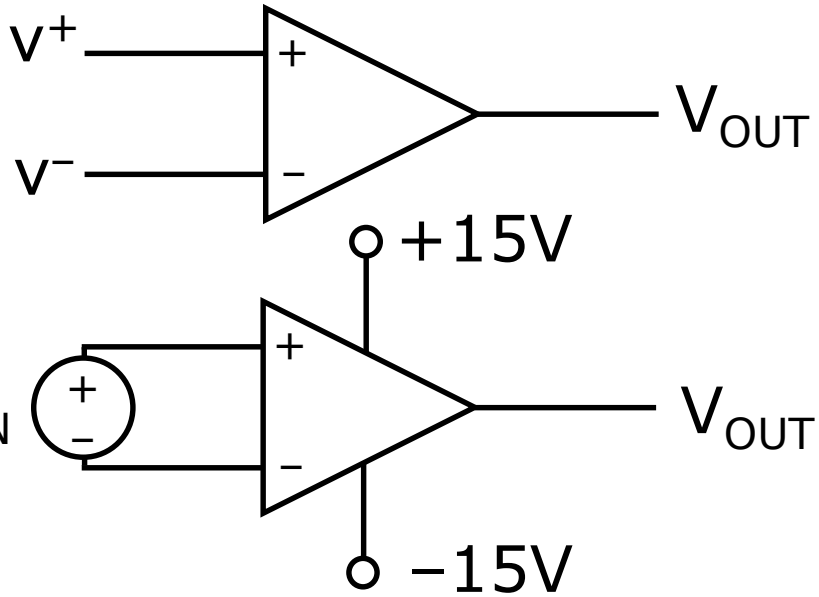
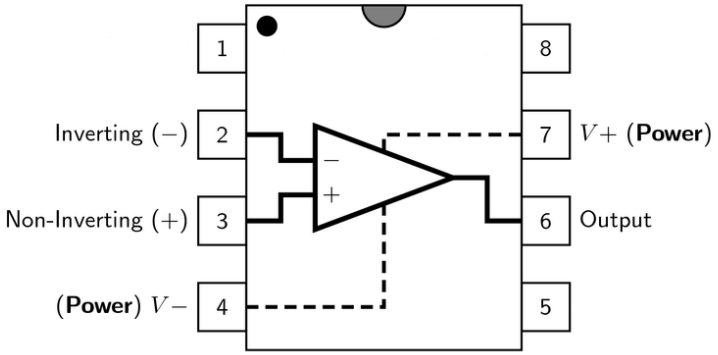
The Ideal Op-amp

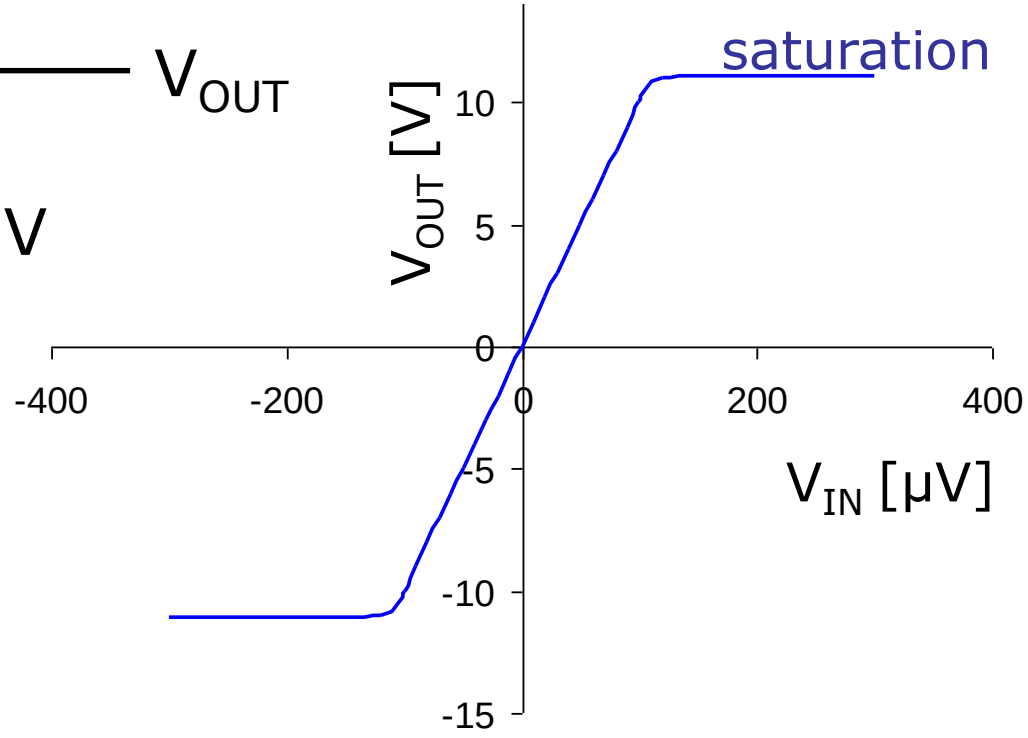
(Operational amplifier)



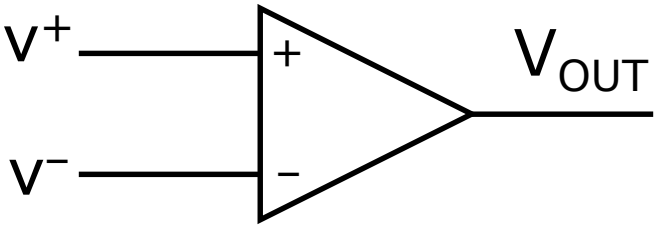


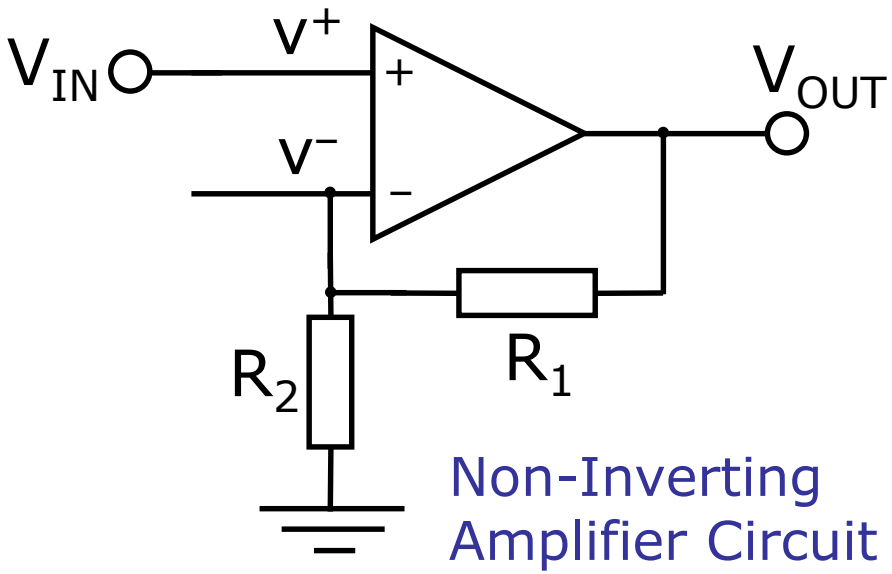
$V_{OUT}=A(v^+-v^-)$

$A\sim10^5$



Op-amp Feedback





Non-Inverting Amplifier Circuit

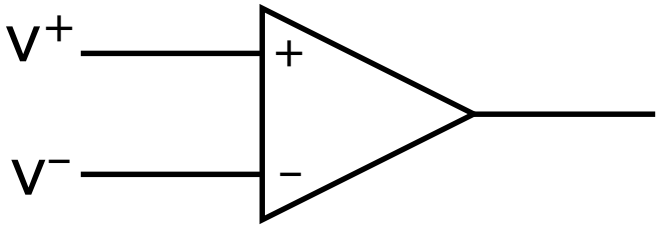
$$V_{OUT} = A\left(v^{+} - v^{-}\right)$$

$$V_{OUT} = A\left(V_{IN} - V_{OUT}\frac{R_2}{R_1 + R_2}\right)$$

$$V_{OUT}\left(1 + A\frac{R_2}{R_1 + R_2}\right) = AV_{IN}$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{A}{1 + \frac{AR_2}{R_1 + R_2}} \approx \frac{R_1 + R_2}{R_2}$$

Op-amp Feedback

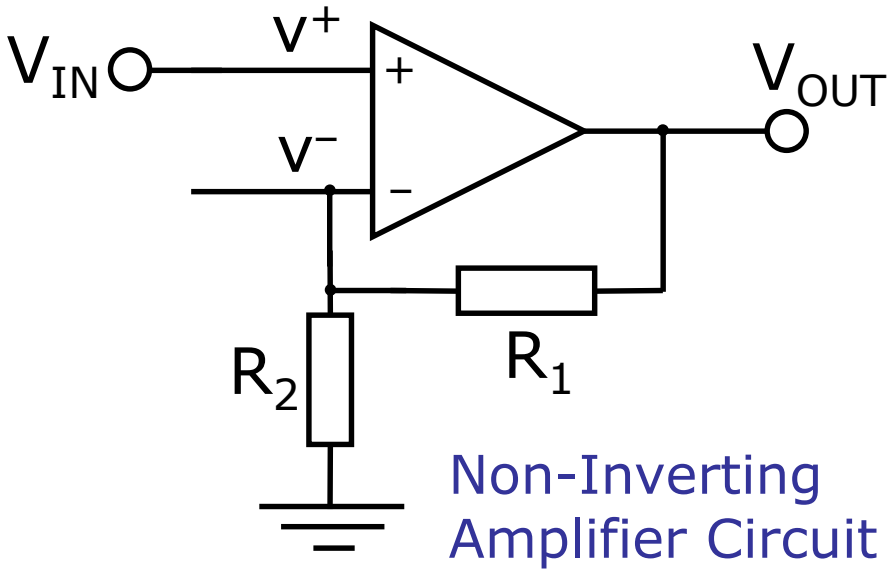


Assumptions:

Gain is very large ($A \rightarrow \infty$)

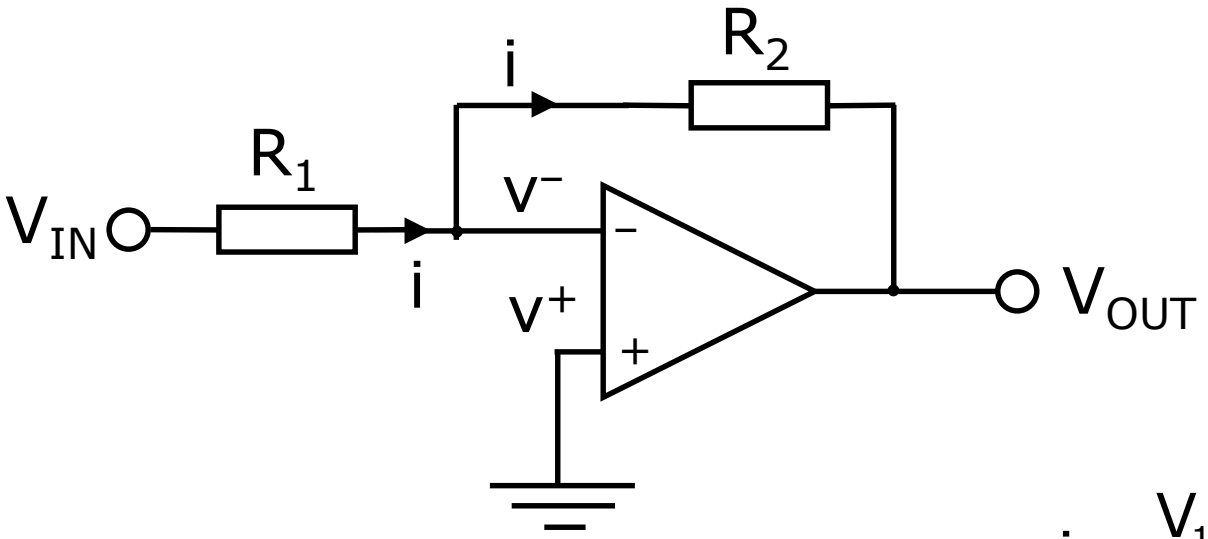
Inputs draw no current ($Z_{IN} = \infty$)

Output attempts to make input voltage difference zero ($v^+ = v^-$)



Non-Inverting Amplifier Circuit

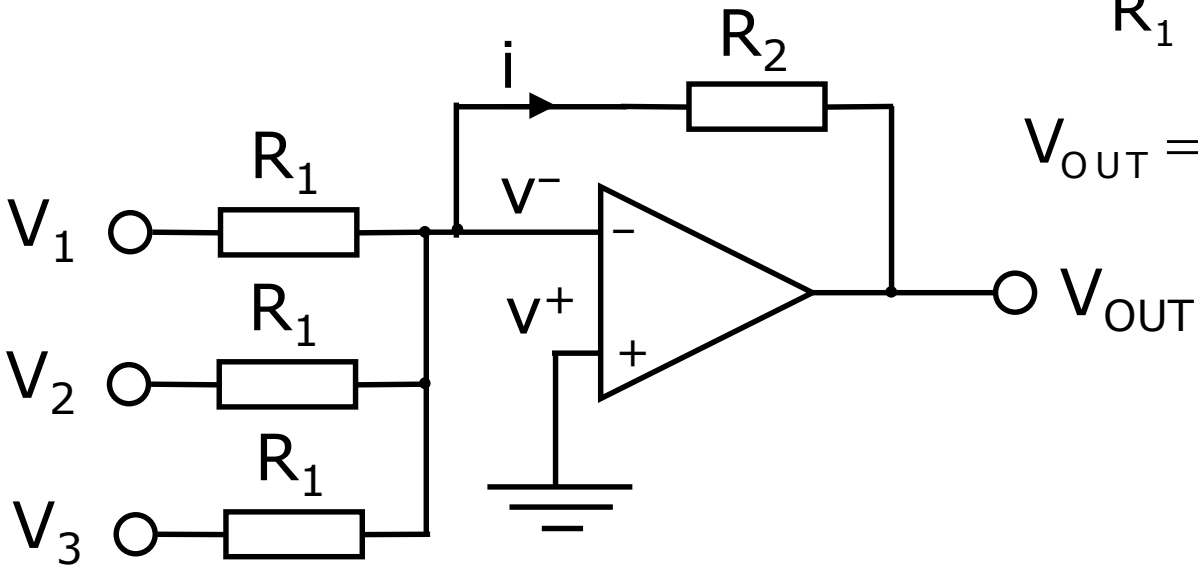
Inverting Amplifier Circuit



$$v^- \approx v^+ = 0$$

$$i = \frac{V_{IN}}{R_1} = -\frac{V_{OUT}}{R_2}$$

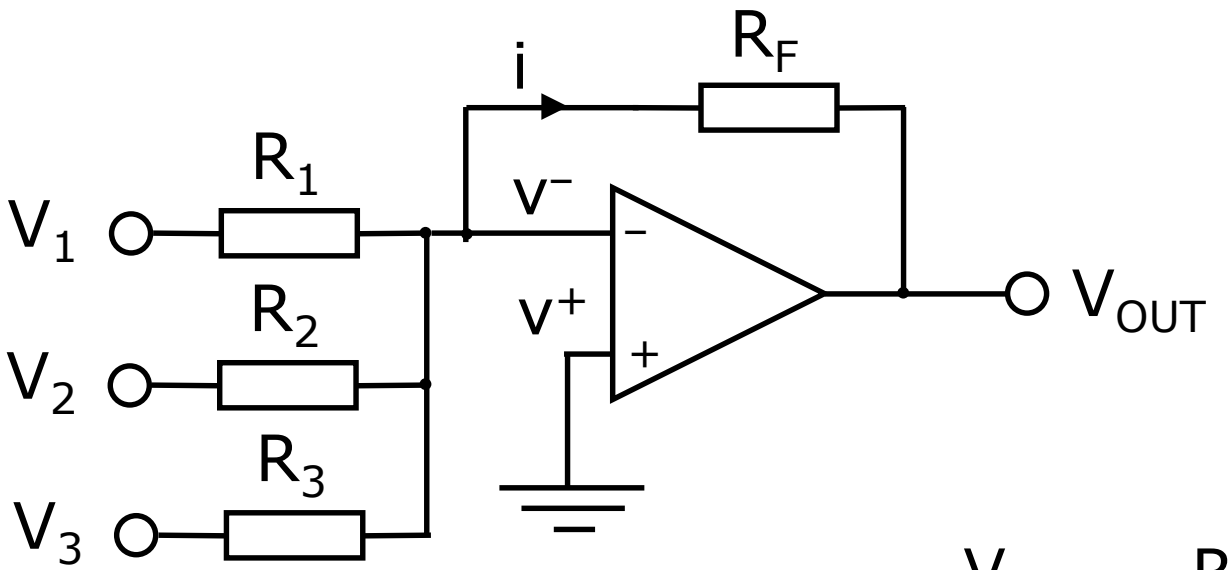
$$\frac{V_{OUT}}{V_{IN}} = -\frac{R_2}{R_1}$$



$$i = \frac{V_1}{R_1} + \frac{V_2}{R_1} + \frac{V_3}{R_1} = -\frac{V_{OUT}}{R_2}$$

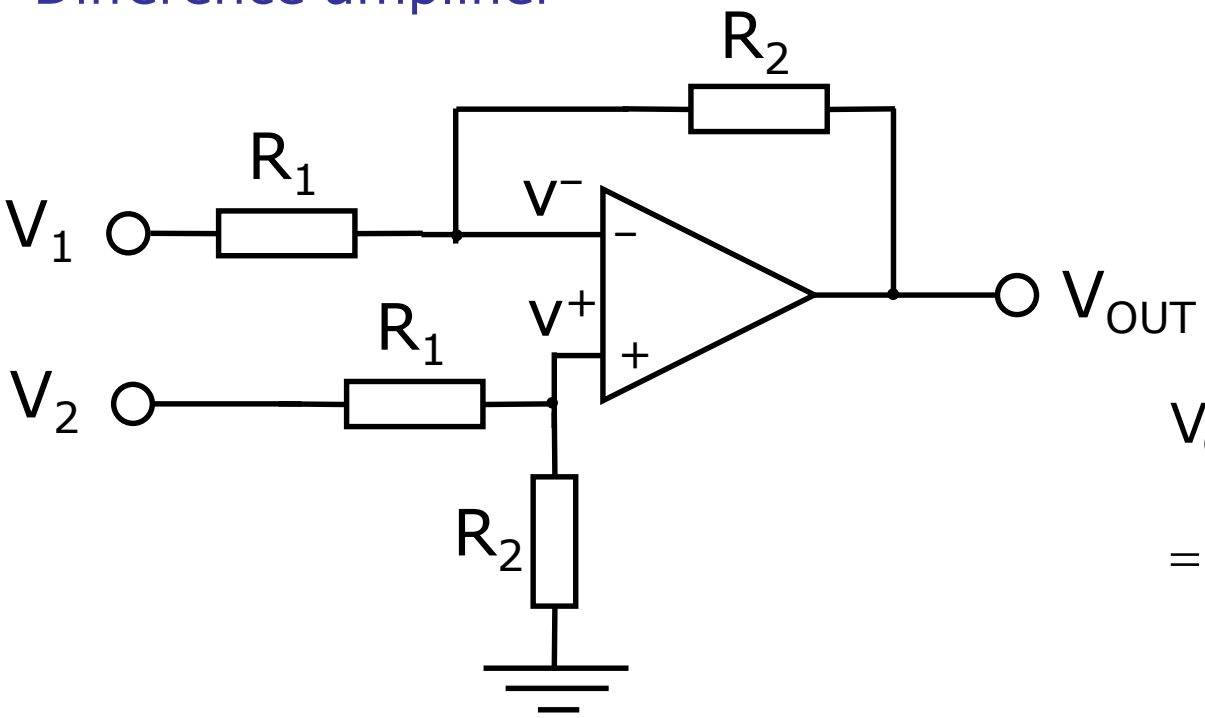
$$V_{OUT} = -\frac{R_2}{R_1}\left(V_1 + V_2 + V_3\right)$$

Summing amplifier



$$V_{OUT} = -R_F\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}\right)$$

Difference amplifier



$$V_{OUT} = v^- - iR_2$$

$$= v^- - \left(\frac{V_1 - v^-}{R_1}\right)R_2$$

$$= v^-\left(1 + \frac{R_2}{R_1}\right) - V_1\frac{R_2}{R_1}$$

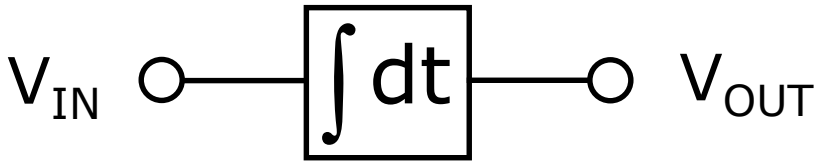
$$v^+ = V_2\frac{R_2}{R_1 + R_2}$$

$$v^+ \approx v^-$$

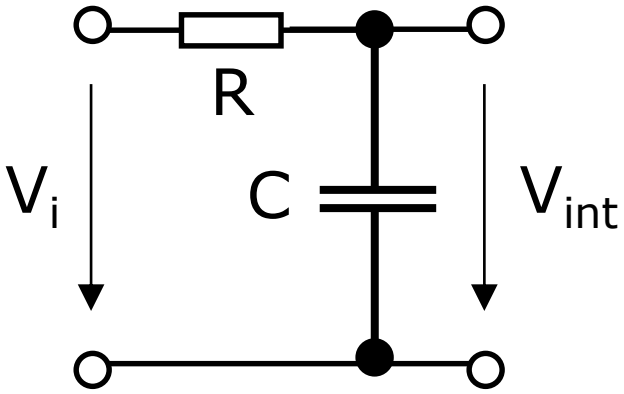
$$V_{OUT} = V_2\frac{R_2}{R_1 + R_2}\left(\frac{R_1 + R_2}{R_1}\right) - V_1\frac{R_2}{R_1}$$

