Universidad
Carlos III de Madrid
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Session 24
Introduction to OA
Operational Amplifier

Electronic Components and Circuits

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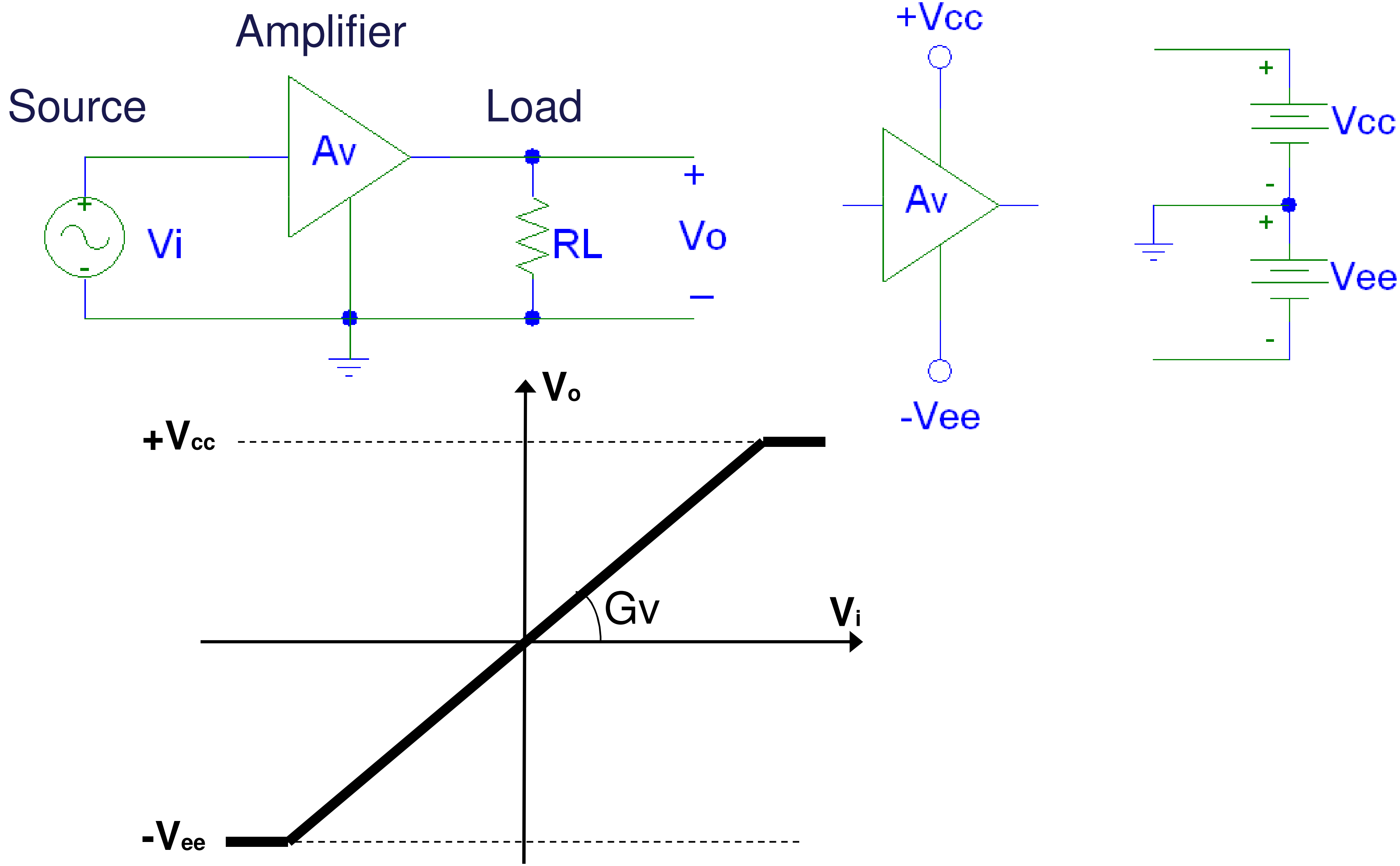
Introduction to Operational Amplifier

OBJECTIVES

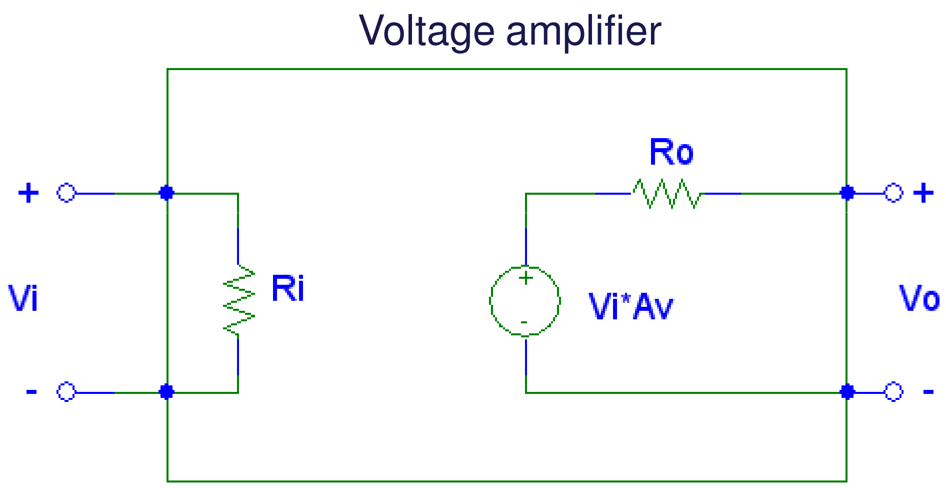
- To know the basic parameters of the ideal operational amplifier
- To understand the methodology of linear circuit analysis with ideal operational amplifiers: virtual short-circuit
- To understand and use the gain-bandwidth product concept
- To know some basic OA applications

Introduction: amplifier

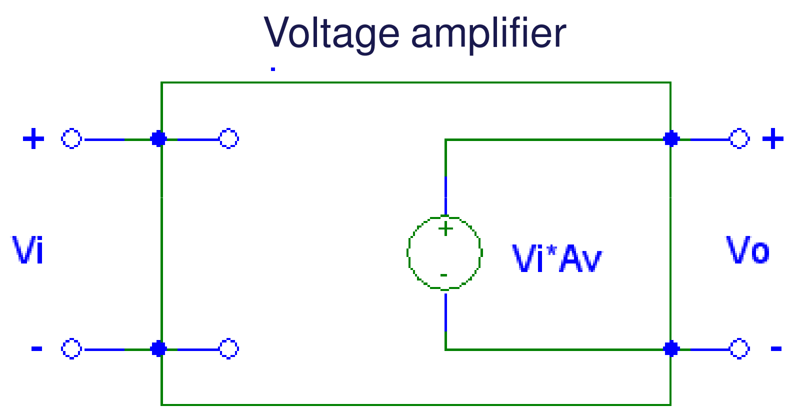


Introduction: Voltage amplifier

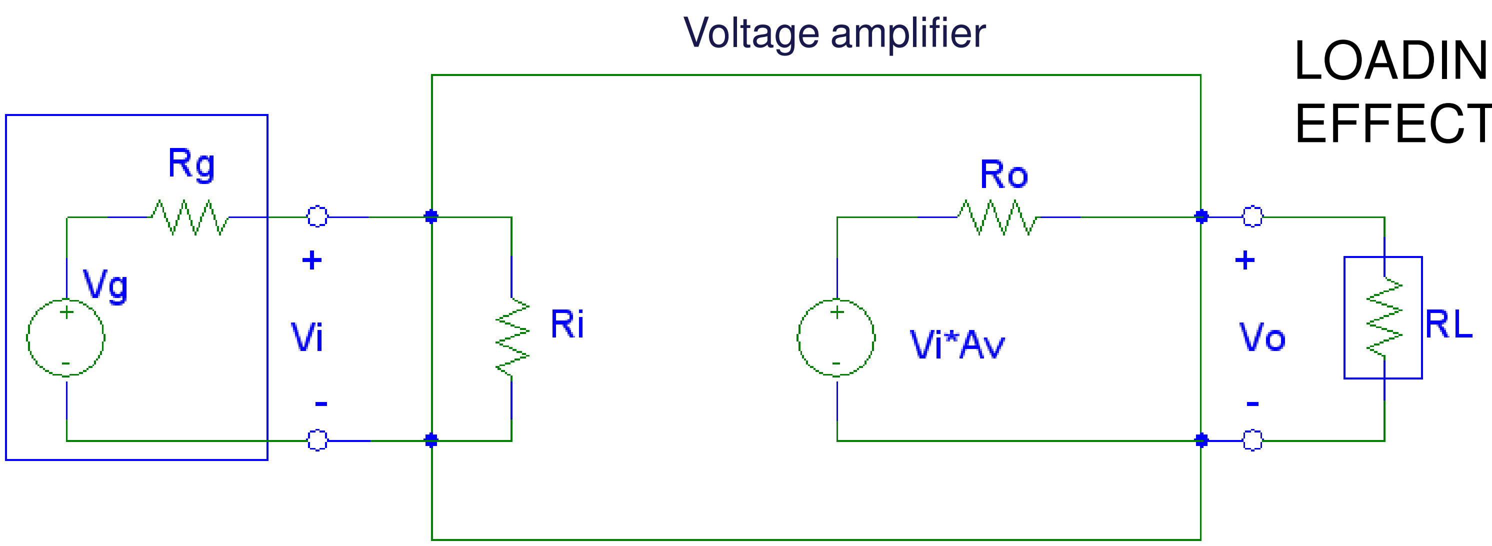
REAL



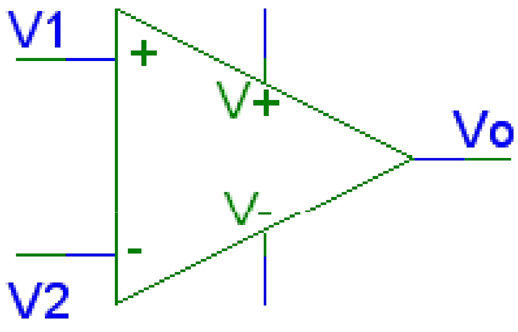
IDEAL



LOADING EFFECT



Introduction: Differential Amplifier



Differential input

$$Vid = V1 - V2$$

Common mode input

$$Vic = \frac{V1 + V2}{2}$$

Differential gain and common mode gain

$$Vo = A_{DM} \cdot Vid + A_{CM} \cdot Vic$$

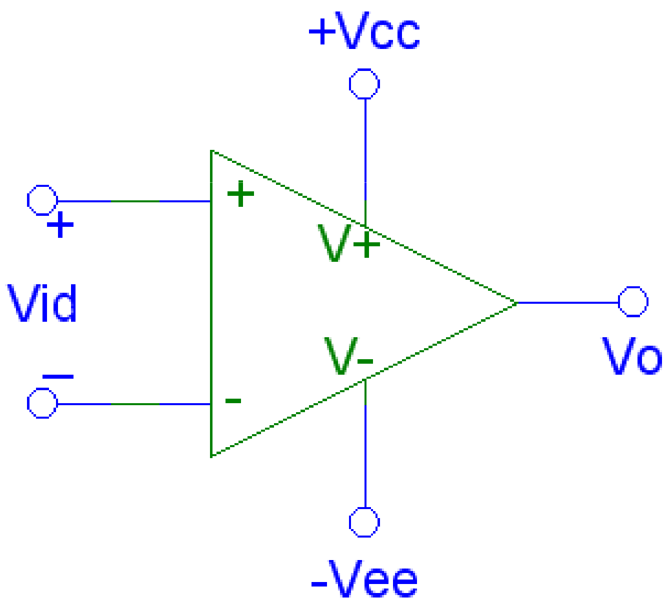
Common mode rejection ratio (CMRR)

