to differential signals. This is usually quantified by a measure known as the **common-mode rejection ratio (CMRR)**, defined as

$$\text{CMRR} = 20 \log \frac{|A_d|}{|A_{cm}|} \tag{2.14}$$

In Db

[2]The terms *difference* and *differential* are usually used to describe somewhat different amplifier types. For our purposes at this point, the distinction is not sufficiently significant. We will be more precise near the end of this section.

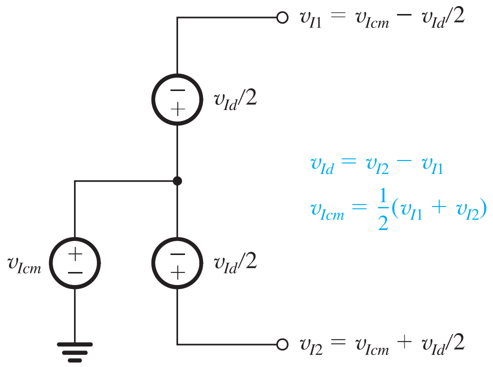


Figure 2.15 Representing the input signals to a differential amplifier in terms of their differential and common-mode components.

The need for difference amplifiers arises frequently in the design of electronic systems, especially those employed in instrumentation. As a common example, consider a transducer providing a small (e.g., 1 mV) signal between its two output terminals while each of the two wires leading from the transducer terminals to the measuring instrument may have a large interference signal (e.g., 1 V) relative to the circuit ground. The instrument front end obviously needs a difference amplifier.

Before we proceed any further we should address a question that the reader might have: The op amp is itself a difference amplifier; why not just use an op amp? The answer is that the very high (ideally infinite) gain of the op amp makes it impossible to use by itself. Rather, as we did before, we have to devise an appropriate feedback network to connect to the op amp to create a circuit whose closed-loop gain is finite, predictable, and stable.

2.4.1 A Single-Op-Amp Difference Amplifier

Our first attempt at designing a difference amplifier is motivated by the observation that the gain of the noninverting amplifier configuration is positive, $(1 + R_2/R_1)$, while that of the inverting configuration is negative, $(-R_2/R_1)$. Combining the two configurations together is then a step in the right direction—namely, getting the difference between two input signals. Of course, we have to make the two gain magnitudes equal in order to reject common-mode signals. This, however, can be easily achieved by attenuating the positive input signal to reduce the gain of the positive path from $(1+R_2/R_1)$ to (R_2/R_1). The resulting circuit would then look like that shown in Fig. 2.16, where the attenuation in the positive input path is achieved by the voltage divider (R_3, R_4). The proper ratio of this voltage divider can be determined from

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

which can be put in the form

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

This condition is satisfied by selecting

$$\frac{R_4}{R_3} = \frac{R_2}{R_1} \tag{2.15}$$

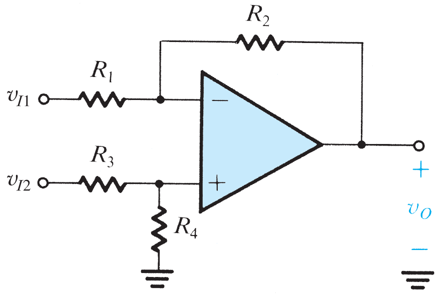


Figure 2.16 A difference amplifier.

This completes our work. However, we have perhaps proceeded a little too fast! Let's step back and verify that the circuit in Fig. 2.16 with R_3 and R_4 selected according to Eq. (2.15) does in fact function as a difference amplifier. Specifically, we wish to determine the output voltage v_O in terms of v_{I1} and v_{I2}. Toward that end, we observe that the circuit is linear, and thus we can use superposition.

To apply superposition, we first reduce v_{I2} to zero—that is, ground the terminal to which v_{I2} is applied—and then find the corresponding output voltage, which will be due entirely to v_{I1}. We denote this output voltage v_{O1}. Its value may be found from the circuit in Fig. 2.17(a), which we recognize as that of the inverting configuration. The existence of R_3 and R_4 does not affect the gain expression, since no current flows through either of them. Thus,

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

Next, we reduce v_{I1} to zero and evaluate the corresponding output voltage v_{O2}. The circuit will now take the form shown in Fig. 2.17(b), which we recognize as the noninverting configuration with an additional voltage divider, made up of R_3 and R_4, connected to the input v_{I2}. The output voltage v_{O2} is therefore given by

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

where we have utilized Eq. (2.15).

