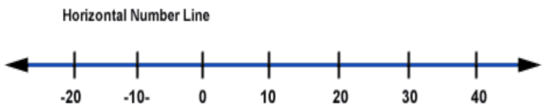
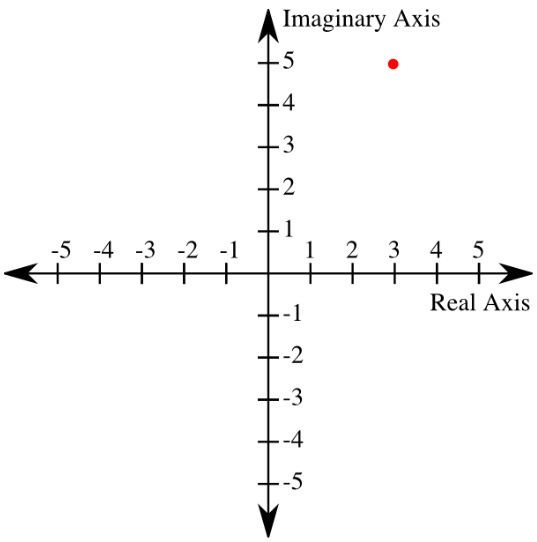
”in English” ☺

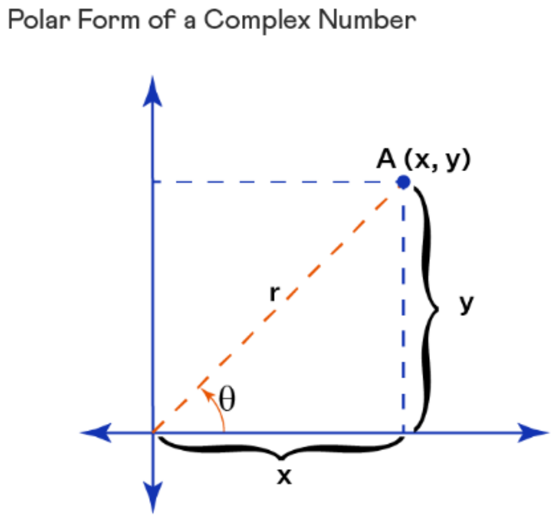
Complex Numbers



The Numbers, as we know !!



And the “new” numbers:



Notice: both **Rectangular** and **polar** form!!

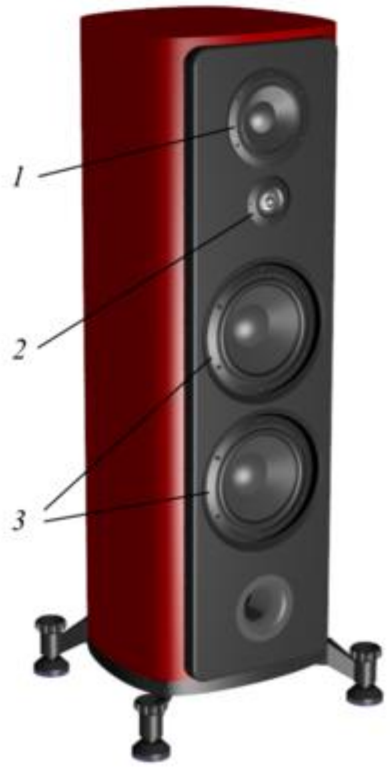
So **Why** new numbers ? - And - For what?

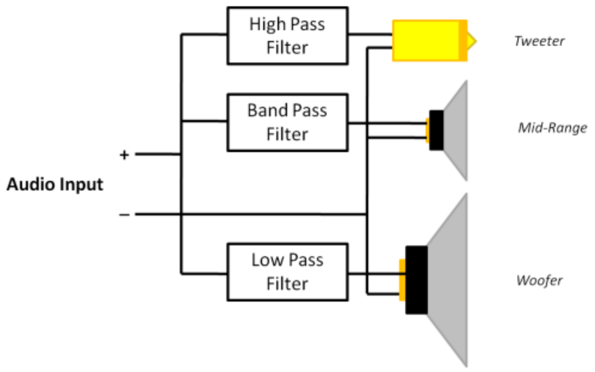
Example. We will examine a circuit

Filter for loudspeaker

Loudspeaker for home use with three types of drivers

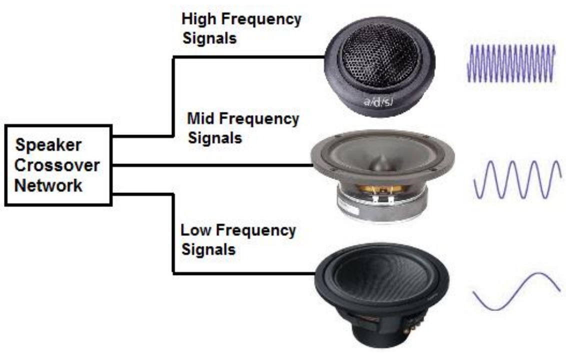
1. Mid-range
2. Tweeter (High frequencies)
3. Woofers (Low frequencies)





A small cone with a small weight can be accelerated as needed fort and back for generating high frequencies !!

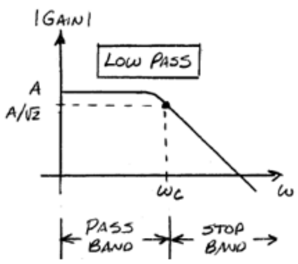
The Woofer is much bigger, with a bigger weight, and so, - only for low frequencies.

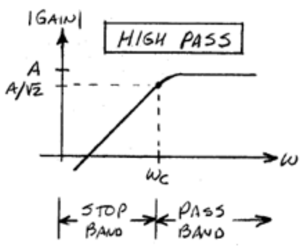


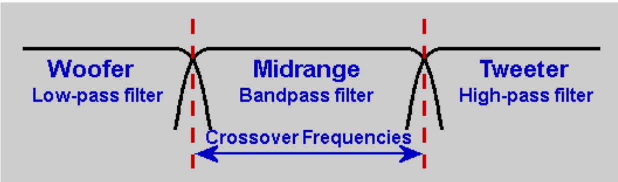
A filter guides low frequencies to the Woofer, high frequencies to the Tweeter, and mid-range frequencies to the Mid-range speaker.

Why? Because the Woofer is so big and heavy, it can´t move so fast. It´s too heavy to be accelerated !!
The Cone can produce high frequencies !

Electronic filters can be arranged to let low, mid or high frequencies pass from input to output.



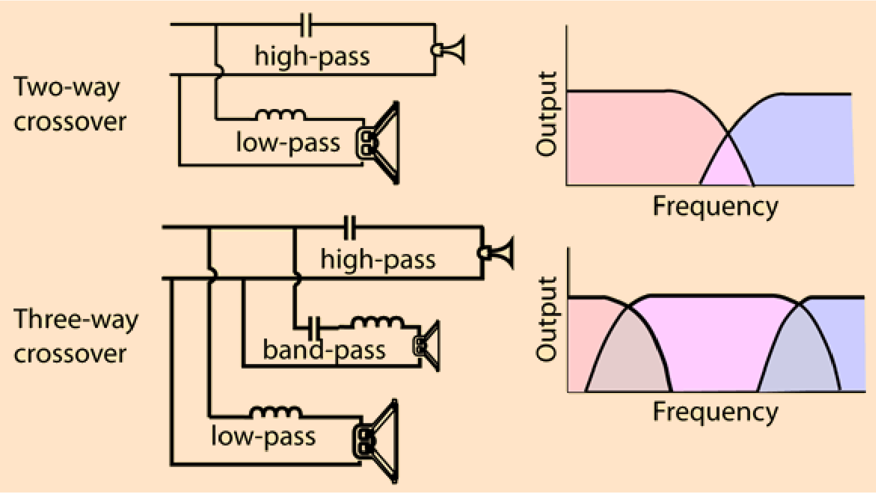




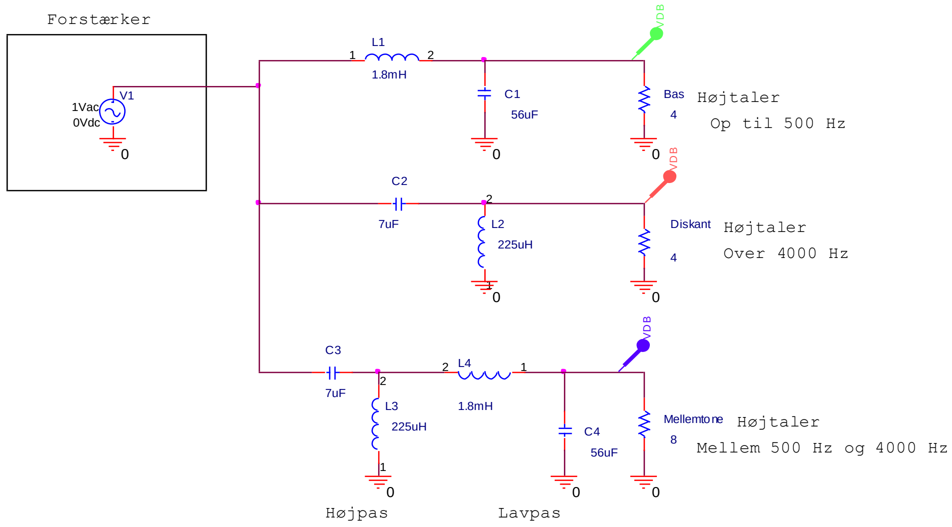
Note that the x-axis is showing the frequency

Here´s some examples how filters can be built.

