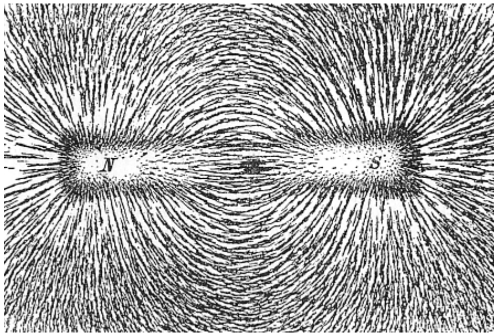
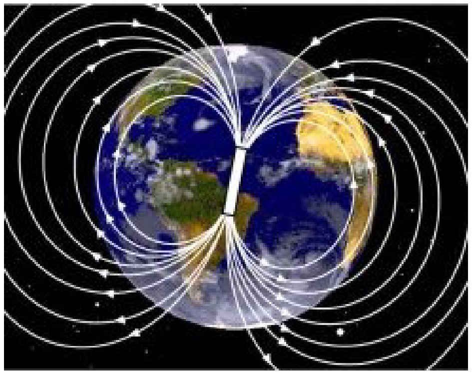
Mechanical Engineering Laboratory

A short introduction to…

MAGNETISM
and its practical applications





Michele Togno – Technical University of Munich, 28th March 2014 – 4th April 2014

Magnetism

A property of matter

A **magnet** is a material or object that produces a magnetic field. This magnetic field is invisible but it is responsible for the most notable property of a magnet: a force that pulls on ferromagnetic materials, such as iron, and attracts or repels other magnets.

Magnetite **Fe_3O_4**

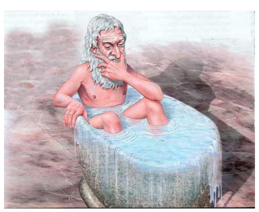
(lodestone)

History of magnetism

Sushruta, VI cen. BCE
(Indian surgeon)

⇩

Archimedes (287-212 BCE)

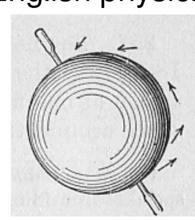


⇨

Shen Kuo, 1031-1095
(Chinese scientist)

⇨

William Gilbert, 1544-1603
(English physician)

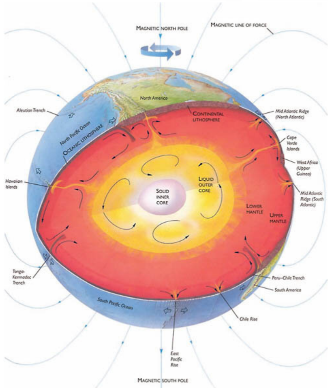


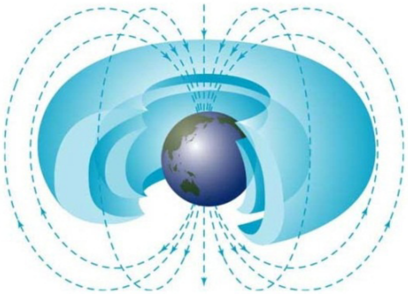
⇨

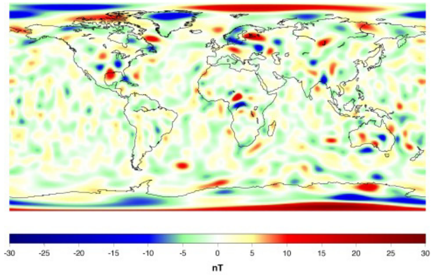
J.B. Biot, 1774-1862
A.M. Ampere, 1775-1836
H.C. Oersted, 1777-1851
C.F. Gauss, 1777-1855
F. Savart, 1791-1841
M. Faraday, 1791-1867
J.C. Maxwell, 1831-1879
H. Lorentz, 1853-1928

