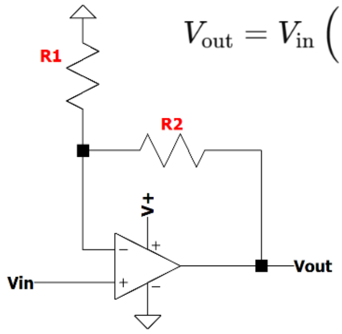
Hardware Engineer's Guide

Operational Amplifiers

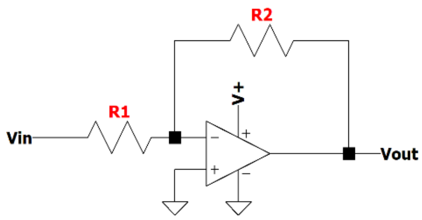
Non-Inverting

$$V_{\text{out}} = V_{\text{in}}\left(1 + \frac{R_2}{R_1}\right)$$



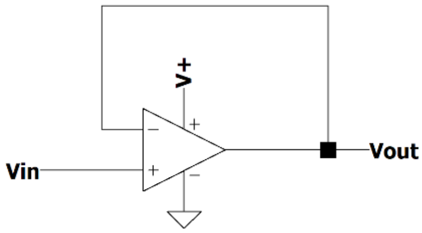
Inverting

$$V_{\text{out}} = -V_{\text{in}}\left(\frac{R_2}{R_1}\right)$$



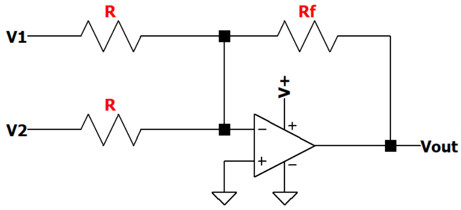
Unity

$$V_{\text{out}} = V_{\text{in}}$$



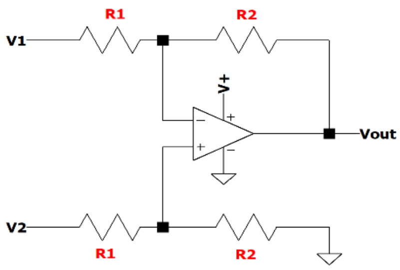
Summing

$$V_{\text{out}} = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2\right)$$



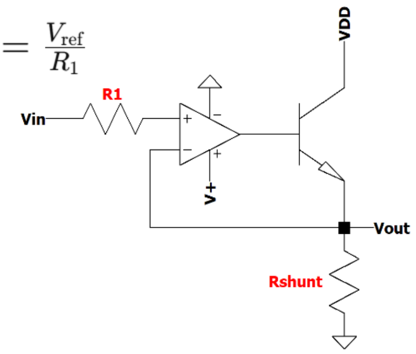
Differential

$$V_{\text{out}} = \left(\frac{R_2}{R_1}\right)(V_2 - V_1)$$



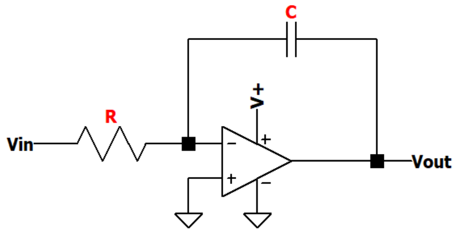
Current Source

$$I = \frac{V_{\text{ref}}}{R_1}$$



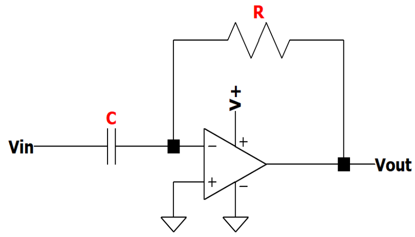
Integrator

$$V_{\text{out}} = -\frac{1}{RC}\int V_{\text{in}}\,dt$$

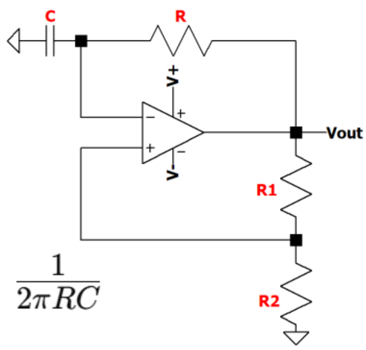


Differentiator

$$V_{\text{out}} = -RC\frac{dV_{\text{in}}}{dt}$$



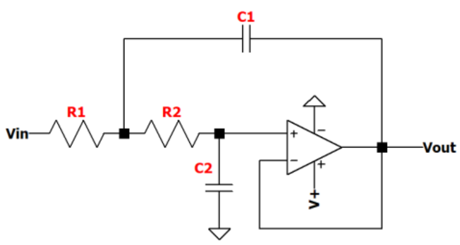
Wein Bridge Oscillator



$$f = \frac{1}{2\pi RC}$$

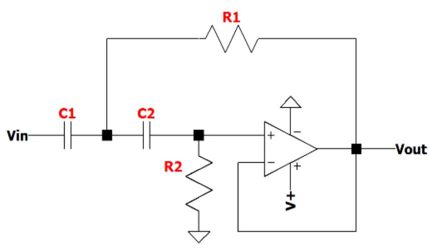
Low Pass Filter

$$V_{\text{out}} = -\left(\frac{1}{j\omega C_1 R_2 + 1}\right)\cdot\left(\frac{1}{j\omega C_2 R_1 + 1}\right)\cdot\left(\frac{R_2}{R_1}\right)\cdot V_{\text{in}}$$



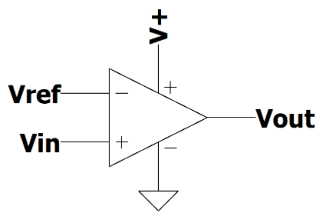
High Pass Filter

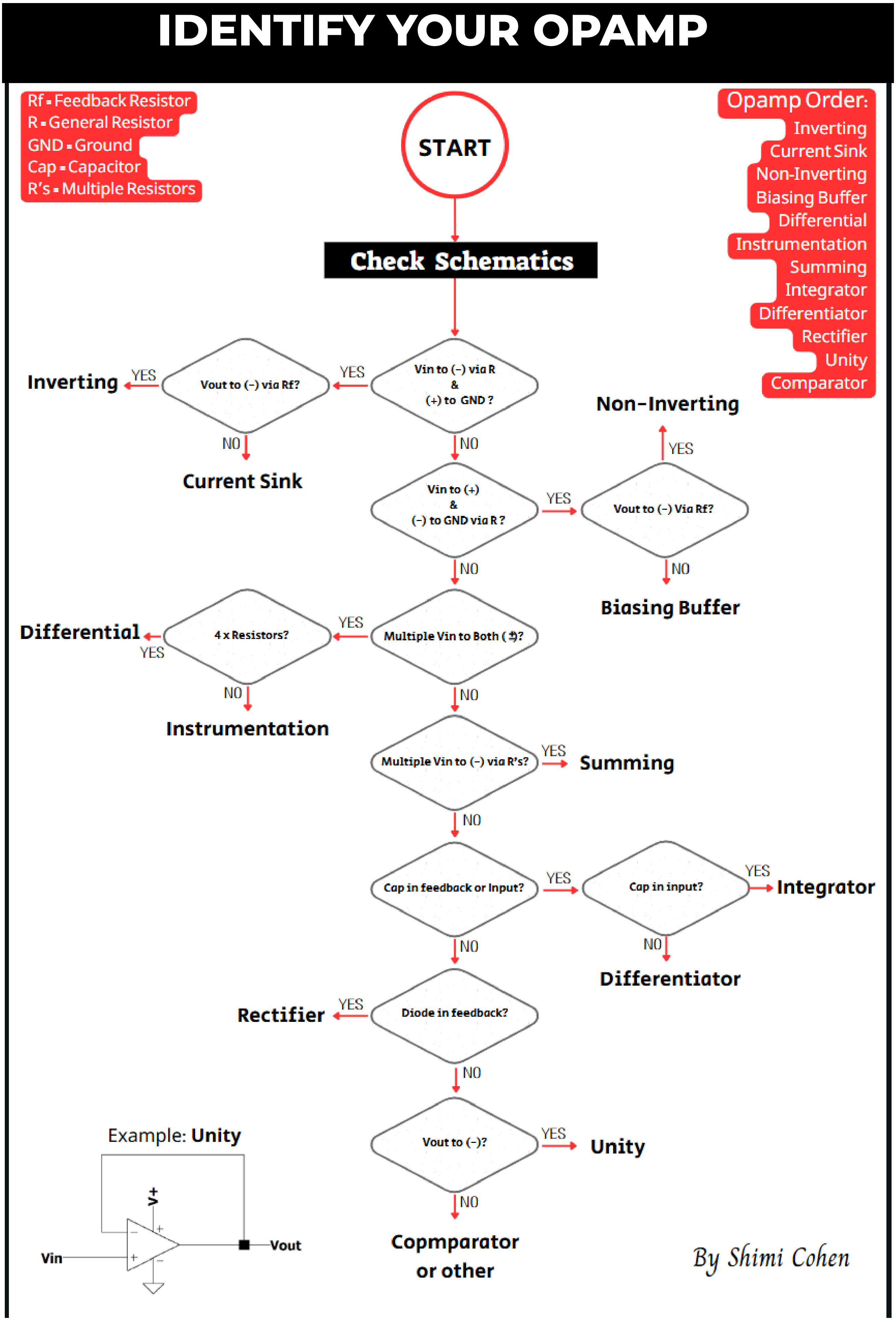
$$V_{\text{out}} = -\left(\frac{R_1}{R_2}\right)\cdot\frac{j\omega C_1 R_2}{1 + j\omega C_1 R_2}\cdot\frac{j\omega C_2 R_2}{1 + j\omega C_2 R_2}\cdot V_{\text{in}}$$



Comparator

$$V_{\text{out}} = \begin{cases} V_{\text{high}} & \text{if } V_{\text{in}} > V_{\text{ref}} \\ V_{\text{low}} & \text{otherwise} \end{cases}$$




IDENTIFY YOUR OPAMP
Rf = Feedback Resistor
R = General Resistor
GND = Ground
Cap = Capacitor
R's = Multiple Resistors
Opamp Order:
Inverting
Current Sink
Non-Inverting
Biasing Buffer
Differential
Instrumentation
Summing
Integrator
Differentiator
Rectifier
Unity
Comparator
START
Check Schematics
Vin to (-) via R & (+) to GND ?
YES
Vout to (-) via Rf?
YES
Inverting
NO
Current Sink
NO
Vin to (+) & (-) to GND via R ?
YES
Vout to (-) Via Rf?
YES
Non-Inverting
NO
Biasing Buffer
NO
Multiple Vin to Both (±)?
YES
4 x Resistors?
YES
Differential
NO
Instrumentation
NO
Multiple Vin to (-) via R's?
YES
Summing
NO
Cap in feedback or Input?
YES
Cap in input?
YES
Integrator
NO
Differentiator
NO
Diode in feedback?
YES
Rectifier
NO
Vout to (-)?
YES
Unity
NO
Cppmparator
or other
Example: Unity
V+
Vin
Vout
By Shimi Cohen

INTRODUCTION

Definition and Basic Concepts

An operational amplifier (op-amp) is an integrated circuit that amplifies the difference between two input voltages and produces a proportional output voltage. Modern op-amps are compact, versatile electronic components used in countless applications ranging from simple signal conditioning to complex analog computing

Historical Development

Era	Development	Significance
1940s	Vacuum tube op-amps	First operational amplifiers designed for analog computers
1960s	µA702, µA709	First commercially successful monolithic op-amps
1968	µA741	Revolutionary design that remains influential today
1970s-present	Specialized designs	Low-power, high-speed, precision, and instrumentation op-amps

Importance in Modern Electronics

Op-amps serve as fundamental building blocks in:

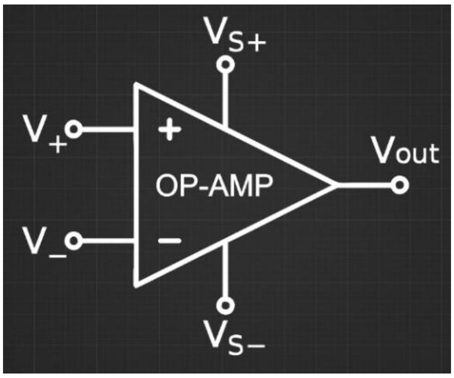
- Signal conditioning and filtering
- Instrumentation and measurement systems
- Audio equipment and sound processing
- Power control systems
- Data acquisition interfaces
- Analog computing circuits

