GUJARAT TECHNOLOGICAL UNIVERSITY

BE-4 SEMESTER – OLD PAPER – S22 TO W25 – QUESTION BANK ANSWER

Subject Name & Code:
ANALOG CIRCUIT DESIGN (3141002)

(Disclaimer: The purpose of these AI-generated responses is just education and reference. Utilise them to grasp topics and structure, but always rewrite in your own words and double-check)

Unit 4: Operational Amplifiers

Q.1 – Draw the schematic diagram of the op-amp and its equivalent circuit. (4 marks)
Appeared in: S23 (Q1b)
Ans:
Schematic diagram prompt (op-amp symbol):
[DG PROMPT]
Title: Operational amplifier symbol and equivalent circuit
Description:

1. **Op-amp symbol:** Draw a triangle pointing right. Left side: two inputs – inverting input (-) at top left, non-inverting input (+) at bottom left. Right side: single output at apex. Draw +Vcc and -Vee (or V+) at top and bottom of triangle (optional). Label pins: Inverting input, Non-inverting input, Output, V+, V- (ground reference).
2. **Equivalent circuit:** Draw a triangle (ideal op-amp). Input stage: differential input resistance R_i between inverting and non-inverting terminals. Input offset voltage V_{OS} in series with non-inverting terminal. Input bias currents I_B^+ and I_B^- drawn as current sources. Output stage: dependent voltage source $A_{OL}V_d$ (where $V_d = V_+ - V_-$) in series with output resistance R_o. Add a voltage source V_{OS} and current sources for bias currents. Label all components.

Q.2 – Explain the concept of virtual ground in an op-amp. (4 marks)
Appeared in: S25 (Q4a, 3 marks), S22 (Q3a, 3 marks), W24 (Q2b, 4 marks), W23 (Q2b, 4 marks) → Highest 4 marks
Ans:
Definition: Virtual ground (or virtual short) is a concept applicable to op-amps with **negative feedback**. It states that the voltage difference between the inverting (-) and non-inverting (+) inputs is approximately zero, making the inverting input appear as if it is at the same potential as the non-inverting input.
Explanation:

- For an ideal op-amp with infinite open-loop gain A_{OL}, the output voltage $V_o = A_{OL}(V_+ - V_-)$.
- With negative feedback, V_o is finite. Therefore, $(V_+ - V_-) = V_o/A_{OL} \to 0$.
- If the non-inverting input is grounded ($V_+ = 0$), then the inverting input is also at 0V – this is called **virtual ground**.
- No current flows into the op-amp inputs (infinite input impedance).

Key points:

- Virtual ground is **not actual ground** – it is a point maintained at 0V by feedback action.
- It applies only when the non-inverting input is grounded. If V_+ is not ground, the concept extends to **virtual short** ($V_- = V_+$).
- Used to simplify analysis of inverting amplifier, summing amplifier, integrator, etc.

Real-world application: Virtual ground allows the inverting amplifier to have gain = $-R_f/R_1$ independent of op-amp parameters.

Q.3 – List the ideal characteristics of an op-amp.
(4 marks)
Appeared in: S25 (Q1b, 4 marks), S22 (Q1a, 3 marks), W24 (Q4a, 3 marks), W23 (Q1a, 3 marks), W22 (Q2a, 3 marks) → Highest 4 marks
Ans:

Parameter	Ideal Value
Open-loop gain A_{OL}	Infinite (∞)
Input resistance R_i	Infinite (∞)
Output resistance R_o	Zero (0)
Bandwidth	Infinite (∞)
Input offset voltage V_{OS}	Zero (0)
Input bias current I_B	Zero (0)
Input offset current I_{OS}	Zero (0)
Common-mode rejection ratio (CMRR)	Infinite (∞)
Supply voltage rejection ratio (SVRR)	Infinite (∞)
Slew rate	Infinite (∞)
Output voltage swing	$\pm V_{CC}$ (rail-to-rail)

Real-world application: Ideal op-amp assumptions simplify circuit analysis (e.g., virtual short, zero output impedance) for designing filters, amplifiers, and oscillators.

Q.4 – Explain the internal block diagram of an op-amp.
(3 marks)
Appeared in: S25 (Q1a)
Ans:
Internal block diagram of a typical op-amp (e.g., 741) consists of four stages:

Stage	Function	Key Components

Stage	Function	Key Components
1. Input stage	High input impedance, differential amplification, high CMRR	Differential amplifier (transistor pair), constant current source
2. Intermediate stage	High voltage gain	Darlington pair or cascode amplifier
3. Level shifting stage	Shift DC level to zero volts at output	Emitter follower with level shifter
4. Output stage	Low output impedance, high current drive	Class AB push-pull amplifier

Diagram prompt:
[DG PROMPT]
Title: Internal block diagram of op-amp (741)
Description: Draw four rectangular blocks in sequence: Input stage (dual-input differential amplifier), Intermediate stage (high gain), Level shifter, Output stage (push-pull). Connect arrows between blocks. Label input pins (-) and (+) at left of input stage. Label output pin at right of output stage. Add V+ and V- power supply connections to output stage (or all stages). Show a constant current source biasing the input stage.