There is used capacitors and coils.



Amplifier and filters:



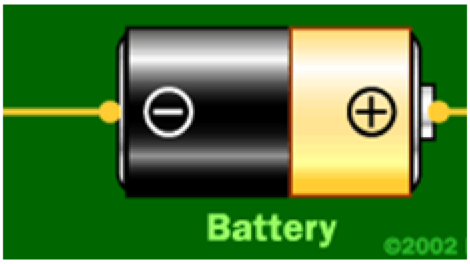
Circuit example:

(Simulation software)

In electronic circuits we find different basic components. **<u>Resistors</u>**, **<u>Capacitors</u>**, **<u>Coils</u>**, Transistors etc.

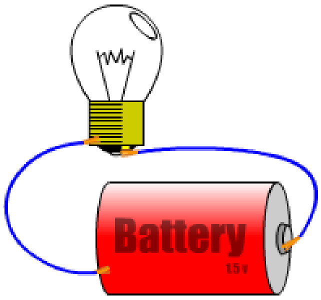
Different components **behave different**, and even different at different frequencies.

<u>We might first take a short look at a battery:</u>

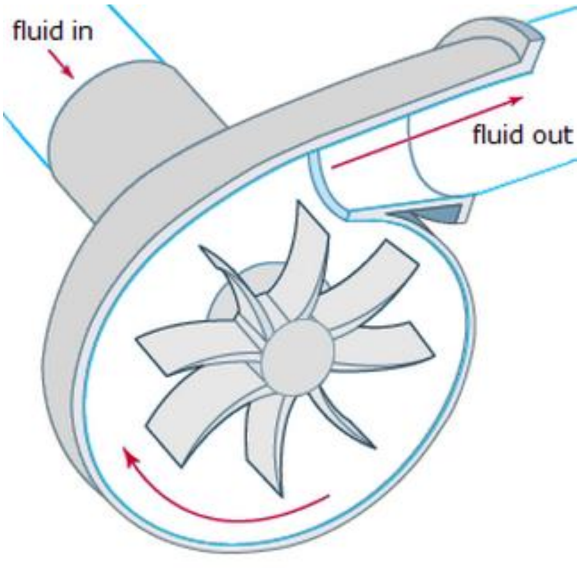


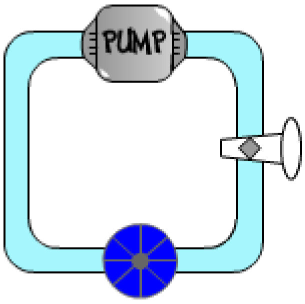
What does a battery really do ??

In a circuit the current is equal all over in the wire.



We can consider the Voltage as an Analogy to pressure in a water pipe.





The water is pressed up to a higher pressure by the pump. It flows to the water-motor forcing it to turn. Thus transferring energy to the motor.

And the water returns to the pump.

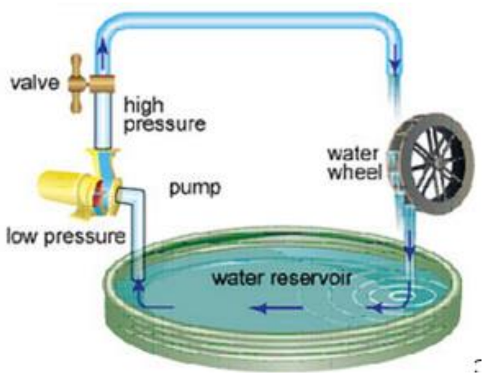
http://www.wermac.org/equipment/pumps_centrifugal.html

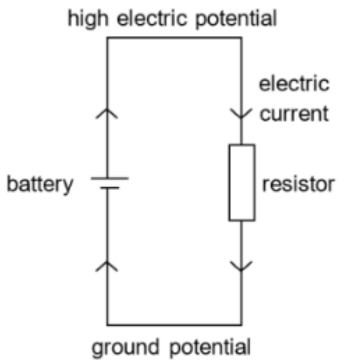
http://www.bgfl.org/bgfl/custom/resources_ftp/client_ftp/ks3/science/elecricity_2/electricity.html

We have a battery giving pressure to electrons.

The current flows trough the resistor and heats it up. Delivering energy to it.

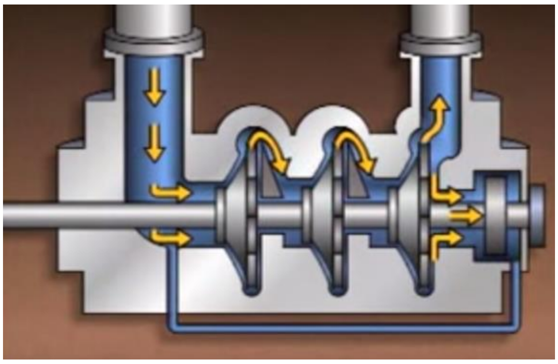
Energy have been tranferred from the battery to the resistor.

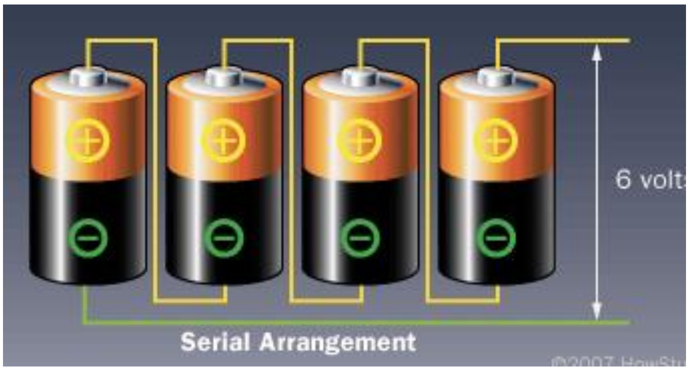




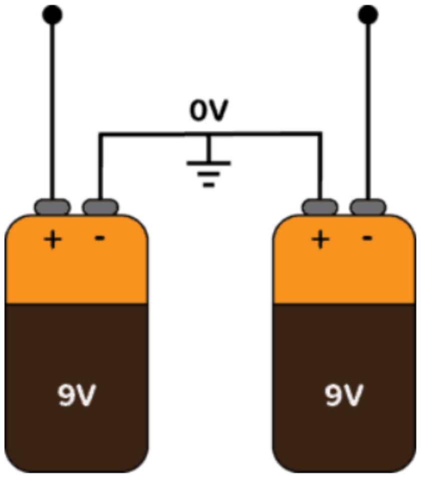
Just like the water-motor.

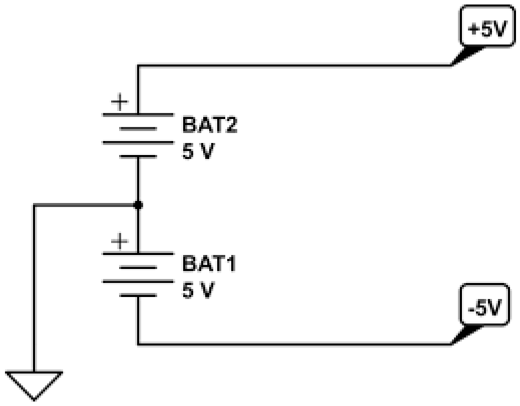
Here´s how we get higher pressure = higher voltage.





