

# ***Corso di Elettronica Applicata II (N.O.)***

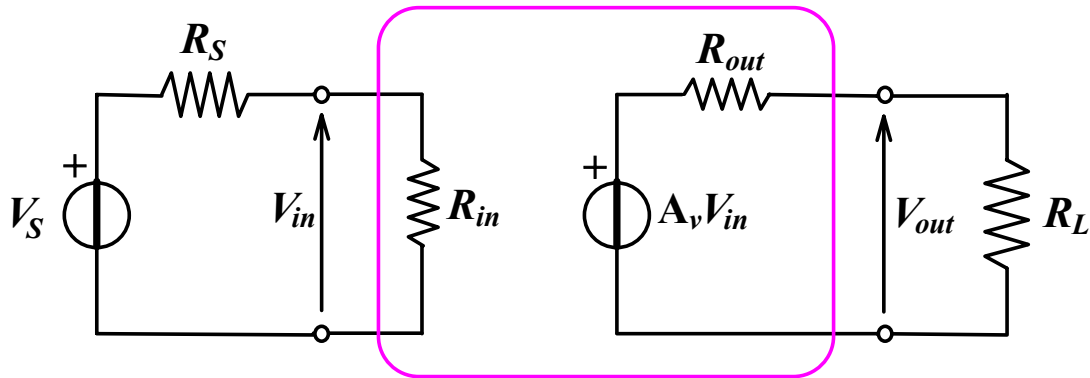
Prof. Ing. L. Masotti

## ■ **Libri di testo**

- Jacob Millman, Arvin Grabel:  
*Microelectronics*  
Mc Graw Hill, 1981
- Ulrich Tietze, Christoph Schenk:  
*Electronic circuits - Design and applications*  
Springer Verlag Heidelberg, 1991
- John G. Kassakian, Martin F. Schlecht, George C. Verghese:  
*Principles of power electronics*  
Addison-Wesley Publishing Company, Inc., 1992

## Reti amplificatrici elementari

Amplificatore di tensione  
(Convertitore tensione/tensione)



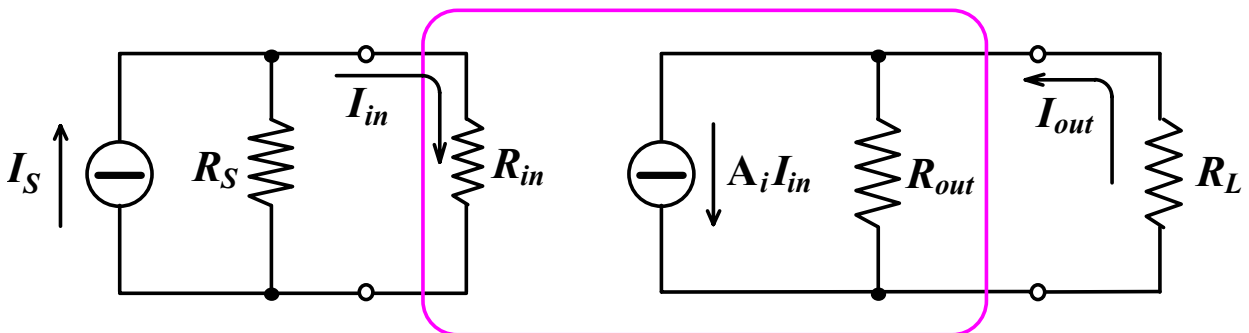
$$se R_{in} \gg R_S \Rightarrow V_{in} \cong V_S$$

$$se R_{out} \ll R_L \Rightarrow V_{out} \cong A_v V_{in}$$

$$\Rightarrow V_{out} \cong A_v V_S$$

$$A_v = \lim_{R_L \rightarrow \infty} \frac{V_{out}}{V_{in}}$$

Amplificatore di corrente  
(Convertitore corrente/corrente)



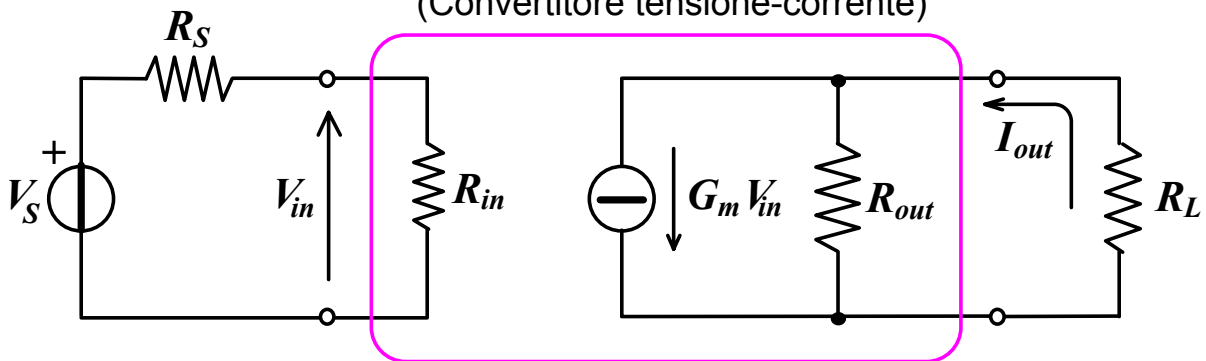
$$se R_{in} \ll R_S \Rightarrow I_{in} \cong I_S$$

$$se R_{out} \gg R_L \Rightarrow I_{out} \cong A_i I_{in}$$

$$\Rightarrow I_{out} \cong A_i I_S$$

$$A_i = \lim_{R_L \rightarrow 0} \frac{I_{out}}{I_{in}}$$

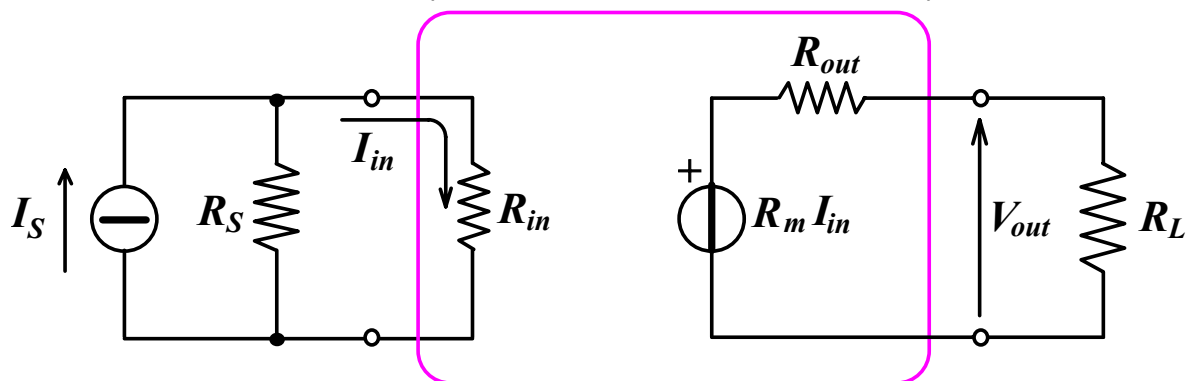
Amplificatore di transconduttanza  
(Convertitore tensione-corrente)



$$\begin{aligned}
 & \text{se } R_{in} \gg R_S \Rightarrow V_{in} \cong V_S \\
 & \text{se } R_{out} \gg R_L \Rightarrow I_{out} \cong G_m V_{in} \Rightarrow \boxed{I_{out} \cong G_m V_S}
 \end{aligned}$$

$$G_m = \lim_{R_L \rightarrow 0} \frac{I_{out}}{V_{in}}$$

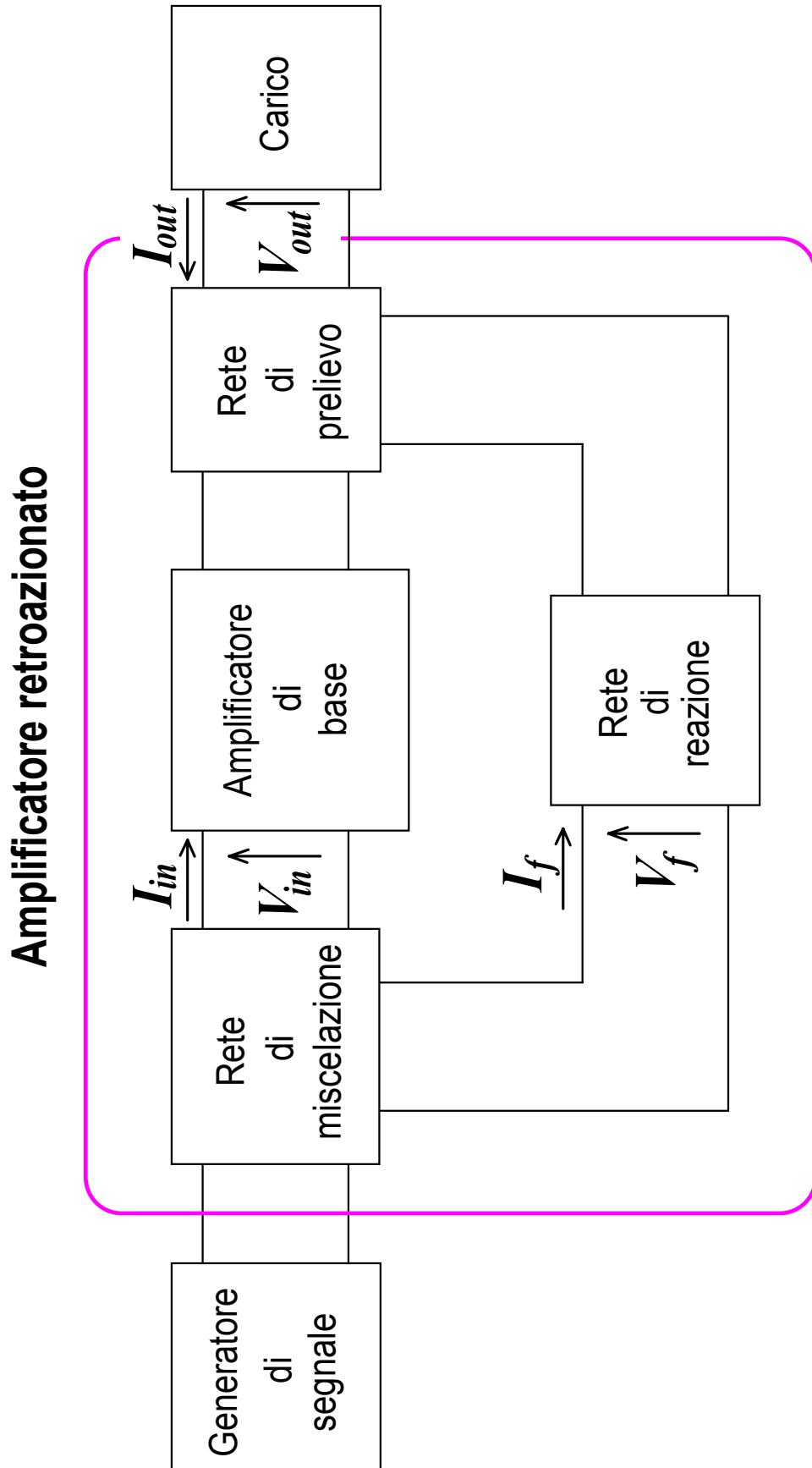
Amplificatore di transresistenza  
(Convertitore corrente-tensione)



$$\begin{aligned}
 & \text{se } R_{in} \ll R_S \Rightarrow I_{in} \cong I_S \\
 & \text{se } R_{out} \ll R_L \Rightarrow V_{out} \cong R_m I_{in} \Rightarrow \boxed{V_{out} \cong R_m I_S}
 \end{aligned}$$

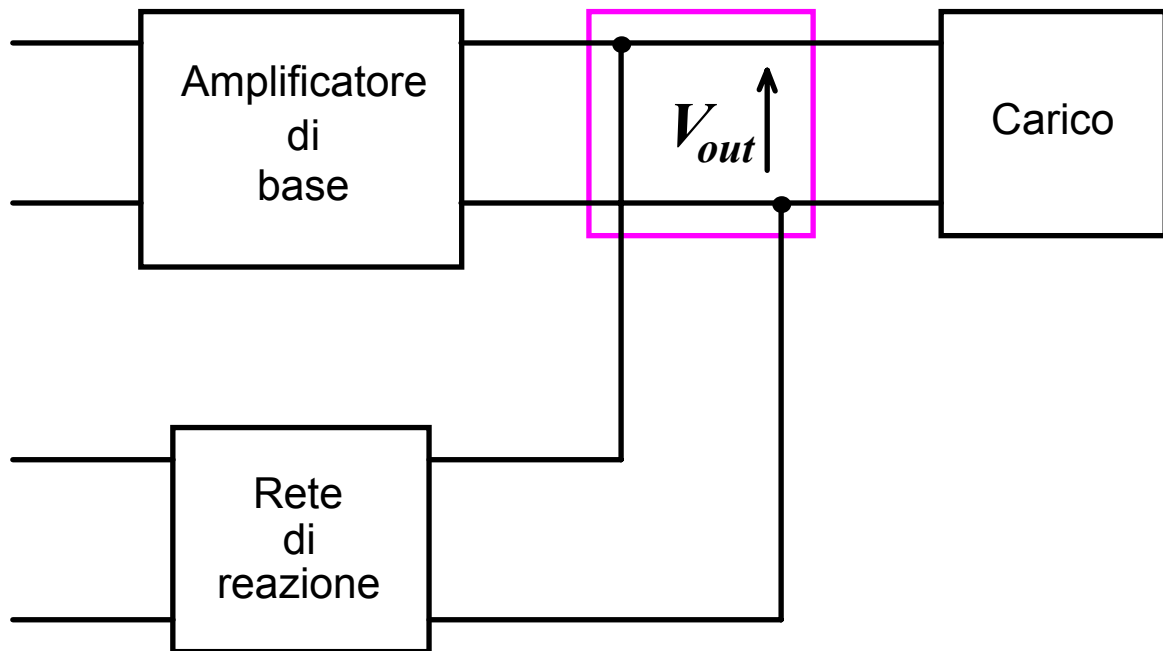
$$R_m = \lim_{R_L \rightarrow \infty} \frac{V_{out}}{I_{in}}$$

## Schema di un amplificatore retroazionato

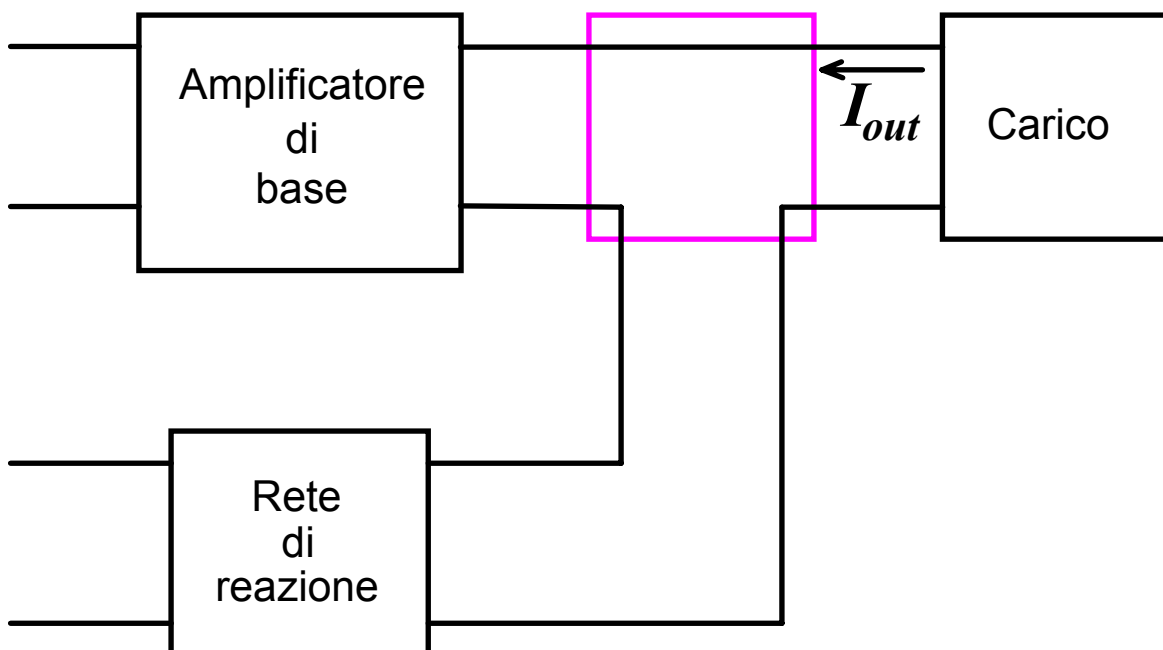


## Reti di prelievo

### Prelievo di tensione (parallelo)

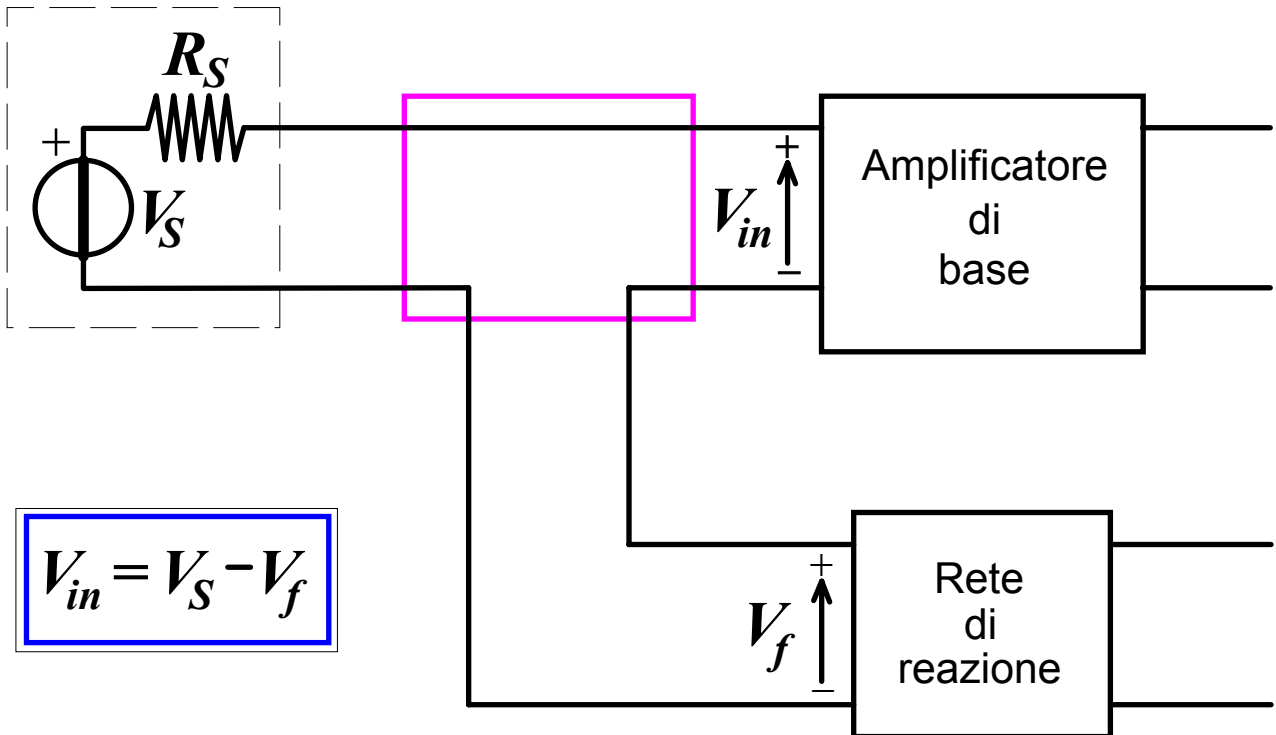


### Prelievo di corrente (serie)

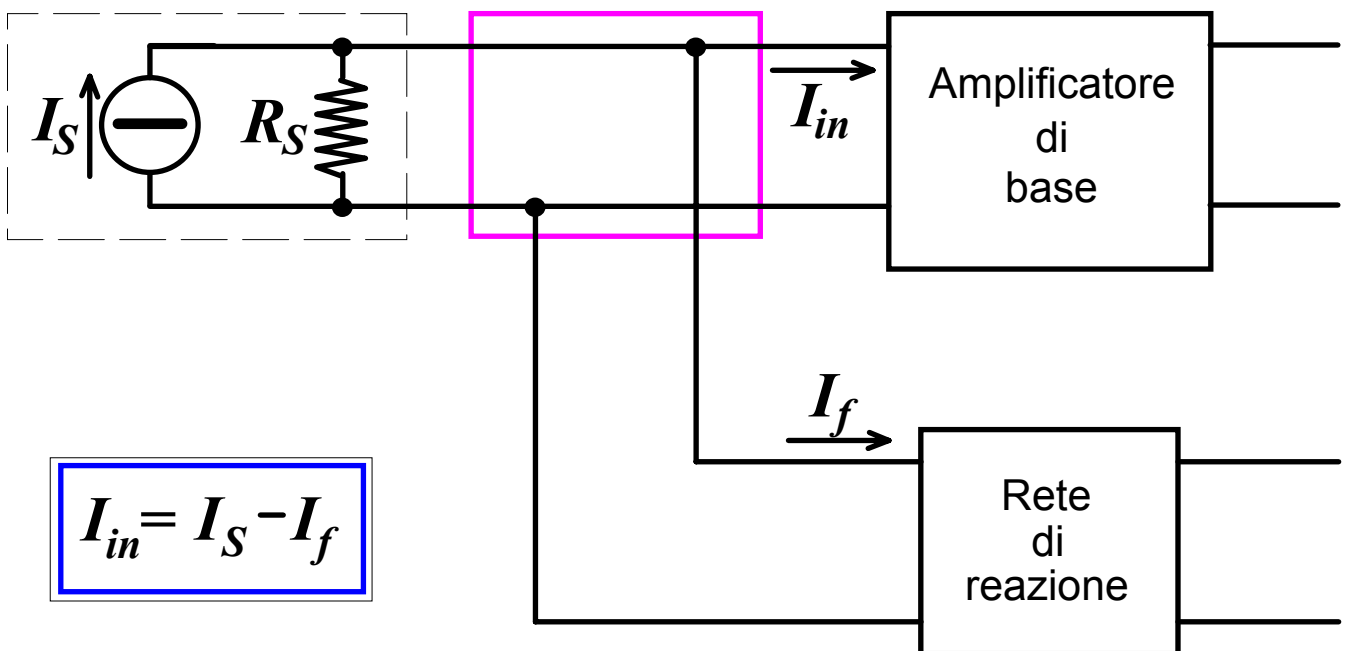


## Reti di miscelazione

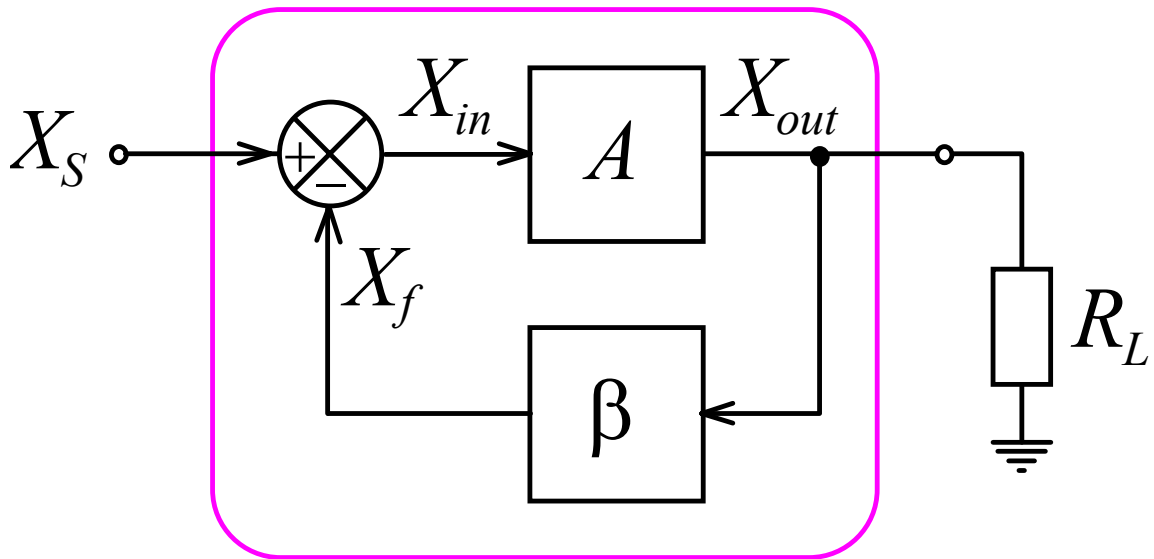
### Miscelazione (somma) di tensioni (o confronto serie)



### Miscelazione (somma) di correnti (o confronto parallelo)



## Grandezze tipiche di un amplificatore retroazionato



$$X_{in} = X_S - X_f \quad A = \frac{X_{out}}{X_{in}} \quad A_f = \frac{X_{out}}{X_S} \quad \beta = \frac{X_f}{X_{out}}$$

$$X_{in} = X_S - \beta X_{out} = X_S - \beta A X_{in} \Rightarrow X_S = X_{in} (1 + \beta A)$$

⇓

$$A_f = \frac{X_{out}}{X_S} = \frac{X_{out}}{X_{in} (1 + \beta A)} = \boxed{\frac{A}{1 + \beta A}} \stackrel{\beta A \gg 1}{\approx} \frac{A}{A\beta} = \frac{1}{\beta}$$

⇓

$$|1 + \beta A| > 1 \Rightarrow |A_f| < |A| \Rightarrow \text{reazione negativa}$$

$$|1 + \beta A| < 1 \Rightarrow |A_f| > |A| \Rightarrow \text{reazione positiva}$$

## Sensibilità e desensibilità

$$S = \frac{\frac{dA_f}{A_f}}{\frac{dA}{A}} \quad \text{ovvero} \quad S = \frac{dA_f}{dA} \cdot \frac{A}{A_f} \quad D = \frac{1}{S}$$

$$\frac{dA_f}{dA} = \frac{1}{1+\beta A} - \frac{\beta A}{(1+\beta A)^2} = \frac{1+\beta A - \beta A}{(1+\beta A)^2} = \frac{A}{A} \cdot \frac{1}{(1+\beta A)(1+\beta A)} = \frac{A_f}{A(1+\beta A)}$$

$$S = \frac{A_f}{A(1+\beta A)} \cdot \frac{A}{A_f} = \boxed{\frac{1}{1+\beta A}} \quad D = \boxed{1+\beta A}$$

*Esempio:*  $\beta A = 9 \Rightarrow 1 + \beta A = 10; \quad \frac{dA}{A} = 20\% \Rightarrow \frac{dA_f}{A_f} = 2\%$

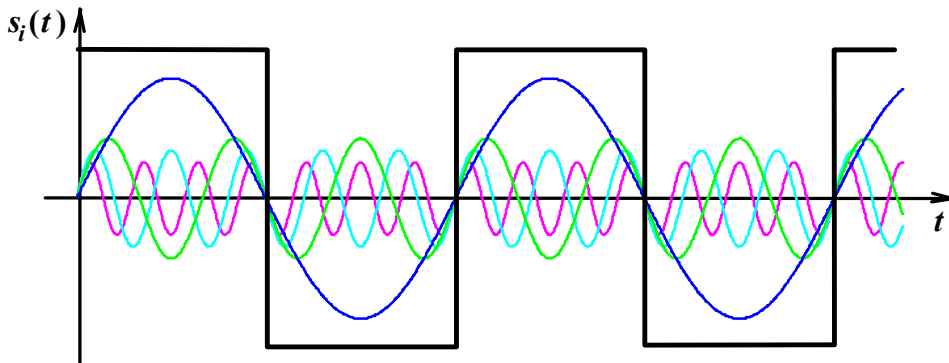
*ovviamente se*  $A = 1000 \Rightarrow A_f = 100$

### Ipotesi

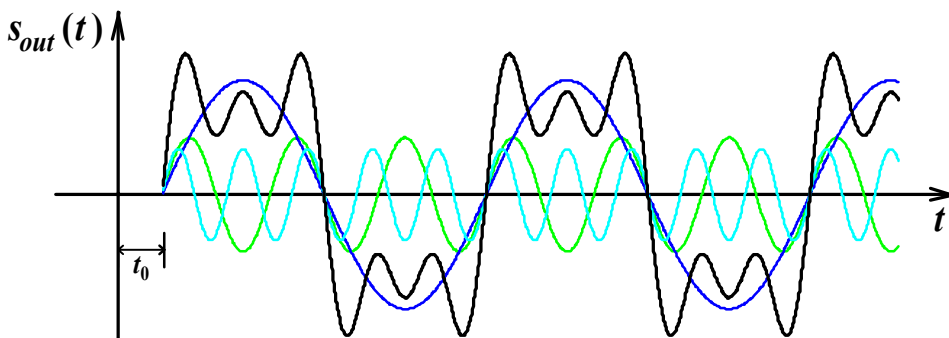
- 1) *Il segnale tra ingresso ed uscita è trasmesso soltanto attraverso A*  
*Quindi*  $A = 0 \Rightarrow X_{out} = 0$ .  
*[la rete  $\beta$  è unilaterale]*
- 2) *Il segnale tra uscita ed ingresso è trasmesso soltanto attraverso  $\beta$*   
*Sono assenti sia l'effetto Early che l'effetto Miller.*  
*[la rete A è unilaterale]*

## Distorsione lineare

$$\left\{ \begin{array}{l} |A(f)| = A_0 \\ \angle A(f) = \varphi(f) = kf \end{array} \right.$$

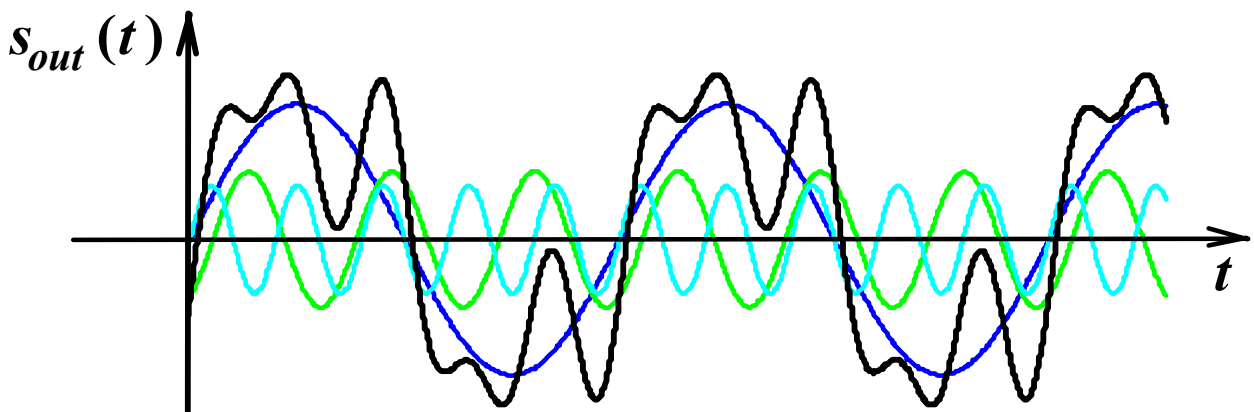


$$\begin{aligned} |S_{out}(\omega_1)| &= A_0 S_{in}(\omega_1) \\ |S_{out}(\omega_3)| &= A_0 S_{in}(\omega_3) \\ &\dots \\ &\dots \end{aligned}$$

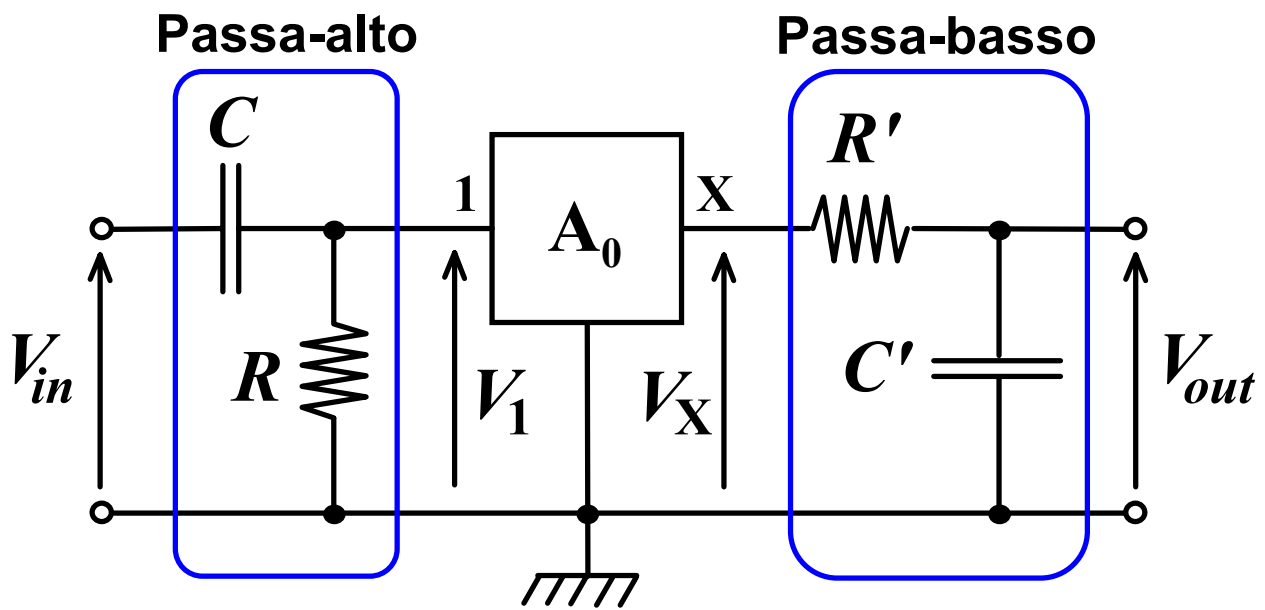


$$\begin{aligned} \varphi_1 &= \omega_1 t_0 \\ \varphi_3 &= \omega_3 t_0 = 3\omega_1 t_0 \\ &\dots \\ &\dots \end{aligned}$$

**Principio di causalità**  $\tau = t_0 = -\frac{d\varphi}{d\omega} > 0$  se  $\begin{matrix} \varphi_1 = \omega_1 t'_0 \\ \varphi_3 = \omega_3 t''_0 \end{matrix}$  con  $t'_0 \neq t''_0 \Rightarrow$  quadripolo dispersivo



## Risposta in frequenza di un amplificatore retroazionato



*Circuito passa-alto*

$$V_X = A_0 V_1$$

$$V_1 = \frac{R}{R + \frac{1}{j\omega C}} \cdot V_{in} = \frac{V_{in}}{1 + \frac{1}{j\omega RC}} = \frac{V_{in}}{1 - j \frac{\omega_L}{\omega}} \quad \text{con } \omega_L = \frac{1}{RC}$$

$$V_{out} \cong V_X = \frac{A_0 V_{in}}{1 - j \frac{f_L}{f}} \quad \text{per frequenze basse}$$

$$A(f) = \frac{V_{out}}{V_{in}} \cong \frac{A_0}{1 - j \frac{f_L}{f}}$$

**Circuito passa-basso**

$$V_{out} = \frac{\frac{1}{j\omega C'} \cdot V_X}{R' + \frac{1}{j\omega C'}} = \frac{V_X}{1 + j\omega R' C'} = \frac{V_X}{1 + j \frac{\omega}{\omega_H}} \quad \text{con} \quad \omega_H = \frac{1}{R' C'}$$

$V_X \cong A_0 V_{in}$  per frequenze alte

$$A(f) = \frac{V_{out}}{V_{in}} \cong \frac{A_0}{1 + j \frac{f}{f_H}}$$

**In bassa frequenza**

$$A_f(f) = \frac{A(f)}{1 + \beta A(f)} = \frac{\frac{A_0}{1 - j \frac{f_L}{f}}}{1 + \beta \frac{A_0}{1 - j \frac{f_L}{f}}} = \frac{A_0}{1 - j \frac{f_L}{f} + \beta A_0} = \frac{\frac{A_0}{1 + \beta A_0}}{\frac{1 + \beta A_0}{1 + \beta A_0} - j \frac{f_L}{(1 + \beta A_0)f}}$$

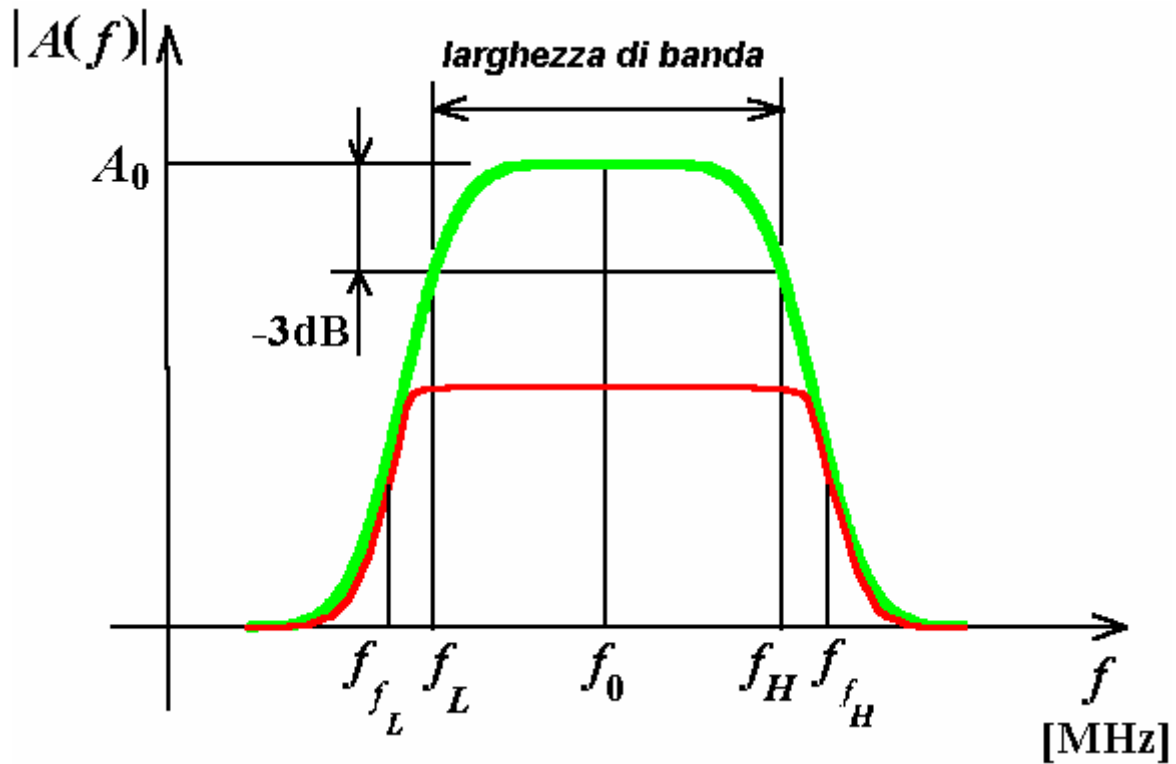
$$A_{0f} = \frac{A_0}{1 + \beta A_0}$$

$\Rightarrow$

$$A_f(f) = \frac{A_{0f}}{1 - j \frac{f_{L_f}}{f}}$$

$$f_{L_f} = \frac{f_L}{1 + \beta A_0}$$

$$\varphi(f) = \text{arctg} \frac{\text{Im}(A_f(f))}{\text{Re}(A_f(f))} = \frac{f_{L_f}}{f} \quad - \frac{d\varphi}{d\omega} > 0$$



