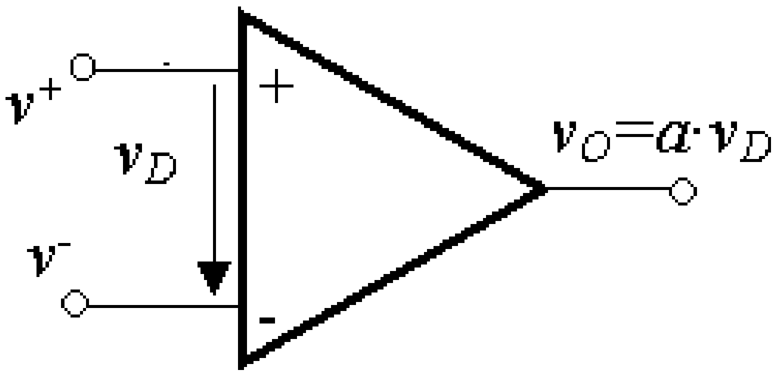
VOLTAGE AMPLIFIERS

WITH

OP-AMPs

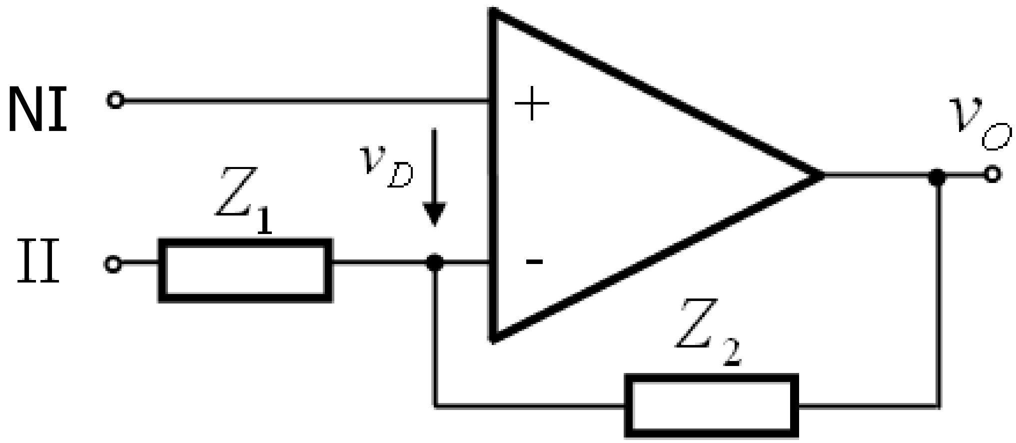
Op-amp to be used as a voltage amplifier



$$v_O = a \cdot v_D = \infty \cdot v_D$$

- ***Utilization as amplifier***
- $v_O \in (V_{OL}\ ;\ V_{OH})$
- required to set $v_D = 0$. $v_O = a \cdot v_D = \infty \cdot 0$ - ***undefined***
- v_D can be kept to 0 by connecting some resistances in the exterior of the op-amp in a ***negative feedback*** configuration. These resistances together with the op-amp maintain v_D to zero and establish the value of the output voltage $\Rightarrow$ op-amp amplifiers.

Op-amp with NF: amplifier



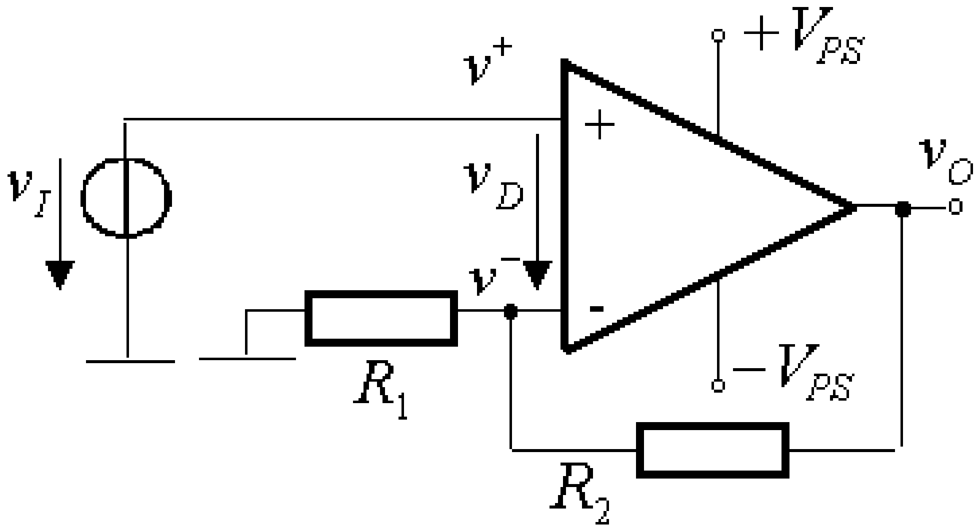
$v_D \uparrow$, $v_O \uparrow$, $v^- \uparrow$, $v_D \downarrow$

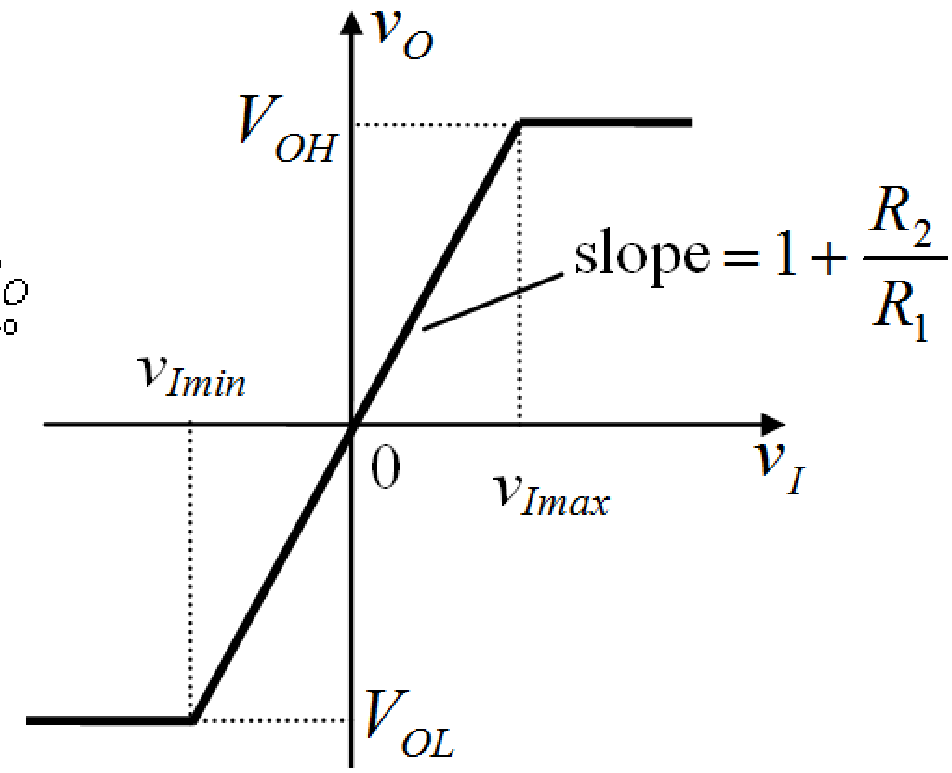
NF
Automatically
maintains v_D to zero, $v_D=0$

What are the possibilities to connect the input terminals?

Inputs		Amplifier
NI	II	
v_I	ground	noninverting
ground	v_I	inverting
v_{I1}	v_{I2}	differential

Noninverting amplifier





$$v^- = \frac{R_1}{R_1 + R_2} v_O$$

$$v_D = v^+ - v^- = v_I - \frac{R_1}{R_1 + R_2} v_O = 0$$

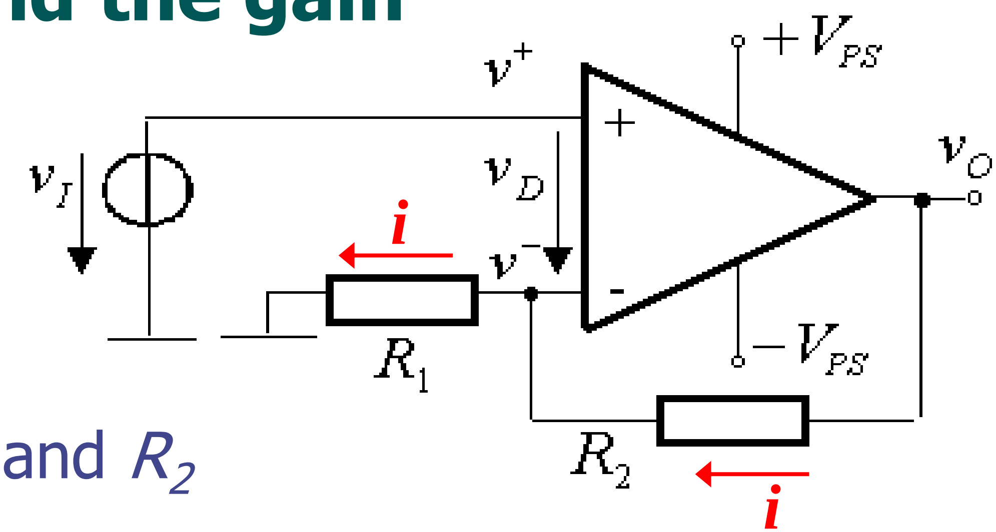
$$v_I = \frac{R_1}{R_1 + R_2} v_O$$

$$A_v = \frac{v_O}{v_I} = 1 + \frac{R_2}{R_1}$$

In a non-inverting amplifier,
the output voltage changes in the same direction as the input voltage.

