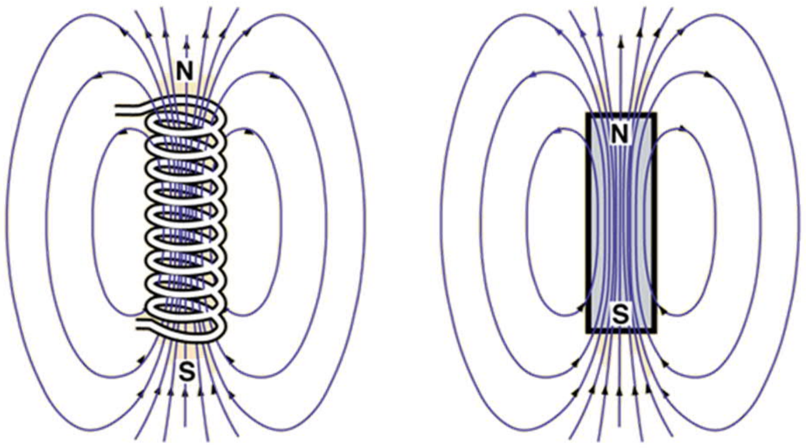
Electromagnetic fields
Learning outcome

At the end of this lecture you will be able to:

- List the most important electromagnetic field quantities
- Explain what these quantities describe
- Calculate some of these quantities from electromagnetic theory

Magnetism and energy conversion

- Electromechanical energy conversion is based on the interaction between magnetic fields
- Magnetic field can be produced by permanent magnets or electromagnets
  - In electromagnets, field is generated by current in the coil (Ampere's law)
  - Unless moving, permanent magnet produces static magnetic field (DC)
- Control of the coil current produces time-varying magnetic field
- Time-varying field induces voltage in coils and conductors (Faraday's law)



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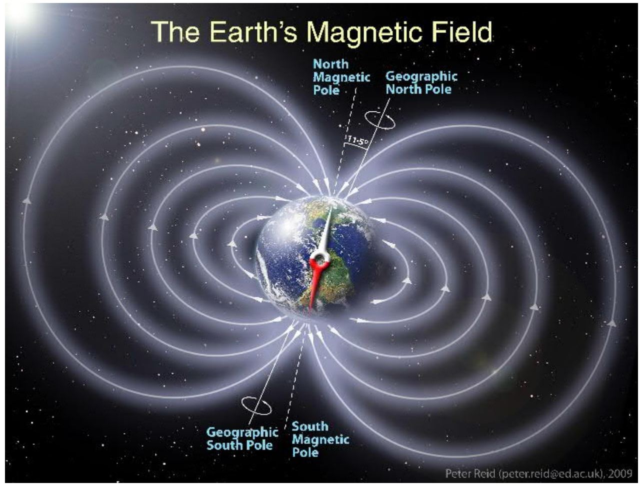


http://www.nasa.gov/sites/default/files/images/607968main_geomagnetic-field-orig_full.jpg

Electromagnetic fields

- The magnetic state of the material is defined by its magnetization ***M*** [A/m]
- The flow of electric charges defines the currents or current density ***J*** [A/m^2]
- The current density produces a magnetic field defined by:
  - the magnetic flux density ***B*** [T] or
  - the magnetic field strength ***H*** [A/m]
- Electric charge density ρ [C/m^3] produce electric fields defined by
  - The electric field strength ***E*** [V/m] or
  - The electric flux density ***D*** [C/m^2]
- In total six vector fields and one scalar filed are required.
- Material properties tight some of these fields to each other

Electromagnetic fields and Maxwell equations

- The electromagnetic fields are ruled by four vector equations: Maxwell equations

$$\nabla \cdot \boldsymbol{D} = \rho$$

$$\nabla \cdot \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}$$

- However, these equations are not enough to solve the fields and there interaction with the materials
- Material properties are also needed

Electromagnetic fields and energy conversion

- Electromagnetic fields have been successfully used in the electromechanical energy conversion.

- By energy conversion we mean conversion of mechanical power to electric power, generators; or vice versa motors and actuators

- To be able to model this energy conversion and the devices that use it, one needs methods

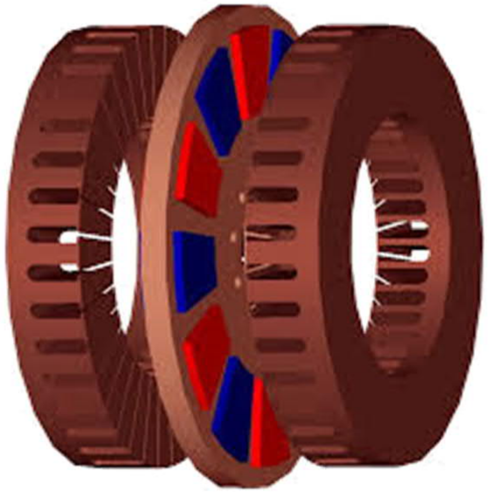
  - to compute the forces and torques
  - to couple electric circuits with field equation
  - to solve dynamic motion equations
  - to couple motion and fields
  - to couple fields and materials

