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6872 Foundations of Electronics

Lecture 11: Operational Amplifier (Op-Amp)

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Abstract

- Op-Amp Basics
- Circuits
  - Inverting Amplifier
  - Summing Amplifier
  - Non-Inverting Amplifier
  - Unit Gain Amplifiers
  - Integrator
  - Differentiator
- Op-Amp Specifications
- Application Examples

Op Amp → Idealizado para ter amplificação ideal:

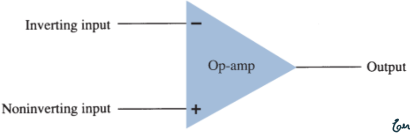
- ganho infinito
- banda de amplificação infinita
- impedância de entrada infinita
  ↳ Não consome potência da fonte
  ↳ Funciona em baixíssimas correntes
- impedância de saída igual a zero

Sensores → médicos / → agrícolas } Op Amp é usado em áreas em que sinais muito baixos são gerados, para amplificá-los.

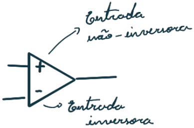
Op-Amp Basics

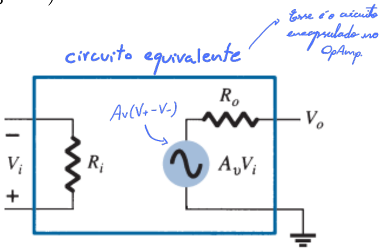
- Op-Amp is an ideal amplifier having:
  - Infinite (open-loop) voltage gain A_v (actual: few thousands to tens of thousands)
  - Infinite bandwidth (actual: MHz to tens of MHz)
  - Infinite input impedance R_i (actual: few megohms)
  - Zero output impedance R_o (actual: less than 100 Ω)
- Inputs (non-inverting v_+ and inverting v_-)
- Output: $V_o = A_v V_i = A_v(V_+ - V_-)$

$V_o = A_v(V_+ - V_-)$



Symbol

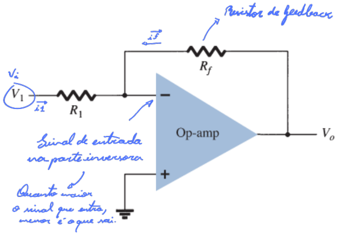




Equivalent circuit

Inverting Amplifier

→ Amplificador inversor



- Assuming $R_i = \infty$ and $R_o = 0$:

$$i = \frac{\overset{V_i}{V_1} - V_-}{R_1} = -\frac{V_o - V_-}{R_f} \qquad \underbrace{\frac{V_i - V_-}{R1}}_{i1} + \underbrace{\frac{V_o - V_-}{Rf}}_{if} = 0$$

$$V_o = A_v(V_+ - V_-) = -A_v V_- \rightarrow V_- = -\frac{V_o}{A_v}$$

A_v → ganho de tensão

- If $A_v \gg 1$

$$V_- = -\frac{V_o}{A_v} \approx 0 \text{ (virtual ground)}$$

↳ Quando V_o tende ao infinito, A_v tende a zero.

$$i = \frac{V_1}{R_1} = -\frac{V_o}{R_f}$$

- Output voltage:

$$\boxed{V_o = -\frac{R_f}{R_1} V_1}$$

- **Example:** If $R_1 = 100$ kΩ and $R_f = 500$ kΩ in the above figure, what output voltage results for an input of $V_1 = 2$ V?

$$V_o = -\frac{R_f}{R_1} V_1 = -\frac{500\text{k}}{100\text{k}} \times 2 = -10 \text{ V}$$

Summing Amplifier → Amplificador somador

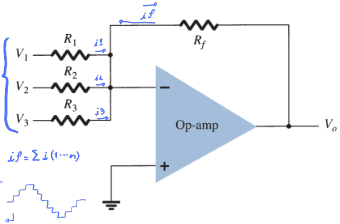
- Assuming $R_i = \infty$ and $R_o = 0$:

$$i = \frac{V_1 - V_-}{R_1} + \cdots + \frac{V_n - V_-}{R_n} = -\frac{V_o - V_-}{R_f}$$

$$V_o = A_v(V_+ - V_-) = -A_v V_- \rightarrow V_- = -\frac{V_o}{A_v}$$

Múltiplas entradas

Quanto mais combinações de R_n aqui, mais perto da perfeição chega o sinal de saída.



Quanto mais R, mais "degraus" na senoidal.

- If $A_v \gg 1$

$$V_- = -\frac{V_o}{A_v} \approx 0 \text{ (virtual ground)}$$

$$i = \frac{V_1}{R_1} + \cdots + \frac{V_n}{R_n} = -\frac{V_o}{R_f}$$

$V_o = -R_f\left(\sum i\,(1 \cdots n)\right)$

$\frac{V_o - V_-}{R_f} = \frac{V_1 - \cancel{V_-}^{0}}{R_1} + \cdots + \frac{V_n - \cancel{V_-}^{0}}{R_n}$

$V_o = -R_f\left(\sum \frac{V_{(1 \cdots n)}}{R_{(1 \cdots n)}}\right)$

- Output voltage:

$$\boxed{V_o = -R_f\left(\frac{V_1}{R_1} + \cdots + \frac{V_n}{R_n}\right)}$$

- **Example:** If $R_f = 1$ MΩ and $V_1 = -2$ V, $V_2 = +3$ V, $V_3 = +1$ V, $R_1 = 200$ kΩ, $R_2 = 500$ kΩ, $R_3 = 1$ MΩ in the above figure, what is the output voltage?

$$V_o = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right) = -1\text{M}\left(\frac{-2}{200\text{k}} + \frac{3}{500\text{k}} + \frac{1}{1\text{M}}\right) = 3 \text{ V}$$

Non-Inverting Amplifier

Amp. não - inversor

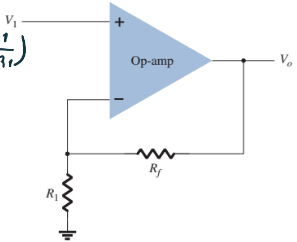
- Assuming $R_i = \infty$ and $R_o = 0$:

$$V_+ = V_1 \text{ and } V_- = \frac{R_1}{R_1 + R_f} V_o$$

$$V_- = A_v\left(V_1 - \frac{V_o \cdot R_1}{R_f + R_1}\right)$$

$$V_o = A_v(V_+ - V_-) = A_v\left(V_1 - \frac{R_1}{R_1 + R_f} V_o\right) \rightarrow$$

$$V_o = \frac{V_1}{1/A_v + R_1/(R_1 + R_f)}$$



- If $A_v \gg 1$

$$V_o = \frac{R_1 + R_f}{R_1} V_1$$

- Output voltage:

$$\boxed{V_o = \frac{R_1 + R_f}{R_1} V_1 = \left(1 + \frac{R_f}{R_1}\right) V_1}$$

- **Example:** If $R_1 = 100\ \text{k}\Omega$ and $R_f = 500\ \text{k}\Omega$ in the above figure, what output voltage results for an input of $V_1 = 2$ V?

$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1 = \left(1 + \frac{500\text{k}}{100\text{k}}\right) \times 2 = 12 \text{ V}$$

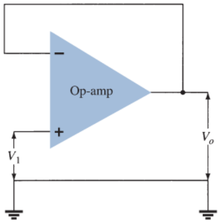
Unit Gain Follower and Unit Gain Inverter

↳ Amp. com ganho unitário

Por que uso esse se não inverte nem amplifica (ganho unitário)?
Porque eu posso querer isolar uma porção do circuito

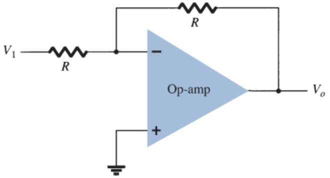
- Unit Gain Follower
  - Non-inverting amplifier with unit gain:

$$\boxed{V_o = V_1}$$



- Unit Gain Inverter
  - Inverting amplifier with unit gain:

$$\boxed{V_o = -V_1}$$



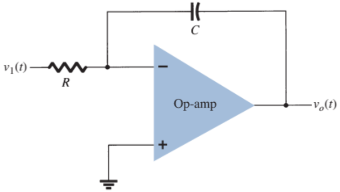
Integrator → acumular um erro com o tempo

É o que usa integral na fórmula

- Remembering that $V_- = 0$:

$$i = \frac{v_1}{R} = -C\frac{dv_o}{dt}$$

$$\boxed{v_o(t) = -\frac{1}{RC}\int_0^t v_1(\tau)d\tau}$$



- **Note:** integration operation sums the area under a waveform over a period of time
- If a fixed voltage is applied as input, the output voltage grows linearly, producing a ramp voltage
- The output voltage ramp is opposite in polarity to the input voltage and is multiplied by $1/RC$
- If $v_1 = 1$ V, $R = 1$ MΩ and $C = 1$ μF, the output ramp voltage grows -1 V/s
- If $v_1 = 1$ V, $R = 100$ kΩ and $C = 1$ μF, the output ramp voltage grows -10 V/s

Differentiator

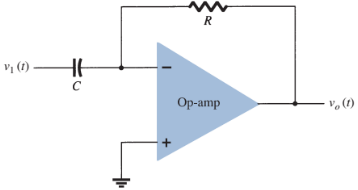
↳ controlar aceleração com o tempo

Diferenciador × Integrador } Depende de onde o capacitor é posto.

- Remembering that $V_{-} = 0$:

$$i = C\frac{dv_1}{dt} = -\frac{v_o}{R}$$

$$\boxed{v_o(t) = -RC\frac{dv_1}{dt}}$$



- **Note:** differentiation operation gives the rate at which the input waveform changes with respect to time

Specifications and Parameters

Input offset voltage

Offset → V_I necessária para que $V_o = 0$

- **Input Offset Voltage:** differential DC voltage required between the inputs to make the output zero
  - Idealy, the op-amp output should be 0 V when the input is 0 V; however there is some offset voltage at the output
  - Typical values range from mV down to μV
- **Input Offset Current:** is equal to the difference between the input bias current at the non-inverting terminal minus the input bias current at the inverting
  - Idealy, input bias currents are zero and therefore the input offset current is also zero
  - Typical values range from nA (BJT Op-Amps) down to pA (MOSFET Op-Amps)
- → Ganho de tensão em malha aberta

  Open-Loop Gain: gain obtained when no feedback is used in the circuit
- **Input Impedance:** given as common mode input impedance (static) and differential input impedance (dynamic with V and I)
- → Idealmente é zero. Fornecida pelo fabricante

  Output Impedance: decreases with feedback
- **Frequency Response:** given as *bandwidth* or *gain bandwidth product*
- **Slew-Rate:** maximum rate at which amplifier output can change in volts per microsecond ↳ O tempo que leva para a tensão variar

Application Examples

- **Constant-Gain Multiplier**

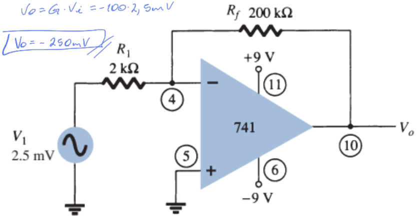
- Inverting Circuit
  - Voltage Gain: $\boxed{G = -\frac{R_f}{R_1}}$
  - Example: $G = -\frac{200\text{k}}{2\text{k}} = -100$
    $V_o = GV_i = -100 \times 2.5\text{m} =$
    -250 mV

$G = -\frac{R_f}{R_i}$

$G = \frac{200k}{2k} = -100$

$V_o = G \cdot V_i = -100 \cdot 2,5\,mV$

$\boxed{V_o = -250\,mV}$



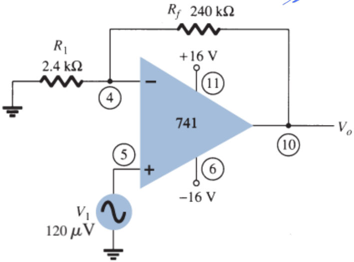
- Non-Inverting Circuit
  - Voltage Gain: $\boxed{G = 1 + \frac{R_f}{R_1}}$
  - Example: $G = 1 + \frac{240\text{k}}{2.4\text{k}} = 101$
    $V_o = GV_i = 101 \times 120\mu =$
    12.1 mV

$G = 1 + \frac{R_f}{R_i}$

$G = 1 + \frac{240k}{2,4k} = 1 + 100 = 101$

$V_o = G \cdot V_i = 101 \cdot 120\mu V =$ $\frac{12000 + 120}{12120\mu V}$

$\boxed{V_o = 12,12\,mV}$



Application Examples

- **Multiple-Stage Multiplier**
  - Voltage Gain: $\boxed{G = G_1 G_2 \ldots G_n}$
  - Example: $G = G_1 G_2 G_3 = \left(1 + \frac{470\text{k}}{4.3\text{k}}\right)\left(-\frac{470\text{k}}{33\text{k}}\right)\left(-\frac{470\text{k}}{33\text{k}}\right) = 22.4 \times 10^3$
    $V_o = GV_i = 22.2 \times 10^3 \times 80\mu = 1.79$ V

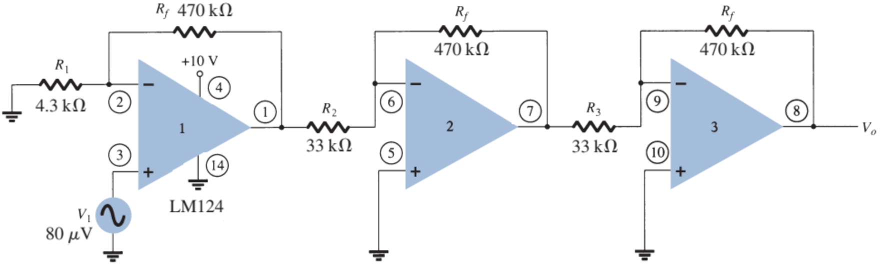
$G = G_1 \cdot G_2 \cdot G_3$

$\left(1 + \frac{470}{4,3}\right) \cdot \frac{470}{33} \cdot \frac{470}{33} = 22,4 \cdot 10^3$

$G = 1 + \frac{R_f}{R_i} = \frac{470k}{4,3k} + 1$

$G = -\frac{470k}{33k}$

$G = -\frac{470k}{33k}$



$V_o = G \cdot V_i$

$V_o = 22,4 \cdot 10^3 \cdot 80\mu V$

$\boxed{V_o = 1,79 V}$

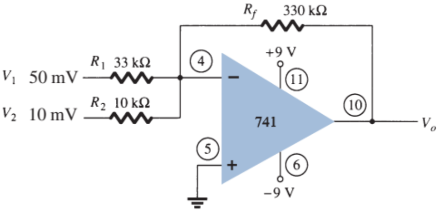
Application Examples

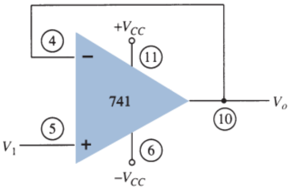
- **Voltage Summing**
  - Output Voltage:

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

  - Example:
    $V_o = -\left(\frac{330\text{k}}{33\text{k}}50\text{m} + \frac{330\text{k}}{10\text{k}}10\text{m}\right) = 830 \text{ mV}$

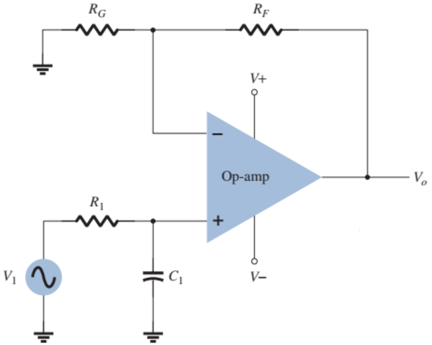
- **Voltage Buffer**
  - Output Voltage:
    $\boxed{V_o = V_i}$

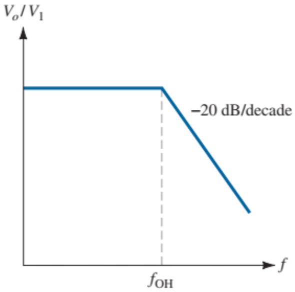




Application Examples

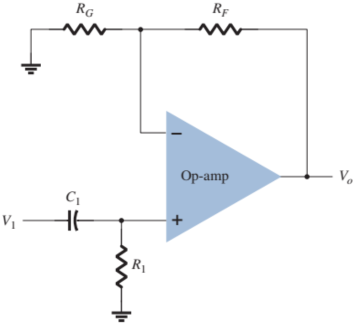
- **Low-Pass Filter**
  - Voltage Gain: $\boxed{G = 1 + \dfrac{R_F}{R_G}}$
  - Cutoff Frequency: $\boxed{f_{OH} = \dfrac{1}{2\pi R_1 C_1}}$

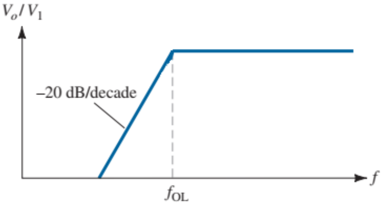




Application Examples

- **High-Pass Filter**
  - Voltage Gain: $\boxed{G = 1 + \frac{R_F}{R_G}}$
  - Cutoff Frequency: $\boxed{f_{OL} = \frac{1}{2\pi R_1 C_1}}$





Application Examples

- **Band-Pass Filter**