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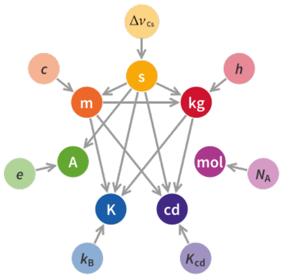
SI UNITS

1



OTHER

The International System of Units is the modern form of the metric system. It is built on seven base units and a set of twenty prefixes to the unit names. Since 2019 all SI units are defined by natural constants.

Base units are length (meter), weight (kilogram), time (second), electric current (ampere), temperature (kelvin), amount of substance (mole) and luminous intensity (candela). The prefixes for factors of a unit include k(ilo) (10^3), M(ega) (10^6), G(iga) (10^9), d(eci) (10^{-1}), c(enti) (10^{-2}) and m(illi) (10^{-3}). Any physical quantity is expressed as a number mulitplied by a unit (with prefix). For example a weight is expressed as 1 kg, meaning One Kilogramm or 1000 grams.

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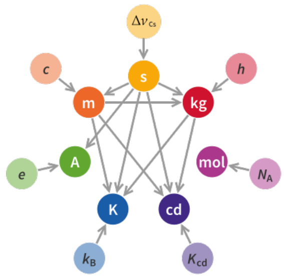
AMPERE

2



OTHER

One ampere corresponds to a flow of 1 coulomb (C) per second through the conductor, with a flow of electrons this is about $6.2 * 10^{18}$ electrons per second.

The Coulomb is defined by the elementary charge $e = 1,602176634 * 10^{-19} As$. One ampere therefore corresponds exactly to a current of $1/1,602176634 * 10^{-19}$ Elementary charges per second.

Dimension name: Electric current
Dimension symbol: I
Size symbol: I
Unit symbol: A

$e = 1,602176634 * 10^{-19}\, C$

$1A = 1\frac{C}{s} = 1,602176634 * 10^{19} * \frac{e}{s}$

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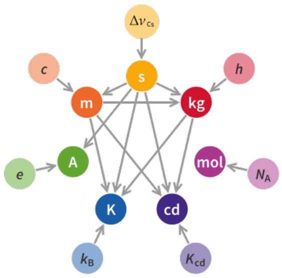
CANDELA

3



OTHER

The SI unit of luminous intensity in a given direction. It is determined by the numerical value of the photometric radiation equivalent for monochromatic radiation of frequency $5.4 * 10^{14}$ Hz(K_{cd}), at 683 when expressed in the unit $\frac{lm}{W}$

It is the luminous intensity, in a given direction, of a source that emits radiation of frequency $5.4 * 10^{14} Hz$ and that has a radiant intensity in that direction of 1/683 watt per steradian (square radian, sr).

Dimension name: Luminous intensity
Dimension symbol: J
Size symbol: I_v
Unit symbol: cd

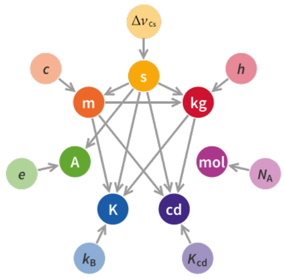
$K_{cd} = 683\frac{lm}{W}$

$1cd = \frac{K_{cd}}{683}\frac{W}{sr} = \frac{K_{cd}}{683}\frac{kg\, m^2}{s^3\, sr}$

▽

KELVIN

4



OTHER

Since 2019, the SI unit Kelvin has been defined by the Boltzmann constant k_B. Until the redefinition the Kelvin was defined by the temperature at the triple point (solid/liquefied/gas) of water. It now depends on three base units ($J = Kg\, m^2\, s^{-2}$).

The freezing and boiling points of water under normal conditions (101.325 kPa) with this definition are (almost exactly) 273.15 K and 373.15 K. The zero point of the Kelvin scale (T = 0 K) is the absolute zero point, which corresponds to -273.15 °C.

Dimension name: Thermodynamic temperature
Dimension symbol: θ
Size symbol: T
Unit symbol: K

$k_B = 1.380649 * 10^{-23}\frac{J}{K}$

$1K = 1.38066 * 10^{-23}\, J$

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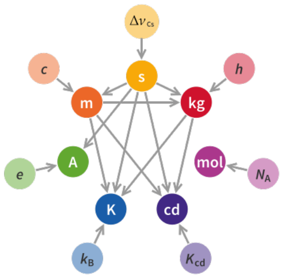
KILO

5



OTHER

From 1889 to 2019, the International Kilogram Prototype (Platinum-Iridium Cylinder) was the reference standard for the Kilogram. Since 20 May 2019, the kilogram has been defined by the numerically determined value of Planck's constants.

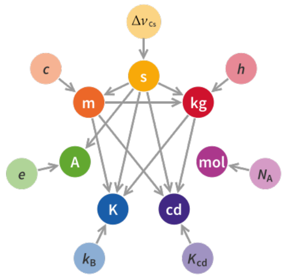
Planck's constant was determined to be
$h = 6.62607015 * 10^{-34} \frac{kg*m^2}{s}$.
Together with the definitions of the units second and meter the kilogram results.

Dimension name: Mass
Dimension symbol: M
Size symbol: m
Unit symbol: kg
$1kg = (\frac{h}{6.62607015*10^{-34}})\frac{s}{m^2}$

▽

METRE

6



OTHER

From 1889 the meter was defined by a prototype meter („Urmeter“) and from 1960 by a special light wavelength. On 20 May 2019, World Metrology Day, a new fundamental revision by the General Conference on Weights and Measures came into force.

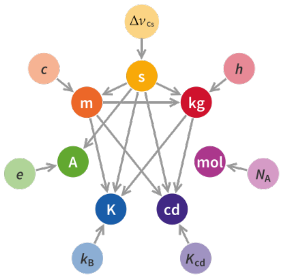
A meter is defined as the length of the distance the light travels in a vacuum for a period of 1/299,792,458 seconds.

Dimension name: Length
Dimension symbol: L
Size symbol: l
Unit symbol: m
$c = \frac{1}{299,792,458}\ m/s$
$1m = \frac{1}{299,792,458}\ s * c$

▽

MOLE

7



OTHER

Since 20 May 2019, the definition has been: A mole of a substance contains exactly $6.02214076 * 10^{23}$(Avogadro constant) particles (atoms, molecules, electrons,...). The mole is thus defined by the Avogadro constant; before it was the other way round.

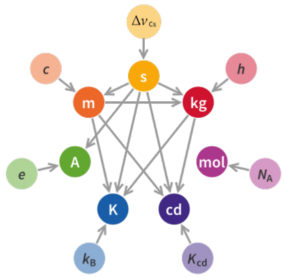
The Avogadro constant N_A is a physical constant which is defined as the number of particles N per quantity of substance n.

Dimension name: Amount of substance
Dimension symbol: N
Size symbol: n
Unit symbol: mol
$N_A = \frac{N}{n} = 6.02214076 * 10^{23} \frac{1}{mol}$
$1mol = \frac{6.02214076*10^{23}}{N_A}$

▽

SECOND

8



OTHER

A second is equal to the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

By definition, the second is a multiple of the period of a microwave resonating with a selected level transition in the caesium atom. Therefore, it is called the atomic second.