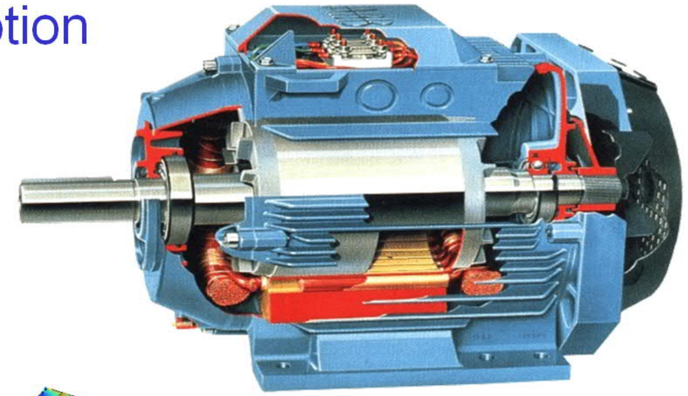
Brain storming

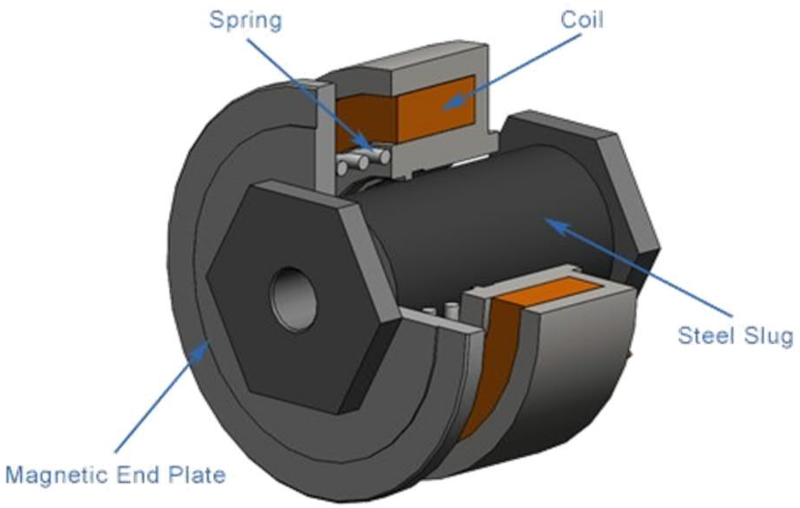
- Take 20 min and think of what kind of devices and components are involved in electrical energy conversion and transmission
- Write down these devices and components, we will compile the results during the lecture
- List of devices and components:
  - Electrical machines (motors and generators)
  - Power electronic components and devices
  - Transformers
  - Batteries and super capacitors
  - Cables and bus bars
  - Solar panels
  - Inductors and heat exchangers
  - Light bubbles and LEDs
  - Antennas, microwave heaters
  - Speakers and microphones
  - Fuel cells, thermocouples

Electromechanical energy conversion

- Examples of electromagnetic energy conversion devices
  - Rotating electrical machine radial and axial flux
  - Linear electrical machines, continuous motion
  - Linear actuator







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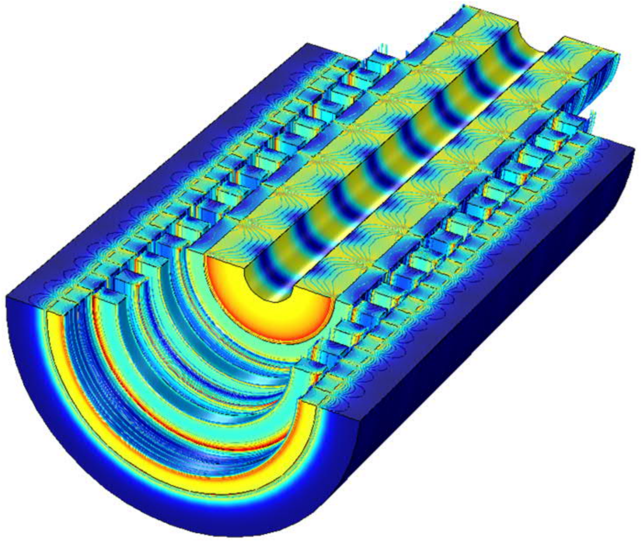
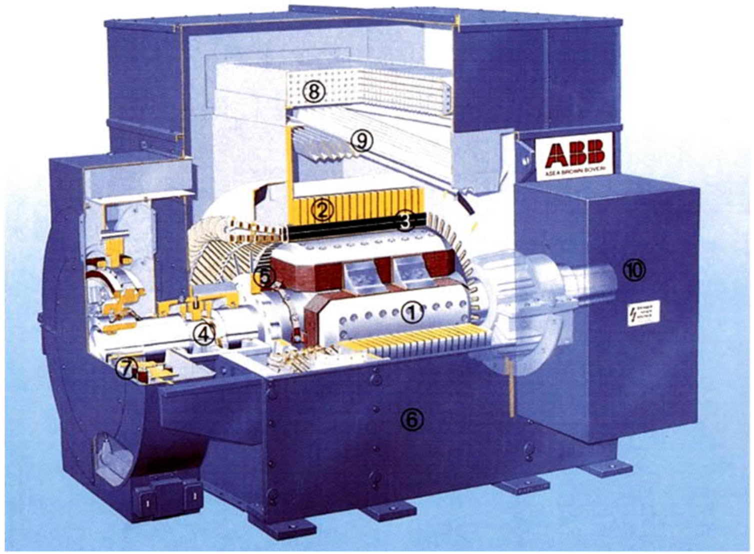