The superposition principle tells us that the output voltage v_O is equal to the sum of v_{O1} and v_{O2}. Thus we have

$$v_O = \frac{R_2}{R_1}(v_{I2} - v_{I1}) = \frac{R_2}{R_1} v_{Id} \tag{2.16}$$

Thus, as expected, the circuit acts as a difference amplifier with a differential gain A_d of

$$A_d = \frac{R_2}{R_1} \tag{2.17}$$

Of course this is predicated on the op amp being ideal and furthermore on the selection of R_3 and R_4 so that their ratio matches that of R_1 and R_2 (Eq. 2.15). To make this matching requirement a little easier to satisfy, we usually select

$$R_3 = R_1 \quad \text{and} \quad R_4 = R_2$$

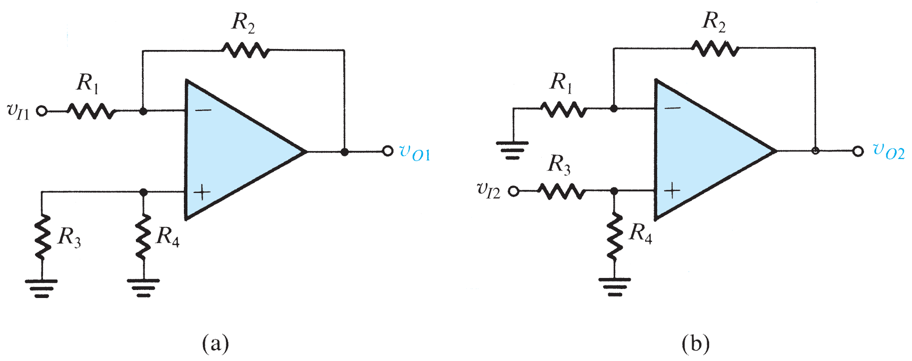


Figure 2.17 Application of superposition to the analysis of the circuit of Fig. 2.16.

Let's next consider the circuit with only a common-mode signal applied at the input, as shown in Fig. 2.18. The figure also shows some of the analysis steps. Thus,

$$i_1 = \frac{1}{R_1}\left[v_{Icm} - \frac{R_4}{R_4+R_3}v_{Icm}\right]$$
$$= v_{Icm}\frac{R_3}{R_4+R_3}\frac{1}{R_1} \tag{2.18}$$

The output voltage can now be found from

$$v_O = \frac{R_4}{R_4+R_3}v_{Icm} - i_2R_2$$

Substituting $i_2 = i_1$ and for i_1 from Eq. (2.18),

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

Thus,

$$A_{cm} \equiv \frac{v_O}{v_{Icm}} = \left(\frac{R_4}{R_4+R_3}\right)\left(1-\frac{R_2}{R_1}\frac{R_3}{R_4}\right) \tag{2.19}$$

For the design with the resistor ratios selected according to Eq. (2.15), we obtain

$$A_{cm} = 0$$

as expected. Note, however, that any mismatch in the resistance ratios can make A_{cm} nonzero, and hence CMRR finite.

In addition to rejecting common-mode signals, a difference amplifier is usually required to have a high input resistance. To find the input resistance between the two input terminals

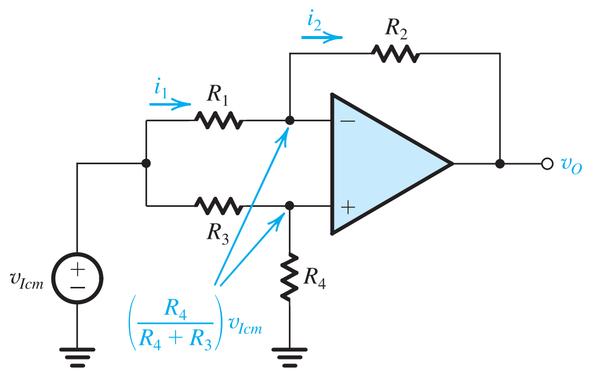


Figure 2.18 Analysis of the difference amplifier to determine its common-mode gain $A_{cm} \equiv v_O/v_{Icm}$.

(i.e., the resistance seen by v_{Id}), called the **differential input resistance** R_{id}, consider Fig. 2.19. Here we have assumed that the resistors are selected so that

$$R_3 = R_1 \quad \text{and} \quad R_4 = R_2$$

Now

$$R_{id} \equiv \frac{v_{Id}}{i_I}$$

Since the two input terminals of the op amp track each other in potential, we may write a loop equation and obtain

$$v_{Id} = R_1 i_I + 0 + R_1 i_I$$

Thus,

$$R_{id} = 2R_1 \tag{2.20}$$

Note that if the amplifier is required to have a large differential gain (R_2/R_1), then R_1 of necessity will be relatively small and the input resistance will be correspondingly low, a drawback of this circuit. Another drawback of the circuit is that it is not easy to vary the differential gain of the amplifier. Both of these drawbacks are overcome in the instrumentation amplifier discussed next.

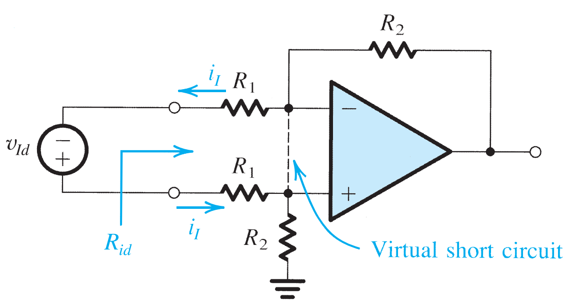


Figure 2.19 Finding the input resistance of the difference amplifier for the case $R_3 = R_1$ and $R_4 = R_2$.