Physics-L2 Electromagnetism

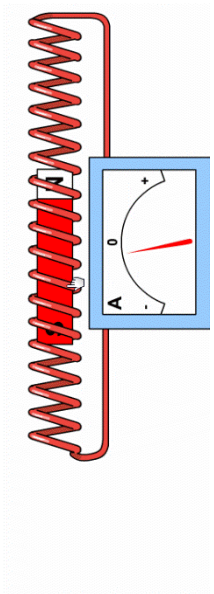
Approximative program

1) Sources –Fields -interactions
2) Fundamentals of magnetism

Chap 1: Electrostatics
Chap 2: Magnetostatics
Chap 3: Time-dependent regime-Induction phenomena
Chap 4: Maxwell equations
Chap 5: Dielectric media and applications
Chap 6: Conducting media and applications
Chap 7: Magnetic media and applications

week	Magistral lectures
1	Electrostatics
2	Electrostatics
3	Electrostatics
4	Electrostatics
5	Magnetostatics
6	Magnetostatics
7	**Induction**
8	**Induction**
9	Maxwell equations
10	Maxwell equations
11	Dielectric media
12	Dielectric / Metallic media
13	Metallic Media
14	Magnetic media

Electromagnetic Induction -L2



1)Experimental approach

a) i) Faraday experiment.

ii) Notion of electromotive force and field.

b) Neumann induction. Time-dependent magnetic field and rigid circuit.

i) Examples

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i) example with « rail of Laplace ». Deformable circuit

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2) Theoretical description

3) Inductance and self inductance

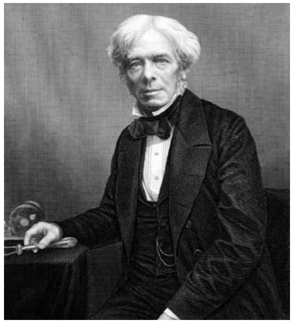
4) Applications

i) Electric transformer

iii) Induction heating

ii) Electro-mechanical conversion: DC and AC motors

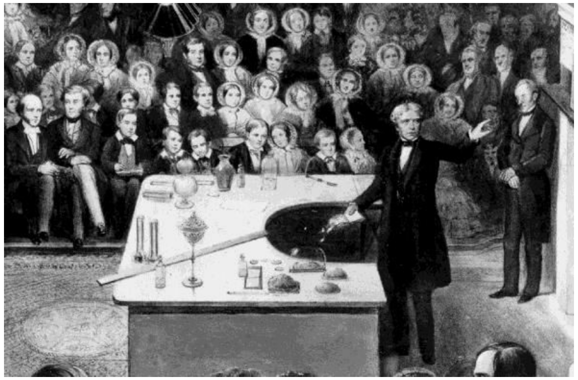
1831: Magnetism can induce electricity

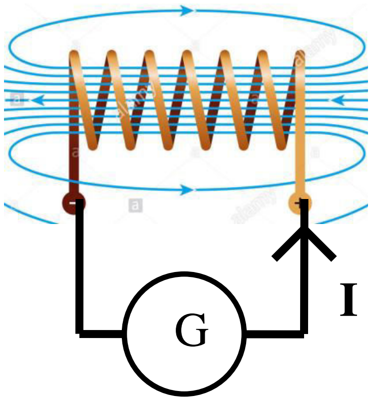


Michael Faraday
1791-1867

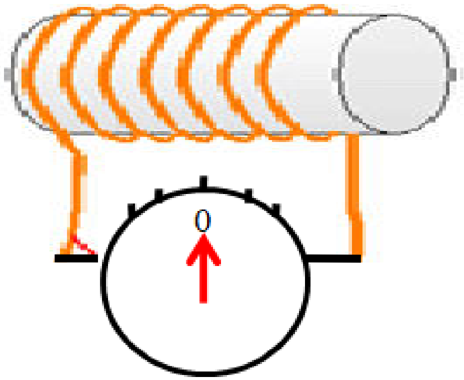
Important contribution

- **Chemistry (electrolysis)**
- **Notion of *vectors fields***
- ***Electromagnetic Induction***



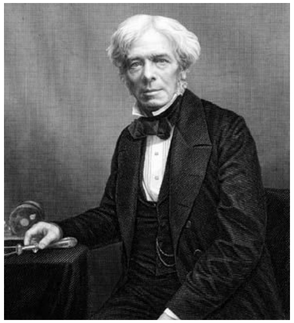


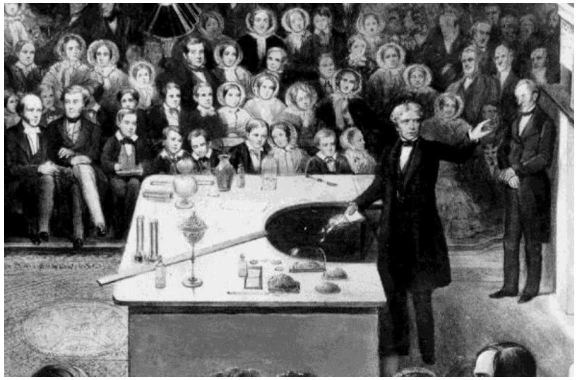
A magnetic coil
that produces
a magnetic field



A magnetic coil related to
a voltmeter.

1831: Magnetism can induce electricity





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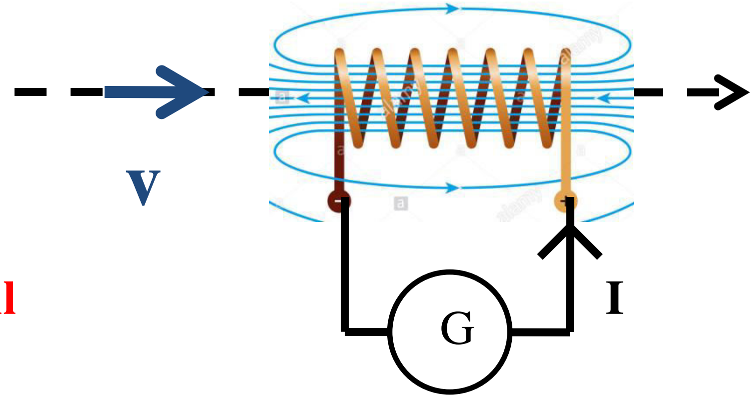
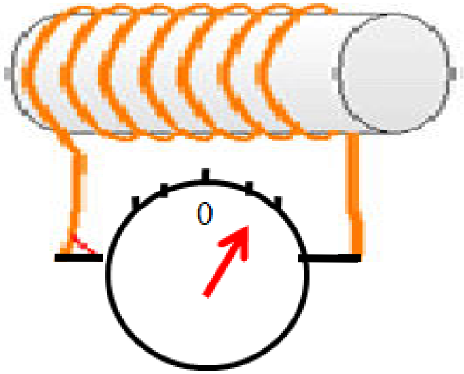
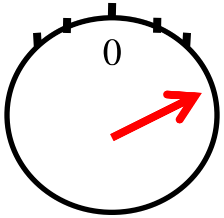




We move the first coil close to the second and a voltage appears <u>during the motion !</u>

If motion is faster, voltage
In the second coil is higher !



<u>We say also: an electromotive force</u>

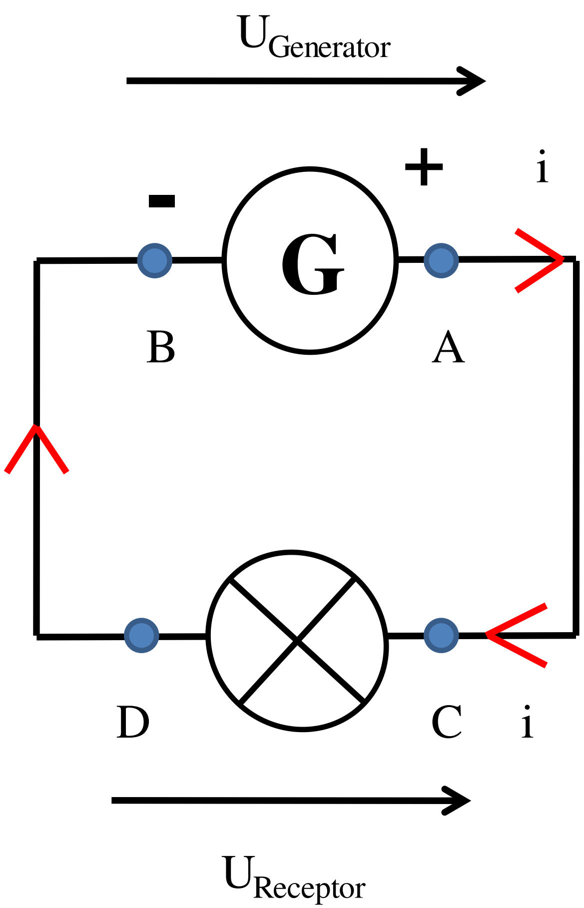
Convention about electric circuit

The value of the voltage will be

$$U = V_{pic} - V_{end}$$

arrow

end pic



For Generator:

Current i gors from + to –

Voltage and current show the same direction.

$U_{Generator} = V_A - V_B$

Convention about electric circuit

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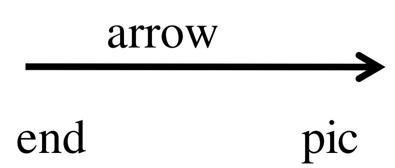

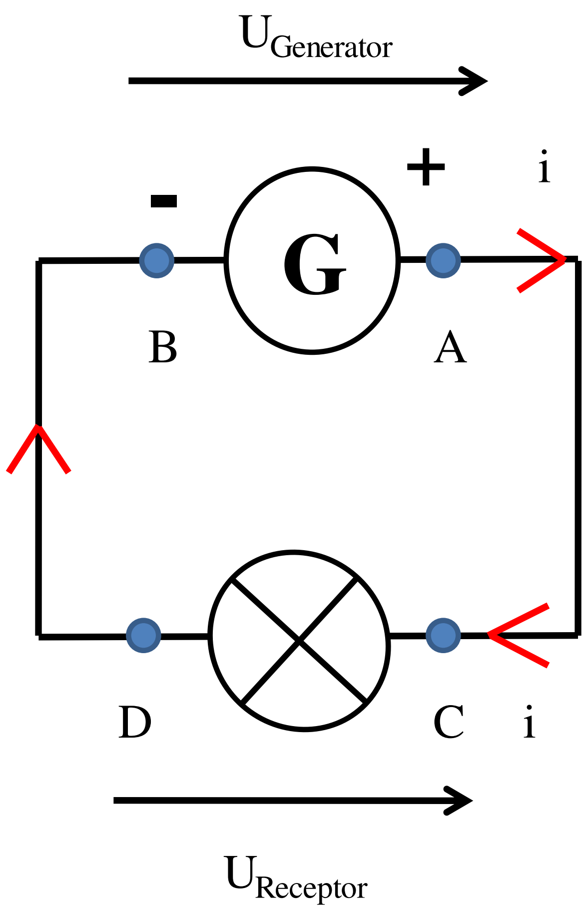

For Generator:

Current i gors from + to –

Voltage and current show the same direction.

$U_{Generator} = V_A - V_B$

For receptor

Voltage and current show opposite directions

$U_{Receptor} = V_C - V_D$

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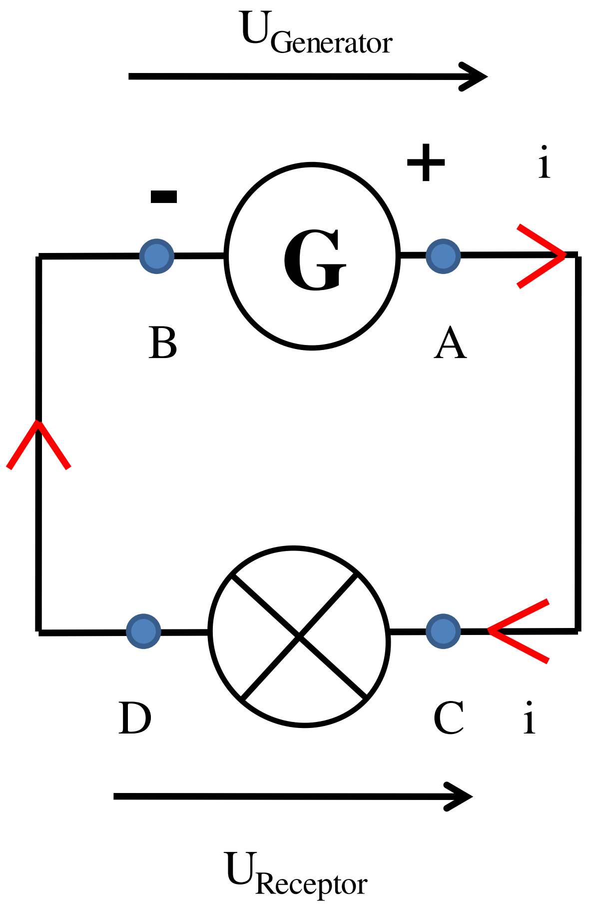
end → pic



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Voltage and current show the same direction.

$U_{Generator}=V_A-V_B$

For receptor

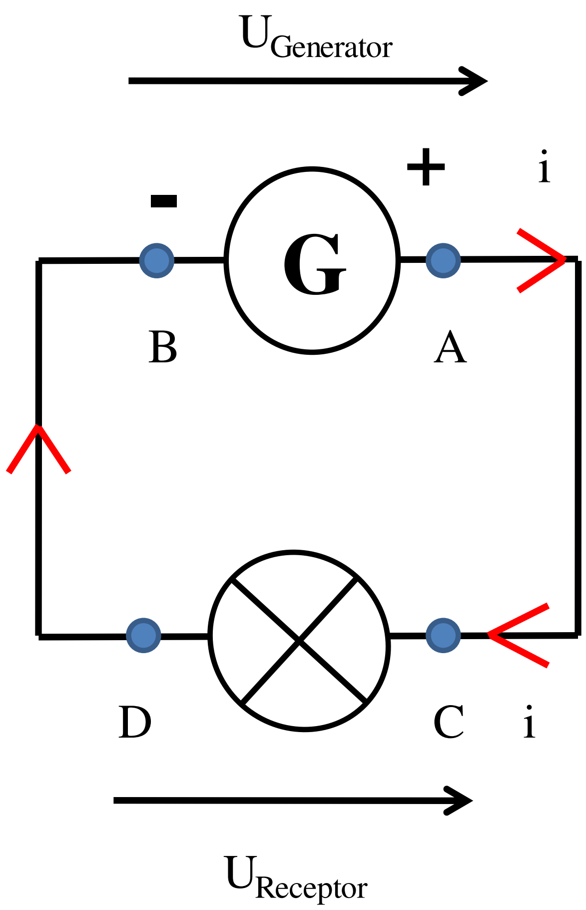
Voltage and current show opposite directions

$U_{Receptor}=V_C-V_D$

Also, an electric wire has the same potential in the begining and in the end $V_A = V_C$ and $V_B = V_D$

$U_{Receptor}=V_C-V_D=V_A-V_B= U_{Generator}$

Notion of electromotive field or electromotive force



$$U = V_A - V_B = \int_A^B \overrightarrow{E_m} \cdot \overrightarrow{dr} = e$$

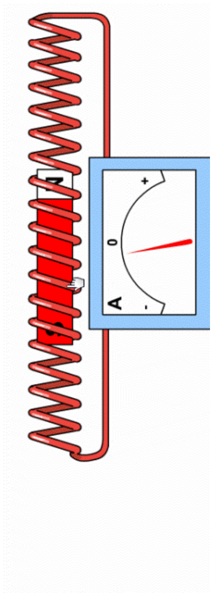
$\mathbf{E_m}$ is called the electromotive field, related to a Electromotive force **f**:

$$\overrightarrow{E_m} = \frac{\overrightarrow{f}}{q}$$

By abuse of language, we can call *e* as electromotive force:

$$e = \int_A^B \overrightarrow{E_m} \cdot \overrightarrow{dr}$$

Electromagnetic Induction -L2



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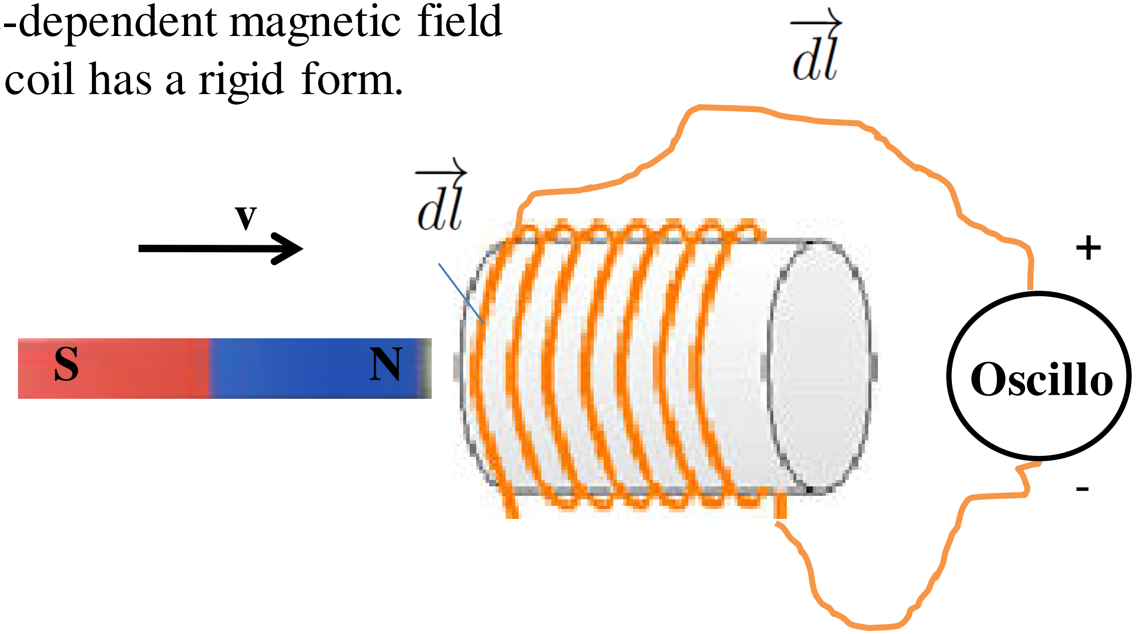
Neumann induction.

