TÉCNICO LISBOA

Circuit Theory and Electronics Fundamentals

Lecture 22: Operational Amplifiers

- What are operational amplifiers (OP-AMPs)
- Design once reuse many times
- The famous μA741 OP-AMP design
- OP-AMP operation with and without feedback
- Inverting amplifier
- Non-inverting amplifier
- Amplifiers with resistive and complex feedback loops

What is an Operational Amplifier

- An OPerational AMPlifier (OP-AMP) is transistor-based amplifier used often as a subcomponent in analogue designs
- OP-AMP main features
  - High gain
  - High input impedance
  - Low output impedance
  - Differential input
- OP-AMP main limitations
  - Frequency response
  - Complexity (due to its generality)
  - Power consumption (due to its generality)

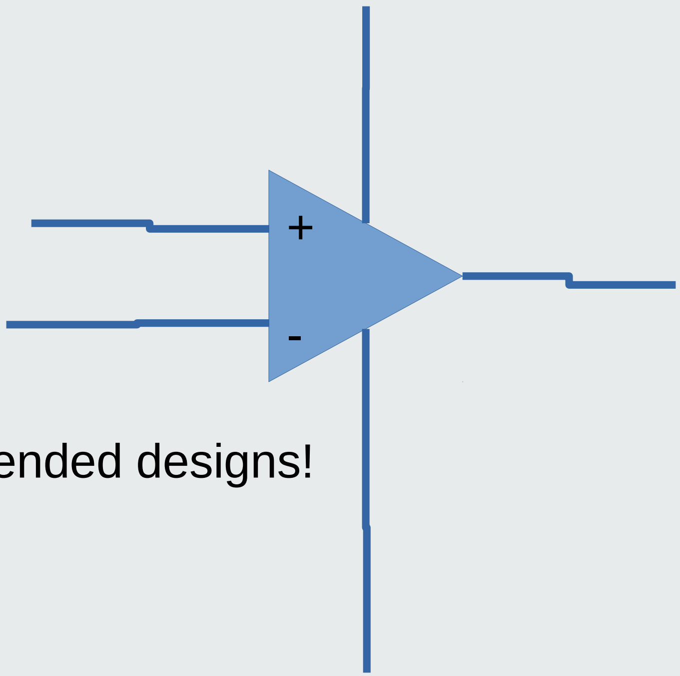
OP-AMP: package and reuse

- A considerable effort goes into designing good analogue circuits:
  - Extensive hand calculations needed
  - Extensive simulations needed
  - Silicon prototyping and validation needed
- It may take years before the circuit is stable
- Unfortunately, if the underlying semiconductor technology changes or evolves, the circuit needs to be redesigned...
- Nevertheless, it is important to have building blocks such as the OP-AMP to speed up development

OP-AMP: symbol and pins

Differential input!
Only the difference
$v_+ - v_-$ matters

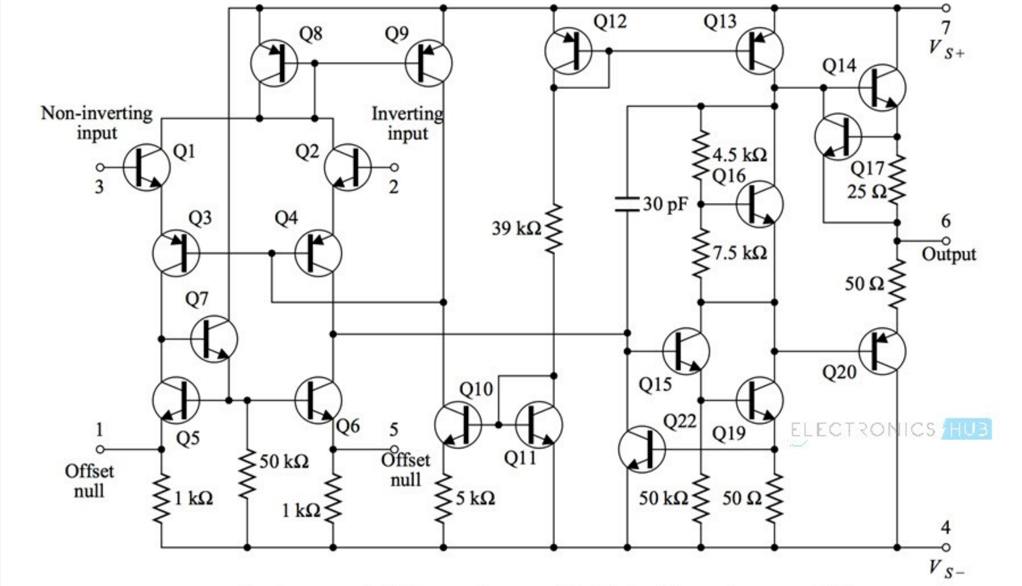
So v_+ and v_- may
have any <u>common</u>
DC offset!



