MIT-WPU

Dr. Vishwanath Karad
MIT WORLD PEACE UNIVERSITY | PUNE
TECHNOLOGY, RESEARCH, SOCIAL INNOVATION & PARTNERSHIPS

Basics of Electrical and Electronics Engineering

ECE1022A

UNIT-III

Introduction to Integrated Circuits Technology

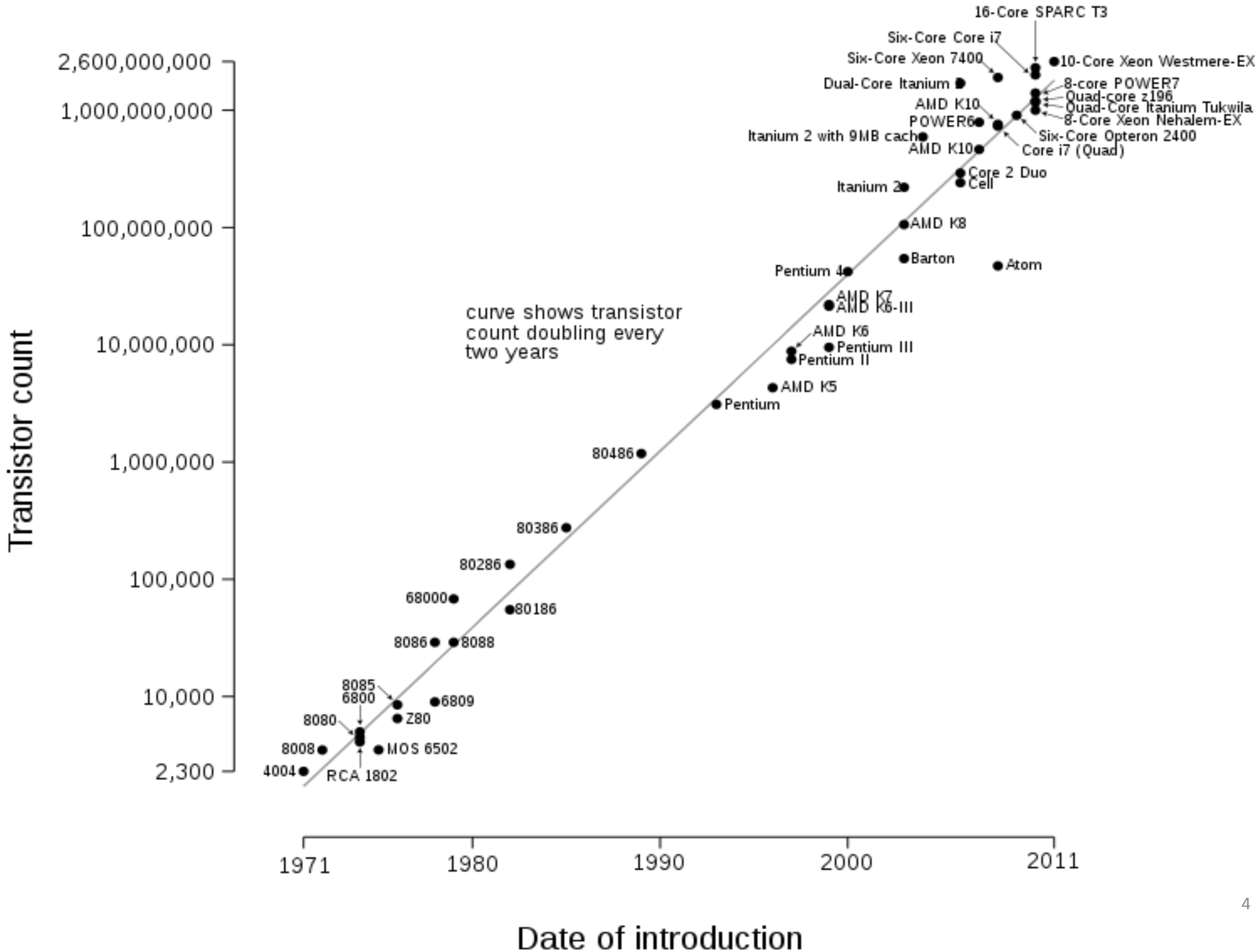
- VLSI
  - **V**ery-**L**arge-**S**cale **I**ntegration
- Today's complex VLSI chips
  - The number of transistors has exceeded 120 million
  - Die area is typically about 1cm^2
- Moore's law

(Gordon Moore, one of the cofounders of the Intel Corporation)

The number of transistors on a chip would double about every 18 months

In 1965, Gordon Moore made a prediction that set the pace for our modern digital revolution. From careful observation of an emerging trend, Moore extrapolated that computing would dramatically increase in power, and decrease in relative cost, at an exponential pace

Microprocessor Transistor Counts 1971-2011 & Moore's Law



Milestones for IC Industry

1947: Bardeen, Brattain & Shockley invented the transistor, foundation of the IC industry.

1952: SONY introduced the first transistor-based radio**.**

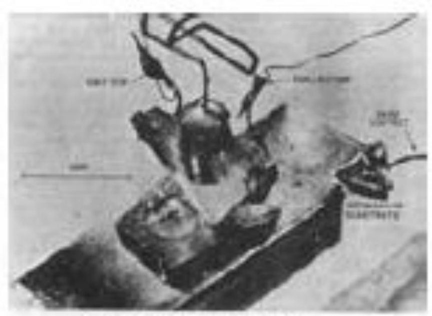
1958: Kilby invented integrated circuits (ICs).

1965: Moore's law.

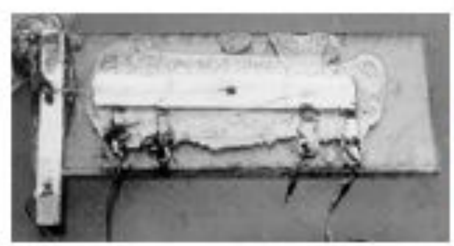
1968: Noyce and Moore founded Intel.

1970: Intel introduced 1K DRAM.

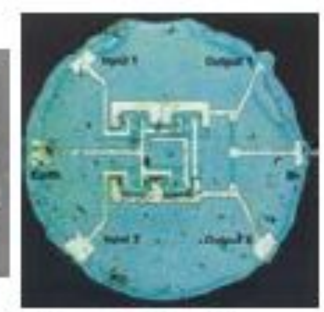
In 1956 John Bardeen, William Shockley and Walter Brattain shared the Nobel Prize in Physics for their discovery of the transistor.



First transistor



First IC by Kilby



First IC by Noyce

Milestones for IC Industry

- **1971:** Intel announced 4-bit 4004 microprocessors (2250 transistors).
- **1976/81:** Apple II/IBM PC.
- **1984:** Xilinx invented FPGA’s.
- **1985:** Intel began focusing on microprocessor products.
- **1987:** TSMC was founded (fabless IC design).
- **1991:** ARM introduced its first embeddable RISC IP core


Intel founders


4004


IBM PC

Milestones for IC Industry (Cont'd)

1996: Samsung introduced 1G DRAM.

1998: IBM announces1GHz experimental microprocessor.

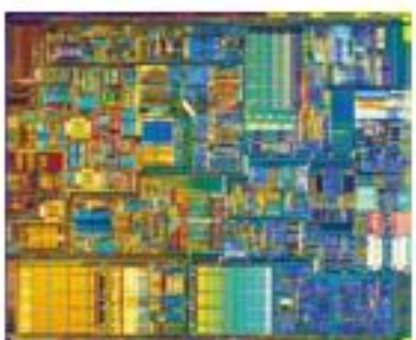
1999/earlier: System-on-Chip (SOC) applications.

2002/earlier: System-in-Package (SIP) technology.

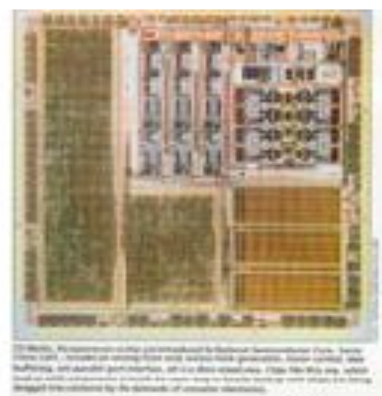
An Intel P4 processor contains 42 million transistors

A dual-core mobile of the Intel Core i3/i5/i7 has around **1.75 Billion transistors** for a die size of 101.83 mm²

4GB DRAM (2001)



Pentium 4

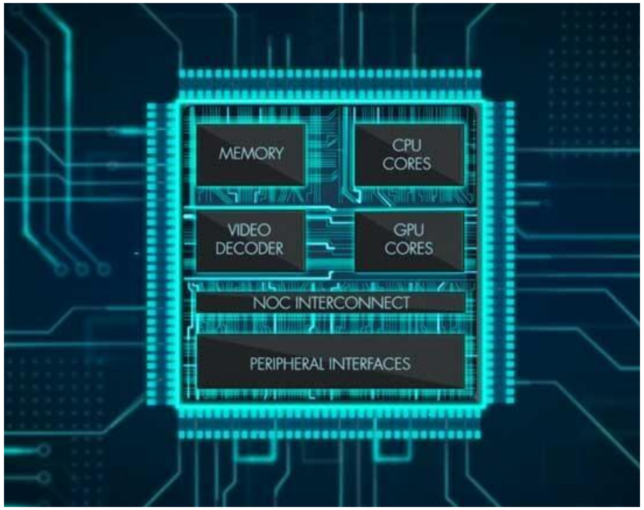


Scanner-on-chip

Blue tooth technology

SoC- System on a chip

An integrated circuit (also known as a "chip") is that which integrates all components of a computer or other electronic system. These components typically (but not always) include a central processing unit (CPU), memory, input/output ports and secondary storage – all on a single substrate or microchip, the size of a coin.



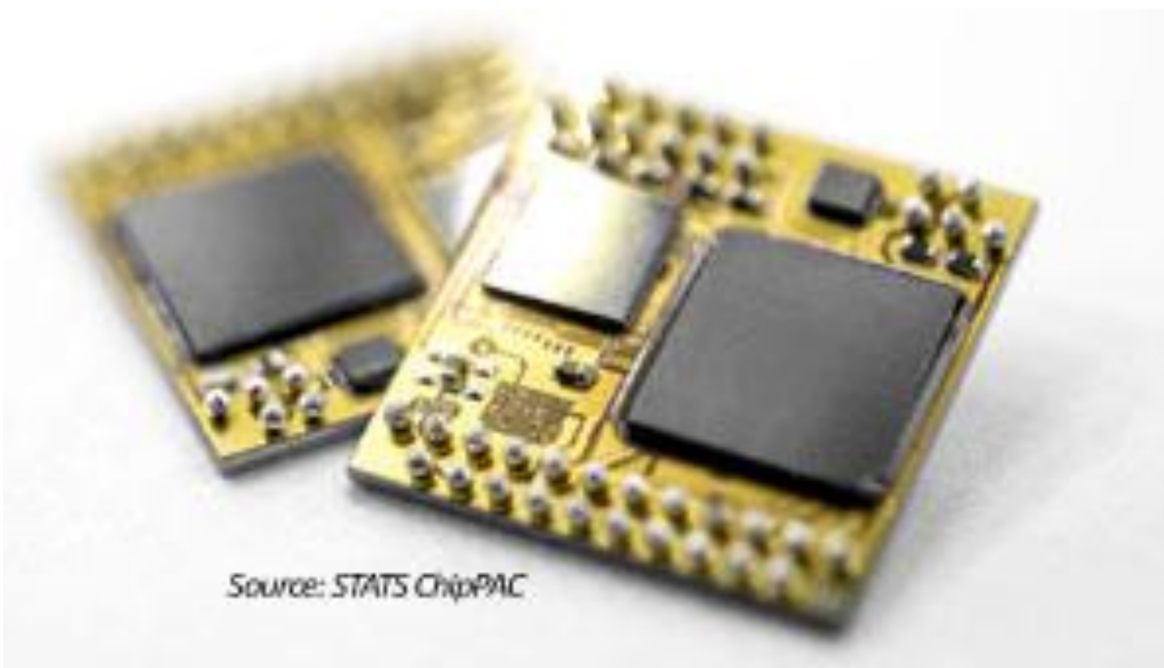
As they are integrated on a single substrate, SoCs consume much less power and take up much less area than multi-chip designs with equivalent functionality

Commonly used in embedded systems and the Internet of Things.

System In Package

A **system in package** (**SiP**) or **system**-in-a-**package** is a number of integrated circuits enclosed in a single module (**package**).

The **SiP** performs all or most of the functions of an electronic **system**, and is typically used inside a mobile phone, digital music player, etc.

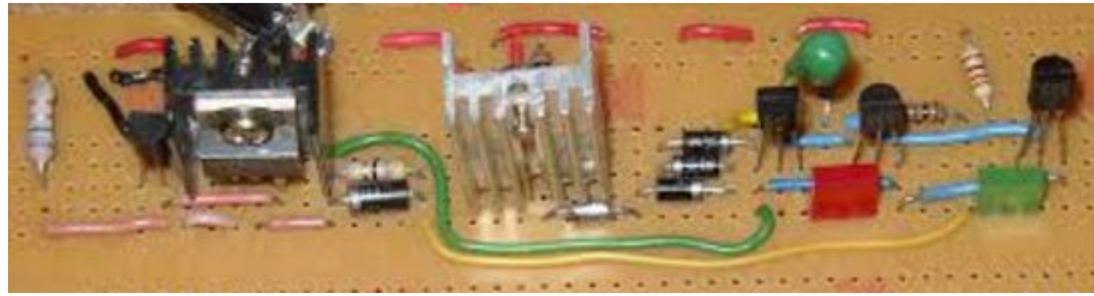


Classification of Circuits based on Different Criteria

Electronic circuits can be classified into different types based on different criteria

- **Based on connections**: Series circuits and Parallel circuits
- **Based on the size and manufacturing process** of circuit: Integrated circuits and Discrete circuits
- **Based on signal used in circuit:** Analog circuits and Digital circuits

Discrete Circuits



Disadvantages of Discrete Circuits

- Assembling and wiring of all individual discrete components take more time and occupies a larger space on PCB
- Replacement of a failed component is complicated in an existing circuit or system.
- The circuit elements are connected using soldering process that may cause less reliability.
- To overcome these problems of reliability and space conservation, integrated circuits are developed.

Integrated Circuits

- It is called Integrated circuit or IC or microchip or chip
- It is a microscopic electronic circuit array formed by the fabrication of various electronic components
- Components (resistors, capacitors, transistors,)are placed on semiconductor material (silicon) wafer
- It can perform operations similar to the large discrete electronic circuits made of discrete electronic components

IC- Integrated circuit

- ICs have three **key advantages** over digital circuits built from discrete components
  - Small size
    - ICs are much smaller, both transistors and wires are shrunk to micrometer sizes, compared to the centimeter scales of discrete components
  - High speed
    - Communication within a chip is faster than communication between chips on a PCB (Printed Circuit Board)
  - Low power consumption
    - Logic operations within a chip take much less power

Different Types of Integrated Circuits

Classification of Integrated Circuits is done based on various criteria.

Based on the intended application, the ICs are classified as:

- Analog integrated circuits
- Digital integrated circuits
- Mixed integrated circuits

Analog Integrated Circuits

- The integrated circuits that operate over a continuous range of signal are called as Analog ICs.

- These are subdivided as linear Integrated Circuits (Linear ICs) and Radio Frequency Integrated Circuits (RF ICs).

- The frequently used analog IC is an operational amplifier or simply called as an op-amp -IC 741

- It consists of very less number of transistors compared to the digital ICs.

Digital Integrated Circuits

- The integrated circuits that operate only at a few defined levels instead of operating over all levels of signal amplitude are called as Digital ICs.

