ELECTRONIC DEVICES

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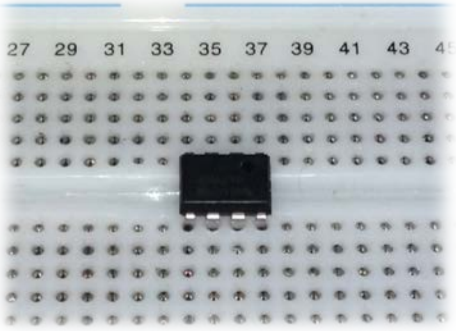
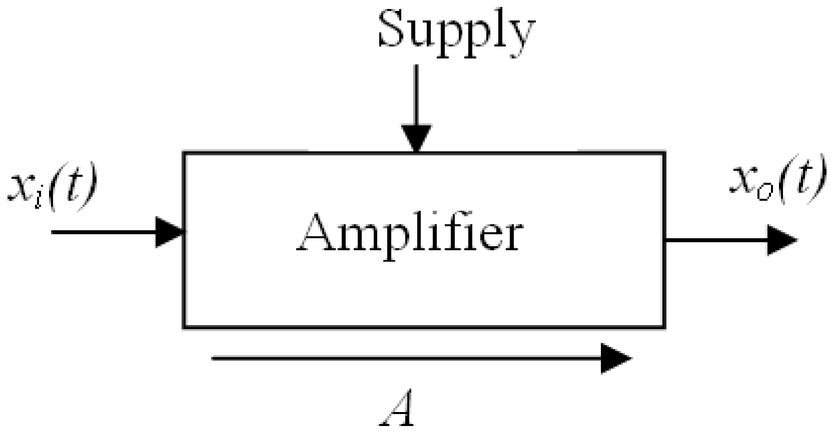
C8 – Electronic amplifiers. Amplifiers with OpAmp.



Contents

Electronic amplifiers

Amplifier = active three-port network that delivers an output signal $x_o(t)$ (voltage or current) with the same shape as the input signal $x_i(t)$ and can provide more power, on an adequate load.



$$x_o(t) = Ax_i(t)$$

A – amplification, gain

A<0 inverting

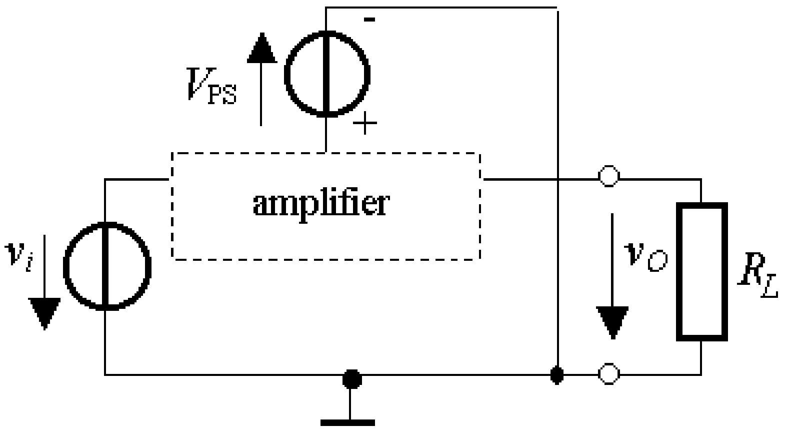
A>0 non-inverting

Linear circuit: x_0 proportional with x_i

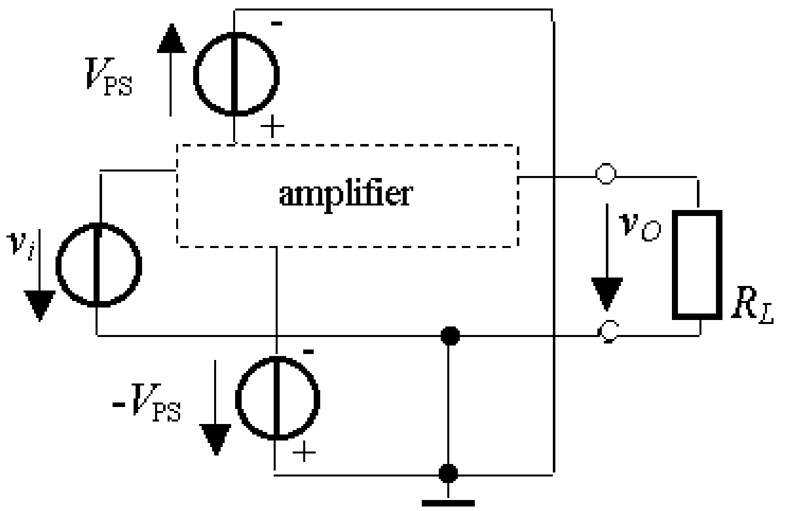
➢ Types of supply

The supply is provided by dc voltage and/or current sources. Voltage sources are most commonly used.

Single source supply



Two source supply (symmetric differential)

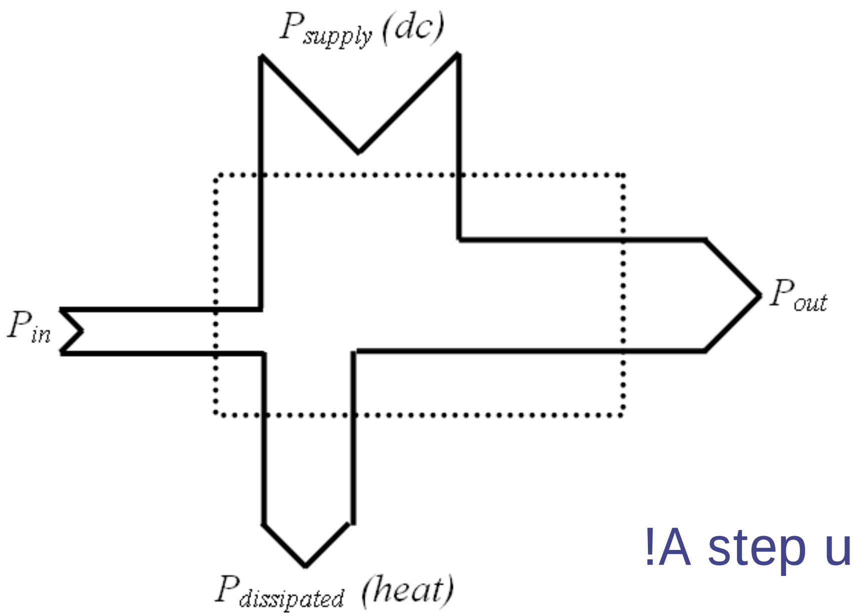


➢ Power transfer and power balance

The average power of the output signal is greater than the average power of the input signal:

$$P_{out} > P_{in}$$

The excess of the output power is taken from the supply sources.



