Operational Amplifiers

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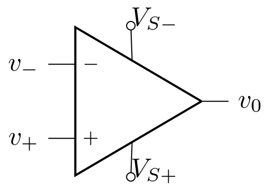
1 Operational Amplifiers

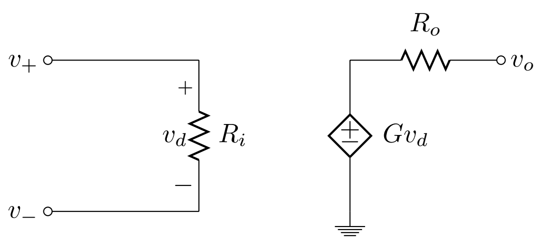
1 The Operational Amplifier



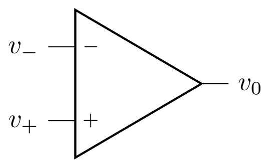
Op-amp terminals The terminals of an op-amp are

- 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 Ideal Operational Amplifier



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

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

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:

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

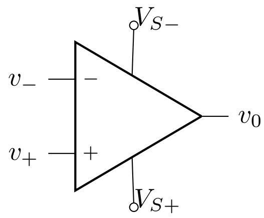
Ideal op-amp golden rules

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]

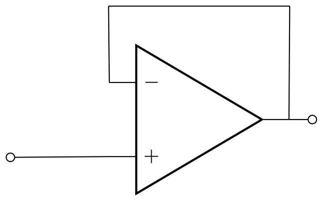
1 Op-amp configurations

1 Comparator



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

1 Voltage follower



$$v_o = v_i$$

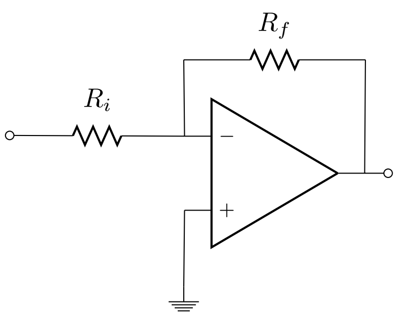
Circuit analysis

a) With the op-amp formula

$$\begin{aligned} v_o &= G(v_i - v_o) \\ v_o &= Gv_i - Gv_o \\ v_o + Gv_o &= Gv_i \\ \frac{v_o}{G} + v_o = v_i &\xrightarrow{G\to\infty} v_o = v_i \end{aligned}$$

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.

1 Inverting amplifier



Circuit analysis

a) With the golden rules

a.1) From the golden rules we know

* $i_{opamp} = 0$

* $v_- = v_+ = 0$

a.2) KCL in the negative terminal

$$i_i = i_o$$

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

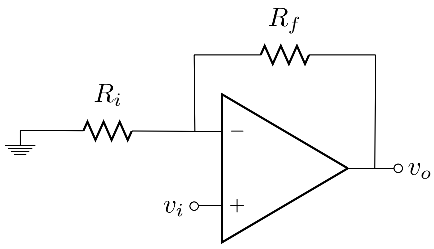
a.3) $v_- = 0$

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

a.4) Obtain v_o

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

1 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

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

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

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

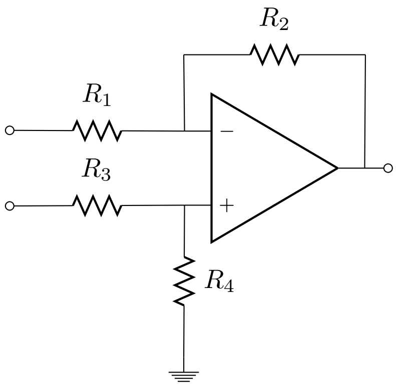
a.6) The transfer function is

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

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

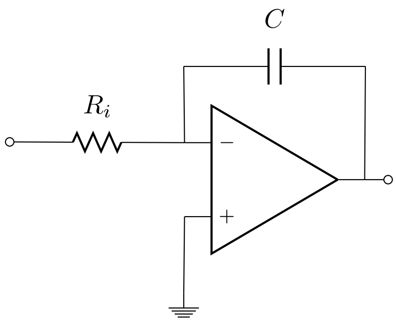
Noninverting amplifier circuit analysis with the golden rules