Positive / negative voltage ?? !





https://www.build-electronic-circuits.com/what-is-negative-voltage/

Why does a resistor get heated by flowing current ?

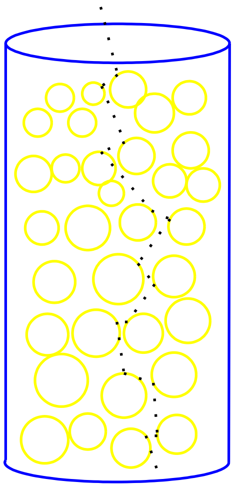
(short)

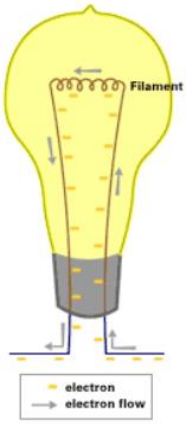
Potential energy and Kinetic energy

Pipe filled up with Coconuts.

Small pieces of sweets. Accelerated by the gravity.

In the electric world its electrons accelerated, gaining kinetic energy, in the electric field !!





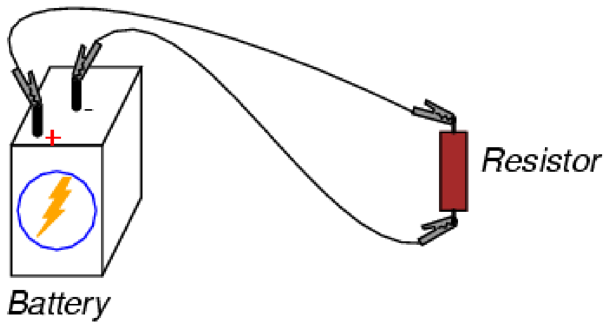
The heat makes electrons in the filament material jump to an Excited state. When returning, radiation is emitted.

Let's examine a resistor and a capacitor:

Resistor:

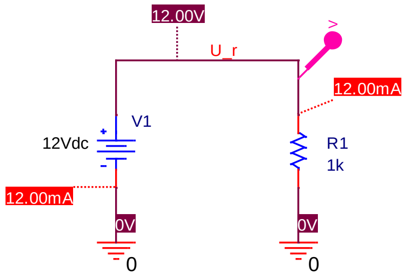
If a voltage generator, (giving the electrons pressure) is applied to a resistor, we can measure a current flowing in the wire.

If the voltage is constant, we can measure the same current over time. The current is constant.



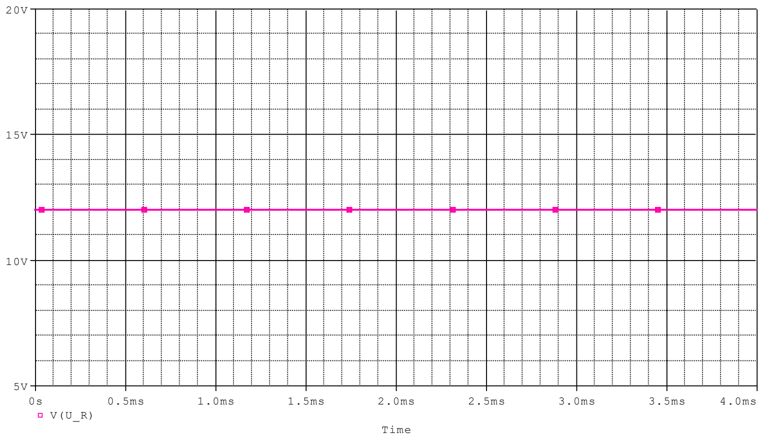
It Follows Ohms Law, $U = I \cdot R$

Here we´ll take a look at some software for simulating circuits. It shows these graphs:



The circuit.

Direct voltage

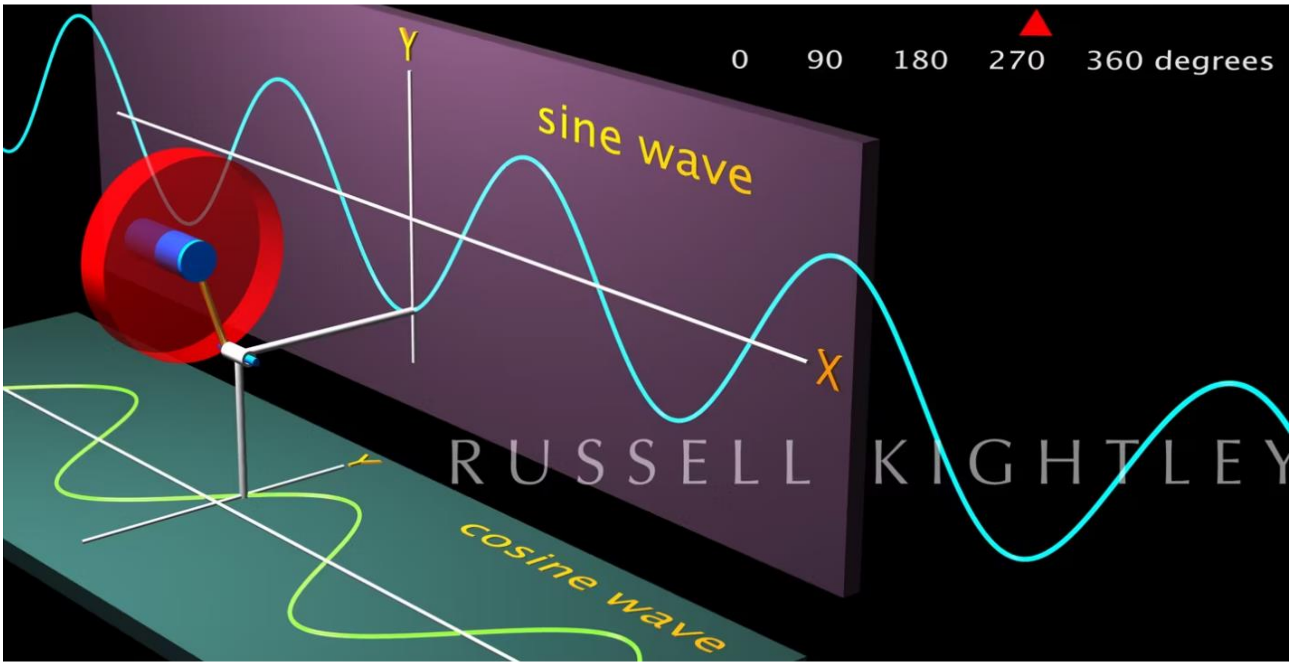


And the graph:

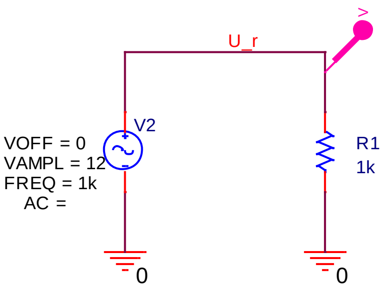
Alternating Voltage

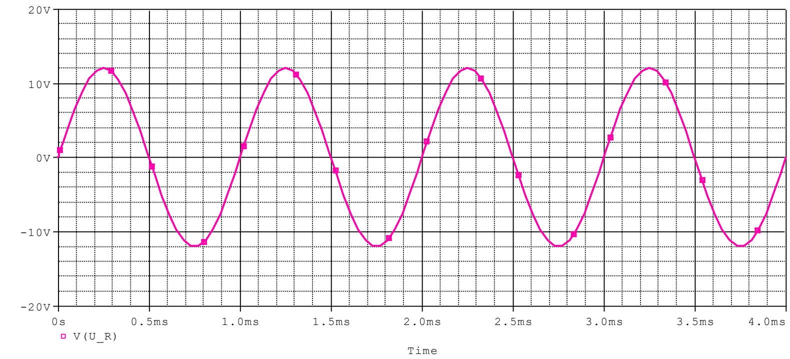
If we now apply an alternating voltage to a resistor, i.e., a sine wave:

Graph showing how a sine wave can be drawn



Se: https://rkm.com.au/ANIMATIONS/animation-sine-wave.html

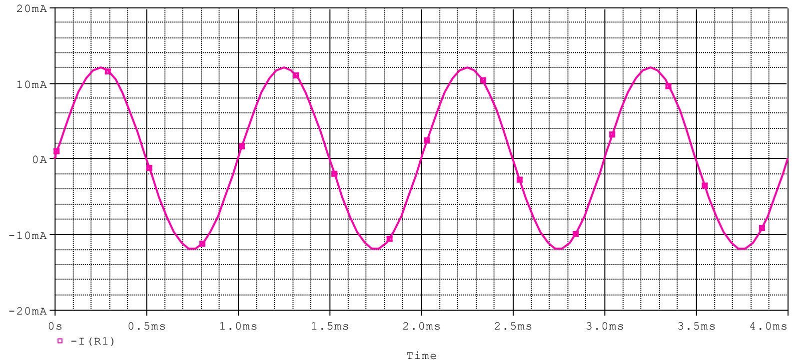




The frequency here is chosen to be 1000 Hz. And the peek voltage is set to12 Volt.