*In alta frequenza*

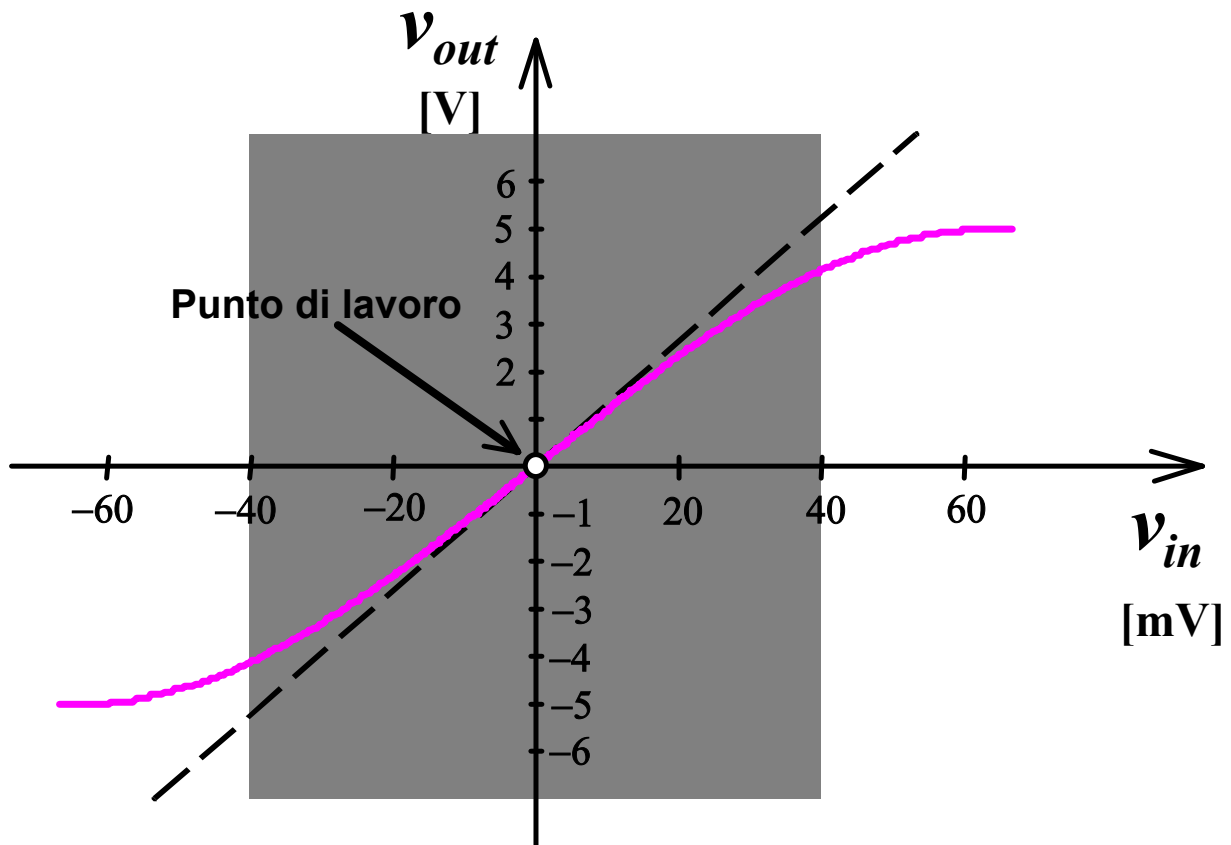
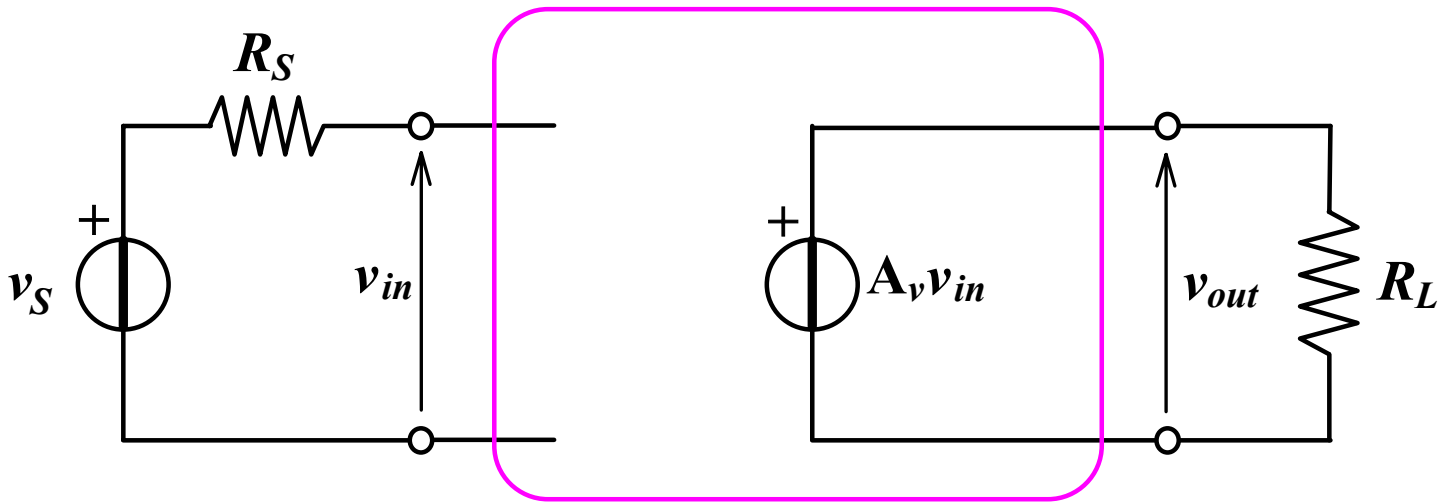
$$A_f(f) = \frac{A(f)}{1 + \beta A(f)} = \frac{\frac{A_0}{1 + j \frac{f}{f_H}}}{1 + \beta \frac{A_0}{1 + j \frac{f}{f_H}}} = \frac{A_0}{1 + j \frac{f}{f_H} + \beta A_0} = \frac{\frac{A_0}{1 + \beta A_0}}{\frac{1 + \beta A_0}{1 + \beta A_0} + j \frac{f}{(1 + \beta A_0) f_H}}$$

$$A_{0f} = \frac{A_0}{1 + \beta A_0} \Rightarrow A_f(f) = \frac{A_{0f} f}{1 + j \frac{f}{f_{Hf}}}$$

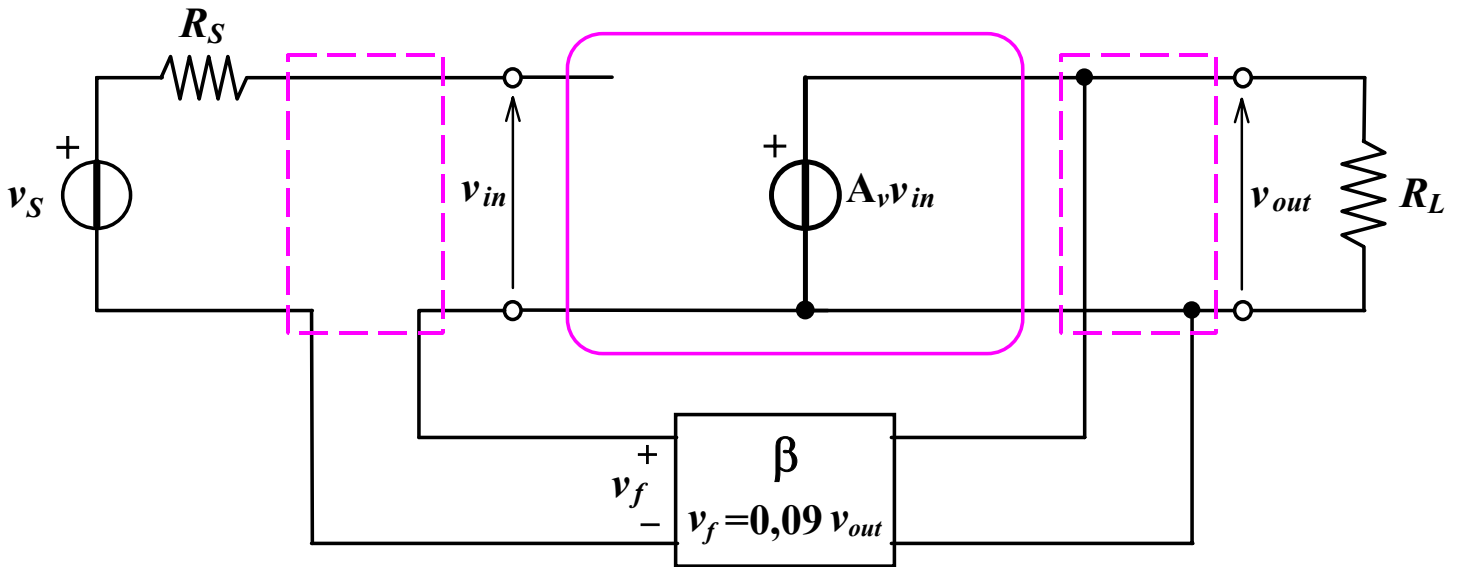
$$f_{Hf} = f_H (1 + \beta A_0)$$

$$\varphi(f) = -\arctg \frac{\text{Im}(A_f(f))}{\text{Re}(A_f(f))} = \frac{f}{f_{Hf}} \quad - \frac{d\varphi}{d\omega} > 0$$

## Distorsione non lineare



- $0 \leq |v_{in}| \leq 40\text{mV} \Rightarrow A_v = 100 \Rightarrow |v_{out}| = 100|v_{in}|$
- $40 \leq |v_{in}| \leq 60\text{mV} \Rightarrow A_v < 100 \Rightarrow |v_{out}| = 100|v_{in}| - 2500(|v_{in}| - 0,04)^2$
- $|v_{in}| > 60\text{mV} \Rightarrow A_v = 0 \Rightarrow |v_{out}| = \text{costante} = 5\text{V}$



$$v_f = 0,09 v_{out}$$

$$1 + \beta A_v = 1 + 100 \cdot 0,09 = 10$$

**Tensione di ingresso:**

$$v_{in} = v_S - v_f = v_S - \beta A_v v_{in} \Rightarrow v_{in} = \frac{v_S}{1 + \beta A_v}$$

**Tensione di uscita:**

$$v_{out} = A_v v_{in} = A_v v_S - A_v v_f = A_v v_S - \beta A_v v_{out} \Rightarrow v_{out} = \frac{A_v v_S}{1 + \beta A_v}$$

⇓

$$A_f = \frac{v_{out}}{v_S} = \frac{A_v}{1 + \beta A_v} = \frac{A_v}{10}$$

Risultati analitici

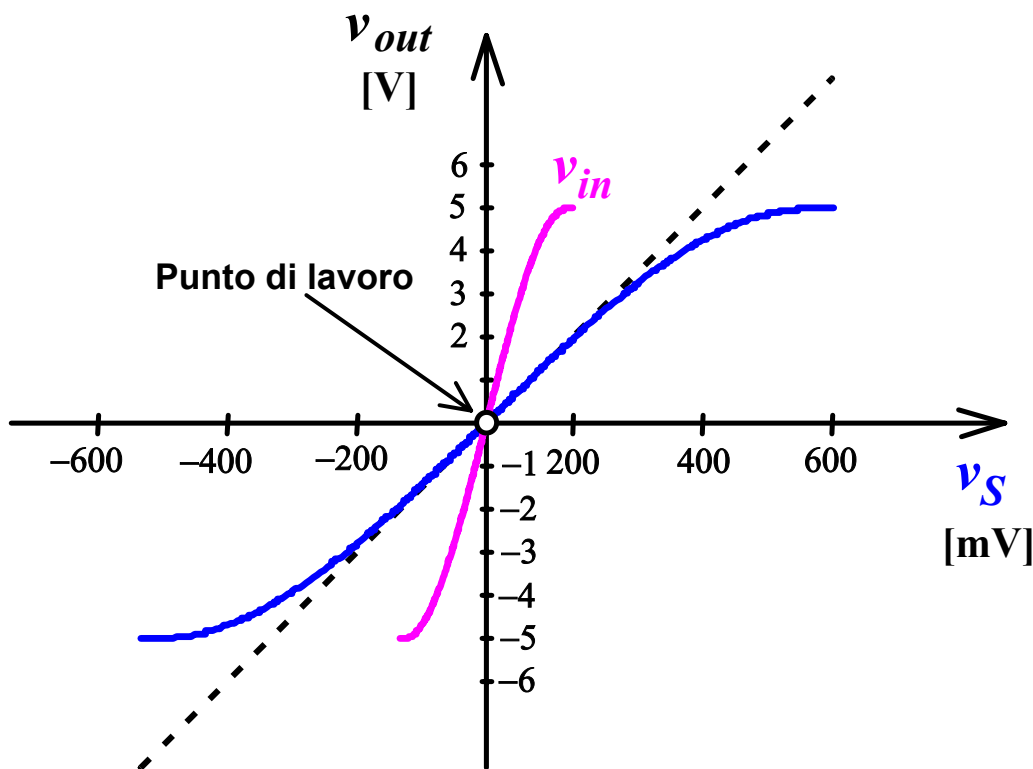
Rete senza reazione

$ v_{in} $ [mV]	$v_{out}$ [V]	$A$	$\frac{dA}{A}$
10	1.0	100	0
20	2.0	100	0
30	3.0	100	0
40	4.0	100	0
45	4.44	98,6	1,4%
50	4.75	95	5%
55	4.94	89,8	10,2%
60	5.0	83,3	16,7%

zona  
di non  
linearità

Rete con reazione

$ v_S $ [mV]	$v_{in}$ [mV]	$v_{out}$ [V]	$A_f$	$\frac{dA_f}{A_f}$
100	10	1.0	10	0
200	20	2.0	10	0
300	30	3.0	10	0
400	40	4.0	10	0
444	45	4.44	10	0
478	50	4.75	9,93	0,7%
500	55	4.94	9,88	1,2%
510	60	5.0	9,8	2%



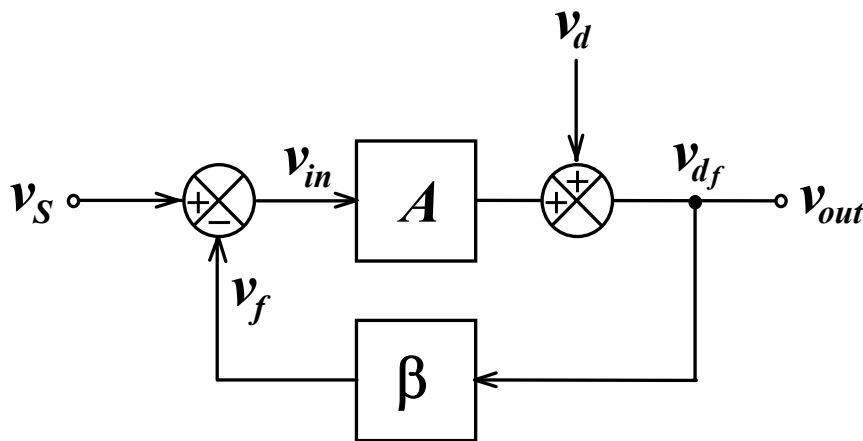
$$\frac{dA_f}{A_f} < \frac{dA}{A}$$

## Effetti della retroazione nei confronti dei disturbi e del rumore

Per un segnale sinusoidale  $\Rightarrow$  termine quadratico (II armonica)

$$v_{in}(t) = V_{iM} \text{sen } \omega t \quad \xrightarrow{V_{iM} > 40mV} \quad \text{sen}^2 \omega t = \frac{1}{2} - \frac{1}{2} \cos 2\omega t$$

In generale  $\Rightarrow$  intermodulazioni



Per la sola  $v_d$  si ha:

$$v_{df} = v_d - v_{df} \beta A$$

$$v_{df} = \frac{v_d}{1 + \beta A}$$

$$v_{out} = A v_S + v_d \quad (\text{senza reazione})$$

$$v_{out} = A_f v_S + v_{df} \quad (\text{con reazione})$$

Utilizzo di un preamplificatore  $\Rightarrow v'_S = A_P v_S = (1 + \beta A) v_S$

$\Downarrow$

$$v_{out_{f,P}} = A_f v'_S + v_{df} = A_f (1 + \beta A) v_S + v_{df} \quad (\text{con reazione})$$

In presenza di rumore si ha:  $v_{N_f} = \frac{v_N}{1 + \beta A}$

Ma deve risultare  $v_{N_P} \ll v_N$  poichè:

$$v_{N_{totale}} = v_{N_f} + v_{N_P} \cdot A_f = \frac{1}{1 + \beta A} (v_N + A \cdot v_{N_P})$$

## Effetti sulla resistenza di ingresso

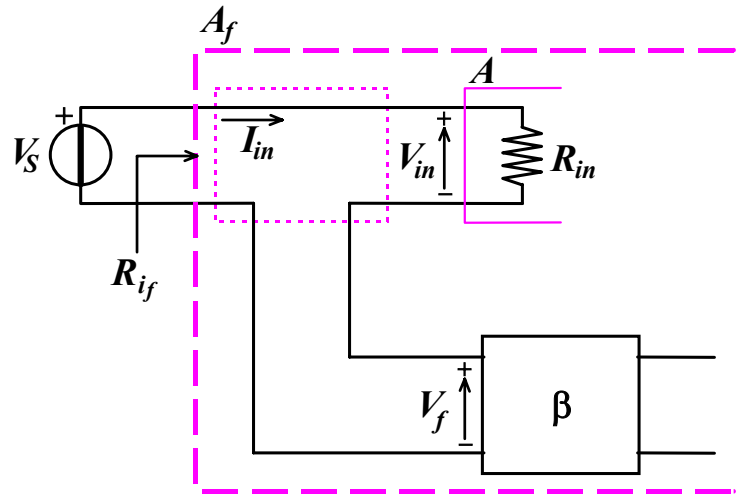
### Reazione serie

$$V_S = V_{in} + V_f = V_{in} + \beta A V_{in} =$$

$$= V_{in} (1 + \beta A)$$

$$V_f = \beta X_{out} \begin{cases} X_{out} = I_{out} \\ X_{out} = V_{out} \end{cases}$$

$$X_{out} = A V_{in}$$



$$R_{if} = \frac{V_S}{I_{in}} = \frac{V_S}{\frac{V_{in}}{R_{in}}} = \frac{V_{in} (1 + \beta A)}{V_{in}} R_{in} = \boxed{(1 + \beta A) R_{in}}$$

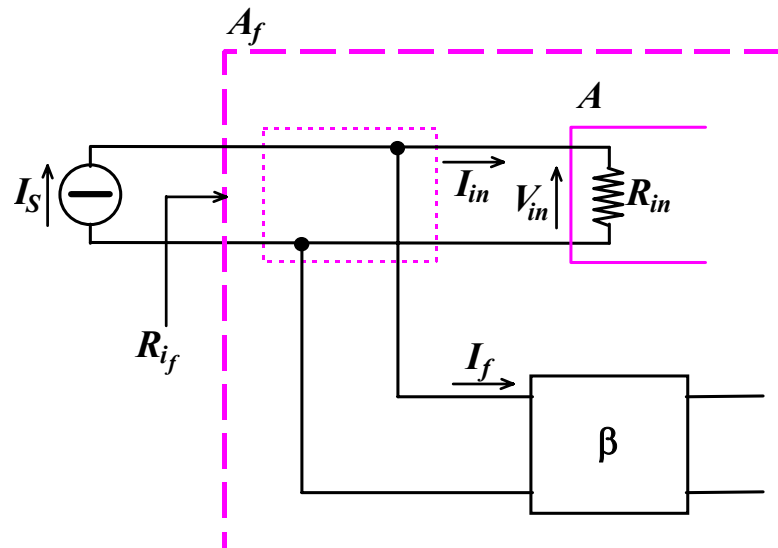
### Reazione parallelo

$$I_S = I_{in} + I_f = I_{in} + \beta A I_{in} =$$

$$= I_{in} (1 + \beta A)$$

$$I_f = \beta X_{out} \begin{cases} X_{out} = I_{out} \\ X_{out} = V_{out} \end{cases}$$

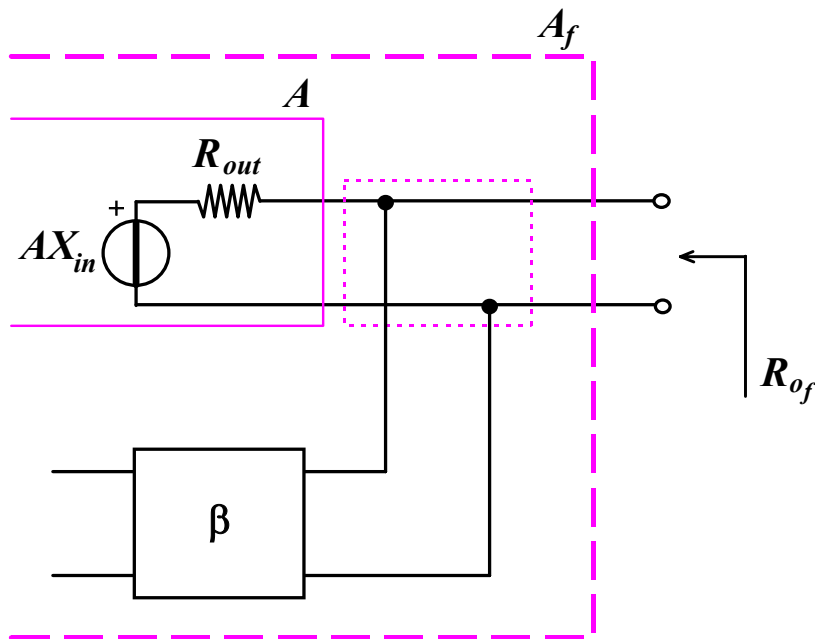
$$X_{out} = A I_{in}$$



$$R_{if} = \frac{V_{in}}{I_S} = \frac{R_{in} I_{in}}{I_S} = \frac{R_{in} I_{in}}{I_{in} (1 + \beta A)} = \boxed{\frac{R_{in}}{1 + \beta A}}$$

## Effetti sulla resistenza di uscita

Reazione di tensione (serie-parallelo, parallelo-parallelo)



**Ipotesi:**

- $A$  unidirezionale
- $\beta$  unidirezionale
- $A$  non risente degli effetti di carico

$$R_{of} = \frac{V_{oc}}{I_{sc}}$$

$oc = open\ circuit$

$sc = short\ circuit$

Poichè  $X_S = X_{in} + X_f = X_{in} + \beta AX_{in} \Rightarrow X_{in} = \frac{X_S}{1 + \beta A}$

⇓

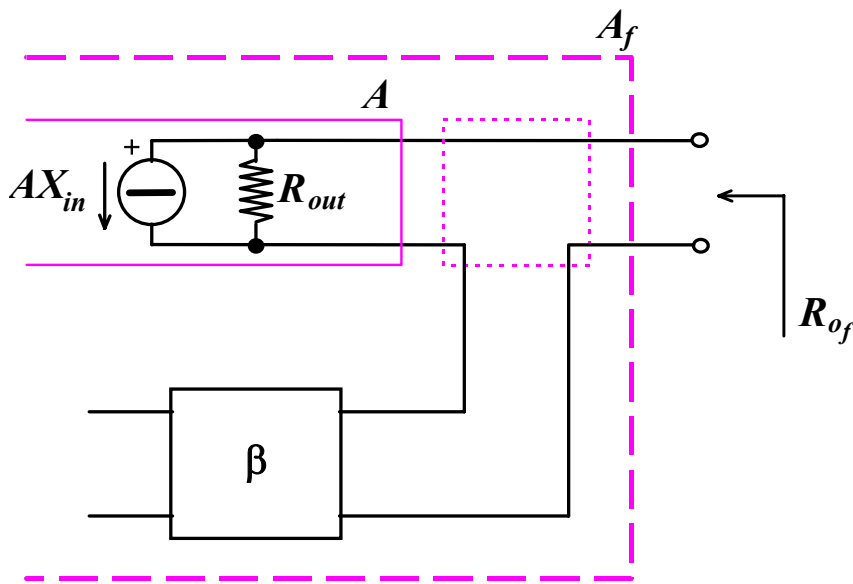
$$V_{oc} = AX_{in} = \frac{AX_S}{1 + \beta A}$$

Se l'uscita è s.c.:  $V_{out} = 0 \Rightarrow X_f = 0 \Rightarrow X_S = X_{in} \Rightarrow I_{sc} = \frac{AX_S}{R_{out}}$

⇓

$$R_{of} = \frac{AX_S}{1 + \beta A} \frac{R_{out}}{AX_S} = \boxed{\frac{R_{out}}{1 + \beta A}}$$

Reazione di corrente (serie-serie, parallelo-serie)



Ipotesi:

- $A$  unidirezionale
- $\beta$  unidirezionale
- $A$  non risente degli effetti di carico

$$R_{of} = \frac{V_{oc}}{I_{sc}}$$

*oc* = open circuit

*sc* = short circuit

Poichè quando l'uscita è o.c. non scorre corrente si ha:

$$X_f = 0 \Rightarrow X_{in} = X_S$$

⇓

$$V_{oc} = -AX_{in} \cdot R_{out} = -AX_S \cdot R_{out}$$

Essendo  $I_{sc} = -AX_{in} = -\frac{AX_S}{1 + \beta A}$

⇓

$$R_{of} = \frac{-AX_S R_{out}}{-AX_S} \cdot (1 + \beta A) = R_{out} (1 + \beta A)$$

**In realtà:**

- la rete  $A$  non è unidirezionale e risente degli effetti di carico della rete  $\beta$ , del carico  $R_L$  e della resistenza interna  $R_S$  del generatore di segnale.
- la rete  $\beta$  non è unidirezionale, carica l'amplificatore di base  $A$  e risente del carico  $R_L$  e della resistenza interna  $R_S$  del generatore di segnale.

$A_{\square}$  = guadagno unidirezionale reale che tiene conto della resistenza di carico ( $A_V, A_I, R_M, G_M$ )

$A$  = guadagno unidirezionale ideale ( $A_v, A_i, R_m, G_m$ ) dove

$$A_v = \lim_{R_L \rightarrow \infty} A_V \quad A_i = \lim_{R_L \rightarrow 0} A_I \quad R_m = \lim_{R_L \rightarrow \infty} R_M$$

$$G_m = \lim_{R_L \rightarrow 0} G_M$$

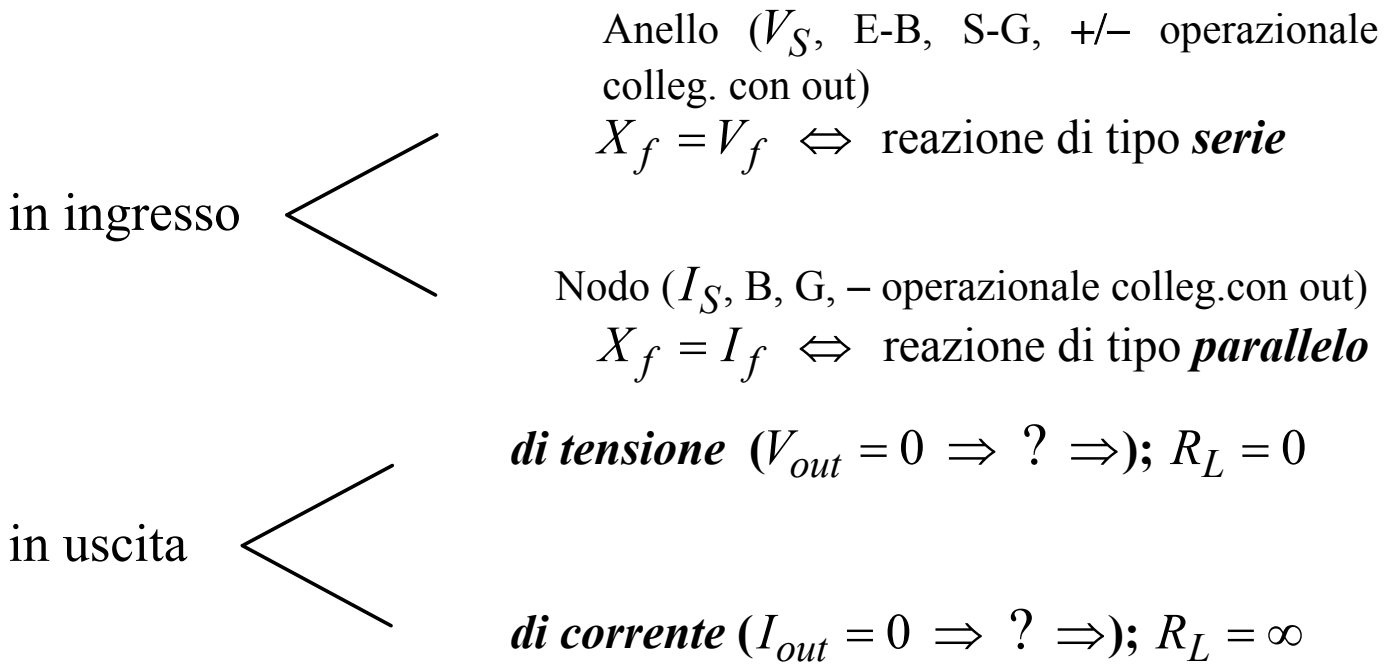
**Tabella riassuntiva**

Grandezza	Tipo di reazione			
	serie di tensione (serie-parallelo)	serie di corrente (serie-serie)	parallelo di corrente (parallelo-serie)	parallelo di tensione (parallelo-parallelo)
$R_{of}$	$\frac{R_{out}}{1 + \beta A_v}$	$R_{out} (1 + \beta G_m)$	$R_{out} (1 + \beta A_i)$	$\frac{R_{out}}{1 + \beta R_m}$
$R'_{of}$	$\frac{R'_{out}}{1 + \beta A_V}$	$\frac{R'_{out} (1 + \beta G_m)}{1 + \beta G_M}$	$\frac{R'_{out} (1 + \beta A_i)}{1 + \beta A_I}$	$\frac{R'_{out}}{1 + \beta R_M}$
$R_{if}$	$R_{in} (1 + \beta A_V)$	$R_{in} (1 + \beta G_M)$	$\frac{R_{in}}{1 + \beta A_I}$	$\frac{R_{in}}{1 + \beta R_M}$

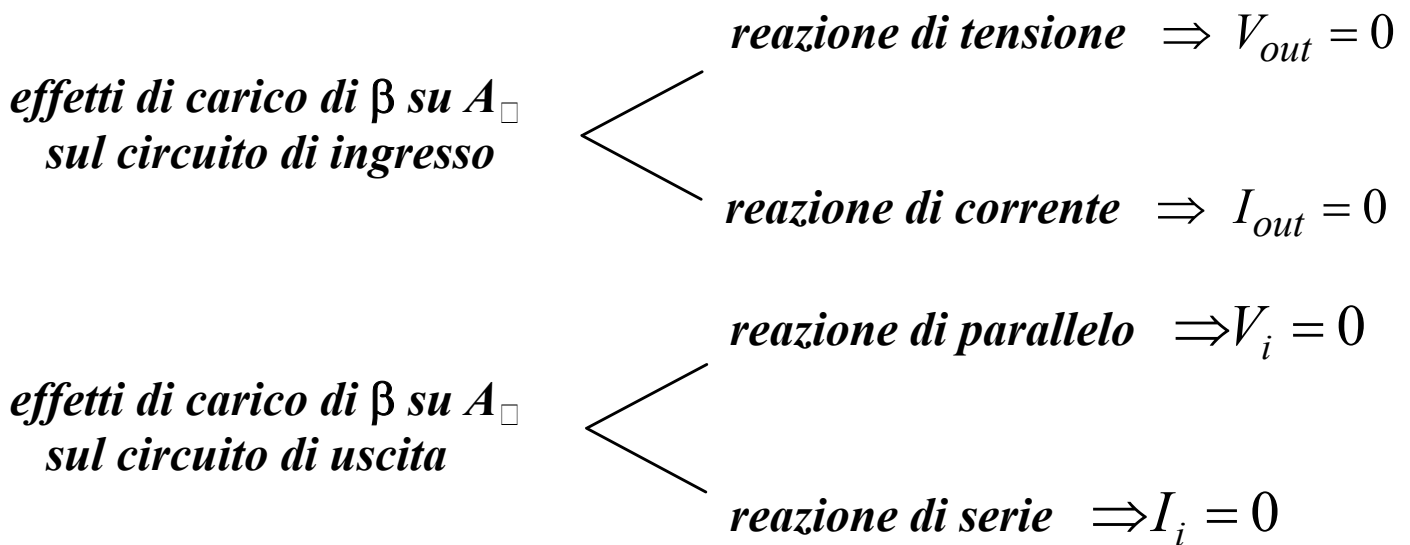
avendo posto  $R'_{of} = R_{of} \parallel R_L$  e  $R'_{out} = R_{out} \parallel R_L$

## Analisi di circuiti in retroazione

### (1) Classificazione del tipo di reazione



### (2) Rappresentazione dell'amplificatore di base



### (3) Sostituzione dei circuiti equivalenti al posto dei dispositivi attivi

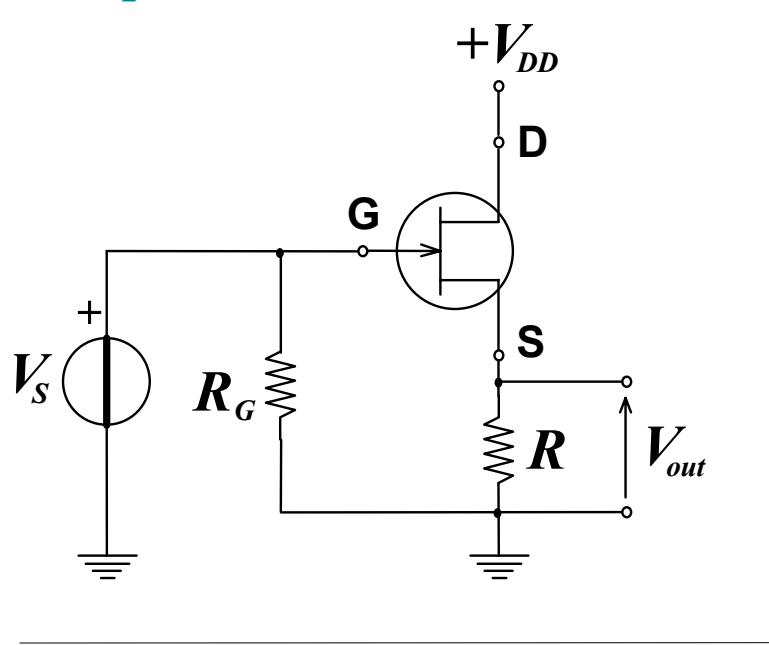
### (4) Calcolo di $X_f$ e $X_{out}$

### (5) Determinazione di $\beta = \frac{X_f}{X_{out}}$

(6) Calcolo di  $A_v$  in base alle leggi di Kirchhoff alle maglie e ai nodi

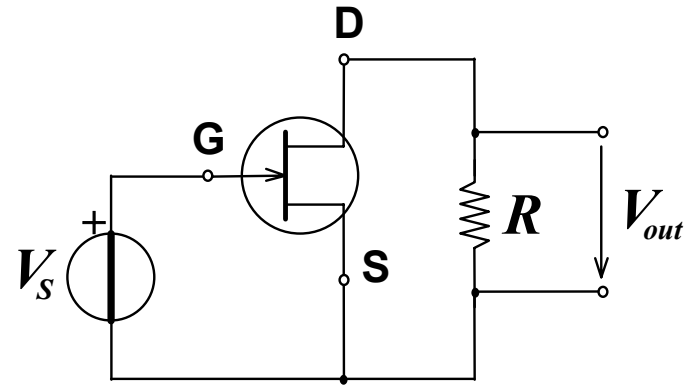
(7) Calcolo di  $S, D, A_f, R_{if}, R_{of}, R'_{of}$  con le formule note

**Esempio 1**

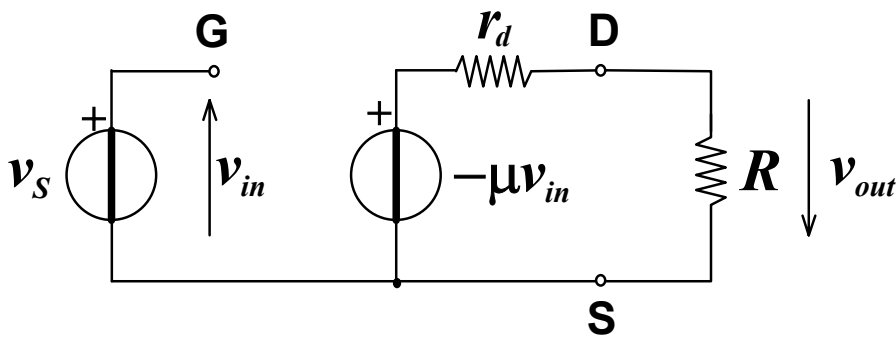


(1) reazione *serie di tensione*

(2)