No coupling capacitors needed, as in single-ended designs!

Examples: signal
from microphone or
antenna

The famous µA741 OP-AMP



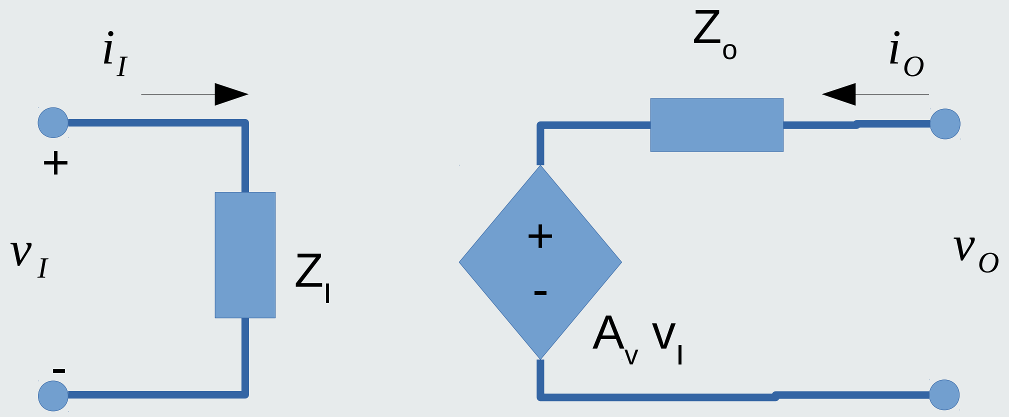
Internal Circutry of 741 Op-Amp IC

- In 1963 Robert Widlar's µA702 design for Fairchild Semiconductor at age 26
- Widlar later designed an improved version, the LM101
- Widlar also has a current source design named after him
- David Fullagar (also Fairchild's) improved the LM101 design, called it µA741, and took it to the head of R&D – Gordon Moore (the legend)

The 20-transistor µA741 circuit became the OP-AMP world standard!

Original price in 1963: US$300
Price now: 60 cents!