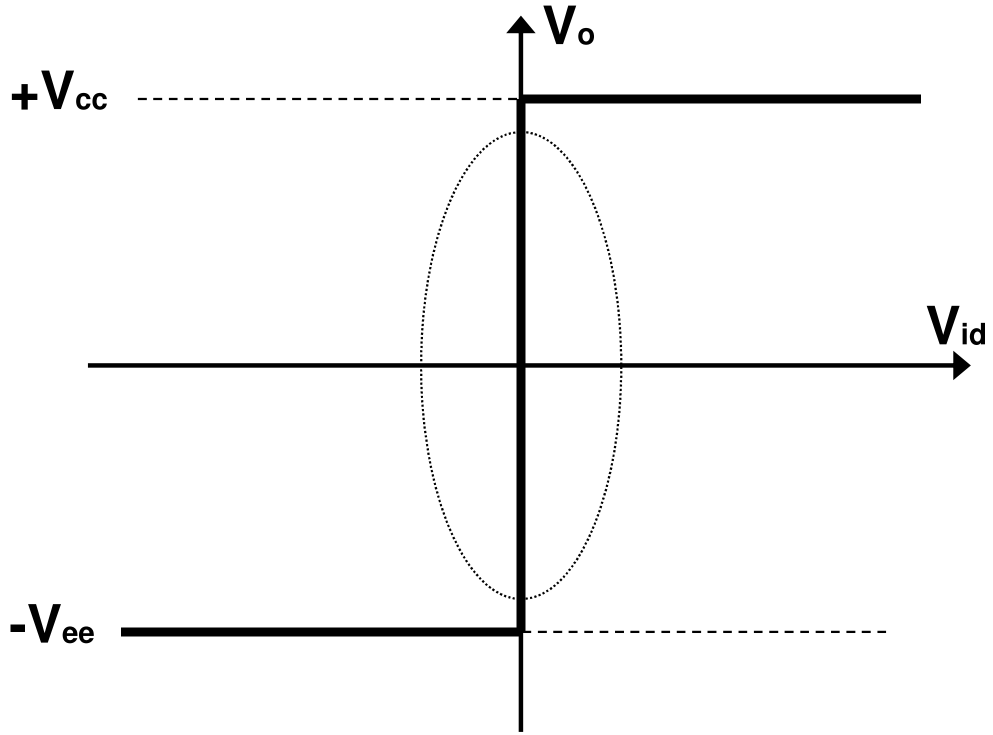
$$Vo = A_{DM}\left(Vid + \frac{Vic}{CMRR}\right)$$

If CMRR $\rightarrow \infty$

$$Vo = A_{DM} \cdot Vid$$

IDEAL operational amplifier





Linear behavior

$$v_o = A_v \cdot V_{id}$$

Within the output range

$$-V_{ee} \leq v_o \leq +V_{cc}$$

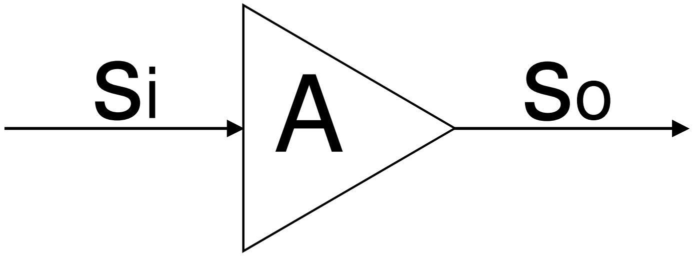
Ideally $A_v \rightarrow \infty$

Parameters of the IDEAL operational amplifier

- Open loop gain (Av) $\rightarrow\infty$
- Input impedance (Ri) $\rightarrow\infty$
- Output impedance (Ro) $\rightarrow 0$
- Common mode rejection ratio (CMRR) $\rightarrow\infty$
- Bandwidth (BW) $\rightarrow\infty$
- Input currents (bias) $\rightarrow 0$
- Offset voltage $\rightarrow 0$

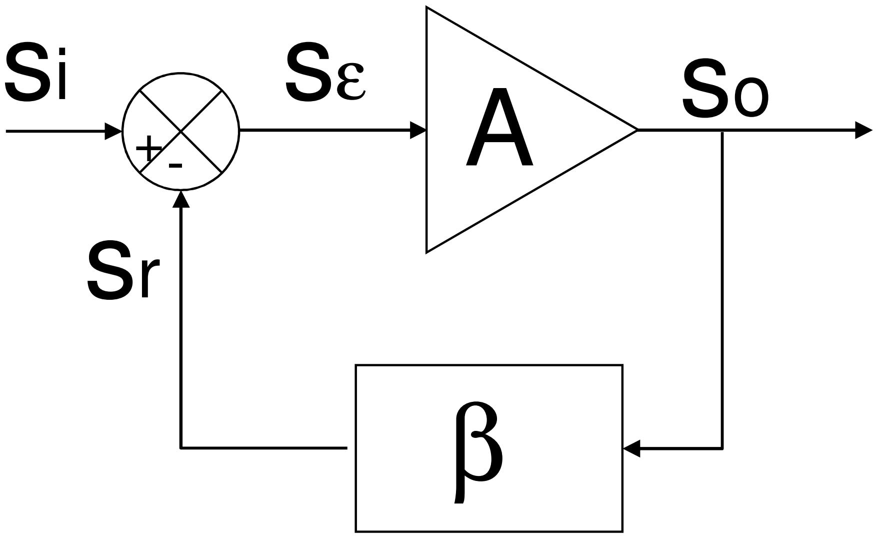
Introduction: Negative feed-back

OPEN LOOP AMPLIFICATION



$$s_o = A \cdot s_i$$

FEED-BACK AMPLIFICATION

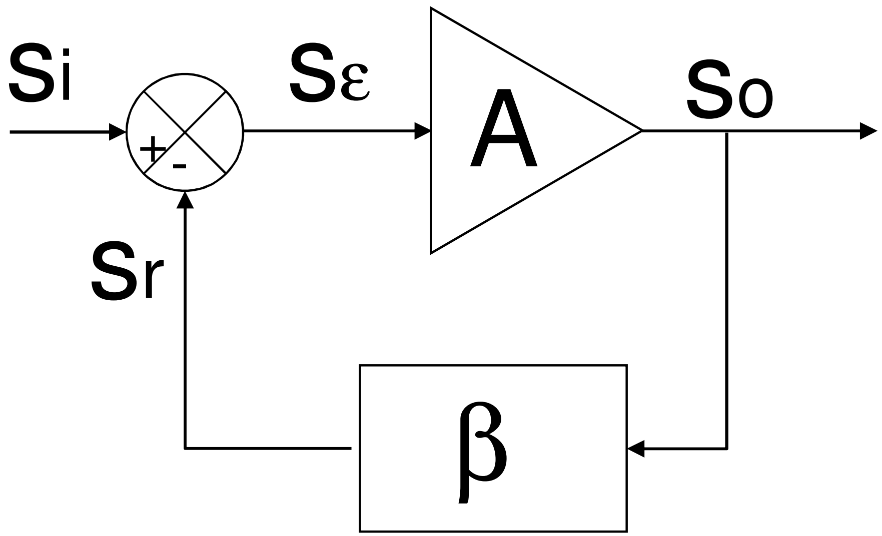


$$s_o = G \cdot s_i$$

$$\left.\begin{aligned} s_\varepsilon &= s_i - s_r \\ s_o &= A \cdot s_\varepsilon \\ s_r &= \beta \cdot s_o \end{aligned}\right\} \quad G = \frac{So}{Si} = \frac{A}{1 + A\beta}$$

Introduction: Negative feed-back

IDEAL FEED-BACK AMPLIFIER



$$s_o = G \cdot s_i$$

$$G = \frac{So}{Si} = \frac{A}{1 + A\beta}$$

Aβ>>1

[$A \rightarrow \infty$]