$$P_{supply} + P_{in} = P_{out} + P_{dissip}$$

$$P_{supply} \approx P_{out} + P_{dissip}$$

Efficiency: $\eta = P_{out}/P_{supply}$

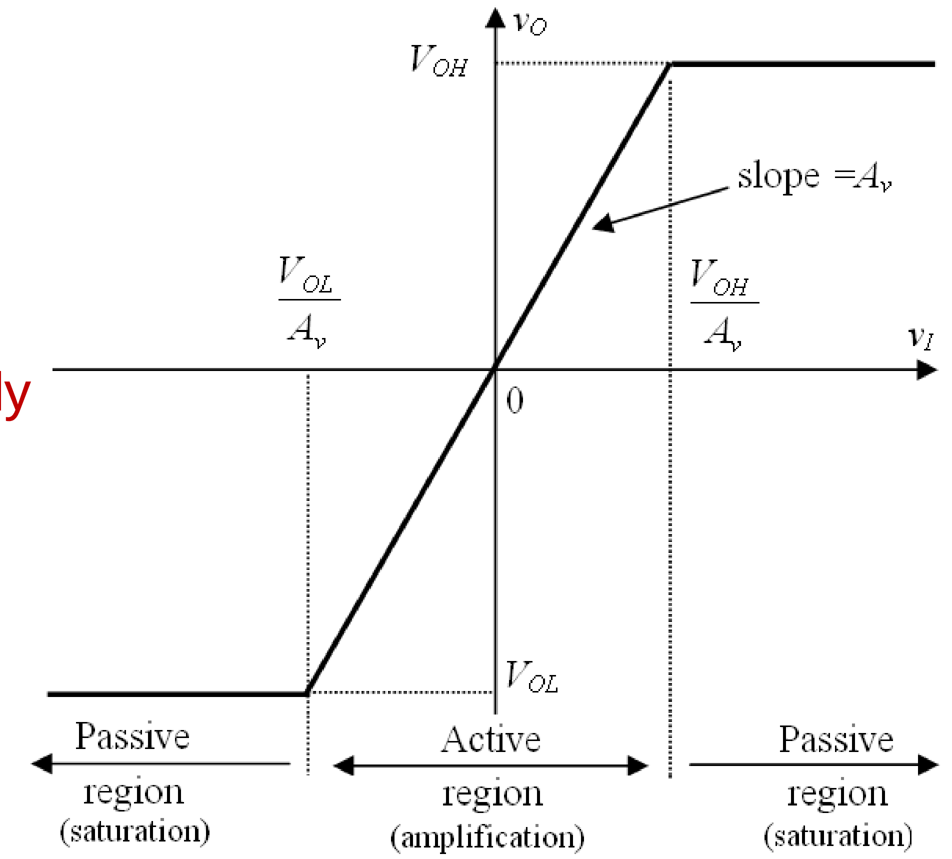
!A step up transformer **is not** an amplifier!

Types of amplifiers

Based on the types of input/output signals (voltage/current):

- voltage amplifier $A_v = v_o/v_I$ - dimensionless
- current amplifier $A_i = i_o/i_I$ - dimensionless
- transconductance amplifier $A_{i/v} = i_o/v_I$ – [S], [mS]
- transresistance amplifier $A_{v/i} = v_o/i_I$ – [Ω], [kΩ]

Electronic amplifiers



➢ VTC

voltage-to-voltage, non-inverting amplifier, symmetric differential supply

- amplification (active) region:

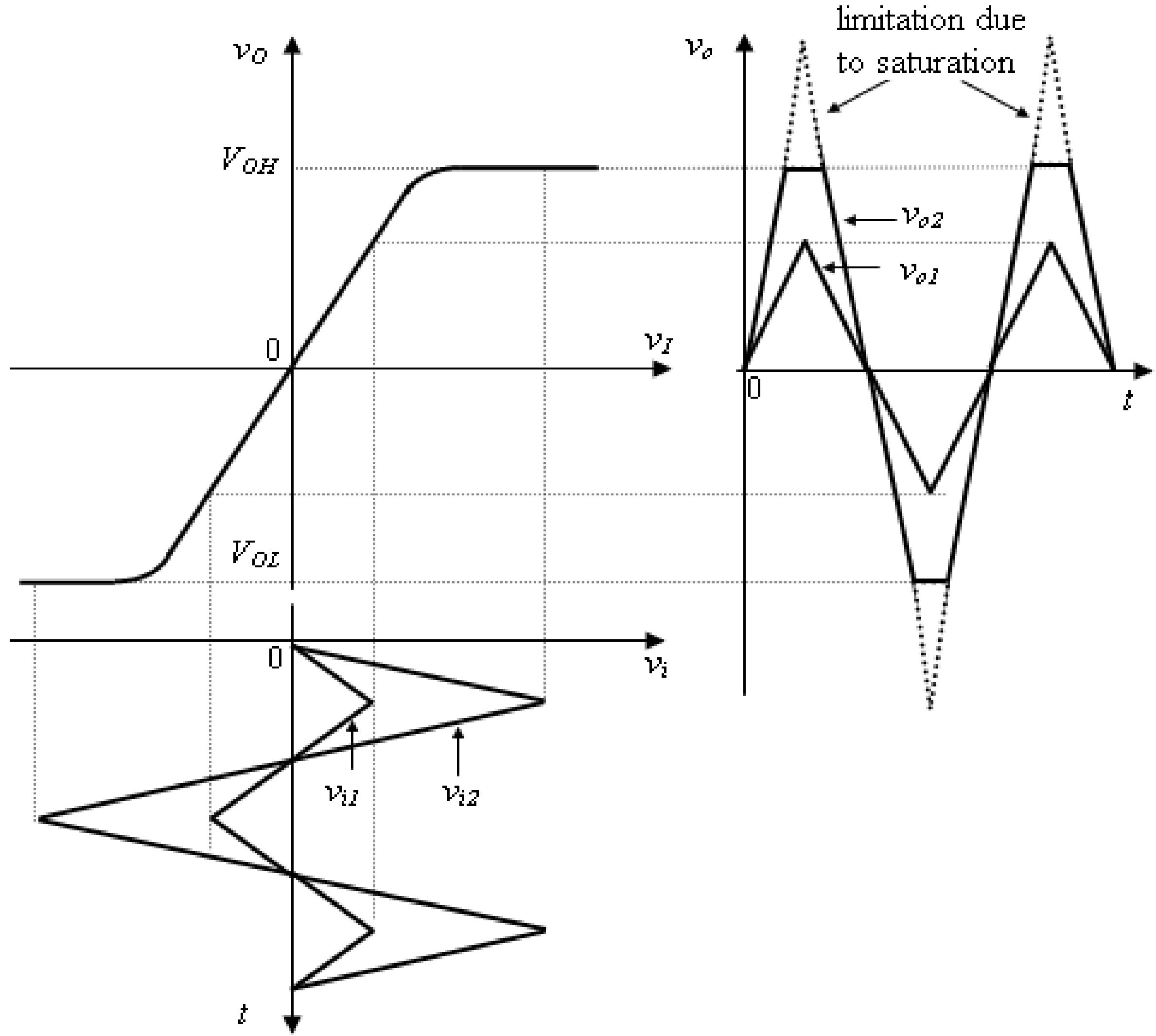
$$v_I \in \left(\frac{V_{OL}}{A_v}; \frac{V_{OH}}{A_v} \right);$$
$$v_O \in (V_{OL}; V_{OH})$$

- ideal amplifier: $V_{OL} = -V_{PS}$; $V_{OH} = +V_{PS}$
- general-purpose OpAamp $v_O \in (-V_{PS} + 1V...2V; +V_{PS} - 1V...2V)$
- rail-to-rail OpAmp: $v_O \in (-V_{PS}; +V_{PS})$

Electronic amplifiers

- ➤ VTC

Signal transfer



Note: if the input signal is low enough for the amplifier to work in a linear region around the OP: **small signal approximation**

Modeling the voltage amplifier

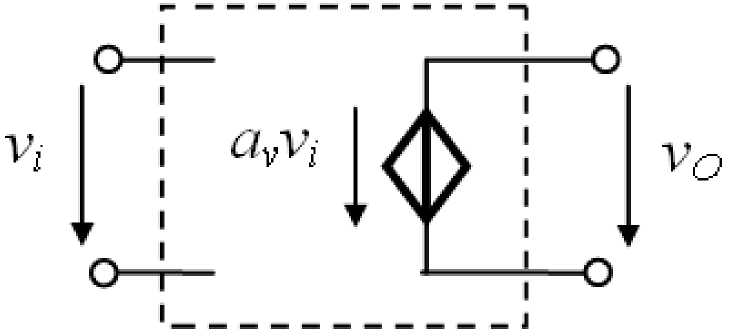
- two-port networks: only the behavior of the input and output ports is explicitly taken into account, and the input-output signal transfer
- valid regardless of the internal complexity of the amplifiers
- valid in the bandpass frequency domain

Linear controlled sources

- active two-port network
- only one finite, non-zero parameter: forward transfer parameter (gain)
- the output signal is controlled by the input signal
- pseudo-sources