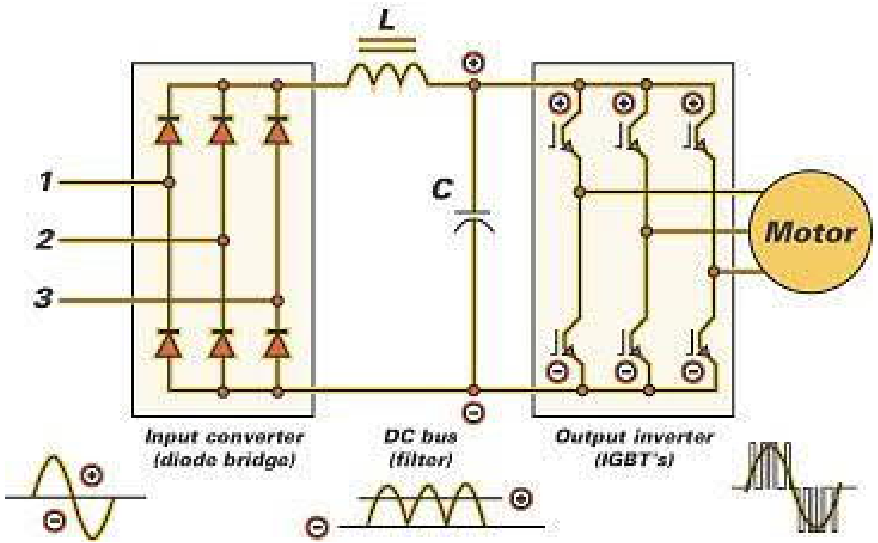


https://cdn.comsol.com/wordpress/2016/04/Magnetic-flux-density.png

Power electronics and energy conversion

- Examples of energy conversion with power electronics
  - Rectifiers, Inverters, Frequency converters
  - Soft starters, Active power factor correction
  - Semiconductor devices

http://www.dynexsemi.com/media//n/e/new-banner-igbt-module_2.png



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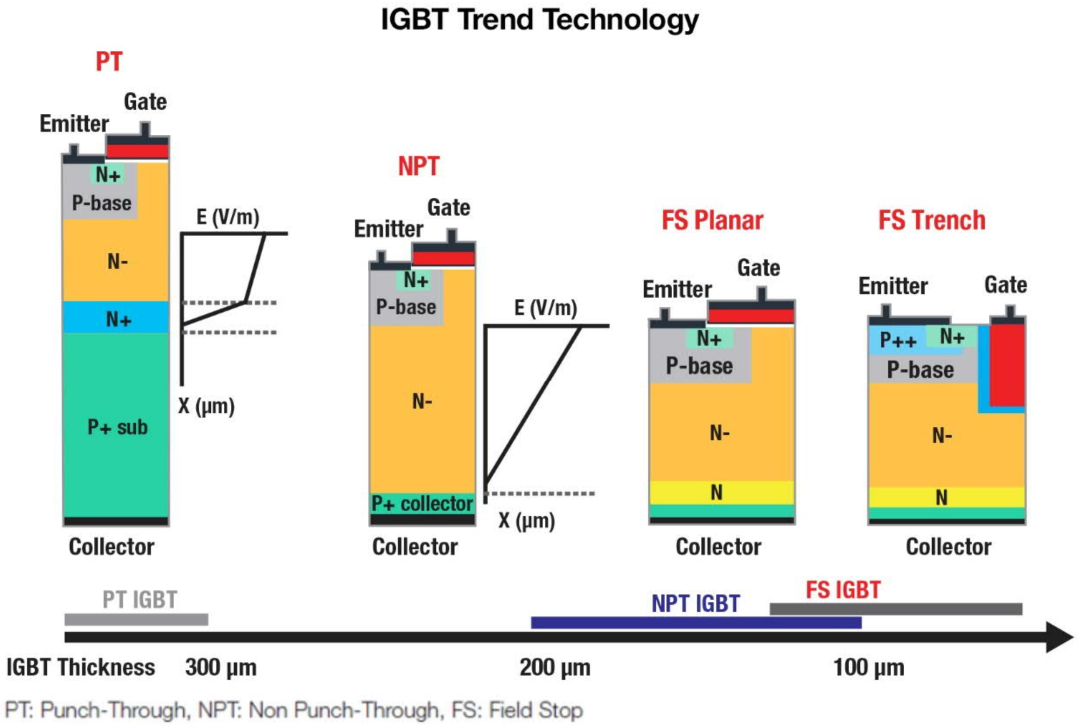

http://blog.fairchildsemi.com.cn/wp-content/uploads/2015/09/IGBT-trend-technology.jpg

