General measurement technology and passive components

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This script was written by Hansjürg Schmutz and translated by Andreas Schneider

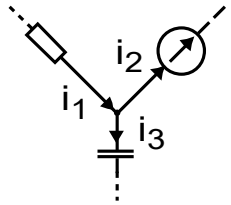
Basic theory and networks of passive components

Some basic laws:

Kirchhoffs Current Law (ger.: Knotensatz)

$\sum i_i = 0$ or $\sum \mathrm{i}_{\mathrm{IN}} = \sum i_{OUT}$

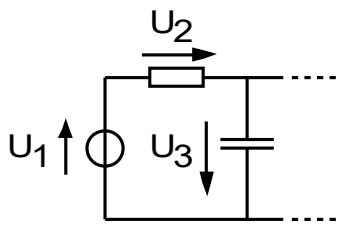
in one node



Kirchhoffs Voltage Law (ger.: Maschensatz)

$\sum u_i = 0$ oder $\sum \mathrm{u}_{\mathrm{cw}} = \sum u_{ccw}$

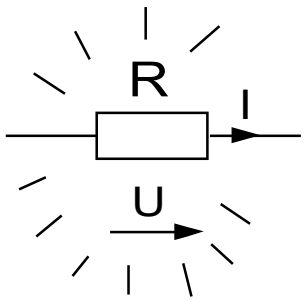
along one loop



Ohm's Law

$U = R \cdot I$

Power: $P = U \cdot I = \frac{U^2}{R} = I^2 \cdot R$



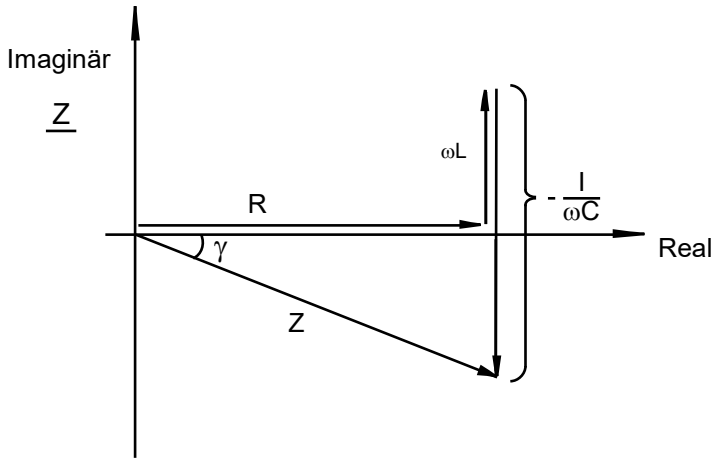
One-port devices

In German: “Zweipole”

Impedance

complex resistance, used for calculations with ac- and arbitrary signals

$$Z = R + j(X_L - X_C) = R + j\left(\omega L - \frac{1}{\omega C}\right)$$



Admittance

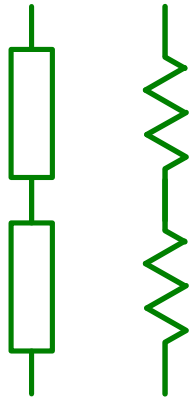
In German: komplexer Leitwert oder Admittanz

$$Y = G + j(B_C - B_L) = G + j\left(\omega C - \frac{1}{\omega L}\right)$$

Series Connection

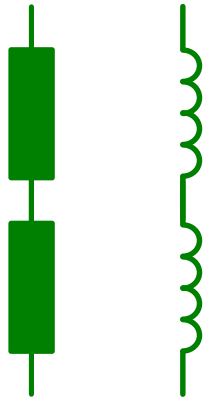
Impedances add up.

$$R_{tot} = \sum R_i$$



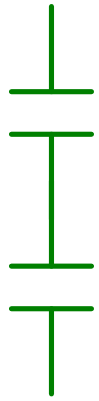
DIN symbol ANSI symbol

$$L_{tot} = \sum L_i$$



(old) DIN & ANSI

$$\frac{1}{C_{tot}} = \sum \frac{1}{C_i}$$

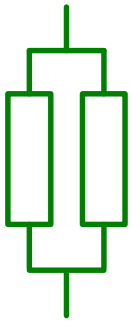


DIN & ANSI symbols

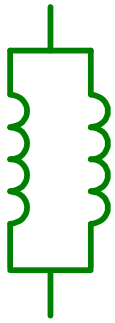
Parallel Connection

Admittances add up

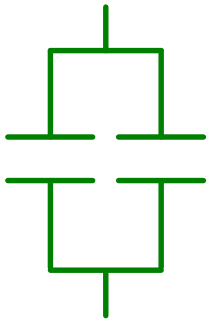
$$\frac{1}{R_{tot}} = \sum \frac{1}{R_i}$$



