

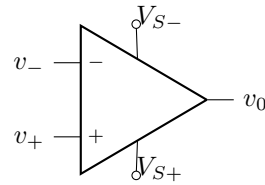
# Operational Amplifiers

Diego Trapero

## Table of contents

<b>1</b>	<b>The Operational Amplifier</b>	<b>2</b>
1.1	Ideal Operational Amplifier . . . . .	2
<b>2</b>	<b>Op-amp configurations</b>	<b>3</b>
2.1	Comparator . . . . .	3
2.2	Voltage follower . . . . .	3
2.3	Inverting amplifier . . . . .	3
2.4	Noninverting amplifier . . . . .	4
2.5	Differential amplifier . . . . .	5
2.6	Integrator . . . . .	5
2.7	Differentiator . . . . .	5
2.8	Inverting amplifier with offset adjustment . . . . .	5
2.9	Summing amplifier . . . . .	6
<b>3</b>	<b>Op Amp table</b>	<b>7</b>

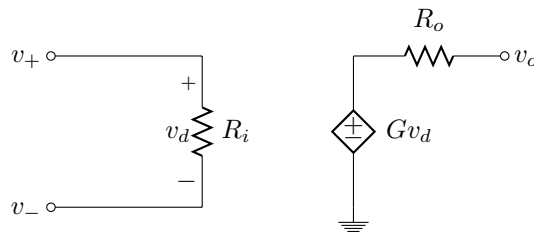
# 1 The Operational Amplifier



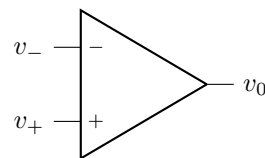
**Op-amp terminals** The terminals of an op-amp are

- Positive terminal, +, non-inverting terminal.
- Negative terminal, -, inverting terminal
- Positive power supply,  $V_{S+}$
- Negative power supply,  $V_{S-}$
- Output terminal,  $v_o$

**Op-amp equivalent circuit** Some of the non-ideal resistive characteristics of an op-amp can be modelled by the following circuit



## 1.1 Ideal Operational Amplifier



The ideal operational amplifier is a model of the real amplifier, where the equivalent circuit has

- Infinite open-loop gain,  $G \rightarrow \infty$ .
- Zero output impedance,  $R_{out} = 0$ .
- Infinite input impedance,  $R_{in} \rightarrow \infty$ .
- None of the other non-ideal behaviours: CMRR, noise, offset, bandwidth...

**Ideal op-amp transfer function, op-amp formula.** With the simplifications of the ideal op-amp mode, the output voltage is

$$v_o = G(v_+ - v_-)$$

where  $G$  is a very large number, and can be considered infinite. Nevertheless, we should take into account saturation, so  $v_o$  must be in the following interval:

$$v_o \in [v_{S-}, v_{S+}]$$

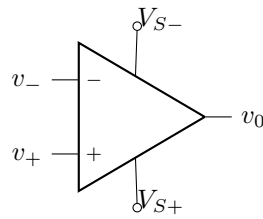
**Ideal op-amp golden rules**

1. In a negative feedback configuration, the output attempts to do whatever is necessary to make the voltage difference between the inputs zero.
2. The inputs draw no current.

[The Art of Electronics, page 177]

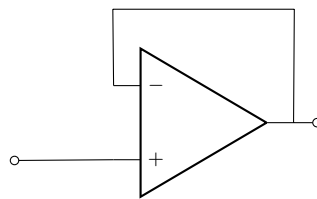
## 2 Op-amp configurations

### 2.1 Comparator



$$v_o = \begin{cases} v_{S+} & \text{if } v_+ > v_- \\ v_{S-} & \text{if } v_- > v_+ \end{cases}$$

### 2.2 Voltage follower



$$v_o = v_i$$

#### Circuit analysis

- a) With the op-amp formula

$$v_o = G(v_i - v_o)$$

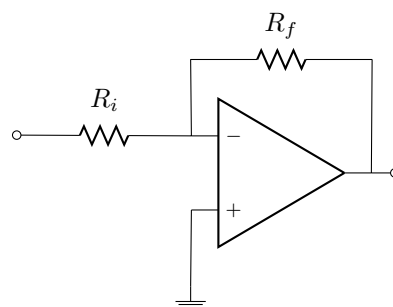
$$v_o = Gv_i - Gv_o$$

$$v_o + Gv_o = Gv_i$$

$$\frac{v_o}{G} + v_o = v_i \xrightarrow{G \rightarrow \infty} v_o = v_i$$

- b) With the golden rules: Since it is a feedback configuration, we can apply the first rule. We obtain that  $v_+ = v_-$ , or  $v_i = v_o$ , which is the transfer function of the voltage follower.