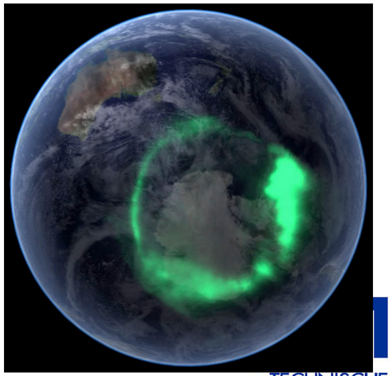
The Earth magnetic field

A sort of cosmic shield









TECHNISCHE UNIVERSITÄT MÜNCHEN

Magnetic domains

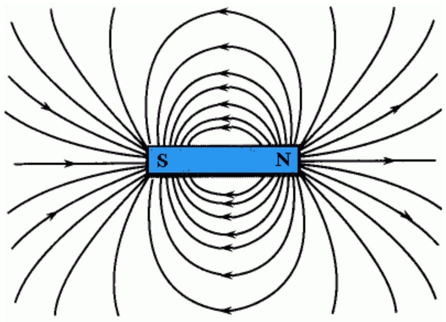
and types of magnetic materials

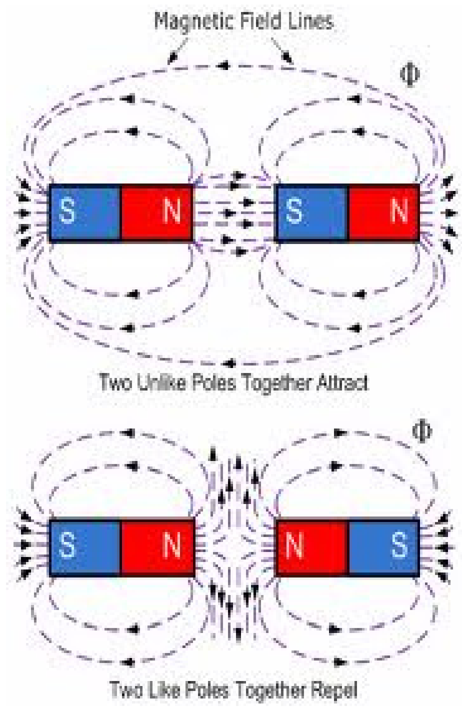
Ferromagnetic: a material that could exhibit spontaneous magnetization, that is a net magnetic moment in the absence of an external magnetic field (iron, nickel, cobalt…).

Paramagnetic: material slightly attracted by a magnetic field and which doesn’t retain the magnetic properties when the external field is removed (magnesium, molybdenum, lithium…).

Diamagnetic: a material that creates a magnetic field in opposition to an externally applied magnetic field (superconductors…).

Magnetic field and Magnetic flux





Every magnet is a **magnetic dipole** (magnetic monopole is an hypothetic particle whose existence is not experimentally proven right now).

$$\oint_{\partial V} \mathbf{B} \cdot \mathrm{d}\mathbf{S} = 0 \qquad \nabla \cdot \mathbf{B} = 0$$

The magnetic field [Wb/m^2] or [T] is the area in which a force is experienced.

The magnetic flux [Wb] or [T·m^2] is a measure of the magnetic field in a certain medium.

B & H…

Relationship between **B** (magnetic flux density) and **H** (magnetic field intensity):

$\mathbf{B} = \mu_0 \cdot \mathbf{H}$ with $\mu_0 = 4 \cdot \pi \cdot 10^{-7}$ [(V·s)/(A·m)] in vacuum

$\mathbf{B} = \mu_0 \cdot (\mathbf{H} + \mathbf{M}) = \mu_0 \cdot (\mathbf{H} + \chi \mathbf{H}) = \mu_0 \cdot \mu \cdot \mathbf{H}$ in a medium

$\mu = 1 + \chi$ is the magnetic permeability constant

For materials which are NOT ferromagnetic or diamagnetic materials, $10^{-6} < \chi < 10^{-4}$

⇩

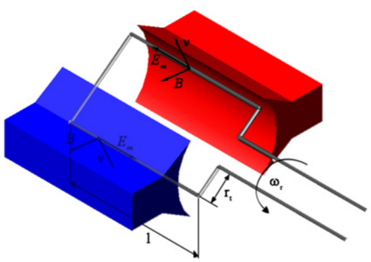
$\mu \approx 1$ without ferromagnetic medium

