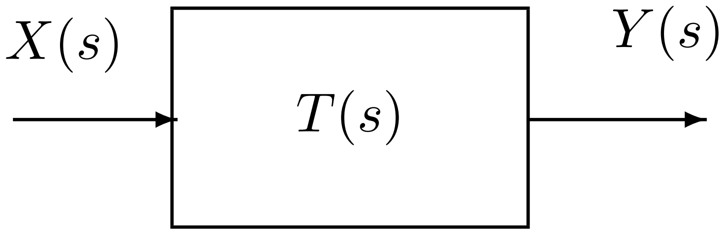
Digital systems and basics of electronics

Adam Szmigielski
aszmigie@pjwstk.edu.pl

materials: $ftp(public)://aszmigie/SYC/ENG$

Operational amplifiers - lecture 5

Recalling idea of transfer function



$$T(s) = \frac{Y(s)}{X(s)}$$

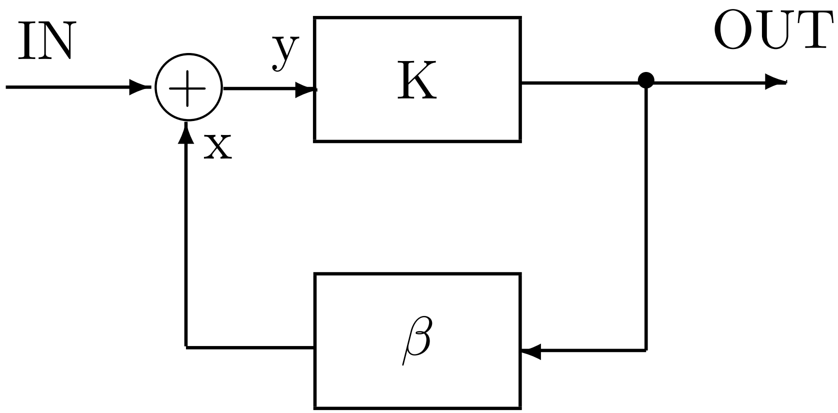
Formally, the transfer function represents the relationship between the output and input of linear systems in the frequency description.

Idea of feedback

In control theory, feedback is a process whereby some proportion of the output signal of a system is passed (fed back) to the input. This is often used to control the dynamic behavior of the system.

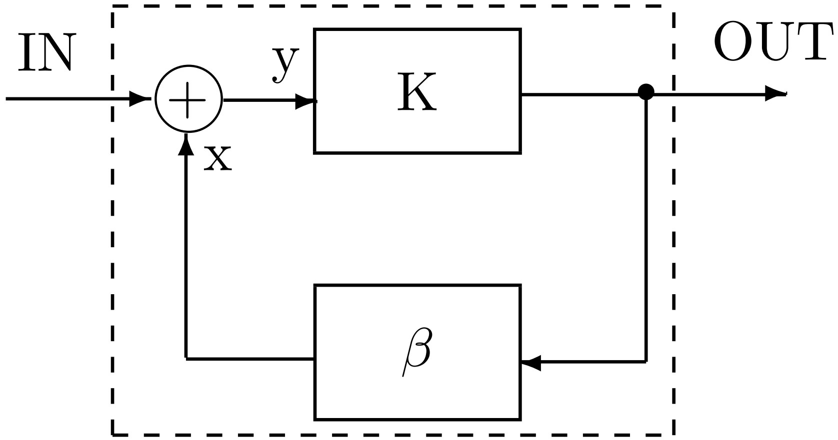
Negative feedback was applied by Harold Stephen Black to electrical amplifiers in 1927.

Types of feedback



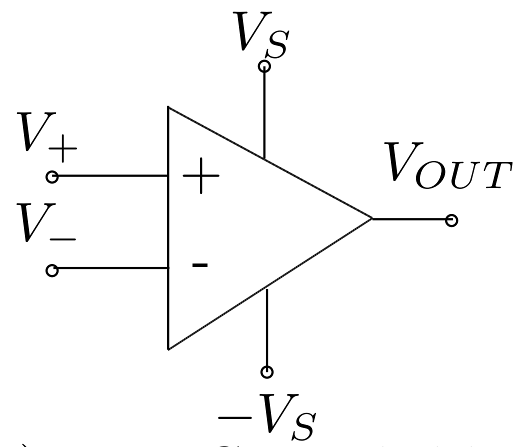
- *negative feedback*: which tends to reduce output (but in amplifiers, stabilizes and linearizes operation),
- *positive feedback*: which tends to increase output,
- *bipolar feedback*: which can either increase or decrease output.