1 Differential amplifier

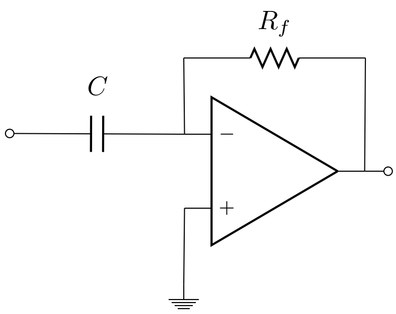


$$v_o = \frac{R_4}{R_3 + R_4}(1 + \frac{R_2}{R_1})v_2 - \frac{R_2}{R_1}v_1$$

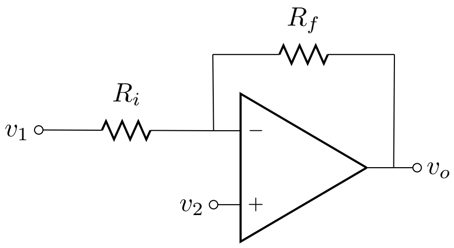
1 Integrator



1 Differentiator



1 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

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

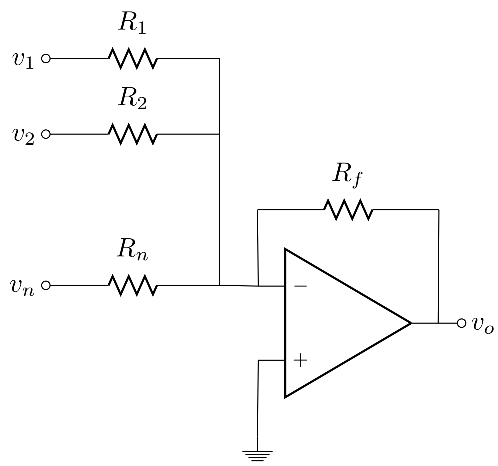
a.2) This op-amp circuit is a special case where $R_4 \to \infty$

$$\text{if } R_4 \to \infty : v_o = \cancelto{1}{\frac{R_4}{R_3 + R_4}} (1 + \frac{R_2}{R_1}) v_2 - \frac{R_2}{R_1} v_1$$

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

b) Using superposition

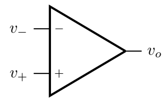
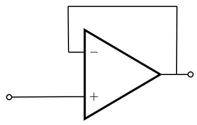
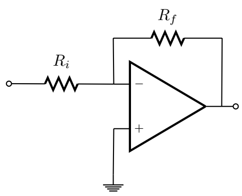
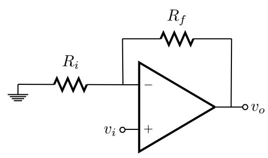
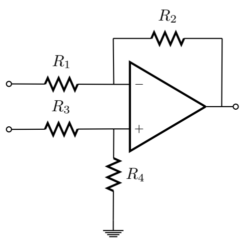
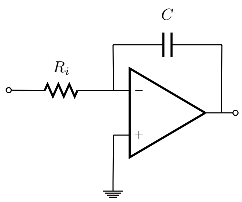
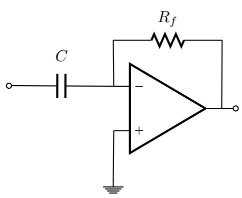
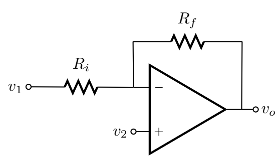
1 Summing amplifier

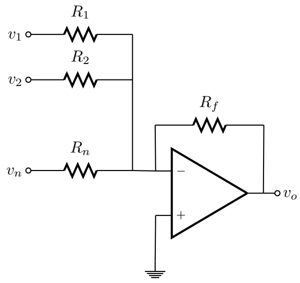


$$v_o = -\frac{R_f}{R_1} v_1 - \frac{R_f}{R_2} v_2 - \ldots - \frac{R_f}{R_n} v_n$$

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

1 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		$v_o = (1 + \frac{R_f}{R_i}) v_i$
Differential amplifier		$v_o = \frac{R_4}{R_3 + R_4}(1 + \frac{R_2}{R_1}) v_2 - \frac{R_2}{R_1} v_1$
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		$v_o = -R_f \sum \frac{v_i}{R_i}$