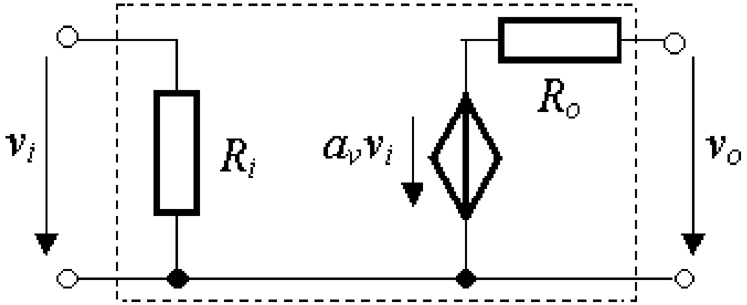
VCVS (voltage controlled voltage source)

$$v_O = a_v v_i$$



Modeling the voltage amplifier

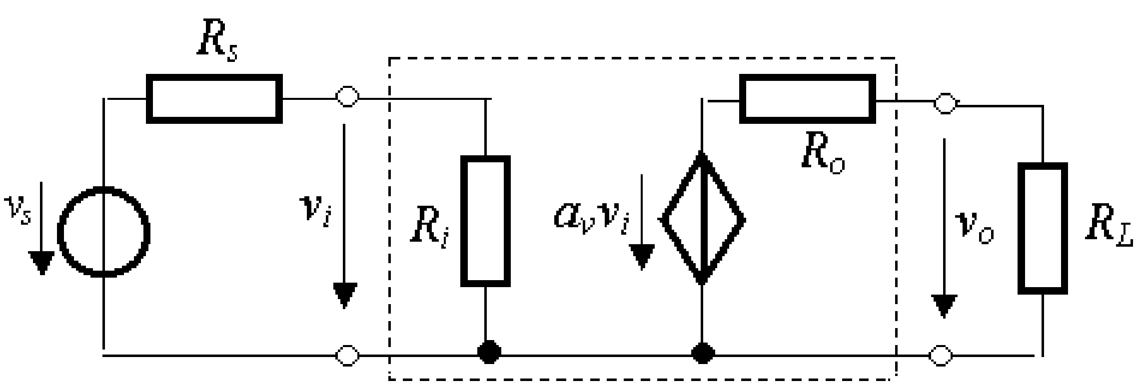
Amplifier model



$$a_v = \frac{v_o}{v_i}$$

a_v – open circuit gain
R_i – draws current from v_i
R_o – deteriorates v_o in the presence of load

Amplifier model connected in a circuit

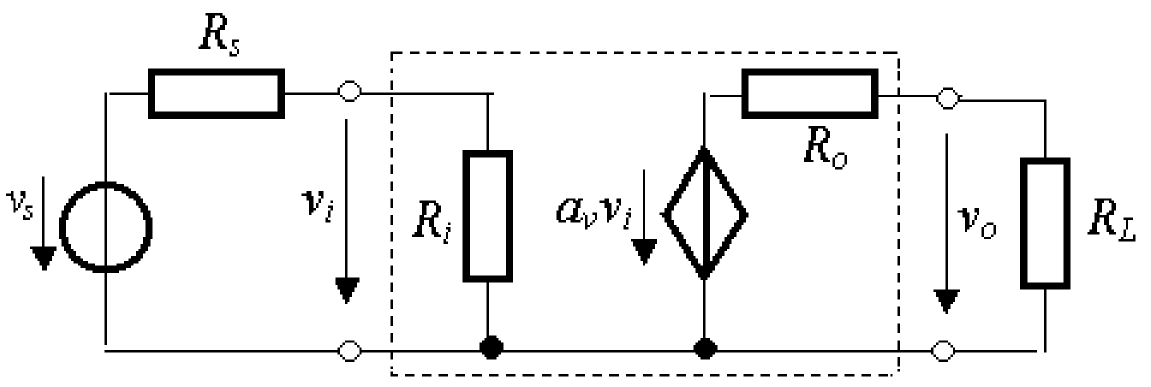


$$A_v = \frac{v_o}{v_s}$$

$$A_v = \frac{R_i}{R_s + R_i} \frac{R_L}{R_L + R_o} a_v$$

Ideal amplifier?

➢ Modeling the voltage amplifier



$$A_v = \frac{v_o}{v_s}$$

$$A_v = \frac{R_i}{R_s + R_i} \frac{R_L}{R_L + R_o} a_v$$

A_v is closer to the open circuit gain a_v when the voltage losses at the input (across R_s) and at the output (across R_o) are reduced.

- $R_i >> R_s$ – the source voltage is transferred to the input $v_i \approx v_s$
- $R_o << R_L$ - the voltage of the VCVS is transferred to the output $v_o \approx a_v v_i$

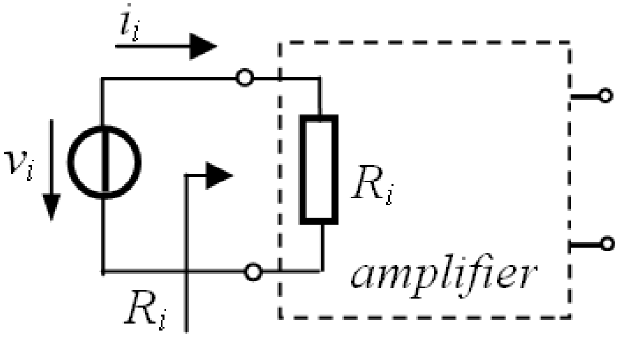
Ideal voltage amplifier: $\mathbf{R_i = \infty; R_o = 0}$

Amplifier performances

- Gain (forward transfer factor)
  - Analyze the circuit, by using circuit theorems and equation (Kirchhoff, Ohm, Millman)
  - Express the output signal as a function of the input signal, then compute the gain

- Input resistance

$$R_i = \frac{v_i}{i_i}$$

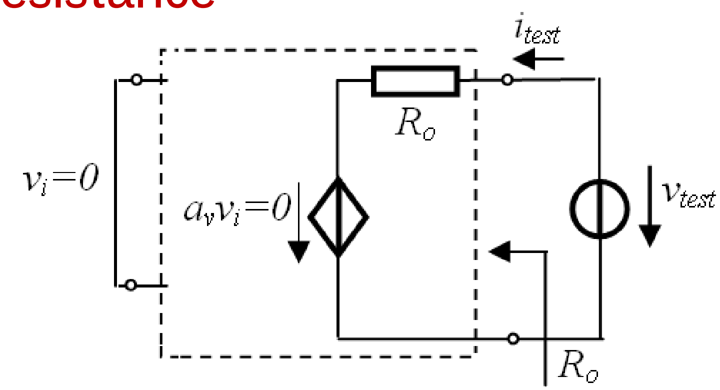


Amplifier performances

- Output resistance

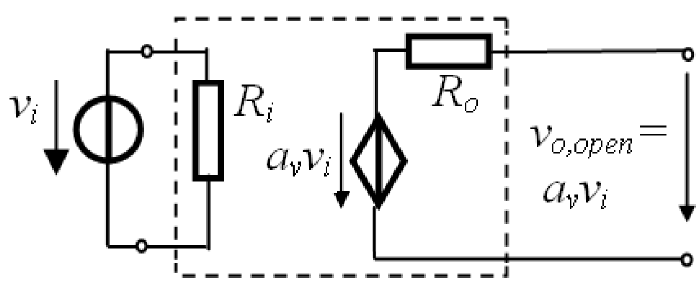
- Set the input signal source to zero
- Connect a test source at the output