Another method to find the gain

$$\left.\begin{array}{l} v_D = 0 \\ v^+ = v_I \end{array}\right\} \Rightarrow v^- = v_I$$



- same current through R_1 and R_2

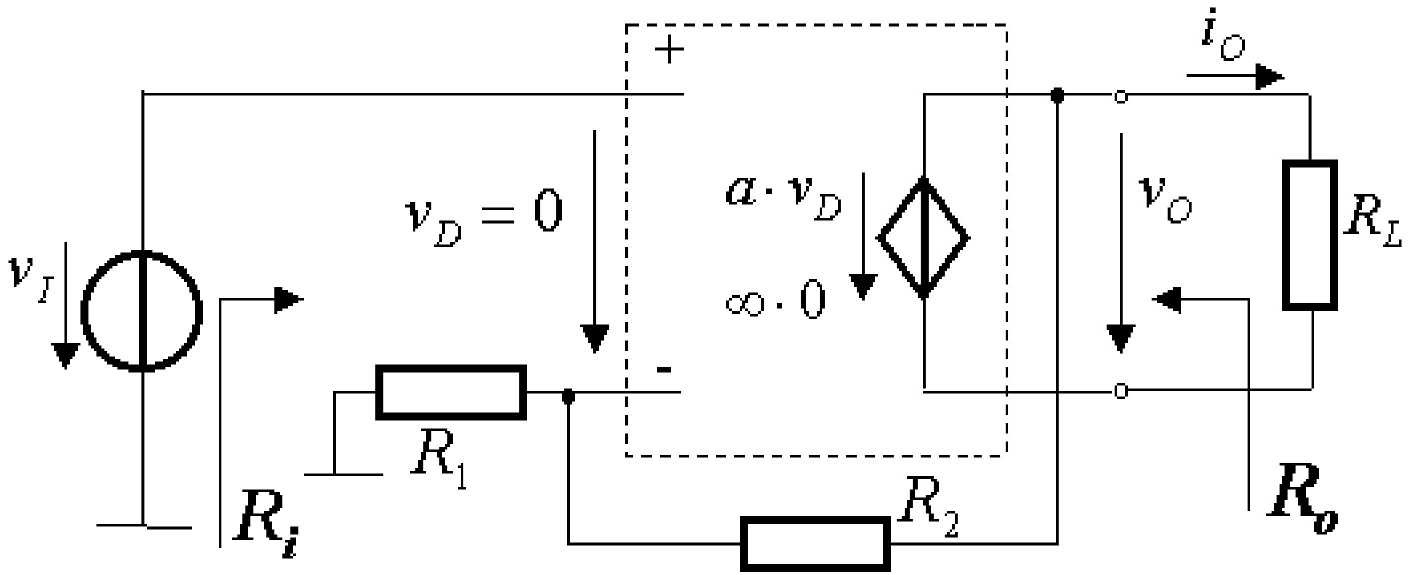
$$\frac{v_I}{R_1} = \frac{v_O - v_I}{R_2} \qquad A_v = \frac{v_O}{v_I} = 1 + \frac{R_2}{R_1}$$

- gain is set only by the ratio of two resistors
- the gain value: precise and stable
- the gain is independent of op-amp; it is not influenced by the technological spread of op-amp parameters
- direct consequence of the NF for the case of a high value of its own gain (a $\rightarrow \infty$ for op-amp)

Input and output resistances

Optional

- computed on the equivalent model



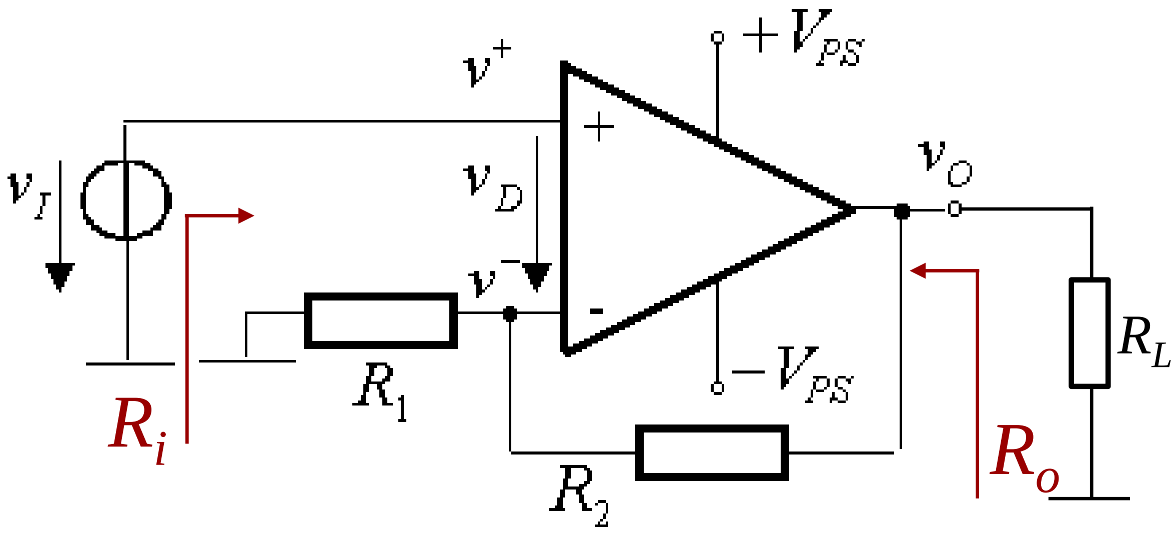
v_I sees an

open circuit, so

$\boldsymbol{R_i = \infty}$

$$R_o = \frac{v_{O_{open}}}{i_{O_{sc}}} = \frac{v_{O_{open}}}{\infty} = 0$$

Input and output resistances



R_i the resistance seen by the input voltage source

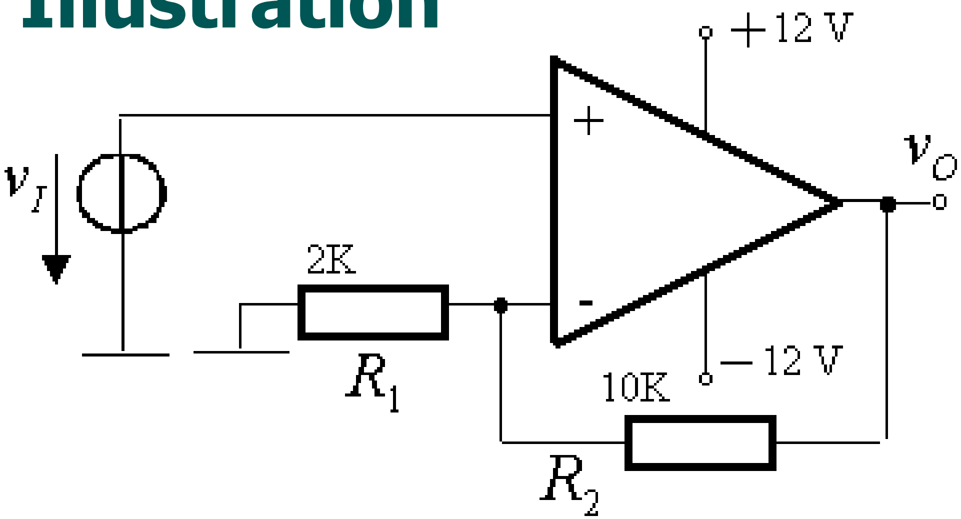
R_o the resistance seen by the load when the input voltage is set to zero

v_I sees an open circuit, so

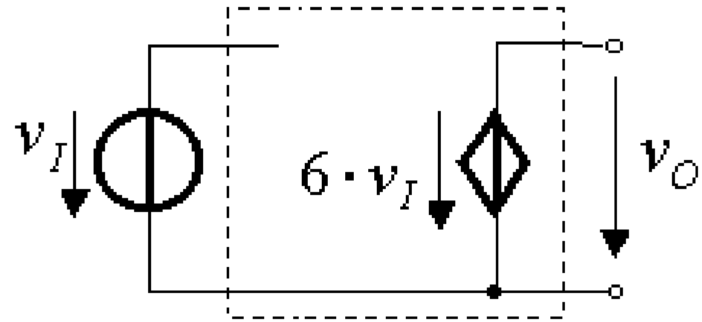
$$\boldsymbol{R_i = \infty}$$

$$\boldsymbol{R_o = 0}$$

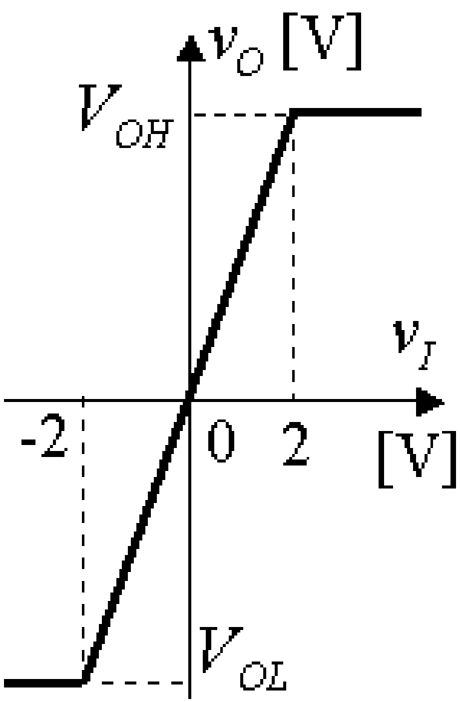
Illustration



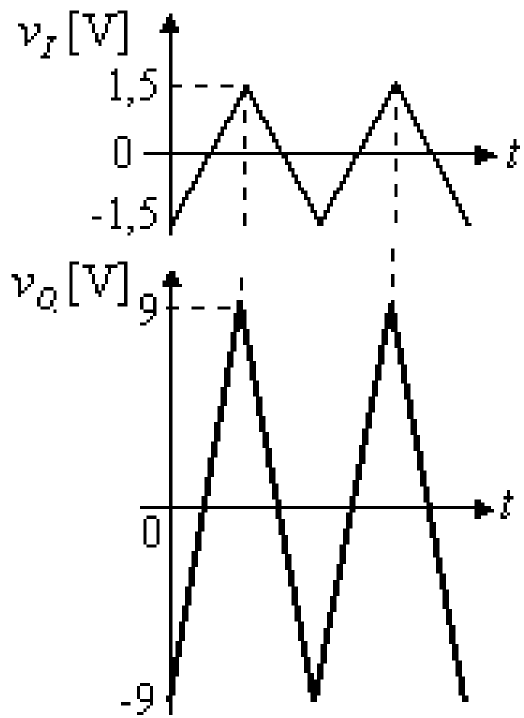
- A_v=6
- Equivalent model.



