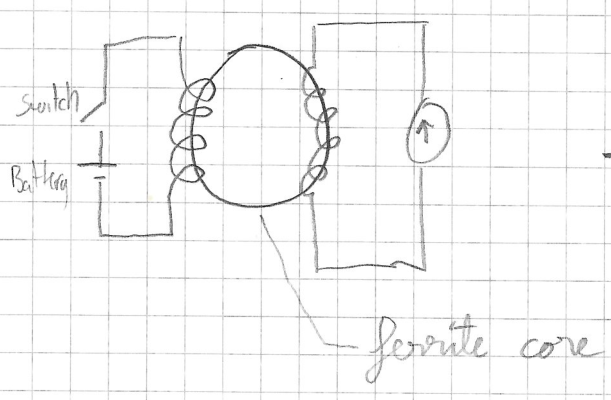
Electromagnetic induction and Faraday's Law

Stigler's law

"No scientific discovery is named after its original discoverer"

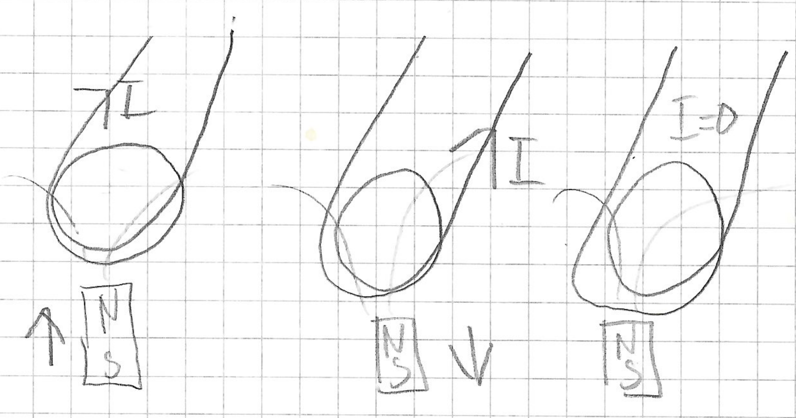
Joseph Henry → Magnetic fields produce electric current
Michael Faraday ↑
(published more effectively)



- no I when switch closes and time passes
- Only I when switch closes

- A changing magnetic field induces an EMF

induced current / electromagnetic induction

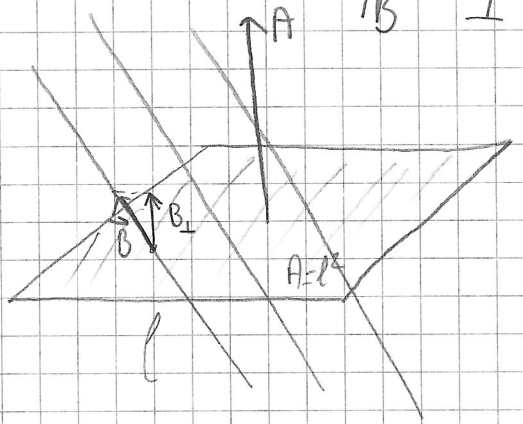


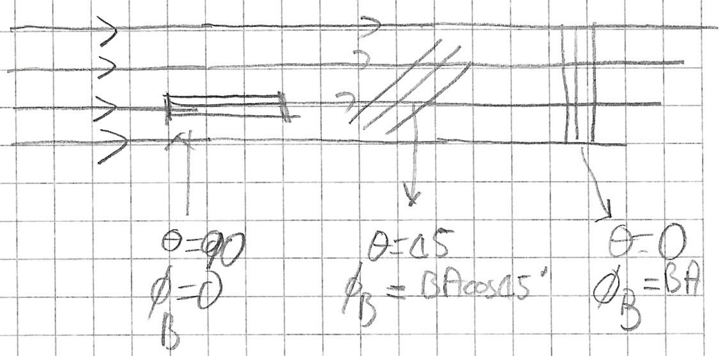
Faraday's Law of Induction;
Lenz's Law

: Faraday found → Area of the circuit changes current

EMF is proportional to magnetic flux

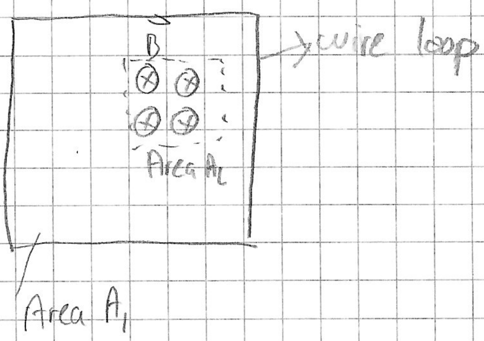
$$\phi_B = B_\perp A = BA\cos\theta = \vec{B}\cdot\vec{A}$$





$$\boxed{\phi_B = \int \vec{B}\cdot d\vec{A}}$$

(when area is not uniform)
(when $\vec{B}$ is not uniform)



BA_2 since in the integral

$$\phi_B = BA_2 + 0(A_1 - A_2)$$

The unit of magnetic flux is
Weber $1\,Wb = 1\,T.m^2$

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Faraday's law of induction:

$$\boxed{\mathcal{E} = -\frac{d\phi_B}{dt}}$$

(the EMF induced in a circuit is equal to the rate of change of magnetic flux through the circuit)

→ If the circuit contains N loops

$$\mathcal{E} = -N\frac{d\phi_B}{dt}$$

A loop of wire in a magnetic field

Square side $l = 5.0\,cm$
uniform magnetic field $B = 0.16\,T$

flux inside a) when face of the loop is perpendicular to $\vec{B}$ b) when there is 30° angle
c) $R = 0.012\,\Omega$ if it rotates $\frac{30°}{0.14s}$ what is I?

a) $\phi_B = \vec{B}\cdot\vec{A} = BA\cos 0 = (0.16T)(2.5\times10^{-3}m^2)(1) = 4\times10^{-4}W$

b) $\phi_B = \vec{B}\cdot\vec{A} = BA\cos 30 = 3.5\times10^{-4}\,wb$

c) $\mathcal{E} = \frac{\Delta\phi_B}{\Delta t} = \frac{(4.0\times10^{-4}wb)-(3.5\times10^{-4}wb)}{0.14s} = 3.6\times10^{-4}V$

$I = \frac{\mathcal{E}}{R} = \frac{3.6\times10^{-4}V}{0.012\Omega} = 0.030A = 30mA$

GÜLPAŞ

The minus in Faraday's Law is very important!

- a current produced by an induced emf moves in a direction so that the magnetic field created by that current opposes the original change in flux

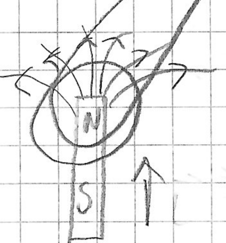
(Lenz's Law)

$$\vec{B} = \vec{B}_E + \vec{B}_i$$

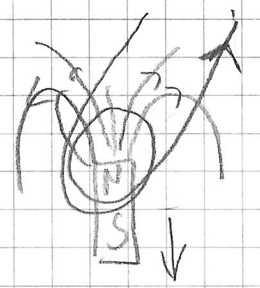
the changing $\vec{B}$ which induced the current

the induced $\vec{B}$ that is opposing the change

- An induced EMF is always in a direction that opposes the original change in flux that caused it



When the magnet is moving towards the loop: flux increases → current induced tries to counteract increasing flux → downwards $\vec{B}$

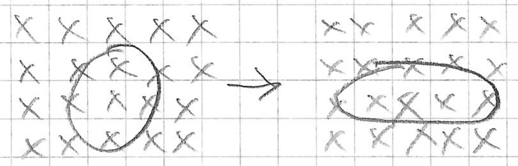


when the magnet is moving down the flux decreases. To oppose the decrease, the induced field is aligned with $\vec{B}$ of the permanent magnet

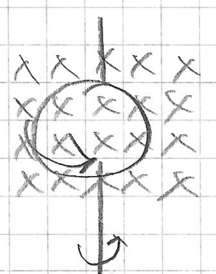
EMF is induced whenever there is a change in flux

$$\phi_B = \int \vec{B} \cdot d\vec{A} - \int B\cos\theta \, dA$$

1) change the magnetic field
2) change the Area A
3) Change the angle



$A_1 > A_2 \rightarrow$ change in flux



change in θ
$\rightarrow$ change in flux

Summary
Lenz's Law
what you need:
a) a closed, conducting loop
b) an external magnetic flux that is changing in time

1) Determine whether the magnetic flux is decreasing, increasing or staying same in the loop

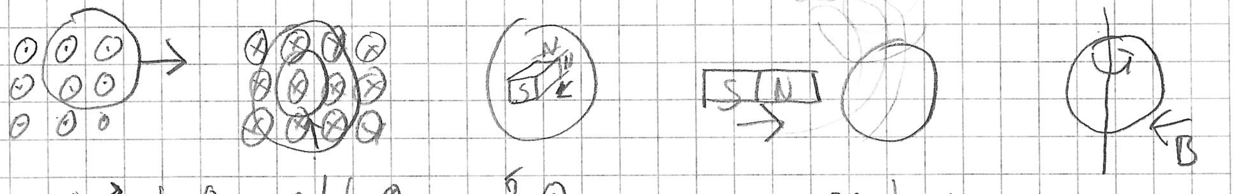
2) The magnetic field due to the induced current:

- points in the same direction of external field if the flux is decreasing
- Points in the opposite direction of external field if the flux is increasing

3) Once you know the direction of the induced magnetic field use right hand rule for the I

4) Keep in mind: There are two magnetic fields

- The external field
- The induced field



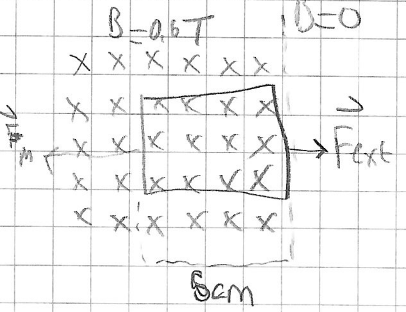
I for ⊙ — ϕ_B decreases same dir

for ⊗ — ϕ_B decreases same dir

⊙ — ϕ_B increases B opposite dir

no change in flux

flux increases in time from 0, B opposite



A 100 loop square coil of side $l = 5.00$ cm and total resistance 100Ω is placed perpendicular to a magnetic field

quickly moved to a region where $B=0$ at constant speed

It takes 0.100 s for the coil to reach completely the $B=0$ region

a) rate of change of flux

b) emf and I

c) How much energy is dissipated in the coil

d) Average force required

a) $A = l^2 = (5.00 \times 10^{-2} m)^2 = 2.5 \times 10^{-3} m^2$

$\phi_B = BA = (0.6T)(2.5 \times 10^{-3} m^2) = 1.5 \times 10^{-3}$ Wb

$$\frac{\Delta \phi_B}{\Delta t} = \frac{0 - (1.5 \times 10^{-3} Wb)}{0.100 s} = -1.5 \times 10^{-2} Wb/s$$

b)

$$\mathcal{E} = -N \frac{\Delta \phi_B}{\Delta t} = -(100)(-1.5 \times 10^{-2} Wb/s) = 1.5 V$$

during 0.100 s

$$I = \frac{\mathcal{E}}{R} = \frac{1.5V}{100\Omega} = 1.5 \times 10^{-2} A = 15 mA$$

clockwise by Lenz's law

c)

Total energy $= E = Pt = I^2Rt = (1.5 \times 10^{-2} A)^2 (100\Omega)(0.100s)$

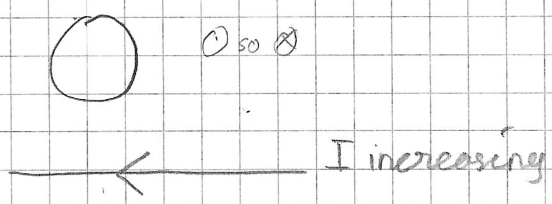
$= 2.25 \times 10^{-3}$ J

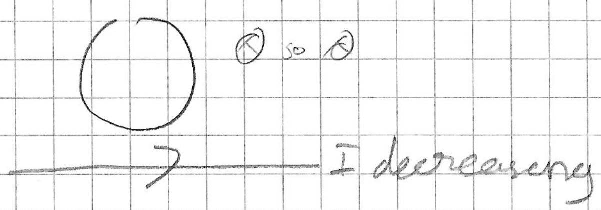
d) Work-Energy

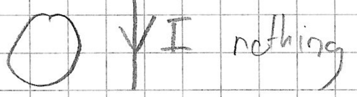
$W = \vec{F} d \qquad d = 5.00\,cm$

$$\vec{F} = \frac{W}{d} = \frac{2.25\times10^{-3}\,J}{5.00\times10^{-2}\,m} = 0.0450\,N$$

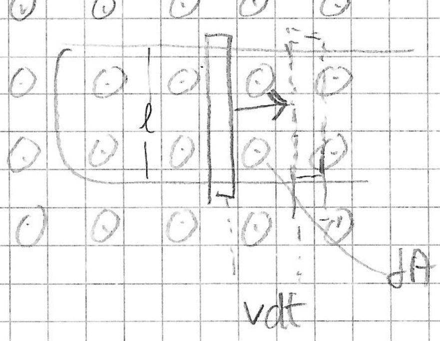
$$F_{ext} = N\underbrace{I}_{\text{induced average } I}lB = (100)(0.0150A)(0.0500m)(0.600T) = 0.0450N$$





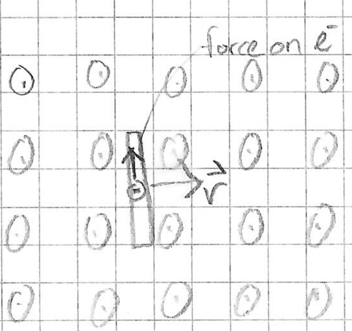


EMF induced in a moving rotor



Faraday's Law

$$\mathcal{E} = \frac{d\Phi_B}{dt} = \frac{B\,dA}{dt} = \frac{Bl\,v\,dt}{dt} = Blv$$



$\vec{F} = q\vec{v}\times\vec{B} \Rightarrow |\vec{F}| = qvB \quad (\vec{v}\perp\vec{B})$

$W = \text{Force} \times \text{distance} = qvBl$

$\mathcal{E} = W/q = qvBl/q = vBl$ (same as Faraday's)

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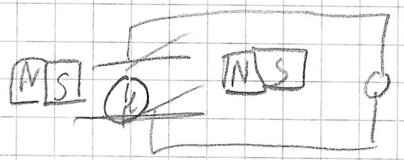
Moving plane in earths B

1000 km/h in 5×10^{-5} T (nearly vertical

wing span 70m

$$\mathcal{E} = Blv = (5\times10^{-5}\,T)(70m)(280\,m/s) \simeq 1V$$

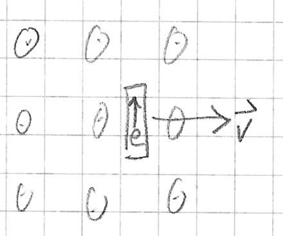
Example : Electromagnetic blood flow



$$v = \frac{\mathcal{E}}{Bl}$$

Example; Force on the rod

For a constant speed → external force to the right



a) $\vec{F}_{ext} = ?$

b) external power ?

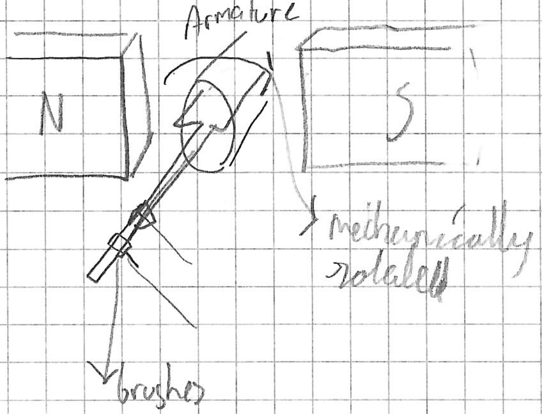
a) $\vec{F}_{ext}$ needs to balance magnetic force

$$F = IlB = \left(\frac{Blv}{R}\right)lB = \frac{B^2l^2v}{R}$$

b) $$P_{ext} = Fv = \frac{B^2l^2v^2}{R}$$

$$P_R = I^2R = \frac{B^2l^2v^2}{R}$$

Electric Generators (dynamo)

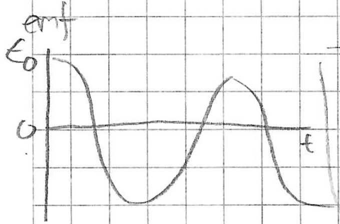


$$\mathcal{E} = -\frac{d\phi_B}{dt} = -\frac{d}{dt}\int \vec{B}\cdot d\vec{A}$$

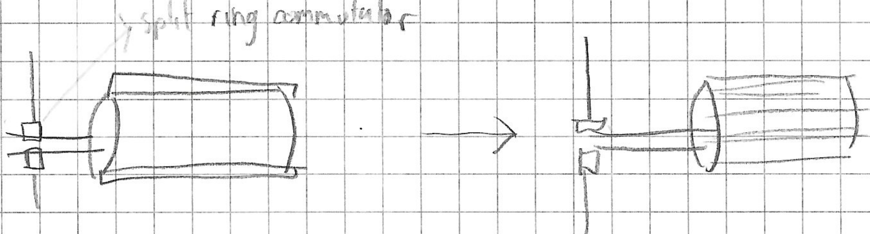
$$= -\frac{d}{dt}\, BA\cos\theta$$

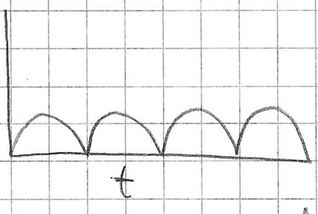
$$w = \frac{d\theta}{dt} \rightarrow \theta = \underbrace{\theta_0}_{0} + wt$$

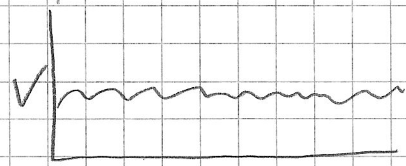
$$\mathcal{E} = -BA\frac{d}{dt}(\cos wt) = BAw\sin wt$$

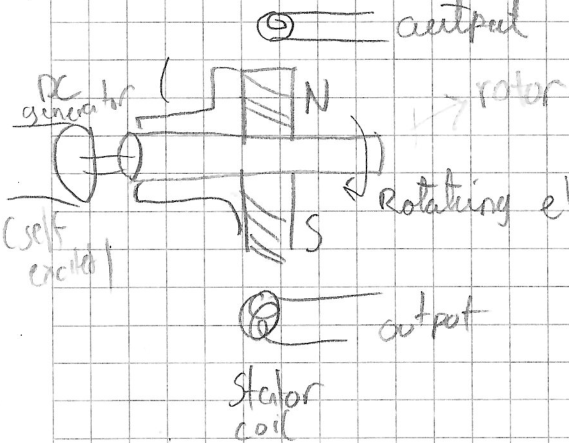


$$\boxed{\mathcal{E} = \underbrace{NBA\,w}_{\mathcal{E}_0}\sin wt = \mathcal{E}_0\sin wt}$$ AC generator







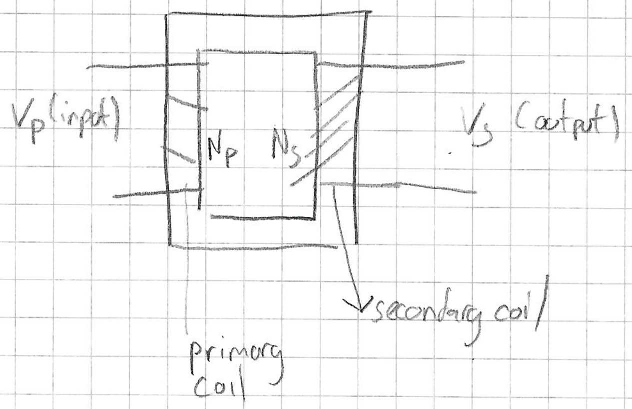


→ DC converter
(better than DC generators
in cars

Transformers and Transmission of power

A transformer is a device for increasing or decreasing an AC voltage

a good tranformer is >%99 efficient



$$V_S = N_S \frac{d\phi_B}{dt}$$

$$V_P = N_P \frac{d\phi_B}{dt}$$

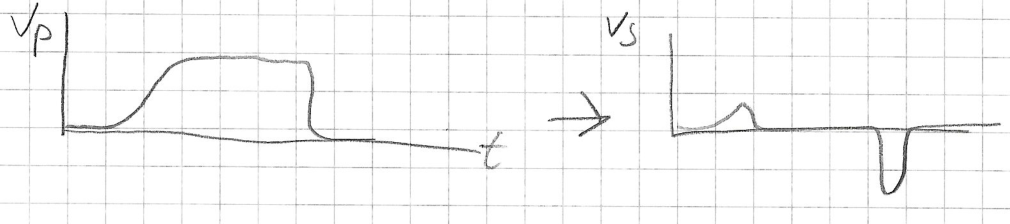
$$\boxed{\frac{V_S}{V_P} = \frac{N_S}{N_P}}$$ transformer equation

Step-up transformer $\rightarrow N_S > N_P$

step-down transformer $\rightarrow N_S < N_P$

$$I_P V_P = I_S V_S \rightarrow \frac{I_S}{I_P} = \frac{N_P}{N_S}$$ (conservation of Energy)

A DC current does not work with transformers but



An average of 120kW is sent to 10km, $R = 0.40\Omega$

240V power loss

$I = \frac{P}{V} = \frac{1.2\times10^5 W}{2.4\times10^2 V} = 500A$

$P_L = I^2 R = (500A)^2(0.40\Omega) = 100kW$

%80 loss

24000V power loss

$I = \frac{P}{V} = 5.0A$

$P_L = 10W$

%1 loss

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General Form of Faraday's Law

$$\mathcal{E} = \oint \vec{E} \cdot d\vec{l}$$

$$\boxed{\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}}$$