Fundamentals

FULL TEXT

FUNDAMENTALS

We study:

- Basic knowledge for every explorer in the electronics domain
- Revision of some notions and knowledge
- Terminology, conventions and notations

Objective

To be armed with appropriate means and tools to understand:

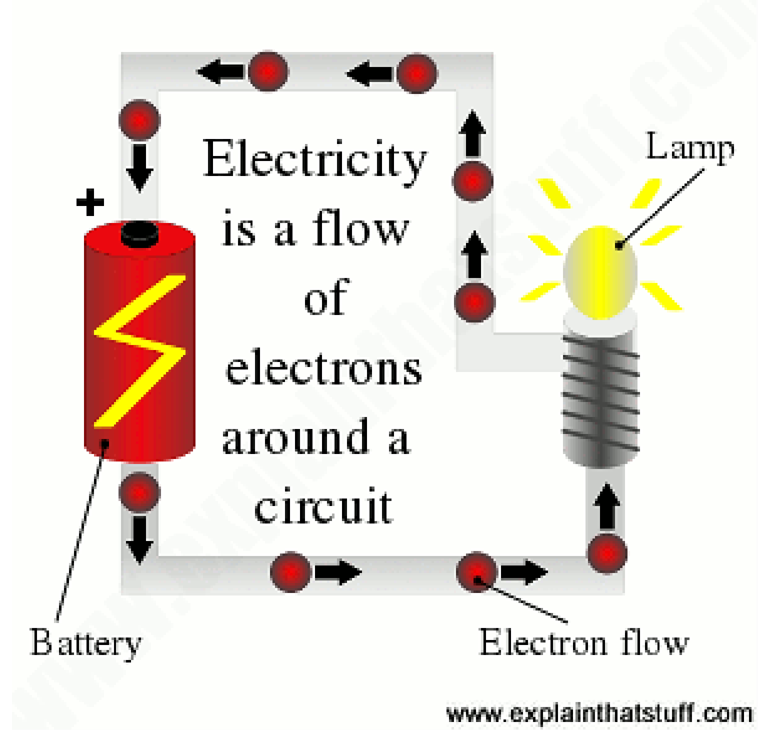
- the operating principle of the electronic devices and their basic applications
- the operation of some fundamental circuits

Electric current?

Electric current:
electric charge in motion.

In electric circuits this charge is often carried by **electrons moving through a wire**.

It can also be carried by ions in an electrolyte, or by both ions and electrons such as in an ionized gas (plasma)



Electric current (I) is defined as the **time rate of change of charge** passing through a specified area (cross section of a conductive material)

$$I = dq/dt$$

1 Ampere = 1 Coulomb /1 Second

The amount of electric charge that passes a point in space in a given amount of time

The magnitude of the electric charge carried by a **single electron** (elementary charge)

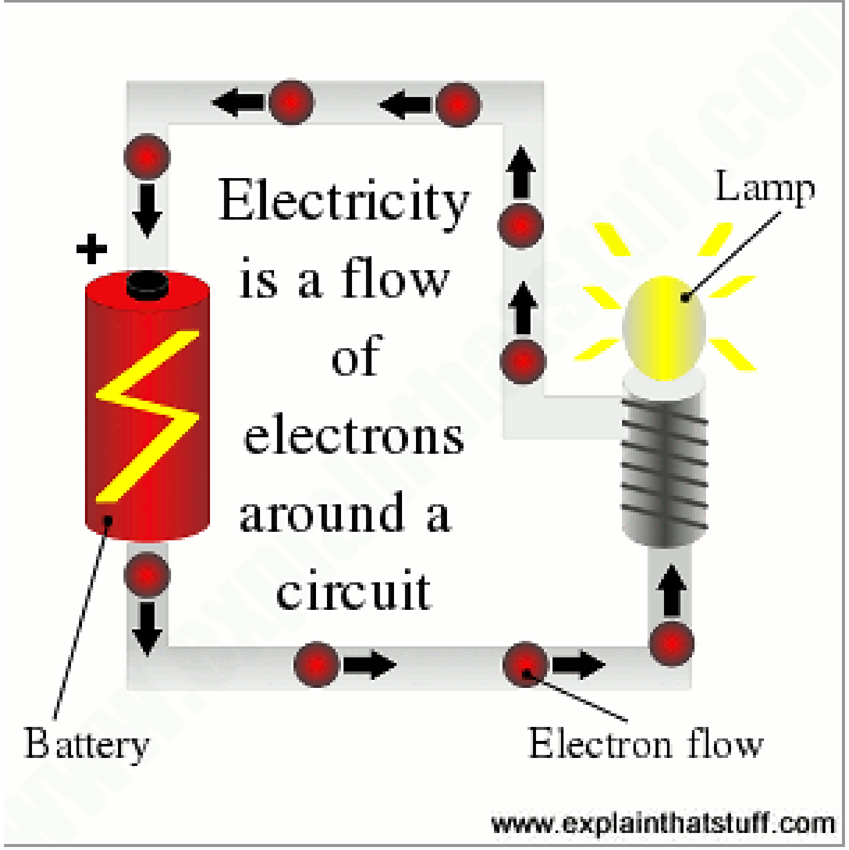
$-1.602176634 \times 10^{-19}$ C

Electric current?

For an electric current to happen, always there must be a **circuit**

(closed loop around which the electric current flows)

No current flows unless there is a **voltage difference** across the circuit



For electricity to flow, there has to be **something to push the electrons** along: electromotive force (EMF).

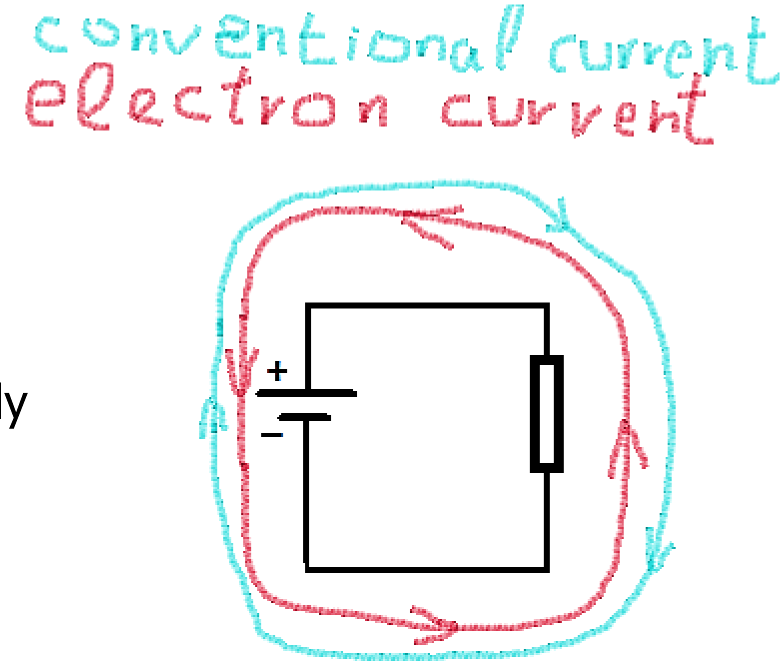
A battery or power outlet (voltage source) creates the electromotive force that makes a current of electrons flow.

An electromotive force is better known as a **voltage source.**

Electric current?

In a conductive material, the **moving charged particles** that constitute the electric current are called **charge carriers**.

In **metals**, which make up the wires and other conductors in most electrical circuits, the positively charged atomic nuclei of the atoms are held in a fixed position, and the **negatively charged electrons are the charge carriers, free to move** about in the metal.



The direction of an electric current is by convention the direction in which a positive charge would move.

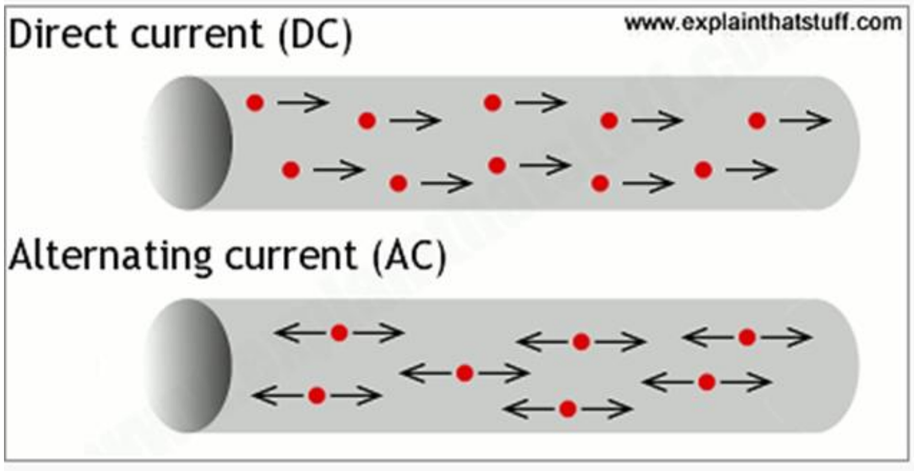
Thus, the current in the external circuit is directed away from the positive terminal and toward the negative terminal of the battery.

Electrons would actually move through the wires in the opposite direction.

Electric current?

Direct current (DC) is the unidirectional flow of electric charge, or a system in which the movement of electric charge is in one direction only.

Direct current is produced by sources such as batteries, thermocouples, solar cells, and commutator-type electric machines of the dynamo type



In **alternating current (AC)** systems, the movement of electric charge periodically reverses direction.

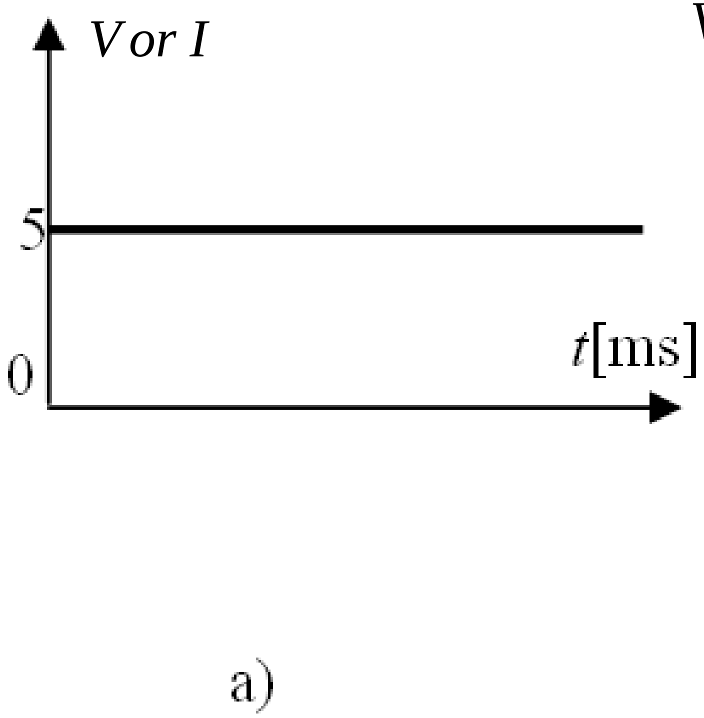
AC is the form of electric power most commonly delivered to businesses and residences.