- VTC



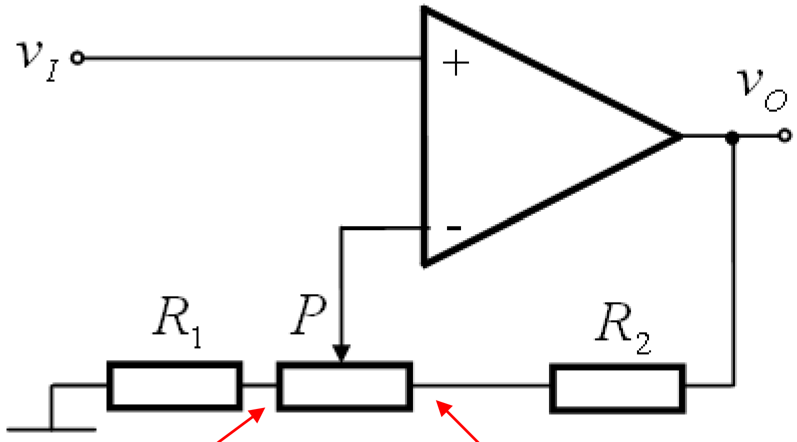
- $v_O(t)$ for triangular $v_I(t)$, 1.5V amplitude, zero dc component



- $v_O(t)$ for triangular $v_I(t)$, 2V amplitude 0.5V dc component

Adjustable gain

version 1



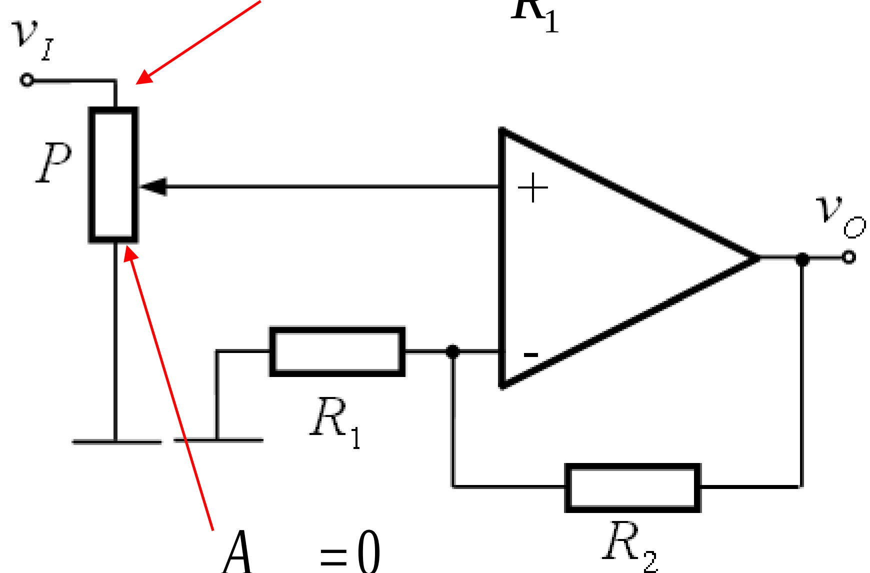
$$A_{v_{max}} = 1 + \frac{R_2 + P}{R_1}$$

$$A_{v_{min}} = 1 + \frac{R_2}{R_1 + P}$$

$$A_v \in \left[1 + \frac{R_2 + P}{R_1}; 1 + \frac{R_2}{R_1 + P}\right]$$

version 2

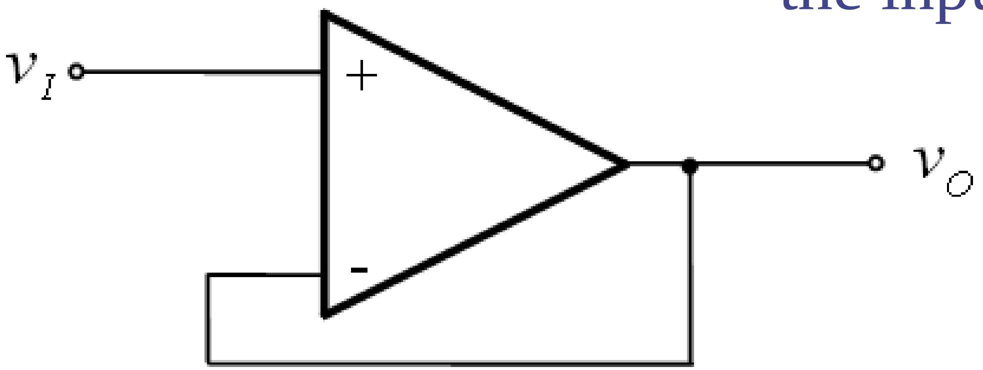
$$A_{v_{\max}} = 1 + \frac{R_2}{R_1}$$



$$A_{v_{\min}} = 0$$

$$A_v \in \left[0; 1 + \frac{R_2}{R_1}\right]$$

Voltage follower



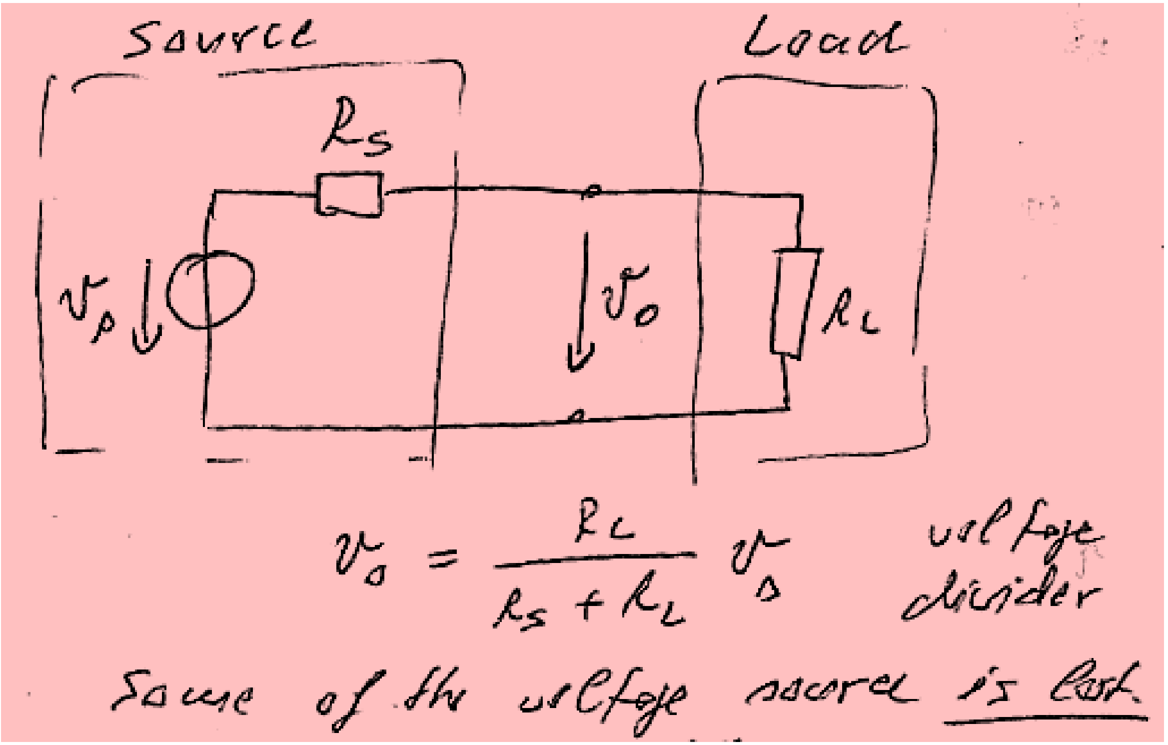
The output voltage **follows** the input voltage