- These ICs using multiple number of digital logic gates, multiplexers, flip flops and other electronic components of circuits.

- These logic gates work with binary input data or digital input data.

- Such as 0 (low or false or logic 0) and 1 (high or true or logic 1).

Digital Integrated Circuits

- These digital ICs are frequently used in the computers, microprocessors, digital signal, processors, computer networks etc.

- There are different types of Digital Integrated Circuits.

- Programmable ICs, memory chips, logic ICs, power management ICs and interface ICs.

Mixed Integrated Circuits

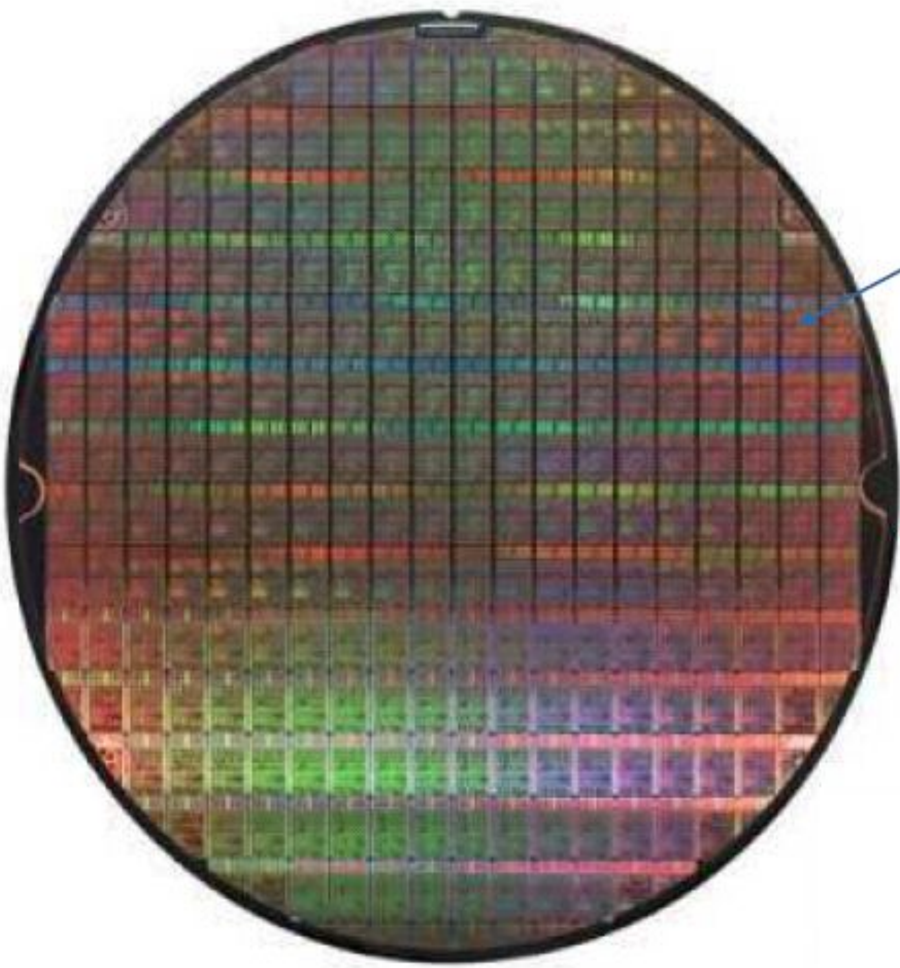
- It is the combination of analog and digital ICs on a single chip are called as Mixed ICs.

- These ICs functions as Digital to Analog converters, Analog to Digital converters and clock/timing ICs.

- This mixed-signal Systems-on-a-chip is a result of advances in the integration technology.

- It enabled to integrate digital, multiple analog and RF functions on a single chip.

IC Fabrication

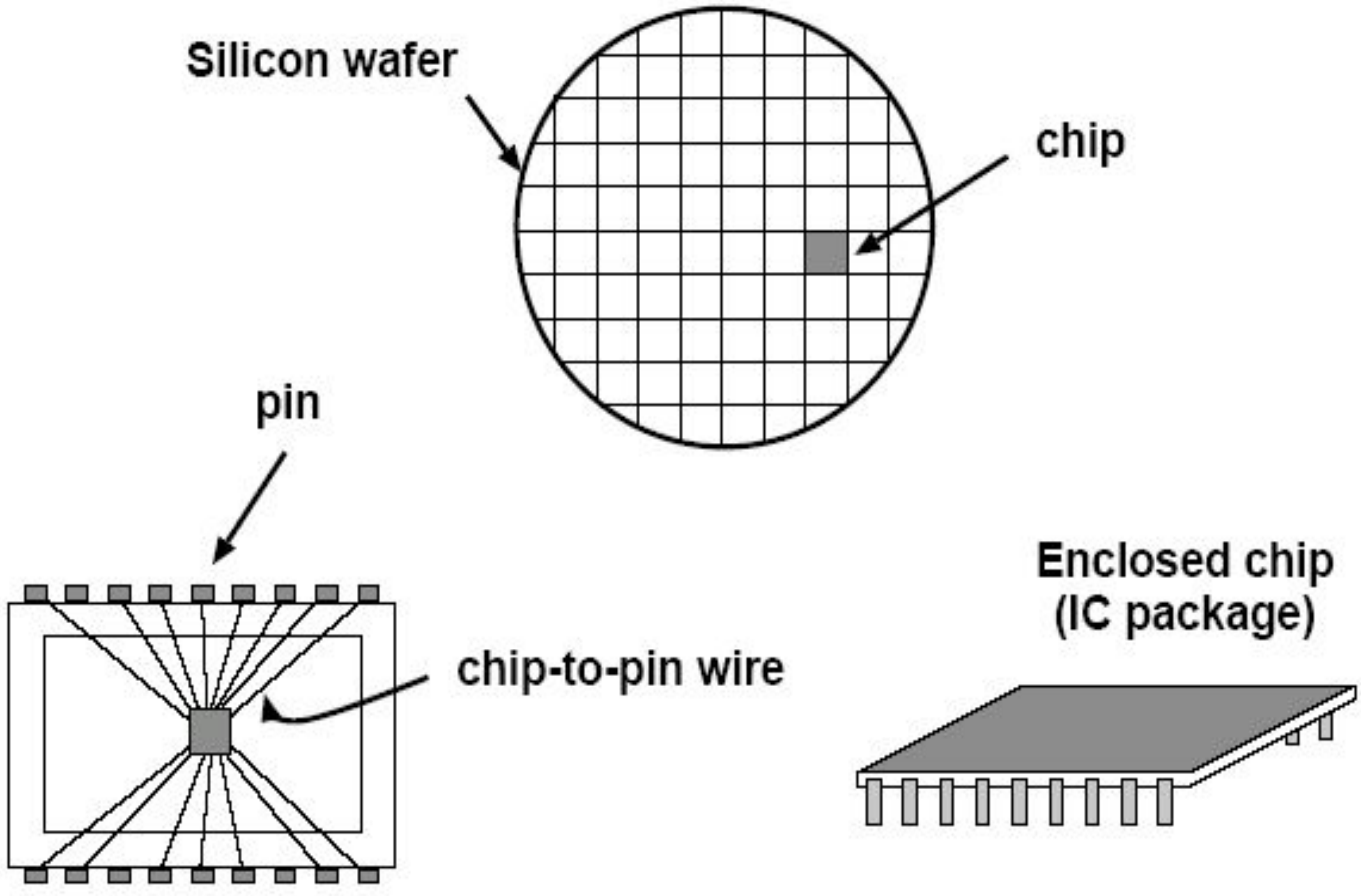


Single die

Wafer

Going up to 12″ (30cm)

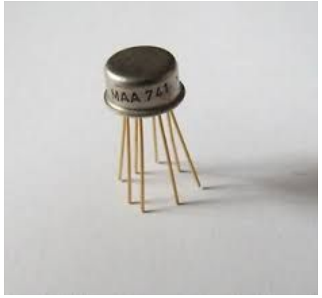
IC Fabrication



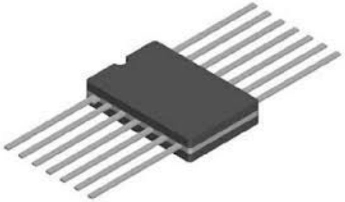
IC Packaging

Basic types of IC packages

- **The metal can or transistor pack**: chip is encapsulated in a metal or plastic case. Available with 3,5,8,10 or 12 pins
  - LM117 (voltage regulator) has 3 pins
  - Power op-amps, audio power amplifiers have 5 pins
  - General purpose op-amps come in 8,10 or 12 pins



- **The flat pack** : the chip is enclosed in a rectangular ceramic case with terminal leads extending through the sides and ends.
  Comes with 8, 10, 14 or 16 pins



- **The dual-in-line package (DIP):** chip is mounted inside a plastic or ceramic case
  - Most widely used
  - Available in 12, 14, 16 and 20 pins

SSI, MSI, LSI and VLSI Packages

ICs are classified according to the number of components integrated on the same chip;

- Small scale integration < 10 components

e.g. gate circuits

- Medium Scale integration < 100 components

e.g. LICs and Combinational Logic Circuits

- Large scale integration > 100 components

e.g. Sequential Logic Circuits

- Very Large Scale integration > 1000 components

e.g. Microprocessor IC

Manufacturer's Designation for ICs

Each manufacturer uses a specific code and assigns a specific type number to the ICs it produces. Examples are-

Fairchild	μA
Analog Devices	AD
Atmel	AT
National Semiconductor	LM
Motorola	MC
Signetics	NE
Texas Instruments	CA/CD

Example of Analog IC

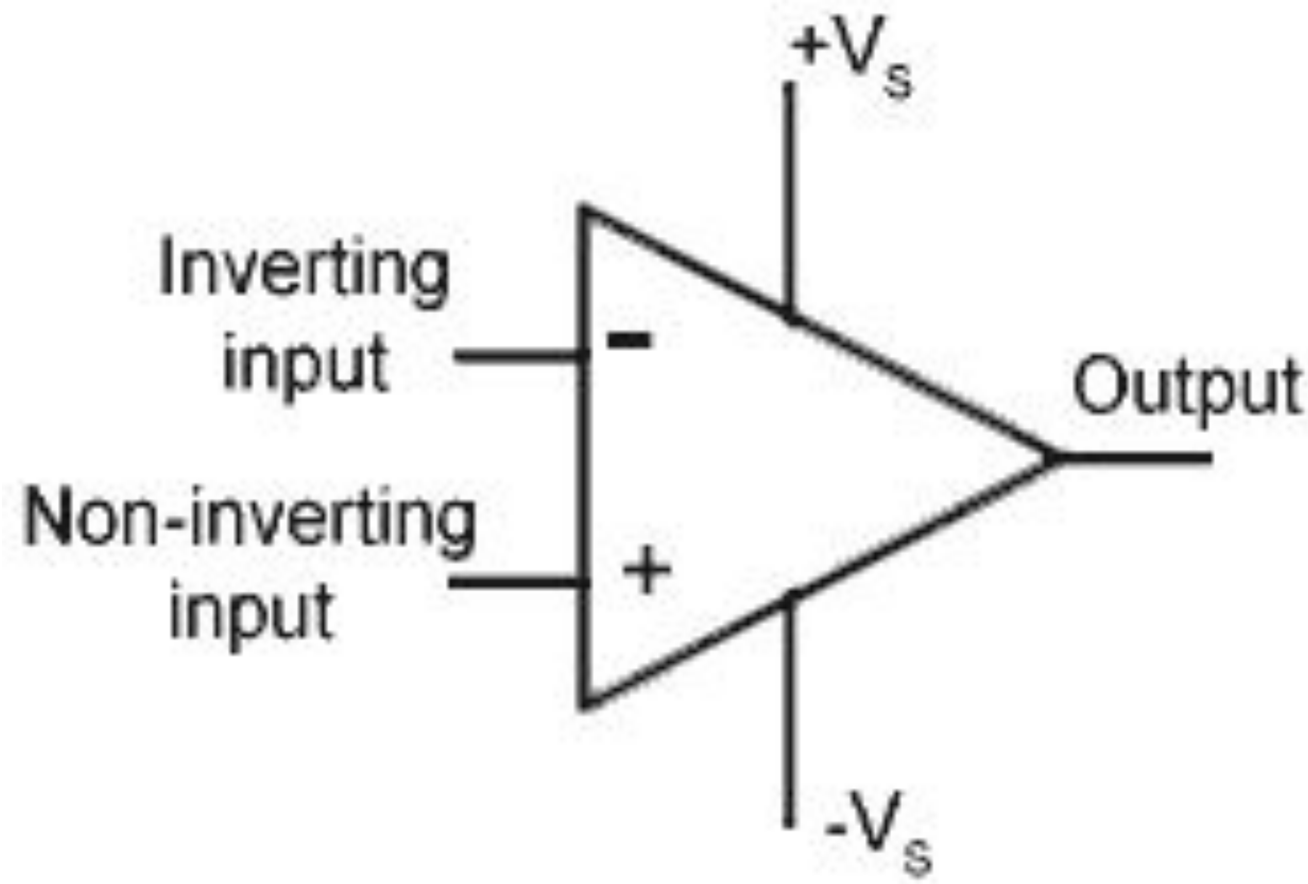
Operational Amplifier

Operational Amplifier: OP-AMP

- Linear Integrated Circuit
- Linear– Output signal varies according to the input signal
- Integrated – all components are fabricated on a single chip

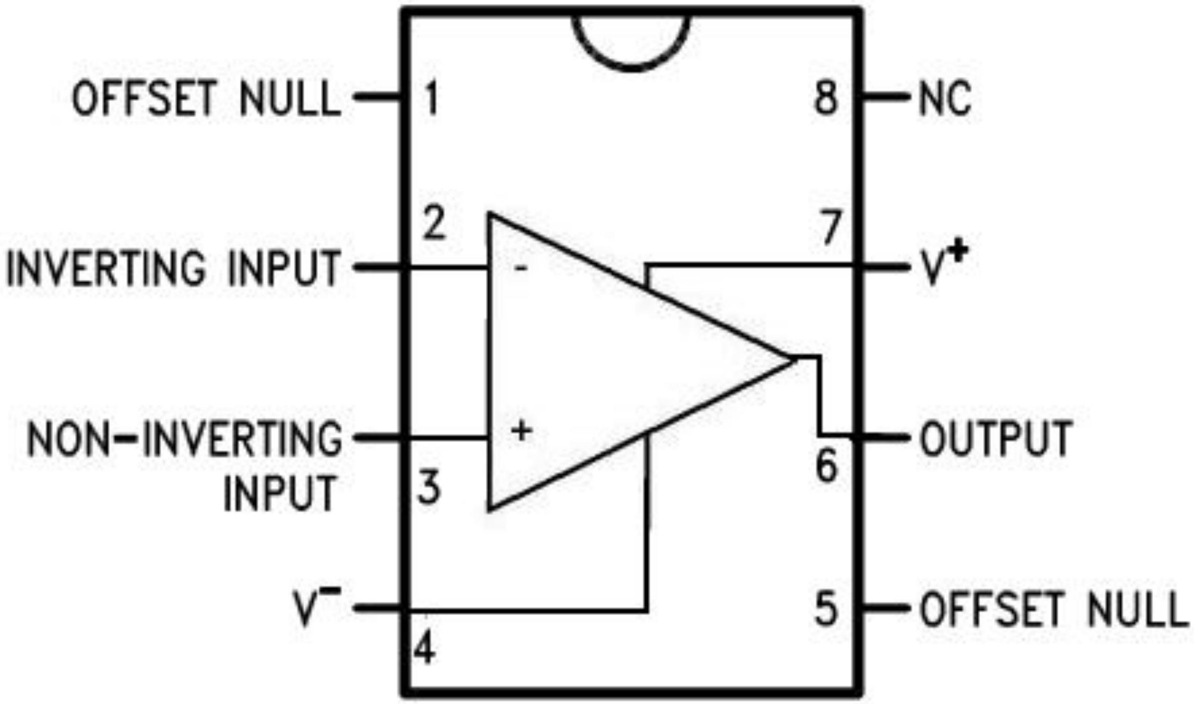
- Direct coupled high gain amplifier
- Versatile device – amplifies ac as well as dc signals
- Originally designed for computing mathematical functions as addition, subtraction, multiplication and division, hence the name OP-AMP
- Used for a variety of applications such as ac and dc signal amplification, active filters, oscillators, comparators, regulators, etc.