Energy transmission and distribution

- Examples of energy transmission devices
  - Transformers, cables and transmission lines
  - Switch gears and contactors
  - protection and measurement devices

https://www.toshiba.com/tic/product_images/Medium-Voltage-Switchgear.jpg

http://www.arresterworks.com/resources/photo_images/big_images/arresters_protecting_230kv_windfarm.jpg

http://www.parsakhgar.com/images/industrial_underground_cable.png

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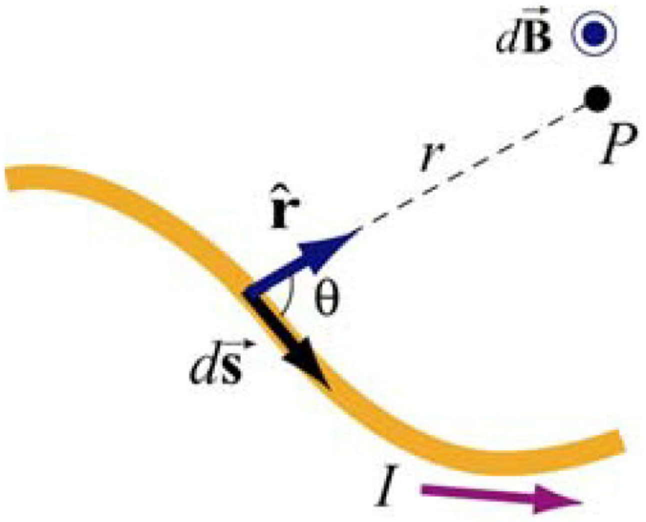
Source of magnetic fields

- The motion of electrically charged particles produces electric currents
- Electric currents produce a magnetic field according to the Biot-Savart law



$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I d\vec{s} \times \vec{e}_r}{r^2}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ T.m/A}$$

$$\vec{B} = \frac{\mu_0 I}{4\pi}\int_{wire}\frac{d\vec{s} \times \vec{e}_r}{r^2}$$

- An other way to look at the field induced by currents is the Ampere law

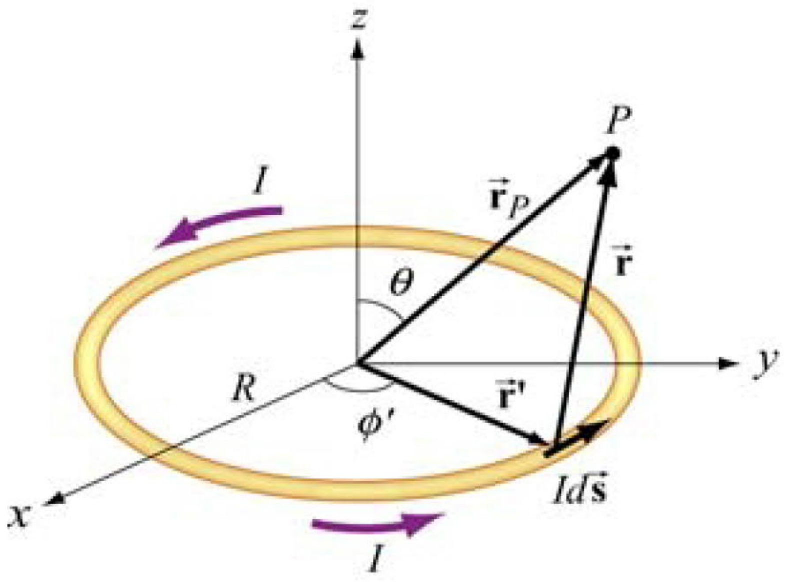
$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

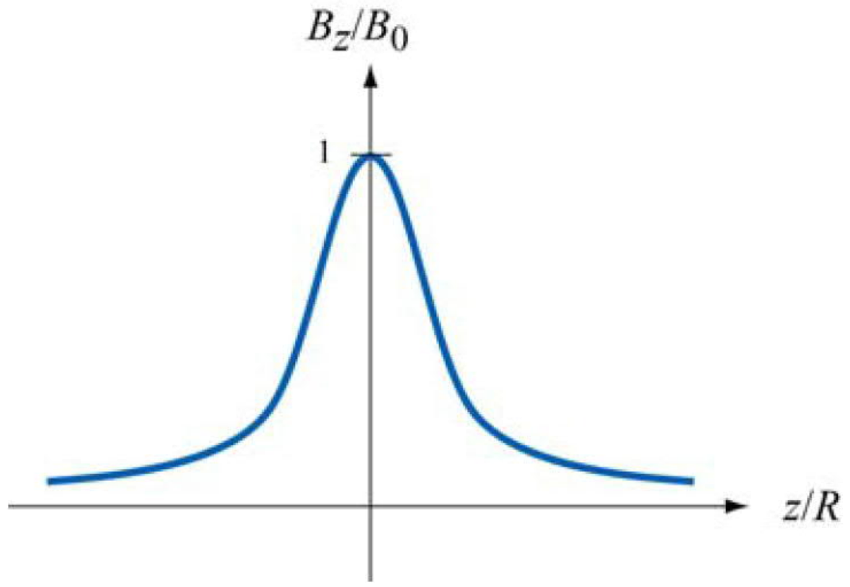
Magnetic field produced by a current loop