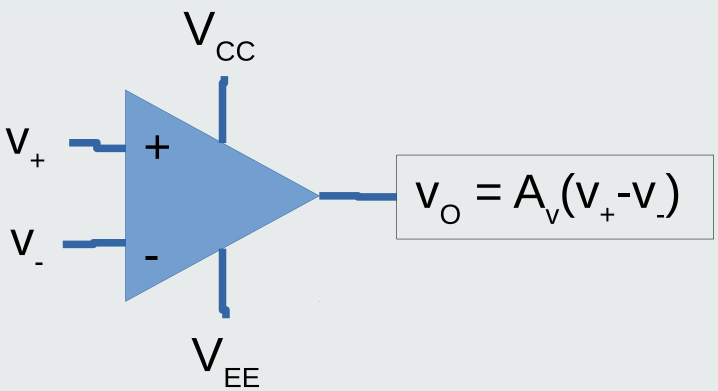
OP-AMP: model



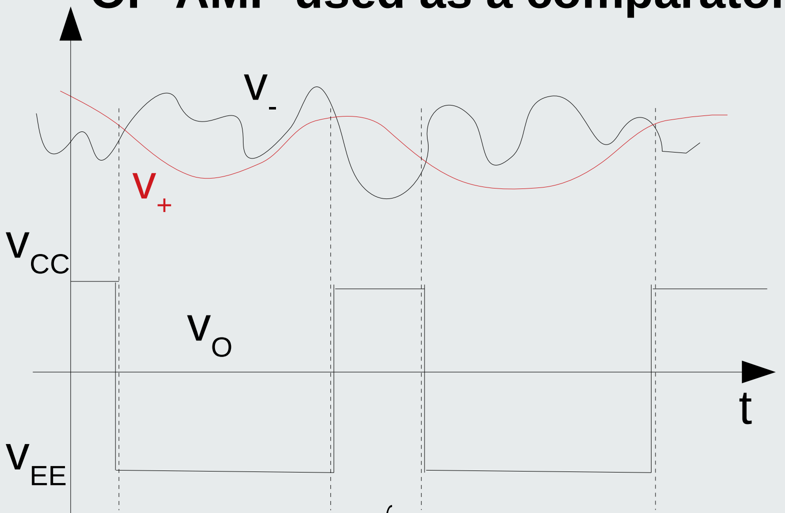
Differential input amplifier model

Ideally, $A_v=\infty$, $Z_I=\infty$, $Z_O=0$

OP-AMP: operation



OP-AMP used as a comparator



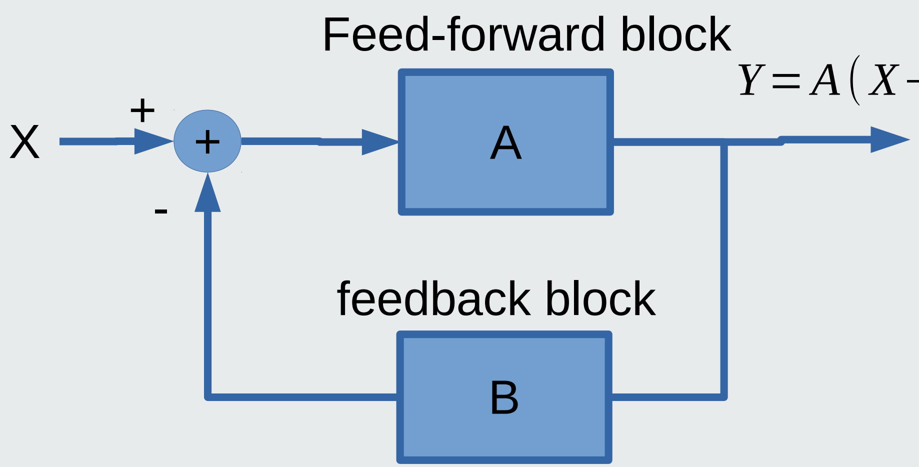
$$v_o = \begin{cases} V_{CC}, & v_+ > v_- \\ V_{EE}, & v_+ < v_- \end{cases}$$

Feature	Ideal	Practical (typical)
Gain	∞	$10^4 – 10^6$
Input impedance	∞ Ω	1-10 M Ω
Output impedance	0 Ω	10 – 100 Ω
Bandwidth	∞ Hz	10 Hz
Power efficiency	100%	50%
Slew rate*	∞ V/s	0.5 V/μs
Output limits	$[V_{EE}, V_{CC}]$	$[V_{EE}+\delta_e, V_{CC}-\delta_c]$

*max output voltage variation rate

OP-AMP: feedback operation

- Question: What can a device with very high gain used for, besides the comparator circuit
- Answer: for many different uses provided a technique called **feedback** is used



$$Y = A\left(X - BY\right)$$

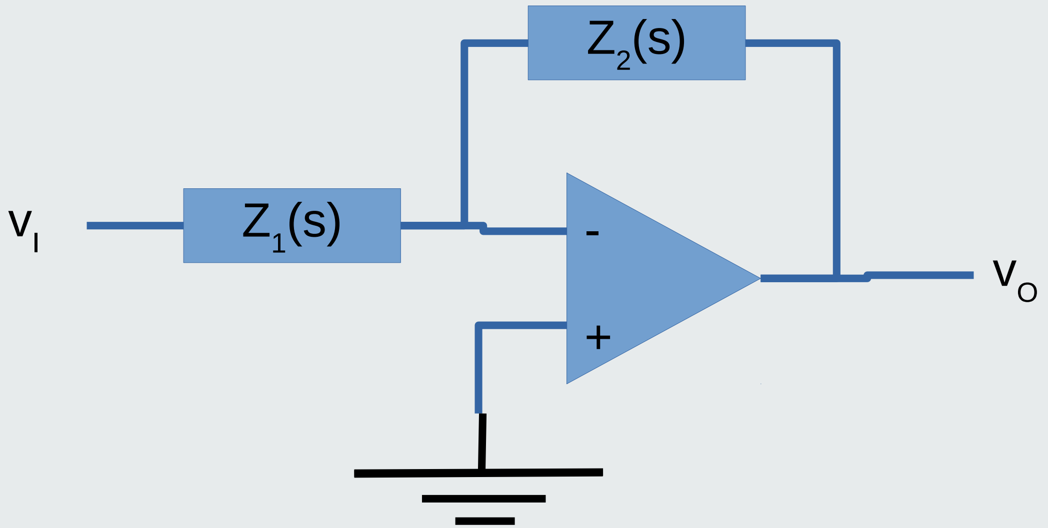
$$Y = \frac{A}{1+AB}X$$

The feedback equation!

$$A \rightarrow \infty \Rightarrow Y \approx \frac{1}{B}X$$

- Gain depends on feedback block only!
- Normally B is made with passive components (less sensitive to temperature, humidity, fabrication variations than active components)
- High gain still possible as we take the inverse of B!

OP-AMP: inverting amplifier



Negative feedback using inverting input:

$$v_O = A_v(v_{+.} - v_{-.})$$

$$v_O = A_v\left(0 - \frac{Z_2}{Z_1+Z_2} v_I - \frac{Z_1}{Z_1+Z_2} v_o\right)$$

$$v_O = -\frac{Z_2}{Z_1+Z_2} \frac{A_v}{1+A_v \frac{Z_1}{Z_1+Z_2}} v_I$$

$v_{+.} = 0$ Connected to ground

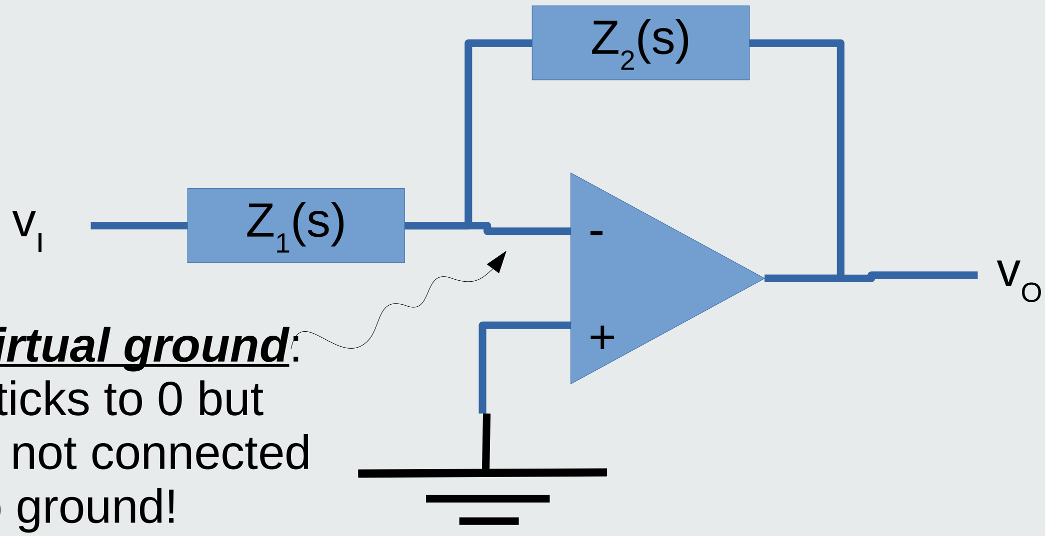
$v_{-.} = \frac{Z_2}{Z_1+Z_2} v_I + \frac{Z_1}{Z_1+Z_2} v_o$ superposition

$$\frac{Y}{X} = \frac{A}{1+AB}$$

$B = \frac{Z_1}{Z_1+Z_2}$ Feedback gain

$$A_v \rightarrow \infty \Rightarrow \frac{v_O}{v_I} = -\frac{Z_2(s)}{Z_1(s)}$$

OPAMP: inverting amplifier – the effect of negative feedback



Virtual ground: Sticks to 0 but is not connected to ground!

$$v_{+.} = 0$$

$$v_{-.} = \frac{Z_2}{Z_1+Z_2} v_I + \frac{Z_1}{Z_1+Z_2} v_o$$

$$\frac{Y}{X} = \frac{A}{1+AB}$$

$v_I \uparrow \Rightarrow v_{-.} \uparrow \Rightarrow v_O \downarrow \Rightarrow v_{-.} \downarrow$ If v_I raises v_- won't raise!

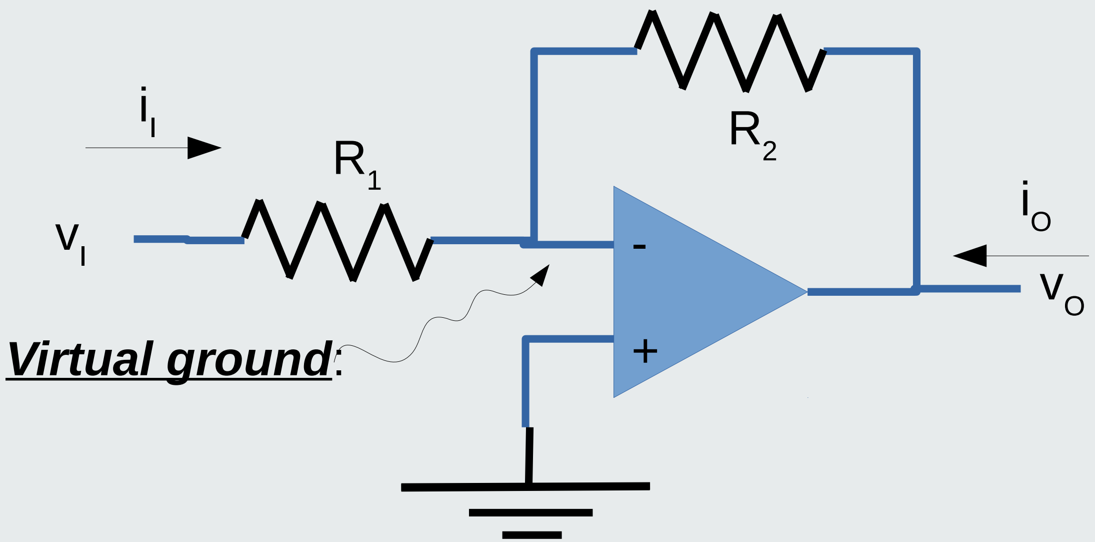
$v_I \downarrow \Rightarrow v_{-.} \downarrow \Rightarrow v_O \uparrow \Rightarrow v_{-.} \uparrow$ If v_I lowers v_- won't lower!

$v_O = A_v (v_+ - v_-)$ If A_v is infinite the only way v_O can be finite is if v_+ - v_- = 0

∞ x 0 = something

$v_- = v_+$ **v_- sticks to v_+ with negative feedback!!!**

OPAMP: inverting amplifier with resistive feedback loop



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

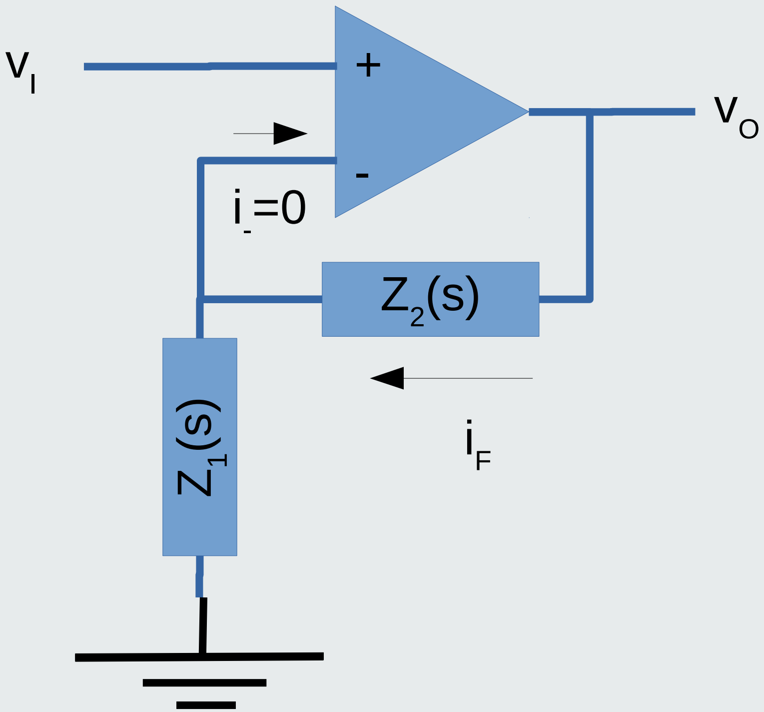
$$Z_I = \left.\frac{v_I}{i_I}\right|_{Z_L=\infty} = \frac{v_i - 0}{\frac{v_i - 0}{R_1}} = R_1$$

$$Z_O = \left.\frac{v_O}{i_O}\right|_{v_I=0} = R_2 || 0 = 0$$

Very stable ***negative*** gain amplifier

R_1 and R_2 also vary with the temperature but if they vary proportionally the gain is kept

OPAMP: non-inverting amplifier



$$v_I\uparrow \Rightarrow v_+\uparrow \Rightarrow v_O\uparrow \Rightarrow v_-\uparrow \Rightarrow v_O\downarrow v_-\downarrow$$
$$v_I\downarrow \Rightarrow v_+\downarrow \Rightarrow v_O\downarrow \Rightarrow v_-\downarrow \Rightarrow v_O\uparrow v_-\uparrow$$

$$v_O = A_v(v_+ - v_-)$$

$$v_- = v_+ = v_I$$

$$v_O = v_- + Z_2 i_F = v_I + Z_2 i_I$$

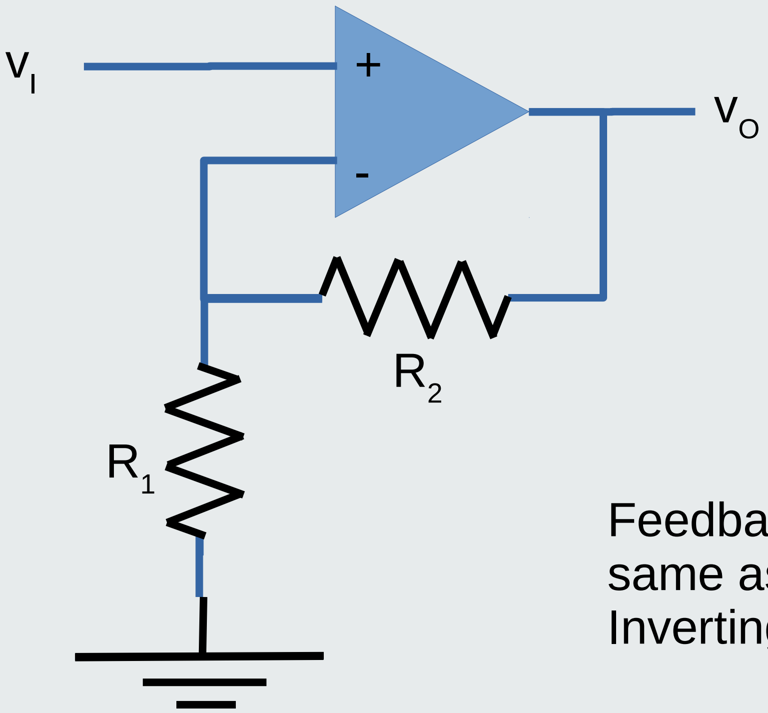
$$i_F = \frac{v_-}{Z_1}$$

$$\frac{v_O}{v_I} = 1 + \frac{Z_2(s)}{Z_1(s)}$$

Another Negative Feedback Amplifier: feedback through inverting input

Gain is positive if Z_2 and Z_1 are positive

OPAMP: non-inverting amplifier with resistive feedback loop



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

$$v_O=A_v\left(v_I-\frac{R_1}{R_1+R_2}v_O\right)$$

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

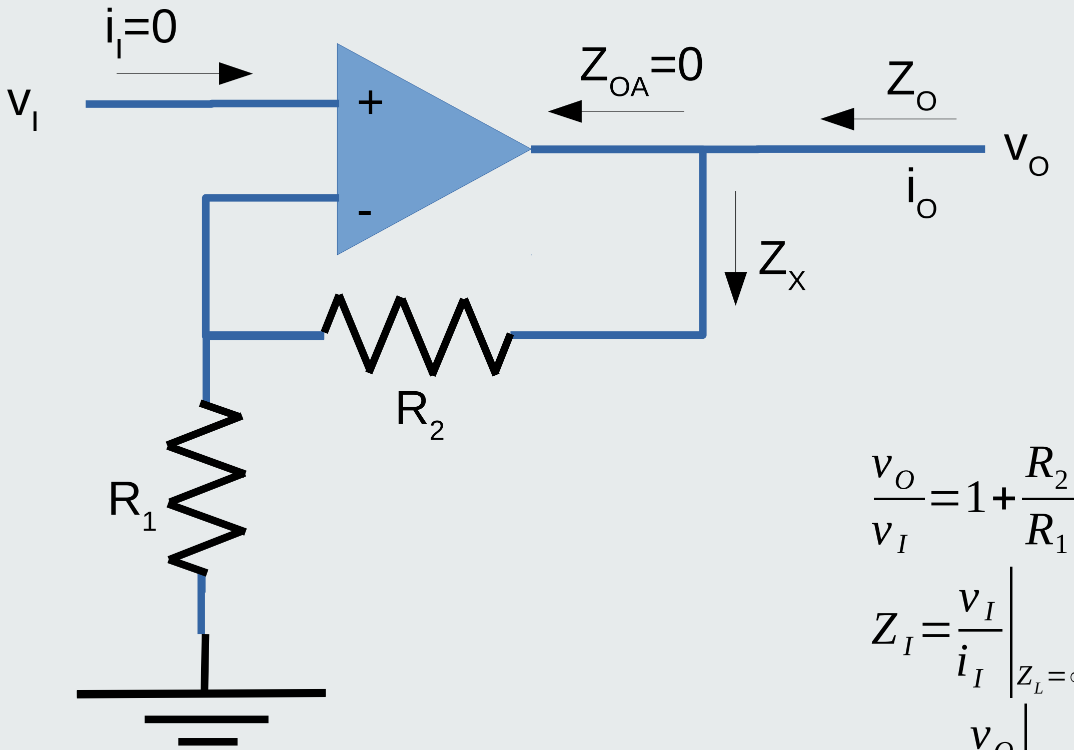
Feedback gain B is the same as the Inverting amplifier:

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

Very stable ***positive*** gain amplifier

R_1 and R_2 also vary with the temperature but proportionally so the gain keeps

OPAMP: non-inverting amplifier – gain, input and output impedance

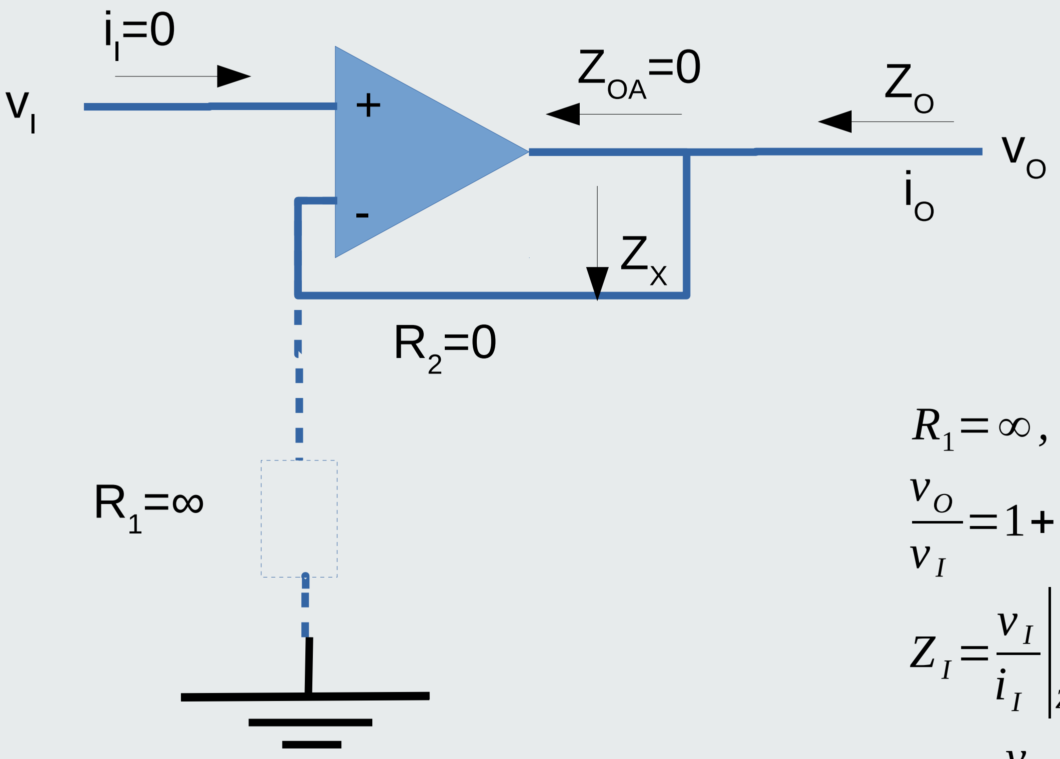


$$\frac{v_O}{v_I}=1+\frac{R_2}{R_1}$$

$$Z_I=\left.\frac{v_I}{i_I}\right|_{Z_L=\infty}=\frac{v_i-v_-}{0}=\infty$$

$$Z_O=\left.\frac{v_O}{i_O}\right|_{v_I=0}=Z_X||Z_{OA}=R_2||0=0$$

OPAMP: non-inverting ampliflier as current buffer



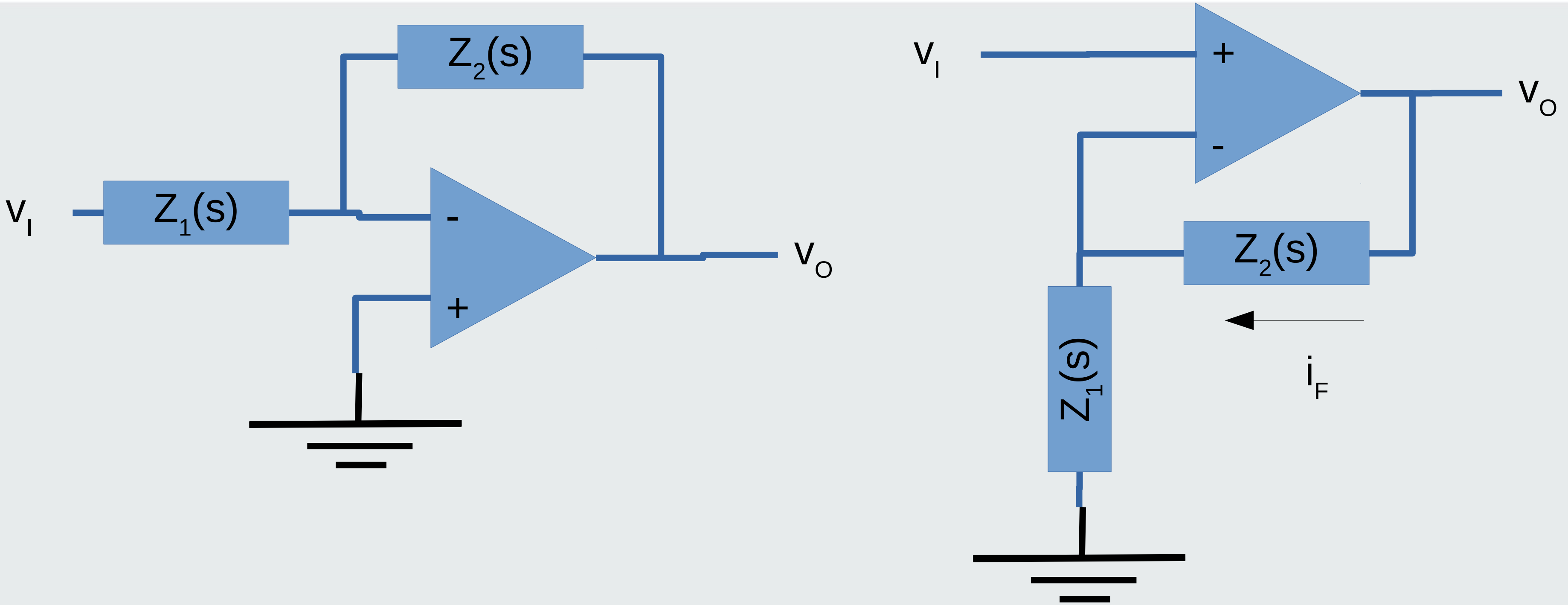
$$R_1=\infty,\quad R_2=0$$

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

$$Z_I=\left.\frac{v_I}{i_I}\right|_{Z_L=\infty}=\frac{v_i-v_-}{0}=\infty$$

$$Z_O=\left.\frac{v_O}{i_O}\right|_{v_I=0}=Z_X||Z_{OA}=R_2||0=0$$

OPAMP: amplifiers complex feedback loop



If $Z_1(s)$ and $Z_2(s)$ are complex impedances then interesting ***filters*** and other operations can be realized

This is what we will in next classes and is done in lab assignment number 5…

Conclusion

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