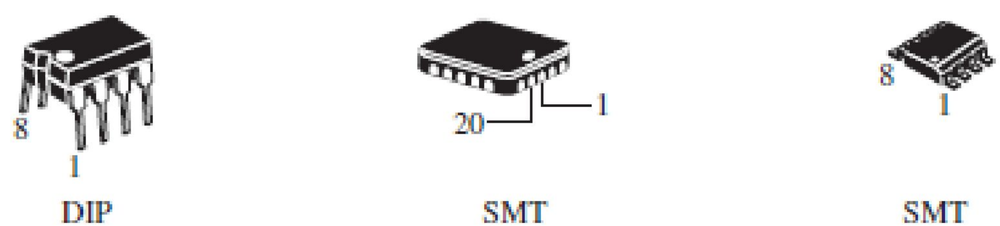
Symbol of Op-Amp



Op-amp IC Pinout diagram

LM741 Pinout Diagram





(c) Typical packages. Pin 1 is indicated by a notch or dot on dual in-line (DIP) and surface-mount technology (SMT) packages, as shown.

Block diagram of op-amp

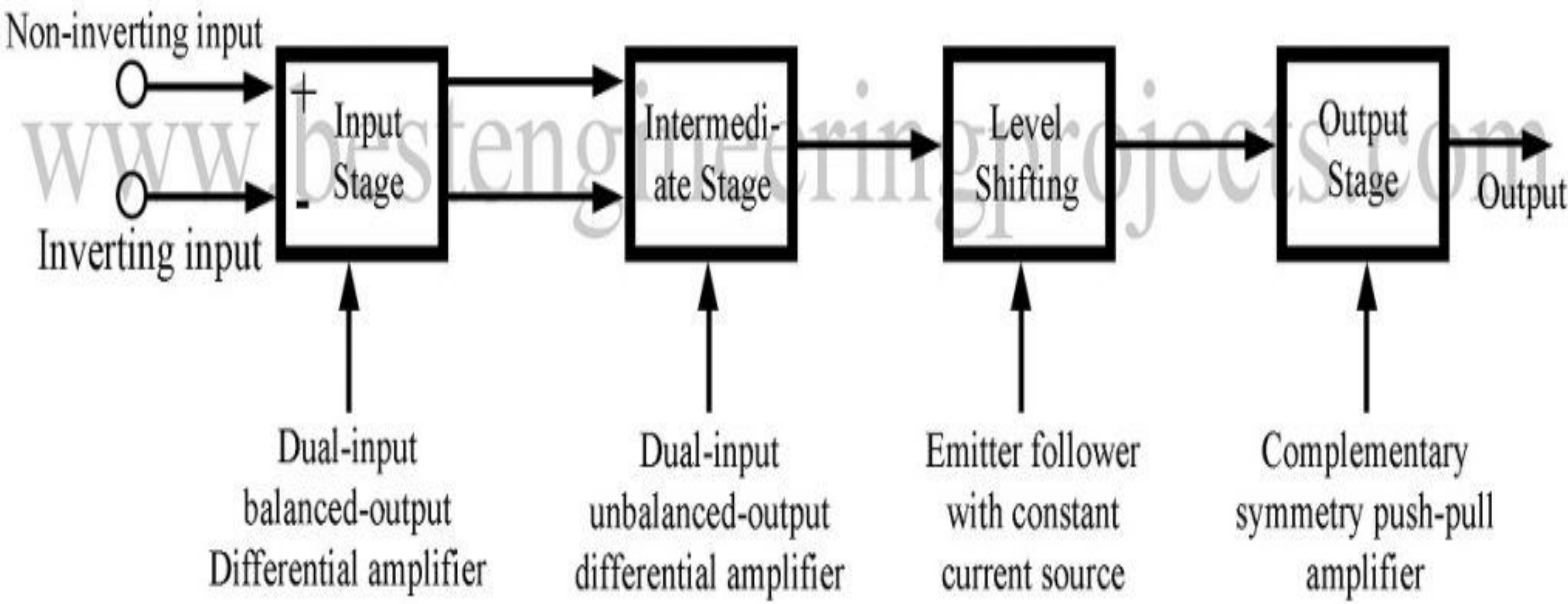
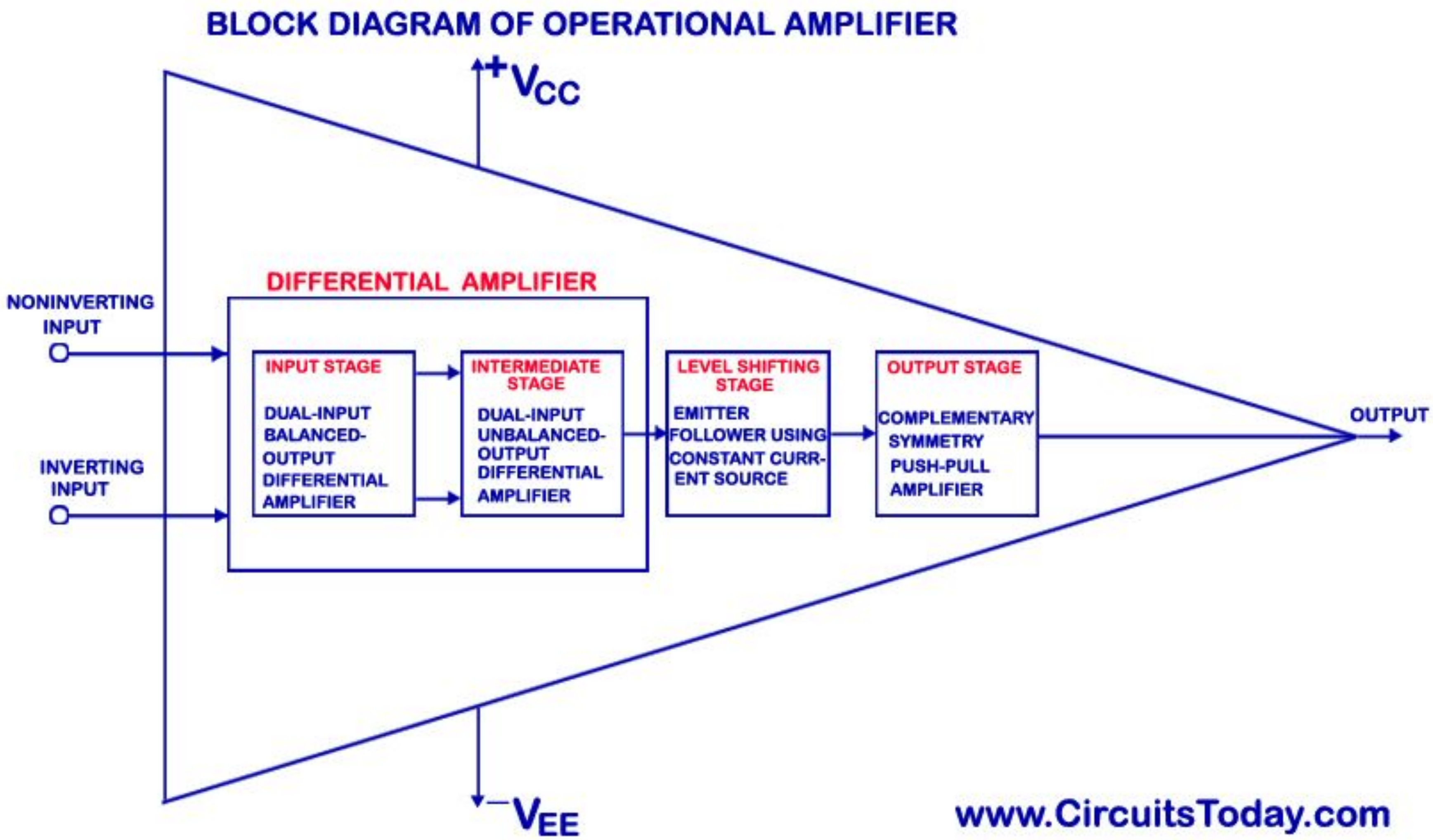
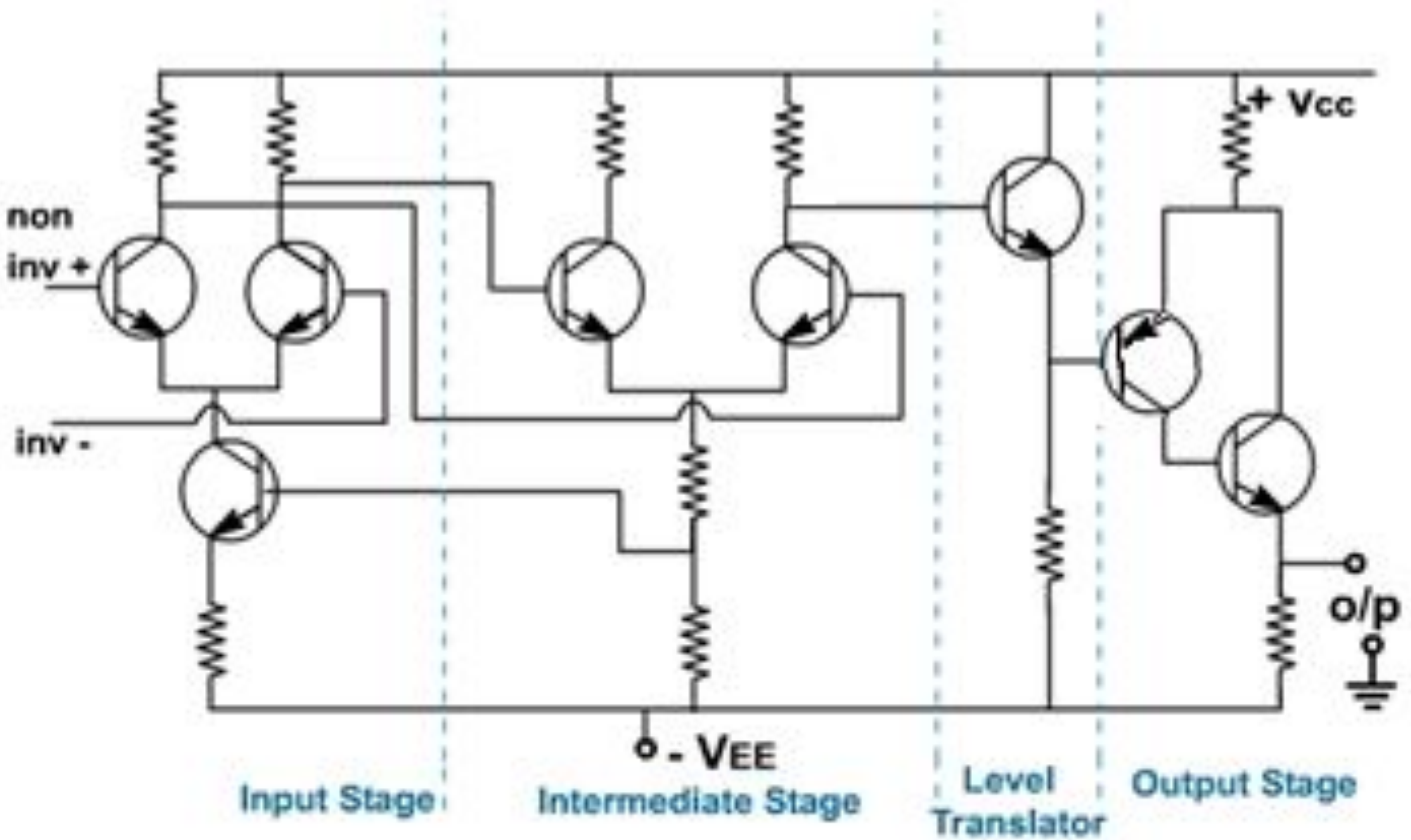


Figure 1: Block Diagram of a Typical Op-amp

Block Diagram of OP-AMP



Internal Diagram of Op-Amp



Stages of internal block diagram

- **Input Stage -** The input stage is a Dual input balanced output differential amplifier. The two amplifiers are applied at inverting or non inverting terminals. This stage provides most of voltage gain of the op-amp and decides input resistance value R1.

- **Intermediate Stage -** It is driven by output of the input stage. This stage is dual input unbalanced output differential amp. This stage provides additional voltage gain to the input signals.

Stages of internal block diagram

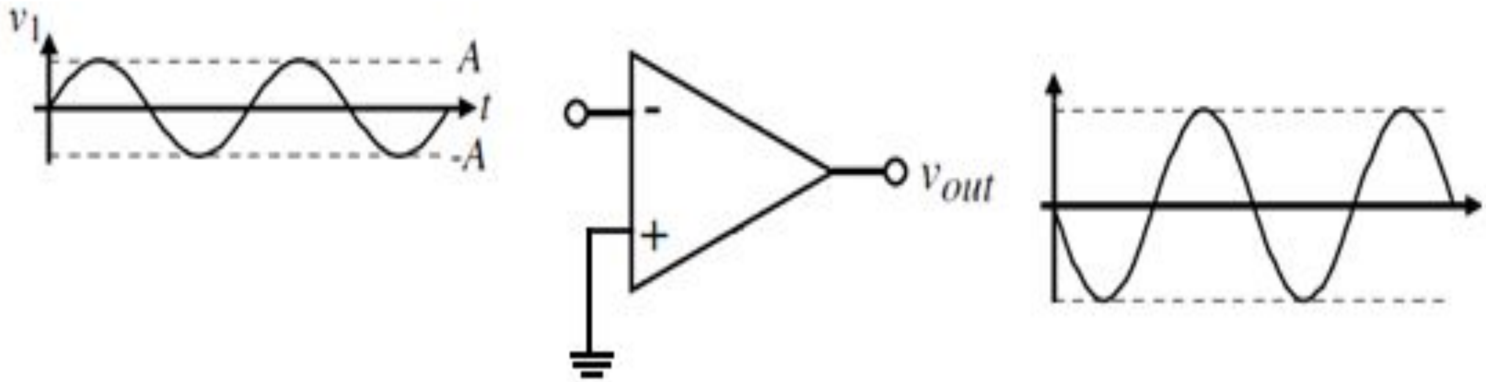
- **Level shifting stage -** This is third stage in the block diagram of op-amp. Due to direct coupling between first two stage the input of level shifting stage is an amplifying system with non-zero DC level. Level shifting stage is used to bring this DC level to a zero volt with respect to ground.

- **Output Stage -** This is normally complementary output stage. It increases magnitude of voltage and rises the current supplying capacity of the op-amp. It also provides low output resistance. The output stage is a push pull of two transistors.