(3)

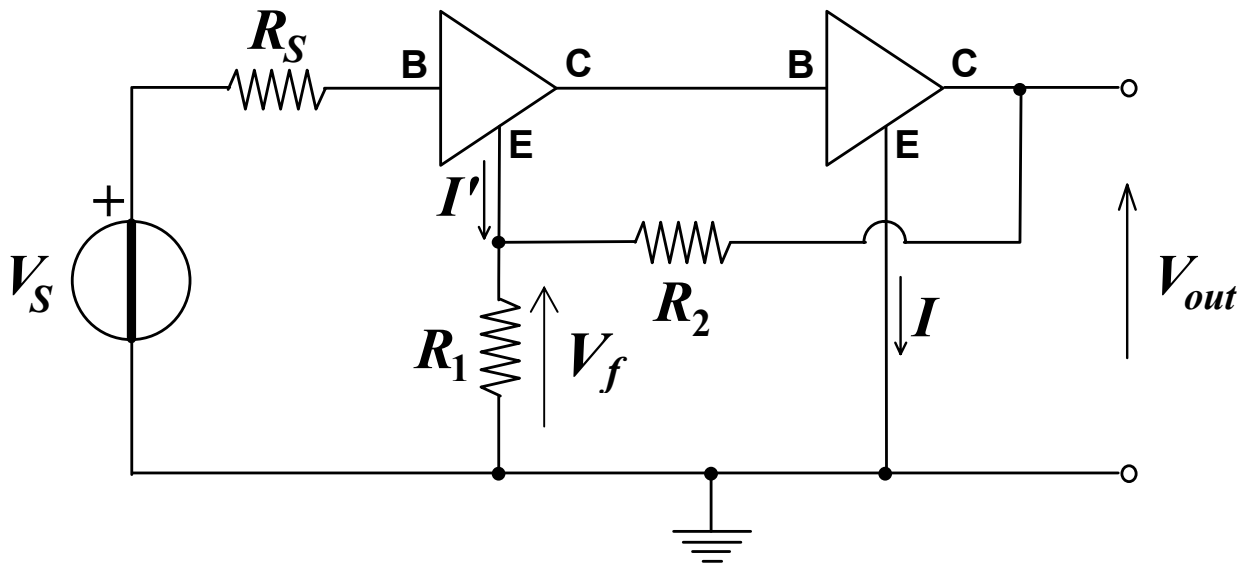


(4)  $V_f = V_{out}$       (5)  $\beta = \frac{V_f}{V_{out}} = 1$       (6)  $A_V = \frac{V_{out}}{V_{in}} = \frac{\mu V_{in}}{V_{in}} \cdot \frac{R}{R + r_d}$

$V_{in} \equiv V_S$

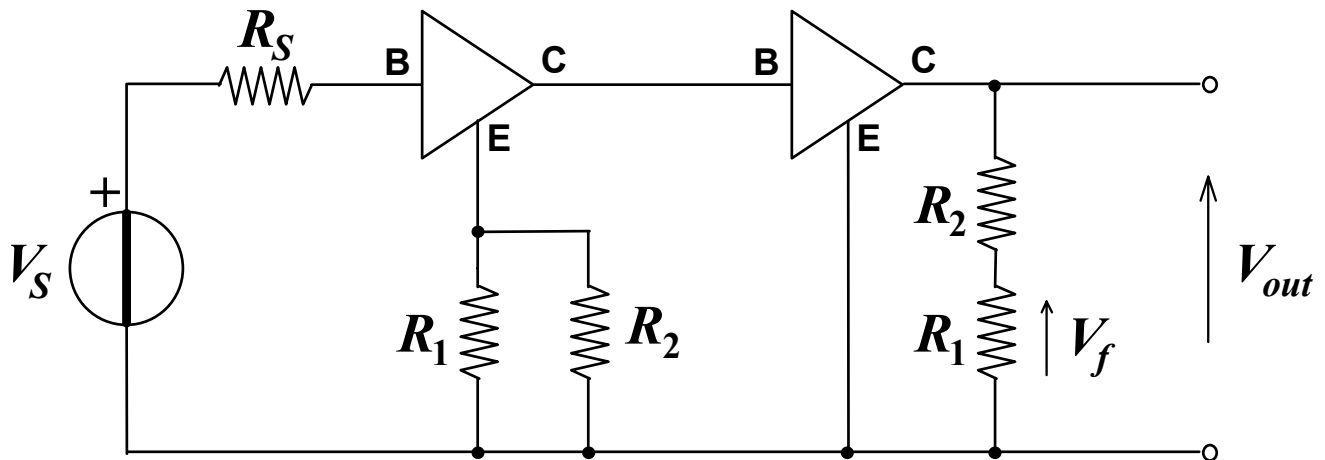
$$D = 1 + \beta A = \frac{r_d + R(1 + \mu)}{R + r_d} \qquad A_{v_f} = \frac{A_v}{D} = \frac{\mu R}{r_d + R(1 + \mu)}$$

## Esempio 2



(1) reazione *serie di tensione*

(2) ( $I' \ll I$ )

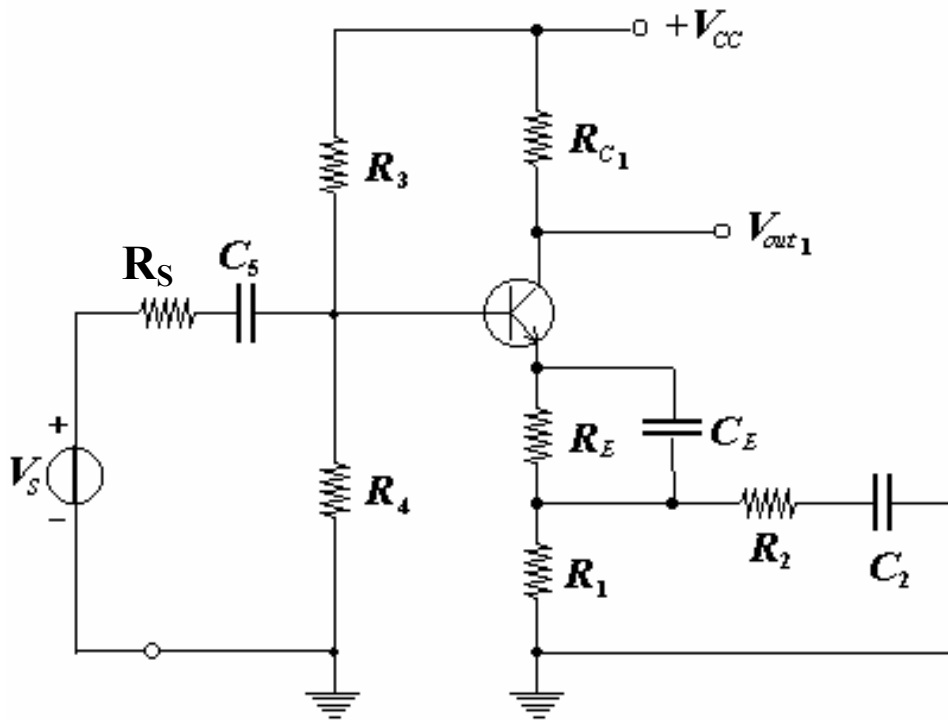


$$(4) V_f = \frac{R_1}{R_1 + R_2} V_{out}$$

$$(5) \beta = \frac{R_1}{R_1 + R_2}$$

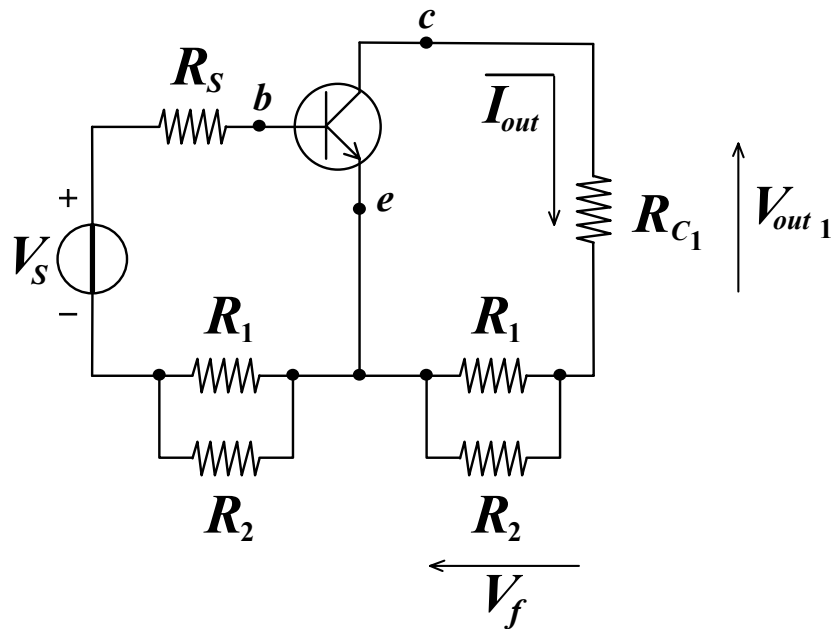
Oss.:  $A \gg 1 \Rightarrow A_{V_f} \cong \frac{1}{\beta}$

### Esempio 3



(1) reazione *serie di corrente*

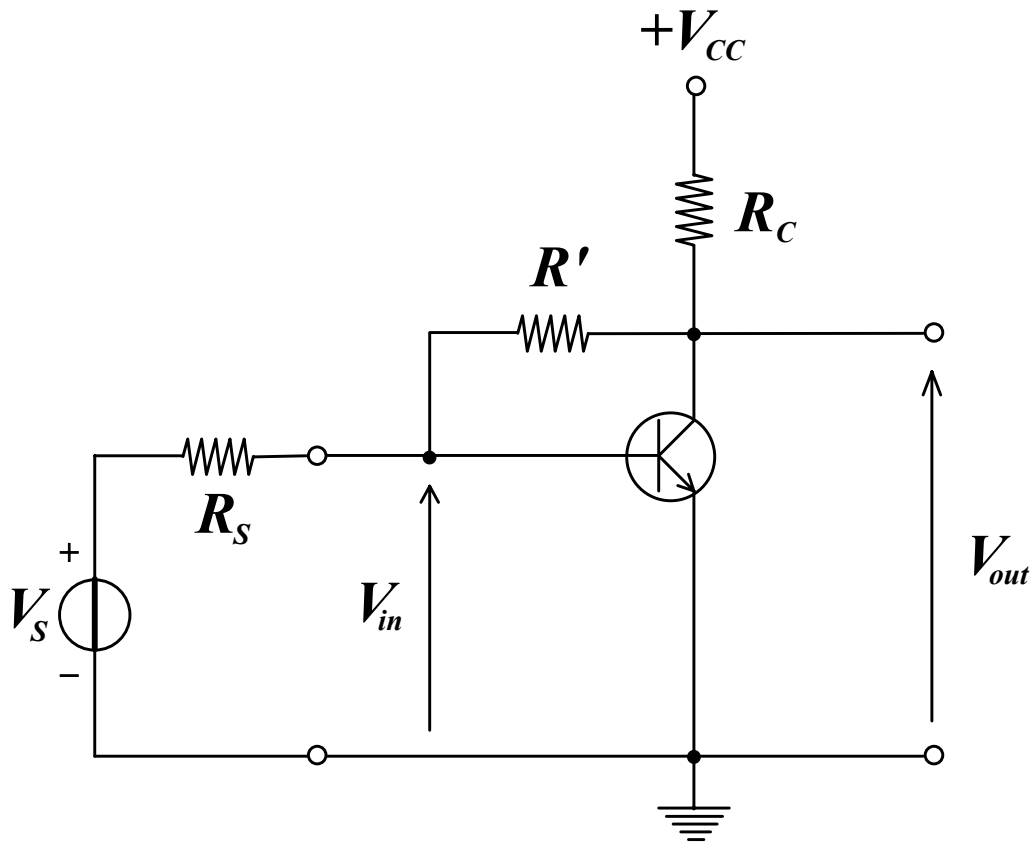
(2)



(4)  $V_f = -I_{out} R_{eq}$ .

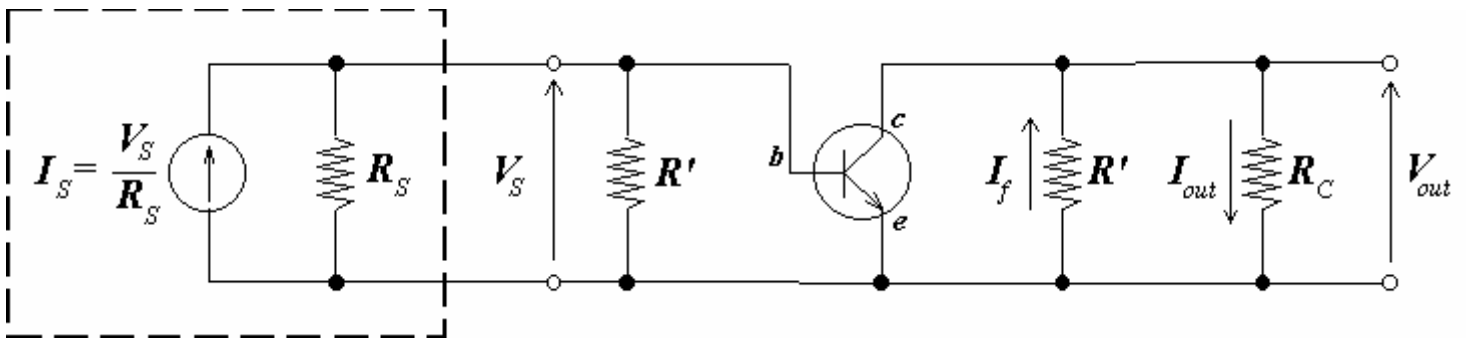
(5)  $\beta = -R_{eq}$ . con  $R_{eq} = R_1 \parallel R_2$

**Esempio 4**



(1) reazione *parallelo di tensione*

(2)



(4)  $I_f = -\frac{V_{out}}{R'}$

(5)  $\beta = -\frac{1}{R'}$

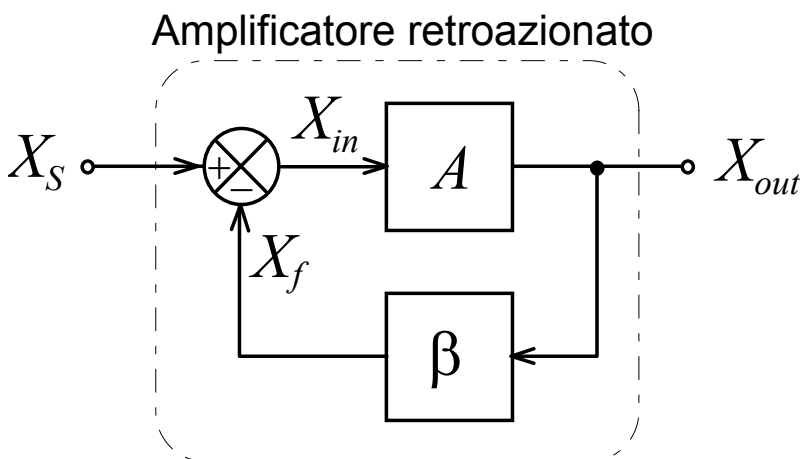
## Stabilità dei sistemi retroazionati

La reazione è **positiva** (rigenerativa) quando  $|A_f| > |A|$

$$|1 + \beta A| < 1 \Rightarrow \beta A < 0 \begin{cases} -1 \leq \beta A < 0 \\ \beta A < -1 \end{cases}$$

⇓

$$S = \frac{\frac{dA_f}{A_f}}{\frac{dA}{A}} = \frac{1}{|1 + \beta A|} > 1$$



Con  $X_S = 0$  si ha:

$$X_{in} = X_S - X_f = -X_f$$

$$X_f = \beta X_{out}$$

⇓

$$X_{out} = AX_{in} = -\beta AX_{out}$$

**Condizioni di Barkhausen:**  $\beta A = -1 \Leftrightarrow \begin{cases} |\beta A| = 1 \\ \angle \beta A = -180^\circ \end{cases}$

*Nascita di una oscillazione che si autosostiene*  $\Rightarrow$  vantaggioso per realizzare un **oscillatore**

*Non linearità dei dispositivi attivi*  $\Rightarrow$  Nascita di **intermodulazioni**

*Interessamento delle porzioni di interdizione e saturazione*  $\Rightarrow$  **Spostamento del punto di lavoro**

## Studio della stabilità

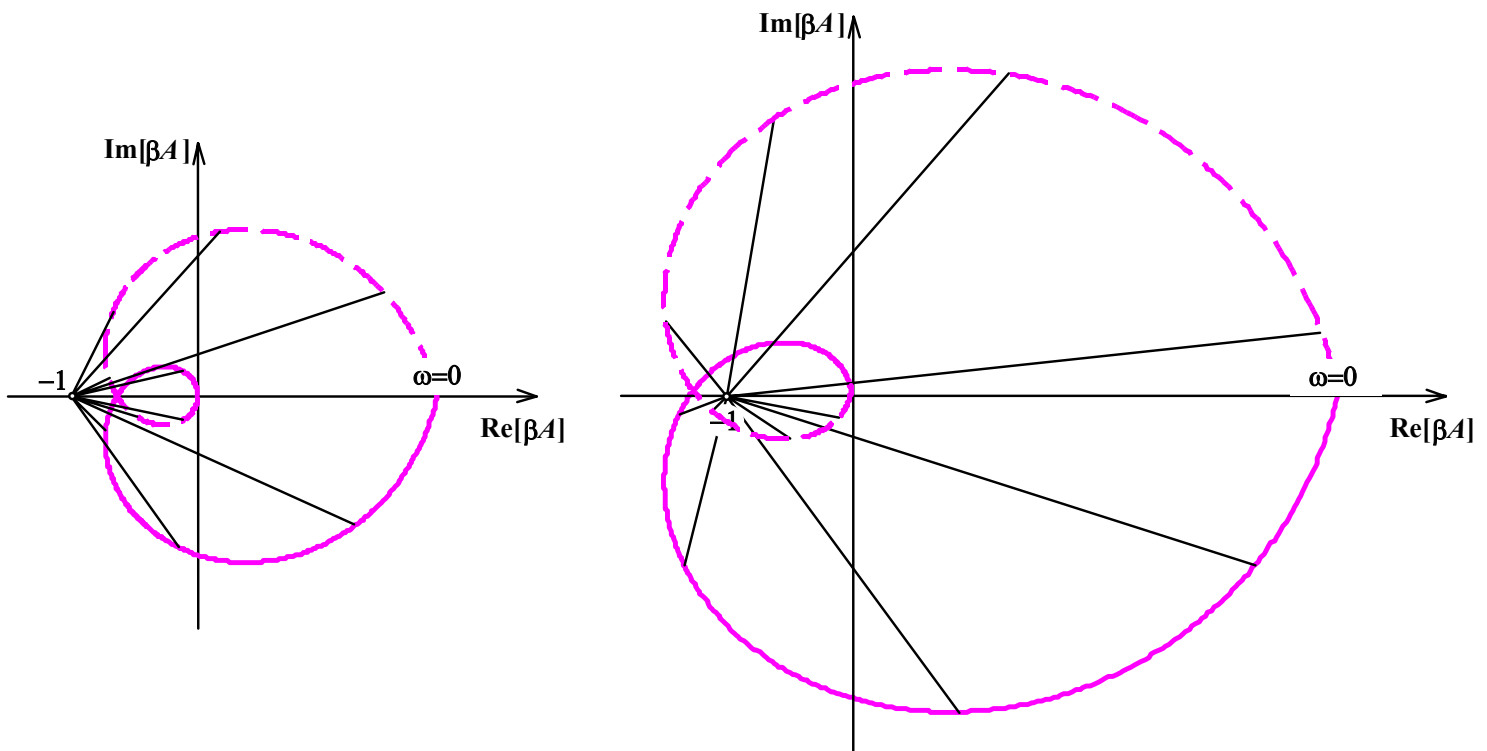
- Un amplificatore deve essere stabile sia in banda che fuori banda;
- Un sistema fisico stabile eccitato con un segnale limitato nel tempo non può rispondere con un segnale non limitato nel tempo, o che tende a crescere indipendentemente, e la funzione di trasferimento del sistema non presenta poli né nel semipiano destro né sull'asse immaginario. **Se  $A$  è stabile lo sarà anche  $A_f$  purché  $1 + \beta A$  abbia zeri solamente nel semipiano sinistro aperto.**

Metodi per lo studio della stabilità di un sistema:

- Determinazione delle radici dell'equazione algebrica che si ottiene eguagliando a 0 il deno-minatore della funzione di trasferimento;
- Criterio di Nyquist (1931);
- Diagramma di Bode.

---

## Criterio di Nyquist



Proprietà delle funzioni di trasferimento delle reti elettriche:

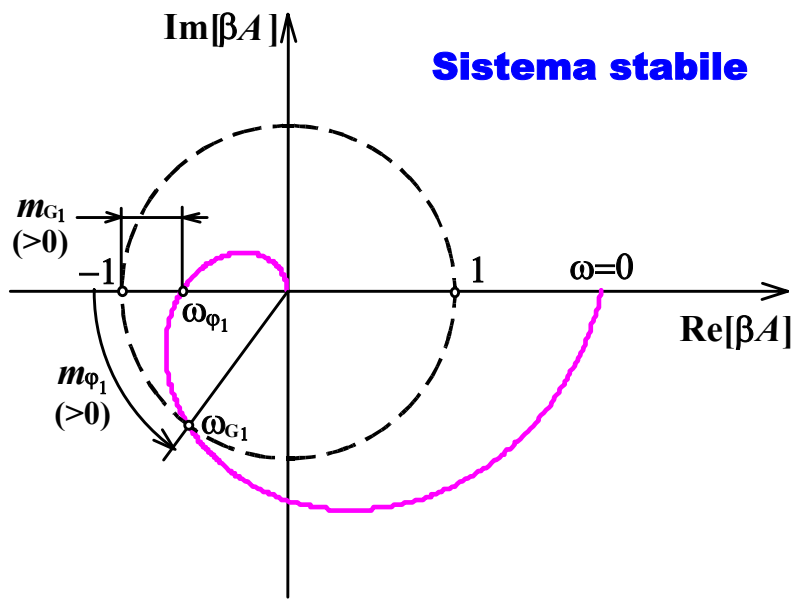
$$\beta A(j\omega) = [\beta A(-j\omega)]^*$$

## Margini di guadagno e di fase

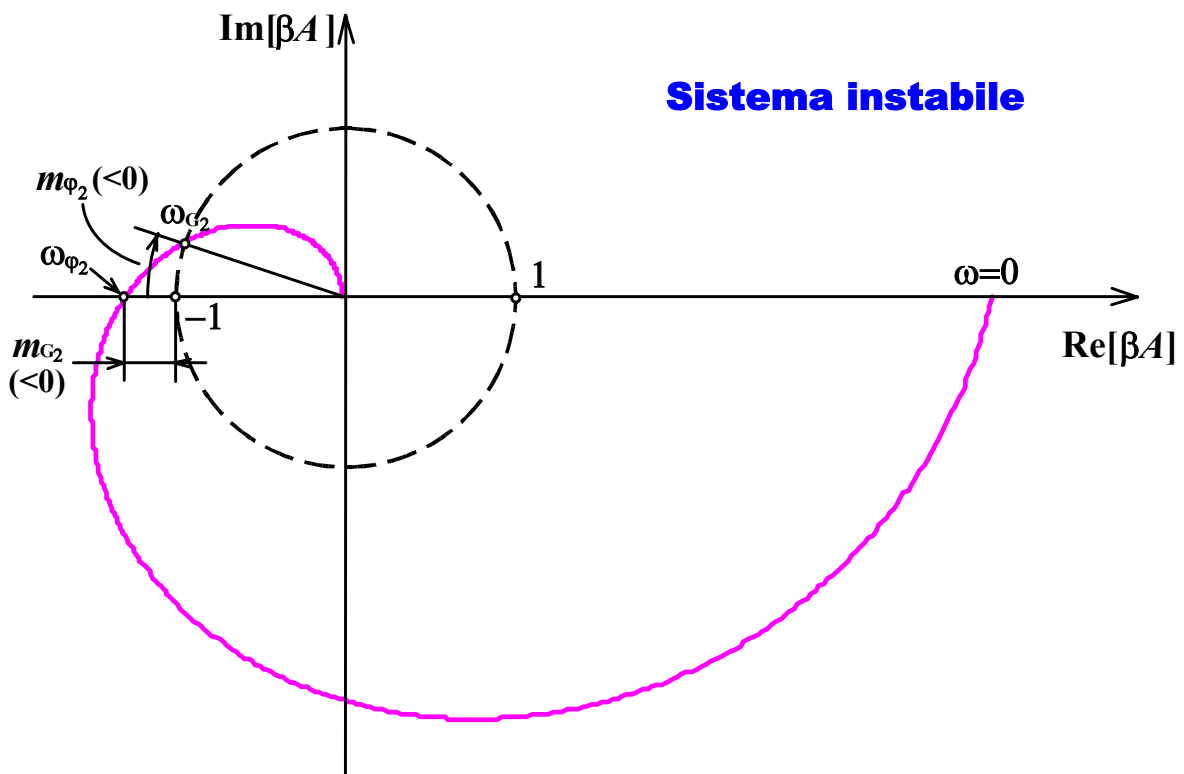
$$m_G = 20 \log 1 - 20 \log(\beta A|_{\omega=\omega_\phi}) = -[\beta A(j\omega_\phi)] \quad \text{dB}$$

$$(m_G \geq 10\text{dB})$$

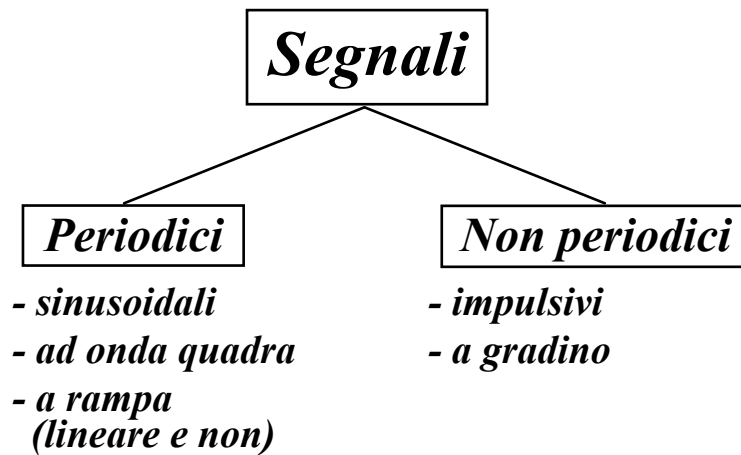
$$m_\phi = \Phi[\beta A(j\omega_G)] + 180^\circ \quad (m_\phi \geq 45^\circ) \quad \Phi[\beta A(j\omega_\phi)] = -180^\circ$$



<i>Stabilità</i>	<i>Instabilità</i>
$\omega_\phi > \omega_G$	$\omega_\phi < \omega_G$
$m_G > 0$	$m_G < 0$
$m_\phi > 0$	$m_\phi < 0$



## Generazione di segnali



## Generazione di segnali sinusoidali - Oscillatori

### Condizioni di

### Barkhausen:

$$\beta A = -1 \Leftrightarrow$$

$$\begin{cases} |\beta A| = 1 \\ \angle \beta A = -180^\circ \end{cases}$$

$$\Leftrightarrow \begin{cases} \omega_G \equiv \omega_\phi \\ m_G = 0; m_\phi = 0^\circ \end{cases}$$

$$\beta A = -1$$

⇓

$$A_f = \frac{V_{out}}{V_S} = \frac{A}{1 + \beta A} \rightarrow \infty$$

⇓

$$V_{out} = A_f \cdot V_S \rightarrow \infty \cdot 0$$

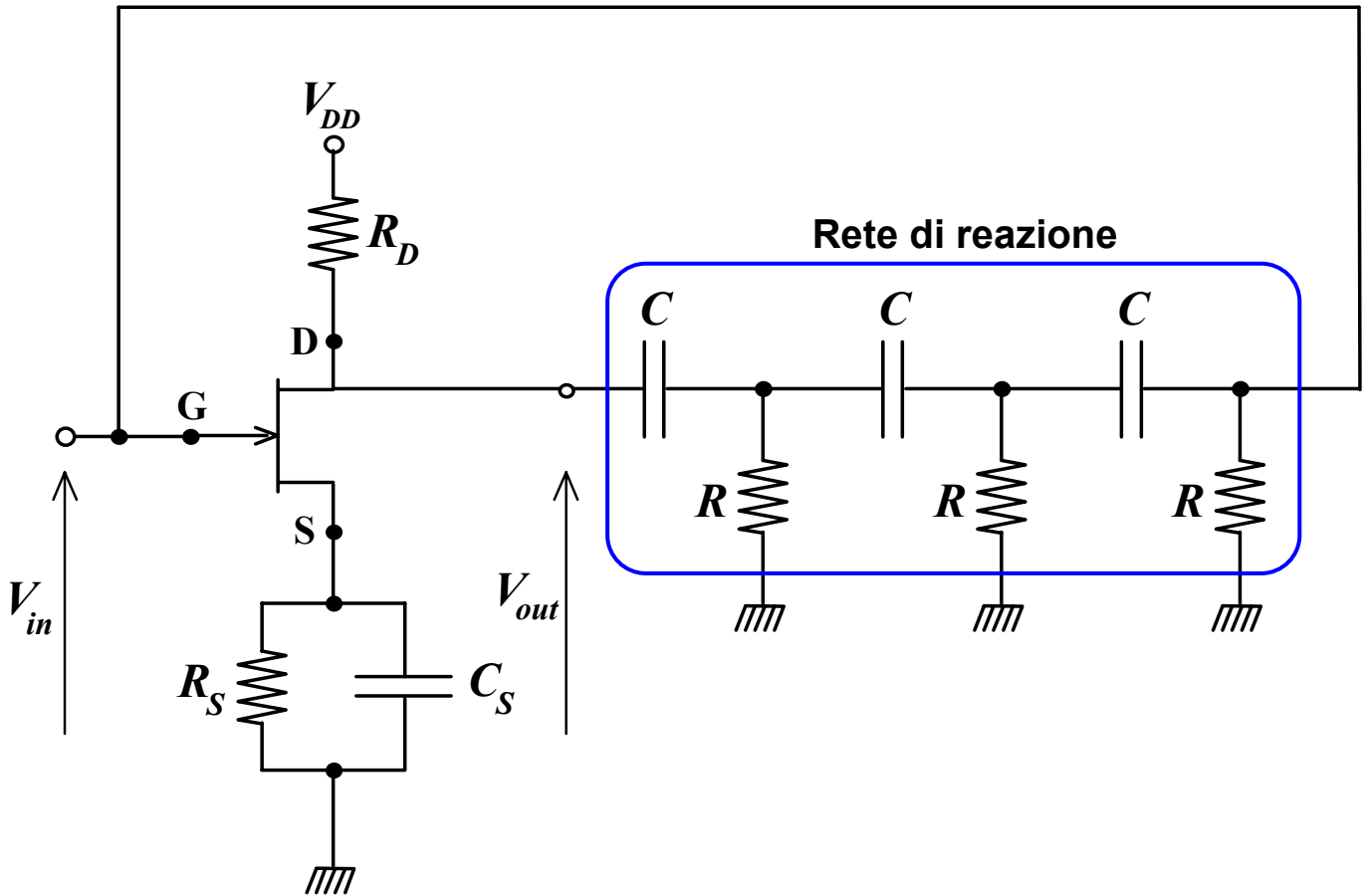
Questa condizione viene soddisfatta per un determinato valore della pulsazione ( $\omega = \omega_G = \omega_\phi$ , vedi diagramma di Nyquist).

Teoricamente lo spettro del segnale generato è costituito da una sola riga. In realtà, per effetto della non costanza dei parametri nel tempo, si ha un allargamento delle righe per cui lo spettro degenera in una banda.

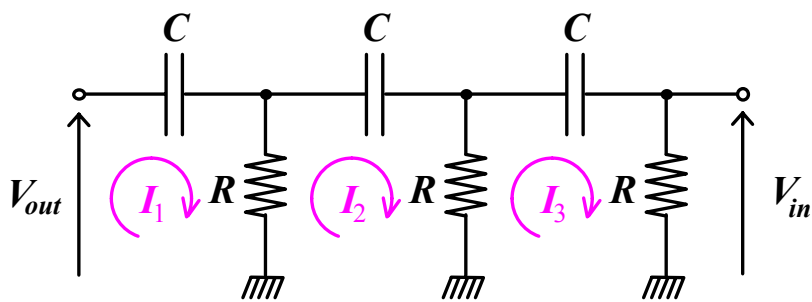
## Oscillatore a sfasamento (100's kHz)

(a FET, config. CS)

Reazione serie di tensione



- Ipotesi:**
- 1)  $A_V$  costante al variare di  $f \quad \forall f \in B$
  - 2)  $R_{in} \gg R$
  - 3)  $Z_{eq.} \gg R_{out}$



$$\begin{cases} V_{out} = I_1 \left( \frac{1}{j\omega C} + R \right) - I_2 R \\ 0 = -I_1 R + I_2 \left( \frac{1}{j\omega C} + 2R \right) - I_3 R \\ 0 = -I_2 R + I_3 \left( \frac{1}{j\omega C} + 2R \right) \end{cases}$$

Posto  $\alpha = \frac{1}{\omega RC}$  si trova

$$\begin{cases} \frac{V_{out}}{R} = I_1(1 - j\alpha) - I_2 \\ 0 = -I_1 + I_2(2 - j\alpha) - I_3 \Rightarrow I_3 = \frac{V_{out}}{R[1 - 5\alpha^2 + j(\alpha^3 - 6\alpha)]} \\ 0 = -I_2 + I_3(2 - j\alpha) \end{cases}$$

↓

$$\frac{V_{in}}{V_{out}} = \frac{I_3 R}{V_{out}} \Rightarrow \frac{V_{in}}{V_{out}} = \frac{1}{1 - 5\alpha^2 + j(\alpha^3 - 6\alpha)}$$

↓

$$\alpha^3 - 6\alpha = 0 \Rightarrow \alpha = \pm\sqrt{6} \Rightarrow \alpha = \frac{1}{\omega RC} = \sqrt{6} \Rightarrow \omega_{osc} = \frac{1}{RC\sqrt{6}}$$

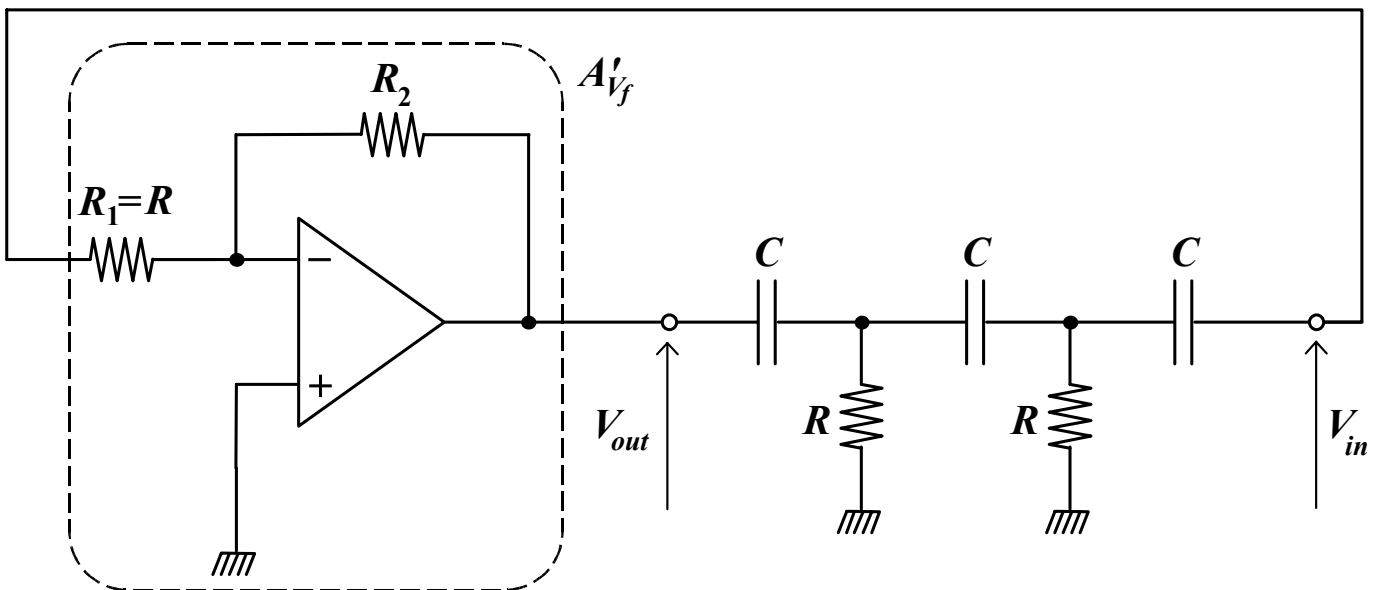
Sostituendo si ottiene  $\left(\frac{V_{in}}{V_{out}}\right)_{\omega=\omega_{osc}} = -\frac{1}{29}$        $V_{in} = V_S - V_f$        $V_{in} = -V_f$

↓

$$|\beta A| = 1 \Rightarrow |A_V| = \frac{1}{|\beta|} = 29 \text{ (meglio } |A_V| = 29 \cdot 1,05 \text{ (+5\%))}$$

(con a.o.)

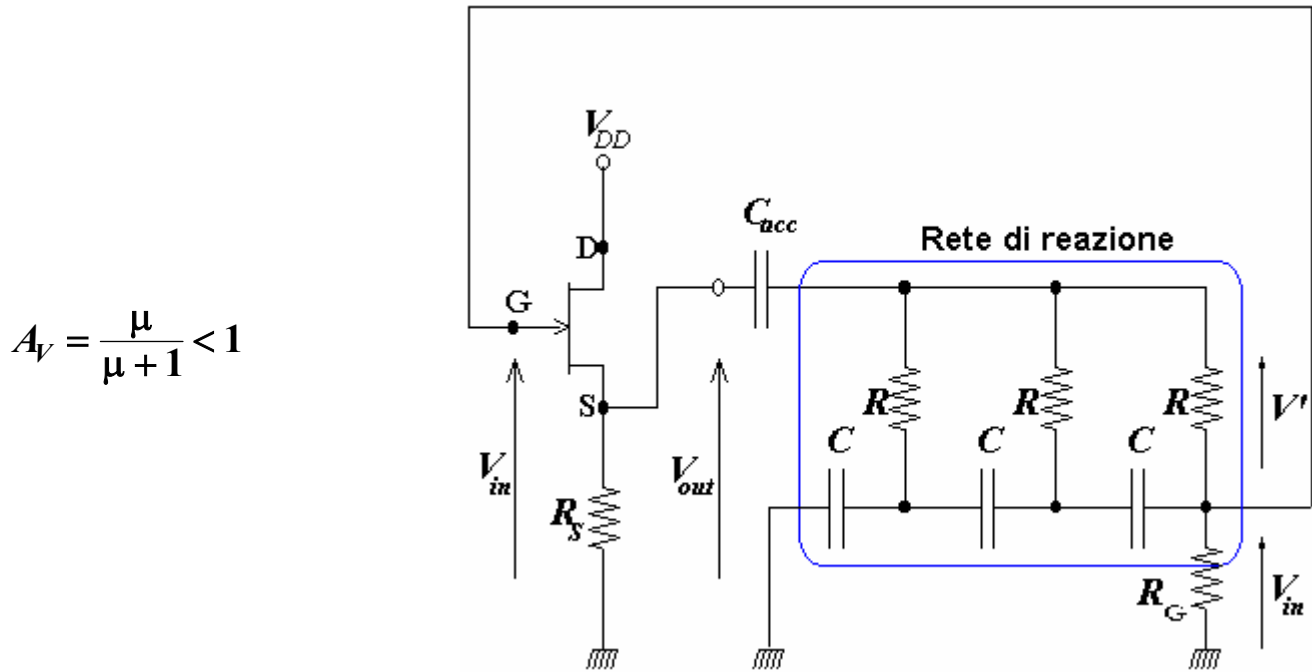
**Reazione positiva serie di tensione**



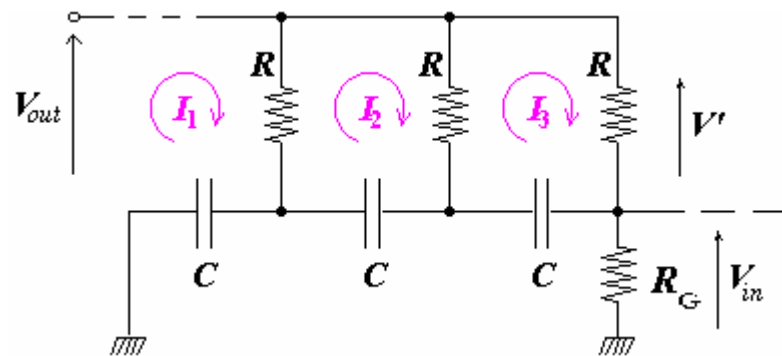
**Reazione negativa parallelo di tensione**

In questo caso risulta  $A_{V_f} = \frac{A'_{V_f}}{1 + \beta A'_{V_f}}$  dove  $A'_{V_f} = -\frac{R}{R} \frac{2}{1} = -29$

(con FET in config. CD)



$$A_v = \frac{\mu}{\mu + 1} < 1$$



Procedendo come nel caso precedente:

$$\frac{V'}{V_{out}} = \frac{1}{1 - 5\alpha^2 + j(\alpha^3 - 6\alpha)}$$

$$\Downarrow$$

$$V' = \frac{V_{out}}{1 - 5\alpha^2 + j(\alpha^3 - 6\alpha)}$$

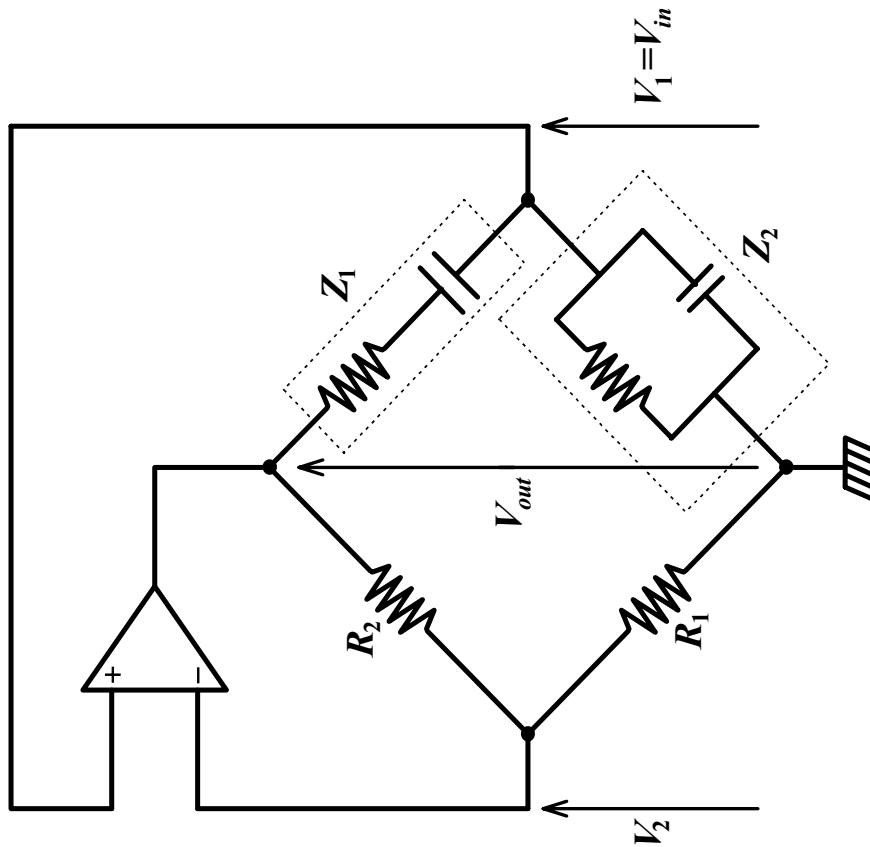
Quindi  $\omega_{osc} = \frac{1}{RC\sqrt{6}}$ . Essendo però  $V_{out} = V_{in} + V'$ , dividendo per  $V_{out}$  si ha:

$$\beta = \frac{V_{in}}{V_{out}} = 1 - \frac{V'}{V_{out}} = 1 - \left(-\frac{1}{29}\right) = 1 + \frac{1}{29} = \frac{30}{29} \cong 1,034$$

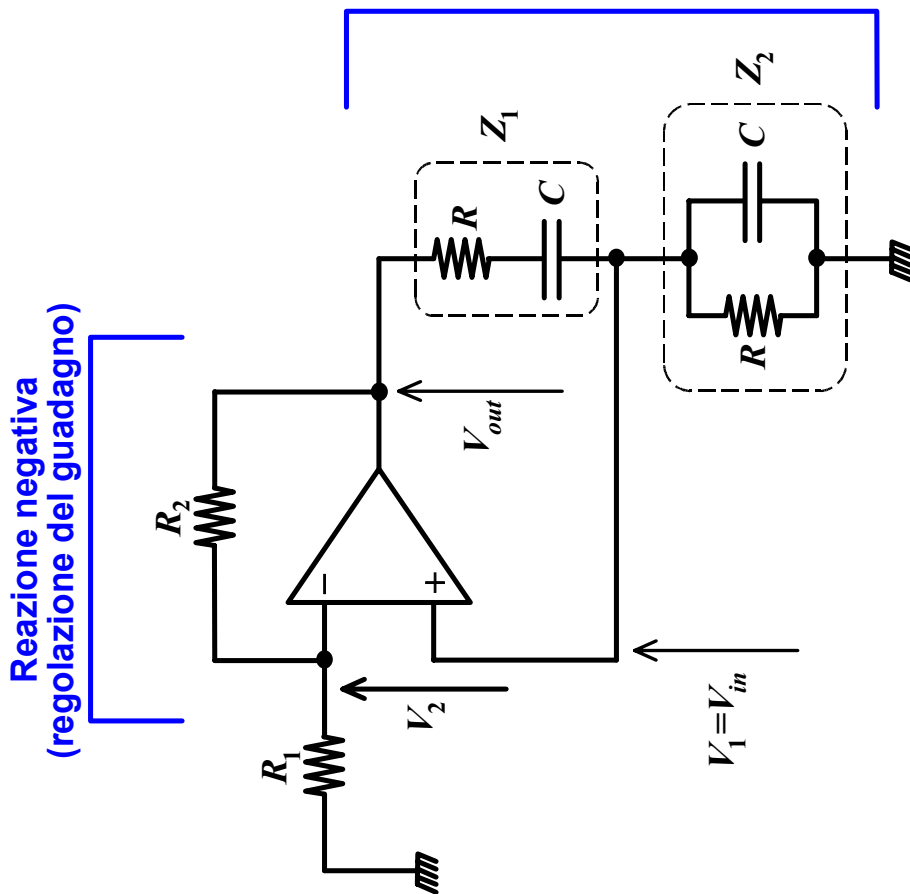
Pur essendo  $A_v < 1$  si riesce ad avere  $|\beta A_v| > 1$  per un valore di  $\mu$  sufficientemente elevato.

Ad esempio, per  $\mu = 50 \Rightarrow |\beta A_v| = 1,034 \cdot \frac{50}{50+1} \cong 1,014$ .

# Oscillatore a ponte di Wien



Reazione positiva (sfasamento e ampiezza)



$$V_{in} = V_1 = V_2 = \frac{R_1}{R_1 + R_2} V_{out} \Rightarrow V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

$$\text{Ma: } V_{in} = \left(\frac{Z_2}{Z_1 + Z_2}\right) V_{out} \Rightarrow V_{out} = \left(\frac{Z_2}{Z_1 + Z_2}\right) \left(1 + \frac{R_2}{R_1}\right) V_{out}$$

$$\Downarrow$$

$$\left(\frac{Z_2}{Z_1 + Z_2}\right) \left(1 + \frac{R_2}{R_1}\right) = 1$$

Posto  $\alpha' = \omega RC$  si trova:

$$\frac{Z_2}{Z_1 + Z_2} = \frac{\frac{R}{1 + j\alpha'}}{\frac{1 + j\alpha'}{j\omega C} + \frac{R}{1 + j\alpha'}} = \frac{\frac{R}{1 + j\alpha'}}{\frac{(1 + j\alpha')^2 + j\alpha'R}{j\omega C (1 + j\alpha')}} = \frac{j\alpha'R}{1 - \alpha'^2 + 2j\alpha'R + j\alpha'R} =$$

$$= \frac{j\alpha'R}{1 - \alpha'^2 + 3j\alpha'R} \cdot \frac{j}{j} = \frac{-\alpha'R}{j - j\alpha'^2 - 3\alpha'R} = \frac{\alpha'R}{3\alpha'R + j(\alpha'^2 - 1)}$$

$$\Downarrow$$

$$\alpha'^2 - 1 = 0 \Rightarrow \alpha' = \omega RC = 1 \Rightarrow$$

$$\omega_{osc} = \frac{1}{RC}$$

$$\Downarrow$$

$$\frac{Z_2}{Z_1 + Z_2} = \frac{1}{3} \Rightarrow 1 + \frac{R_2}{R_1} = 3 \Rightarrow$$

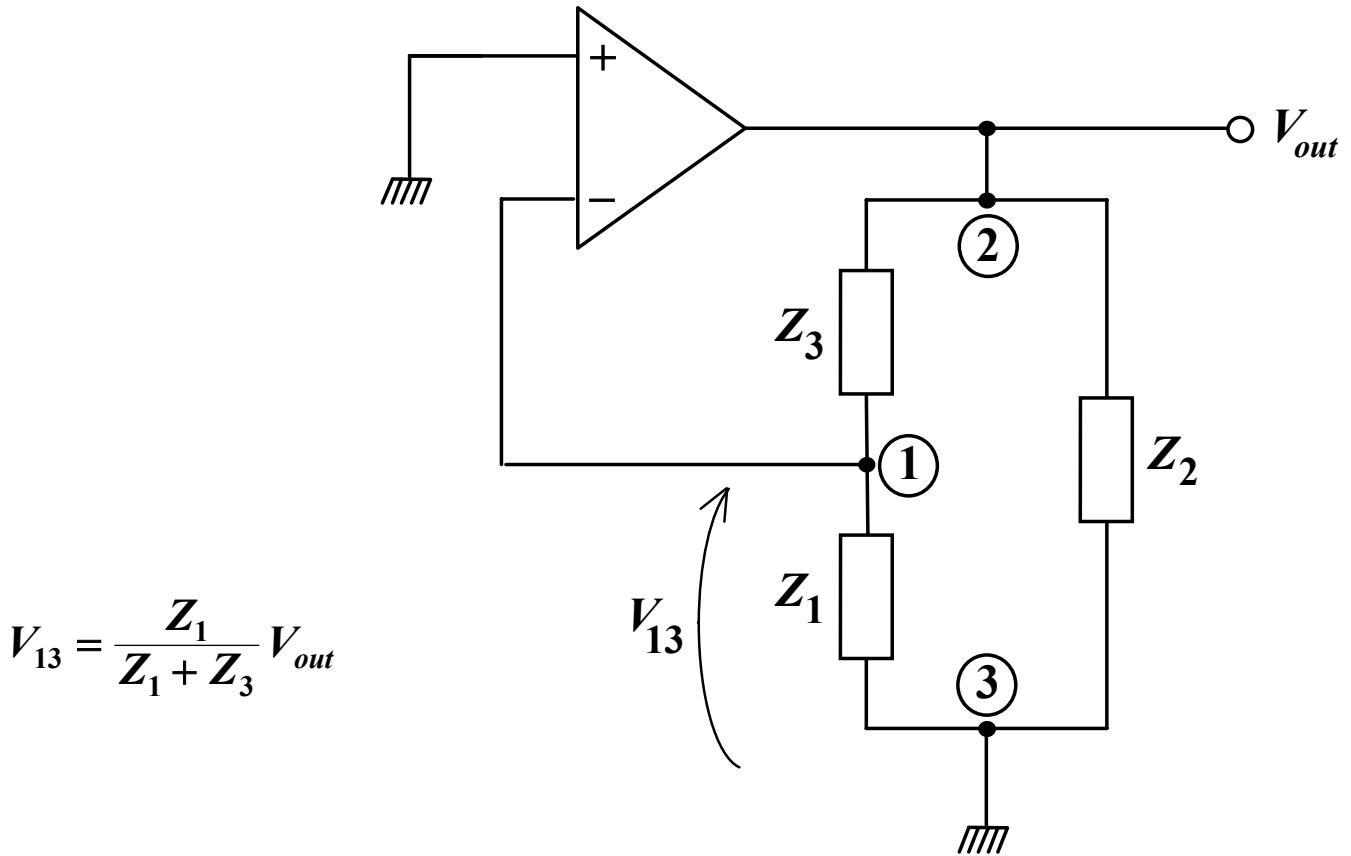
$$R_2 = 2R_1$$

**Problema della stabilizzazione dell'ampiezza della tensione di uscita. Soluzioni:**

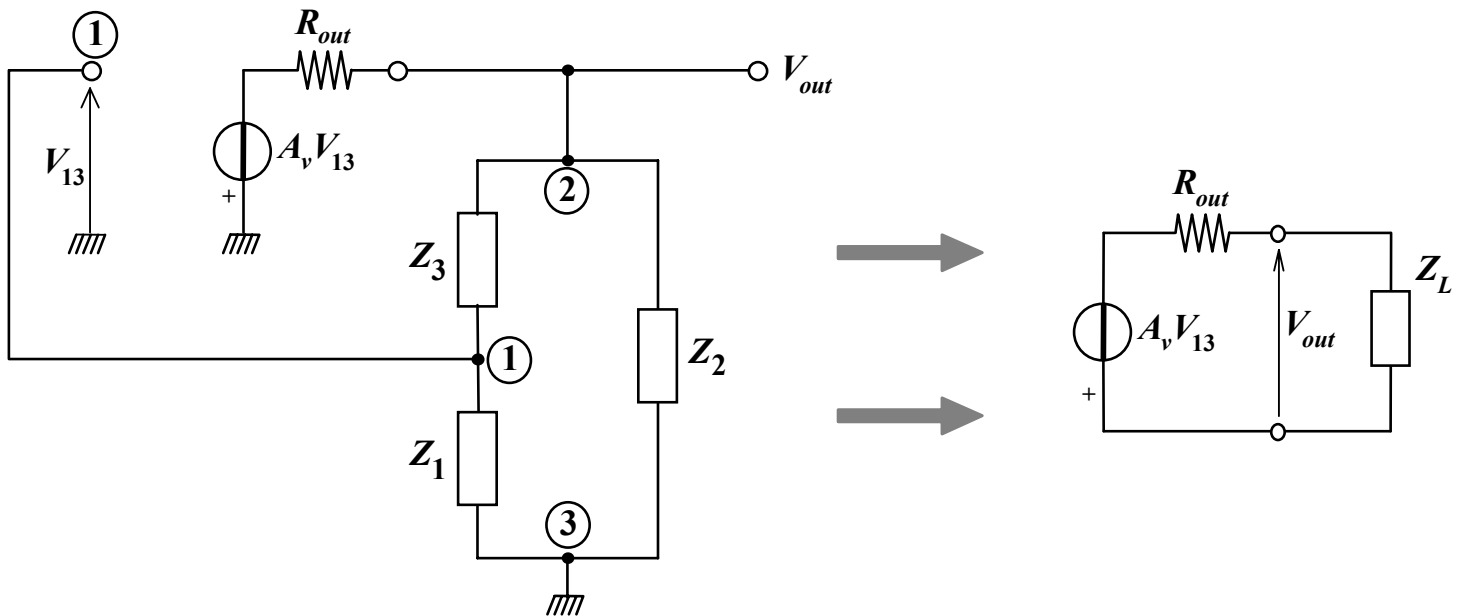
*Al posto di  $R_1$  si può inserire un sensistor (coefficiente termico positivo)*

*Al posto di  $R_2$  si può inserire un termistor (coefficiente termico negativo)*

## Oscillatori a tre punti



### Schematizzazione adottata per l'analisi del circuito



dove  $Z_L = Z_2 \parallel (Z_1 + Z_3) = \frac{(Z_1 + Z_3) Z_2}{Z_1 + Z_2 + Z_3}$

$$V_{out} = ?$$

$$V_{out} = -A_v V_{13} \cdot \frac{Z_L}{R_{out} + Z_L} \Rightarrow V_{out} = -A_v \cdot \frac{Z_L}{R_{out} + Z_L} \cdot V_{out} \frac{Z_1}{Z_1 + Z_3}$$

⇓

$$-A_v \cdot \frac{Z_L}{R_{out} + Z_L} \cdot \frac{Z_1}{Z_1 + Z_3} = 1$$

⇓

$$-A_v \cdot \frac{(Z_1 + Z_3) \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3}}{R_{out} + (Z_1 + Z_3) \cdot \frac{Z_2}{Z_1 + Z_2 + Z_3}} \cdot \frac{Z_1}{Z_1 + Z_3} = \frac{-A_v Z_1 Z_2}{R_{out}(Z_1 + Z_2 + Z_3) + Z_2(Z_1 + Z_3)} = 1$$

$$Z_i = jX_i \begin{cases} j\omega L \\ \frac{1}{j\omega C} \end{cases}$$

⇓

$$\begin{aligned} & \frac{-A_v jX_1 \cdot jX_2}{jR_{out}(X_1 + X_2 + X_3) + jX_2(jX_1 + jX_3)} = \\ & = \frac{A_v X_1 X_2}{jR_{out}(X_1 + X_2 + X_3) - X_2(X_1 + X_3)} = 1 \end{aligned}$$

⇓

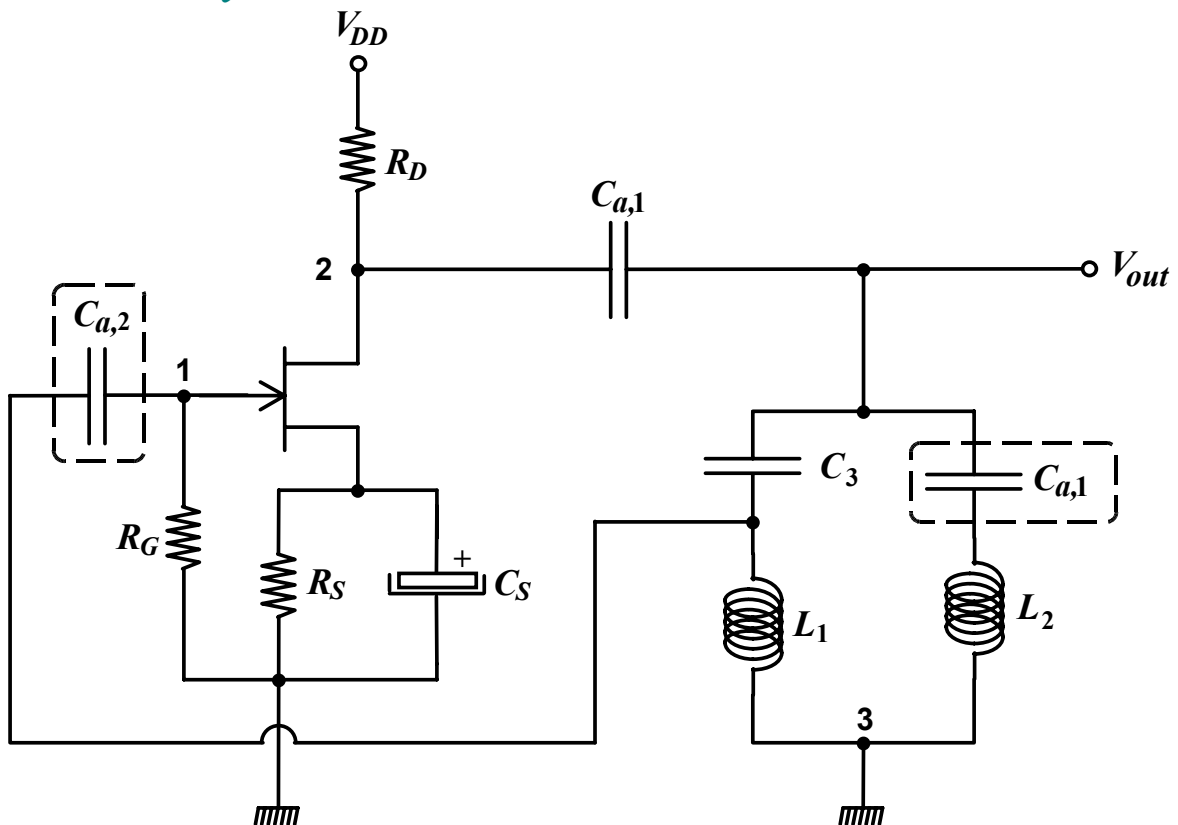
$$\boxed{X_1 + X_2 + X_3 = 0} \Rightarrow X_1 + X_3 = -X_2$$

⇓

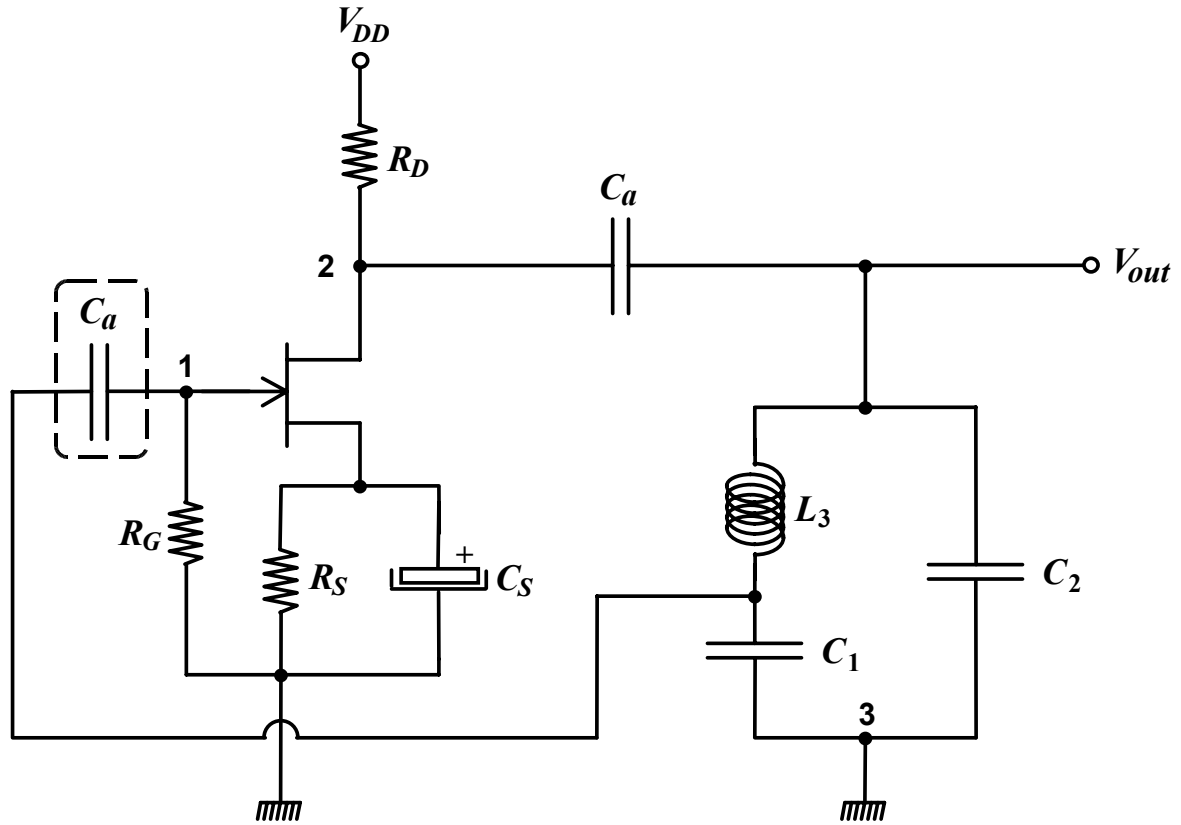
$$\frac{A_v X_1 X_2}{-X_2(-X_2)} = \frac{A_v X_1}{X_2} = 1 \Rightarrow \boxed{A_v = \frac{X_2}{X_1}} \quad \text{P } X_1 \text{ e } X_2 \text{ dello stesso segno}$$

Oscillatore Hartley	Oscillatore Colpitts
$X_1 = \omega L_1$	$X_1 = -\frac{1}{\omega C_1}$
$X_2 = \omega L_2$	$X_2 = -\frac{1}{\omega C_2}$
$X_3 = -\frac{1}{\omega C_3}$	$X_3 = \omega L_3$
$\omega L_1 + \omega L_2 - \frac{1}{\omega C_3} = 0 \Big _{\omega=\omega_{osc}}$	$-\frac{1}{\omega C_1} - \frac{1}{\omega C_2} + \omega L_3 = 0 \Big _{\omega=\omega_{osc}}$
$\omega_{osc} = \sqrt{\frac{1}{C_3} \left( \frac{1}{L_1 + L_2} \right)}$	$\omega_{osc} = \sqrt{\frac{1}{L_3} \left( \frac{1}{C_1} + \frac{1}{C_2} \right)}$
$A_V = \frac{L_2}{L_1}$	$A_V = \frac{C_1}{C_2}$

### Oscillatore Hartley

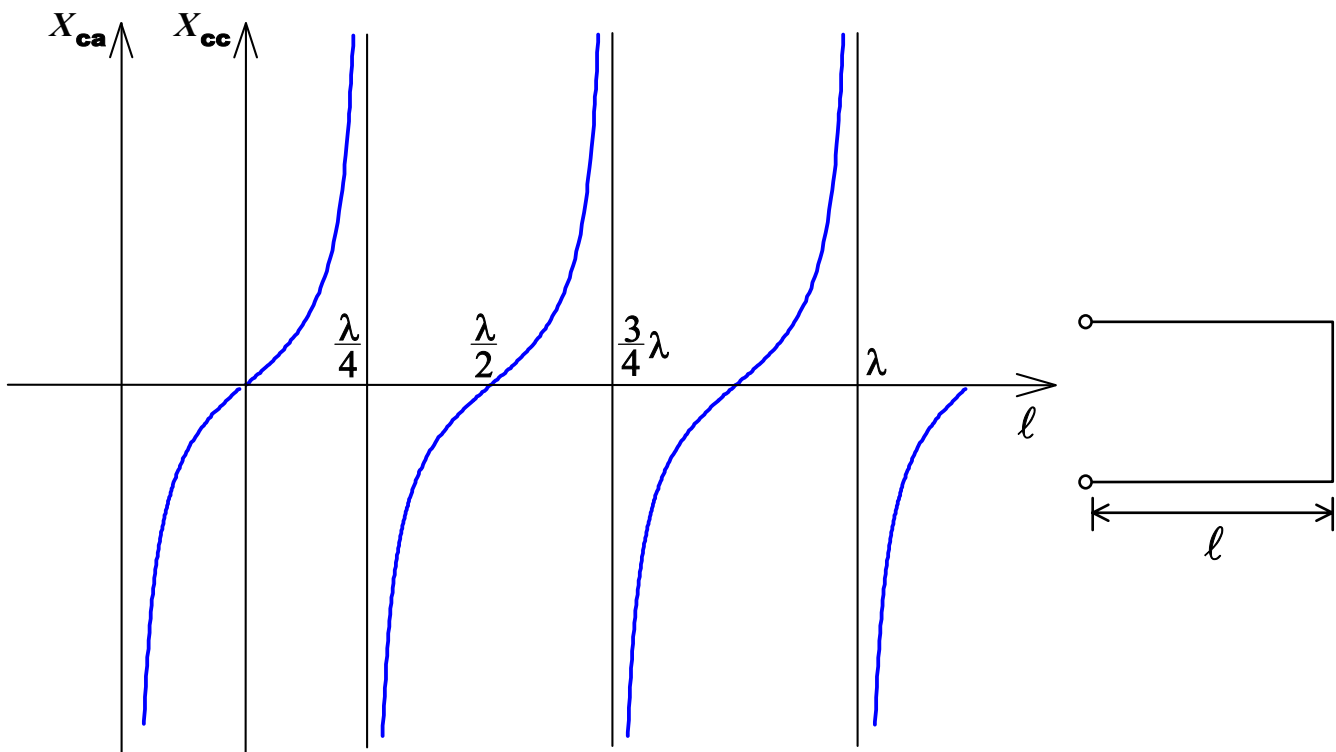


## Oscillatore Colpitts

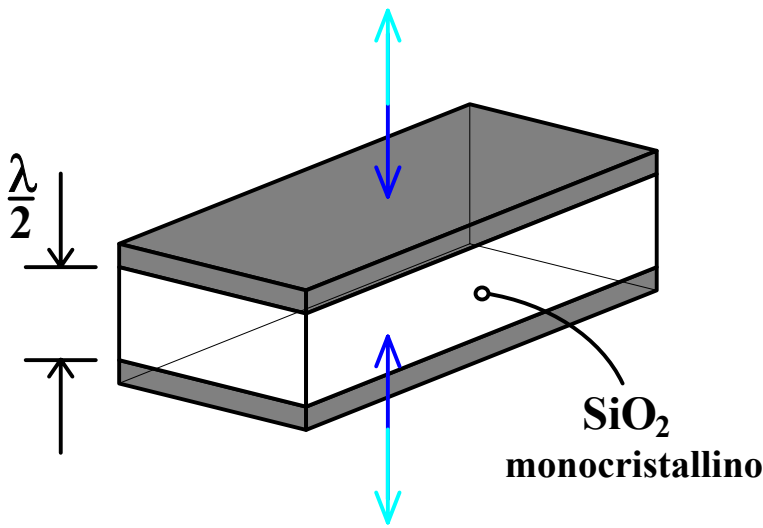


### Utilizzo di stub alle alte frequenze

Parametri parassiti: tempo, temperatura, pressione, dispersione dei parametri, ecc.



## Oscillatori a quarzo



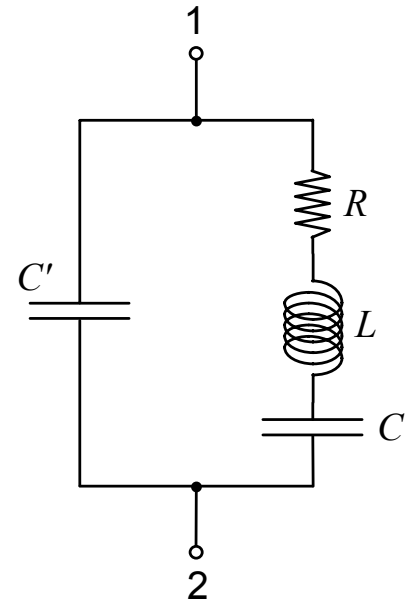
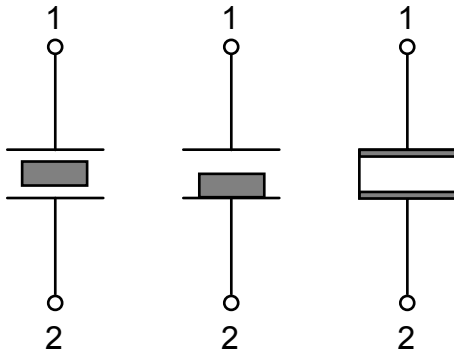
### Piezolettricità (Curie, 1880)

$$X_2 + X_3 = -X_1$$

$$\Delta X_2 + \Delta X_3 = -\Delta X_1$$

$$\frac{\Delta X_1}{\Delta \omega} = S_f \Rightarrow \Delta \omega = \frac{\Delta X_1}{S_f}$$

### Simboli circuitali e modello di un quarzo (Mason)



$$Z_{eq.} = \frac{\frac{1}{sC'} \left( R + sL + \frac{1}{sC} \right)}{\frac{1}{sC'} + R + sL + \frac{1}{sC}} =$$

$$= \frac{\frac{1}{s^2 C C'} (sRC + s^2 LC + 1)}{\frac{1}{s C C'} (C + sR C C' + s^2 L C C' + C')} \stackrel{s=j\omega}{=} \frac{1 - \omega^2 LC + j\omega R}{j\omega [(C + C') - \omega^2 L C C' - RC]}$$

Per  $R \cong 0$  si ha:

$$Z_{eq.} = \frac{1 - \omega^2 LC}{j\omega[(C + C') - \omega^2 LCC']} = \frac{LC\left(\frac{1}{LC} - \omega^2\right)}{j\omega LCC'\left[\frac{C + C'}{LCC'} - \omega^2\right]} = \frac{\omega^2 - \frac{1}{LC}}{j\omega C'\left[\omega^2 - \frac{1}{L} \frac{C + C'}{CC'}\right]}$$

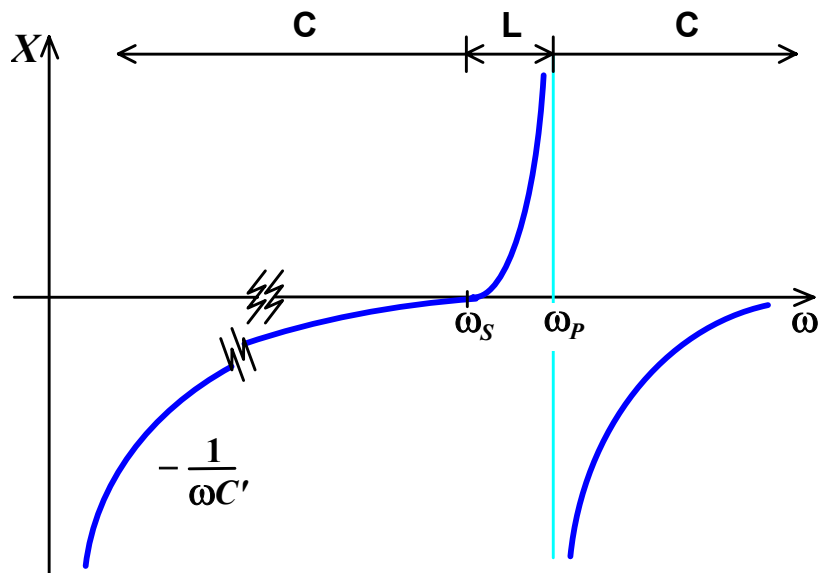
Posto  $\omega_S = \frac{1}{\sqrt{LC}}$  e  $\omega_P = \sqrt{\frac{1}{L} \left(\frac{C + C'}{CC'}\right)}$  si ottiene:

$$Z_{eq.} = \frac{1}{j\omega C'} \frac{\omega^2 - \omega_S^2}{\omega^2 - \omega_P^2}$$

$C' \gg C \Rightarrow \omega_S \cong \omega_P$

$Q = \frac{\omega_0}{\omega_P - \omega_S} = 1000 \div 10000$

con  $\omega_0 = \frac{\omega_P + \omega_S}{2}$



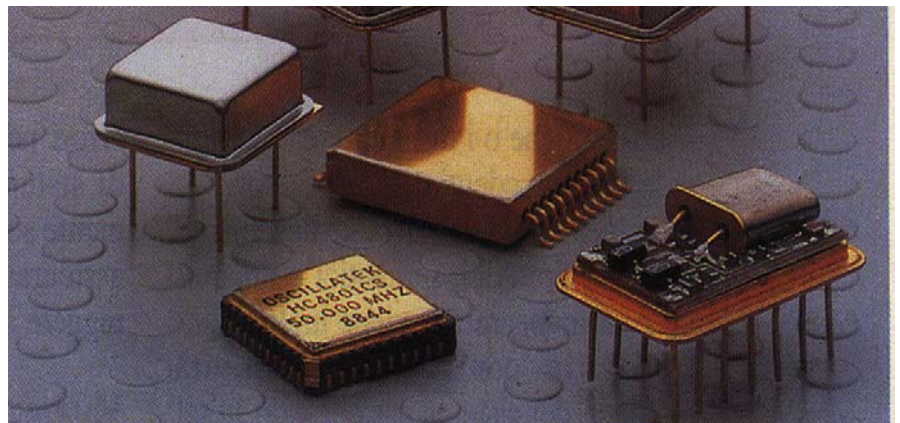
$f = \text{decine...di...MHz}$

⇓

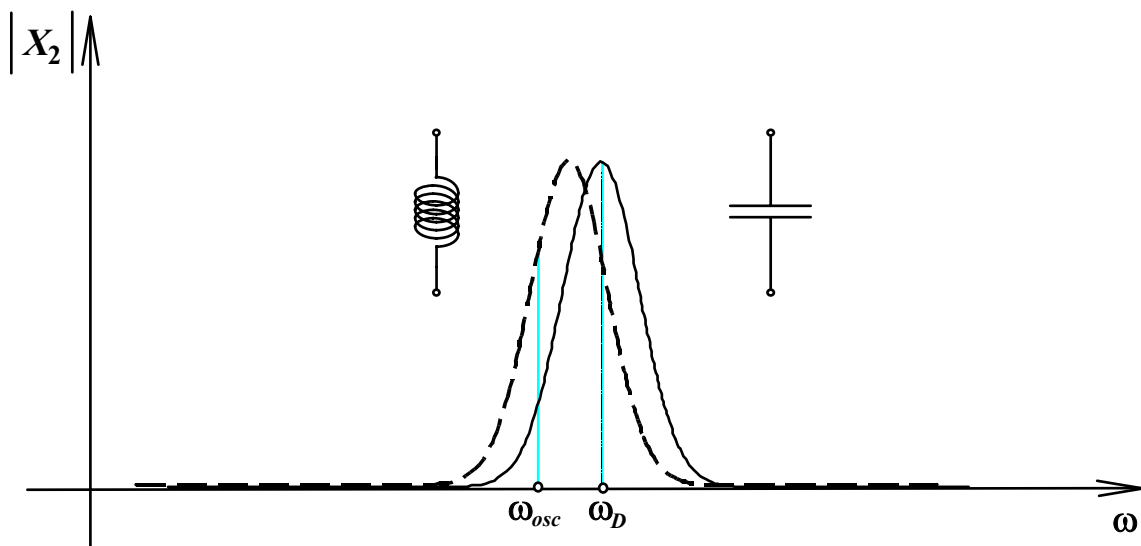
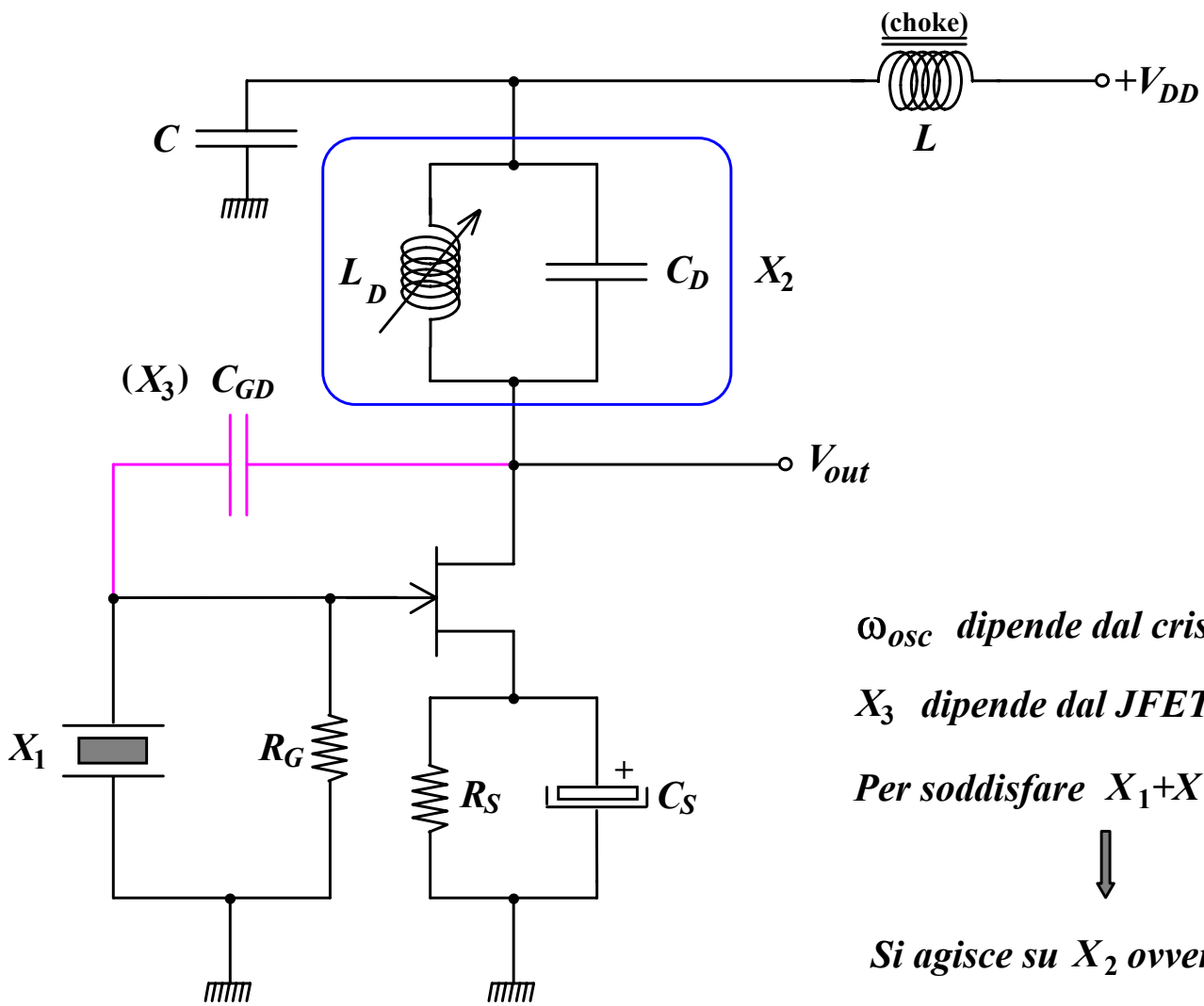
$d = \frac{\lambda}{2} = \text{decimi...di...mm}$

⇓

Quarzi.in.."overtone"

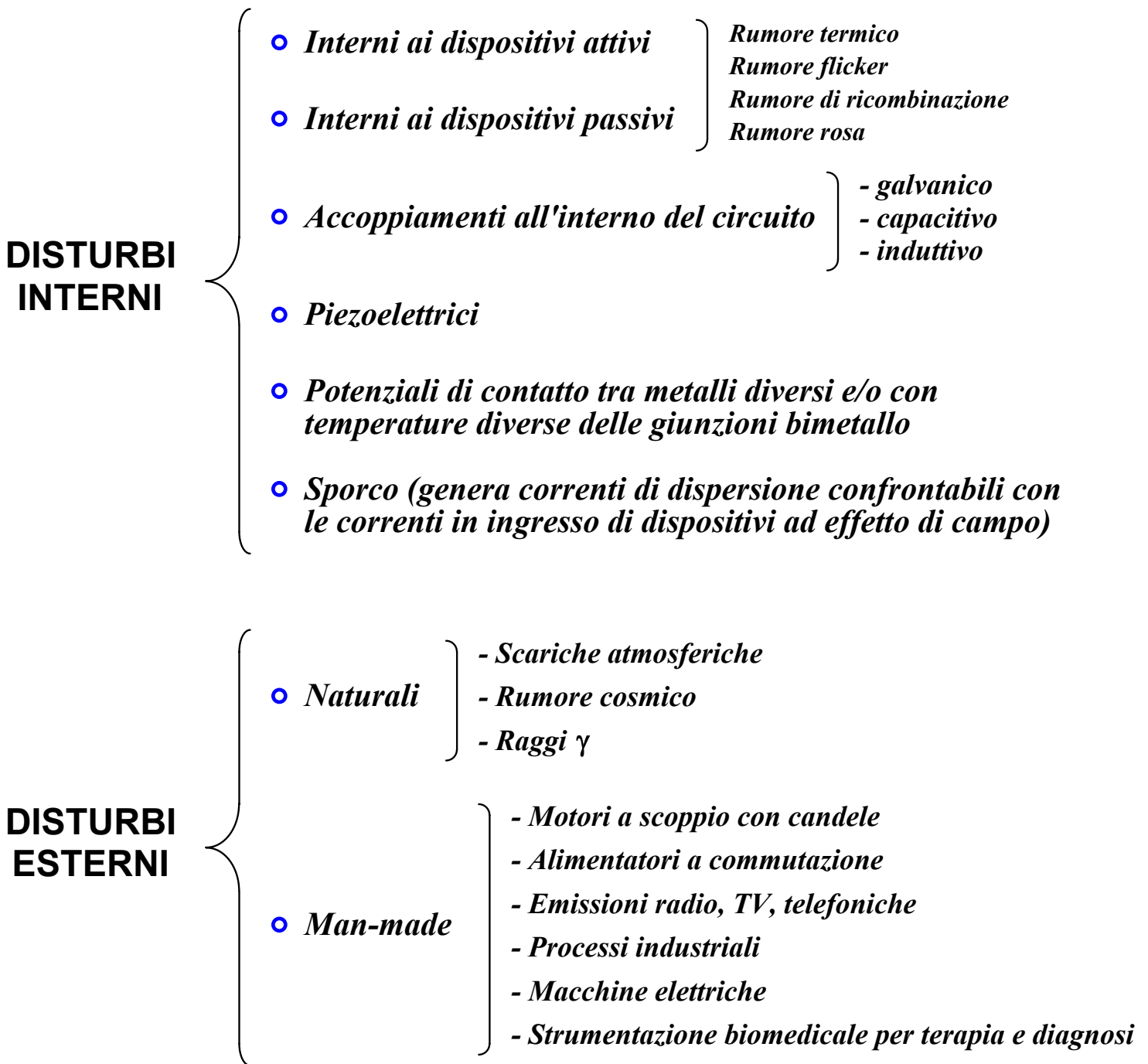


## Oscillatore Hartley a quarzo



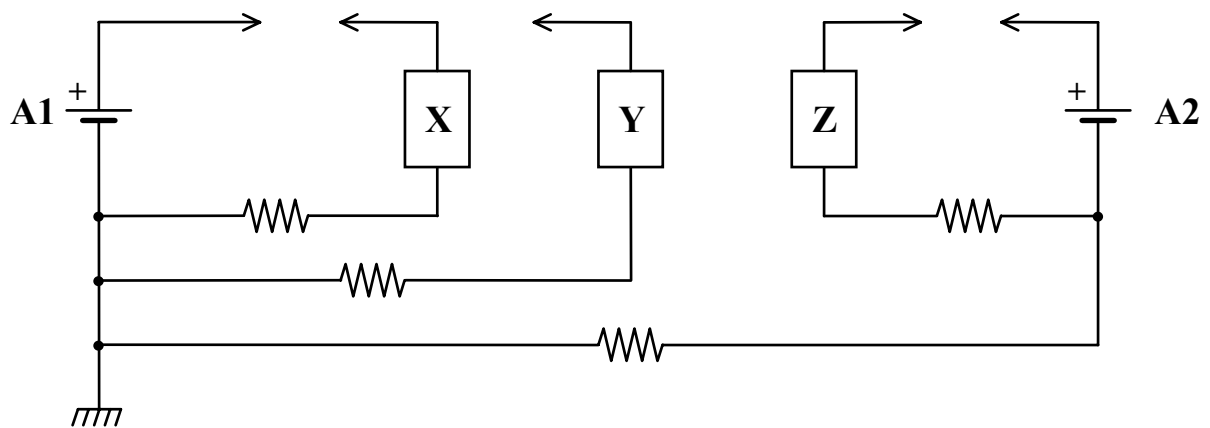
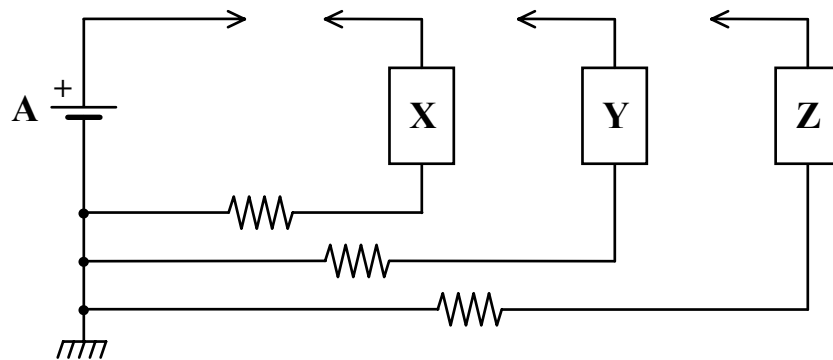
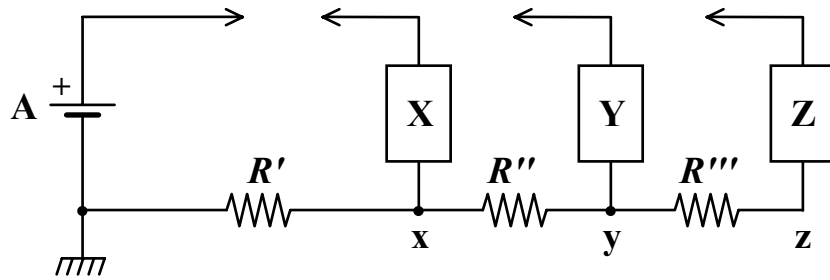
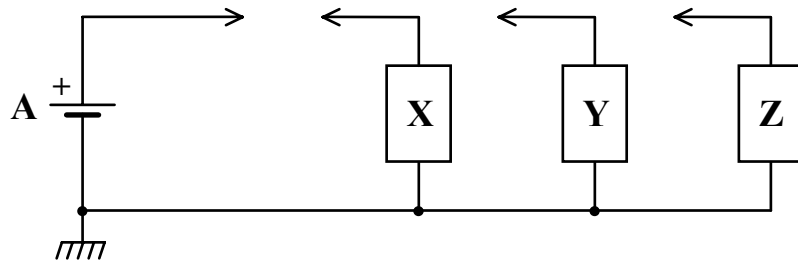
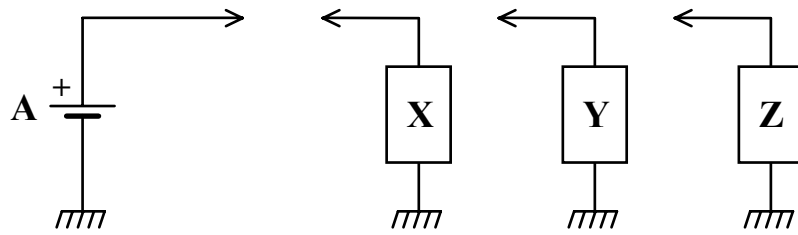
$$\omega_D = \frac{1}{\sqrt{L_D C_D}}$$

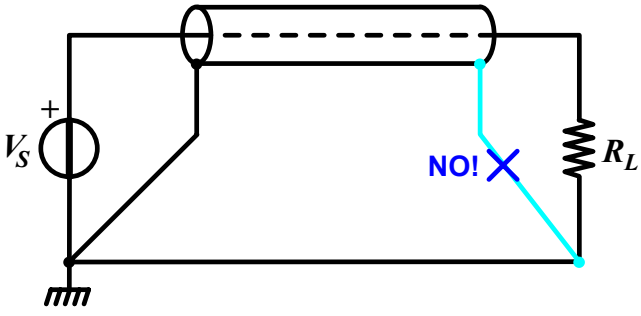
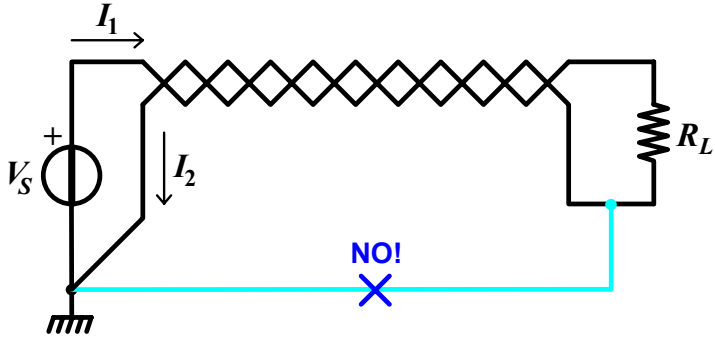
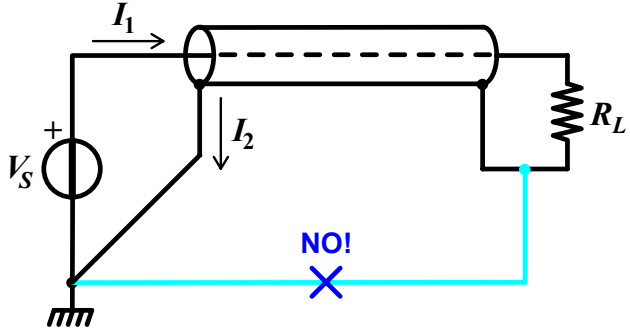
## Tipi di disturbi e metodi per la loro riduzione



***Problema della Compatibilità Elettromagnetica***  
*(e.m.c.=electromagnetic compatibility)*

# Accoppiamento galvanico

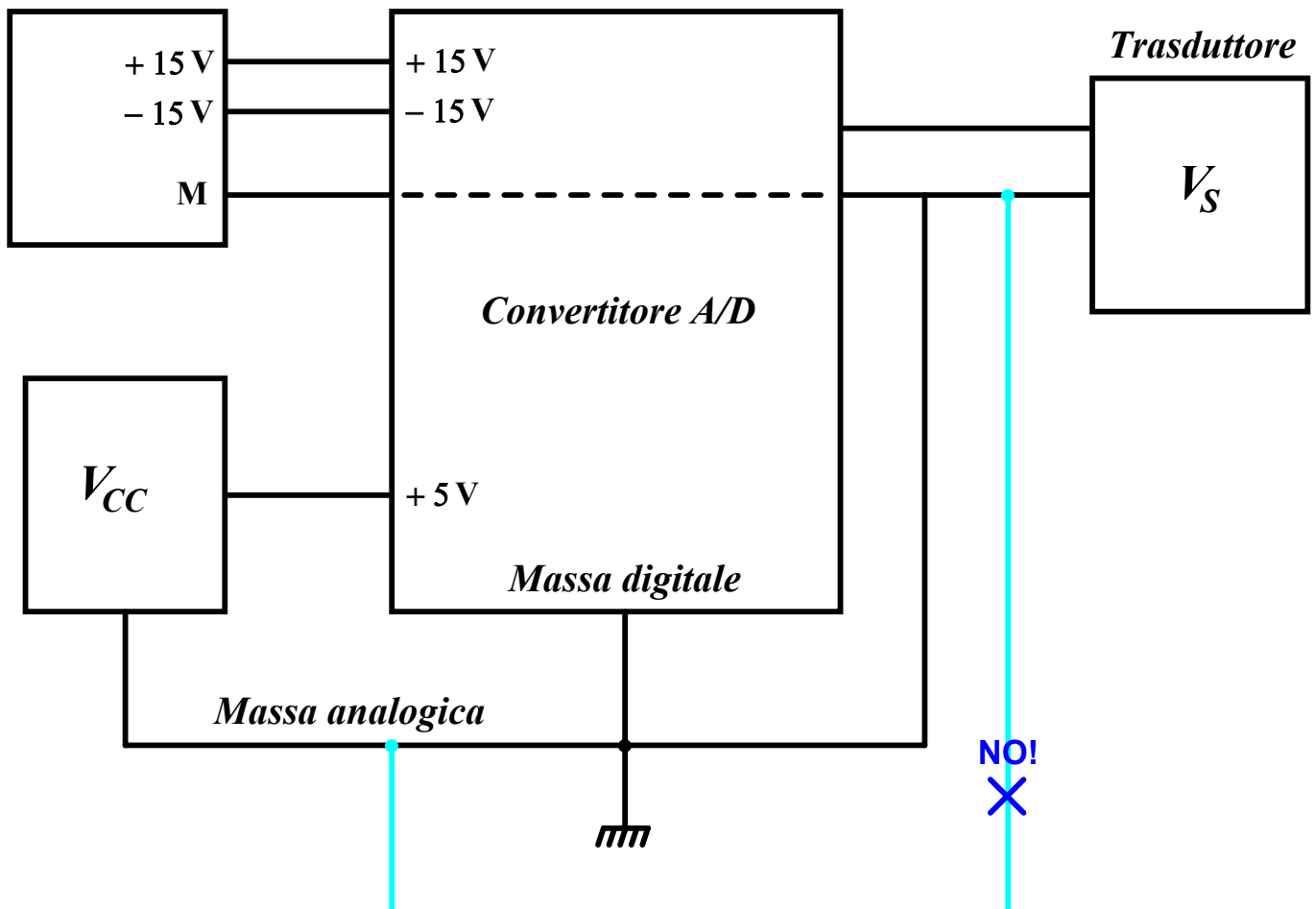
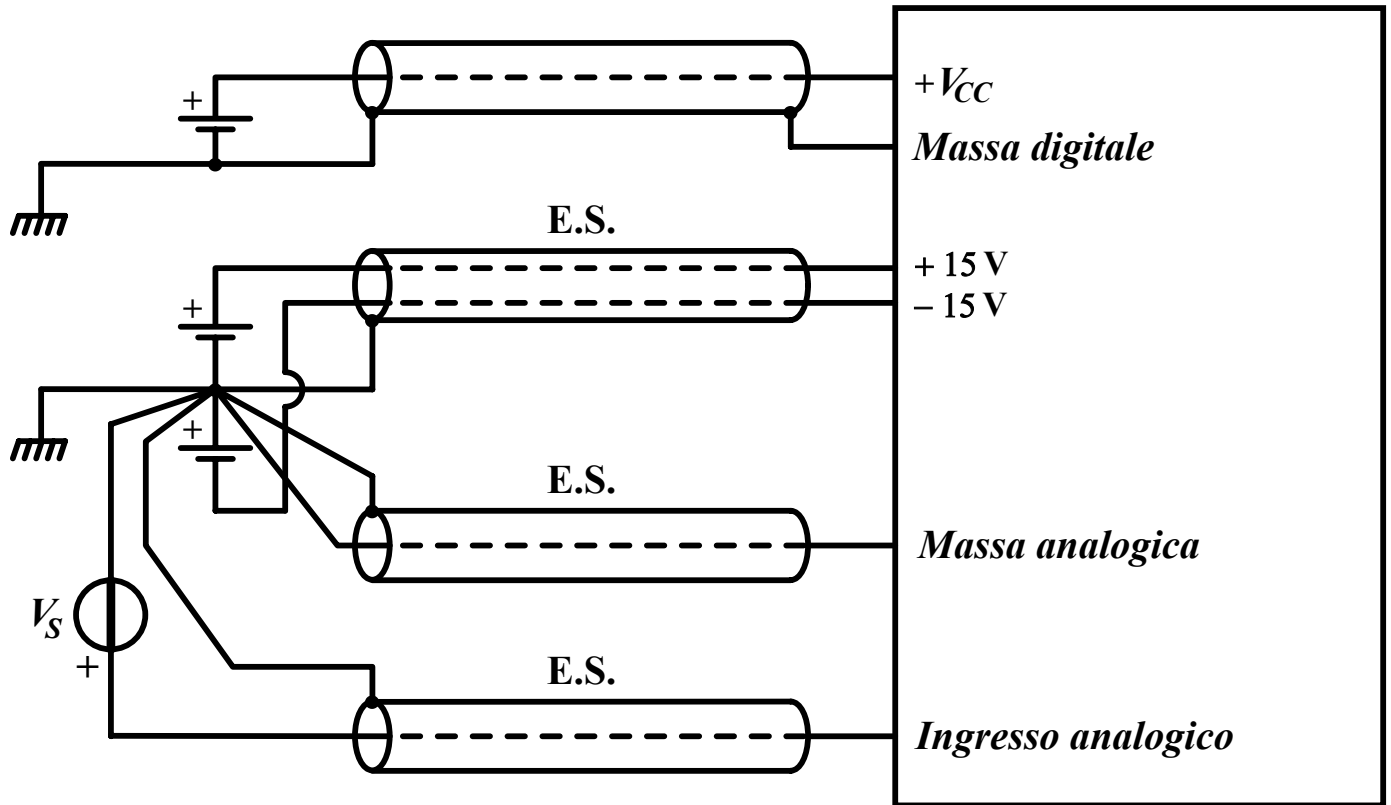


<i>Schermo elettrostatico (E.S.)</i>	<i>Sistemi per la riduzione della potenza irradiata</i>
	
	

### *Suggerimenti per la realizzazione di un circuito stampato*

- Tutte le masse locali sono da connettersi ad un unico grande piano di massa;
- Le capacità di by-pass (10÷100nF) sono da collegarsi il più vicino possibile ai circuiti integrati;
- Le aree libere da componenti e piste vanno collegate al piano di massa;
- Si deve cercare di realizzare circuiti con minime dimensioni.

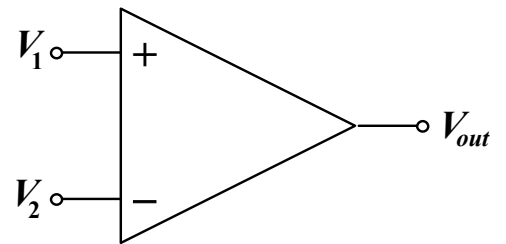
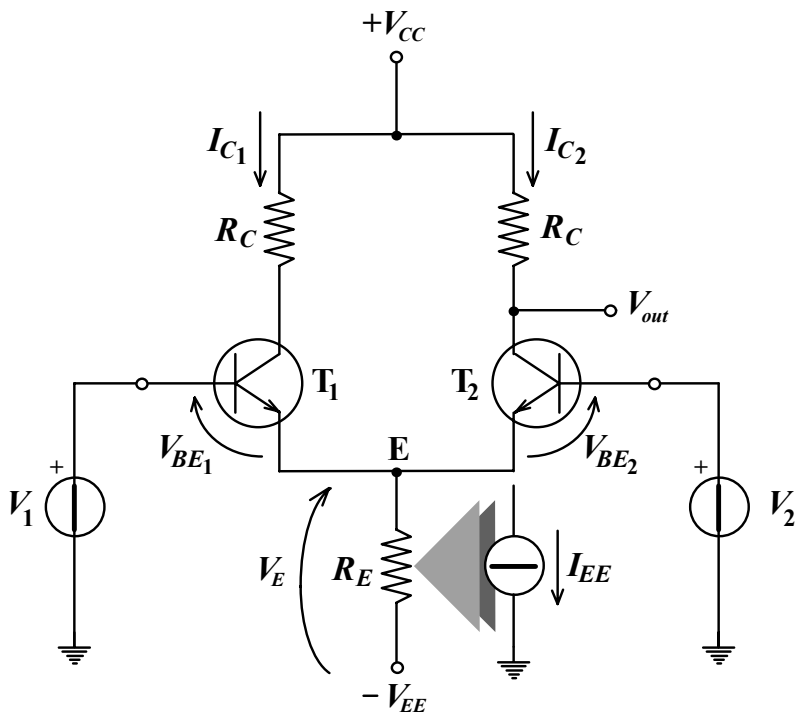
Esempi



## Amplificatore differenziale

$$I_{C_1} \left( 1 + \frac{I_{C_2}}{I_{C_1}} \right) = \alpha_F I_{EE} \Rightarrow I_{C_1} = \frac{\alpha_F I_{EE}}{1 + \frac{I_{C_2}}{I_{C_1}}}$$

$$I_{E_1} + I_{E_2} = I_{EE} \Rightarrow I_{C_2} \left( 1 + \frac{I_{C_1}}{I_{C_2}} \right) = \alpha_F I_{EE} \Rightarrow I_{C_2} = \frac{\alpha_F I_{EE}}{1 + \frac{I_{C_1}}{I_{C_2}}}$$



$$V_1 = V_{BE_1} + V_E; \quad V_2 = V_{BE_2} + V_E \quad \Rightarrow \quad V_1 - V_2 = V_{BE_1} - V_{BE_2} = V_d$$

$$I_C = \alpha_F I_{E_S} \left( e^{-\frac{V_{BE}}{\eta V_T}} - 1 \right) - I_{C_S} \left( e^{-\frac{V_{CB}}{\eta V_T}} - 1 \right)$$

⇓ (regione attiva)

$$I_{C_1} = \alpha_F I_{E_S} e^{-\frac{V_{BE1}}{V_T}} \quad I_{C_2} = \alpha_F I_{E_S} e^{-\frac{V_{BE2}}{V_T}}$$

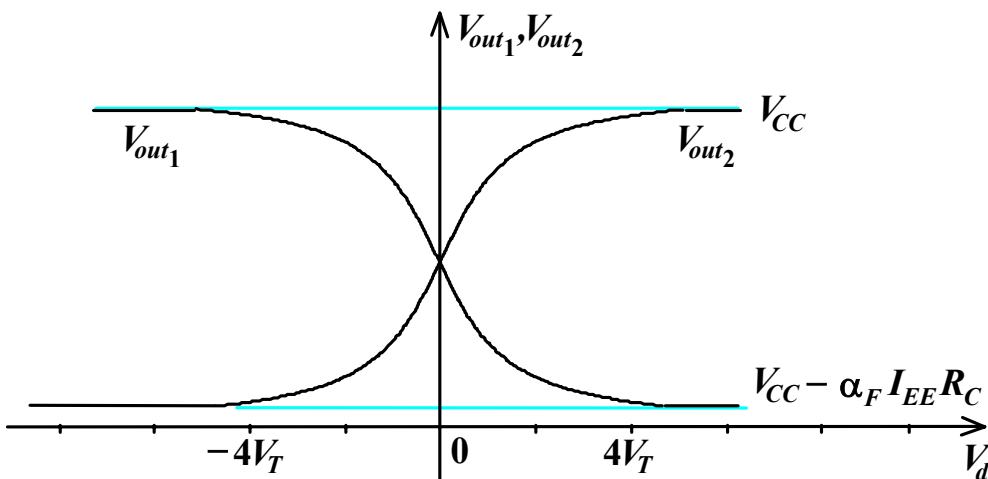
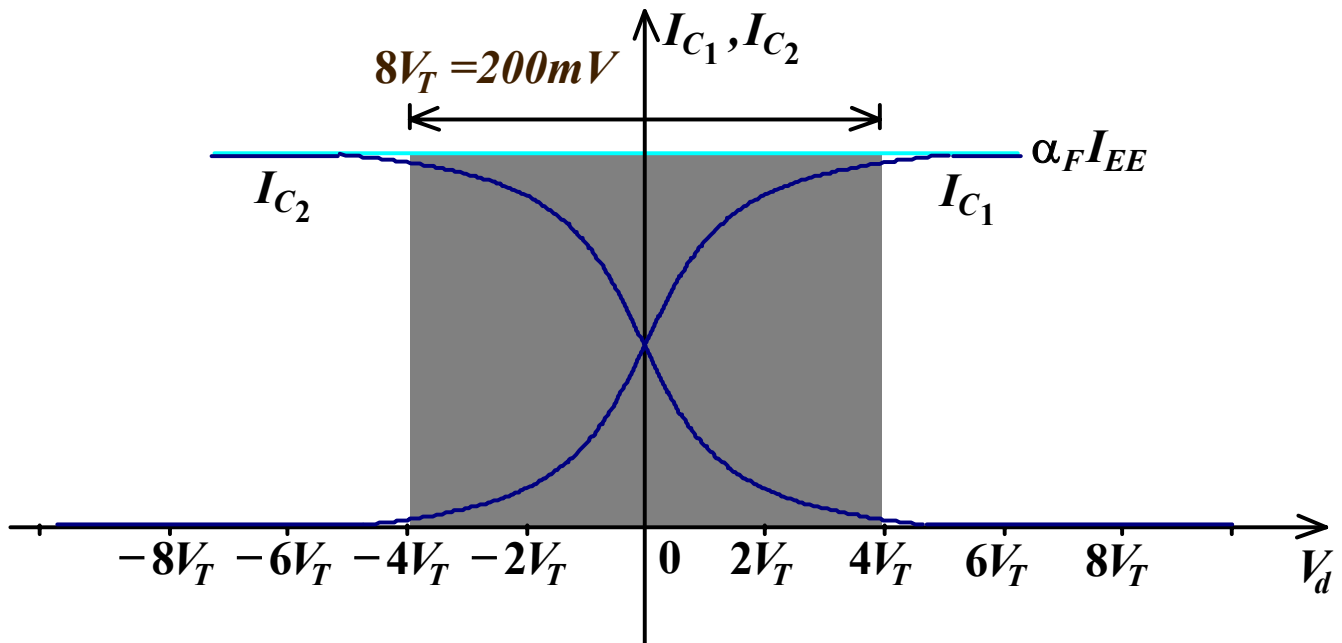
Supposti uguali i guadagni di corrente si ha:

$$\frac{I_{C1}}{I_{C2}} = e^{\frac{V_{BE1} - V_{BE2}}{V_T}} = e^{\frac{V_d}{V_T}} \Rightarrow \frac{I_{C2}}{I_{C1}} = e^{-\frac{V_d}{V_T}}$$

⇓

$$I_{C1} = \frac{\alpha_F I_{EE}}{1 + e^{-\frac{V_d}{V_T}}} \quad I_{C2} = \frac{\alpha_F I_{EE}}{1 + e^{\frac{V_d}{V_T}}}$$

Graficamente

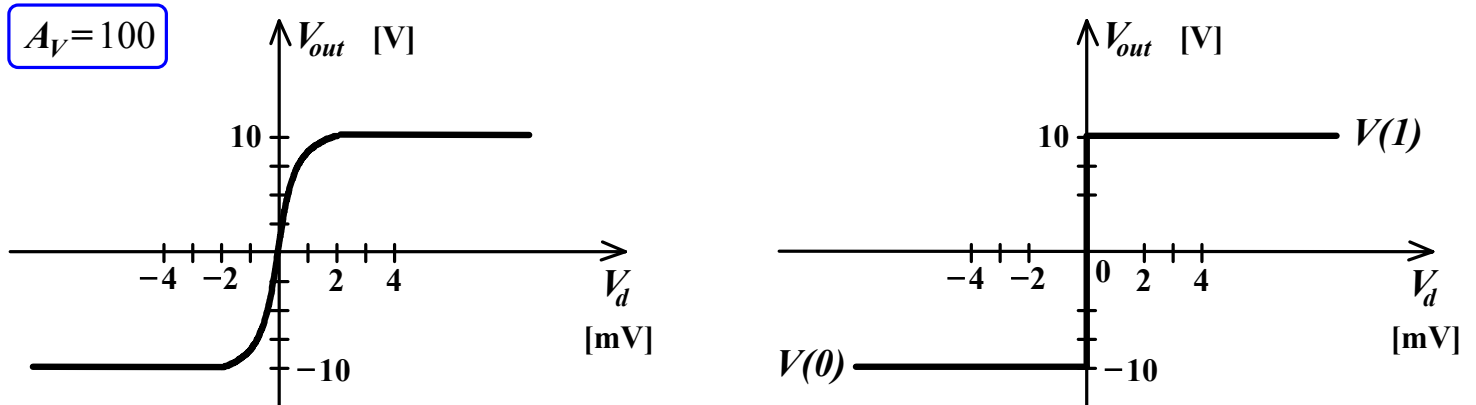


$$V_{out1} = V_{CC} - R_C I_{C1}$$

$$V_{out2} = V_{CC} - R_C I_{C2}$$

# Comparatori

## Caratteristiche a confronto



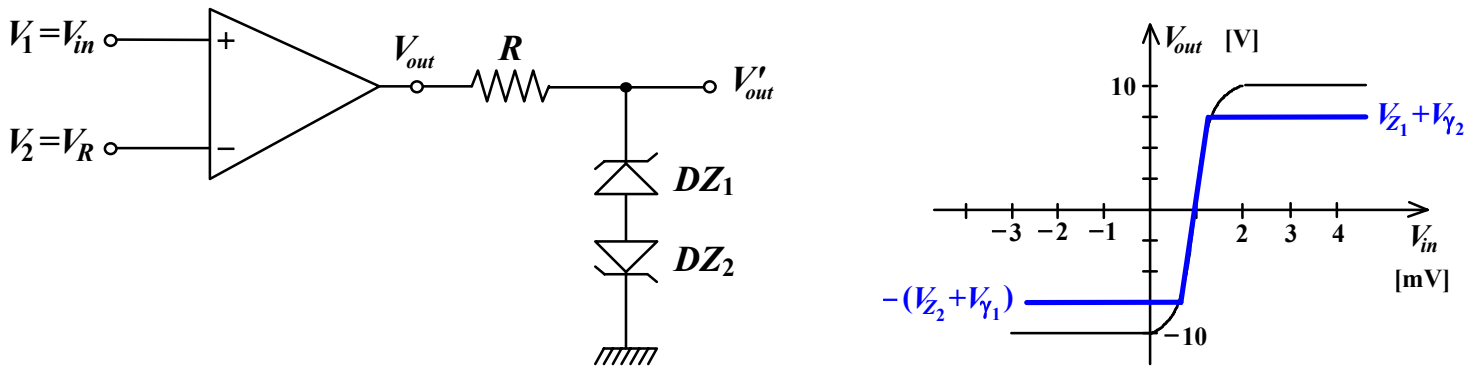
Modelli di comparatori ( $\Delta V_i$  fino a  $15\mu\text{V}$  e ritardi di  $20 \div 200$  ns):