Q.5 – Define: SVRR, slew rate, input offset voltage, input bias current, input offset current, CMRR, output offset voltage.
(7 marks)
Appeared in: S25 (Q1c, 7 marks), S23 (Q1a, 3 marks), S22 (Q1b, 4 marks), W25 (Q1a, 3 marks), W24 (Q2a, 3 marks), W23 (Q4a, 3 marks), W22 (Q1a, 3 marks) → Highest 7 marks
Ans:

Term	Definition	Formula/Unit	
SVRR (Supply Voltage Rejection Ratio)	Ratio of change in supply voltage to the resulting change in input offset voltage. Measures immunity to power supply variations.	SVRR $= \frac{\Delta V_{supply}}{\Delta V_{OS}}$ (dB)	
Slew rate (SR)	Maximum rate of change of output voltage per unit time. Limited by internal compensation capacitor.	(SR = \frac{dV_o}{dt}\big	_{max}) (V/µs)
Input offset voltage (V_{OS})	The differential DC voltage that must be applied between input terminals to make output zero.	Typically µV to mV	

Term	Definition	Formula/Unit
Input bias current (I_B)	Average of the two input currents flowing into the op-amp inputs.	$I_B = \frac{I_{B+}+I_{B-}}{2}$ (nA to µA)
Input offset current (I_{OS})	Difference between the two input bias currents.	(I_{OS} = I_{B+} - I_{B-}) (nA)
CMRR (Common-Mode Rejection Ratio)	Ratio of differential gain A_d to common-mode gain A_{cm}. Measures ability to reject common-mode signals.	CMRR $= \frac{A_d}{A_{cm}}$ (dB)
Output offset voltage	The DC voltage present at output when both inputs are grounded. Caused by V_{OS} and I_{OS}.	$V_{oo} = V_{OS} \times (1 + \frac{R_f}{R_1}) + I_{OS}R_f$

Real-world application: These parameters determine op-amp selection for precision applications (e.g., instrumentation amplifiers require low V_{OS}, high CMRR).

Q.6 – Explain summing, scaling, and averaging amplifier.
(4 marks)
Appeared in: S25 (Q4b), S22 (Q3b)
Ans:
Summing amplifier (inverting summer):

- Circuit: Multiple inputs $V_1, V_2, \ldots, V_n$ each through resistor R to inverting terminal. Feedback resistor R_f. Non-inverting terminal grounded.
- Output: $V_o = -\frac{R_f}{R}(V_1 + V_2 + \ldots + V_n)$
- Summing with equal weights.

Scaling amplifier:

- Same as summing but input resistors $R_1, R_2, \ldots$ can be different.
- Output: $V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \ldots\right)$
- Each input gets a different scale factor (gain).

Averaging amplifier:

- Special case of summing where $R_f/R = 1/n$ to get average.
- For n inputs, choose $R_f = R/n$. Then $V_o = -\frac{V_1+V_2+\ldots+V_n}{n}$
- Output is negative average. To get positive average, use non-inverting configuration or invert again.

Diagram prompt (summing):
[DG PROMPT]
Title: Inverting summing amplifier (op-amp)
Description: Draw op-amp triangle. Inverting input (-) at left, non-inverting (+) connected to ground. Connect three input resistors R1, R2, R3 from three voltage sources V1, V2, V3 to the inverting node. Connect feedback resistor R_f from output to inverting node. Output taken from op-amp output. Label all components.

Real-world application: Audio mixer (summing), digital-to-analog converter (weighted resistor DAC), sensor signal conditioning (averaging).

Q.7 – Explain differential amplifier using two op-amps.
(7 marks)
Appeared in: S25 (Q4b OR, 4 marks), S22 (Q5a, 3 marks), W22 (Q1c, 7 marks) → Highest 7 marks
Ans:
Circuit description: A differential amplifier with two op-amps provides high input impedance and adjustable gain. Also known as **instrumentation amplifier** (simplified two-op-amp version).
Diagram prompt:
[DG PROMPT]
Title: Differential amplifier using two op-amps
Description: Draw two op-amps (A1 and A2). Op-amp A1: non-inverting input connected to input V_1 through resistor R_1. Inverting input connected to ground via R_2? Wait – standard two-op-amp differential amplifier:

- Input V_1 to non-inverting of A1. A1 in non-inverting configuration with gain $1 + R_f/R$ (feedback from output to inverting input, inverting input also to A2 output?). Better: Use standard circuit: A1 and A2 both in non-inverting configuration, their outputs subtracted by a differential amplifier. I'll describe the **two-op-amp differential amplifier** (also called instrumentation amplifier with two op-amps): First stage: A1 and A2 as buffers with gain. V_1 to A1 (+), V_2 to A2 (+). Resistors R_1 connected between inverting inputs of A1 and A2, with a variable resistor R_G across them. Feedback resistors R_f from each output to respective inverting input. Output of A1 and A2 are V_{o1} and V_{o2}. Second stage: subtractor using one op-amp? But question says "using two op-amps" – only two op-amps total. So the two op-amps directly produce differential output.
  Actually the standard two-op-amp differential amplifier:
  A1: non-inverting input V_1. A2: inverting input V_2 through R, non-inverting grounded. Resistors connect to give differential output. Let me provide the correct known topology:

Configuration (Two-op-amp diff amp):

- Op-amp A1: non-inverting input V_1. Feedback resistor R_f from output to inverting input. Inverting input also connected to A2 output through R.
- Op-amp A2: inverting input connected to V_2 through R. Non-inverting grounded. Feedback resistor R_f from output to inverting input.
- Output V_o taken from A1 output.
- Gain: $V_o = \frac{R_f}{R}(V_1 - V_2)$

Working principle:

- A2 acts as an inverting amplifier for V_2 with gain $-R_f/R$.
- A1 sums V_1 (non-inverting gain) and the inverted V_2 from A2.
- Result: Differential output proportional to $(V_1 - V_2)$.

Advantages:

- High input impedance (both inputs go to op-amp non-inverting/inverting with high R_i)
- Single resistor sets gain
- Good CMRR

Limitations:

- Input common-mode range limited
- Requires matched resistors for good CMRR

Applications: Medical instrumentation (ECG amplifiers), bridge amplifier, differential signal conditioning.

Q.8 – Explain subtractor using op-amp.
(4 marks)
Appeared in: W25 (Q2b)
Ans:
Subtractor (Differential amplifier) using single op-amp:
Circuit:

- Input V_1 through resistor R_1 to non-inverting terminal.
- Input V_2 through resistor R_2 to inverting terminal.
- Feedback resistor R_f from output to inverting terminal.
- Non-inverting terminal to ground through resistor R_3.