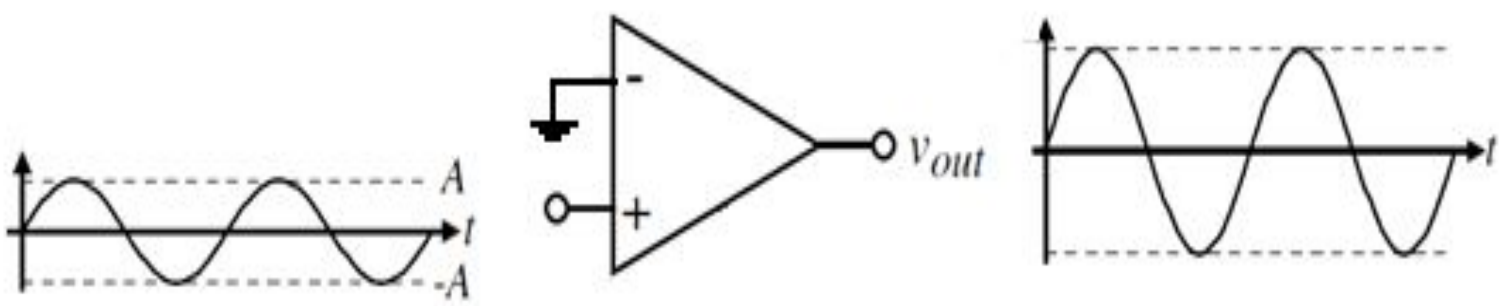
Op Amps Input Modes

Single Ended Mode

Signal is applied to inverting terminal

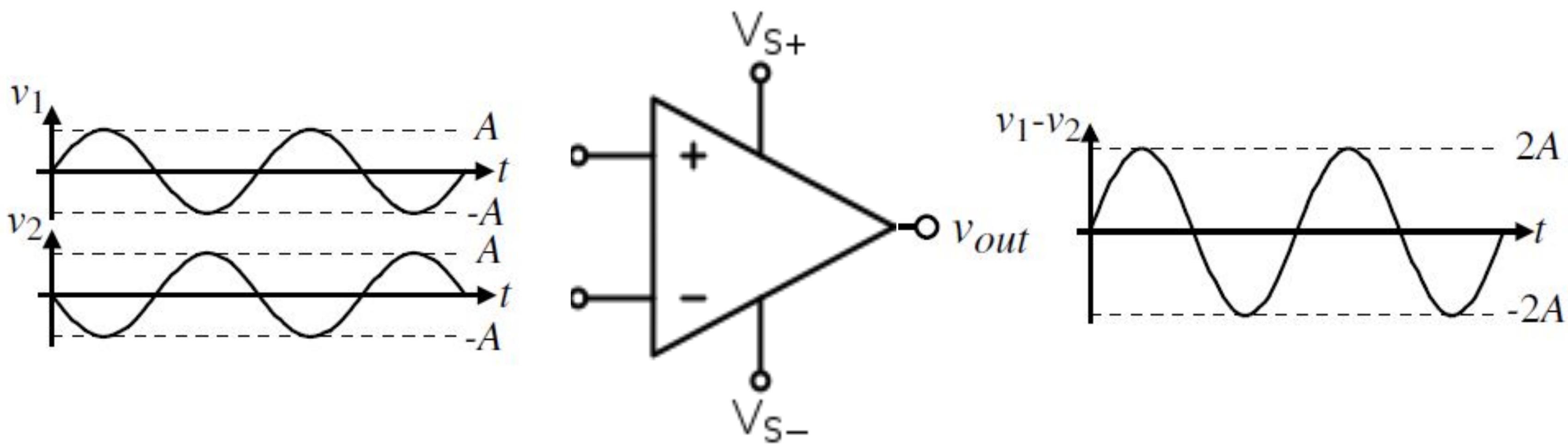


Signal is applied to non-inverting terminal

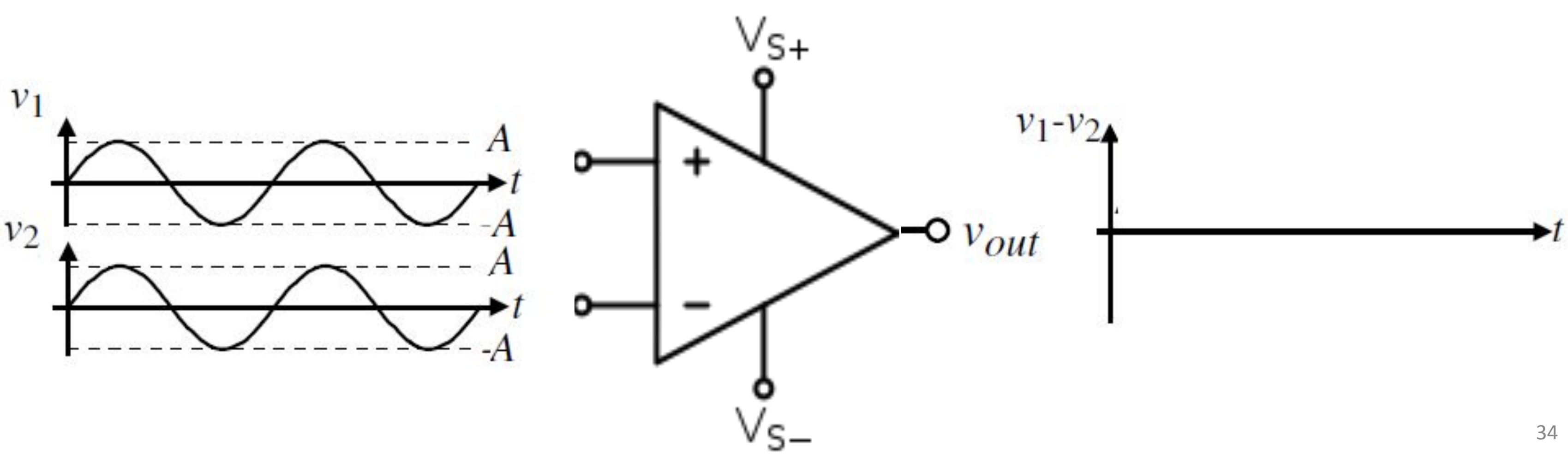


Op Amps Input Modes

Differential Mode



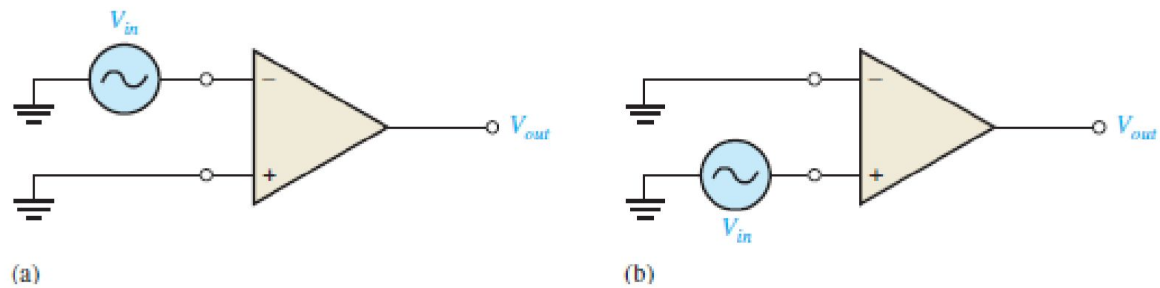
Common Mode



Input Signal Modes

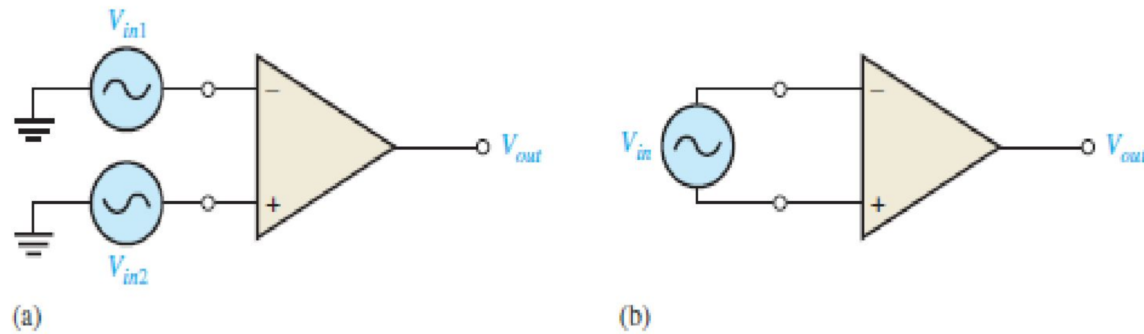
▶ FIGURE 12–4

Single-ended differential mode.



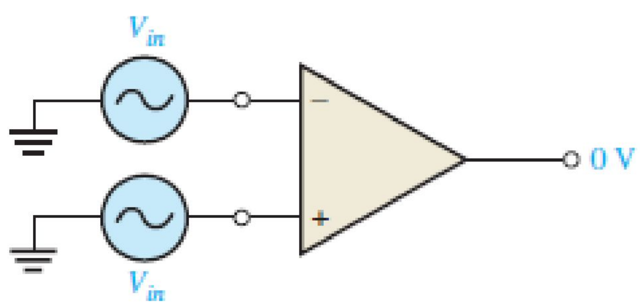
▶ FIGURE 12–5

Double-ended differential mode.

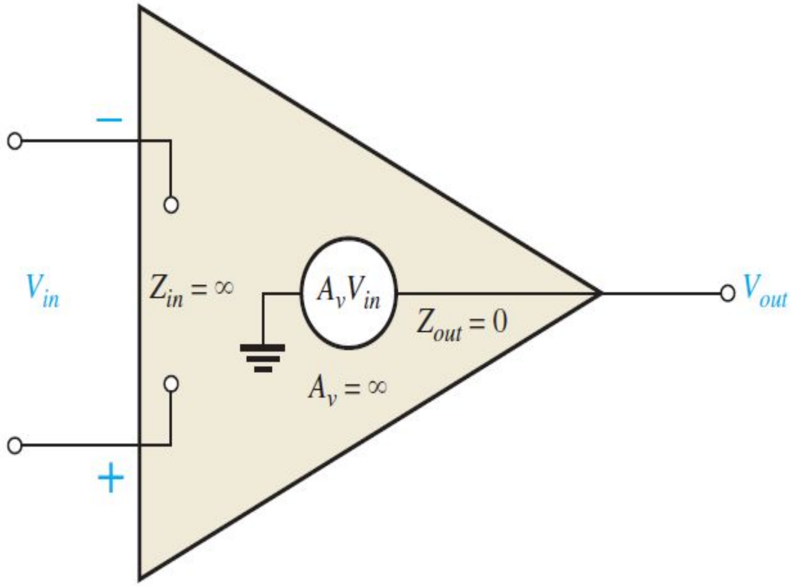


▶ FIGURE 12–6

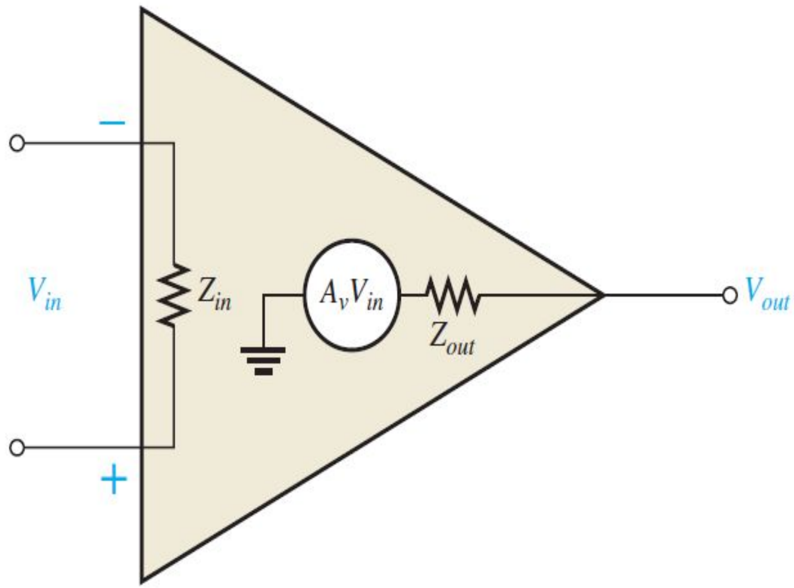
Common-mode operation.



Ideal Op-amp and Practical Op-amp Circuit



(a) Ideal op-amp representation



(b) Practical op-amp representation

Op-Amp Parameters

- **1. Open-loop voltage gain, Go**
- **2. Input impedance, Zin(Ω)**
- **3. Output impedance, Zo(Ω)**
- **4. Input Offset current, Ios (nA)**
- **5. Input Bias current, I_{BIAS} (nA)**
- **6. Input Offset voltage, Vos (mV)**
- **7. Slew rate, SR (V/µs)**
- **8. CMRR**
- **9. SVRR / PSRR**
- **10 Gain Bandwidth product**

Op-Amp Parameters

Maximum Output Voltage Swing ($V_{O(p-p)}$)

- With no input signal, the output of an opamp is ideally 0 V.
- When an input signal is applied, the ideal limits of the peak-to-peak output signal are Vcc.
- In practice, however, this ideal can be approached but never reached. It varies with the load connected to the op-amp and increases directly with load resistance.
- For example, the Fairchild KA741 datasheet shows a typical Vo(p-p) of 13V for Vcc = 15V when RL = 2KΩ and

  Vo(p-p) increases to 14V when RL = 10KΩ.

Op-Amp Parameters

Open-loop voltage gain

- The open-loop voltage gain, A_{ol}, of an op-amp is the internal voltage gain of the device and represents the ratio of output voltage to input voltage when there are no external components.
- The open-loop voltage gain is set entirely by the internal design.
- Open-loop voltage gain can range up to 200,000 (106 dB) and is not a well-controlled parameter.
- Datasheets often refer to the open-loop voltage gain as the large-signal voltage gain.

Op-Amp Parameters

Input offset voltage

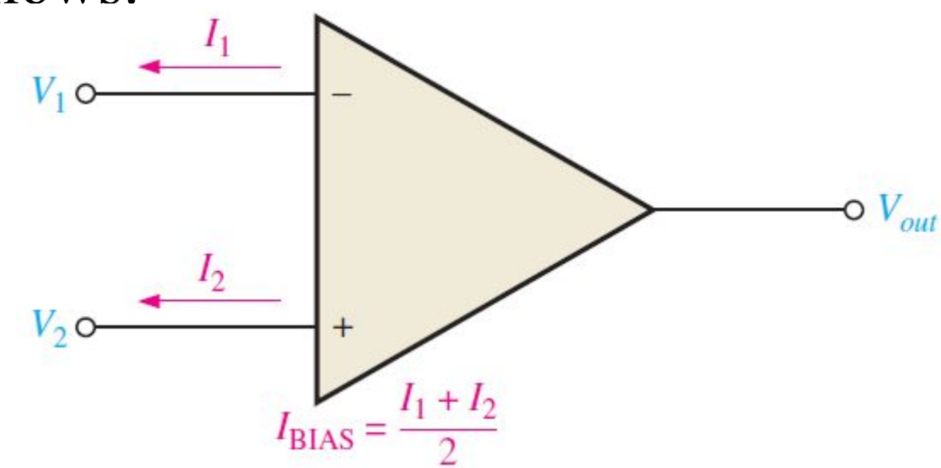
- The ideal op-amp produces zero volts out for zero volts in.
- In a practical op-amp, however, a small dc voltage, $V_{OUT(error)}$, appears at the output when no differential input voltage is applied.
- Its primary cause is a slight mismatch of the base-emitter voltages of the differential amplifier input stage of an op-amp.
- The **input offset voltage, V_{OS},** is the differential dc voltage required between the inputs to force the output to zero volts.
- Typical values of input offset voltage are in the range of 2 mV or less. In the ideal case, it is 0 V.

Op-Amp Parameters

Input bias current

- The input terminals of a bipolar differential amplifier are the transistor bases and, therefore, the input currents are the base currents.
- The input bias current is the dc current required by the inputs of the amplifier to properly operate the first stage.
- By definition, the input bias current is the average of both input currents and is calculated as follows:

$$I_{BIAS} = \frac{I_1 + I_2}{2}$$



Op-Amp Parameters

Input offset current

- Ideally, the two input bias currents are equal, and thus their difference is zero.
- In a practical op-amp, however, the bias currents are not exactly equal.
- The input offset current, I_{OS}, is the difference of the input bias currents, expressed as an absolute value.

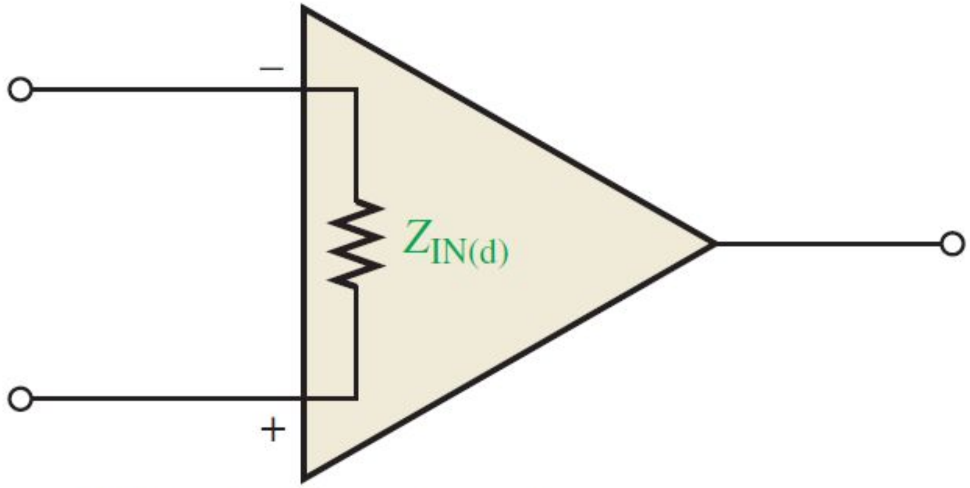
$$I_{OS} = | I_1 - I_2 |$$

- *Typical value is 200 nA*

Op-Amp Parameters

Input Impedance

- The differential input impedance is the total resistance between the inverting and the noninverting inputs, as illustrated in Figure
- It is measured by determining the change in bias current for a given change in differential input voltage.

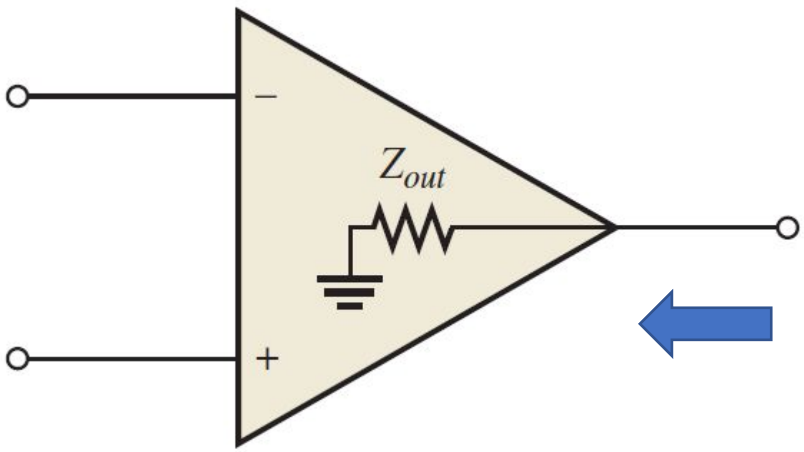


(a) Differential input impedance

Op-Amp Parameters

Output Impedance

- The output impedance is the resistance viewed from the output terminal of the op-amp, as indicated in Figure

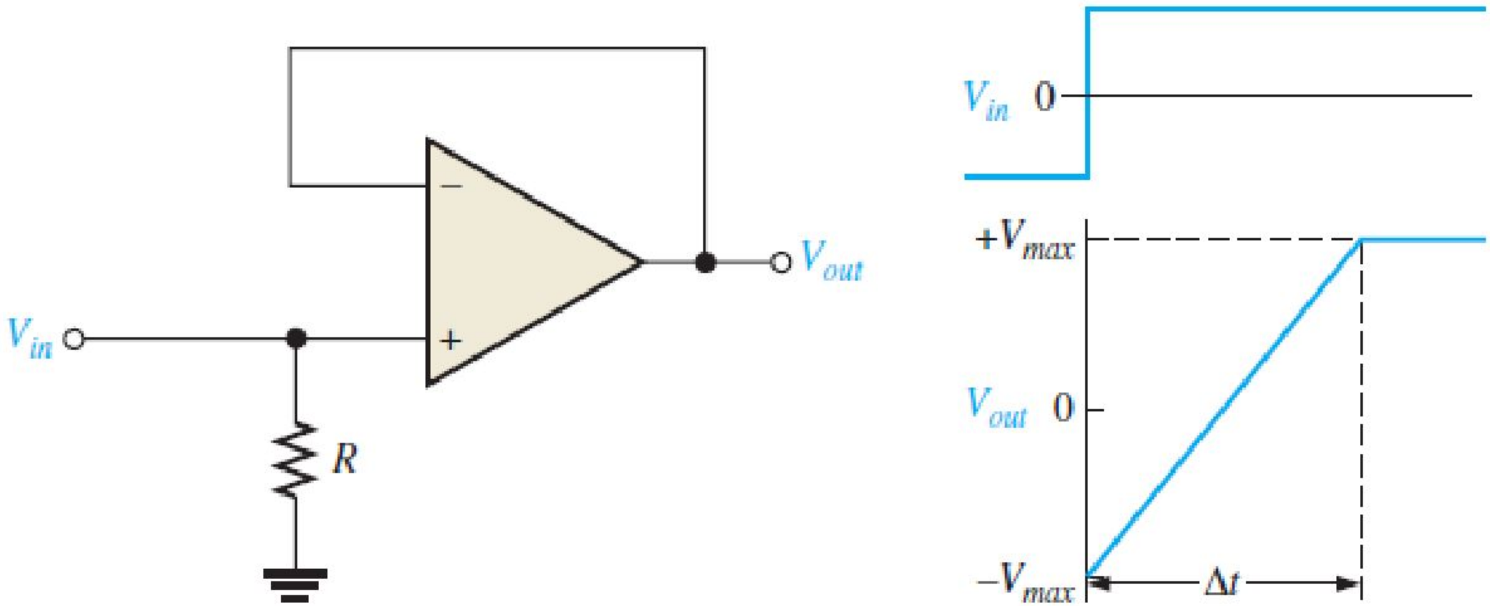


Op-Amp Parameters

Slew rate

- The slew rate is the maximum rate of change of output voltage for a step input voltage.
- The slew rate makes the output voltage to change at a slower rate than the applied input.
- Max rate of change of output voltage with time. i.e. dv/dt (max) or $\Delta V/\Delta t$ max expressed in (volts/μs) .
- Slew rate is usually measured in the unity gain non-inverting amplifier configuration
- Typically it is 0.5 V/μs

Slew rate



(a) Test circuit

(b) Step input voltage and the resulting output voltage

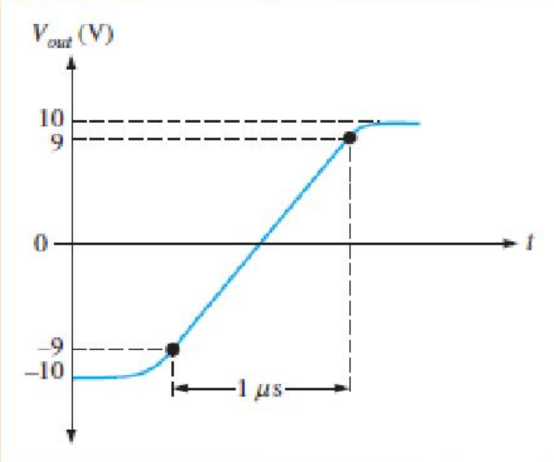
$$\textbf{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

where $\Delta V_{out} = +V_{max} - (-V_{max})$. The unit of slew rate is volts per microsecond (V/μs).

Slew Rate Numerical

EXAMPLE 12–2 The output voltage of a certain op-amp appears as shown in Figure 12–12 in response to a step input. Determine the slew rate.

▶ **FIGURE 12–12**



Solution The output goes from the lower to the upper limit in 1 μs. Since this response is not ideal, the limits are taken at the 90% points, as indicated. So, the upper limit is +9 V and the lower limit is −9 V. The slew rate is

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t} = \frac{+9\text{ V} - (-9\text{ V})}{1\ \mu\text{s}} = \mathbf{18\ V/\mu s}$$

Related Problem When a pulse is applied to an op-amp, the output voltage goes from −8 V to +7 V in 0.75 μs. What is the slew rate?

Op-Amp Parameters

SVRR (Supply Voltage Rejection Ratio) or

Power Supply Rejection Ratio (PSRR)

- Power-supply rejection ratio PSRR is the ratio of the change in input offset voltage to the corresponding change in power-supply.
- The PSRR is expressed in mV/V or dB

$$PSRR = \Delta Vos / \Delta V$$

Op-Amp Parameters

Common Mode Rejection Ratio (CMRR)

- The output signal due to the common mode input voltage is zero, but it is nonzero in a practical device.
- CMRR is the measure of the amplifier's ability to reject common mode signals
- The output voltage is proportional to the difference between the voltages applied to its two input terminals.
- When the two input voltages are equal, ideally the output voltage should be zero.
- It is a metric used to quantify the ability of the device to reject common-mode signals, i.e. those that appear simultaneously and in-phase on both inputs.

Common Mode Rejection Ratio (CMRR)

- A signal applied to both input terminals of the op-amp is called as common-mode signal. Usually it is an unwanted noise voltage.
- CMRR is defined as the ratio of the open loop differential voltage gain A_{ol} to the common mode voltage gain A_{cm}

$$CMRR = A_{ol} / A_{cm}$$

$$CMRR = 20 \log[A_{ol} / A_{cm}] \quad dB$$

CMRR Example

EXAMPLE 12–1 A certain op-amp has an open-loop differential voltage gain of 100,000 and a common-mode gain of 0.2. Determine the CMRR and express it in decibels.

Solution $A_{ol} = 100{,}000$, and $A_{cm} = 0.2$. Therefore,

$$\text{CMRR} = \frac{A_{ol}}{A_{cm}} = \frac{100{,}000}{0.2} = \mathbf{500{,}000}$$

Expressed in decibels,

$$\text{CMRR} = 20 \log (500{,}000) = \mathbf{114\ dB}$$

*Related Problem** Determine the CMRR and express it in dB for an op-amp with an open-loop differential voltage gain of 85,000 and a common-mode gain of 0.25.

Op-Amp Parameters

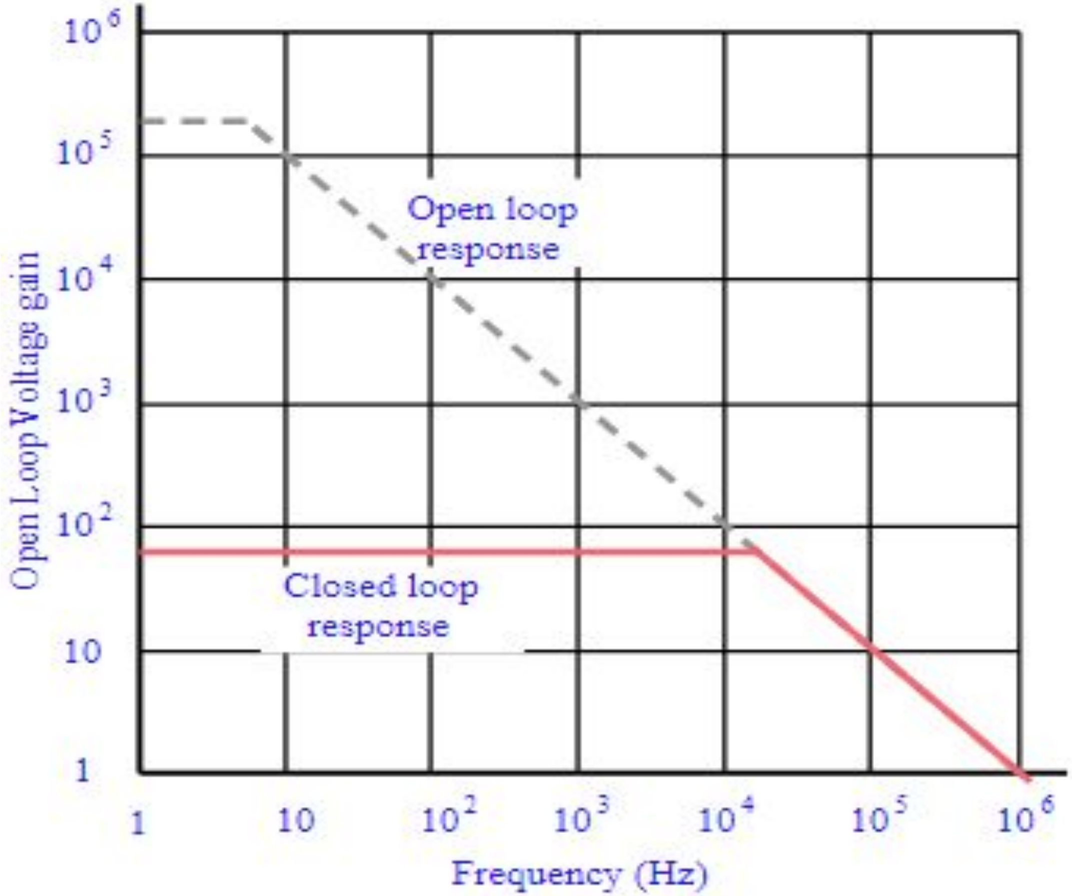
Gain Bandwidth Product

- It is the bandwidth of the op-amp when the voltage gain is 1
- Typically it is 1 MHz
- Also called *closed-loop bandwidth, unity gain bandwidth and small-signal bandwidth*

$$GBP = Av \times f$$

Where:
GBP = op amp gain bandwidth product
Av = voltage gain
f = cutoff frequency (Hz)

Frequency Response of OP-AMP and Bandwidth



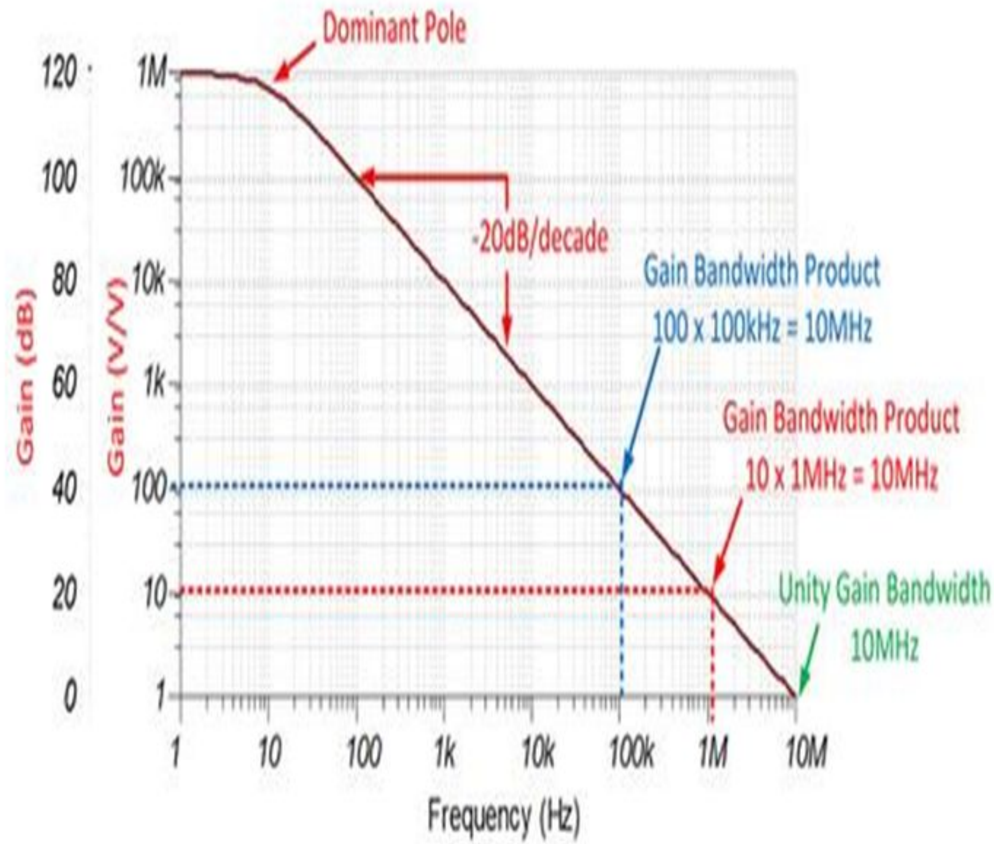
Gain Bandwidth Product (GBP)

Gain-bandwidth (GBW) product is defined as the open-loop gain multiplied by the bandwidth. The GBW product can be used to calculate the closed-loop gain bandwidth.

GBW = A x BW   where A is in ratio (not in dB)

GBW/closed-loop gain = closed-loop BW
Closed-loop BW = GBW / A

Example 1: If the GBW is 10 MHz @ unity gain and the closed-loop gain is 10.
Closed-loop BW = 10 MHz/10 = 1 MHz
Example 2: GBW 1 MHz @ unity gain, closed loop gain 70 dB. Closed-loop BW?
Gain: 20 log A = 70 dB ➔ log A = 70/20 = 3.5
➔ A = $10^{3.5}$ = 3162
Closed-loop BW = 1 MHz/3162 = 316 Hz



Gain-bandwidth product and unity-gain bandwidth on A_{OL} curve.

Op Amp Parameters

Parameter values for op-amps	IDEAL	PRACTICAL
1. Open-loop voltage gain, Go(V/V)	INF	2,00,000
2. Input impedance, Zin(Ω)	INF	2 MΩ
3. Output impedance, Zo(Ω)	0	75 Ω
4. Input Offset current, Ios (nA)	0	20 nA
5. Input Bias current, I_{BIAS} (nA)	0	80 nA
6. Input Offset voltage, Vos (mV)	0	2 mV
7. Slew rate, SR (V/µs)	INF	0.5 V/microsec
8. CMRR	INF	90 dB
9. SVRR / PSRR	INF	96 dB
10 Gain Bandwidth product	INF	1 MHz

Comparison of Parameters

OP-AMP	CMRR (dB) (TYP)	OPEN-LOOP GAIN (dB) (TYP)	GAIN-BANDWIDTH PRODUCT (MHz) (TYP)	INPUT OFFSET VOLTAGE (mV) (MAX)	INPUT BIAS CURRENT (nA) (MAX)	SLEW RATE (V/µs) (TYP)	COMMENT
AD8009	50	N/A	320[1]	5	150	5500	Extremely fast, low distortion, uses current feedback
AD8055	82	71		5	1200	1400	Low noise, fast, wide bandwidth, gain flatness 0.1 dB, video driver
ADA4891	68	90[2]		2500	0.002	170	CMOS-extremely low bias current, very fast, useful as video amplifier
ADA4092	85	118	1.3	0.2	50	0.4	Single supply (2.7 V to 36 V) or two supply operation, low power
FAN4931	73	102	4	6	0.005	3	Low cost CMOS, low power, output swings to within 10 mV of rail, extremely high input resistance
FHP3130	95	100	60	1	1800	110	High current output (to 100 mA)
FHP3350	90	55	190	1	50	800	High speed; useful as video amp
LM741C	70	106	1	6	500	0.5	General-purpose, overload protection, industry standard
LM7171	110	90	100	1.5	1000	3600	Very fast, high CMRR, useful as an instrumentation amplifier
LMH6629	87	79	800[3]	0.15	23000	530	Fast, ultra low noise, low voltage
OP177	130	142		0.01	1.5	0.3	Ultra-precision; very high CMRR and stability
OPA369	114	134	0.012	0.25	0.010	0.005	Extremely low power, low voltage, rail-to-rail.
OPA378	100	110	0.9	0.02	0.15	0.4	Precision, very low drift, low noise
OPA847	110	98	3900	0.1	42,000	950	Ultra low-noise, wide bandwidth amplifier, voltage feedback

What is negative feedback?

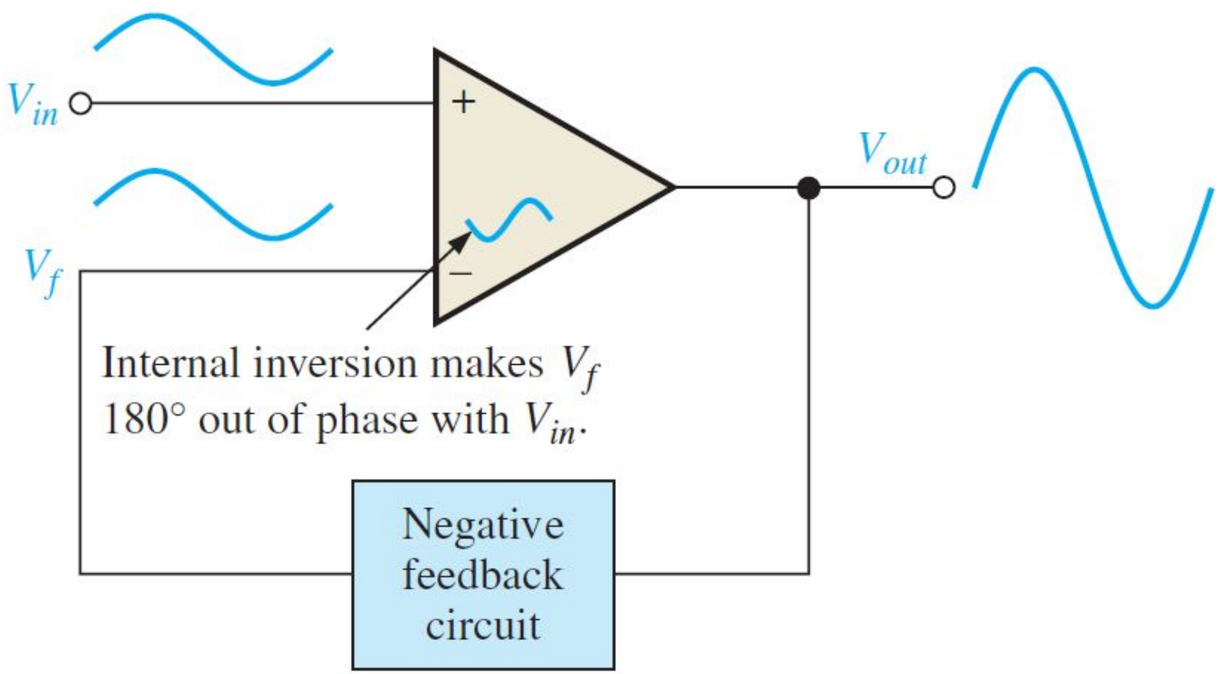
- Negative feedback is the most useful concepts in OPAMP applications.

- It is the process whereby a portion of the output voltage of an amplifier is returned to the input with a phase angle that opposes the input signal.

Negative Feedback / Closed Loop configuration

Negative feedback is illustrated in the Figure.

The inverting input effectively makes the feedback signal 180° out of phase with the input signal.



Why Use Negative Feedback?

- The inherent open-loop voltage gain of a typical op-amp is very high (usually greater than 100,000).
- Therefore, an extremely small input voltage drives the op-amp into its saturated output states.
- In fact, even the input offset voltage of the op-amp can drive it into saturation.
- For example, assume V_{in} = 1 mV and A_{ol} = 100,000. Then:

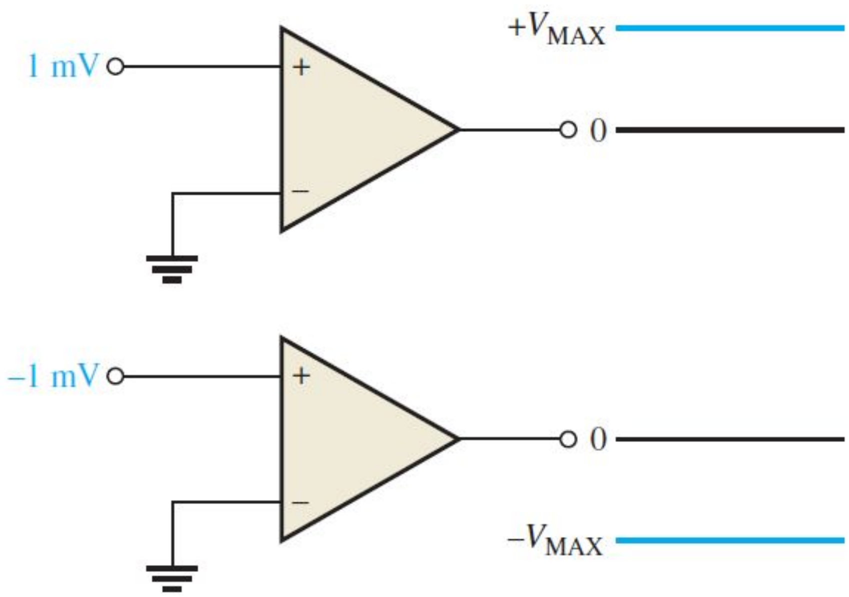
$$V_{\text{in}}A_{ol} = (1\text{ mV})(100{,}000) = 100\text{ V}$$

- **Since the output level of an op-amp can never reach 100 V, it is driven deep into saturation** and the output is limited to its maximum output levels, i. e. Vcc.
- With negative feedback, the closed loop voltage gain (A_{cl}) can be reduced and controlled so that the op-amp can function as a linear amplifier.
- In addition to providing a controlled, stable voltage gain, negative feedback also provides for control of the input and output impedances and amplifier bandwidth.

Why Use Negative Feedback?

Without negative feedback, a small input voltage drives the op-amp to its output limits and it becomes nonlinear.

Positive Saturation



Negative Saturation

Effects of negative feedback on op-amp performance

TABLE 2–2

	VOLTAGE GAIN	INPUT Z	OUTPUT Z	BANDWIDTH
Without negative feedback	A_{ol} is too high for linear amplifier applications	Relatively high (see Table 12–1)	Relatively low	Relatively narrow (because the gain is so high)
With negative feedback	A_{cl} is set to desired value by the feedback circuit	Can be increased or reduced to a desired value depending on type of circuit	Can be reduced to a desired value	Significantly wider

Closed-Loop Voltage Gain, Acl

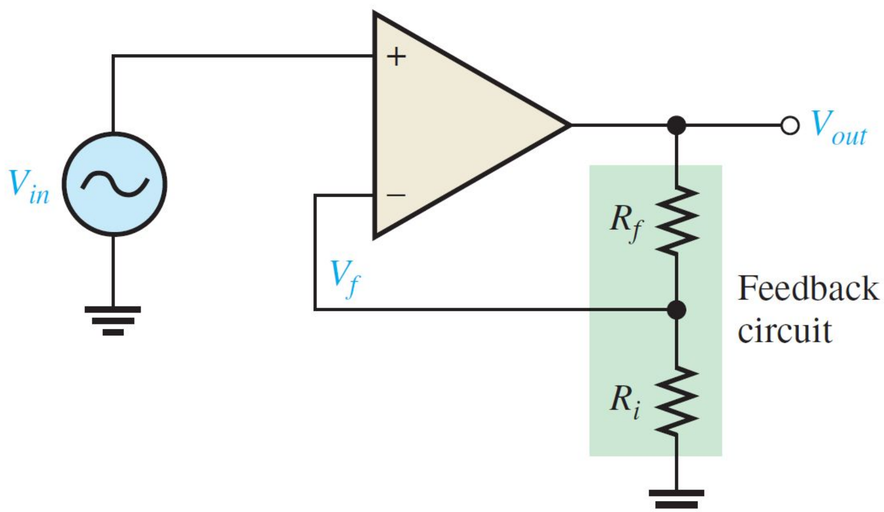
- The amplifier configuration consists of the op-amp and an external negative feedback circuit that connects the output to the **inverting input**.

- The closed-loop voltage gain is the voltage gain of an op-amp with external feedback.

- The closed-loop voltage gain is determined by the external component values and can be precisely controlled by them.

Noninverting Amplifier

- An op-amp connected in a closed-loop configuration as a noninverting amplifier with a controlled amount of voltage gain is shown in Figure.
- The input signal is applied to the noninverting (+) input.
- The output is applied back to the inverting input through the feedback circuit (closed loop) formed by the input resistor Ri and the feedback resistor Rf.
- This creates negative feedback as: Resistors Ri and Rf form a voltage-divider circuit, which reduces Vout and connects the reduced voltage Vf to the inverting input.



The feedback voltage is expressed as

$$V_f = \left(\frac{R_i}{R_i + R_f}\right)V_{out}$$

Noninverting Amplifier

$$V_{out} = A_{ol}(V_{in} - V_f)$$

The attenuation, B, of the feedback circuit is

$$B = \frac{R_i}{R_i + R_f}$$

Substituting BV_{out} for V_f in the V_{out} equation,

$$V_{out} = A_{ol}(V_{in} - BV_{out})$$

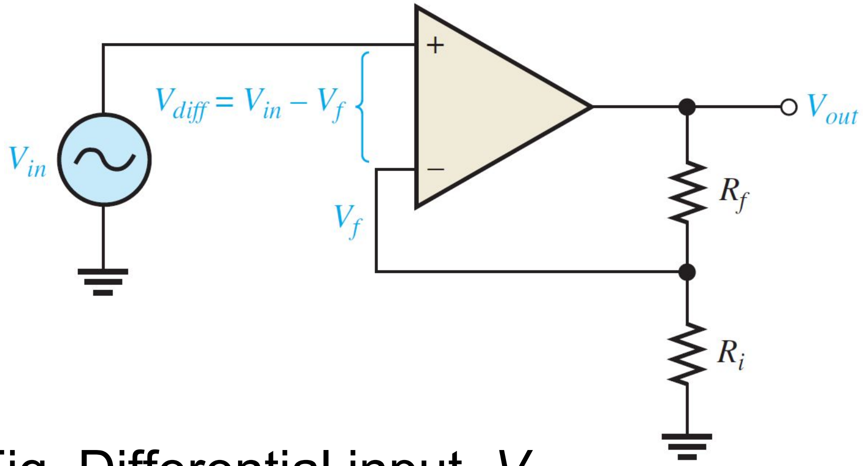


Fig. Differential input, V_{in} - V_f.

Then applying basic algebra,

$$V_{out} = A_{ol}V_{in} - A_{ol}BV_{out}$$

$$V_{out} + A_{ol}BV_{out} = A_{ol}V_{in}$$

$$V_{out}(1 + A_{ol}B) = A_{ol}V_{in}$$

Noninverting Amplifier

Since the overall voltage gain of the amplifier in is Vout/Vin, it can be expressed as

$$\frac{V_{out}}{V_{in}} = \frac{A_{ol}}{1 + A_{ol}B}$$

The product $A_{ol}B$ is typically much greater than 1, so the equation simplifies to

$$\frac{V_{out}}{V_{in}} \cong \frac{A_{ol}}{A_{ol}B} = \frac{1}{B}$$

The closed-loop gain of the noninverting (NI) amplifier is the reciprocal of the attenuation (B) of the feedback circuit (voltage-divider).

$$A_{cl(\mathrm{NI})} = \frac{V_{out}}{V_{in}} \cong \frac{1}{B} = \frac{R_i + R_f}{R_i}$$

Therefore,

$$\boldsymbol{A_{cl(\mathrm{NI})} = 1 + \frac{R_f}{R_i}}$$

Closed loop Gain

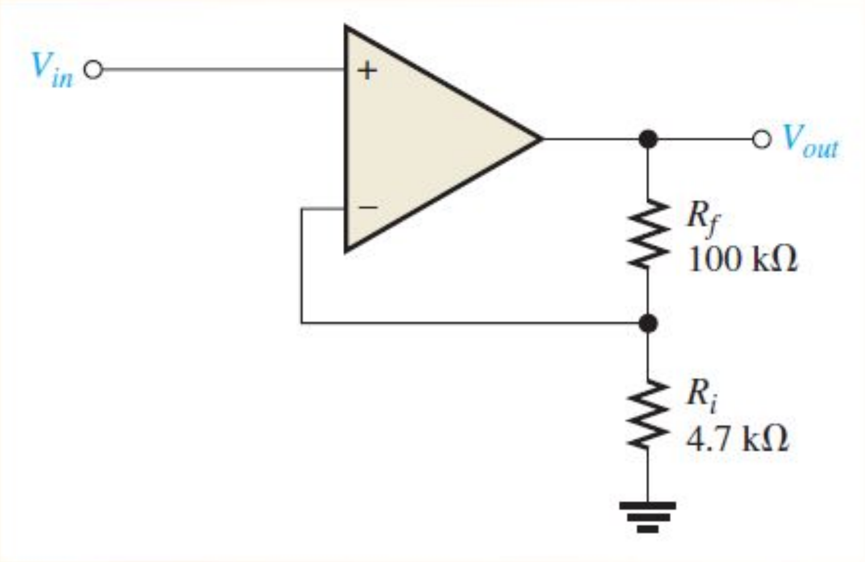
- Notice that the closed-loop voltage gain is not at all dependent on the op-amp's open-loop voltage gain under the condition $A_{ol} B >> 1$
- Example : Aol= 100000 , B<1

- The closed-loop gain can be set by selecting values of *Ri* and *Rf*

Numerical

Determine the closed-loop voltage gain of the amplifier in Figure 12–18.

FIGURE 12–18



Solution This is a noninverting op-amp configuration. Therefore, the closed-loop voltage gain is

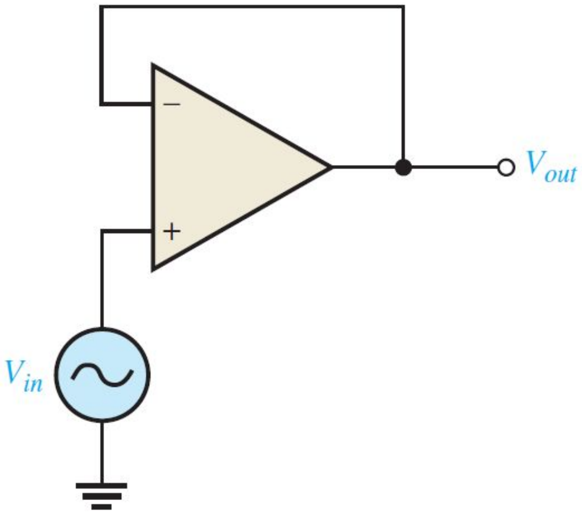
$$A_{cl(\mathrm{NI})} = 1 + \frac{R_f}{R_i} = 1 + \frac{100\ \mathrm{k}\Omega}{4.7\ \mathrm{k}\Omega} = \mathbf{22.3}$$

Practice problem: Find Ri to get gain as 30 with the same value of Rf.

Voltage-Follower

- The voltage-follower configuration is a special case of the noninverting amplifier where all of the output voltage is fed back to the inverting input by a straight connection, as shown in Figure.
- The straight feedback connection has a voltage gain of 1 (which means there is no gain).
- Since B = 1 for a voltage-follower, the closed-loop voltage gain of the voltage-follower is 1/B

$$A_{cl(VF)} = 1$$



- The most important features of the voltage-follower configuration are its very high input impedance and its very low output impedance.
- These features make it a nearly ideal buffer amplifier for interfacing high-impedance sources and low-impedance loads.

Virtual short and Virtual ground

- Voltage between inverting and non-inverting terminals of OP-AMP is output voltage divided by open loop gain of OP-AMP.
- Open loop gain being very large, this voltage is very small. Practically zero. This is virtual short.

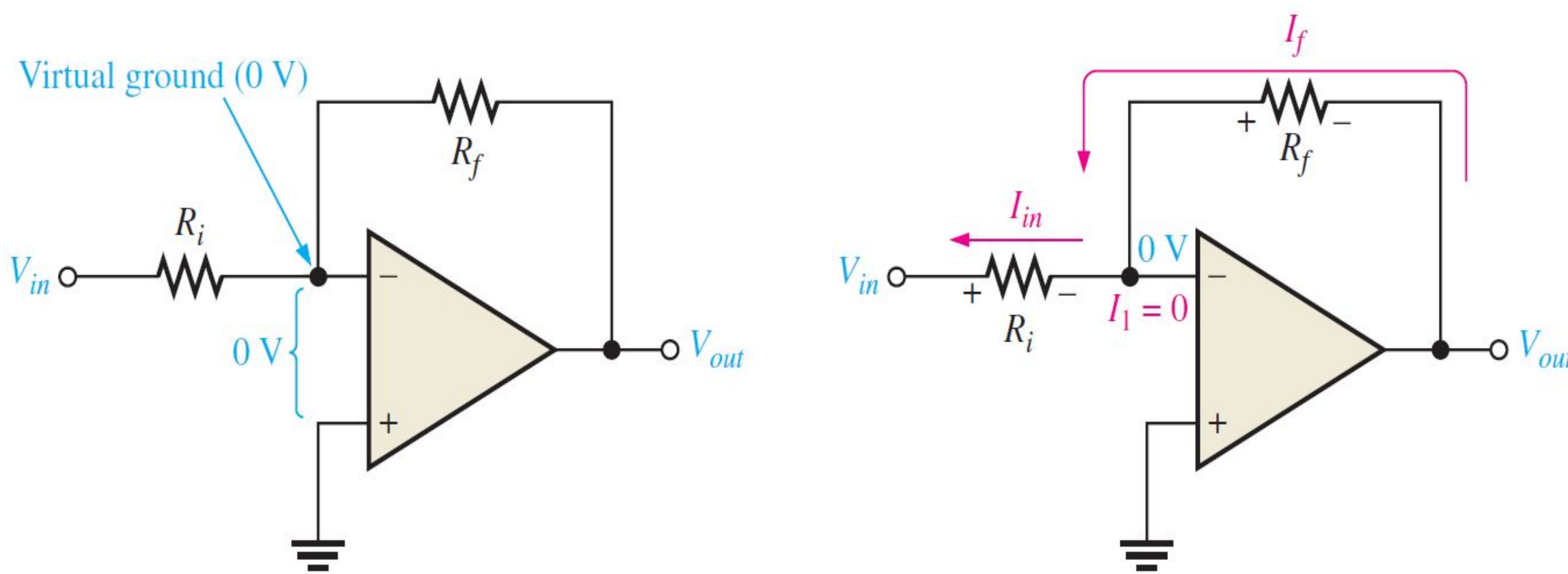
$$\frac{V_{out}}{A} = V_{in+} - V_{in-}$$

- Both input terminals will be at the same potential. In other words they are virtually shorted to each other.

- Virtual ground concept is NOT valid for positive feedback or open loop operation of OPAMP.

Virtual Ground

- If the non-inverting (+) terminal of OP-AMP is connected to ground, then due to the "virtual short" existing between the two input terminals, the inverting (-) terminal also be at ground potential. hence it is said to be as "virtual ground".
- The input impedance (Ri) of an OP-AMP is ideally infinite. Hence current "I" flowing from one input terminal to the other will be zero.

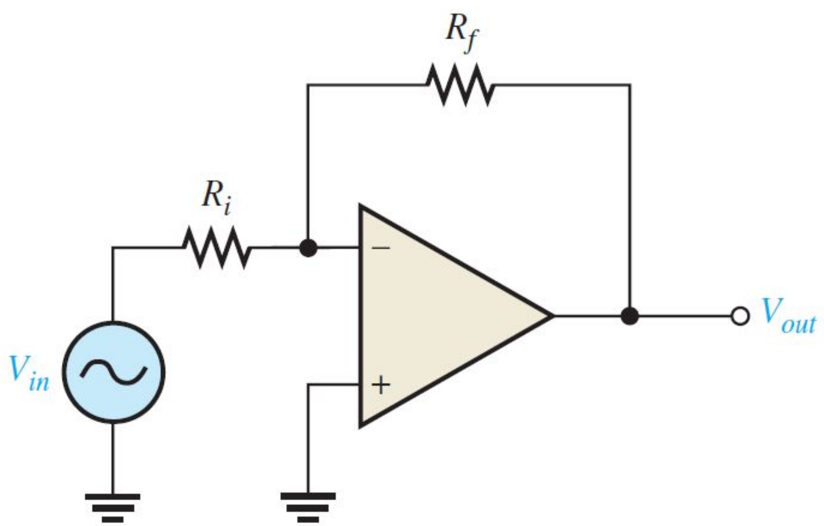


(a) Virtual ground

(b) $I_{in} = I_f$ and current at the inverting input (I_1) is 0.

Inverting Amplifier

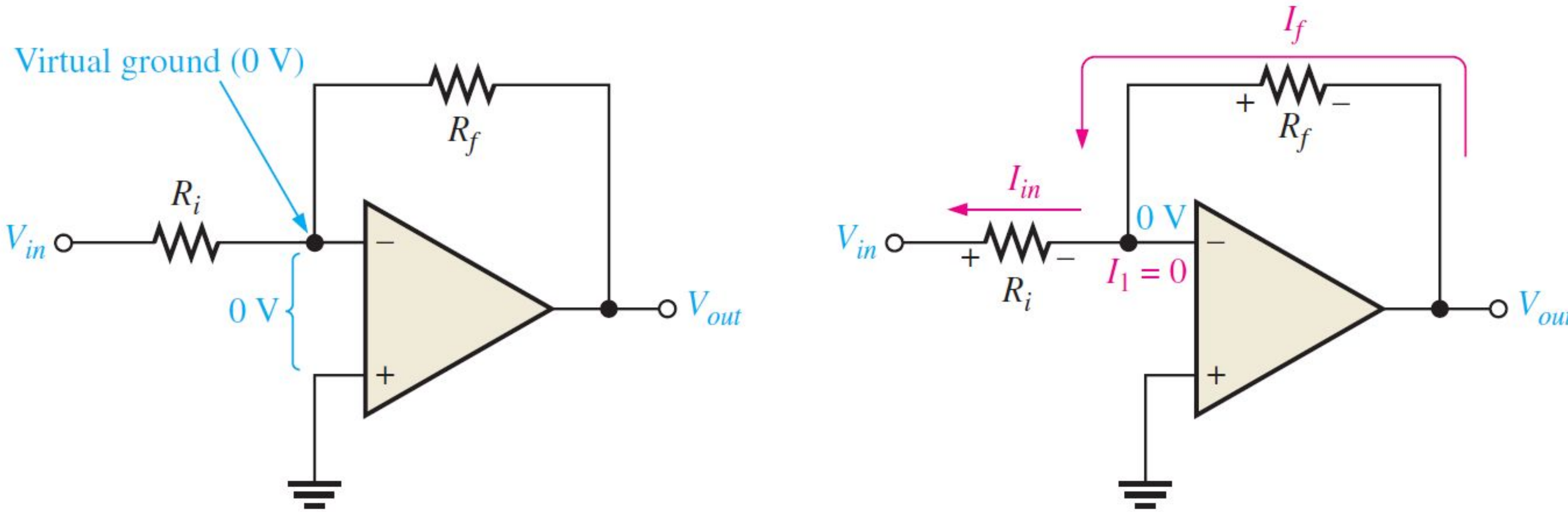
- An op-amp connected as an inverting amplifier with a controlled amount of voltage gain is shown in Figure
- The input signal is applied through a series input resistor Ri to the inverting (-) input.
- Also, the output is fed back through Rf to the same input. The noninverting (+) input is grounded.



Inverting Amplifier

- Since there is no current at the inverting input, the current through *Ri* and the current through *Rf* are equal, as shown in Figure

$$I_{in} = I_f$$



(a) Virtual ground

(b) $I_{in} = I_f$ and current at the inverting input (I_1) is 0.

FIGURE: Virtual ground concept and closed loop voltage gain development for the inverting amplifier.

Inverting Amplifier

The voltage across R_i equals V_{in} because the resistor is connected to virtual ground at the inverting input of the op-amp. Therefore,

$$I_{in} = \frac{V_{in}}{R_i}$$

Also, the voltage across R_f equals $-V_{out}$ because of virtual ground, and therefore,

$$I_f = \frac{-V_{out}}{R_f}$$

Since $I_f = I_{in}$,

$$\frac{-V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

Rearranging the terms,

$$\frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

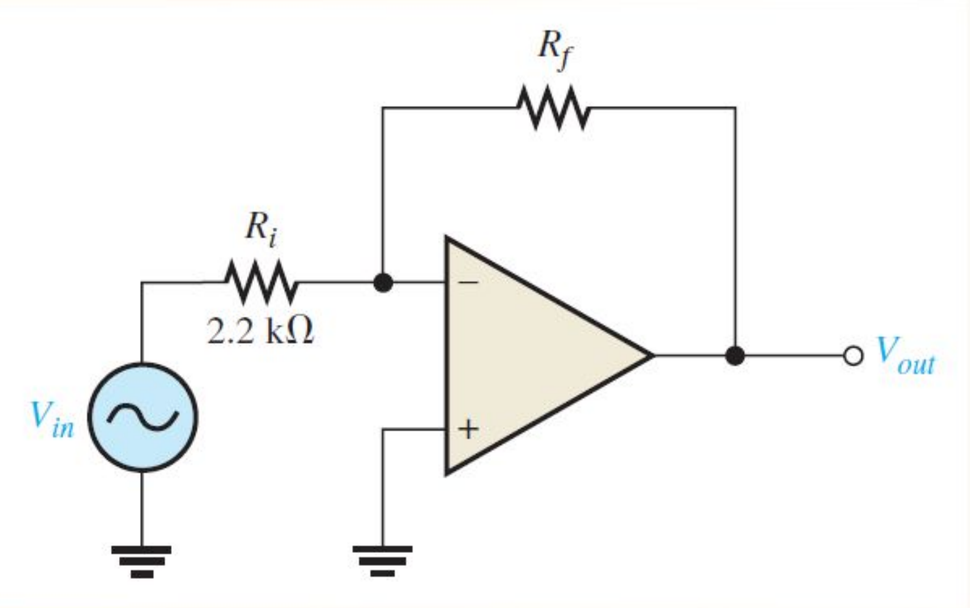
Of course, V_{out}/V_{in} is the overall gain of the inverting (I) amplifier.

$$\boldsymbol{A_{cl(\mathrm{I})} = -\frac{R_f}{R_i}}$$

The closed-loop gain is independent of the op-amp's internal open-loop gain.

Given the op-amp configuration in Figure 12–22, determine the value of R_f required to produce a closed-loop voltage gain of -100.

▶ FIGURE 12–22

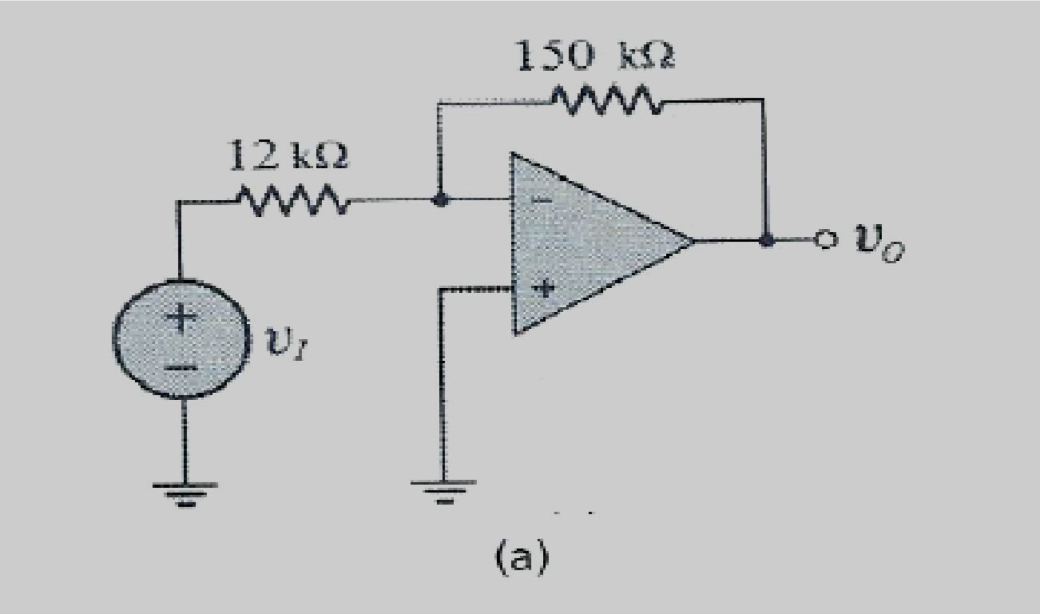


Solution Knowing that $R_i = 2.2\ \text{k}\Omega$ and the absolute value of the closed-loop gain is $|A_{cl(\text{I})}| = 100$, calculate R_f as follows:

$$|A_{cl(\text{I})}| = \frac{R_f}{R_i}$$

$$R_f = |A_{cl(\text{I})}|R_i = (100)(2.2\ \text{k}\Omega) = \mathbf{220\ k\Omega}$$

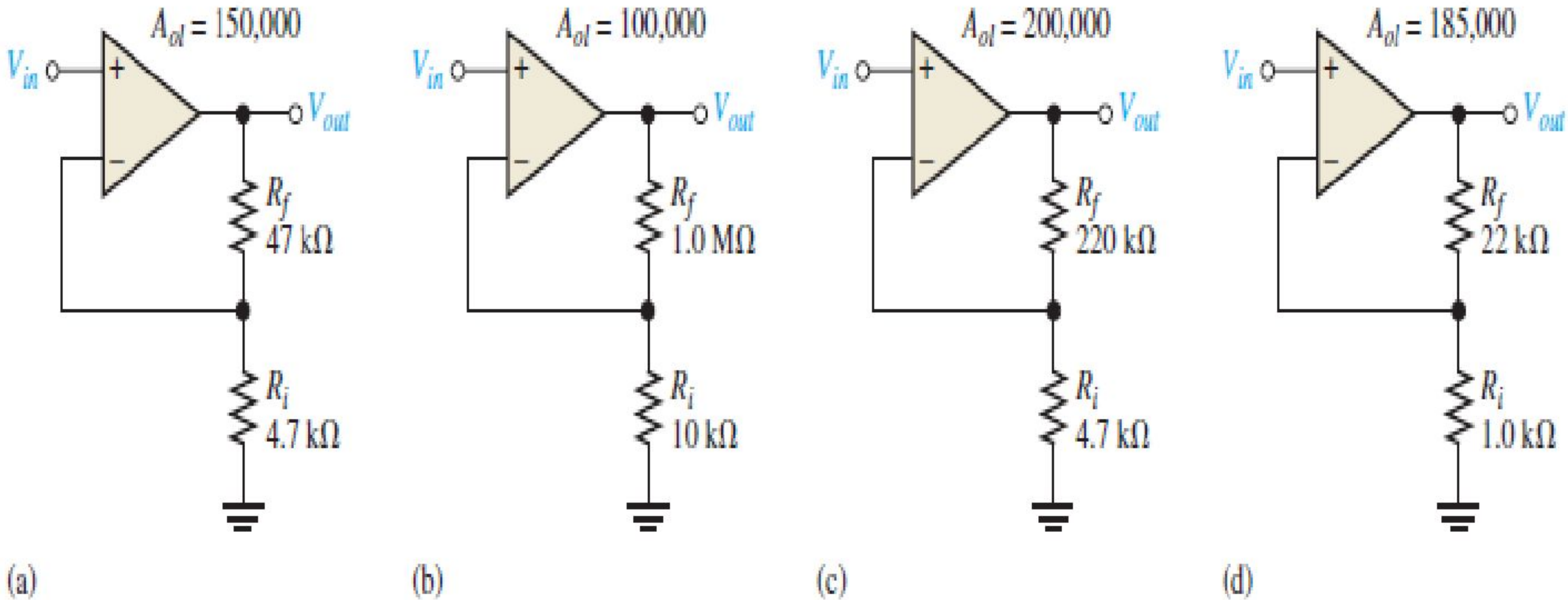
Exercise



Acl = -12.5

Exercise

Determine closed loop gain of each amplifier

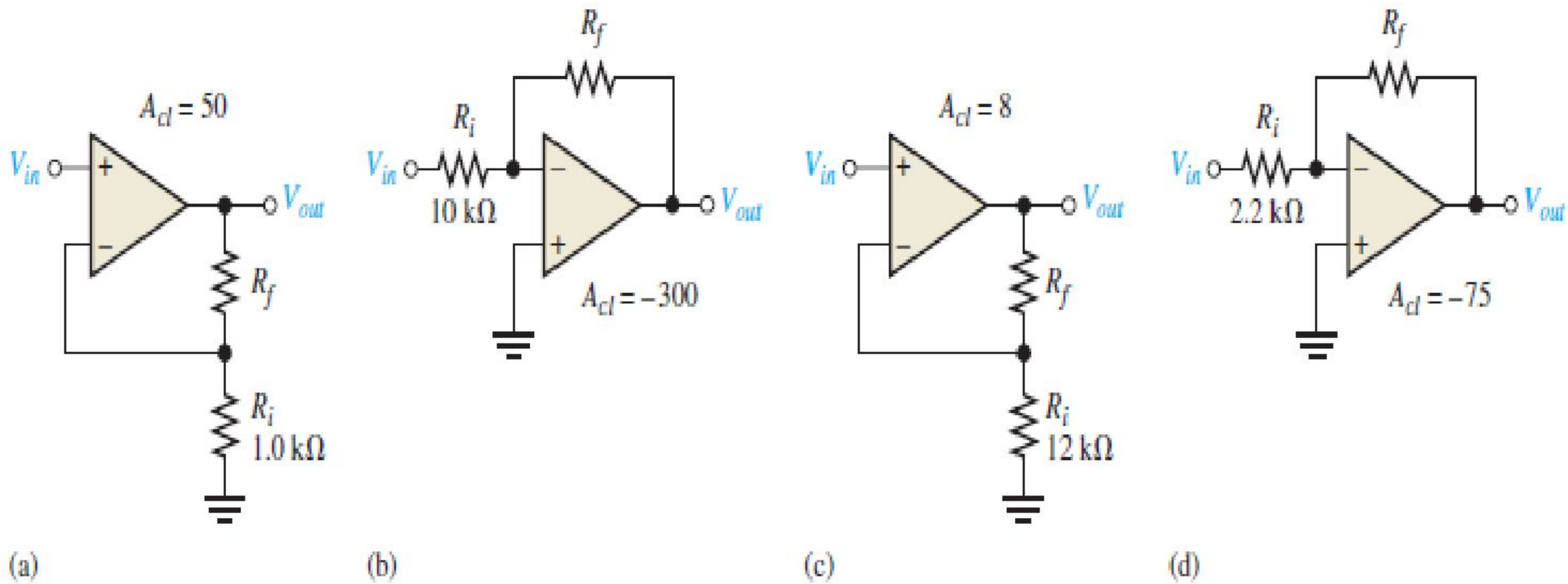


Ans. 11 101 47.8 23

Exercise

Find Rf Value for the each op amp.

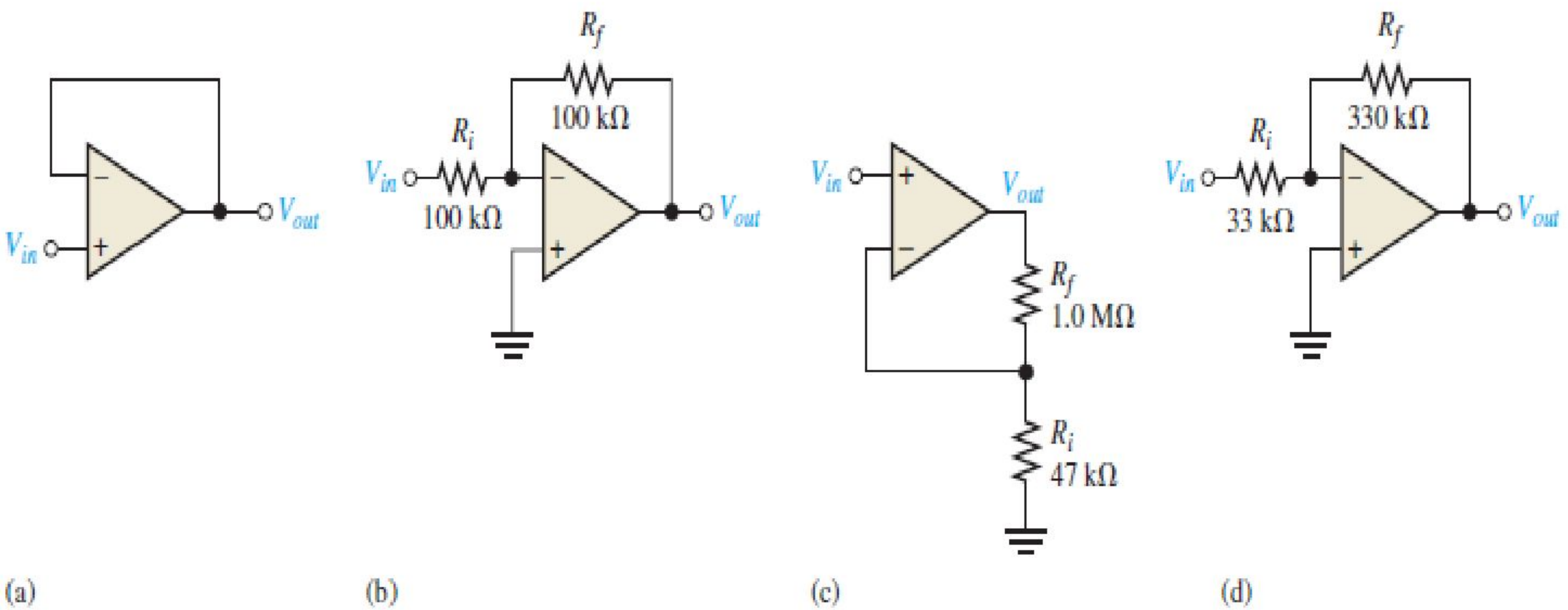
Ans. 49K 3M 84K 165K



Exercise

If signal voltage is 10mVrms, find the output voltage.

Ans. a)10mVrms, in phase b) -10mVrms,out of phase
c) 223 mVrms, in phase d) -100 mVrms, out of phase



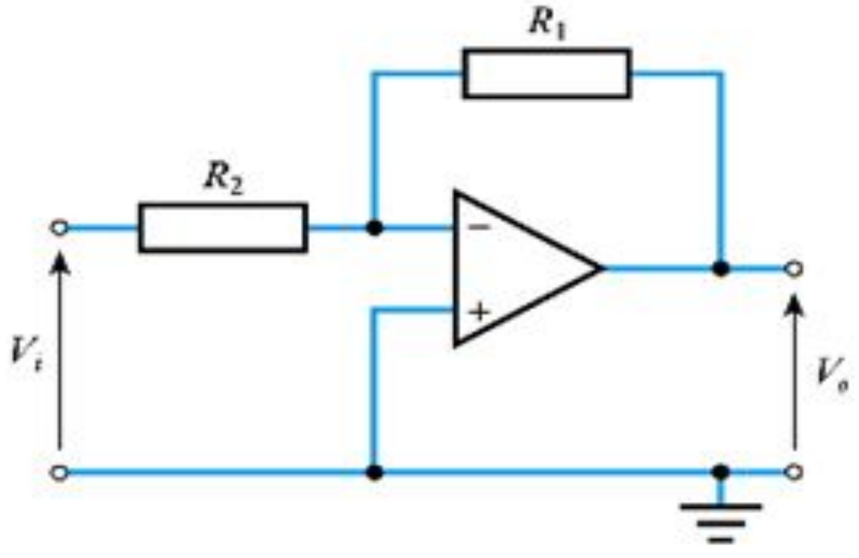
Exercise

In the circuit given below, if $R_2 = 1$ K & $R_1 = 10$ K & input in 0.1V what will be the output

Ans. Acl = - R1/R2 = 10

Vout = Vin * Acl

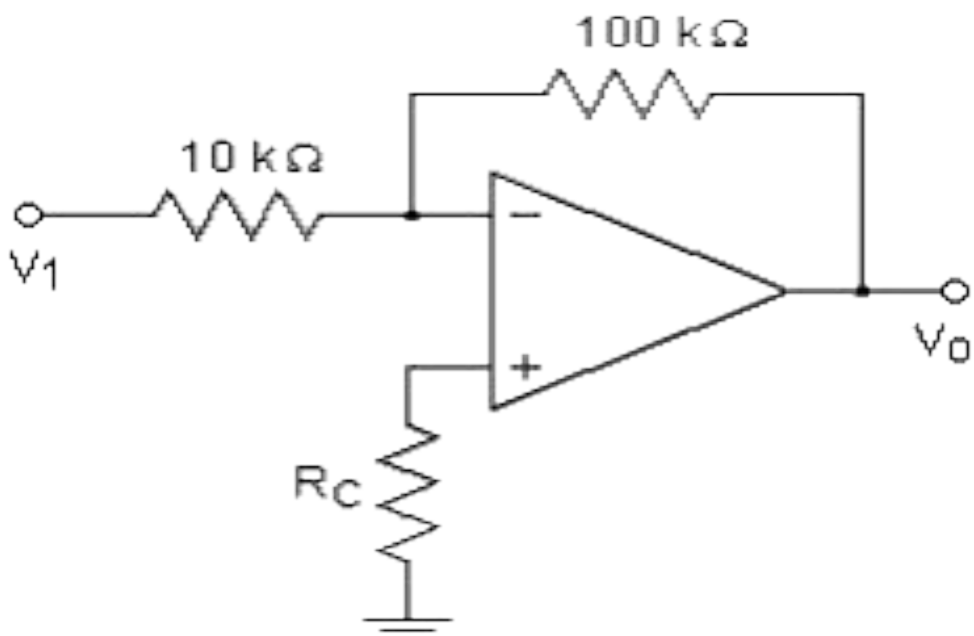
Vou = -1V, out of phase



Exercise

Calculate the input voltage for this circuit if $V_o = -11$ V.

Ans. Vin = 1.1 V



Exercise

An OP-AMP is used in inverting mode with R_1= 1K Ω and R_F = 15KΩ. Vcc = +/- 15V. Calculate the output voltage for i) Vi= 150 mV ii) Vi= 1V

Solution:

$A = -R_F/R_1 = -(15\ K\Omega\ /\ 1K\Omega) = -15$

i) Vi= 150 mV
Vo= (-15 × 150 mV) = -0.225V

ii) Vi= 1V
Vo= (-15 × 1V) = -15V

THANK YOU