⇨

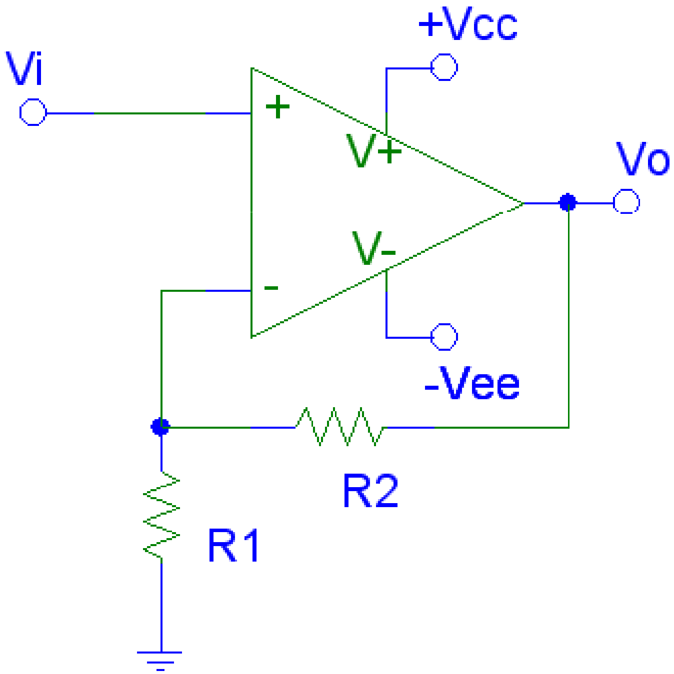
$$G \approx \frac{1}{\beta}$$

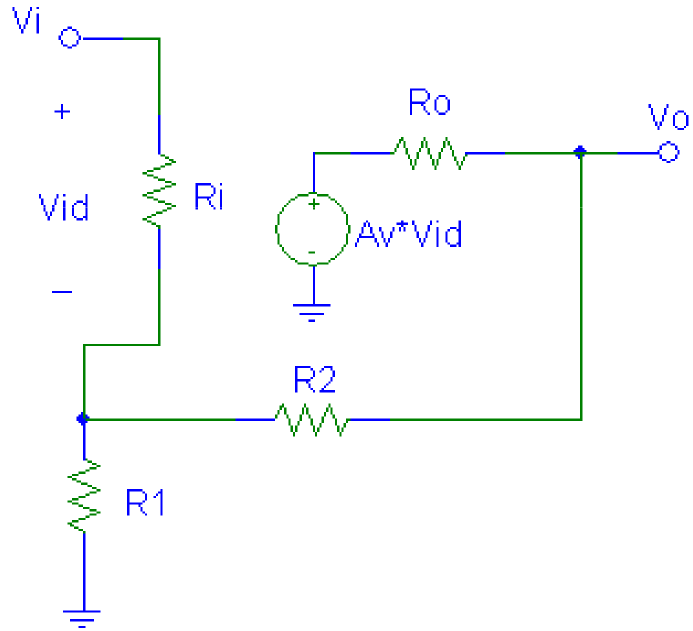
$$s_\varepsilon \rightarrow 0$$

⇨

$$So \approx \frac{1}{\beta} \cdot Si$$

Example: Non-inverting OA

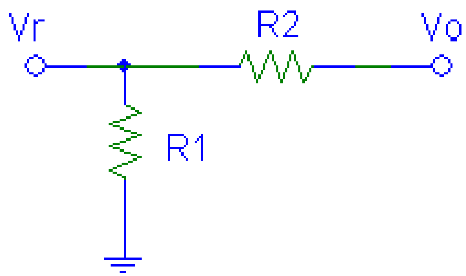




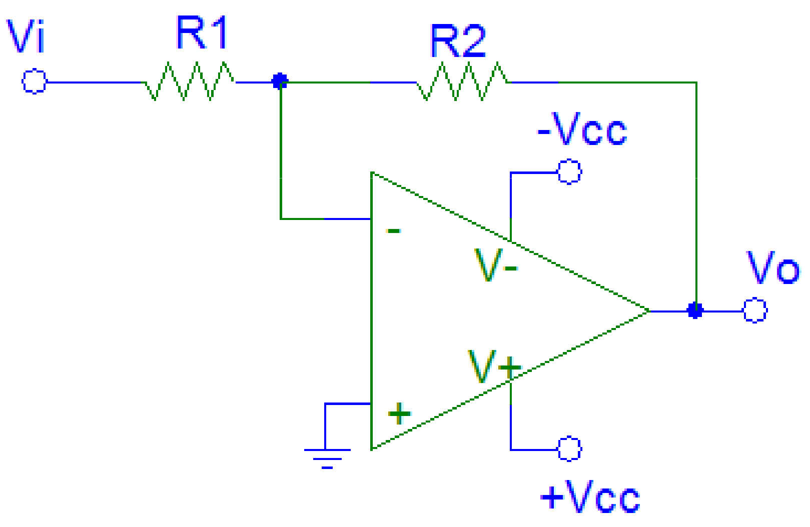
Ri →∞, Ro →0 + Av →∞

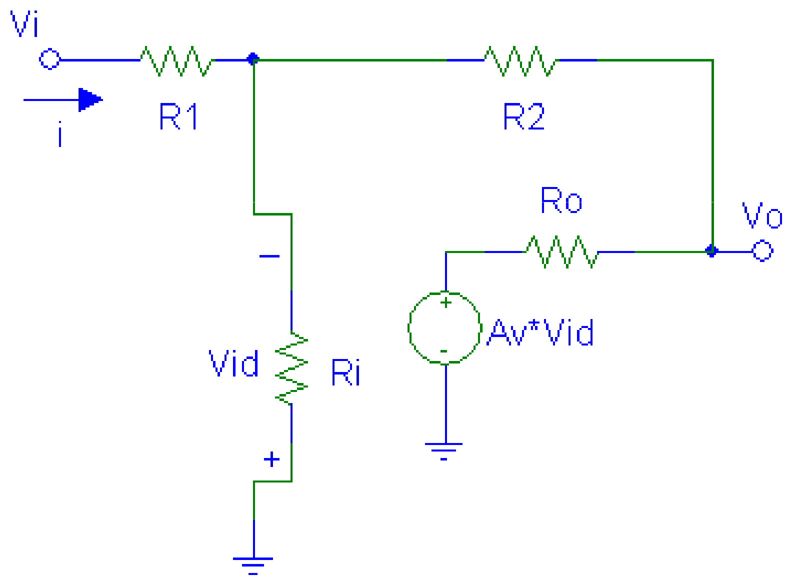
$$Gv \approx \frac{A_V}{1 + A_V \dfrac{R_1}{R_1 + R_2}}$$

$$Gv \approx 1 + \frac{R_2}{R_1}$$



Example: Inverting OA

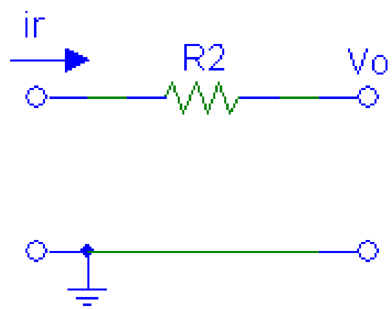




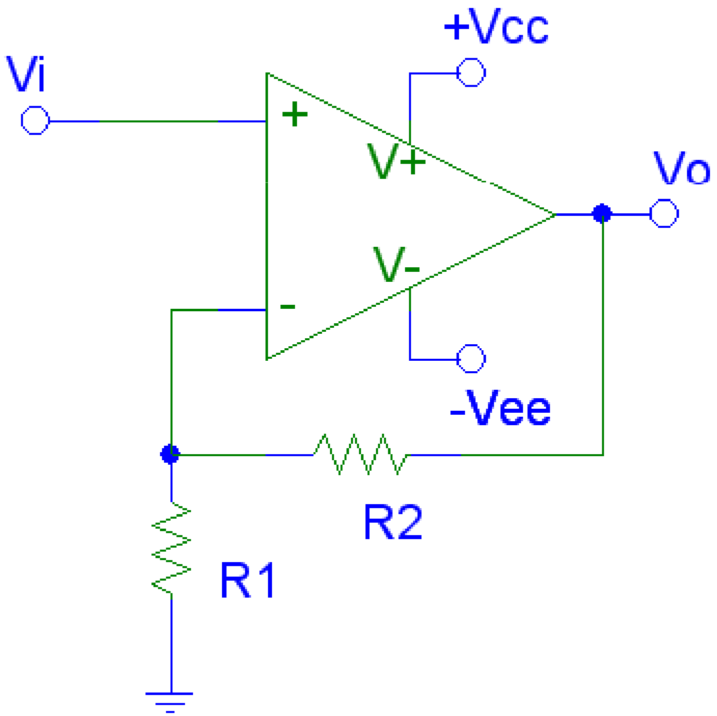
Ri →∞, Ro →0 + Av →∞

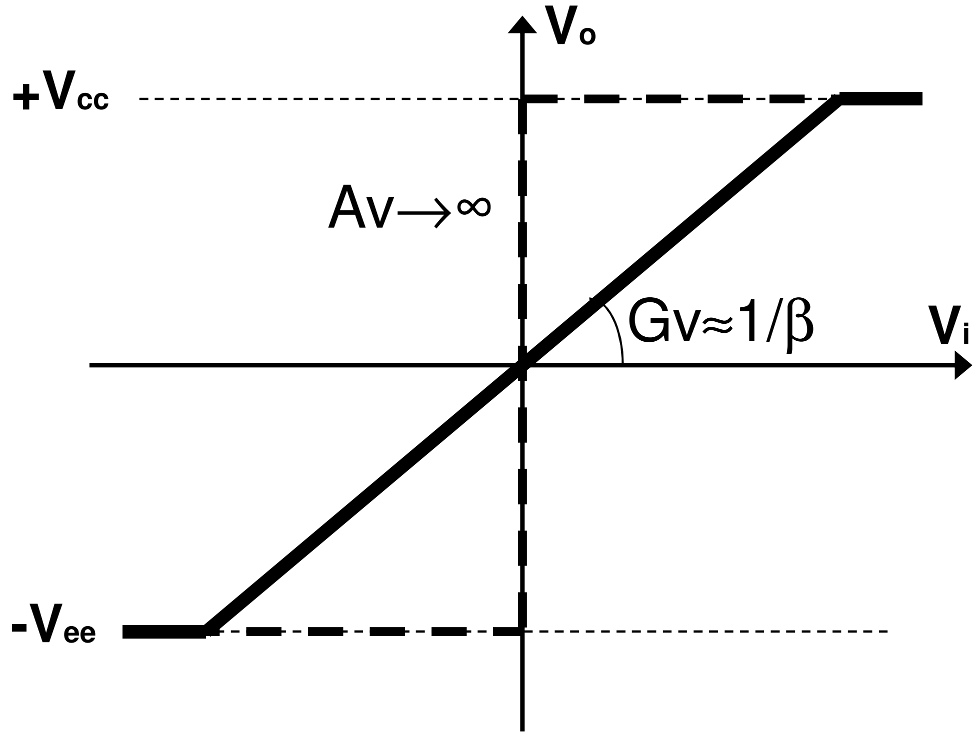
$$Gv \approx -\frac{A_V (R_1 \| R_2)}{1 + \frac{A_V}{R_2}(R_1 \| R_2)} \cdot \frac{1}{R_1}$$