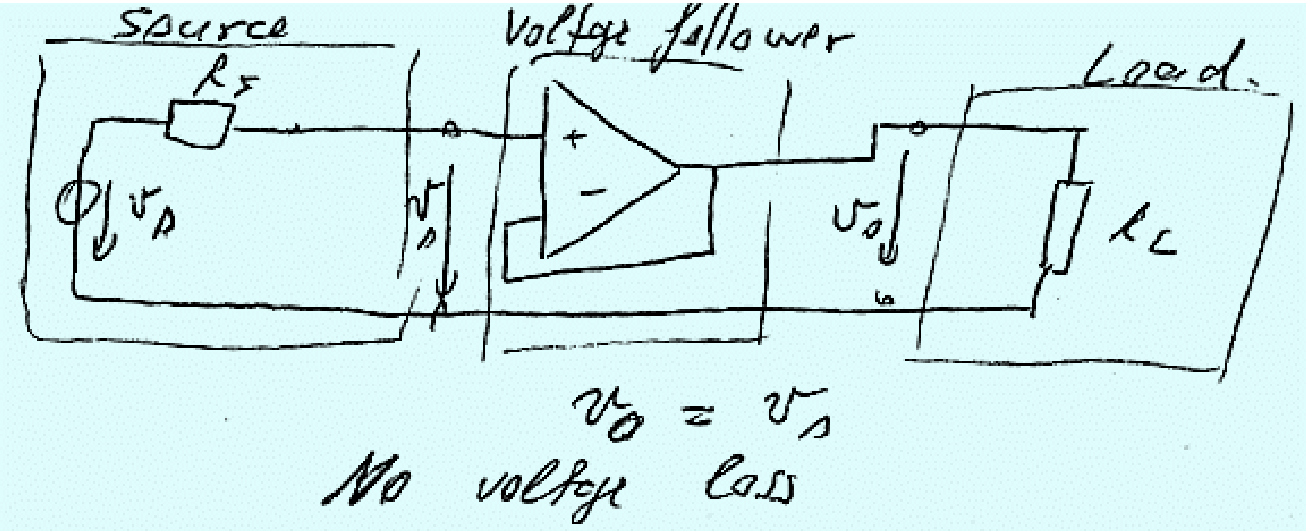
$$v_O = v_I$$

- Total NF
- No voltage gain
- Infinite current gain

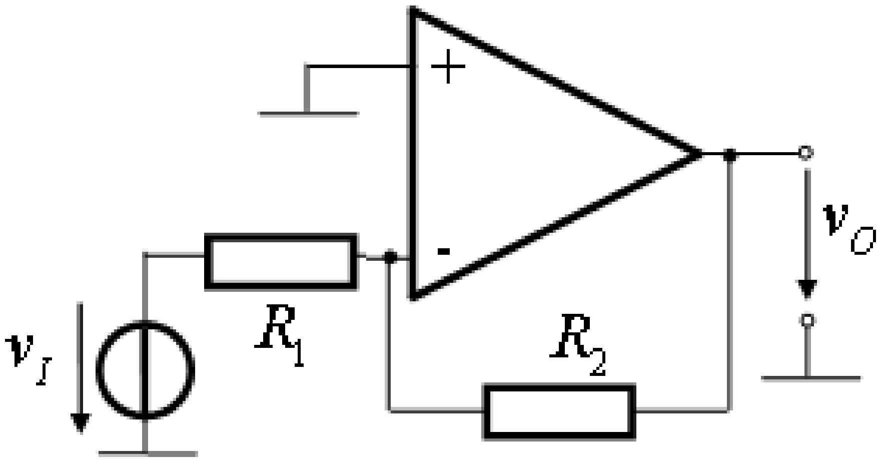
Buffer stage

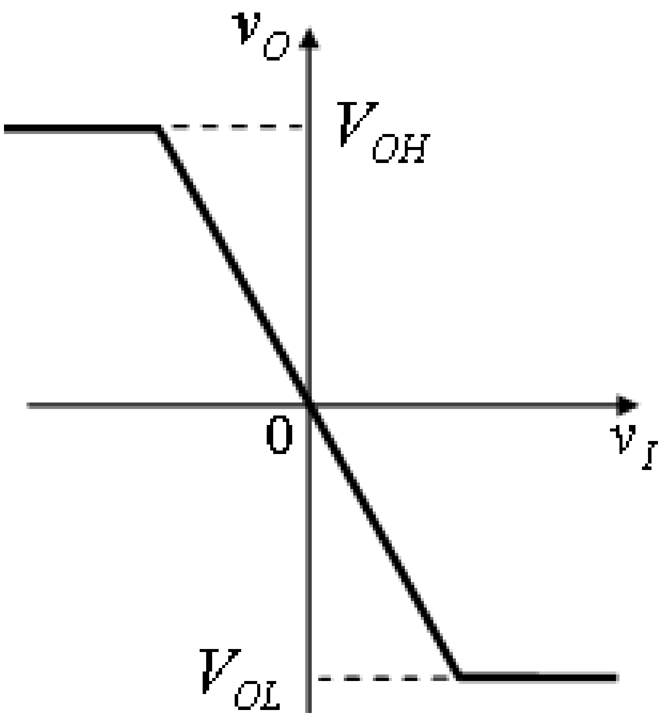
Connects a source (or the output of a circuit) with a high output resistance (can only provide low current) to a low load resistance (needs high current).





Inverting amplifier





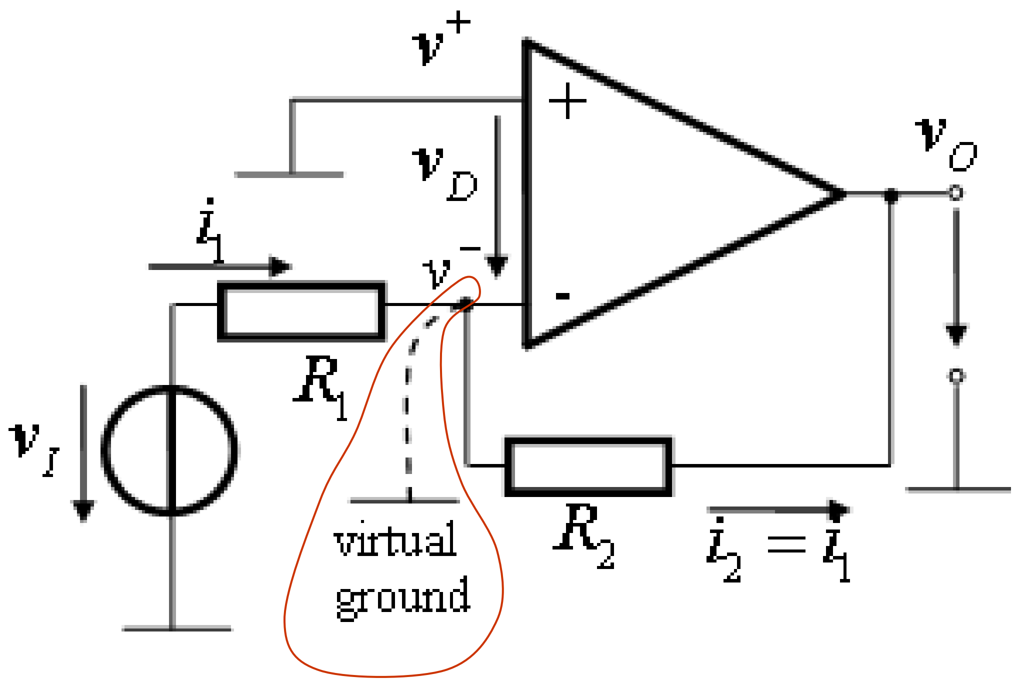
$$v^+ = 0; v^- = \frac{R_2}{R_1 + R_2} v_I + \frac{R_1}{R_1 + R_2} v_o$$

$$v_D = v^+ - v^- = 0 - \frac{R_2}{R_1 + R_2} v_I - \frac{R_1}{R_1 + R_2} v_o = 0$$

$$A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1}$$

In an inverting amplifier, the output voltage changes in an opposite direction to the input voltage

Alternative to comprehend the operation of the circuit



$$v^+ = v^-$$

$$v^+ = 0$$

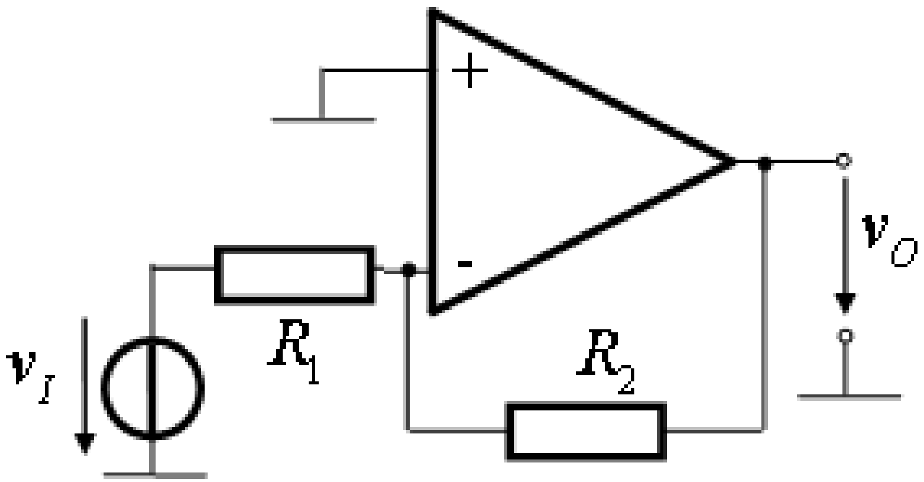
$$v^- = 0$$

virtual ground

$$i_1 = i_2 \qquad i_2 = \frac{0 - v_O}{R_2}$$

$$i_1 = \frac{v_I - 0}{R_1} \qquad \frac{v_I}{R_1} = -\frac{v_O}{R_2} \qquad A_v = \frac{v_O}{v_I} = -\frac{R_2}{R_1}$$

