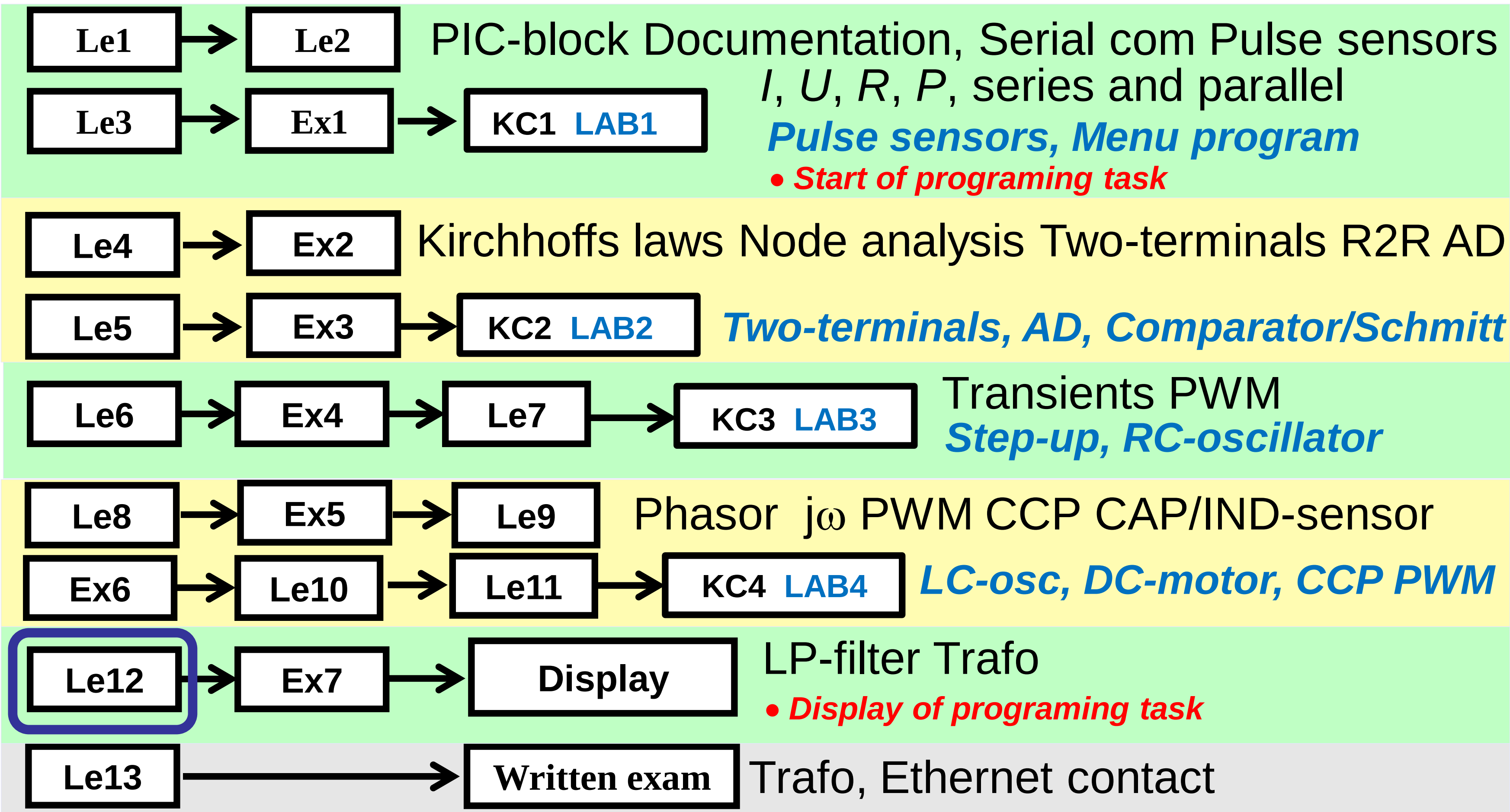
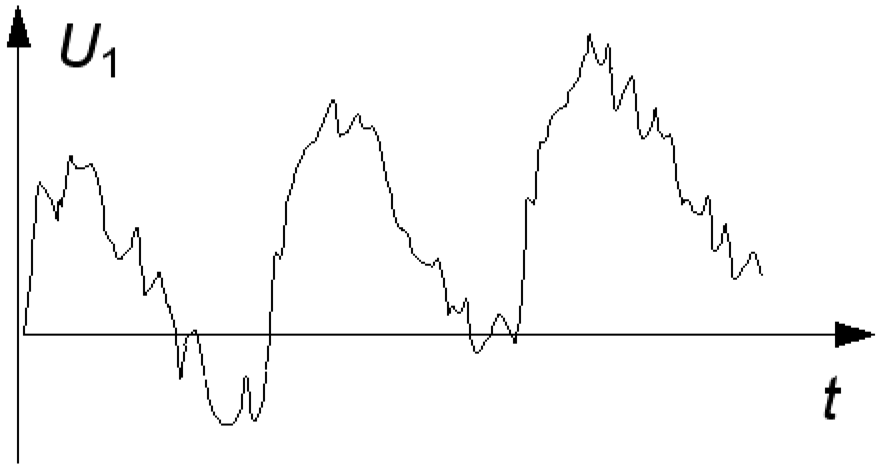
IE1206 Embedded Electronics



William Sandqvist william@kth.se

A signal from reality …



Actual signals are difficult to interpret. They are often disturbed by noise and hum.

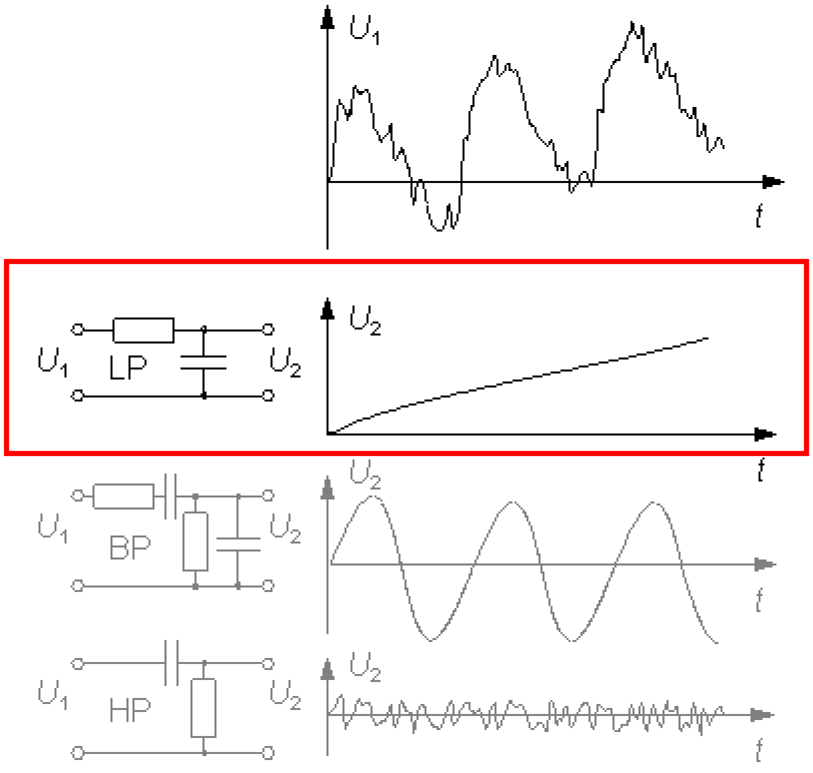
Hum is our 50Hz network induced into the signal lines.

Noise is random disturbances from amplifiers (or even resistors).

Maybe a slow DC …

Perhaps the signal is a slowly increasing direct voltage from eg. a temperature sensor?

In this case, the interference consist of 50 Hz hum and high frequency noise.



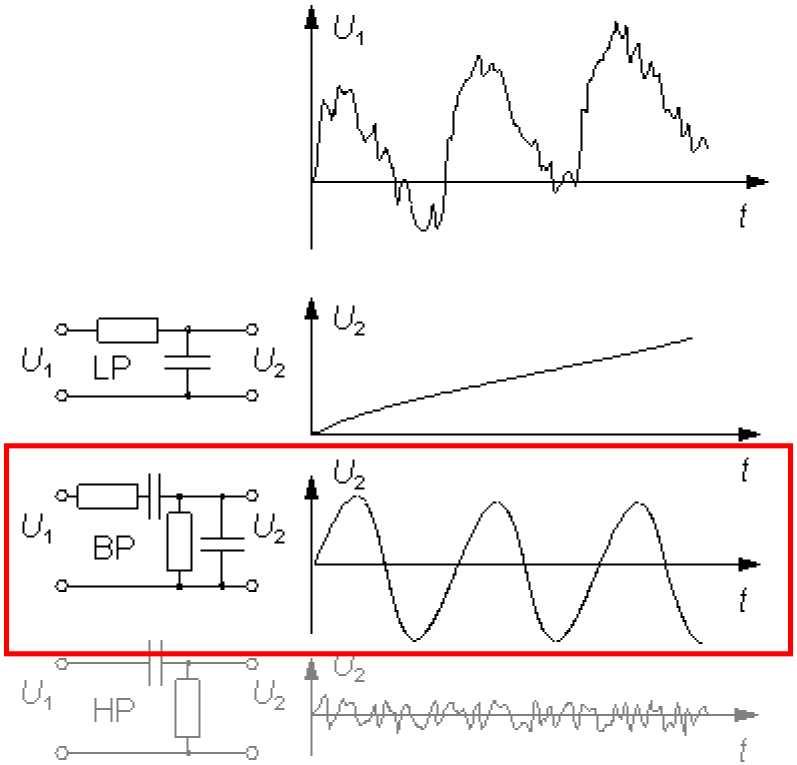
A **LP-filter** (=LowPass) filters away the interference and removes the interferences from the signal.

William Sandqvist william@kth.se

Maybe a sine wave …

Maybe the signal is a sine wave?

In this case, the interference consist of the DC voltage level slowly changing, offst, and that noise is added.

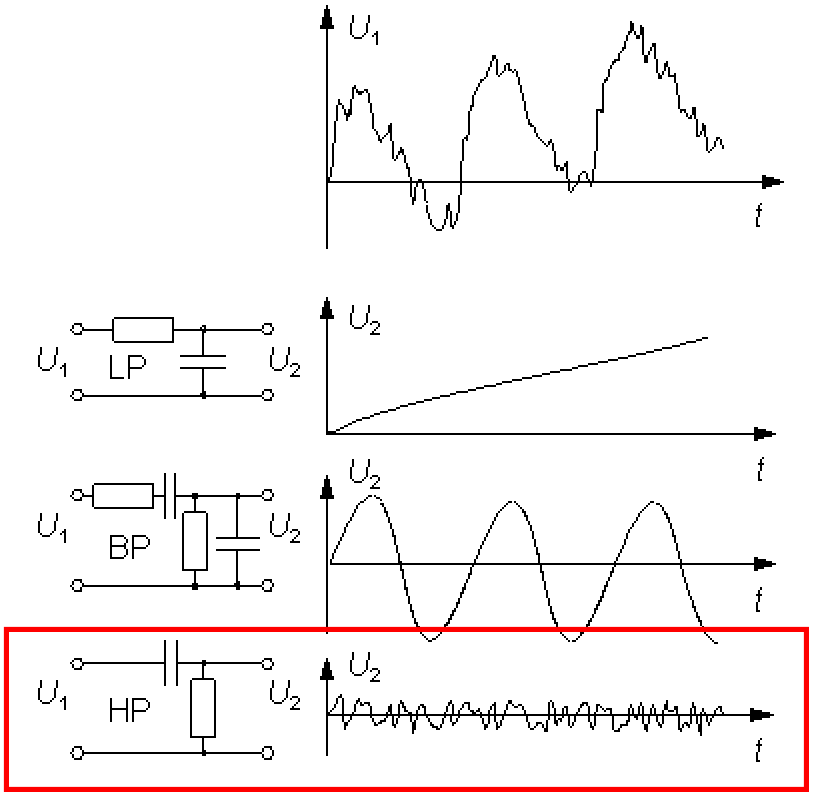


A **BP-filter** (BandPass) will block the offset and filters out the noise.

Maybe rapid variations …

Perhaps the signal is the rapid variations?

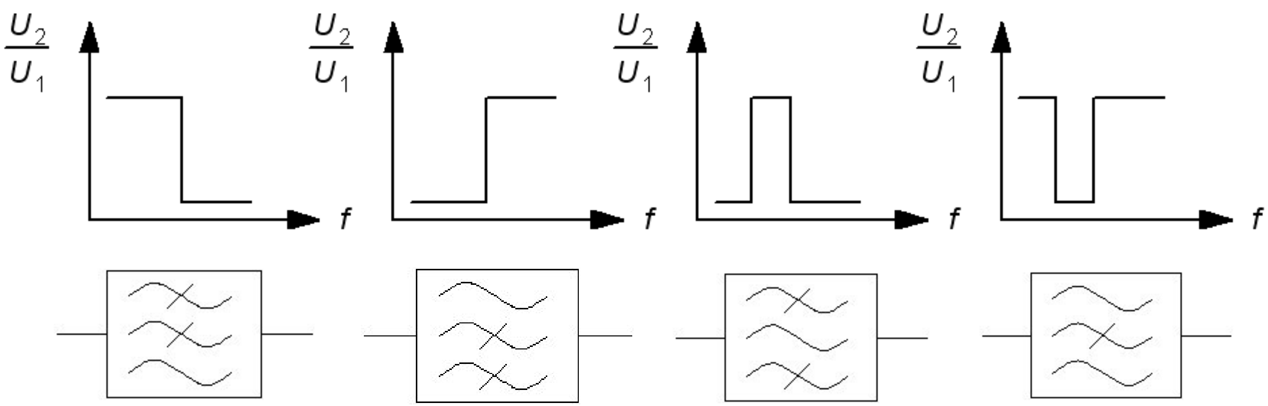
In this case, the interference consist of the DC voltage level slowly changing, and that hum has been added.



A **HP-filter** (HighPass) removes the interferences from the signal.

LP HP BP BS

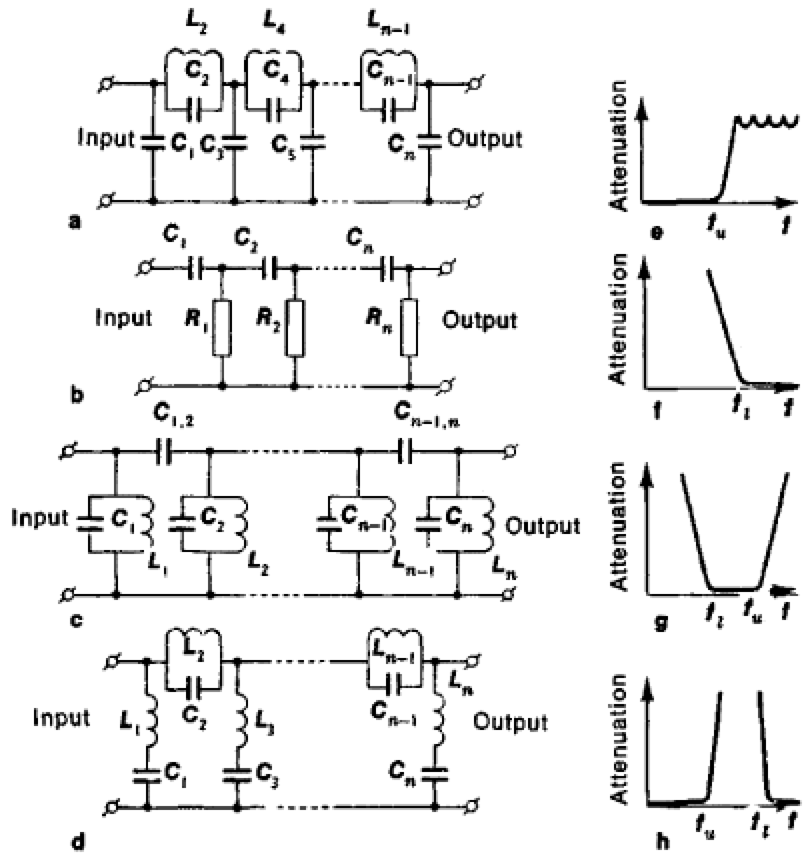
LP lowpass HP highpass BP bandpass BS bandstop



BP and BS filters can be seen as different combination of LP and HP filters.

(RLC-Filter)

With *R L* and *C* one can build effective **filters**, and this was formerly one of the most important branches of electronics.



Simple Filters

Inductors are more complicated to manufacture than capacitors and resistors, therefore, is typically only combination *R* and *C* used.

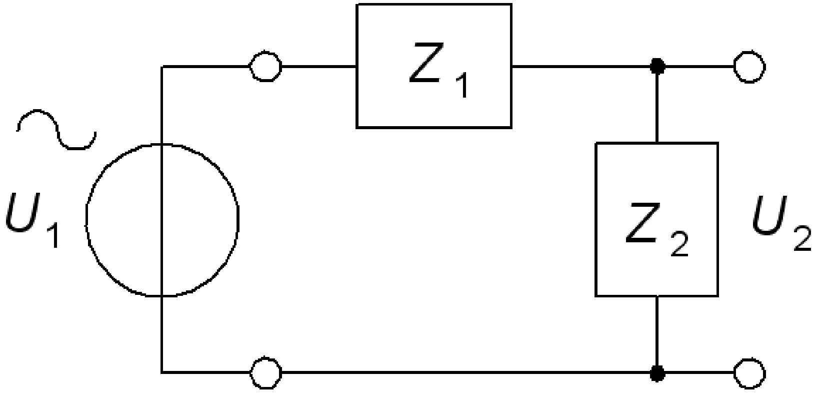
Fast computers can filter signals digitally. Calculating a signal's moving average can for example correspond to the LP filter. Nowadays dominates the digital filter technology over the analog.

Simple RC filter are natural parts in most measuring instruments, or are even arising from "itself" when we are linking equipment together.

This is the reason that one must know and be able to calculate on simple RC-links, even though they regarded as filters are very incomplete.

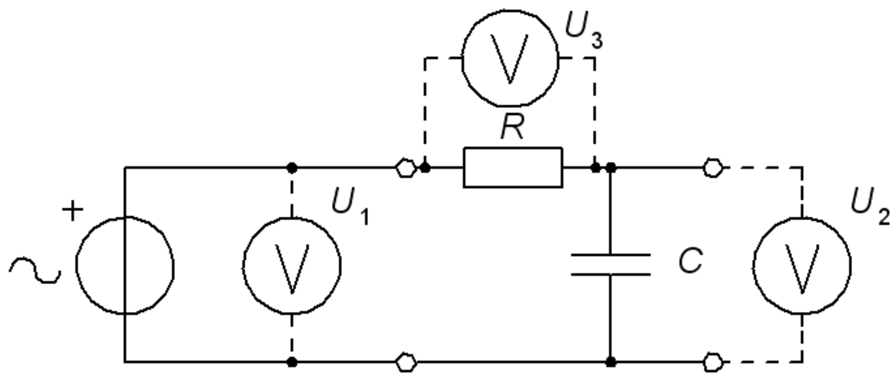
Voltage divider, Transfer function

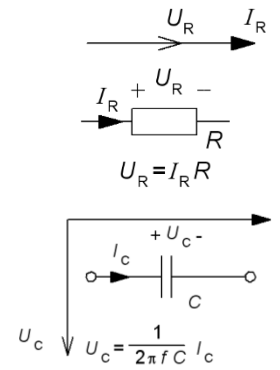
Simple filters are often designed as a voltage dividers.A filter **transfer function**, $H(\omega)$ or $H(f)$, is the ratio between output voltage and input voltage. This ratio we get directly from the voltage divider formula!

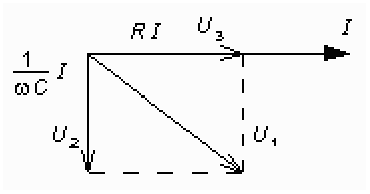


$$\underline{U}_2 = \underline{U}_1 \frac{\underline{Z}_2}{\underline{Z}_1 + \underline{Z}_2} \quad \Rightarrow \quad \boxed{\underline{H}(\omega) = \frac{\underline{U}_2}{\underline{U}_1} = \frac{\underline{Z}_2}{\underline{Z}_1 + \underline{Z}_2}}$$

RC LP-filter, vectors



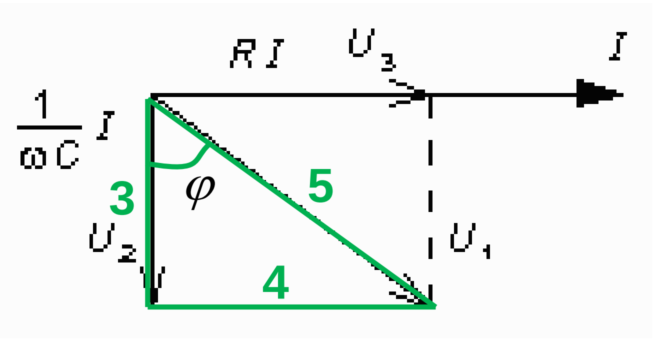




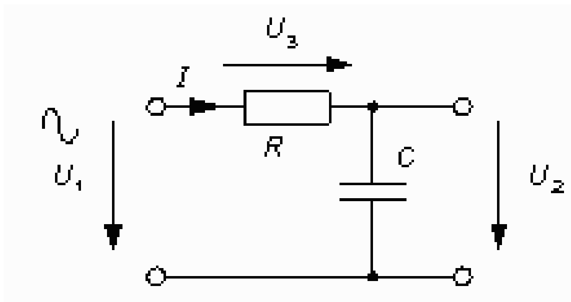
Phasor diagram: *R* and *C* has the current *I* in common. Volyage over resistor and voltage over capacitors kondensatorn therefore becomes perpendicular. Pythagorean theorem can be used:

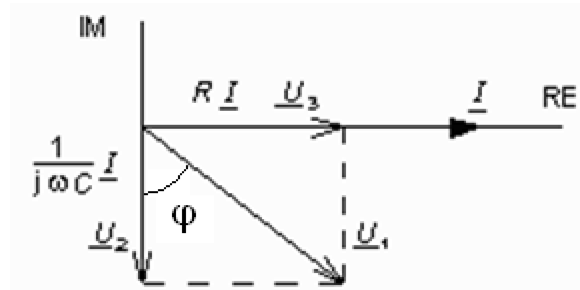
$$U_1^2 = U_3^2 + U_2^2$$

$$|\varphi| = \arctan\frac{U_2}{U_1}$$



RC LP-filter, jω





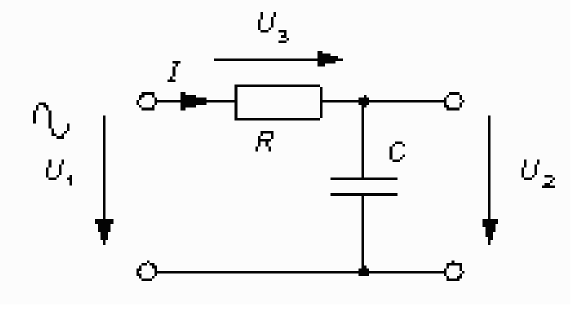
$$\frac{\underline{U}_2}{\underline{U}_1} = \frac{\frac{1}{\mathrm{j}\omega C}}{R + \frac{1}{\mathrm{j}\omega C}} \cdot \frac{\mathrm{j}\omega C}{\mathrm{j}\omega C} = \frac{1}{1 + \mathrm{j}\omega RC}$$

$$\frac{U_2}{U_1} = \frac{1}{\sqrt{1 + (\omega RC)^2}}$$

$$\varphi = \arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) = \arg(1) - \arg(1 + \mathrm{j}\omega RC) = 0 - \arctan\left(\frac{\omega RC}{1}\right) = -\arctan(\omega RC)$$

William Sandqvist william@kth.se

RC LP-filter, $H(\omega)$

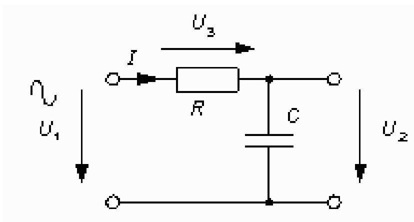


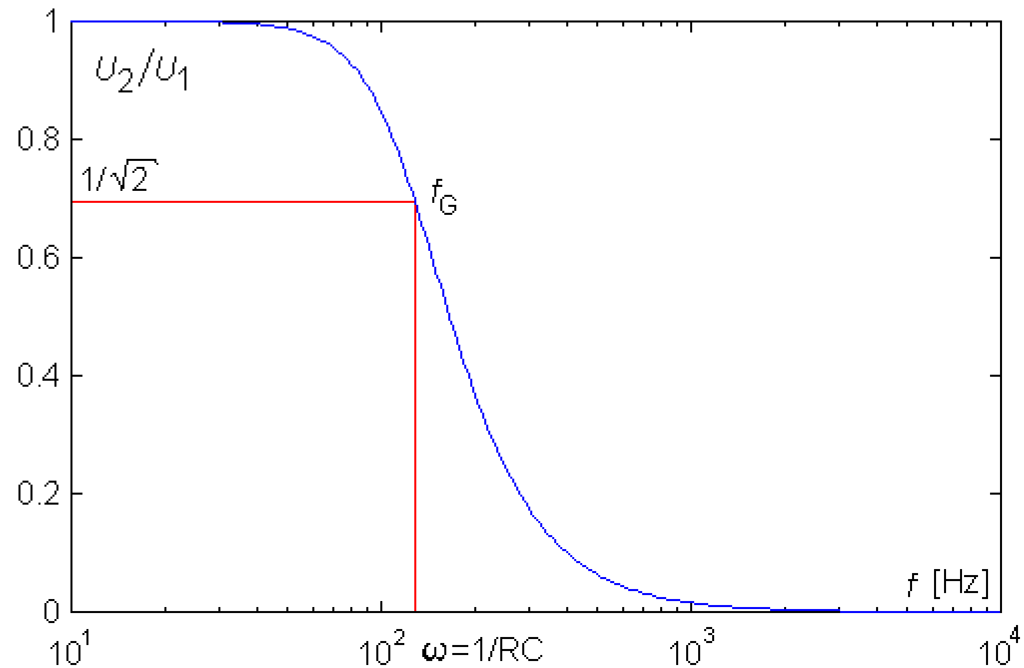
$$\boxed{\underline{H} = \frac{1}{1 + \mathrm{j}\omega RC}} \qquad \mathrm{abs}(\underline{H}) = H = \frac{1}{\sqrt{1 + (\omega RC)^2}} \qquad \arg(\underline{H}) = -\arctan(\omega RC)$$

At the angular frequency when $\boxed{\omega RC = 1}$, will the numerator real part and imaginary part be equal. This is the filter cutoff frequency.

$\omega \approx 0$	$\omega \approx \frac{1}{RC} \quad \omega RC = 1$	$\omega >> \frac{1}{RC}$	$\omega \to \infty$
$\frac{U_2}{U_1} \approx \frac{1}{\sqrt{1+0}} \approx 1$	$\frac{U_2}{U_1} \approx \frac{1}{\sqrt{1^2+1^2}} \approx \frac{1}{\sqrt{2}} \approx 0{,}71$	$\frac{U_2}{U_1} \approx \frac{1}{\omega RC}$ avtar med ω 0,1ggr/dekad	$\frac{U_2}{U_1} \to 0$
$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) \approx \arctan 0 \approx 0°$	$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) \approx 0 - \arctan 1 = -45°$	$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) \approx -\arctan(\omega RC)$	$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) \to -90°$

LP-magnitude function





$R = 1\ \text{k}\Omega$

$C = 1\ \mu\text{F}$

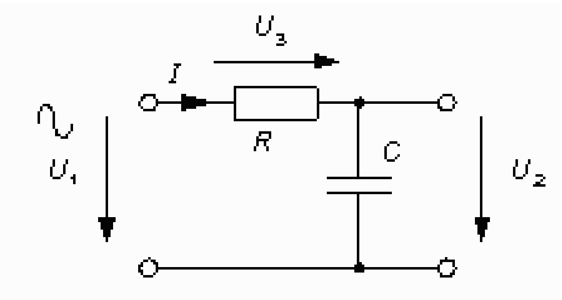
$$f_G = \frac{1}{2\pi \cdot 1 \cdot 10^3 \cdot 1 \cdot 10^{-6}}$$

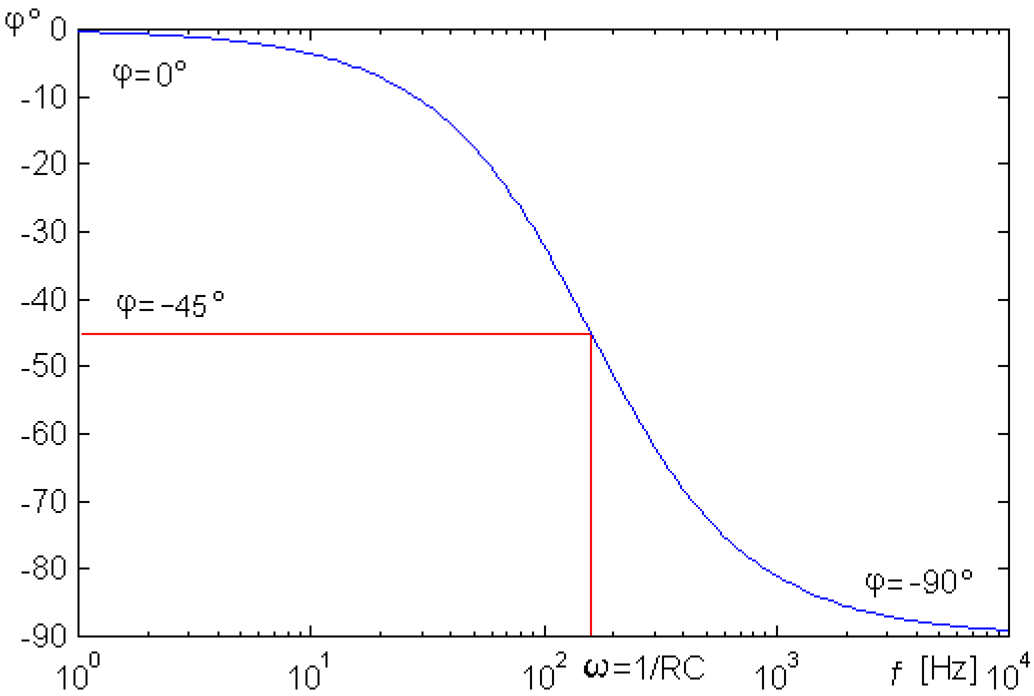
≈ 160 Hz

$$H = \frac{1}{\sqrt{1+(\omega RC)^2}} \qquad \omega_G = \frac{1}{RC} \qquad f_G = \frac{1}{2\pi RC}$$

William Sandqvist william@kth.se

LP-Phase function

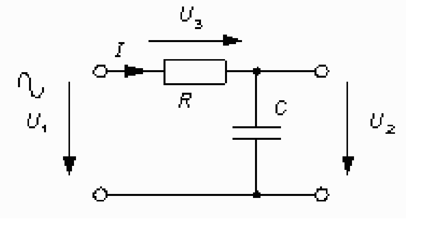




$$\varphi = \arg\left(\underline{H}\right) = -\arctan(\omega RC)$$

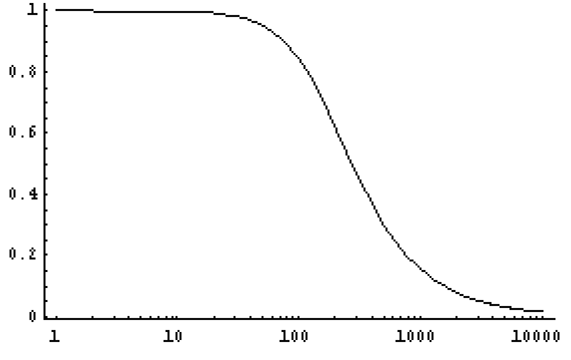
Graphs with Mathematica

Mathematica has commands for complex absolute value (abs []) and argument (arg [], in radians).

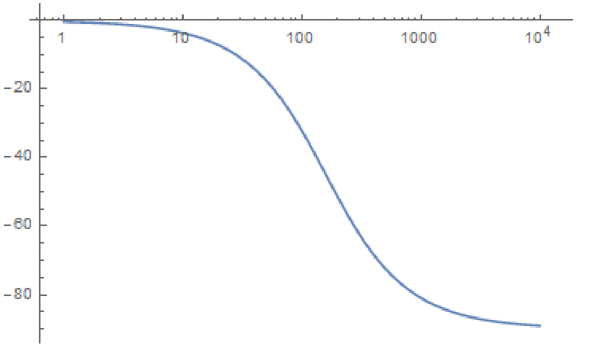



```
r=1*10^3;
c=1*10^-6;
u2u1[f_]:=1/(1+I*2*Pi*f*r*c);
LogLinearPlot[Abs[u2u1[f]],{f,1,10000},PlotRange->All,PlotPoints->100];
LogLinearPlot[(180/Pi)*Arg[u2u1[f]],{f,1,10000},
PlotRange->All,PlotPoints->100];
```

Press SHIFT + ENTER to start the calculation and the plot.



Amount plot



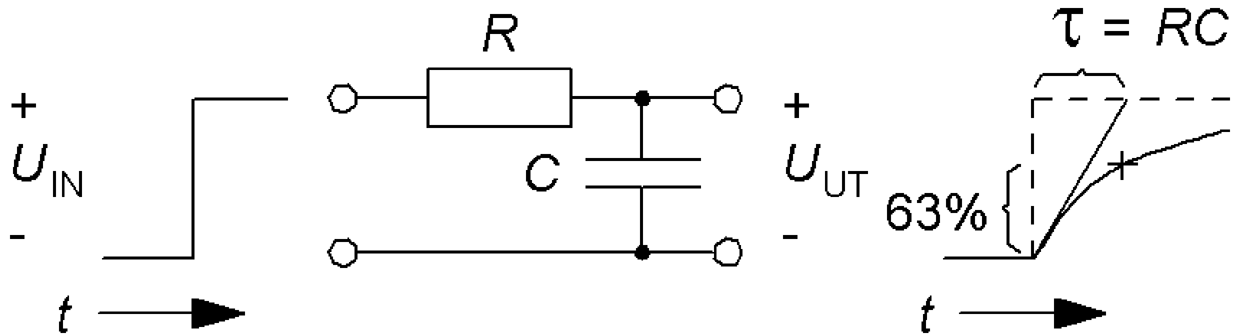
Phase plot [degres] ([rad]×180/π)

William Sandqvist william@kth.se

RC Two sides of the same coin

$$\omega_G = \frac{1}{\boxed{RC}} \qquad \tau = \boxed{RC}$$

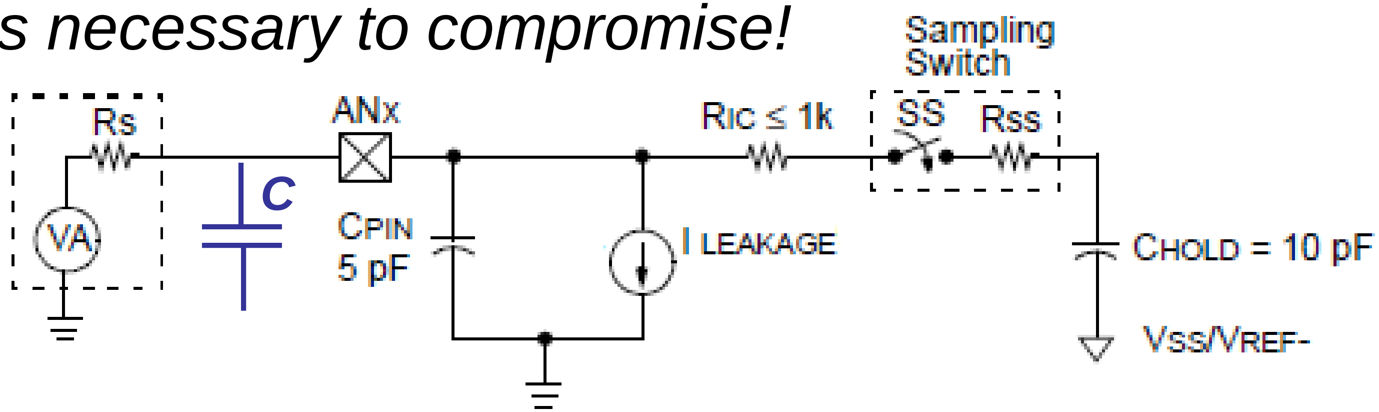
Low **cut off frequency** ω_G will supresses interference good, but it will also mean that the time constant τ is long so it takes time until U_{UT} reaches its final value and can be read.



William Sandqvist william@kth.se

(AD-converter LP-filter)

- *It is necessary to compromise!*



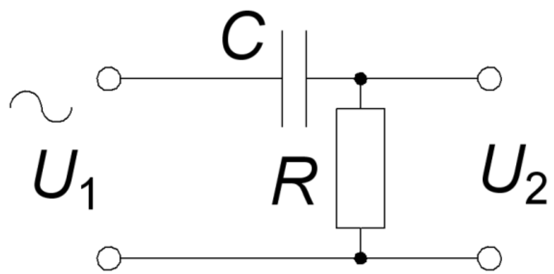
In order to remove noise from the input signal to the AD converter one usually add a capacitor ***C***.

- R_S must have no bigger value than 10kΩ – otherwise you risk losing accuracy because of the leakage current $I_{LEAKAGE}$.

- When the sample charge from ***C*** is taken to sampling capacitor C_{HOLD}. ***C*** should therefore be at least 1024 times greater than C_{HOLD} (10pF) if you do not want to lose accuracy.

- ***C***$\cdot R_S$ gives the cutoff frequency of how fast signals AD converter can follow.

RC HP-filter, jω



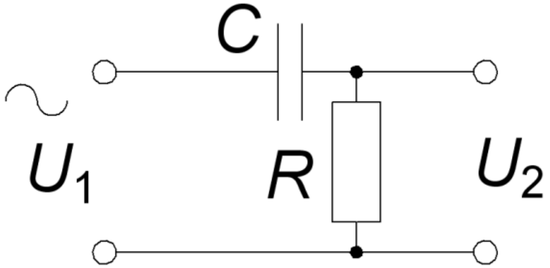
$$\frac{\underline{U}_2}{\underline{U}_1} = \frac{R}{R + \frac{1}{\mathrm{j}\omega C}} \cdot \frac{\mathrm{j}\omega C}{\mathrm{j}\omega C} = \frac{\mathrm{j}\omega RC}{1 + \mathrm{j}\omega RC}$$

$$\frac{U_2}{U_1} = \frac{\omega RC}{\sqrt{1 + (\omega RC)^2}}$$

$$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) = \arg(\mathrm{j}\omega RC) - \arg(1 + \mathrm{j}\omega RC) = \underbrace{90^\circ - \arctan\left(\frac{\omega RC}{1}\right)}_{= \operatorname{arccot}()} = \arctan\left(\frac{1}{\omega RC}\right)$$

William Sandqvist william@kth.se

RC HP-filter, $H(\omega)$

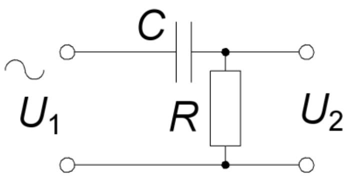


$$\boxed{\underline{H} = \frac{\mathrm{j}\omega RC}{1+\mathrm{j}\omega RC}} \quad \mathrm{abs}(\underline{H}) = \frac{\omega RC}{\sqrt{1+(\omega RC)^2}} \quad \arg(\underline{H}) = \arctan\left(\frac{1}{\omega RC}\right)$$

At the angular frequency when $\boxed{\omega RC = 1}$, will the numerator real part and imaginary part be equal. This is the filter **cutoff frequency**.

$\omega \approx 0$	$\omega << \frac{1}{RC}$	$\omega = \frac{1}{RC}$	$\omega \to \infty$
$\frac{U_2}{U_1} \approx 0$	$\frac{U_2}{U_1} \approx \frac{\omega RC}{1+0} \approx \omega RC$ stiger med ω 10ggr/dekad	$\frac{U_2}{U_1} = \frac{1}{\sqrt{1^2+1^2}} = \frac{1}{\sqrt{2}} \approx 0{,}71$	$\frac{U_2}{U_1} \to 1$
$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) \approx \arg\left(\frac{\approx \mathrm{j}}{1+0\cdot \mathrm{j}}\right) = \arg \mathrm{j} = 90°$	$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) \approx 90° - \arctan(\omega RC)$	$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) \approx 90° - \arctan 1 = 45°$	$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) = 90° - 90° = 0°$

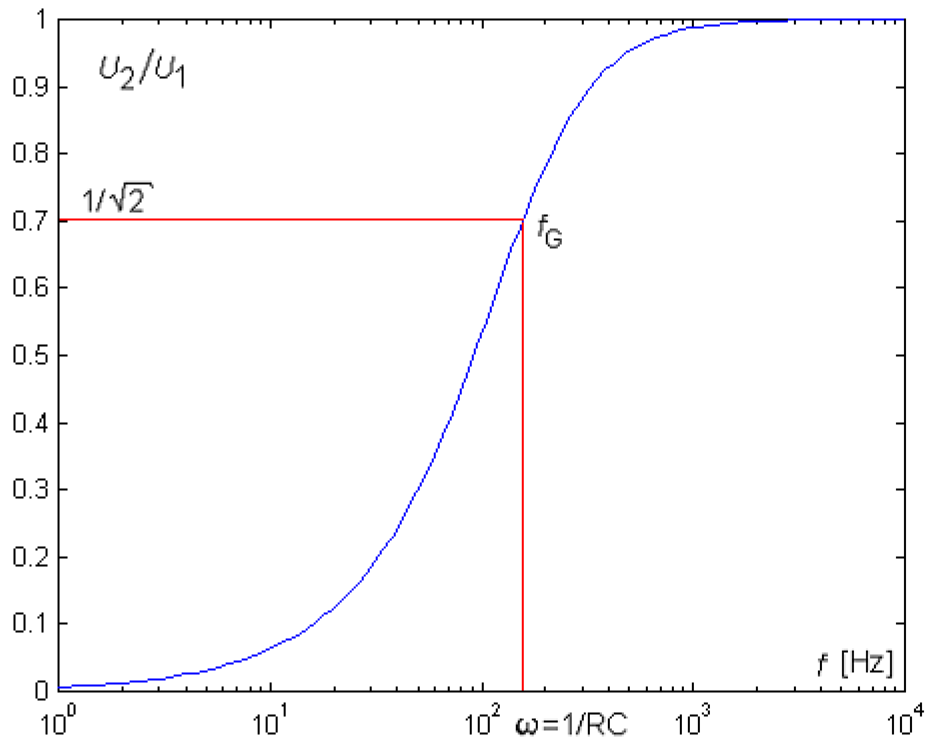
HP-magnitude function



$R = 1\ \mathrm{k\Omega}$

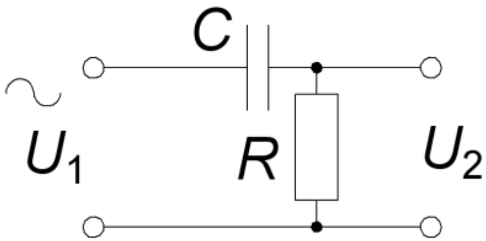
$C = 1\ \mu\mathrm{F}$

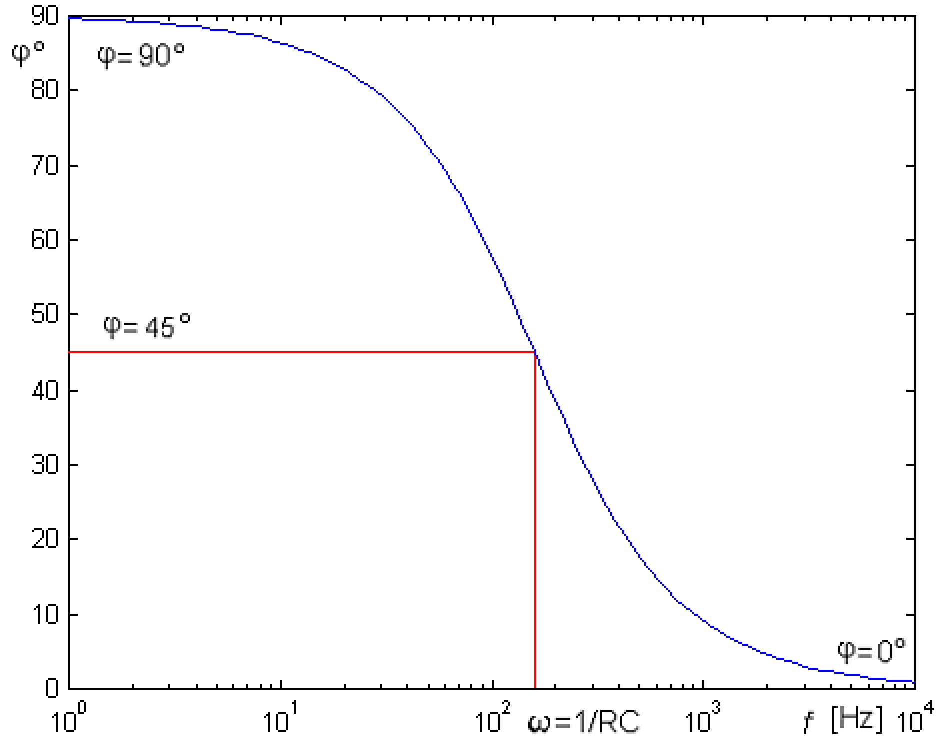
$$f_G = \frac{1}{2\pi \cdot 1 \cdot 10^3 \cdot 1 \cdot 10^{-6}}$$
$$\approx 160\ \mathrm{Hz}$$



$$\mathrm{abs}\left(\underline{H}\right) = \frac{\omega RC}{\sqrt{1 + (\omega RC)^2}}$$

HP-phase function

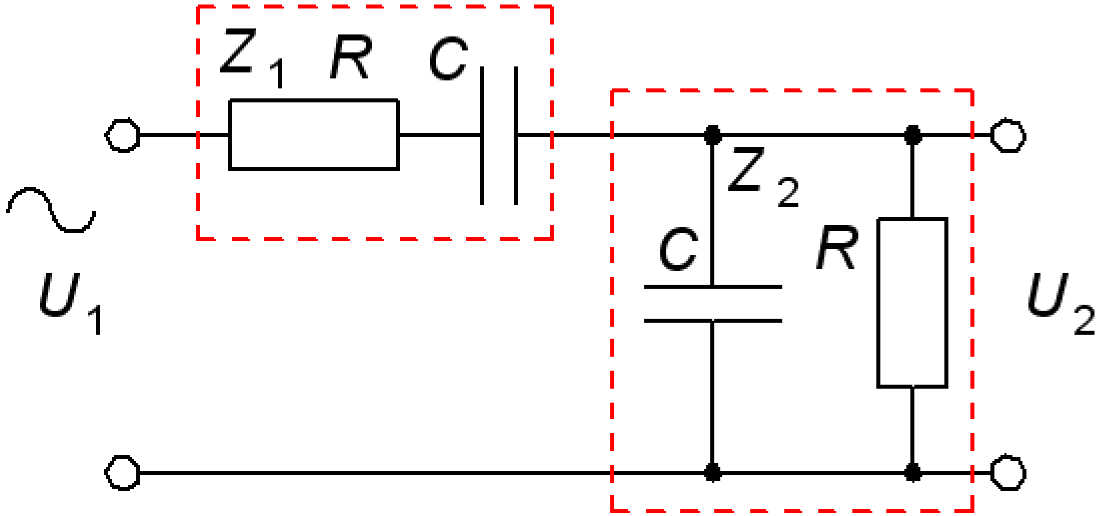




$$\varphi = \arg(\underline{H}) = \arctan\left(\frac{1}{\omega RC}\right)$$

Wien bridge (14.5)

Was investigated by Max Wien 1891

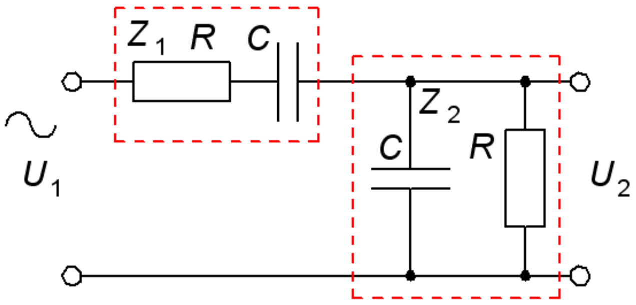


For a certain frequency U_1 and U_2 are in phase. What frequency?

Wien bridge

$$\underline{Z}_1 = R + \frac{1}{j\omega C}$$

$$\underline{Z}_2 = \frac{R \cdot \frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} \cdot \frac{j\omega C}{j\omega C} = \frac{R}{1 + j\omega RC}$$

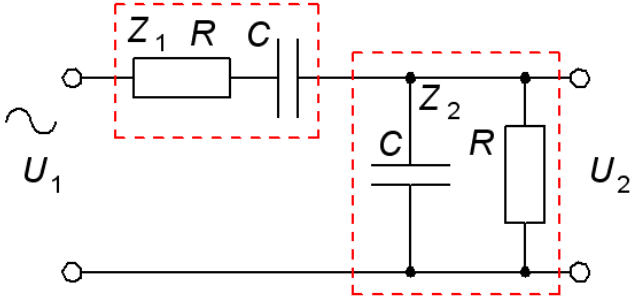


U_1 and U_2 are in phase if the transfer function imaginary part is 0!

Wien bridge

$$\underline{Z}_1 = R + \frac{1}{\mathrm{j}\omega C}$$

$$\underline{Z}_2 = \frac{R \cdot \frac{1}{\mathrm{j}\omega C}}{R + \frac{1}{\mathrm{j}\omega C}} \cdot \frac{\mathrm{j}\omega C}{\mathrm{j}\omega C} = \frac{R}{1 + \mathrm{j}\omega RC}$$



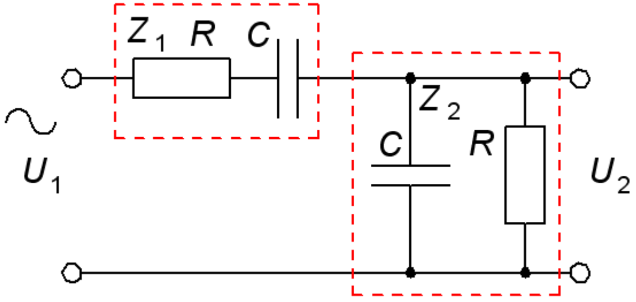
U_1 and U_2 are in phase if the transfer function imaginary part is 0!

$$\frac{\underline{U}_2}{\underline{U}_1} = \frac{\frac{R}{1 + \mathrm{j}\omega RC}}{R + \frac{1}{\mathrm{j}\omega C} + \frac{R}{1 + \mathrm{j}\omega RC}}$$

Wien bridge

$$\underline{Z}_1 = R + \frac{1}{j\omega C}$$

$$\underline{Z}_2 = \frac{R \cdot \frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} \cdot \frac{j\omega C}{j\omega C} = \frac{R}{1 + j\omega RC}$$



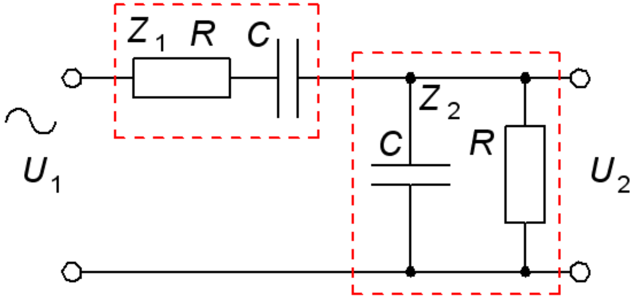
U_1 and U_2 are in phase if the transfer function imaginary part is 0!

$$\frac{\underline{U}_2}{\underline{U}_1} = \frac{\frac{R}{1 + j\omega RC}}{R + \frac{1}{j\omega C} + \frac{R}{1 + j\omega RC}} \cdot \frac{\frac{(1 + j\omega RC)}{R}}{\frac{(1 + j\omega RC)}{R}} = \frac{1}{R \cdot \frac{(1 + j\omega RC)}{R} + \frac{1}{j\omega C} \cdot \frac{(1 + j\omega RC)}{R} + 1} =$$

Wien bridge

$$\underline{Z}_1 = R + \frac{1}{\mathrm{j}\omega C}$$

$$\underline{Z}_2 = \frac{R \cdot \frac{1}{\mathrm{j}\omega C}}{R + \frac{1}{\mathrm{j}\omega C}} \cdot \frac{\mathrm{j}\omega C}{\mathrm{j}\omega C} = \frac{R}{1 + \mathrm{j}\omega RC}$$



U_1 and U_2 are in phase if the transfer function imaginary part is 0!

$$\frac{\underline{U}_2}{\underline{U}_1} = \frac{1}{1 + \mathrm{j}\omega RC + \frac{1}{\mathrm{j}\omega RC} + 1 + 1} = \frac{1}{3 + \mathrm{j}\omega RC + \frac{1}{\mathrm{j}\omega RC}} = \frac{1}{3 + \mathrm{j}\left(\omega RC - \frac{1}{\omega RC}\right)}$$

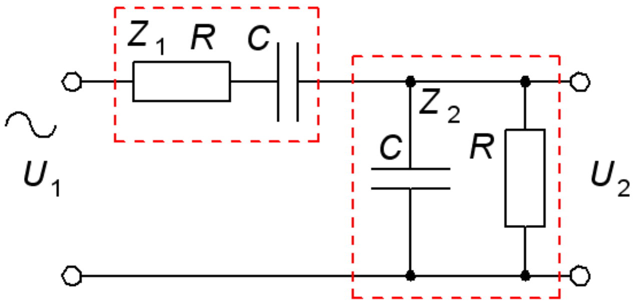
$$\left(\omega RC - \frac{1}{\omega RC}\right) = 0$$

William Sandqvist william@kth.se

Wien bridge

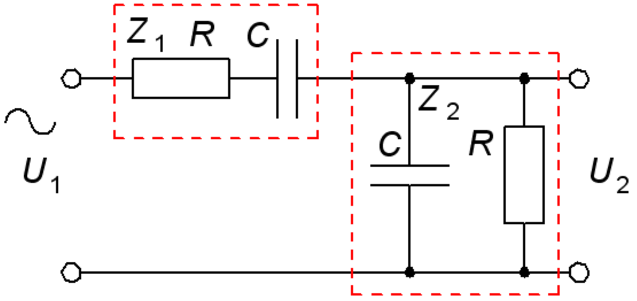
$$\frac{\underline{U}_2}{\underline{U}_1} = \frac{1}{3 + \mathrm{j}(\omega RC - \frac{1}{\omega RC})} \quad \Rightarrow$$

$$\omega RC - \frac{1}{\omega RC} = 0 \quad \Rightarrow \quad \omega_0 = \frac{1}{RC}$$

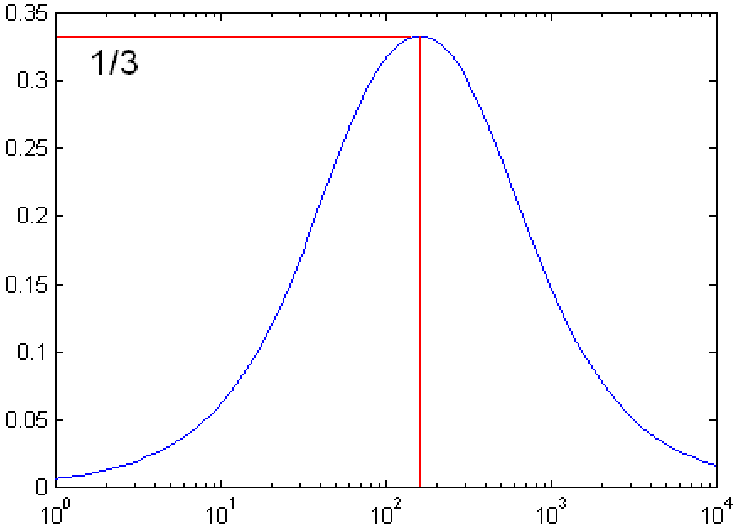


$\omega \approx 0$	$\omega = \frac{1}{RC} \quad (\omega RC - \frac{1}{\omega RC}) = 0$	$\omega \approx \infty$
$\frac{U_2}{U_1} \approx \frac{1}{\sqrt{\ldots + (-\infty)^2}} \approx 0$	$\frac{U_2}{U_1} = \frac{1}{\sqrt{3^2 + 0^2}} = \frac{1}{3} \approx 33\%$	$\frac{U_2}{U_1} \approx \frac{1}{\sqrt{\ldots + (\infty)^2}} \approx 0$
$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) \approx \arg\left(\frac{1}{\ldots + (-\infty \cdot \mathrm{j})}\right) = 90°$	$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) = \arg\left(\frac{1}{1 + \mathrm{j} \cdot 0}\right) = 0°$	$\arg\left(\frac{\underline{U}_2}{\underline{U}_1}\right) \approx \arg\left(\frac{1}{\ldots + \infty \cdot \mathrm{j}}\right) \approx -90°$

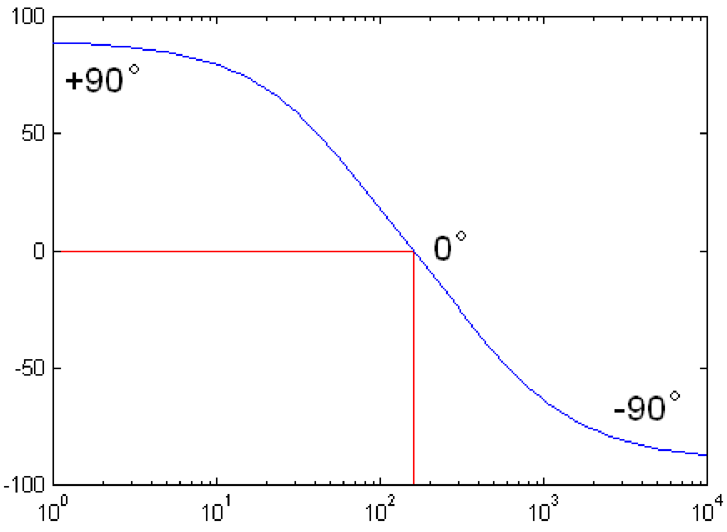
Wien bridge



$$\omega_0 = \frac{1}{RC} \qquad f_0 = \frac{1}{2\pi RC}$$



Magnitude plot



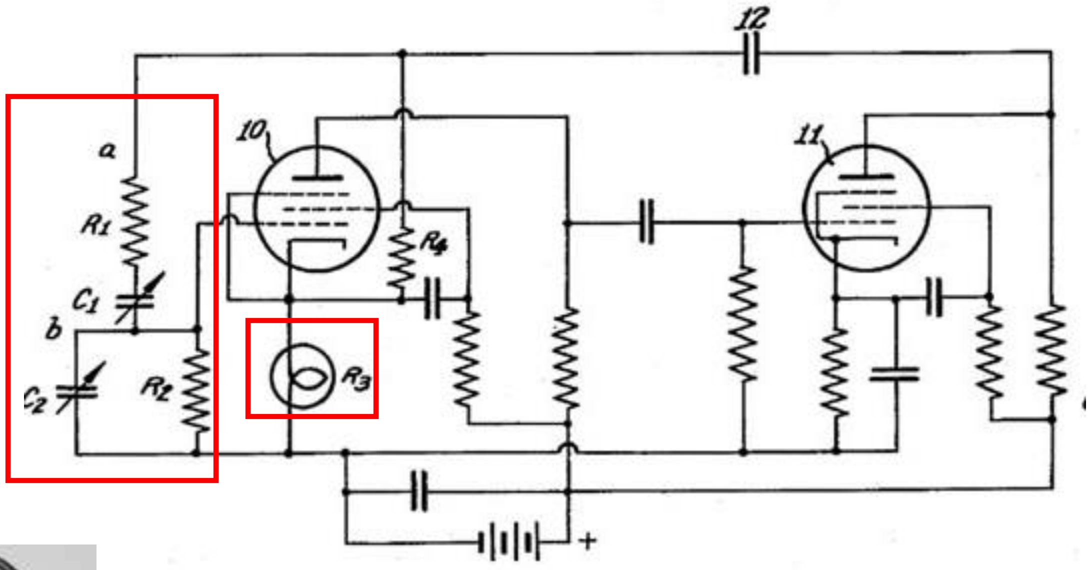
Phase plot

Wienbridge is a band pass filter.

William Sandqvist william@kth.se

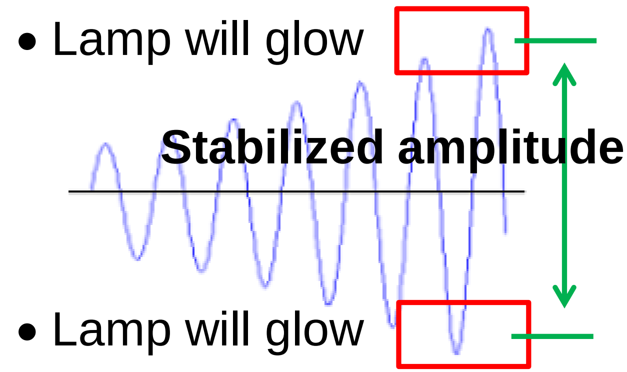
William Hewlett's master thesis

Master thesis 1930. Wien bridge with lamp!

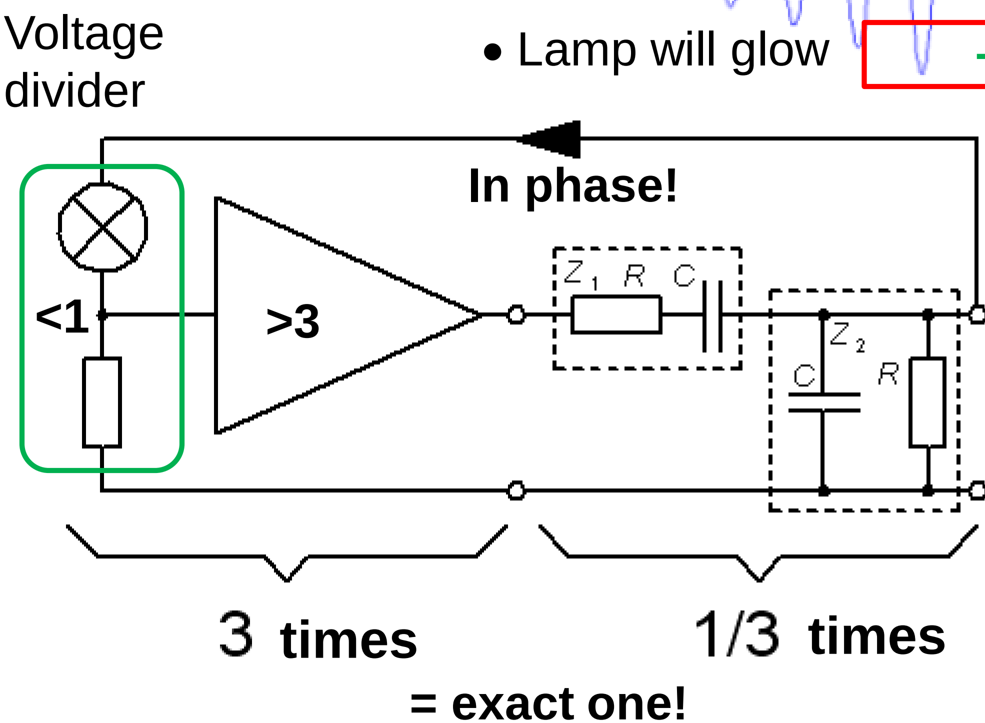


William Hewletts master thesis

Hewlett constructed a tone generator. Wien bridge attenuates the signal to **1/3** so he needed a amplifier with the gain exactly three times.



The bulb stabilizes the signal. If the amplitude becomes too large the lamp will glow and then the signal is attenuated in the voltage divider at the amplifier input.



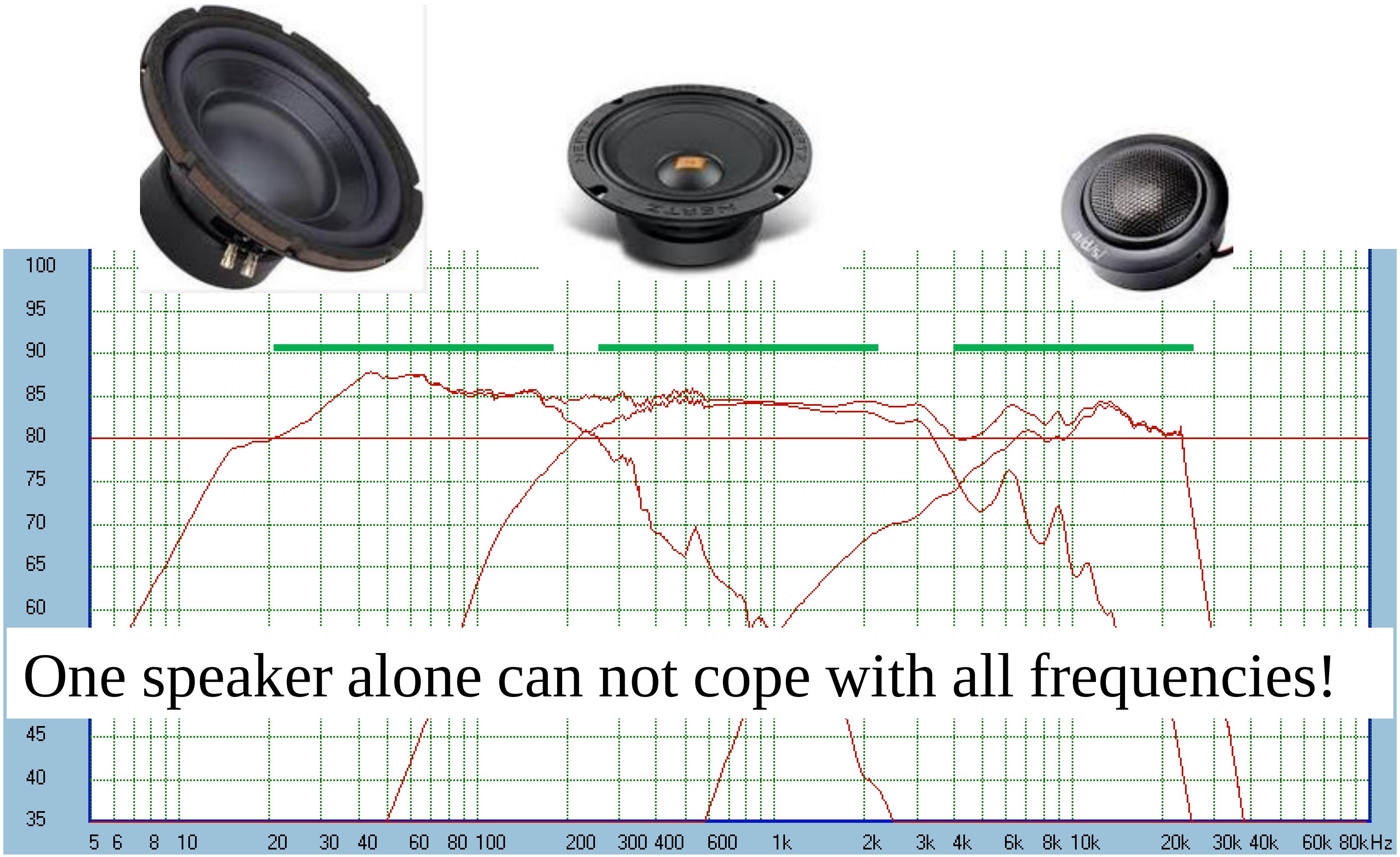
William Sandqvist william@kth.se

The Palo Alto garage
the birthplace of **Silicon Valley**

Which global business will you start with your thesis?

William Sandqvist william@kth.se

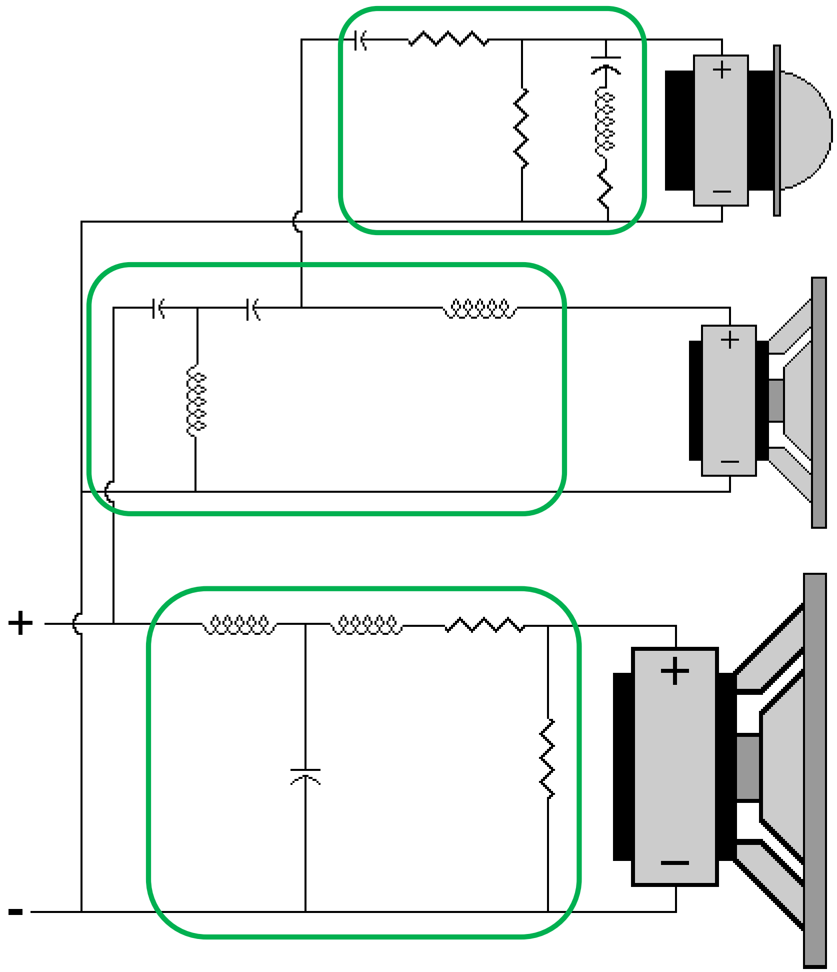
When are filters used?

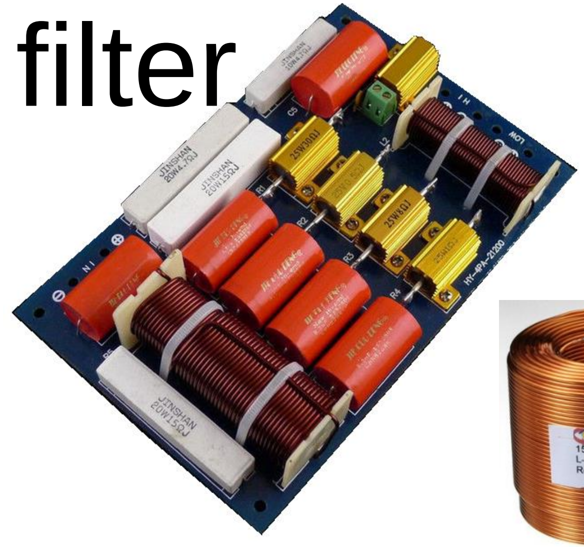


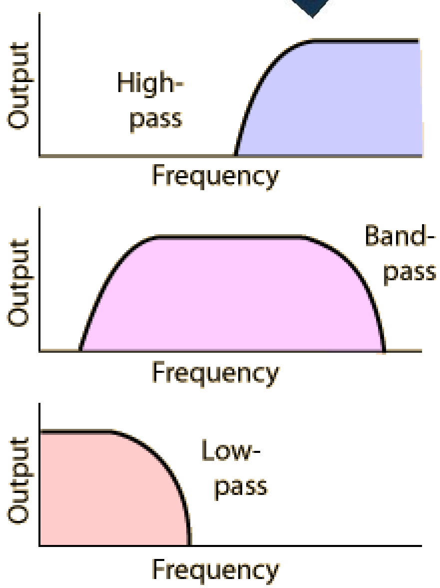
One speaker alone can not cope with all frequencies!

William Sandqvist william@kth.se

Cross over filter





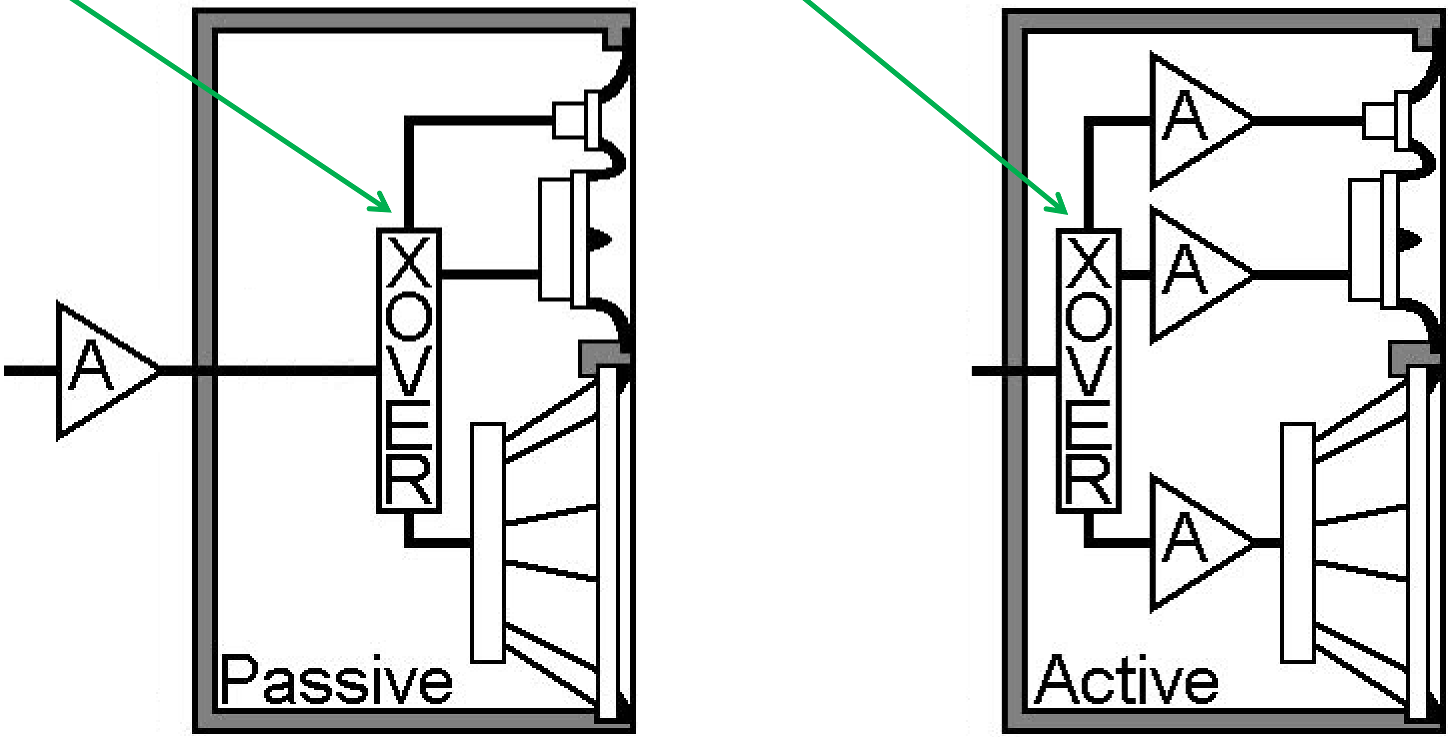


No iron core for audio.

The crossover filter split the frequencies between the speakers.

Passive/Active speaker

- **Analog** crossover filter *R L C*
- **Digital** crossover filter = computer program

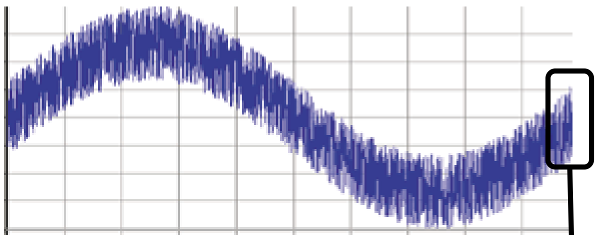


When the amplifier is built in the speaker it becomes possible to use digital crossovers. (XOVER = crossover filter)

William Sandqvist william@kth.se

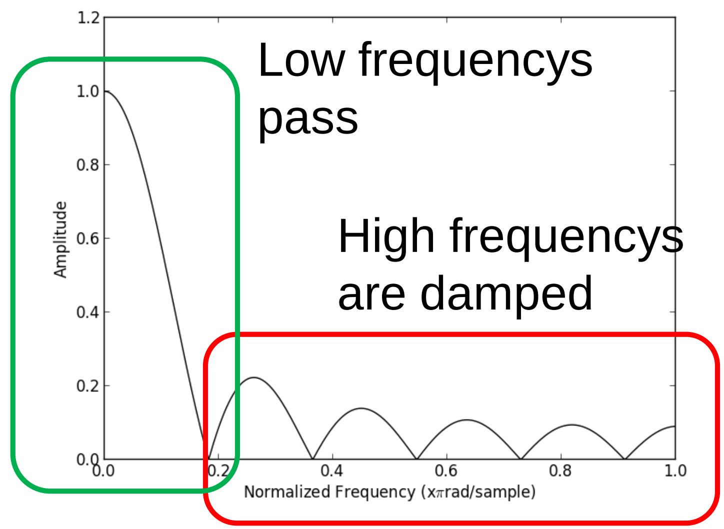
(Digital filter)

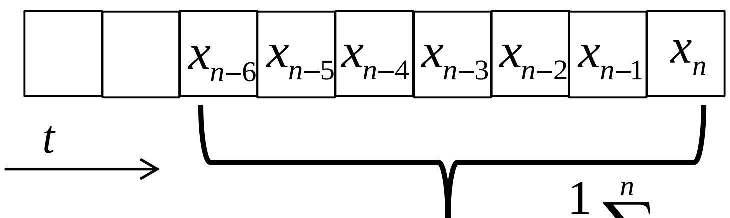
Ex. a "rolling" average of the 7 most recent readings.



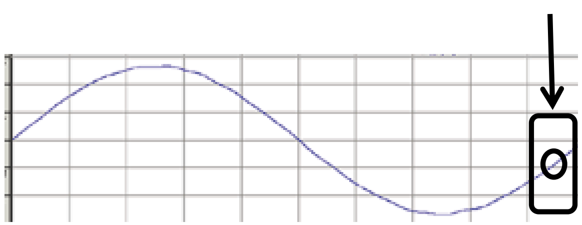
- Noisy signal

LP-filter





$$y_n = \frac{1}{7}\sum_{n-6}^{n} x_n$$



- Filtered signal

There are much better digital filters than this ...