1

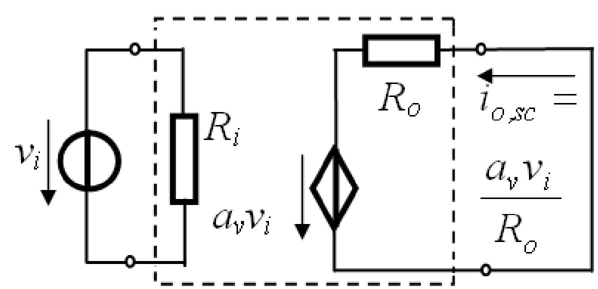


$$R_o = \frac{v_{test}}{i_{test}}$$

2



open circuit

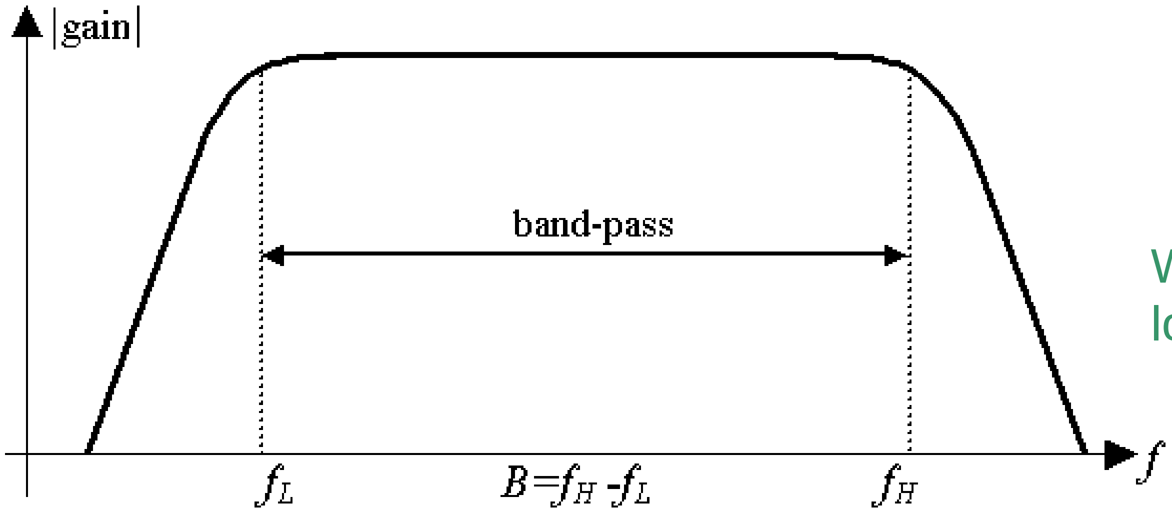


short-circuit

$$R_o = \frac{v_{o,open}}{i_{o,sc}}$$

➢ Frequency response

- analyze the equivalent model of the amplifier including capacitive components too, by means of their complex impedances: 1/jωC
- complex transfer function for the gain: $A(j\omega) = \frac{v_o(j\omega)}{v_i(j\omega)}$
- input and output impedances are now complex $Z_i(j\omega)$ $Z_o(j\omega)$

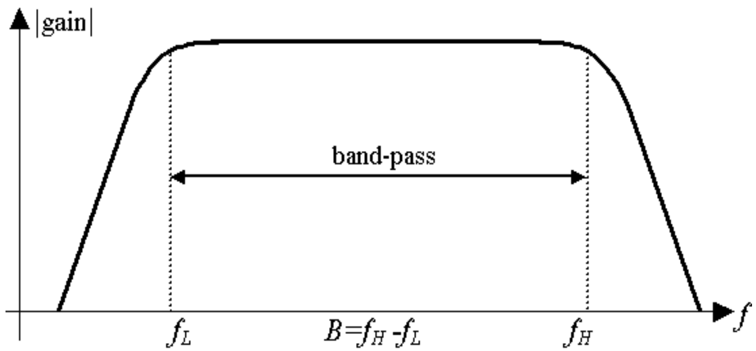


Band-pass amplifier

Why does the gain decrease at low/high frequencies?

Electronic amplifiers

➢ Frequency response

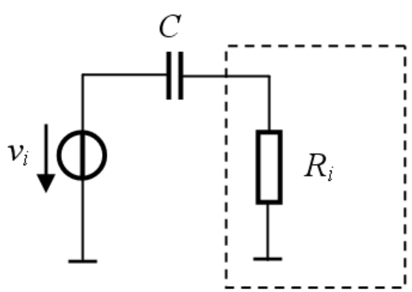


internal capacitances (parasitic) of active devices

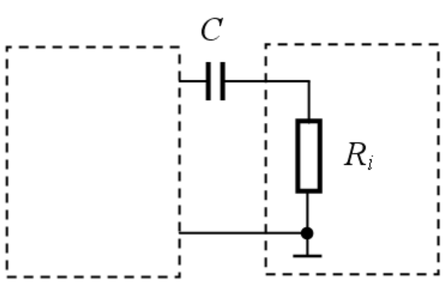
=> Av ↘ @ f ↗

coupling/decoupling capacitors (tens of µF)

=> Av ↘ @ f ↘ (zero dc gain)

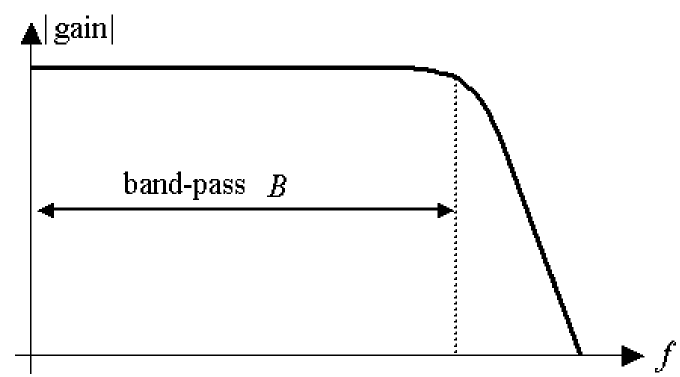


capacitive coupling at input

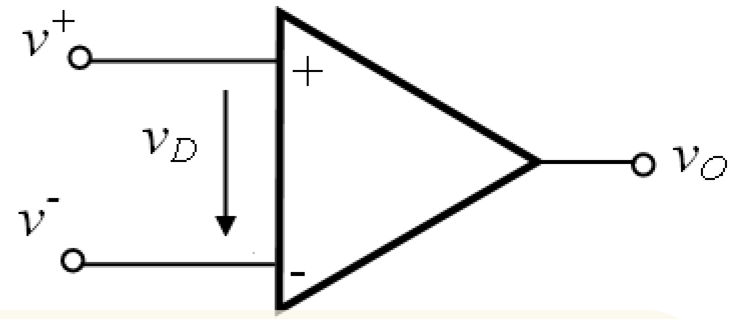


capacitive coupling of two amplifier stages

Direct coupling amplifier (LPF)



Amplifiers with OpAmp



$$v_O = av_D = \infty \cdot v_D$$

I. Utilization as comparator, in switching mode

C6 + C7

$$v_O \in \{V_{OL} ; V_{OH}\}$$

$v_D > 0$, $v_O \rightarrow +\infty$, v_O limited by the positive supply $v_O = V_{OH} \approx +V_{PS}$

$v_D < 0$, $v_O \rightarrow -\infty$, v_O limited by the negative supply $v_O = V_{OL} \approx -V_{PS}$

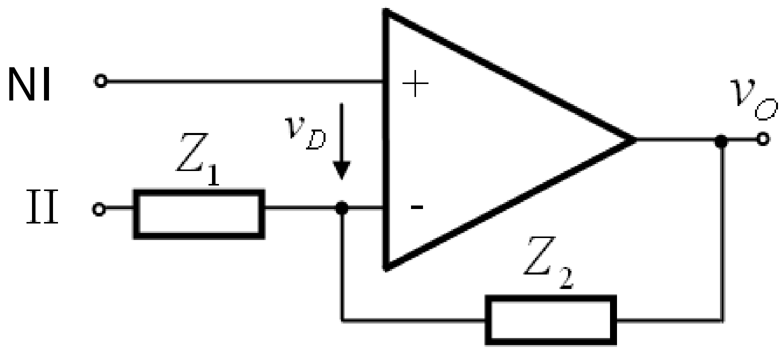
II. Utilization as amplifier

$$v_O \in (V_{OL} ; V_{OH})$$

It is mandatory that $v_D = 0$, so then $v_O = a \cdot v_D = \infty \cdot 0$ - indetermination

v_D is kept at 0 by means of external components (R) arranged in a negative feedback **(NF)** configuration

Amplifiers with OpAmp



$v_O = av_D$

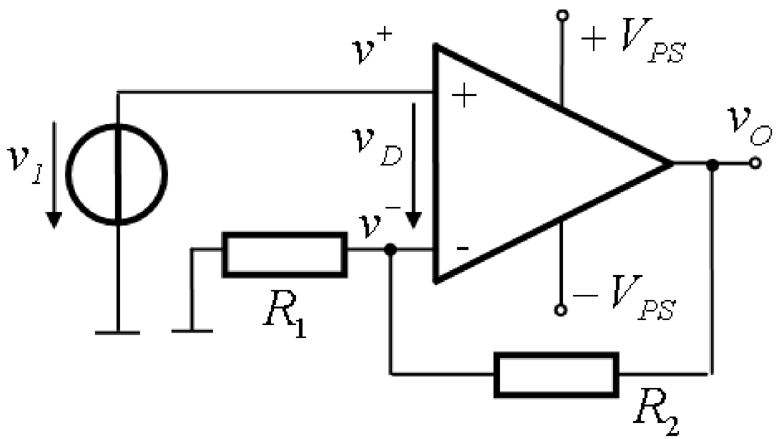
$v_D = 0$ $\quad$ $v_D \uparrow, v_O \uparrow, v^- \uparrow, v_D \downarrow$

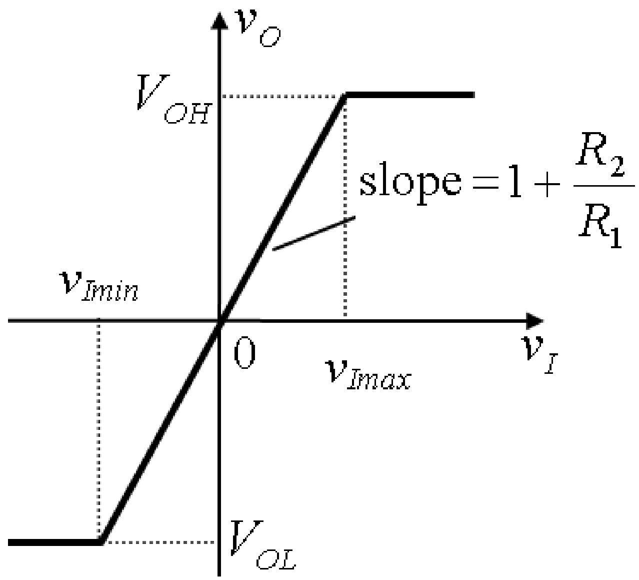
NF automatically keeps v_D at zero

NI	II	Amplifier
v_I	ground	non-inverting
ground	v_I	inverting
v_{I1}	v_{I2}	differential

Amplifiers with OpAmp

➢ Non-inverting amplifier





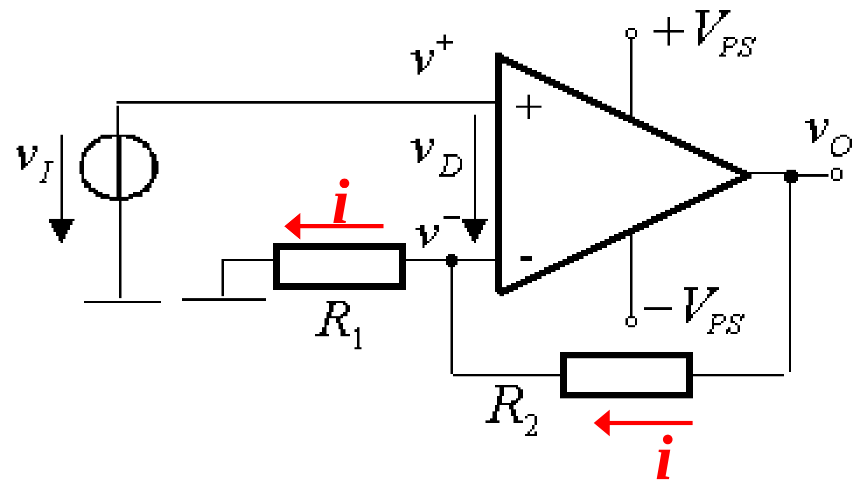
$$v^- = \frac{R_1}{R_1 + R_2} v_O$$

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

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

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

Amplifiers with OpAmp



➢ Non-inverting amplifier

Alternative method for computing A_v

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

The same current goes through R_1 and R_2

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

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

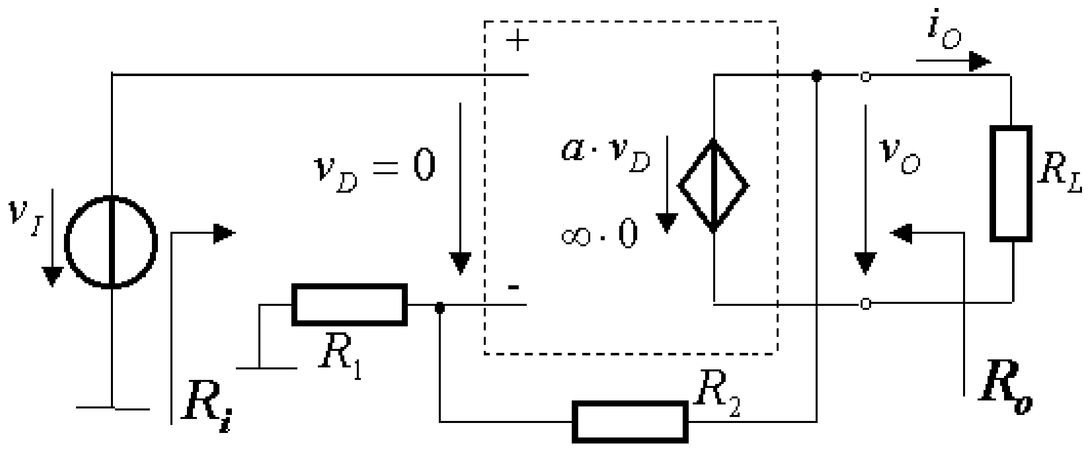
Direct consequences of NF for an OpAmp with very high intrinsic gain ($a \to \infty$ for ideal op-amp):

- gain is set only by the ratio of two resistors (external components)
- the gain value: precise and stable
- the gain is independent of the OpAmp, it is not influenced by the technological spread of the OpAmp's parameters

Amplifiers with OpAmp

➢ Non-inverting amplifier

Input and output resistances



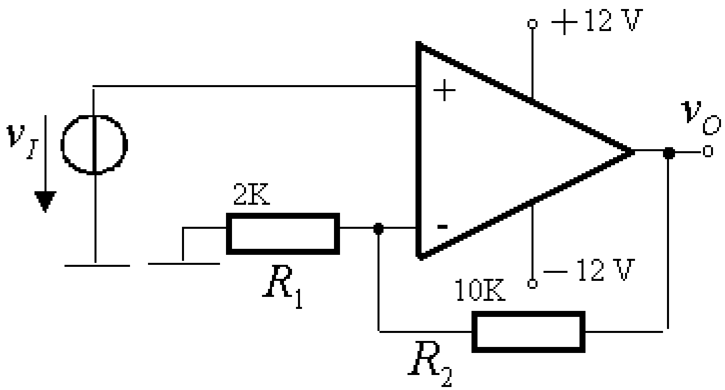
Computed on the equivalent model

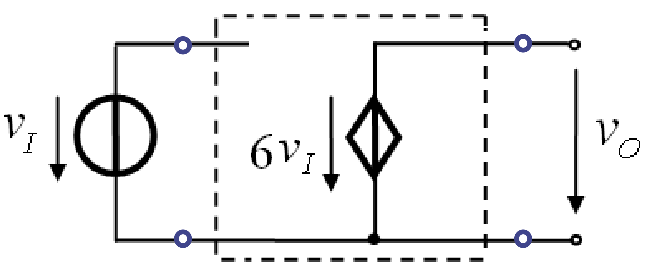
v_I sees an open circuit, so $\mathbf{R_i} = \infty$

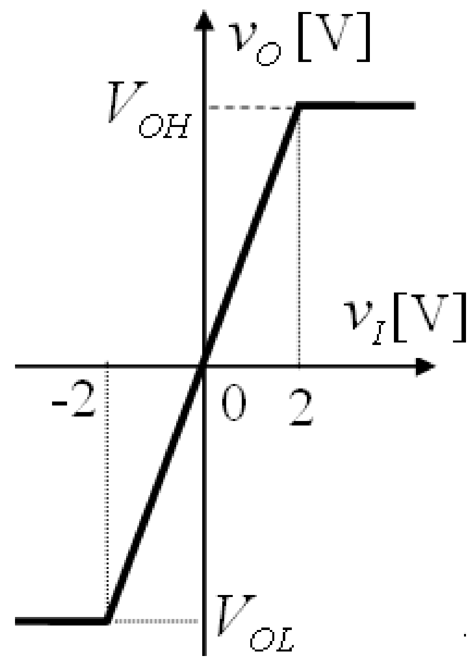
$$R_o = \frac{v_{O_{open}}}{i_{O_{sc}}} = \frac{v_{O_{open}}}{\infty} = 0$$

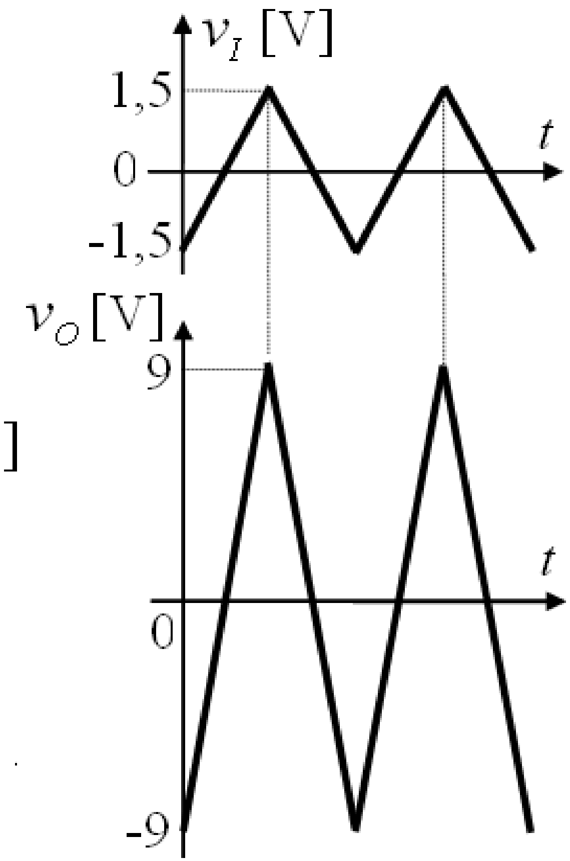
- Non-inverting amplifier

Example







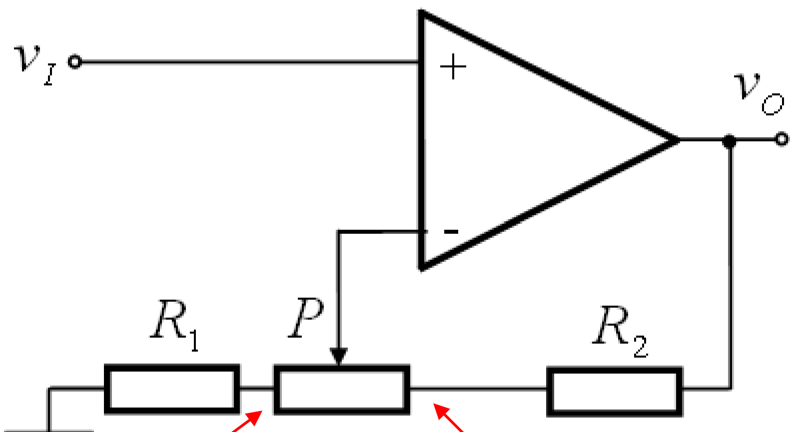


- $v_O(t)$ for triangular $v_I(t)$, 3 V amplitude, zero dc component

Amplifiers with OpAmp

➢ Non-inverting amplifier

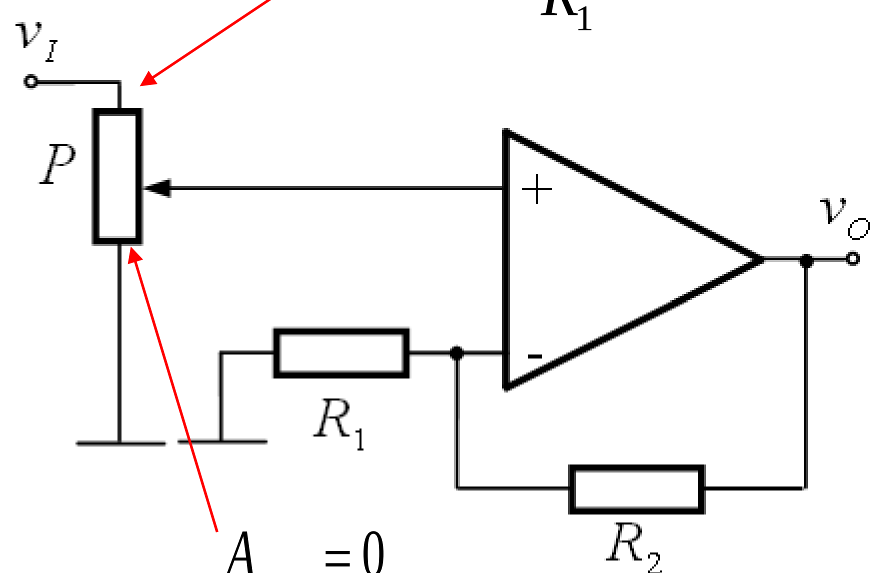
Adjustable gain



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

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

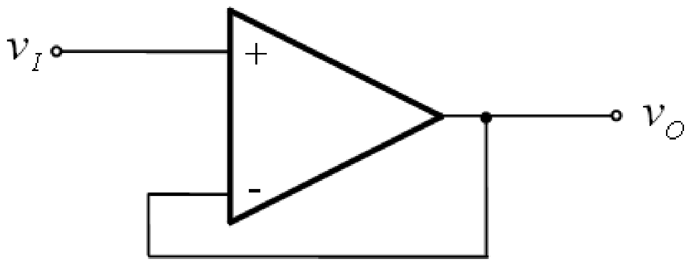
$$A_{v_{\max}} = 1 + \frac{R_2}{R_1}$$



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

➢ Non-inverting amplifier

Voltage follower



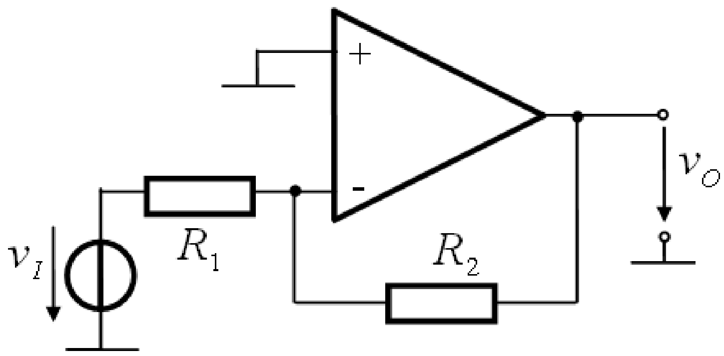
$$v_O = v_I$$

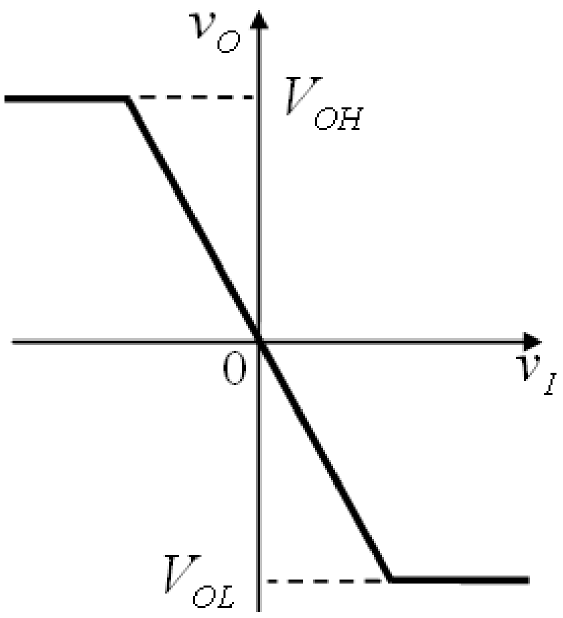
the output voltage follows the input voltage

- total (full) NF
- no voltage gain (A_v = 1)
- infinite current gain (A_i = ∞)

Voltage followers are used as a buffer stages between a source (or the output of a circuit) with high R_O (can only supply low current) to a low R_L (needs high current) – impedance matching.

➢ Inverting amplifier





$$v^+ = 0$$

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

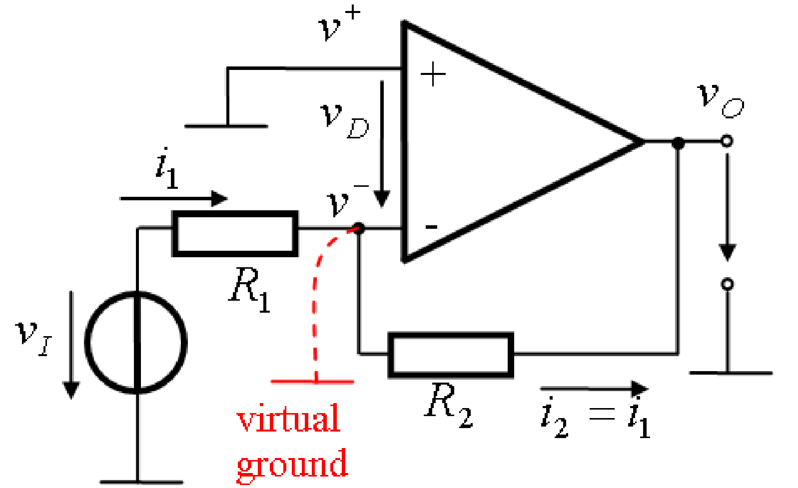
$$v_D = v^+ - v^- = 0 - \frac{R_2}{R_1 + R_2} v_I - \frac{R_1}{R_1 + R_2} v_O = 0$$

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

Amplifiers with OpAmp

➢ Inverting amplifier

Alternative method for computing A_v



NF => $v_D = 0$

$$v^+ = v^-$$
$$v^+ = 0$$

=> $v^- = 0$ virtual ground

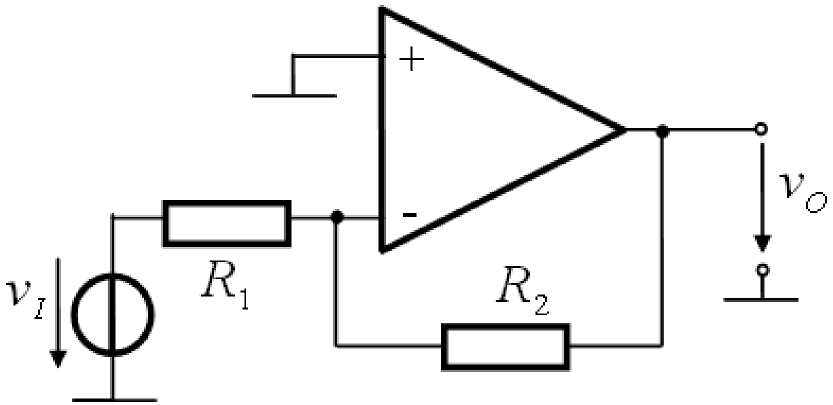
$$i_1 = i_2 \qquad i_1 = \frac{v_I - 0}{R_1} \qquad i_2 = \frac{0 - v_O}{R_2}$$

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

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

Inverting amplifier

Input and output resistances



The input source "sees" only R_1 (the inverting input is virtual ground)

$$R_i = R_1$$

$$R_o = 0$$

- Noninverting amplifier: $R_i \rightarrow \infty$
- Inverting amplifier: $R_i \rightarrow$ finite (units, tens of kΩ)

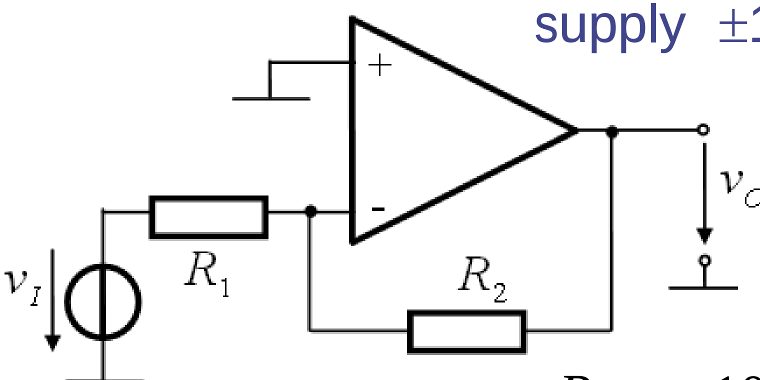
➢ Inverting amplifier

✓ R_i, R_o, A_v
✓ v_I range for active region
✓ equivalent model

Example

R_1 = 10 K, R_2 = 100K,

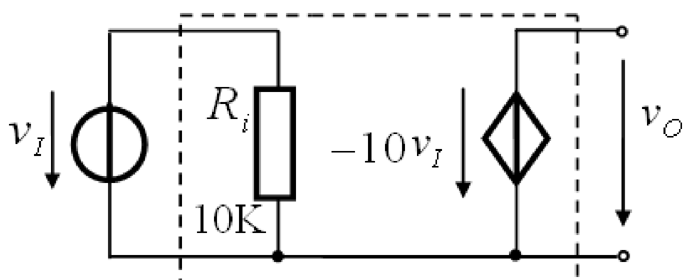
supply ±12 V

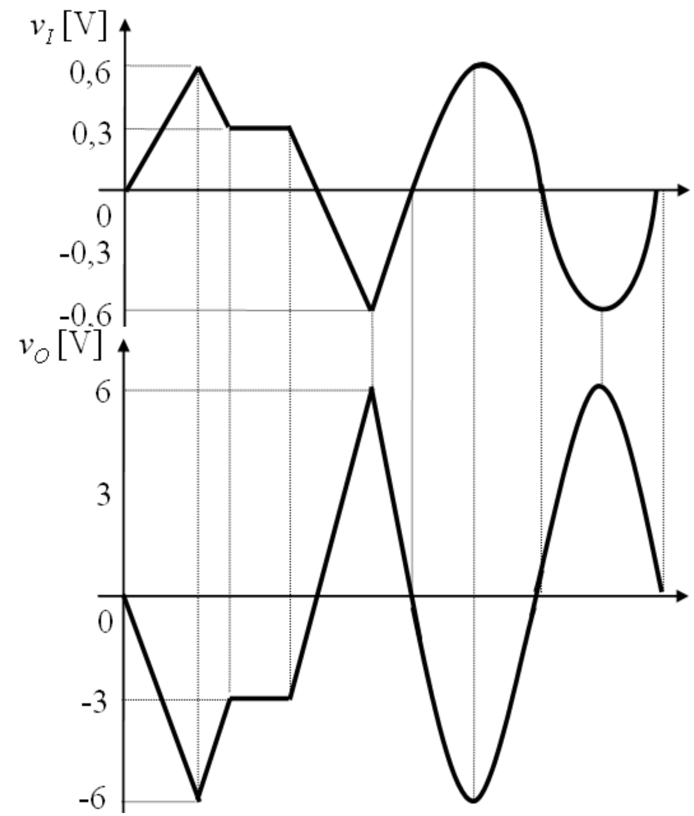


$$R_i = R_1 = 10\text{k} \qquad A_v = -\frac{R_2}{R_1} = -\frac{100}{10} = -10$$

$$R_o = 0$$

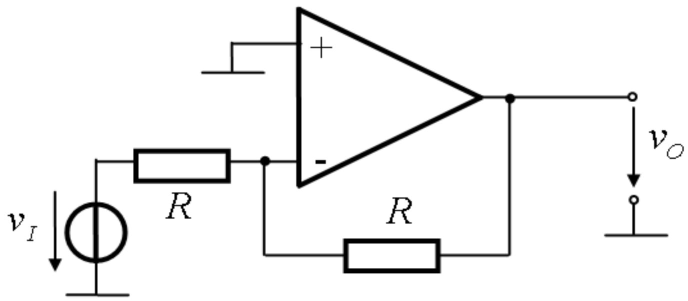
v_I range: $(-1.2\text{V}; +1.2\text{V})$





➢ Inverting amplifier

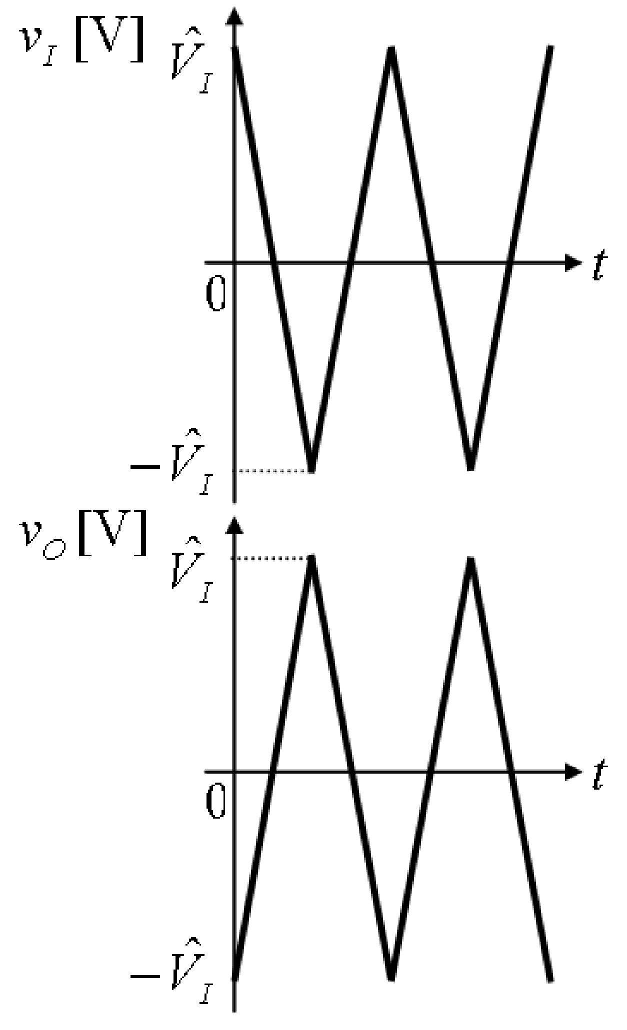
Voltage follower



$$v_O = -v_I$$

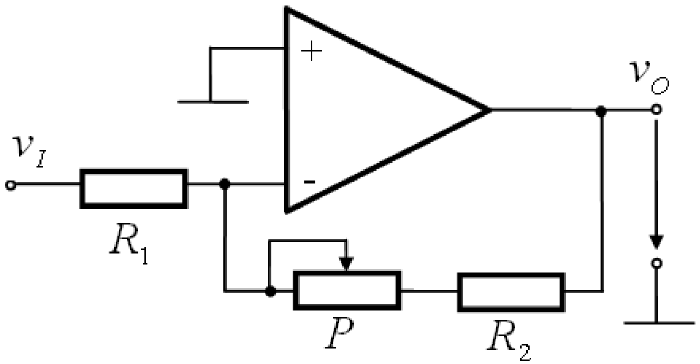
$$A_v = \frac{v_O}{v_I} = -1$$

$$R_i = R$$



➢ Design example

Design an inverting amplifier with $R_i > 8\ k\Omega$ and $|A_v|$ adjustable in the range [10, 18].



$$\left|A_v\right|_{\min} = \frac{R_2}{R_1} = 10$$

$$\left|A_v\right|_{\max} = \frac{R_2 + P}{R_1} = 18$$

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

What next?

➢ Design example

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

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

Solution 1

$R_i = R_1 \geq 8\text{k}\Omega$ Choose $R_1 = 10\text{k}\Omega$

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

$$R_2 = 10 \cdot 10 = 100\text{k}\Omega$$

P = 100 kΩ will be used. Keeping R_2 = 100 kΩ will result in:

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

R_2 = 100 kΩ P = 100kΩ

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

➢ Design example

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

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

Solution 2

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

$$\begin{cases} R_2 = 10R_1 \\ R_2 + 100\text{k} = 18R_1 \end{cases} \qquad \begin{cases} R_1 = 12.5\text{k}\Omega \\ R_2 = 125\text{k}\Omega \end{cases} \qquad R_i = R = 12{,}5\text{k}\Omega > 8\text{k}\Omega$$

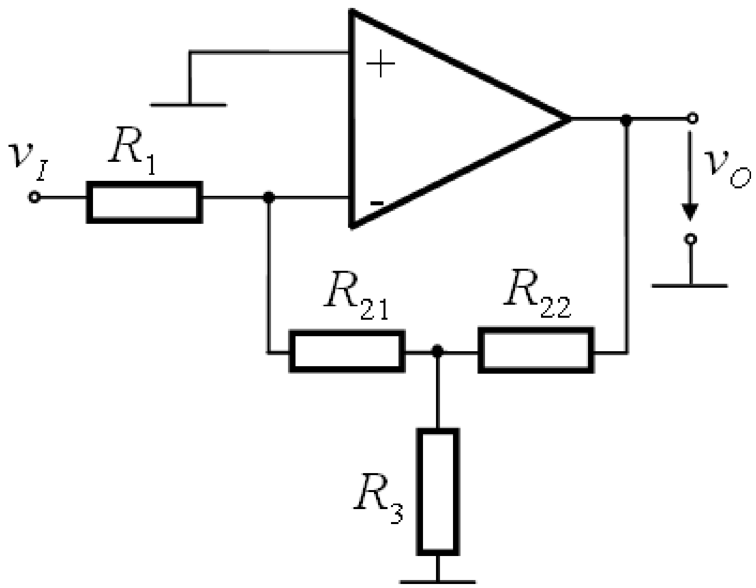
What if we began w/ P = 10kΩ?

Verification: $\left|A_v\right|_{\min} = 10 \qquad \left|A_v\right|_{\max} = 18$

OPTIONAL

➢ High gain and high input resistance

$$R_i = R_1$$



- same current through R_1 and R_{21}
- same voltage across R_3 and R_{21}

$$A_v = \frac{v_O}{v_I} = -\left(\frac{R_{21}+R_{22}}{R_1} + \frac{R_{21}R_{22}}{R_1 R_3}\right)$$

For $R_1 = 1\text{k},\ R_{21} = 10\text{k}$

$R_{22} = 10\text{k},\ R_3 = 0.1\text{k}$

$$A_v = -\left(\frac{10+10}{1} + \frac{10\cdot 10}{1\cdot 0.1}\right) = -1020$$

$$R_i = 1\text{k}$$

Summary

The *little black bug* (OpAmp) is also able to make:

- Amplifiers with OpAmp
  - Non-inverting amplifiers
  - Inverting amplifiers

Next week: Summing and differential amplifiers with OpAmp.

To do: Homework 6