EE2013

NON-LINEAR CIRCUIT ANALYSIS

LECTURE 17: BASIC OPAMP CIRCUITS

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Coordinator: Prof. Pádraig Cantillon-Murphy

LECTURE SCHEDULE

Thursdays 11am-1pm
(with short break)

Monday 9am-10am slot not used!

LECTURE NOTES

https://www.jaeger.ie/ee2013/lec17

Uploaded before lecture takes place

QUESTIONS?

Just ask whenever it comes to you!

OR:

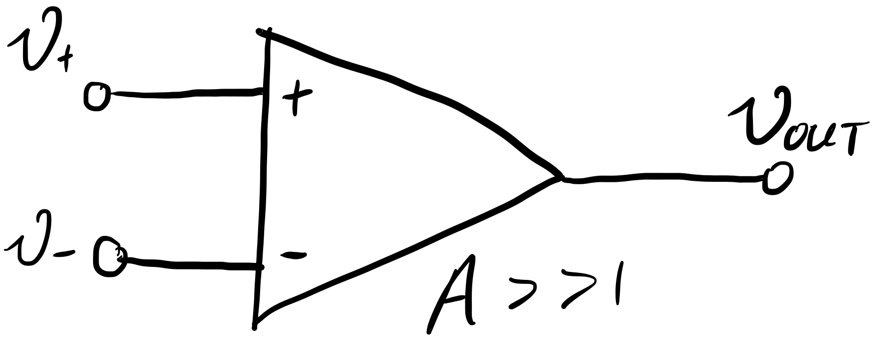
anthony.wall@mcci.ie on Email, Teams or Canvas

1 Review from Last Time

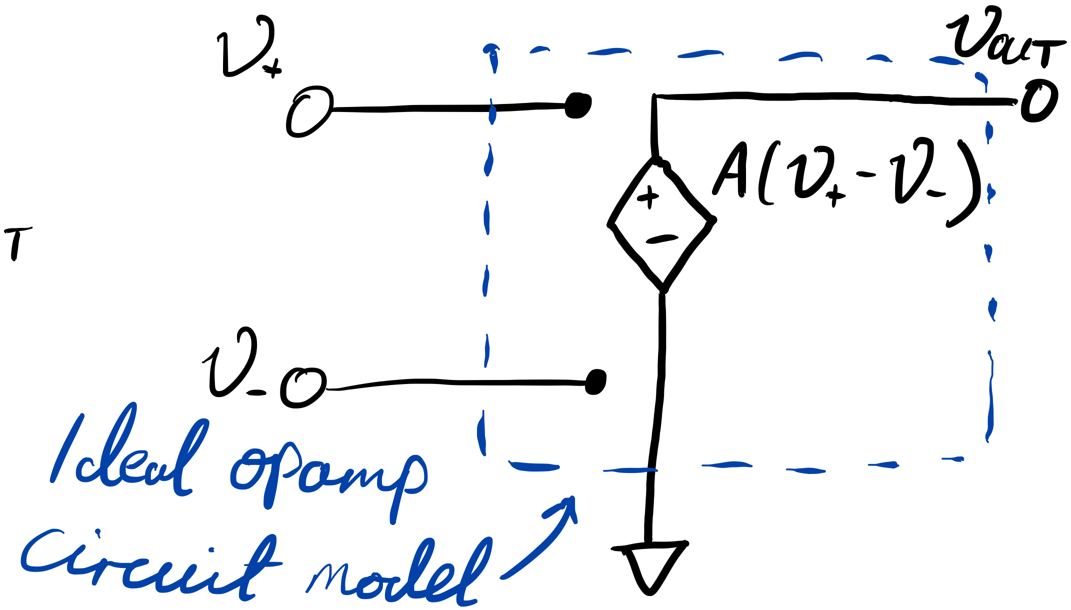
1.1 Operational Amplifiers

The operational amplifier (op-amp) is a ubiquitous and very useful electronic component that enables the circuit designer to implement a large number of mathematical and logical functions (*e.g.*, addition, subtraction).

The circuit model for the op-amp is a high-gain, differential voltage source.



$$v_{OUT} = A(v_+ - v_-)$$



The analysis of op-amp circuits with NEGATIVE FEEDBACK is made significantly simpler by the following approximation which states that the positive and negative input terminal voltages of the op-amp are approximately equal in value.

$$\boxed{v^+ \approx v^-}$$

Using this approximation, we can find the input-output relation for a number of useful op-amp circuits.

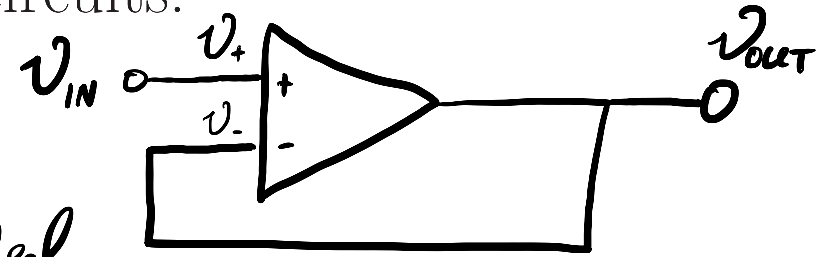
If $v_+ \uparrow$

then $v_{OUT} \uparrow$

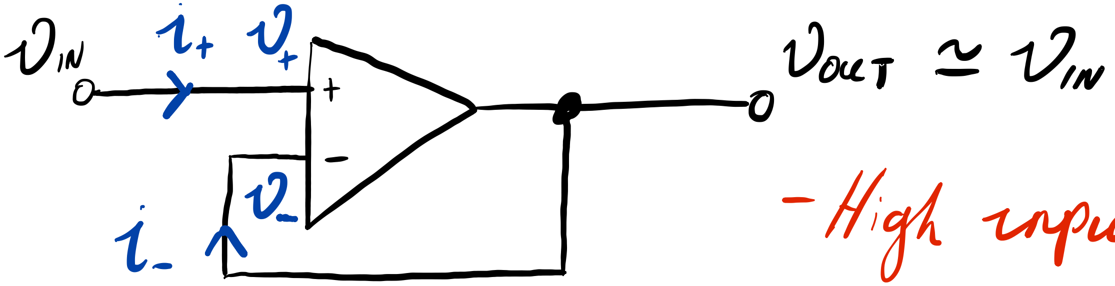
BUT: v_- Also $\uparrow$

until $v_+ \simeq v_-$

equilibrium is reached

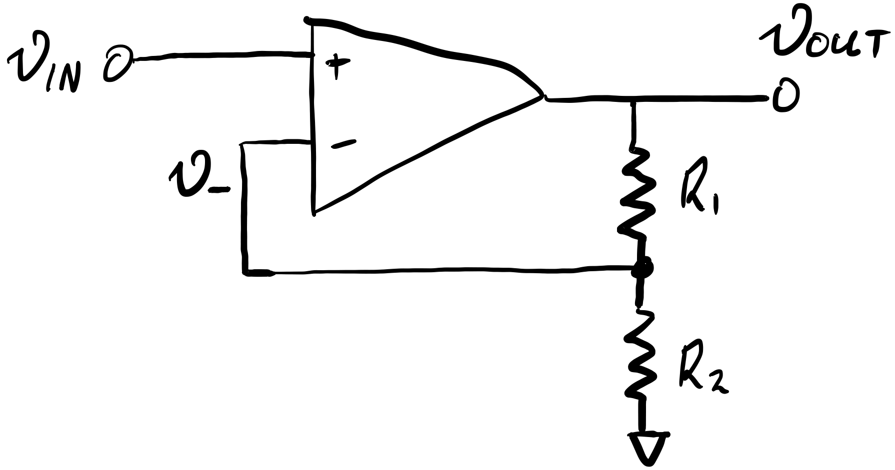


1.2 Op-Amp Buffer



- High input impedance
- Low output impedance

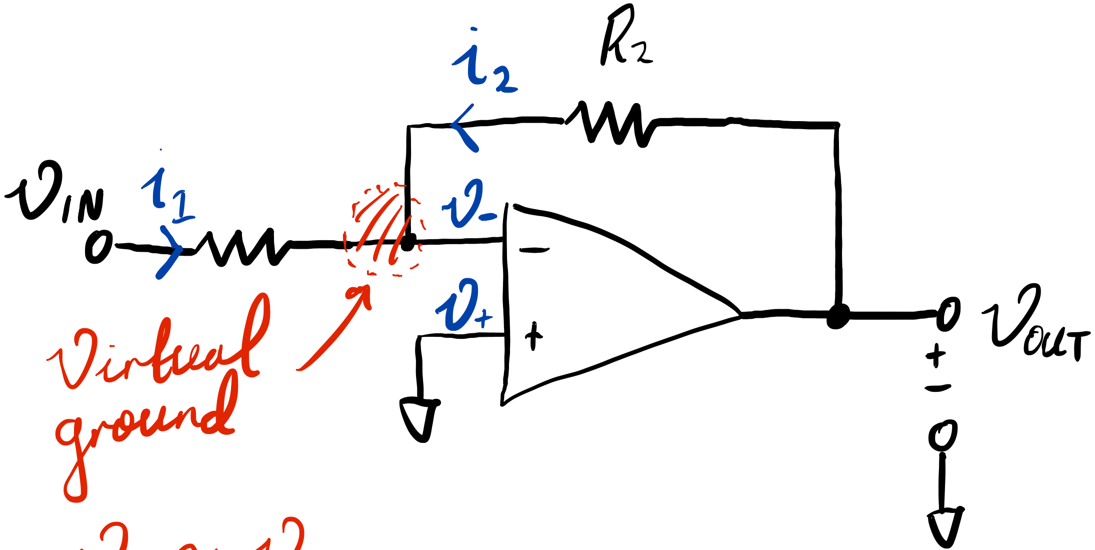
1.3 Non-inverting Amplifier



$$v_- = v_{OUT}\,\frac{R_2}{R_1+R_2}$$

$$v_{OUT} = v_{IN}\left(\underbrace{1+\frac{R_2}{R_1}}_{\text{Gain}}\right)$$

1.4 Inverting Amplifier



$v_- \simeq v_+$

$i_- \simeq 0$

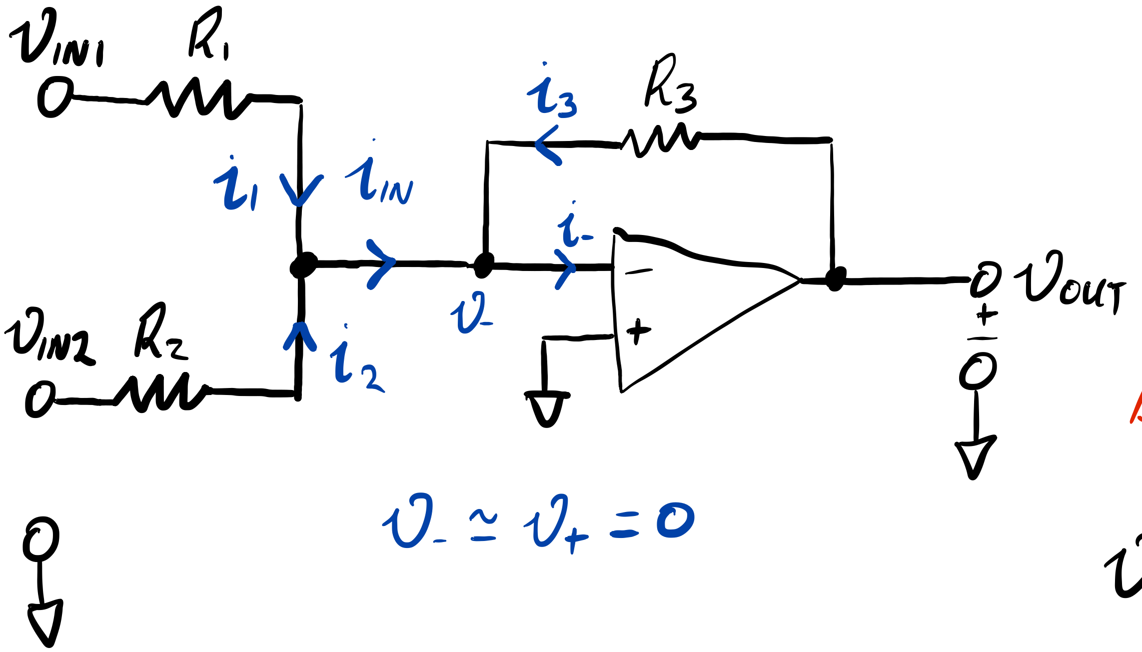
$i_1 + i_2 = 0$

180deg Phase Shift

$$v_{OUT} \simeq \left(\frac{-R_2}{R_1}\right) v_{IN}$$

Gain

1.5 Op-Amp Adder



$$v_- \simeq v_+ = 0$$

$$i_{IN} = i_1 + i_2$$

$$i_{IN} + i_3 = 0$$

Same as inverting amp!

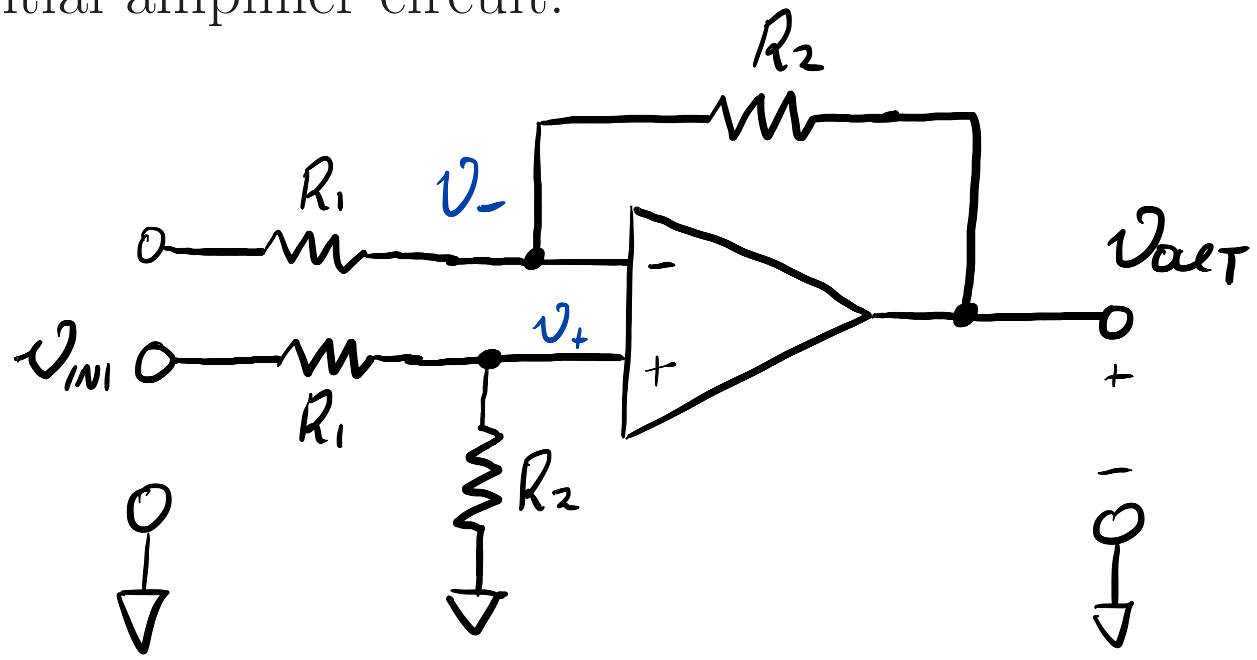
By Superposition:

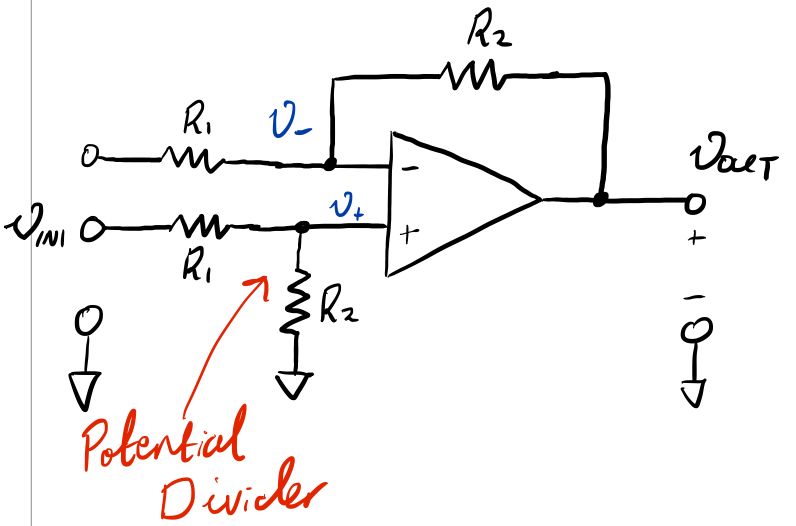
$$v_{OUT} = v_{IN1}\left(\frac{-R_3}{R_1}\right) + v_{IN2}\left(\frac{-R_3}{R_2}\right)$$

2 Advanced Op-Amp Circuit Applications

2.1 Example 1: The Op-amp as a Differential Amplifier (Subtractor)

As we have already seen, the op-amp itself is essentially a differential amplifier. However, some modification is necessary to configure this differential gain to a designed value. The result is the differential amplifier circuit:



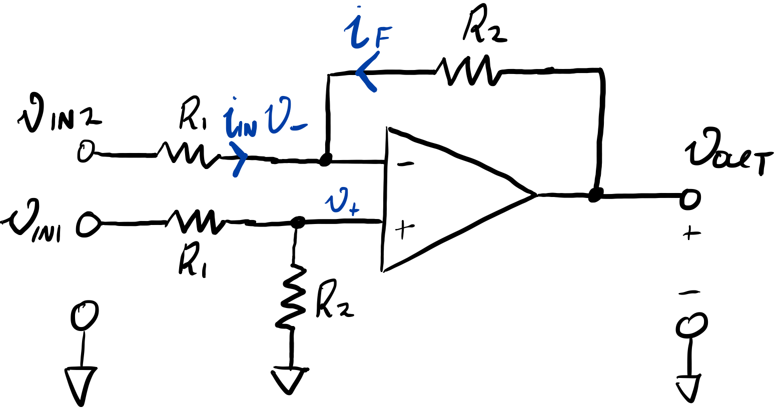


The analysis is simplified by the presence of negative feedback so that $v^+ \approx v^-$. The voltage at v^+ is given by potential division of v_1:

$$v_+ = v_{IN1}\left(\frac{R_2}{R_1+R_2}\right)$$

$$v_- \simeq v_+$$

$$\hookrightarrow v_- \simeq v_{IN1}\left(\frac{R_2}{R_1+R_2}\right)$$



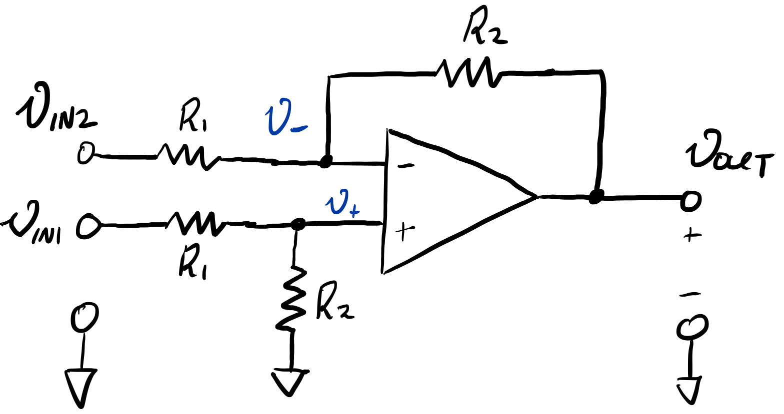
This leads to the following expression for the current i_{in}:

$$i_{IN} = \frac{v_{IN2} - v_-}{R_1} \simeq \frac{v_{IN2} - v_+}{R_1} = \frac{v_{IN2}}{R_1} - \frac{R_2 v_{IN1}}{R_1(R_1+R_2)}$$

Similarly, i_F:

$$i_F = \frac{v_{OUT} - v_-}{R_1} \simeq \frac{v_{OUT} - v_+}{R_1} = \frac{v_{OUT}}{R_2} - \frac{v_1 \cancel{R_2}}{\cancel{R_2}(R_1+R_2)}$$

$$i_F = \frac{v_{OUT}}{R_2} - \frac{v_1}{R_1+R_2}$$



Since no current flows into the input terminals of an ideal op-amp:

KCL: $$i_F + i_{IN} = 0$$

$$\overbrace{\frac{v_O}{R_2} - \frac{v_1}{R_1 + R_2}}^{F} + \overbrace{\frac{v_2}{R_1} - \frac{v_1 R_2}{R_1(R_1 + R_2)}}^{IN} = 0$$

Gathering similar terms:

$$v_1\left(\frac{R_2}{R_1(R_1 + R_2)} + \frac{1}{R_1 + R_2}\right) - v_2\frac{1}{R_1} = \frac{v_O}{R_2}$$

Multiplying by R_1:

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

This yields the characteristic input-output relation for the differential op-amp circuit:

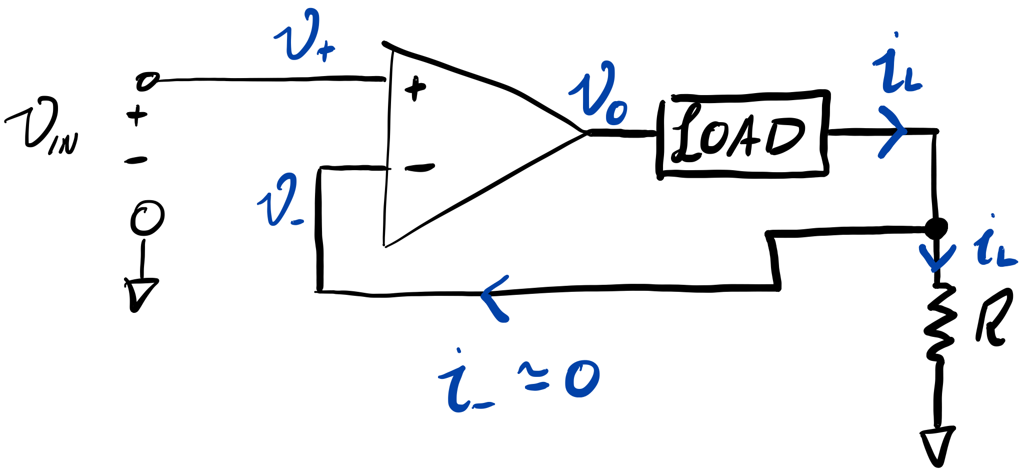
$$v_{IN1}\left(\cancel{\frac{R_2 + R_1}{R_1 + R_2}}\right) - v_{IN2} = v_{OUT}\frac{R_1}{R_2}$$

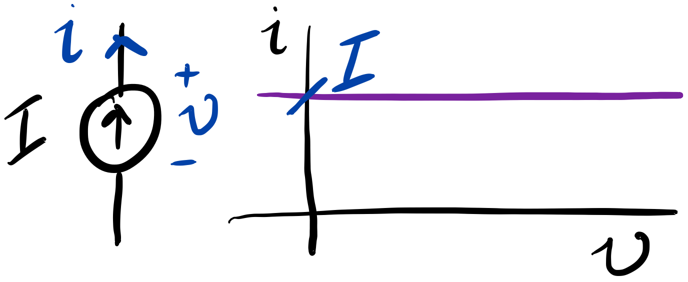
$$v_{OUT} = \frac{R_2}{R_1}(v_1 - v_2)$$

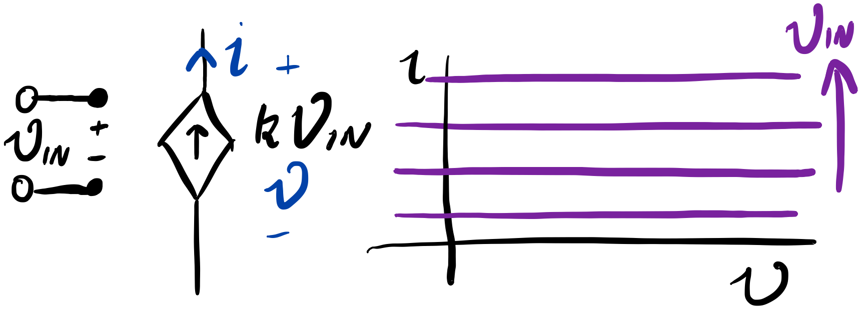
Subtractor

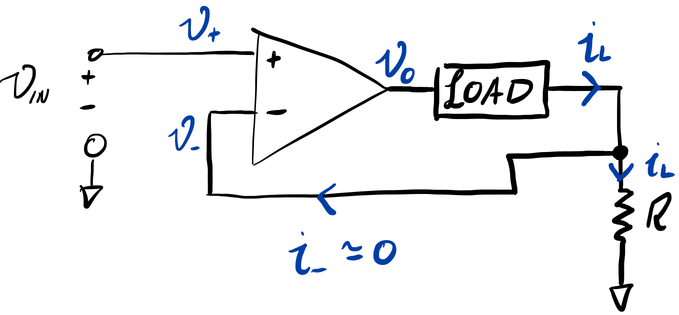
2.2 Example 2: The Op-amp as a Current Source

A modification to the non-inverting amplifier configuration allows the op-amp to function as a voltage-controlled current source:









Assume that the op-amp drives a load of unknown resistance. A small resistor R, is placed in series with the load. Then the inverting input is $v^- = iR$. At the output of the amplifier:

$$v_o = A(v_+ - v_-)$$

$$v_o = A(v_{IN} - iR)$$

$$i = \frac{1}{R}\left(v_{IN} - \frac{v_o}{A}\right)$$

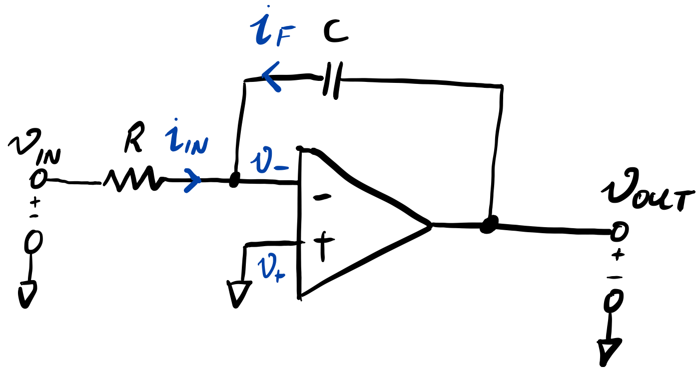
$$i = \frac{v_{IN}}{R}$$

i = Load current is independent of output voltage v_o and LOAD.
Its value depends on v_{IN}

$\Rightarrow$ Voltage Controlled Current Source

2.3 Example 3: The Op-amp as an Integrator

If the feedback resistor in the inverting amplifier is replaced by a capacitor, C the amplifier becomes an integrator:



$$v_- \simeq v_+ = 0$$

At the v^- terminal, we apply Kirchoff's current law as before but the feedback current is now defined by the elemental relationship for the capacitor:

$$i_{IN} + i_F = 0 \quad \rightarrow KCL \ @ \ v_-$$

$$\frac{v_{IN} - v_-}{R} + C\,\frac{d(v_{OUT} - v_-)}{dt} = 0 \qquad i_c = C\,\frac{dv_c}{dt}$$

$$v_- \simeq 0$$

$$\frac{v_{IN}}{R} + C\,\frac{dv_{OUT}}{dt} = 0$$

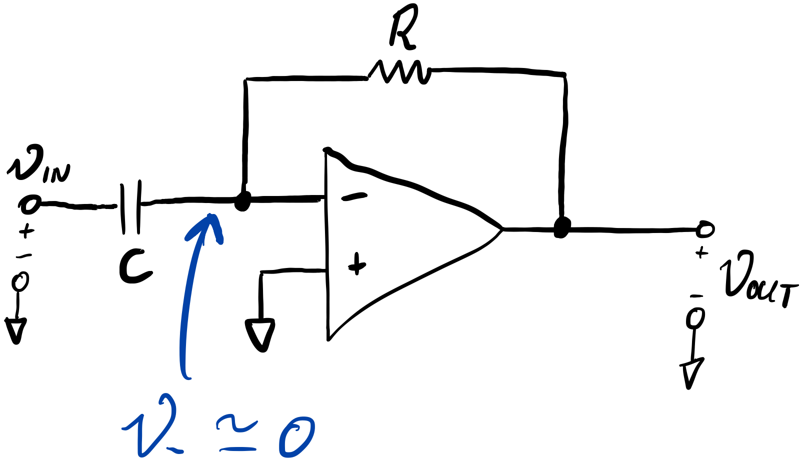
$$\int$$

Initial Conditions

$$v_o = -\frac{1}{RC}\int_0^t v_{IN}(t')\,dt' + v_c(0)$$

The result is a linear integration of the input voltage at the output.

If the input resistor in the inverting amplifier is replaced by a capacitor, the circuit becomes a differentiator:



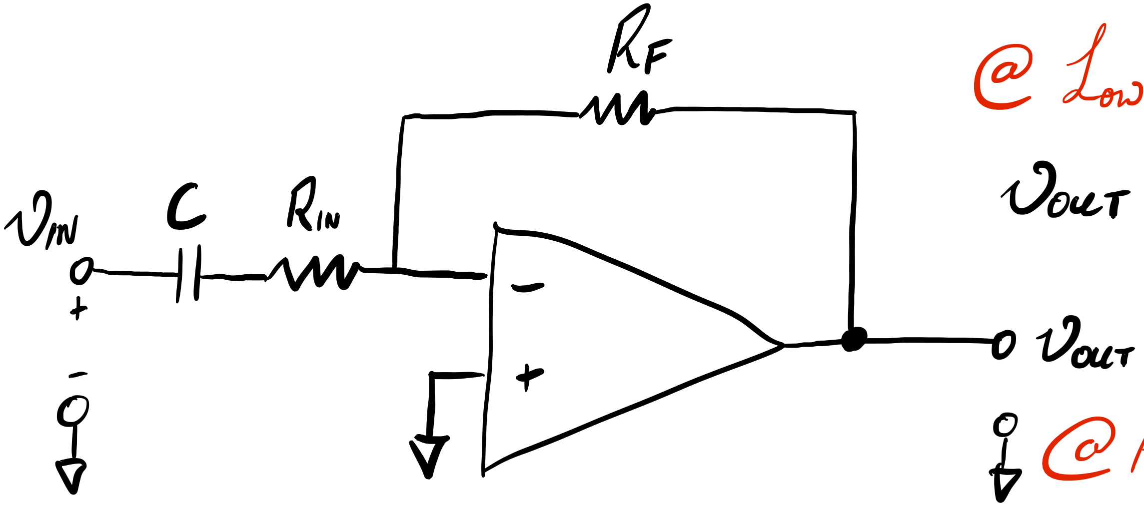
At the v^- terminal, we apply Kirchoff's current law as before but the input current is now defined by the elemental relationship for the capacitor:

$$i_{IN} + i_F = 0 \qquad i_c = C\frac{dv_c}{dt}$$

$$C\frac{dv_{IN}}{dt} + \frac{v_{OUT}}{R} = 0$$

$$\Rightarrow v_{OUT} = -RC\frac{dv_{IN}}{dt}$$

Design Note: While the op-amp differentiator circuit is easily implemented, pure differentiators are rarely used because of their susceptibility to electrical noise. In practice, it is common to put a resistor in series with the capacitor to alleviate this issue.



@ Low frequencies:

$$v_{OUT} \simeq -R_F C \frac{d\,v_{IN}}{dt}$$

@ High frequencies:

$$v_{OUT} \simeq \frac{R_F}{R_{IN}} v_{IN}$$