Dimension name: Time
Dimension symbol: T
Size symbol: t
Unit symbol: s
$\Delta v_{cs} = 9,192,631,770\,Hz$
$1s = \frac{9,192,631,770}{\Delta v_{cs}}$

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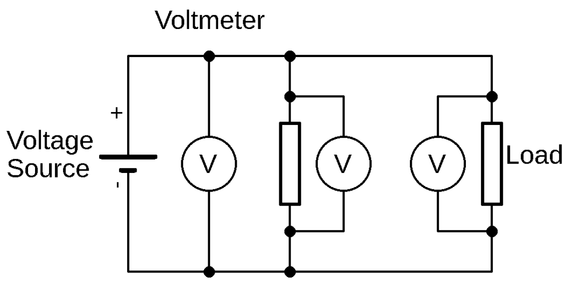
VOLTAGE MEASUREMENT

9



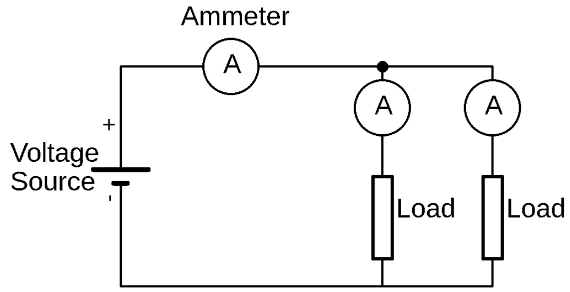
MEASUREMENT

A voltmeter is always connected in parallel to the load. The internal resistance of the voltmeter should be as high as possible. Voltage Dividers are used to change the range. Many digital meters are auto-ranging.

The following instructions must be observed before current measurement:
-The correct type of current must be selected (AC/DC).
-For DC the polarity must be observed.
-The correct measuring range must be set.
-If the load is unknown: set the largest measuring range, slowly switched to the lower measuring range.
These instructions generally only apply to analog measuring instruments. Digital multimeters set these values automatically. They only have to be set to voltage measurement.

CURRENT MEASUREMENT

10



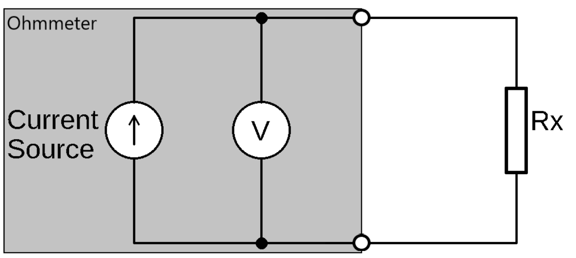
MEASUREMENT

The ammeter is always connected in series to the load. The internal resistance of the meter should be as low as possible. Shunts are used to change the range of DC ammeters. Clamp-on ammeters read only one conductor at a time.

The following instructions must be observed before current measurement:
-The correct type of current must be selected (AC/DC).
-For DC the polarity must be observed.
-The correct measuring range must be set.
-If the load is unknown: set the largest measuring range, slowly switched to the lower measuring range.
-The circuit must be disconnected.
-The ammeter must be connected in series with the current-carrying components.

RESISTANCE MEASUREMENT

11



MEASUREMENT

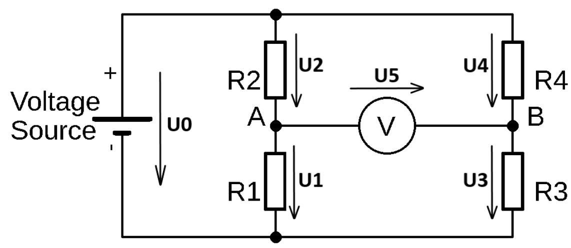
The Ohmmeter is used to meassure resistance. There are analog and digital devices, both measure the resistance over the current. With a digital ohmmeter, a constant current is passed over the resistor and the voltage drop is measured.

The following instructions must be observed before measurement:

Test objects must always be desoldered.
The component to be measured must not be connected to a voltage source during the measurement because the measuring instrument determines the resistance value via voltage and current.
An ohmmeter should always be readjusted to zero when the scale is changed.

WHEATSTONE BRIDGE

12



MEASUREMENT

The Wheatstone bridge is a circuit for measuring electrical resistances (DC resistance) and small ohmic resistance changes. The applications are mainly found in measurement and control technology.

If the ratio of the voltage divider resistances is the same, then both points (A,B) have the same potential(balance condition: $\frac{R1}{R2} = \frac{R3}{R4}$). If a resistance is changed, a current flows from A to B or vice versa.

e.g.: A fixed resistor is replaced by a semiconductor component. The semiconductor reacts to voltage changes, temperature, light or similar. In this way, changes due to a current flow or potential change between points A and B can be used for evaluation.

$U5 = U1 - U3 = U0(\frac{R1}{R1+R2} - \frac{R3}{R3+R4})$

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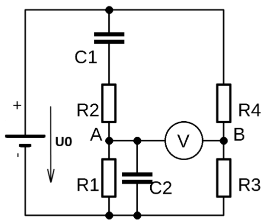
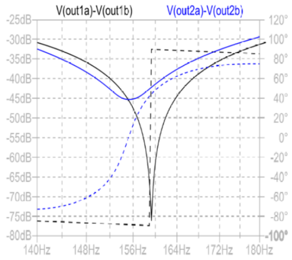
WIEN BRIDGE

13





MEASUREMENT

A Wien bridge is a bridge circuit in which one bridge branch is formed by a bandpass and the other by a 2:1 voltage divider ($B = \frac{1}{3}U_0$). The Wien bridge is used for precision measurement of capacitance in terms of resistance and frequency.

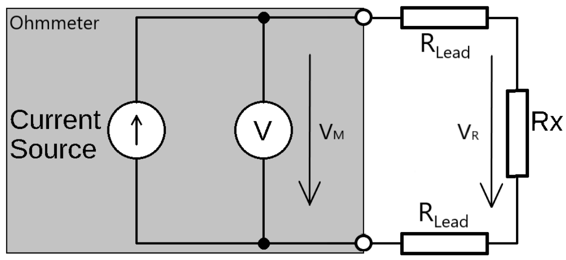
The differential voltage U5 is evaluated, which shows a minimum at the frequency $f = 1/2\pi RC$. There is also a phase shift from $-90°$ to $+90°$.
The picture shows two frequency responses: the sharp curve (black) for ideal components, the flat curve (blue) when R1 is increased by 5 %: Even small tolerances worsen the quality factor.
Balance Condition:
R1 = R2; C1 = C2; R4= 2*R3

$\omega^2 = \frac{1}{R1R2C1C2}$

$\frac{C2}{C1} = \frac{R4}{R3} - \frac{R2}{R1}$

2 WIRE MEASUREMENT

14



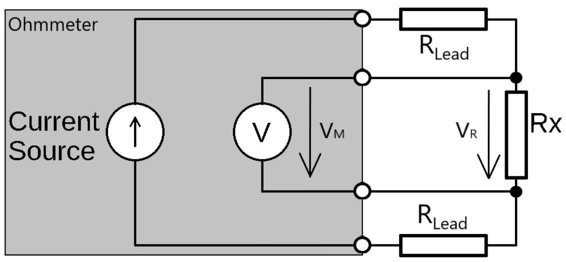
MEASUREMENT

With the 2-wire measurement the line resistance R_{Lead} is also measured, therefore this measuring method for small resistances R_x becomes less accurate. The advantage of this method is the lower effort of the wiring.