### 2.3 Inverting amplifier



#### Circuit analysis

- a) With the golden rules  
a.1) From the golden rules we know

$$* \ i_{\text{opamp}} = 0$$

$$* \ v_- = v_+ = 0$$

a.2) KCL in the negative terminal

$$i_i = i_o$$

$$\frac{v_i - v_-}{R_i} = \frac{v_- - v_o}{R_f}$$

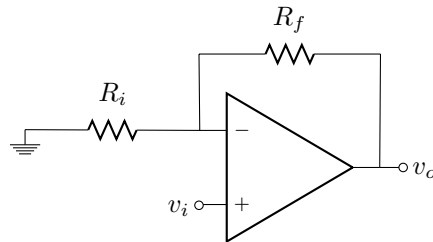
a.3)  $v_- = 0$

$$\frac{v_i}{R_i} = -\frac{v_o}{R_f}$$

a.4) Obtain  $v_o$

$$v_o = -\frac{R_f}{R_i} v_i$$

## 2.4 Noninverting amplifier



### Circuit analysis

a) With the op-amp formula

a.1) Op-amp formula

$$v_o = G(v_i - v_-)$$

a.2) Calculate  $v_-$  with the voltage divider formula:

$$v_- = \frac{R_i}{R_i + R_f} v_o$$

a.3) Substitute  $v_-$  in the op-amp formula

$$v_o = G\left(v_i - \frac{R_i}{R_i + R_f} v_o\right)$$

a.4) Take all  $v_o$  to the left

$$v_o + G \frac{R_i}{R_i + R_f} v_o = G v_i$$

a.5) Divide all by  $G$  and take the limit when  $G$  tends to infinity

$$\frac{v_o}{G} + \frac{R_i}{R_i + R_f} v_o = v_i \xrightarrow{G \rightarrow \infty} \frac{R_i}{R_i + R_f} v_o = v_i$$

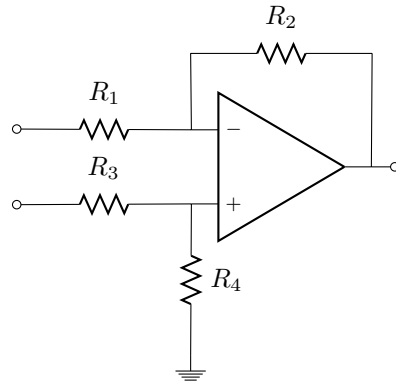
a.6) The transfer function is

$$v_o = \frac{R_i + R_f}{R_i} v_i$$

$$v_o = \left(1 + \frac{R_f}{R_i}\right) v_i$$

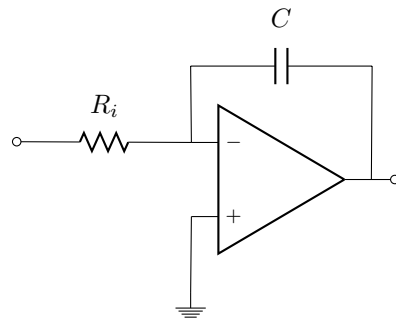
### Noninverting amplifier circuit analysis with the golden rules

## 2.5 Differential amplifier

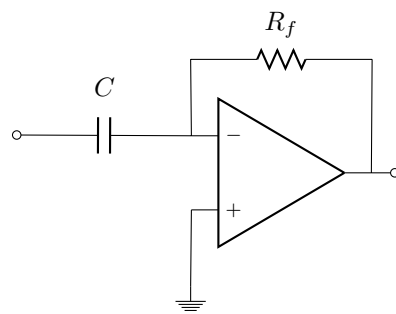


$$v_o = \frac{R_4}{R_3 + R_4} \left(1 + \frac{R_2}{R_1}\right) v_2 - \frac{R_2}{R_1} v_1$$