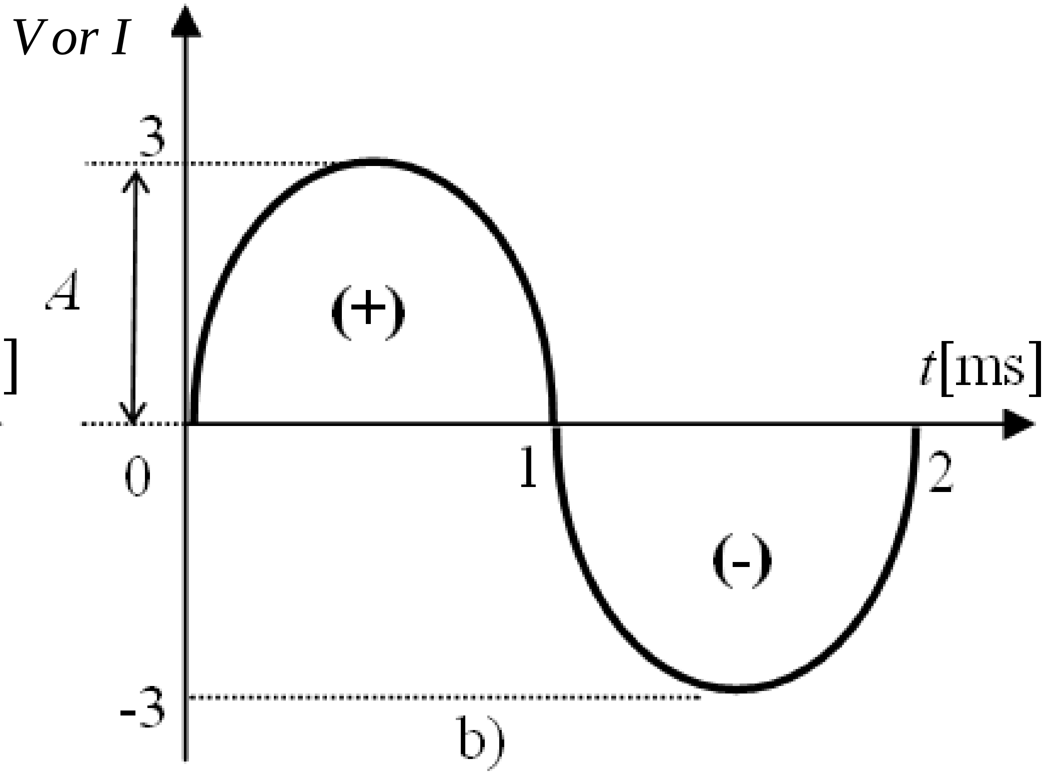
The usual waveform of an AC power circuit is a sine wave.

Certain applications use different waveforms, such as triangular or square waves.

Audio and radio signals carried on electrical wires are also examples of alternating current

Electrical signals



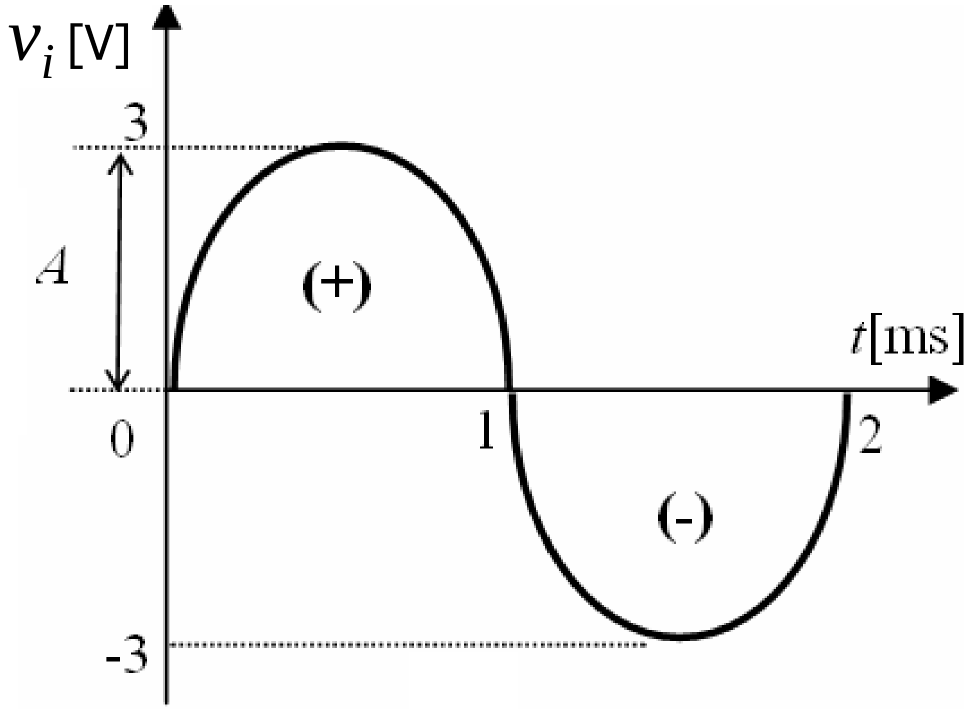


Time variation of a:

a) continous signal (dc);

b) sinusoidal signal (ac)

Sinusoidal voltage (ac voltage)



- Amplitude: A = 3V;
- Peak to peak value: 6V;
- Root-mean-square (rms) value of the signal

$$V_{rms} = \frac{A}{\sqrt{2}} = 2.12\text{V}$$

- Period T = 2ms; Frequency f =500Hz
- Average value, or dc component (zero);
- Instantaneous value: for t = T/4 the instantaneous value is +3V.

Exercise

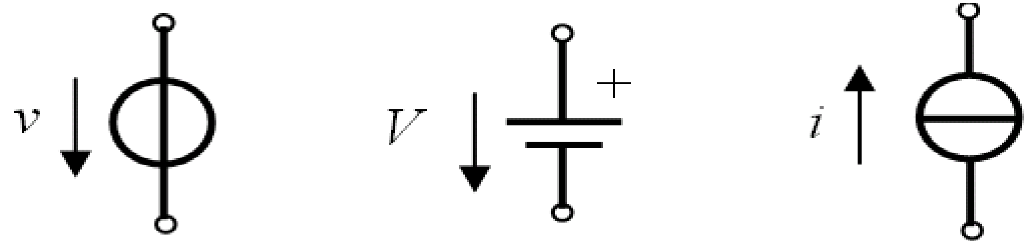
Plot the following signals (voltages):

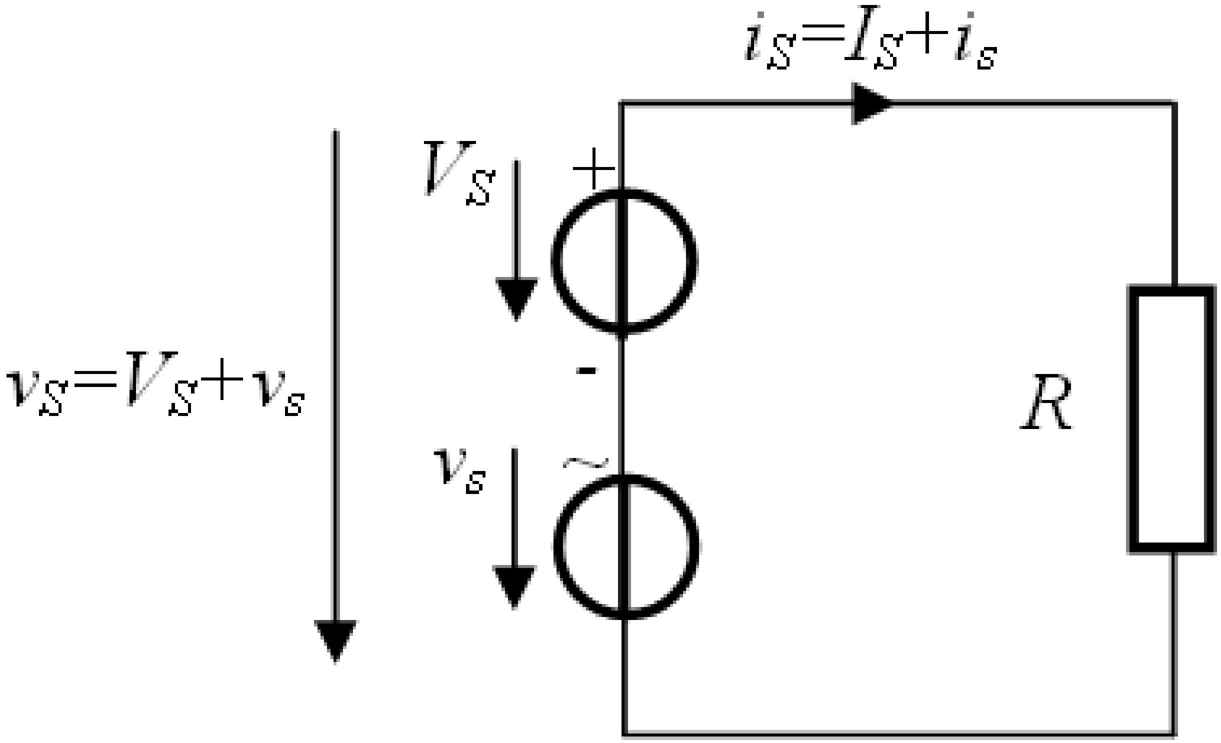
a) $V_S = 5\text{V}$

b) $v_s(t) = 3\sin(2\pi \cdot 50t)[\text{V}][\text{Hz}]$

c) $v_S(t) = V_S + v_s(t) = 5\,\text{V} + 3\sin(2\pi \cdot 50t)\ [\text{V}][\text{Hz}]$

Sources. Notations



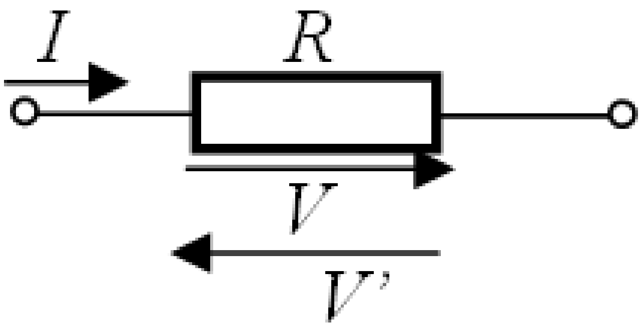


- only continuous signal (dc value) V_S, I_S ;
- only time-varying signal v_s, i_s;
- total instantaneous signal

(continuous + time-varying component) v_S , i_S

Relations, laws and theorems of electric circuits

➢ Ohm's law



$$\boldsymbol{I = V/R}; \quad V = RI; \quad R = V/I$$

$$V' = -RI$$

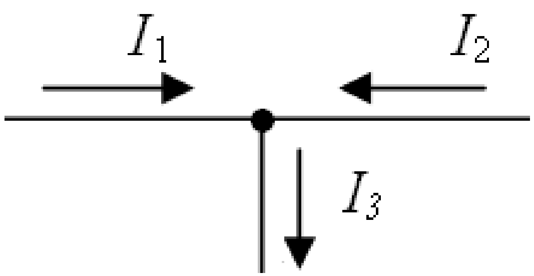
$$R = 2.2\,\mathrm{k\Omega}; \qquad I = 5\,\mathrm{mA}$$

$$V =$$

➢ Kirchhoff's law

1. Kirchhoff's first law or ***Kirchhoff's current law*** **(KCL)**

The total current entering a circuit junction (node) is exactly equal to the total current leaving the junction.



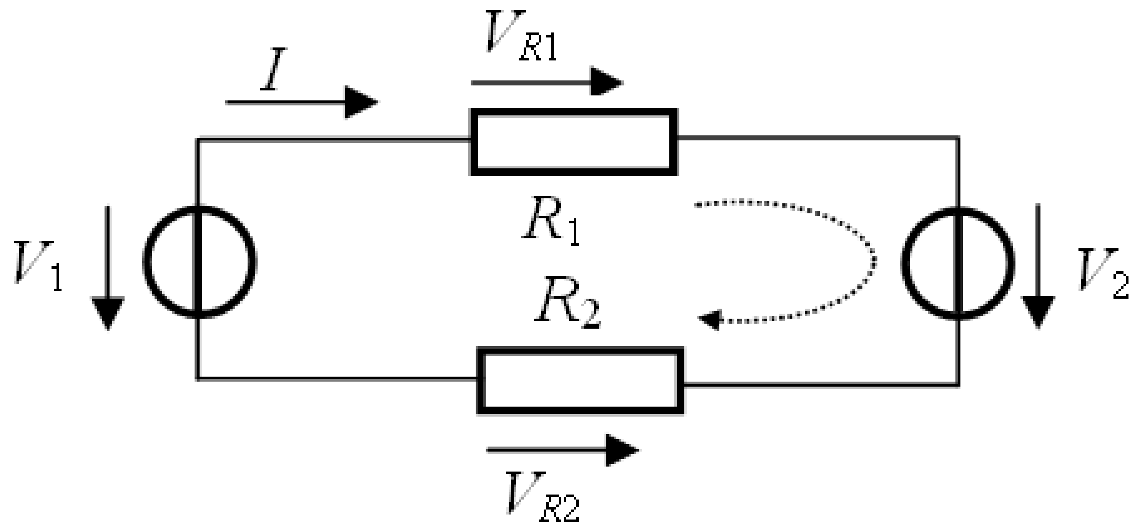
$$I_1 + I_2 - I_3 = 0$$

The algebraic sum of all the currents in a circuit node equals zero.

➢ Kirchhoff’s law

2. Kirchhoff’s second law or ***Kirchhoff’s voltage law*** **(KVL):**

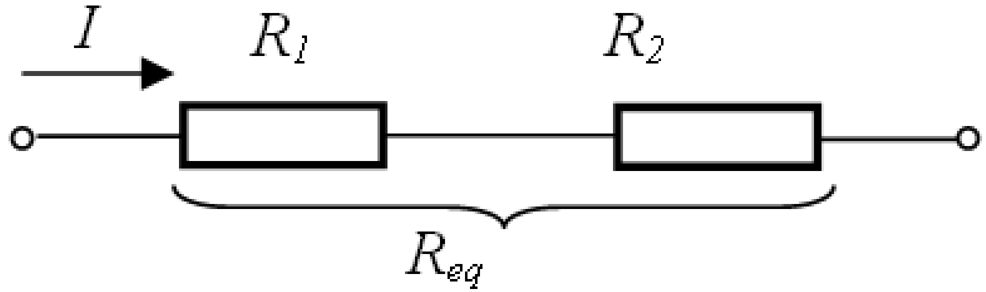
The algebraic sum of all the voltages around any closed loop in a circuit is equal to zero.



$-V_1+V_{R1}+V_2-V_{R2}=0$ $\qquad$ $-V_1+R_1I+V_2+R_2I=0$

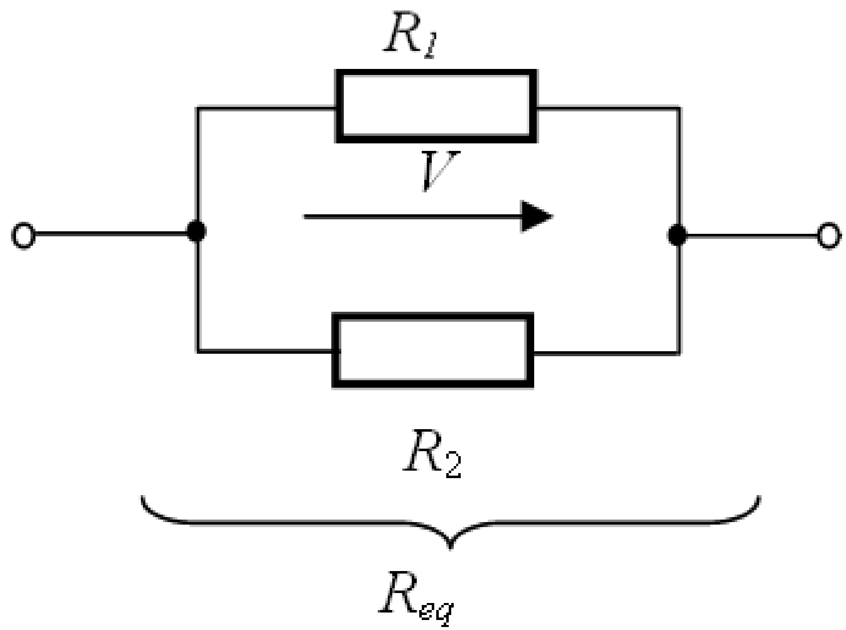
➢ Resistor connections

Series connection



$$R_{eq} = R_1 + R_2$$

Parallel connection



$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$$

$$R_1 = R_2 = R$$

$$R_{ech,series} =$$

$$R_{ech,parallel} =$$

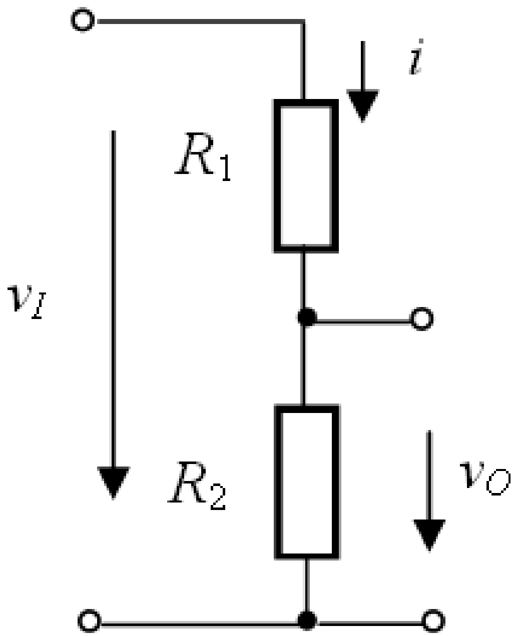
$$R_1 = 100\,\mathrm{k\Omega}; \quad R_2 = 1\,\mathrm{k\Omega};$$

$$R_{ech,series} =$$

$$R_{ech,parallel} =$$

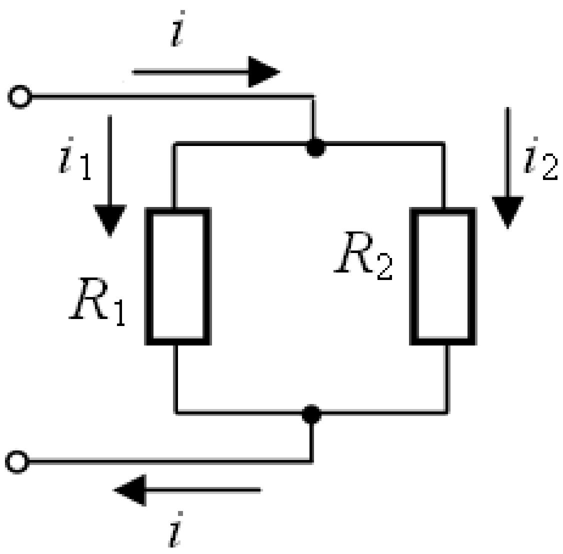
➢ Resistive dividers

Voltage divider



$$v_O = \frac{R_2}{R_1 + R_2} v_I$$

Current divider



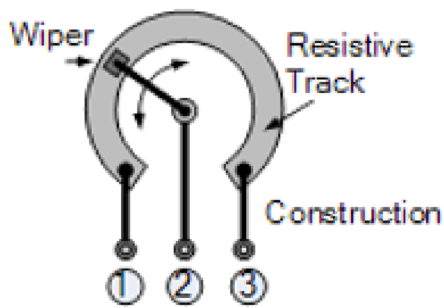
$$i_1 = \frac{R_2}{R_1 + R_2} i$$

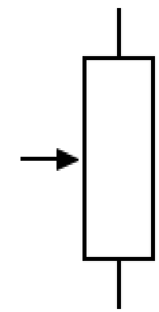
$$i_2 = \frac{R_1}{R_1 + R_2} i$$

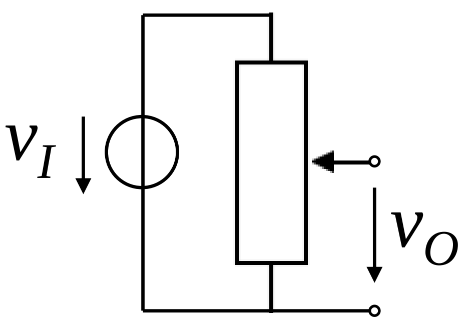
Potentiometer vs. Rheostat (variable resistor)

Manually adjustable variable resistor with 3 terminals.
Two terminals are connected to the ends of a resistive element, and the third terminal connects to a sliding contact, called a wiper, moving over the resistive element.

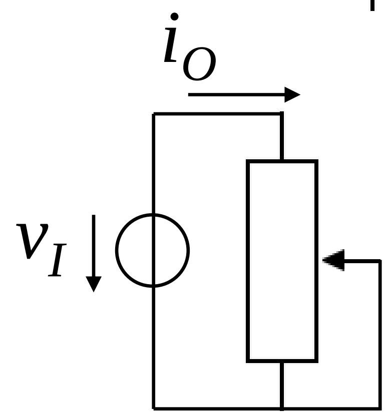
Read more http://www.resistorguide.com/potentiometer/







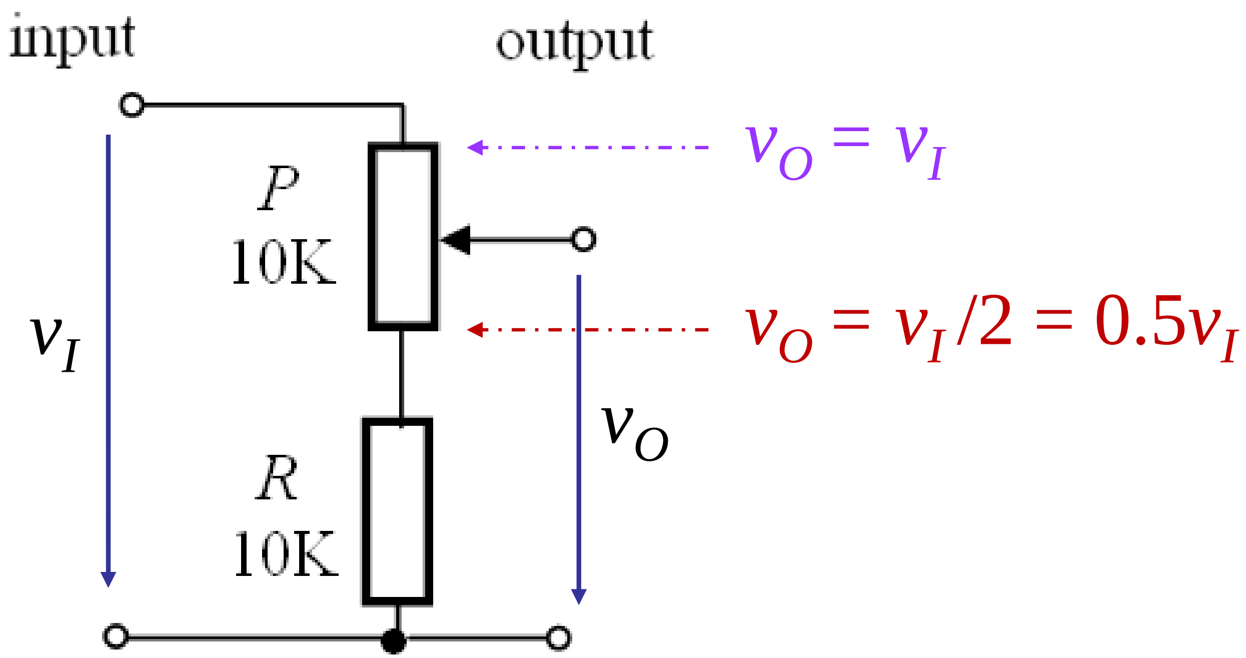
Potentiometer
Adjusts the voltage – voltage divider



Rheostat
Adjusts the current

Adjustable voltage dividers

Adjustable divider in the range [0.5; 1]



➢ The superposition theorem

The superposition theorem states that :

The response (voltage or current) of a **linear circuit** having more than one independent source equals the **algebraic sum of the responses** caused by each independent **source acting alone**, where all the other independent sources are set to zero (replaced by their internal impedances).

A linear function *f* satisfies the additive property:

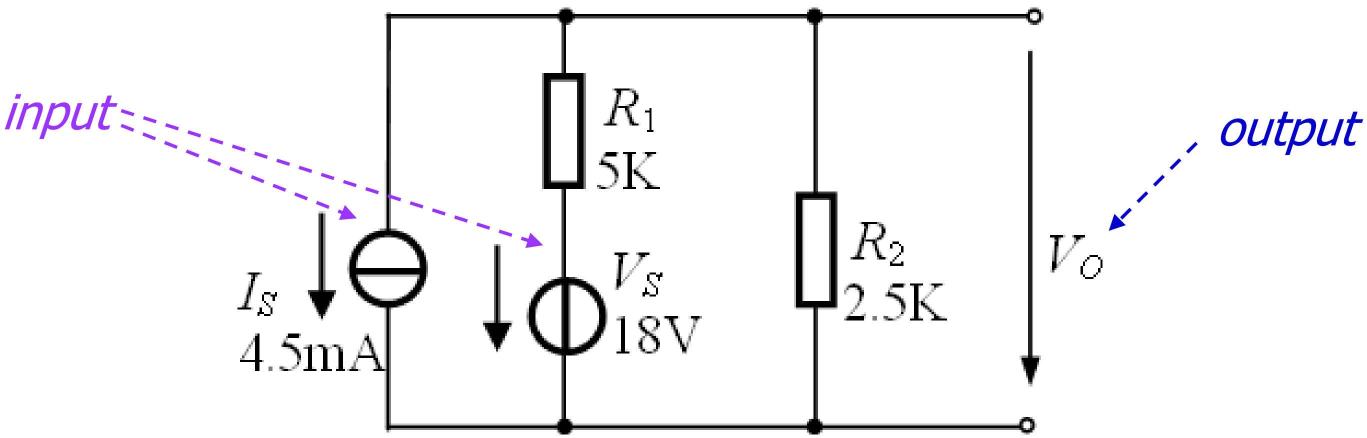
$$f(x_1, x_2) = f(x_1) + f(x_2)$$

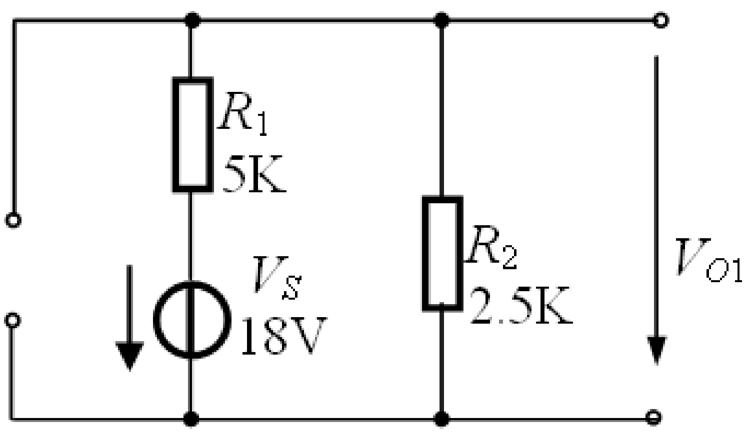
sum of causes

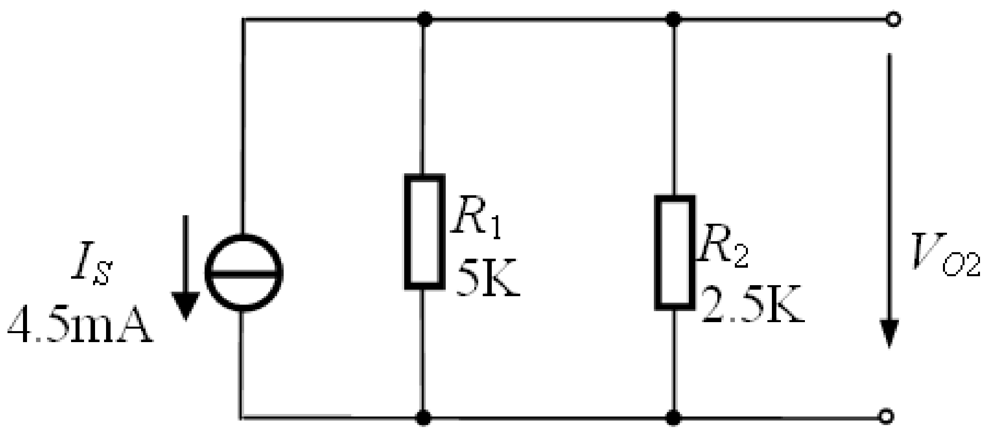
sum of effects

➢ The superposition theorem

- Valid only for **linear circuits** (the output of the circuit is a linear function of its inputs)







$$V_0 = V_{01} + V_{02}$$

Capacitor and inductor

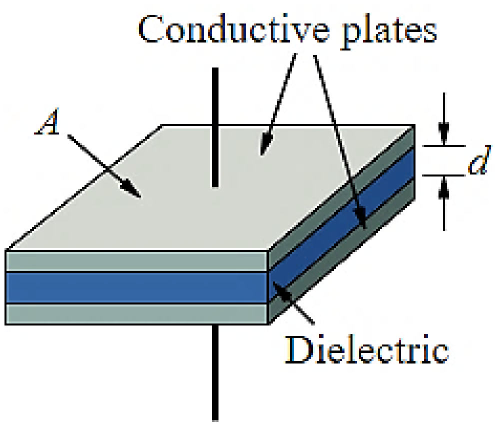
- Current - voltage relation
  - time domain
  - frequency domain
- Series and parallel connection
- Frequency domain analyses

The capacitor *C*

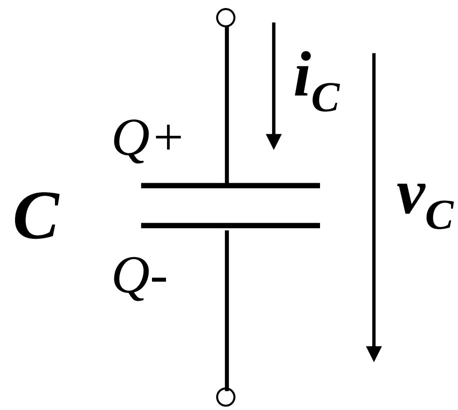
A **capacitor** is a device that **stores electrical energy** in its electric field.

It is a passive electronic component with two terminals.

A capacitor consists of two conductors (plates) separated by a non-conductive (dielectric) region.



Parallel plate capacitor model
[https://en.wikipedia.org/wiki/Capacitor]



Circuit symbol

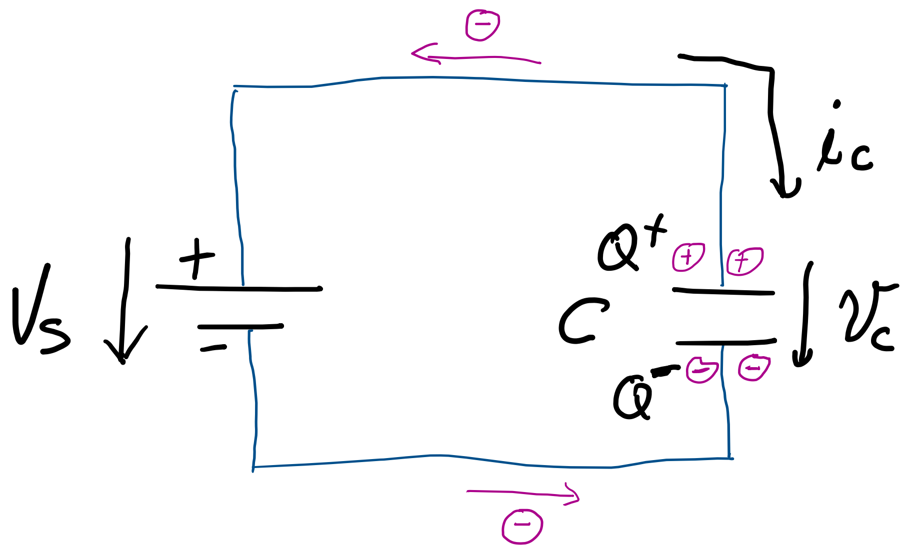
$$C = \frac{Q}{v_C}\ [\mathrm{F}]$$

C – capacitance, [F];
Q - electric charge [C];
v_C – voltage [V]

A capacitance of one farad (F) means that one coulomb (C) of charge on each conductor causes a voltage of one volt (V) across the device.

In terms of incremental changes: $$C = \frac{dQ}{dv_C}\ [\mathrm{F}]$$

Capacitor charging



The electric current can flow only in the circuit outside the capacitor (inside the capacitor there it is an insulator), in fact it consists in moving the electric charges from one plate to the another.

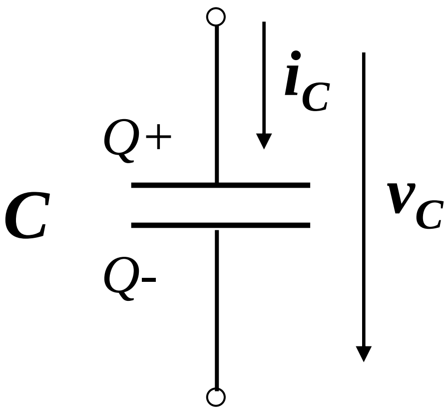
The plate from which the electrons leave becomes positively charged, and the one where the electrons arrive becomes negatively charged.

Electrons are put in motion under the influence of an external voltage source

C in the time domanin

Defining relation between current and voltage

$$C = \frac{dQ}{dv_C} \qquad dQ = i_C dt \qquad C = \frac{i_C dt}{dv_C}$$



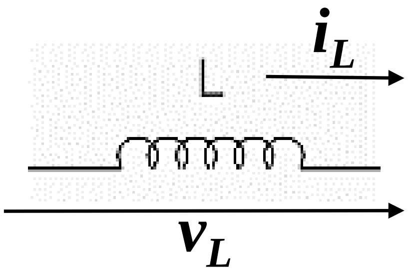
$$\boxed{C dv_C(t) = i_C(t) dt}$$

$$\boldsymbol{i_C(t)} = C\frac{dv_C(t)}{dt} \qquad \boldsymbol{v_c(t)} = \frac{1}{C}\int_{t_0}^{t} i_c(t)dt + v_c(t_0)$$

The inductor *L*

The dual of the capacitor is the **inductor**, which stores **energy in a magnetic field** rather than an electric field.

Its current-voltage relation is obtained by exchanging current and voltage in the capacitor equations and replacing *C* with the inductance *L*.



$$\boxed{L\,di_L(t) = v_L(t)\,dt}$$

L – inductance, [H]

Reactive components in ac regime

Frequency domain

$$v_S(t) = \hat{V}_S \sin(\omega t) = \hat{V}_S \sin(2\pi f t)$$

Reactance

capacitor

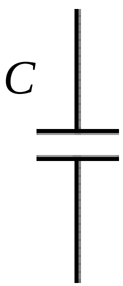
$$X_C = \frac{1}{\omega C} = \frac{1}{2\pi f C}$$

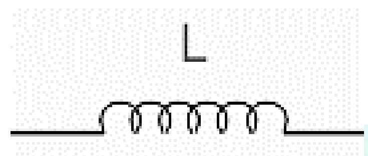
inductor

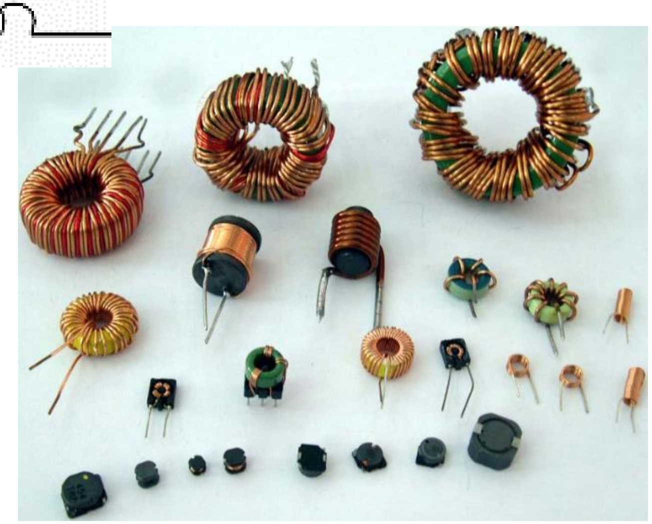
$$\mathrm{X_L} = \omega L = 2\pi f L$$

Frequency dependent passive electrical components

Frequency dependent behavior







Frequency domain

Reactive components in ac regime

Complex impedance of any passive component

$$Z = R + j\left(X_L - X_C\right)$$

Impedances of ideal reactive elements

$$C: \quad Zc = -jX_C = -j\frac{1}{\omega C} = \frac{1}{j\omega C};$$

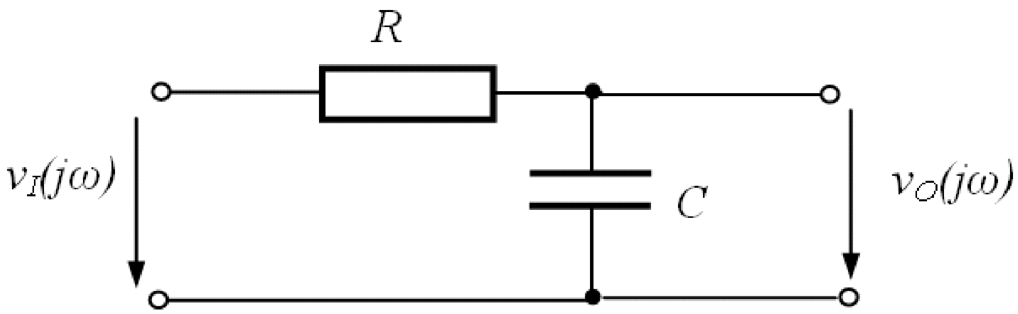
$$L: \quad Z_L = jX_L = j\omega L$$

What are the equivalent of C and L in dc ($f = 0$) ?

What about for very high frequency ($f \to \infty$)

RC circuit - frequency response (LPF)

OPTIONAL



Passive
low-pass filter (LPF)

Transfer function

$$F(j\omega) = \frac{v_O(j\omega)}{v_I(j\omega)} = \frac{1}{1 + j\omega RC} = \frac{1}{1 + j \cdot 2\pi f RC}$$

$F(j\omega)$ is a complex number: - module
- phase

module:

$$\left|F(j\omega)\right| = \frac{1}{\sqrt{1 + (\omega RC)^2}} = \frac{1}{\sqrt{1 + (2\pi f RC)^2}}$$

phase:

$$\varphi(\omega) = -\operatorname{arctg}(\omega RC) = -\operatorname{arctg}(2\pi f RC)$$

RC circuit - frequency response (LPF) – *cont.*

OPTIONAL

Graphical representation

module:

$$\boxed{\left|F(j\omega)\right| = \frac{1}{\sqrt{1+(\omega RC)^2}} = \frac{1}{\sqrt{1+(2\pi f RC)^2}}}$$

f – very low; $|F(j\omega)| \approx 1$ asymptote

f – high; $|F(j\omega)| \approx \dfrac{1}{\omega RC} = \dfrac{1}{2\pi f RC}$ asymptote

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

cutoff frequency

LPF: frequency response

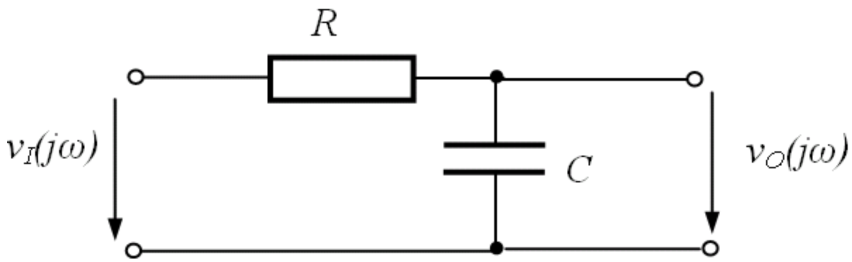
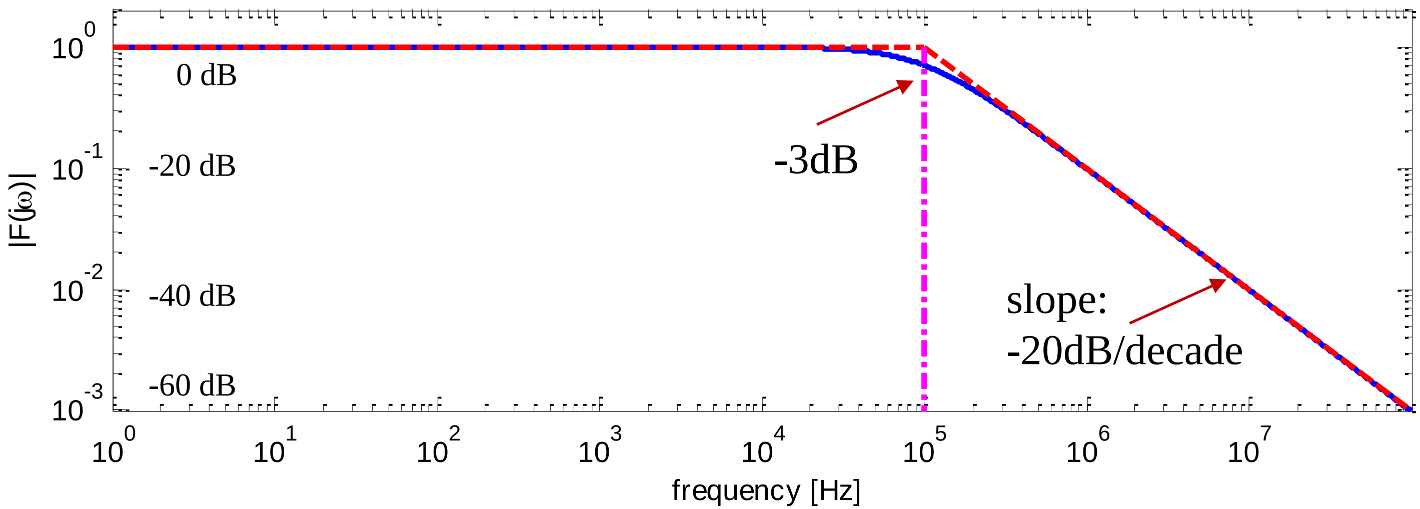
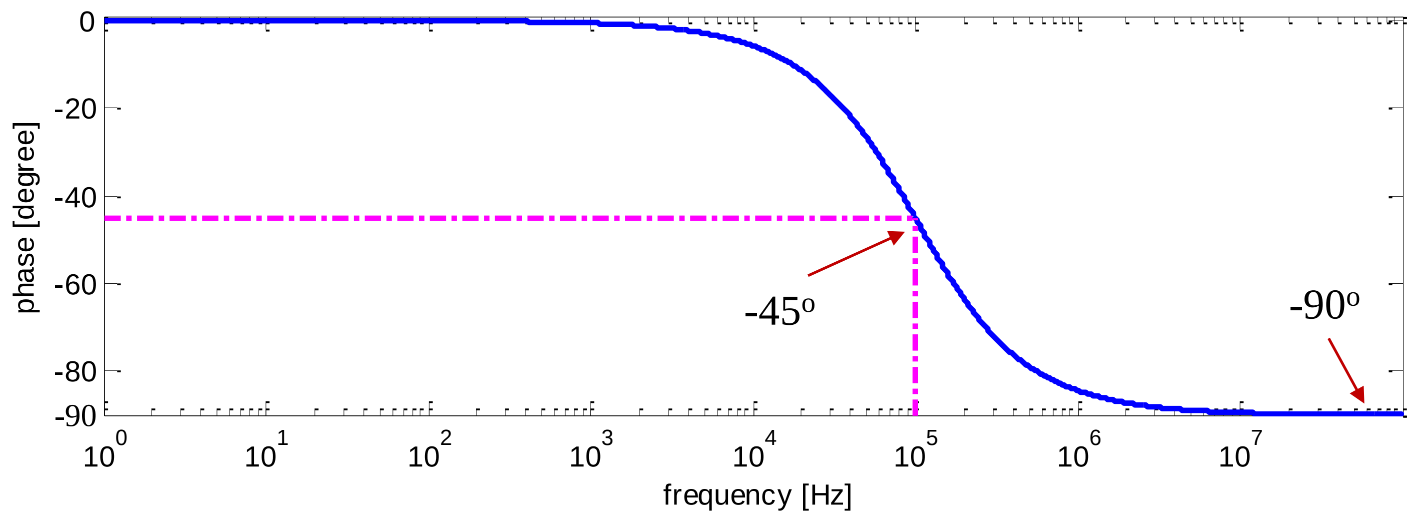


Illustration for
$f_0 = 100\,\text{kHz}$

Logarithmic scales



magnitude response (log-log plot)



phase response (lin-log plot)

Decibels

$$|F|_{dB} = 20\log_{10}|F| \text{ dB}$$

$|F| = 1$ $\qquad$ $|F|_{dB} = 20\log_{10} 1 = 0\,\text{dB}$

$|F| = 3.162$ $\qquad$ $|F|_{dB} = 20\log_{10} 3.162 = 10\,\text{dB}$

$|F| = 10$ $\qquad$ $|F|_{dB} = 20\log_{10} 10 = 20\,\text{dB}$

$|F| = 100$ $\qquad$ $|F|_{dB} = 20\log_{10} 100 = 40\,\text{dB}$

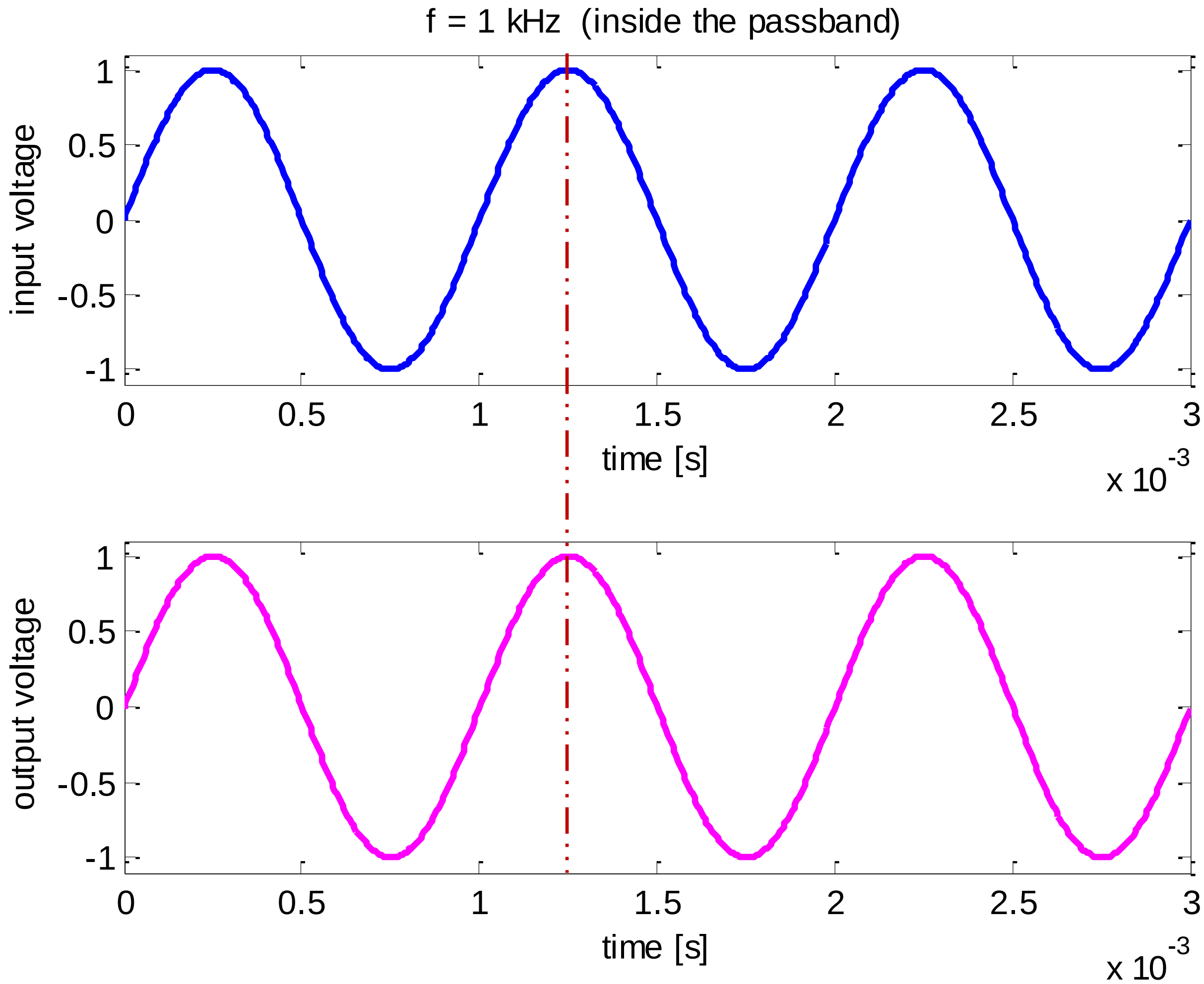
$|F| = 0.1$ $\qquad$ $|F|_{dB} = 20\log_{10} 0.1 = -20\,\text{dB}$

$|F| = 0.01$ $\qquad$ $|F|_{dB} = 20\log_{10} 0.01 = -40\text{ dB}$

$$|F|_{dB} = 20\log_{10}\frac{1}{\sqrt{2}} = 20\log_{10} 0.707 = \text{-3dB}$$

LPF: $f_0 = 100\,\text{kHz}$

ex. #1



Input:

sinewave

1V amplitude

1 kHz frequency

inside the passband

Output:

Sinewave

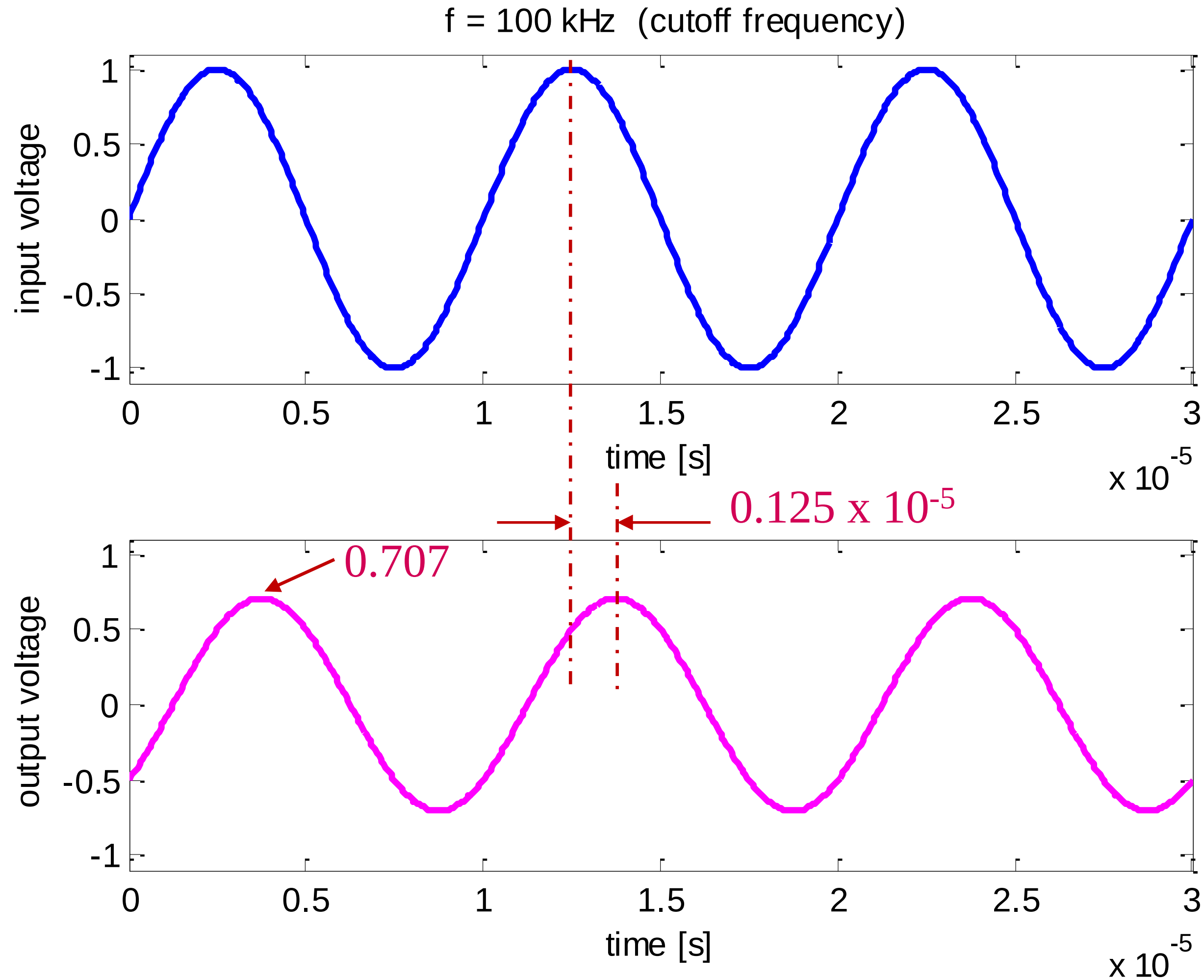
no attenuation: 1V amplitude

no phase shift

no modification of the output voltage

LPF: $f_0 = 100$ kHz

ex. #2



Input:

sinewave

1V amplitude

100 kHz frequency

@ cutoff frequency

Output:

Sinewave

attenuation: 0.707V amplitude

phase shift: -45^{o} (0.125×10^{-5} s)

smaller, phase-shifted

LPF: $f_0 = 100$ kHz

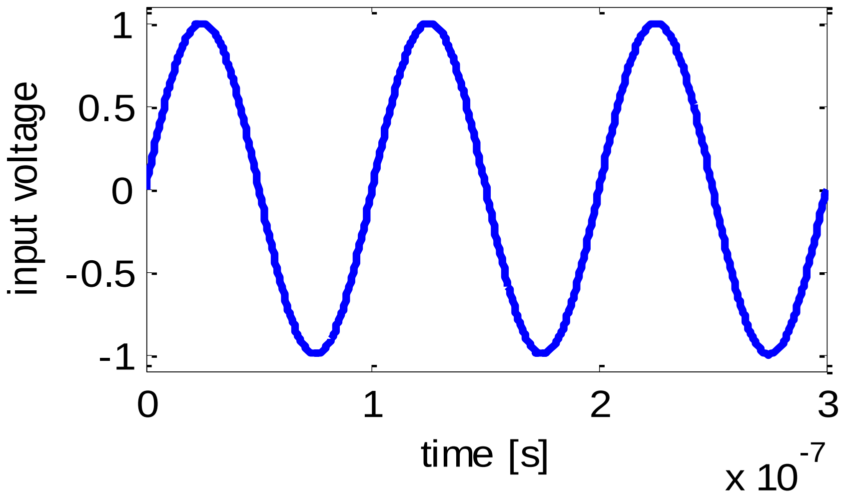
ex. #3

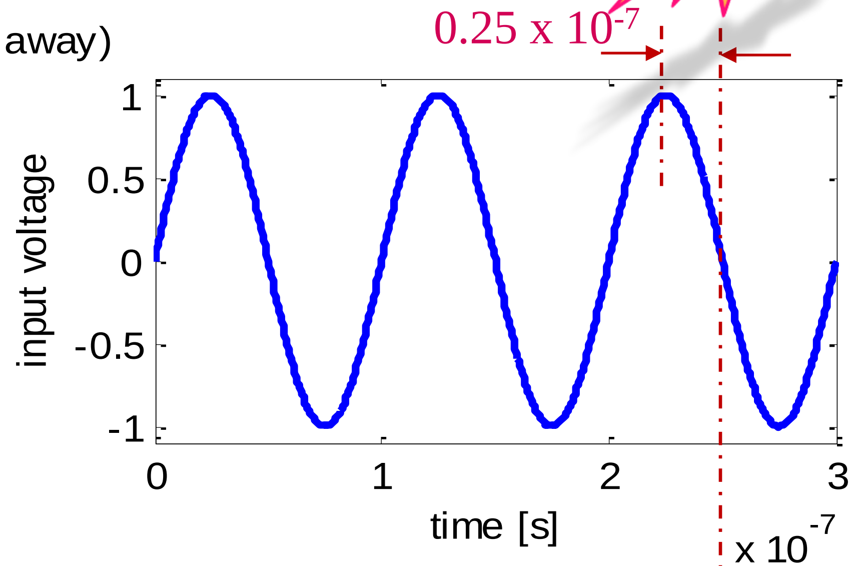
Output: high attenuation: 0.01V amplitude

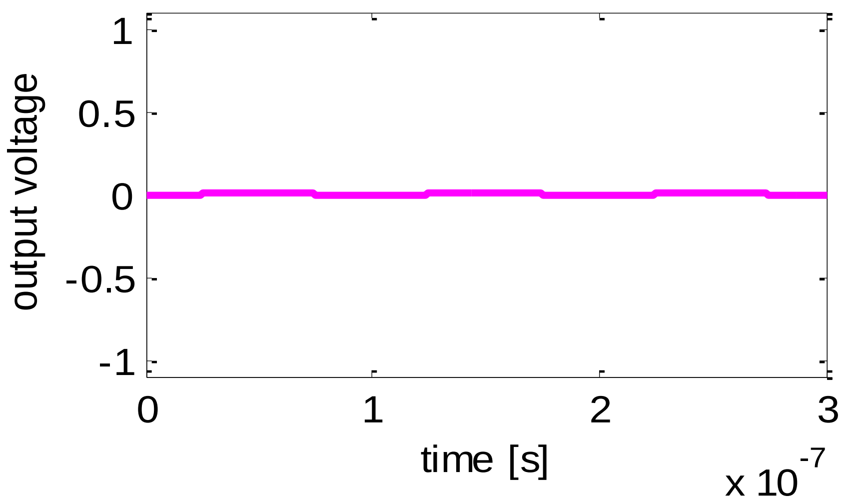
phase shift: -90° (0.25 x 10^{-7} s)

Input:

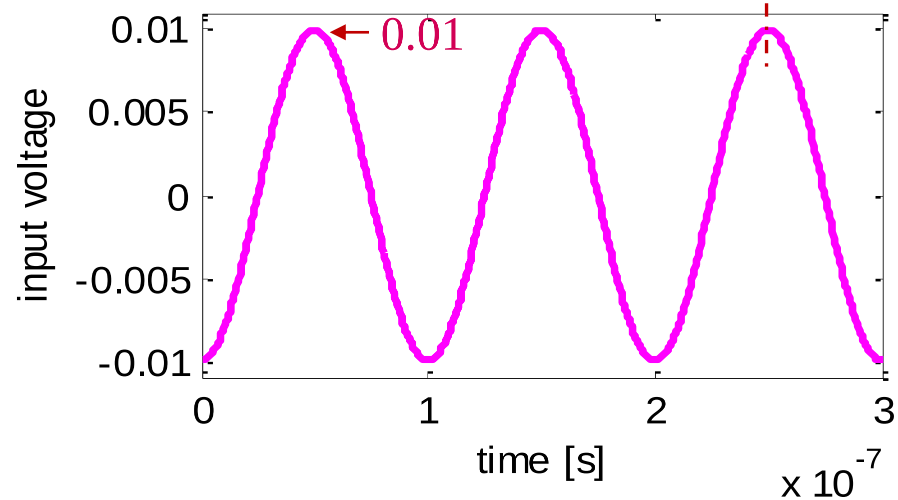
f = 10 MHz (outside of the passband - two decades away)



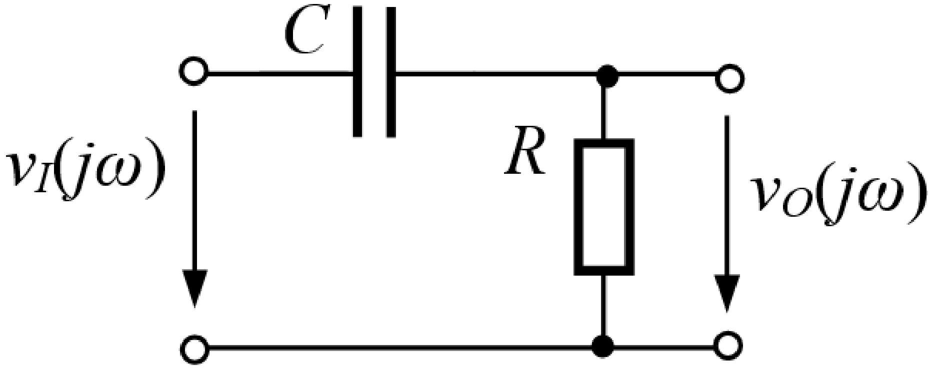




zoom in x100 on the vertical scale



RC circuit - frequency response (HPF)



Low frequency:

$$f \to 0; \quad Z_C \to \infty; \quad \text{input} - \text{output} \to \text{open circuit}; \quad v_O(j\omega) \to 0$$

don't pass

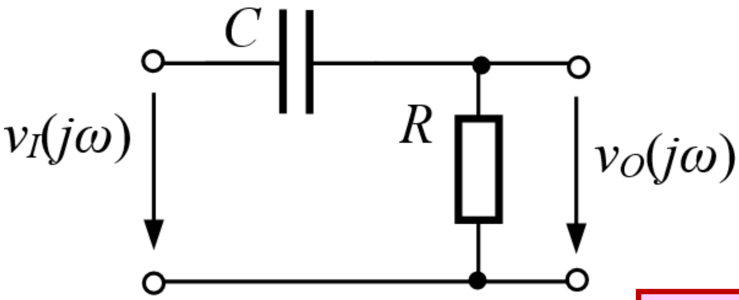
High frequency:

$$f \to \infty; \quad Z_C \to 0; \quad \text{input} - \text{output} \to \text{short - circuit}; \quad v_O(j\omega) \to v_I(j\omega)$$

pass

First order, passive, high-pass filter (HPF)

RC circuit - frequency response (HPF) – *cont.*



High low-pass filter (HPF)

Transfer function

$$F(j\omega) = \frac{v_O(j\omega)}{v_I(j\omega)} = \frac{j\omega RC}{1 + j\omega RC}$$

$$\left|F(j\omega)\right| = \frac{\omega RC}{\sqrt{1 + (\omega RC)^2}}$$

$$\Phi(\omega) = 90^o - arctg(\omega RC)$$

$$f \ - \text{very low}; \ |F(j\omega)| \approx \omega RC$$

$$f \ - \text{high}; \ |F(j\omega)| \approx 1$$

$$\omega_0 RC = 1 \quad \Rightarrow \omega_0 = \frac{1}{RC} \quad \Rightarrow$$

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

cutoff frequency

HPF: frequency response

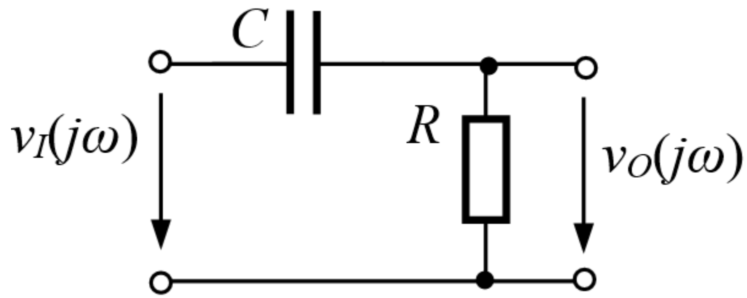
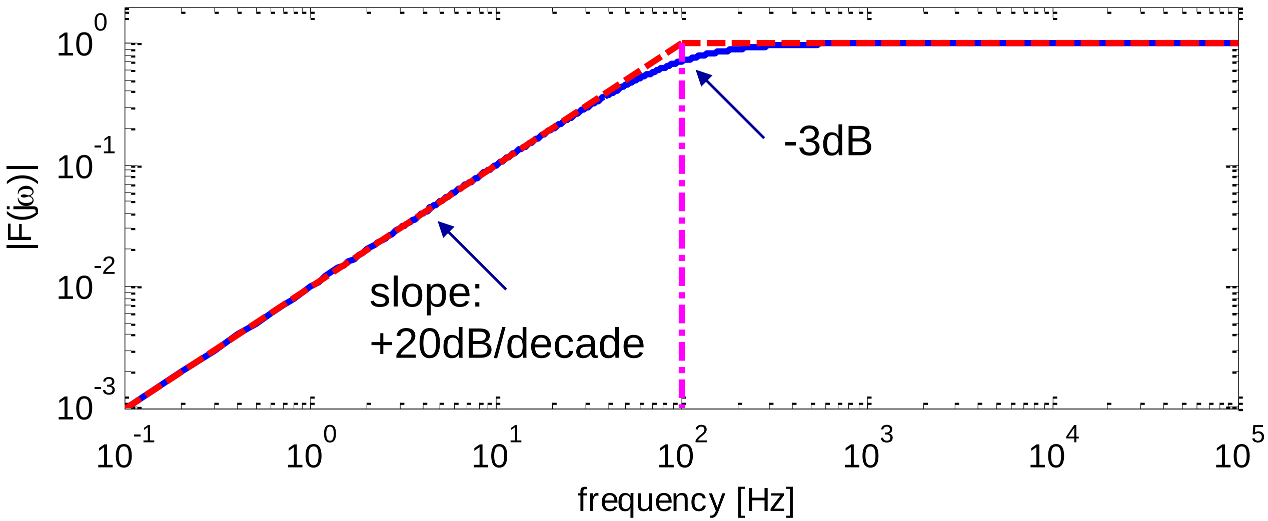
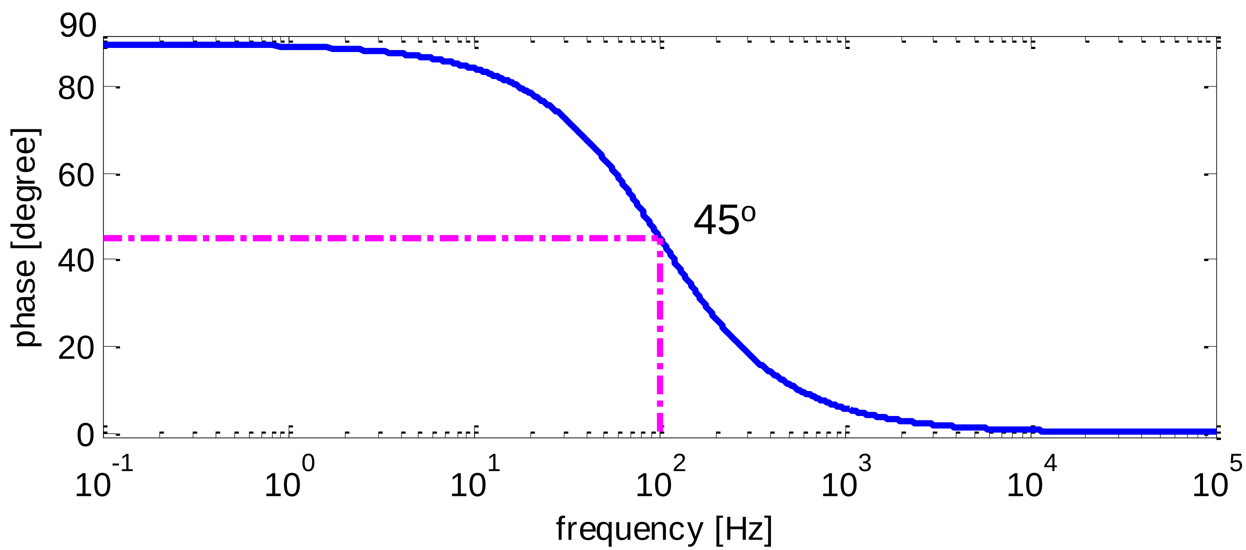


Illustration for $f_0 = 100\,\text{Hz}$



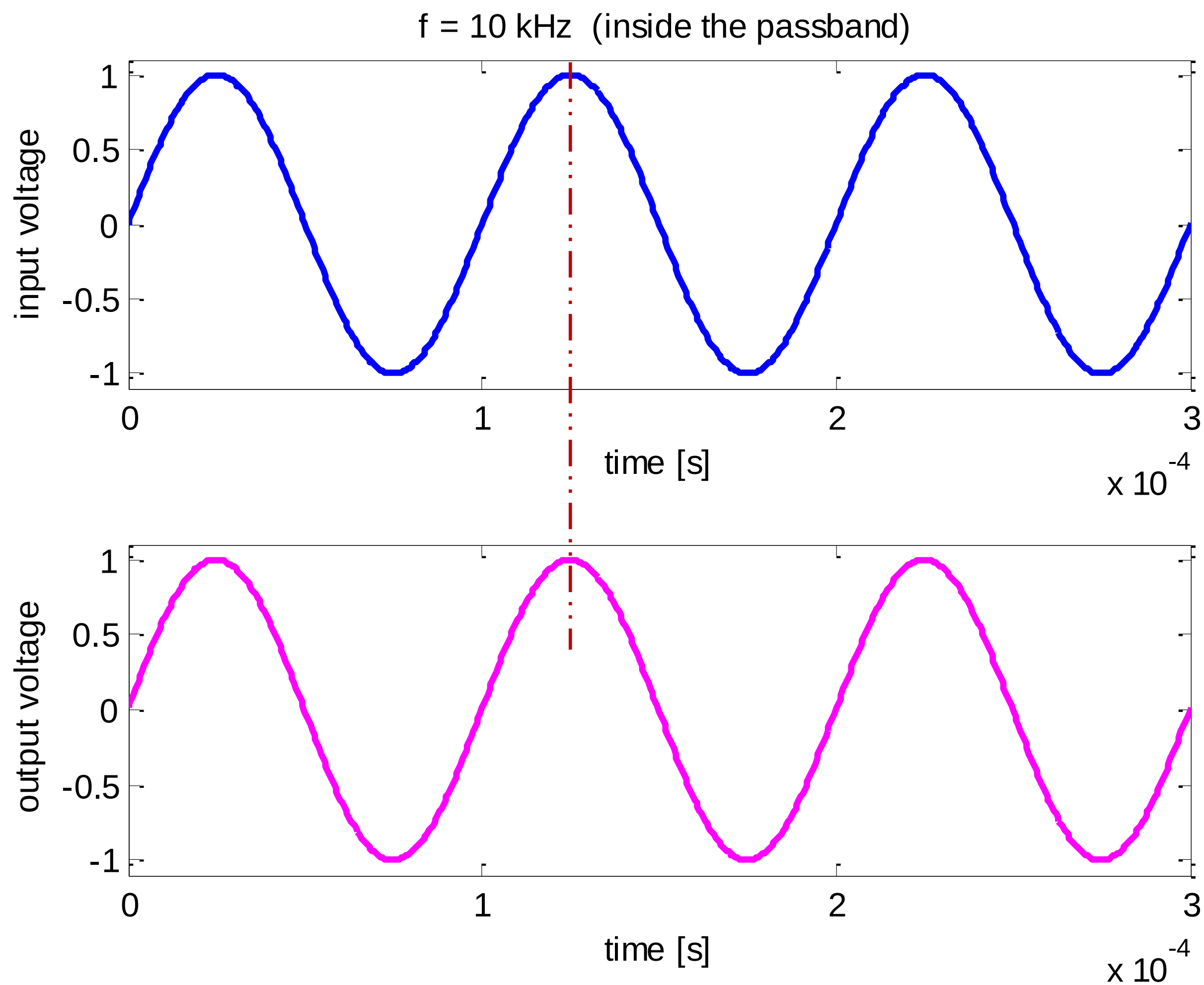
magnitude response



phase response

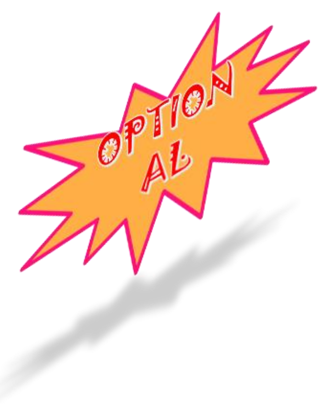
LPF: $f_0 = 10\,\text{kHz}$

ex. #1



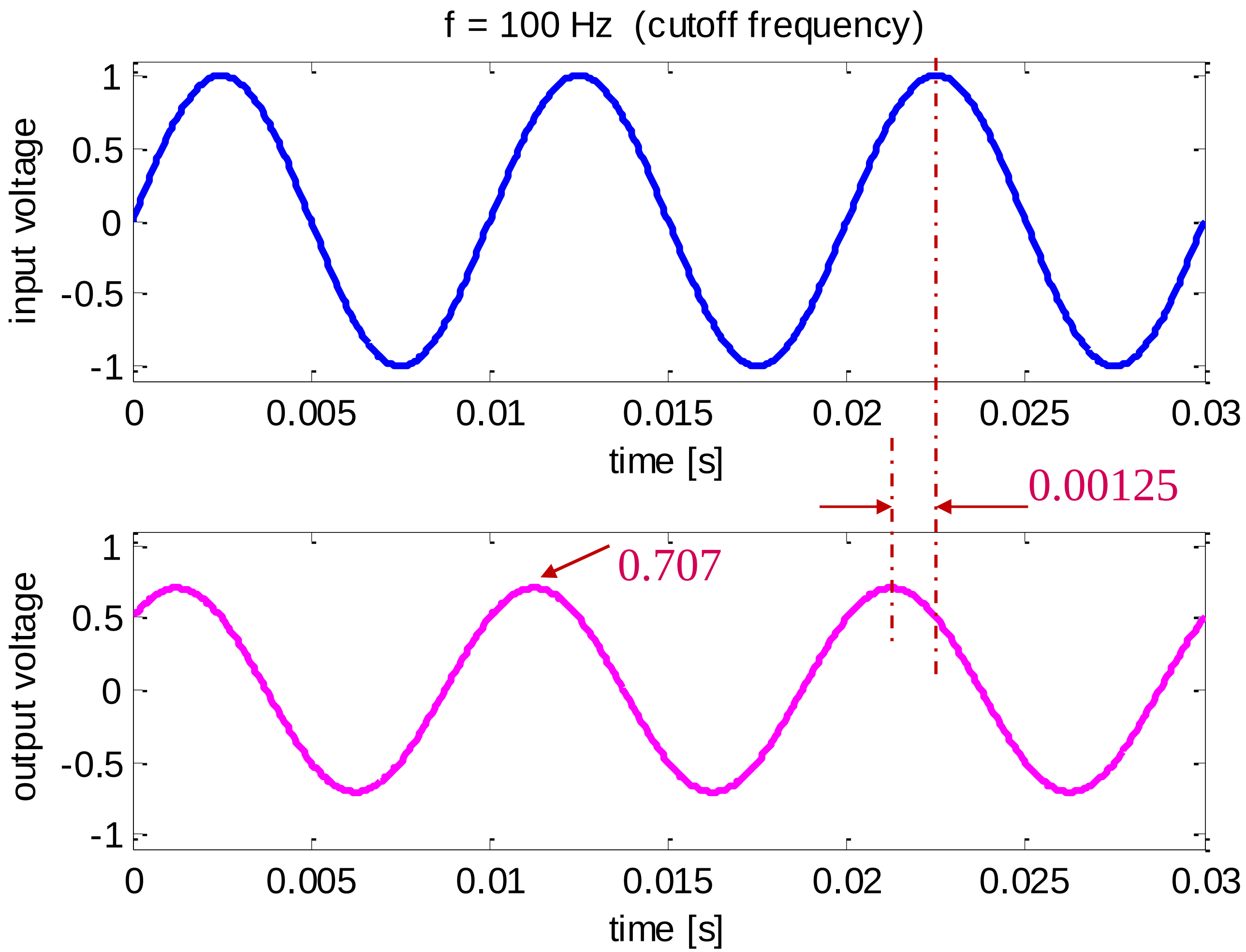
Input:
sinewave
1V amplitude
10 kHz frequency
inside the passband

Output:
Sinewave
no attenuation: 1V amplitude
no phase shift



LPF: $f_0 = 100$ Hz

ex. #2



Input:

sinewave

1V amplitude

100 Hz frequency

cutoff frequency

Output:

Sinewave

attenuation: 0.707V amplitude

phase shift: $+45^{o}$ (0.00125 s)

LPF: $f_0 = 100\,\mathrm{Hz}$

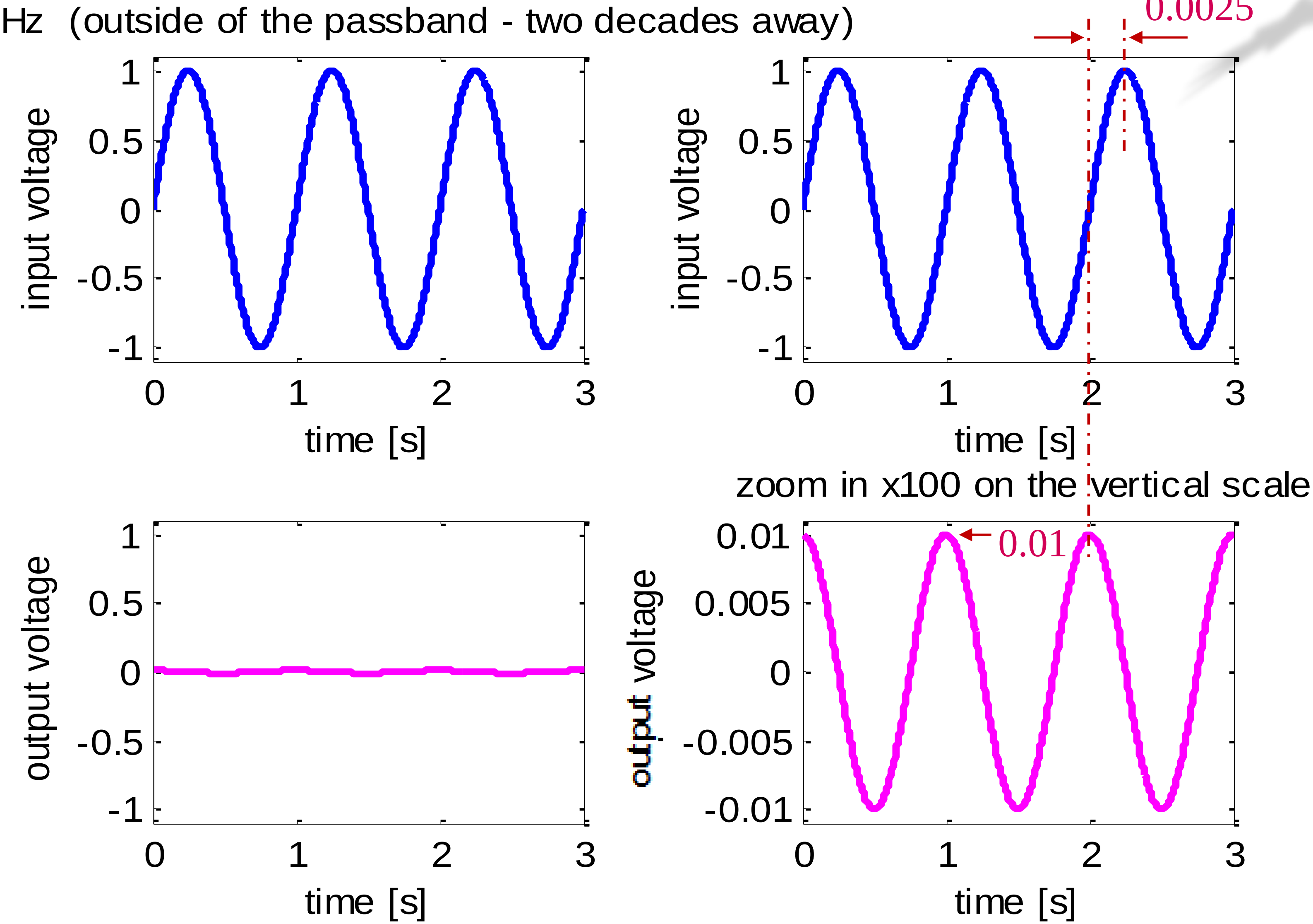
ex. #3

Output: high attenuation: 0.01V amplitude
phase shift: +90° (0.0025 s)

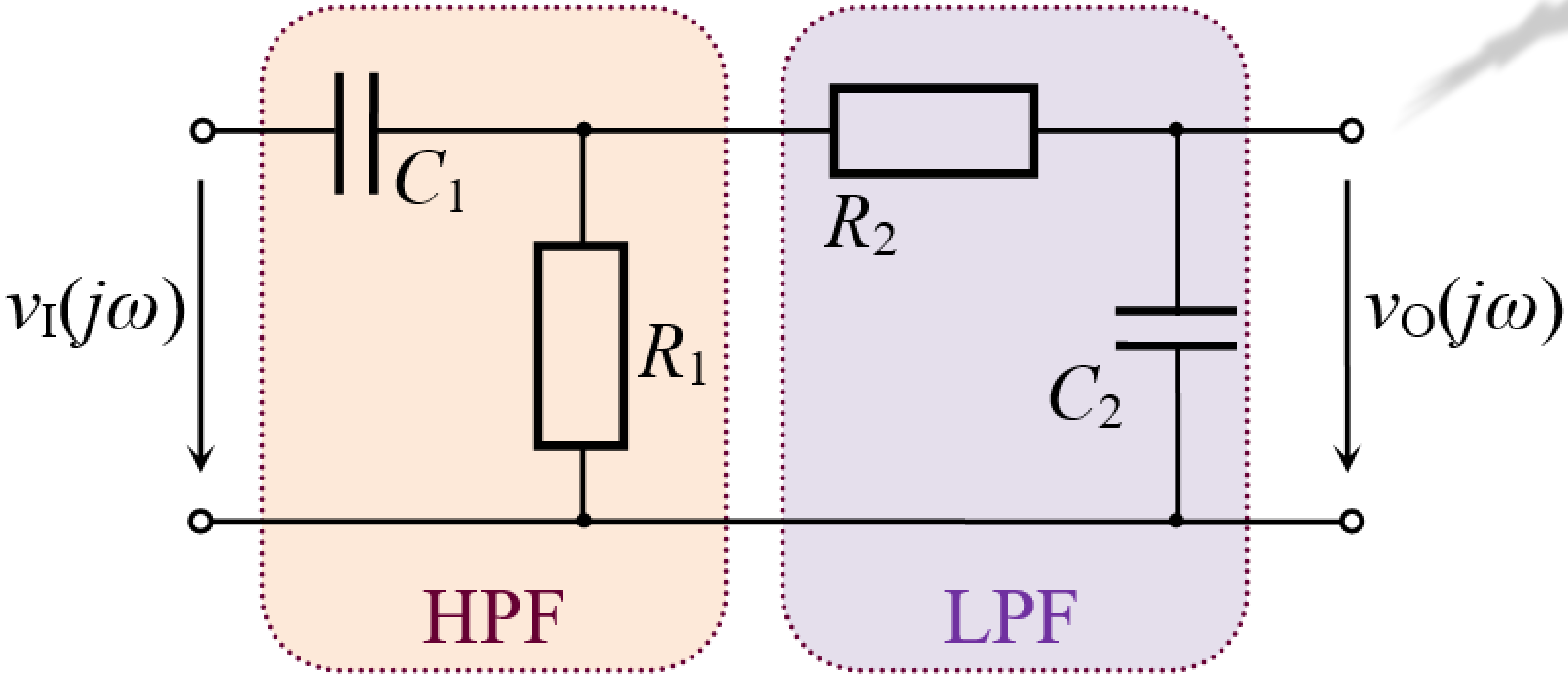
OPTIONAL

Input:

f = 1 Hz (outside of the passband - two decades away)

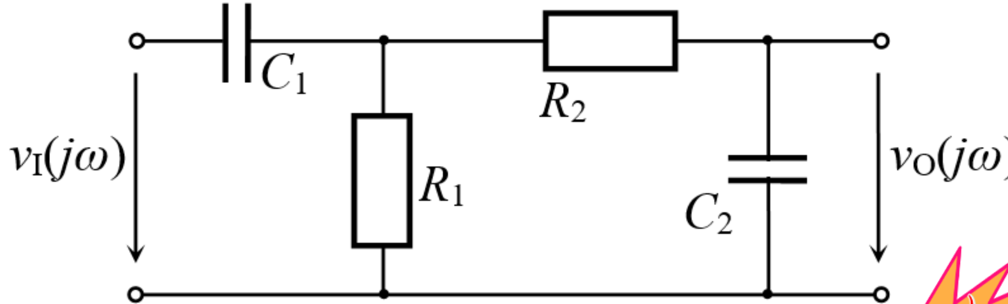


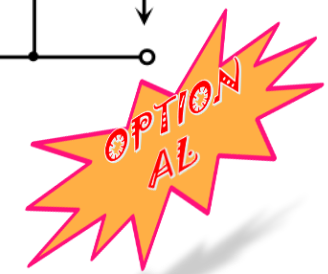
RC circuit - frequency response (BPF)



Second order, passive, band-pass filter (BPF)

RC circuit - frequency response (BPF) – *cont.*





$$F(j\omega) = \frac{v_O(j\omega)}{v_I(j\omega)} = \frac{j\omega R_1 C_1}{(1 + j\omega R_1 C_1)(1 + j\omega R_2 C_2)}$$

$$\left| F(j\omega) \right| = \frac{\omega R_1 C_1}{\sqrt{1 + (\omega R_1 C_1)^2}\sqrt{1 + (\omega R_2 C_2)^2}}$$

$$\Phi(\omega) = 90^o - arctg(\omega R_1 C_1) - arctg(\omega R_2 C_2)$$

cutoff frequencies

$$f_L = \frac{1}{2\pi R_1 C_1} \qquad f_H = \frac{1}{2\pi R_2 C_2}$$

bandwidth

$$B = f_H - f_L$$

BPF: frequency response

Illustration for $f_L = 10\,\text{Hz}, f_H = 1\,\text{MHz}$