This measuring method is used e.g. with all multimeters.
V_M = Voltage meassured by Meter
V_R = Voltage across load R_x
Measured Resistance: $\frac{V_M}{I} = 2 * R_{Lead} + Rx$

4 WIRE MEASUREMENT

15



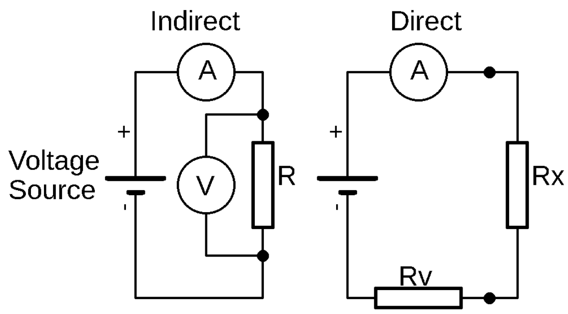
MEASUREMENT

In the 4-wire measuring arrangement, a known electrical current flows through the resistor via two of the wires. The voltage drop at the resistor is measured by a voltmeter with an high input impedance via two further lines.

Four-wire measurement is mainly used for measuring small resistances when the parasitic resistances are no longer negligibly small compared to the resistance to be measured.
Due to the high input resistance of the voltmeter, the line resistance can be neglected.
$R_{Lead} \ll R_V \rightarrow I_{Lead} \gg I_V \rightarrow V_M = V_R$
Measured Resistance: $\frac{V_M}{I} = \frac{V_R}{I}$

IN- /DIRECT MEASUREMENT

16



MEASUREMENT

There are two measuring methods. The indirect measurement is a measurement with subsequent calculation. Direct measurement is the usual measuring method in a measuring instrument, where the value can be read off from the display.

With indirect resistance measurement, the voltage U at the resistance and the current flowing through the resistance must be measured simultaneously. With ohms law R can be calculated.
With direct measurement, the value is determined directly; e.g. the current can be read directly from the pointer of an analog amperemeter.

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ACCURACY VS PRECISION

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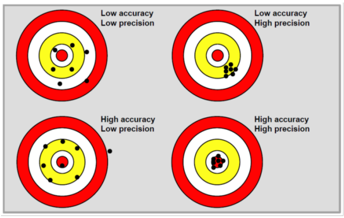
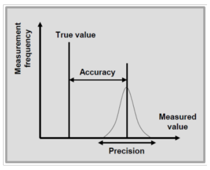




The first of many distributions in this talk!...

STATISTICS

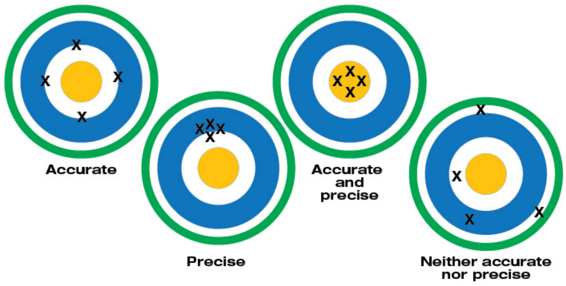
Every measurement is subject to errors. Normally the true value of the measurand is not known. We distinguish two kinds of errors:

- Statistical Errors
- Systematic Errors

Precision describes the consistency of repeated measurements with each other and relates to statistical errors. Accuracy describes the absence of a systematic bias.

ACCURACY, PRECISSION & SUCH

18



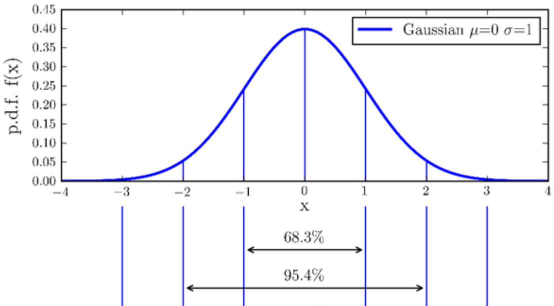
STATISTICS

As all measurements are performed by imperfect devices they show errors. Two of the most common attributes to describe how much error an instrument produces are accuracy and precision.

Accuracy: An instrument's degree of veracity—how close its measurement comes to the actual or reference value of the signal being measured.
Resolution: The smallest increment an instrument can detect and display—hundredths, thousandths, millionths.
Range: The upper and lower limits an instrument can measure a value or signal such as amps, volts and ohms.
Precision: An instrument's degree of repeatability—how reliably it can reproduce the same measurement over and over.

GAUSSIAN (NORMAL) DISTRIBUTION

19



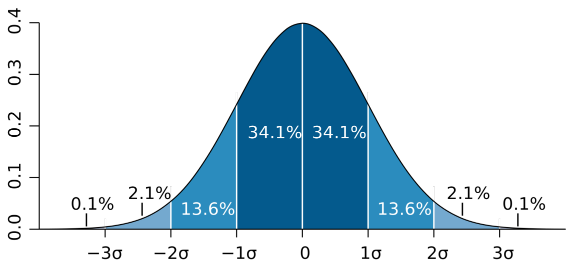
STATISTICS

The probability density function for the Gaussian is $f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$

Central Limit Theorem states that for a sample of N independent Variables x_i that are identically distributed with finite population mean μ and finite standard deviation σ the distribution of the means of these $\bar{x}$ converges to a Gaussian around μ with s.d. $\sigma/\sqrt{N}$ for large N.

STANDARD ERROR

20



STATISTICS

Thus: Standard Error of the Mean: $s_{\bar{x}} \approx \frac{s}{\sqrt{n}}$ where s is the sample s.d. of the means and n the number of means taken.When sampled with an unbiased normally distributed error, the above depicts the proportion of samples that would fall between 0, 1, 2, and 3 standard deviations above and below the actual value

---

The sampling distribution of a population mean is generated by repeated sampling and recording of the means obtained. This forms a distribution of different means, and this distribution has its own mean and variance. Mathematically, the variance of the sampling distribution obtained is equal to the variance of the population divided by the sample size. Picture: By M. W. Toews - Own work, based (in concept) on figure by Jeremy Kemp, on 2005-02-09, CC BY 2.5, https://commons.wikimedia.org /w/index.php?curid=1903871

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BOXPLOT

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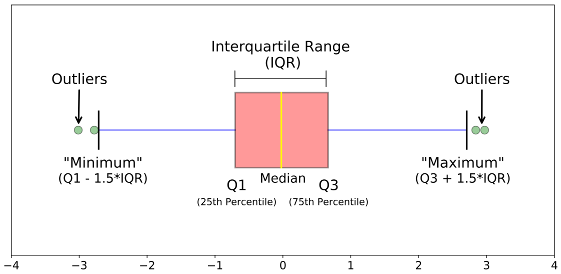


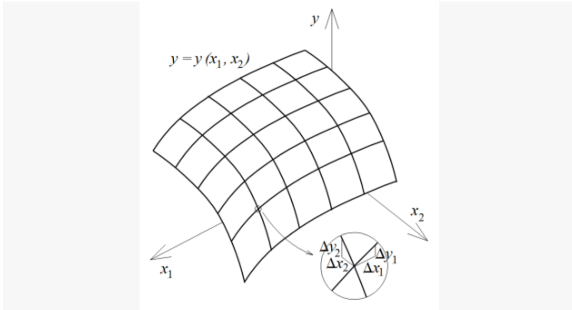
STATISTICS

A boxplot is a convenient figure to capture the essence of a dataset. The box stretches from the 1st quartile to the third quartile, meaning it takes the middle half of all samples. The whiskers extend to 1.5 that distance from the median. Outliers are given separately.

In addition to the box and whiskers it is possible to give the mean and standard error underneath the box. See Krzywinski, Altman, Nature Methods, 2013, 'Visualizing samples with box plots'

ERROR PROPAGATION

22



STATISTICS

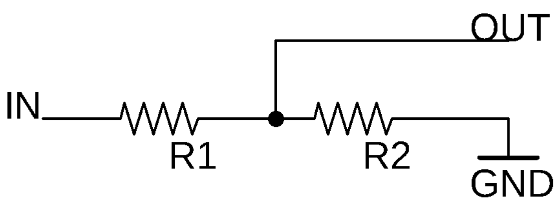
Error propagation means that when a measured value depends on several variables its total error has to be derived from their individual errors. If we measure a current I that is dependent on a Voltage V and a resistance R as $I = V/R$ the we start by calculating the total derivative $dI = \frac{\partial I}{\partial V} dV + \frac{\partial I}{\partial R} dR$

---

dI represents the deviation of individual measurements. $dI = I_i - \bar{I}$. The squared error is $(dI)^2 = (I_i - \bar{I})^2 = (\frac{\partial I}{\partial V} dV)^2 + (\frac{\partial I}{\partial R} dR)^2 + \frac{\partial I}{\partial V} \frac{\partial I}{\partial R} dV dR$. This we can use to calculate absolute errors. For a general error treatment we average over many measurements, whence the mixed term $dV dR$ will average out, and dV^2 and dR^2 will remain. $\langle (I_i - \bar{I}) \rangle = \sigma_I^2 = (\frac{\partial I}{\partial V} dV)^2) + (\frac{\partial I}{\partial R} dR)^2$. The standard deviation is then $\sigma_I = \sqrt{(\frac{\partial I}{\partial V} dV)^2) + (\frac{\partial I}{\partial R} dR)^2}$. In our example $\sigma_I^2 = \sqrt{\frac{1}{R^2} dV + \frac{V^2}{R^4} dR}$ and relative (divide by $I = V/R$) $\frac{\sigma_I}{I} = \sqrt{\frac{dV^2}{V^2} + \frac{dR^2}{R^2}}$

VOLTAGE DIVIDER

23



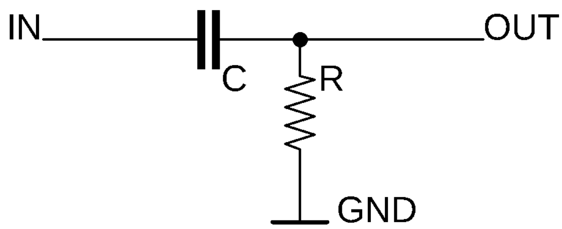
CIRCUIT KNOWOME

A voltage divider produces an output voltage that's a fraction of its input voltage, determined by the two resistors R1 and R2. The output voltage is determined by $V_{out} = V_{in} \frac{R2}{R1+R2}$.

Resistor dividers are often used to generate reference voltages or as level shifters; their high impedance means that attempting to draw significant current from them will cause the voltage to vary.

RC HIGH-PASS FILTER

24



FILTER CIRCUIT

A Resistor-Capacitor Highpass Filter is a simple analog filter that allows high frequencies to pass but attenuates lower frequencies.

An RC highpass filter effectively forms a frequency dependent voltage divider. At low frequencies, the capacitor acts as a very high resistance, so the signal is attenuated a lot. At higher frequencies, the capacitor has less resistance, so the signal is attenuated less. The cutoff frequency of the filter is determined by $F_c = \frac{1}{2\pi * RC}$.

Transfer function: $H(f) = \frac{\omega * RC}{\sqrt{1+(\omega * RC)^2}}$

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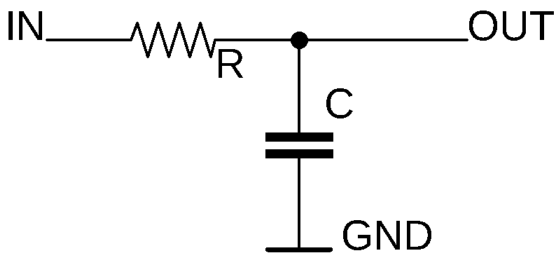
RC LOW-PASS FILTER

25



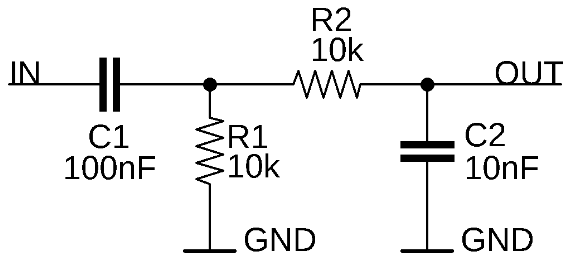
FILTER CIRCUIT

A Resistor-Capacitor Lowpass Filter is a simple analog filter that allows low frequencies to pass but attenuates higher frequencies.

An RC lowpass filter effectively forms a frequency dependent voltage divider. At low frequencies, the capacitor acts as a very high resistance, so the signal is attenuated very little. At higher frequencies, the capacitor has less resistance, so the signal is attenuated more. The cutoff frequency of the filter is determined by $F_c = \frac{1}{2\pi * RC}$.
Transfer function: $H(f) = \frac{1}{\sqrt{1+(\omega * RC)^2}}$

BAND PASS FILTER

26



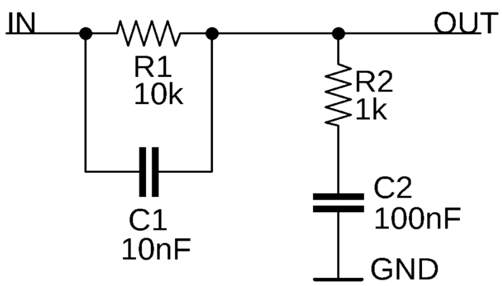
FILTER CIRCUIT

A bandpass is a filter that only allows signals from one frequency band to pass through. The frequency ranges below and above the passband are blocked or significantly attenuated.

The series connection of high pass (HP) and low pass (LP) results in a bandpass if the cutoff frequency of the LP is equal to or greater than that of the HP. The center frequency of the bandpass is also calculated as the geometric mean of the unloaded cutoff frequencies of HP and LP. The mutual loading results in different cutoff frequency values for the bandpass, the geometric mean of which again produces the same center frequency.
LP cutoff: $F_{c1} = \frac{1}{2\pi * RC} = 159Hz$
HP cutoff: $F_{c2} = \frac{1}{2\pi * RC} = 1,592kHz$
BP center frequency: $F_o = \sqrt{F_{c1} * F_{c2}} = 504Hz$

BANDSTOP FILTER / REJECT FILTER

27



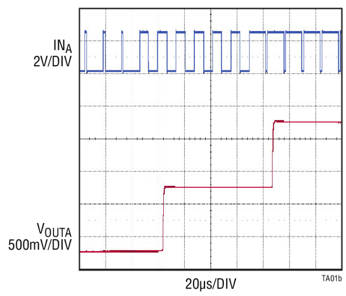
FILTER CIRCUIT

The bandstop is the opposite of a bandpass. It only blocks or attenuates signals from one frequency band. All frequencys above or below pass through.

The parallel connection of high pass (HP) and low pass (LP) leads to a bandstop if the cutoff frequency of the LP is lower than that of the HP. The center frequency of the bandpass is calculated as the geometric mean of the unloaded cutoff frequencies of HP and LP. The mutual loading leads to different cut-off frequency values for the bandpass, whose geometric mean in turn produces the same center frequency.
BS center frequency: $F_o = \sqrt{F_{c1} * F_{c2}} = 1,63kHz$

DAC - PWM

28



CIRCUIT KNOWOME

The pulse width modulation(PWM) is a indirekt method of D/A-convertion. A standard pulse is generated from each period of the input signal. With a downstream RC low-pass filter or better an integrator, this pulse sequence can be averaged.

This creates ripples in the output voltage. The time constant RC must be selected so that the desired D/A accuracy (e.g. +- 1/2 LSB) is maintained. This results in a slow response time at the output of the converter(~90µs) and a settling time (~0.5ms) to charge the capacitance.The largest ripples occur at a duty cycle of 50%.
Advantages: simply to control small DC-motors with it
Disadvantages:slow response, ripples at the output

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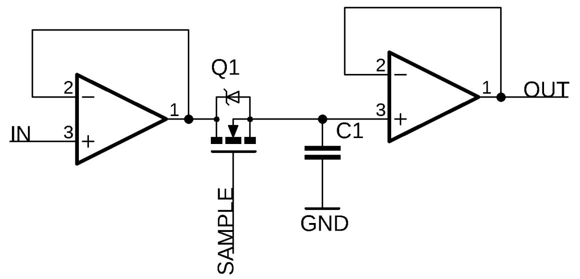
SAMPLE AND HOLD
29

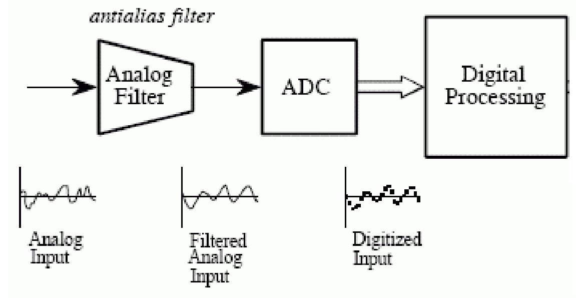


CIRCUIT KNOWOME

A sample and hold circuit is used to sample a voltage, and retain it for some period of time. This is particularly useful in digital applications where a stable voltage is required in order to take accurate measurements (e.g. ADC).

An Opamp follower on the input ensures that the circuit provides a low impedance copy of the input signal. The FET Q1 enables sampling; when the gate is high, current can flow to charge or discharge the capacitor C1, which serves to maintain the voltage while Q1 is off. Another opamp follower allows measurement of the voltage without discharging the capacitor in the process.

ADC - GENERAL
30

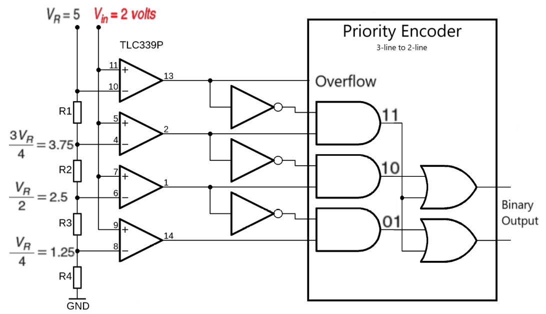


CIRCUIT KNOWOME

An ADC converts a time- and value-continuous input signal (analog signal) into a time-discrete and value-discrete sequence of digitally represented values. This is called quantization, due to a finite number of possible output values.

In order to completely reconstruct the signal later, the sampling frequency must be greater than twice the maximum possible frequency in the input signal (Nyquist theorem). Otherwise, a sub-sampling will occur that contains frequencies that are not present in the input signal. Therefore an antialiasing lowpass-filter is connected in front of it.

ADC - FLASH
31

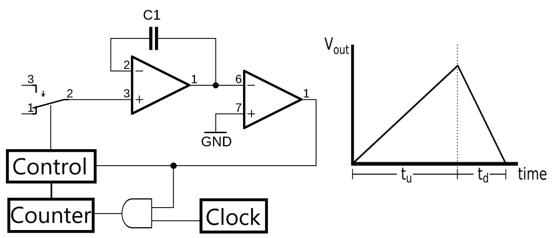


CIRCUIT KNOWOME

The Flash ADC consists of a series of comparators, each one comparing the input signal to a unique reference voltage. The comparator outputs connect to the inputs of a priority encoder circuit, which produces a binary output.

The analog input signal is compared simultaneously by all comparators in the flash converter (1 clock). A separate comparator is required for each possible output value. For example, an 8-bit flash converter requires $2^8 - 1 = 255$ comparators. Three comparators are required for the four possible values of a two-bit converter. The fourth has only the function to signal an overrange and to support the code conversion.
Advantages: very fast, simplest in terms of operational theory
Disadvantages: bad scalability(lower resolution), high power losses and expensive

ADC - DUAL SLOPE
32



CIRCUIT KNOWOME

The dual slope ADC essentially consists of an integrator and several counters and electronic switches. It is commonly used in digital multimeters.

In the dual ramp method, the integrator input is first connected to the unknown ADC input voltage, and charged over a fixed time interval(t_u). For the subsequent discharge, the integrator is connected to a known reference voltage of opposite polarity. The required discharge time(t_d) is determined by a counter; the counter directly stands for the input voltage with suitable dimensioning.
Advantages:high accuracy, high resolution, cheap
Disadvantages: slow(~20ms), high precision external components required to achieve accuracy

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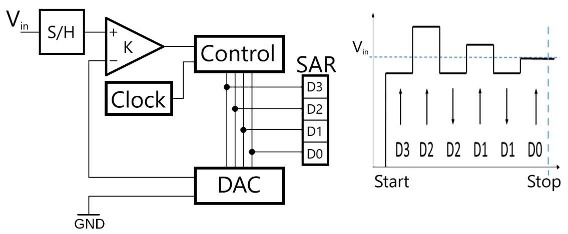
ADC - SUCCESSIVE APPROXIMATION

33



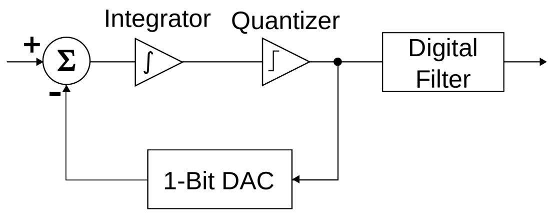
CIRCUIT KNOWOME

In successive approximation, the comparison is performed step by step and is repeated continuously, whereby the reference voltage is changed in such a way that it approaches the input voltage more and more.

A Successive Approximation Register (SAR) is added to the circuit This register counts by trying all values of bits starting with the MSB and finishing at the LSB. The logic monitors the comparators output to see if the binary count is greater or less than the analog signal input and adjusts the bits accordingly (max. 15-20Bit resolution).
Advantages: Capable of high speed and reliable, medium accuracy, good tradeoff between speed and cost, output in serial or parallel format.
Disadvantages: Speed limited to ~5Msps, higher resolution will be slower.

ADC - DELTA-SIGMA

34



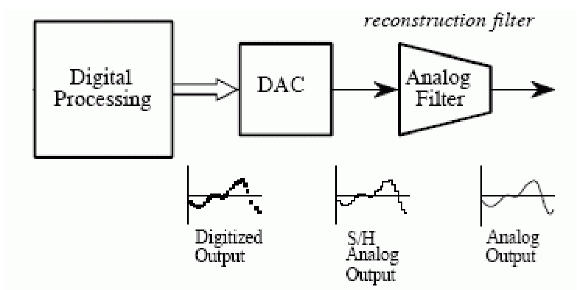
CIRCUIT KNOWOME

The principle of ΔΣ-modulation is based on an initial rough measurement of the signal. The resulting measurement error is integrated and compensated step-by-step via feedback.

These steps are carried out very frequently, for example with 128 times the sampling rate. This method has the property of shifting the noise to higher frequencies, which can then be removed with the anti-alaising filter.
Advantages: High resolution, no precision external components needed
Disadvantages: Slow due to oversampling

DAC - GENERAL

35



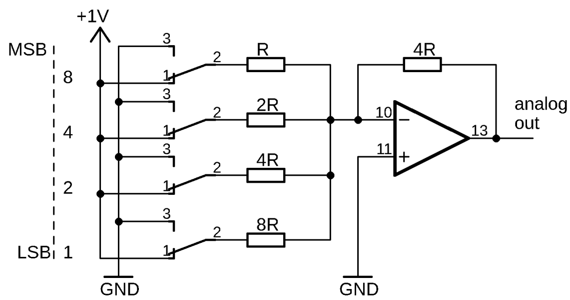
CIRCUIT KNOWOME

A DAC takes an exact number (usually a integer) and converts it into a physical quantity (e.g. voltage or pressure). DA converters are often used to convert time series data with fixed accuracy into a continuously varying physical signal.

The voltage at the output has a stepped shape. The step-shaped signal must then be reconstructed and smoothed in a low-pass filter, which must have a cut-off frequency corresponding to half the sampling frequency (Nyquist Theorem). The filtering cuts off the higher frequencies and harmonics, as well as the frequencies around the sampling rate.

DAC - FLASH

36



CIRCUIT KNOWOME

The simplest design of a DAC is derived from the summing amp. If the summing resistors are selected in steps of two powers, all bits which are set to logical 1 are summed according to their weight to a voltage.

This can be easily achieved with a reference voltage source and low impedance FET as switch.
Here's the output voltage:
$V_{out} = -4R(\frac{V_{ref}}{R} + \frac{V_{ref}}{2R} + \frac{V_{ref}}{4R} + \frac{V_{ref}}{8R})$
Simplyfied:
$V_{out} = -\frac{1}{2}(8V_{ref} + 4V_{ref} + 2V_{ref} + V_{ref})$
Advantages: very fast
Disadvantages: bad scalability(lower resolution), high power losses and expensive

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DAC - R2R LADDER

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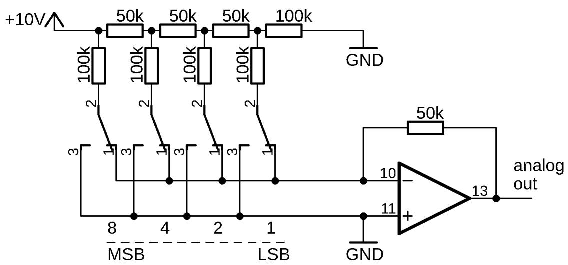


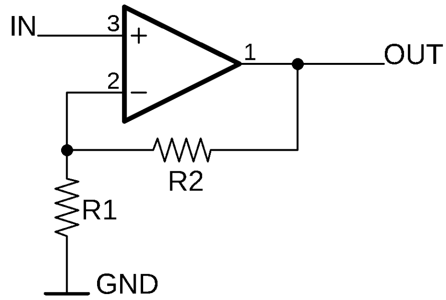
CIRCUIT KNOWOME

The R2R DAC uses only two resistance values R and 2R regardless of the number of bits of the converter compared to the summing amplifier implementation where each bit resistor has a different value.

The choice of the absolute resistance value is free, but the relative accuracy must be sufficiently high.
Advantages: very fast
Disadvantages: bad scalability(lower resolution), high power losses, with increasing resolution the accuracy decreases.

NONINVERTING AMPLIFIER

38



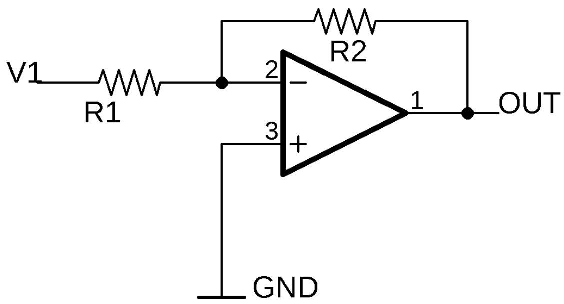
OPV CIRCUIT

Along with the inverting amplifier, the noninverting amplifier is one of the simplest opamp configurations. It amplifies the signal by a fixed gain.

This is accomplished with negative feedback from the output to the inverting input of the opamp via R2. Combined with R1, this forms a voltage divider that attenuates the output; the opamp then acts to ensure this attenuated version of the output signal is equal to the input signal. The gain of this circuit is thus $G = 1 + \frac{R2}{R1}$.

INVERTING AMPLIFIER

39



OPV CIRCUIT

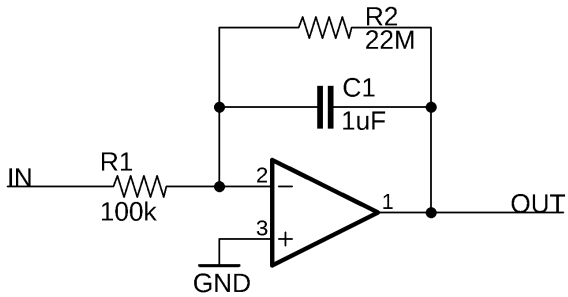
Along with the noninverting amplifier, the inverting amplifier is one of the simplest opamp configurations. It amplifies the signal by a fixed gain, while inverting it relative to the supply rails.