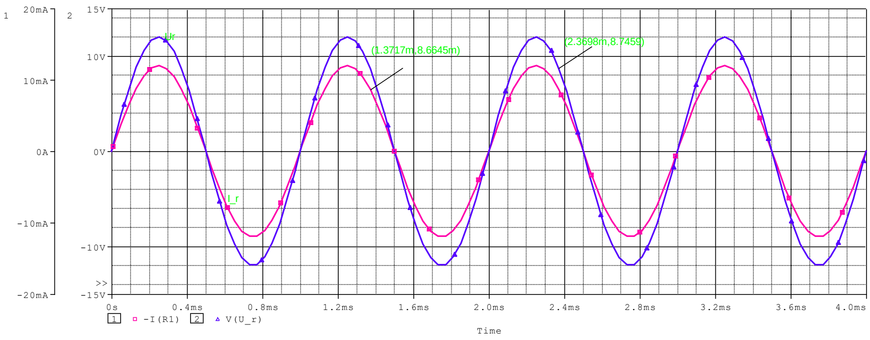
A graph for the current looks like this:

When the voltage is zero, the pressure also zero, thus the **Current** is zero.



Put together:

Obs.! Different Y-axis!!



We see, that when the voltage is zero, the current also is zero. And, - When the voltage is at its highest, the current also is at its highest.

Thus:

If a changing voltage is applied directly to a resistor, we find, that the current also changes, - proportional to the voltage.

The generator pumps the charges forward and back.

It's the same electrons that are pushed a bit forward and again back again according to the frequency. In a Sine shape.

The charges only travel very short distance, less than 1 mm!! But all the electrons push to the next, and they push to the next etc.

Just like a long train. Each wagon pushes the next. They all have the same speed. Just moving a bit back and forth!

Phase angle:

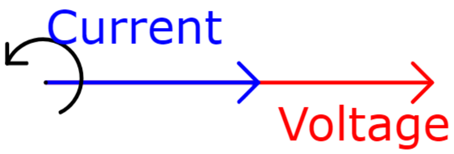
Also, we see in the graph above, that the current and voltage are in phase. They are present at the same time!

If two things are out of phase with each other, they are not working or happening together as they should. If two things are in phase, they are working or occurring together as they should.

The phase-angle is = 0.

Drawn with a vector-diagram it´ll look like this:

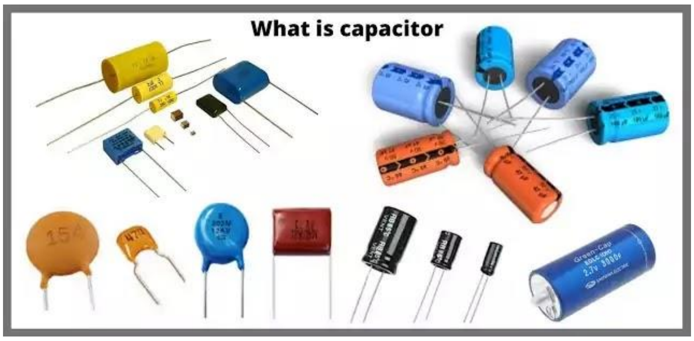
One whole turn equals each whole sine wave.



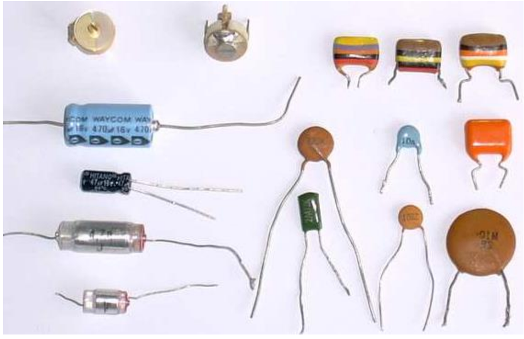
The angle between the **Voltage** and **Current** is called Fi, φ. The angle between them are 0 degrees.

Capacitor

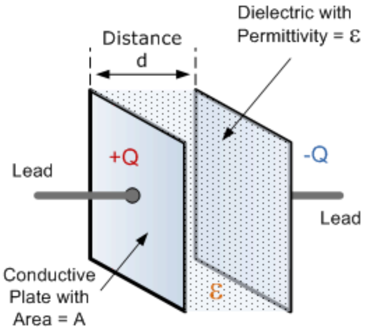
Now let´s examine a capacitor:

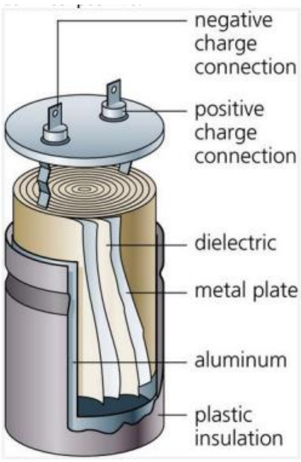


Different capacitors:



A capacitor just consists of two conductive plates, insulated from each other.



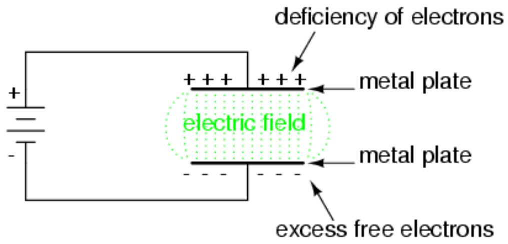


We can perceive a capacitor as a kind of small rechargeable battery.

But here with the energy stored in the electrical field between the plates, - instead of in the chemicals inside the battery.

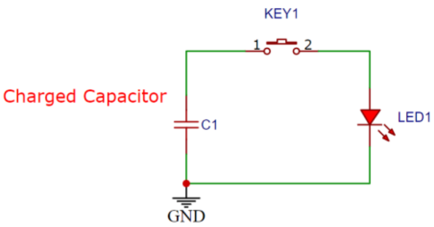
When a capacitor is charged, current flows to the one side, and electrons are stopped there and stored.

But from the other side **just as many** electrons leaves the plate. Leaving "**holes**".



Energy thus is stored in **charge separation**.

If we take the charged battery out of the circuit, the energy remains inside, in Charge separation, producing an **electrical field**. And can be used later



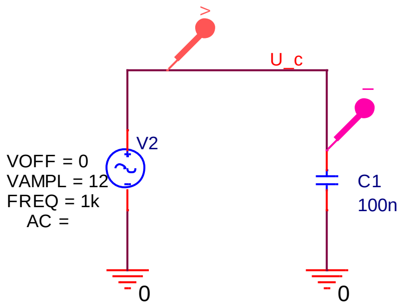
The energy in a capacitor is given by:

$$E = \frac{1}{2} \cdot C \cdot V^2$$

Now we apply a voltage generator directly to a capacitor.

The capacitor-voltage will always be the same as the voltage of the voltage-generator.

It means, that the charging of the capacitor happens immediately if the applied voltage changes.



The capacitor is charged up and down as the applied voltage changes.

To charge a capacitor, electrons are moved, a current is flowing to / from the capacitor.

If the voltage across the capacitor is changing fast, the current must be bigger.

If the voltage across the capacitor doesn't change up or down, the current must be zero.

This happens when the applied voltage is in its top or in bottom of the sine wave.

Here the slope of the **sine voltage** is **zero**. $\frac{dU}{dt} = 0$

So: At max voltage, $U_{C\text{-max}}$, the current Ic = 0. (Same for max negative voltage.)