Transmittance of closed-loop circuit



- Transmittance of block K: $K = \frac{Out}{y}$
- Transmittance of block B: $B = \frac{x}{Out}$
- Transmittance of system with close loop: $T = \frac{Out}{In} = \frac{K}{1 - K \cdot B}$

Operational amplifier



- An *operational amplifier* (op-amp) is a DC-coupled high-gain electronic voltage amplifier with *differential inputs* and a single *output*.
- The output of the op-amp is controlled by negative feedback which largely determines the magnitude of its output voltage gain, input impedance at one of its input terminals and output impedance.
- *Operational amplifiers* are the most widely used electronic devices today.

Historical remarks

- The operational amplifier was originally designed to perform mathematical operations by using voltage as an analogue of another quantity (hence the name, “operational amplifier”).
- This is the basis of the analog computer, where op-amps were used to model the basic mathematical operations (addition, subtraction, integration, differentiation, and so on).
- Operational amplifier is an extremely versatile circuit element, with a great many applications beyond mathematical operations.
- The first integrated op-amp to become widely available, in the late 1960s (it was the bipolar $\mu A709$ in 1965). The 741 quickly replaced $\mu A709$, which has better performance, stability, and is easier to use. The $\mu A741$ is still in production

Basic operation

- The amplifier's differential inputs consist of an *inverting input* and a *non-inverting input*, and ideally the op-amp amplifies only the difference in voltage between. This is called the *differential input voltage*.
- The op-amp's output voltage is controlled by feeding a fraction of the output signal back to the input (feedback).
- If there is no feedback the amplifier is said to be running ópen loop". and its output is the differential input voltage multiplied by the total gain of the amplifier:

$$V_{out} = k_{OpenLoop} \cdot (V_+ - V_-)$$

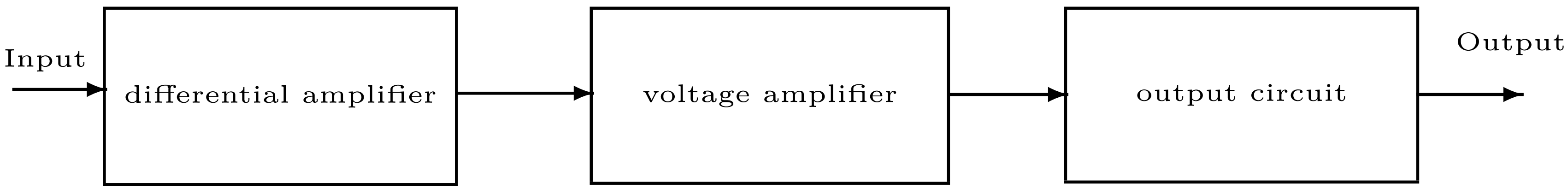
Parameters of ideal operational amplifiers

- infinite open-loop gain,
- infinite bandwidth,
- infinite input impedances
- infinite slew rate,
- zero input currents,
- zero offset voltage,
- zero output impedance
- zero noise.

The real operational amplifiers

- Real op-amps can only approach this ideal. Modern integrated FET or MOSFET op-amps approximate more closely these ideals than bipolar.
- Where the limitations of real devices can be ignored, an operational amplifier can be viewed as a black box with gain.
- Circuit function and parameters are determined by feedback, usually negative.

Internal structure of operational amplifier



All op-amps have basically the same internal structure, which consists of three stages:

1. *Differential amplifier* - provides low noise amplification, high input impedance, usually a differential output.
2. *Voltage amplifier* - provides high voltage gain, a single-pole frequency roll-off, usually single-ended output Output amplifier
3. *Output circuit* — provides high current driving capability, low output impedance, current limiting and short circuit protection circuitry

Parameters of real operational amplifier

- *Finite gain* — $10^5 \div 10^7 \frac{V}{V}$. The magnitude of the open-loop gain is not well controlled by the manufacturing process ($\mu A741 \breve{} 2 \cdot 10^5$).
- *Finite input resistance* — about few mega Ohms ($\mu A741 \breve{} 2M\Omega$).
- *Nonzero output resistance* — about few hundred Ohms ($\mu A741 \breve{} 75\Omega$).
- *Input bias current* — (typically $\sim 10nA$ for bipolar op-amps, or picoamperes for CMOS designs).
- *Input offset voltage* — the voltage required across the op-amp's input terminals to drive the output voltage to zero. In the perfect amplifier, there would be no input offset voltage. ($\mu A741 \breve{} 1mV$)