$$= (V_2 - V_1)\frac{R_2}{R_1}$$

Integrator



Capacitor as integrator

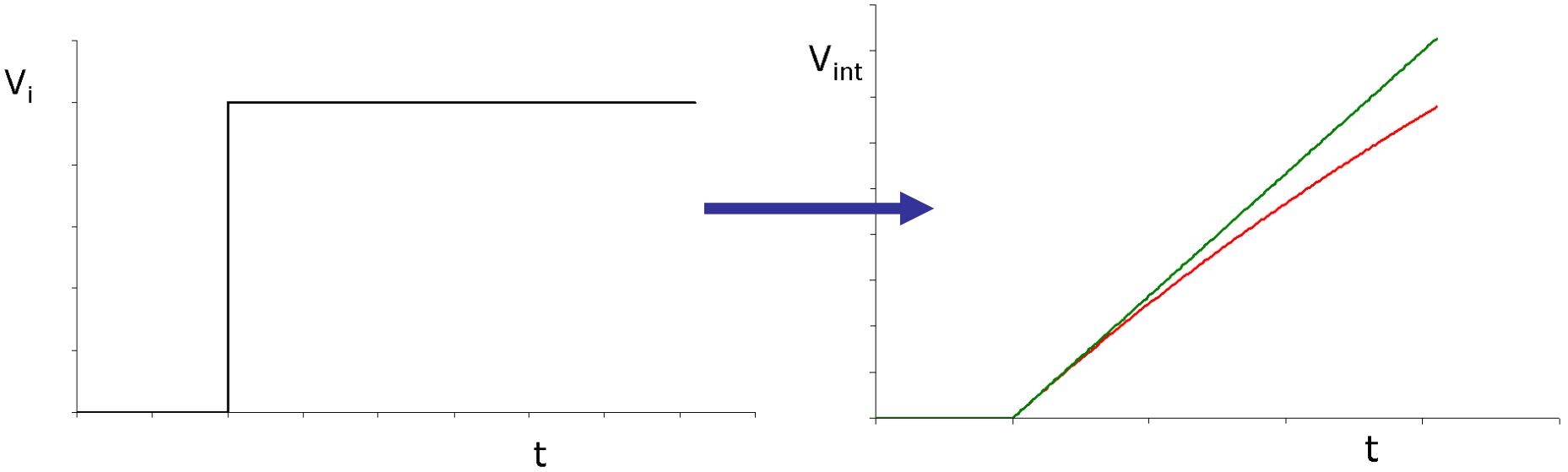


$$V_{int} = V_C = \frac{1}{C}\int_0^t I dt'$$

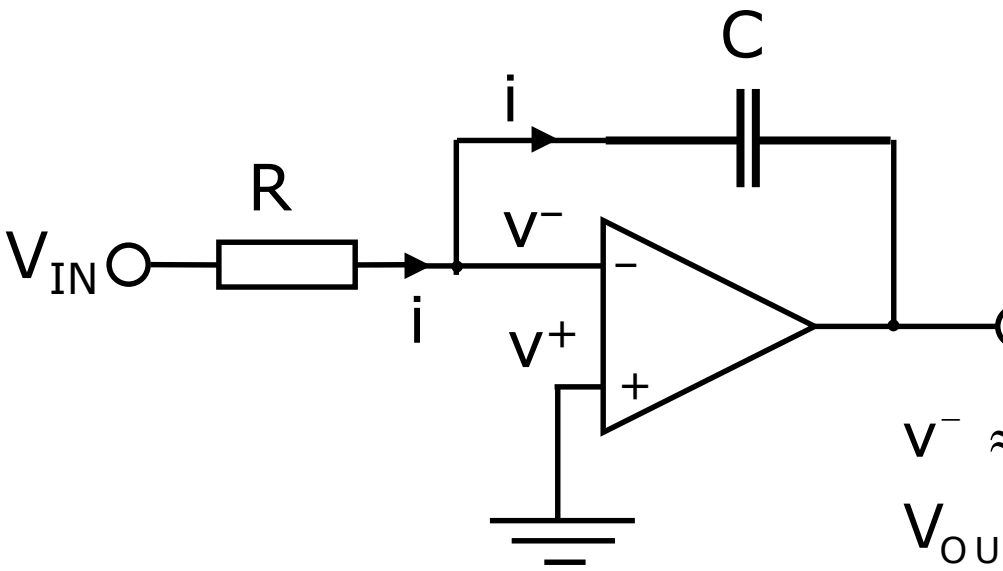
$$V_C = \frac{1}{C}\int_0^t \frac{V_i - V_C}{R} dt' \quad \text{If } RC >> t$$

$$V_C << V_i$$

$$\approx \frac{1}{RC}\int_0^t V_i dt'$$



Op-amp Integrator



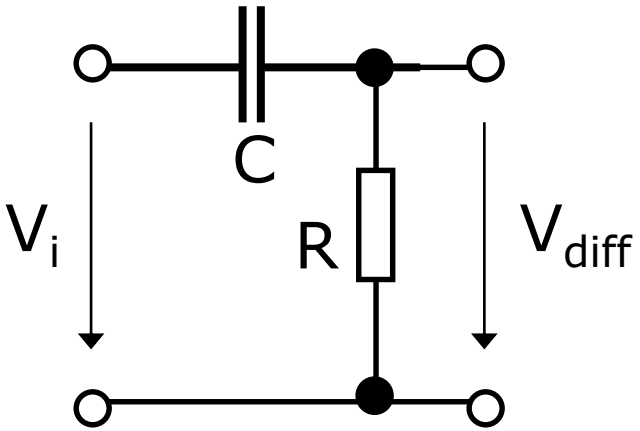
$$v^- \approx v^+ = 0$$

$$V_{OUT} = -V_C$$

$$V_{OUT} = -\frac{1}{C}\int_0^t i\,dt$$

$$V_{OUT} = -\frac{1}{C}\int_0^t \frac{V_{IN}}{R}\,dt$$

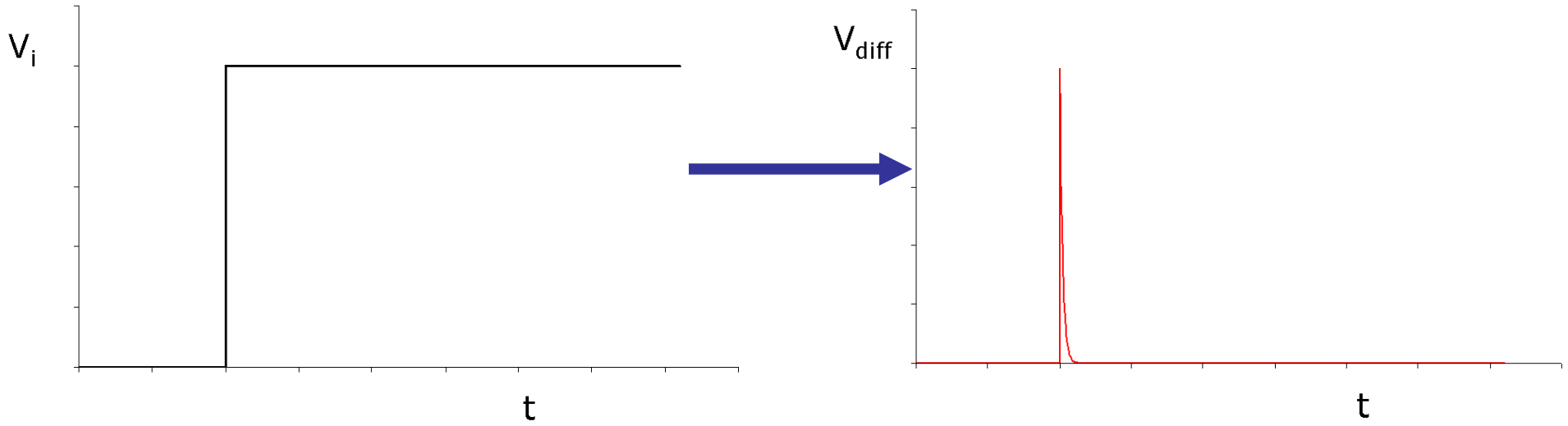
Differentiation



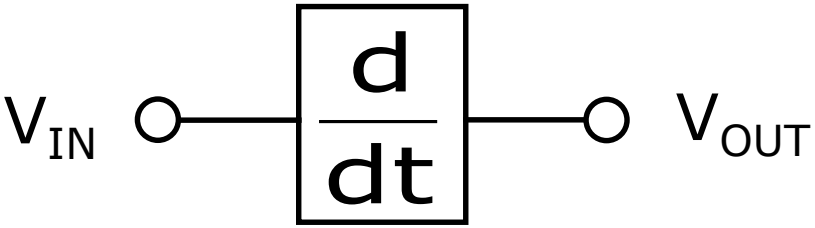
$$V_{diff} = V_R = RI = RC\left(\frac{dV_i}{dt} - \frac{dV_R}{dt}\right)$$

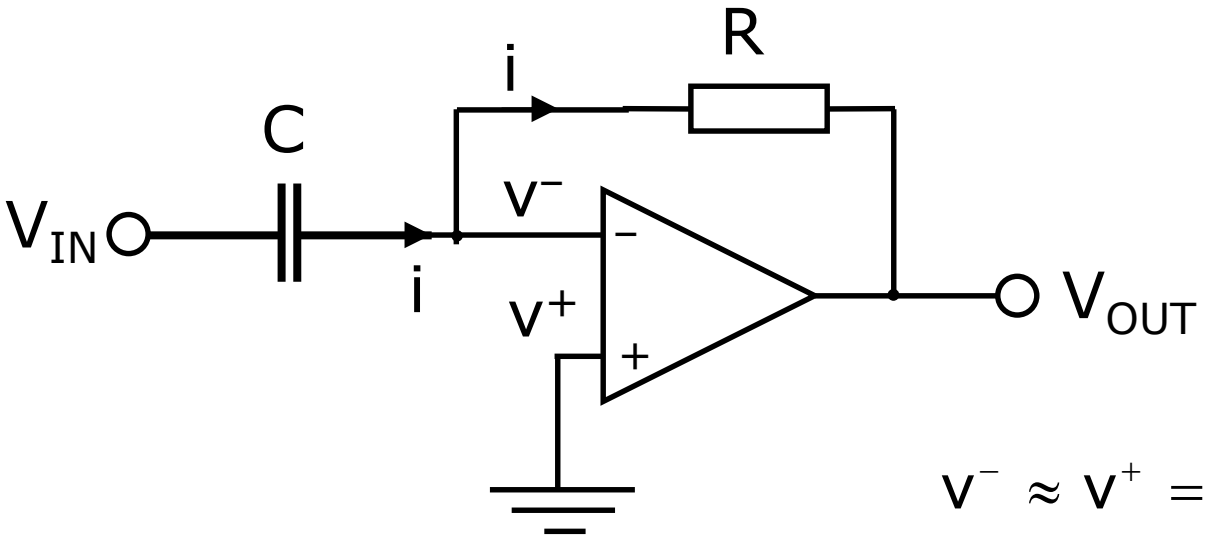
$$\text{Small } RC \rightarrow \quad \frac{dV_i}{dt} >> \frac{dV_R}{dt}$$

$$V_{diff} \approx RC\frac{dV_i}{dt}$$



Op-amp Differentiator



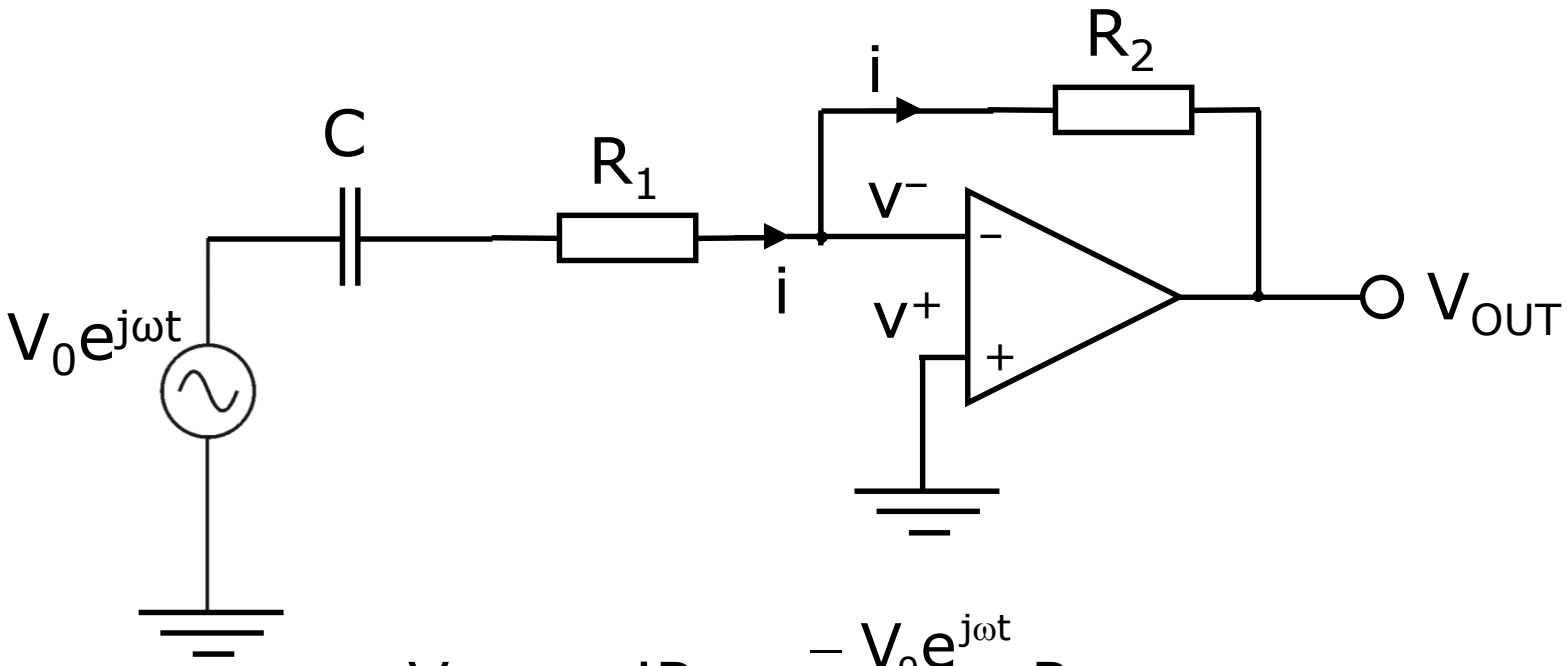


$$v^- \approx v^+ = 0$$

$$V_{OUT} = -iR$$

$$V_{OUT} = -RC\frac{dV_{IN}}{dt}$$

Complex analysis



$$V_{OUT} = -iR_2 = \frac{-V_0 e^{j\omega t}}{R_1 - \frac{j}{\omega C}} R_2$$

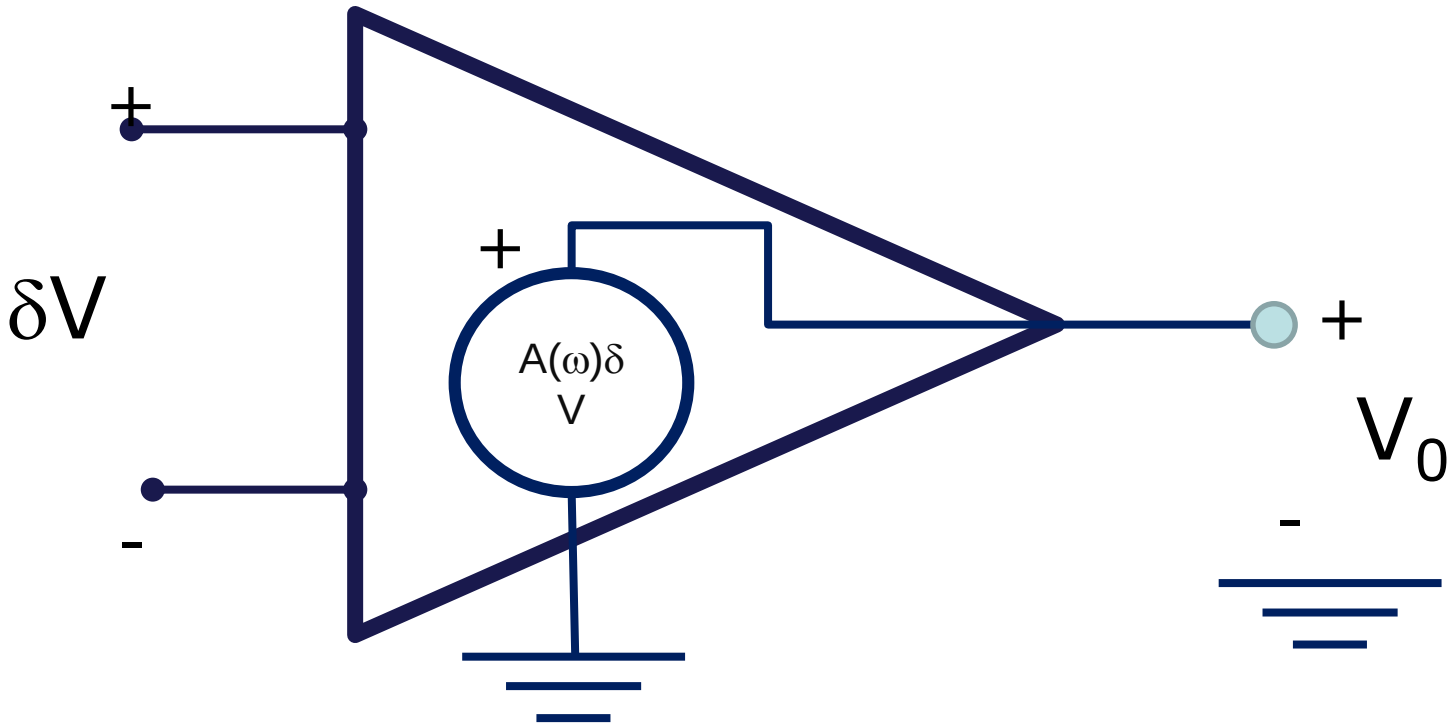
$$= \frac{-j\omega C R_2 e^{j\omega t}}{1 + j\omega C R_1} V_0$$

$\omega \to 0 \quad V_{OUT} = 0$

$\omega \to \infty \quad V_{OUT} = -\frac{R_2}{R_1} V_0 e^{j\omega t}$

High pass filter

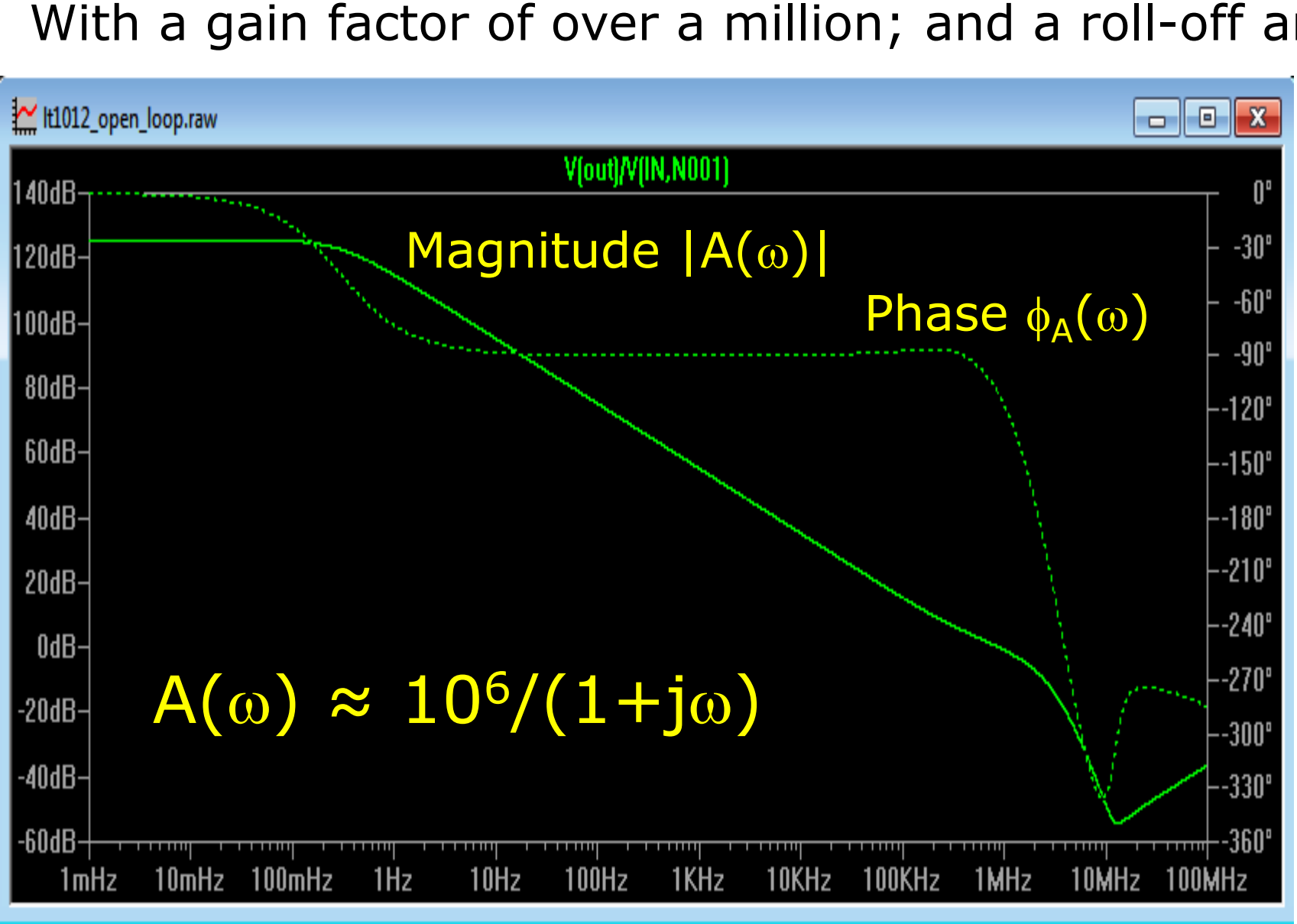
First Non-ideal model



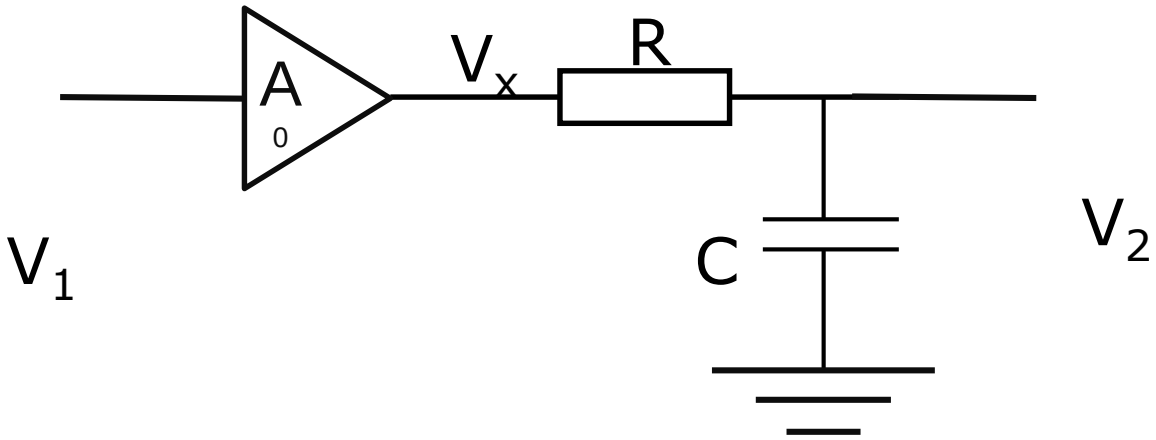
Instead of infinite gain, the
has finite, and frequency de

A(ω) behaves like an RC filter.

With a gain factor of over a million; and a roll-off around ω



Model of this non-ideal gain curve



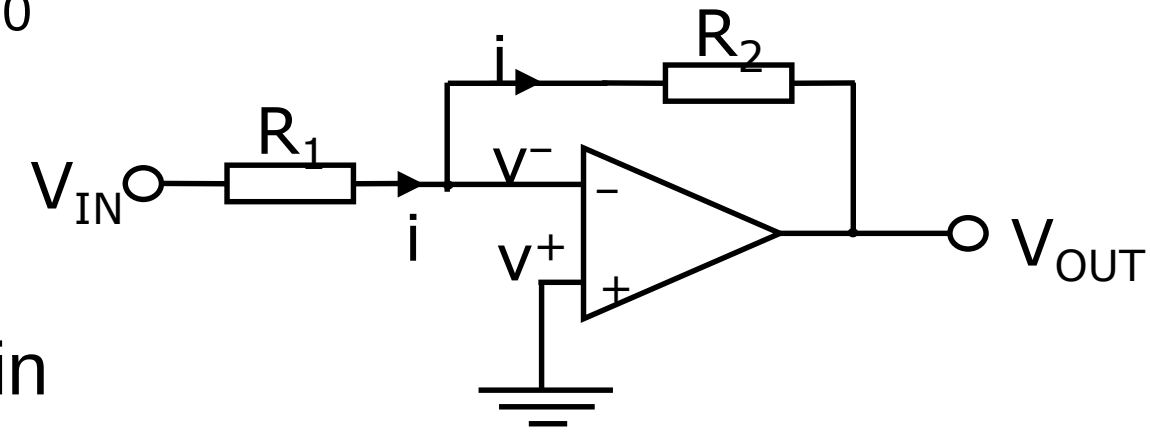
Note:
Also Draw filte
on Blackboard

- $V_x = A_0 V_1$
- KCL
  - $(V_2 - V_x)/R + j\omega C V_2 = 0$
    - Substitute expression for Vx above and some algebra
  - $V_2(1 + j\omega CR) = A_0 V_1$
- $V_2/V_1 = A_0/(1 + j\omega CR) \equiv A(\omega)$

How does this effect our negative feedback circuits?

- KVL
  - $V_{R1} - \delta V - V_{in} = 0$
  - $V_{R2} + \delta V + V_0 = 0$
- KCL
  - $V_{R1}/R_1 = V_{R2}/R_2$
- And also the Gain relationship
  - $\delta V A(\omega) = V_0$

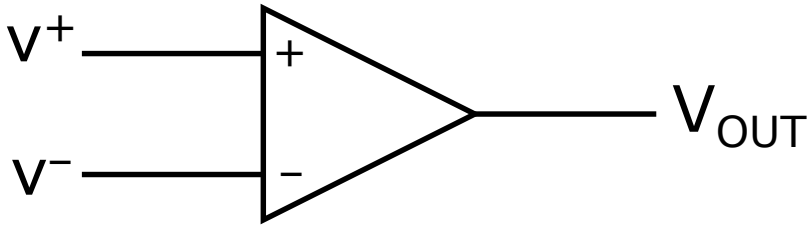
Inverting Amplifier Circuit



Solve on board

$$\frac{V_0}{V_{in}} = \frac{-R_2}{R_1 + \frac{(R_1 + R_2)(1 + j\omega)}{10^6}}$$

Exploiting op-amp saturation



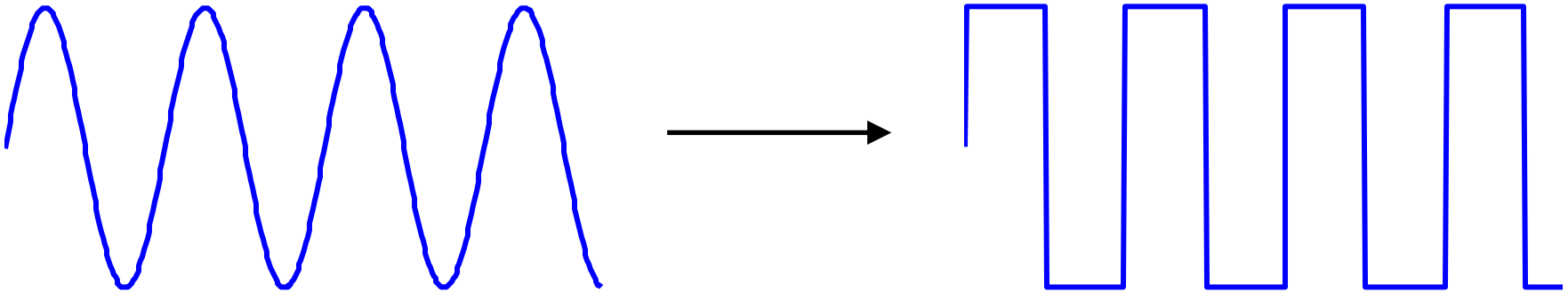
$V_{OUT} = A(v^+ - v^-)$

Saturation voltage

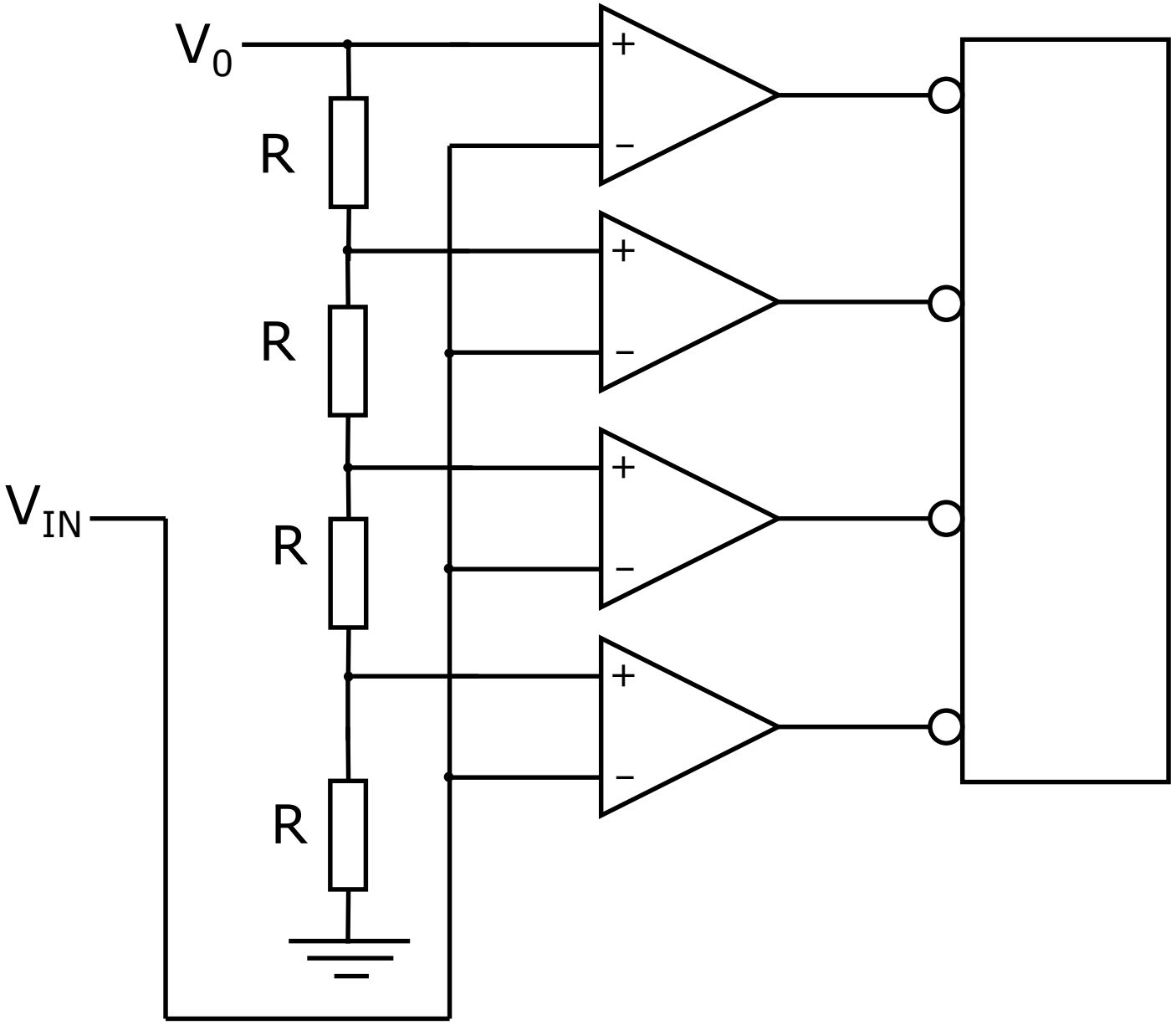
$A \rightarrow \infty$

$V_{OUT} = +V_{Sat}$ $\quad v^+ > v^-$

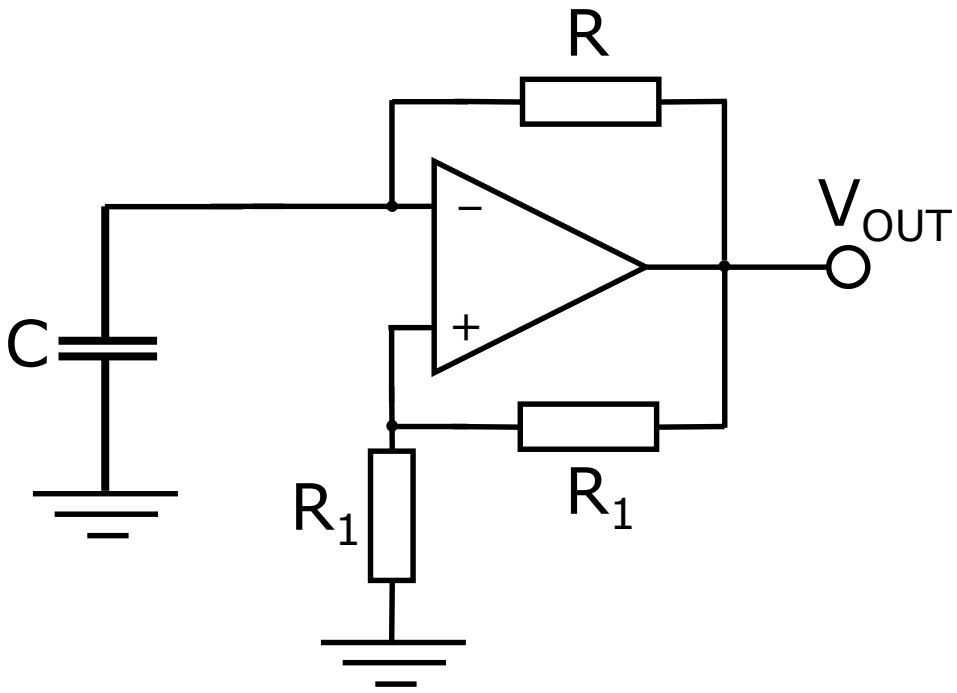
$V_{OUT} = -V_{Sat}$ $\quad v^+ < v^-$



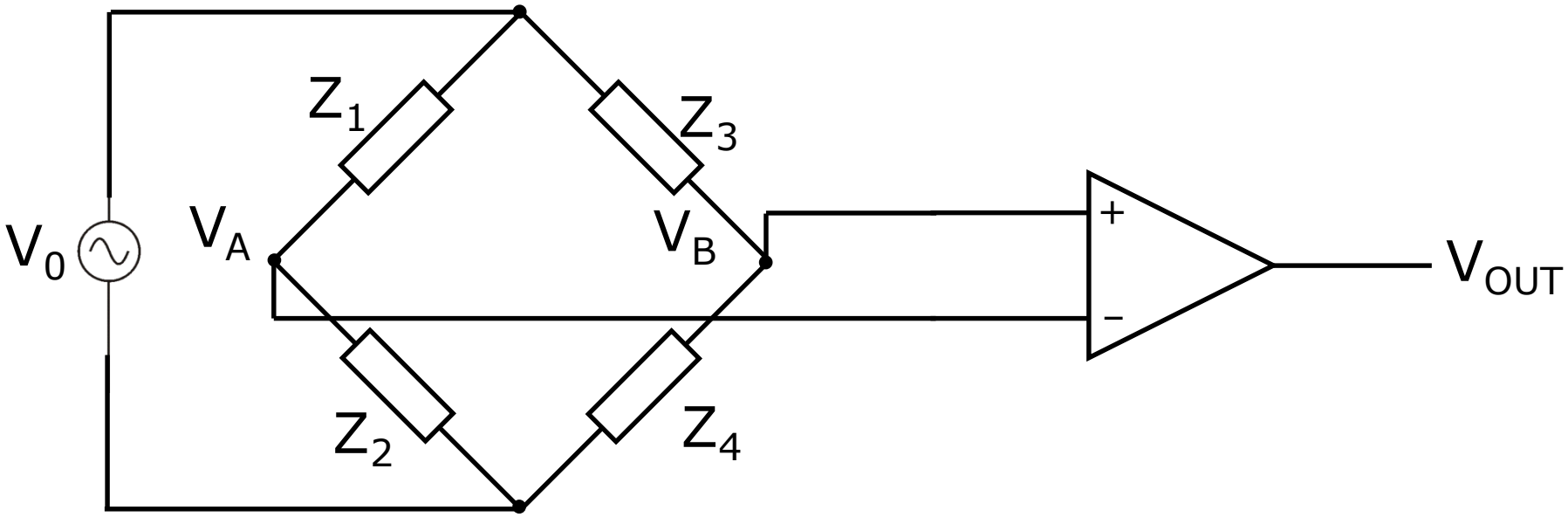
Analogue – digital conversion (ADC)



Oscillator



Bridge circuits



Bridge balanced when $V_A - V_B = 0$

$$Z_2 Z_3 = Z_4 Z_1$$

Op-amp applications

Building block of analogue electronics

- Signal amplifiers
- Audio amplifiers
- Integrators / differentiators
- Voltage / current sources
- Active filters
- Oscillators
- Digital-analogue and analogue-digital convertors



END OF OP-AMPS!