- If the current is circulating in a thin circular wire the produced magnetic filed at its origin is along the z-direction and it can be calculated with the Biot-Savart law:

$$B_z = \frac{\mu_0 I R^2}{2\left(R^2 + z^2\right)^{3/2}}$$

$$B_0 = \frac{\mu_0 I}{2R} \quad \text{at} \quad z = 0$$



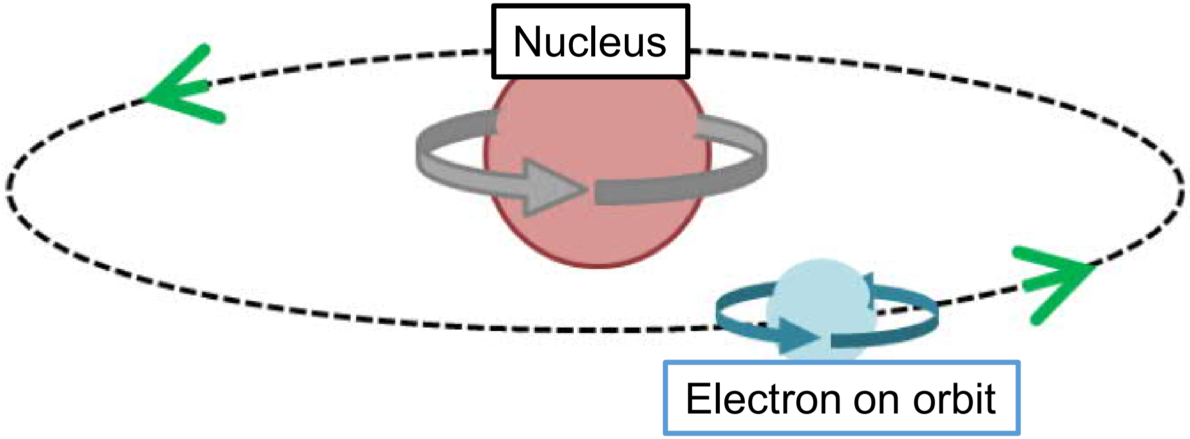


- If the loop has small radius and is in a uniform magnetic field it experiences a torque, which aims at aligning it with the external field $\boldsymbol{\tau} = \boldsymbol{m} \times \boldsymbol{B}$

- ***m*** is called the magnetic moment and is given by $m = I_{loop} A_{loop}$

Origins of magnetism in material

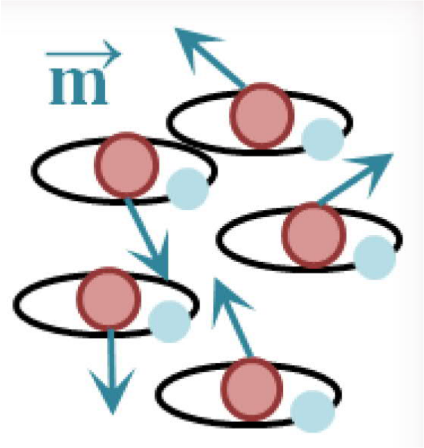
- Magnetism has its origins in the motion of charges and the atomic structure.
- A full understanding of magnetism requires quantum theory
- Most of magnetic phenomena can be understood with classic theory.
- Electron motion on orbit produces magnetic moment (orbital moment)
- Rotation of electron around itself produces spin moment
- There is also a moment produced by the rotation of nucleus around itself but it is negligible

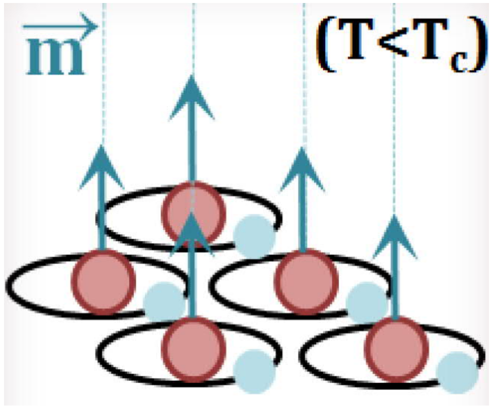


Origins of magnetism in material

- The atomic moment is the vector sum of all the orbital moments of its electrons
- For atoms with full electron shells, the resulting moment is null
- In some atomic structures with incomplete electron shells, the resultant is different from zero and thus the material is said to be magnetic.
- Not all the atoms with incomplete electron shells are magnetic. This is due to the fact that the combination of atoms results in most case in a global neutralization of magnetic moments of the atoms.