$$Gv \approx -\frac{R_2}{R_1}$$



Linear application IDEAL-OA





Linear behaviour

$$v_o = A_v \cdot V_{id}$$

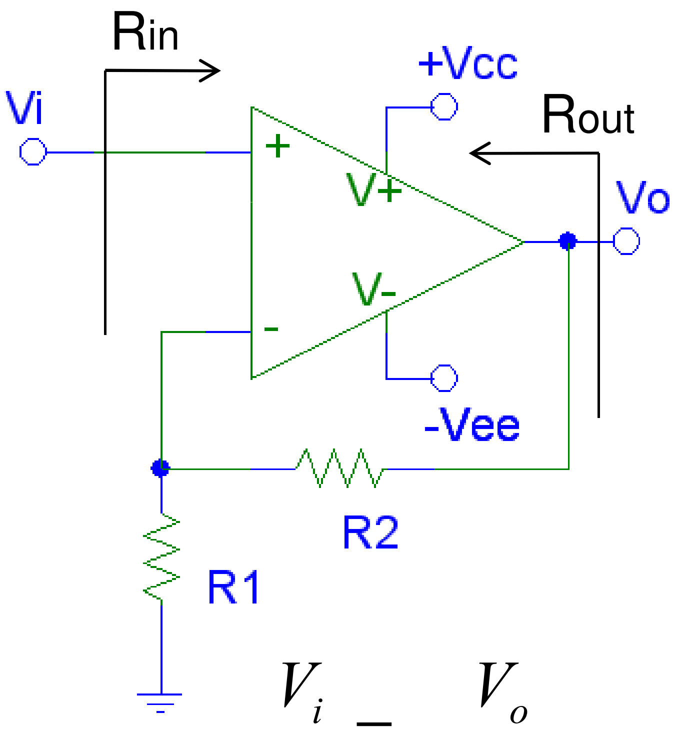
Negative feed-back

Virtual short-circuit

$$V_{id} = 0$$

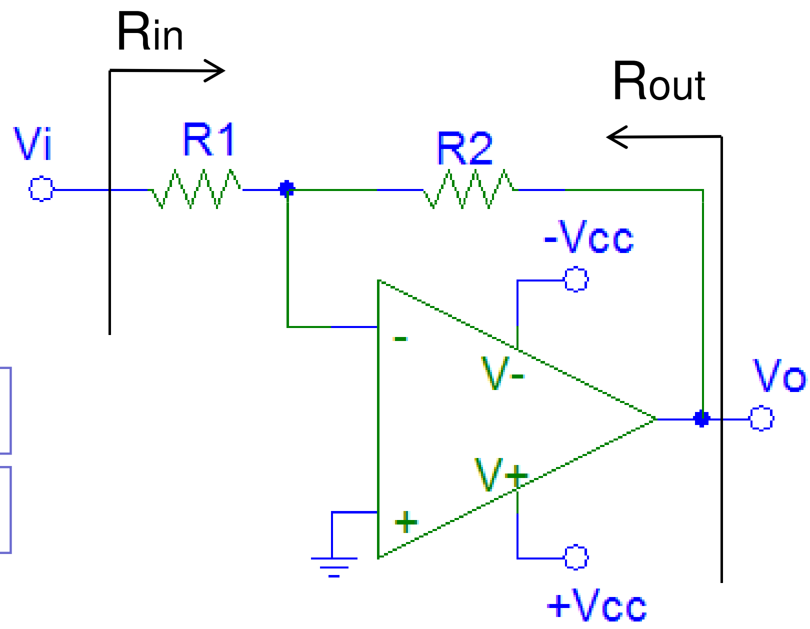
$$V_+ = V_-$$

Examples: Virtual short-circuit



V+ = V-

i+ = i- = 0



$$\frac{V_i}{R_1} = \frac{V_o}{R_1 + R_2}$$

$$\frac{V_i}{R_1} = -\frac{V_o}{R_2}$$

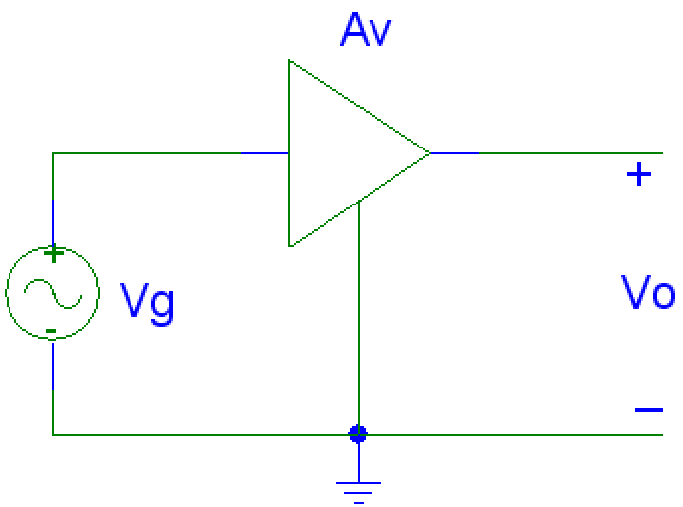
$$G_V = \frac{V_o}{V_i} = 1 + \frac{R_2}{R_1}$$

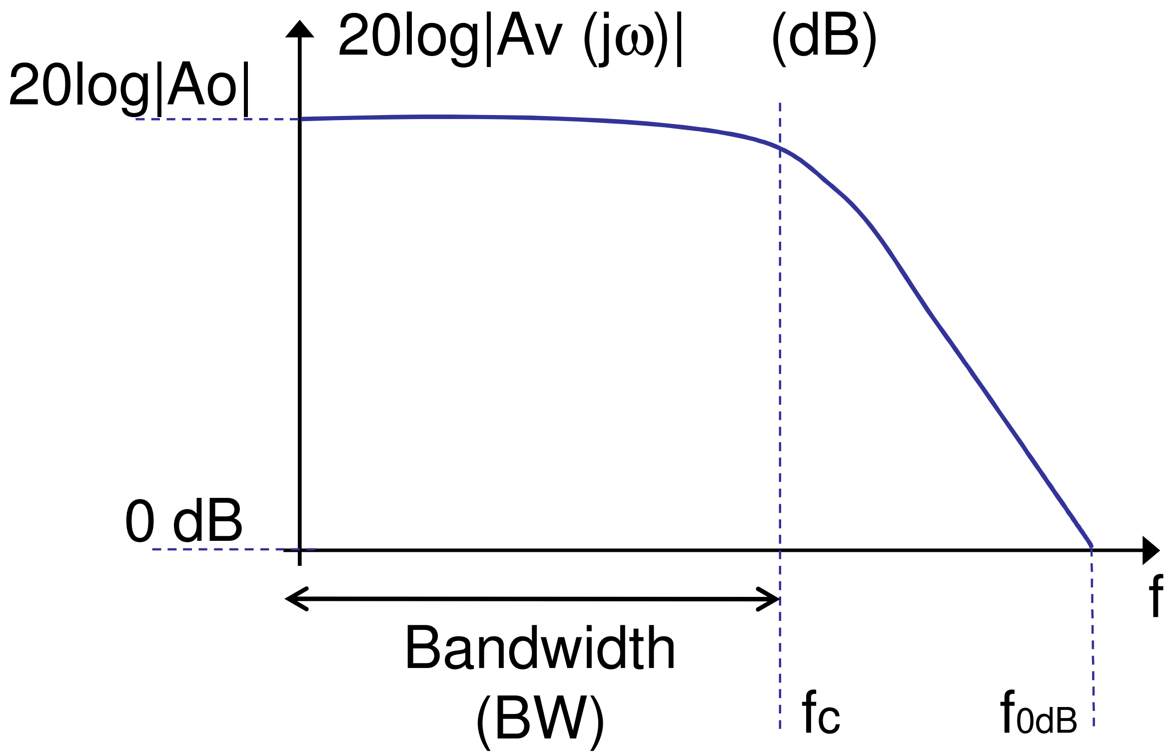
Rin $\rightarrow \infty$
Rout $\rightarrow$ 0

$$G_V = \frac{V_o}{V_i} = -\frac{R_2}{R_1}$$

Rin $\rightarrow$ R1
Rout $\rightarrow$ 0

Frequency response of the operational amplifier: continuous coupled





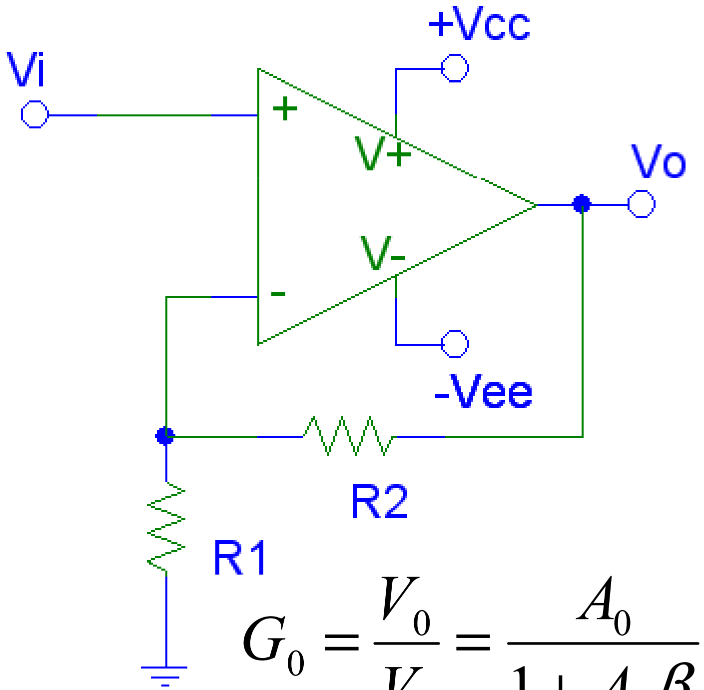
$$A_V(j\omega) = \frac{V_o(j\omega)}{V_g(j\omega)}$$

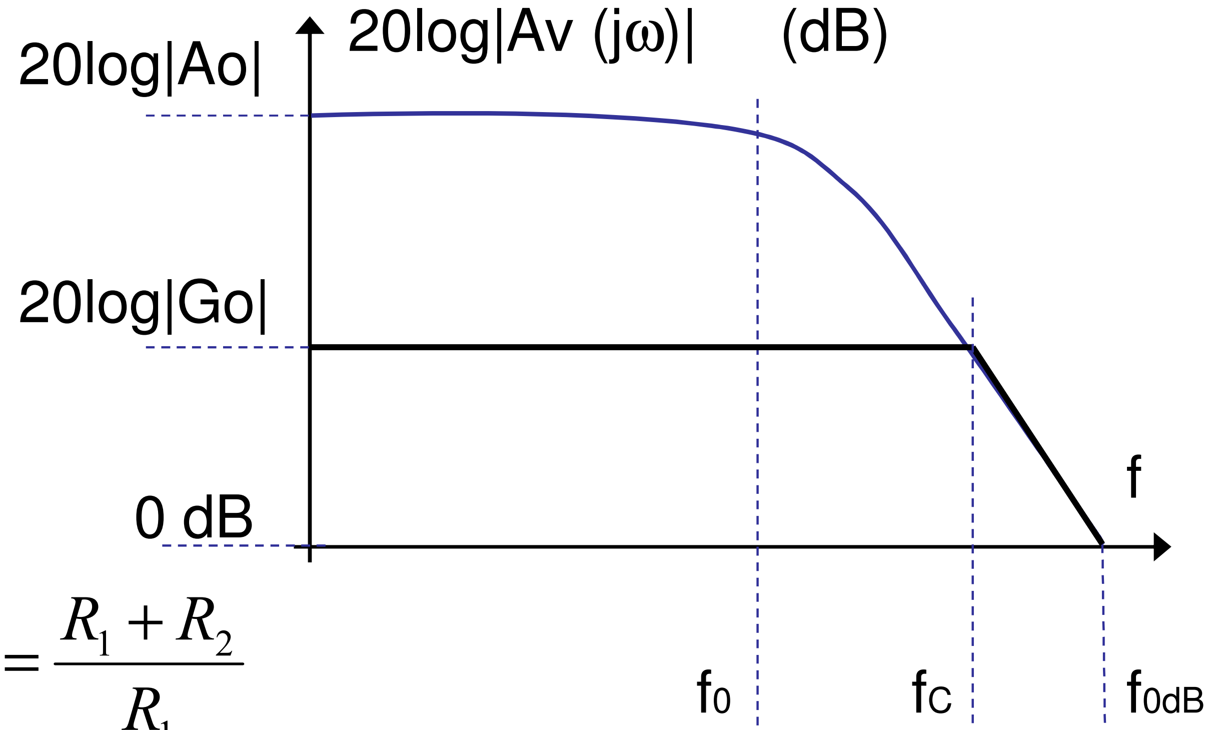
$$A_0 = A_V(\omega = 0)$$

Gain x Bandwidth = constant

$$A_0 \cdot f_c = 1 \cdot f_{0dB}$$

Gain x Bandwidth = constant





$$G_0 = \frac{V_0}{V_i} = \frac{A_0}{1 + A_0\beta} = \frac{R_1 + R_2}{R_1}$$

Open Loop Bandwidth (f_0)

$$G_0 \cdot f_C = A_0 \cdot f_0 = f_{0dB}$$

Feed-back amplifier Bandwidth (f_C)