Input and output resistances



$$R_i = R_1$$

$$R_o = 0$$

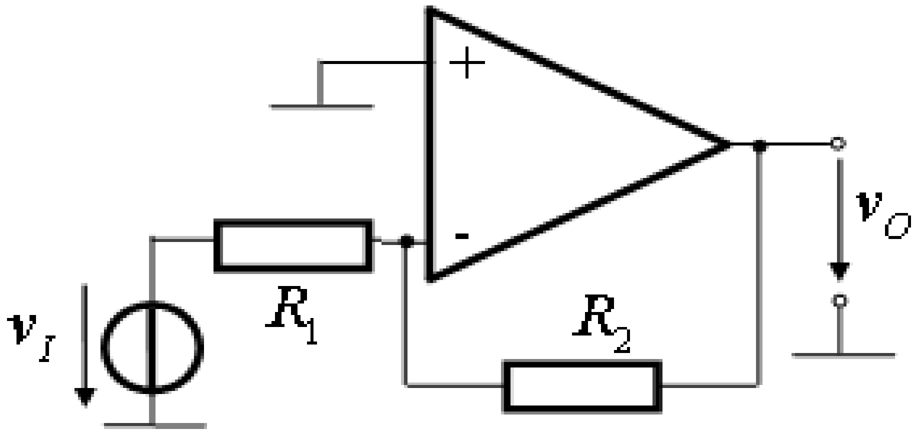
- Compared with the noninverting amplifier where $R_i \to \infty$, for the inverting amplifier we have a smaller input resistance.
- Usually, the magnitude order is units of KΩ, tens of KΩ
- If a high input impedance is required the noninverting connection is recommended

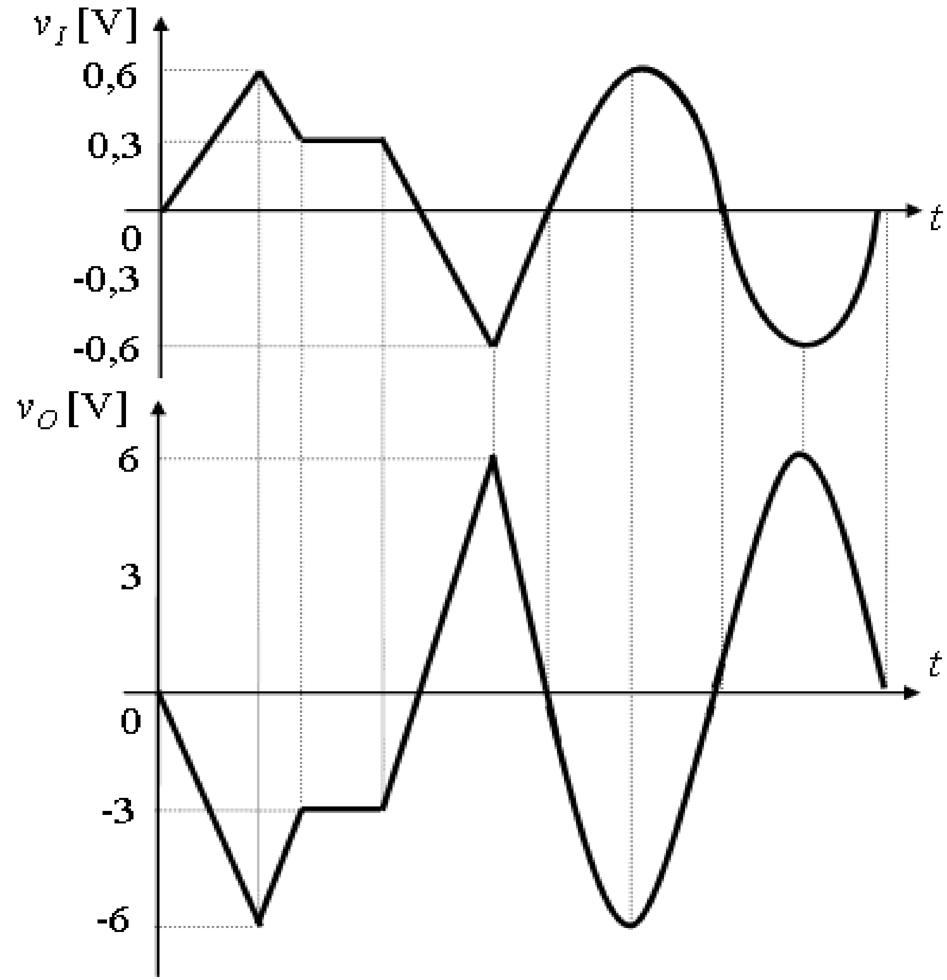
Illustration

R_1=10K, R_2=100K, supply ±12V

? R_i, R_o, A_v

? v_i range so that the amplifier operate only in its active region



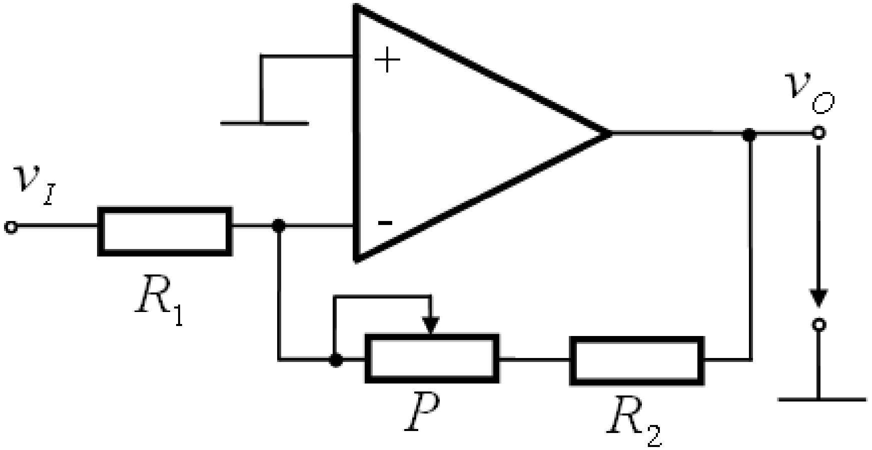


$$A_v = -\frac{R_2}{R_1} = -\frac{100}{10} = -10$$

$$R_i = R_1 = 10\text{k}\Omega; \qquad R_o = 0$$

Design example

Design an inverting amplifier with $R_i > 8K$ and $|A_v|$ adjustable in the range of [10,18]



$$|A_v|_{min} = \frac{R_2}{R_1} = 10 \qquad |A_v|_{max} = \frac{R_2 + P}{R_1} = 18$$

$$R_2 = 10 R_1 \qquad R_2 + P = 18 R_1$$

Solution 1

From R_i requirement: $R_i = R_1 \geq 8\text{k}\Omega$ **Choose** $R_1 = 10\text{k}\Omega$

$$R_2 = 10 \cdot 10 = 100\text{k}\Omega \qquad P = 18 \cdot 10 - 100 = 80\text{k}\Omega$$

No potentiometer is manufactured with this value, they are available only for a few discrete values, with decimal multiples and submultiples (1, 2.2, 2.5, 4.7, 5)

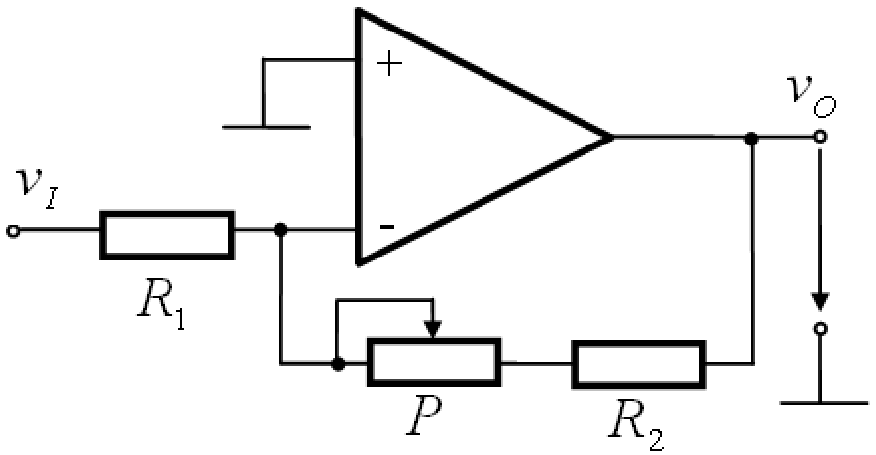
We must use P =100 k. Keeping R_2=100 K, it results:

$$R_1 = \frac{R_2 + P}{18} = \frac{100 + 100}{18} = 11{,}1\text{k}\Omega \qquad R_2 = 100\text{k}\Omega \qquad P = 100\text{k}\Omega$$

Verification: $|A_v|_{min} = 9.1$ $|A_v|_{max} = 18$ Acceptable ?

Design example (cont.)

Solution 2



$$|A_v|_{\min} = \frac{R_2}{R_1} = 10 \qquad |A_v|_{\max} = \frac{R_2 + P}{R_1} = 18$$

$$R_2 = 10R_1 \qquad R_2 + P = 18R_1$$

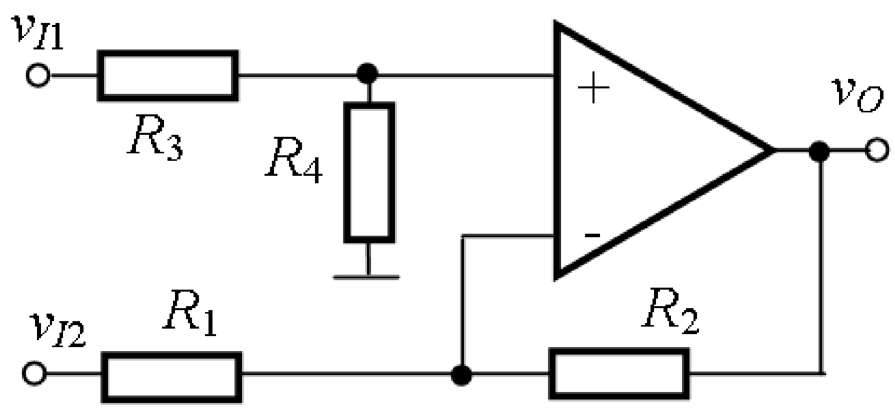
Select $P = 100\,\text{k}$

$$\begin{cases} R_2 = 10R_1 \\ R_2 + 100\text{k} = 18R_1 \end{cases} \qquad \begin{cases} R_1 = 12.5\,\text{k} \\ R_2 = 125\,\text{k} \end{cases}$$

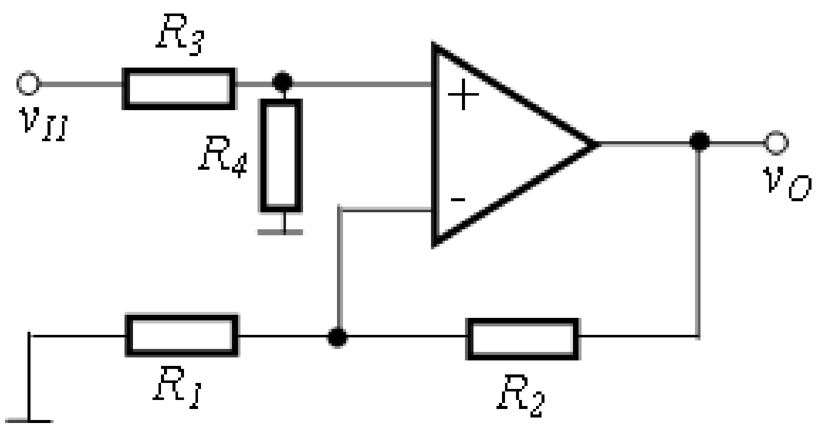
Verification: $|A_v|_{\min} = 10 \quad |A_v|_{\max} = 18 \quad R_i = R \;= 12{,}5\text{k}\Omega > 8\text{k}\Omega$

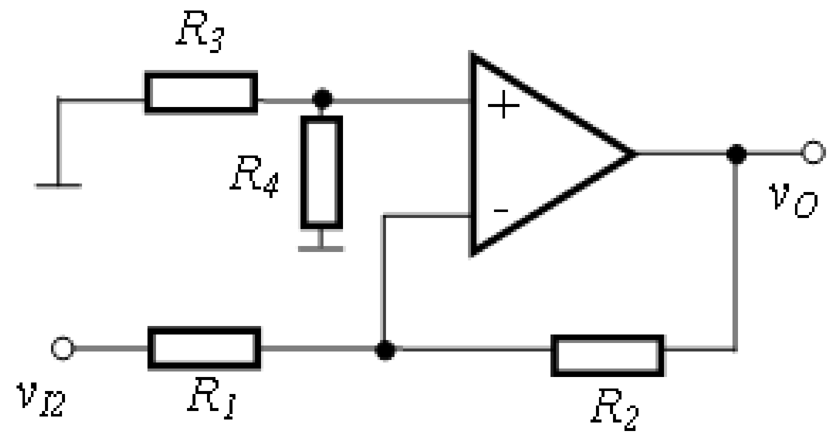
What if we select $P = 10\,\text{k}$?

Differential amplifier



Superposition method

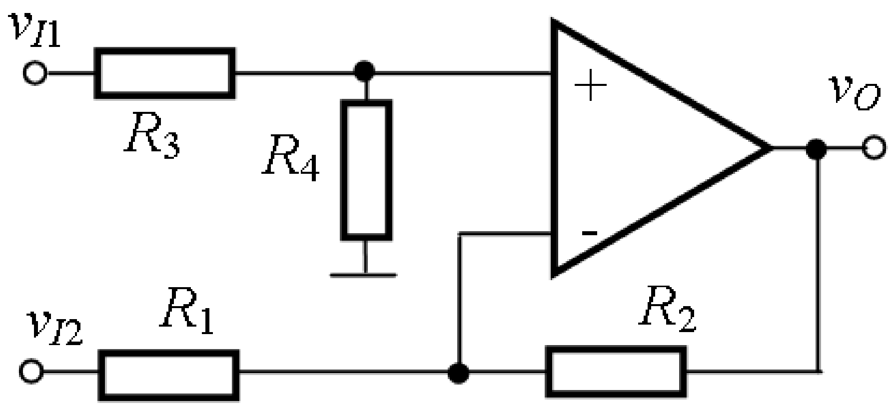




$$v_{O1} = \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)v_{I1}$$

$$v_{O2} = -\frac{R_2}{R_1}v_{I2}$$

$$v_O = v_{O1} + v_{O2} = \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)v_{I1} - \frac{R_2}{R_1}v_{I2}$$



$$v_O = \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)v_{I1} - \frac{R_2}{R_1}v_{I2}$$

$$v_O = A_d\left(v_{I1} - v_{I2}\right)\,?$$

$$\frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right) = \frac{R_2}{R_1} = A_d$$

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

$$v_O = \frac{R_2}{R_1}\left(v_{I1} - v_{I2}\right)$$

for $v_{I1}=v_{I2}$ results $v_O=0$,

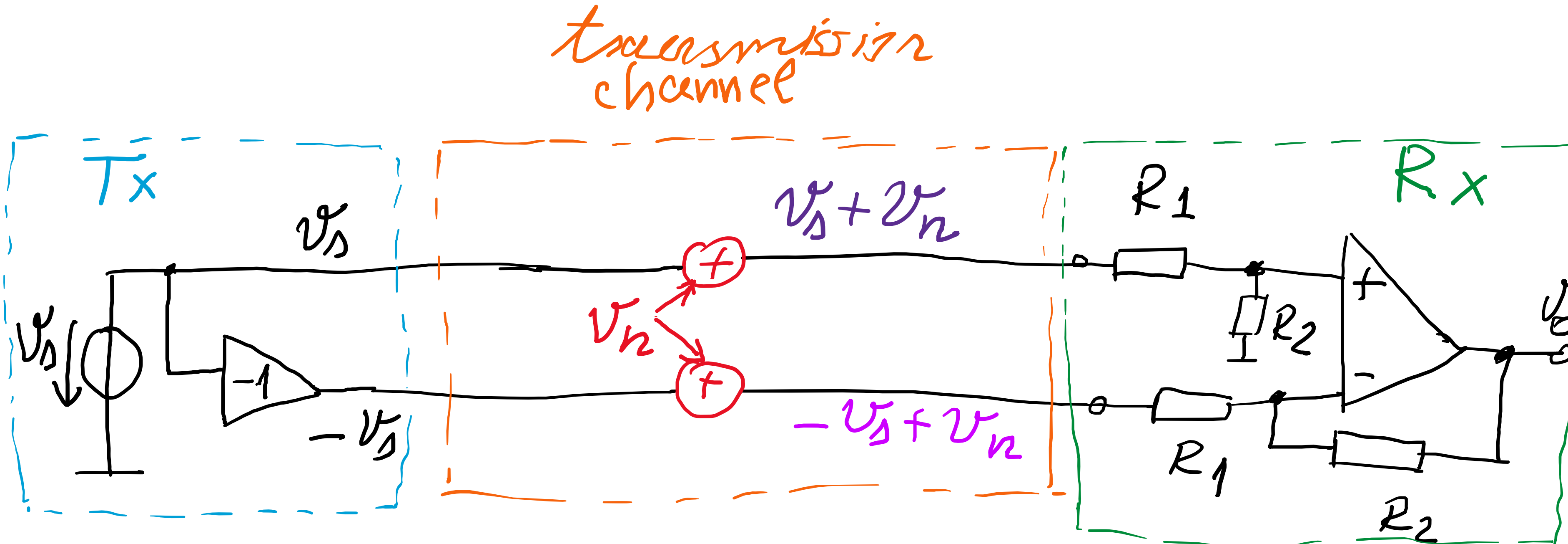
The circuit **amplifies only the difference** of the voltages and **rejects de common mode** signals.

in practical situations: $R_1=R_3$ and $R_2=R_4$.

Utilization of the differential amplifier

Noise suppression for:

- Signal measurements
- Biomedical signal measurements
- Data transmission



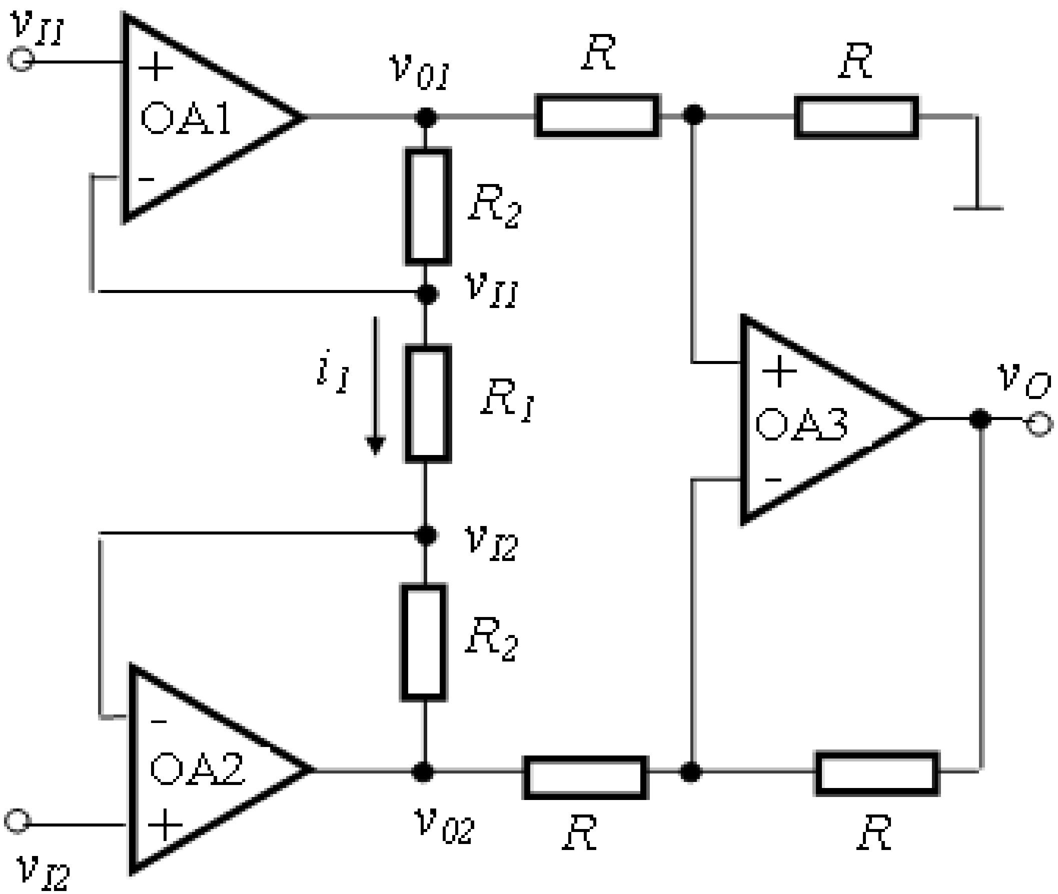
$$v_o = \frac{R_2}{R_1}\left[(v_s + v_n) - (-v_s + v_n)\right] = \frac{R_2}{R_1}(v_s + v_n + v_s - v_n)$$

$$v_o = 2\frac{R_2}{R_1} v_s$$ no noise!!

Standard instrumentation amplifier

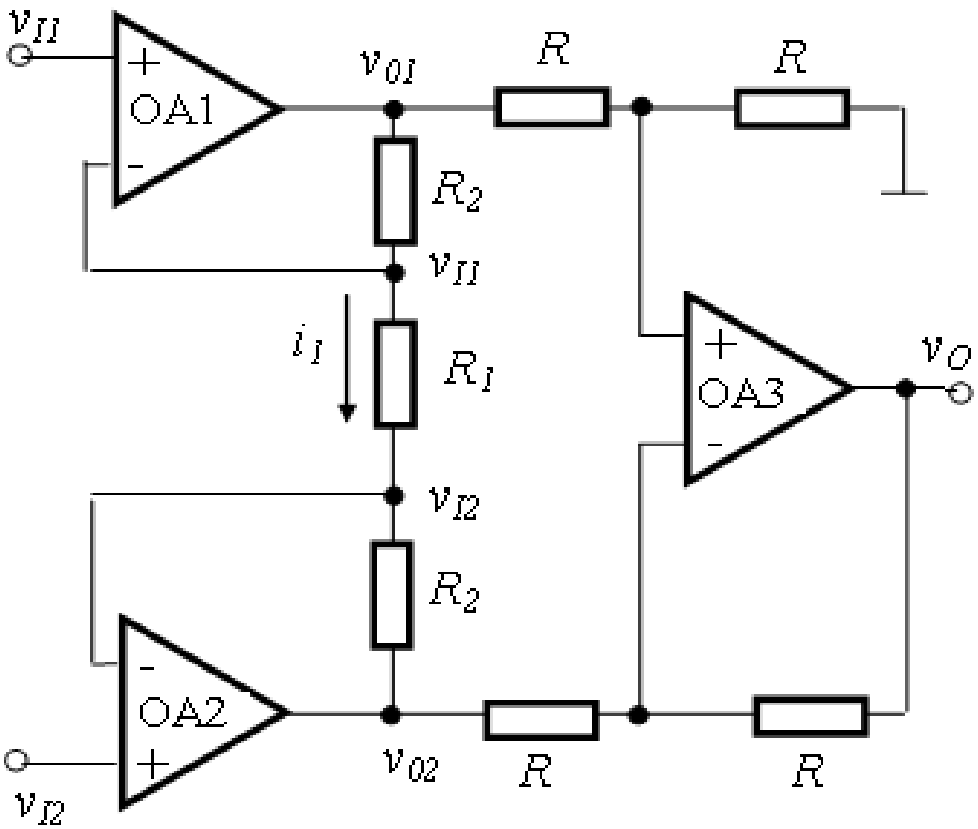
OPTIONAL

- high input resistance
- as good as possible common mode rejection



OA1 and OA2:
high input resistance
assures the gain,

OA3:
gain=1
Conversion from two voltages v_{O1} and v_{O2} to a single voltage v_O.
Supplementary rejection of the common mode



OPTIONAL

Superposition method:

$$v_{O1} = \left(1 + \frac{R_2}{R_1}\right) v_{I1} - \frac{R_2}{R_1} v_{I2}$$

$$v_{O2} = \left(1 + \frac{R_2}{R_1}\right) v_{I2} - \frac{R_2}{R_1} v_{I1}$$

$$v_O = \frac{R}{R}\left(v_{O1} - v_{O2}\right)$$

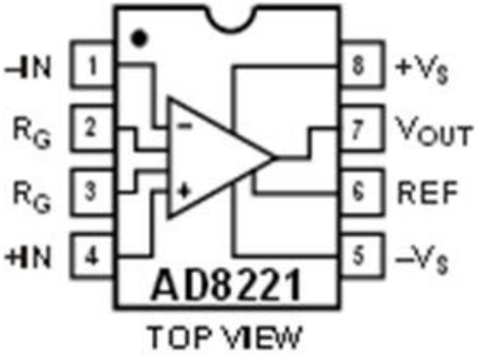
$$v_O = \left(1 + \frac{2R_2}{R_1}\right)\left(v_{I1} - v_{I2}\right)$$

Integrated precision differential amplifiers

- **AD8221** *Analog Devices*

Precision Instrumentation Amplifier

$$A_v = 1 + (49.4\ k\Omega/R_G)$$



https://www.analog.com/media/en/technical-documentation/data-sheets/AD8221.pdf

- **MAX4194**, **MAX4195**, **MAX4196**, **MAX4197**

Micropower, Single-Supply, Rail-to-Rail, Precision Instrumentation Amplifiers *Maxim Integrated*

- **LT1167** *Linear Technology*

Exercise

Assume suitable values for v_{I1}, v_{I2} to have the op-amp in the active region.

a) What is the application of the circuit?

b) What is the expression $v_O(v_{I1}, v_{I2})$?

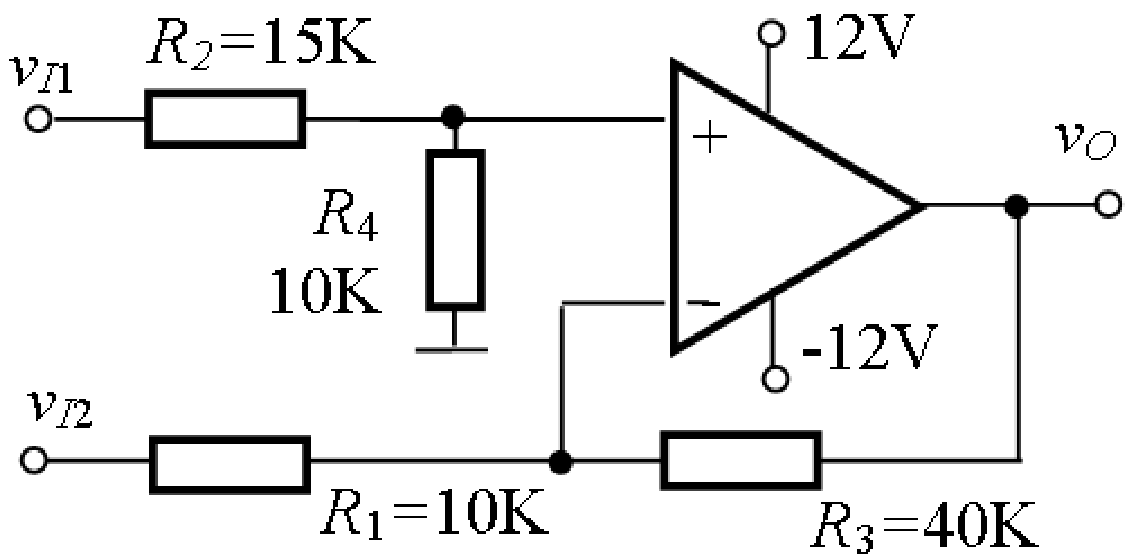
c) What is the input resistance seen by v_{I1}?

d) What should be the relationship between resistances to obtain:

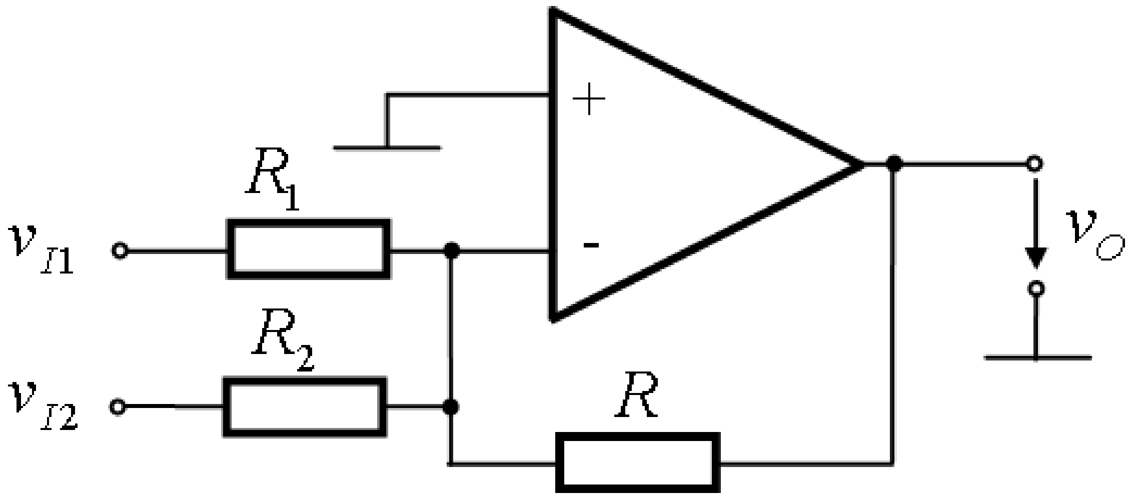
$v_O = 5(v_{I1} - v_{I2})$?

e) Plot $v_{I1}(t)$, $v_{I2}(t)$ and $v_O(t)$ if $v_{I1}(t) = 0.5\sin\omega t$ [V] + v_{noise}

$v_{I2}(t) = -0.5\sin\omega t$ [V] + v_{noise}



Inverting summing amplifier



$$v_O = ?$$

$$v_O = -\left(\frac{R}{R_1} v_{I1} + \frac{R}{R_2} v_{I2}\right)$$

$$R_1 = R_2 = 2R$$

Average of input voltages

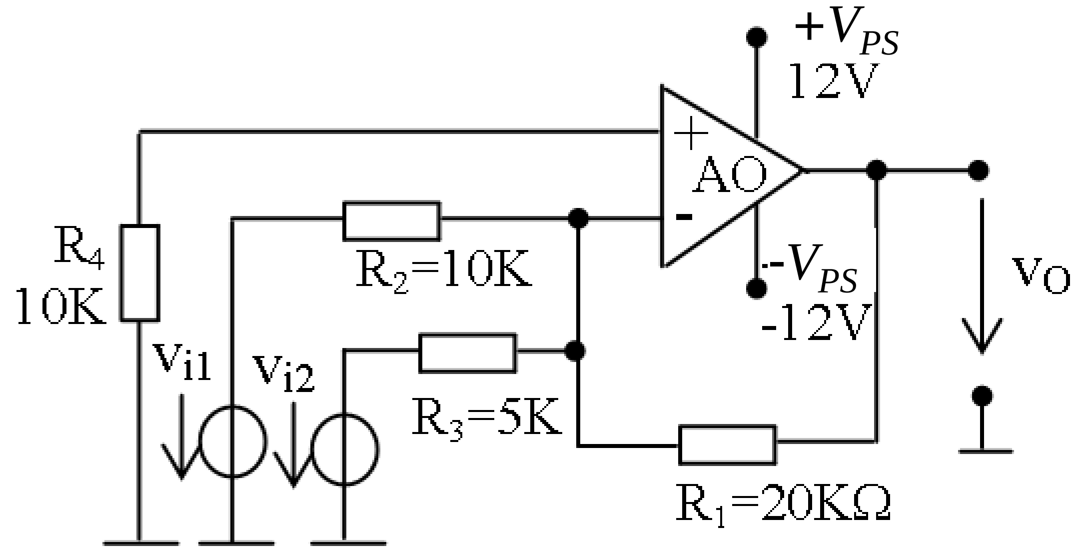
Exercise

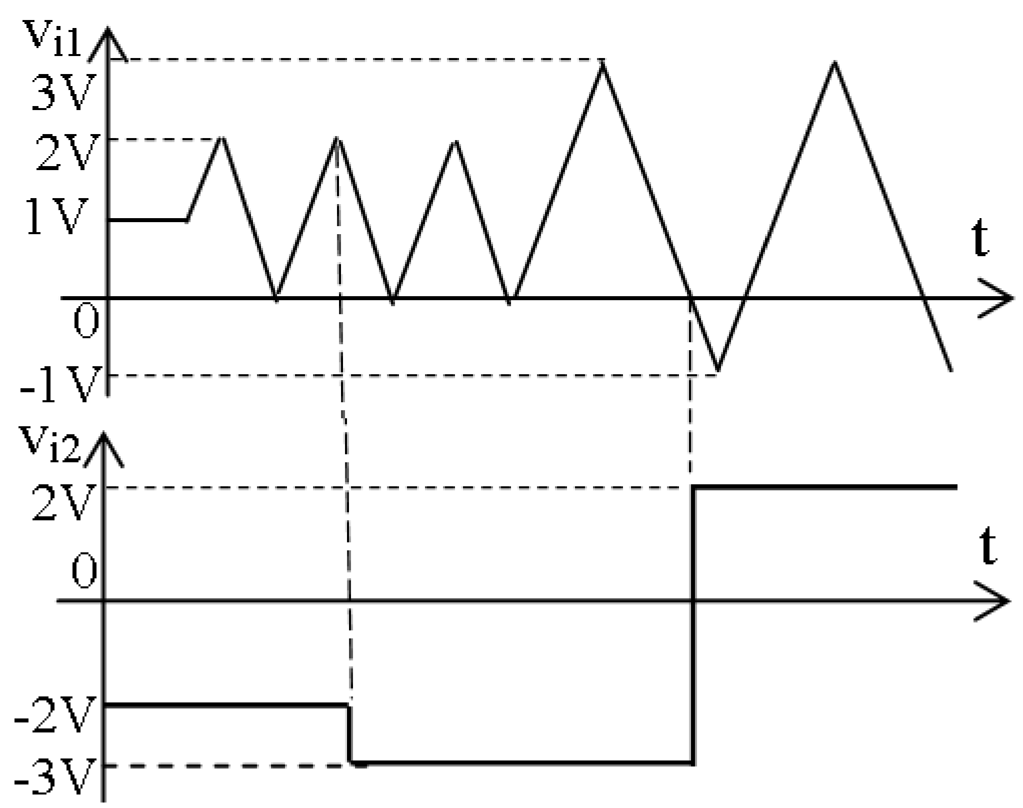
a) $v_O(v_{i1}, v_{i2})$ assuming op amp in the active region. What is the application of the circuit?

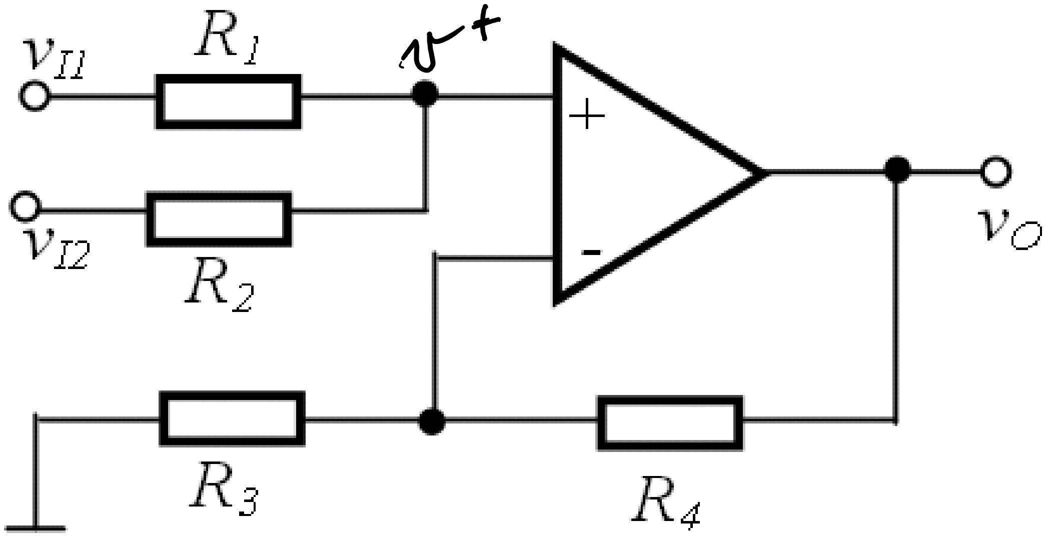
b) Considering v_{i1}=2V, how does the VTC $v_O(v_{i2})$ look like for $v_{i2} \in$[-5V; 5V]? In this situation what is the v_{i2} range to maintain the amplifier in its active region?

c) For the resistances in figure how does $v_O(t)$ look like for the input voltages in the figure?

d) Size R_1, R_2, R_3, R_4 so that the output will be v_O= -(v_{i1}+ v_{i2}). How can the circuit be modified to obtain a noninverting summing circuit v_O= v_{i1}+ v_{i2}?







Non-inverting summing amplifier

$$v_O = \left(1 + \frac{R_4}{R_3}\right)\underbrace{\left(\frac{R_2}{R_1 + R_2} v_{I1} + \frac{R_1}{R_1 + R_2} v_{I2}\right)}_{v^+}$$

weighted average

Relationship between resistors to have $v_O = v_{I1} + v_{I2}$?

$$R_1 = R_2 \quad \text{and} \quad R_3 = R_4$$

Usually $R_1 = R_2 = R_3 = R_4$