Automatic Control

Control system technologies for automation

Conditioning, filtering, A/D and D/A conversion

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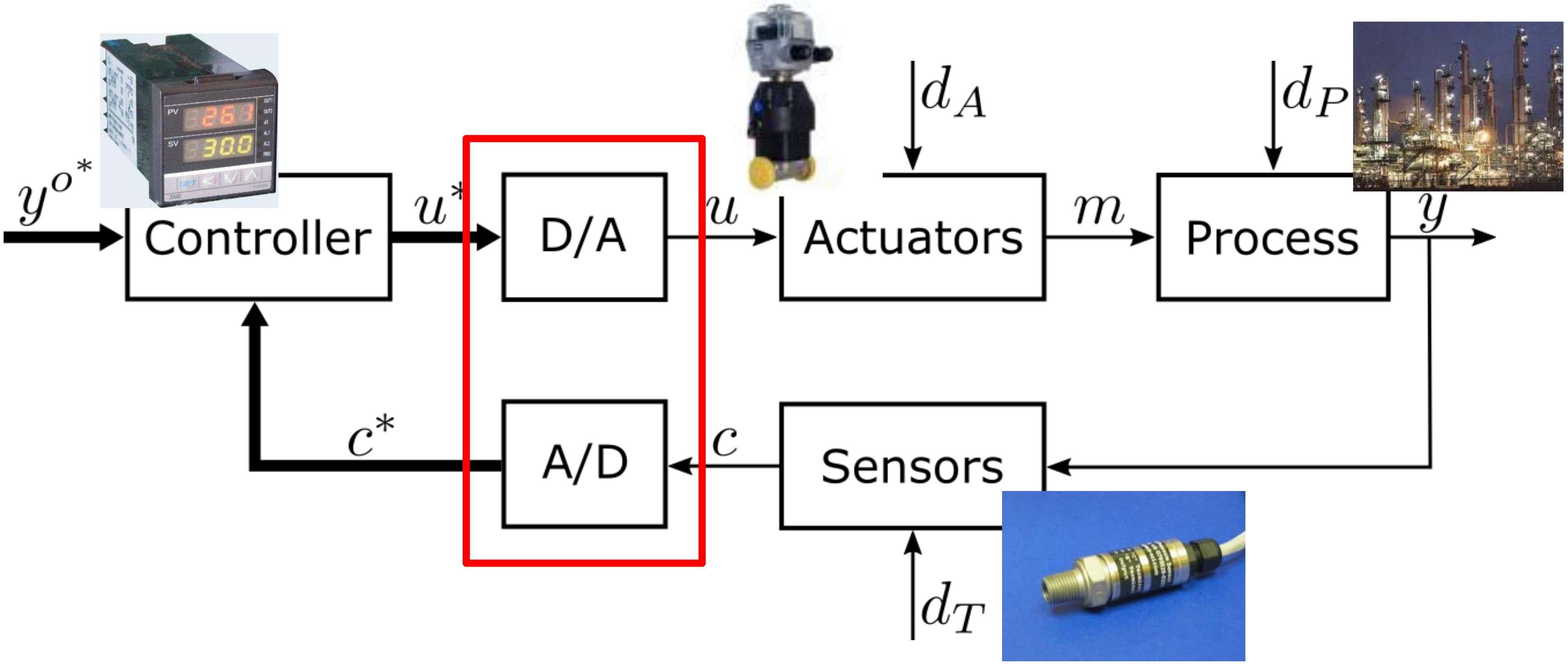
Motivations



To set up an industrial control system, besides the design of the controller, there are many technological issues, ranging from the selection of suitable sensors and actuators to the choice of the electronic interfaces.

Signals and data acquisition (I)

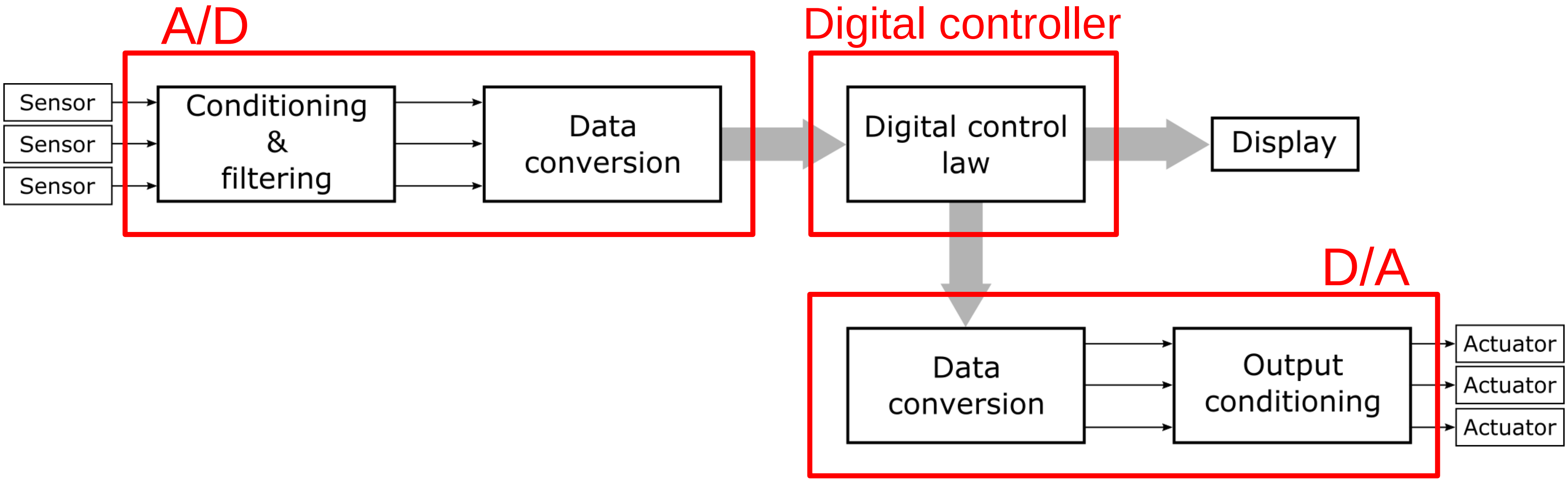
In a control system we have different kinds of input and output signals, that can be classified as follows:

- Analog input/output signals, represent continuous time physical quantities
- Digital input/output signals, represent a logical (binary) state of a plant component (i.e., a switch, a light barrier, an end-stop, etc.)

For each class of signals a different technique should be adopted for filtering, conditioning, and doing the analog-to-digital and digital-to-analog conversion.

Let’s have a look to a functional diagram representing the digital controller including A/D and D/A interfaces, and all the electronic devices required to perform conditioning and filtering.

Signals and data acquisition (II)



Signals and data acquisition (III)

The previous diagram includes, together with data conversion (analog-to-digital and digital-to-analog), conditioning and filtering functionalities.

Conditioning and filtering have the following purposes:

- signal scaling
- electrical isolation
- impedance matching
- signal conversion (from current to voltage and vice versa)
- noise and antialiasing filtering

There are other issues that must be taken into account in the design of the data acquisition system:

- ground connection
- single-ended/differential signaling
- cable shielding
- etc.

Ground connection

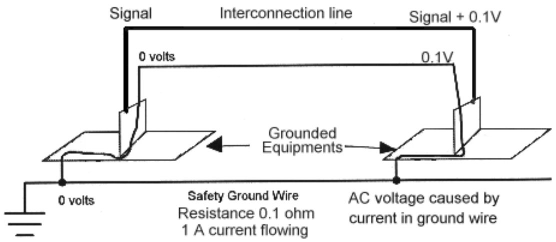
Let’s first clarify the difference between signal ground and earth ground.

Voltage is a differential quantity, to measure the voltage of a single point a reference point must be selected. This common reference point is called signal ground and is considered to have zero voltage.

Signal grounds are usually connected to the earth ground for safety reasons, and to set a constant potential reference against which other potentials can be measured.

In industrial plants, where sensors and actuators can be far from data acquisition racks, we have:

- sensor and actuator signal grounds
- acquisition system signal grounds



Each set of signal grounds is locally connected to an earth ground, but the Earth surface is not perfectly equipotential. Signal grounds are connected together through earth ground, generating a ground loop in which ground currents can flow.

Coupling and cable shielding (I)

Coupling is the desirable or undesirable transfer of electrical energy from one circuit segment to another.

We will consider three different couplings that can generate noise on a signal:

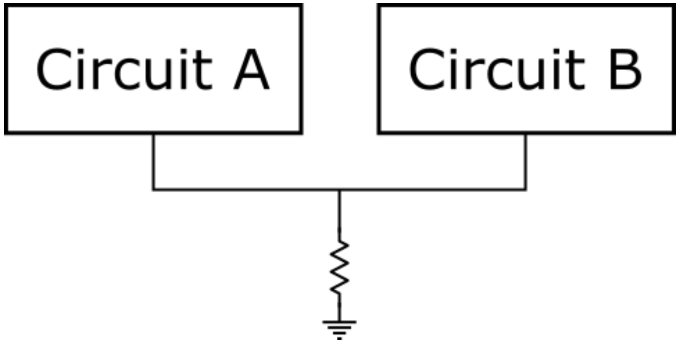
- conductive coupling
- capacitive coupling
- inductive coupling

Coupling and cable shielding (II)

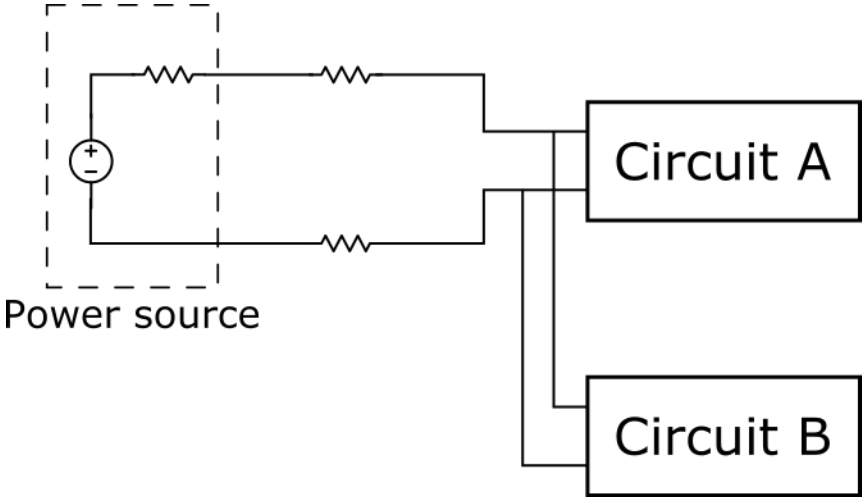
Conductive coupling is the transfer of electrical energy by means of physical contact via a conductive medium, in contrast to inductive coupling and capacitive coupling.