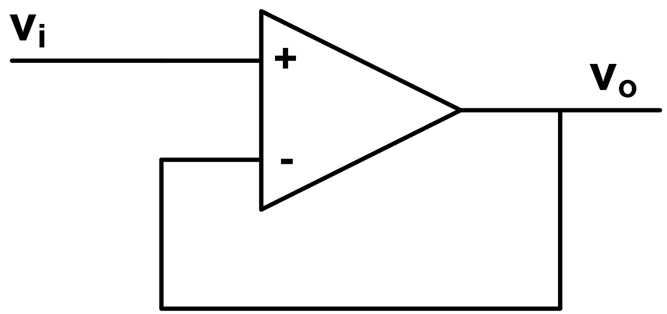
$$f_C = (1 + A_0\beta) \cdot f_0$$

Linear applications of operational amplifier

INDEX

- Voltage follower
- Inverting adder
- Differenctial amplifier
- Current-voltage converter
- Voltage-current converter
- Low-pass filter / Integrator

Voltage follower

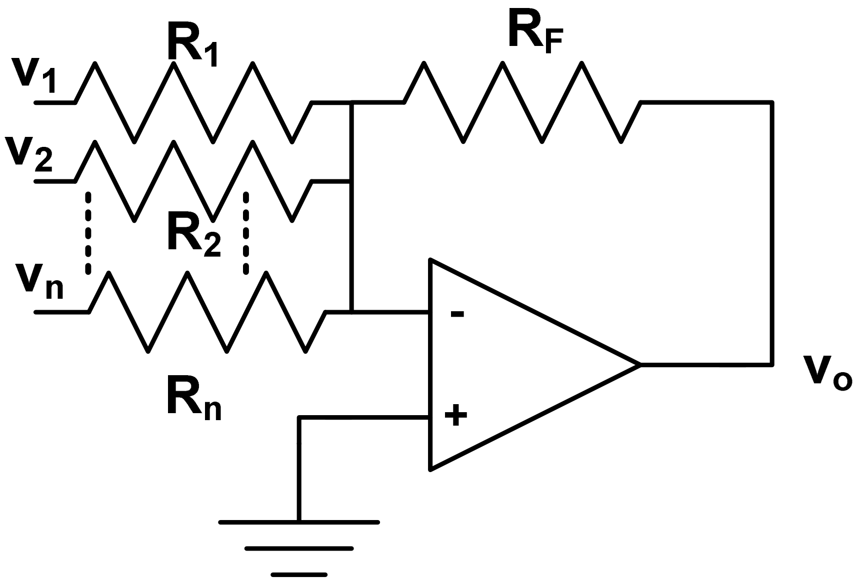


• Virtual short-circuit: v+=v-

$$v_o = v_i \Rightarrow \frac{v_o}{v_i} = 1$$

$$\left.\begin{array}{l} R_i \to \infty \\ R_o \to 0 \end{array}\right\} \Rightarrow$$ IMPEDANCE MATCHING

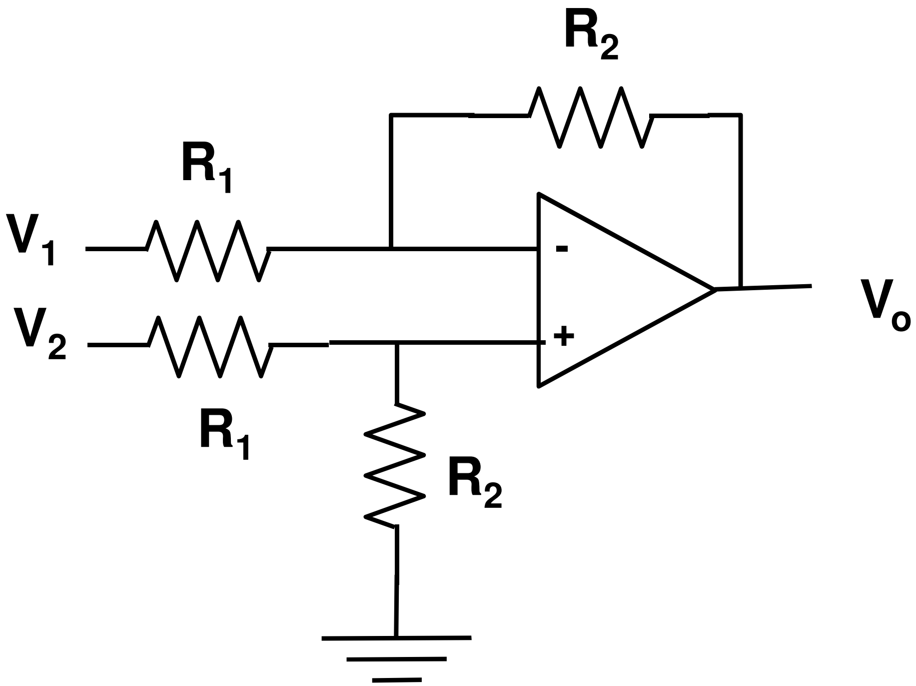
Inverting adder



- Virtual short-circuit: v+ = v -= 0
- $i(R_F) = i(R_1) + i(R_2)_{...} + i(R_n)$

$$\frac{-v_o}{R_F} = \frac{v_1}{R_1} + \frac{v_2}{R_2} \ldots + \frac{v_n}{R_n} \Rightarrow v_o = -\left(\frac{R_F}{R_1} v_1 + \frac{R_F}{R_2} v_2 \ldots + \frac{R_F}{R_n} v_n \right)$$

Differential amplifier



- Superposition

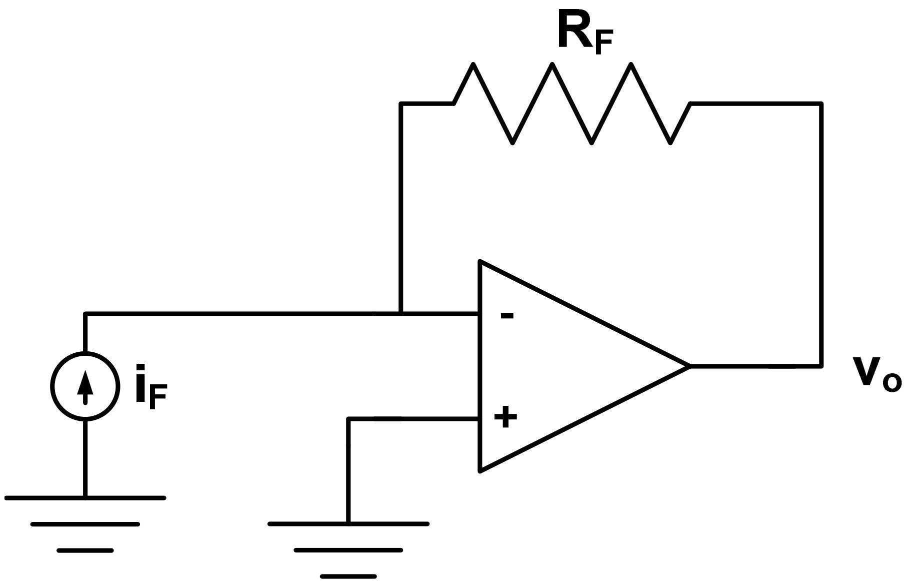
$$v_o = v_o\big|_{v1} + v_o\big|_{v2}$$

$$v_o\big|_{v1} = -\frac{R_2}{R_1} v_1$$

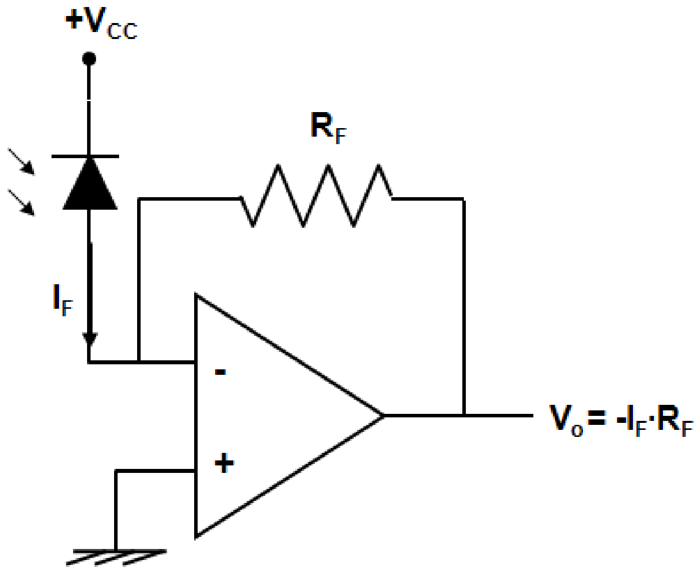
$$v_o\big|_{v2} = \left(1 + \frac{R_2}{R_1}\right) \cdot \frac{R_2}{R_1 + R_2} \cdot v_2 = \frac{R_2}{R_1} \cdot v_2$$