This is accomplished with negative feedback from the output to the inverting input of the opamp via R2. Combined with R1, this forms a voltage divider that attenuates the output; the opamp then acts to ensure this attenuated version of the output signal is equal to the input signal. The gain of this circuit is thus: $G = -\frac{R2}{R1}$.

$V_{out} = -\frac{R2}{R1} * V_1$.

INTEGRATOR

40



OPV CIRCUIT

An Opamp Integrator performs the mathematical operation of integration on its input signal - that is, its output voltage is proportional to the input voltage over time.

The resistor R1 converts the input voltage to a current, which charges capacitor C1 at a rate determined by the values of R1 and C1. The negative input is a virtual ground, and the opamp acts to maintain that by linearly increasing the voltage on the output while an input signal is present - performing the integration operation. R2 ensures the output voltage doesn't drift over time.

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DIFFERENTIAL AMPLIFIER

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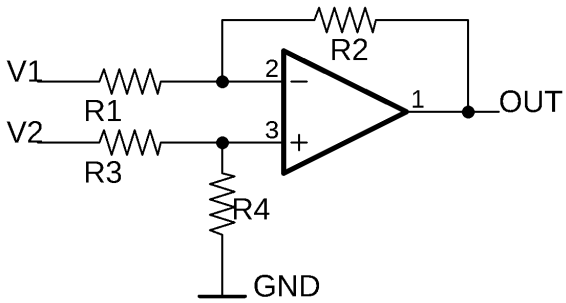


OPV CIRCUIT

A differential amplifier amplifies the difference between its two input signals.
If the inputs are equal, the output is set to zero.

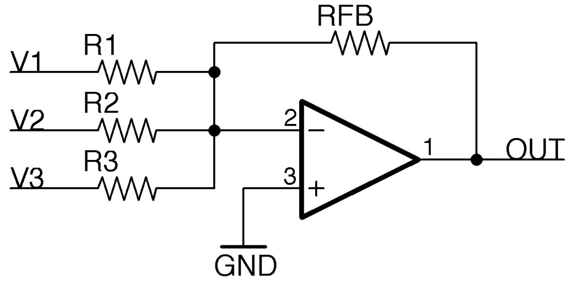
The voltage at the noninverting terminal is determined by the input signal and the resistor divider formed by the lower two resistors. This is matched at the inverting terminal by opamp action. The output of the amplifier is:
$V_{out} = \frac{R1+R2}{R1} * \frac{R4}{R3+R4} * V2 - \frac{R2}{R1} * V1.$

If R1=R3 and R2=R4: $V_{out} = \frac{R2}{R1}(V2 - V1).$

A differential amplifier requires very close matching of resistor values R1 and R2 to achieve high common-mode rejection ratios.

SUMMING AMPLIFIER

42



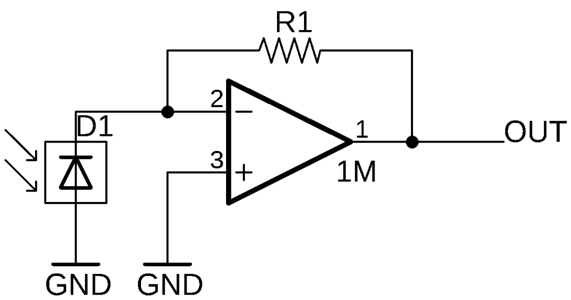
OPV CIRCUIT

A summing amplifier amplifies the weighted sum of its inputs, outputting an inverted result.

Any number of inputs can be connected via series resistors to the negative input terminal. The ratio of each input's resistor to the feedback resistor determines its weighting. In the example above, the output voltage of the amplifier will be $V_{out} = -R_{FB}(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}).$

TRANSIMPEDANCE AMPLIFIER

43



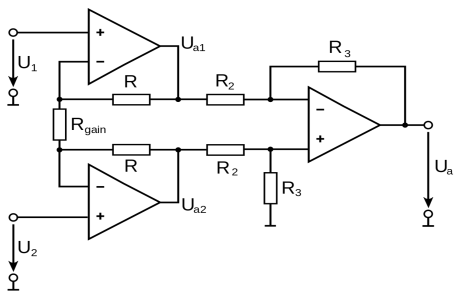
OPV CIRCUIT

A transimpedance amplifier converts a current to a voltage. They're particularly useful for sensors that output currents, like the photodiode depicted above.

The inverting input of the opamp forms a virtual ground. This requires the current through R1 to be equal to the current being sunk by the photodiode, which results in an increase in the output voltage equal to the product of the input current and the feedback resistor.
Because a transimpedance amplifier has an input measured in amps(A) and an output measured in volts (V), its gain is measured in ohms(Z).
$Z = G = \frac{U_{out}}{I}$

INSTRUMENTATION AMPLIFIER

44



OPV CIRCUIT

This circuit consists of a differential amplifier on the right ($G = \frac{R_3}{R_2}$) and two non-inverting amplifiers on the left($G = 1 + \frac{R_1}{R_{Gain}}$). The advantages are a high input impedance and a increased common-mode rejection ratio(CMRR).

Putting the gain resistor between the two inverting inputs (instead of 2 resistors to ground) increases the differential-mode gain of the buffer pair while leaving the common-mode gain equal to 1. They are very effective at extracting a weak differential signal out of a large common mode signal. Available as integrated circuit with fixed and factory trimmed resistors.

$U_{a1} = U_1 + \frac{R1}{R_{gain}}(U_1 - U_2)$

$U_{a2} = U_2 + \frac{R1}{R_{gain}}(U_2 - U_1)$

$U_a = \frac{R3}{R2}(U_{a2} - U_{a1}) = \frac{R3}{R2}(1 + \frac{2R_1}{R_{Gain}})(U_2 - U_1)$

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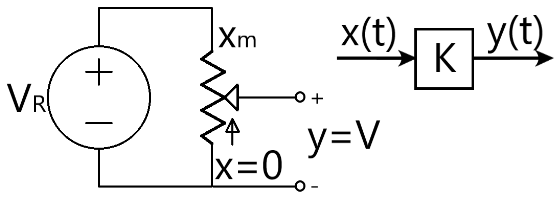
ZERO-ORDER SYSTEM

45



OTHER

A linear potentiometer used as position sensor is a zero-order sensor. For these systems all coefficients of the function, except of the first ones (a_0, b_0), are zero.

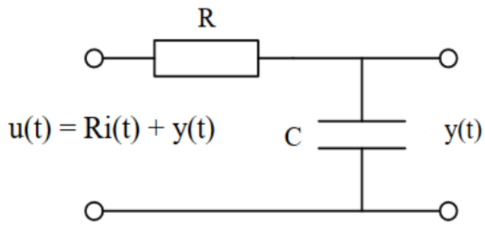
The output is equal to the input, multiplied by its static sensitivity K($\frac{b_0}{a_0}$ → DC Gain), which describes the behavior of the circuit. These systems are always linear and frequency independent(ideal dynamic characteristic). They consist only of passive elements(R).

$a_0 y(t) = b_0 x(t) \rightarrow y(t) = Kx(t)$

For the figure:
$V = V_R * \frac{x}{x_m}$ here, $K = \frac{V_R}{x_m}$
where $0 \leq x \leq x_m$ and Vr is a reference voltage

FIRST ORDER SYSTEM

46



OTHER

First order systems are, by definition, systems whose input-output relation is a first order differential equation. Electric 1.order systems contain a single energy storage element(C,L). For these systems all coefficients, except of a_0, a_1, b_0, are zero.

Transfer function:
$a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t) \rightarrow \tau \frac{dy(t)}{dt} + y(t) = Kx(t)$
$K = \frac{b_0}{a_0}$ → static sensitivity
$\tau = \frac{a_1}{a_0} = RC = \frac{L}{R}$ → time constant

Here:
$i(t) = C\frac{dy(t)}{dt}$
$RC\frac{dy(t)}{dt} + y(t) = u(t)$

with:
$b_0 = 1, a_0 = 1, a_1 = RC$

DIRAC DELTA FUNCTION

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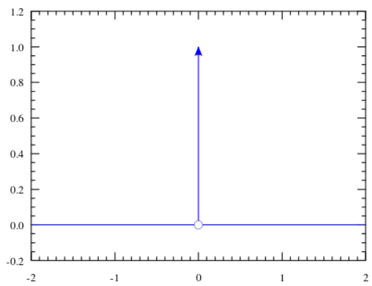


OTHER

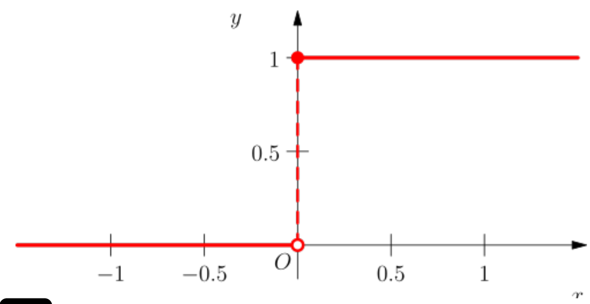
The δ-function, also known as the unit impulse, is a generalized function or distribution. It is always zero, except when t=0. This peak is infinitely thin and infinitely high. An arrow is drawn symbolically.

Each circuit has its own transmission behavior. The system response can be determined with a Dirac pulse. It is used to characterize the response of systems to brief transient inputs. Technically the pulse can be approximated to 10ps half width. The function can be moved with $\delta(t - t_0)$. If the δ-function is integrated, the result is the step response.

$$\delta(t) = \begin{cases} 0 & t \neq 0 \\ \infty & t = 0 \end{cases} \qquad \int_0^\infty \delta(t)dt = 1 = \sigma(t)$$

HEAVISIDE STEP FUNCTION

48



OTHER

The Heaviside-function, or unit step function, is zero for all negative values, otherwise 1. The step function corresponds to the integral of the pulse function. If the function is further integrated, the ramps function is obtained.

The function finds numerous applications, for example in communications engineering to determine the system response or as a mathematical filter, because everything is cut off before the step.

$$\sigma(t) = \begin{cases} 0 & t < 0 \\ 1 & t \geq 0 \end{cases} \qquad \frac{d}{dt}\sigma(t) = \delta(t)$$

$$\int_0^\infty \sigma(t)dt = r(t)$$

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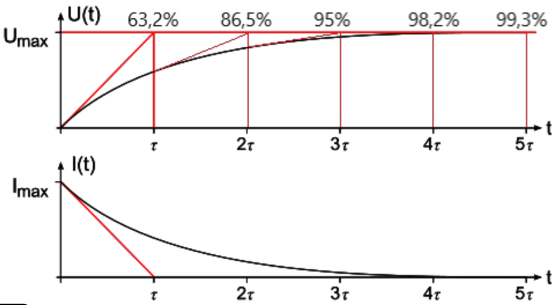
STEP RESPONSE

49



OTHER

In electronic engineering and control theory, step response is the time behaviour of the outputs of a general system when its input is a step function. The unit step is commonly used to characterize a system's response to sudden changes in its input.

The picture shows the step response of an RC low pass. The step response always consists of a stationary part (1) and a transient part $(-e^{\frac{t}{\tau}})$. τ is called the time constant. It is the time it takes for the step response to rise to 63.2% of its final value. The steady-state error is the error after the transient response has decayed leaving only the continuous response. The error signal:

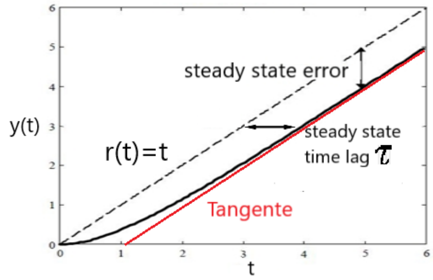
$e(t) = U_{in} - U_{out} = 1 - 1 + e^{-\frac{t}{\tau}} = e^{-\frac{t}{\tau}}$

The step response of the system is:

$U(t) = U_{max}(1 - e^{-\frac{t}{\tau}})$

RAMP RESPONSE

50



OTHER

The integration property of linear systems allows the characteristic response $y_r(t)$ to a ramp forcing function r(t) to be found by integrating the step response $y_s(t)$.

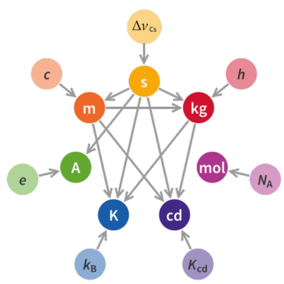
$$y_r(t) = \int_0^t y_s(t)dt = \int_0^t (1 - e^{-\frac{t}{\tau}})dt$$
$$= t - \tau(1 - e^{-\frac{t}{\tau}})$$

As t becomes large the exponential term decays to zero and the response becomes $y_r(t) = t - \tau$ for $t \gg \tau$.

steady state time lag: τ
steady state error: $q_{is}\tau$
with q_{is} = const. change rate

SI UNITS

1



OTHER

The International System of Units is the modern form of the metric system. It is built on seven base units and a set of twenty prefixes to the unit names. Since 2019 all SI units are defined by natural constants.

Base units are length (meter), weight (kilogram), time (second), electric current (ampere), temperature (kelvin), amount of substance (mole) and luminous intensity (candela). The prefixes for factors of a unit include k(ilo) (10^3), M(ega) (10^6), G(iga) (10^9), d(eci) (10^{-1}), c(enti) (10^{-2}) and m(illi) (10^{-3}). Any physical quantity is expressed as a number mulitplied by a unit (with prefix). For example a weight is expressed as 1 kg, meaning One Kilogramm or 1000 grams.

SI UNITS

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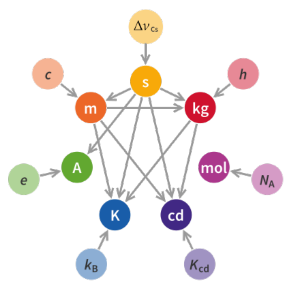

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