FUNDAMENTALS

Ideal Op-Amp Characteristics

The ideal op-amp exhibits the following characteristics:

- Infinite open-loop gain
- Infinite input impedance
- Zero output impedance
- Infinite bandwidth
- Zero input offset voltage
- Zero input bias current
- Zero noise contribution
- Infinite common-mode rejection ratio (CMRR)
- Infinite power supply rejection ratio (PSRR)
- Instantaneous response (zero slew rate limitations)



Real Op-Amp Parameters

DC Parameters

- Open-loop gain (AOL): Typically, 100,000 to 1,000,000 (100-120 dB)
- Input offset voltage (VOS): 0.05mV to 5mV
- Input bias current (IB): 1nA to 1μA
- Input offset current (IOS): 0.5nA to 20nA
- Common-mode rejection ratio (CMRR): 80dB to 120dB
- Power supply rejection ratio (PSRR): 80dB to 120dB
- Output voltage swing: Typically, VCC - 1.5V to VEE + 1.5V

AC Parameters

- Gain-bandwidth product (GBP): 1MHz to 1GHz
- Slew rate (SR): 0.5V/μs to 1000V/μs
- Settling time: 0.1μs to 10μs
- Input and output impedances: Non-ideal values
- Noise specifications: Various types including voltage and current noise densities

ARCHITECTURE

OPAMP structure

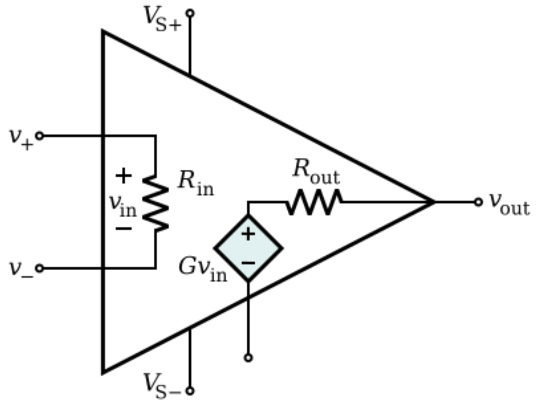
Differential input stage

Inverting input– Connects to 'V-'

Non-Inverting input – connects to 'V+'

Ideally, Rin is infinite (zero current in)

Vin equals to V+ - (V-)



Voltage gain stage

The letter G represents the Gian

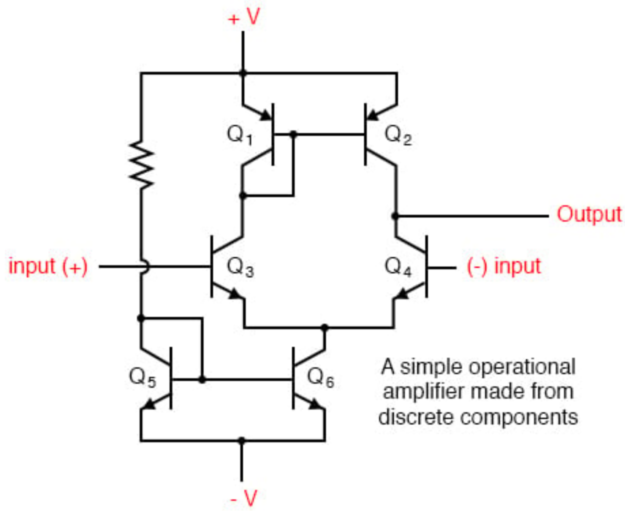
Gain = Vout/Vin

Gain[dB] = 20log(Vout/Vin)

Output stage

Vout is an amplified vin

Ideally, Rout is zero.



Bandwidth

The bandwidth gain frequency response

Gain is max in open loop (below cutoff)

Half power occurs at -3dB cutoff

The slope : -20dB/decade (single pole)

GBW = A x BW (unity gain frequency)

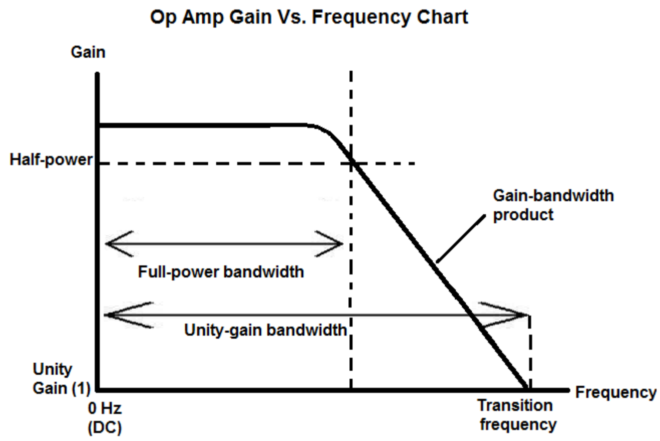
Example:

GBP = 1MHz (unity gain frequency)

Gain@Cutoff = 21dB

21dB = 20log(A)

A = 10^(21/20) = 11.2



AMPLIFICTION TYPES

amplification methods

Voltage Amplifier

Voltage in → Voltage out

Standard known operational amplifier configuration such as "inverting OPAMP".

Gain will be determined by the configuration and resistor values.

Current Amplifier

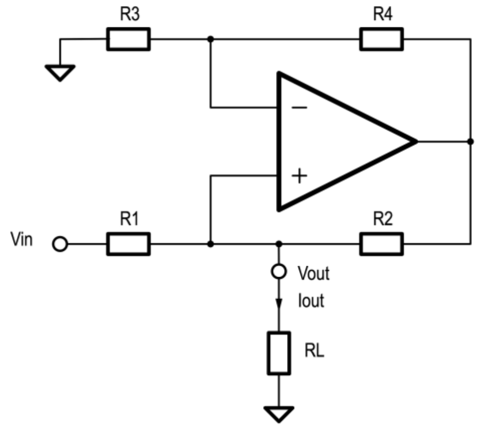
Current in → Current out

Howland Current source is a good example:

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

In case R =R1=R2=R3=R4 :

$$i_o = v_i \frac{1}{R} + v_o \left(\frac{1}{R^2} - \frac{1}{R^2} \right) = \frac{v_i}{R}$$



Transconductance Amplifier

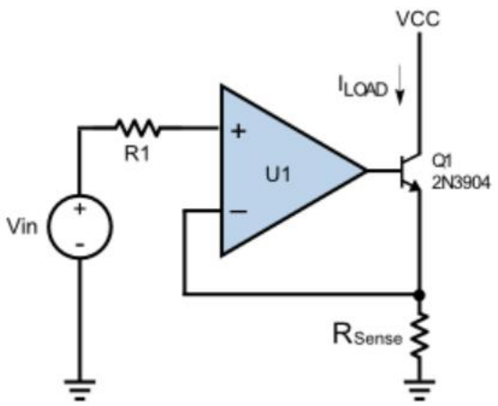
Voltage in → Current out

Voltage controlled **current source**.