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

Current-voltage converter

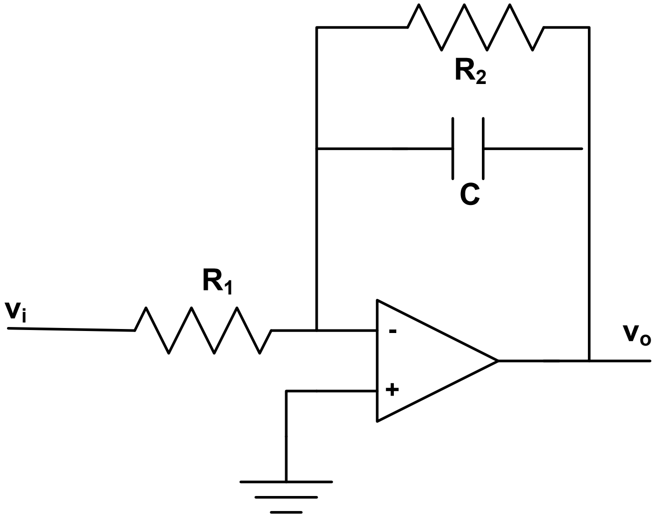


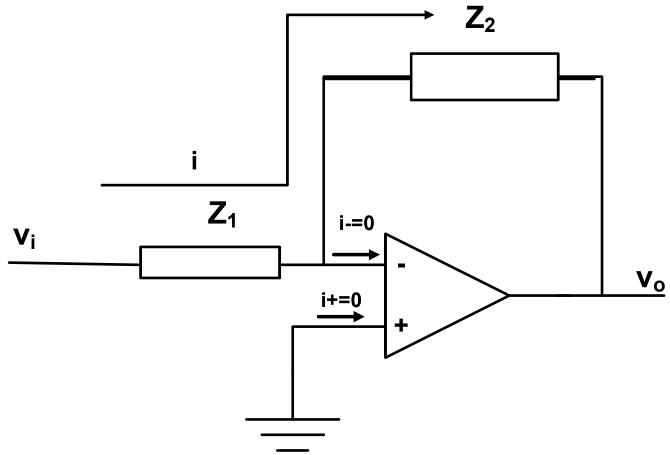
$$v_o = -R_F \cdot i_F$$



Conditioning circuit of photodiode

Low pass filter / integrator

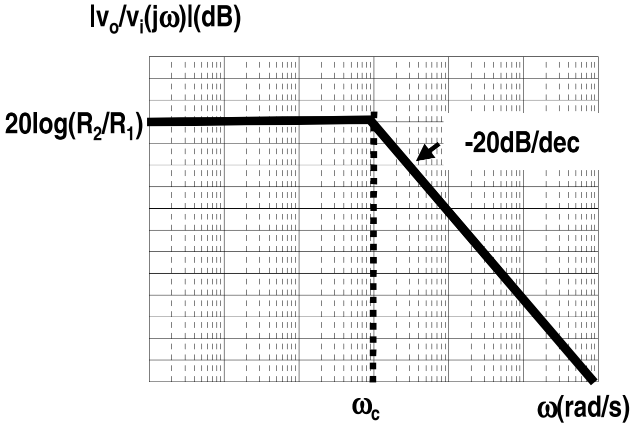


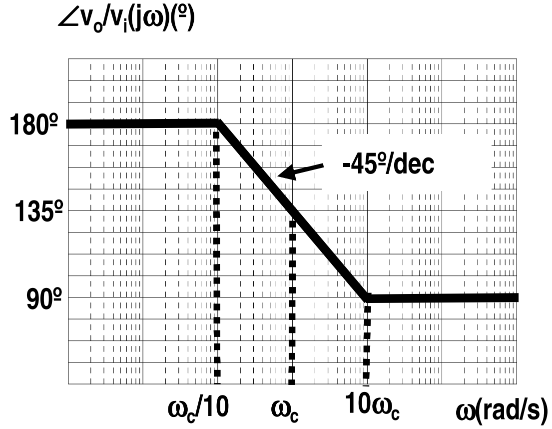


- Virtual short circuit: v+=v-
- $i(Z_1)=i(Z_2)=i$

$$\frac{v_o}{v_i}(j\omega) = -\frac{Z_2}{Z_1} = -\frac{\dfrac{R_2}{1+j\omega R_2 C}}{R_1} = \frac{-\dfrac{R_2}{R_1}}{1+j\omega R_2 C}$$

Pole: $\omega_c = \dfrac{1}{R_2 C}$



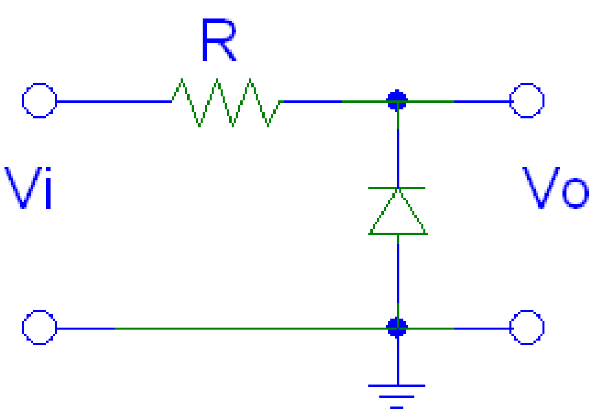


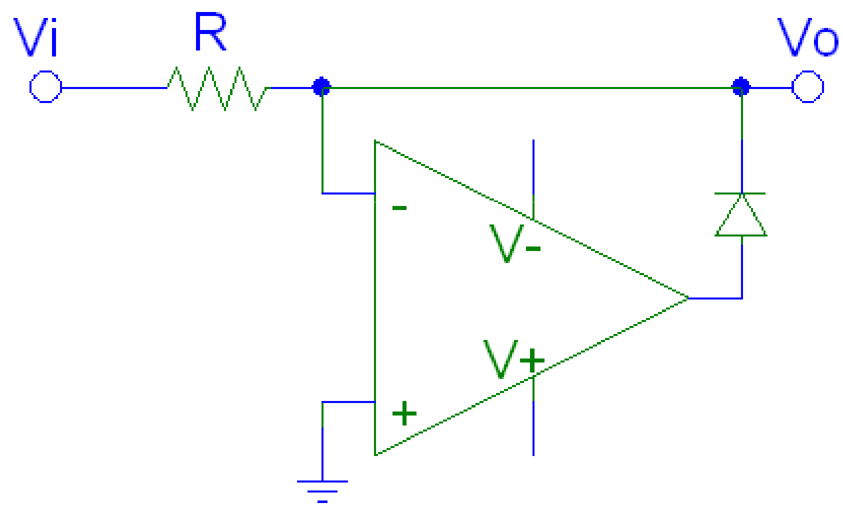
Non-linear applications of operational amplifier

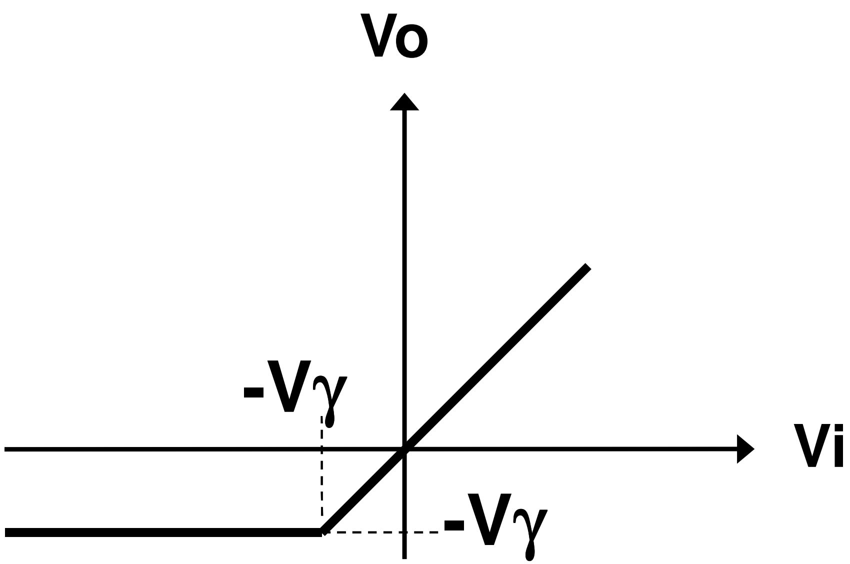
INDEZ

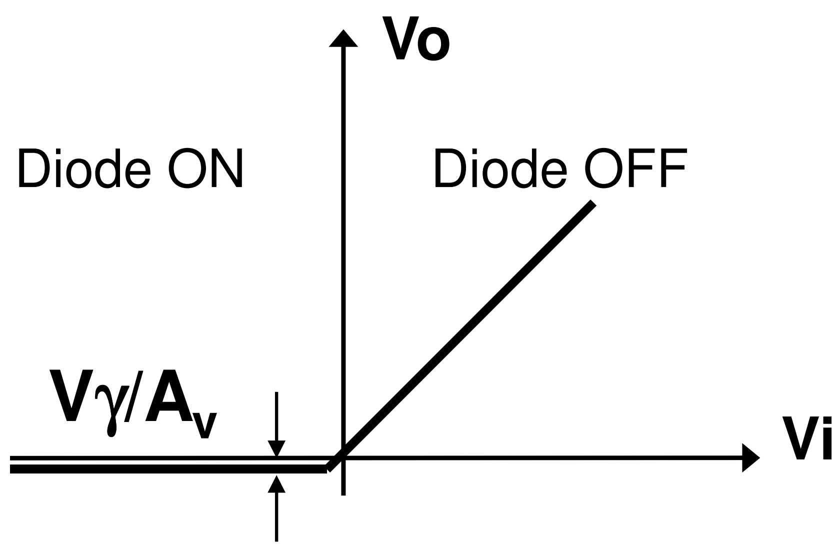
- Circuits with diodes in the feed-back loop
  Limitters and rectifiers
- Comparators with a reference (saturated operation of OA)

Basic Limitter (analogously)

