What is an Op-Amp? – The Surface

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

• We recognize an Op-Amp as a mass-produced component found in countless electronics.

![What an Op-Amp looks like to a lay-person](image1.png)

![What an Op-Amp looks like to an engineer](image2.png)
What is an Op-Amp? – The Layout

• There are 8 pins in a common Op-Amp, like the 741 which is used in many instructional courses.
What is an Op-Amp? – The Inside

• The actual count varies, but an Op-Amp contains several Transistors, Resistors, and a few Capacitors and Diodes.
• For simplicity, an Op-Amp is often depicted as this:
History of the Op-Amp – The Dawn

- Before the Op-Amp: Harold S. Black develops the feedback amplifier for the Western Electric Company (1920-1930)
History of the Op-Amp – The Dawn

• **The Vacuum Tube Age**
  
  • The First Op-Amp: (1930 – 1940) Designed by Karl Swartzel for the Bell Labs M9 gun director
  
  • Uses 3 vacuum tubes, only one input, and ± 350 V to attain a gain of 90 dB
  
  • Loebe Julie then develops an Op-Amp with two inputs: Inverting and Non-inverting
History of the Op-Amp – The Shift

• The end of Vacuum Tubes was built up during the 1950’s-1960’s to the advent of solid-state electronics

1. The Transistor
2. The Integrated Circuit
3. The Planar Process
History of the Op-Amp – The Shift

• 1960s: beginning of the Solid State Op-Amp
• Example: GAP/R P45 (1961 – 1971)
  – Runs on ± 15 V, but costs $118 for 1 – 4
• The GAP/R PP65 (1962) makes the Op-Amp into a circuit component as a potted module
History of the Op-Amp – The Evolution

• The solid-state decade saw a proliferation of Op-Amps
  – Model 121, High Speed FET family, etc.
• Robert J. Widlar develops the μA702 Monolithic IC Op-Amp (1963) and shortly after the μA709
• Fairchild Semiconductor vs. National Semiconductor
  – National: The LM101 (1967) and then the LM101A (1968) (both by Widlar)
  – Fairchild: The “famous” μA741 (by Dave Fullager 1968) and then the μA748 (1969)
Mathematics of the Op-Amp

• The gain of the Op-Amp itself is calculated as:

\[ G = \frac{V_{\text{out}}}{(V_+ - V_-)} \]

• The maximum output is the power supply voltage

• When used in a circuit, the gain of the circuit (as opposed to the op-amp component) is:

\[ A_v = \frac{V_{\text{out}}}{V_{\text{in}}} \]
• As mentioned earlier, the maximum output value is the supply voltage, positive and negative.

• The gain (G) is the slope between saturation points.
741 Op-Amp Schematic

current mirror
current mirror

differential amplifier

Non-inverting input

Inverting input

Q1 Q2 Q3 Q4 Q5 Q6 Q7 Q8 Q9

3 2 1 5

Q10 Q11 Q12 Q13 Q14 Q15 Q16 Q17 Q18

Offset null

4.5 kΩ 7.5 kΩ 39 kΩ 30 pF

45 kΩ 25 Ω 50 Ω

output stage

offset null

1 kΩ 1 kΩ 5 kΩ

50 kΩ 50 kΩ 50 Ω

voltage level shifter

high-gain amplifier $V_{S-}$

Output

$V_{S+}$
Op-Amp Characteristics

- Open-loop gain $G$ is typically over 9000
- But closed-loop gain is much smaller
- $R_{\text{in}}$ is very large (MΩ or larger)
- $R_{\text{out}}$ is small (75Ω or smaller)
- Effective output impedance in closed loop is very small
Ideal Op-Amp Characteristics

- Open-loop gain $G$ is infinite
- $R_{in}$ is infinite
  - Zero input current
- $R_{out}$ is zero
Ideal Op-Amp Analysis

To analyze an op amp feedback circuit:
- Assume no current flows into either input terminal
- Assume no current flows out of the output terminal
- Constrain: $V_+ = V_-$
Inverting Amplifier Analysis

\[ V_{\text{out}} = -\frac{R_f}{R_{\text{in}}} V_{\text{in}} \]
Non-Inverting Amplifier Analysis

\[ V_{out} = V_{in} \left(1 + \frac{R_2}{R_1}\right) \]
Op-Amp Buffer

\[ V_{\text{out}} = V_{\text{in}} \]

Isolates loading effects

A
High output impedance

B
Low input impedance
Op-Amp Differentiator

\[ V_{out} = -RC \frac{dV_{in}}{dt} \]
Op-Amp Integrator

\[ V_{out} = -\int_{0}^{t} \frac{V_{in}}{RC} \, dt + V_{initial} \]
Op-Amp Summing Amplifier

\[ V_{\text{out}} = -R_f \left( \frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \right) \]
If $R_1 = R_2$ and $R_f = R_g$:

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