Design for balanced condition: To get $V_o = V_1 - V_2$, set $R_1 = R_2$ and $R_f = R_3$. Then:

$$V_o = \frac{R_f}{R_1}(V_1 - V_2)$$

Working:

- Superposition: Output due to V_1 alone (non-inverting gain $1 + R_f/R_1$ with divider) and V_2 alone (inverting gain $-R_f/R_1$).
- The resistor R_3 equal to R_1 ensures proper cancellation.

Diagram prompt:
[DG PROMPT]
Title: Op-amp subtractor (differential amplifier)
Description: Draw op-amp triangle. Inverting input (-) connected to input V_2 through resistor R_2 and to output through feedback resistor R_f. Non-inverting input (+) connected to input V_1 through resistor R_1 and to ground through resistor R_3. Label $R_1 = R_2 = R$, $R_f = R_3 = R'$. Output $V_o = (R'/R)(V_1 - V_2)$.
Real-world application: Signal subtraction in instrumentation, bridge sensor readout, noise cancellation.

Q.9 – Explain V to I converter with grounded load.
(3 marks)
Appeared in: S25 (Q3a)
Ans:
Voltage-to-current converter (transconductance amplifier) with grounded load:
Circuit (using op-amp):

- Input voltage V_{in} applied to non-inverting terminal.
- Output of op-amp drives the load R_L which is grounded at one end.
- Feedback: Current through load flows through a sense resistor R_s (connected from output to inverting terminal). The inverting terminal is at virtual ground.

Analysis:

- Since $V_+ = V_{in}$, virtual short gives $V_- = V_{in}$.
- The feedback resistor R_s has voltage V_{in} across it (since $V_- = V_{in}$, and output is at $V_o = V_{in} + I_L R_s$).
- Current through R_s is $I_s = V_{in}/R_s$.
- This current flows through load: $I_L = I_s = V_{in}/R_s$ (assuming negligible op-amp input

current).
Output current:

$$I_L = \frac{V_{in}}{R_s}\text{(independent of } R_L\text{)}$$

Limitation: Load current is limited by op-amp output current capability.
Diagram prompt:
[DG PROMPT]
Title: Voltage-to-current converter (grounded load)
Description: Draw op-amp. Non-inverting input connected to voltage source V_{in}. Inverting input connected to ground through resistor R_s? Wait – correct: Inverting input to output through R_s, and load R_L from output to ground. Actually standard: Load is between op-amp output and ground. Feedback resistor R_s connects from output to inverting input. Inverting input also connected to ground? No – Let me redraw correctly: Use Howland current pump or simpler: The load is grounded, so the current must be sourced from op-amp output. Feedback resistor R_s is connected from output to inverting input. The inverting input is at virtual ground, so V_{in} appears across R_s. Then $I_L = V_{in}/R_s$ flows through load. So load is from output to ground, feedback resistor from output to inverting input. Label: V_{in} to (+), (-) to R_s to output, load R_L from output to ground.

Q.10 – Explain floating load V to I converter using op-amp.
(3 marks)
Appeared in: W22 (Q4a)
Ans:
Floating load voltage-to-current converter:
- Load is not connected to ground (floating).
- Simple circuit: Op-amp with load in feedback path.

Circuit:
- Input voltage V_{in} to non-inverting terminal.
- Load R_L connected between output and inverting terminal.
- Feedback resistor? No – the load itself is the feedback element.

Working:
- Virtual short: $V_- = V_{in}$.
- The voltage across the load is $V_o - V_- = V_o - V_{in}$. But also $V_o = V_{in} + I_L R_L$. So $I_L R_L = V_o - V_{in}$.
- Actually simpler: Current through load I_L must also flow through the feedback path? In this configuration, the load is between output and inverting input. So $I_L = (V_o - V_{in})/R_L$. But V_o is determined by op-amp action.

Better known circuit: **Basic floating load V-to-I** – Connect load in feedback loop.
Input V_{in} to non-inverting input. A sense resistor R_s from output to inverting input. Load in series with R_s? Actually the floating load converter: Load is connected between output and inverting input, and a resistor to ground from inverting input. Let me provide standard answer:
Standard floating load V-to-I:
- Non-inverting input: V_{in}.
- Inverting input: connected to ground through resistor R_1, and to output through load R_L.
- Then $I_L = V_{in}/R_1$ (independent of R_L).

Derivation: Virtual short: $V_- = V_{in}$. Current through R_1 is $I_1 = V_{in}/R_1$. This current must come from the load (since op-amp input current is zero). So $I_L = I_1 = V_{in}/R_1$.

Advantage: Load floating, can be any value within op-amp output limits.
Diagram prompt:
[DG PROMPT]
Title: Floating load voltage-to-current converter
Description: Draw op-amp. Non-inverting input connected to V_{in}. Inverting input connected to ground through resistor R_1, and also connected to output through the floating load R_L. Output voltage adjusts to maintain $V_- = V_{in}$. Label currents: $I_L = I_{R1} = V_{in}/R_1$.

Q.11 – Explain I to V converter using op-amp.
(3 marks)
Appeared in: W25 (Q4a)
Ans:
Current-to-voltage converter (transimpedance amplifier):
Circuit:

- Op-amp with feedback resistor R_f from output to inverting input.
- Non-inverting input grounded.
- Input current I_{in} applied to inverting terminal.

Working:

- Virtual ground at inverting terminal ($V_- = 0$).
- The input current I_{in} cannot flow into op-amp (infinite input impedance), so it flows through R_f.
- Output voltage $V_o = -I_{in} \times R_f$.

Output expression:

$$V_o = -I_{in}R_f$$

Features:

- Low input impedance (virtual ground) – ideal for current sources.
- Gain is set by R_f.
- Photodiode, photomultiplier tube, current-output sensors.

Real-world application: Photodiode amplifier in light meters, optical receivers.
Diagram prompt:
[DG PROMPT]
Title: Current-to-voltage converter (transimpedance amplifier)
Description: Draw op-amp. Non-inverting input grounded. Inverting input connected to input current source I_{in} (arrow pointing into node). Feedback resistor R_f from output to inverting input. Output voltage V_o. Optionally add a capacitor in parallel with R_f for stability.

Q.12 – Explain the basic differentiator using an op-amp. What are the problems? How are they overcome?
(7 marks)
Appeared in: S22 (Q1c)
Ans:
Basic differentiator circuit:

- Input resistor replaced by capacitor C in series with inverting terminal.
- Feedback resistor R_f. Non-inverting terminal grounded.

Output voltage:

$$V_o = -R_f C \frac{dV_{in}}{dt}$$

Working: Virtual ground at inverting terminal, current through capacitor $i_c = C \cdot dV_{in}/dt$ flows through R_f, giving $V_o = -i_c R_f$.
Problems with basic differentiator:

1. **High frequency noise amplification** – Gain increases with frequency ($|A| = 2\pi f R_f C$), amplifying high-frequency noise and causing instability.
2. **Oscillation tendency** – Phase shift from capacitor can cause positive feedback at high frequencies.
3. **Input impedance capacitive** – May cause ringing with source resistance.
4. **Saturation** – Fast transients can drive op-amp into saturation.

Overcoming methods (Practical differentiator):

- Add a **series resistor** R_1 with C to limit high-frequency gain.
- Add a **parallel capacitor** C_f across R_f to provide a roll-off.
- Result is a **band-limited differentiator** (active high-pass filter).

Modified circuit:

- R_1 in series with C.
- C_f in parallel with R_f.
- Transfer function becomes: $V_o(s)/V_{in}(s) = -sR_f C/[(1 + sR_1 C)(1 + sR_f C_f)]$.
- Gain rolls off at high frequencies.

Real-world application: Wave shaping (edge detection), rate-of-change measurement, control systems (PID controller derivative term).
Diagram prompt (practical differentiator):
[DG PROMPT]
Title: Practical op-amp differentiator
Description: Draw op-amp. Inverting input connected to input V_{in} through series capacitor C and resistor R_1. Feedback path: resistor R_f in parallel with capacitor C_f from output to inverting input. Non-inverting input grounded. Label components: R_1 (10kΩ typical), C (0.1μF), R_f (100kΩ), C_f (0.001μF). Output V_o.

Q.13 – Derive the expression for the output of a differentiator circuit using op-amp. (4 marks)
Appeared in: W24 (Q4b)
Ans:
Given: Basic op-amp differentiator with capacitor C at input and feedback resistor R_f.
To find: Output voltage expression.
Assumptions: Ideal op-amp (infinite input impedance, zero offset, virtual ground).
Derivation:

1. Virtual ground: $V_- = 0$ (since $V_+ = 0$).
2. Current through capacitor: $i_C = C\frac{d(V_{in} - V_-)}{dt} = C\frac{dV_{in}}{dt}$.
3. This current flows through feedback resistor R_f because no current enters op-amp. $i_{R_f} = i_C = C\frac{dV_{in}}{dt}$.
4. Output voltage: $V_o = V_- - i_{R_f} R_f = 0 - \left(C\frac{dV_{in}}{dt}\right) R_f$.

Final expression:

$$\boxed{V_o(t) = -R_f C\frac{dV_{in}(t)}{dt}}$$

In s-domain: $V_o(s) = -sR_f C\, V_{in}(s)$.
Numerical example: If $R_f = 10\ k\Omega$, $C = 0.01\ \mu F$, and $V_{in} = 5\sin(2\pi 1000t)$, then $dV_{in}/$

$dt = 5 \times 2\pi 1000\cos(\dots) = 31416\cos(\dots)$, so $V_o = -10k \times 0.01\mu \times 31416\cos(\dots) = -3.1416\cos(\dots)$ volts.

Q.14 – Explain an inverting differentiator circuit using op-amp.
(7 marks)
Appeared in: W22 (Q2c)
Ans:
(Note: This is same as Q.12 but with emphasis on inverting configuration. The standard differentiator is already inverting. Provide answer covering practical differentiator with design considerations.)
Inverting differentiator circuit:

- Input via series capacitor C.
- Feedback resistor R_f.
- Non-inverting input grounded.
- Output is inverted derivative.

Detailed explanation:
1. Basic operation:

- Virtual ground at inverting terminal.
- $i_C = C\frac{dV_{in}}{dt} \rightarrow i_{R_f} = i_C \rightarrow V_o = -i_{R_f}R_f = -R_f C\frac{dV_{in}}{dt}$.

2. Frequency response:

- Gain magnitude $|A| = 2\pi f R_f C$ – increases with frequency.
- Phase shift: Input to output: -90° (ideal differentiator).

3. Practical implementation issues (as in Q.12) and solutions:

- Add R_1 in series with C to limit HF gain to R_f/R_1.
- Add C_f in parallel with R_f to roll off gain above $f = 1/(2\pi R_f C_f)$.
- Typical component values: Choose C_f such that $R_f C_f = R_1 C$ for proper compensation.

4. Design steps (GTU style):

- Choose cut-off frequency f_c for differentiation range: $f < 1/(2\pi R_1 C)$.
- Above f_c, circuit behaves as inverting amplifier with gain R_f/R_1.
- Ensure $R_f C_f = R_1 C$ to maintain stability.

5. Waveform example:

- Input: square wave → output: positive and negative spikes.
- Input: triangular wave → output: square wave.
- Input: sine wave → output: cosine wave (phase shifted).

Diagram prompt: Same as Q.12 practical differentiator.
Real-world application: Rate-of-change detection in automotive sensors, FM demodulation, edge triggering.

Q.15 – Derive gain expression for inverting and non-inverting configuration of op-amp.
(4 marks)
Appeared in: S25 (Q5b), W25 (Q2a), W24 (Q5b)
Ans:
Inverting amplifier:
Circuit: Input V_{in} via resistor R_1 to inverting terminal. Feedback resistor R_f from output to inverting terminal. Non-inverting terminal grounded.
Derivation: Virtual ground → $V_- = 0$.
Current $i_1 = V_{in}/R_1$ flows through $R_f \rightarrow V_o = -i_1 R_f = -(R_f/R_1)V_{in}$.

Gain:

$$A_{inv} = \frac{V_o}{V_{in}} = -\frac{R_f}{R_1}$$

Non-inverting amplifier:
Circuit: Input V_{in} to non-inverting terminal. Inverting terminal connected to ground through R_1, and to output through R_f.
Derivation: Virtual short: $V_- = V_+ = V_{in}$.
Voltage divider: $V_- = V_o \times \frac{R_1}{R_1+R_f} \rightarrow V_{in} = V_o \frac{R_1}{R_1+R_f} \rightarrow V_o = V_{in}\left(1+\frac{R_f}{R_1}\right)$.
Gain:

$$A_{non} = \frac{V_o}{V_{in}} = 1 + \frac{R_f}{R_1}$$

Comparison:
- Inverting: negative gain, input impedance = R_1.
- Non-inverting: positive gain ≥1, very high input impedance.

Q.16 – Draw and explain VTC (Voltage Transfer Curve) of op-amp.
(4 marks)
Appeared in: W25 (Q1b), W22 (Q1b)
Ans:
Voltage Transfer Characteristic (VTC) plots output voltage V_o vs differential input voltage $V_d = V_+ - V_-$.
Diagram prompt:
[DG PROMPT]
Title: Voltage transfer curve of op-amp
Description: Draw axes: horizontal axis V_d (differential input) from -few mV to +few mV, vertical axis V_o from -V_{sat} to +V_{sat}. Draw a linear region (steep slope) passing through origin, with slope equal to open-loop gain A_{OL}. For positive V_d beyond a few µV, V_o saturates at $+V_{sat}$ (positive rail). For negative V_d, V_o saturates at $-V_{sat}$. Label: Linear region (active), Positive saturation, Negative saturation, Saturation voltages = ±V_{CC} - 1.5V (for 741). Indicate typical A_{OL} = 10^5, input offset voltage V_{OS} shift (if not ideal).
Explanation:
- **Linear region:** Very narrow input range (≈ ±100 µV for $A_{OL} = 10^5$ and ±10V output). Slope = A_{OL}.
- **Positive saturation:** $V_d > V_{sat}/A_{OL} \rightarrow V_o = +V_{sat}$.
- **Negative saturation:** $V_d < -V_{sat}/A_{OL} \rightarrow V_o = -V_{sat}$.
- For real op-amps, the curve may have offset (shifted from origin).

Real-world application: Comparator operation, open-loop applications, understanding op-amp limitations.

Q.17 – Explain op-amp functionality as a comparator.
(7 marks)
Appeared in: W25 (Q1c)
Ans:
Comparator function: Compares two input voltages and outputs a digital signal indicating which is larger.
Basic comparator circuit:

- Op-amp in open-loop (no feedback).
- V_{ref} applied to one input, unknown V_{in} to the other.
- Output saturates at $+V_{sat}$ or $-V_{sat}$ depending on input difference.

Operation:

- If $V_{in} > V_{ref}$, output = $+V_{sat}$ (for non-inverting comparator).
- If $V_{in} < V_{ref}$, output = $-V_{sat}$.
- Transition occurs when $V_{in} = V_{ref}$.

Types:

Type	Configuration	Output Logic
Non-inverting	V_{in} to (+), V_{ref} to (-)	$V_o = +V_{sat}$ when $V_{in} > V_{ref}$
Inverting	V_{in} to (-), V_{ref} to (+)	$V_o = +V_{sat}$ when $V_{in} < V_{ref}$

Practical issues and solutions:

- **Slow response** due to saturation – use dedicated comparator IC (LM311, LM339).
- **Oscillation near threshold** – use positive feedback (Schmitt trigger) to add hysteresis.
- **Input offset voltage** causes error – use low offset op-amp or trim.

Real-world application: Zero-crossing detector, over-voltage protection, analog-to-digital converter front-end, temperature control (thermostat).

Diagram prompt (non-inverting comparator):
[DG PROMPT]
Title: Op-amp as non-inverting comparator
Description: Draw op-amp triangle. Non-inverting input (+) connected to input voltage source V_{in}. Inverting input (-) connected to reference voltage source V_{ref}. No feedback resistors. Output connected to a load resistor R_L (pull-up if open-collector). Show output waveform: when $V_{in} > V_{ref}$, output high (near V_{CC}); when $V_{in} < V_{ref}$, output low (near $-V_{EE}$ or 0V for single supply).

Q.18 – Explain window detector using op-amp.
(3 marks)
Appeared in: S22 (Q2a)
Ans:
Window detector (also called window comparator) detects whether an input voltage lies within a specific range (window) between two thresholds V_L (low) and V_H (high).

Circuit:

- Two op-amps (or comparators) used.
- Op-amp A1: V_{in} to non-inverting, V_H to inverting – output high when $V_{in} > V_H$.
- Op-amp A2: V_{in} to inverting, V_L to non-inverting – output high when $V_{in} < V_L$.
- Outputs combined using logic gates (AND or OR depending on active state).

Common configuration (active high inside window):

- Connect outputs of both comparators to a **AND gate** (or use open-collector wired-AND).
- The AND output is high only when $V_L < V_{in} < V_H$.

Working:

- If V_{in} is between V_L and V_H: both comparators output high → window output high.
- If V_{in} outside: at least one comparator output low → window output low.

Real-world application: Battery level monitor (acceptable voltage range), temperature

controller (window), go/no-go tester.
Diagram prompt:
[DG PROMPT]
Title: Window detector using two op-amps
Description: Draw two op-amps (A1 and A2). A1: non-inverting input to V_{in}, inverting input to V_H (high threshold). A2: inverting input to V_{in}, non-inverting input to V_L (low threshold). Outputs of both op-amps go to a 2-input AND gate. Output of AND gate is window output. Label $V_H > V_L$.

Q.19 – Explain Schmitt trigger circuit using op-amp.
(4 marks)
Appeared in: W25 (Q5a, 3 marks), W22 (Q3b, 4 marks) → Highest 4 marks
Ans:
Schmitt trigger is a comparator with positive feedback (hysteresis). It has two threshold voltages – upper threshold (UTP) and lower threshold (LTP) – to prevent output oscillation near the reference point.
Circuit (non-inverting Schmitt trigger):

- Input V_{in} to non-inverting terminal.
- Feedback resistor R_f from output to non-inverting terminal.
- Inverting terminal connected to reference voltage V_{ref} (often ground).
- Voltage divider R_1, R_2 from output to ground? Actually standard non-inverting: V_{ref} to inverting input via R_1, and non-inverting input gets V_{in} and feedback.

Better known **inverting Schmitt trigger**:

- Input V_{in} to inverting terminal through R_1.
- Feedback R_f from output to non-inverting terminal.
- Non-inverting terminal to ground through R_2? Let me describe the common circuit.

Standard inverting Schmitt trigger:

- Op-amp in inverting configuration with feedback from output to non-inverting input (positive feedback).
- V_{in} to inverting terminal through R_1.
- Non-inverting terminal connected to voltage divider from output and ground: R_2 from non-inverting to ground, R_f from output to non-inverting.
- Output saturates at $\pm V_{sat}$.

Threshold voltages:

$$V_{UT} = \frac{R_2}{R_2 + R_f} V_{sat}, V_{LT} = -\frac{R_2}{R_2 + R_f} V_{sat}$$

For non-inverting version, thresholds depend on V_{ref}.
Hysteresis width: $\Delta V = V_{UT} - V_{LT} = 2\frac{R_2}{R_2+R_f}V_{sat}$.
Advantage: Noise immunity; output switches cleanly once.
Real-world application: Waveform shaping (square wave from sine), noise filtering in digital inputs, switch debouncing.
Diagram prompt (inverting Schmitt trigger):
[DG PROMPT]
Title: Inverting Schmitt trigger using op-amp
Description: Draw op-amp. Inverting input (-) connected to input V_{in} through resistor R_1. Non-inverting input (+) connected to a voltage divider: resistor R_f from output to (+),

resistor R_2 from (+) to ground. Output V_o. Label hysteresis thresholds.

Q.20 – Explain instrumentation amplifier circuit operation using op-amp.
(7 marks)
Appeared in: W22 (Q2c OR)
Ans:
Instrumentation amplifier (IA) is a high-precision differential amplifier with very high input impedance, high CMRR, and adjustable gain.
Three-op-amp instrumentation amplifier (classic):
Circuit description:

- **First stage:** Two non-inverting amplifiers (op-amps A1 and A2). Inputs V_1 and V_2 go to non-inverting terminals. Resistors R_1 and R_2 (equal) connect from each output to the respective inverting input. A gain-setting resistor R_G connects between the two inverting inputs.
- **Second stage:** Differential amplifier (op-amp A3) with resistors R_3, R_4, R_5, R_6 (typically all equal). Inputs are the outputs of A1 and A2.

Diagram prompt:
[DG PROMPT]
Title: Three-op-amp instrumentation amplifier
Description: Draw three op-amps (A1, A2, A3). A1: non-inverting input V_1, inverting input connected to output through R_1 and also to A2's inverting input through R_G. A2: non-inverting input V_2, inverting input connected to output through R_2 (with $R_1 = R_2$). Outputs of A1 and A2 feed into A3 differential stage: A3 non-inverting through R_3 to ground via R_5? Standard: Output of A1 to A3 (+) through R_3; output of A2 to A3 (-) through R_4; feedback R_6 from A3 output to (-); R_5 from (+) to ground. Set $R_3 = R_4 = R_5 = R_6$ for unity differential gain. Label R_G as gain setting resistor.
Operation:

- First stage provides high input impedance and differential gain: $V_{o1} - V_{o2} = (1 + \frac{2R_1}{R_G})(V_1 - V_2)$.
- Second stage (differential amplifier) rejects common-mode and provides additional gain: $V_o = \frac{R_6}{R_3}(V_{o2} - V_{o1})$ or vice versa.
- Total gain: $A_v = (1 + \frac{2R}{R_G}) \times \frac{R_f}{R_{in}}$.

Key features:

- Very high input impedance (both inputs)
- High CMRR (typically 80–120 dB)
- Single resistor R_G controls gain
- Low offset voltage and drift

Applications:

- Medical ECG, EEG amplifiers
- Bridge sensor (strain gauge, pressure) conditioning
- Data acquisition systems
- Thermocouple amplifiers

Numerical example: If $R_1 = R_2 = 10k\Omega$, $R_G = 1k\Omega$, and second stage gain = 1, then total gain = $1 + 2(10k/1k) = 21$.

Q.21 – Explain sample and hold circuit using op-amp.
(7 marks)
Appeared in: S23 (Q4b, 4 marks), S22 (Q5a OR, 3 marks), W25 (Q2c, 7 marks), W22 (Q4a

OR, 3 marks) → Highest 7 marks
Ans:
Sample and hold (S/H) circuit captures an analog voltage at a specific instant and holds it constant for a period of time.
Basic circuit:
- Op-amp as voltage follower (buffer)
- Analog switch (MOSFET or CMOS analog switch)
- Hold capacitor C_H
- Output buffer (second op-amp)

Operation phases:
1. **Sample mode:** Switch closed. Input voltage V_{in} charges capacitor C_H quickly through low on-resistance of switch. Output follows input.
2. **Hold mode:** Switch opened. Capacitor retains the voltage. Output buffer (high input impedance) reads the stored voltage without discharging it.

Improved circuit (two op-amps):
- Input buffer (op-amp) drives the switch and capacitor to reduce charge injection.
- Second op-amp (unity gain) buffers the capacitor voltage to output.

Important parameters:
- **Acquisition time:** Time to charge capacitor to final value (depends on switch resistance and C_H).
- **Aperture time:** Delay between hold command and actual switch opening.
- **Hold step (pedestal):** Voltage error due to charge injection from switch.
- **Drop rate:** Voltage decay during hold due to leakage currents.

Applications:
- Analog-to-digital converters (ADC) front-end
- Signal processing (pulse amplitude modulation, PAM)
- Data acquisition systems
- De-glitching circuits

Diagram prompt:
[DG PROMPT]
Title: Sample and hold circuit using op-amp
Description: Draw input voltage source V_{in} connected to non-inverting input of first op-amp (buffer). Output of first op-amp goes to an analog switch (MOSFET symbol: drain-source, gate driven by control signal). Switch output connects to one terminal of hold capacitor C_H (other terminal grounded). Also connect to non-inverting input of second op-amp (voltage follower). Output of second op-amp is V_{out}. Label: Sample switch control, acquisition time, hold capacitor.

Q.22 – Explain peak detector circuit using op-amp.
(7 marks)
Appeared in: S25 (Q5a, 3 marks), W25 (Q2c OR, 7 marks), S22 (Q5b OR, 4 marks) → Highest 7 marks
Ans:
Peak detector captures and holds the maximum positive (or negative) voltage of an input signal.
Circuit (positive peak detector):
- Op-amp (as comparator/buffer)
- Diode D (in feedback path)
- Hold capacitor C
- Buffer op-amp (optional)

Operation:

- When input voltage V_{in} rises, op-amp output drives diode forward, charging capacitor C to V_{in} (minus diode drop, but op-amp compensates because feedback is from capacitor).
- When V_{in} falls, diode reverse-biased. Capacitor holds the peak voltage.
- The op-amp's inverting input follows capacitor voltage via feedback; non-inverting input sees V_{in}.
- The diode is placed in the feedback loop so that the op-amp overcomes the diode drop ($V_{out} = V_{in}$ when charging).

Improved precision peak detector:

- Use a second op-amp as a buffer to prevent discharge through the first op-amp's input.
- Add reset switch (MOSFET) across capacitor to clear the peak.

Negative peak detector: Reverse diode polarity.

Key parameters:

- **Droop rate:** Voltage decay due to leakage (use FET input op-amp).
- **Acquisition time:** Time to charge capacitor to new peak.
- **Accuracy:** Limited by diode leakage, op-amp offset.

Applications:

- Peak amplitude measurement (audio level meters)
- Envelope detection in AM demodulation
- Overvoltage detection
- Peak-to-peak detectors

Diagram prompt (positive peak detector):

[DG PROMPT]

Title: Positive peak detector using op-amp

Description: Draw op-amp. Input V_{in} to non-inverting input (+). Inverting input (-) connected to capacitor C (other side to ground) and also to output via a diode (anode to op-amp output, cathode to inverting input? Actually standard: Op-amp output to diode anode, diode cathode to capacitor and to inverting input feedback. That creates a precision half-wave rectifier charging the cap. Label diode D, capacitor C. Output taken from capacitor (through buffer op-amp). Add reset switch (MOSFET) across capacitor.

Q.23 – Explain voltage limiter circuit using op-amp.
(3 marks)

Appeared in: S25 (Q4a OR), W25 (Q4a)

Ans:

Voltage limiter (clipper) restricts output voltage to a preset maximum or minimum level.

Circuit using op-amp with Zener diodes in feedback:

- Op-amp in inverting or non-inverting configuration.
- Two Zener diodes connected back-to-back in parallel with the feedback resistor.
- When output tries to exceed Zener voltage + diode drop, one Zener conducts, clamping the output.

Operation (inverting limiter):

- For normal input levels, output is within $\pm(V_Z + 0.7V)$.
- When output reaches $+V_Z + 0.7V$, the Zener conducts, providing a low-impedance path, preventing further increase.
- Negative excursion clamped similarly by the other Zener.

Types:

- **Single polarity limiter:** One Zener and a diode.
- **Dual polarity (symmetrical):** Two Zeners back-to-back.

- **Adjustable limiter:** Use external reference voltage and diodes.

Real-world application: Protecting ADC inputs from overvoltage, waveform shaping (square wave from sine), audio compressor.
Diagram prompt:
[DG PROMPT]
Title: Voltage limiter using op-amp (inverting)
Description: Draw inverting op-amp with R_1 and R_f. In parallel with R_f, connect two Zener diodes in series opposing (anode to cathode). Label Zener voltage V_Z. Output is clamped to $\pm(V_Z + 0.7V)$.

Q.24 – Explain half-wave rectifier circuit using op-amp.
(3 marks)
Appeared in: W22 (Q5a OR)
Ans:
Precision half-wave rectifier (super diode) using op-amp eliminates the diode drop error.
Circuit (positive half-wave):

- Op-amp in inverting configuration with a diode in the feedback path.
- Input V_{in} through resistor R to inverting terminal.
- Non-inverting terminal grounded.
- Diode D connected from op-amp output to inverting terminal (anode to output, cathode to inverting).
- Output taken from diode cathode through another resistor or directly.

Operation:

- **Positive V_{in}:** Op-amp output goes negative to forward bias the diode. The inverting terminal is virtual ground, so output voltage across load = 0? Wait, need correct topology.

Better known **precision half-wave rectifier (non-inverting):**

- Input to non-inverting terminal.
- Diode from op-amp output to load, and feedback from load to inverting terminal.
- For positive input, output positive, diode conducts, output follows input (minus diode drop compensated by feedback).
- For negative input, output negative, diode reverse biased, output = 0.

Standard circuit (positive half-wave):

- Op-amp, diode in feedback loop, output = V_{in} for $V_{in} > 0$, 0 for $V_{in} < 0$.
- Resistor from diode cathode to inverting terminal, load resistor to ground.

Advantage: Accurate rectification for small signals (< 0.7V).
Diagram prompt:
[DG PROMPT]
Title: Precision half-wave rectifier (positive)
Description: Draw op-amp. Input V_{in} to non-inverting input. Output to diode anode. Diode cathode to load resistor R_L (other side to ground) and also to inverting input through feedback resistor R_f. Output taken across R_L. For positive V_{in}, output positive; for negative, output zero.
Real-world application: AC-to-DC conversion in digital voltmeters, signal demodulation.

Q.25 – Derive gain expression for voltage series feedback amplifier using op-amp.
(4 marks)
Appeared in: W22 (Q2b)
Ans:
Voltage series feedback amplifier is the non-inverting configuration (as derived in Q.15).

The derivation using feedback theory:
Given:

- Basic amplifier: op-amp with open-loop gain A_{OL}.
- Feedback network: resistive voltage divider R_1 (to ground) and R_f (feedback resistor).
- Feedback factor $\beta = \frac{R_1}{R_1+R_f}$ (since output voltage is sampled and fed back to inverting input).

Derivation using feedback equation:
Closed-loop gain $A_f = \frac{A}{1+A\beta}$ for positive gain? For non-inverting, the feedback is negative, so $A_f = \frac{A}{1+A\beta}$ where $A = A_{OL}$.
Substitute $\beta = \frac{R_1}{R_1+R_f}$:

$$A_f = \frac{A_{OL}}{1 + A_{OL} \cdot \frac{R_1}{R_1 + R_f}}$$

For ideal op-amp, $A_{OL} \to \infty$:

$$A_f = \frac{1}{\beta} = 1 + \frac{R_f}{R_1}$$

Alternative derivation using virtual short (as Q.15):
$V_- = V_+ = V_{in}$. Voltage divider gives $V_- = V_o \cdot \frac{R_1}{R_1+R_f}$. Equate: $V_{in} = V_o \cdot \frac{R_1}{R_1+R_f} \to V_o = V_{in} \cdot \frac{R_1+R_f}{R_1} = V_{in}(1 + \frac{R_f}{R_1})$.
Final gain:

$$\boxed{A_{vf} = 1 + \frac{R_f}{R_1}}$$

Q.26 – For a non-inverting op-amp summing circuit with inputs 1V, 2V, 3V, $R_f = 2\ k\Omega$, $R_i = 1\ k\Omega$ determine output voltage.
(4 marks)
Appeared in: W23 (Q5b)
Ans:
Given: Non-inverting summing amplifier (using multiple inputs to non-inverting terminal via equal resistors? Actually non-inverting summing requires a different topology. The standard non-inverting summer: inputs through equal resistors to non-inverting terminal, with feedback to inverting terminal. But the problem likely means **inverting summing** because R_i and R_f are given. Many GTU papers ask for inverting summing. I'll solve as inverting summing.)
Assuming **inverting summing amplifier** with each input having $R_i = 1\ k\Omega$, $R_f = 2\ k\Omega$.
Given: $V_1 = 1V$, $V_2 = 2V$, $V_3 = 3V$, $R_i = 1k\Omega$ (all input resistors equal), $R_f = 2k\Omega$.
Formula for inverting summing:

$$V_o = -\frac{R_f}{R_i}(V_1 + V_2 + V_3)$$

Solution:

$$V_o = -\frac{2k}{1k}(1+2+3) = -2 \times 6 = -12\ V$$

Final Answer:

$$\boxed{V_o = -12\ V}$$

(If non-inverting summing is intended, the output would be different. But standard GTU question with R_f and R_i refers to inverting summing.)

Q.27 – Explain a circuit made up of op-amp that does scaling of inputs. (3 marks)
Appeared in: W25 (Q3a)
Ans:
Scaling amplifier is a summing amplifier where each input has a different gain factor (scale factor).
Circuit: Inverting summing amplifier with different input resistors $R_1, R_2, \ldots, R_n$ for each input $V_1, V_2, \ldots, V_n$. Common feedback resistor R_f.
Output expression:

$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \ldots + \frac{R_f}{R_n}V_n\right)$$

Scaling factors: Each input is multiplied by a factor $k_i = -R_f/R_i$.
Example: To get $V_o = -(2V_1 + 3V_2)$, choose $R_f = 6k\Omega$, then $R_1 = 3k\Omega$, $R_2 = 2k\Omega$.
Real-world application: Weighted DAC (binary-weighted or R-2R ladder), audio mixer with channel gain controls.
Diagram prompt: See summing amplifier (Q.6) with different input resistors.

Q.28 – Explain a circuit made up of op-amp that does averaging of inputs. (3 marks)
Appeared in: W22 (Q3a)
Ans:
Averaging amplifier is a special case of summing amplifier where the output is the average of the inputs.
Circuit: Inverting summing amplifier with n inputs, each input resistor R, feedback resistor $R_f = R/n$.
Output:

$$V_o = -\frac{R_f}{R}(V_1 + V_2 + \ldots + V_n) = -\frac{1}{n}(V_1 + V_2 + \ldots + V_n)$$

To get positive average, use an additional inverting stage with gain -1.
Non-inverting averaging: Use non-inverting summing configuration (requires equal resistors to non-inverting terminal and proper feedback). But the simplest is inverting with $R_f = R/n$.
Example (n=3): $R = 1k\Omega$, $R_f = 333\Omega$, inputs 1V,2V,3V → $V_o = -(1+2+3)/3 = -2V$. Then invert to +2V.
Real-world application: Signal averaging to reduce noise, sensor arrays, analog computing.

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