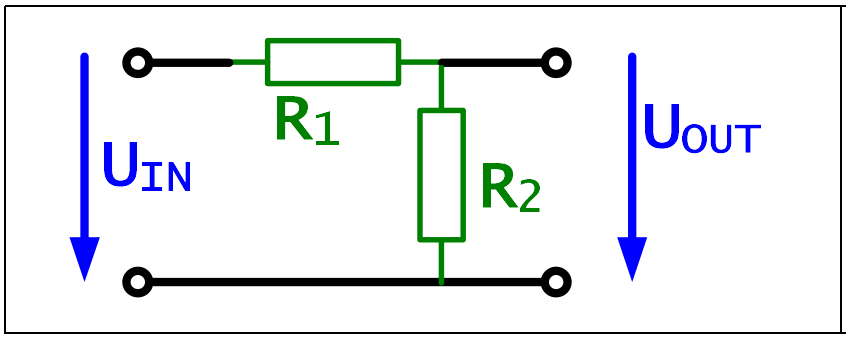
$$\frac{1}{L_{tot}} = \sum \frac{1}{L_i}$$



$$C_{tot} = \sum C_i$$



Voltage Divider

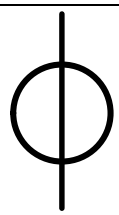
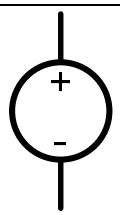
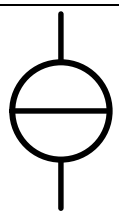
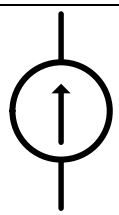


$$U_{out} = U_{in} \cdot \frac{Rx}{Rx + R_2} \qquad R_{ersatz} = \frac{1}{\frac{1}{R_2} + \frac{1}{R_L}} = \frac{R_1 \cdot R_2}{R_1 + R_2}$$

$$U_{out} = U_{in} \cdot \frac{R_2}{R_1 + R_2}$$

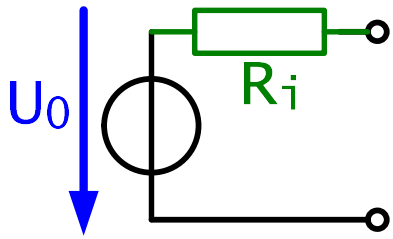
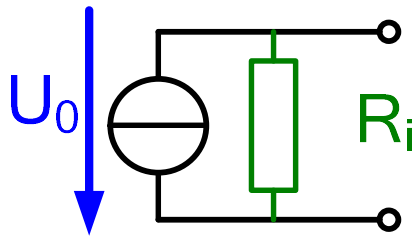
Sources

Symbols

Ideal Voltage Source		Ideal Current Source	
			
DIN	ANSI	DIN	ANSI

Real sources

Real sources always exhibit an internal resistance. This means that no real voltage source can supply an infinitely high current, where no real current source can supply an infinitely high voltage.

Real Voltage Source	Real Current Source
	

$$R_i = \frac{\text{unloaded voltage}}{\text{short circuit current}}$$

In circuits with solely linear components, the superposition theorem applies.

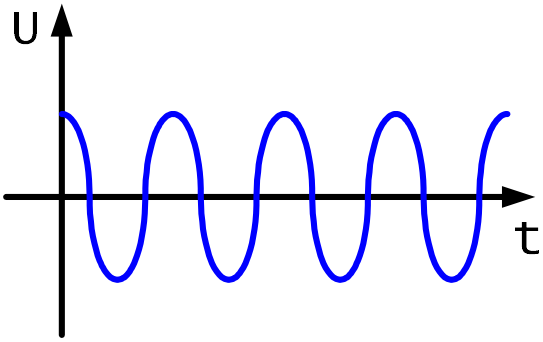
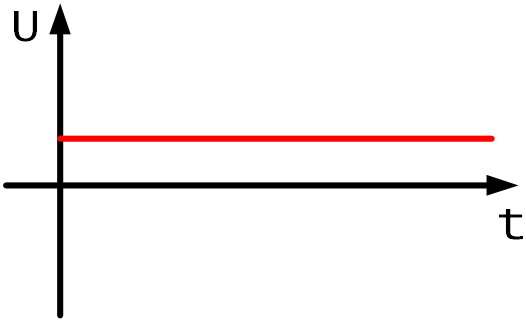
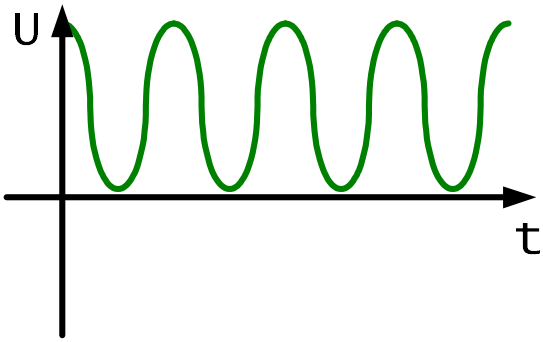
That means, that one can calculate the effect of several sources on one parameter by adding up the result of each individual source on this parameter. Thereby the sources which are not under consideration are 'switched off' the following way:

voltage source:	terminals shorted
current source:	terminals open

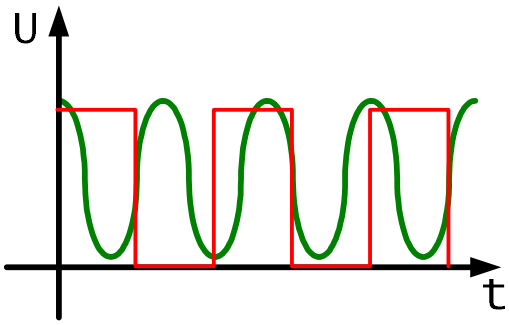
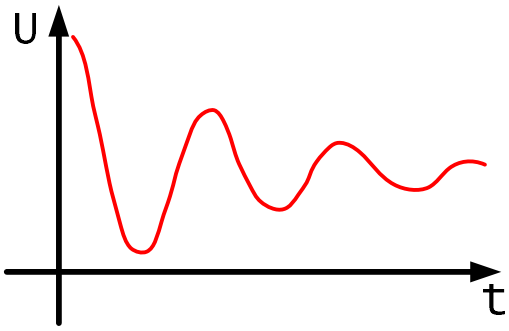
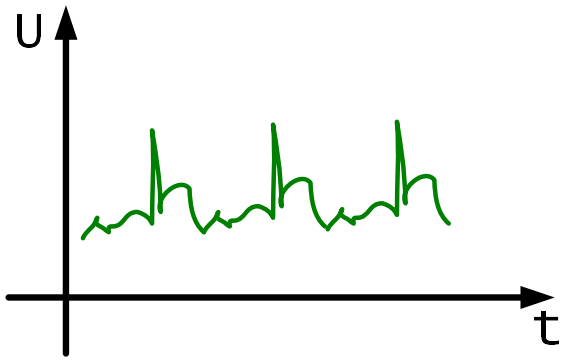
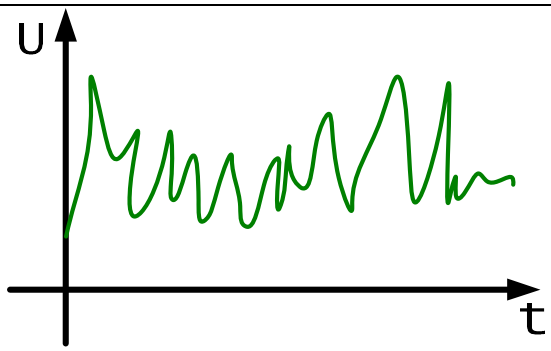
Now, have a look at the DIN symbols for sources again.

Characterization of signals

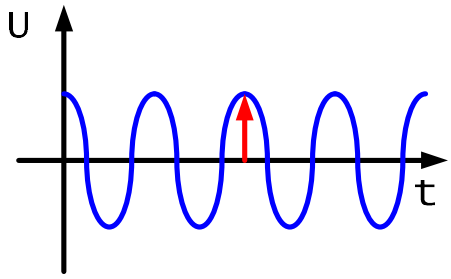
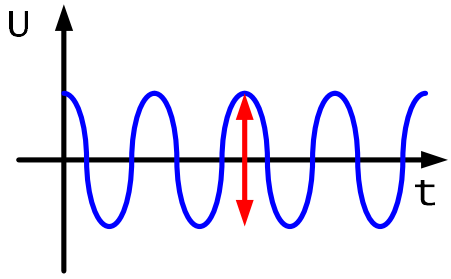
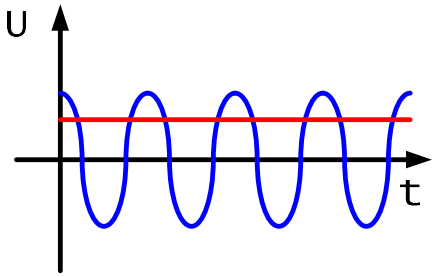
Signals may have many different properties. However there are even more ways to describe these properties. Let us start with a coarse classification.

AC Signal (AC: alternating current)	DC signal (direct current)
 The signal changes its polarity over time, i.e. the direction of the current reverses. The signal can have any shape like square, triangular, sawtooth, etc. For a pure AC signal, the mean value is zero.	 The value of the signal stays constant over time
Mixed forms  Alternating signals with a non- zero mean value	

Signals can also be classified by their appearance in time.

Deterministic signals	Periodic signal (square wave, sine)	
	Non periodic signal (damped oscillation)	
	Quasi periodic signal (electrocardiogram)	
Stochastic signals	Noise	

A very important parameter of a signal is its amplitude. Again there are many different ways to specify an amplitude. Here are some common ways to describe voltages.

Peak Voltage	U_P (engl: V_P)	
Peak to peak Voltage	U_{PP} (engl: V_{PP})	
RMS or effective Voltage	U_{RMS} (engl: V_{RMS}) Or U_{eff} (engl: V_{eff}) $RMS: \sqrt{\frac{1}{T}\int_0^T U^2(t)dt}$	 An AC signal with a certain RMS value contains the same amount of power as a DC signal of the same value.
Logarithmic Voltage Ratios	dBV dBu used in audio technology	$dBV: 20 \cdot \log\left(\frac{U}{1\,\mathrm{V}}\right)$ $dBu: 20 \cdot \log\left(\frac{U}{0{,}7746\,\mathrm{V}}\right)$ The base to which the voltage to be expressed is measured to, is chosen. A factor of ten is added in order to get convenient numbers. A factor of two is added to be proportional to a power ratio.

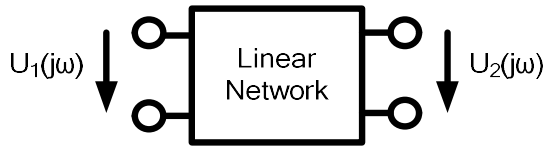
Often, mainly in radio frequency or high frequency applications one describes the magnitude of a signal by a power ratio. For example the unit dBm is a power ratio with the base of one milliwatt:

$$dBm: 10 \cdot \log\left(\frac{P}{1\,\mathrm{mW}}\right)$$

The Bode Diagram

The Bode Diagram is a useful tool to describe the transfer function of a certain linear circuit. This kind of diagram consist of two individual diagrams. The upper one shows the amplitude- the lower one the phase response. Typically the axis of frequency and amplitude are in logarithmic scale. The amplitude is given in decibel.

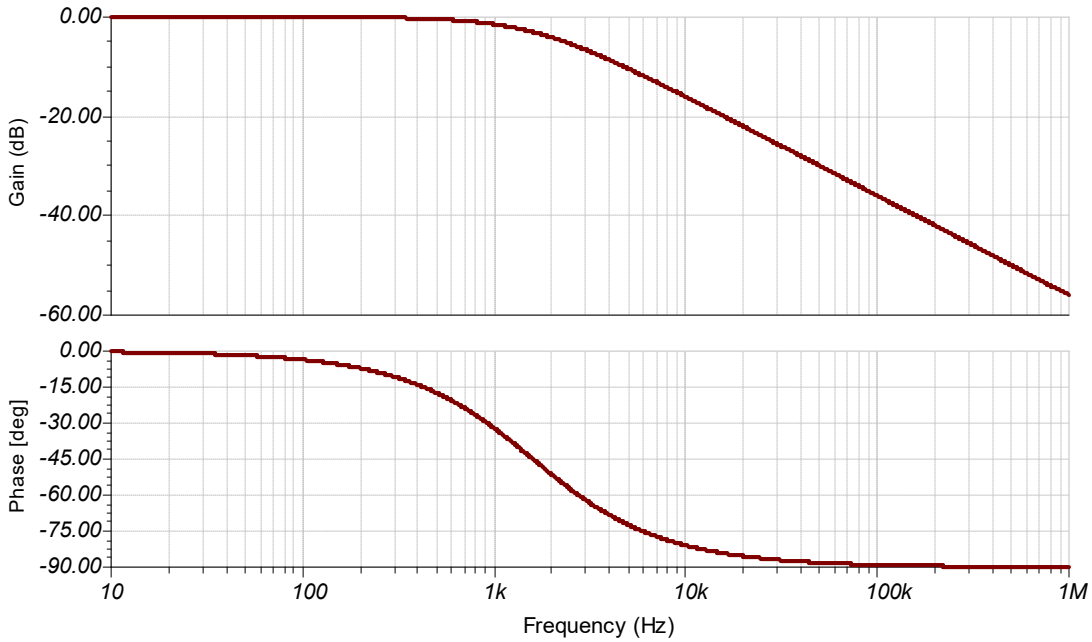
A transfer function is defined as follows:



Transfer Function

$$H(j\omega) = \frac{U_2(j\omega)}{U_1(j\omega)}$$

The load at U_2 has to be specified if it is not clear out of the context (For example in radio- or high-frequency technology the load is almost always 50 Ω).

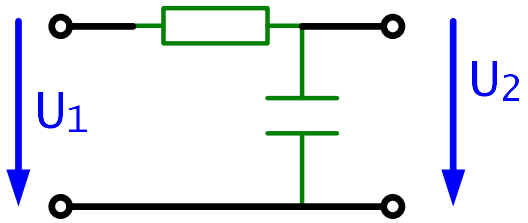


Example of a Bode Plot of a low pass filter

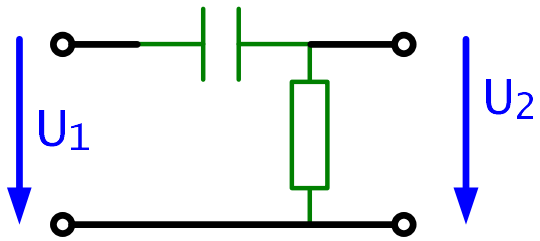
Complex transfer functions can be factorized in to known transfer function parts. In the bode diagram, these individual terms can the simply be added.

Example: Combination of low- and high pass

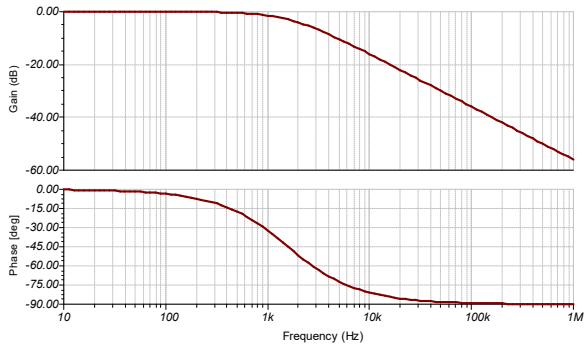
Low pass



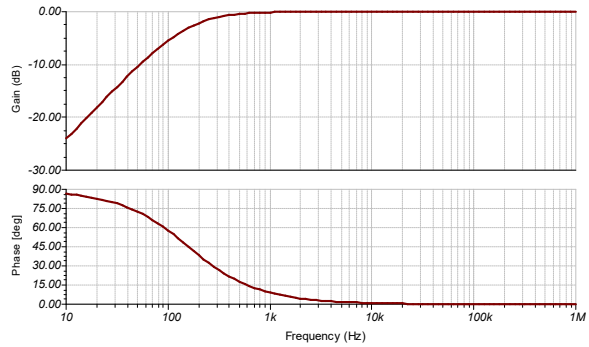
High pass



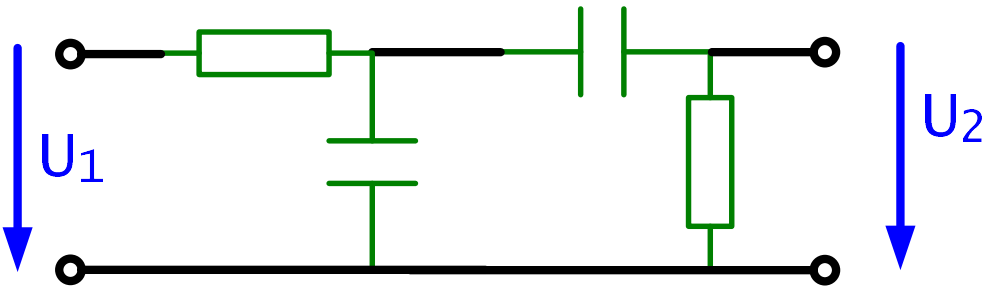
R = 100 Ω
C = 1µF

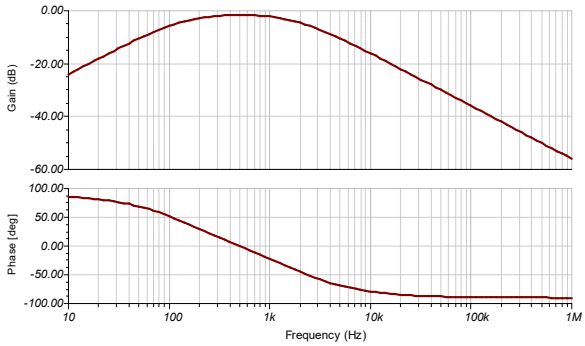


R = 1 kΩ
C = 1µF



Combination:





Where in the transfer function, the combination of the two circuits is formed by product, in the logarithmic diagram, the combination can be formed as an addition. This can be very useful for a quick estimation of the qualitative behavior of a circuit.

Devices

DC Sources

Every electronic circuit needs a supply of energy. This supplier can be of many different forms like a battery, a photovoltaic cell, etc. In the lab, the most common source is a regulated DC power supply. Sometimes, especially for heating purpose also AC supplies or simple transformers are used.
As mentioned before, an ideal voltage source would deliver any amount of current, which would correspond to an inner resistance of 0 Ω. Of course in real life, there is no such device. All voltage- or current sources have a limited voltage- or current range and thereby a certain inner resistance. A real source exhibits a complex inner resistance. For you as user, the following facts are important:

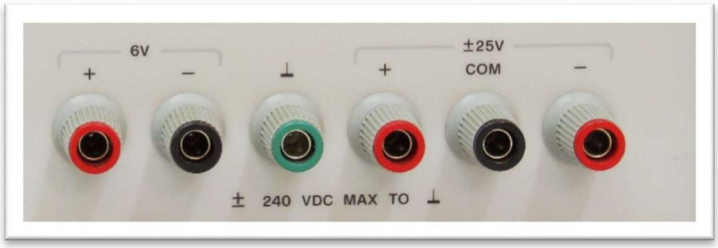
- The inner resistance is very small due to an active control loop.
- Also the output impedance is very small. Often, close to the devices output is a capacitor which serves as a short term energy reservoir.
- Only if individual sources are isolated from earth, they can be connected in series in order to get higher or negative voltages
- Some source can be connected in parallel to increase the available current. Consult the manual to check whether this is allowed.

Types of DC Sources

As Power supplies are almost everywhere, they come in many different forms, sizes and shapes.

Most common are probably the plug-in modules. Most of them have a badge on it which informs about their main specifications voltage, maximum current and polarity of the plug. All of these plug- in modules are switched power supplies (see below).

In the lab we often use table top power supplies. These come with various adjustment possibilities, like set voltage and current limit. High voltage power supplies have also a tripping functionality. This works like a fast resettable fuse, which switches the device of whenever the drawn current exceeds a certain limit. Most table top devices incorporate two or more individual sources, which might or might not be electrically isolated from each other. Table top devices have 4mm lab connectors. Whenever connecting a device or circuit to it, one should consider the polarity of the connection and whether there are extraneous connections needed to define the potential between individual sources. Devices where the common terminal is isolated, often provide a separate terminal with earth potential.



Example of the different terminal types on a table top DC power supply (commonm, earth, plus, minus.

The technology incorporated in power supplies can be divided in two classes: switched power supplies and linear regulated power supplies. Here are the advantages and disadvantages of them:

Switched	Linear
+ Very high efficiency (70% to 95%) + Small and lightweight + Can convert from DC to DC + Inexpensive - The output signals are noisy (often spikes at different frequencies in the kHz range)	+ Very clean output signals (only very low disturbances at 50Hz and its harmonics) + Tolerant against fluctuations of the load - Poor efficiency (40%-60%) - Bulky and heavy - Expensive

To supply energy to a digital circuit (i.e. a computer) a switched power supply is favorable. For a circuit which processes very small signals one should prefer a linear regulated power supply.

Connecting to DC Sources

Most DC power supplies (except most high voltage sources) have terminals which are completely isolated against the casing and also against earth potential. Therefore it is the user or the load which defines the absolute potential (voltage between terminal and earth) at the terminals. This property allows to make series connection of individual sources to increase the available voltage or to get negative voltages out of two sources. Be aware that this is not possible if one terminal is hard connected to earth. This is for example the case with most high voltage power supplies. It is advisable to read the manual if you are unsure how to connect.

The main specifications of dc power supplies are:

- Output Voltage Range: Many devices have adjustable voltages, however there are some with fixed voltages.
- Maximum Available Current
- Maximum Available Power: This number might be smaller than the product of maximum voltage times maximum current
- Load regulation: This parameter tells how the device reacts to a sudden change of the load (from no to maximum load). The number is usually given in percent
- Line regulation: This parameter tells how the device reacts to a sudden change of the line voltage. The number is usually given in percent

- Ripple and Noise: Specifies the voltage noise in a frequency range of usually 20 Hz to 20 MHz. Often the value is given as an RMS value, which might differ strongly from a peak to peak value. This is especially true for switched power supplies
- Long Time Drift
- Temperature Stability
- Precision and Resolution of the displays

Manufacturers

Here, a collection of proven manufacturers of table top dc sources

- HP, Agilent, Keysight, USA: All three names are the same company. It has a broad range of high class devices
- E/A (Elektro - Automatik), D: Cheap but nevertheless high quality devices made in Germany.
- K. Witmer, CH: This company does not produce anymore but at LPC we still have plenty of those devices which not only proved the quality of their specifications but also their durability

Good quality table top high voltage sources can be obtained from the companies:

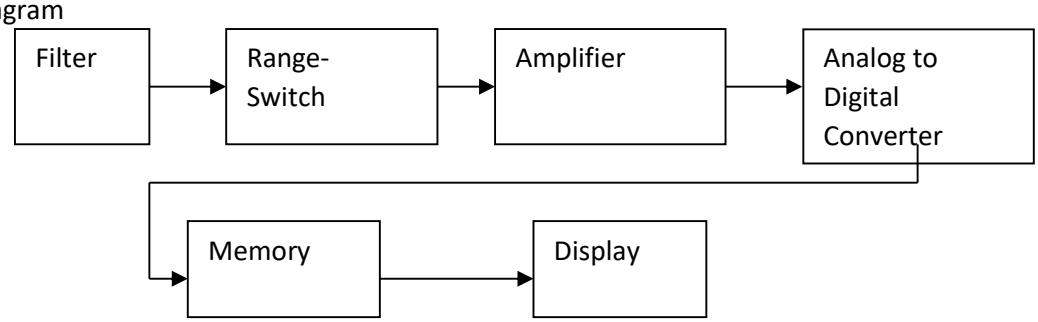
- Iseg, D: Broad range of easy to use high voltage supplies
- FUG, D: German quality. They also make reasonable priced customizations
- Stanford Research Systems (SRS), USA: only three models but good quality, moderately priced

Digital Multimeters

A digital multimeter is a very versatile device. It can measure far more than just voltage and current. A modern multimeter measures for example: voltage, current, resistance, continuity, diode forward voltage, capacitance, frequency, temperature, harmonics of the mains.

Digital multimeters basically contain a slow but very high resolution analog to digital converter (ADC). The measured data is then displayed on a simple display. Before the physical parameters like current, temperature etc. can be measured by the ADC, they have to be converted into an adequate voltage. The ADC itself only measures voltages. The refresh rate (how often a measurement is performed) is usually a few Hertz and depends on the precision (resolution) of the measurement.
Many multimeters provide a bar graph display in addition to the alphanumerical one. The bar graph lets one recognize trends much faster.

Block diagram



As the analog to digital conversion is the most critical process, it can be performed in a variety of methods. The Dual Slope Integration (Dual Slope Integration) is usually used; the charge balancing method is used for high precision, whereas in applications where a high conversion rate is important, the method of successive approximation is used.

Multimeters come either as handheld or table top devices. In former times the table top devices provided more functionality and could be remotely controlled. Nowadays, both types offer the same functionality although the table top devices still offer more precision.

Usage

The signal or device to be measured is connected by standard 4mm lab connectors. All terminals at the multimeter (regardless if handheld or table top) are isolated and have no connection to earth. Table top devices might offer a dedicated earth terminal for shielding purpose. They often also come with an additional set of terminals for high precision measurement of very small resistances.

Following, some typical measuring ranges. Consult the manual of your individual device for the exact data (often you also find some useful information on the front panel):

	Minimum (strongly dependent on the type)	Maximum
Gleichspannung	1 mV	1000 V
Wechselspannung	5 mV	1000 V
Gleichstrom	5 uA	10 A
Wechselstrom	5 uA	10 A
Widerstand	5 Ω	40MΩ

The input resistance for voltage measurements is 10 MΩ. The input resistance for current measurements is several tens of ohms at the measuring range up to 1000mA and 0.01 ohms at the 10A range.

The selection of the measuring range can often be adapted to the measurement signal by the measuring device That means the user can connect any signal and the measuring device will select the correct measuring range itself, provided the choice of the measurement type is correct (AC or DC) . The only exception: the 10A range must always be selected manually and usually has its own input jack.

Types of measurement

Digital multimeters can measure static quantities very accurately. Even the cheapest versions have a resolution of 3 ½ digits for DC voltages, which corresponds to 1/1999 = 0.05%. Also dynamic ac values (non-sinusoidal signals) can be measured. In this case, however, you have to study the data sheet carefully in order to interpret the results correctly. Devices with 'True RMS' specification incorporate a circuit which allows it to measure effective values also of non- sinusoidal signals. Still, it has to be clarified whether in this kind of measurement, the DC-part of the signal (the offset) is taken into account. With most devices, this is not the case and one has to measure the DC offset and the effective value of the signal separately and add them

AC values are determined up to a frequency component of about 100 kHz and a ratio of peak value to effective value up to 5. This ratio is called the crest factor (in German: Scheitelfaktor). The accuracy of the measurement depends to a large extent on the crest factor and is specified in the data sheet.

Crest factor = peak value / effective value		Form factor = peak value / mean value	
Crest factor of different symmetric signals		Form factor of different symmetric signals	
Sine	1.414	Sine	1.11
Square	1	Square	1
Triangle	1.732	Triangle	1.1547
Sawtooth	1.732	Sawtooth	1.1547

Multimeters without a 'True RMS' method, measure the rectified mean value of the ac signal and show this value multiplied by a factor of 1.11. This corresponds precisely to the ratio of the rectified mean value to the effective value of a sinusoidal signal. The multimeter therefore measures only one sinusoidal size with a single fixed frequency. One could speak of a 'faked RMS' measurement.

Example of multimeters

Manufacturer of high-quality multimeters with a wide pallet, also of precision devices:

- Fluke, USA: The best known manufactuer of handheld devices
- Keithley, USA
- HP, Agilent, Keysight, USA: All three names are the same company. It has a broad range of high class devices
-

Device	Features	Price CHF (Jan 2017)
Keysight 34401A	6 ½ digits resolution,table top, remotely controllable	1428.-
Agilent U1242b	Handheld, robust, True RMS	307.-

Cheaper devices can be found easily. However, one should always choose a device that one trusts. Otherwise you might do the same measurement twice.

Digital Storage Oscilloscope

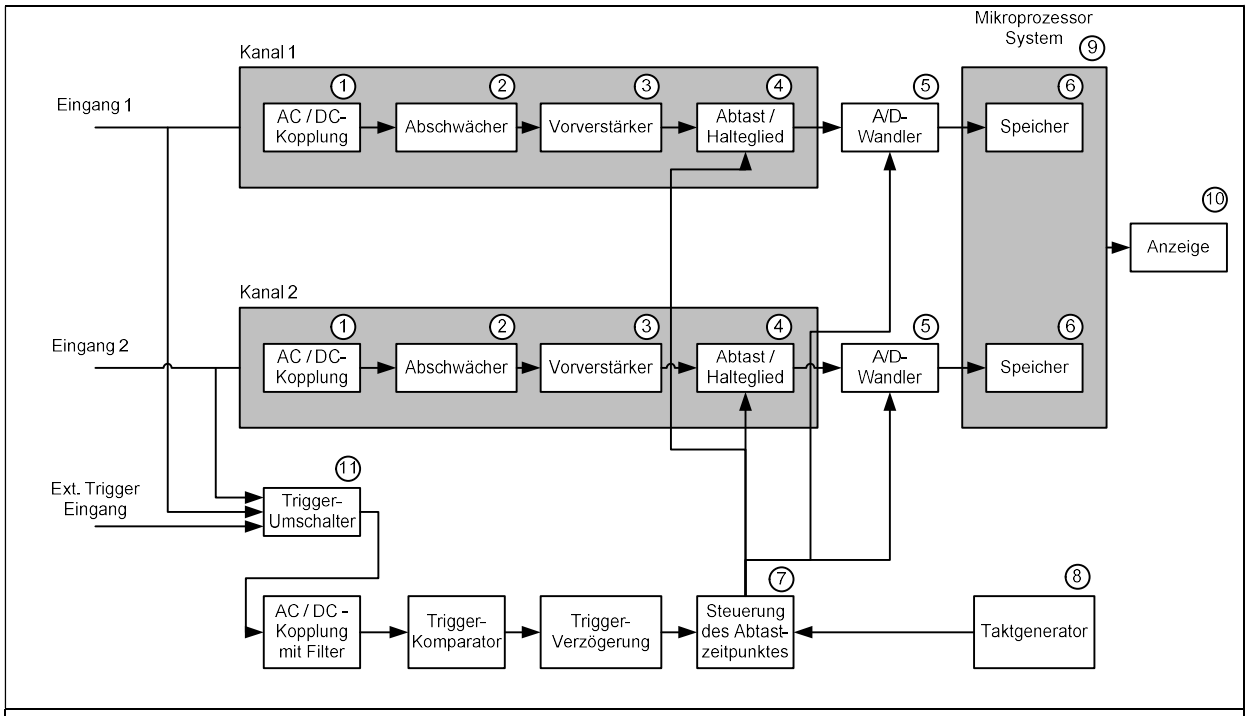
The digital storage oscilloscope is certainly the most versatile and valuable electronic measuring device in research and development. It measures time-dependent electrical voltages and displays them in a two-dimensional image. If necessary, various parameters can be automatically measured from the measured voltages, or the entire measurement curve is processed using DSP (digital signal processing) techniques such as FFT (Fast Fourier Transform) or digital Filters and the results are also displayed. It is worth taking a short look back in the not too distant past to get a feeling for the huge development jump and so also to appreciate this kind of measuring device.

Beginning with the end of the Second World War, its analogue predecessor have made electrical signals visible to the user and made many developments in modern electronics possible.

Tektronix 535, built in 1954, 15 MHz analog bandwidth, already with, Delayed Sweep '

Clever electronic circuits synchronized the measurement to the signal to be measured if it fulfilled certain conditions. This synchronization point (trigger) was the beginning of the observation window, but the signal before this time remained hidden to the user. For the duration of the afterglow of the phosphor screen, irradiated by the electron beam, the signal was visible. In order to obtain a standing image, the signal had to be periodic, the duration of the period not being much larger than the afterglow period. This obstacle could still be taken by tube technology.

To display the parts of the signal before the point in time ehere the trigger condition was fulfilled, digital technology is needed. At the beginning of the 1980s, real DSO (Digital Storage Scopes) came onto the market and in the meantime they almost completely replaced the analog ones



This block diagram shows the basic principle of a Digital Storage Oscilloscope. Before the input signal is amplified by an input amplifier, its DC offset can be filtered away by a high pass filter, also refered to as 'AC Coupling' (1). The input amplifier (3) together with the attenuator (2) and the AC/DC Coupling are a high impedance load, 1 MΩ. This means that also weak signal sources are not much distorted due to the load. However, most oscilloscopes provide the ability to load the signal with 50 Ω instead of 1 MΩ. This is advantageous for example for high frequency signals from strong sources. After the amplification and pre- processing, the signal enters a so called sample and hold circuit (4). This circuit ensures that the signal does not change its value during the time it is being discretized by the analog to digital converter (5). The exact point in time, when the signal has to be sampled is set by the sample rate generator (7) together with the clock (8). The digitized values have to be stored into the memory (6) between two sampling points. After a certain number of sampling points around the trigger condition have been measured, the whole set of data is digitally processed (9) and displayed (10)

.

Nowadays, many oscilloscopes use ordinary computers as a front end. These devices can directly be connected to PCs by USB, GPIB or Ethernet (be aware of viruses and malware). Nevertheless the data acquisition electronics are still highly specialized circuits.

Analog oscilloscopes can still be found on the market as low cost devices. They can be very useful for monitoring repetitive signals.

Specifications

The following ranges shall give you an idea what specifications are available nowadays for table top devices. The list might not be complete and probably no device will cover all ranges.

Vertical System

Number of inputs	2 to 4
Analog bandwidth	50MHz to 100GHz
Vertical resolution	8 to 16 bits
Vertical scale range	1mV/div to 10V/div (up to several kV/div with appropriate probe)

Horizontal System

Sampling rate	100MS/s to 240GS/s (Mega Samples per second)
Acquisition Memory	100kS to several hundred MS per channel
Acquisition Rate	up to a few million acquisitions per second (!)

Usage

Due to their large functionality, using an oscilloscope in an efficient way needs some training. In the practical lessons of this course, you will have the chance to learn all the basics and to further improve your skills.
Nevertheless here are some important steps:

- Coupling: Before connecting a signal to the oscilloscope, consider what input impedance might be suitable for your signal. Choose 50 Ω only for high frequency signals which originate from a strong source. However if the amplitude of the signal is higher than the damage threshold (see front panel), choose 1 MΩ as input impedance (for low frequency) or attenuate with an external attenuator. Either with an oscilloscope probe (DC to moderate frequency) or an RF (radio frequency) attenuator
- Vertical Scale: Set the vertical scale large enough that you will be able to see the whole signal
- Trigger Mode: Set the Trigger Mode to ‘Auto’. The oscilloscope will then do acquisitions even if the trigger condition is not fulfilled.
- Connect the signal
- Choose the horizontal scale and an appropriate trigger condition.

To set these parameters there are either buttons or soft keys, depending on the type of oscilloscope you use. Most oscilloscope still provide rotary knobs for the vertical and horizontal scales and the vertical and horizontal position. Also for the level of the edge trigger mode there is a rotary knob on most oscilloscopes.

Further Reading

- Oscilloscope Fundamentals by Rhode & Schwarz.