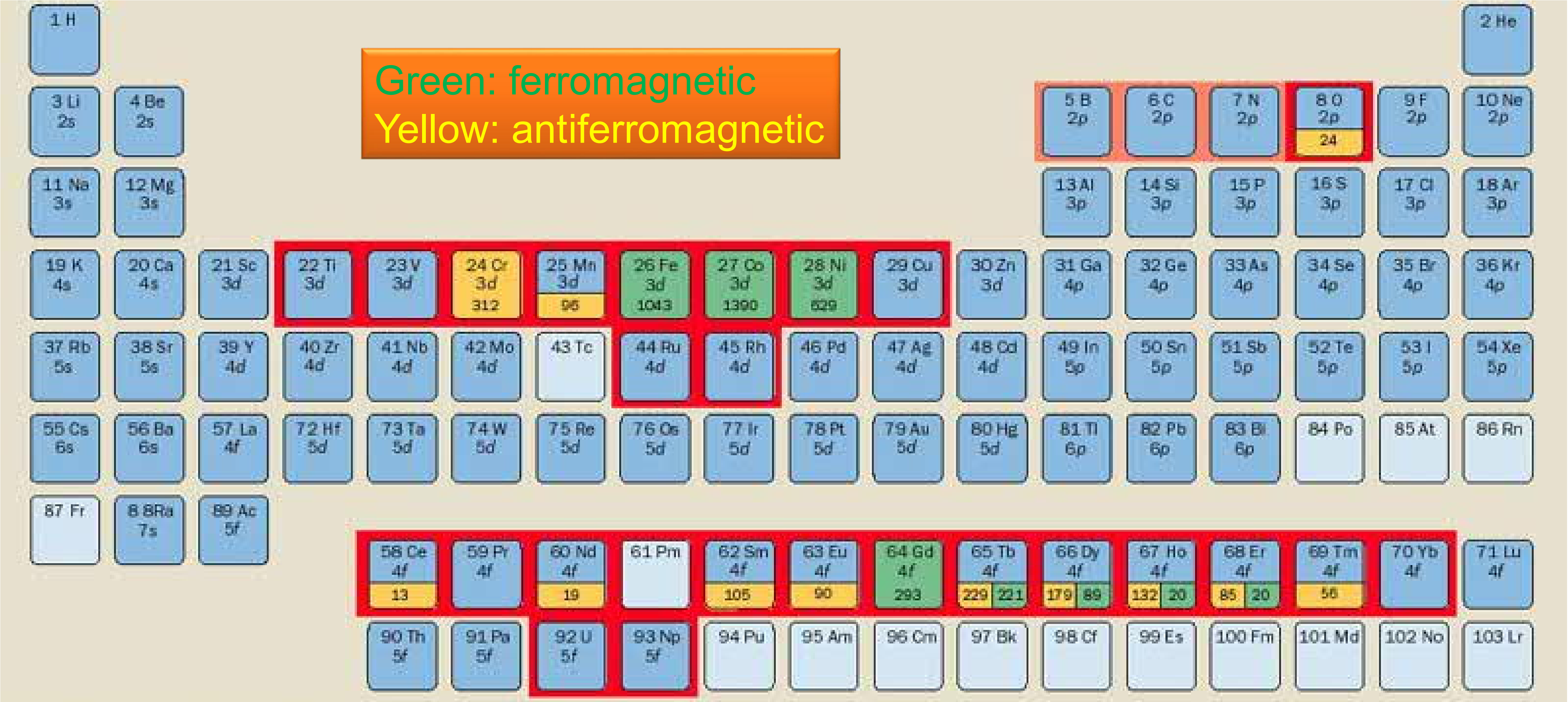
Diamagnetic material





Ferromagnetic material

Magnetic materials



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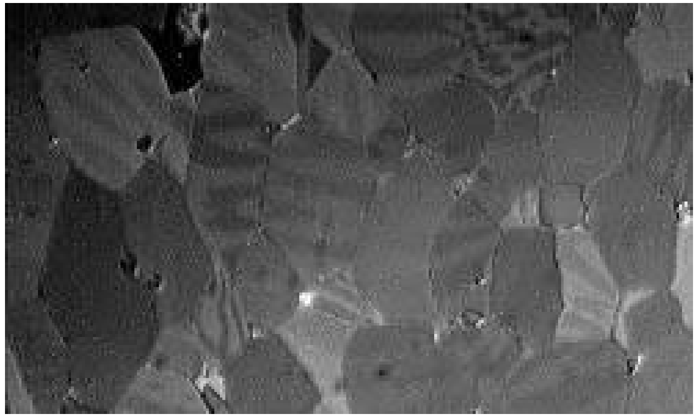
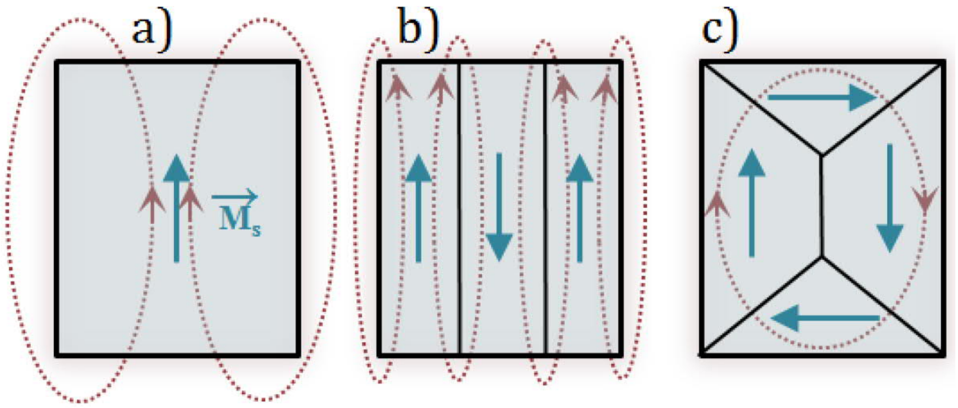
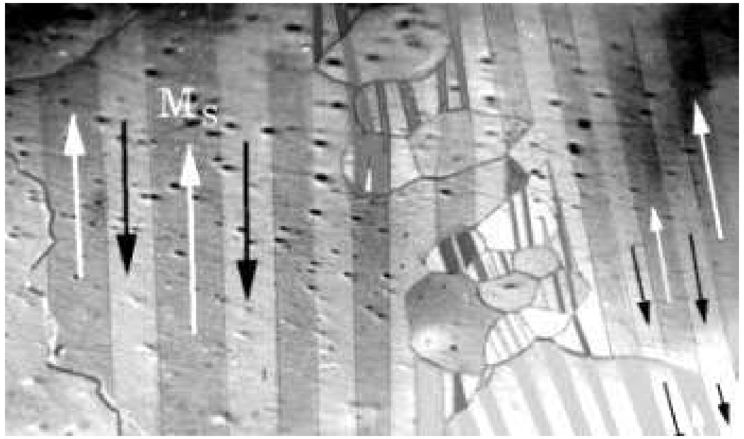
Ferromagnetic materials

- Due to different interactions in the matter the moments of a ferromagnetic material are forced to group in small domains, called Weiss domains
- The grouping in domains minimizes the total energy of the material
- In each domain, all the moments are aligned, the domain is saturated
- The domains are separated by small regions called Bloch walls



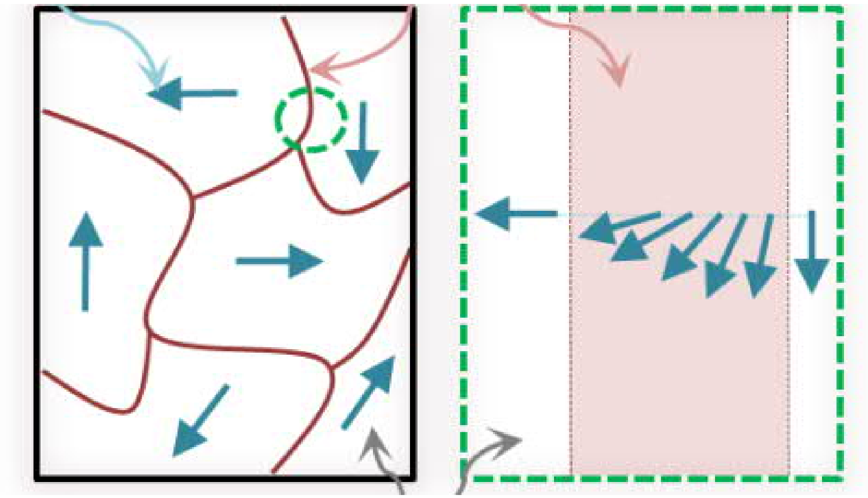




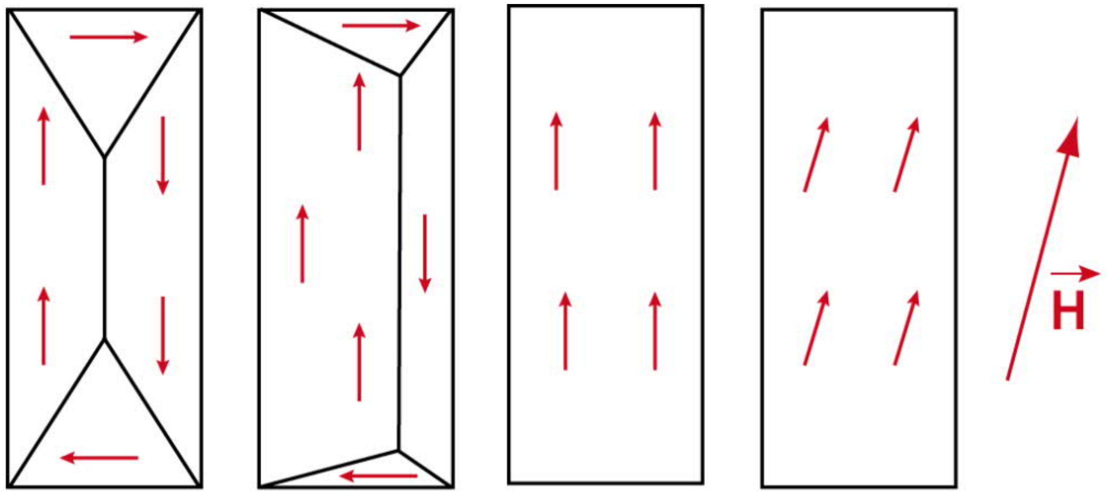
a) Maximum energy, b) lower energy, c) minimum energy

Domain structure

- Magnetic domains in magnetic materials are separated by domain wall: Bloch walls
- The magnetic moments in the wall rotate progressively from one direction to the other. This transition minimizes the wall energy.
- Under external applied field the domain walls move and collapse
- The wall motion is not continuous, impurities and other *obstacles (pinning sites)* stop the motion until it jumps to the next obstacle: hysteresis



Weiss domains and Bloch walls



Wall motion under increasing external field

Source of electric fields

- From the Maxwell equations it is clear that the origin of an electric field is either a charge density or a time varying magnetic field

$$\nabla \cdot \boldsymbol{D} = \rho$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

- D, the electric flux density is related to the electric charge density
- E, the electric field strength is related to the potential difference, which is caused by the varying flux density

- E and D are related by the material property, permittivity ε
  - ε_r is the relative permittivity and ε_0 is the vacuum permittivity

$$\boldsymbol{D} = \varepsilon \boldsymbol{E}$$

$$\varepsilon = \varepsilon_r \varepsilon_0$$

$$\varepsilon_0 = \frac{1}{4\pi \times 10^{-7} c^2} \approx 8.854 \times 10^{-12}$$

Electric fields and materials

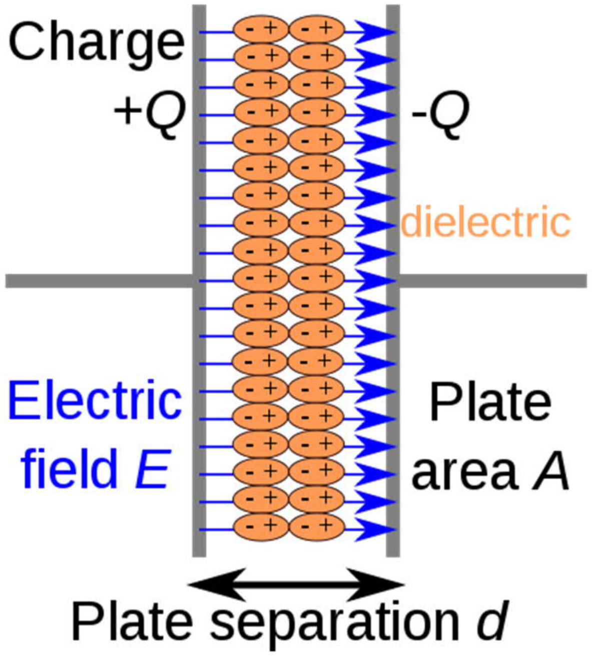
- Electric field causes the free charges of a conductor material to move; this motion results in electric currents (or current density).

- The electric conductivity of the material is a description of how easily the free charges move, and it is used to relate the electric field strength and the current density

$$J = \sigma E$$

- Electric charges produce electric flux, or electric flux density ***D***; this reacts with material to produce an electric field ***E***, which depends on how the material structure is able to polarize.

$$D = \varepsilon E$$



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Electromagnetic fields and materials

- The application of an external field to a magnetic material causes domain walls to move and thus produce net magnetization of the material. This reaction is described by the material susceptibility

$$\mathbf{M} = \chi \mathbf{H}$$

- The magnetic flux density in the material is the sum of the one in air and that due to the magnetization

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$$

- We can then describe the total flux density with a material constant called permeability

$$\mathbf{B} = \mu \mathbf{H}$$

- We thus end up with three material parameters and relations

$$\mathbf{D} = \varepsilon \mathbf{E}$$

$$\mathbf{J} = \sigma \mathbf{E}$$

$$\mathbf{B} = \mu \mathbf{H}$$

Magnetic Materials

- Magnetic materials are usually classified according to their response to an external field. Tree main categories can be differentiated:
- Diamagnetic
  - Low but negative susceptibility, consequence of local eddy current at orbital level (reduced loop current of the electron)
  - Atoms with closed electron shells such as monoatomic rare gases He, Ne, A, polyatomic gases H2, N2, and ionic solids NaCl.
- Paramagnetic
  - Low but positive susceptibility, which changes with temperature
  - consequence of thermal agitation.
  - Atoms with incomplete electron inner shells
  - compounds of transition metal ions and rare earth ions
- Ferromagnetic

$$\chi_m = \frac{C}{(T-\theta)}$$

C: Curie constant
T: temperature
θ: constant

Investigation work 20 min

- List the magnetic materials that you know or find from the internet (5 min)
- With your mate, classify these materials as soft or hard (5 min)
- Present your list and classification to the class (10 min)
  - You might use internet

Reading

- Read the paper: Recent Trends and Future Prospects of IGBT and Power MOSFET (40 min)

- Choose one concept that you find interesting from the paper and present it to the class
  - Make a first read through the whole paper quickly to understand what it is about
  - Make a second read focusing on the concept you chose to deepen your understanding
  - If necessary find more about that concept from the internet

- Concepts discussed: