ELECTRONIC DEVICES

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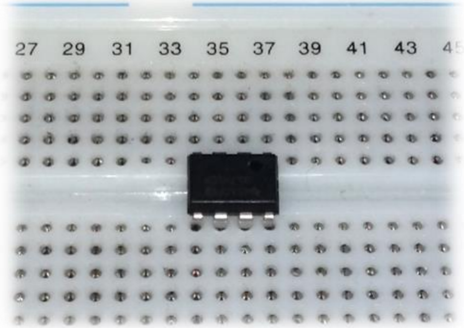
C10 – Applications with OpAmp



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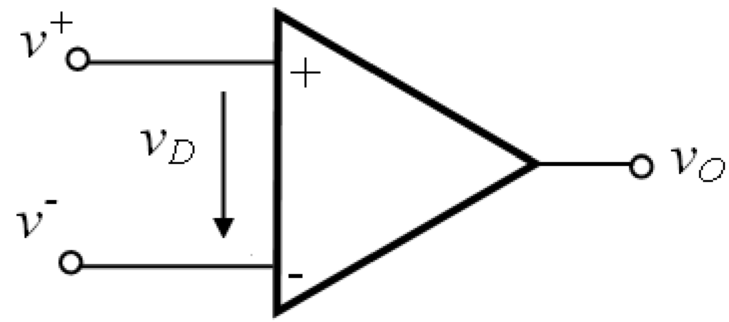


Type of feedback	v_I goes to	Application	We compute	v_O
No feedback	NI	Simple comparator, non-inverting	V_{Th}	$v_O \in \{V_{OL} ; V_{OH}\}$
	II	Simple comparator, inverting		
Positive feedback	NI	Hysteresis comparator, non-inverting	V_{ThL} V_{ThH}	$v_O \in \{V_{OL} ; V_{OH}\}$
	II	Hysteresis comparator, inverting		
Negative feedback	NI	Amplifier, non-inverting	A_v	$v_O \in (V_{OL} ; V_{OH})$
	II	Amplifier, inverting		

Basic applications of OpAmps with negative feedback

- Inverting/non-inverting amplifier **(C8, L11)**
- Differential amplifier **(C9, L11)**
- Summing amplifier (inverting/non-inverting) **(C9)**

Other applications of OpAmps with negative feedback:

- Voltage domain conversion circuits
- Capacitively coupled amplifiers
- Op-amp amplifiers operated from a single power supply
- Integrators and differentiators – active filters
- Half-wave and full-wave precision rectifiers
- Precision peak detectors
- Current sources
- Logarithmic and exponential amplifiers
- Circuits for multiplication and division

Linear conversion of the voltage domain

$$v_{cd} \in \left[v_{cd_{\min}} ; v_{cd_{\max}} \right] \rightarrow v_O \in \left[v_{O_{\min}} ; v_{O_{\max}} \right]$$

- inverting amplifier

$v_{cd_{\min}} \rightarrow v_{O_{\max}}$ $\qquad$ $v_{cd_{\max}} \rightarrow v_{O_{\min}}$

- non-inverting amplifier

$v_{cd_{\max}} \rightarrow v_{O_{\max}}$ $\qquad$ $v_{cd_{\min}} \rightarrow v_{O_{\min}}$

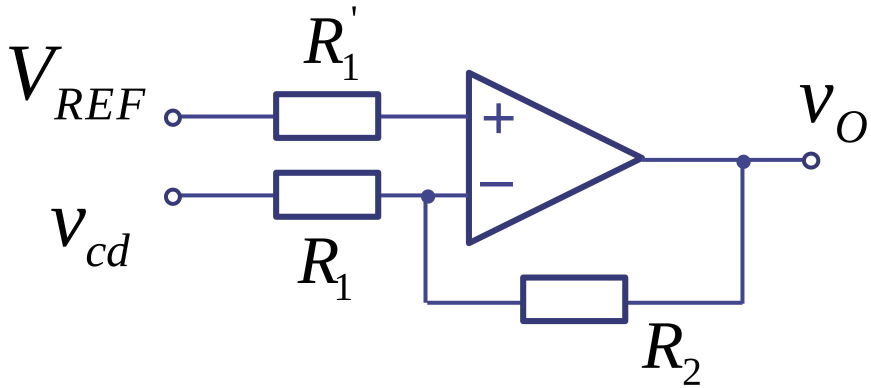
Circuits?

Linear conversion of the voltage domain

- inverting amplifier

$v_{cd_{\min}} \rightarrow v_{O_{\max}}$

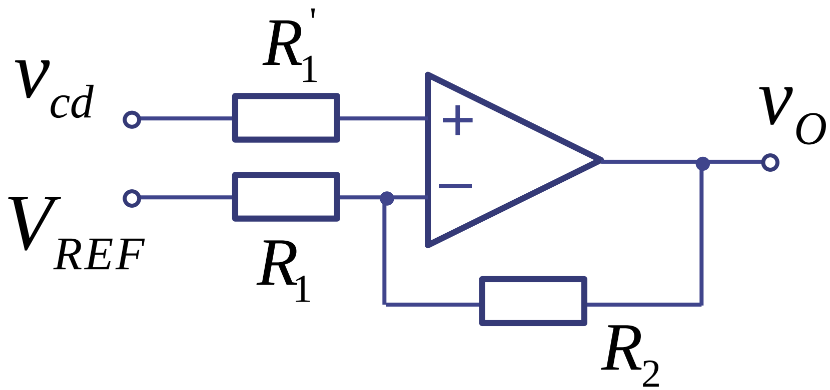
$v_{cd_{\max}} \rightarrow v_{O_{\min}}$



- non-inverting amplifier

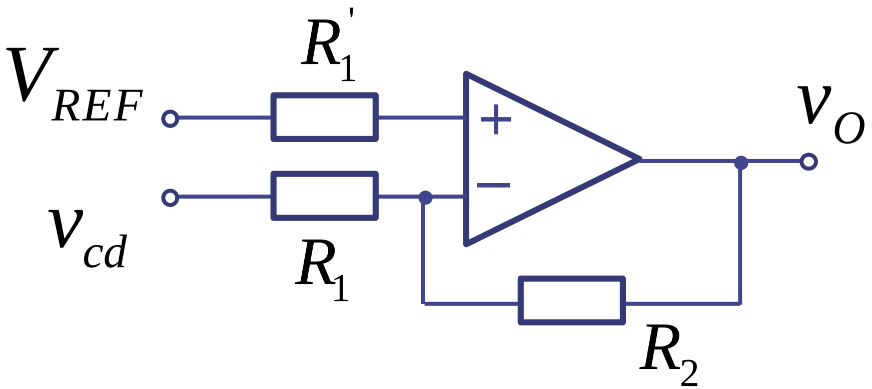
$v_{cd_{\max}} \rightarrow v_{O_{\max}}$

$v_{cd_{\min}} \rightarrow v_{O_{\min}}$



Why is V_{REF} necessary?

➢ Inverting voltage domain conversion amplifier

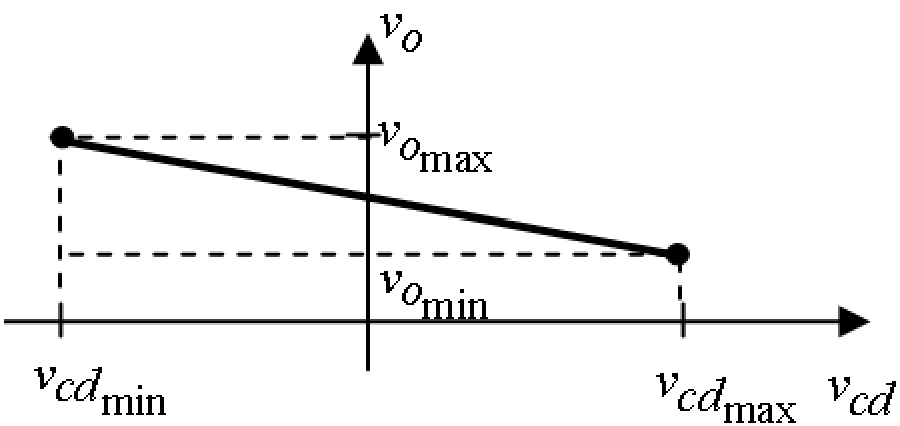


$v_{cd_{min}} \rightarrow v_{O_{max}}$

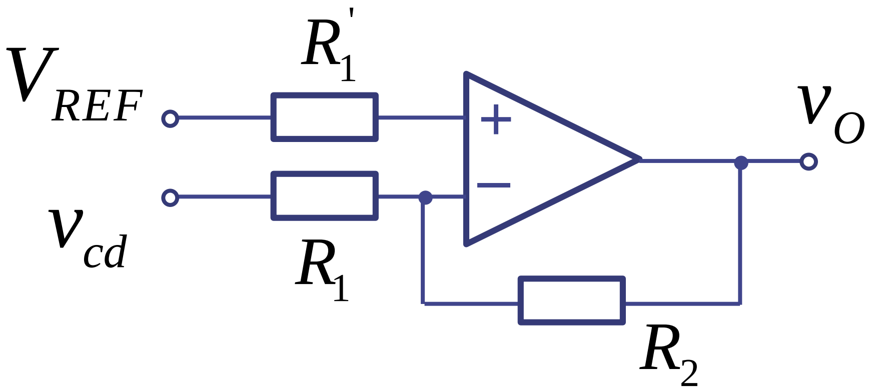
$v_{cd_{max}} \rightarrow v_{O_{min}}$

$$v_O = -\frac{R_2}{R_1} v_{cd} + \left(1 + \frac{R_2}{R_1}\right) V_{REF}$$

$$V_{REF} = \frac{v_{O\,min} + \frac{R_2}{R_1} v_{cd\,max}}{1 + \frac{R_2}{R_1}}$$



Inverting voltage domain conversion amplifier



$v_{cd\,min} \rightarrow v_{O\,max}$

$v_{cd\,max} \rightarrow v_{O\,min}$

$$v_O = -\frac{R_2}{R_1} v_{cd} + \left(1 + \frac{R_2}{R_1}\right) V_{REF}$$

$$\frac{R_2}{R_1} = \frac{v_{O\max} - v_{O\min}}{v_{cd\max} - v_{cd\min}}$$

$$R_1^{'} = R_1 \,||\, R_2$$

$$V_{REF} = \frac{v_{O\min} + \frac{R_2}{R_1} v_{cd\max}}{1 + \frac{R_2}{R_1}}$$

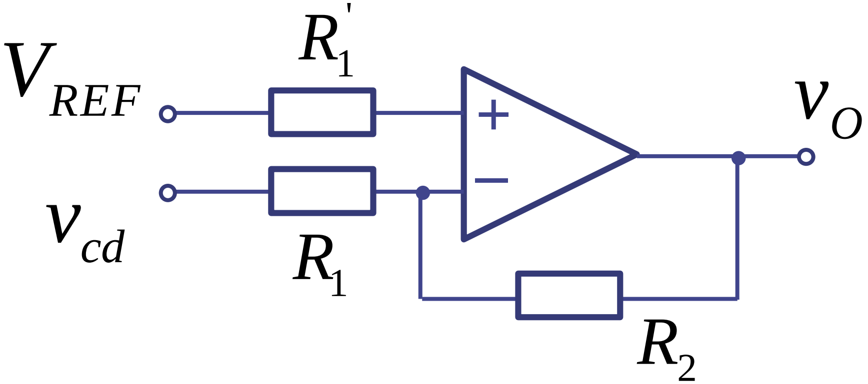
$$v_{O\min} = -\frac{R_2}{R_1} v_{cd\max} + \left(1 + \frac{R_2}{R_1}\right) V_{REF}$$

$$v_{O\max} = -\frac{R_2}{R_1} v_{cd\min} + \left(1 + \frac{R_2}{R_1}\right) V_{REF}$$

Inverting voltage domain conversion amplifier

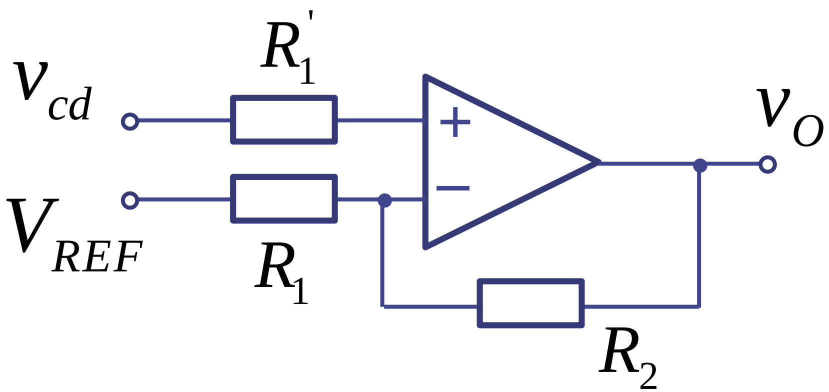
Example

$$v_{cd} \in (2;7)\text{V} \qquad v_O \in (-1;6)\text{V}$$



- VTC
- Values for resistors
- V_{REF}

➢ Non-inverting voltage domain conversion amplifier



$$v_{cd_{\min}} \rightarrow v_{O_{\min}}$$
$$v_{cd_{\max}} \rightarrow v_{O_{\max}}$$

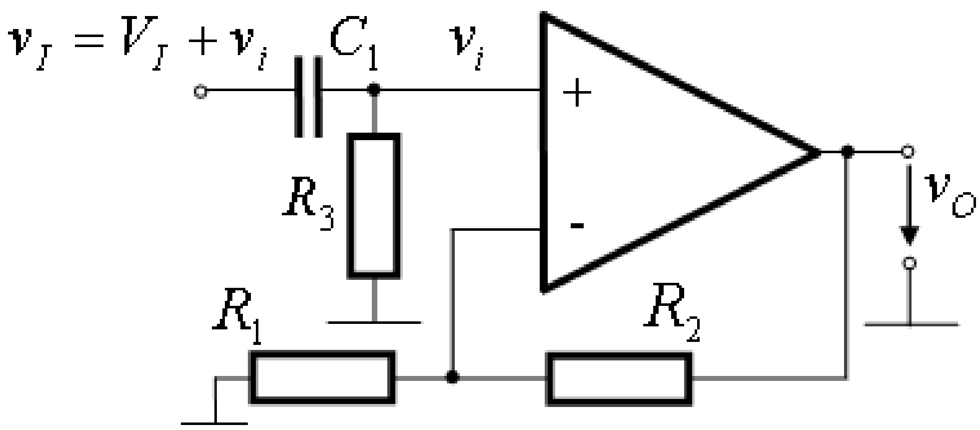
- VTC
- Values for resistors
- V_{REF}

$v_I(t) = V_I + v_i(t)$

To do: amplify only the variable signal, $v_i(t)$

Solution: differential amplifier (C9)

capacitively coupled amplifier

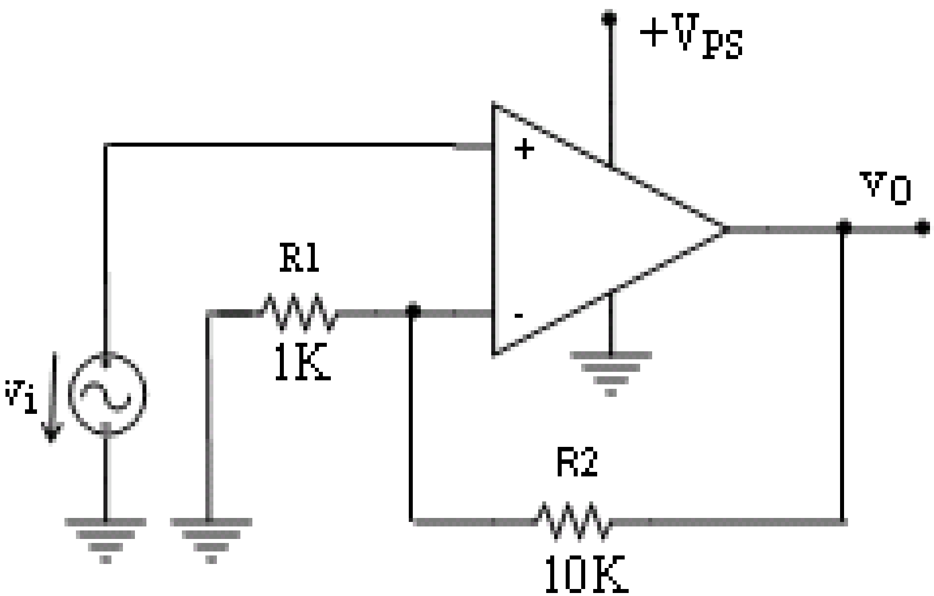


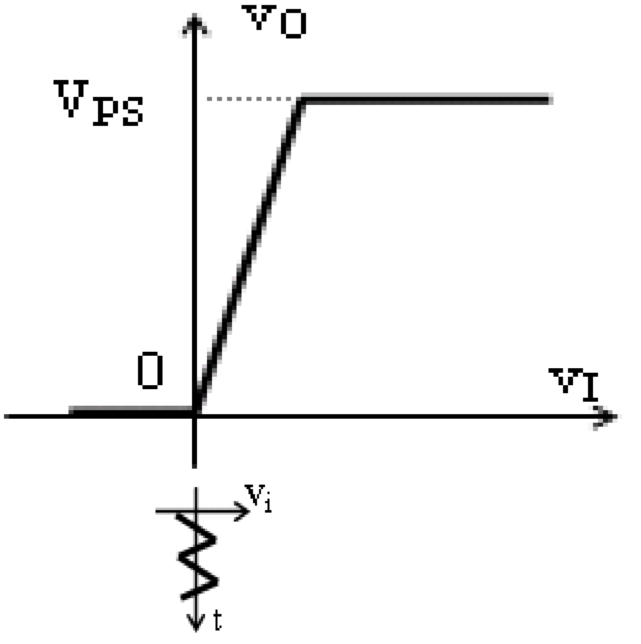
$$v_o(t) = v_i(t)\left(1 + \frac{R_2}{R_1}\right)$$

Role of R_3?

OpAmp amplifiers operated from a single power supply

- Non-inverting configuration

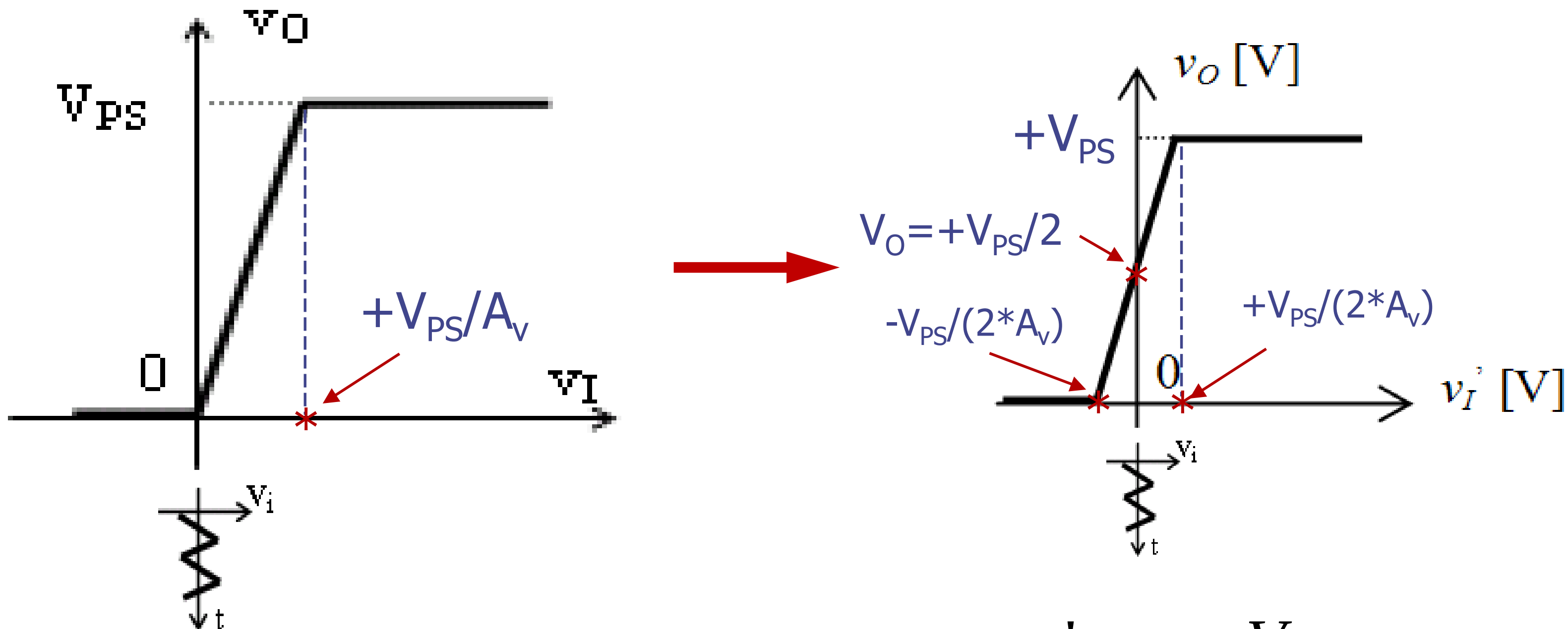




How can we amplify the entire $v_i(t)$ (not just the positive halfwave), in the case of unipolar supply?

- Non-inverting configuration

Solution: translate the VTC

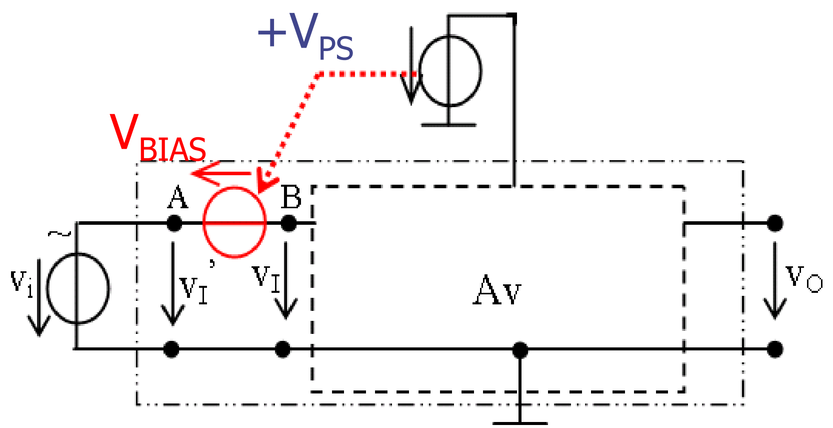


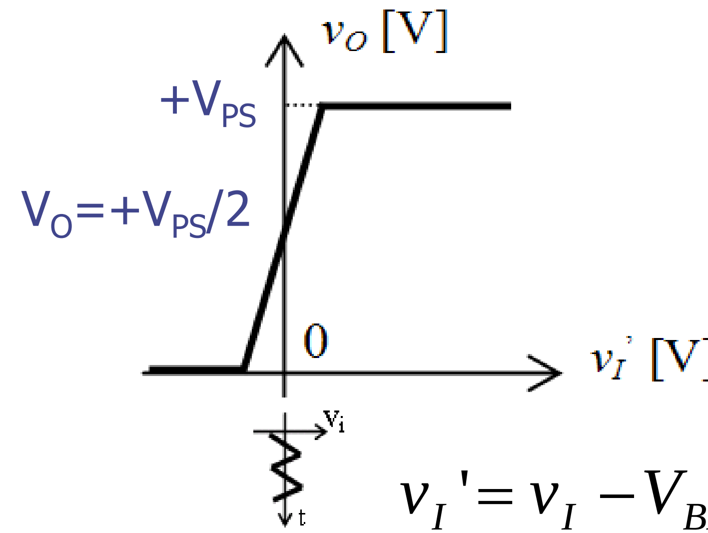
$$v_I' = v_I - V_{BIAS}$$

OpAmp amplifiers operated from a single power supply

- Non-inverting configuration

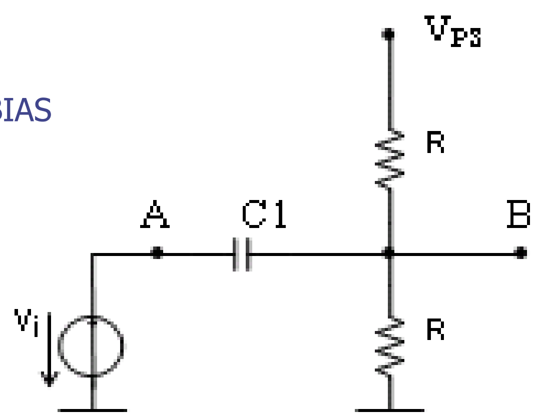
Solution: translate the VTC



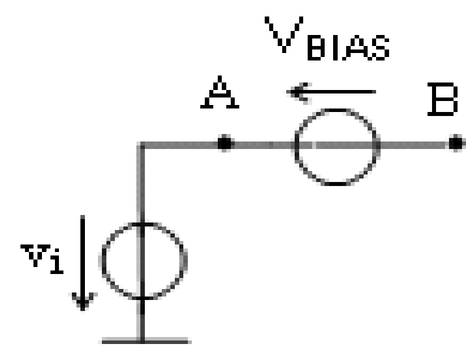


$$v_I' = v_I - V_{BIAS}$$

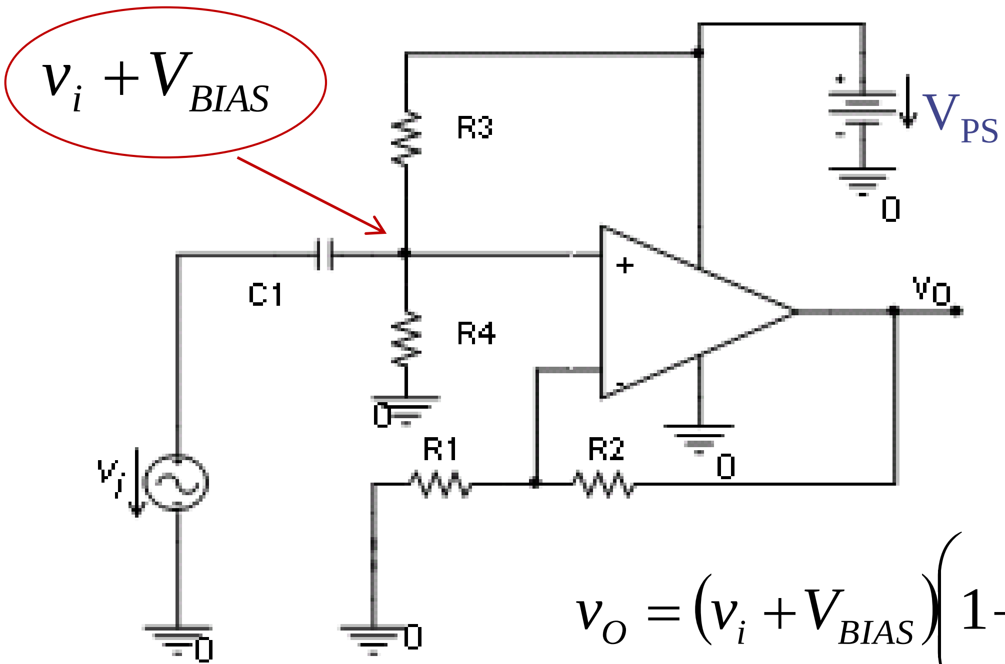
- obtaining V_{BIAS}



- equivalence in steady-state regime



➢ Non-inverting configuration



$$V_{BIAS} = \frac{R_4}{R_4 + R_3} V_{PS}$$

$$v_O = \left(v_i + V_{BIAS}\right)\left(1 + \frac{R_2}{R_1}\right) = v_i\left(1 + \frac{R_2}{R_1}\right) + V_{BIAS}\left(1 + \frac{R_2}{R_1}\right)$$

Problem: V_{BIAS} is also amplified (dc gain is too high)

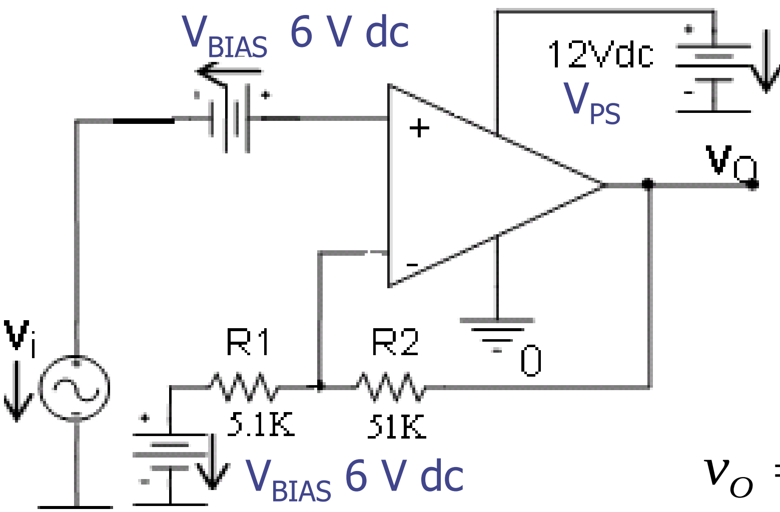
Possible solution: to implement

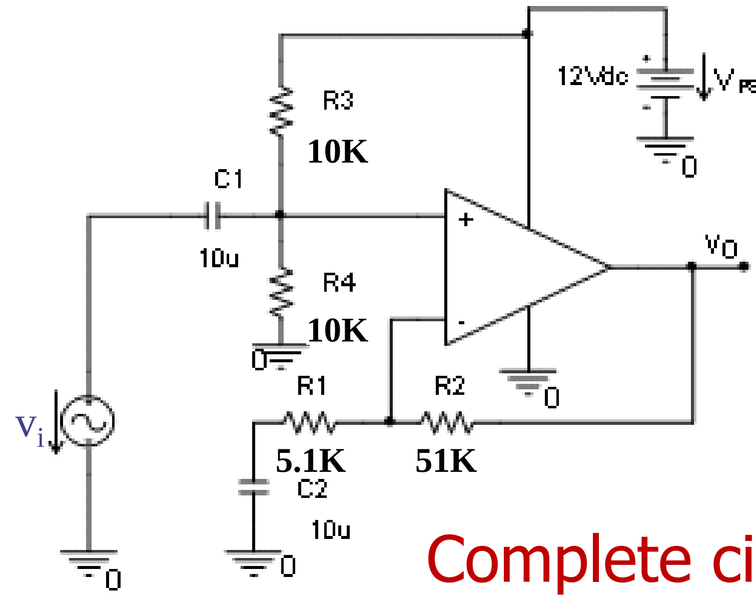
$$v_O = v_i\left(1 + \frac{R_2}{R_1}\right) + V_{BIAS}\left(1 + \frac{R_2}{R_1}\right) - V_{BIAS}\frac{R_2}{R_1}$$

OpAmp amplifiers operated from a single power supply

- Non-inverting configuration

Equivalent circuit in steady-state regime





Complete circuit

$$v_O = (v_i + V_{BIAS})\left(1 + \frac{R_2}{R_1}\right) - V_{BIAS}\frac{R_2}{R_1}$$

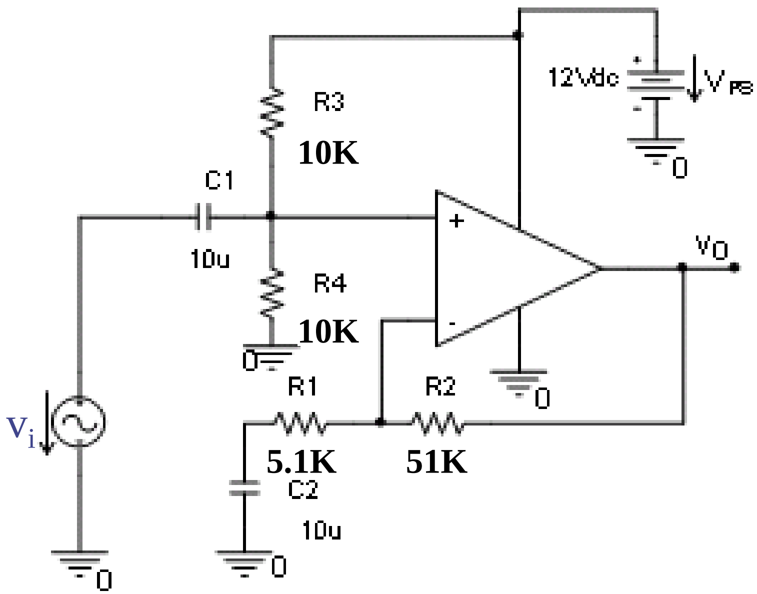
$$v_O = v_i\left(1 + \frac{R_2}{R_1}\right) + 1 * V_{BIAS}$$

$A_{v,\,ac}$ $A_{v,\,dc}$

$A_{v,\,ac} = 1 + R_2/R_1$
$A_{v,\,dc} = 1$

OpAmp amplifiers operated from a single power supply

➢ Non-inverting configuration



$$v_O = (v_i + V_{BIAS})\left(1 + \frac{R_2}{R_1}\right) - V_{BIAS}\frac{R_2}{R_1}$$

$$v_O = v_i\left(1 + \frac{R_2}{R_1}\right) + 1 * V_{BIAS}$$

$A_{v,\ ac}$

$A_{v,\ dc}$

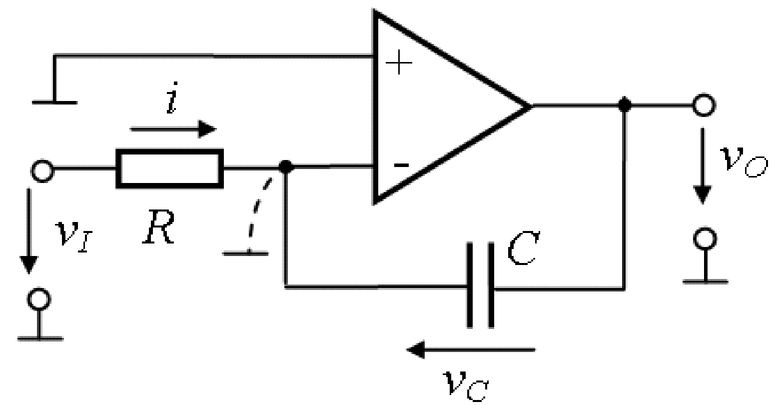
$A_{v,\ ac} = 1 + R_2/R_1$

$A_{v,\ dc} = 1$

- Equivalent ac circuit?
- Equivalent dc circuit?
- Inverting configuration?

OPTIONAL

➢ Integrator – active LPF



Time domain analysis

$$i(t) = \frac{v_I(t)}{R} \qquad C dv_c = -i dt$$

$$v_O(t) = v_C(t) = -\frac{1}{C}\int_0^t i(t)dt + v_C(0) \qquad v_O(t) = -\frac{1}{C}\int_0^t \frac{v_I(t)}{R}dt + v_C(0)$$

$$v_O(t) = -\frac{1}{RC}\int_0^t v_I(t)dt + v_C(0)$$

RC – time constant, integrating constant

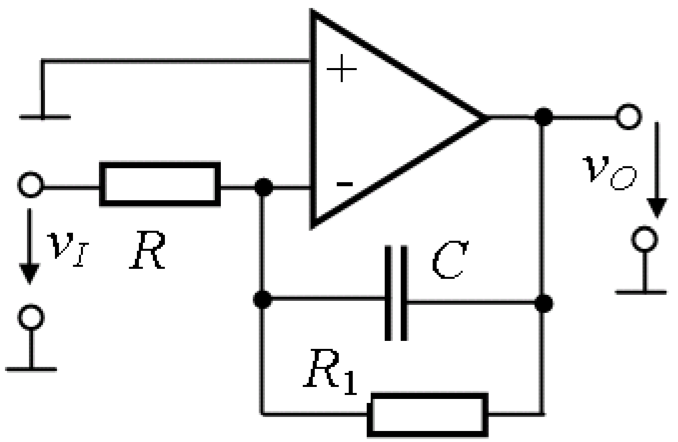
Problem: The op-amp can become saturated due to the dc offset voltage and / or biasing currents, because there is no NF in dc

Solution: Introduce a NF path in dc

OPTIONAL

- Integrator – active LPF

Integrator with NF in dc (lossy integrator)



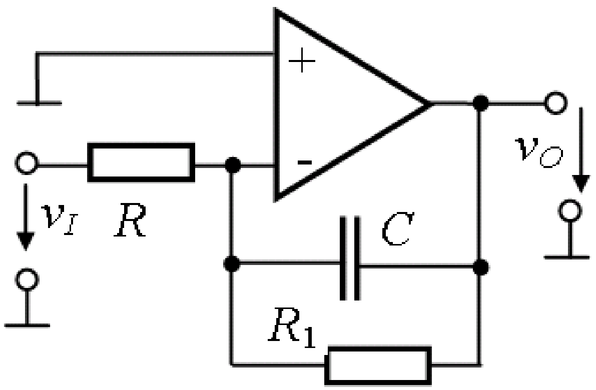
R_1 - large enough to be neglected when compared to Z_C @working frequency

!To be used in practical applications!

OPTIONAL

➢ Integrator – active LPF

Frequency domain analysis



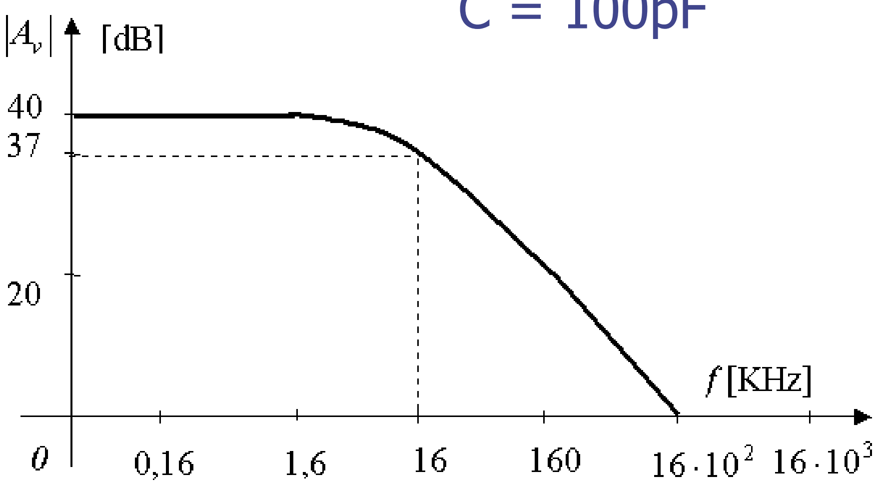
$$A_v(j\omega) = \frac{v_O(j\omega)}{v_I(j\omega)} = -\frac{Z_{ech}}{R}$$

$$Z_{ech} = R_1 \parallel \frac{1}{j\omega C} = \frac{R_1}{1 + j\omega R_1 C}$$

$$A_v(j\omega) = -\frac{R_1}{R}\frac{1}{1 + j\omega R_1 C}$$

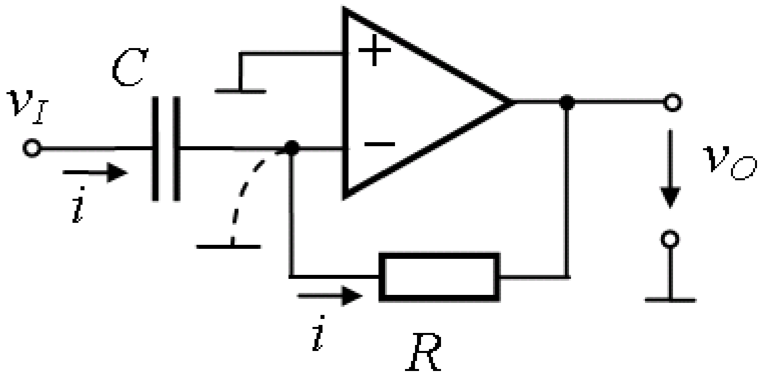
Example:

R = 1 kΩ
R_1 = 100 kΩ
C = 100pF



OPTIONAL

➢ Differentiator – active HPF



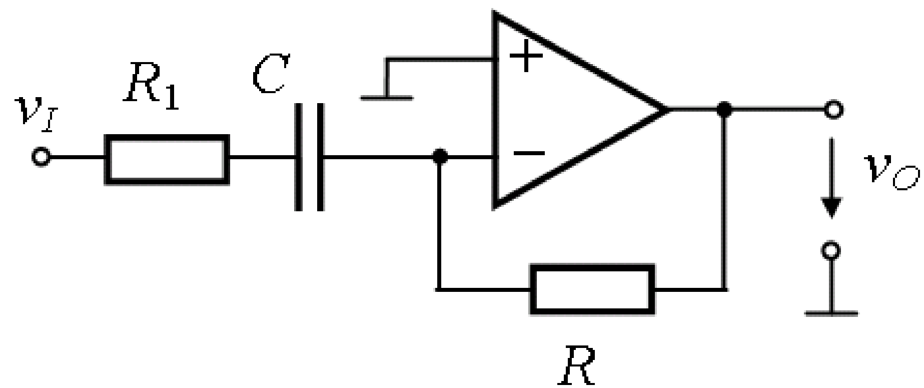
The circuit acts as a "noise amplifier" because of the derivation of the input signal.

$$i(t) = C\frac{dv_I(t)}{dt}$$

$$v_O(t) = -Ri = -RC\frac{dv_I(t)}{dt}$$

$$A_v(j\omega) = \frac{v_O(j\omega)}{v_I(j\omega)} = \frac{R}{Z_C} = j\omega RC$$

$$|A_v(j\omega)| = \omega RC$$



R_1 – small, in series with C, used in practical applications

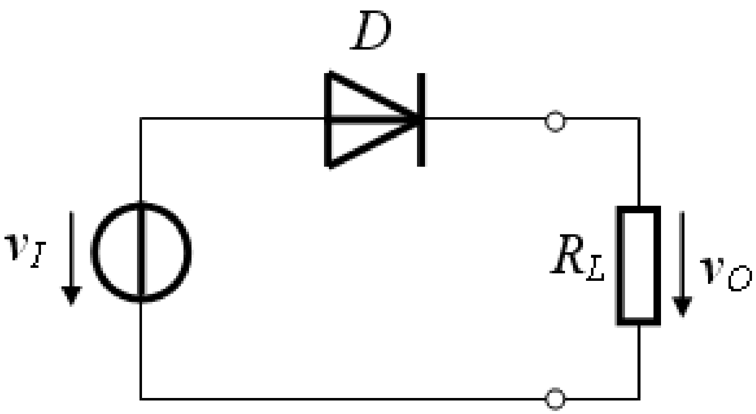
Active high-pass filter $f_0 = \infty$ $$f_0 = \frac{1}{2\pi R_1 C}$$

Half-wave and full-wave precision rectifiers

OPTIONAL

Previously on ED (C3)

Half-wave rectifier



Problems:

- small signals can't be rectfied (D - off)
- some voltage (0.7 V) is wasted across the conducting diode

Solution:

Precision rectifier: $v_O = v_I$

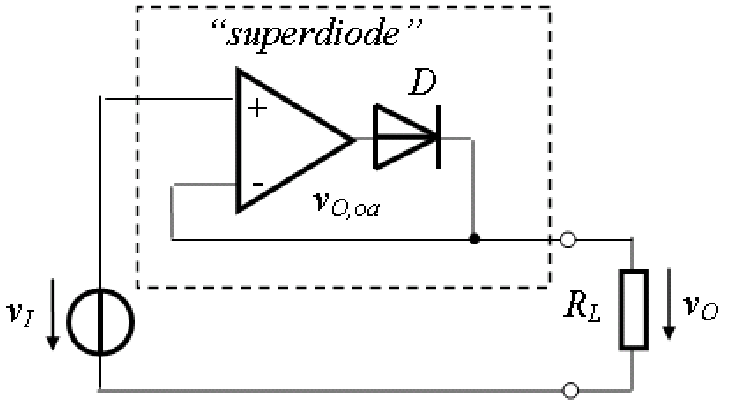
Superdiode – (almost) zero voltage drop across the conducting superdiode

Circuit?

Half-wave and full-wave precision rectifiers

OPTIONAL

➢ Half-wave precision rectifier



v_O cannot become negative

$$i_D \geq 0$$

Operating principle:

$v_I > 0$

$v_{O,oa}$ > 0.6 V, (D) – on, NF

$v_O = v_I$ for $v_I > 0$

- -

$v_I < 0$

$v_{O,oa}$ < 0, (D) – off

No NF -> OpAmp works as a simple comparator, non-inverting

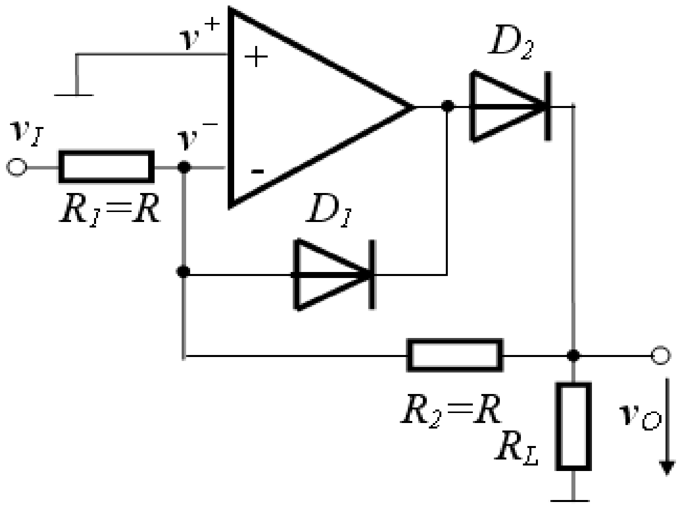
$v_{O,oa} = V_{OL}$, $v_O = 0$ (no current through R_L) for $v_I < 0$

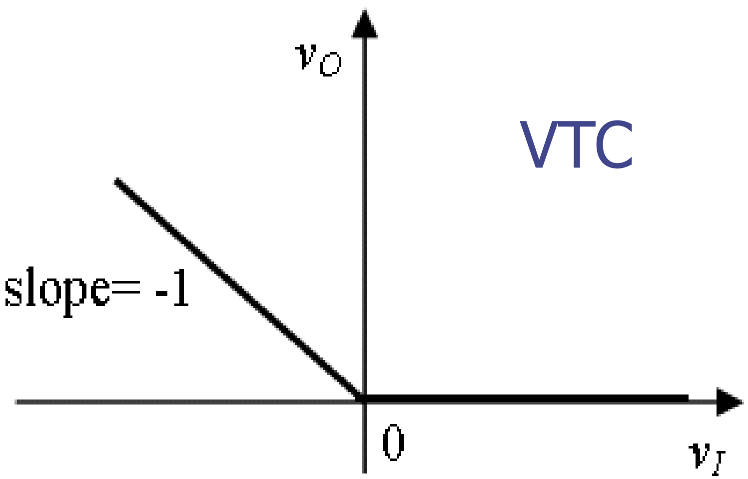
Circuit for rectifying the negative half-wave?

Half-wave and full-wave precision rectifiers

➢ Inverting half-wave precision rectifier avoiding saturation

OPTIONAL





$v_I < 0;\ \ D_2 - (on); D_1 - (off)$ NF through D_2 and $R_2;\ v_O = -v_I$

$v_{O,oa} = v_O + 0.7\text{V}$ OpAmp – active region

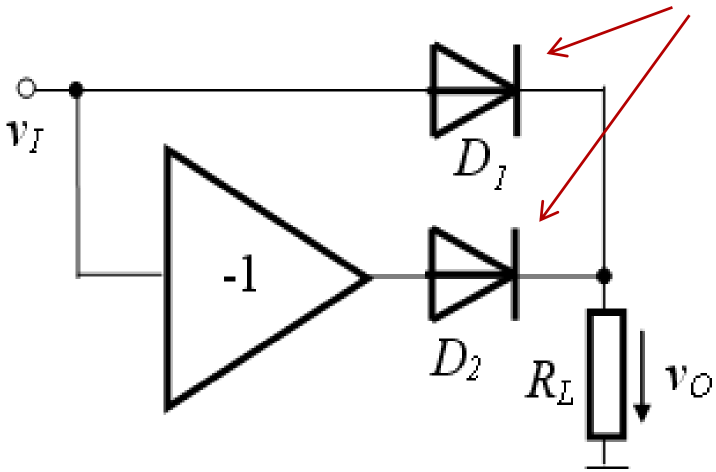
$v_I > 0;\ \ D_2 - (off); D_1 - (on)$ NF through $D_1;\ v^- = v^+ = 0;\ \ v_O = 0$

$v_{O,oa} = -0.7\text{V}$ OpAmp – active region

Half-wave and full-wave precision rectifiers

OPTIONAL

- Full-wave precision rectifier



Operating principle

$v_I > 0$, D_1-(on), D_2 – (off) $v_O = v_I$

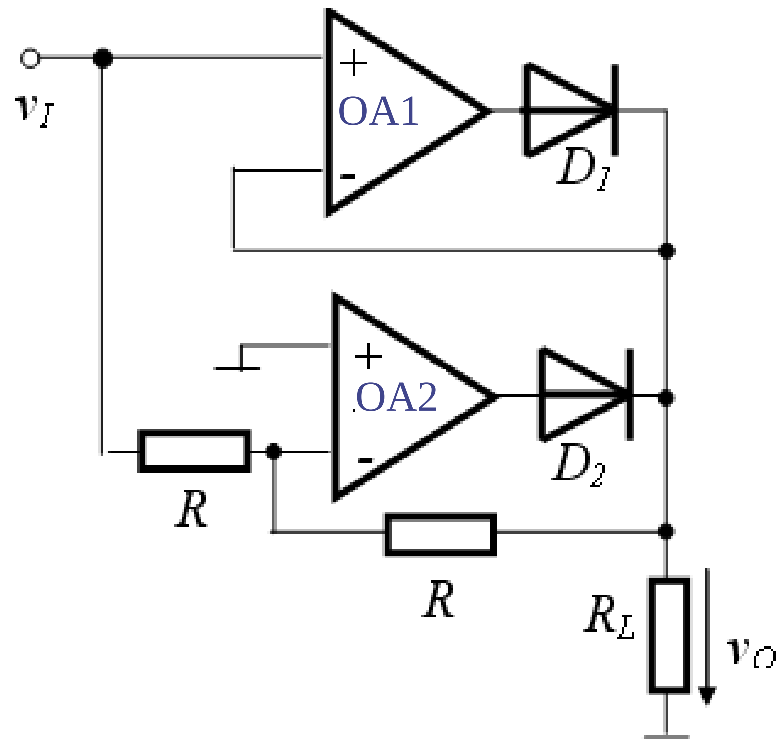
$v_I < 0$, D_1-(off), D_2 – (on) $v_O = -v_I$

Circuit?

Half-wave and full-wave precision rectifiers

OPTIONAL

- Full-wave precision rectifier



$v_I > 0$, D_1 - (on), D_2 – (off)

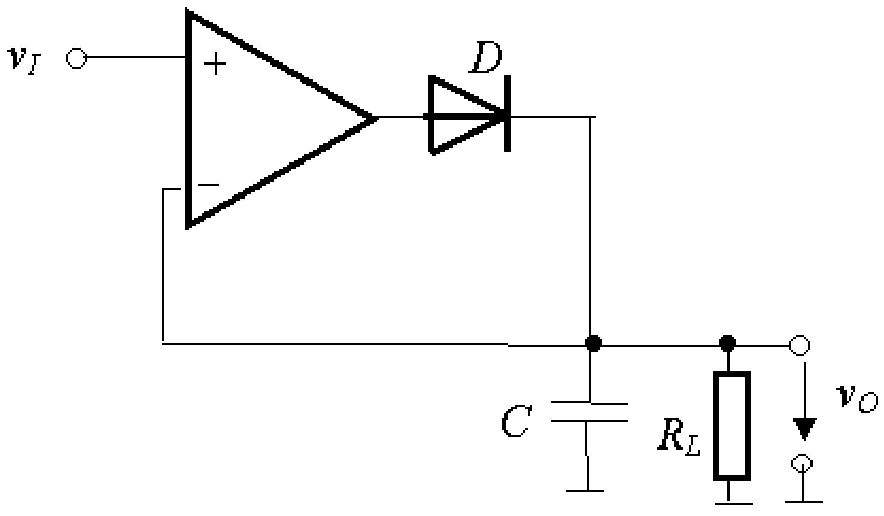
NF only for OA1, **$v_O = v_I$**

$v_I < 0$, D_1-(off), D_2–(on)

NF only for OA2, $v_O = -(R/R)\cdot v_I$ **$v_O = - v_I$**

OPTIONAL

➢ Precision positive peak detector



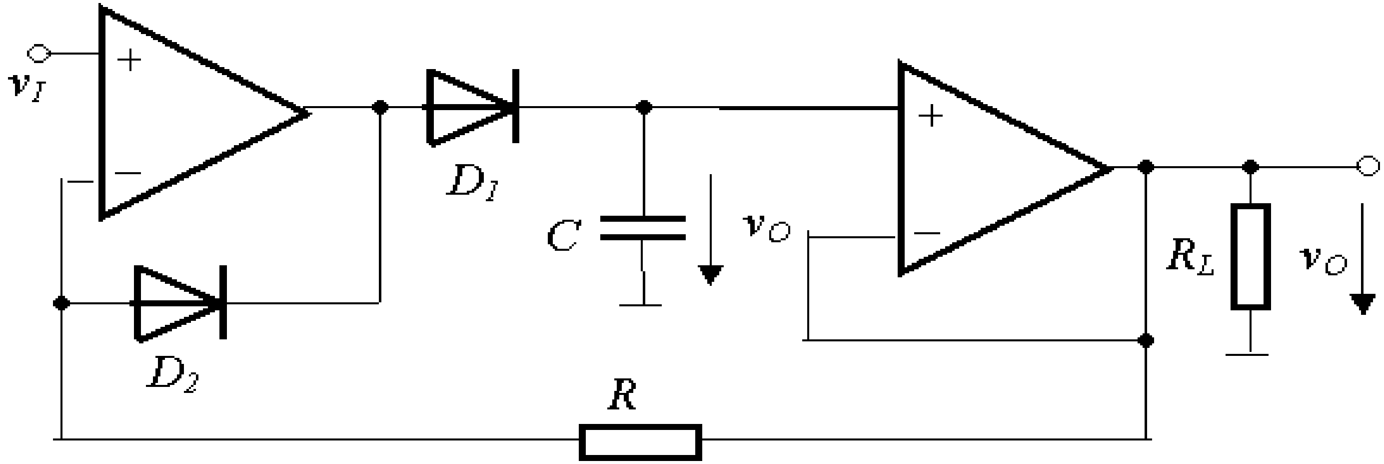
The diode from the common peak detector is replaced with a superdiode.

Precision peak detectors

OPTIONAL

➢ Precision positive peak detector

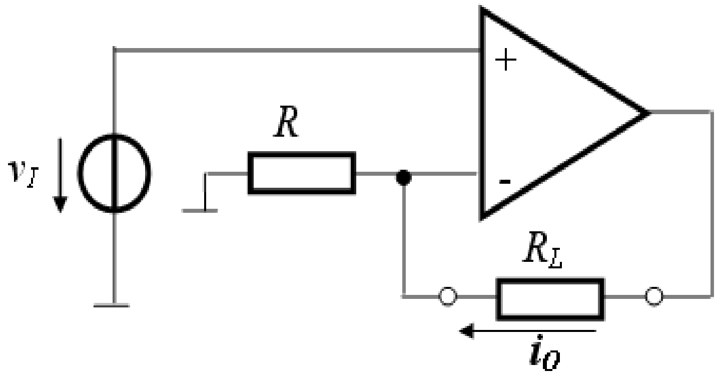
Precision positive peak detector that holds the voltage



- D_2 prevents negative saturation of OA1
- OA2 – voltage follower (buffer)
- OA1 – local NF, when D_2 - (on), $v_{O,\ OA1}$ is limited to v_I – 0.7 V
- R provides a small current through D_2

➢ Voltage controlled current source

OPTIONAL



$$i_O = \frac{v_I}{R}$$

- i_O does not depend on the value of R_L
- adjustable i_O - replace R with (R + P)

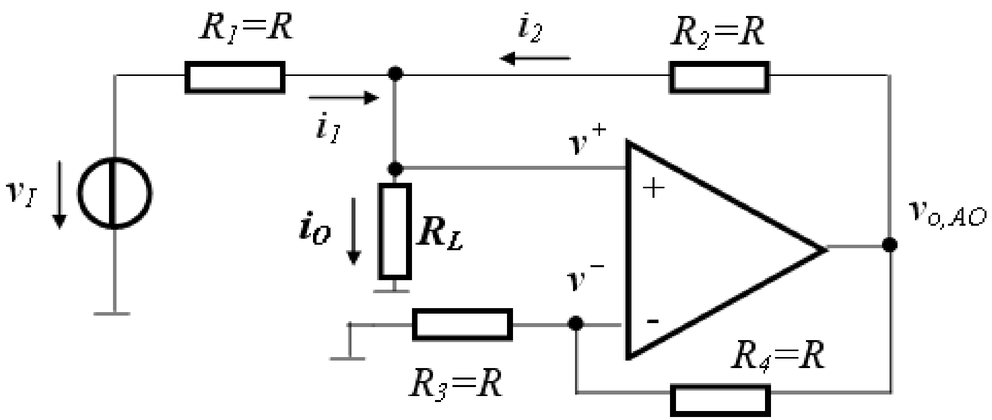
Circuit? Why can't R be replaced only with P?

- value of i_O is controlled by the value of v_I
- R_L is not connected to ground -> floating load

?Circuit with non-floating load?

➢ Current source with non-floating load

OPTIONAL



Howland source

NF and PF, NF is dominant

$$K^- = \frac{R_3}{R_3+R_4} = \frac{R}{R+R} = \frac{1}{2}$$

$$K^+ = \frac{R_1 \| R_L}{R_1 \| R_L + R} = \frac{R \| R_L}{R \| R_L + R}$$

Since $R||R_L < R$,
$K^- > K^+$ -> NF

$$v^+ = v^-$$

$$i_O = i_1 + i_2 = \frac{v_I - v^+}{R_1} + \frac{v_{o,OA} - v^+}{R_2}$$

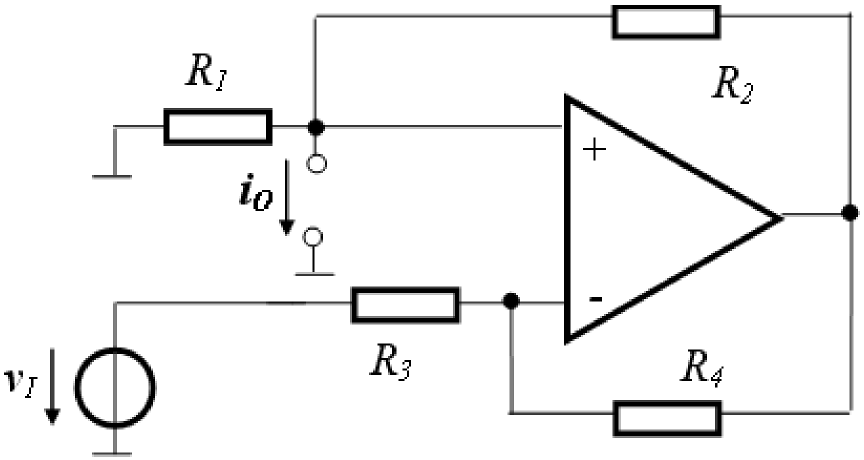
$$v^+ = v^- = \frac{R_3}{R_3+R_4} v_{o,OA} = \frac{1}{2} v_{o,OA}$$

$$v_{o,OA} = 2 i_O R_L$$

$$i_0 = \frac{v_I}{R}$$

Current sources

OPTIONAL



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

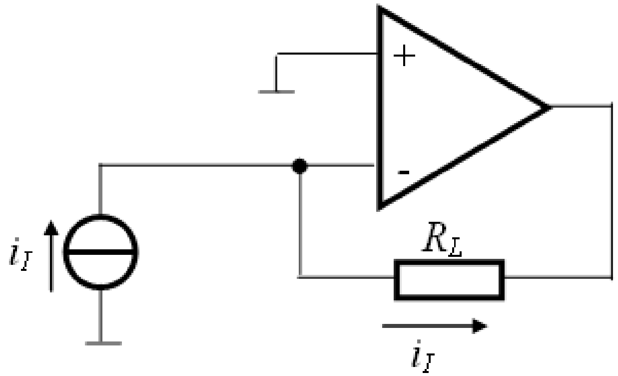
$$i_O = -\frac{v_I}{R_1}$$

The pairing of the resistors should be very accurate, in order to obtain a perfect current source (infinite output resistance).

Practical solution: current source using OpAmp and BJT/MOS

➢ Current follower

OPTIONAL

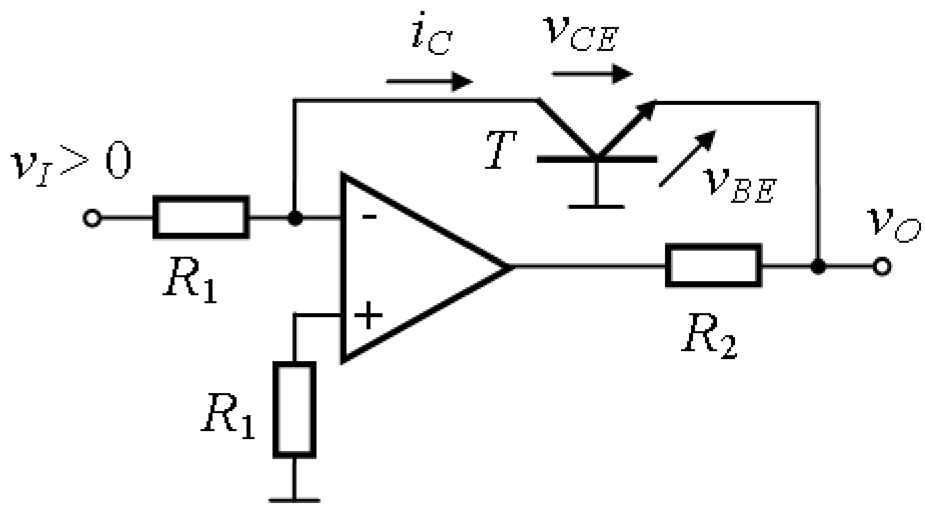


- The current source does not generate power
- The power in the load resistor, R_L, is obtained from the power supplies of the OpAmp

Logarithmic and exponential amplifiers

➢ Logarithmic amplifier

OPTIONAL



$$v_O = -v_{BE}$$

$$i_C = I_S e^{\frac{v_{BE}}{V_T}}$$

$$i_C = \frac{v_I}{R_1} \qquad v_{BE} = V_T \ln \frac{i_C}{I_S}$$

$$v_O = -V_T \ln \frac{v_I}{R_1 I_S}$$

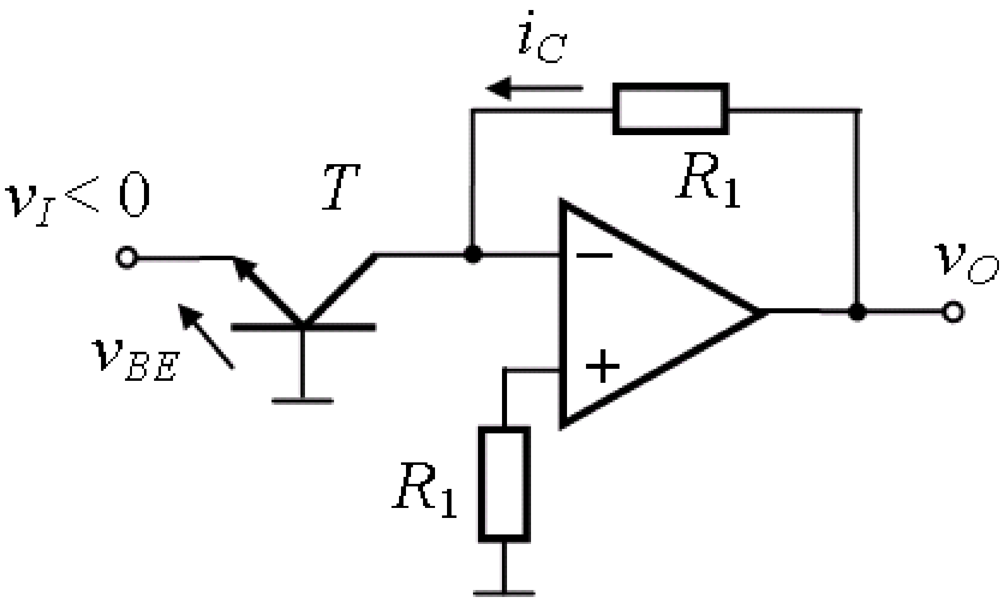
For $v_I < 0$ - use *pnp* transistor

Limitations of the circuit:
- the range of the output voltage is narrow, hundreds of mV (v_O is a base to emitter voltage);
- temperature dependence of the output voltage (V_T and I_S)

Logarithmic and exponential amplifiers

- Exponential amplifier

OPTIONAL



$$v_O = R_1 i_C$$

$$v_{BE} = -v_I$$

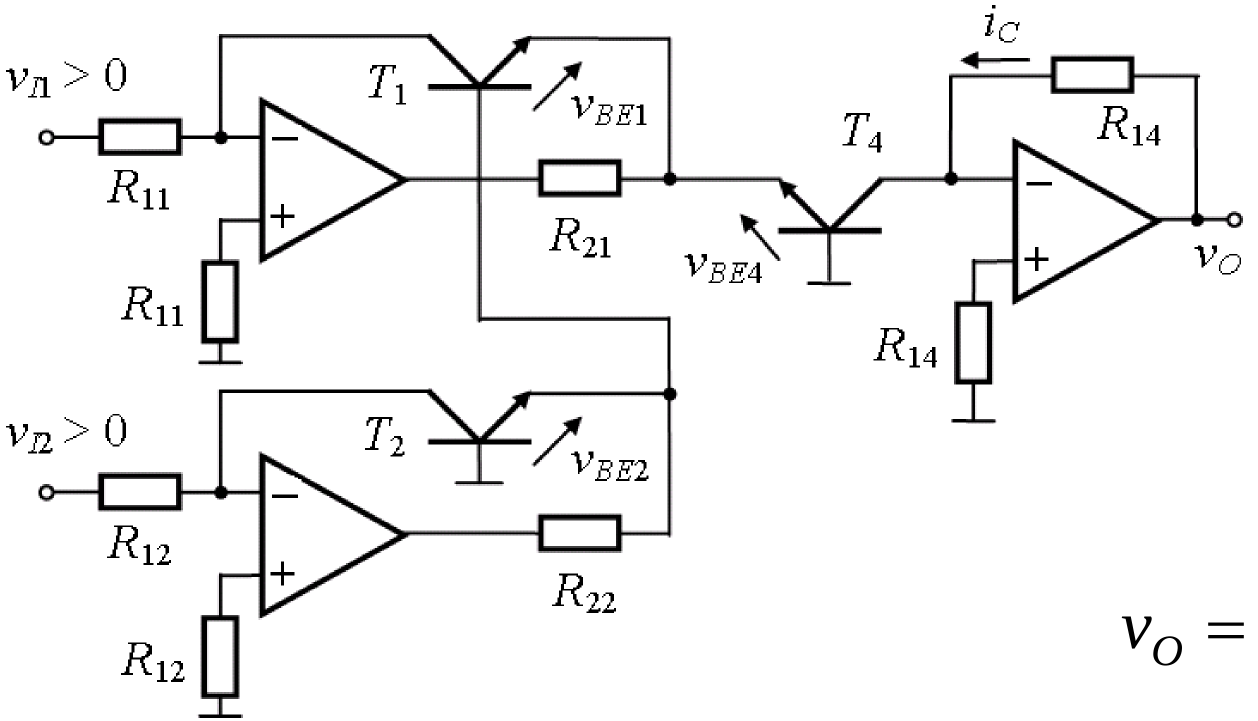
$$i_C = I_S e^{\frac{v_{BE}}{V_T}} = I_S e^{-\frac{v_I}{V_T}}$$

$$v_O = R_1 I_S e^{-\frac{v_I}{V_T}}$$

Circuits for multiplication and division

- Multiplication circuit

OPTIONAL



$$v_{BE1} = V_T \ln \frac{v_{I1}}{R_{11} I_S}$$

$$v_{BE2} = V_T \ln \frac{v_{I2}}{R_{12} I_S}$$

$$v_{BE4} = v_{BE1} + v_{BE2}$$

$$v_O = R_{14} I_S e^{\frac{v_{BE4}}{V_T}}$$

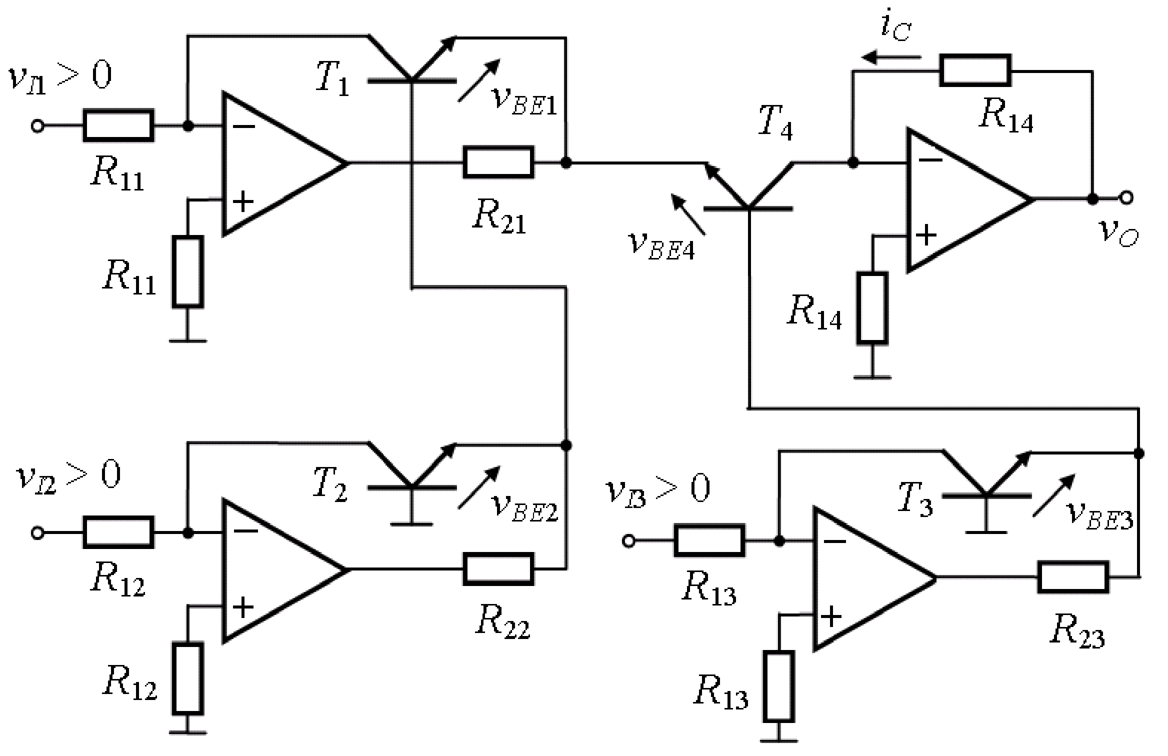
$$v_{I1} v_{I2} = e^{\ln(v_{I1} v_{I2})} = e^{(\ln v_{I1} + \ln v_{I2})}$$

$$v_O = \frac{R_{14}}{R_{11} R_{12} I_S} v_{I1} v_{I2}$$

Circuits for multiplication and division

➢ Multiplication and division circuit

OPTIONAL



$$v_{BE1} = V_T \ln \frac{v_{I1}}{R_{11} I_S}$$

$$v_{BE2} = V_T \ln \frac{v_{I2}}{R_{12} I_S}$$

$$v_{BE3} = V_T \ln \frac{v_{I3}}{R_{13} I_S}$$

$$v_{BE4} = v_{BE1} + v_{BE2} - v_{BE3}$$

$$v_O = R_{14} I_S e^{\frac{v_{BE4}}{V_T}}$$

$$v_O = \frac{R_{14} R_{13}}{R_{11} R_{12}} \frac{v_{I1} v_{I2}}{v_{I3}}$$

For equal resistances:

$$v_O = \frac{v_{I1} v_{I2}}{v_{I3}}$$

No temperature dependence!

Summary

Our last encounter with the OpAmp (this semester) showed us how it can be used to obtain more specialized applications.

New challenges await.

Next week: Transistors. BJTs.

To do: Homework 8