- *Common mode gain* — A perfect operational amplifier amplifies only the voltage difference between its two inputs, completely rejecting all voltages that are common to both. However, the differential input stage of an operational amplifier is never perfect, leading to the amplification of these identical voltages to some degree. The standard measure of this defect is called the *Common-Mode Rejection Ratio* (denoted, CMRR).
- *Temperature effects* — all parameters change with temperature.
- *Finite bandwidth* — all amplifiers have a finite bandwidth.
- *Input capacitance* — most important for high frequency operation because it further reduces the open loop bandwidth of the amplifier.

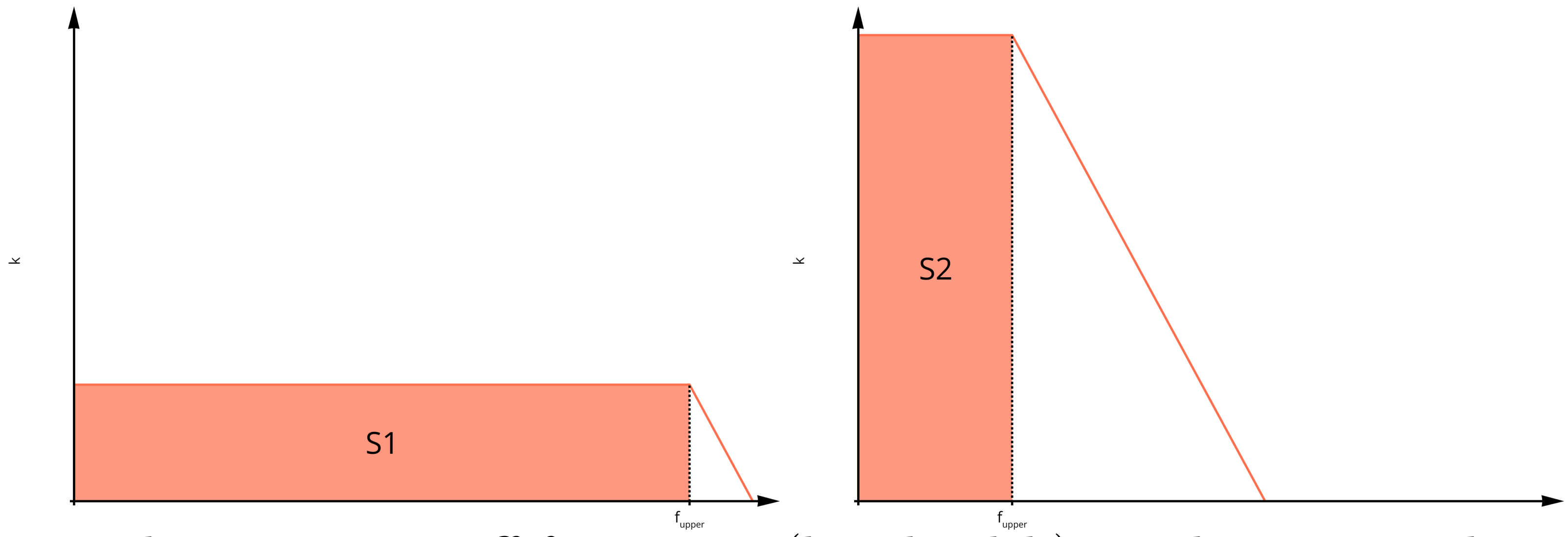
Nonlinearity of real operational amplifier

- *Saturation* — output voltage is limited to a minimum and maximum value close to the power supply voltages.
- *Slewing* — the amplifier's output voltage reaches its maximum rate of change. Measured as the *slew rate*, it is usually specified in volts per microsecond. When slewing occurs, further increases in the input signal have no effect on the rate of change of the output. Slewing is usually caused by internal capacitances in the amplifier, especially those used to implement its frequency compensation.