I_Load is proportional to Vin

Because V+ and V- are virtually equal.

$$I_{LOAD} = \frac{V_{in}}{R_{Sense}}$$

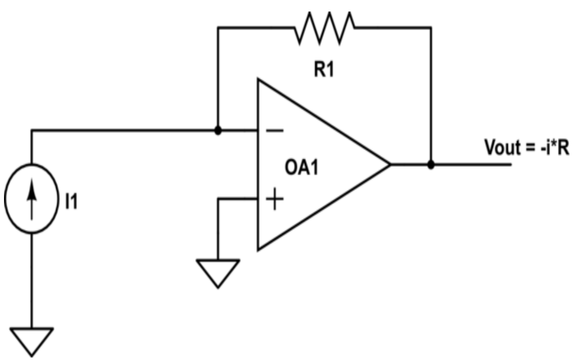


Transimpadance Amplifier

Current in → Voltage out

The simplest configuration is resistor feedback.

$$V_{out} = -I_1 \cdot R_1$$



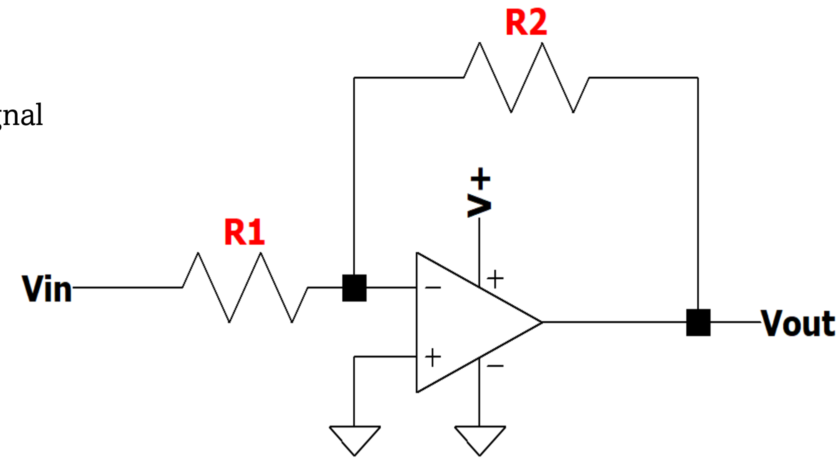
OPAMP TOPOLOGIES

Non-Inverting OPAMP

Circuit configuration:

- High input impedance
- Low output impedance
- Positive gain ≥ 1
- Non-inverted output signal

$$Av = 1 + \frac{R2}{R1}$$



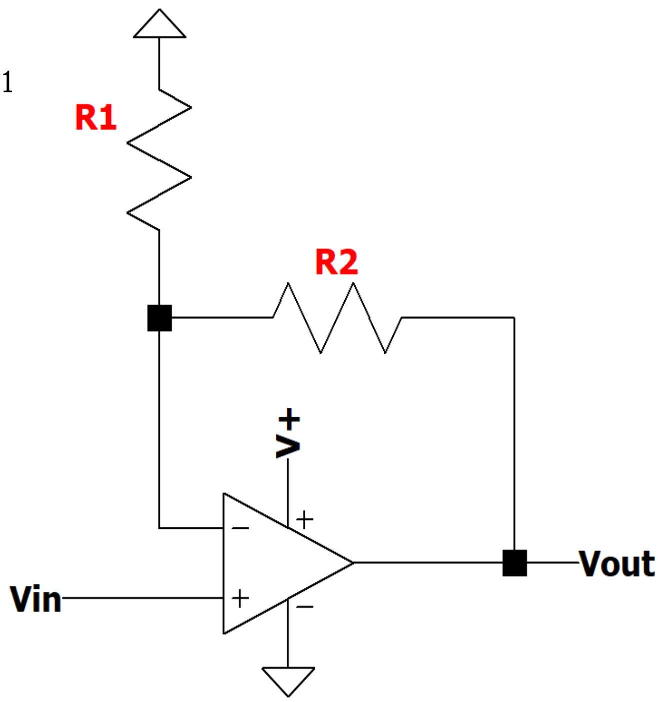
Inverting OPAMP

The inverting configuration produces 180° output voltage

Circuit configuration:

- Input impedance = R1
- Low output impedance
- Negative gain determined by -R2/R1
- Inverted output signal

$$Av = -\frac{R2}{R1}$$

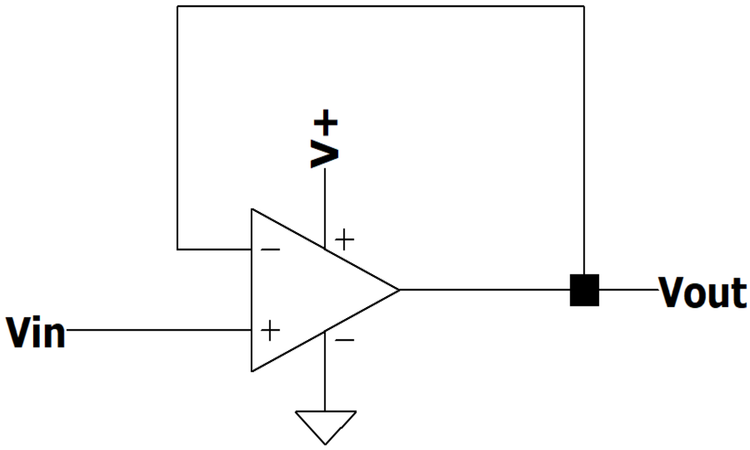


Voltage Follower (Unity Gain buffer)

The voltage follower provides unity gain with high input/ low output impedance.

Circuit configuration:

- Extremely high input impedance
- Ideal for impedance matching
- Ideal for buffering
- Very low output impedance
- Unity gain



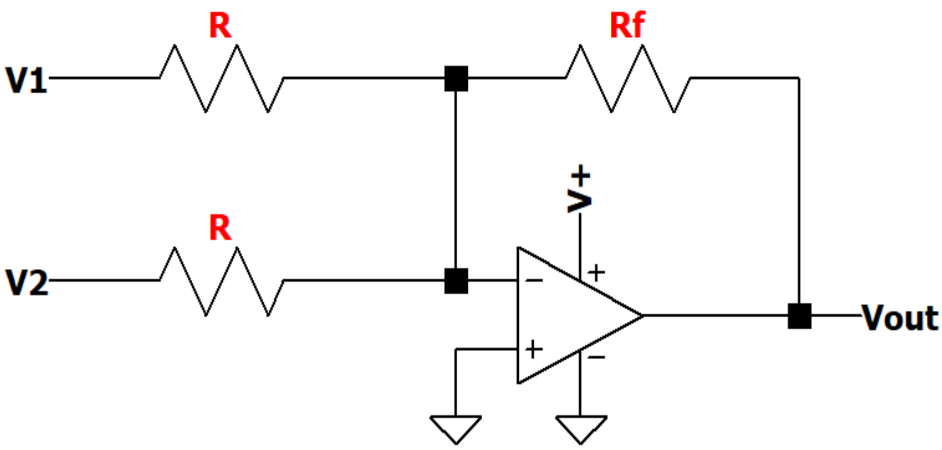
$$Av = 1$$

Summing Amplifier

The summing amplifier combines multiple input signals with different weights.

Circuit configuration:

- Can mix multiple signals with different weights
- Inverts all input signals
- Each input is independently weighted



$$Vout = -Rf\left(\frac{V1}{R} + \frac{V2}{R}\right) = -\frac{Rf}{2}(V1 + V2)$$

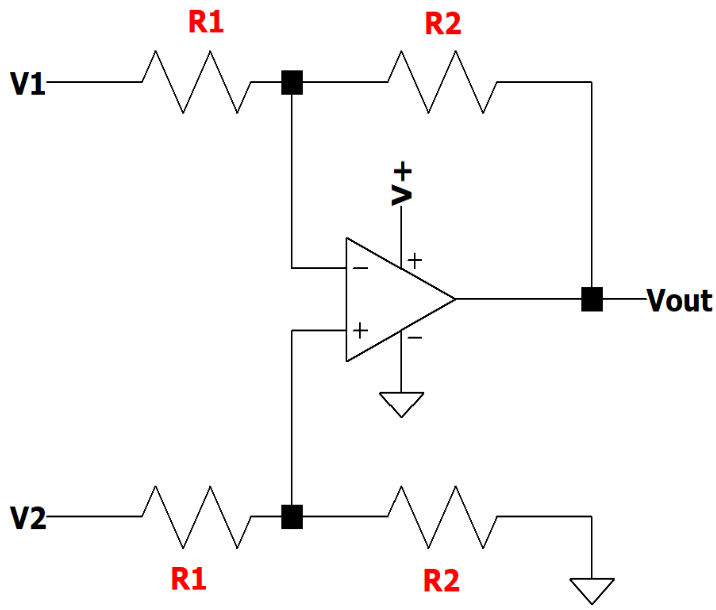
Differential Amplifier

The differential amplifier amplifies the voltage difference between two inputs.

Circuit configuration:

- Amplifies the difference between two inputs
- Used in instrumentation applications

$$Vout = (V2 - V1)$$



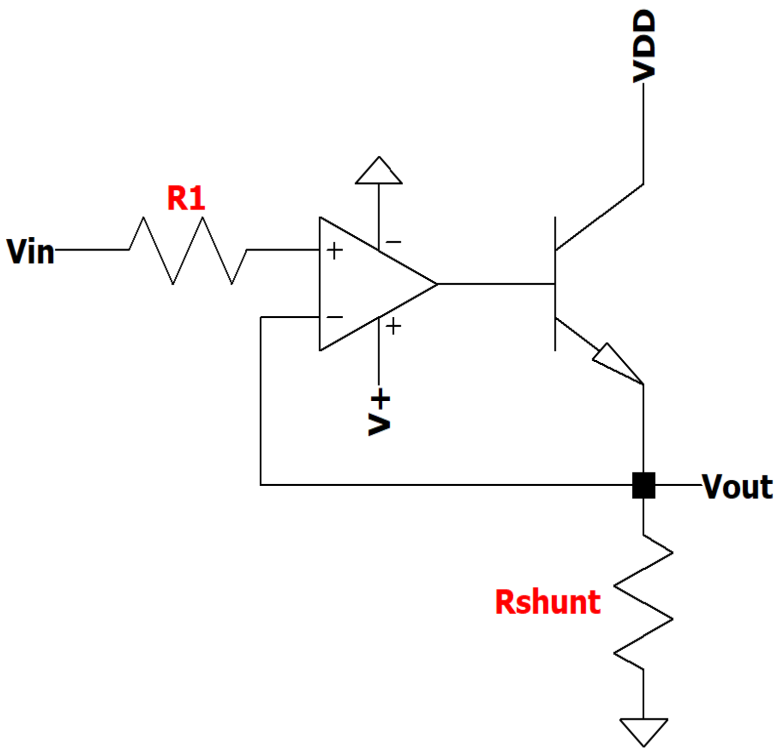
Current Source

The current Source implements Voltage in Current out topology.

Circuit configuration:

- Voltage controlled current
- Shunt Resistor sets the gain

$$Iout = \frac{Vin}{Rshunt}$$



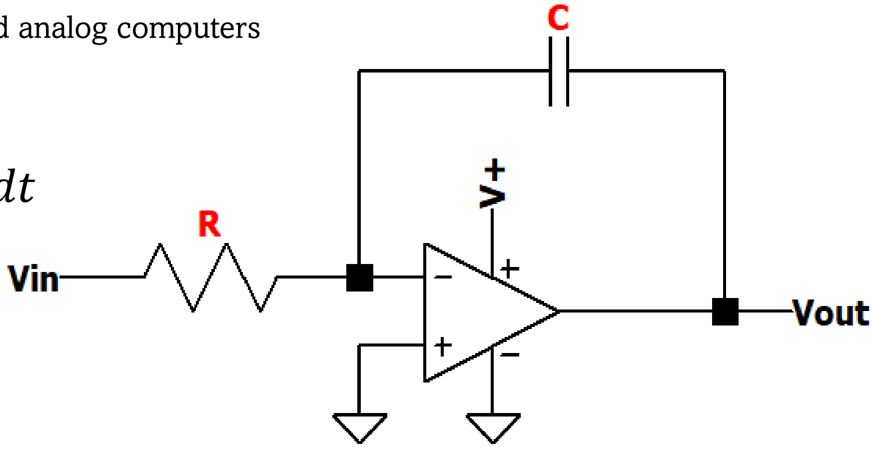
Integrator

The integrator produces an output voltage proportional to the time integral of the input voltage.

Circuit configuration:

- Output proportional to integral input
- Acts as a low-pass filter
- Used in control systems and analog computers

$$Vout = -\frac{1}{RC}\int Vin(t)dt$$



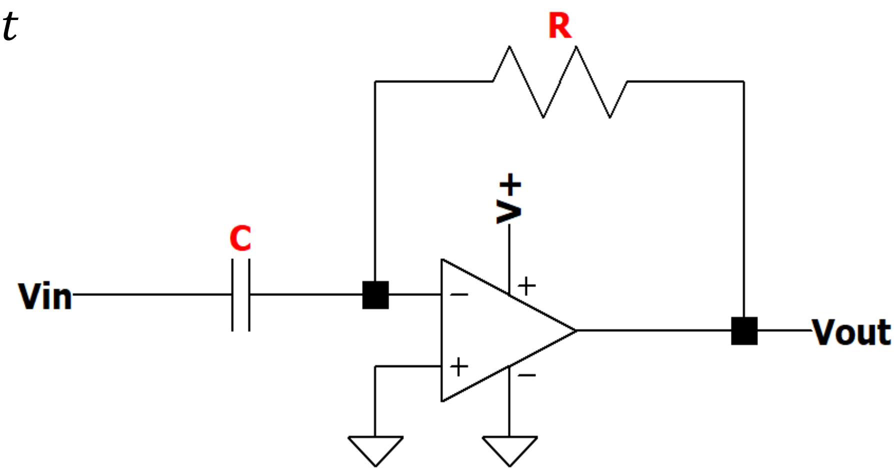
Differentiator

The differentiator produces an output voltage proportional to the rate of change of the input voltage.

Circuit configuration:

- Output proportional to the derivative of the input
- Acts as a high-pass filter
- Susceptible to noise (often requires modification)

$$Vout = -RC\frac{dVin(t)}{dt}$$



OPAMP PERFORMANCE

Frequency Response and Stability

Op-amps have frequency-dependent gain characterized by:

- DC gain (open-loop gain at low frequencies)
- Unity gain frequency (where gain = 1)
- Phase margin (stability indicator)
- Gain-bandwidth product (constant for most op-amps)

Parameter	Description	Typical Value
Input Offset Voltage	Voltage diff to zero output	0.1–5mV (chopper: <10µV)
Input Bias Current	Current into op-amp inputs	1nA – 500nA (CMOS: <1nA)
Slew Rate	Max output voltage change rate	0.1 – 10 V/µs (audio: ≥1V/µs)
Gain Bandwidth Product	Unity gain frequency	0.1 – 100 MHz (Typ: 1–10MHz)
CMRR	Rejection of common-mode signals	60 – 130 dB
PSRR	Rejection of power supply noise	60 – 120 dB
Output Swing	Max output voltage range	~0–VCC (RRIO: close to rails)
Quiescent Current (Iq)	Current draw with no signal	50 µA – 2 mA (low-power: <500µA)
Noise Density	Input-referred voltage noise	5 – 30nV/√Hz (chopper: <10nV)
Open-Loop Gain (AOL)	Gain with no feedback	80 – 130 dB

Slew Rate Limitations

The slew rate limits how quickly an op-amp's output voltage can change:

- Maximum rate of change = slew rate (V/µs)
- Can cause distortion with fast-changing signals
- Critical parameter for high-frequency applications

Noise Considerations

Op-amp noise sources include:

- Thermal noise (Johnson noise)
- Shot noise
- Flicker noise (1/f noise)
- Popcorn noise

OPAMP COMPARISON

Type	GBP	Slew Rate	Input Bias Current	Key Applications
General Purpose	1-10MHz	0.5-20V/µs	20-200nA	Basic, filtering
Precision	0.5-5MHz	0.1-5V/µs	0.5-50nA	Instrumentation
High Speed	50-1000MHz	100-6000V/µs	1-20µA	Video, RF, communications
Low Power	0.1-1MHz	0.01-1V/µs	0.1-10nA	Battery-powered devices
JFET Input	2-10MHz	5-20V/µs	1-50pA	High impedance sensors
CMOS	1-4MHz	1-10V/µs	0.1-10pA	Portable electronics
Current Feedback	100-2000MHz	1000-6000V/µs	1-10µA	Video, high-speed buffers
Rail-to-Rail	1-10MHz	1-10V/µs	1-100nA	Single-supply systems

General Purpose Op-Amps

Examples: 741, LM358, TL072

- Moderate specifications
- Wide supply voltage range
- Economical
- Suitable for non-critical applications

Precision Op-Amps

Examples: OP07, LT1001, AD8628

- Very low input offset voltage
- Low drift with temperature
- High CMRR and PSRR
- Suitable for instrumentation and measurement

High-Speed Op-Amps

Examples: LM6172, AD8099, LT1363

- High slew rate
- Wide bandwidth
- Fast settling time
- Suitable for video, RF applications

DESIGN CONSIDERATIONS

Power Supply Considerations

- Single vs. dual supply operation
- Bypass capacitors: 0.1µF ceramic near device pins
- Power supply rejection ratio (PSRR)
- Ground loops and proper grounding techniques

Input Protection

- ESD protection diodes
- Current limiting resistors
- Overvoltage protection circuits
- Common-mode voltage range limitations

Output Protection

- Short-circuit protection
- Thermal shutdown
- Load considerations
- Output current limitations

PCB Layout Considerations

- Keep analog and digital grounds separate
- Short, direct traces for critical signals
- Place bypass capacitors close to power pins
- Consider thermal effects in layout

TROUBLESHOOTING

Common Failure Modes

- Oscillation due to instability
- Output saturation
- Unexpected offset voltage
- Thermal issues
- Incorrect bias conditions

Diagnostic Procedures

- Check power supplies and connections
- Verify input signal integrity
- Measure DC voltages at all pins
- Probe for oscillations
- Check for thermal issues

Common Circuit Problems

Problem	Possible Causes	Solutions
Oscillation	Inadequate phase margin	Add compensation capacitor, improve bypassing
Excessive offset	Input bias current, input offset voltage	Use offset nulling, choose better op-amp
Distortion	Slew rate limitation, output saturation	Select faster op-amp, reduce gain or frequency
Noise	Poor layout, improper grounding	Improve layout, add filtering, better grounding
Drift	Temperature effects, component aging	Use temperature compensation

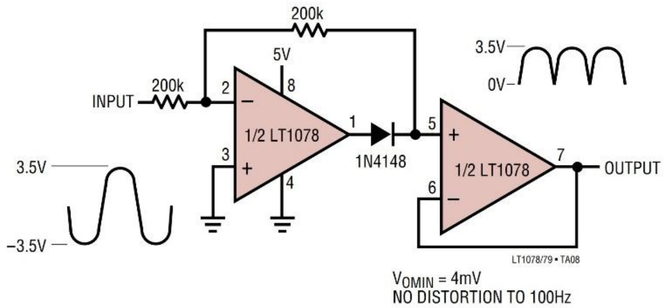
Testing and Measurement Techniques

- DC offset measurement
- Open-loop gain testing
- CMRR measurement
- Bandwidth characterization
- Slew rate testing

PRACTICAL DESIGN

Precision Rectifier Circuit

Parameter	Value
Input Range	±3.5V
Output Range	0V to 3.5V
Supply Voltage	Single 5V
Op-Amp Model	LT1078 (dual)
Frequency Response	100Hz
Diode Type	1N4148
Minimum Input	4mV



Block Description

Precision Half-Wave Rectifier (U1A)

- Op-amp + diode combo.
- Acts like a smart diode
- Uses resistor matching (200k/200k) to give unity gain.
- Output only follows positive half-cycles; negative ones get blocked.

Inverting Summing Amplifier (U1B)

- Adds the inverted version signal to the rectified output of U1A.
- This forms the second half of the waveform (i.e., the negative half inverted).

How It Works – Step-by-Step

1. Input Waveform: A ±3.5V sine wave is applied.
2. U1A Inverts & clips the signal (diode), positive voltage passes through
3. U1B Inverts the input signal & combines with rectified signal.
4. The combination of positive rectified + inverted negative = full-wave.

Instrumentation Amplifier

Instrumentation can handle very low signal and maintain very accurate gain with extremely low noise (used in Audio or small signal differences).

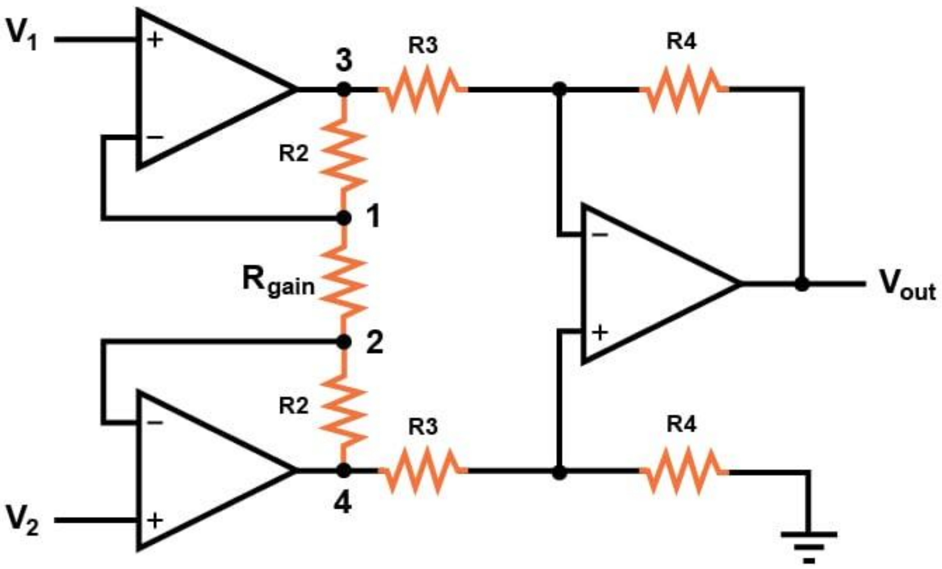
Circuit Architecture

This is a **3-op-amp instrumentation amplifier**, ideal for precision differential signal amplification. Op-Amps example : Dual op-amp model (e.g., LT1078)

Block Functionality

1. Buffer Stage - Left Pair OPAMPs
2. Gain Stage - Resistor Outputs
3. Output Stage – Final Amplification

$$V_{\text{out}} = \left(\frac{R_4}{R_3}\right) \cdot (V_1 - V_2) \cdot \left(1 + \frac{2R_2}{R_{\text{gain}}}\right)$$



OPAMP IDENTIFICATION

Step-by-Step Visual Guide (See Page 2)

Identify Key Components

- **Resistors**: Classic for amplifiers (inverting, non-inverting, summing, differential).
- **Capacitors**: Look for integrators, differentiators, or filters.
- **Diodes**: Look for rectifiers, clampers, or precision limiters.
- **Transistors**: Usually for current sources, buffers, or log/antilog circuits.

Decision Tree

Question 1 : Input connected to (V−) via resistor, and (V+) input grounded? **YES** → Is there feedback resistor from output to inverting input? • YES → **Inverting Amplifier** • NO → **Current Source**
Question 2: Input connected to (V+), and (V-) connected to ground via resistor? **YES** → Is there a feedback resistor from output to inverting input? • YES → **Non-Inverting Amplifier** • NO → **Voltage Follower**
Question 3: Are both inputs connected to different input signals (not ground)? **YES** → Are there four resistors in a bridge? • YES → **Differential Amplifier** • NO → **Instrumentation Amplifier** (3 op-amps)
Question 4: Are there multiple input resistors going to the inverting input? **YES** → **Summing Amplifier**
Question 5: Are there capacitors in the feedback or input path? **YES** → Where is the capacitor? • Capacitor in feedback → **Integrator** • Capacitor in input → **Differentiator**
Question 6: Is there a diode in the feedback? **YES** → **Precision Rectifier**
Question 7: Is the output directly connected to the non-inverting input? **YES** → **Voltage Follower** **NO** → **Comparator** or custom circuit

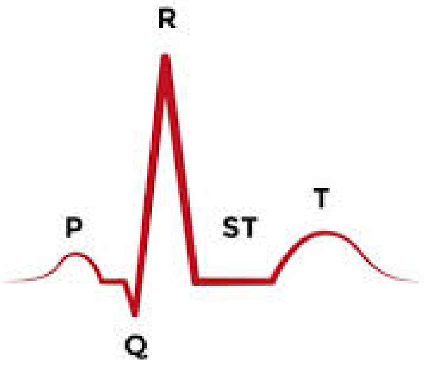
REAL LIFE EXAMPLES

Medical Equipment

Application: ECG Signal Conditioning

Requirements:

- High CMRR (>100dB)
- Low noise (<1μV)
- High input impedance (>10MΩ)
- Bandwidth: 0.05Hz to 150Hz



Solution:

Three-op-amp instrumentation amplifier with:

- Right-leg drive circuit for CMRR improvement
- Precision op-amps for low noise
- High-pass and low-pass filtering stages
- Notch filter for 50/60Hz rejection

Audio Equipment

Application: Studio Microphone Preamplifier

Requirements:

- Low noise (<-120dBu EIN)
- Variable gain (0 to 60dB)
- Wide bandwidth (20Hz to 20kHz ±0.1dB)
- Low distortion (<0.005% THD)

Solution:

JFET-input op-amp circuit with:

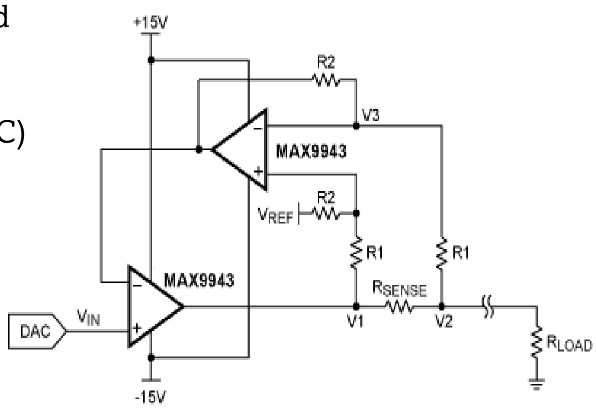
- Balanced input with CMRR optimization
- Multiple gain stages with proper compensation
- DC servo loop for offset elimination
- Output driver stage for headroom

Industrial Control Systems

Application: 4-20mA Current Loop Interface

Requirements:

- Convert sensor voltages to 4-20mA standard
- High accuracy (<0.1% error)
- Wide operating temperature (-40°C to +85°C)
- Protection against industrial noise



Solution:

Precision op-amp circuit with:

- Voltage-to-current conversion stage
- Temperature compensation
- Galvanic isolation

$$V_{OUT} = I_{OUT} \cdot R_{LOAD} = \frac{V_{IN}}{R_{SENSE}} \cdot R_{LOAD}$$

Consumer Electronics

Application: Smartphone Audio Codec

Requirements:

- Low power operation (<10mW)
- High SNR (>90dB)
- Small footprint
- Single supply operation (3.3V)

Solution:

CMOS rail-to-rail op-amps with:

- Class AB output stage for power efficiency
- Chopper-stabilized design for low noise
- Advanced filtering for audio enhancement
- Power management with sleep modes

APPENDICES

Common Op-Amp

These are common OPAMPs used today:

Part Number	Type	Key Specifications	Typical Applications
LM741	General Purpose	1 MHz GBP, 0.5 V/µs SR	Basic amplification
LM358	General Purpose Dual	1 MHz GBP, 0.3 V/µs SR	Single supply circuits
TL072	JFET-Input	3 MHz GBP, 13 V/µs SR	Audio applications
OP07	Precision	0.6 MHz GBP, 0.3 V/µs SR	Instrumentation
LM324	Quad General Purpose	1 MHz GBP, 0.5 V/µs SR	Multiple stage filtering
AD620	Instrumentation	120 dB CMRR, 800 kHz GBP	Bridge amplifiers
OPA627	High Precision	16 MHz GBP, 55 V/µs SR	Test equipment
LT1028	Low Noise	75 MHz GBP, 15 V/µs SR	Audio preamplifiers
OPA656	High Speed	500 MHz GBP, 290 V/µs SR	Video circuits
AD8000	Current Feedback	1.5 GHz GBP, 4100 V/µs SR	RF applications

Decibel Conversion Table

Voltage Gain	Power Gain	dB
1	1	0
2	4	6.02
3.16	10	10
10	100	20
31.6	1,000	30
100	10,000	40
316	100,000	50
1,000	1,000,000	60
10,000	100,000,000	80
100,000	10,000,000,000	100

USEFUL EQATIONS

Use the following table according **to Page one circuits**:

Circuit	V_{out} Equation
Non-Inverting	$V_{\text{out}} = V_{\text{in}} \left(1 + \frac{R_2}{R_1}\right)$
Inverting	$V_{\text{out}} = -V_{\text{in}} \left(\frac{R_2}{R_1}\right)$
Unity (Buffer)	$V_{\text{out}} = V_{\text{in}}$
Summing	$V_{\text{out}} = -\left(\frac{R_f}{R_1} V_1 + \frac{R_f}{R_2} V_2\right)$
Differential	$V_{\text{out}} = \left(\frac{R_2}{R_1}\right) (V_2 - V_1)$
Current Source	$V_{\text{out}} = I \cdot R_{\text{load}} \quad \text{where } I = \frac{V_{\text{ref}}}{R_1}$
Integrator	$V_{\text{out}} = -\frac{1}{RC} \int V_{\text{in}} \, dt$
Differentiator	$V_{\text{out}} = -RC \frac{dV_{\text{in}}}{dt}$
Wein Bridge Oscillator	$f = \frac{1}{2\pi RC} \quad \text{(oscillation frequency)}$
Low Pass Filter	$V_{\text{out}} = \frac{1}{1 + j\omega RC_1} V_{\text{in}}$
High Pass Filter	$V_{\text{out}} = \frac{j\omega R_2 C_1}{1 + j\omega R_2 C_1} V_{\text{in}}$
Comparator	$V_{\text{out}} = \begin{cases} V_{\text{high}} & \text{if } V_{\text{in}} > V_{\text{ref}} \\ V_{\text{low}} & \text{otherwise} \end{cases}$