Electromagnetism II

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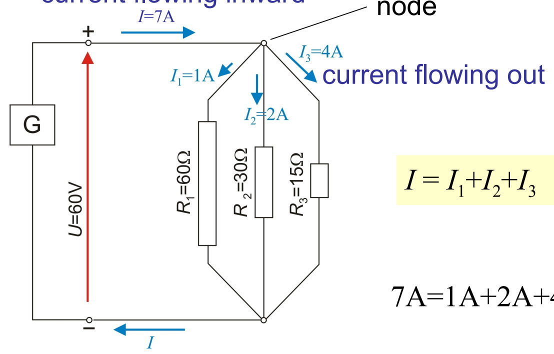
Kirchhoff's current law (Kirchhoff's first law)

The **conservation of charge** implies that: at any node, the sum of currents flowing into the node is equal to the sum of currents flowing out of that node.



$I_1 = U / R_1 = 1\text{A}$

$I_2 = U / R_2 = 2\text{A}$

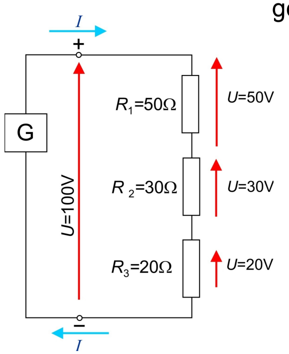
$I_3 = U / R_3 = 4\text{A}$

$I = I_1+I_2+I_3$

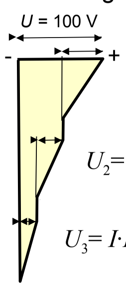
7A=1A+2A+4A

Kirchhoff's voltage law (Kirchhoff's second law)

The **conservation of energy** implies that: the sum of the electron motive forces in any closed loop is equivalent to the sum of the potential drops in that loop.



genrator voltage:



voltage drop on the resistors:

$U_1= I{\cdot}R_1= 50\text{V}$

$U_2= I{\cdot}R_2= 30\text{V}$ $I = 1\text{A}$

$U_3= I{\cdot}R_3= 20\text{V}$

$U=U_1+U_2+U_3$ 100V= 50V+30V+20V

Voltage source

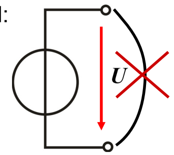
An ideal voltage source is a circuit element that generates constant voltage independently of the load current through it.

e.g.: $U = 10$ **V = constant**

If $R = 1\ \Omega$, then $I = U/R = 10$ A.
If $R = 10\ \Omega$, then $I = U/R = 1$ A

A voltage source has very small (ideally zero) internal resistance. It is forbidden to short it!

symbol:



$(R=0)$; $I = U/R = \infty$

In practice most electric power sources can be considered voltage source.

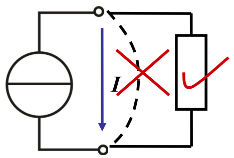
constant difference of level, constant pressure difference

different loads means different flow rates

Current source

An ideal current source is a circuit element that generates constant current independently of the resistance of the load.

voltage changes according to the load

symbol: 

e.g: $I = 1$ A = constant

If $R = 1\ \Omega$, then $U = I{\cdot}R = 1{\cdot}1 = 1$ V.
If $R = 10\ \Omega$, then $U = I{\cdot}R = 1{\cdot}10 = 10$ V

Th einternal resistance of the current source is very large (ideally infinite). A load always has to be applied.

Electrical work

Electrical work is done if charges move between two points with different potential.

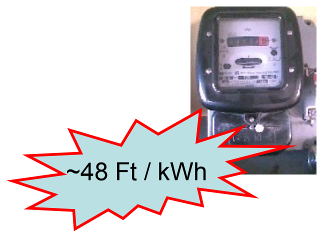
symbol: W

$$dW = U{\cdot}dQ \xrightarrow{Q = I{\cdot}t} W = U{\cdot}I{\cdot}t$$

$$V{\cdot}C = V{\cdot}A{\cdot}s = W{\cdot}s = J$$

Units of electric work: joule (J), Ws, Wh, kWh (kilowatt hour)

1 kWh = 1000·W· 3600s = 3.6 MJ



Electrical power

Electrical power is the amount of electrical work done in unit time.

symbol: P

$$P = W / t = U{\cdot}I{\cdot}t / t = U{\cdot}I$$

J / s = V·A·s / s = V·A = W

unit: watt, (W = J/s)

$$P = U{\cdot}I = I^2{\cdot}R = U^2/R$$

100 W continuous

1000 W continuous

one trillion watts - one "terawatt" (10^{12} W)
pulsed: stroke lasts for about 30 microseconds

Electric field, Coulomb's law

An electric field surrounds electric charges and time-varying magnetic fields. This electric field exerts a force on other electrically charged objects.