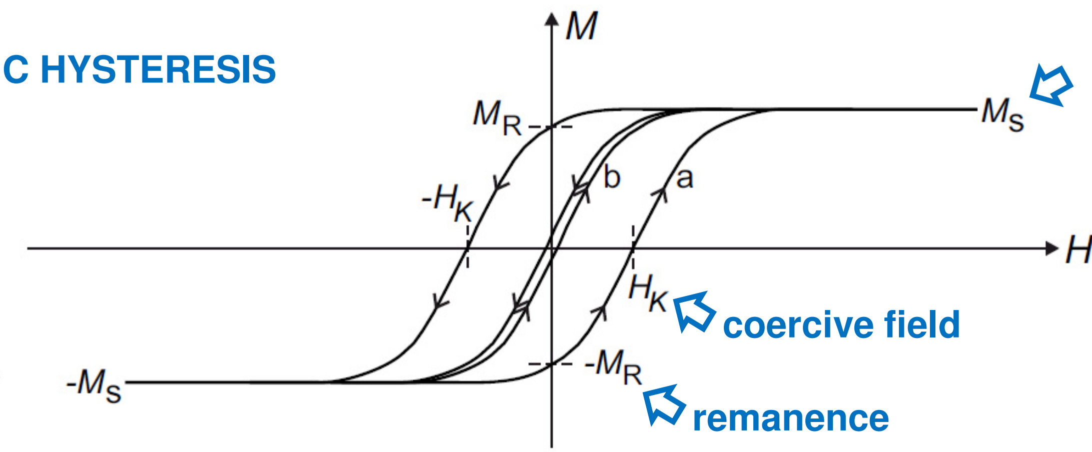
$\mu \approx 1500$ with the iron yoke in our experiment

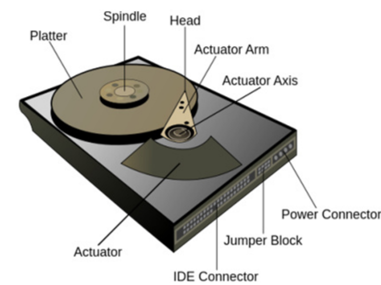
B(H) (or M(H)) in a ferromagnetic material

The relationship between field strength **H** and magnetization **M** is not linear in ferromagnetic materials:

MAGNETIC HYSTERESIS







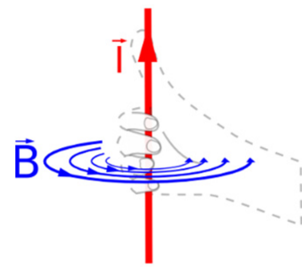
When an external magnetic field is applied to a ferromagnetic material such as iron, the atomic dipoles align themselves with it. Even when the field is removed, part of the alignment will be retained: the material has become *magnetized*. Once magnetized, the magnet will stay magnetized indefinitely. To demagnetize it, heat or a magnetic field in the opposite direction are required.

TECHNISCHE UNIVERSITÄT MÜNCHEN

Magnetic field and currents/1

Oersted, 1820: he discovered the connection between electricity and magnetism

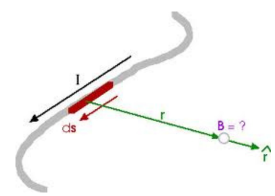
When he turned on the electric current in a wire, a compass needle that was on another experiment changed its position.



Mind the right-hand rule

The Biot–Savart law is used for computing the resultant magnetic field **B** at position **r** generated by a *steady* current *I* (for example due to a wire):

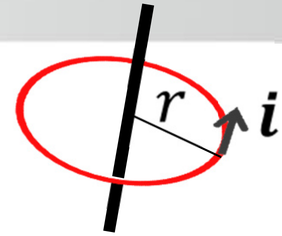
$$\mathbf{B} = \frac{\mu_0}{4\pi}\int_C \frac{I\, d\mathbf{l} \times \mathbf{r}}{|\mathbf{r}|^3}$$



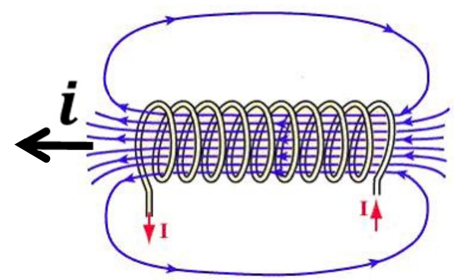
TECHNISCHE UNIVERSITÄT MÜNCHEN

Magnetic field and currents/2

- Infinite wire: $\boldsymbol{B}(r) = \frac{\mu_0 \cdot I}{2\pi \cdot r}\boldsymbol{i}$

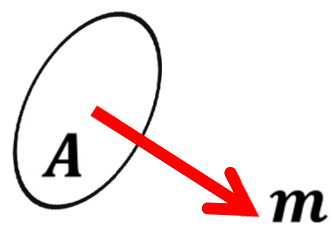


- Solenoid: $\boldsymbol{B_{int}} = \mu_0 \cdot \frac{N \cdot I}{l}\boldsymbol{i}$



$$\boldsymbol{B_{ext}} = \mu_0 \cdot \frac{\boldsymbol{m}}{2\pi \cdot s^3}$$

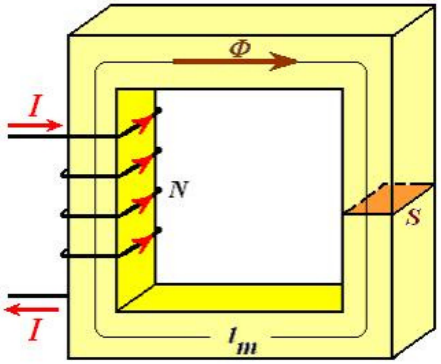
$$\boldsymbol{m} = I \cdot N \cdot \boldsymbol{A}$$

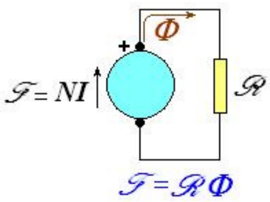


TECHNISCHE UNIVERSITÄT MÜNCHEN

Magnetic circuit

Hopkinson's law is the magnetic analogy to Ohm's law.





Magnetomotive 'force' or magnetic Spannung:

$$U_m = N \cdot I \quad \text{[A]}$$

Magnetic flux:

$$\boldsymbol{\Phi}_m = \frac{U_m}{R_m} \quad \text{[Wb]}$$

Where the total magnetic reluctance R [H=Wb/A] is the sum of the reluctances of different materials in the circuit.

$$\Rightarrow \quad B = \frac{\boldsymbol{\Phi}_m}{S}$$

and the energy per unit volume stored in the magnetic field: $E_m = \frac{1}{2\mu_0} \cdot B^2$

$$F_m = \left| -\frac{dE_m}{dx} \right|$$ is the magnetic force

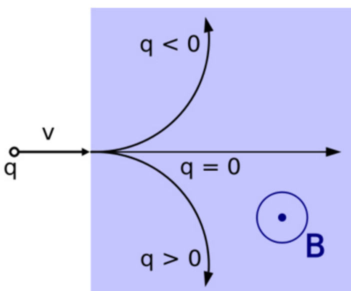
TECHNISCHE UNIVERSITÄT MÜNCHEN

Faraday law and Lorentz force

Faraday law of induction: $\varepsilon = -\frac{d\Phi_B}{dt}$ $\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = \mathbf{0}$

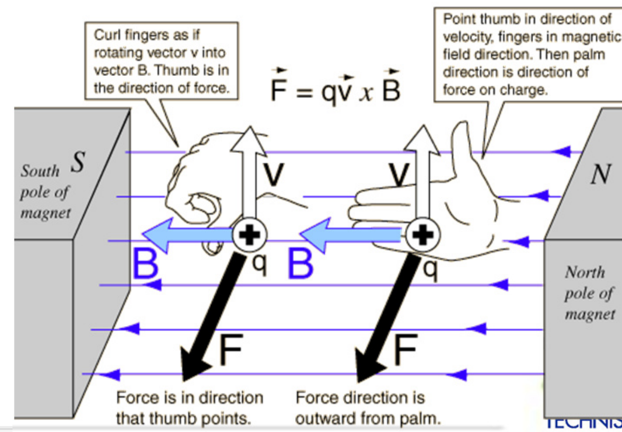
Given a loop of wire in a magnetic field, Faraday's law of induction states the induced electromotive force ε in the wire.

From Faraday's law of induction and the Maxwell equations, the Lorentz force can be deduced:



$$\boldsymbol{F} = q \cdot \boldsymbol{v} \times \boldsymbol{B}$$

Lorentz force is the force experienced by a charged particle in a magnetic field



Lenz law and eddy currents

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

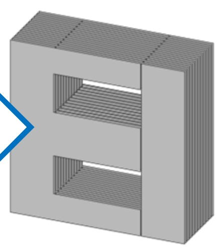
+ law of conservation of energy and 3rd Newton's law

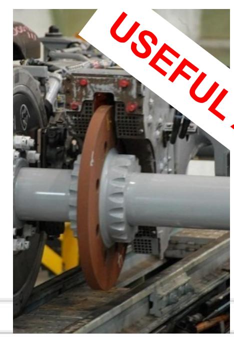
Lenz's law states that the current induced in a circuit due to a change or a motion in a magnetic field is so directed as to oppose the change in flux or to exert a mechanical force opposing the motion.

The total amount of electromagnetic energy cannot change!

Eddy currents (also called **Foucault currents**) are electric currents induced within conductors by a changing magnetic field in the conductor. Eddy currents will be generated wherever a conducting object experiences a change in the intensity or direction of the magnetic field.

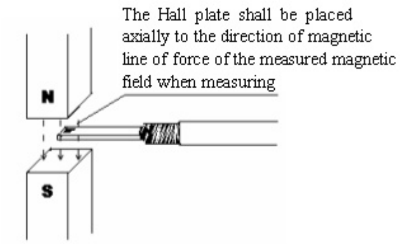
UNDESIRED EFFECTS



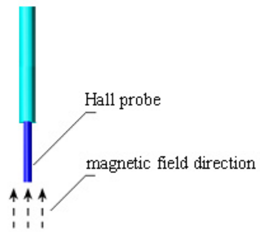


USEFUL APPLICATIONS

How to measure a magnetic field



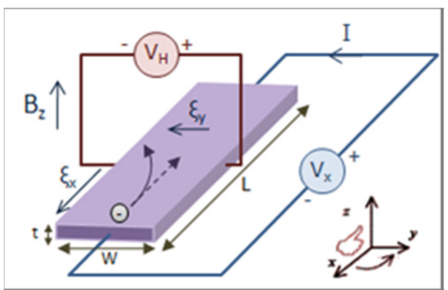
(Fig.1 Transverse probe)



(Fig.2 Axial probe)

The magnetic field can be measured with a probe based on the Hall effect.

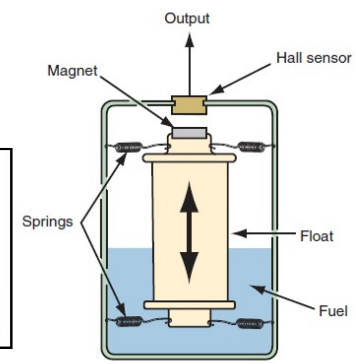
The **Hall effect** is the production of a voltage difference (the **Hall voltage**) across an electrical conductor, transverse to an electric current in the conductor and a magnetic field perpendicular to the current.



at equilibrium:

$$q \cdot v \cdot B = q \cdot E_H$$

$$V_H = \frac{I \cdot B}{n \cdot e \cdot t}$$



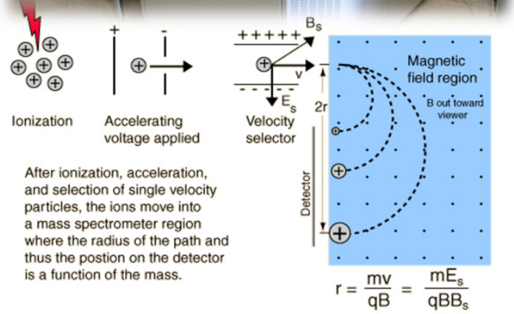
Some more applications of the Hall effect: automotive fuel level indicators, ABS break system, old PC keyboards…

TECHNISCHE UNIVERSITÄT MÜNCHEN

Further practical applications of magnetic fields

Bending and focusing magnets
in particle accelerators (LHC 8.4T!)

Mass spectrometer



Magnetic Resonance Imaging
(1.5T– 3T)

TECHNISCHE UNIVERSITÄT MÜNCHEN

Thank you for your attention

and

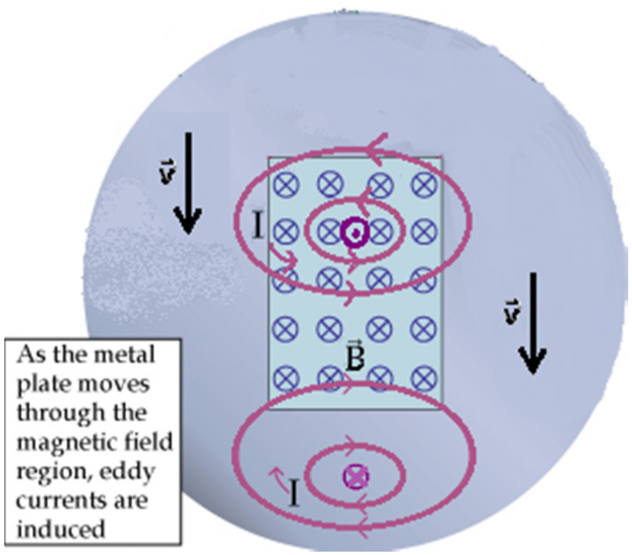
Enjoy your experiments!

Are you interested in radiation applied science & research? Have a look at our website and my personal logbook:

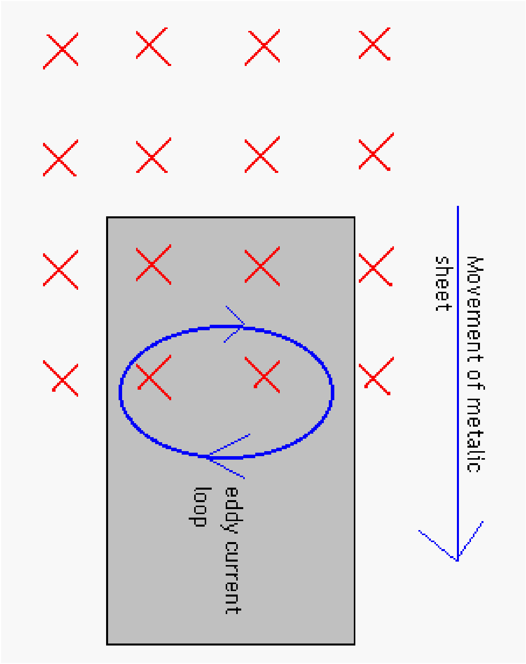
http://ardent.web.cern.ch/ardent/ardent.php
http://ardent.web.cern.ch/ardent/ardent.php?link=esr11-logbook

Eddy currents experiment explanation

Slab of non-ferromagnetic material dropping between two permanent magnets:



For instance, at the 'exit' we can imagine this situation:



TECHNISCHE UNIVERSITÄT MÜNCHEN

Magnetic susceptibility of some materials

Material	**Magnetic susceptibility [Vs/Am]**
Water	-9.0E-06
Iron	>1000
Aluminum	2.22E-05
Graphite	-1.4E-05
Oxygen	3.73E-07
Diamond	-2.2E-05
Helium	-9.85E-10