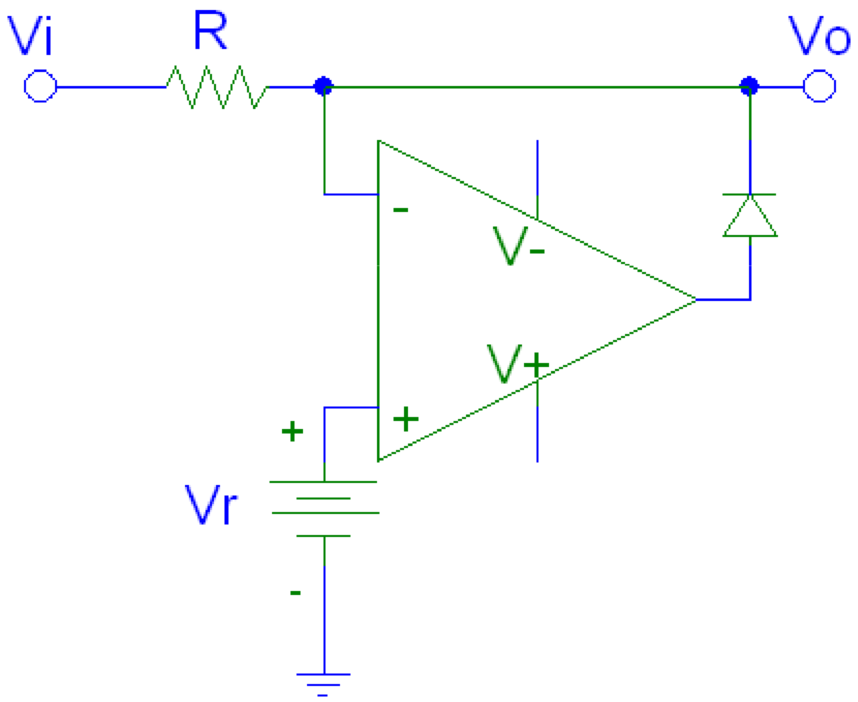


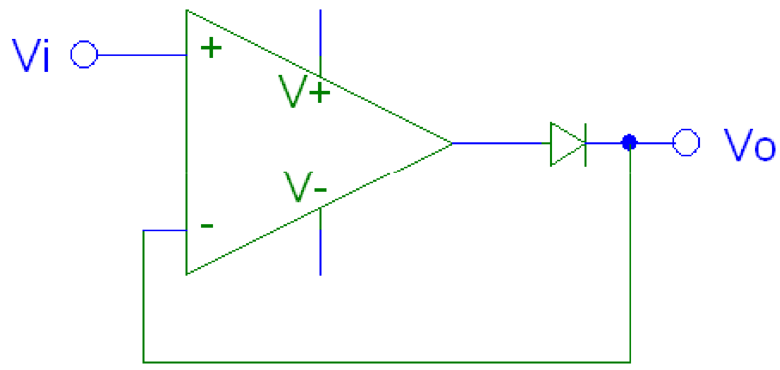


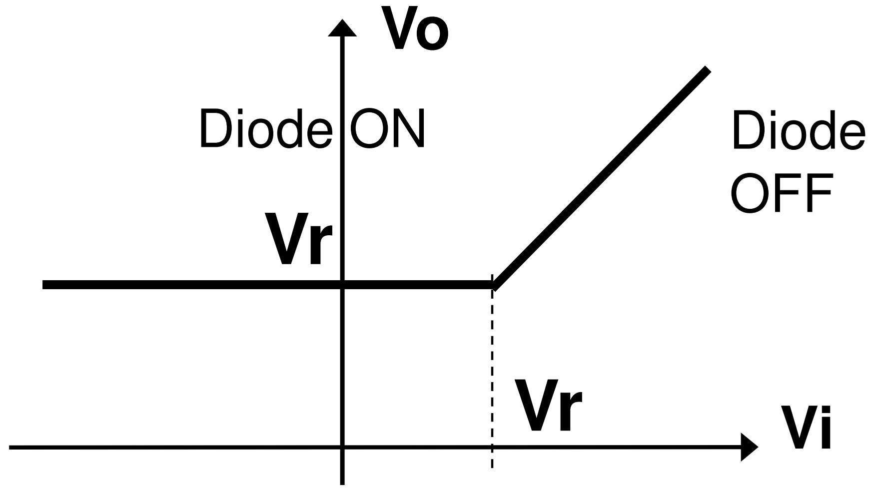


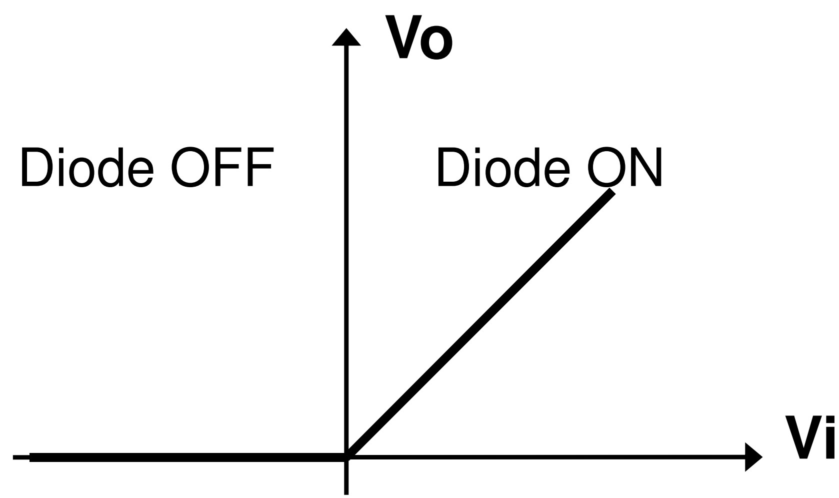


Other limitters

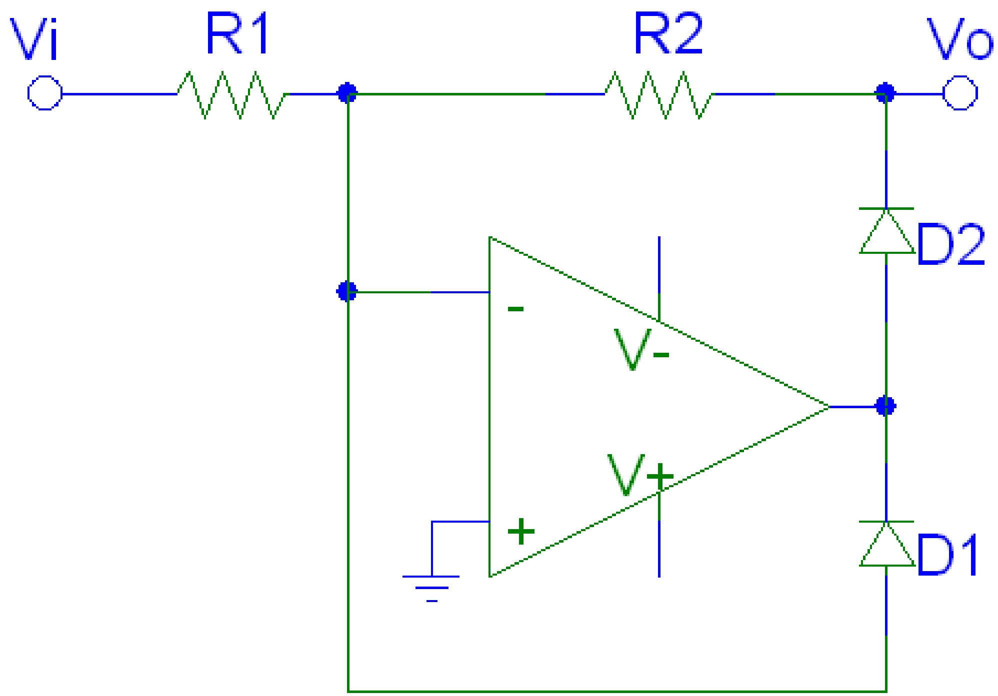


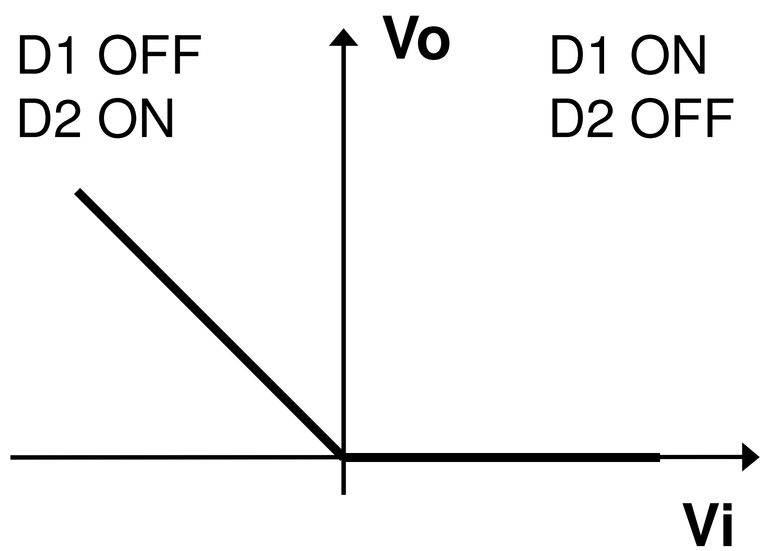




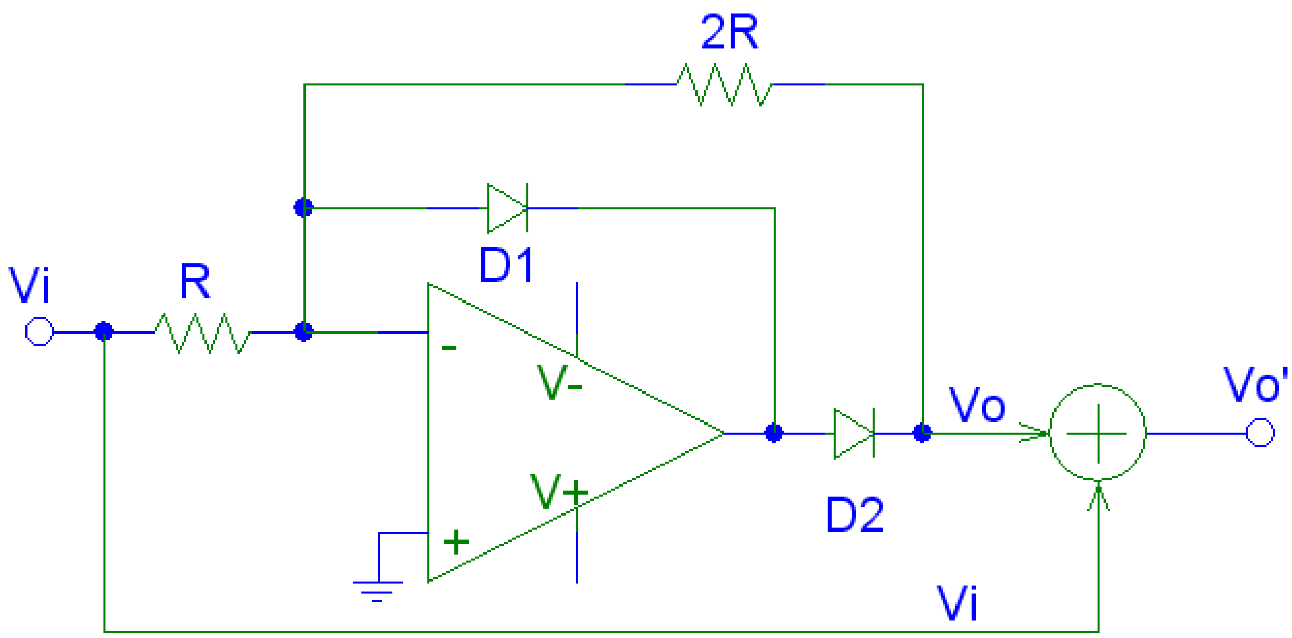


Precission half-wave rectifier