Fairchild  $\mu\text{A}710$

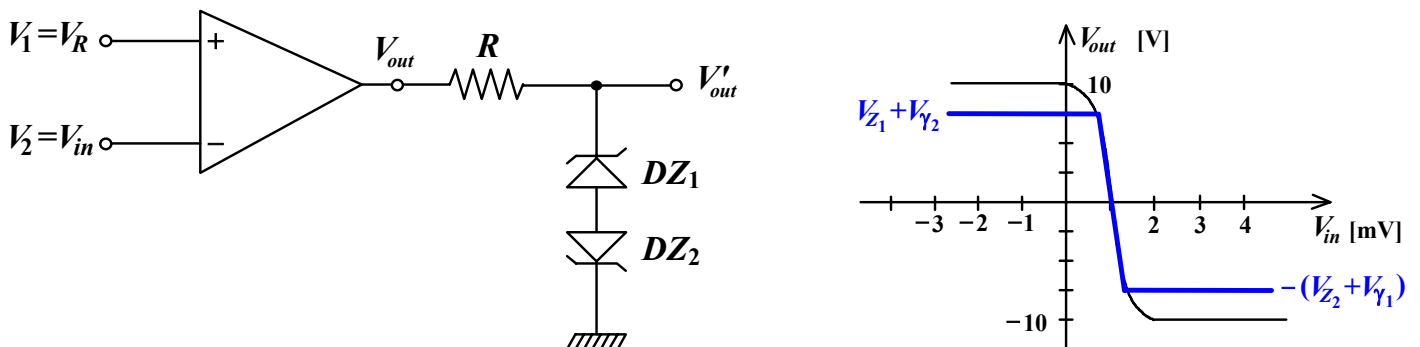
National LM111  
Harris HA2111

Analog Devices AD604

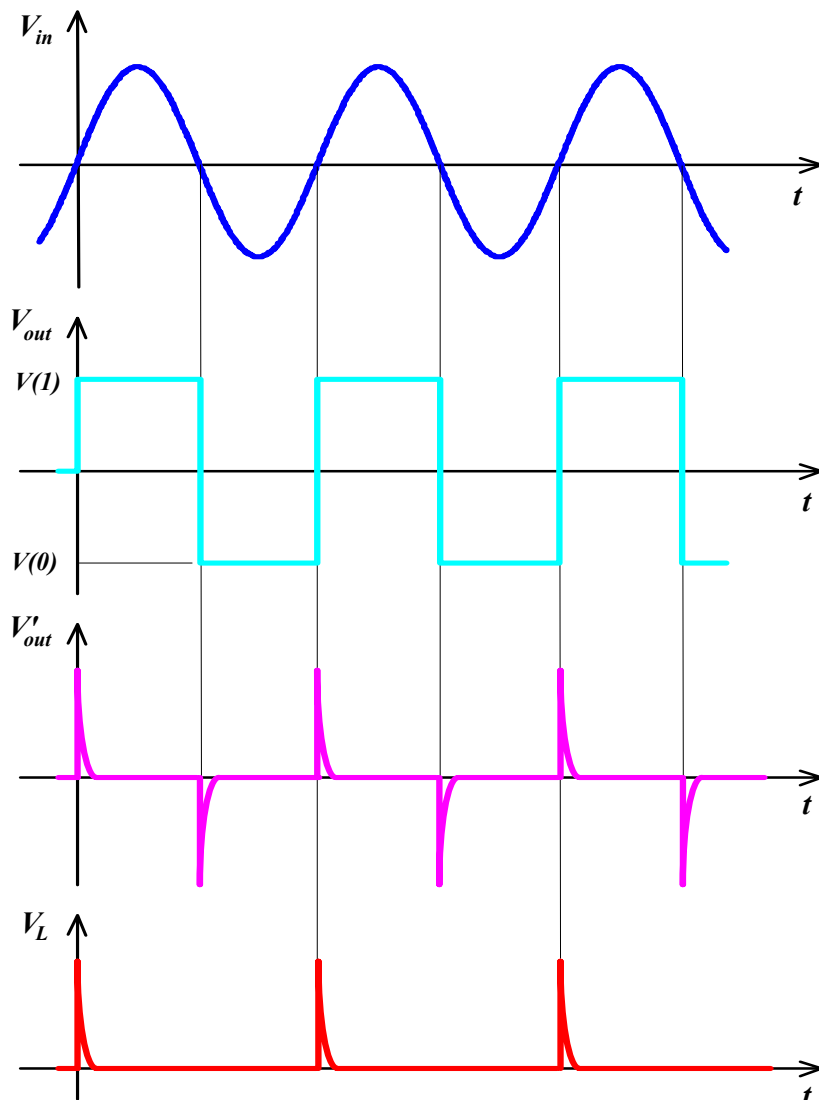
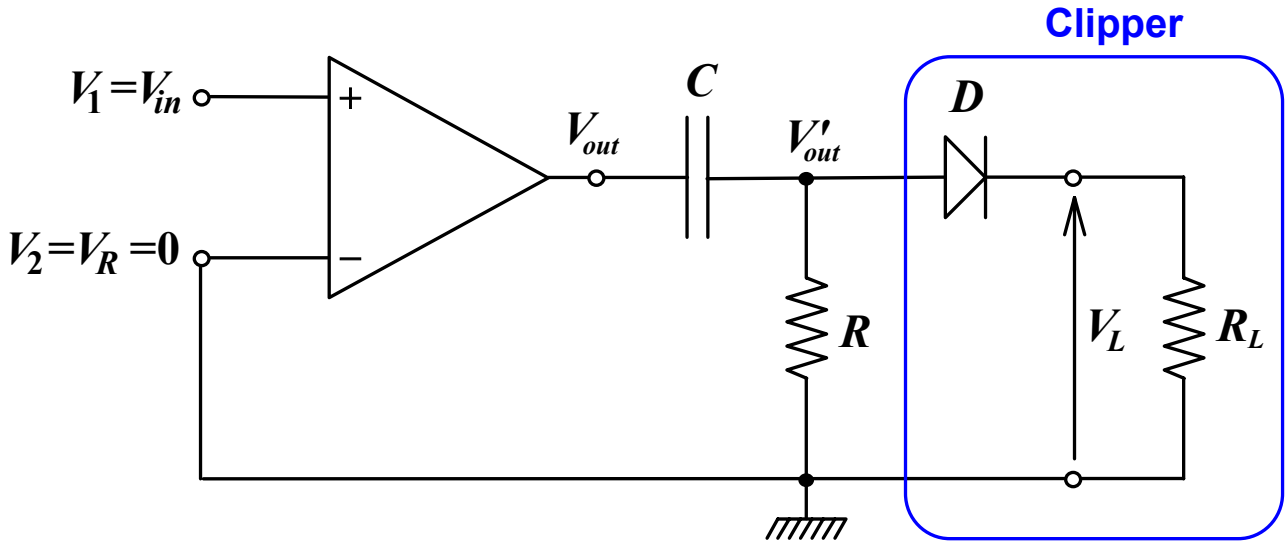
## Funzionamento non invertente



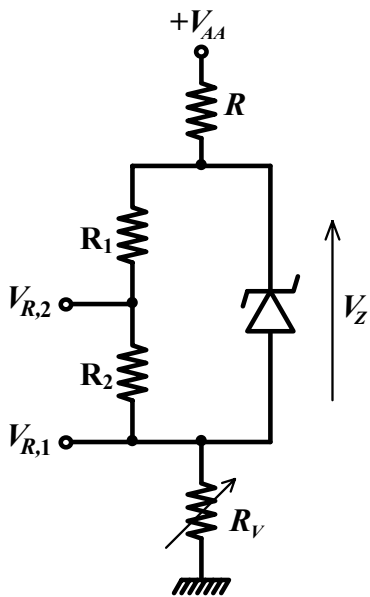
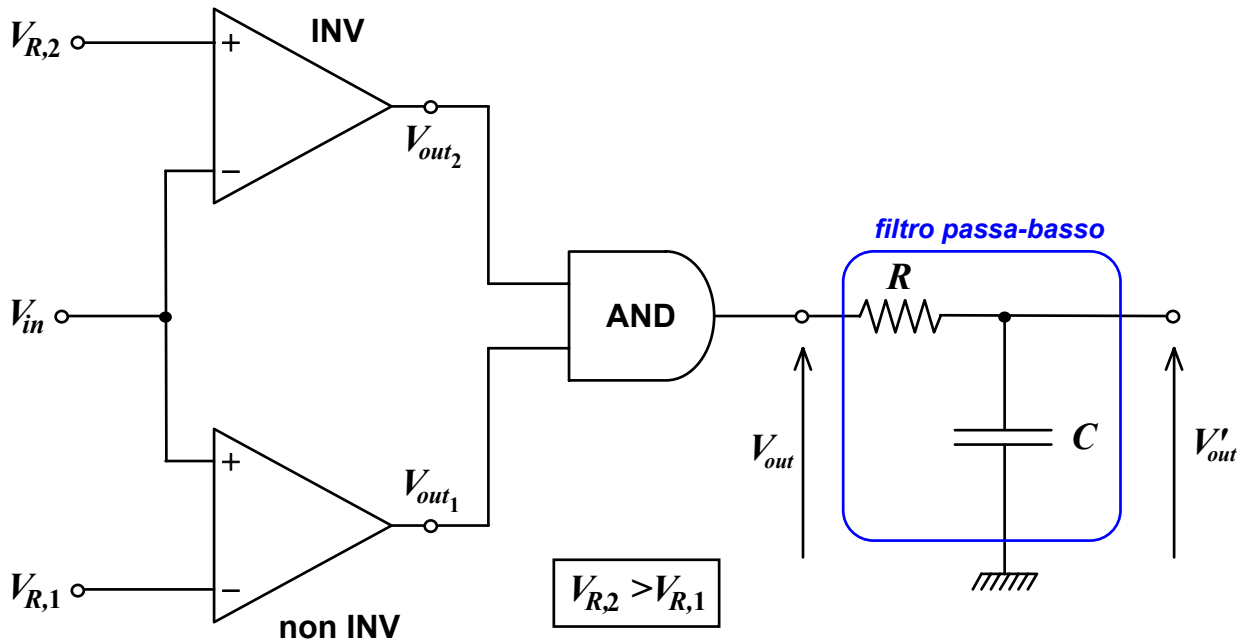
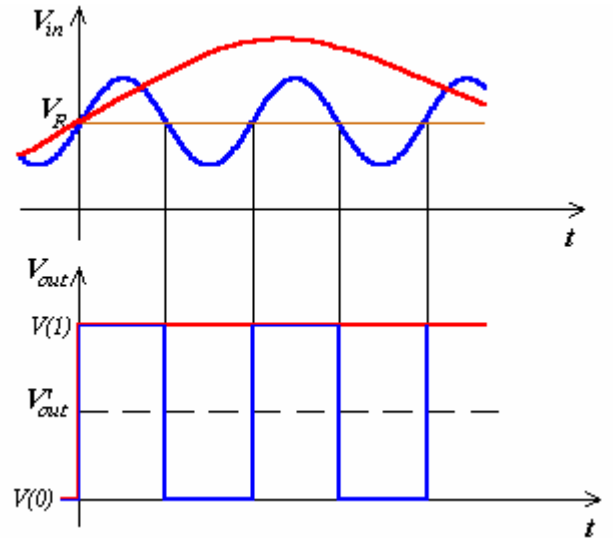
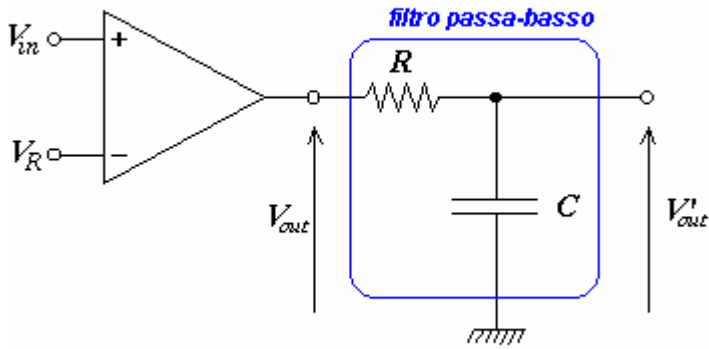
## Funzionamento invertente



## Zero crossing detector



Altri circuiti con comparatori

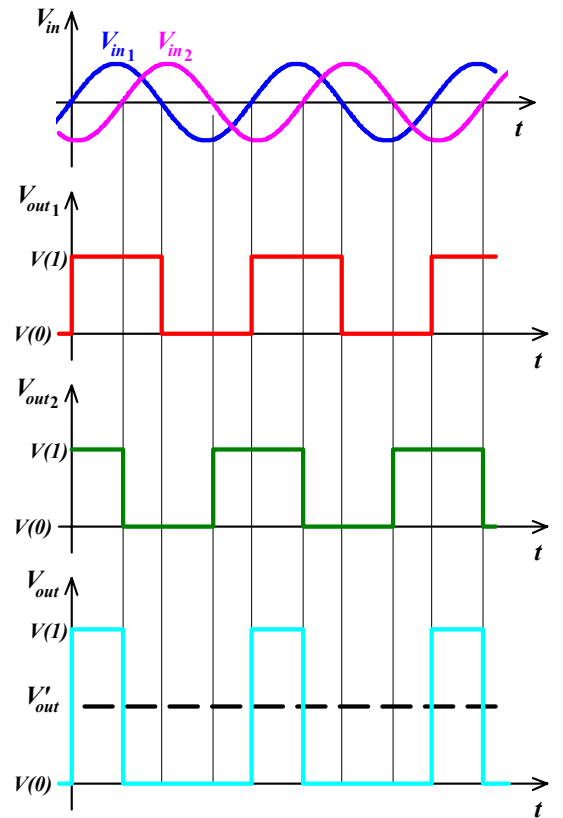
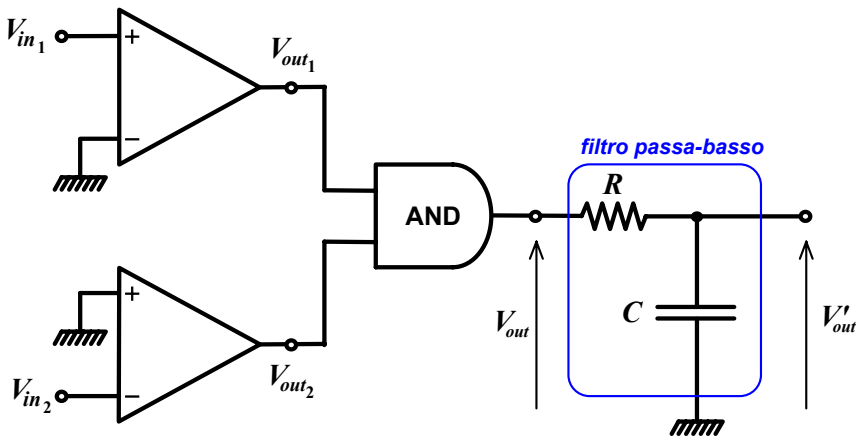
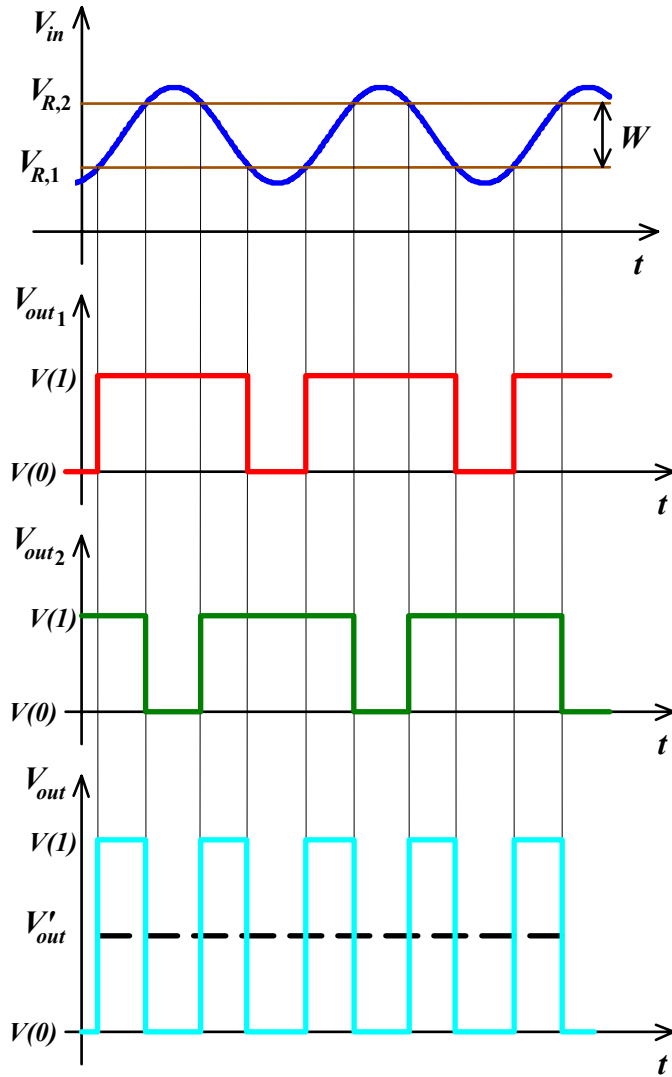


$$V_{R,1} = \frac{R_V}{R + R_V} (V_{AA} - V_Z)$$

$$V_{R,2} = \frac{R_V}{R + R_V} (V_{AA} - V_Z) + \frac{R_2}{R_1 + R_2} V_Z$$

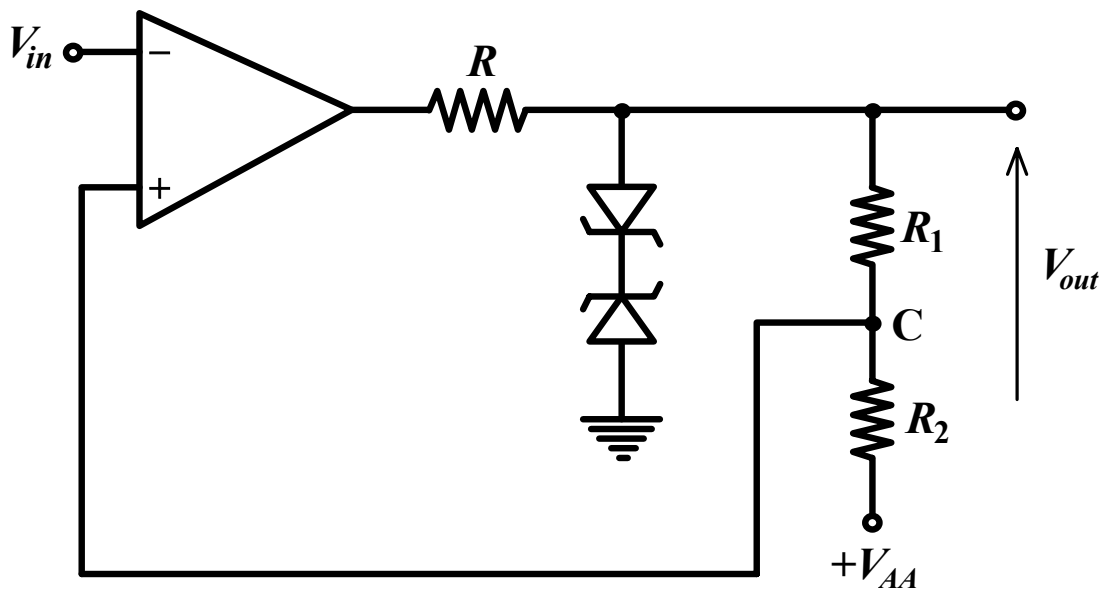
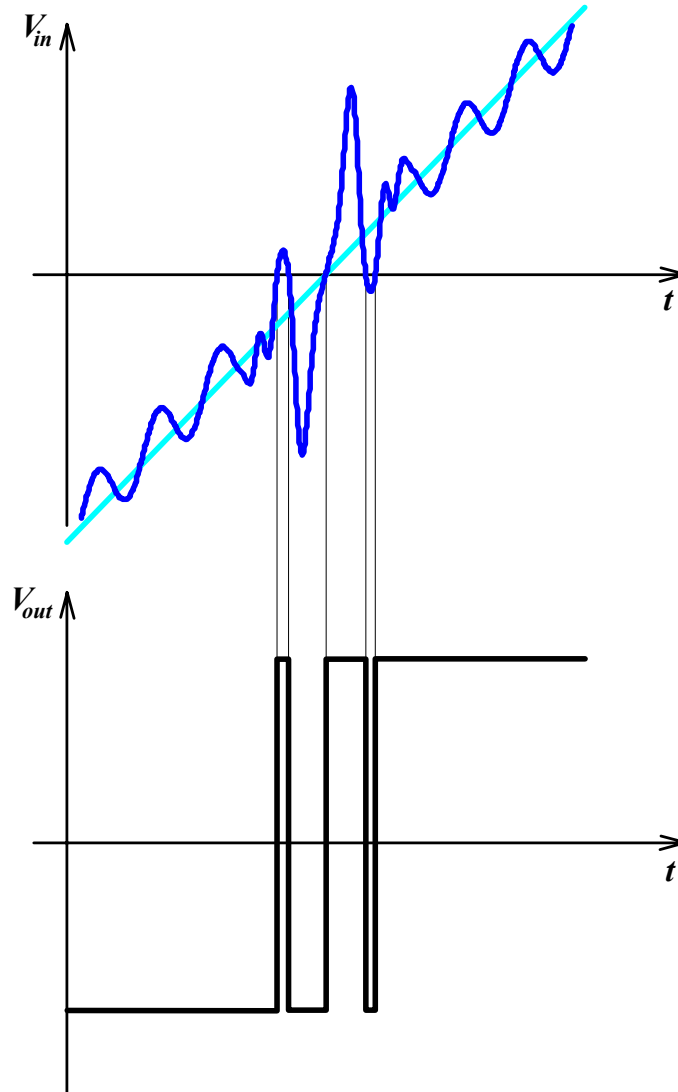
$$W = V_{R,2} - V_{R,1} = \frac{R_2}{R_1 + R_2} \cdot V_Z$$

$$\bar{V}_R = \frac{2 \left[ \frac{R_V}{R + R_V} (V_{AA} - V_Z) \right] + \frac{R_2}{R_1 + R_2} V_Z}{2} = V_{R,1} + \frac{W}{2}$$



# Trigger di Schmitt

## Fenomeno del chattering



$$V(1) = 5V$$

$$V(0) = -5V$$

$$A = 10.000$$

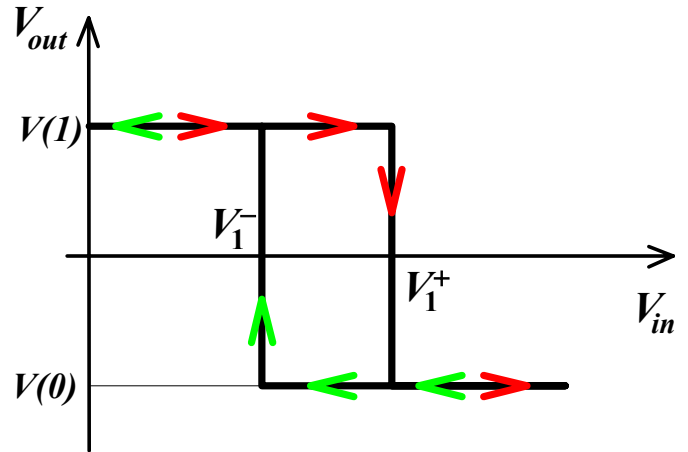
$$|\beta A| > 1$$

$$V_1^+ = \frac{R_2}{R_1 + R_2} V_{out} + \frac{R_1}{R_1 + R_2} V_{AA}$$

$$V_1^- = -\frac{R_2}{R_1 + R_2} V_{out} + \frac{R_1}{R_1 + R_2} V_{AA}$$

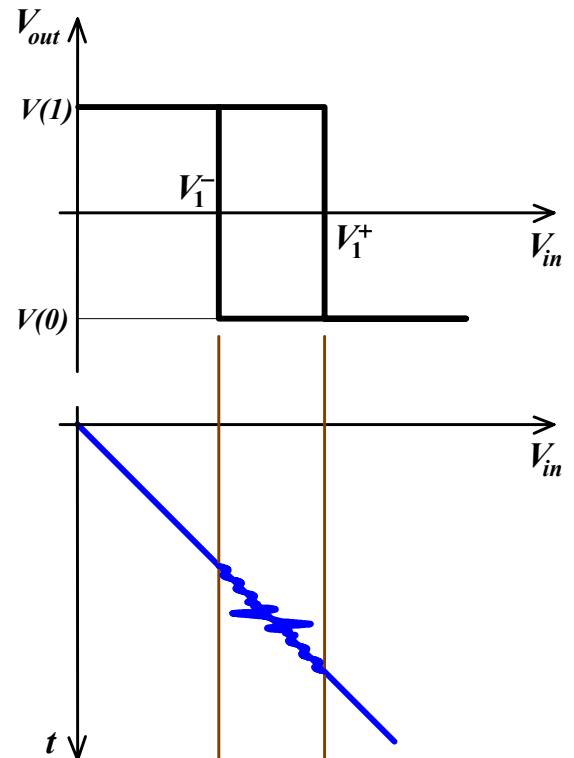
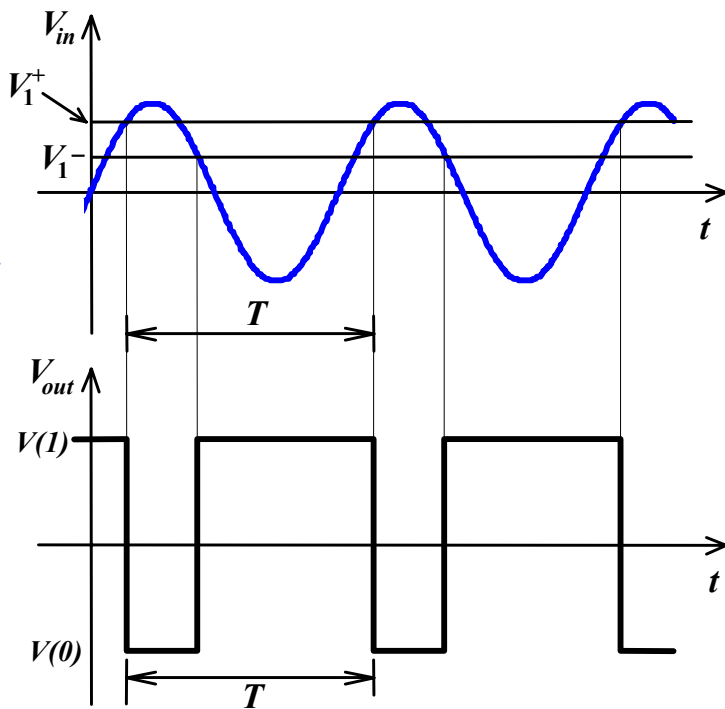
$$\Downarrow$$

$$V_1^- < V_1^+$$

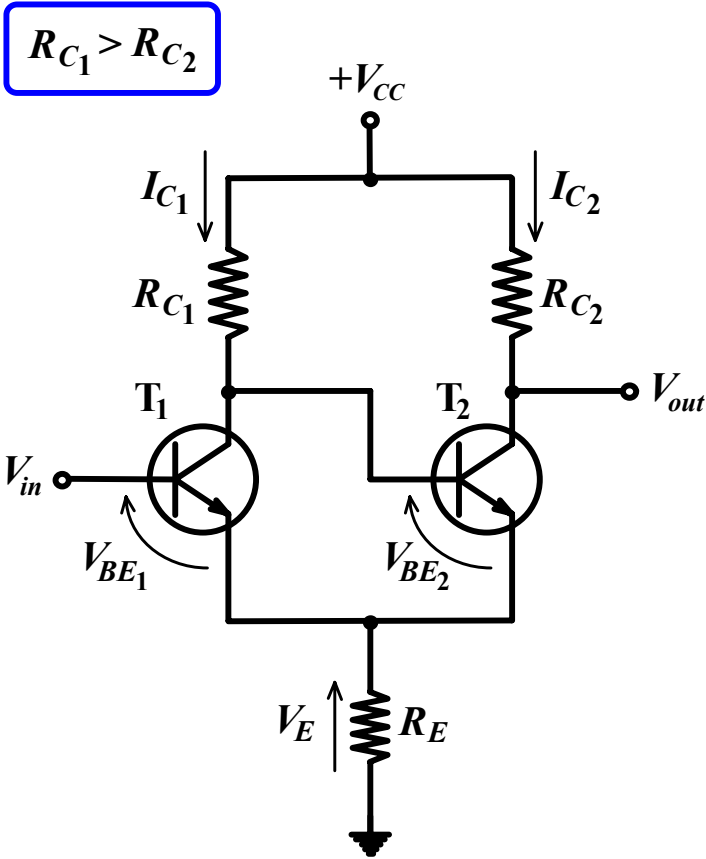


$$V_1^+ - V_1^- = \frac{2R_2}{R_1 + R_2} V_{out} \Rightarrow \text{se } R_2 \rightarrow 0 \Rightarrow V_1^+ - V_1^- \rightarrow 0$$

$$\frac{V_1^+ - V_1^-}{2} = \frac{R_1}{R_1 + R_2} V_{AA} \Rightarrow \text{se } V_{AA} = 0 \text{ la curva di isteresi si pone a cavallo dello } 0$$



## Trigger di Schmitt realizzato a BJT



**T<sub>1</sub> interdetto, T<sub>2</sub> saturo**

$$\left( I_{C1} = I_{B2} \geq \frac{I_{C2,sat}}{h_{fe2}} \right)$$

⇓

$$V_{out} = V_{CC} - R_{C2} I_{C2,sat} \quad \text{(bassa)}$$

**Quando**

$$V_{in}^+ = V_E + V_{BE1,ON} = R_E I_{C2,sat} + V_{BE1,ON}$$

⇓

$$V_{out} \cong V_{CC} \quad \text{(alta)}$$

⇓

**Quando**

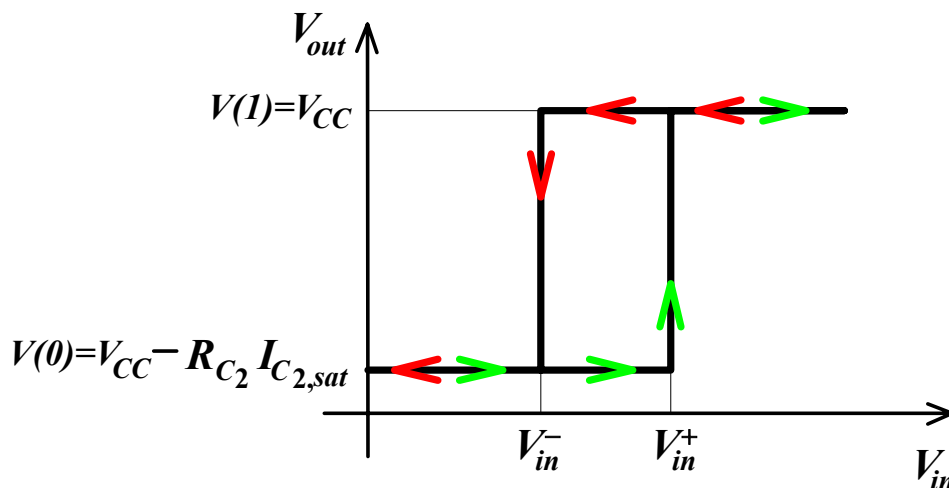
$$V_{in}^- = V_E + V_{BE2,ON} = R_E I_{C1,sat} + V_{BE2,ON}$$

⇓

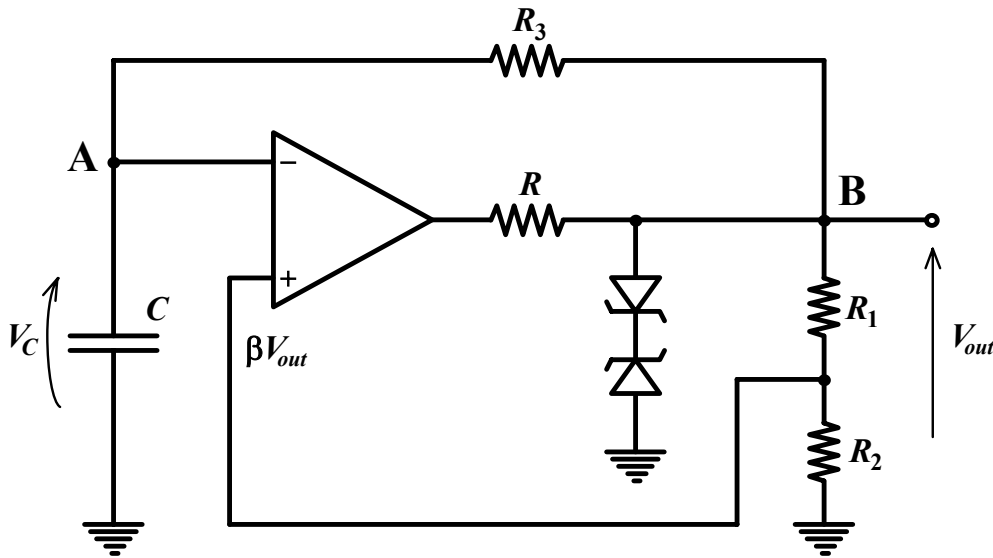
$$V_{out} = V_{CC} - R_{C2} I_{C2,sat}$$

**(bassa)**

$$V_H = V_{in}^+ - V_{in}^- = R_E (I_{C2,sat} - I_{C1,sat})$$



## Generatori di onda quadra e triangolare (10÷10<sup>4</sup> Hz)



$$V(1) = V_\gamma + V_Z$$

$$V(0) = -V_\gamma - V_Z$$

$$\beta = \frac{R_2}{R_1 + R_2}$$

$$V_d = V_C - \beta V_{out}$$

$$V_C(t) = A + B e^{-\frac{t}{\tau}} \quad \tau = R_3 C$$

$$V_C(0) = -\beta V_{out} = A + B$$

$$V_C(+\infty) = V_{out} = A$$

$$V_C(t) = V_{out} - V_{out}(1 + \beta) e^{-\frac{t}{\tau}}$$

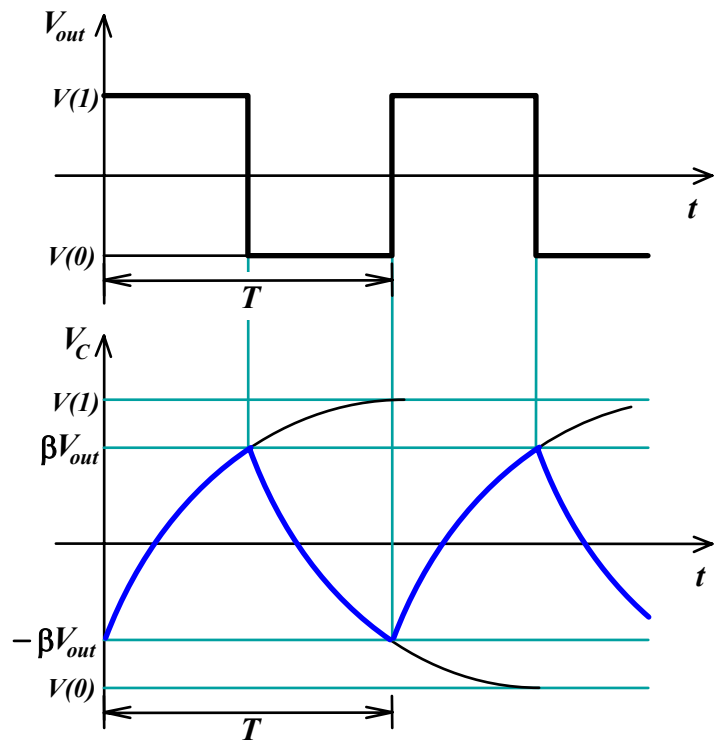
Poichè

$$V_C\left(\frac{T}{2}\right) = \beta V_{out} = V_{out} \left[ 1 - (1 + \beta) e^{-\frac{T}{2\tau}} \right]$$

dividendo per  $V_{out}$  si trova:

$$(1 + \beta) e^{-\frac{T}{2\tau}} = 1 - \beta \Rightarrow$$

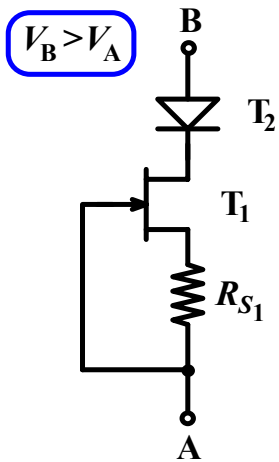
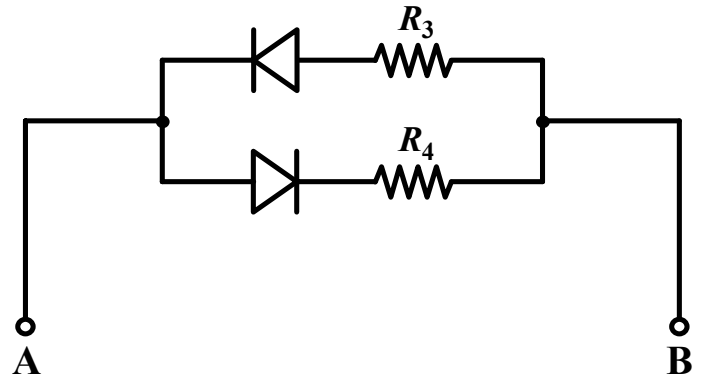
$$T = 2\tau \left[ \ln\left(\frac{1 + \beta}{1 - \beta}\right) \right] = 2\tau \ln\left(1 + \frac{2R_1}{R_2}\right)$$



In generale  $T = T_1 + T_2$  dove:

$$T_1 = R_3 C \ln \left( \frac{V(1) + \beta V(0)}{V(1) - \beta V(1)} \right)$$

$$T_2 = R_4 C \ln \left( \frac{V(0) + \beta V(1)}{V(0) - \beta V(0)} \right)$$



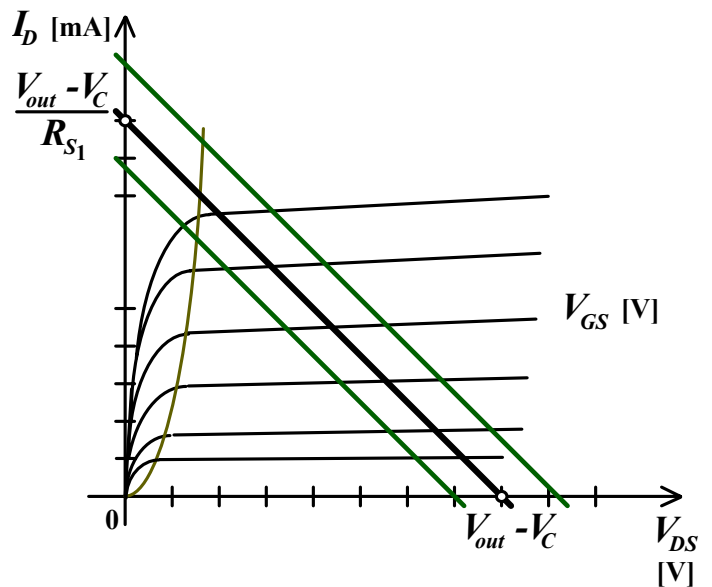
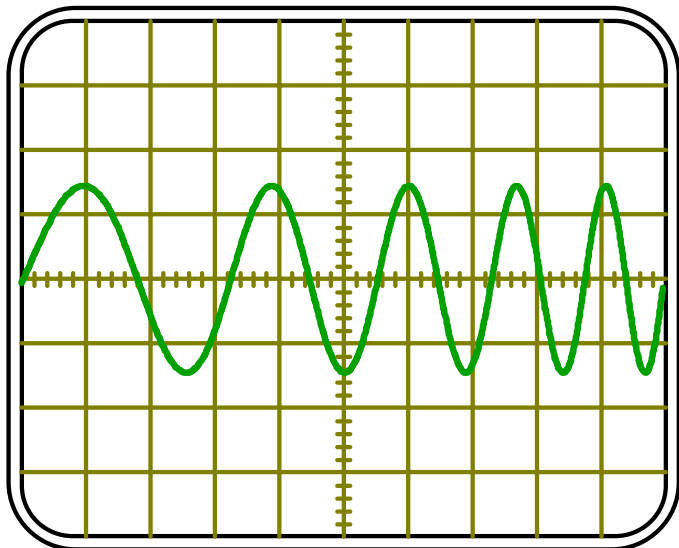
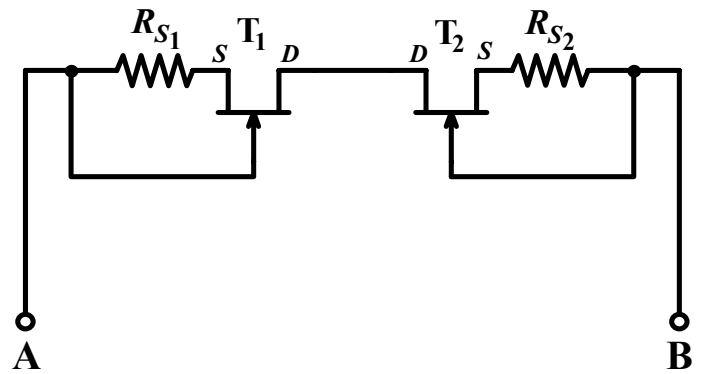
$$v_C = \frac{1}{C} \int i_C dt$$

$\Downarrow$

$i_C$  costante

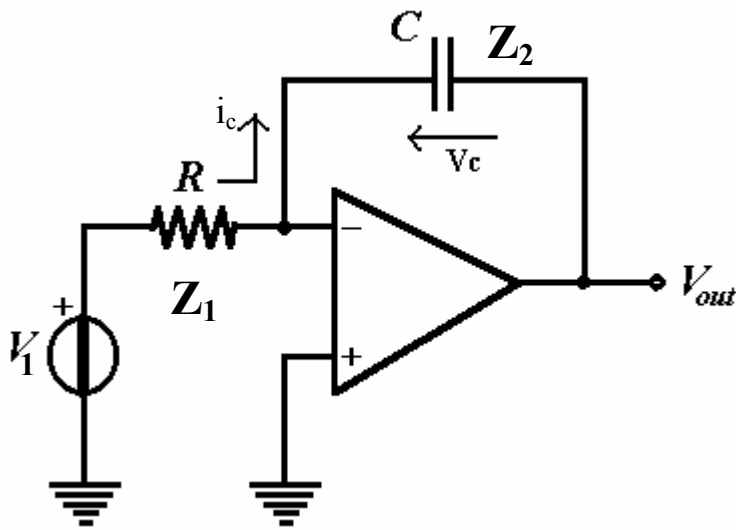
$\Downarrow$

$$v_C(t) = \frac{I_C}{C} t$$



$$I_D \uparrow \Rightarrow V_{R_{S1}} \uparrow \Rightarrow V_{SG1} \uparrow \Rightarrow I_D \downarrow$$

Utilizzo di un integratore di Miller



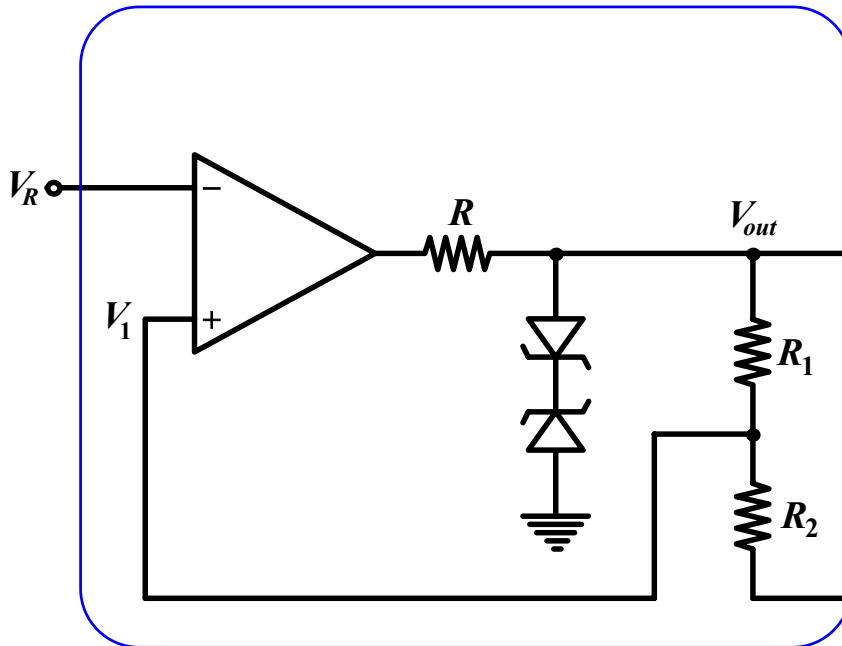
$$A_V = \frac{V_{out}}{V_1} = -\frac{Z_2}{Z_1} = -\frac{1}{j\omega RC}$$

$$\frac{V_1}{R} = I_1 = i_C$$

$$i_C = C \frac{dV_C}{dt} = -C \frac{dV_{out}}{dt} = \frac{V_1}{R}$$

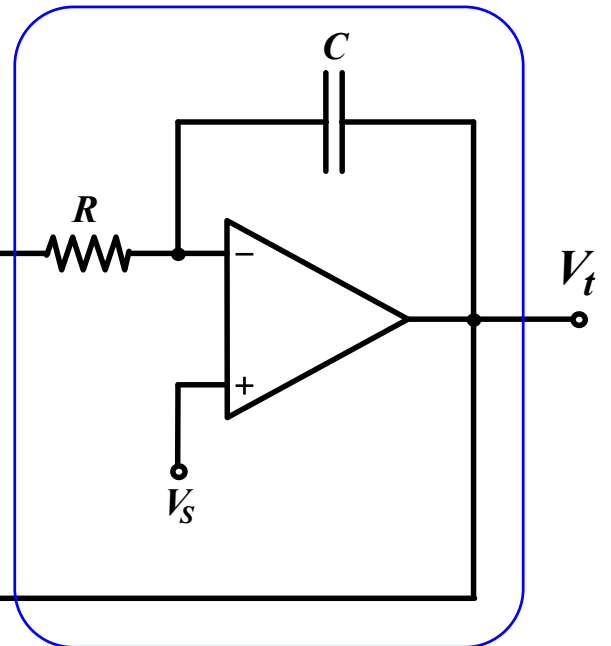
$$V_{out} = -\frac{1}{RC} \int_0^t V_1 dt + V_{out}(0)$$

trigger di Schmitt



$$V(1) = V_\gamma + V_Z$$

integratore di Miller

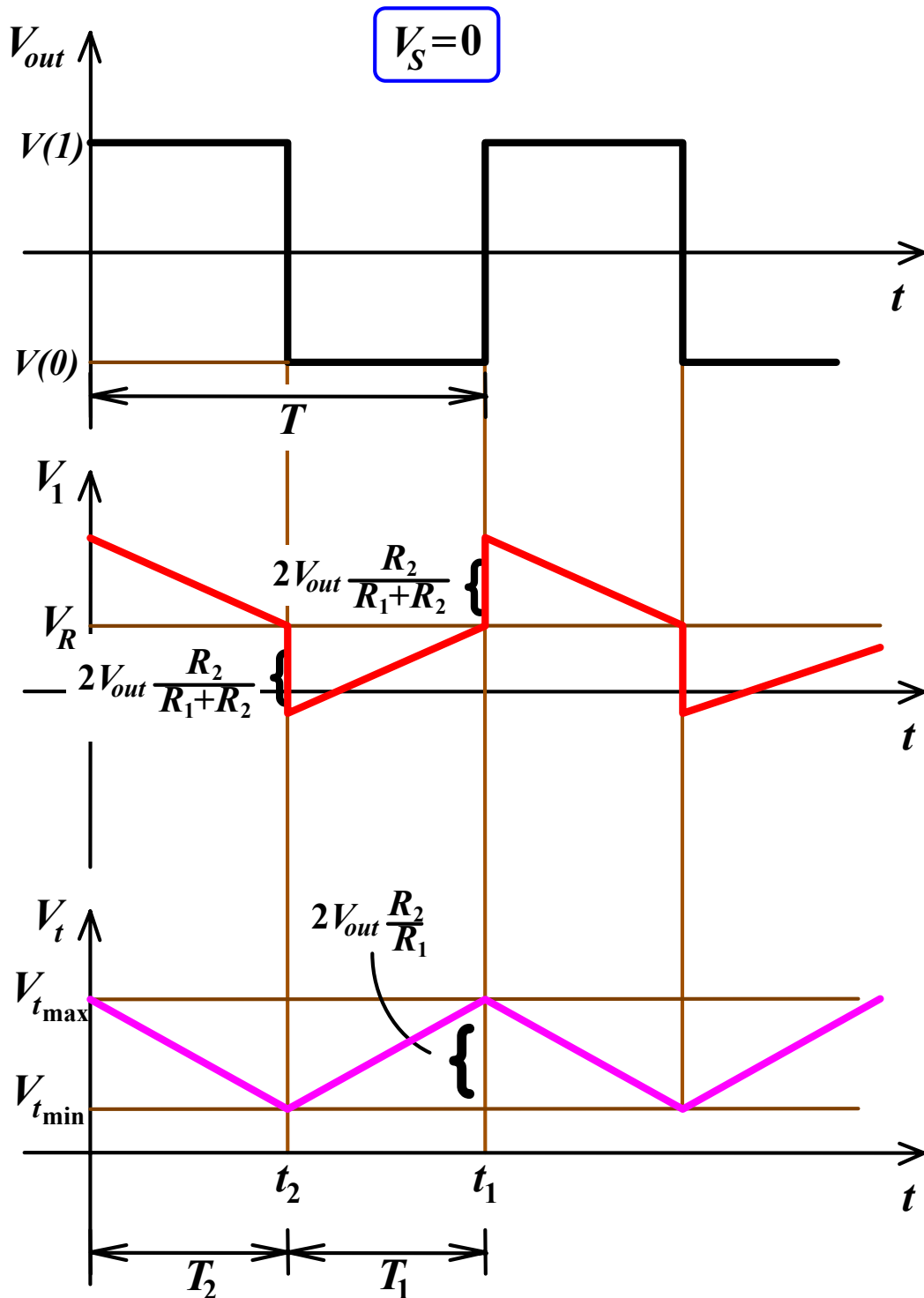


$$V(0) = -V_\gamma - V_Z$$

$$Hp: V_S = 0 \Rightarrow T_1 = T_2 = \frac{T}{2}$$

$$I_C = \frac{V_{out}}{R} \quad V_1 = \frac{R_1}{R_1 + R_2} V_t + \frac{R_2}{R_1 + R_2} V_{out}$$

$$V_C = \frac{I_C}{C} t + K = \frac{V_{out}}{R_C} t + K$$



$$V_1(t_2) = \frac{R_1}{R_1 + R_2} V_{t_{\min}} + \frac{R_2}{R_1 + R_2} V_{out} = V_R \Rightarrow V_{t_{\min}} = \frac{R_1 + R_2}{R_1} V_R - \frac{R_2}{R_1} V_{out}$$

$$V_1(t_1) = \frac{R_1}{R_1 + R_2} V_{t_{\max}} - \frac{R_2}{R_1 + R_2} V_{out} = V_R \Rightarrow V_{t_{\max}} = \frac{R_1 + R_2}{R_1} V_R + \frac{R_2}{R_1} V_{out}$$

$$\Delta V_t = V_{t_{\max}} - V_{t_{\min}} = 2V_{out} \frac{R_2}{R_1} \qquad \frac{V_{t_{\max}} + V_{t_{\min}}}{2} = \frac{R_1 + R_2}{R_1} V_R$$

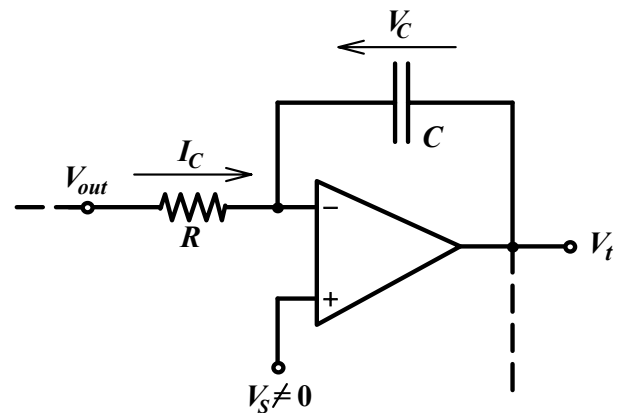
$$\frac{V_{t_{\max}} - V_{t_{\min}}}{T/2} = \left| \frac{dV_C}{dt} \right| = \frac{V_{out}}{RC} \Rightarrow 2V_{out} \frac{R_2}{R_1} = \frac{V_{out}}{RC} \frac{T}{2} \Rightarrow$$

$$T = 4RC \frac{R_2}{R_1}$$

$$V_S \neq 0 \Rightarrow T_1 \neq T_2$$

$$I_R = I_C = \frac{V_{out} - V_S}{R} \Rightarrow V_t \downarrow \Rightarrow T_2$$

$$I_R = I_C^* = \frac{-V_{out} - V_S}{R} \Rightarrow V_t \uparrow \Rightarrow T_1$$



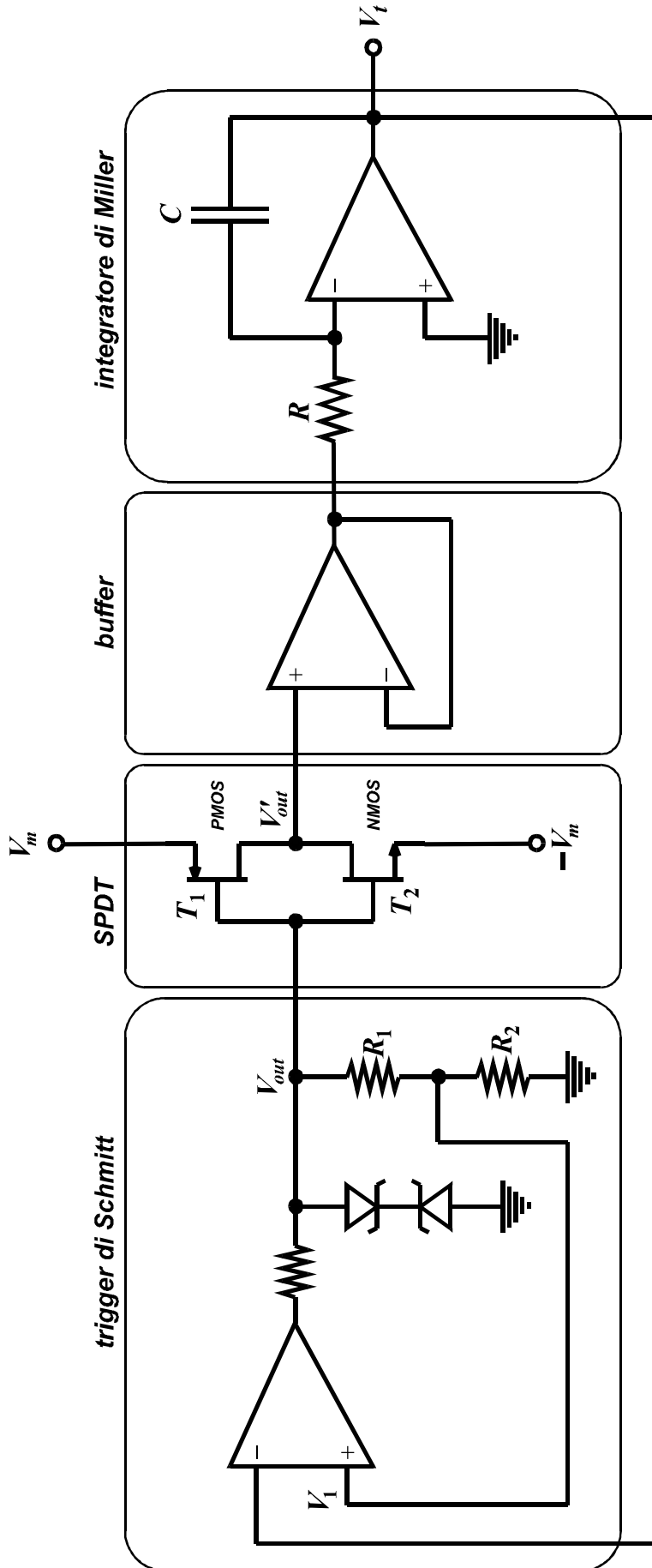
$$T_1 = 2V_{out} \frac{RC}{V_{out} + V_S} \frac{R_2}{R_1} \qquad T_2 = 2V_{out} \frac{RC}{V_{out} - V_S} \frac{R_2}{R_1}$$

$$T = T_1 + T_2 = 2V_{out} RC \frac{R_2}{R_1} \left[ \frac{1}{V_{out} + V_S} + \frac{1}{V_{out} - V_S} \right] = 4RC \frac{R_2}{R_1} \frac{1}{1 - \left( \frac{V_S}{V_{out}} \right)^2}$$

$$f = \frac{R_1}{4RCR_2} \left( 1 - \left( \frac{V_S}{V_{out}} \right)^2 \right) \qquad \frac{T_1}{T_1 + T_2} = \delta = \dots = \frac{1}{2} \left( 1 - \frac{V_S}{V_{out}} \right)$$

$$V_S = 0 \Rightarrow \delta = 0,5 \qquad V_S = V_{out} \Rightarrow \delta = 0 \qquad V_S = -V_{out} \Rightarrow \delta = 1$$

V.C.O. (Voltage Controlled Oscillator)



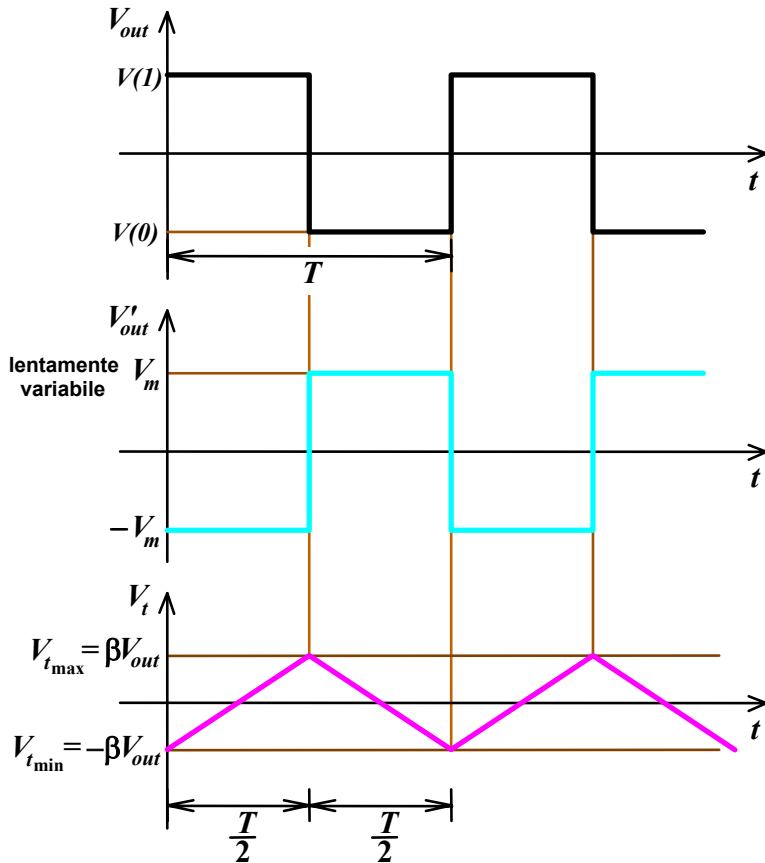
**S.P.D.T. = Single Pole Double Throw**

**Ipotesi:**  $|V_{out}| > |V_m|$

$V_m$  lentamente variabile  $\Rightarrow$  P.F.M. (Pulse Frequency Modulation)

$$V_{out} = V(1) \Rightarrow V'_{out} = -V_m \Rightarrow V_t \text{ sale}$$

$$V_{out} = V(0) \Rightarrow V'_{out} = V_m \Rightarrow V_t \text{ scende}$$

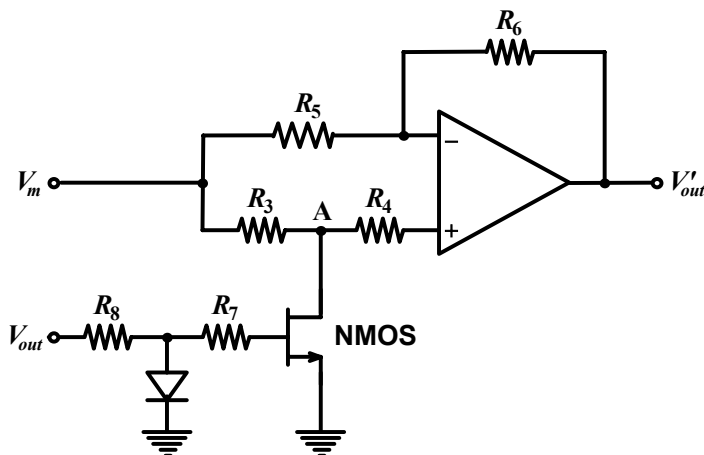


$$\frac{2\beta V_{out}}{T/2} = \frac{V_m}{RC}$$

$\Downarrow$

$$f_{osc} = \frac{1}{4\beta V_{out} RC} V_m$$

### Amplificatore bifase



$$V_{out} > 0 \Rightarrow V'_{out} = -V_m \frac{R_6}{R_5}$$

$$\Downarrow R_5 = R_6 \Downarrow$$

$$V'_{out} = -V_m$$

---

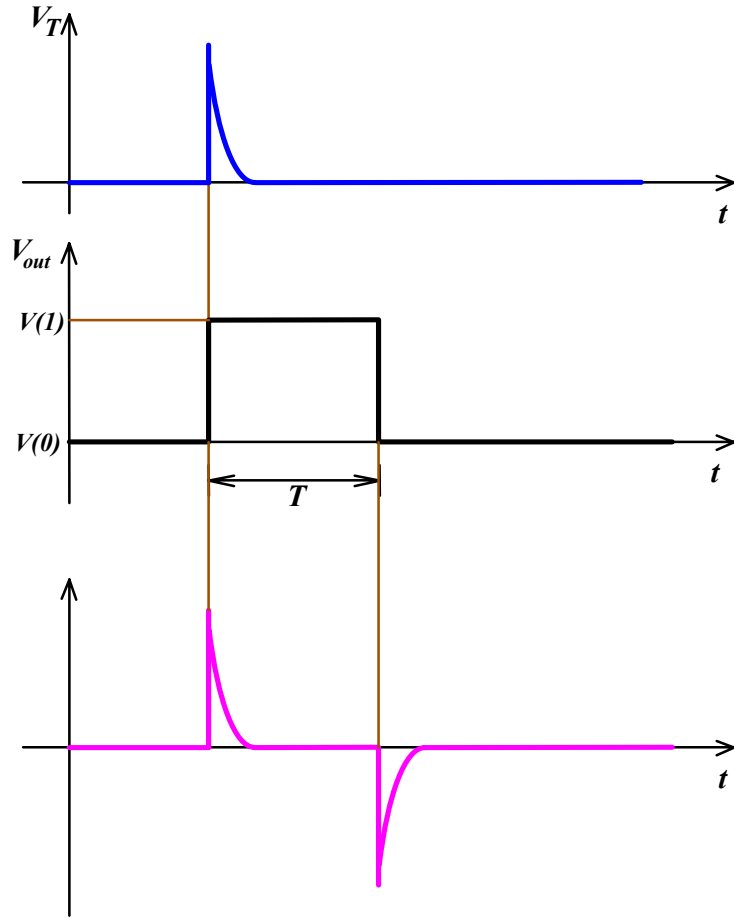

$$V_{out} < 0 \Rightarrow V'_{out} = -V_m \frac{R_6}{R_5} + V_m \left(1 + \frac{R_6}{R_5}\right)$$

$$\Downarrow R_5 = R_6 \Downarrow$$

$$V'_{out} = V_m$$

# Multivibratori monostabili

## Funzionamento

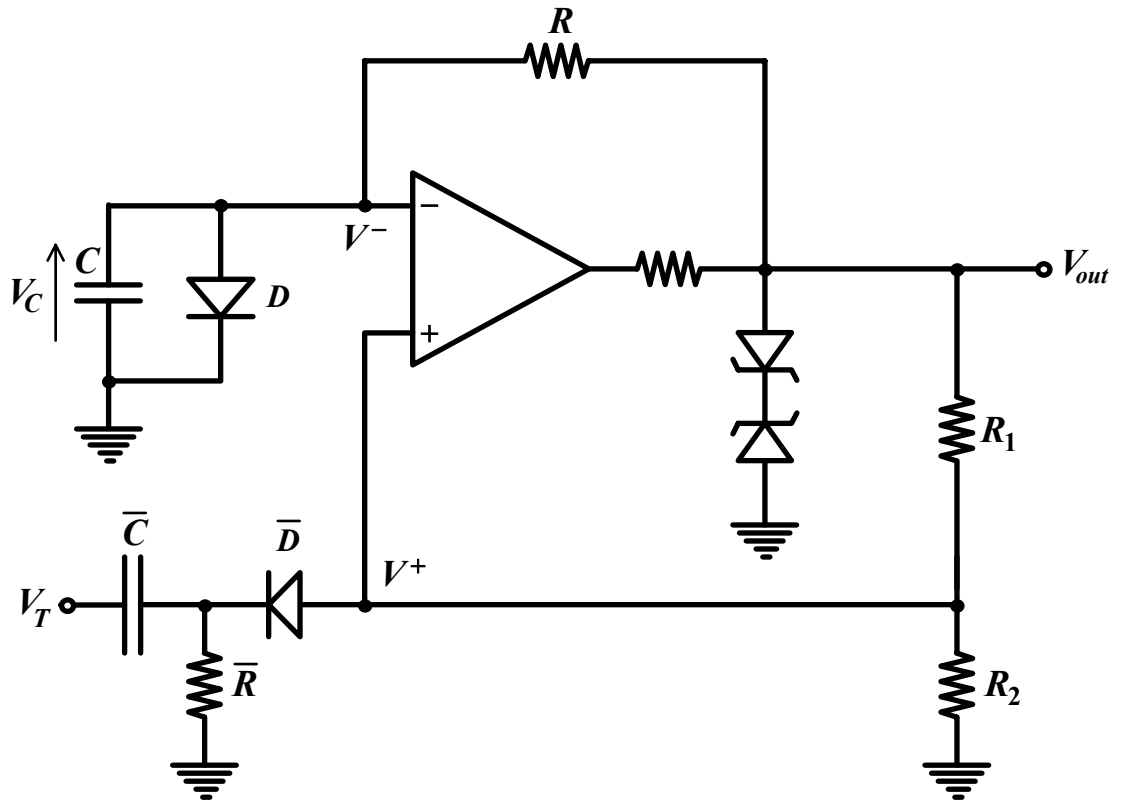


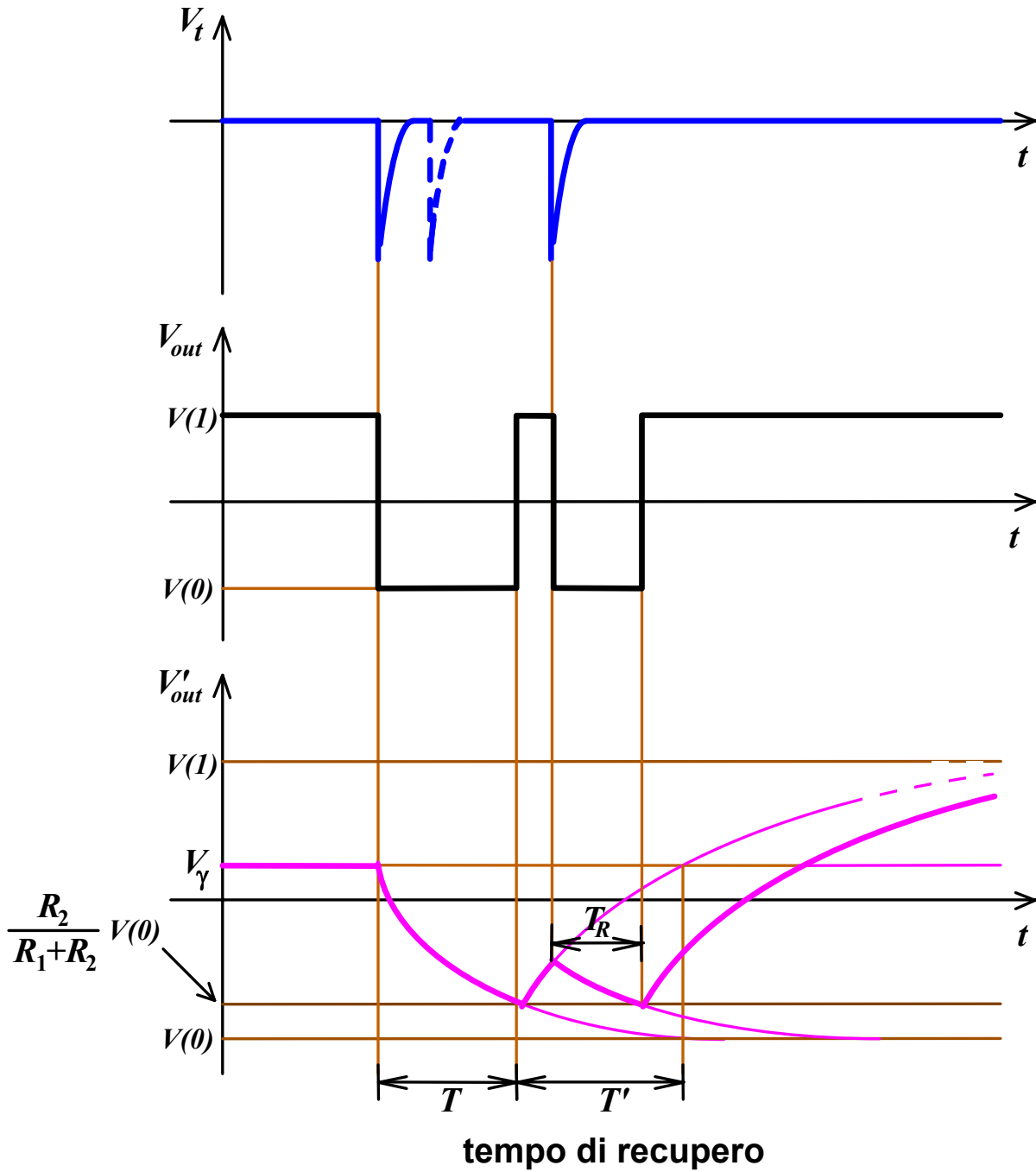
**Monostabile  
non  
risincronizzabile**

**Ipotesi:**

$$V_\gamma \ll \frac{R_2}{R_1 + R_2} V(1)$$

$$|V_T| > |\beta V_{out} - V_\gamma|$$





$R, C = ?$

$$V_c(t) = -V_o + (V_\gamma + V_o)e^{-\frac{t}{RC}}$$

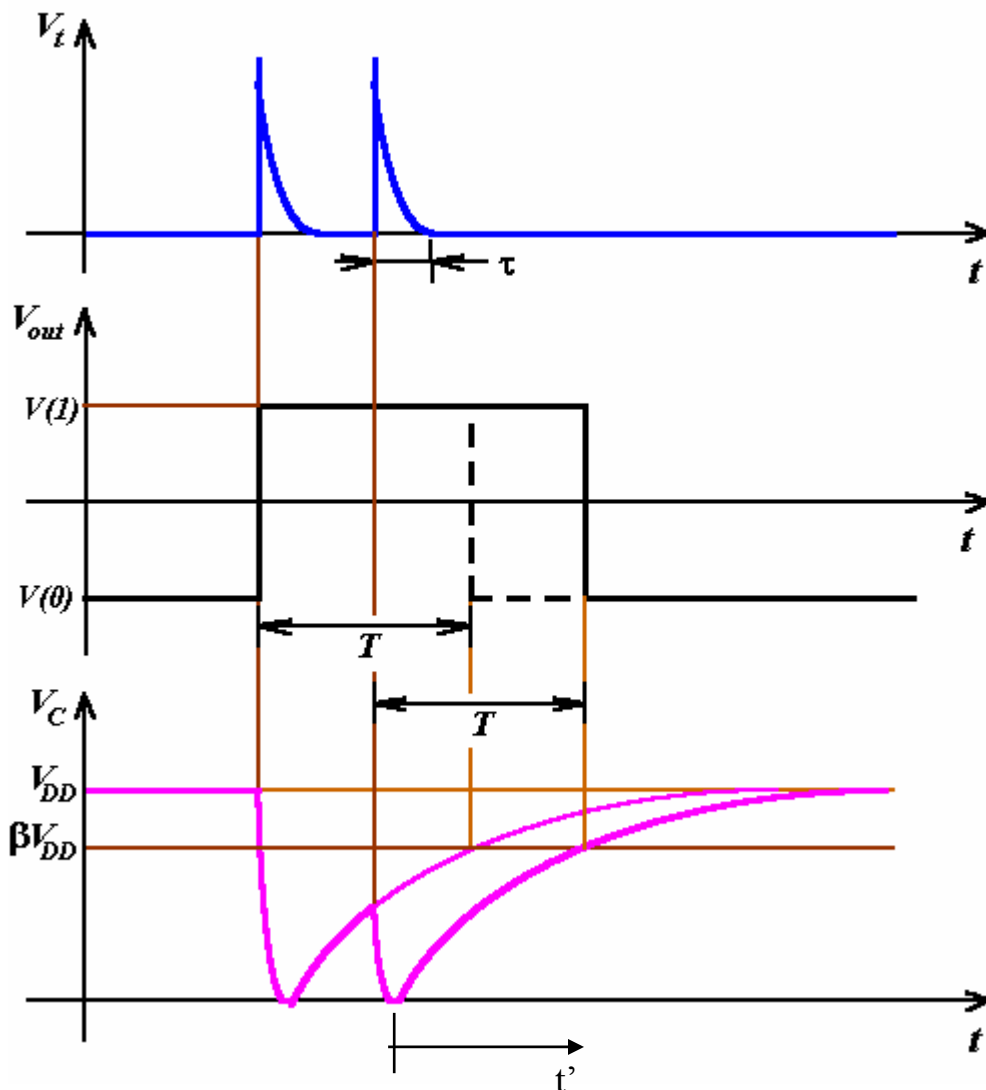
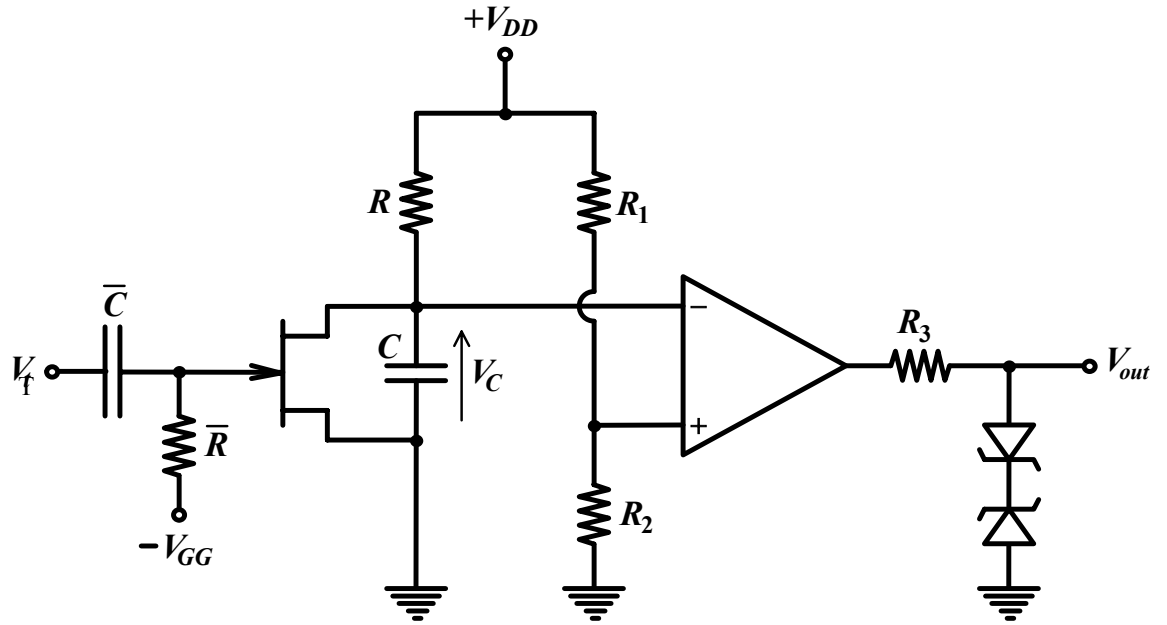
$$V_c(t) = -\beta V_o$$

$$T = RC \ln \frac{1 + \frac{V_\gamma}{V_{out}}}{1 - \beta} \quad \text{con} \quad \beta = \frac{R_2}{R_1 + R_2}$$

$$R_1 = R_2 \Rightarrow \beta = \frac{1}{2}; \quad V_\gamma \ll V_{out} \Rightarrow$$

$$T = RC \ln 2 = 0,69 RC$$

**Monostabile  
risincronizzabile**



$$V_C = V_{DD} \left( 1 - e^{-\frac{t'}{RC}} \right)$$

*Carica di C:*

$$\tau = CR$$

*Scarica di C:*

$$\tau = C \cdot r_{dON}$$

$$T = RC \ln \left( \frac{1}{1 - \beta} \right) =$$

$$= RC \ln \left( 1 + \frac{R_2}{R_1} \right)$$

$$R_1 = R_2$$

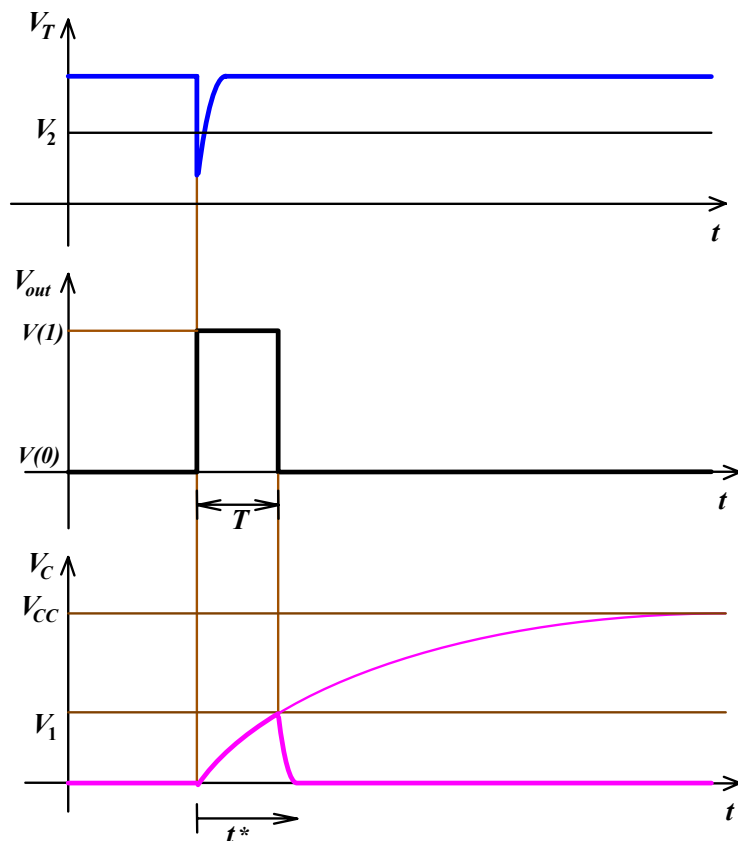
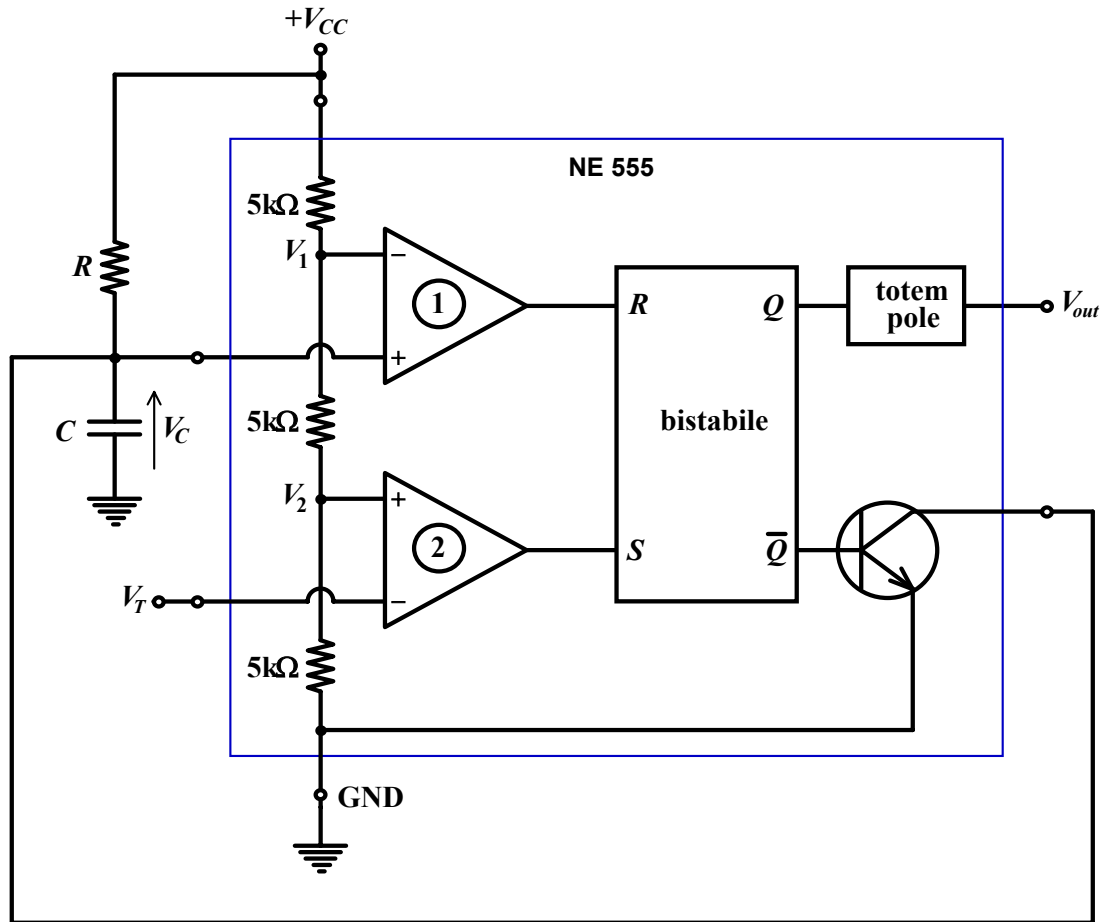


$$T = 0,69 RC$$

## Monostabile con NE555

$$V_1 = \frac{2}{3} V_{CC}$$

$$V_2 = \frac{1}{3} V_{CC}$$

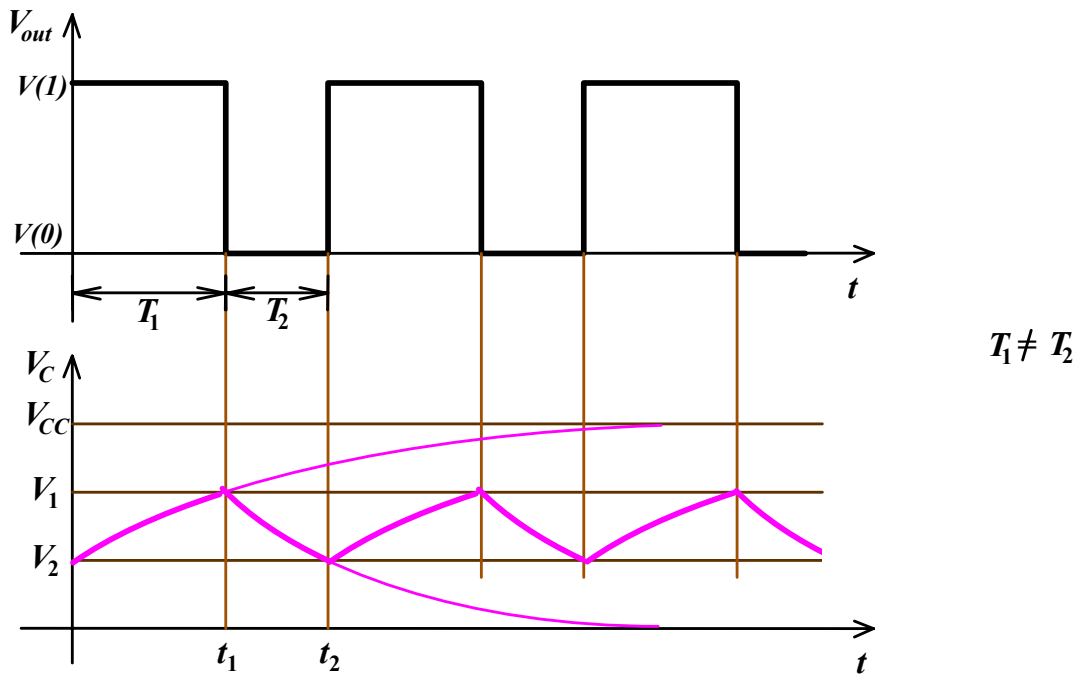
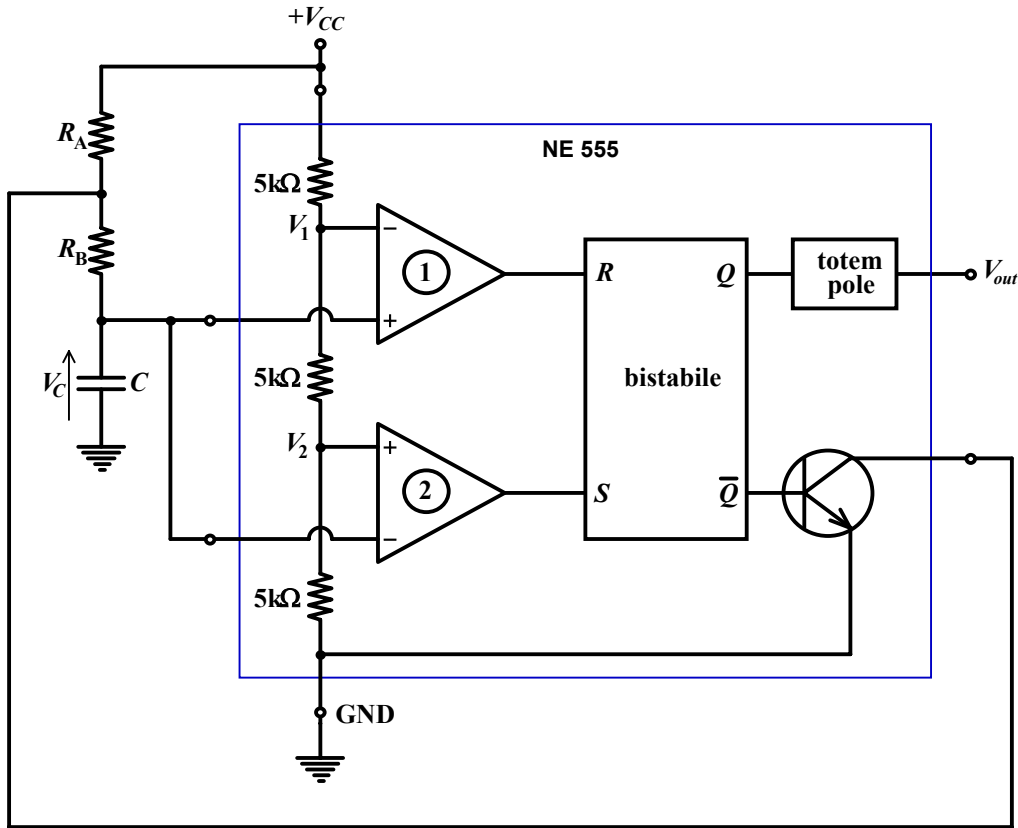


$$V_C(t) = V_{CC} (1 - e^{-\frac{t^*}{RC}})$$

$$V_C(T) = \frac{2}{3} V_{CC} = V_{CC} (1 - e^{-\frac{T}{RC}})$$

$$T = RC \ln 3 = 1,1 RC$$

## Astabile con NE555



$$V_C(t) = V_{CC} - \left[ (V_{CC} - V_2) \exp\left(\frac{-t}{(R_A + R_B)C}\right) \right] = V_{CC} - (V_2 - V_{CC}) \exp\left(\frac{-t}{(R_A + R_B)C}\right)$$

$$V_C(t_1) = V_C(T_1) = V_1 \Rightarrow \dots \Rightarrow T_1 = (R_A + R_B) C \ln 2; \quad T_2 = R_B C \ln 2$$

## Tecniche di modulazione con portante armonica

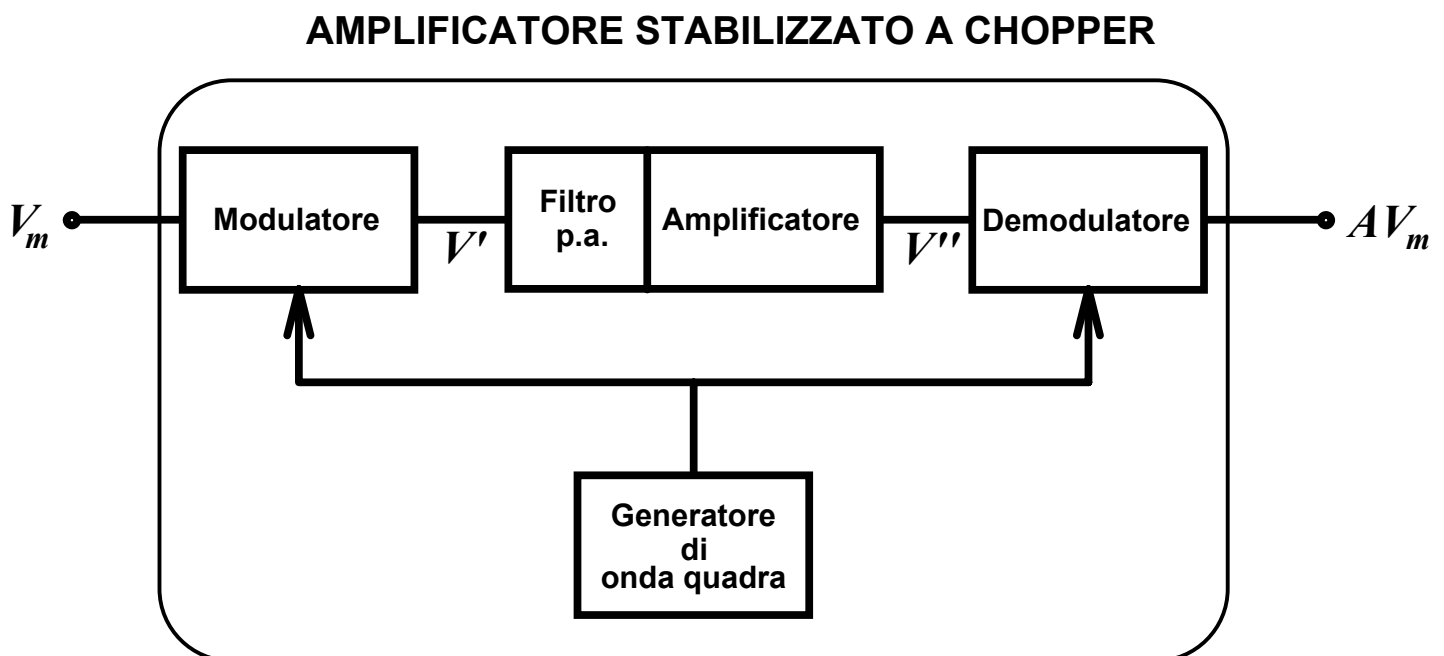
### Con portante sinusoidale

- Modulazione di ampiezza o **AM** (Amplitude Modulation)
- Modulazione di frequenza o **FM** (Frequency Modulation)
- Modulazione di fase o **PM** (Phase Modulation)

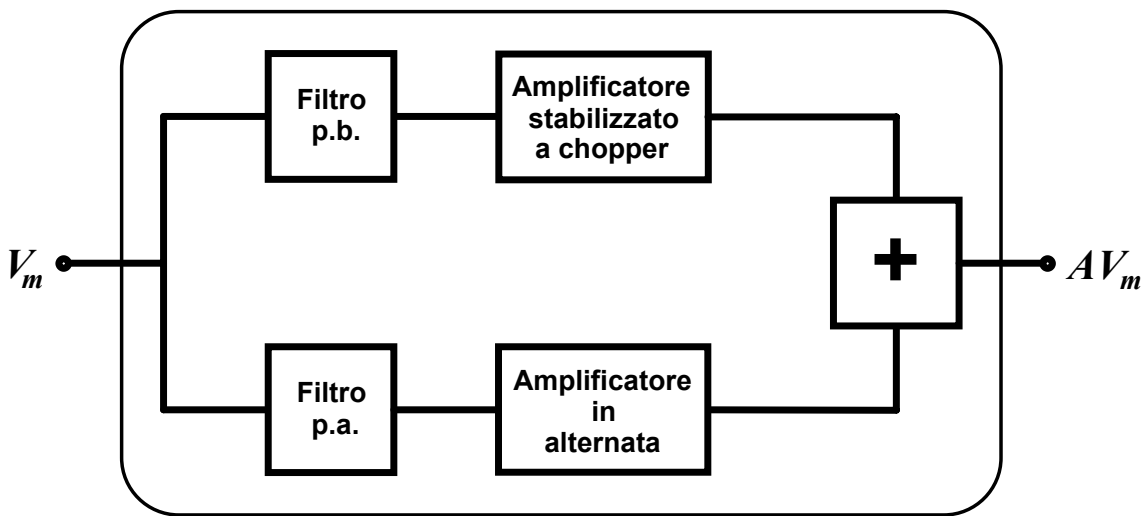
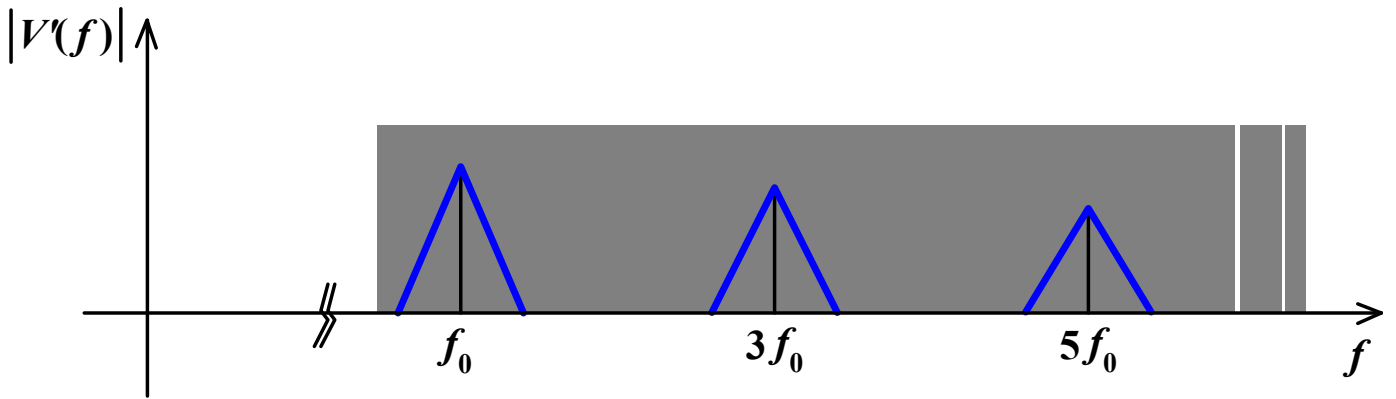
### Con portante ad impulsi

- Modulazione di ampiezza di impulsi o **PAM** (Pulse Amplitude Modulation)
- Modulazione di larghezza di impulsi o **PWM** (Pulse Width Modulation)
- Modulazione di posizione di impulsi o **PPM** (Pulse Position Modulation)
- Modulazione di frequenza di impulsi o **PFM** (Pulse Frequency Modulation)

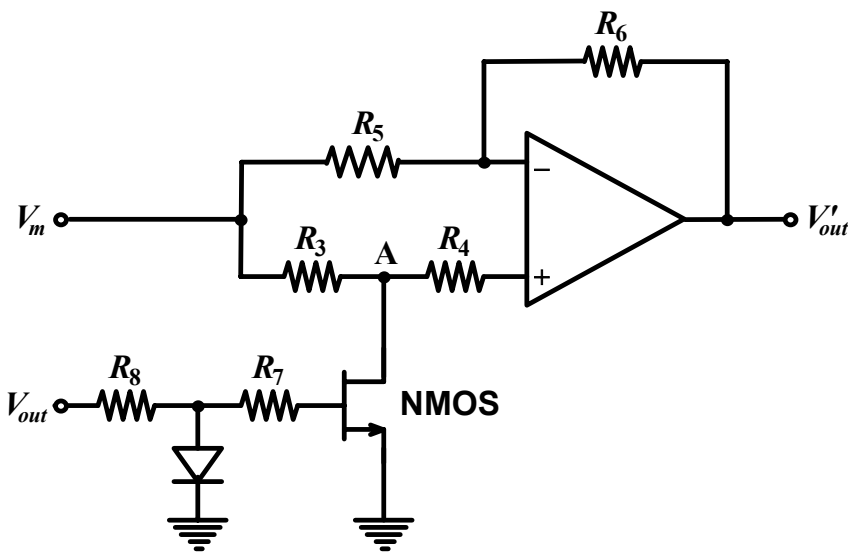
## Amplificatore stabilizzato a chopper



**Modulazione PAM**

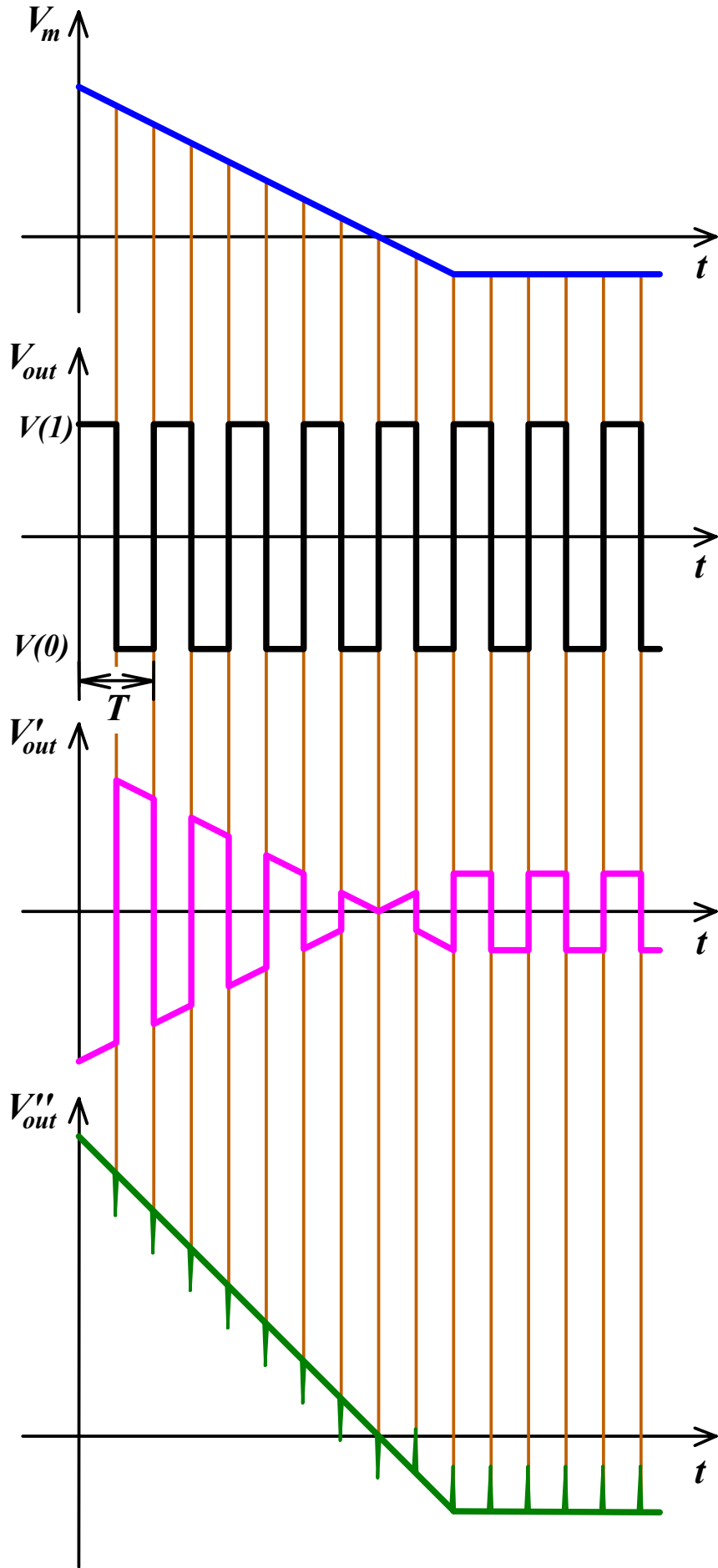


**Modulatori e demodulatori**

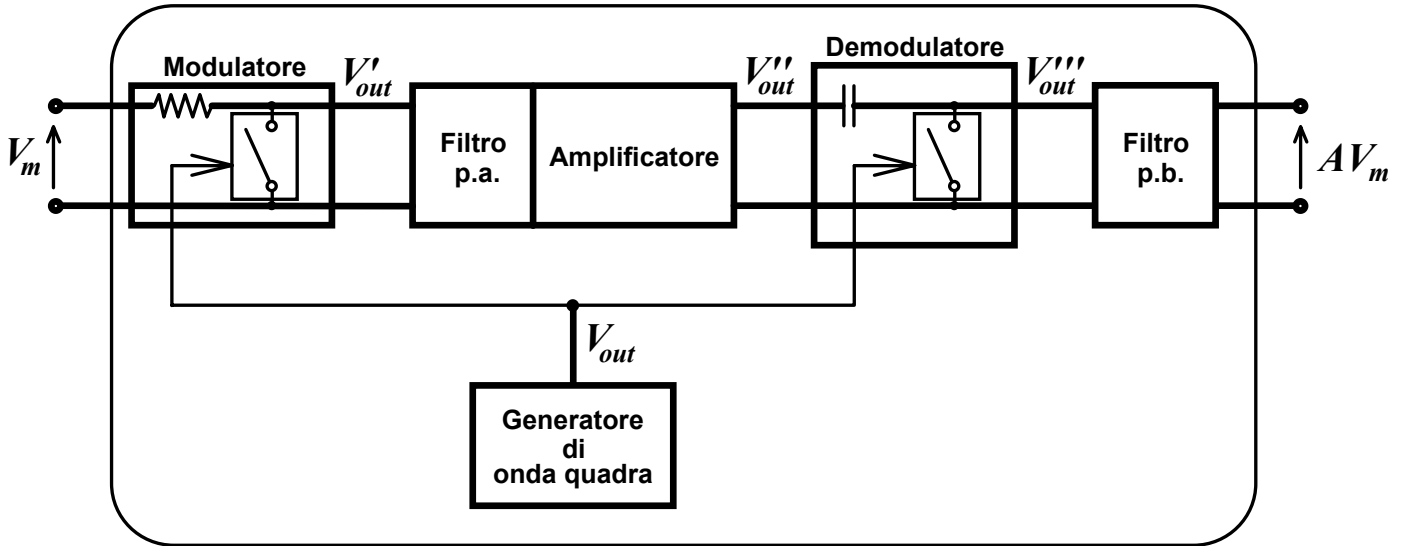


$$V_{out} = V(1) \Rightarrow V'_{out} = V_m$$

$$V_{out} = V(0) \Rightarrow V'_{out} = -V_m$$



**AMPLIFICATORE STABILIZZATO A CHOPPER**

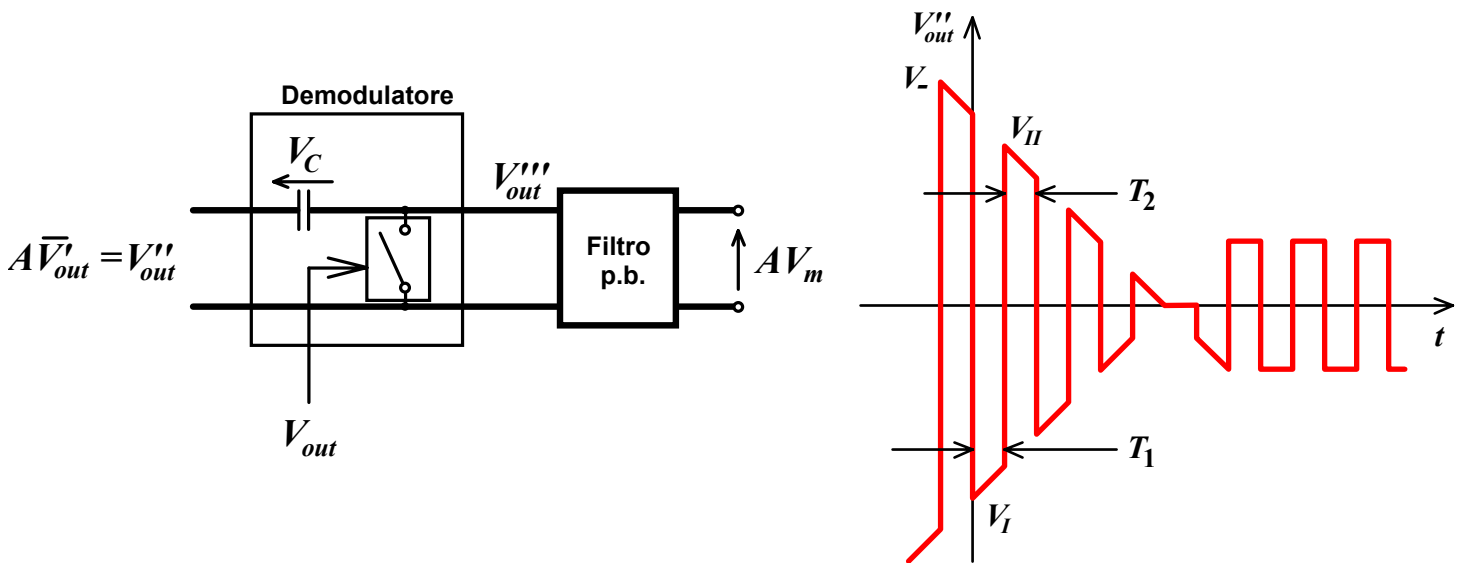


*Ricostruzione del segnale modulato:*

$$V_{out} = V(1) \Rightarrow JFET = ON \Rightarrow V'_{out} \approx 0$$

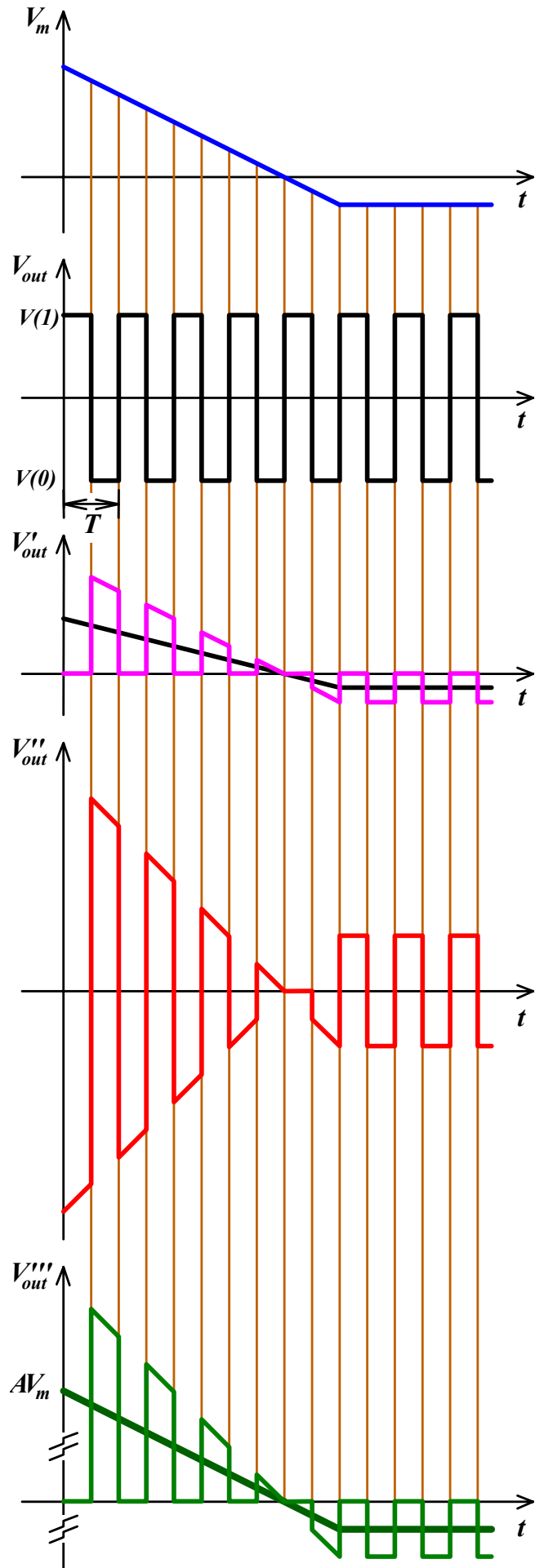
Ipotesi: Interruttore = JFET a canale n  $\Rightarrow$

$$V_{out} = V(0) \Rightarrow JFET = OFF \Rightarrow V'_{out} \approx V_m$$

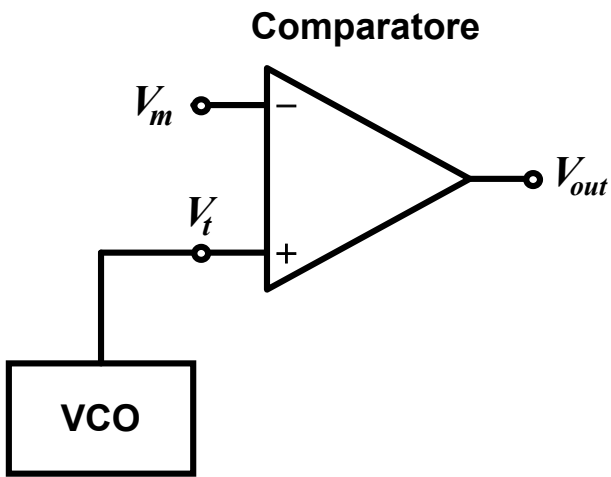


*durante  $T_1 \Rightarrow JFET = ON \Rightarrow V'''_{out} \Rightarrow V_I = V_C$*

*durante  $T_2 \Rightarrow JFET = OFF \Rightarrow V'''_{out} \Rightarrow V_{II} = V_C$*



## Modulatore PWM



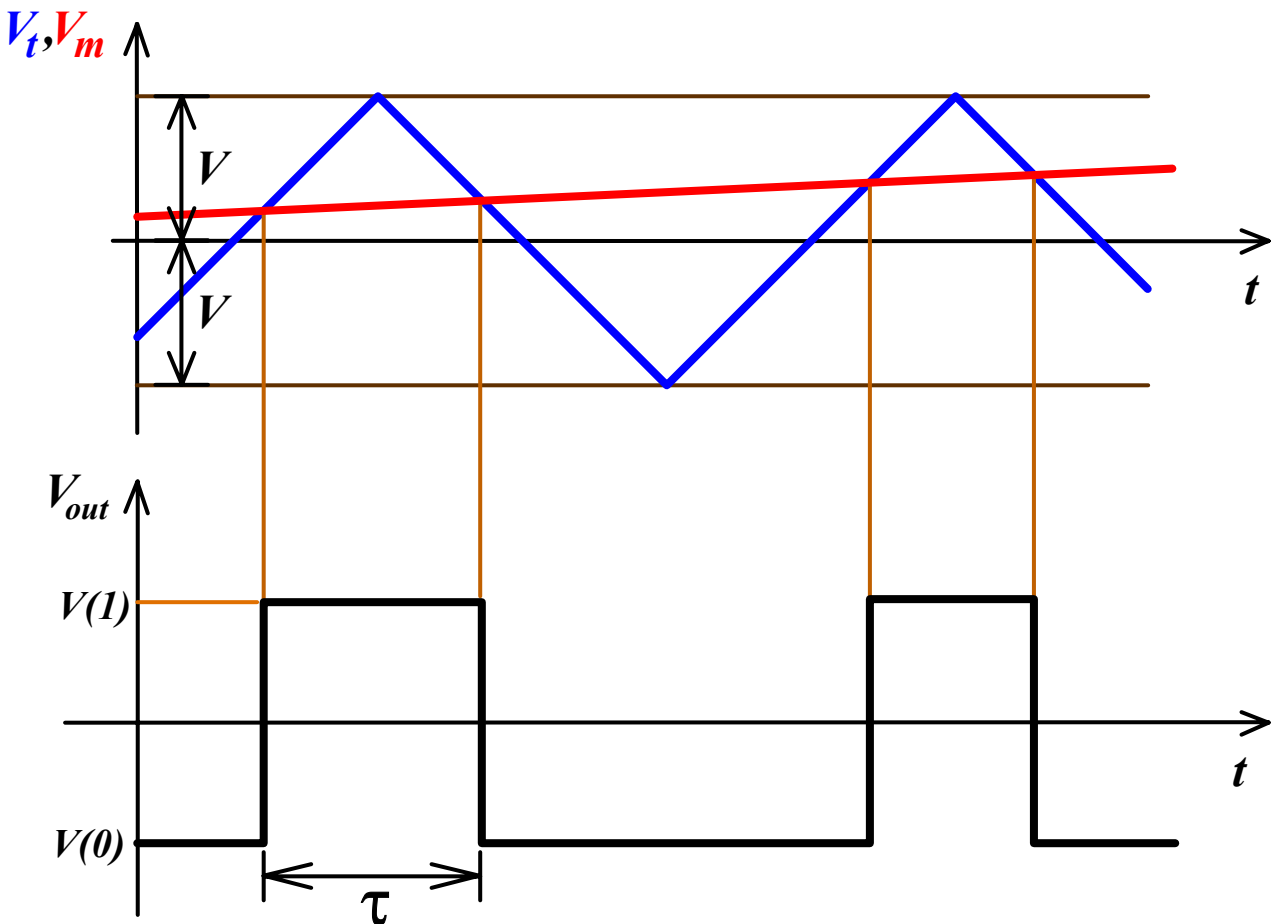
Ipotesi:  $V_m$  varia lentamente rispetto a  $V_t$ ;

$$|V| > |V_m|$$

$$|V_{t_{\min}}| = |V_{t_{\max}}| = V \Rightarrow \frac{2V}{T} = \frac{V - V_m}{\frac{\tau}{2}}$$

↓

$$\delta = \frac{\tau}{T} = \frac{1}{2} \left( 1 - \frac{V_m}{V_{t_{\max}}} \right)$$



$$V_m = 0 \Rightarrow \delta = 0,5; \quad V_m = V_{out} \Rightarrow \delta = 0; \quad V_m = -V_{out} \Rightarrow \delta = 1$$