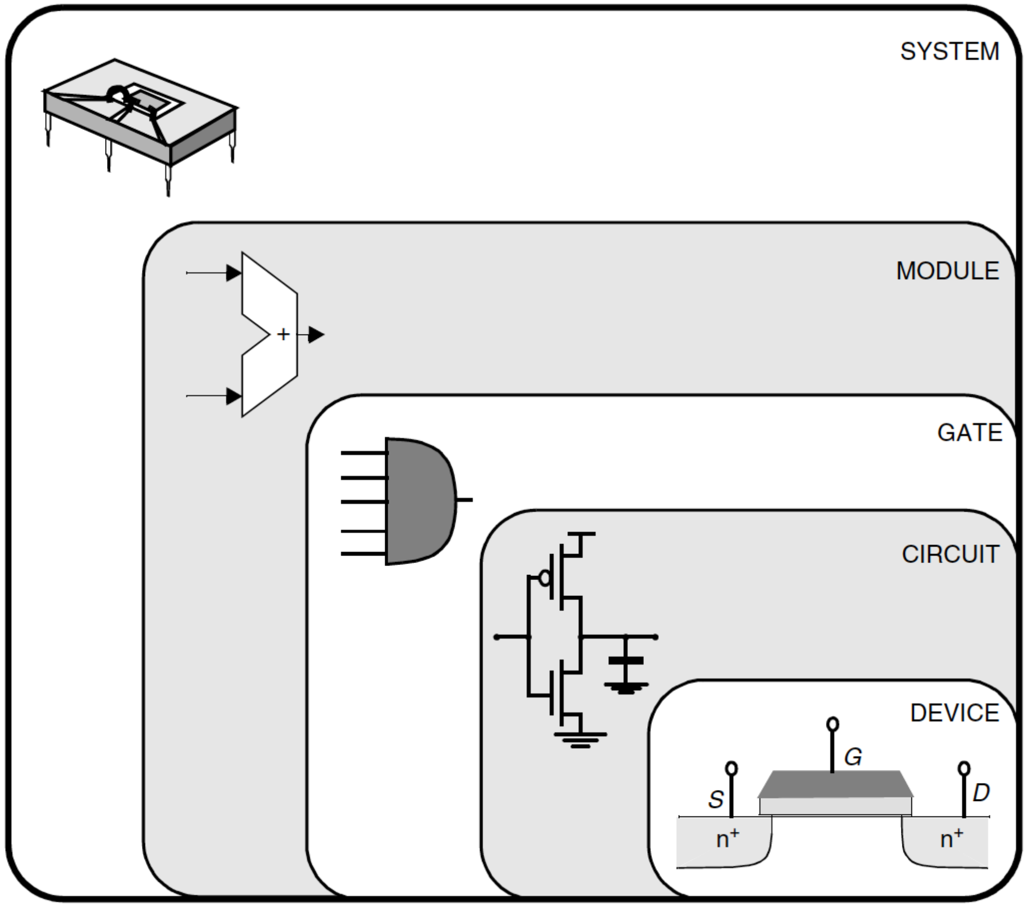
Fundamentals of Electronics

# ECE 101

# Design abstraction in digital electronics




Digital Integrated Circuits by Rabaey et. al.

# Operational Amplifier

- An Operational Amplifier (Op-Amp) is an integrated circuit that uses external voltage to amplify the input with a very high gain.

- The term "operational" was used as a descriptor early-on because this form of amplifier can perform operations of
  - Adding signals
  - Subtracting signals
  - Integrating signals

- The applications of Op-Amps have grown beyond those listed above.

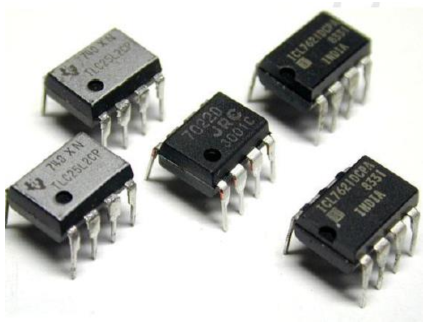
- Therefore, Op-Amp is an active circuit element designated to perform mathematical operations of addition, subtraction, multiplication, division, differentiation and integration.

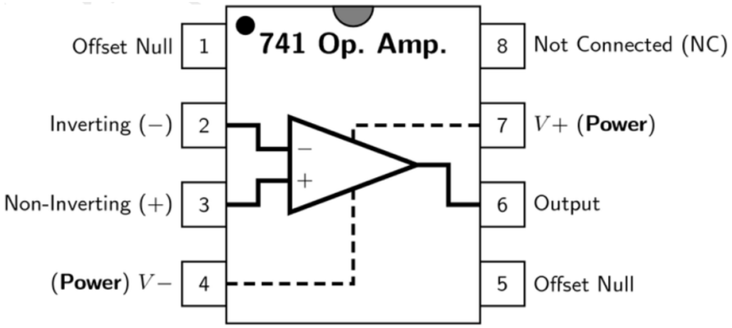
- Examples:
  - LM 111
  - LM 324
  - LM 741

LM stands for linear monolithic.

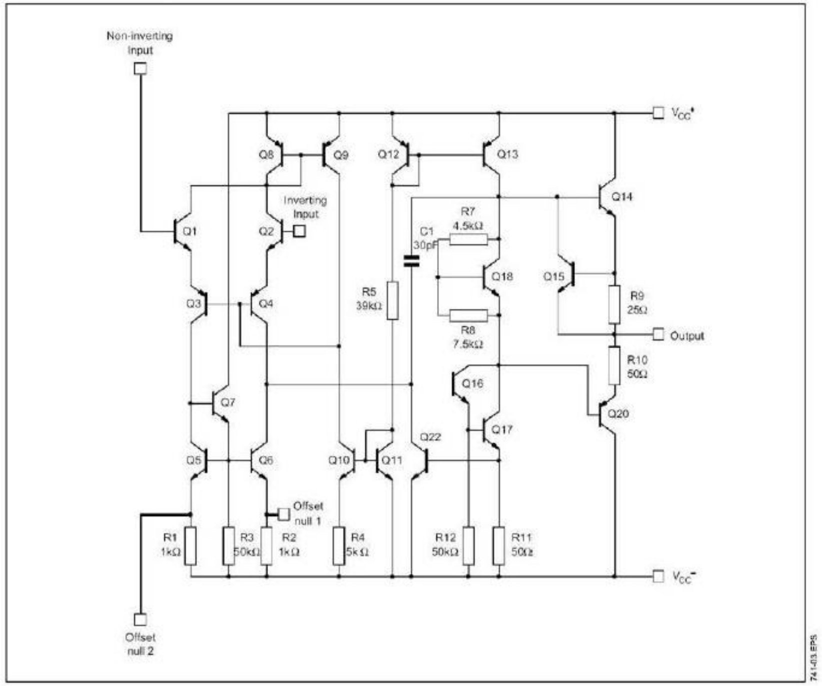
# LM 741

- One of the most commonly used Op-Amp.
- Packaged device look like:



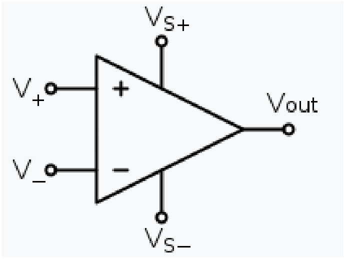


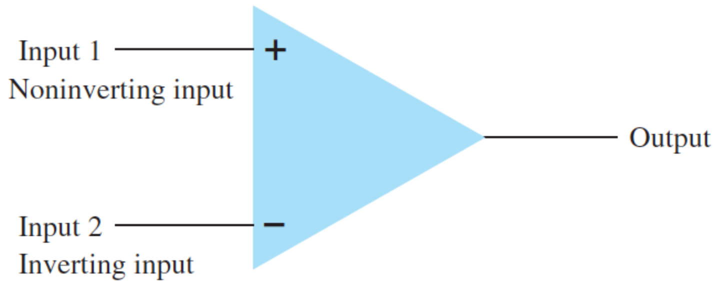

SCHEMATIC DIAGRAM



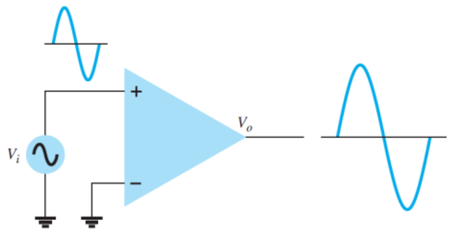

Offset null is a calibration feature of an operational amplifier (op amp) that allows the output voltage to be adjusted to zero when the input is zero. This helps to eliminate signal noise and interference.

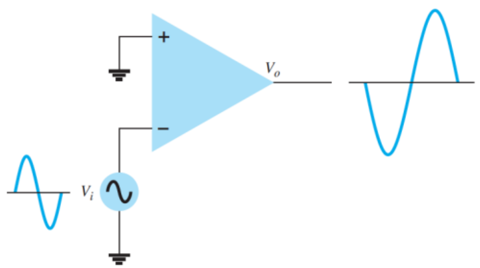
- An Op-Amp contains several transistors, resistors, and a few capacitors and diodes.
- More simply, an Op-Amp is depicted as:



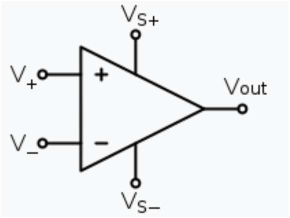


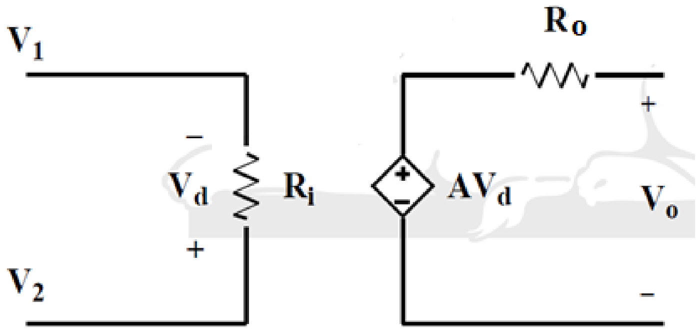

$$V_{\text{out}} = A_{\text{OL}}(V_+ - V_-)$$

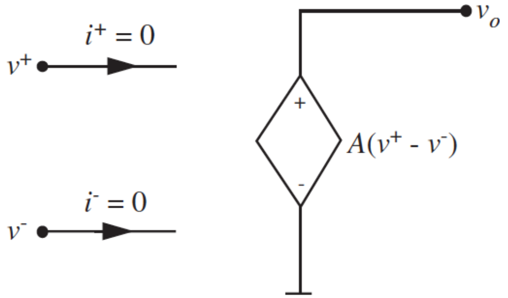



| Parameter | Variable | Ideal Values | Typical Ranges |
|---|---|---|---|
| Open-Loop Voltage Gain | A | $\infty$ | $10^5$ to $10^8$ |
| Input Resistance | Ri | $\infty$ Ω | $10^5$ to $10^{13}$ Ω |
| Output Resistance | Ro | 0 Ω | 10 to 100 Ω |
| Supply Voltage | Vcc/$V^+$<br>-Vcc/$V^-$ | N/A<br>N/A | 5 to 30 V<br>-30V to 0V |



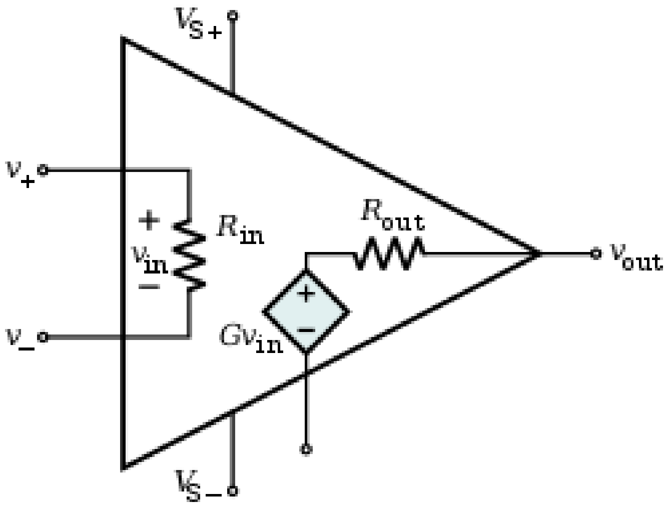



# Ideal Op-Amp Summary

## An ideal op amp has the following characteristics

- Infinite open-loop gain $\mathbf{G = V_{out} / V_{in}}$
- Infinite input impedance Rin, and so zero input current
- Zero input offset voltage
- Infinite output voltage range
- Zero output impedance $R_{out}$, and so infinite output current range
- Zero noise
- Infinite bandwidth with zero phase shift and infinite slew rate
- Infinite common-mode rejection ratio (CMRR)
- Infinite power supply rejection ratio




## These can be summarized by the two rules

- In a closed loop (negative feedback) the output does whatever is necessary to make the voltage difference between the inputs zero
- The inputs draw zero current

# Op-Amp Terminology: Explained

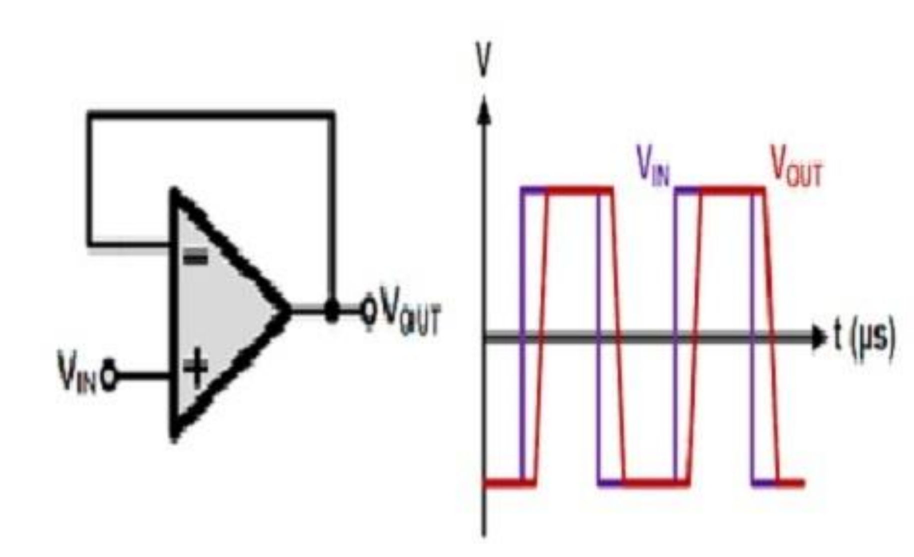
**Slew Rate:** Slew rate is defined as the maximum rate of change of an op amps output voltage, and is given in units of volts per microsecond.

Slew rate is measured by applying a large signal step, such as one volt, to the input of the op amp, and measuring the rate of change from 10% to 90% of the output signal's amplitude.

**CMRR:** If a signal is applied equally to both inputs of an op amp, so that the differential input voltage is unaffected, the output should not be affected.

In practice, changes in common mode voltage will produce changes in output. The op amp common-mode rejection ratio (CMRR) is the ratio of the common-mode gain to differential-mode gain.

**For example: if a differential input change of Y volts produces a change of 1 V at the output, and a common-mode change of X volts produces a similar change of 1 V, then the CMRR is X/Y.**



# Op-Amp Terminology

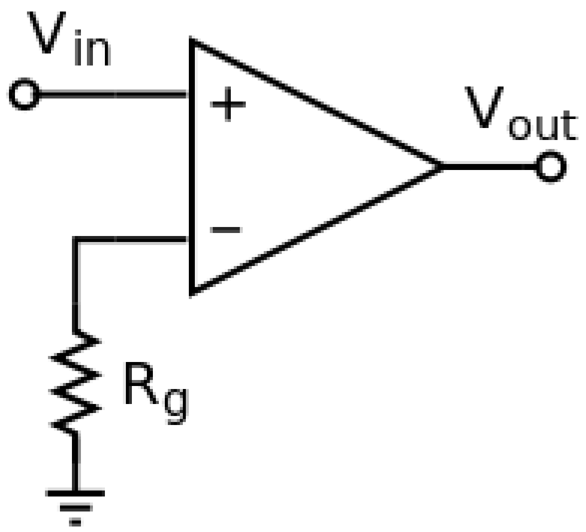
PSRR: A measure of how well the Op Amp can reject noise and ripple on its power inputs

The power supply rejection ratio is defined as the changes in input offset voltage per unit changes in the DC supply voltage. The power supply is also calculated in the format of dB. The mathematical equation of the power supply rejection ratio is given below.

$$\mathrm{PSRR[dB]} = 10\log_{10}\left(\frac{\Delta V_{\mathrm{supply}}{}^{2} A_v{}^{2}}{\Delta V_{\mathrm{out}}{}^{2}}\right)\mathrm{dB}$$

# Op-Amp: Open Loop Configuration

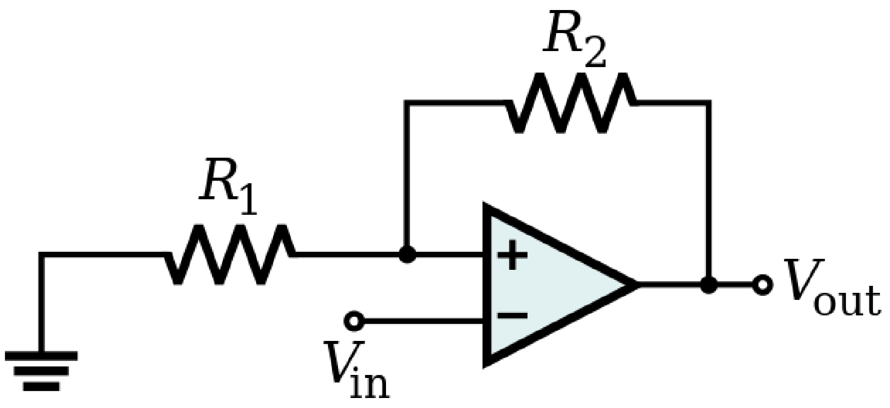
$$V_{\mathrm{out}} = A_{\mathrm{OL}}(V_{+} - V_{-})$$




**Comparator**

# Op-Amp with closed loop configuration: Positive Feedback

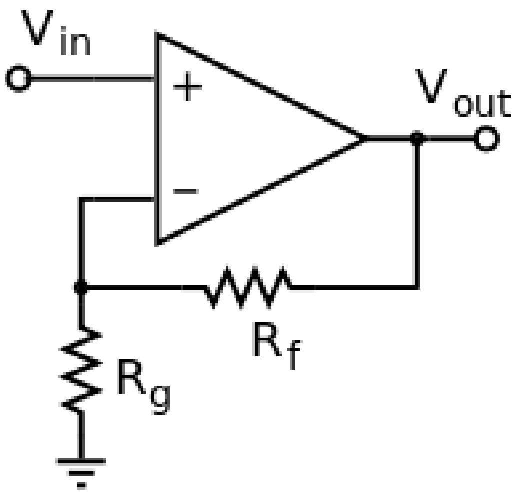
**What is the output voltage?**



# Op-Amp: Negative Feedback

**Equilibrium?**

**What is:** $A_{CL} = V_{out} / V_{in}$




- **When an op amp operates in linear (i.e., not saturated) mode, the difference in voltage between the non-inverting (+) and inverting (−) pins is <u>negligibly small</u>.**

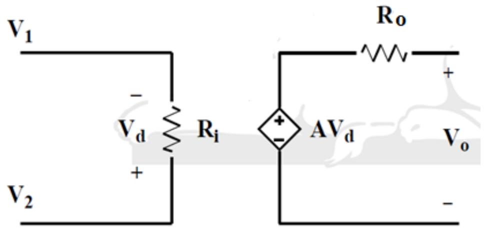
- **The input impedance of the (+) and (−) pins is much larger than other resistances in the circuit.**

# Op-Amp analysis [Negative Feedback]

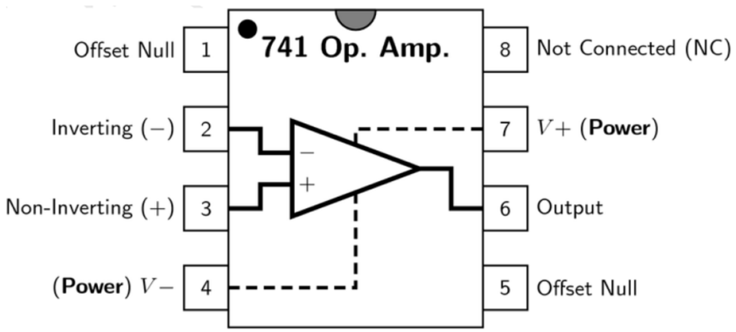
$R_i = \infty\ \Omega$

– Therefore, $i_1 = i_2 = 0A$

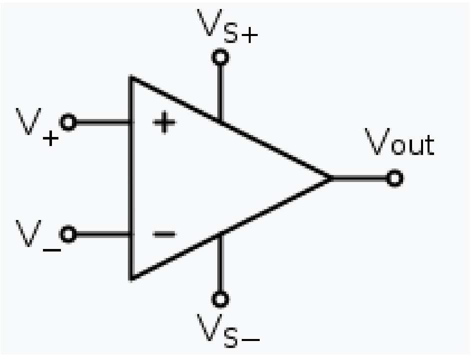
$R_o = 0\ \Omega$




$V_d = 0V$ and so $V_1 = V_2$

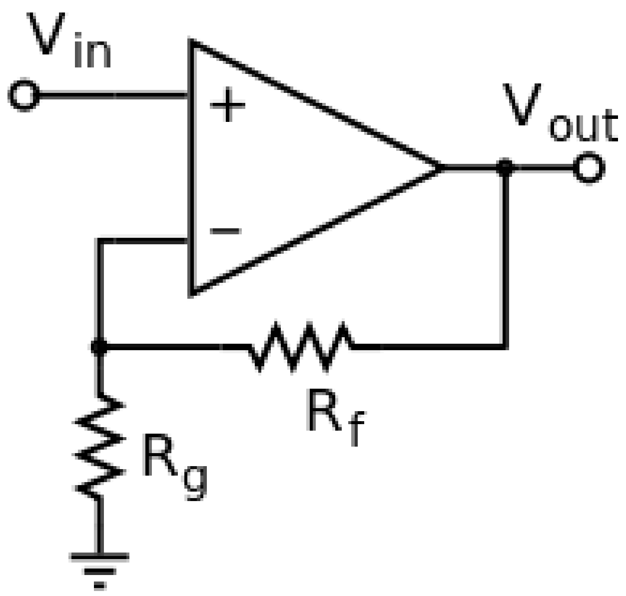



- The internal circuitry in the op-amp tries to force the voltage at the inverting input to be equal to the non-inverting input.




- **While analyzing an Op-Amp circuit [In negative feedback]**
  - **No current flows into either input terminal**
  - **In negative feedback, voltage difference between the terminals is zero**
  - **Therefore, no current flows out of the output terminal**

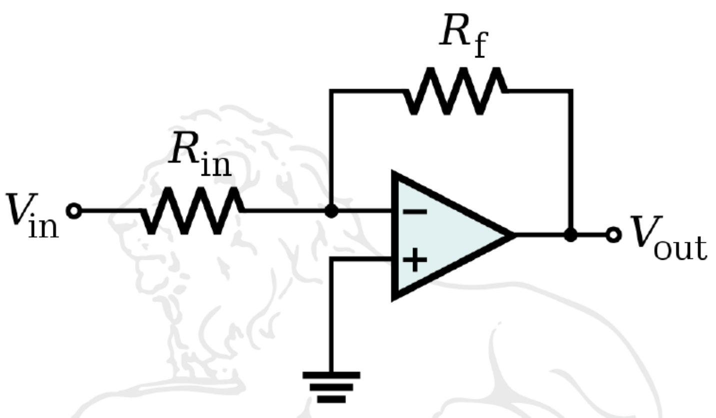
# Op-Amp: An Example



# Op-Amp usages

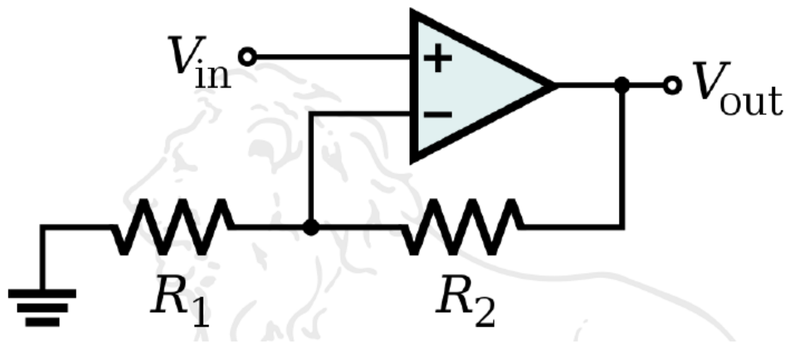
- While analyzing an Op-Amp circuit
  - Assume no current flows into either input terminal
  - Assume no current flows out of the output terminal
  - Virtual Ground

**Inverting Amplifier**




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

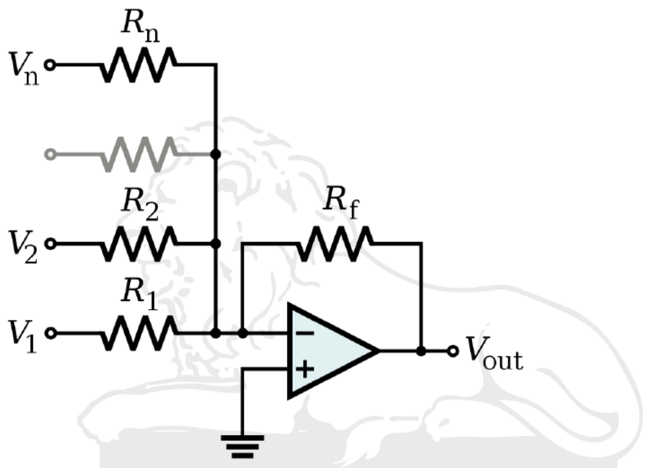
**Non-inverting Amplifier**




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

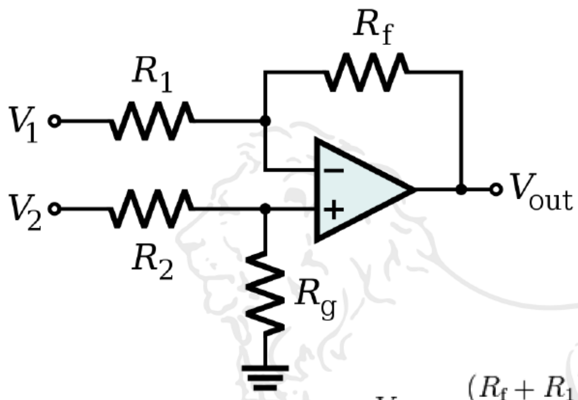
# Op-Amp usages

## Summing amplifier




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

## Difference amplifier



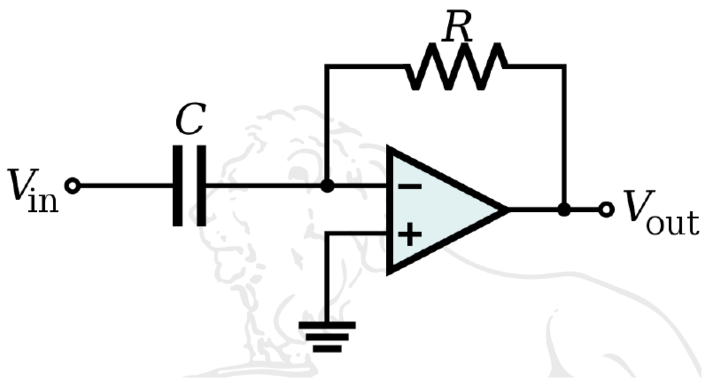

$$V_{out} = \frac{(R_f + R_1)\,R_g}{(R_g + R_2)\,R_1}V_2 - \frac{R_f}{R_1}V_1$$

If $R_1 = R_2$ and $R_f = R_g$: $V_{out} = \frac{R_f}{R_1}(V_2 - V_1)$

# Op-Amp usages

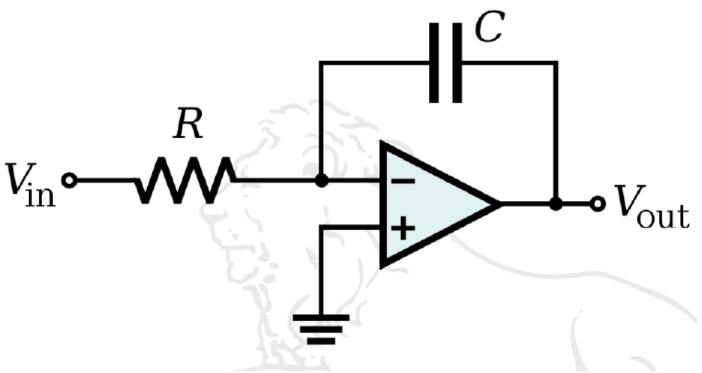
- While analyzing an Op-Amp circuit in negative feedback
  - Assume no current flows into either input terminal
  - Assume no current flows out of the output terminal

## Differentiator




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

## Integrator

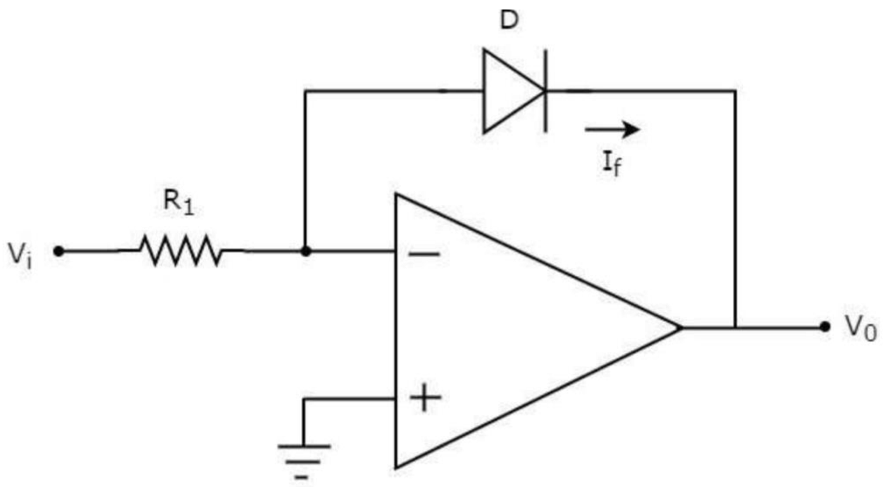



$$V_{out} = -\int_0^t \frac{V_{in}}{RC}\,dt + V_{initial}$$

# Op-Amp usages

## Log and Antilog Amplifiers

### Log

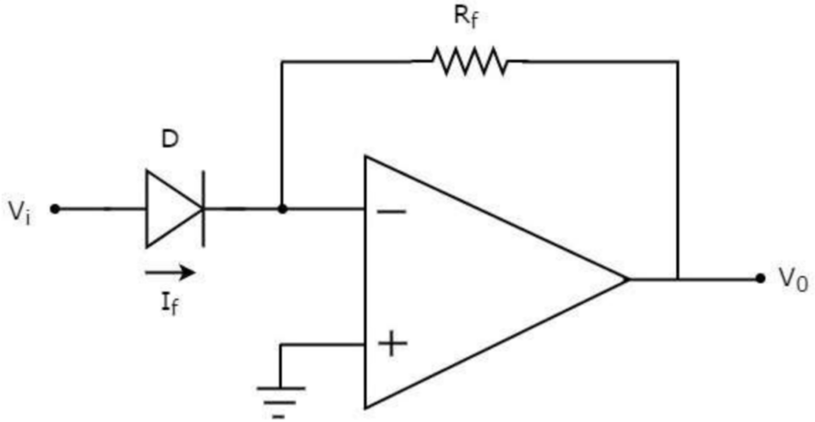



$$\frac{0-V_i}{R_1}+I_f=0 \qquad => I_f=\frac{V_i}{R_1}$$

$$I_f=I_s e^{\left(\frac{V_f}{nV_T}\right)} \qquad V_f=-V_0 \qquad I_f=I_s e^{\left(\frac{-V_0}{nV_T}\right)}$$

$$\frac{V_i}{R_1 I_s}=e^{\left(\frac{-V_0}{nV_T}\right)} \qquad \boxed{V_0=-nV_T In\left(\frac{V_i}{R_1 I_s}\right)}$$

### Antilog




$$-\frac{V_0}{R_f}=I_f \qquad I_f=I_s e^{\left(\frac{V_f}{nV_T}\right)}$$

$$V_0=-R_f I_s e^{\left(\frac{V_f}{nV_T}\right)}$$

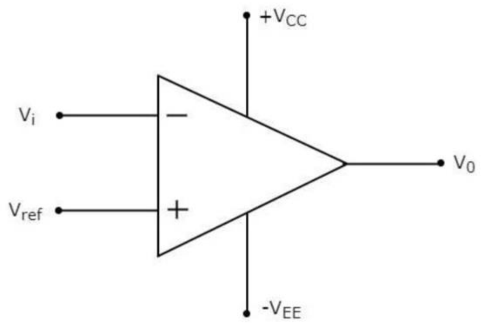
$$V_f=V_i$$

$$V_0=-R_f I_s e^{\left(\frac{V_i}{nV_T}\right)}$$

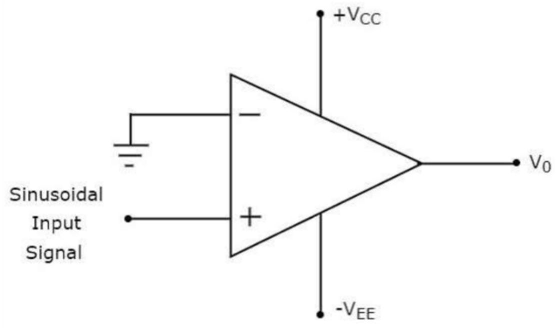
# Op-Amp usages

## Comparator

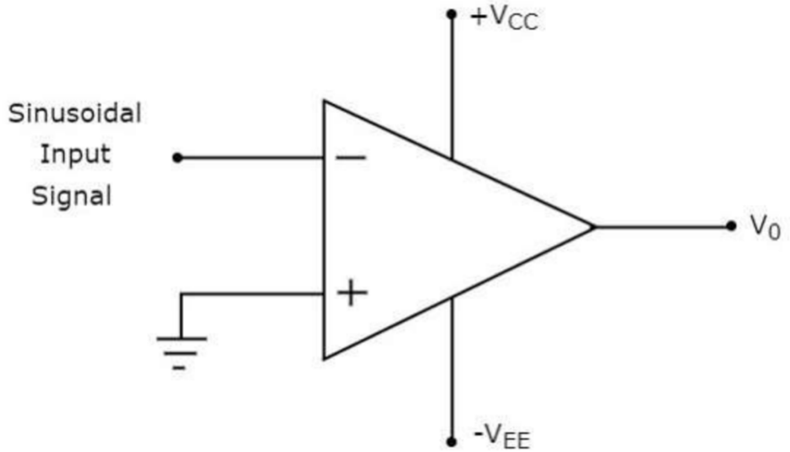
The output value of the comparator indicates which of the inputs is greater or lesser.

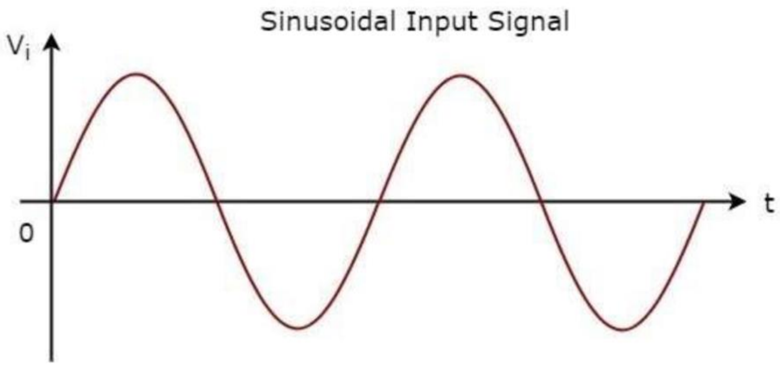


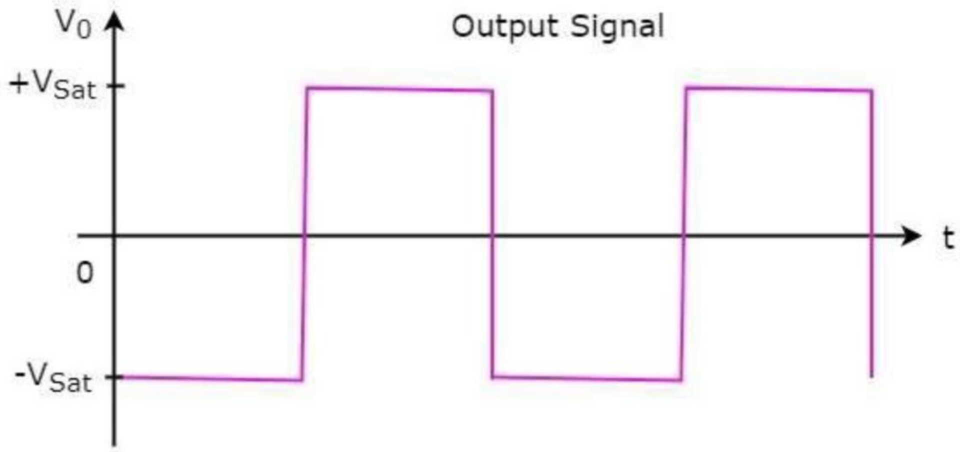

**Inverting comparator**




**Non-inverting comparator**

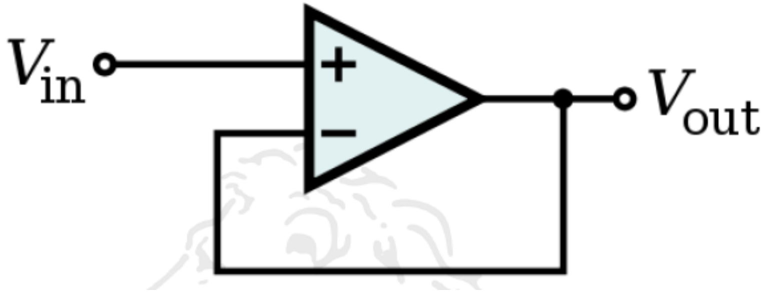


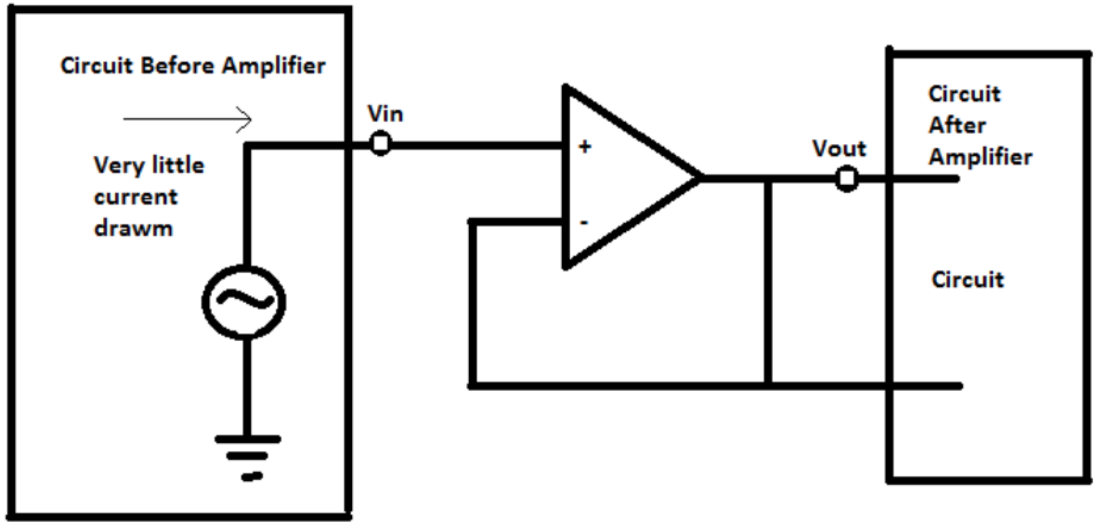



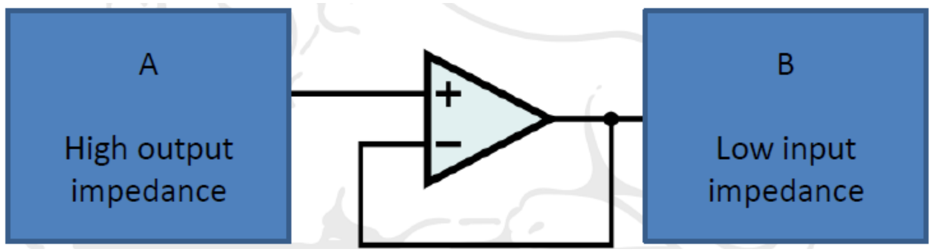



# Op-Amp usages

## Buffer/Voltage follower or Isolation Amplifier



**Thank you**