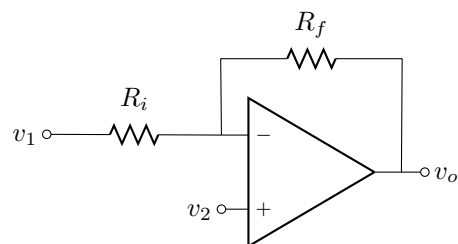
## 2.6 Integrator



## 2.7 Differentiator



## 2.8 Inverting amplifier with offset adjustment



$$v_o = \left(1 + \frac{R_2}{R_1}\right) v_2 - \frac{R_2}{R_1} v_1$$

Circuit analysis

a) Using the differential amplifier formula

a.1) The differential amplifier formula is

$$v_o = \frac{R_4}{R_3 + R_4} \left( 1 + \frac{R_2}{R_1} \right) v_2 - \frac{R_2}{R_1} v_1$$

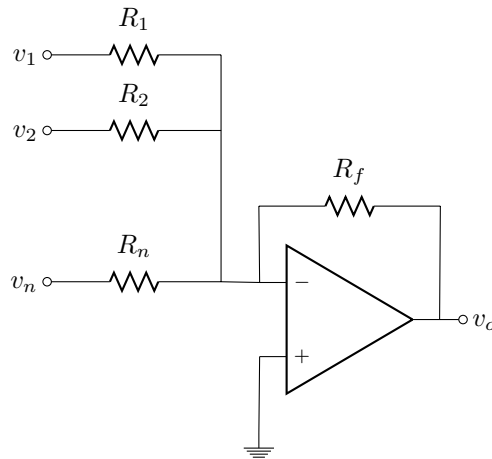
a.2) This op-amp circuit is a special case where  $R_4 \rightarrow \infty$

$$\text{if } R_4 \rightarrow \infty : v_o = \frac{\cancel{R_4}}{\cancel{R_3} + \cancel{R_4}} \overset{1}{\left( 1 + \frac{R_2}{R_1} \right)} v_2 - \frac{R_2}{R_1} v_1$$

$$v_o = \left( 1 + \frac{R_2}{R_1} \right) v_2 - \frac{R_2}{R_1} v_1$$

b) Using superposition

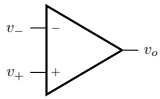
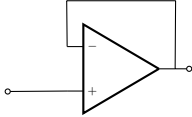
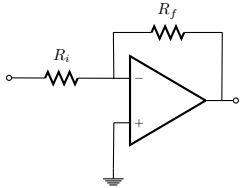
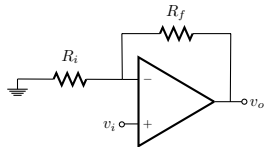
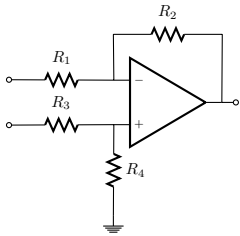
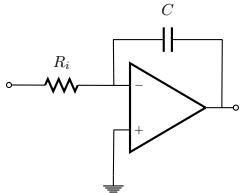
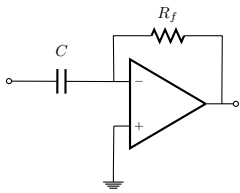
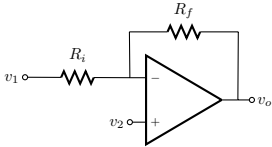
## 2.9 Summing amplifier



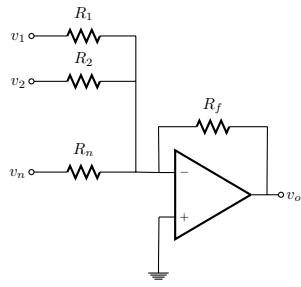
$$v_o = -\frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2 - \dots - \frac{R_f}{R_n} v_n$$

$$v_o = -R_f \sum \frac{v_i}{R_i}$$

### 3 Op Amp table

Op Amp	Circuit	Formula
Comparator		$v_o = \begin{cases} v_{S+} & \text{if } v_+ > v_- \\ v_{S-} & \text{if } v_- > v_+ \end{cases}$
Voltage follower		$v_o = v_i$
Inverting amplifier		$v_o = -\frac{R_f}{R_i}v_i$
Non-inverting amplifier		$v_o = \left(1 + \frac{R_f}{R_i}\right)v_i$
Differential amplifier		$v_o = \frac{R_4}{R_3 + R_4} \left(1 + \frac{R_2}{R_1}\right)v_2 - \frac{R_2}{R_1}v_1$
Integrator		?
Differentiator		?
Inverting amplifier with offset adjustment		$v_o = \left(1 + \frac{R_2}{R_1}\right)v_2 - \frac{R_2}{R_1}v_1$

Summing  
amplifier



$$v_o = -R_f \sum \frac{v_i}{R_i}$$