Bandwidth and amplification exchanging

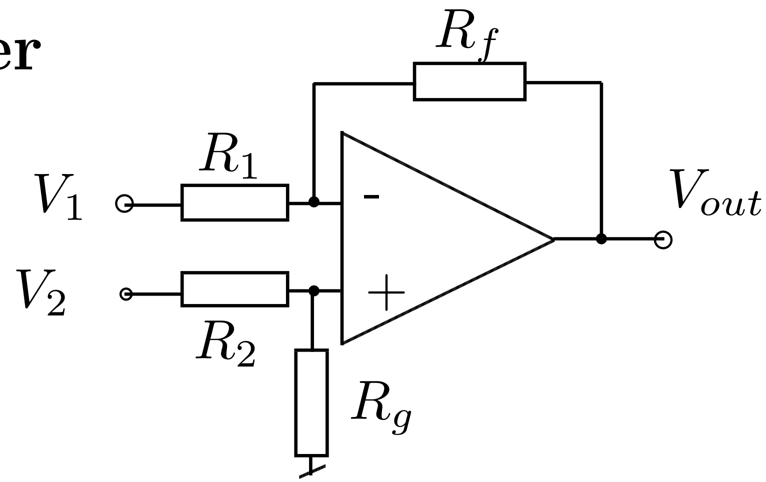
- For linear model of operational amplifier product of bandwidth and amplification is constant

$$f_{3dB} \cdot k_{max} = const$$



- The upper cut-off frequency (bandwidth) can be increased at cost of decreasing amplification and vice versa.

Differential amplifier



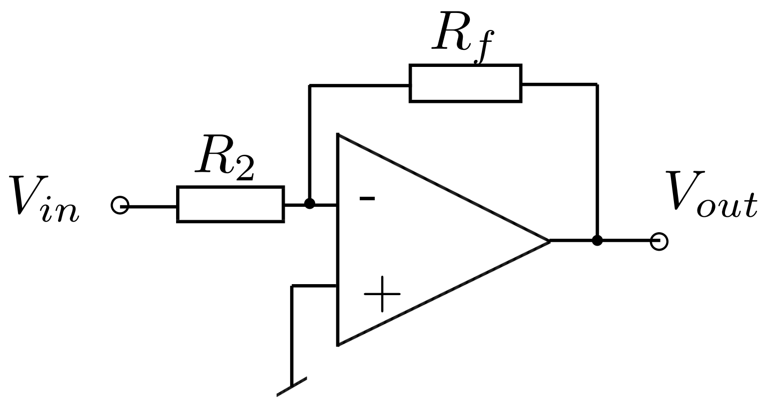
The circuit shown is used for finding the difference of two voltages each multiplied by some constant (determined by the resistors).

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

Whenever $R_1 = R_2$ and $R_f = R_g$

$$V_{out} = \frac{R_f}{R_1}(V_2 - V_1)$$

Inverting amplifier

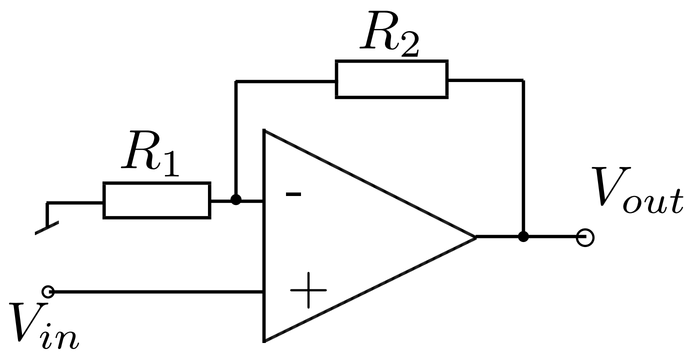


- Inverts and amplifies a voltage (multiplies by a negative constant)

$$V_{out} = -\frac{R_f}{R_2} \cdot V_{in} = -\frac{R_f}{R_{in}} \cdot V_{in}$$

- $Z_{in} = R_{in}$

Non-inverting amplifier

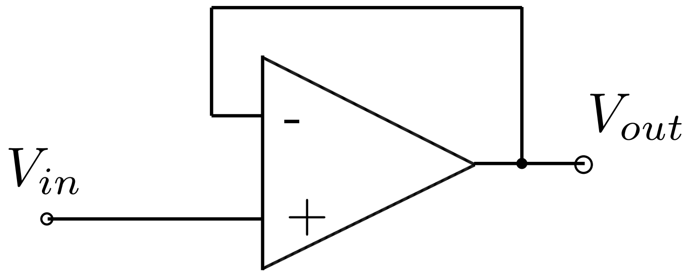


- Amplifies a voltage (multiplies by a constant greater than 1)

$$V_{out} = (1 + \frac{R_2}{R_1}) \cdot V_{in}$$

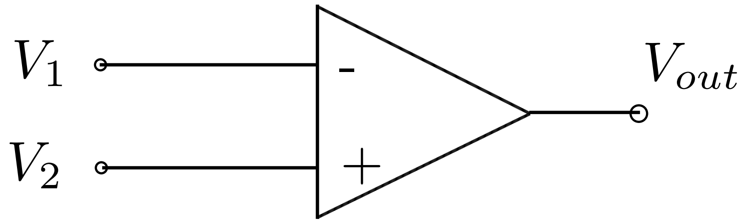
- $Z_{in} = \infty$ - realistically, the input impedance of the opamp itself, $1M\Omega$ to $10T\Omega$
- A third resistor, of value $R_f || R_{in}$, added between the V_{in} source and the non-inverting input, while not necessary, minimizes errors due to input bias currents.

Voltage follower



- Used as a buffer amplifier, to eliminate loading effects or to interface impedances (connecting a device with a high source impedance to a device with a low input impedance)
- $V_{out} = V_{in}$
- $Z_{in} = \infty$ - realistically, the input impedance of the opamp itself, $1M\Omega$ to $10T\Omega$

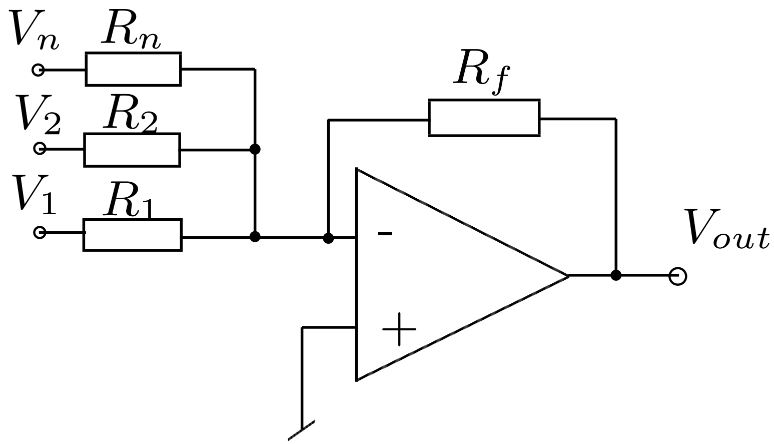
Comparator



Compares two voltages and outputs one of two states depending on which is greater:

$$V_{out} = \begin{cases} V_c & when \quad V_1 > V_2 \\ -V_c & when \quad V_1 < V_2 \end{cases}$$

Summing amplifier



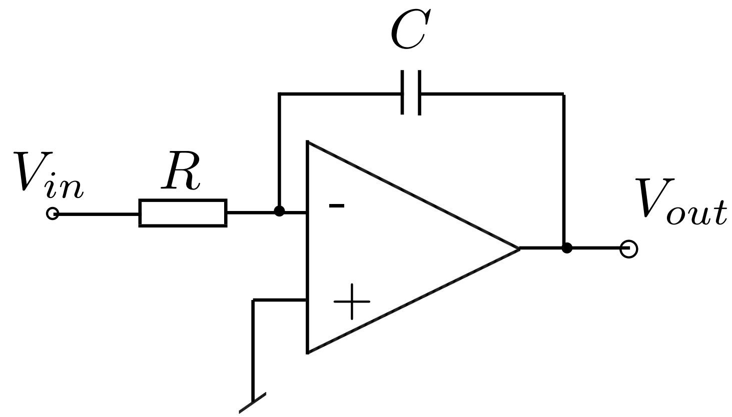
- Sums several (weighted) voltages

$$V_{out} = -R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \ldots + \frac{V_n}{R_n}\right)$$

When $R_1 = R_2 = \ldots = R_n$, and R_f is independent then

$$V_{out} = -\frac{R_f}{R_1}(V_1 + V_2 + \ldots + V_n)$$

Integrator



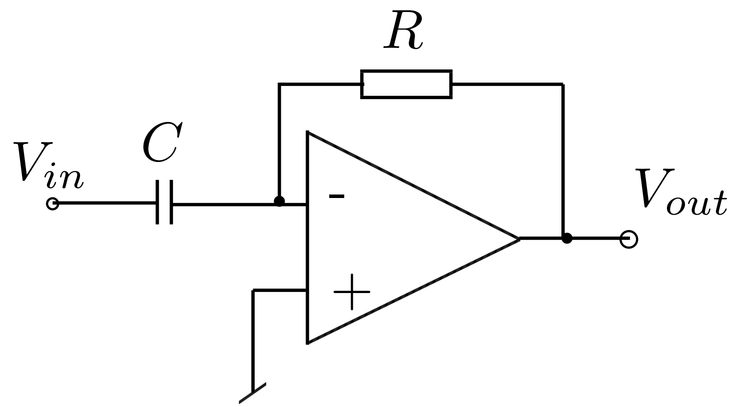
- Integrates the (inverted) signal over time

$$V_{out} = \int_0^t -\frac{V_{in}}{RC} dt + V_{initial}$$

where V_{in} and V_{out} are functions of time, $V_{initial}$ is the output voltage of the integrator at time $t = 0$.

- This can also be viewed as a type of electronic filter.

Differentiator



- Differentiates the (inverted) signal over time.

$$V_{out} = -RC(\frac{dV_{in}}{dt})$$

where V_{in} and V_{out} are functions of time.

- This can also be viewed as a type of electronic filter.

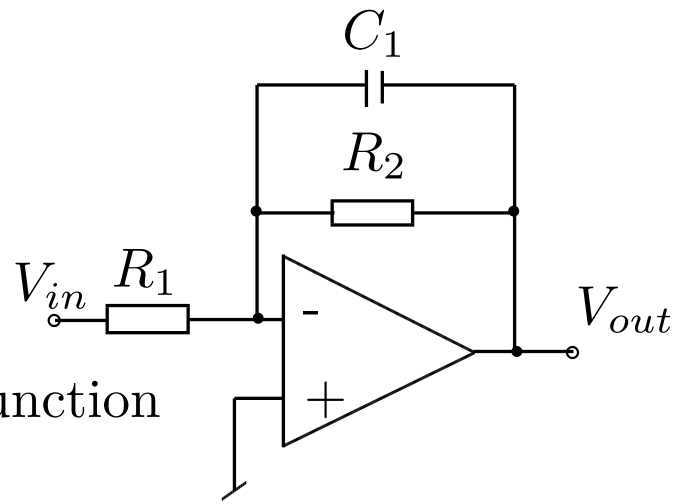
Active filters

An active filter is a type of analog electronic filter, distinguished by the use of one or more active components i.e. operational amplifier.

There are two principal reasons for the use of active filters.

1. The first is that the amplifier powering the filter can be used to shape the filter's response,
2. Amplifier powering the filter can be used to buffer the filter from the electronic components it drives. This is often necessary so that they do not affect the filter's actions.

First-Order Inverting Low-Pass Filter

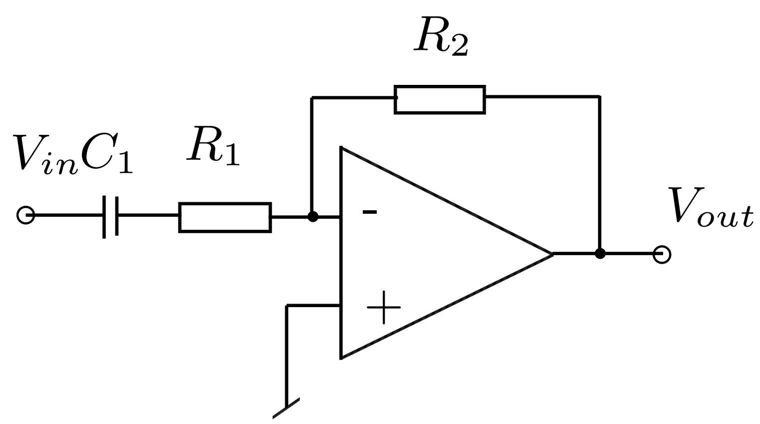


- The transfer function

$$T(s) = \frac{-\frac{R_2}{R_1}}{1 + sC_1R_2}$$

- The negative sign indicates that the inverting amplifier generates a 180° phase shift from the filter input to the output.

First-Order Inverting High-Pass Filter



- The transfer function

$$T(s) = \frac{-sC_1R_2}{1 + sC_1R_1}$$

- The negative sign indicates that the inverting amplifier generates a 180° phase shift from the filter input to the output.