Franz Ernst Neumann
1798-1895

We move the magnet inside the coil that simulate the time-dependent magnetic field
The coil has a rigid form.



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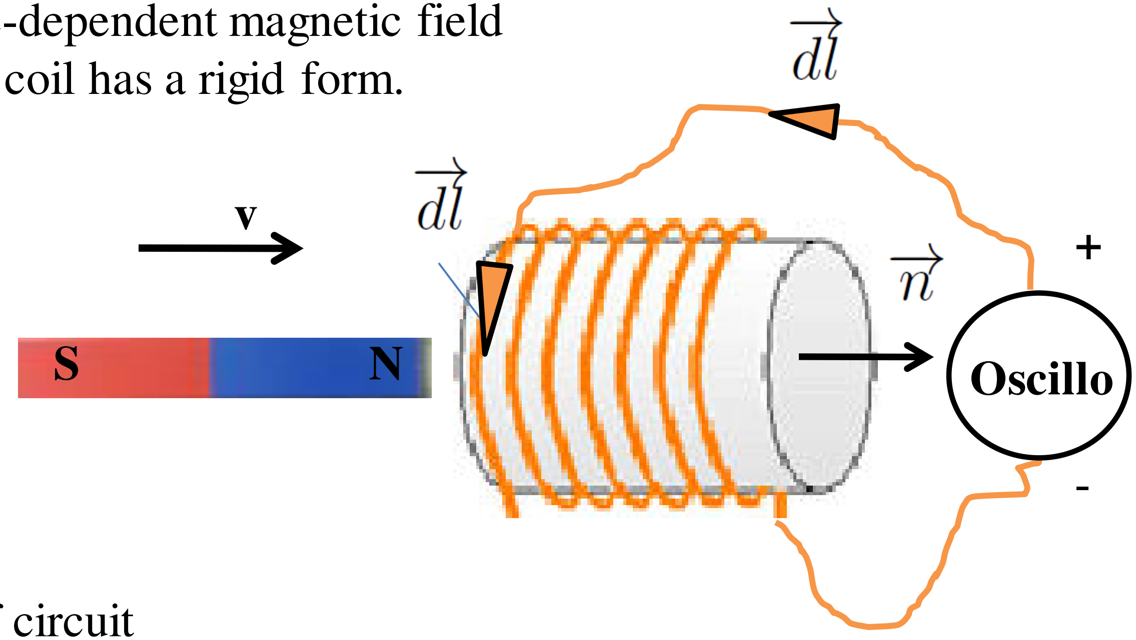
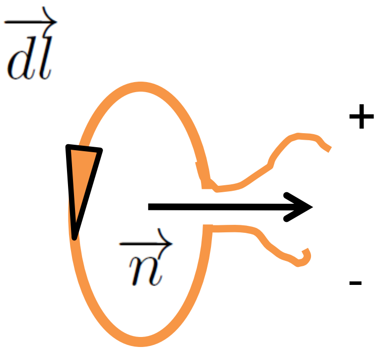


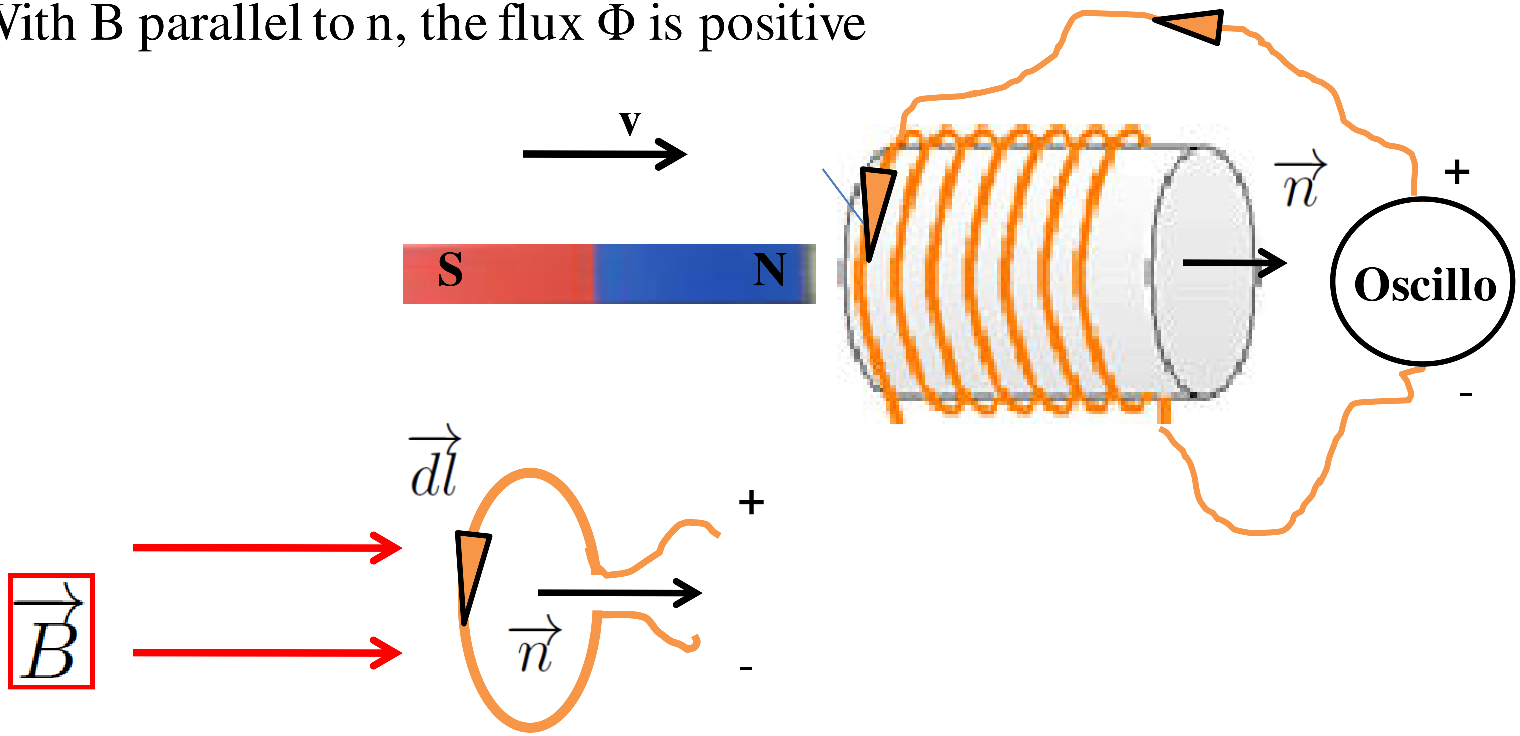
Before, we need to

i) Make the orientation of circuit



ii) Discuss the direction of the magnetic field

With B parallel to n, the flux Φ is positive



$$\Phi = \iint \overrightarrow{B} \cdot dS\overrightarrow{n} > 0$$

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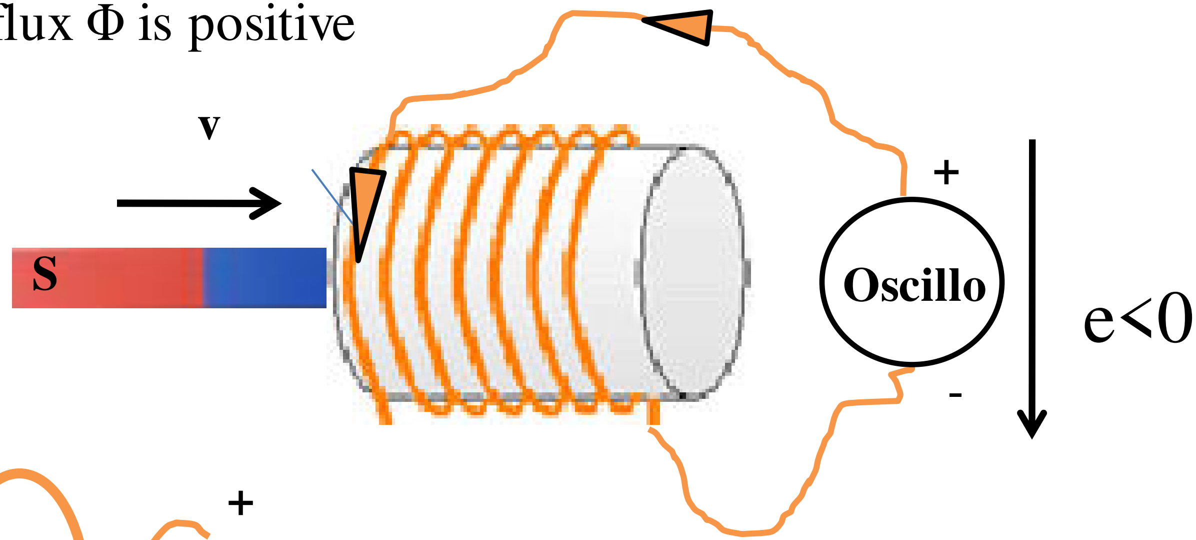
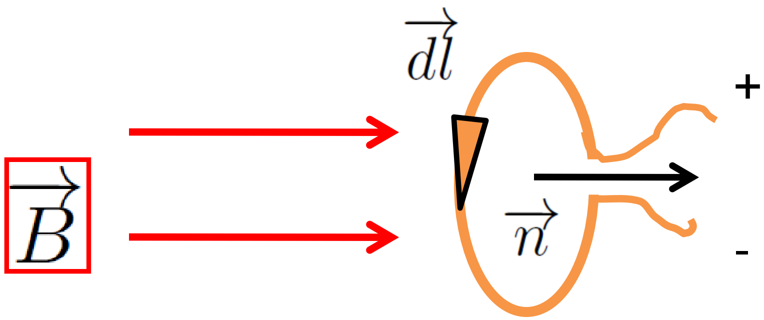
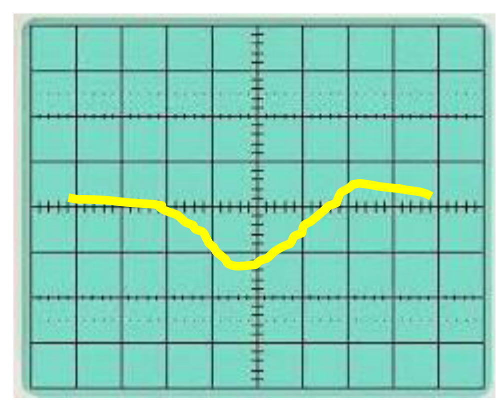


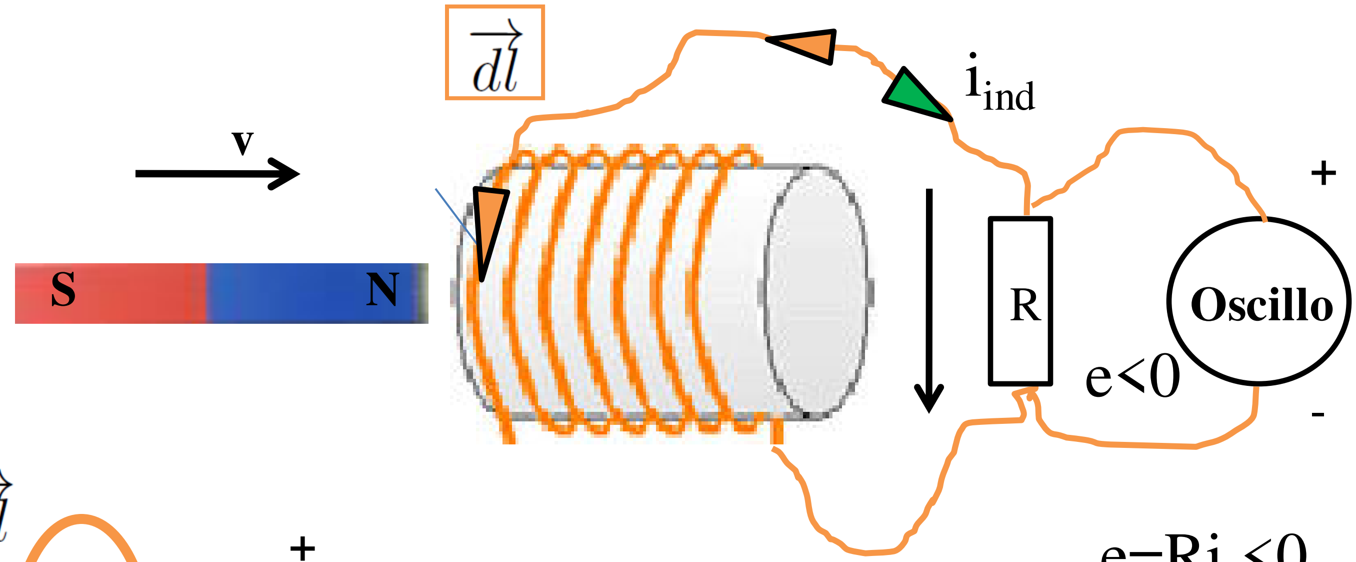


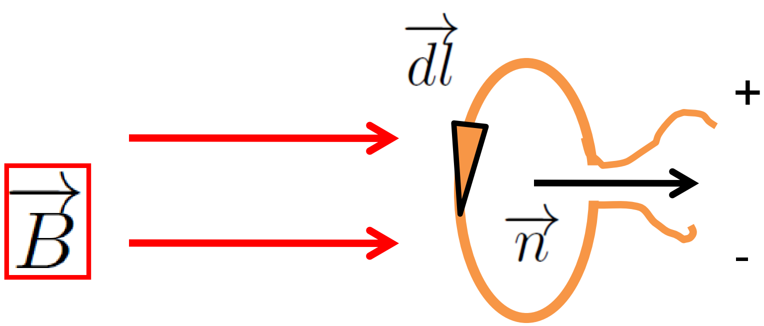
When moving magnet inside the coil
We observe negative voltage, a negative electromotive « force » appears

$$\Phi = \iint \overrightarrow{B} \cdot dS\overrightarrow{n} > 0$$



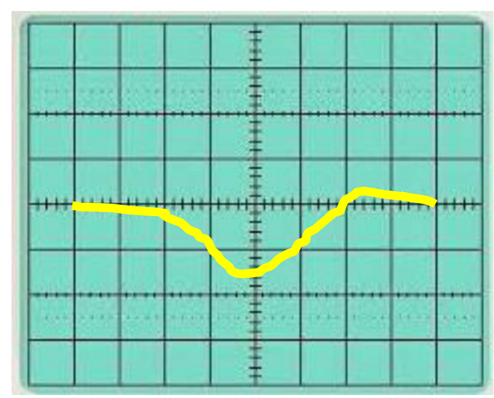
Same experiment by plugging a resistance, whose voltage e=Ri will be negative.
The electromotive force is proportional to the current i so we have apparition of a negative current





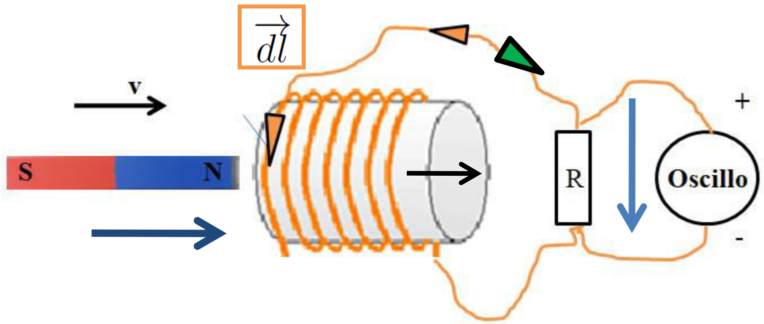
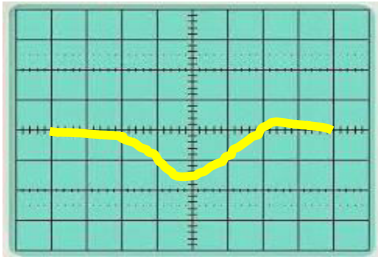
$e=Ri<0$

$\mathbf{i=i_{ind}<0}$



$$\Phi = \iint \overrightarrow{B} \cdot dS\overrightarrow{n} > 0$$

Playing with parameters:

Input (the flux)	Output (the electromotive force)
$\Phi>0$ 	 $e=Ri<0$ $i=i_{ind}<0$

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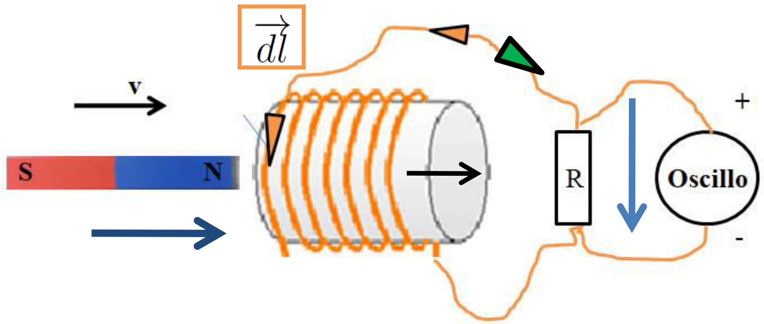
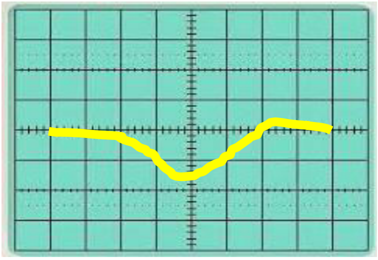
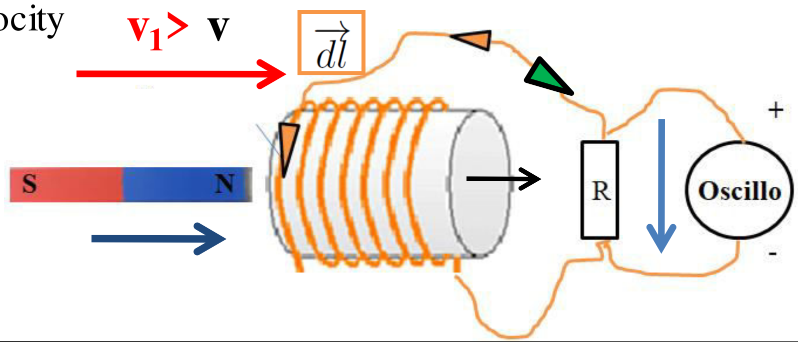
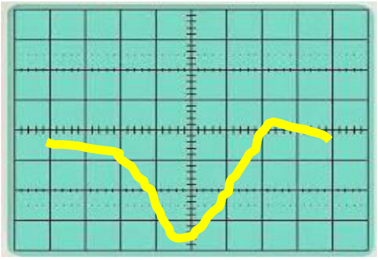
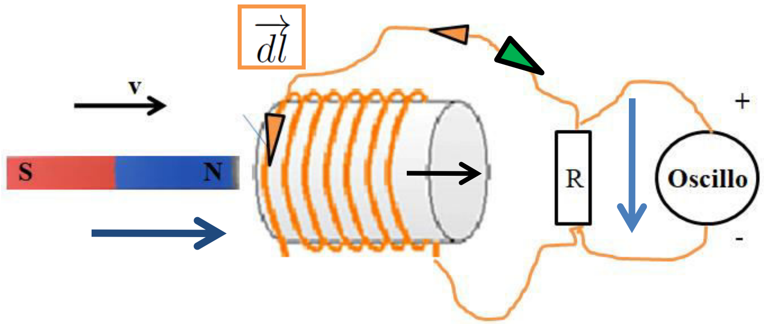
$\Phi>0$		 $e=Ri<0$ $i=i_{ind}<0$
Enters with faster velocity Influence of TIME VARIATION $\frac{d\Phi}{dt}>0$		 $e_1=Ri<0$ and $\lvert e_1\rvert>\lvert e\rvert$ $i=i_{ind}<0$

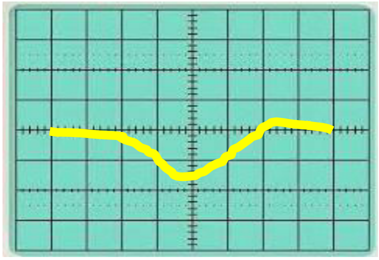
Time-dependent magnetic field and rigid circuit.

Playing with parameters:

	Input (the flux)	Output (the electromotive force)

$\Phi>0$



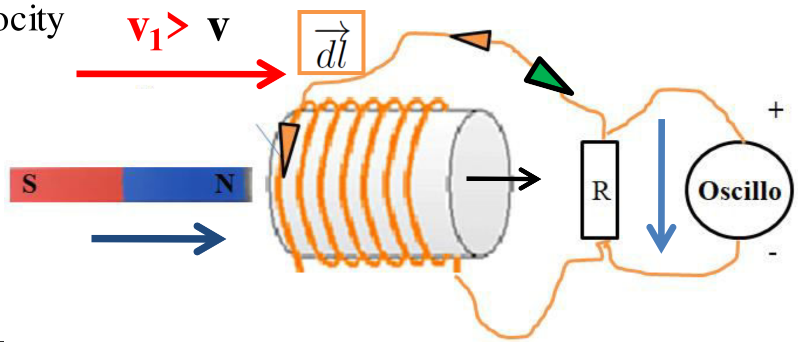


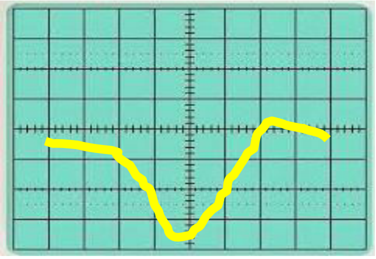
$e=Ri<0$

$i=i_{ind}<0$

Enters with faster velocity
Influence of TIME
VARIATION

$$\frac{d\Phi}{dt}>0$$



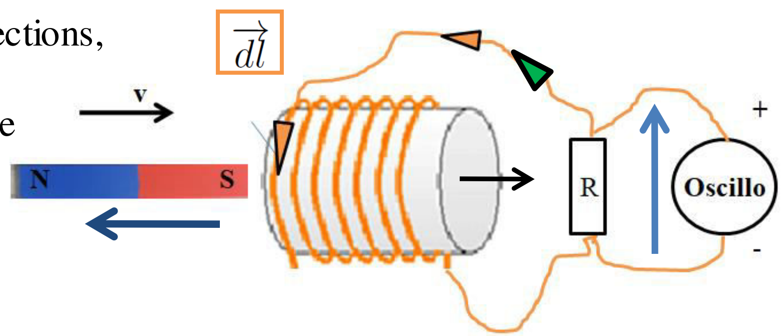


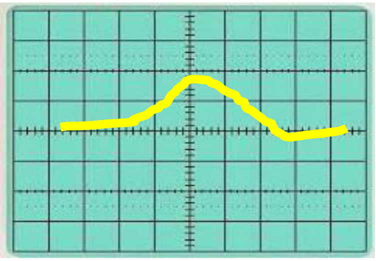
$e_1=Ri<0$
and
$|e_1|>|e|$

$i=i_{ind}<0$

We switch the pole directions,
B opposite to **n**
and Φ becomes negative
$\Phi<0$

$$\frac{d\Phi}{dt}<0$$





$e=Ri>0$

$i=i_{ind}>0$

Results

Lets look first the units: [e]=[V]= Volt

$$\left[\frac{d\Phi}{dt}\right] = \frac{[B][S]}{[t]} = \frac{[B][m]}{[t]}[m] = [E][m] = [V] = \mathrm{Volt}$$

Results

Lets look first the units: [e]=[V]= Volt

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When the flux variation is positive $\frac{d\Phi}{dt} > 0$ the electromotive force is negative $e<0$

When the flux variation is negative $\frac{d\Phi}{dt} < 0$ the electromotive force is positive $e>0$

Results

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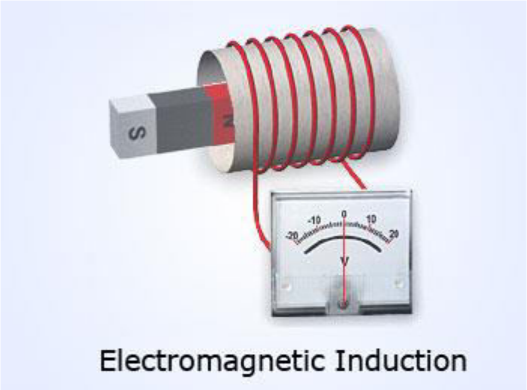
$$\boxed{\frac{d\Phi}{dt} = -e}$$

Faraday law



Connection with electromotive force

$$
\begin{aligned}
e = -\frac{d\Phi}{dt} &= -\frac{d}{dt}\iint \overrightarrow{B}\cdot\overrightarrow{dS} \\
&= -\frac{d}{dt}\iint \overrightarrow{\mathrm{rot}}\,\overrightarrow{A}\cdot\overrightarrow{dS} \\
&= -\frac{d}{dt}\oint \overrightarrow{A}\cdot\overrightarrow{dl} \\
&= \oint -\frac{\partial\overrightarrow{A}}{\partial t}\cdot\overrightarrow{dl} \\
&= \oint \overrightarrow{E_m}\cdot\overrightarrow{dl}
\end{aligned}
$$

Stockes

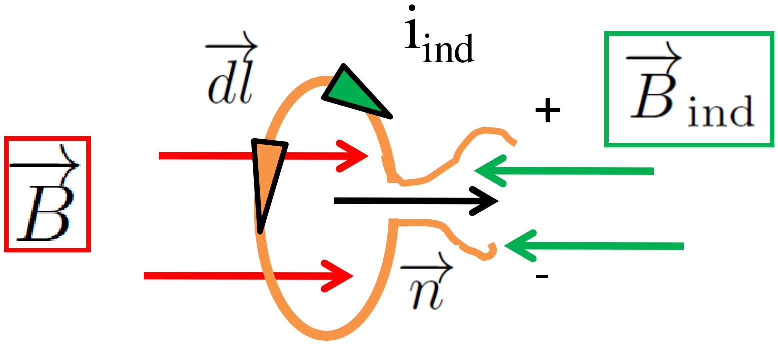
$$\boxed{\overrightarrow{E_m} = -\frac{\partial\overrightarrow{A}}{\partial t}}$$

Time-dependent magnetism generates electricity !!!

Lenz Law

Friedrich Emil Lenz
1804-1865

Fact:
a positive variation of flux (an increase) creates an electromotive force that generates a negative current. This negative current will create a magnetic field whose flux is opposite to the initial flux.

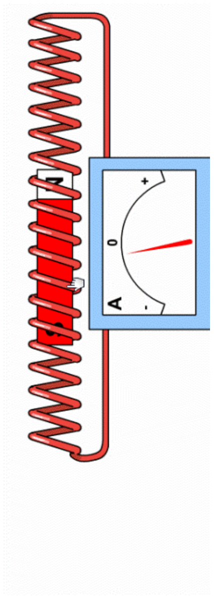


<u>Traduction of the usual french statement about Lenz law</u>

L'induction génère des effets qui s'opposent aux causes qui leur donnent naissance

Induction generates effects that oppose themselves to what gave them birth

Electromagnetic Induction -L2



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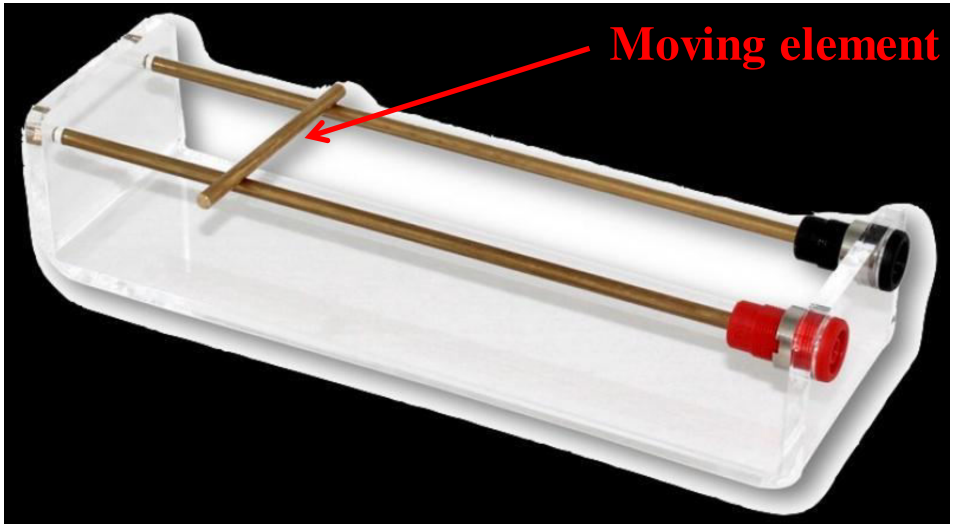
We consider now the opposite case: the magnetic field is constant but the circuit can move

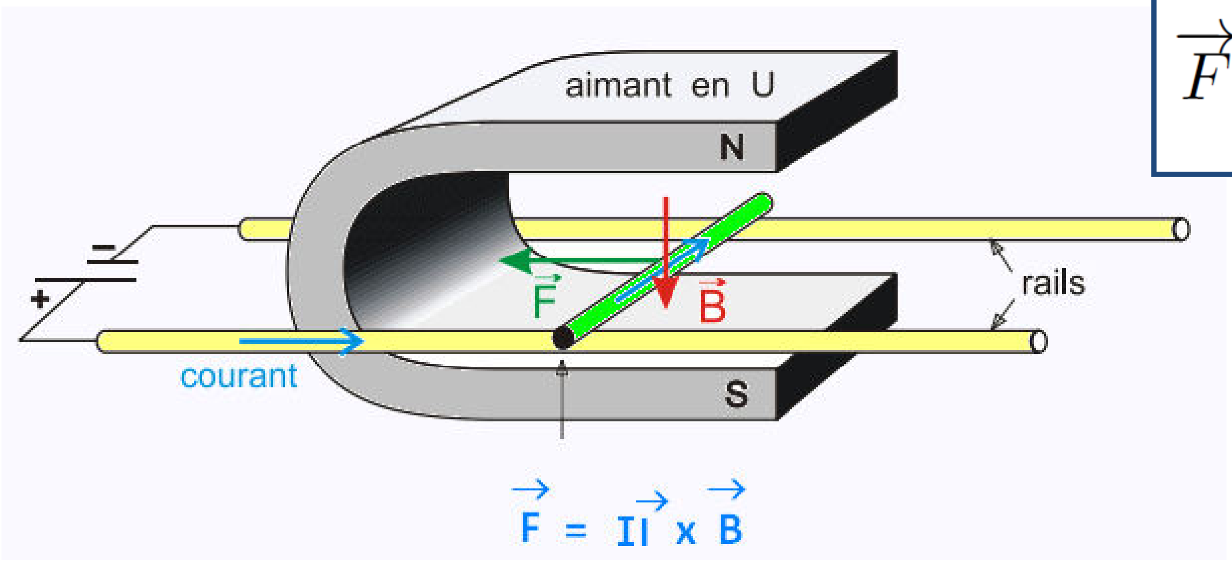
In a first approach, we will consider a deformable circuit : its form can change.
The device is called **« rail de Laplace »** :
It is made of a two parallel conductors in contact with a third one than can move just because it is not fixed to the two first.
Consequently, the circuit can change its form….



Rail in french

The principle

- We connect the « rail » to a generator being able to generate an electric current i.
- When turning the current on, nothing happens.
- However, when diving the system in a constant magnetic field, for instance the one created by a U-Magnet (*aimant en U*), it appears that the small stick (**in green**) starts to move.
- The reason is given by the action of the **Laplace force.**
- If we change the current direction, or the magnetic field direction, the force will be in the opposite direction.



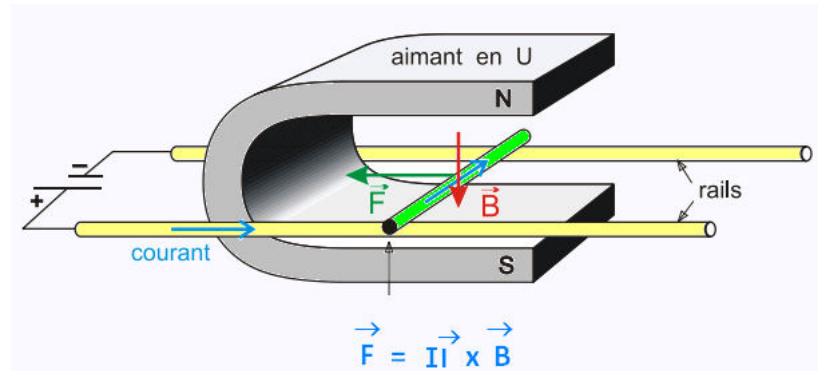
$$\vec{F} = \int i\,\vec{dl} \wedge \vec{B}$$

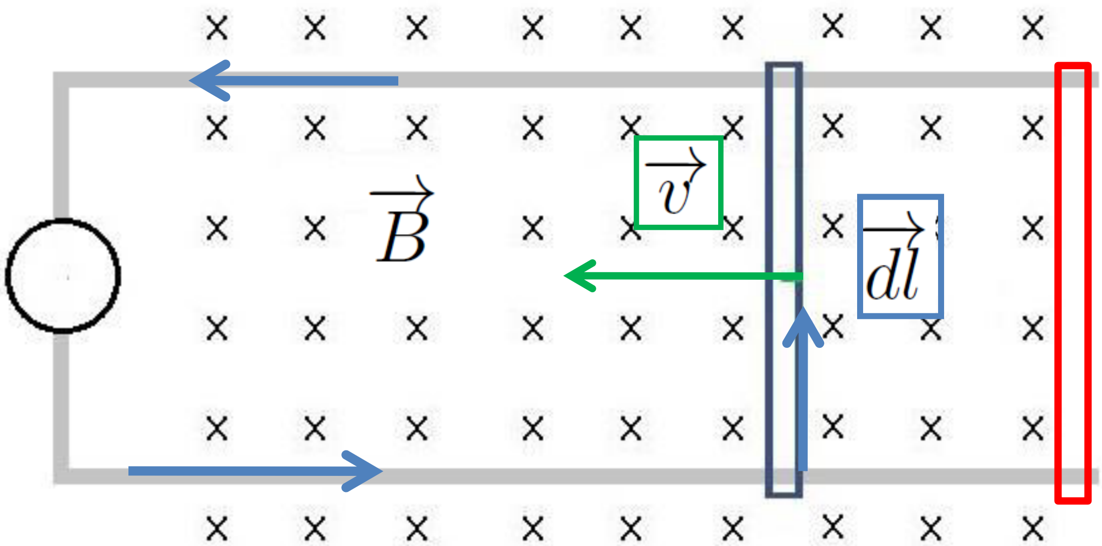
Lorentz induction. Constant magnetic field and moving circuit.

View from Samaliot

The mobile stick moves with a velocity v

The x represent direction of magnetic field





Initial position of mobile stick

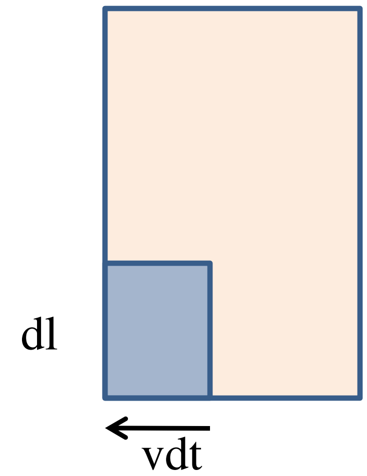
v

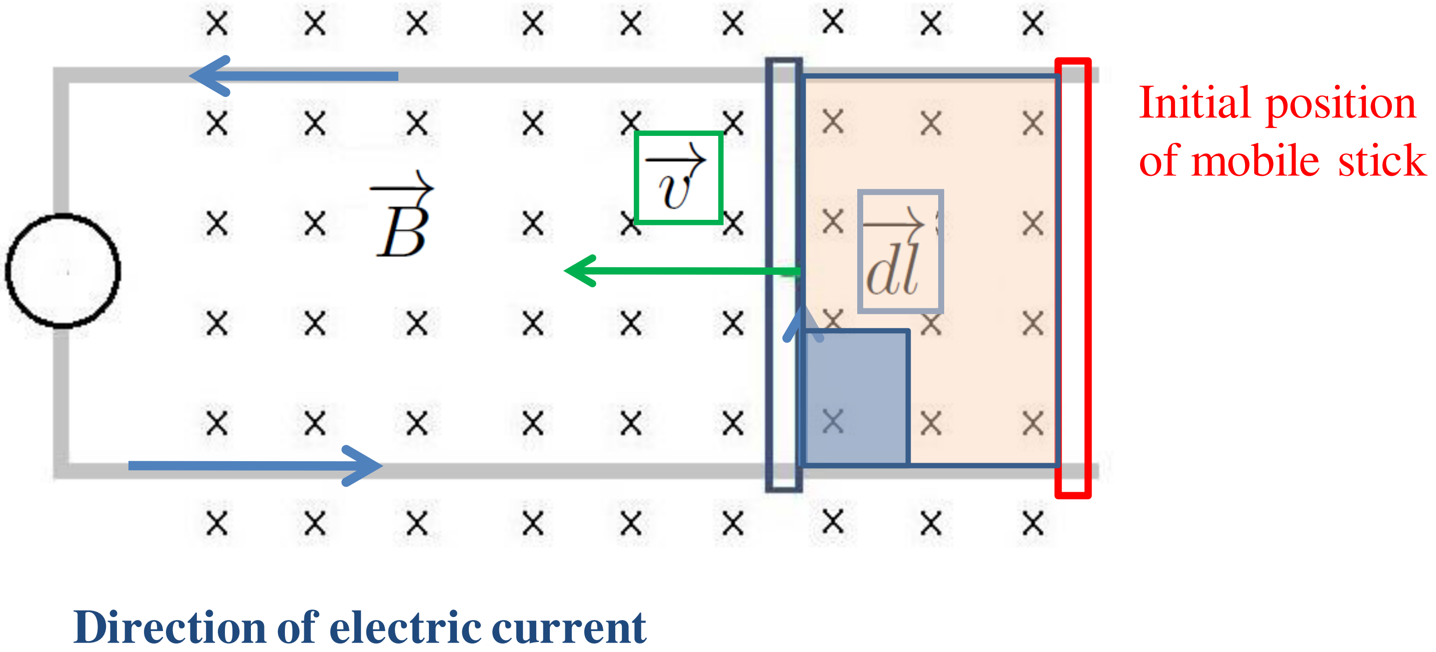
Direction of electric current

Surface covered by the mobile stick during the motion

Elementay surface covered during time dt: given by dS=vdt*dl

Oriented surface is $\overrightarrow{dS} = (\overrightarrow{v}\,dt \wedge \overrightarrow{dl}) = dl v dt \overrightarrow{n}$





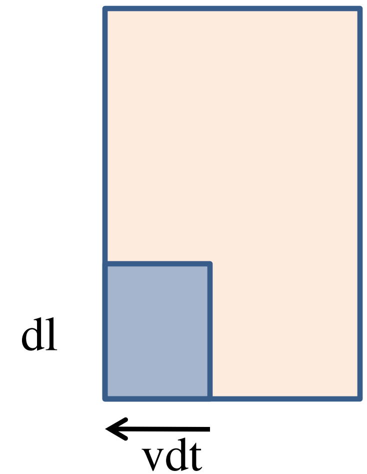
Surface covered by the mobile stick during the motion

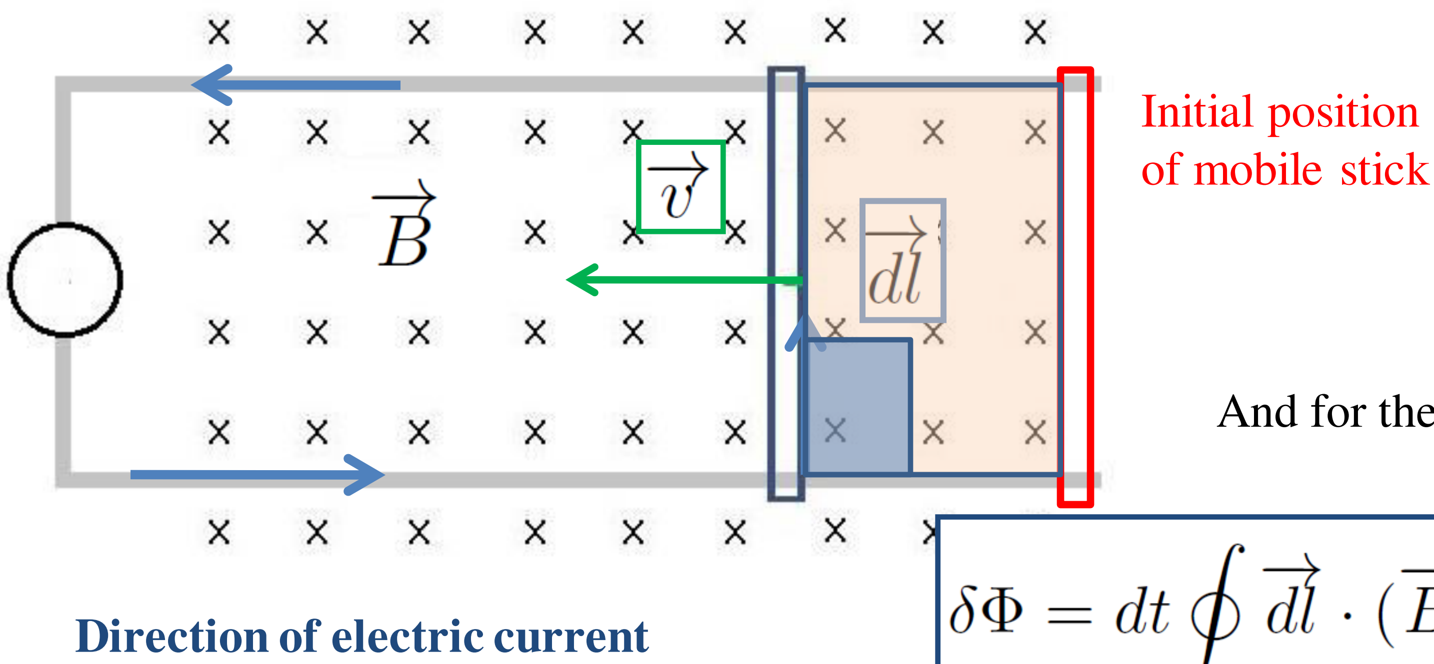
Elementay surface covered during time dt: given by dS=vdt*dl

Oriented surface is $\overrightarrow{dS} = (\overrightarrow{v}\,dt \wedge \overrightarrow{dl}) = dl v dt \overrightarrow{n}$

Elementary Flux through dS is

$$\boxed{\begin{aligned}\delta^2\Phi &= \overrightarrow{B}\cdot(\overrightarrow{v}\,dt \wedge \overrightarrow{dl}) \\ &= \overrightarrow{dl}\cdot(\overrightarrow{B}\wedge\overrightarrow{v}\,dt)\end{aligned}}$$

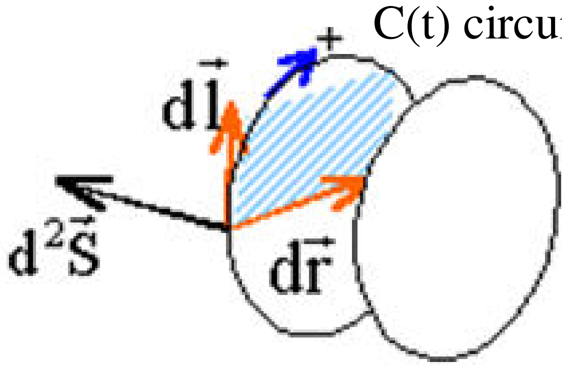


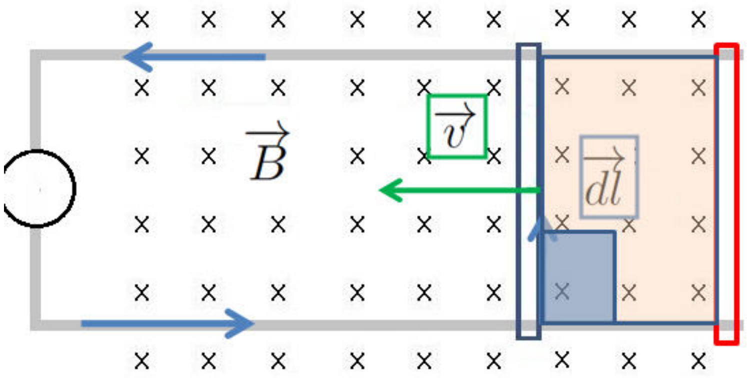


And for the circuit

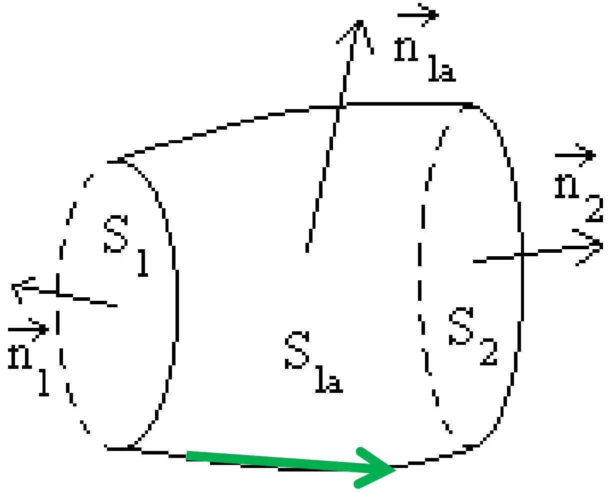
$$\boxed{\delta\Phi = dt \oint \overrightarrow{dl}\cdot(\overrightarrow{B}\wedge\overrightarrow{v})}$$

Interlude: Flux through a moving circuit





Φ_{sla} is the $\delta\Phi$ in



Flux conservation

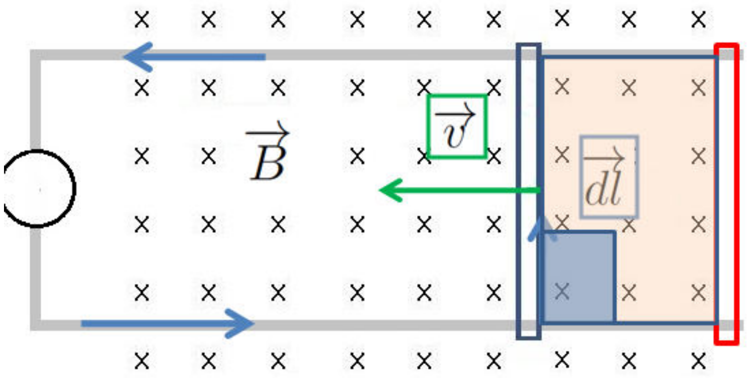
$-\Phi_{S1}(t)+\Phi_{Sla}+\Phi_{S2}(t+dt)= 0$

$\Phi_{Sla}=\Phi_{S1}(t)- \Phi_{S2}(t+dt)=d\Phi$

$\delta\Phi=d\Phi$

Finally we have

$$d\Phi = dt \oint \overrightarrow{dl} \cdot (\overrightarrow{B} \wedge \overrightarrow{v})$$



And by expressing the flux appears also an **electromotive force**

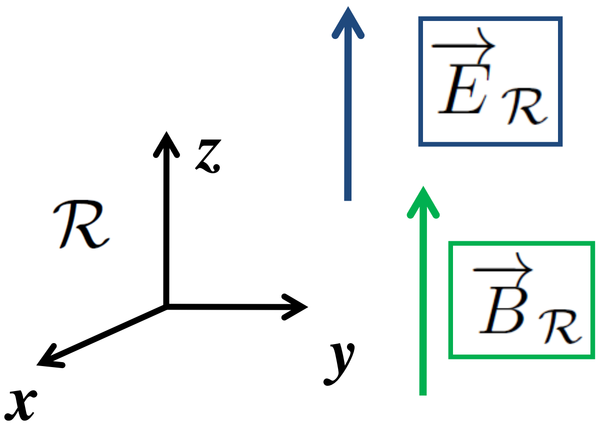
$$\begin{aligned}\frac{d\Phi}{dt} &= \oint \overrightarrow{dl} \cdot (\overrightarrow{B} \wedge \overrightarrow{v}) = \oint (\overrightarrow{B} \wedge \overrightarrow{v}) \cdot \overrightarrow{dl} \\ &= -\oint (\overrightarrow{v} \wedge \overrightarrow{B}) \cdot \overrightarrow{dl} = -\oint \overrightarrow{E_m} \cdot \overrightarrow{dl} = -e\end{aligned}$$

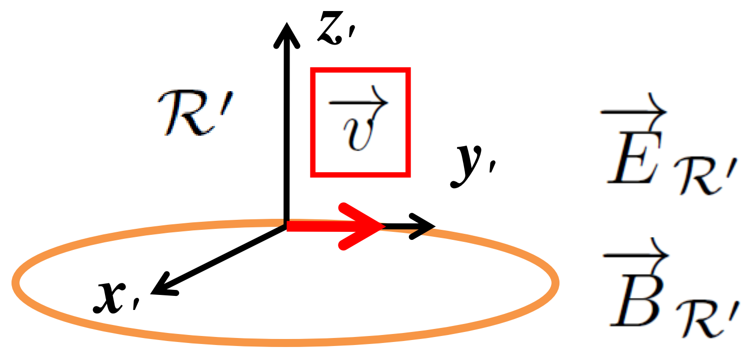
With the **electromotive field**

$$\boxed{\overrightarrow{E_m} = \overrightarrow{v} \wedge \overrightarrow{B}}$$

Generalization of Lorentz electromotive field

Be a **fixed frame R** in which we set an electric field (with a capacitor for instance) and a magnetic field (with coils or a magnet for instance)
Be a *moving circuit* attached to the **moving frame R'** at velocity v



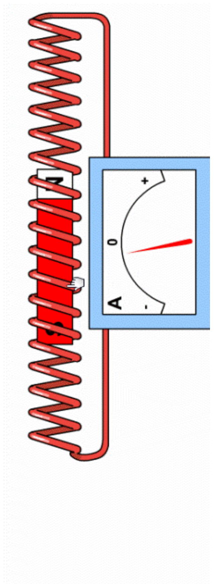


The electric field and the magnetic field in the moving frame are given by

$$\overrightarrow{E}_{\mathcal{R}'} = \overrightarrow{E}_{\mathcal{R}} + \overrightarrow{v} \wedge \overrightarrow{B}_{\mathcal{R}}$$

$$\overrightarrow{B}_{\mathcal{R}'} = \overrightarrow{B}_{\mathcal{R}}$$

Electromagnetic Induction -L2



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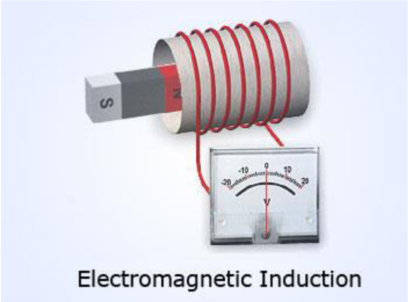
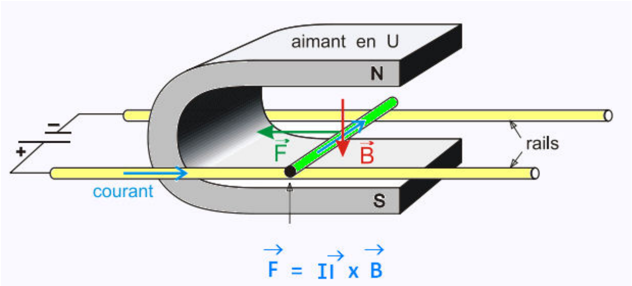
RESULTS ABOUT INDUCTION

A time-dependent Magnetic field in a rigid circuit AND a **constant magnetic field in a moving circuit** can generate an electromotive force e.

$$\frac{d\Phi}{dt} = -e = -\oint \overrightarrow{E_m} \cdot \overrightarrow{dl}$$





$$\overrightarrow{E_m} = -\frac{\partial \overrightarrow{A}}{\partial t}$$

$$\overrightarrow{E_m} = \overrightarrow{v} \wedge \overrightarrow{B}$$

Neumann electromotive field

Lorentz electromotive field

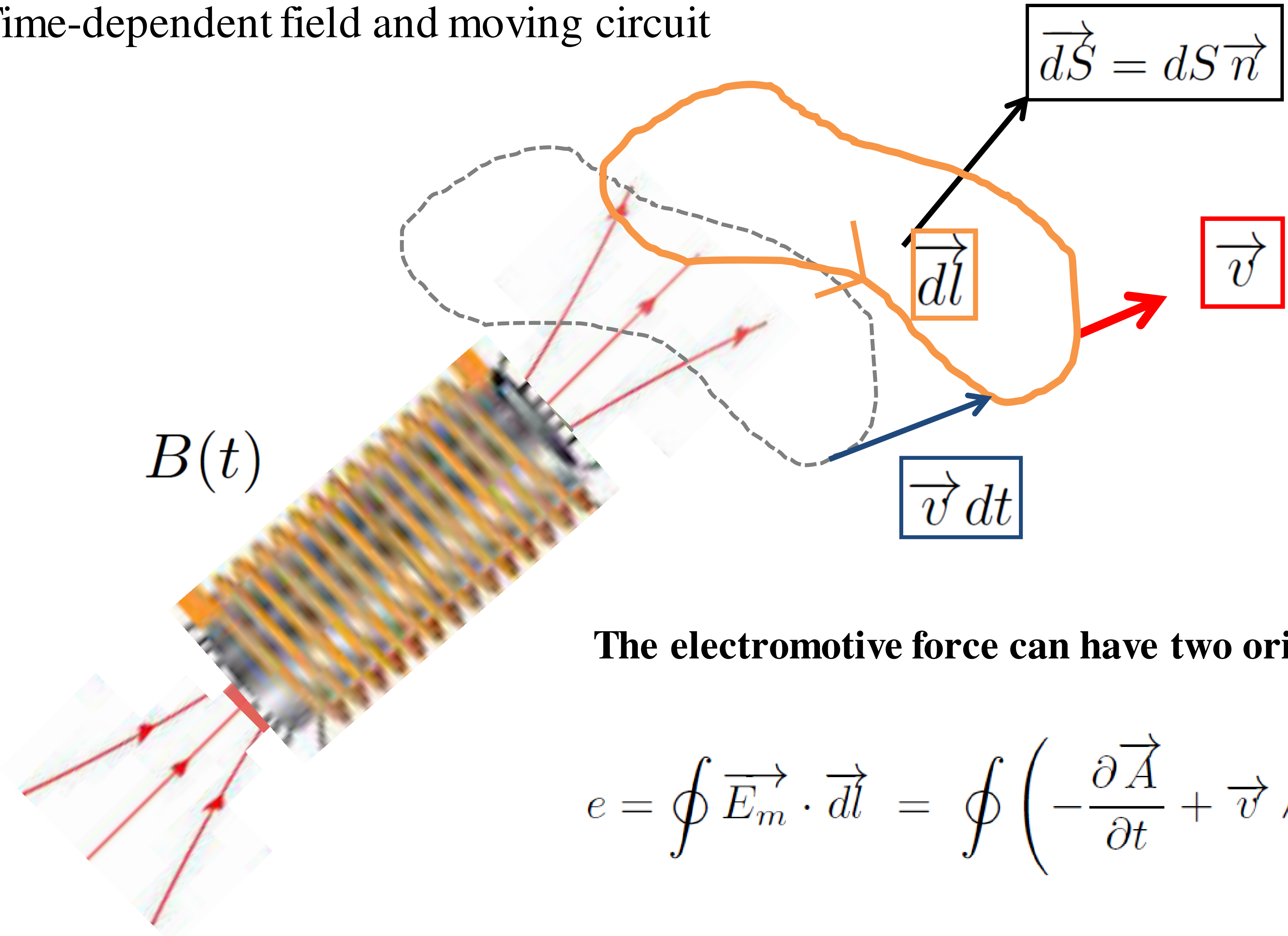
RESULTS ABOUT INDUCTION

A time-dependent Magnetic field in a rigid circuit AND a **constant magnetic field in a moving circuit** can generate an electromotive force e.

$$\boxed{\overrightarrow{E_m} = -\frac{\partial \overrightarrow{A}}{\partial t} + \overrightarrow{v} \wedge \overrightarrow{B}}$$

General case:

Time-dependent field and moving circuit



The electromotive force can have two origins

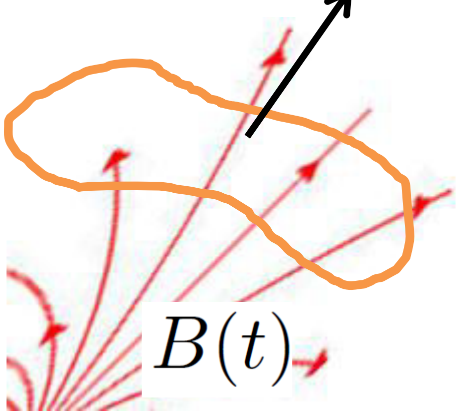
$$e = \oint \overrightarrow{E_m} \cdot \overrightarrow{dl} = \oint \left(-\frac{\partial \overrightarrow{A}}{\partial t} + \overrightarrow{v} \wedge \overrightarrow{B} \right) \cdot \overrightarrow{dl}$$

Theoretical description

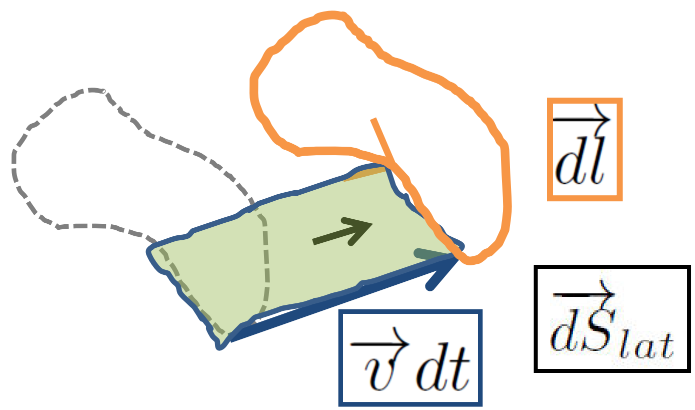
$$
\begin{aligned}
e = \oint \overrightarrow{E_m}\cdot\overrightarrow{dl} &= \oint\left(-\frac{\partial\overrightarrow{A}}{\partial t}+\overrightarrow{v}\wedge\overrightarrow{B}\right)\cdot\overrightarrow{dl}\\
&= -\oint\frac{\partial\overrightarrow{A}}{\partial t}\cdot\overrightarrow{dl}+\oint\left(\overrightarrow{v}\frac{dt}{dt}\wedge\overrightarrow{B}\right)\cdot\overrightarrow{dl}\\
&= -\frac{\partial}{\partial t}\iint\overrightarrow{\mathrm{rot}}\,\overrightarrow{A}\cdot\overrightarrow{dS}-\frac{1}{dt}\oint\left(\overrightarrow{vdt}\wedge\overrightarrow{dl}\right)\cdot\overrightarrow{B}\\
&= -\frac{d}{dt}\iint\overrightarrow{B}\cdot\overrightarrow{dS}-\frac{1}{dt}\underbrace{\oint\overrightarrow{dS}_{lat}\cdot\overrightarrow{B}}_{\delta\Phi=d\Phi}\\
&= -\frac{d\Phi}{dt}^{\text{Neumann}}-\frac{d\Phi}{dt}^{\text{Lorentz}}
\end{aligned}
$$

$$\boxed{\overrightarrow{dS}=dS\,\overrightarrow{n}}$$

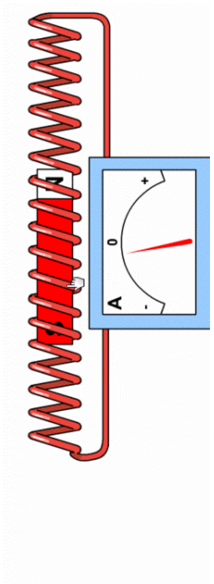
$$\overrightarrow{vdt}\wedge\overrightarrow{dl}=\overrightarrow{dS}_{lat}$$



$$\boxed{\frac{d\Phi}{dt}=-e}$$



Electromagnetic Induction -L2



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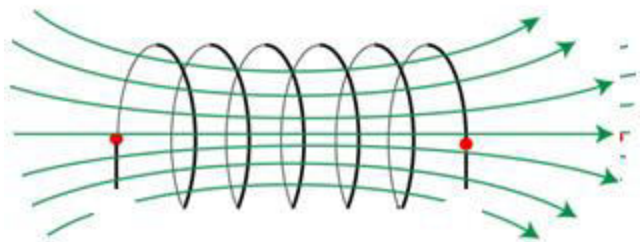
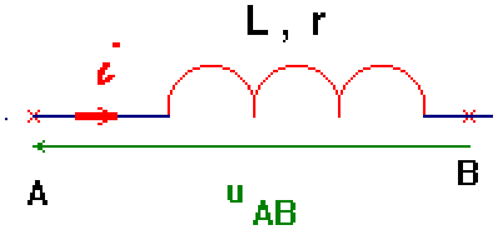
Inductance and self-inductance

Phenomena of self-induction: 1832

When a current propagates in a coil, the current generates a magnetic field leading to a flux through the coil itself.





Joseph Henry
1797-1868

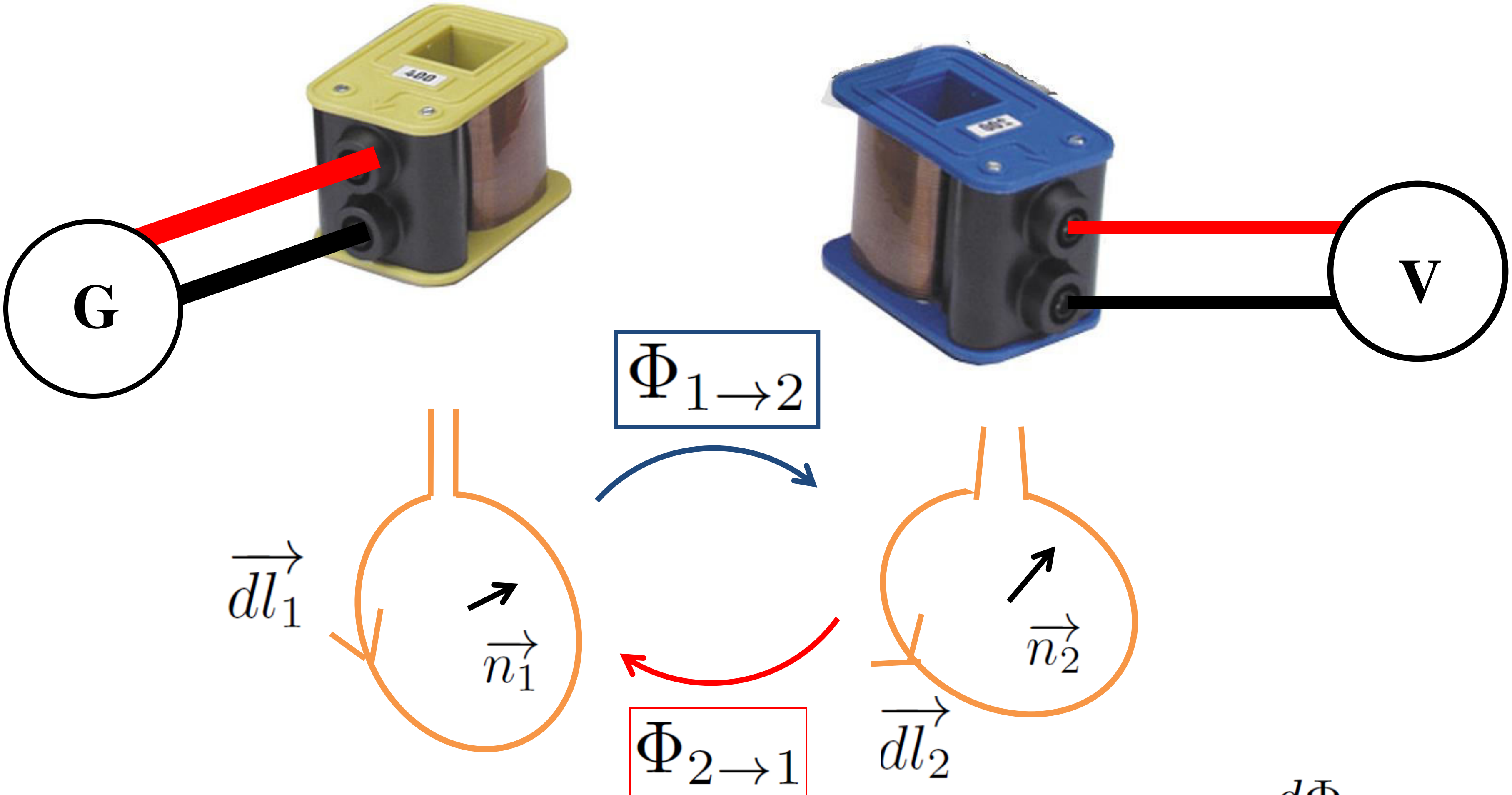
$$\vec{B} = \mu_0 n i \, \vec{e_z}$$

$$\Phi = BS$$

Consequently appears a negative electromotive force

$$U_L = -e = L\frac{di}{dt}$$

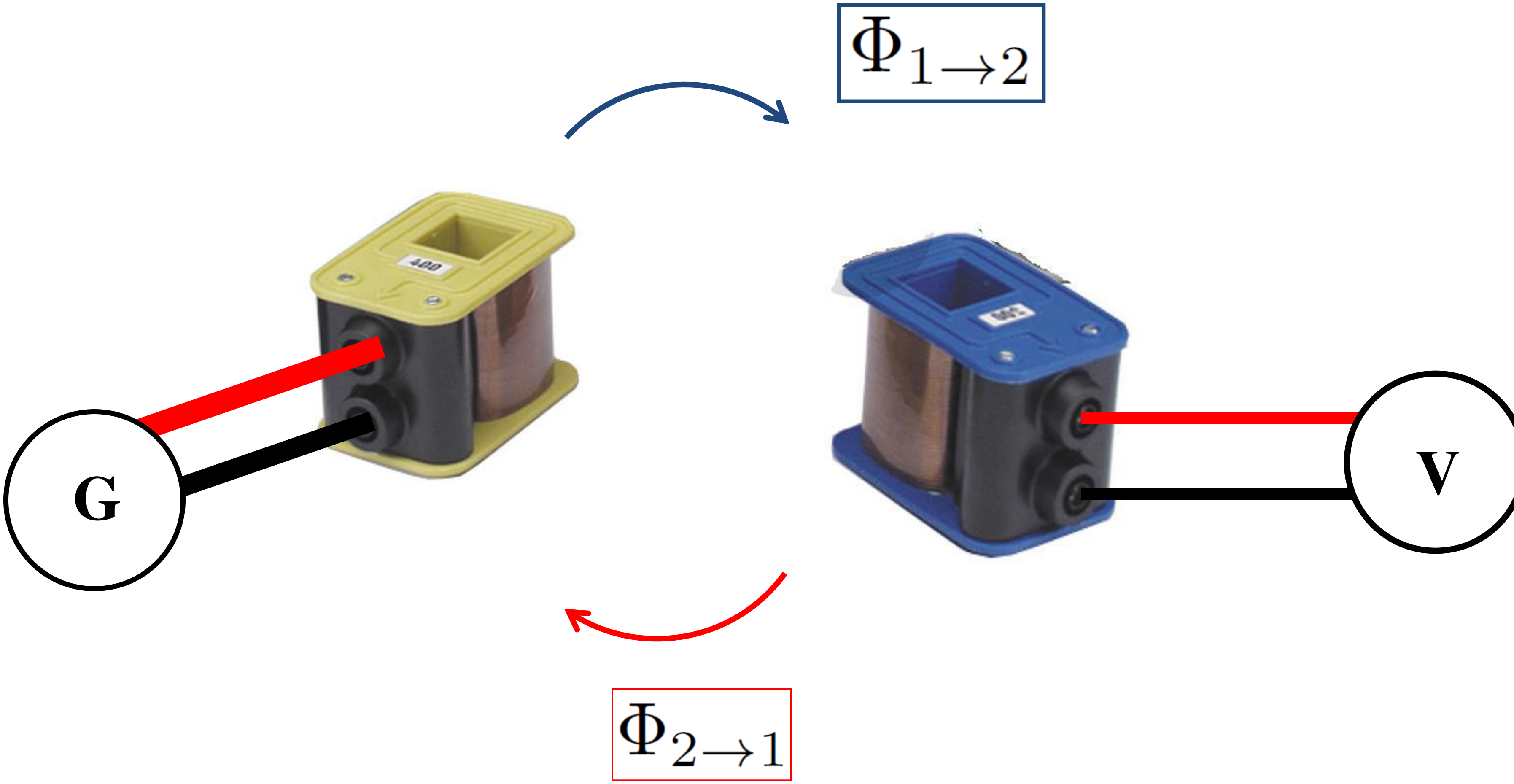
Mutual inductance: coupling between two coils L1 and L2:



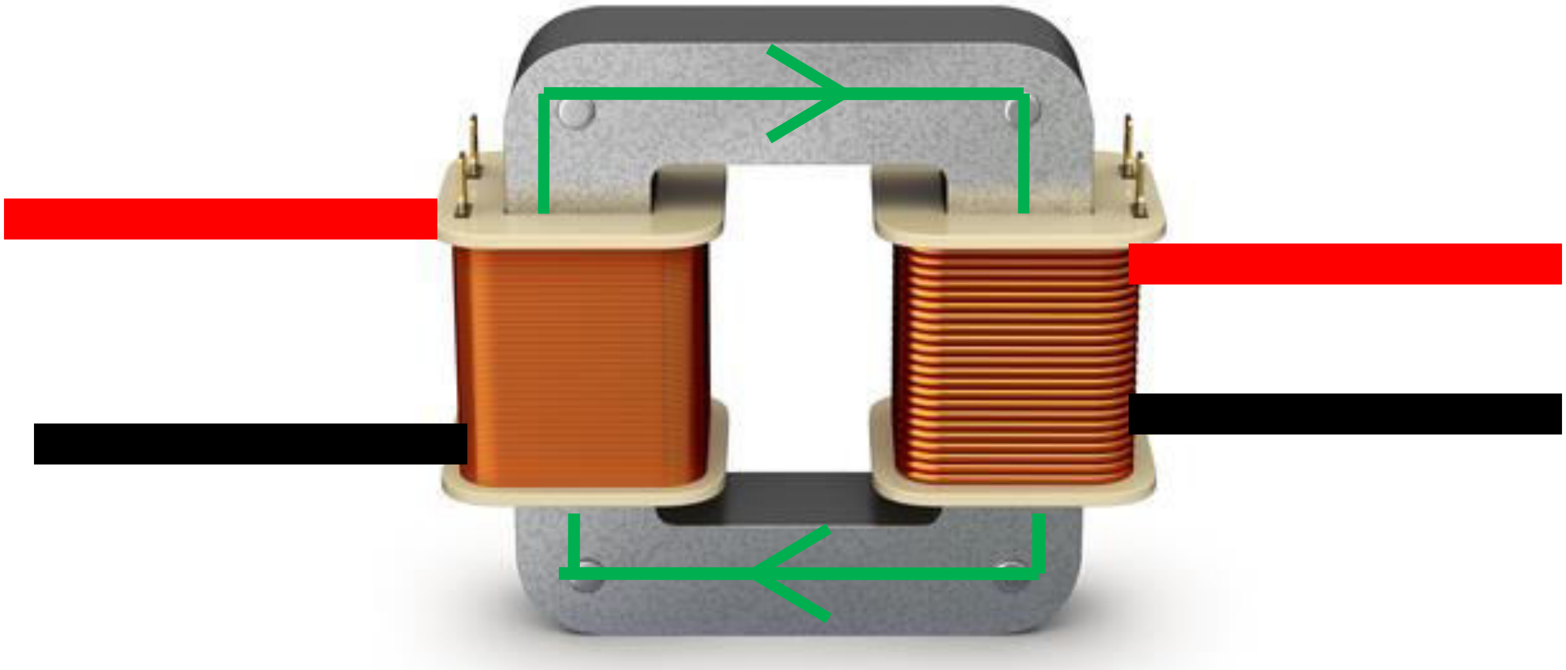
$$e_1 = -\frac{d\Phi_{2\to 1}}{dt}$$

$$e_2 = -\frac{d\Phi_{1\to 2}}{dt}$$

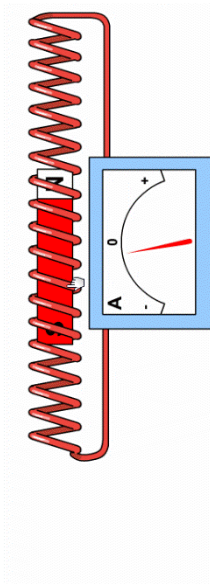
How to optimize the Fluxes ??



Use of a ferromagnetic core that will kept and drive the magnetic field lines from The first coil to the second one



Electromagnetic Induction -L2



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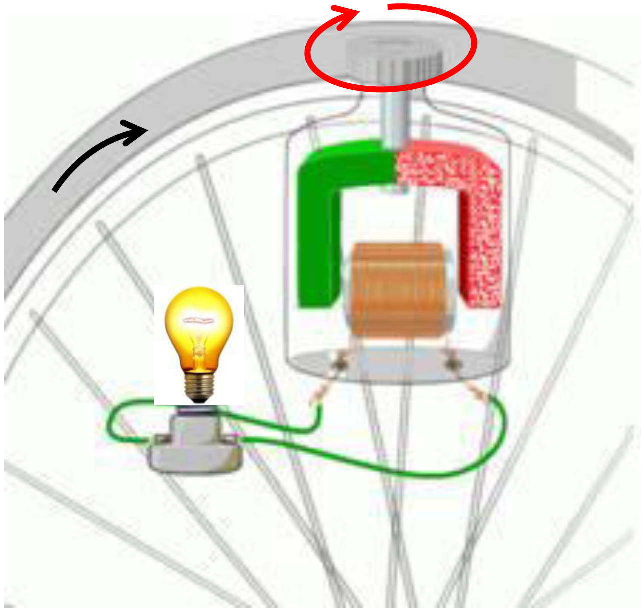
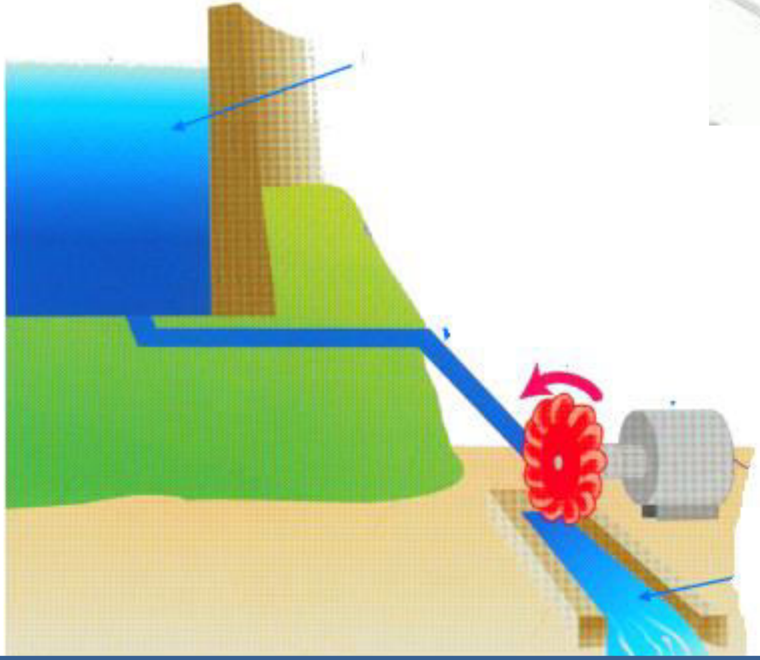
Dynamo / Electric generator

Rotation of the wheel leads to the rotation of the magnet

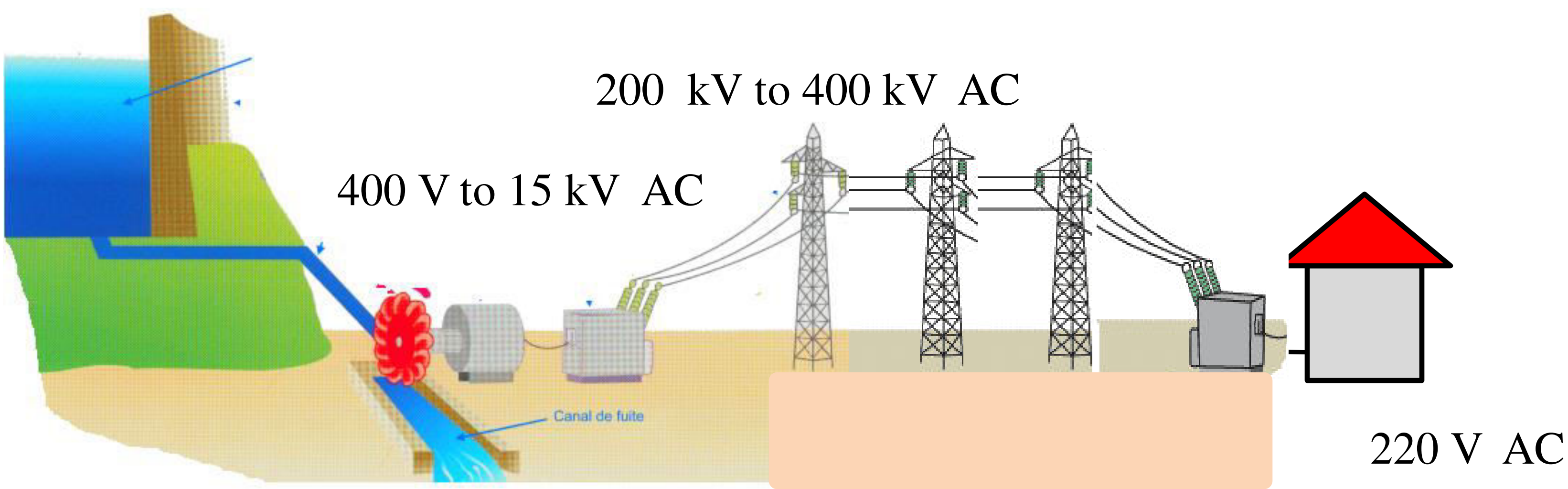


A time depending
Magnetic flux is created
In the coil and it generate
A voltage used to make
Shining a lamp

Electric central



Dynamo / Electric generator



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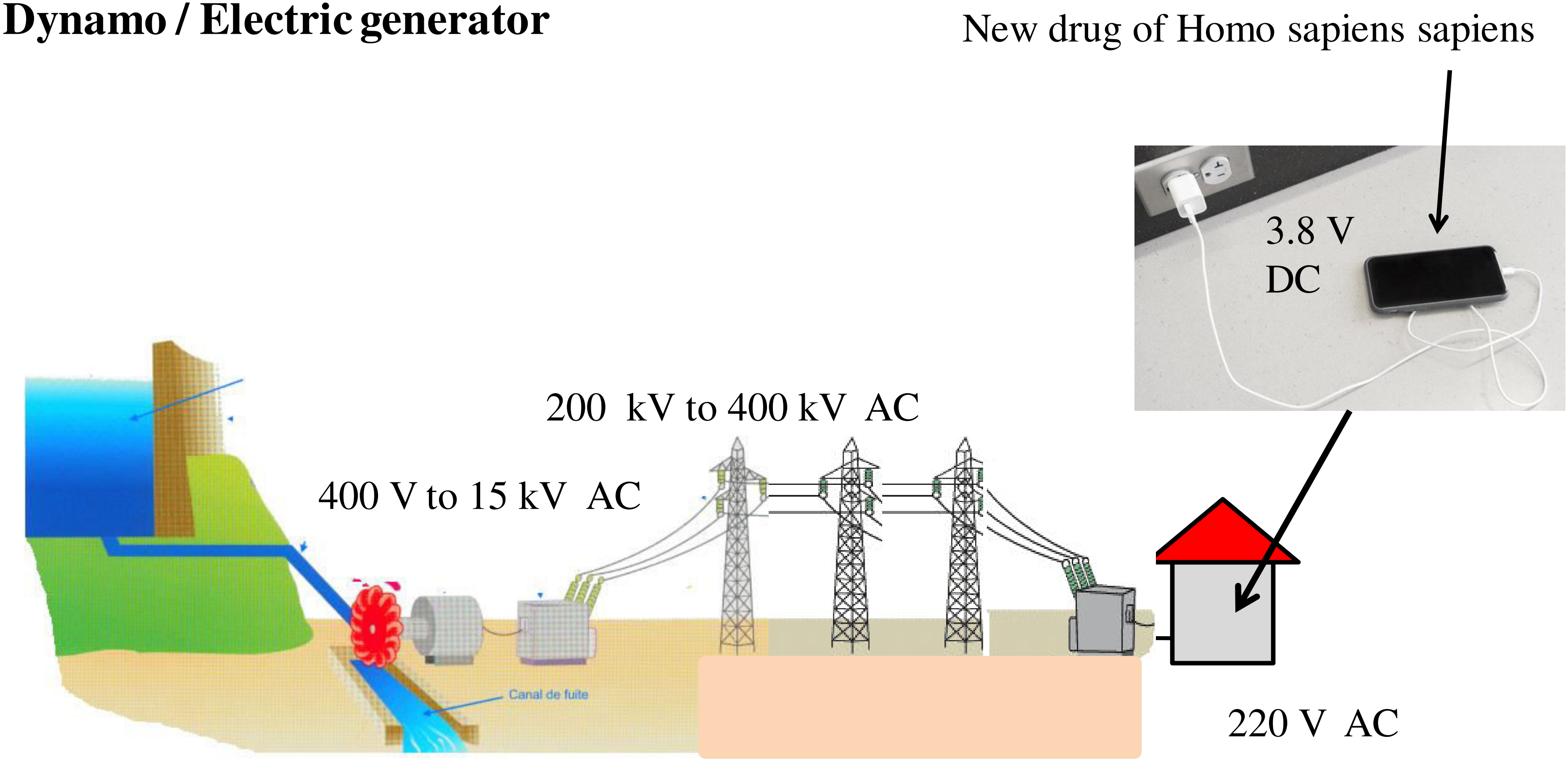

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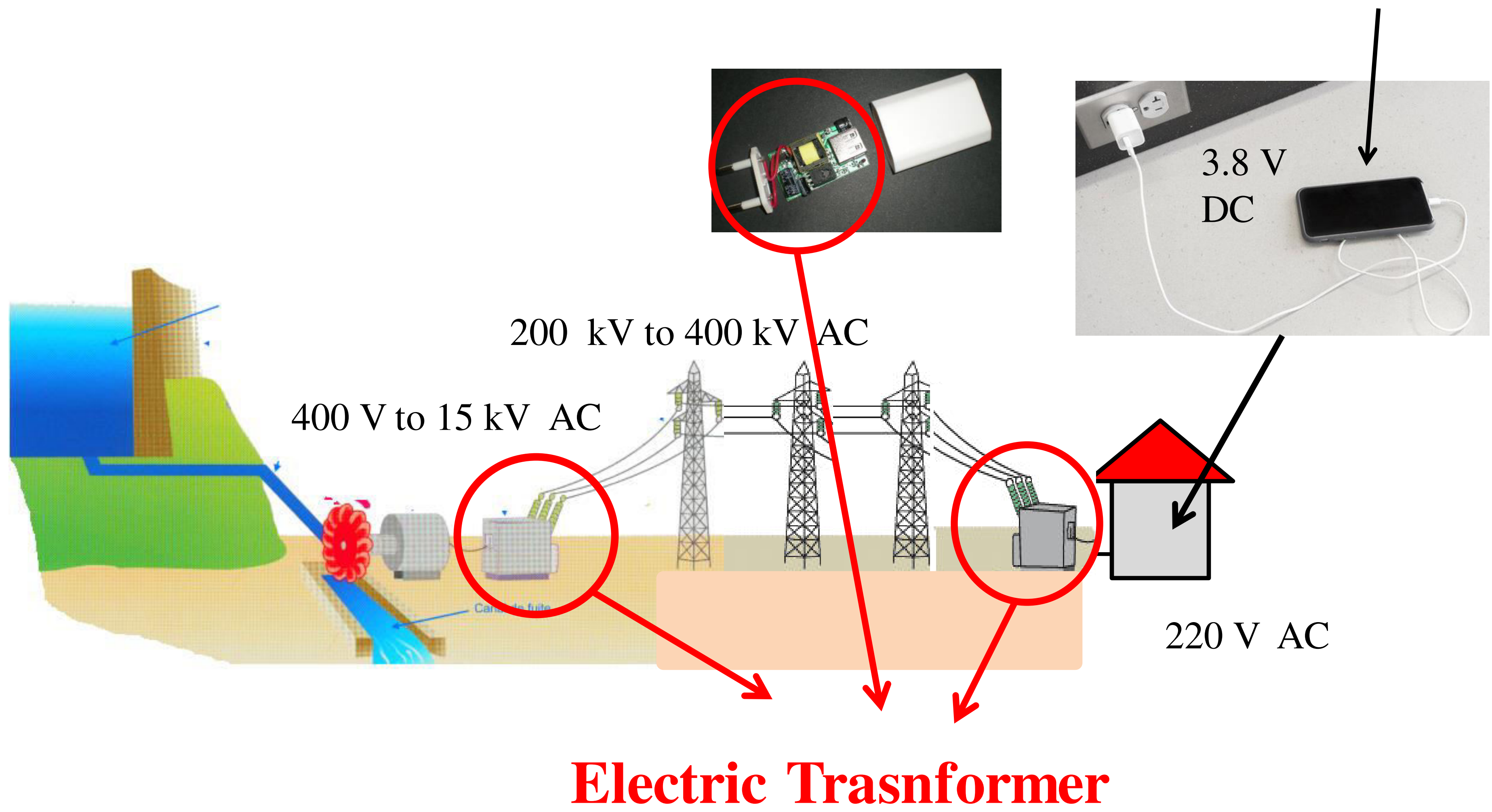
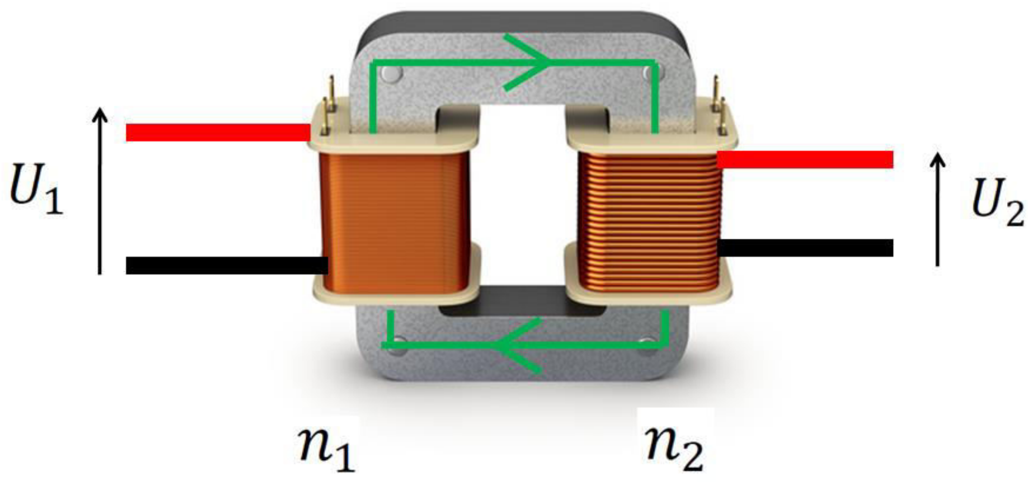


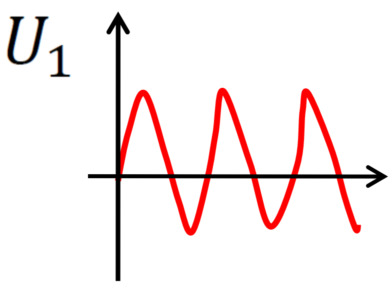
Principle of an electric transformer

Increasing or decreasing an output voltage

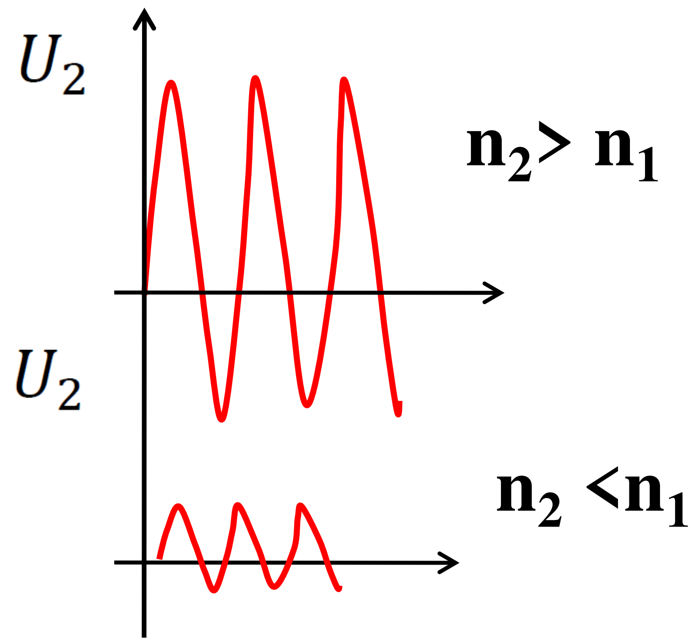


Ideal transformer

$$\frac{U_2}{U_1} = \frac{n_2}{n_1}$$

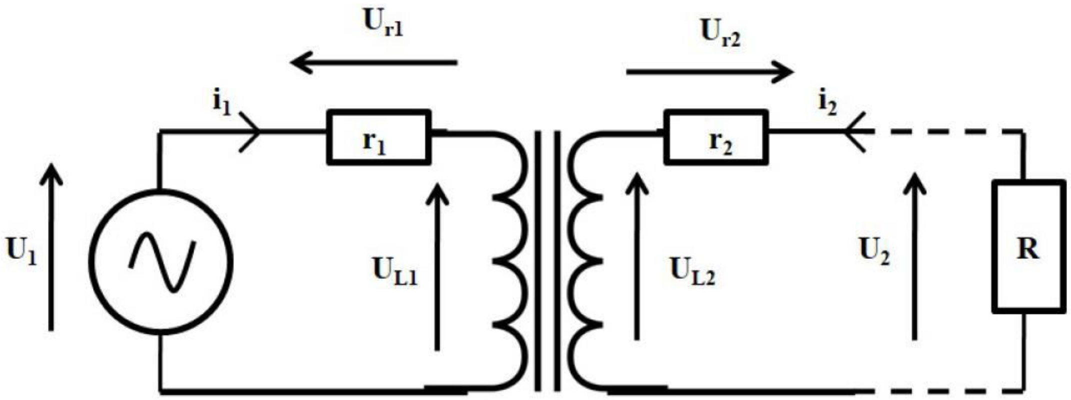


$$U_2 = \frac{n_2}{n_1} U_1$$



UFAZ-L2-Practical Work

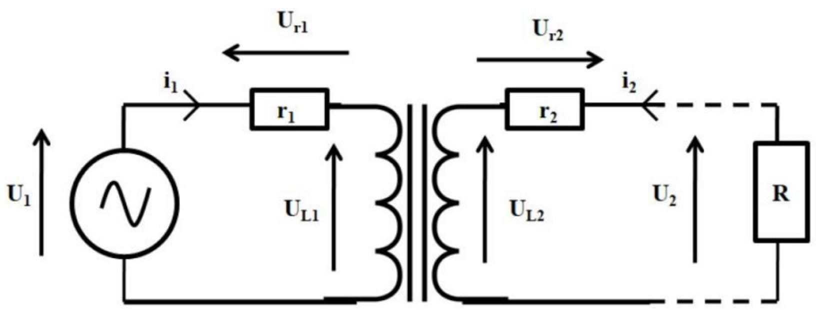
PW n° 2: Study of an electric transformer



$$U_1 = r_1\, i_1 \; + L_1 \frac{di_1}{dt} + M \frac{di_2}{dt}$$

$$U_2 = r_2\, i_2 + L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}$$

Transformer yield



Input power:

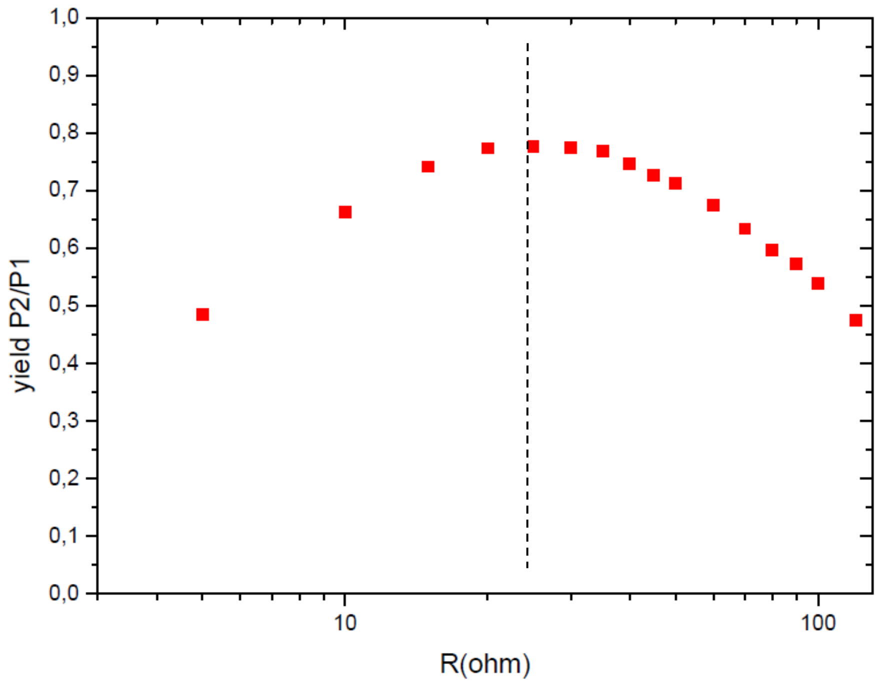
$$P_1 = U_1 i_1$$

Output power:

$$P_2 = U_2 i_2$$

Yield $\eta = \dfrac{P_2}{P_1}$

Results from our Lab (anonymous teacher)

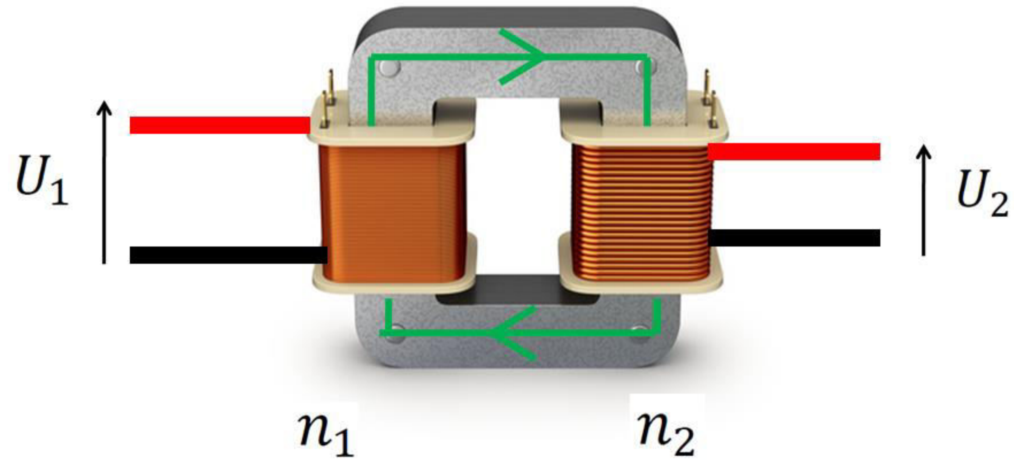


Usually, transformers have a yield of 95%

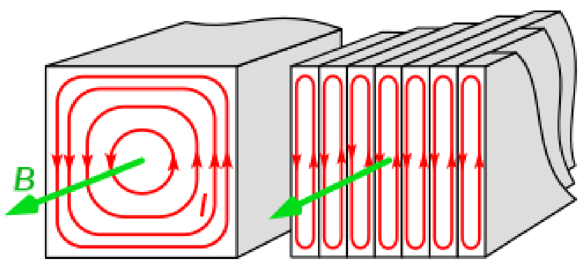
The losses are mainly due to the i) **joule effect** (copper losses of electric elements)

ii) the **iron losses (magnetic origin)**

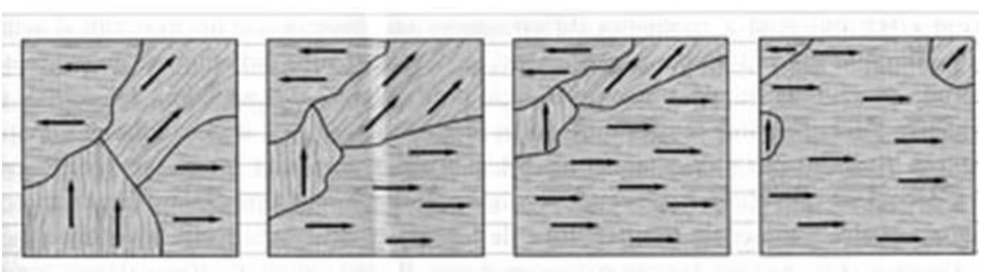
About Iron losses



The magnetic field propagating in the magnetic material (and conductor) induces also an electromotive force leading to the creation of surface currents INSIDE the magnetic core. These currents lose energy due to Joule effect. (*courants de Foucault* or *Eddy currents*)

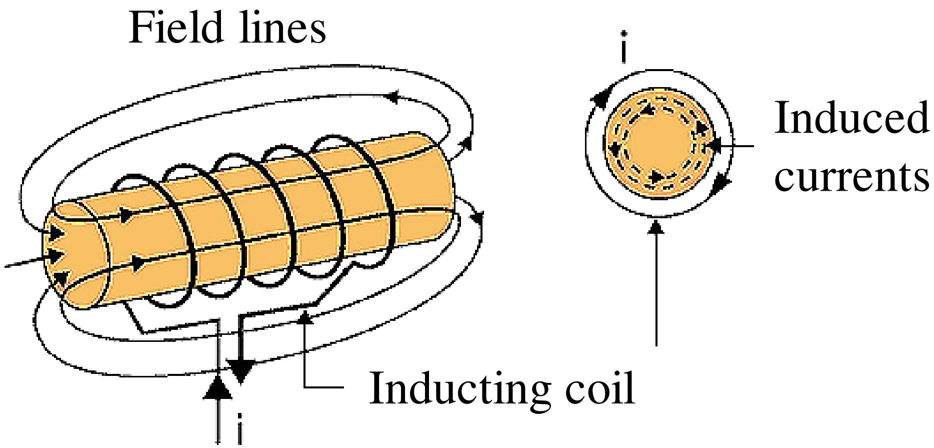


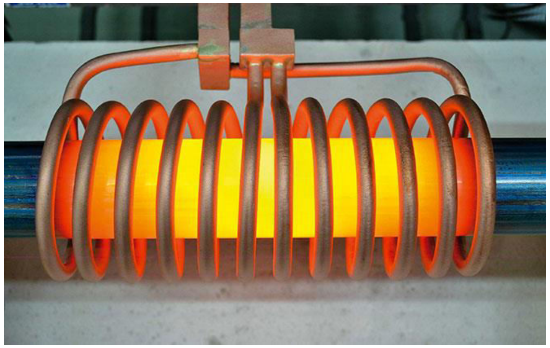
Friction between the walls of magnetic domains



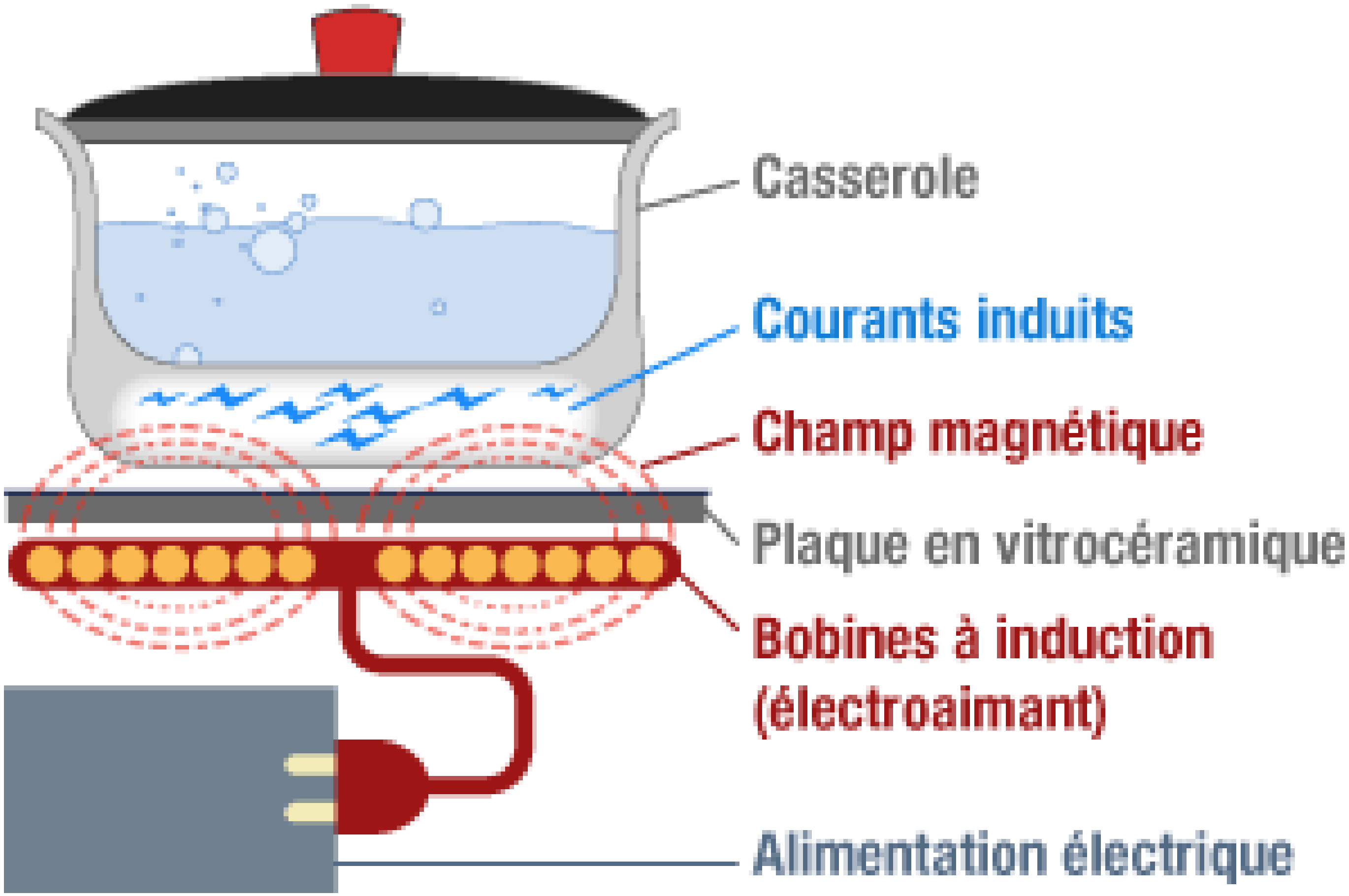
Induction heating

Foucault currents (I am subject also to mental sickness) can be used to increase temperature of a metal submitted to a magnetic field

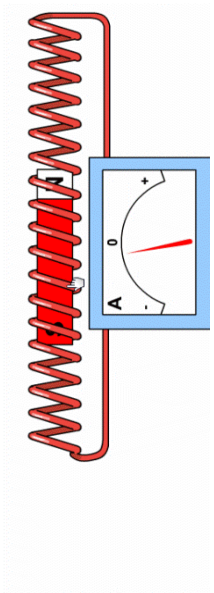




Induction heating



Electromagnetic Induction -L2



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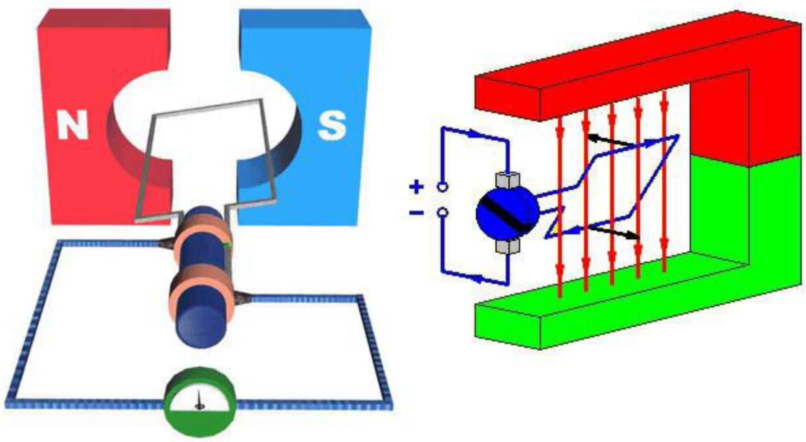
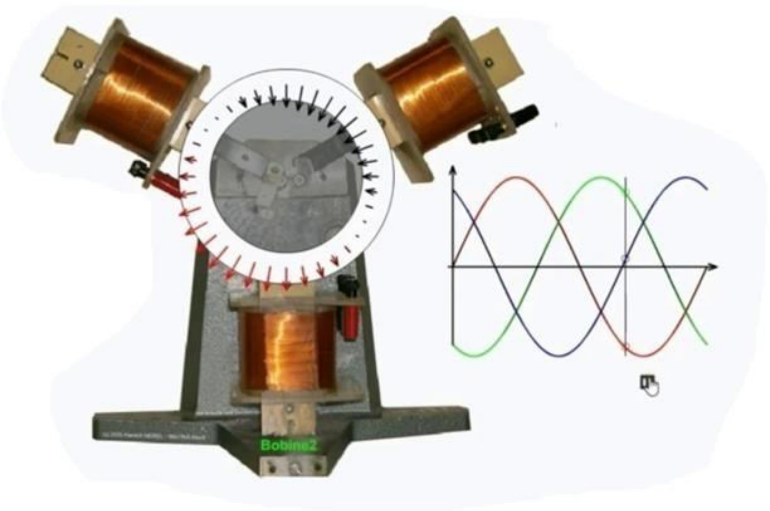
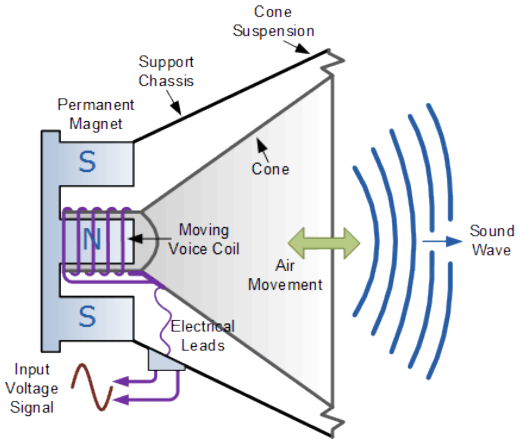
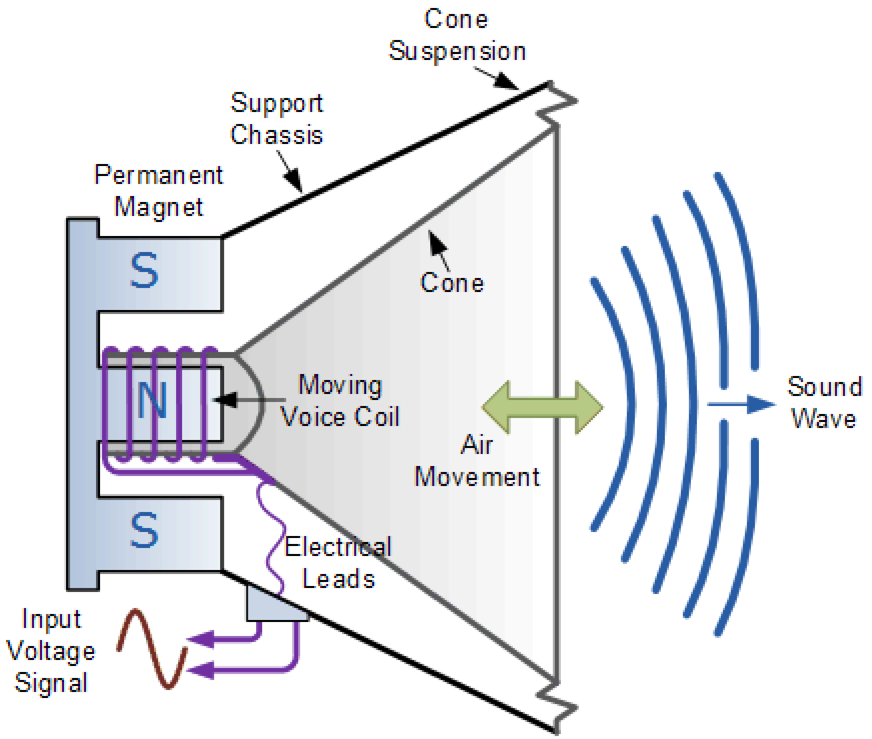
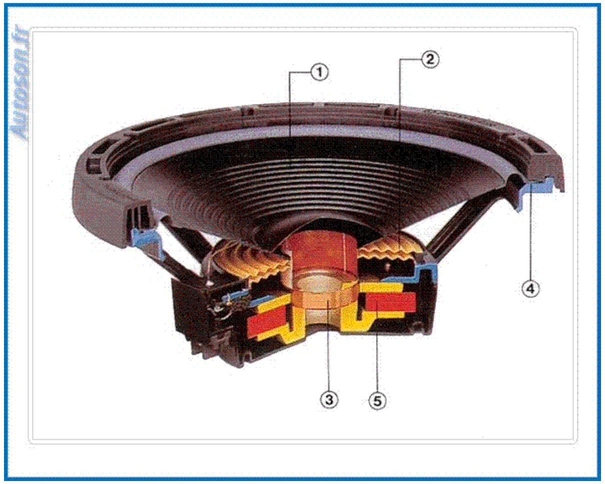
Electro-mechanical conversion








Cone
Suspension
Support
Chassis
Permanent
Magnet
S
N
S
Cone
Moving
Voice Coil
Air
Movement
Sound
Wave
Electrical
Leads
Input
Voltage
Signal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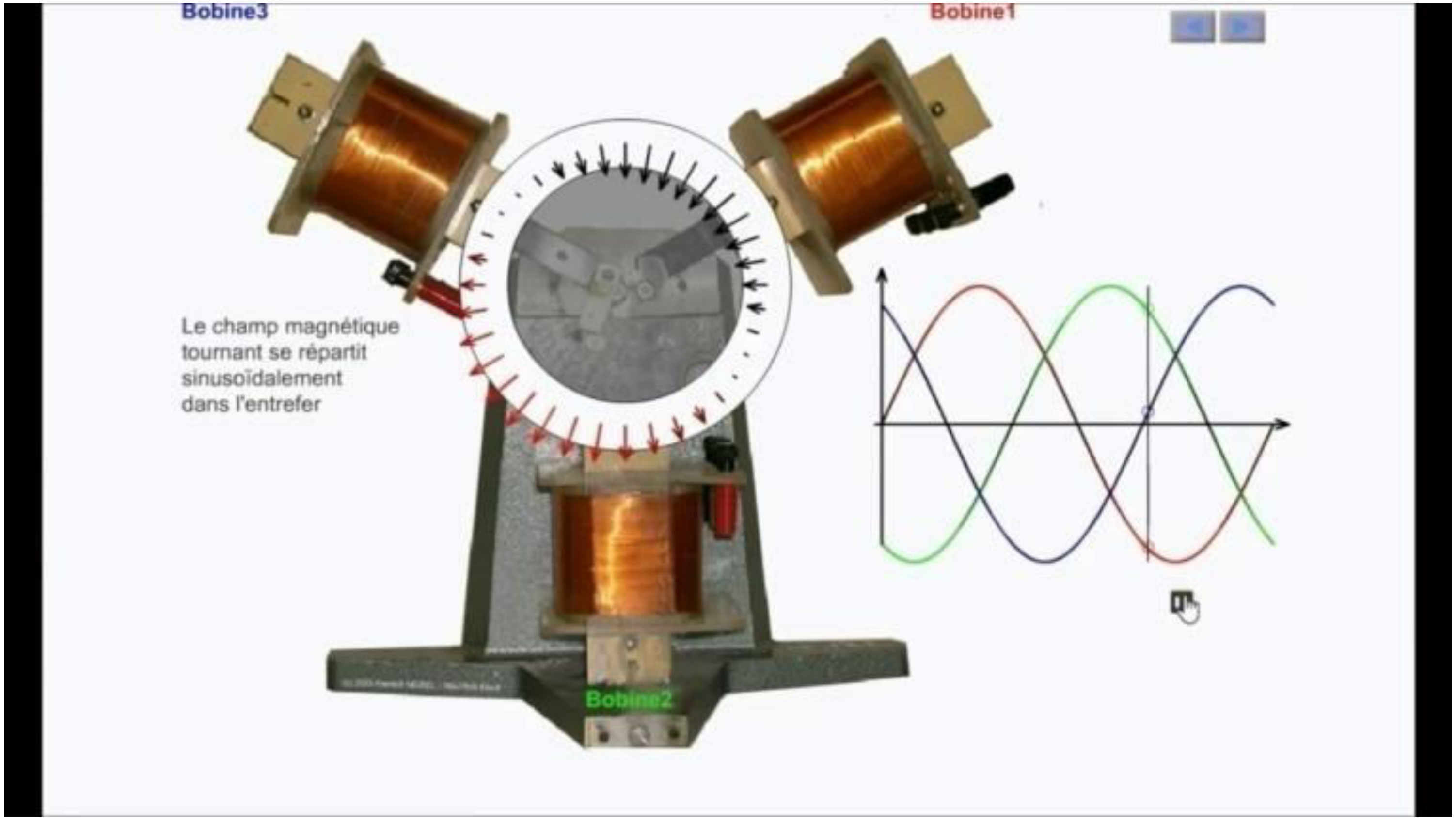
Bobine3
Bobine1
Le champ magnétique
tournant se répartit
sinusoïdalement
dans l'entrefer
Bobine2