Let’s consider two examples.

The two circuits share the same line to ground. The potential of Circuit A (B) with respect to ground is related to the amount of current flowing from Circuit B (A) to ground.



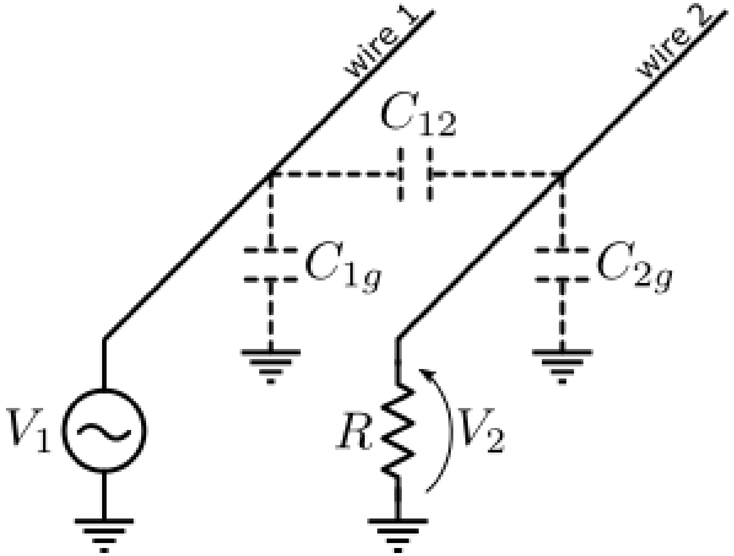
Circuit A and B share the same power source. Current drawn by Circuit A (B) affects the power source voltage of Circuit B (A).



Coupling and cable shielding (III)

Capacitive coupling is the transfer of energy within an electrical network by means of the capacitance between circuit nodes.

Let's consider two wires next to each other. We can have a parasitic capacitive coupling (C_{12}) between the two wires, and a parasitic capacitive coupling (C_{1g} and C_{2g}) between each wire and ground.



The voltage induced by the parasitic capacitive coupling on the resistor, considering only the effect of C_{12}, is given by

$$V_2(s) = \frac{sRC_{12}}{1+sRC_{12}} V_1(s)$$

and considering that $|1/sC_{12}| \gg R$

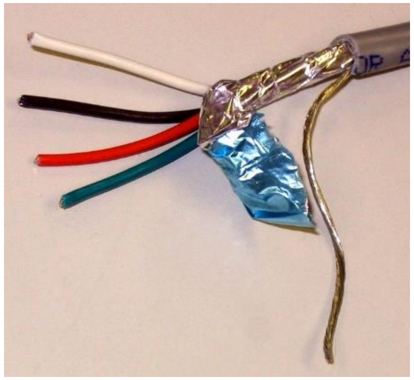
$$V_2(s) = sRC_{12}V_1(s)$$

Taking into account the parasitic coupling towards ground as well, the relation is no more an ideal derivative action.

Coupling and cable shielding (IV)

Noise generated by capacitive coupling is thus proportional to

- amplitude and frequency of the signal generating noise (V_1)
- parasitic capacitive coupling

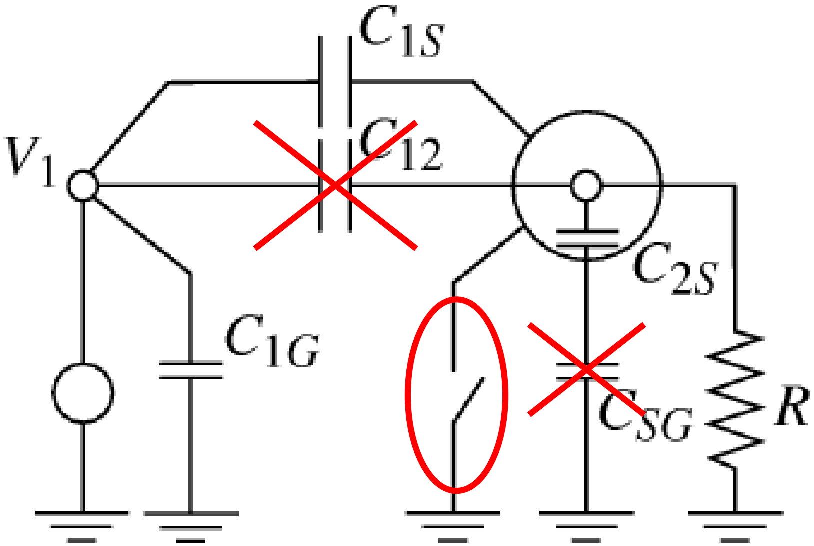


Noise can be thus reduced decreasing the parasitic capacity between wires, i.e.

- increasing the distance between wires or changing wires positioning
- using cable shielding

Shield acts as a Faraday cage reducing electrical noise affecting the signal (minimizing the capacitive coupling), and electromagnetic radiation that may interfere with other devices.

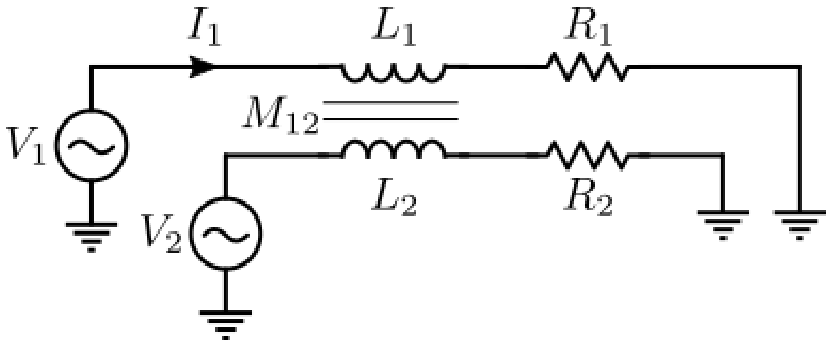
Shield should be grounded at one end only in order to prevent current loops in the shield.



Coupling and cable shielding (V)

Two conductors are referred to as mutual-inductively coupled when they are configured such that change in current through one wire induces a voltage across the ends of the other wire through electromagnetic induction.

The amount of inductive coupling between two wires is measured by their mutual inductance.



Let's consider an example with two parallel wires.
Current I_1 flowing in the first wire generates a magnetic field proportional to its amplitude.
The second wire is subject to a magnetic flux $\Phi_{12} = M_{12} I_1$ that is proportional to the mutual inductance between the wires.

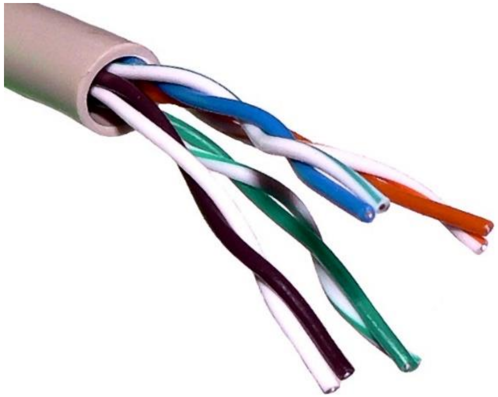
If the magnetic flux changes with time, it induces an undesired electromotive force $V_2 = -M_{12} \dot{I}_1$.

High frequency PWM motor currents are typical source of this kind of noise.

Coupling and cable shielding (VI)

Inductive coupling can be thus reduced

- increasing the distance between wires or changing wires positioning in order to minimize the area they enclose
- using twisted pairs

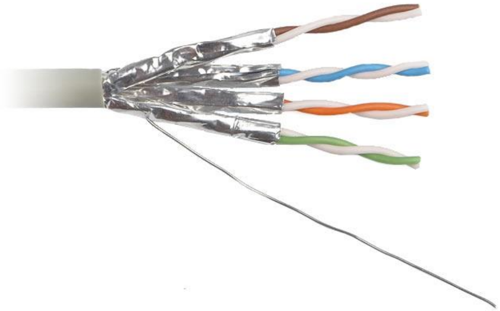


In a twisted pair the area enclosed by the two wires is minimized with respect to a pair of parallel wires.

The total noise voltage for each period of the twisted pair induce by a magnetic field is zero.

In conclusion, the cables used in a plant to connect sensors and actuators to the control system are:

- shielded cables
- twisted pairs
- shielded twisted pairs



Signal scaling (I)

Scaling is used to match the voltage level of a sensor to the voltage level of the analog-to-digital converter (analyzing the A/D and D/A components we will better explain the reason why we need to match these voltage levels).

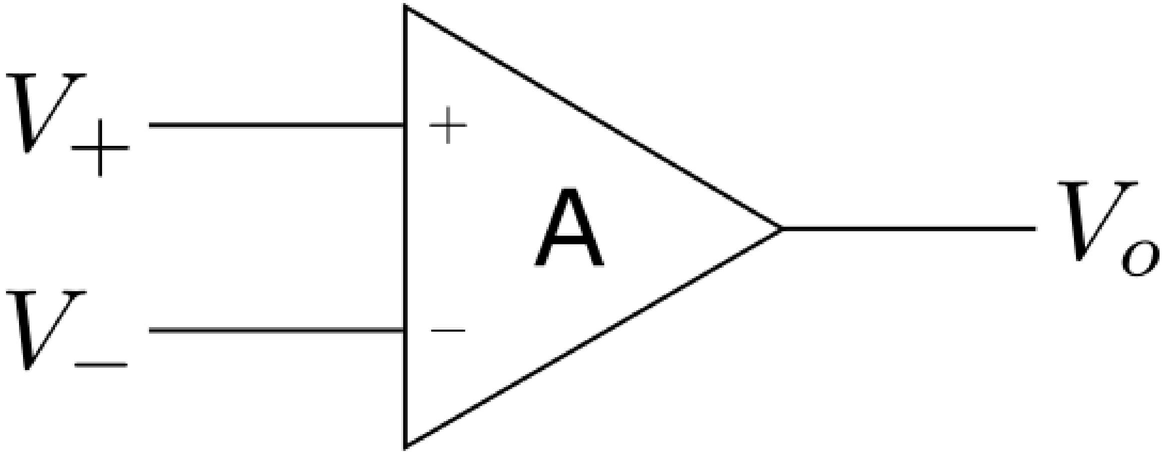
We will consider three different types of amplifiers:

- operational amplifiers
- instrumentation amplifiers
- isolation amplifiers

Let’s start introducing the model of the ideal operational amplifier.

Signal scaling (II)

An ideal operational amplifier is represented by the following symbol



and is characterized the following properties:

- positive and negative terminals have an infinite input impedance
- $V_o = A(V_+ - V_-)$
- the differential gain A is infinite

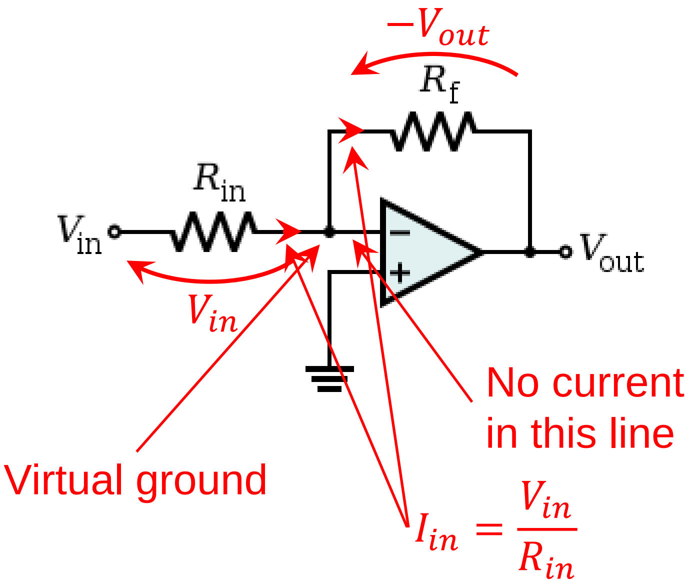
as a consequence

- inputs draw no current
- to have a finite output voltage the operational amplifier should be part of a negative feedback circuit ensuring that $V_+ - V_- \approx 0$

Signal scaling (III)

Let’s consider standard op amp configurations:

- inverting amplifier



$-V_{out}$

V_{in}

Virtual ground

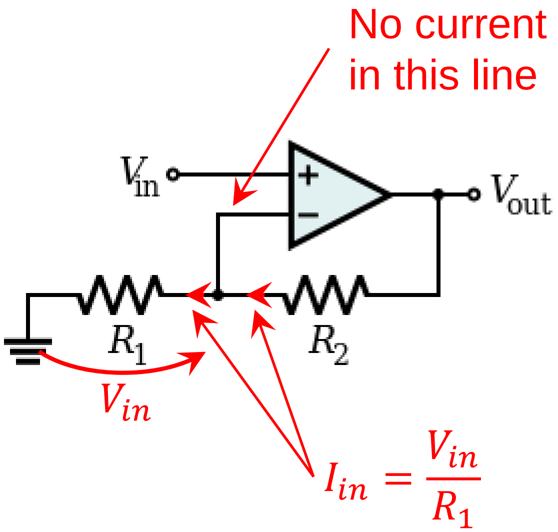
No current in this line

$I_{in} = \frac{V_{in}}{R_{in}}$

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

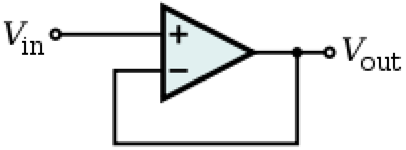
Signal scaling (IV)

- non-inverting amplifier



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

- voltage follower

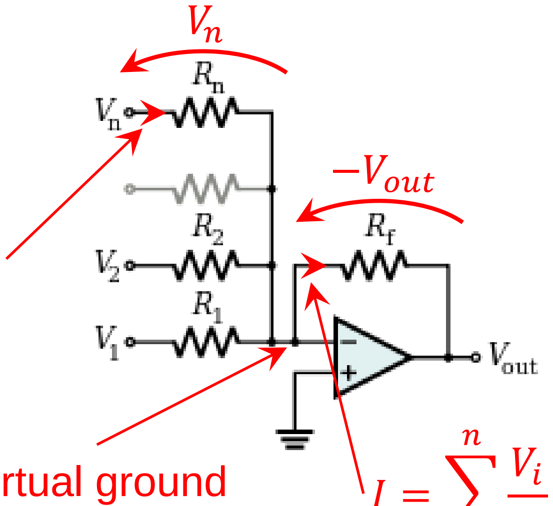


assuming $R_2 = 0$ and $R_1 \rightarrow +\infty$

$$V_{out} = V_{in}$$

Signal scaling (IV)

- summing amplifier



$I_n = \frac{V_n}{R_n}$

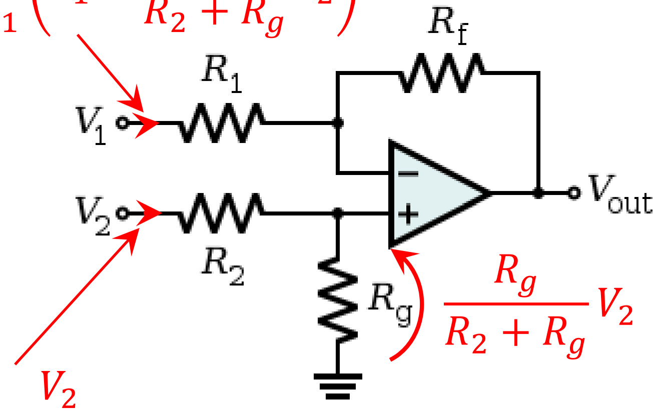
Virtual ground

$I = \sum_{i=1}^{n} \frac{V_i}{R_i}$

$$V_{out} = -R_f \sum_{i=1}^{n} \frac{V_i}{R_i}$$

- differential amplifier

$I_1 = \frac{1}{R_1}\left(V_1 - \frac{R_g}{R_2 + R_g} V_2\right)$



$\frac{R_g}{R_2 + R_g} V_2$

$I_2 = \frac{V_2}{R_2 + R_g}$

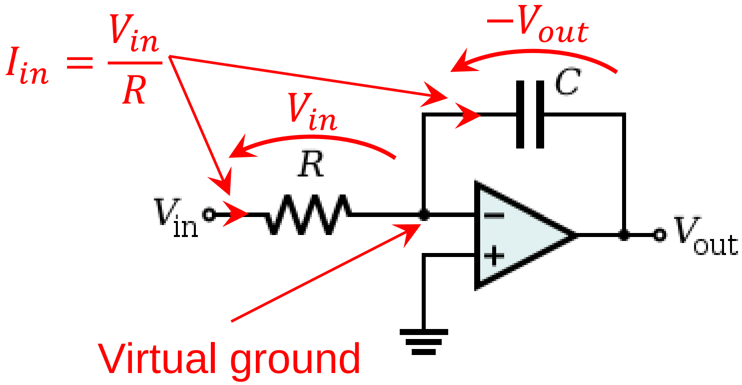
$$V_{out} = \frac{\left(R_f + R_1\right) R_g}{\left(R_g + R_2\right) R_1} V_2 - \frac{R_f}{R_1} V_1$$

and assuming $R_f = R_g$ and $R_2 = R_1$

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

Signal scaling (V)

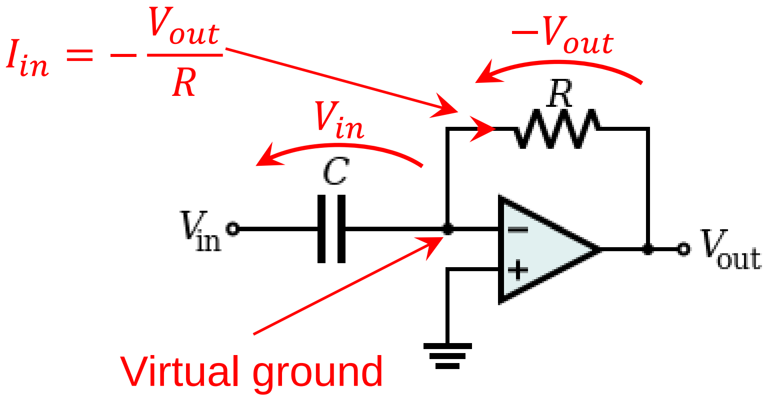
- inverting integrator



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

$$V_{out}(t) = V_{out}(t_0) - \frac{1}{RC}\int_{t_0}^{t} V_{in}(t)dt$$

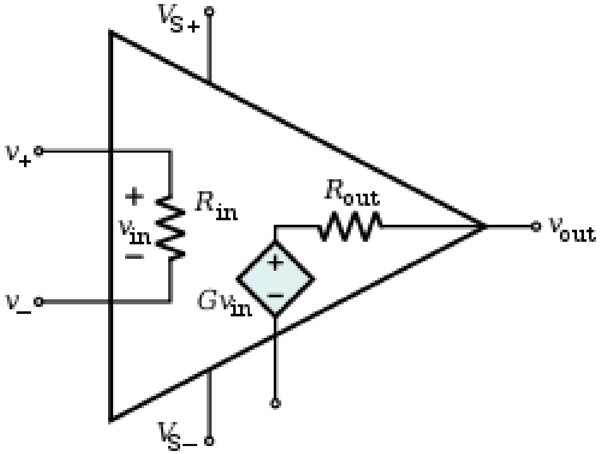
- inverting differentiator



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

Signal scaling (VI)

A simplified equivalent circuit of an operational amplifier is given by



This model shows that a real op amp suffers from several non-ideal effects:

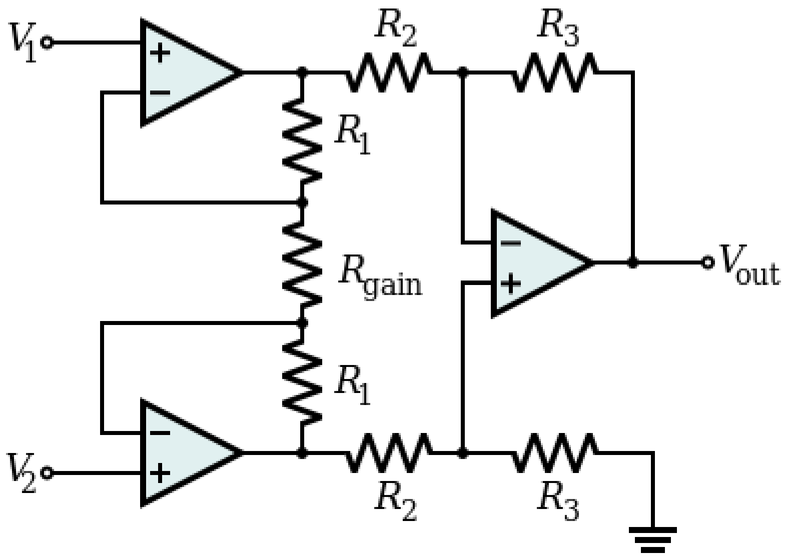
- finite input impedance, i.e., the input current is thus greater than zero
- finite open-loop gain
- non-zero output impedance
- limited voltage range available at the output
- …

Signal scaling (VII)

A very common differential amplifier is the Instrumentation Amplifier.

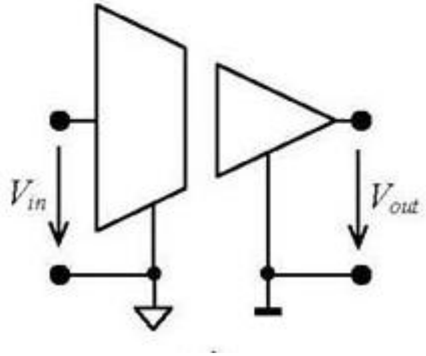
It has the following characteristics:

- the gain can be changed by the user changing a resistor
- very high input impedance
- low output impedance
- linear behavior in a wide operational range
- stable gain
- …



Signal scaling (VIII)

The Isolation Amplifier is an Instrumentation Amplifier providing electrical isolation between input and output, and power supply and output.



The electrical isolation ensures an impedance greater than $100\ M\Omega$, for continuous and low-frequency currents ($50\ Hz$ and multiples), among the two circuits.

The iso amp can be used for one of the following reasons:

- safety, to protect a circuit or a person (i.e., in biomedical devices) from high voltages
- measurement of small signals in the presence of a high common mode voltage

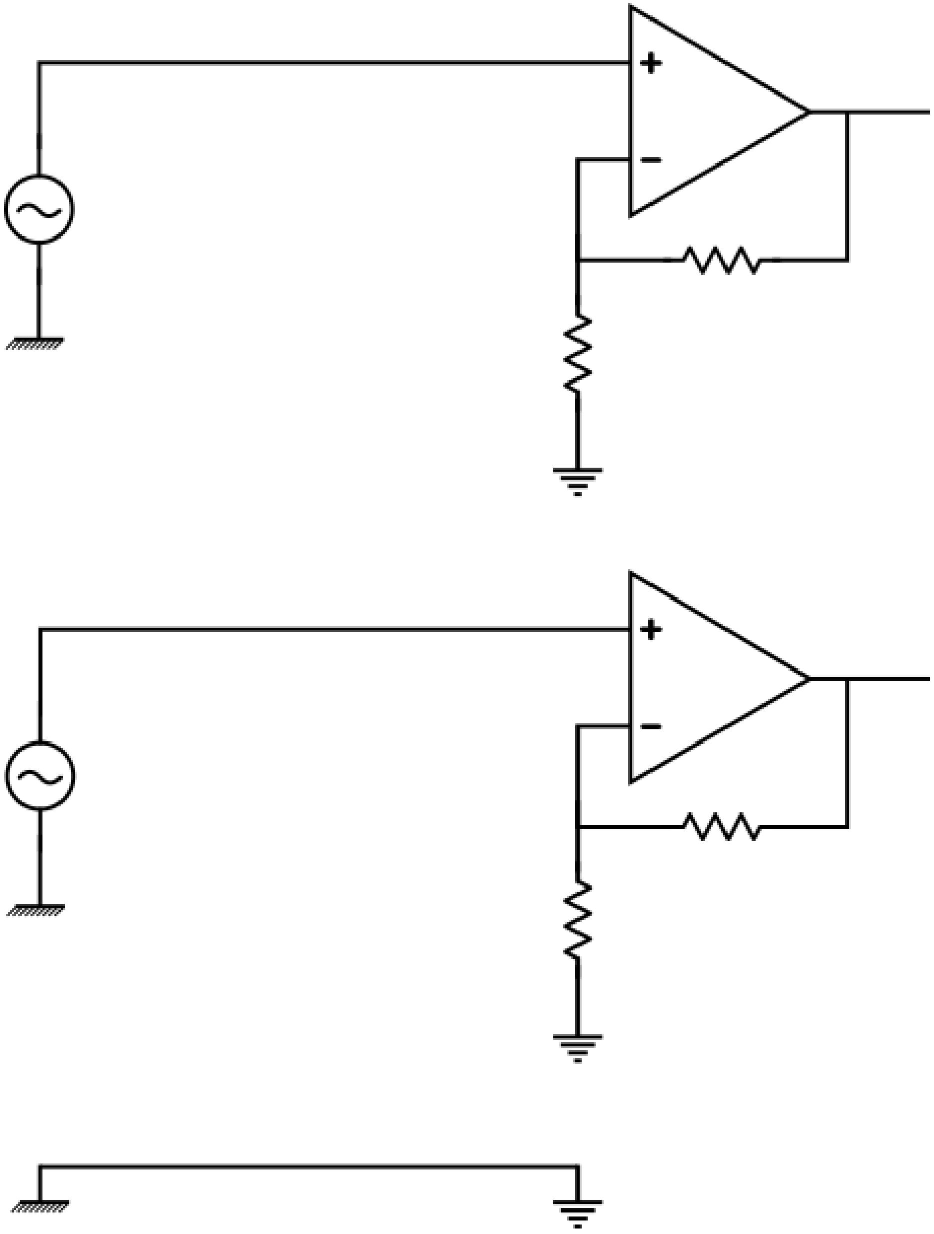
There are different methods of providing the electrical isolation:

- transformer coupling
- LED optocoupler
- …

Single-ended and differential signaling (I)

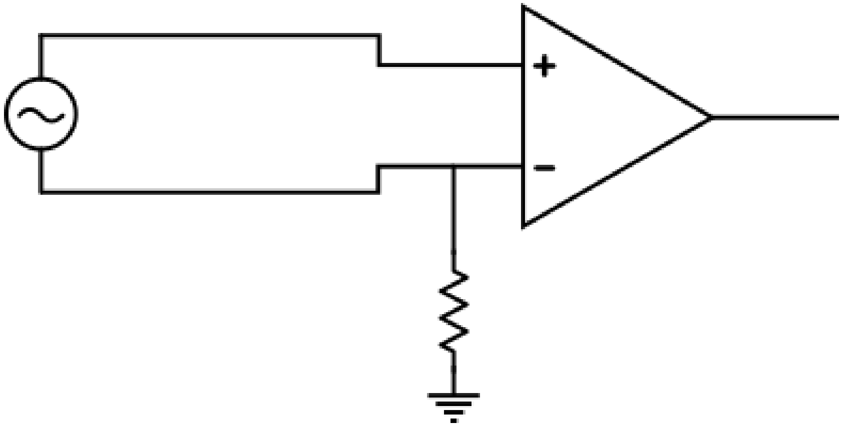
A sensor can transmit electrical signals over wires using two different configurations:

- <u>single-ended signaling</u>
  - is the simplest and most commonly used method of transmitting electrical signals
  - one wire carries a varying voltage that represents the signal, while the other wire is connected to a reference voltage, usually ground
  - if there are n signals, then there are $n+1$ wires, one for each signal and one for ground

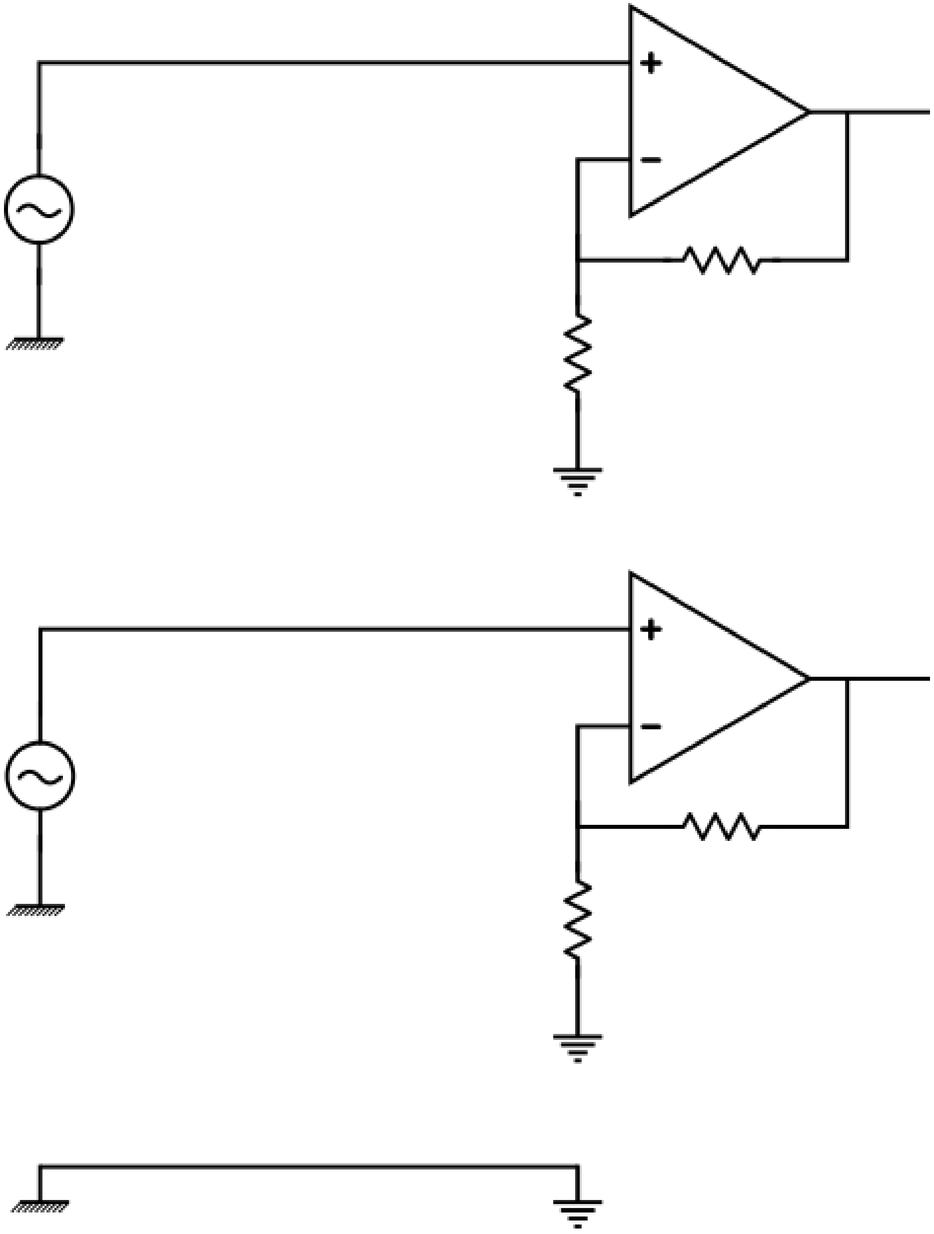


Single-ended and differential signaling (II)

- <u>differential signaling</u>
  - is a method for electrically transmitting information using two complementary signals
  - the technique sends the signal as a *differential pair* of signals, each in its own conductor
  - the receiving circuit responds to the electrical difference between the two signals
  - if there are n signals, then there are $2n$ wires

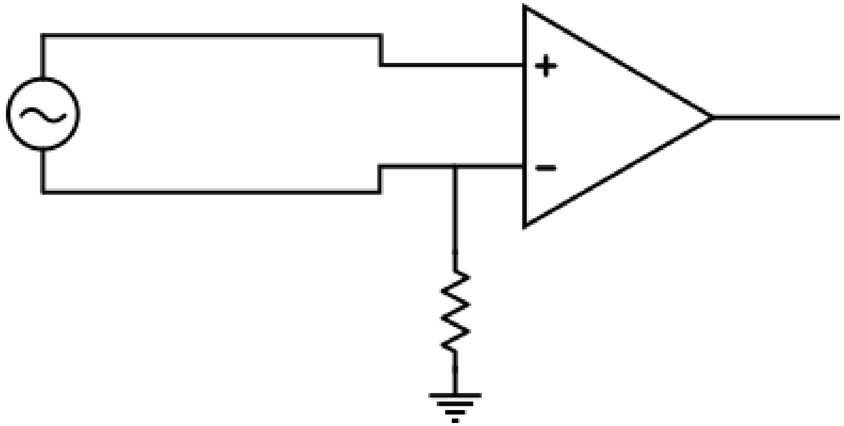


Single-ended and differential signaling (III)



- single-ended signaling is less expensive to implement than differential
- it is subjected to differences in ground voltage level between transmitting and receiving circuits
- and to noise generated by induction picked up on the signal wire
- the return currents for all the signals share the same conductor causing interference between the signals

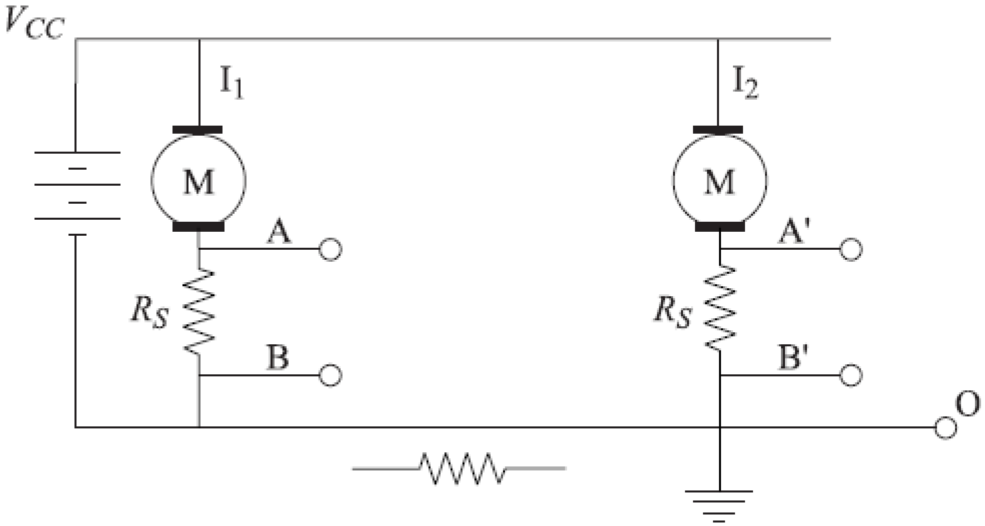
Single-ended and differential signaling (IV)



- differential signaling is more expensive, 2 wires are needed for each signal
- external electromagnetic interference tends to affect both conductors identically
- the technique resists electromagnetic noise compared to one conductor with an un-paired reference (ground)

Single-ended and differential signaling – Example

We would like to measure the current flowing in the two motors measuring the voltage across the resistors R_s.



We can use:

- a differential measurement (V_{AB} and $V_{A'B'}$)
- a single-ended measurement (V_{AO}, $V_{A'O}$)

If we have a non-ideal grounding (the impedance of the wire cannot be neglected), voltage V_{AO} is affected by current I_1 flowing in R_S and by current I_2 flowing to the power source.

The single-ended measurement is thus affected by an error that depends on the amount of current I_2 and on the wire impedance.

Standard signals

Information from sensors to the control unit is transmitted using current and voltage signals.

The most common current signal standard is the 4 to 20 milliamp loop, with 4 milliamp representing 0 percent of measurement, 20 milliamp representing 100 percent.
A simple $250\ \Omega$ precision resistor connected in series with the circuit converts a $4-20\ mA$ signal to a $1-5\ V$ signal.

Representing 0 percent of measurement with $4\ mA$ allows to

- supply energy to the receiver
- distinguish the transmission of 0 percent from a circuit fault condition (live zero)

One common voltage signal standard is $0-10\ V$, meaning that a signal of 0 volt represents 0 percent of measurement, 10 volt represents 100 percent of measurement. Other common voltage ranges are $0-5\ V$, $0-10\ V$, $-10-10\ V$.

The transmission distance, however, is reduced due to voltage drops.

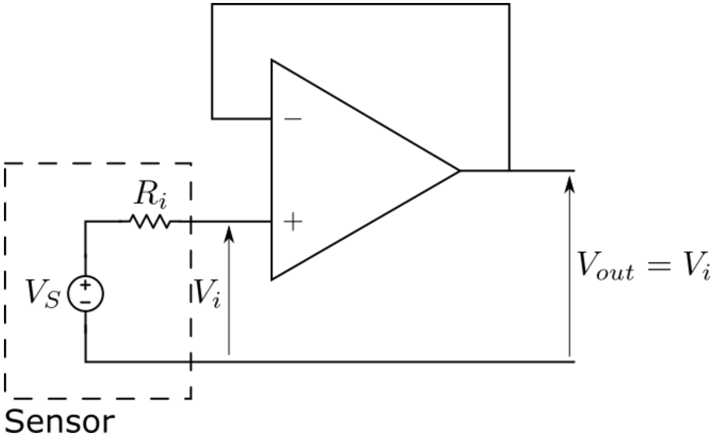
Impedance matching

Considering that a sensor can be represented as a real voltage source, the measurement circuit should have an high input impedance.

Otherwise, the current drawn by the measurement circuit generates a voltage drop across the voltage source internal resistance, causing an error in the measured voltage.

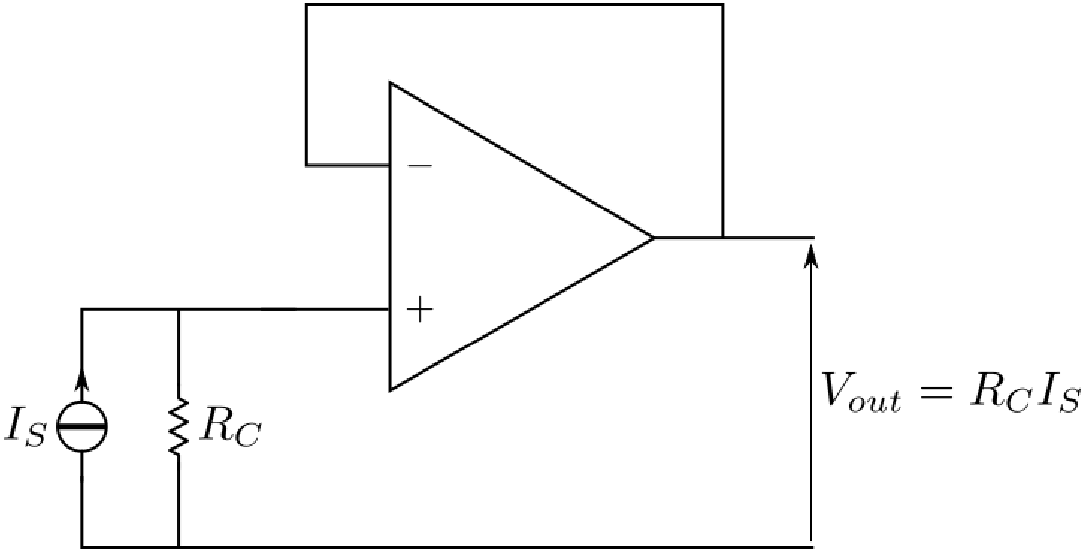
On the other hand, the measurement circuit should have a low output impedance, so that it allows the conversion circuit to sink in all the required current without changing its output.

These two characteristics are usually called impedance matching, and can be achieved using a voltage follower.



Current to voltage conversion

To convert current signals ($4 - 20\ mA$) into voltage signals ($0 - 5\ V$) one can introduce a resistor and read the voltage across it using a voltage follower.



Selecting $R_C = 250\ \Omega$, with a current signal I_S $4 - 20\ mA$ we obtain an output voltage of $1 - 5\ V$.

Different circuits should be used for lower currents.

Filtering (I)

Analog filters can be used to reduce the effect of noise or as antialiasing filters.

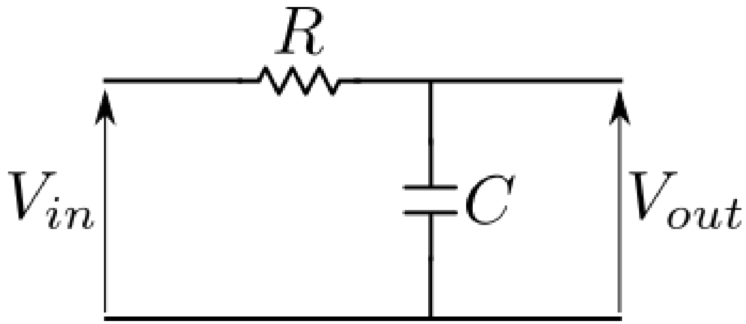
We can consider two different kinds of filters:

- passive filters, are based on combinations of resistors, inductors and capacitors. They do not depend upon an external power supply and/or they do not include active components such as transistors.
- active filters, are implemented using a combination of passive and active (amplifying) components, and require an external power source.

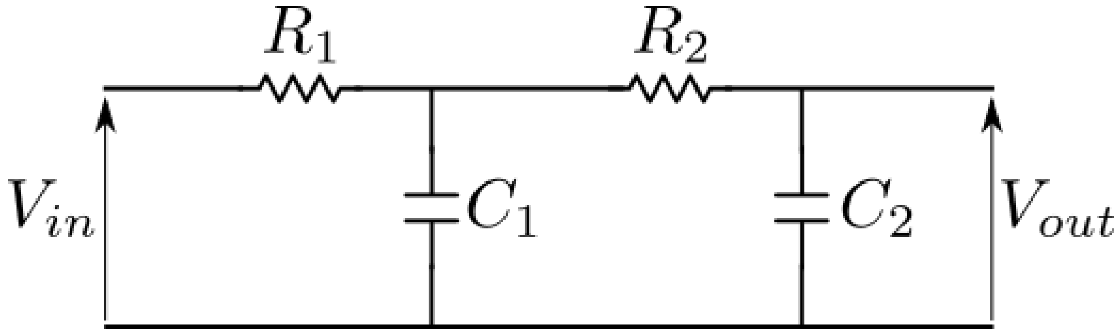
We will now introduce some examples of passive and active filters.

Filtering (II)

We start considering first order and second order passive filters for single-ended signals.



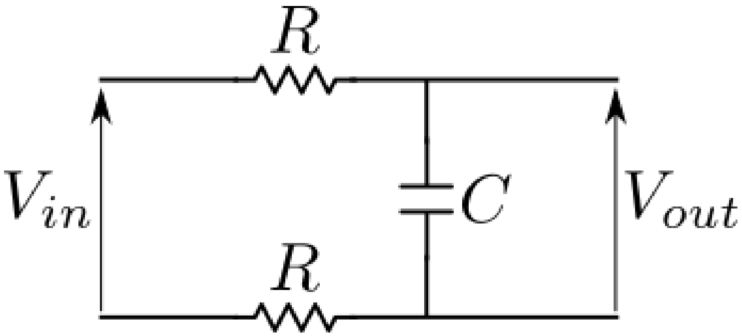
First order filter



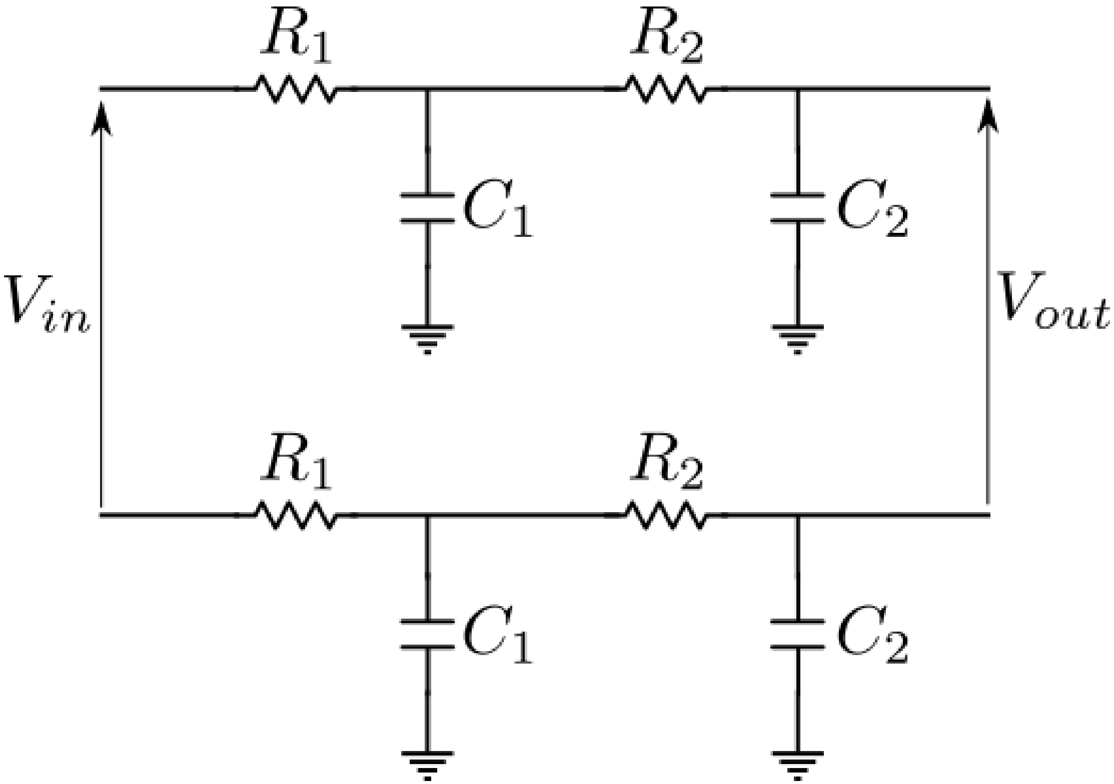
Second order filter

Filtering (III)

And first order and second order passive filters for <u>differential signals</u>.



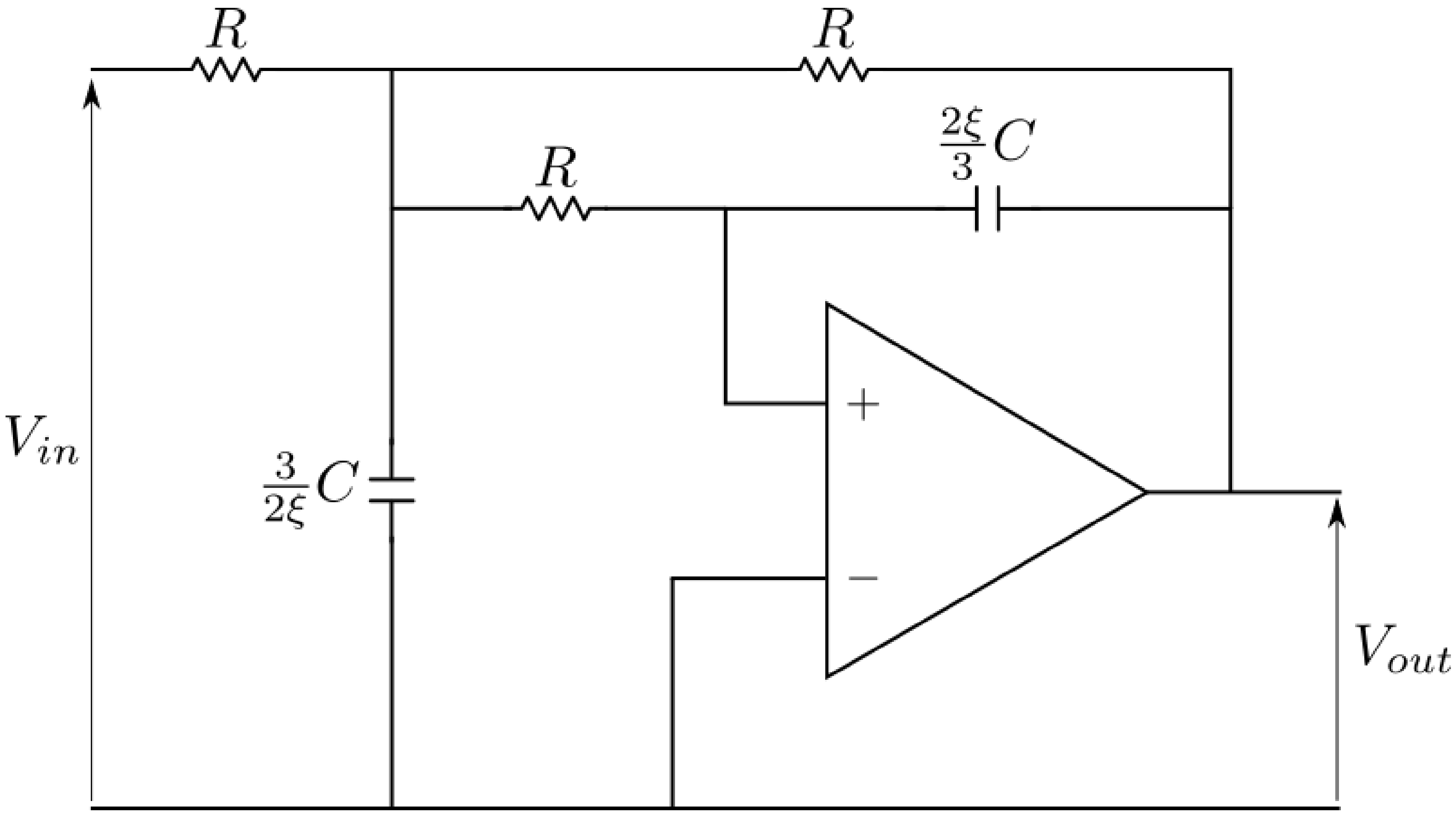
First order filter



Second order filter

Filtering (IV)

Finally an example of an active second order filter.

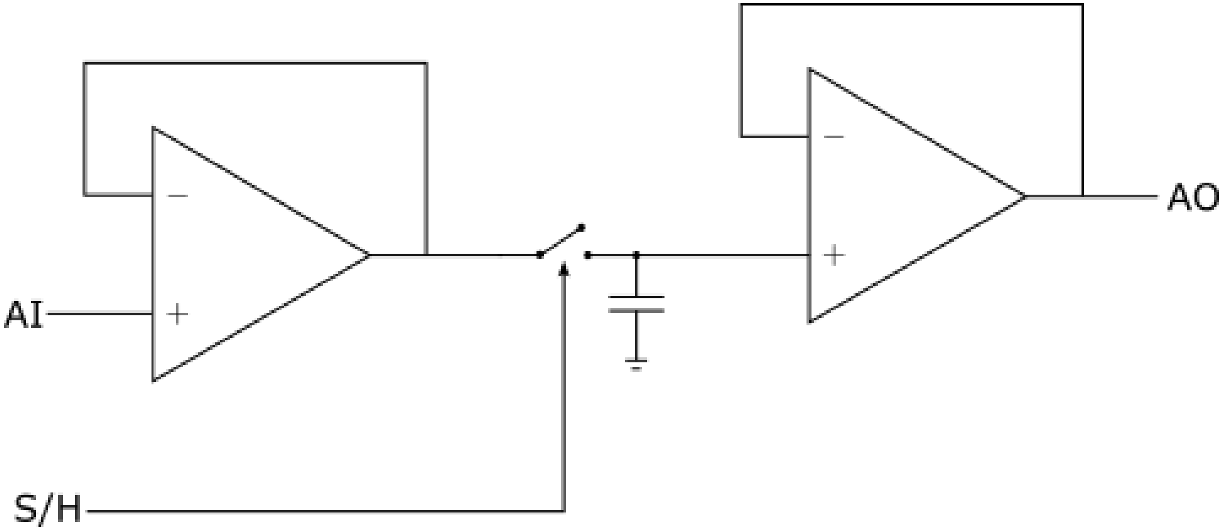


$$G_f(s) = \frac{\omega_f^2}{s^2 + 2\xi\omega_f s + \omega_f^2} \qquad \omega_f = \frac{1}{RC}$$

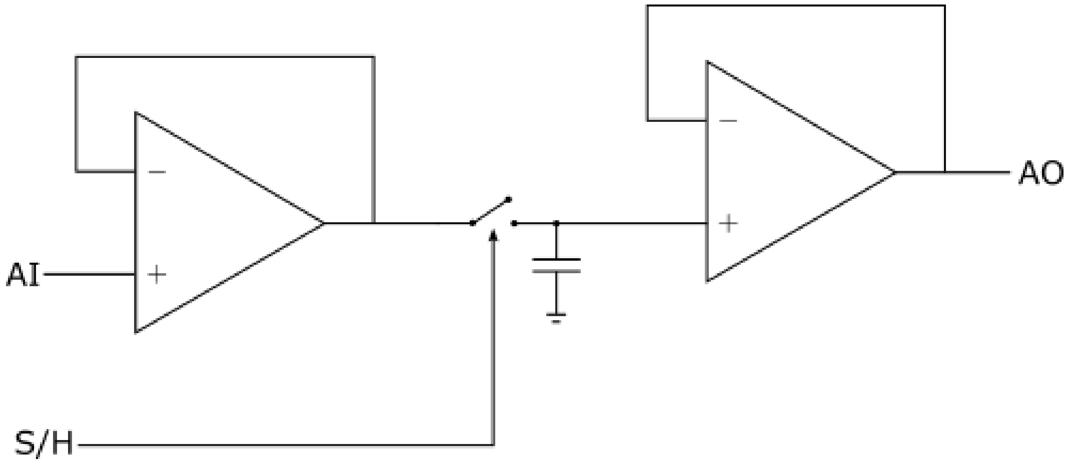
Analog-to-digital conversion (I)

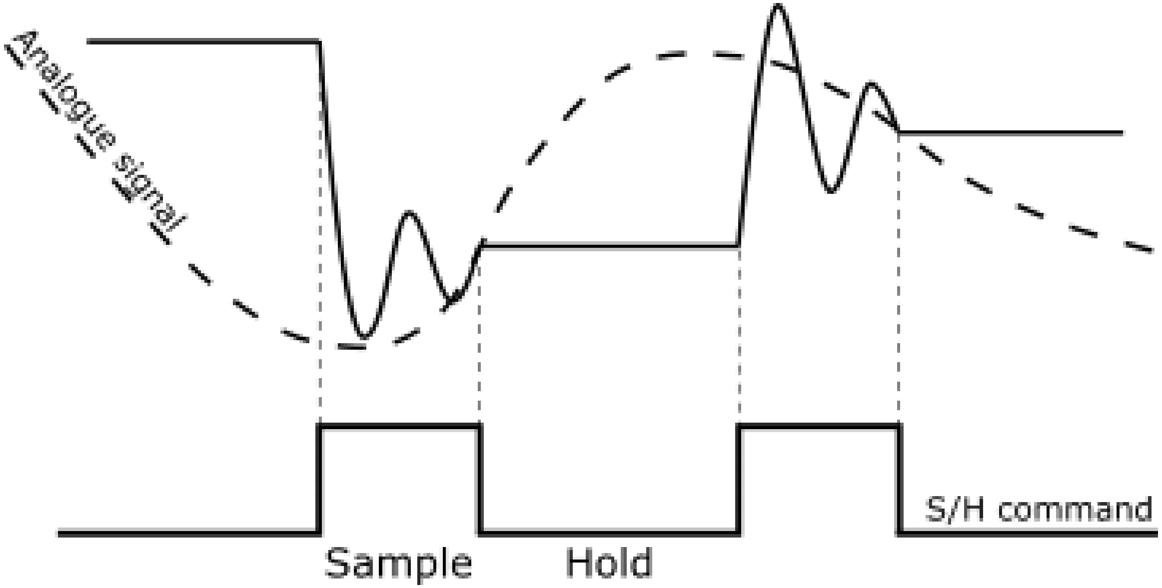
We already know what an A/D is, but we are now interested in examining some technological issues related to the analog-to-digital conversion.

First of all, many converters need the input signal to be constant during the conversion interval. For this reason, sample and hold circuits are used to sample the voltage of a continuously varying analog signal and hold its value at a constant level for a specified minimum period of time.



Analog-to-digital conversion (II)





Analog-to-digital conversion (III)

When is the sample and hold required?

Assume that Δt_a is the time required by the analog-to-digital converter to perform a conversion, and

$$V(t) = A \sin(\omega t)$$

is the analog signal we would like to convert.

The maximum variation of the analog signal in the conversion interval is

$$\Delta V = \Delta t_a \frac{\mathrm{d}}{\mathrm{d}t} \left(A \sin(\omega t)\right)\Big|_{t=0} = \Delta t_a A \omega$$

In the absence of a sample and hold circuit this gives rise to the following percentage error

$$\varepsilon = \frac{\Delta V}{2A} = \frac{\Delta t_a \omega}{2} = \pi f \Delta t_a$$

Depending on the accuracy required by the application this error can be acceptable or a sample and hold is required.

Analog-to-digital conversion (IV)

An n bit analog-to-digital converter converts each sample of the analog signal into an n bit digital binary number (2^n levels). This process is called quantization.

Assuming that V_{FSR} is the converter full scale voltage range, each level corresponds to a voltage $V_{FSR}/2^n$.

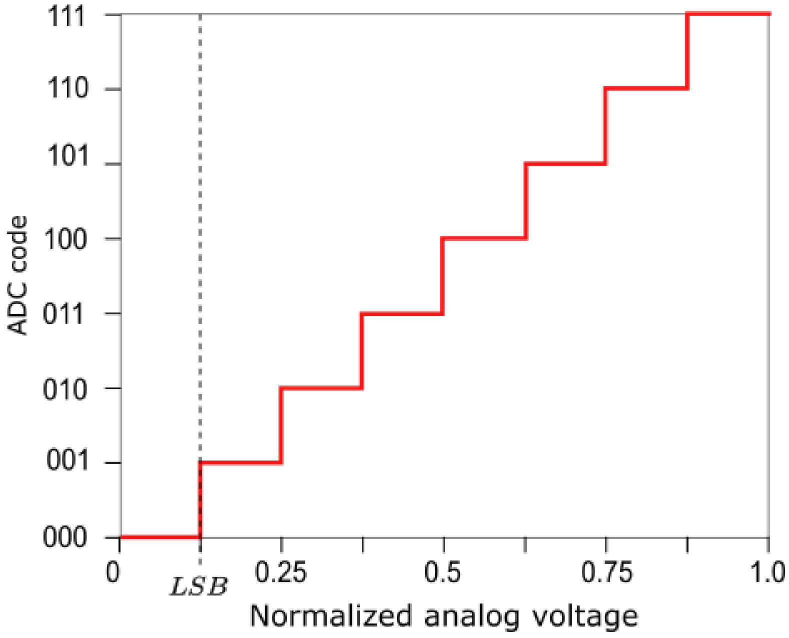
Each digital number is the binary conversion of the integer part of the ratio between the analog voltage V_x and the voltage range V_{FSR}.

Given two analog voltages V_{x_1} and V_{x_2} with

$$|V_{x_1} - V_{x_2}| < \frac{V_{FSR}}{2^n}$$

they are converted into the same digital number.

The analog-to-digital conversion entails an error, called quantization error, equal to $V_{FSR}/2^n$.



Analog-to-digital conversion (V)

How to select the number of bits of the analog-to-digital converter?

Assuming that we would like to have a resolution $\bar{V}$ in volt, i.e., the minimum voltage the converter can distinguish is equal to $\bar{V}$, the following inequality should hold

$$\frac{V_{FSR}}{2^n} < \bar{V}$$

and thus

$$2^n > \frac{V_{FSR}}{\bar{V}} \quad \Rightarrow \quad n > \log_2\left(\frac{V_{FSR}}{\bar{V}}\right)$$

Analog-to-digital conversion (VI)

We can now consider again the question “when is the sample and hold required?”

It is reasonable to assume that the maximum percentage error obtained in the absence of the sample and hold is less than the normalized quantization error, i.e.

$$\pi f \Delta t_a \leq \frac{1}{2^n}$$

Let’s consider the following examples:

- $n = 10$ and $f = 1\ kHz$, then $\Delta t_a \leq 311\ ns$
- $n = 8$ and $\Delta t_a = 150\ \mu s$, then $f \leq 8.29\ Hz$

In the first example the inequality is satisfied only if the A/D converter has a frequency greater than $3.2\ MHz$, a very high frequency.

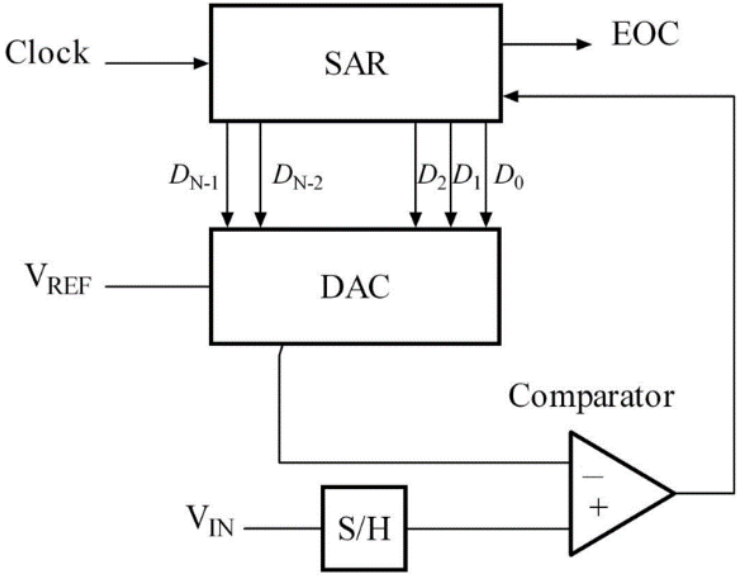
In the second example only for signals with a frequency less than $8.29\ Hz$.

We conclude that, in both cases, a sample and hold circuit is required.

Analog-to-digital conversion (VII)

There are many different ways of implementing an analog-to-digital converter.

We analyze the successive-approximation ADC.



The conversion process works in this way:

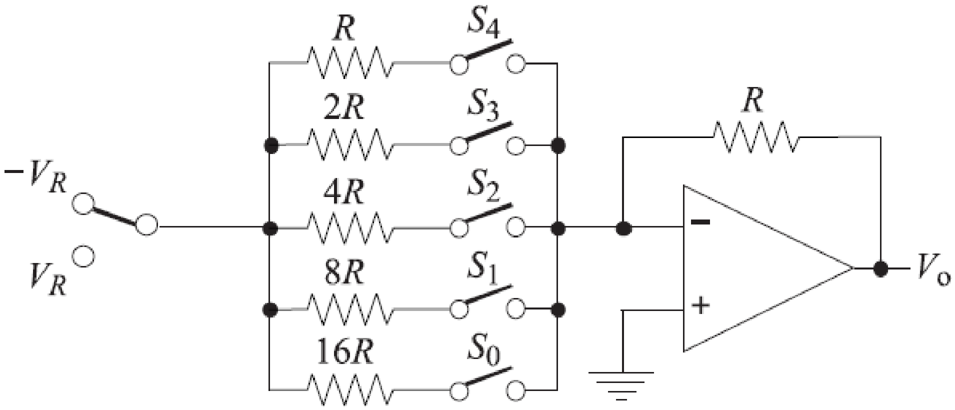
1. the Successive Approximation Register is initialized so that the most significant bit is equal to a digital 1
2. DAC then supplies the analog equivalent of this digital code ($V_{REF}/2$) into the comparator circuit
3. if this voltage exceeds V_{IN} the comparator causes the SAR to reset this bit; otherwise, the bit is left a 1
4. the next bit is set to 1 and the same test is done, continuing this binary search until every bit in the SAR has been tested.

The resulting code is the digital approximation of the sampled input voltage.

Digital-to-analog conversion (I)

A digital-to-analog converter is a component that converts digital data into an analog signal.

As for analog-to-digital converters, there are many different ways of implementing a digital-to-analog converter.



Let’s start analyzing the <u>binary weighted resistor ladder</u> digital-to-analog converter.

Each bit drives a switch, connecting or disconnecting the corresponding resistor. The output of the summing amplifier is given by

$$V_O = \pm V_R \left(S_4 + \frac{S_3}{2} + \frac{S_2}{4} + \frac{S_1}{8} + \frac{S_0}{16} \right)$$

$$= \pm \frac{V_R}{16} \left(2^4 S_4 + 2^3 S_3 + 2^2 S_2 + 2^1 S_1 + 2^0 S_0 \right)$$

Digital-to-analog conversion (II)

Another example of simple digital-to-analog converter is the R–2R resistor ladder network converter.

Each bit drives a switch, connecting the corresponding resistor to ground or to the reference voltage. The output of the amplifier, assuming

$$R_1 = R_2 = R_4 = R_6 = R_7 = 2R$$

$$R_3 = R_5 = R$$

is given by

$$V_O = -\frac{V_R}{24}\frac{R_r}{R}\left(2^2 S_2 + 2^1 S_1 + 2^0 S_0\right)$$