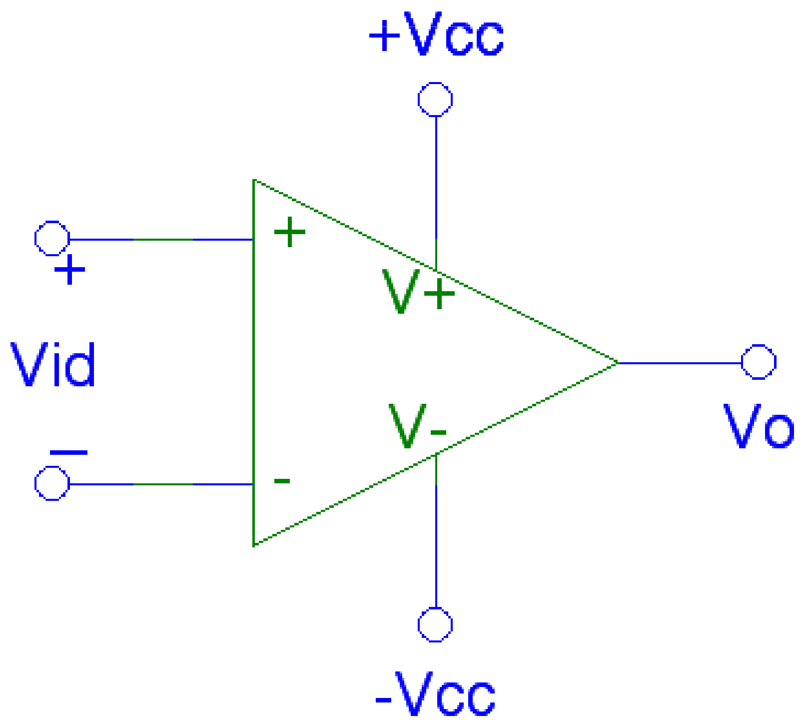


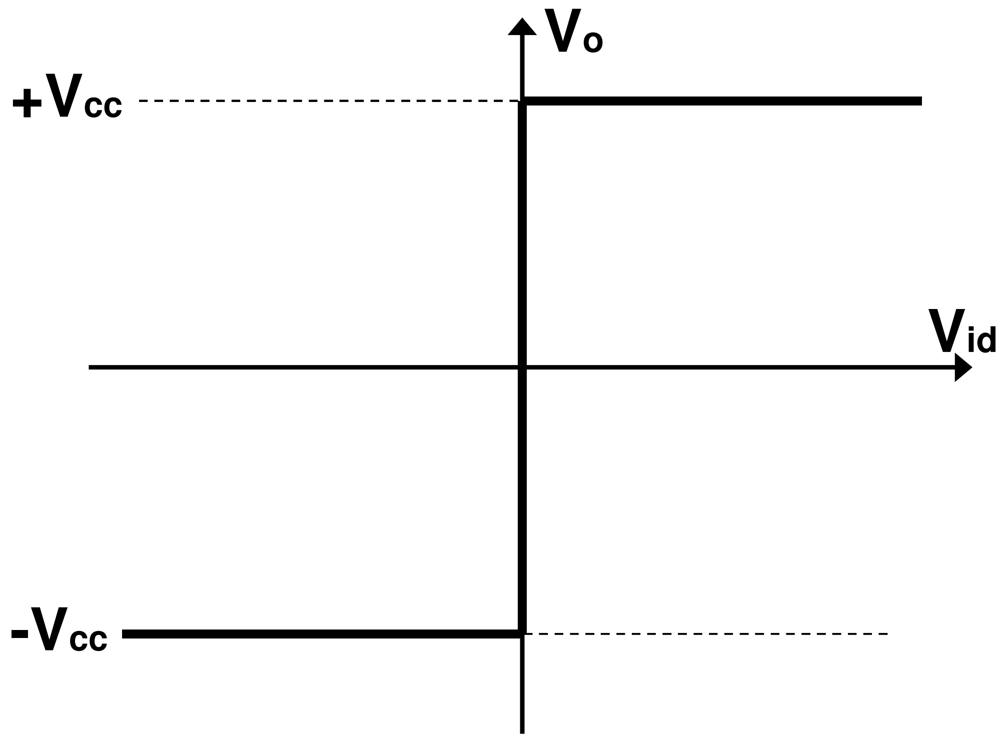


Precission full-wave rectifier

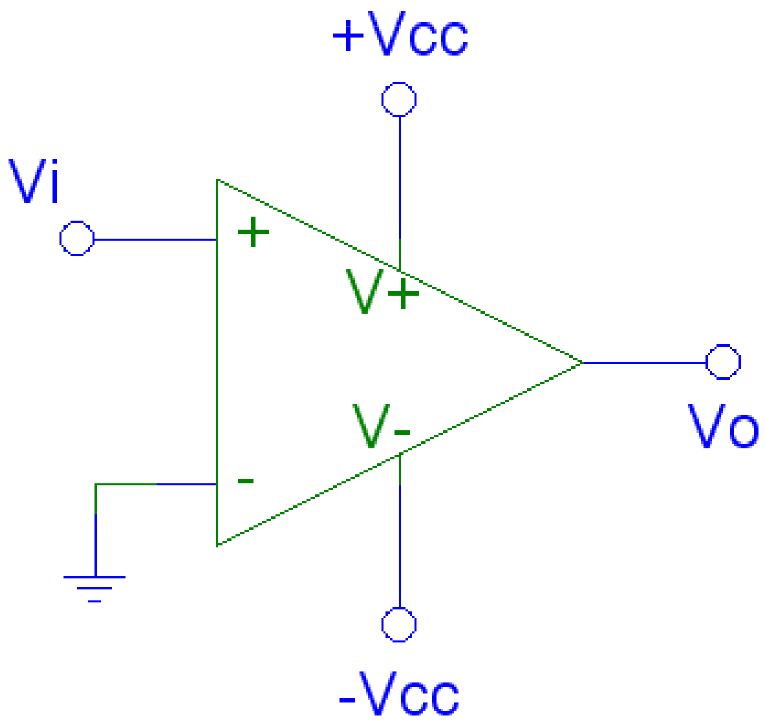


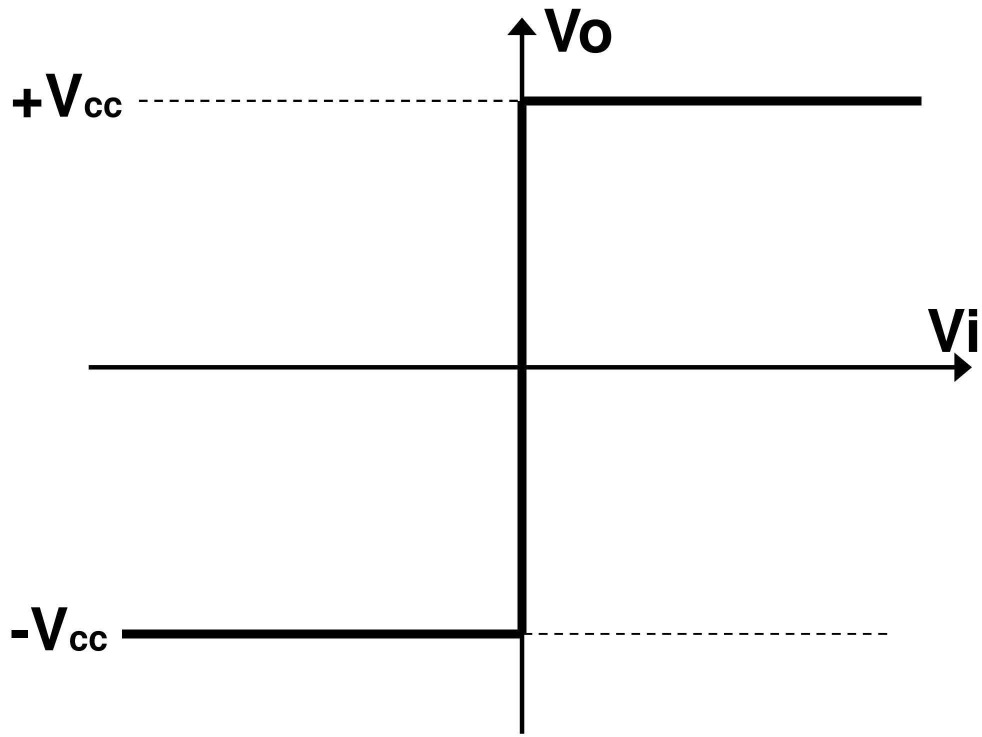
O.A. as a comparator



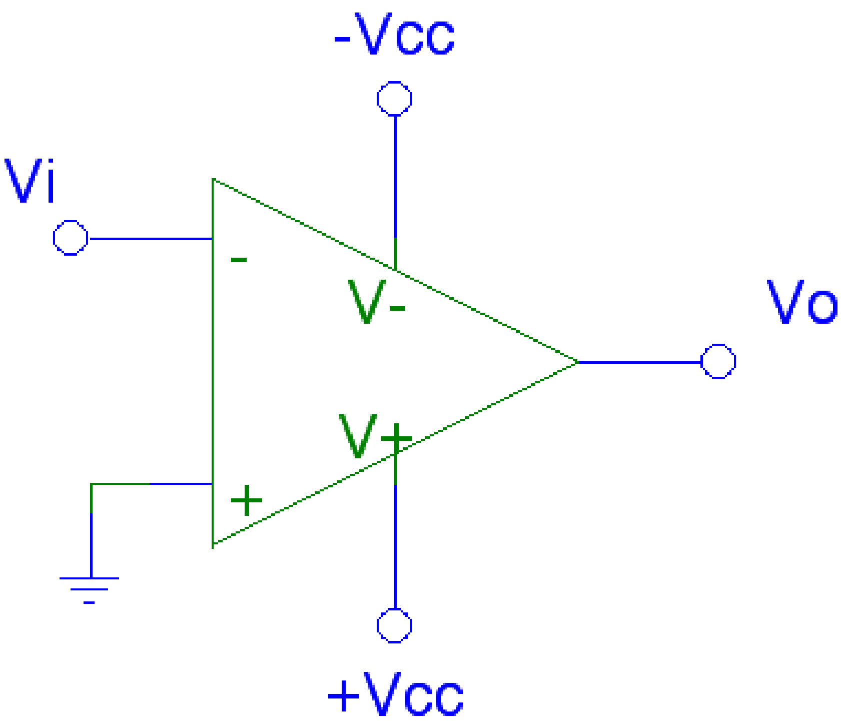


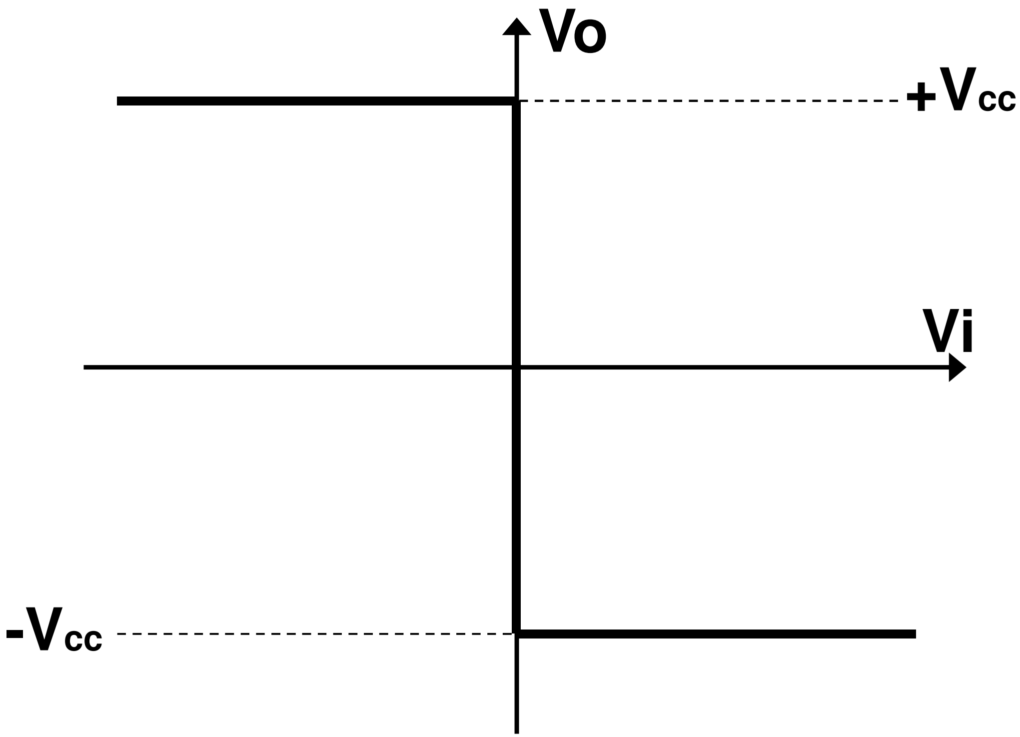
Non-inverting comparator





Inverting comparator





Comparator with a reference