Electric field lines can be used to represent the electric field.

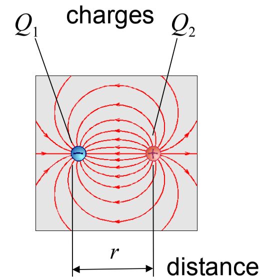
Opposite charges attract each other.

Same charges repel each other.

$F \sim Q_1, Q_2$ $\qquad F \sim 1/r^2$

Coulomb's law: $F = k\dfrac{Q_1 \cdot Q_2}{r^2}$

constant



Electric field strength

The electric field strength at a given point is defined as the force that would be exerted on a positive test charge of 1 coulomb placed at that point.

symbol: E

unit: V/m

$$E = F/Q$$

$$N / C = (J/m) / C = V{\cdot}A{\cdot}s / m{\cdot}A{\cdot}s = V/m$$

examples for field strengths

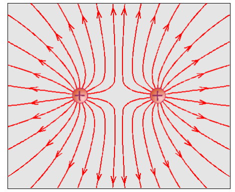
break down limit in air: $3{\cdot}10^6$ V/m

radio waves in the antena: 1-100 µV/m

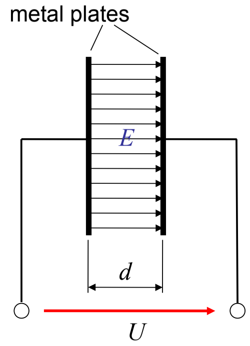
across the cell membrane: ~10^7 V/m

Inhomogeneous and homogeneous electric fields

The density of the field lines is different in every point of space → inhomogeneous field



Between two parallel charged metal plates the electric field is homogeneous.

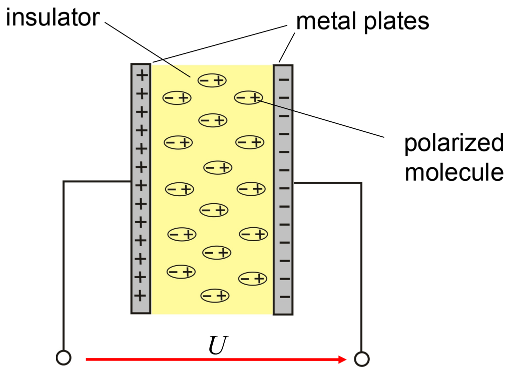


$E \sim U$ $\qquad$ $E \sim 1/d$

$$E = U/d$$

Dielectric polarization

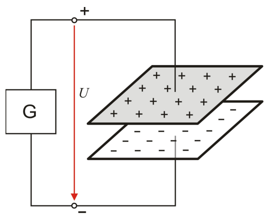
The atoms and molecules of insulators are deformed in electric field. Charges separate, the particle is polarized.



At the break down electric field strength the positive and negative charges separate, and the material becomes conductive (spark, lightning).

Capacitor, capacity

The capacitor consists of two conductor plates separated by an insulator layer.



Capacitors store charge proportional to the applied voltage.

The proportionality constant is called capacity.

$$Q = C{\cdot}U$$

symbol: C

unit: F (farad)

leyden jar

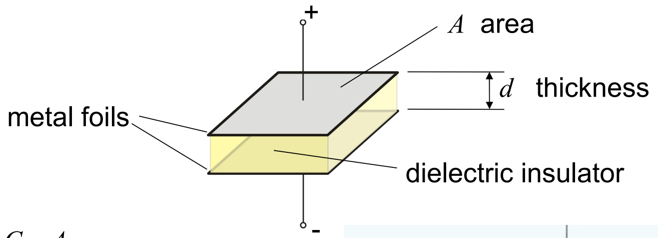
$$C = Q/U$$

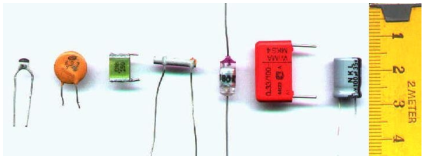
$$F = C/V$$

1F is the capacity of a capacitor that stores 1C charge when it is charged to 1 V.

Capacitor, electric permittivity

Capacitors are usually built of two metal foils separated by an insulator dielectric layer.





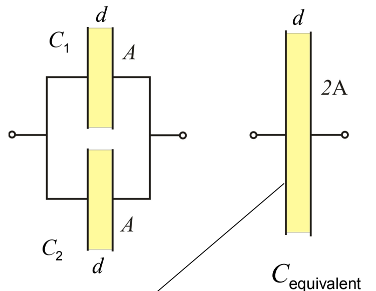
$C \sim A$

$C \sim 1/d$

$C = \varepsilon \cdot A/d$

The proportionality constant ε is called electric permittivity.

Capacitors connected in parallel



$C = \varepsilon \cdot \frac{A}{d}$

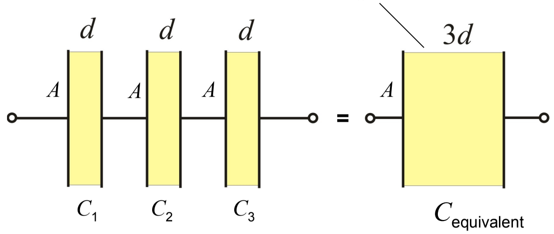
d = unchanged

$C_1 + C_2 = C_{equivalent}$

Capacitors connected in series

$C = \varepsilon \cdot \frac{A}{d}$

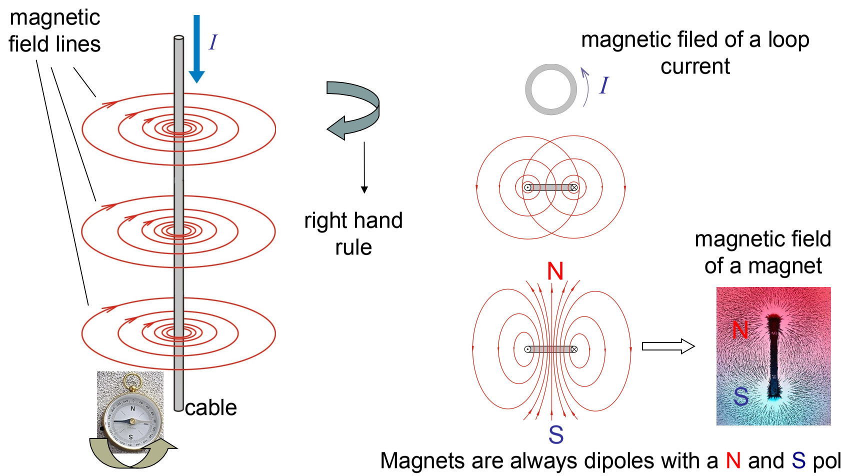
A = unchanged



$$\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} = \frac{1}{C_{equivalent}}$$

Magnetic field

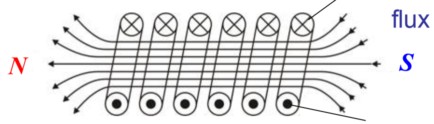
A magnetic field is a force field produced by ferromagnetic materials, moving charges, and changing electric fields.



Magnets are always dipoles with a N and S pole.

Magnetic flux

Flux is the total number of magnetic force field lines passing through a specified area.



symbol: Φ

unit: weber, Wb

Magnetic induction

Magnetic induction (flux density) is the flux that crosses unit area perpendicularly.

symbol: B

unit: T (tesla)

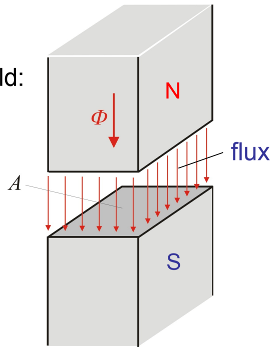
$$\frac{\mathrm{Wb}}{m^2}=T$$

In homogeneous magnetic field:

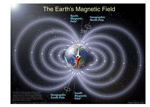
$B \sim \Phi$

$B \sim 1/A$

$$B=\frac{\Phi}{A}$$



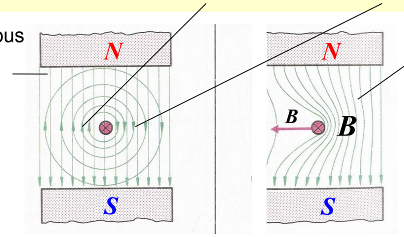
the magnetic induction of the Earth in Hungary: ~ 50 µT



magnetic induciton inside an MRI: ~ 1T

Forces in magnetic fields

The magnetic field of the electric current and the static magnetic field superimpose. In some places they weaken, in others they strengthen each other.



The current-carrying wire will experience a force that is pushing it towards the weaker magnetic field.

induction: $F \sim B$

current intensity: $F \sim I$

length of the wire: $F \sim l$

force: $F = B \cdot I \cdot l$

Lorenz force

Lorenz force: is the force acting on a charge Q moving with velocity v in a static magnetic field.

$F = B \cdot I \cdot l$

$I=\frac{Q}{t}$ $\qquad$ $\frac{l}{t}=v$

$$F=B\cdot\frac{Q}{t}\cdot l=B\cdot Q\cdot v$$

$B \perp v \perp F$

⇩

F will be a centripetal force

⇩

the charge will move on a circular path