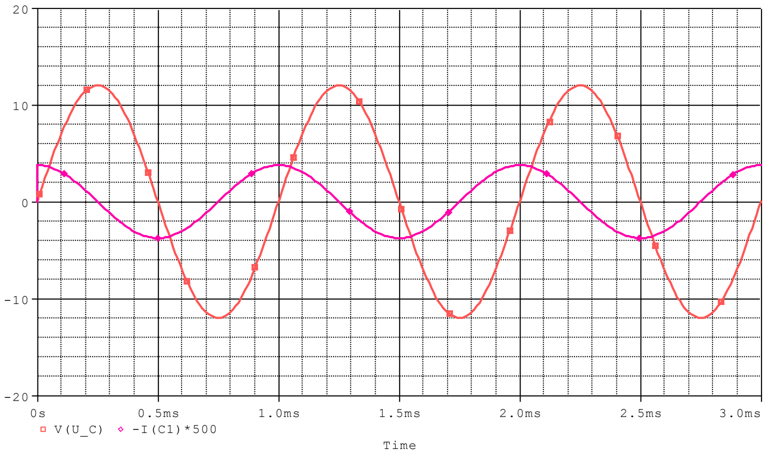
And when the voltage crosses zero, its slope is max. $\frac{dU}{dt}\ is\ biggest$

Thus, when the voltage change is biggest, the current will be biggest.

That's when the voltage is crossing zero.

On a graph it looks like this:

Just as expected.



Graph for the voltage and the current in a capacitor. The phase angle Φ = 90 degrees

We see that the current is before the voltage.

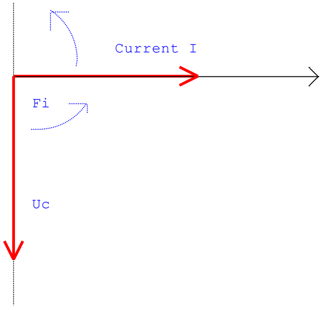
Thus:

In a capacitor, the Current leads the Voltage by 90 degrees.

In a vector diagram it can be drawn like this:

The phase shift is 90 degrees.

The Current is 90 degrees in front of the voltage



Examples of phase shift

We might know the phase shift concept from our daily life.

The highest temperature normally is about a month after midsummer

The coldest period is after Dec. 21. It lags the calendar.

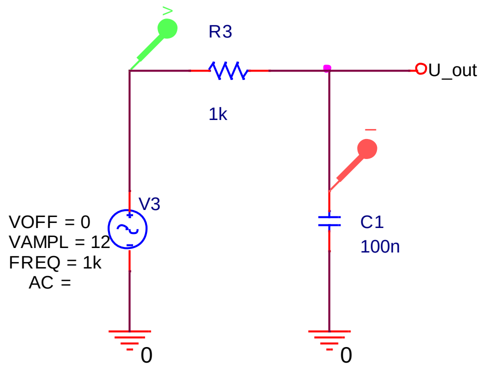
Also, our day is phase shifted. Our waken period is not centered around noon when the sun is at its highest.

RC-Circuit

Now we combine a resistor and a capacitor:

We apply a sine voltage to a resister in series with a capacitor

Still with 12 Volt and 1 KHz applied.



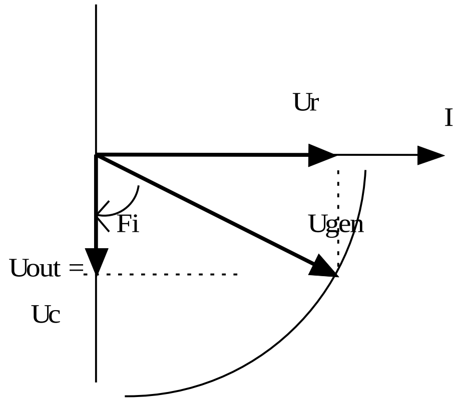
The applied voltage is divided between the resistor and the capacitor.

When the current is flowing, same amount flows in all components. It cannot be stored anywhere.

Like all wagons in a train have same speed!

The current is equal in both components. It´s common to draw it on the X-axis.

From before we know that the voltage across the resistor is present, when current flows.



Vector diagram for U_R, U_C and U_{GEN} in a RC-circuit.

The current in the capacitor is in front of the voltage, thus the capacitor voltage is drawn downwards.

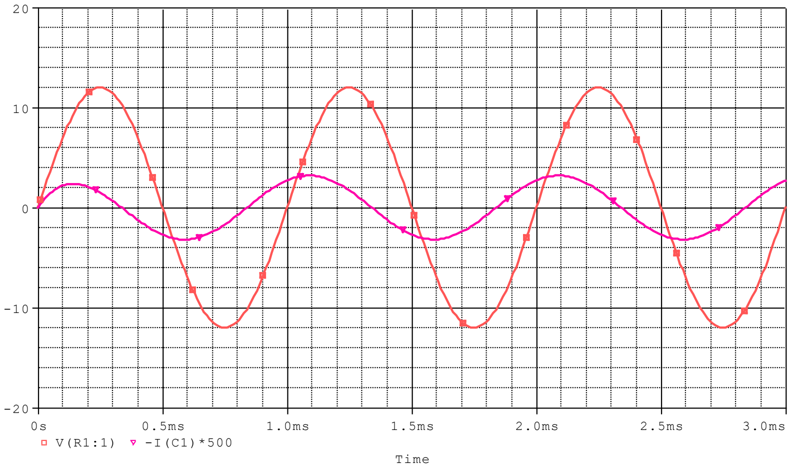
The applied voltage is then found as the geometric sum of $U_{resistor}$ and $U_{capacitor}$.

They can't be added directly because they both have **value** and **direction**. And different !!

In the circuit, we are interested in U_{OUT}. And U_{OUT} is equal to U_C, and is lagging the generator voltage.

We have a phase angle between $U_{generator}$ and U_{out}. Called φ, "Fi".

The graph again:

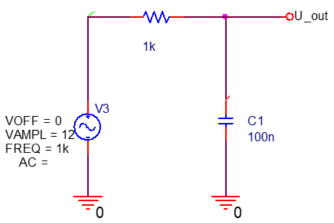


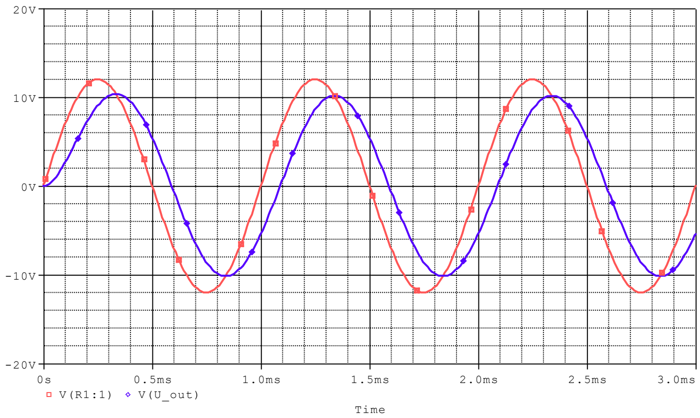
On a graph it looks like this example:

Now the phase between the voltage and current has changed.

And if we examine the **output voltage,** we get these graphs:

The output lags the applied voltage!

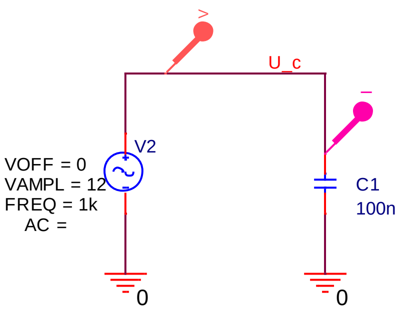




<u>The resistance of a capacitor is frequency dependent</u>

In a normal resistor, the resistance always is the same value, no matter the frequency.

But in a capacitor we find, that if we increase the applied frequency, that means faster charging and discharging, the current has to be bigger in order to charge up and down the capacitor.

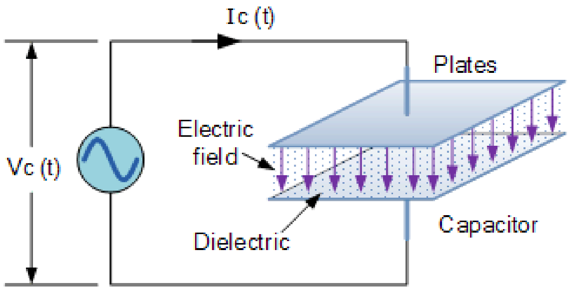


Thus, the more charges can be measured flowing fort and back, the bigger the current must be!

