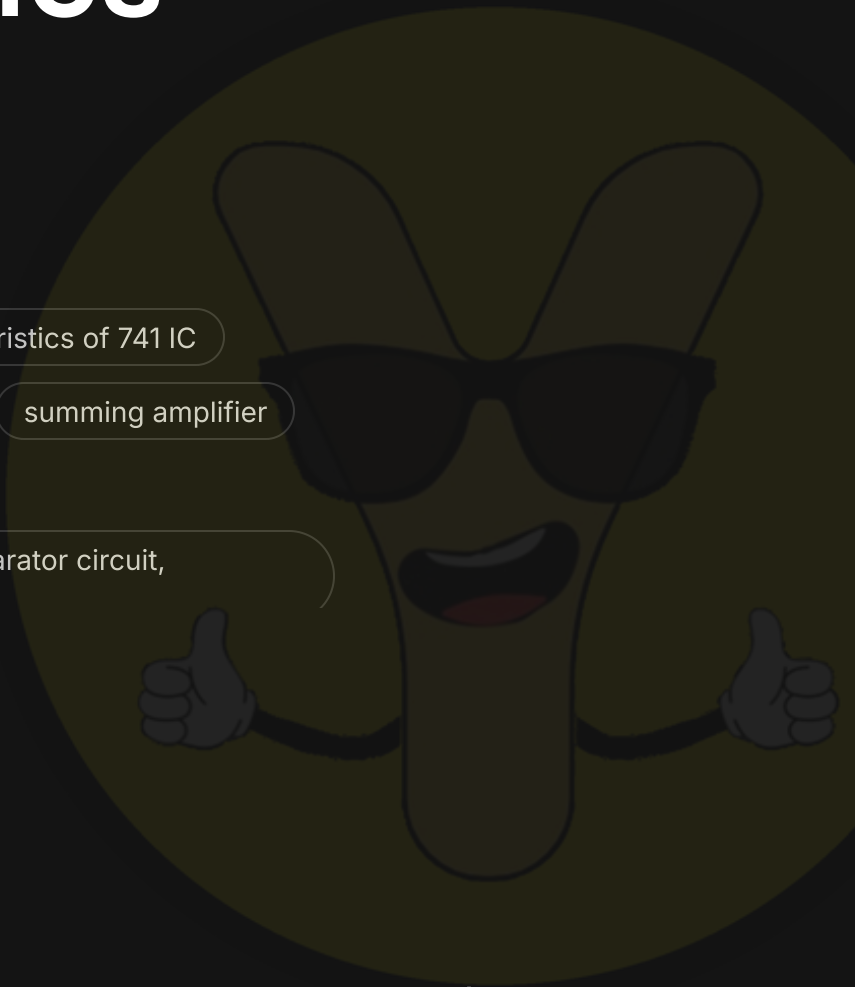
AKTU · 1ST YEAR · AEC101A / AEC201A

Fundamentals of Electronics Engineering

Unit 3 — Operational Amplifier (Op-Amp)

- Ideal op-amp characteristics: infinite gain, infinite input impedance, zero output impedance
- practical characteristics of 741 IC
- inverting amplifier: voltage gain formula
- non-inverting amplifier: gain formula
- voltage follower (buffer)
- summing amplifier
- comparator: op-amp as comparator, threshold detection
- applications: sensor signal amplification (temperature, light, pressure), audio amplifier, automatic night lamp comparator circuit, differential amplifier for ECG/EEG front-end (concept)



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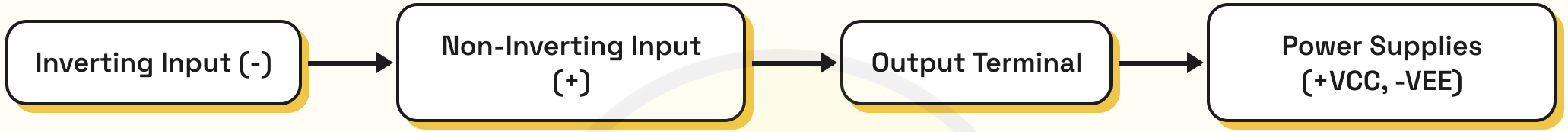
Introduction to Operational Amplifier

OP-AMP

An Operational Amplifier is a high-gain electronic voltage amplifier with differential inputs and, usually, a single output, capable of performing mathematical operations like addition, subtraction, integration, and differentiation.

- Originally designed for analog computers to perform mathematical operations.
- Comes in an Integrated Circuit (IC) package, most famously the 741 IC.
- Direct-coupled high-gain amplifier operating from positive and negative power supplies.

Op-Amp Terminal Diagram and Symbol



Standard triangular symbol of an operational amplifier showing dual inputs and single output.

Ideal Op-Amp Characteristics

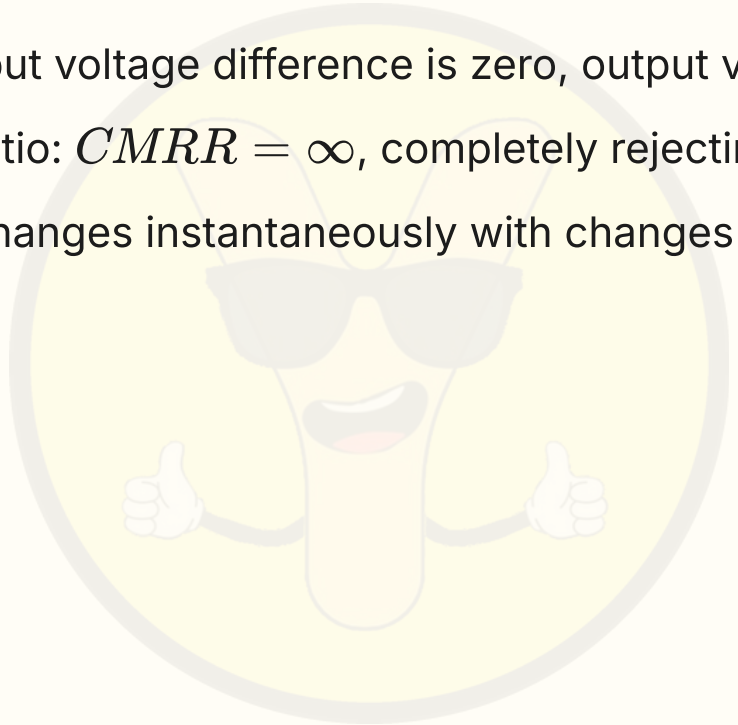
An ideal operational amplifier possesses theoretical properties that simplify circuit analysis.

- Infinite Open-Loop Voltage Gain: $A_{OL} = \infty$, meaning even a microscopic input difference yields a massive output.
- Infinite Input Impedance: $R_{in} = \infty$, ensuring zero input current flows into the terminals.
- Zero Output Impedance: $R_{out} = 0$, allowing the output voltage to remain independent of the load current.
- Infinite Bandwidth: $BW = \infty$, capable of amplifying signals from DC to extremely high frequencies with zero phase shift.

Ideal Op-Amp Characteristics (Continued)

Additional parameters that define an ideal op-amp behavior.

- Zero Input Offset Voltage: When input voltage difference is zero, output voltage is exactly zero.
- Infinite Common Mode Rejection Ratio: $CMRR = \infty$, completely rejecting noise common to both inputs.
- Infinite Slew Rate: Output voltage changes instantaneously with changes in input voltage.



Practical Characteristics of 741 IC

Parameter	Ideal Value	Practical 741 IC Value
Voltage Gain (A_OL)	Infinite	100,000 to 200,000
Input Impedance (R_in)	Infinite	2 Megaohms
Output Impedance (R_out)	Zero	75 Ohms
Bandwidth	Infinite	1 Megaherz
Slew Rate	Infinite	0.5 V per microsecond

Inverting Amplifier Configuration

In an inverting amplifier, the input signal is applied to the inverting terminal while the non-inverting terminal is grounded.

- Input voltage V_{in} is connected through resistor R_1 to the inverting terminal.
- Feedback resistor R_f connects the output back to the inverting terminal.
- Non-inverting terminal is tied directly to ground $V_+ = 0$.
- Virtual ground concept applies at the inverting input node due to infinite open-loop gain.

Voltage Gain Formula Derivation: Inverting Amplifier

Derive the expression for closed-loop voltage gain A_v of an inverting amplifier.

1. Apply Kirchhoff's Current Law at the inverting node: $\frac{0-V_{in}}{R_1} + \frac{0-V_{out}}{R_f} = 0$ considering virtual ground.
2. Rearrange the equation: $-\frac{V_{in}}{R_1} = \frac{V_{out}}{R_f}$.
3. Solve for voltage gain $A_v = \frac{V_{out}}{V_{in}}$.

Voltage gain $A_v = -\frac{R_f}{R_1}$. The negative sign indicates a 180-degree phase inversion.

Non-Inverting Amplifier Configuration

In a non-inverting amplifier, the input signal is applied directly to the non-inverting terminal.

- Input voltage V_{in} is applied to the $(+)$ terminal.
- Resistor R_1 connects the $(-)$ terminal to ground, and R_f provides negative feedback.
- Input impedance is extremely high because the signal goes directly into the op-amp terminal.
- Output is in phase with the input signal, meaning no phase inversion occurs.

Voltage Gain Formula Derivation: Non-Inverting Amplifier

Derive the closed-loop voltage gain A_v for a non-inverting amplifier.

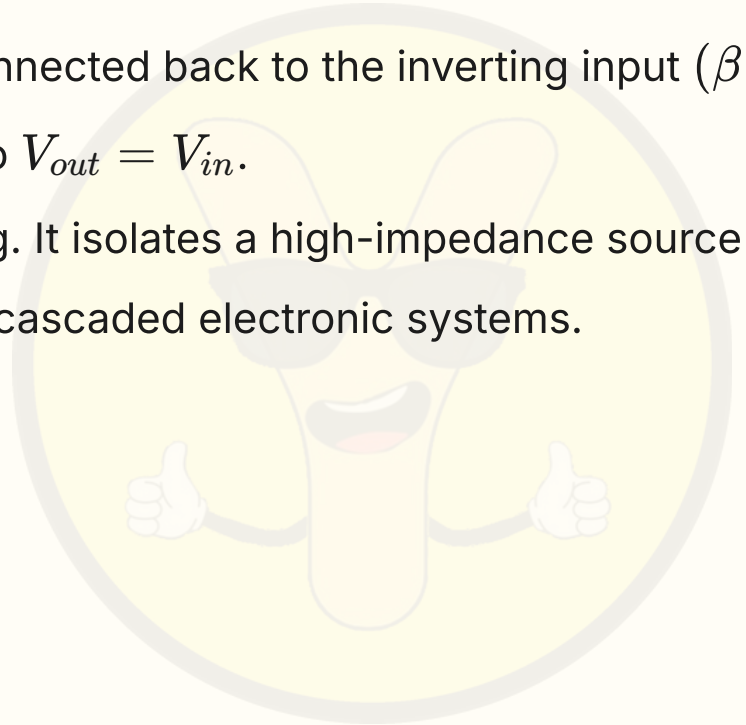
1. Using voltage division at the inverting node: $V_{in} = V_- = V_{out} \times \frac{R_1}{R_1 + R_f}$.
2. Rearrange terms to find the ratio of output to input voltage.
3. $\frac{V_{out}}{V_{in}} = \frac{R_1 + R_f}{R_1}$.

Voltage gain $A_v = 1 + \frac{R_f}{R_1}$. Gain is always greater than or equal to one.

Voltage Follower (Buffer)

A voltage follower is a non-inverting amplifier with a voltage gain of exactly one.

- Configuration: Output is directly connected back to the inverting input ($\beta = 1$), with $R_f = 0$ and $R_1 = \infty$.
- Gain Formula: $A_v = 1 + \frac{0}{\infty} = 1$, so $V_{out} = V_{in}$.
- Main Purpose: Impedance matching. It isolates a high-impedance source from a low-impedance load.
- Prevents loading effect in complex cascaded electronic systems.



Summing Amplifier (Adder)

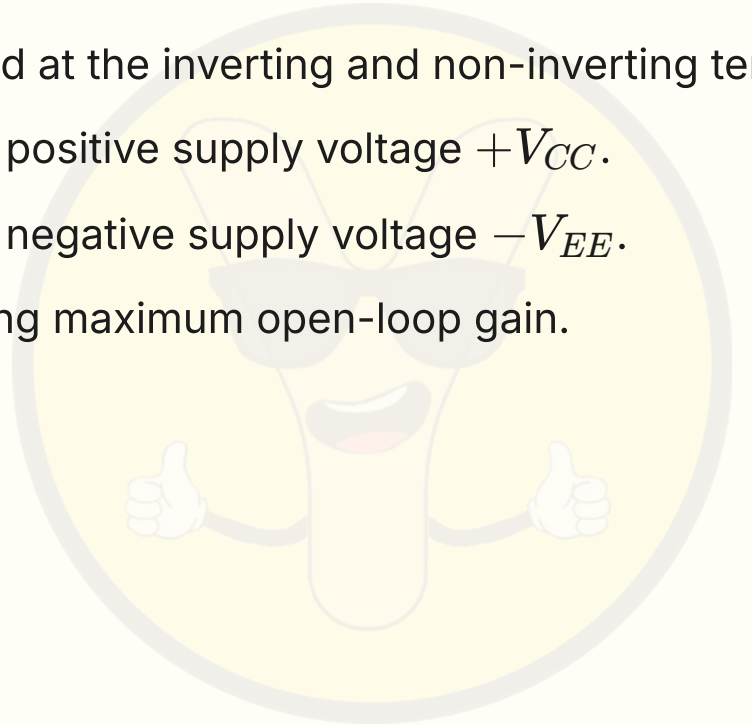
A summing amplifier produces an output voltage proportional to the weighted sum of multiple inputs.

- Can be built using an inverting amplifier configuration with multiple input resistors connected to the inverting node.
- Uses superposition theorem to find the total output voltage.
- Output Equation: $V_{out} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$.
- If all input resistors are equal $(R_1 = R_2 = R_3 = R)$ and $R_f = R$, then $V_{out} = -(V_1 + V_2 + V_3)$.

Op-Amp as a Comparator

When operated in open-loop mode, an op-amp acts as a voltage comparator.

- Compares two voltage levels applied at the inverting and non-inverting terminals.
- If $V_+ > V_-$, output saturates at the positive supply voltage $+V_{CC}$.
- If $V_+ < V_-$, output saturates at the negative supply voltage $-V_{EE}$.
- No feedback resistor is used, utilizing maximum open-loop gain.



Threshold Detection using Comparator

A threshold detector compares an input signal against a fixed reference voltage.

- Reference voltage V_{ref} is applied to one terminal (e.g., inverting input), and varying input V_{in} to the other.
- When input crosses the threshold V_{ref}, output abruptly switches states.
- Used in pulse generation, zero-crossing detectors, and alarm triggering systems.
- Disadvantage: Noise near the threshold voltage can cause false multiple triggering (solved using hysteresis/schmitt trigger).

Application: Sensor Signal Amplification

Physical sensors generate very weak electrical signals that require amplification before processing.

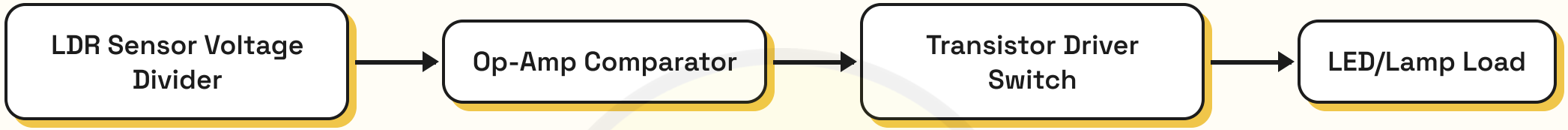
- Temperature Sensors: Thermocouples or RTDs produce millivolt-level changes; op-amps scale these to readable voltage ranges.
- Light Sensors: Photodiodes or LDRs convert light intensity into tiny currents converted to voltages by transimpedance op-amp circuits.
- Pressure Sensors: Strain gauges produce microvolt outputs under mechanical stress, amplified precisely by instrumentation op-amp topologies.
- Ensures high signal-to-noise ratio before analog-to-digital conversion.

Application: Audio Amplifier

Op-amps are widely used in audio signal chains for pre-amplification and tone control.

- Audio Preamplifier: Boosts weak signals from microphones or guitar pickups to standard line levels.
- Active Filters: Uses op-amps combined with RC networks to create bass, treble, and crossover tone control circuits.
- Low Distortion: High input impedance and low output impedance maintain audio fidelity.
- Operates efficiently in both inverting and non-inverting configurations depending on phase requirements.

Automatic Night Lamp Comparator Circuit



Block diagram of an automatic night lamp turning on when ambient light falls below a set threshold.

Application: Differential Amplifier for ECG/EEG Front-End

Biomedical signals like ECG (heart) and EEG (brain) are extremely weak and masked by high common-mode noise.

- Concept: Biomedical electrodes pick up weak differential bio-potentials alongside large common-mode power line interference $(50/60\ \text{Hz})$.
- Differential amplification subtracts identical noise present on both input leads while amplifying the actual signal difference.
- High Common Mode Rejection Ratio (CMRR) is critical to suppress ambient electrical noise.
- Forms the crucial first stage (front-end) of medical diagnostic equipment.

Exam Corner

Q1 State the characteristics of an ideal operational amplifier and compare them with a 741 IC.

Q2 Derive the voltage gain expression for an inverting and a non-inverting amplifier configuration.

Q3 Explain the working of an op-amp as a voltage follower and list its primary applications.

Q4 Design a summing amplifier circuit using an op-amp to obtain an output $V_{out} = -(2V_1 + 3V_2 + 5V_3)$.

Q5 Explain how an op-amp works as a comparator with the help of transfer characteristics.

Q6 Discuss the role of operational amplifiers in biomedical signal processing (ECG/EEG front-end).

Q7 Write short notes on: (a) Virtual Ground concept, (b) Slew Rate, (c) Automatic night lamp circuit.

Unit 3 done. You are exam-ready.

Revise the Exam corner once more, then open Unit 4 on theycotes.com. Every AKTU subject, unit by unit, free. Notes by Chirag Jain, Ycotes.