And the bigger current, ***<u>the smaller the resistance in the capacitor seems to be</u>***.

The resistance in a capacitor can be calculated from:

We see the frequency dependency:



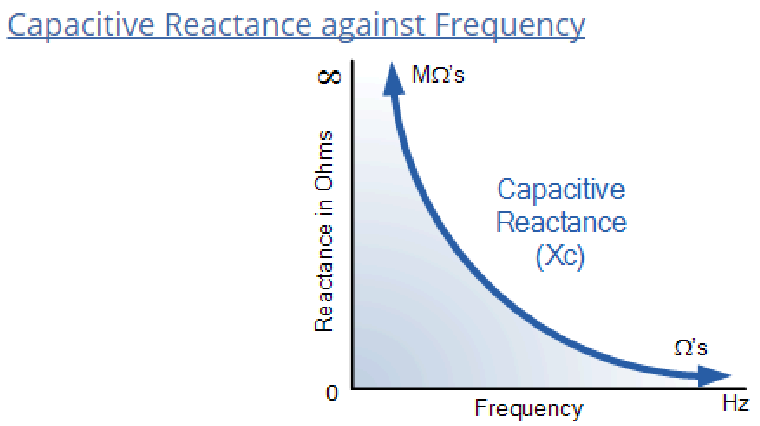
$$Xc = \frac{1}{2\pi f C}$$

Capacitive Reactance Formula

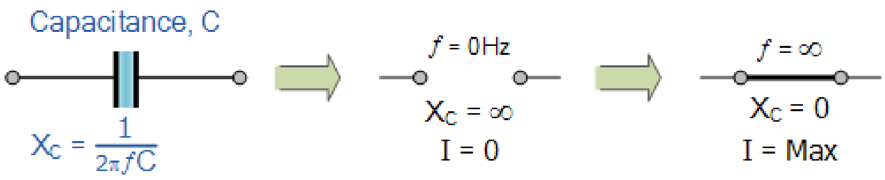
And a graph:

The higher the frequency, the lower the resistance in a capacitor.

The resistance is called Xc.
Or Reactance.



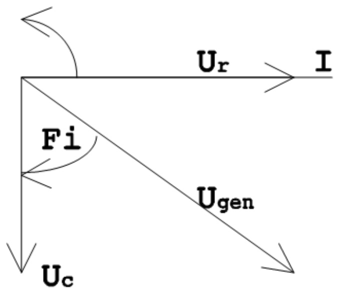
Xc at different frequencies

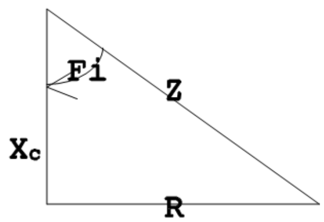


So,

when the frequency is changed, it has to give an influence on the vector diagram

We'll see more later





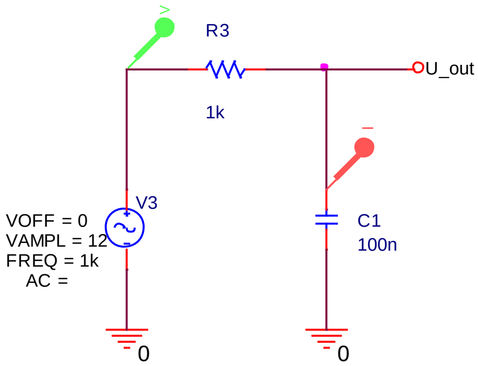
The RC-circuit seen as a voltage divider

Again a look at the RC circuit.

It is a voltage divider

It's also called a "Low Pass" circuit.

Why?

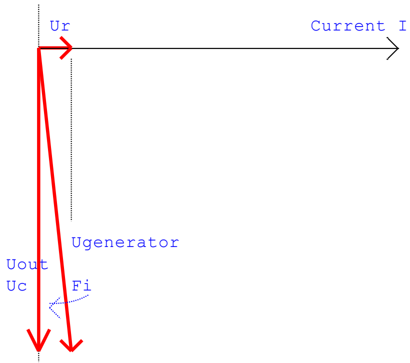


First we look **at low frequencies**

The capacitor don´t steel much of the signal

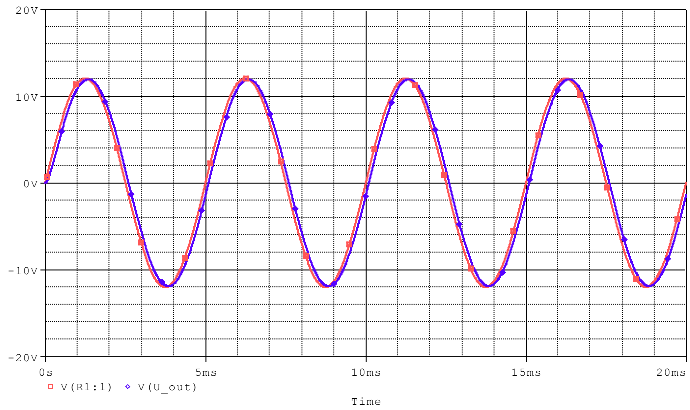
There´s time enough to charge and discharge the capacitor.

Thus: U_{Out} is nearly equally to U_{In} at very low frequencies.



Here a frequency of 200 Hz is applied.

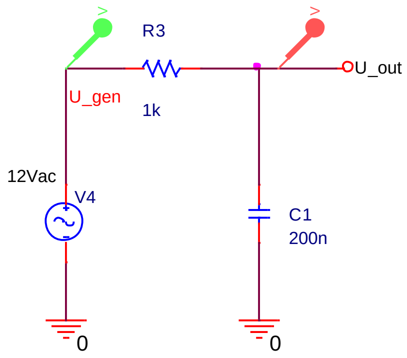
We see the output voltage is close to the input voltage



At high frequencies

Xc will be low, nearly a short circuit. The capacitor attenuates or steels the signal, U_{out} is very low.

There isn't time enough to charge totally up and down for each cycle

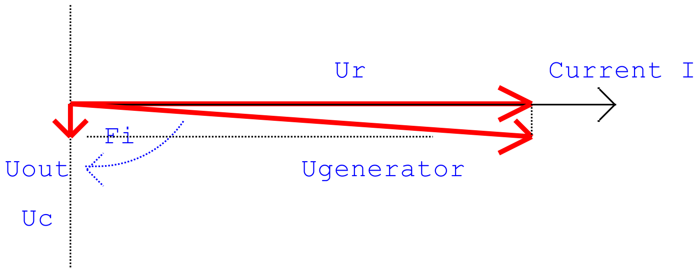


Thus the voltage across the capacitor will not change much.

I.e. At high frequencies the capacitor will be nearly a short circuit, because the Xc is very small

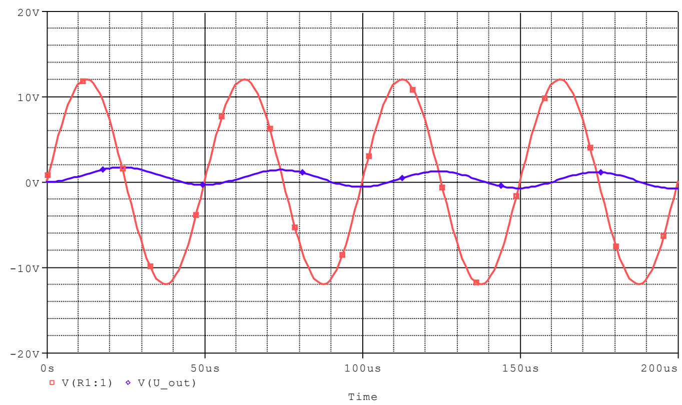
At high frequencies the U_{Out} – signal is attenuated!

In a vector diagram it will look like this:



Here 20 KHz is applied.

The output voltage is very low!

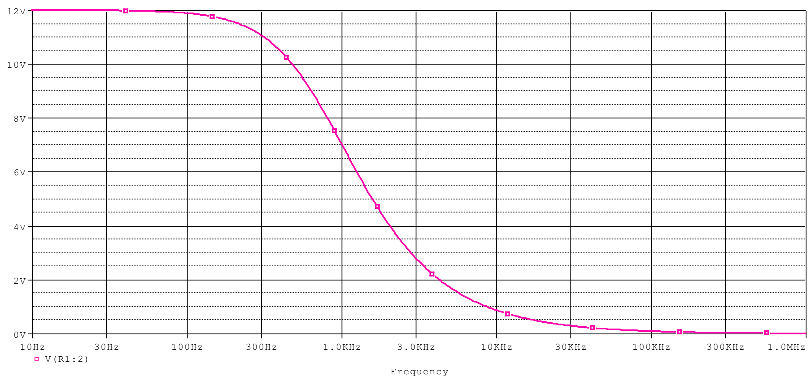


A graph for a frequency sweep can show the **output voltage** like this:

Graph for “ all “ frequencies:
From 10 Hz to 1 MHz.

At low frequencies the output voltage is equally to the input voltage.

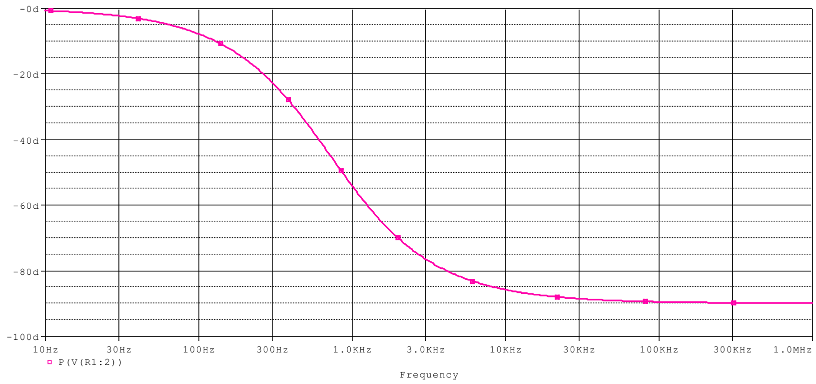
They can “ pass “ the circuit.



And we see, for high frequencies, the output voltage is very low.

This gives the name to the circuit: Low Pass Filter. Low frequencies passes, the high frequencies is attenuated by the filter.

And the phase angle:



Calculating the phase angle:

U_C is behind $U_{Generator}$. The angle "fi" gives the phase angle. The angle between U_{gen} and U_{Out} can be calculated by:

$$\text{Tangent "fi"} = \frac{\text{Opposite}}{\text{Adjacent}} = \frac{U_R}{U_C} = \frac{R}{X_C}$$

$$\text{"fi" then is} \quad tg^{-1}\left(\frac{R}{X_C}\right)$$

Obs. Frequency dependent because Xc is frequency dependent!

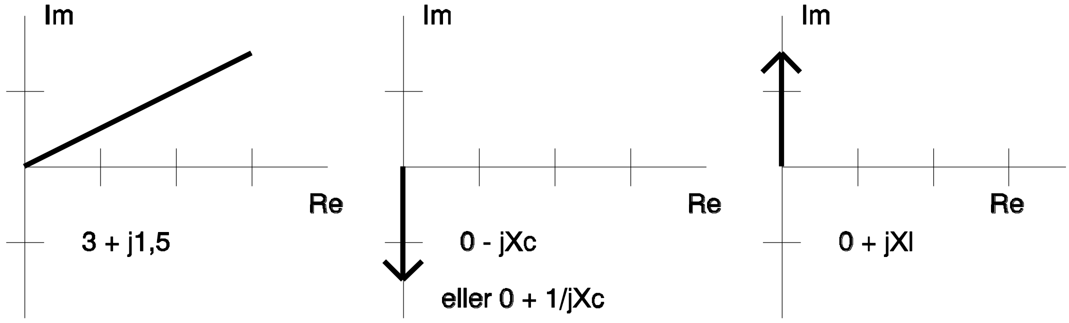
Use of complex numbers.

If now we want to use math to describe the graphs for output Voltage and Phase-angle as function of the frequencies, and we know, the vectors have different directions, we might get a bit stuck.

Here we need to use complex numbers to describe the vectors, or the phase angle between voltage and current.

We find:

A random vector, Capacitor Coil



In electronic ‘j’ is used instead of ‘i’ – for describing the imaginary axis!!

The j tells us that the vector is 90 degrees out of phase.

+j is upwards, -j is downwards

When we consider a resistance ac complex, - out of phase – we use Z instead of R for the resistance

Resistor:

A complex notation for a resistance in a resistor will be: "j0" tells, that the resistor has no imaginary part, thus pure reel.	$Z_R = R + j0$

Capacitor:

For the capacitor, in Complex notation we find, that The vector starts in Origo, and the minus tells, it´s pointing downwards	$Zc = 0 - jXc$

Previously we found the resistance in a capacitor to be calculated from:

$$X_C = \frac{1}{2 \cdot \pi \cdot f \cdot c}[\Omega]$$

So, we get:

$$Zc = 0 - j\frac{1}{2\pi fC}$$

And, because $2\pi f C$ also can be written shorter as ωC , (omega * C) we can write:

$$Zc = 0 - j\frac{1}{\omega C}$$

Or, because $$-j\ \frac{1}{\omega C} = -\frac{j}{\omega C} = -\frac{j \cdot j}{j \cdot \omega C} = \frac{1}{j\omega C}$$

$$Zc = 0 + \frac{1}{j\omega C}$$

Notice that j*j = -1 !

But why is j^2 = -1 ??

The complex vector j can be described as 0 + j1. Meaning, 0 along the x-axis, and 1 upwards

In polar form it equals 0 + j1 = 1 ∠90

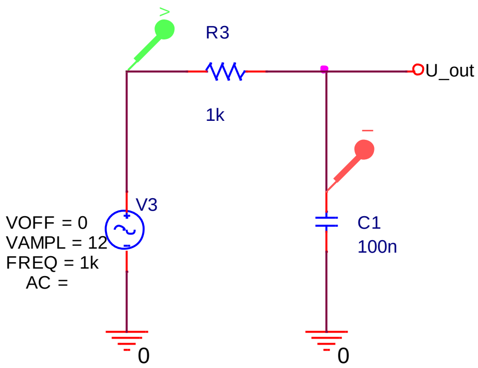
So, j * j equals (1∠90) * (1∠90). This equals 1*1∠(90 + 90) = 1∠180.

1∠180 is the same as –1.

Again, we look at the RC circuit.

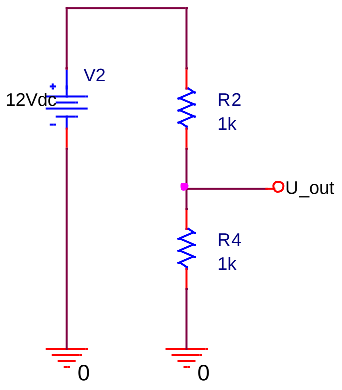
Also called a low pass filter

(low frequencies " passes ", high frequencies are " shortened " to ground, meaning – damped.



R and C makes a voltage divider.

Like these 2 resistors:



U_{out} equals the applied voltage, times R4 , divided with the sum of resistors

$$Uout = Uin \cdot \frac{R4}{R2 + R4}$$

The fraction $\frac{R_4}{R_2+R_4}$ can be considered as a “gain”. Less than one, but anyway!

Thus, for the RC-circuit we have:

$$Gain = A` = \frac{\overline{X_C}}{\overline{R} + \overline{X_C}}$$

We find:

$$A` = \frac{\overline{X_C}}{\overline{R} + \overline{X_C}} = \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}} = \frac{1}{1 + j\omega CR}$$

We need to get rid of the "j" in the denominator. We multiply with the complex conjugated.

$$A` = \frac{1}{1 + j\omega CR} * \frac{1 - j\omega CR}{1 - j\omega CR} = \frac{1 - j\omega CR}{1^2 - j\omega CR + j\omega CR - j^2(\omega CR)^2}$$

The two middle terms in the D disappear. And j*j is equal -1.

We get:

$$A` = \frac{1 - j\omega CR}{1^2 + (\omega CR)^2}$$

This equation describes the gain at all frequencies!

It consists of a **reel part** and an **imaginary part**.

The terms with a “j” describe “vertically to the x-axis”.

The equation can be divided up into a reel part, without “j”, and an imaginary part, with “j” in front.

The denominator is common.

$$A' = \frac{1}{1^2 + (\omega CR)^2} \cdot (1 - j\omega CR)$$

Or

$$A` = \frac{1}{1^2 + (\omega CR)^2} - j\frac{\omega CR}{1^2 + (\omega CR)^2}$$

The length of the sum of the real and the imaginary vectors are calculated as:

$$A` = \sqrt{\left(\frac{1}{1 + (\omega CR)^2}\right)^2 + \left(\frac{\omega CR}{1 + (\omega CR)^2}\right)^2}$$

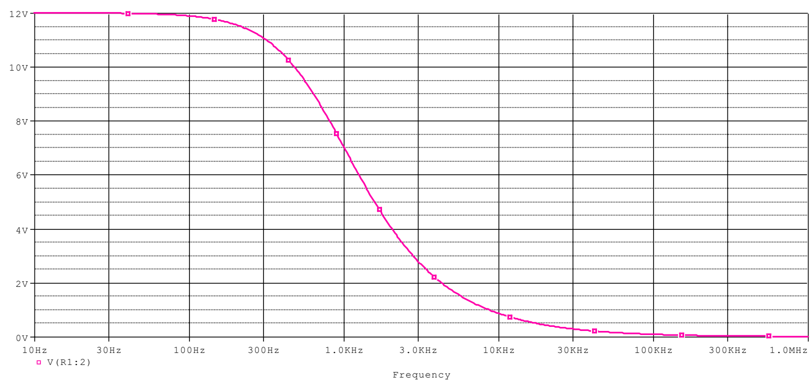
And the phase angle $\varphi = tg^{-1}\left(\frac{\mathrm{Im}}{\mathrm{Re}}\right) \quad or \quad \varphi = tg^{-1}\left(\frac{-\omega CR}{1}\right)$

The Simulating software – fx. ORCAD - uses complex numbers to calculate graphs for circuits. Here a frequency sweep is shown.

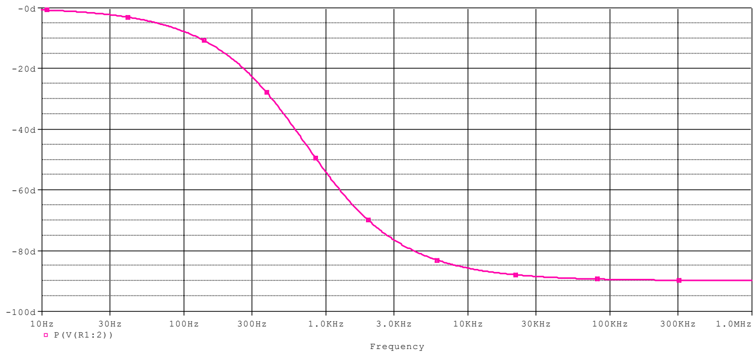
Using the simulating software we get:

This upper graph shows the output voltage

And below we see the phase



The Phase.



Bonus:

<u>The rest is just test for frequencies → 0, and → infinite.</u>

Test for very low frequencies frequency → 0, and thus also ω → 0

We had the equation:

$$A` = \sqrt{\left(\frac{1}{1+(\omega CR)^2}\right)^2 + \left(\frac{\omega CR}{1+(\omega CR)^2}\right)^2}$$

And the phase angle $\varphi = tg^{-1}\left(\frac{-\omega CR}{1}\right)$

We get for ω → 0

$$A` \to \sqrt{\left(\frac{1}{1+0^2}\right)^2 + \left(\frac{0}{1+0}\right)^2} \angle tg^{-1}\left(-\frac{0}{1}\right)$$

$$A` \to \sqrt{1^2} \ \angle tg^{-1}(-0) \to 1\angle 0$$

Telling us, that at very low frequencies U_{out} = U_{in} multiplied with $1\angle 0$

That means, that U_{out} → U_{in} and with "0" degrees phase angle.

It also is the result of a logically view of the circuit. The capacitor does not cause any load for very low frequencies.

Test for very high frequencies

Now an examination for f → infinite. Meaning also ω → infinite:

Again we had:

$$A` = \sqrt{\left(\frac{1}{1+(\omega CR)^2}\right)^2 + \left(\frac{\omega CR}{1+(\omega CR)^2}\right)^2}$$

And the phase angle $\varphi = tg^{-1}\left(\frac{-\omega CR}{1}\right)$

Giving us for ω → infinite:

$$A` \to \sqrt{\left(\frac{1}{1+\infty^2}\right)^2 + \left(\frac{\infty}{1+\infty^2}\right)^2} \angle tg^{-1}\left(\frac{-\infty}{1}\right)$$

$$A' \to \sqrt{\frac{1}{\infty^4}+\frac{1}{\infty^2}} \angle -90$$

$$A' \to 0\angle -90$$

So, at very high frequencies $U_{out} = U_{in}$ times $0\angle -90$. I.e. $U_{out} = U_{in}$ times 0 and "90" degrees behind.

The output amplitude → "0", act as a short circuit, and the phase angle is -90 degrees.

Finally Test for the frequency → f_0

If the frequency → f_0, i.e. the corner frequency in the Bode Plot, - or also the frequency, where **the size of** R = Xc we find:

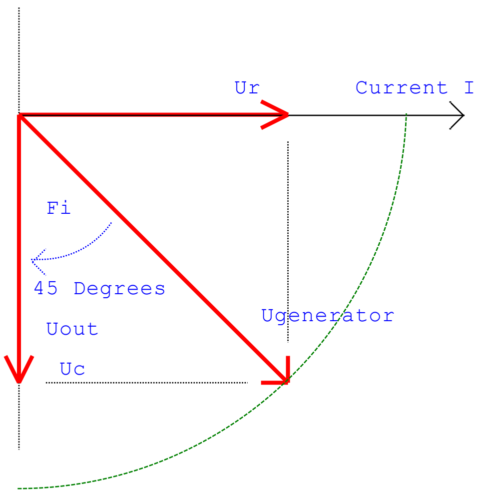
$$R = Xc \Leftrightarrow R = \frac{1}{\omega C} \Leftrightarrow \omega CR = 1$$

$$A` \to \sqrt{\left(\frac{1}{1+1^2}\right)^2 + \left(\frac{1}{1+1^2}\right)^2}\, tg^{-1} - \left(\frac{1}{1}\right)$$

$$A` \rightarrow \sqrt{\left(\frac{1}{2}\right)^2 + \left(\frac{1}{2}\right)^2} \angle -45$$

$$A` \rightarrow \sqrt{\frac{1}{4} + \frac{1}{4}} \angle -45 \rightarrow \sqrt{\frac{2}{4}} \angle -45 \rightarrow \frac{\sqrt{2}}{2} \angle -45$$

$$A` \rightarrow 0{,}707 \angle -45$$



$$U_{Out} = \frac{U_{In}}{Cos(45)} = \frac{U_{In}}{\sqrt{2}} = Uin \cdot 0{,}707$$

A` = 0,707

Phase angle is - 45 degrees

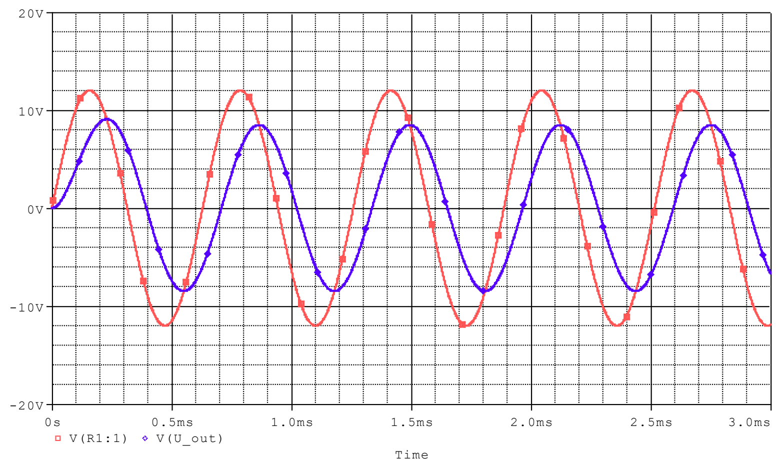
(at the corner frequency f0)

Here the output is equal to the applied voltage times 0,707.

The frequency applied is 1590 Hz.

It´s where the value of the resistor equals Xc.

Thus: $1K = \frac{1}{2 \cdot \pi \cdot f \cdot c}$



The following shows a sketch of the Bode Plot and the phase angle: