MSE-432
Introduction to magnetic materials in modern technologies

2024/2025, Spring term

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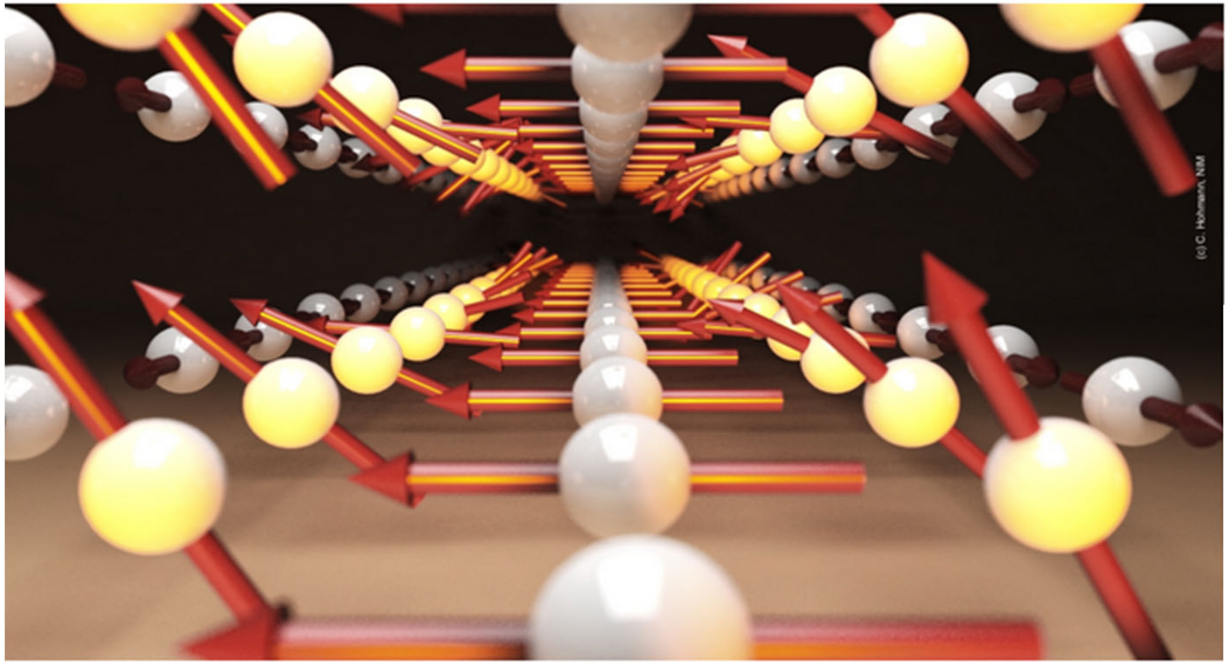
Institute of Materials

Introduction

LABORATORY OF NANOSCALE MAGNETIC MATERIALS AND MAGNONICS LMGN

Welcome to LMGN



The **Laboratory of Nanoscale Magnetic Materials and Magnonics (LMGN)** aims at the exploitation of magnetic nanomaterials for information technology (data processing, transmission, logic), sensing and multifunctional devices. In our experiments and simulations, we prepare and explore individual ferromagnetic nanostructures such as **nanotubes**, periodic and aperiodic nanomagnet arrangements such as **magnonic crystals**, artificial spin ice and quasicrystals as well as Skyrmion lattices. We study their fundamental properties and aim at novel functionalities.

The focus is devoted to the microwave properties of magnetic materials in the few GHz to 100 GHz frequency regime. Here, electromagnetic waves that, in free space, exhibit a wavelength of several

Competences and Objectives

- Magnetic properties of nanostructured materials
- Nanofabrication and cleanroom processing
- Microwave properties of magnetic nanomaterials
- GHz spectroscopy
- Magnonics
- Spintronics
- Skyrmionics

MSE-432 **Introduction to magnetic materials in modern technologies**

Grundler Dirk

Cursus	Sem.	Type
Materials Science and Engineering	MA2, MA4	Opt.

Language	English
Credits	4
Session	Summer
Semester	Spring
Exam	During the semester
Workload	120h
Weeks	14
Hours	**4 weekly**
Lecture	2 weekly
Exercises	2 weekly

Summary

Interactive course addressing bulk and thin-film magnetic materials that provide application-specific functionalities in different modern technologies such as e.g. wind energy harvesting, electric article surveillance, spintronics, sensing, and data storage.

Content

The course explains the relation between properties of magnetic materials and their composition, structure, as well as underlying preparation techniques.

1.Introduction to magnetic phenomena

2.Basic concepts of magnetic materials

3.Fabrication and synthesis techniques (bulk materials, thin films, nanoscale materials)

4.Electric, magnetic, mechanical, and optical properties depending on composition, structure, preparation technique

5.Figure-of-merits of magnetic materials in different technologies and performance tests

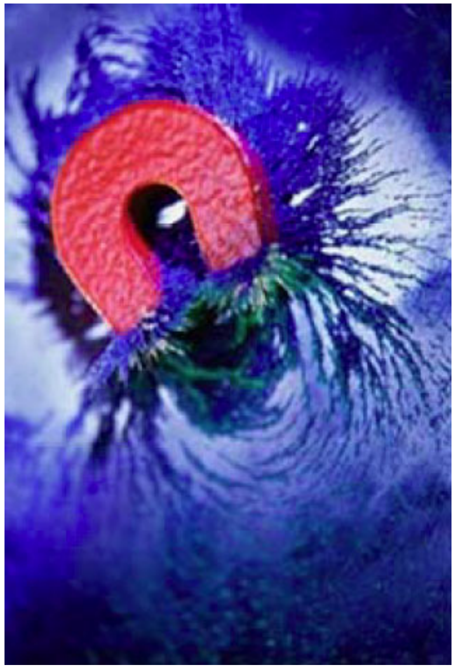
6.Applications (e.g. storage, electric article surveillance, sensors, spintronics)

7.Abundance of relevant elements, sustainability

Introduction to magnetic materials in modern technologies

Synopsis: Magnetic materials offer a rich versatility in modern technologies (information technology, daily appliances, renewable energy production, …)

Learning outcomes: how to engineer, characterize and optimize magnetic materials to obtain functionalities relevant for state-of-the-art applications (amorphous vs crystalline, elemental vs alloy, bulk vs thin film/nanostructures, metallic vs insulating, …)

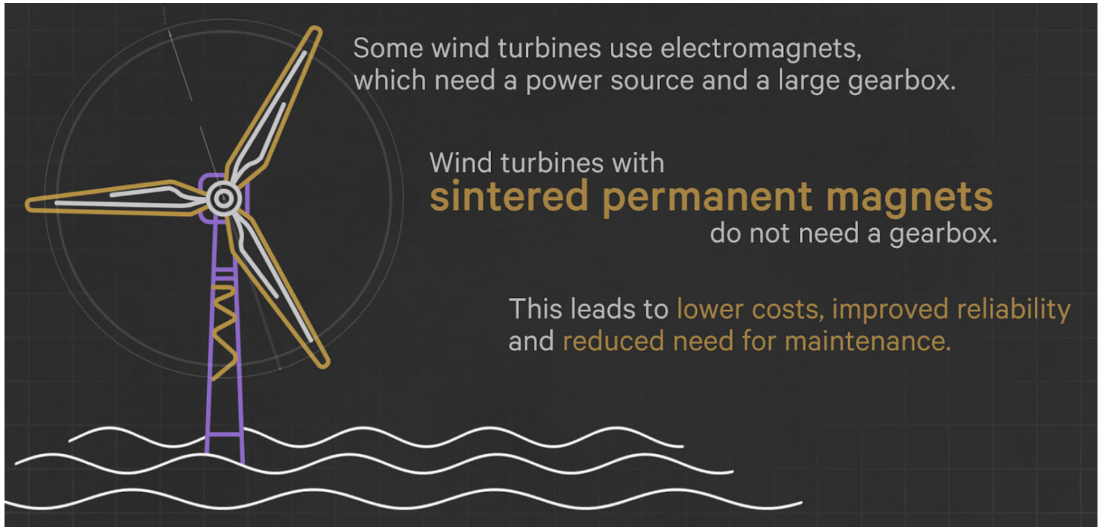


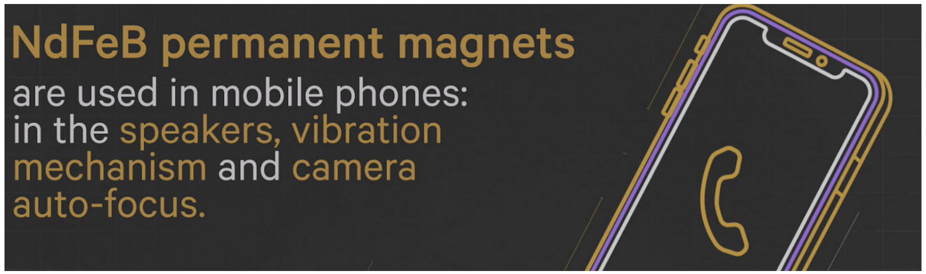
TDK commercialized “ferrite,” a magnetic material invented in Japan.
Ever since that time, TDK develops electronic materials from scratch, starting with raw materials. Devices include ferrite cores, coils, transformers, RF components, magnetic heads, and magnets.
Taken from : http://www.global.tdk.com/about_tdk/corporate_message/

Queen Elizabeth Prize for Engineering honours magnet pioneer (01. Feb. 2022)

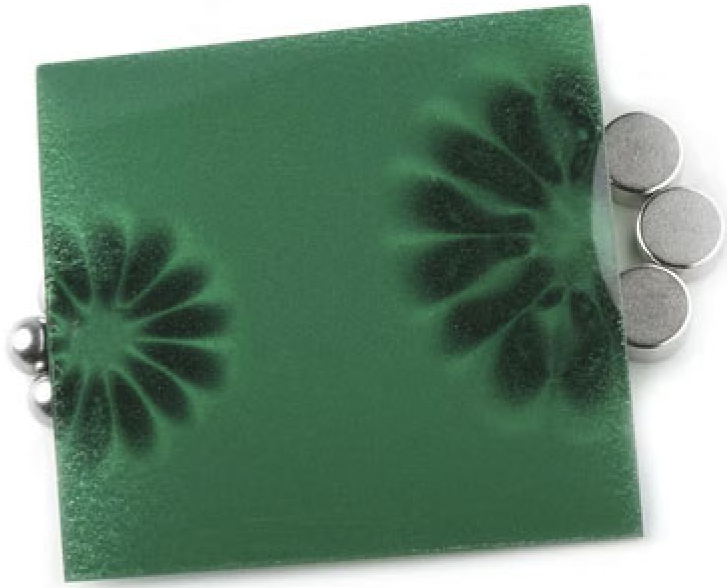
Dr Masato Sagawa

https://qeprize.org/





Flux detector



The Flux Detector makes magnetic fields visible.

It's accomplished by a foil filled with nickel particles in a gelatinous suspension.

The Flux Detector turns

dark in colour
when the magnetic field is perpendicular to the foil
(for example, near the poles) and

lighter when the magnetic field runs
parallel to the foil.

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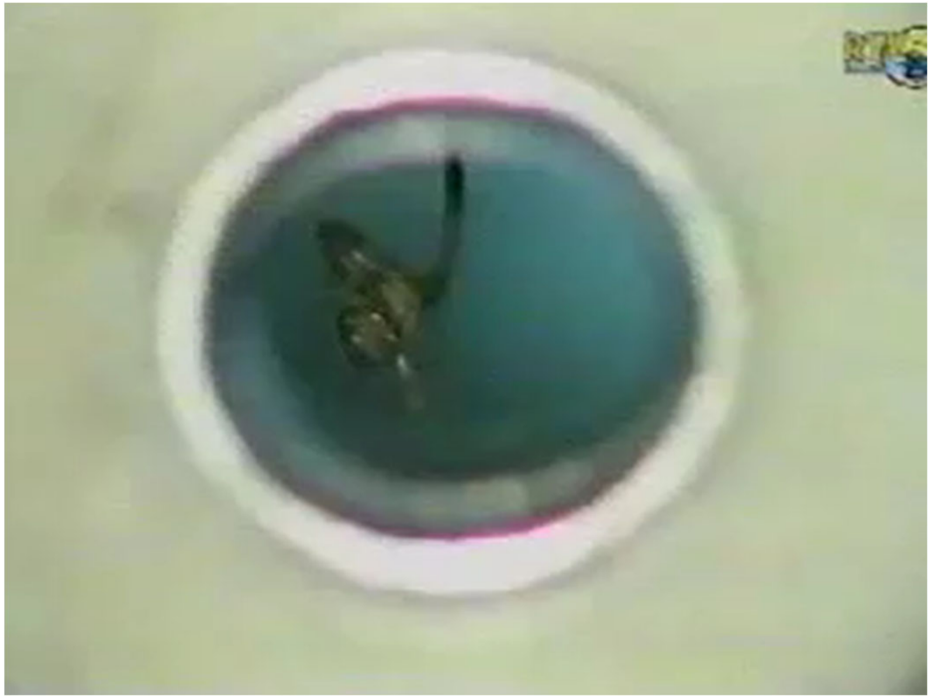


Diamagnetism was used here
to levitate objects in a strong
and inhomogeneous
magnetic field
(magnetic force acting against the
gravitational force)
(A.K. Geim et al.)

https://www.ru.nl/hfml/research/levitation-explained/diamagnetic-levitation/

20 T Bitter Solenoid

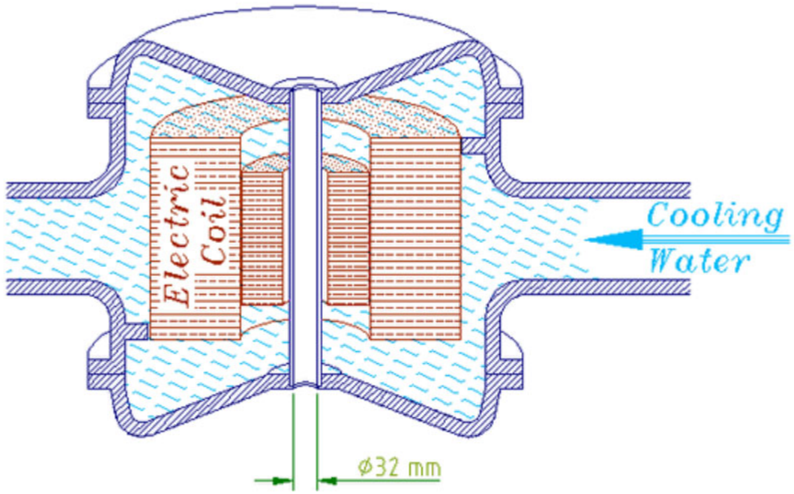


Figure 1: Schematic cross section of a 20 tesla Bitter Magnet.

Magnetically ordered systems =>
Functional magnetic materials

Types of “magnetic materials”

What types do you know?

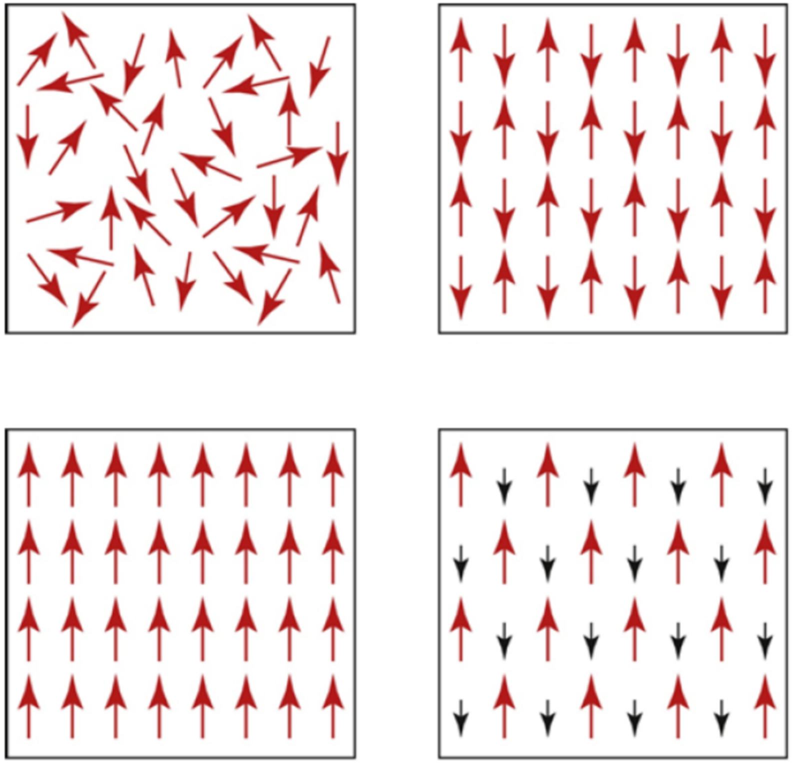
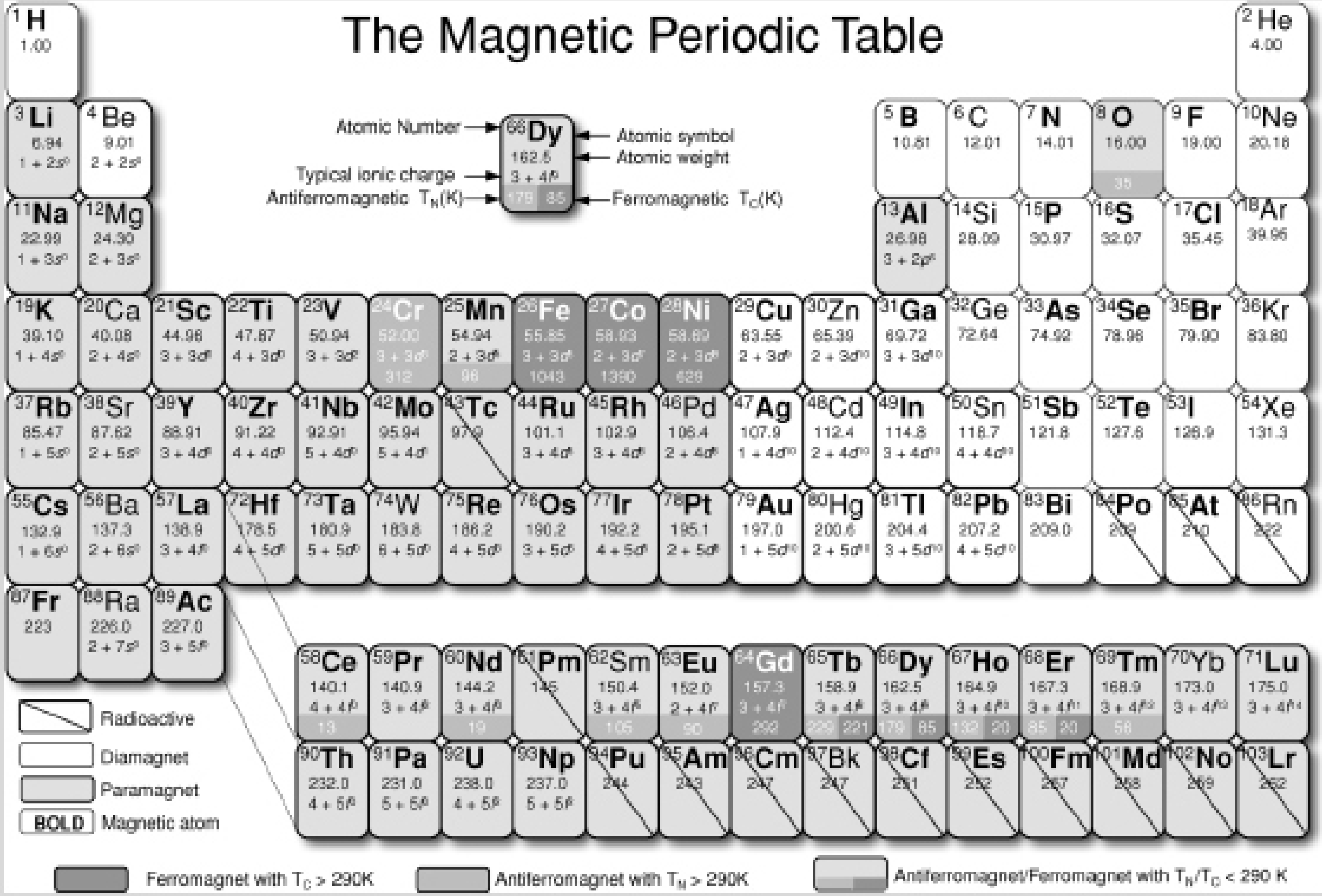


Table A The magnetic periodic table. Diamagnetic elements are uncoloured, paramagnets are pale grey, ferromagnets are dark grey, antiferromagnets are mid grey, and the Curie or Néel temperatures are marked. Common paramagnetic ions are indicated. Elements which bear a magnetic moment as isolated atoms are marked in bold type.



At room temperature only Fe, Co and Ni are known to form a ferromagnet starting from a single element of the periodic table of elements. Nowadays many alloys and compounds are known to be ferromagnetic at room temperature as well. (Graph taken from J.M.D. Coey)

From Fe to Iron Oxides

In air Fe oxidizes. The most common forms are α-Fe_2O_3 (hematite is the mineral) and Fe_3O_4 (magnetite is the mineral). The latter contains iron in oxidization states 2^+ and 3^+.
Magnetite is a so-called ferrimagnet, which means that microscopic magnetic moments of the Fe ions are aligned antiparallel, thereby reducing the saturation magnetization $\mu_0 M_s$ of the bulk material below the value of iron (which is about 2.2 to 2.3 T at room temperature).

Iron crystal

Hematite:
canted antiferromagnetic phase

Magnetite (lodestone):
$\mu_0 M_s = 0.56$ T

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Maxwell's equations and polarizable matter

Review: Maxwell's equations in polarizable matter

For **magnetic materials** and **dielectric materials** in which polarization occurs one needs to consider fields *E* and *D* as well as *H* and *B*:

$$\vec{\nabla} \cdot \vec{D} = \rho_{free} \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad \vec{\nabla} \times \vec{H} = \vec{j}_{free} + \frac{\partial \vec{D}}{\partial t}$$

Constituent equations:

$\vec{D} = \varepsilon_r \varepsilon_0 \vec{E}$ or $\vec{D} = \varepsilon_0 \vec{E} + \vec{P}$

$\vec{j}_{free} = \sigma \vec{E}$ (Ohm's law where applicable)

$$\vec{B} = \hat{\mu}_r \mu_0 \vec{H} = \mu_0 (\vec{H} + \vec{M})$$

Magnetic field density B

The lines of the magnetic field:

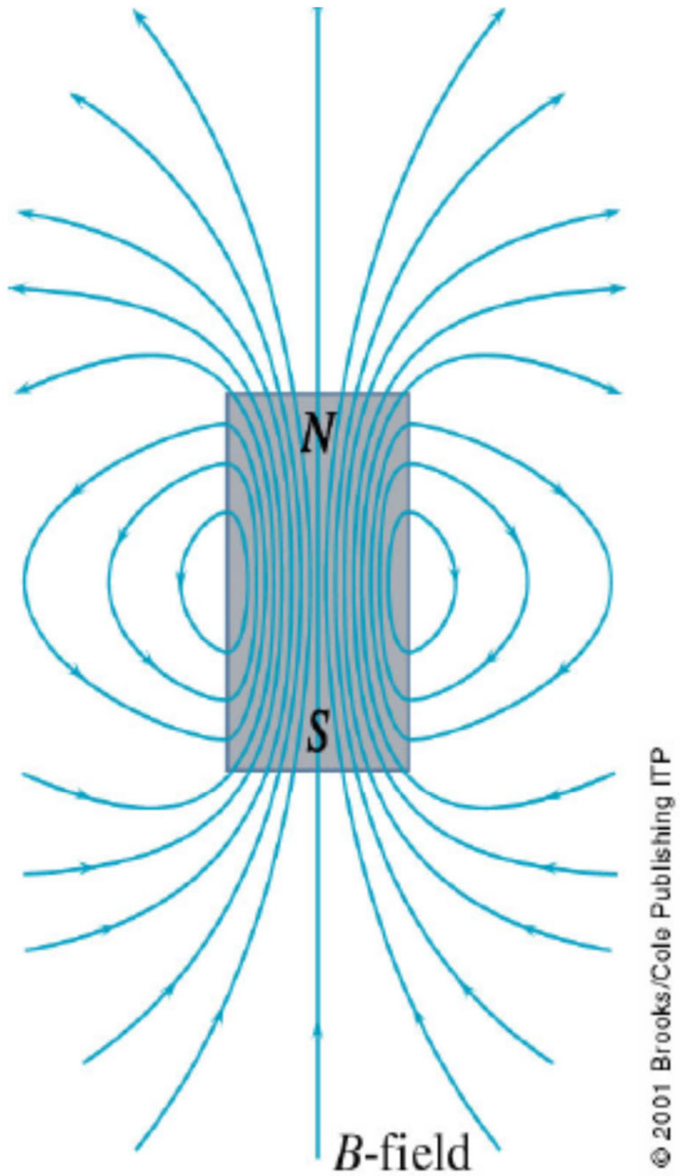
- Never intersect
- Have neither sources or sinks, unlike electrical and gravitational fields. Therefore, a magnetic field always froms a closed loop.
  $\vec{\nabla} \cdot \vec{B} = 0$

One distinguishes two magnetic fields *B* and *H*, only for

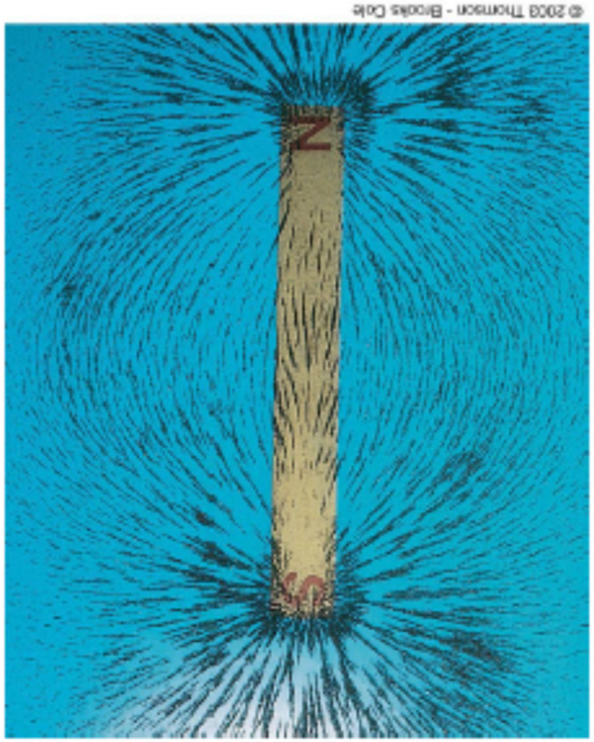
$$\vec{B} = \hat{\mu}_r \mu_0 \vec{H} = \mu_0 (\vec{H} + \vec{M}),$$

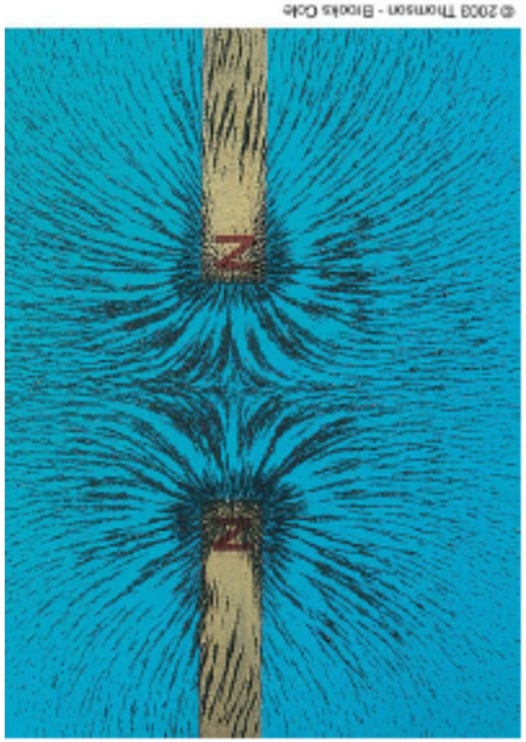
the field lines are closed

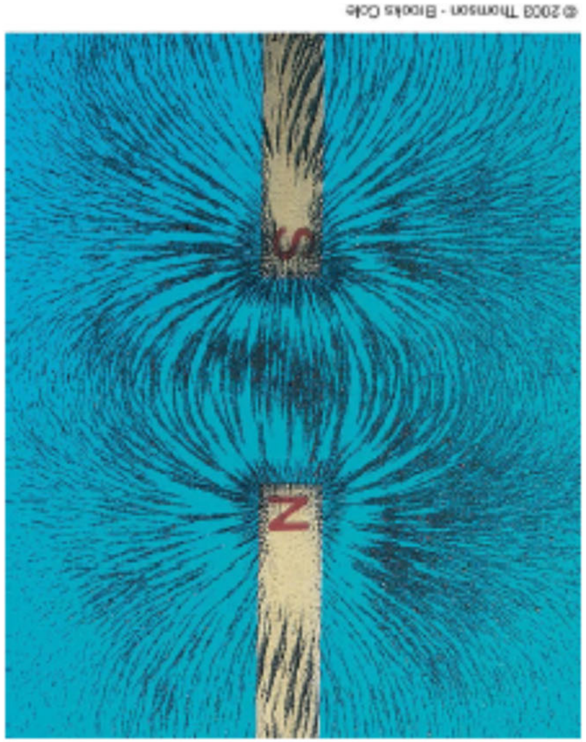
The density of the magnetic field lines is proportional to the magnitude of the field.

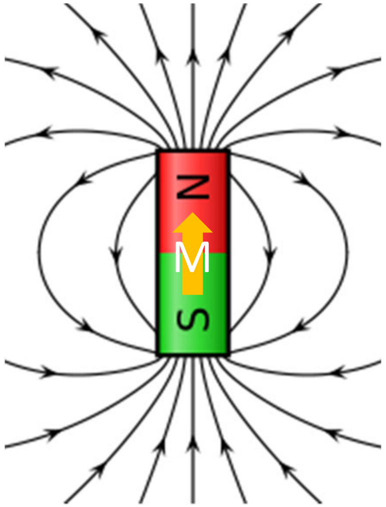


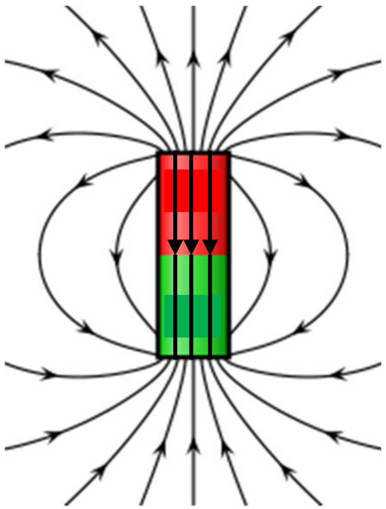
Magnetic field strength H











Here we sketch the **field lines of field H.** They do not form closed loops. This can be seen as follows

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

$$\Rightarrow \vec{\nabla} \cdot (\vec{H} + \vec{M}) = 0$$

$$\Rightarrow \vec{\nabla} \cdot \vec{H} = -\vec{\nabla} \cdot \vec{M}$$

The field ***H*** is
not divergence-free.

In magnetism two main unit systems coexist: CGS and SI. In the lecture we will use mainly the SI system.

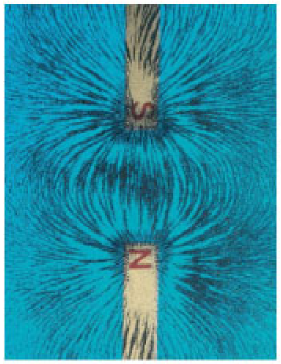
Table 1.6.1 *Key relationships and conversions between SI and CGS units in magnetism.*

	CGS	SI	Conversions
Magnetic field [**H**]	[Oersted]	[A/m]	1 A/m = $4\pi.10^{-3}$ Oe
Magnetic inductance [**B**]	[Gauss]	[Tesla] = [Weber/m^2] = [V s m^{-2}]	1 T = 10^4 Gauss
Pole strength [p]	[dynes/Oe]	[A m]	
Magnetic moment [**m**]	[ergs/Oe] = emu	[A m^2]	1 emu = 10^{-3} A m^2
Magnetization [**M**]	emu/cm^3	[A/m]	1 emu cm^{-3} = 10^3 A/m
Permeability of free space	1	$\mu_0 = 4\pi \times 10^{-7}$ [Wb A^{-1}m^{-1}] = [H m^{-1}].	
Field of a straight wire carrying current i [A] at a distance, r	$H = \frac{2i}{10r}$ (Oe)	$H = \frac{i}{2\pi r}$ [A/m]	
Relationship between **M**, **H**, and **B**	$\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$	$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$	
Torque on a moment, m	$\tau = \mathbf{m} \otimes \mathbf{H}$	$\tau = \mathbf{m} \otimes \mathbf{B}$	
Potential energy of **m**	$E_{pot} = -\mathbf{m} \cdot \mathbf{H}$ [erg]	$E_{pot} = -\mathbf{m} \cdot \mathbf{B}$ [J]	1 J = 10^7 ergs

Taken from Kannan Krishnan (Fundamentals and Applications of Magnetic Materials)

Summary: Different types of magnetism

Large stray field (field B) possible at zero applied magnetic field H:



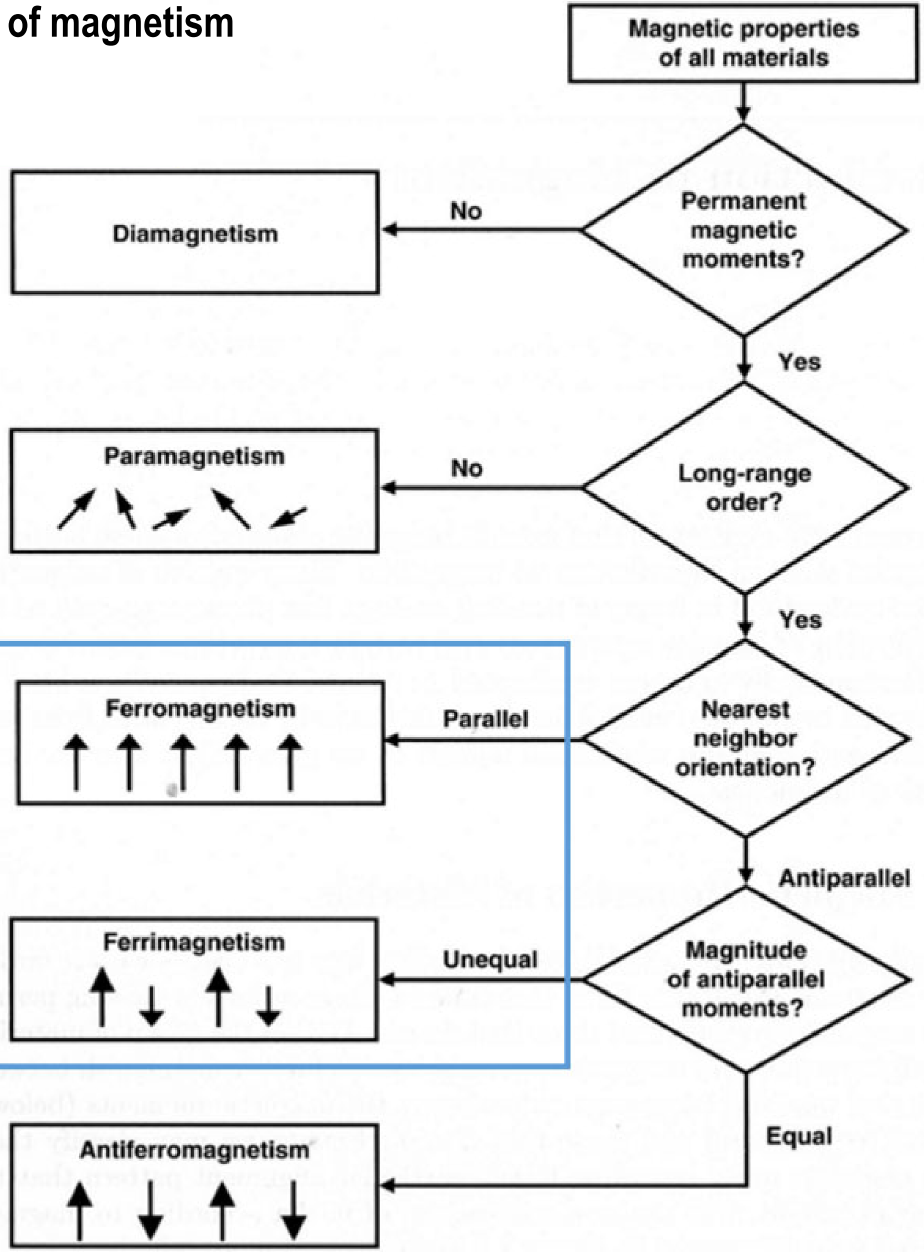
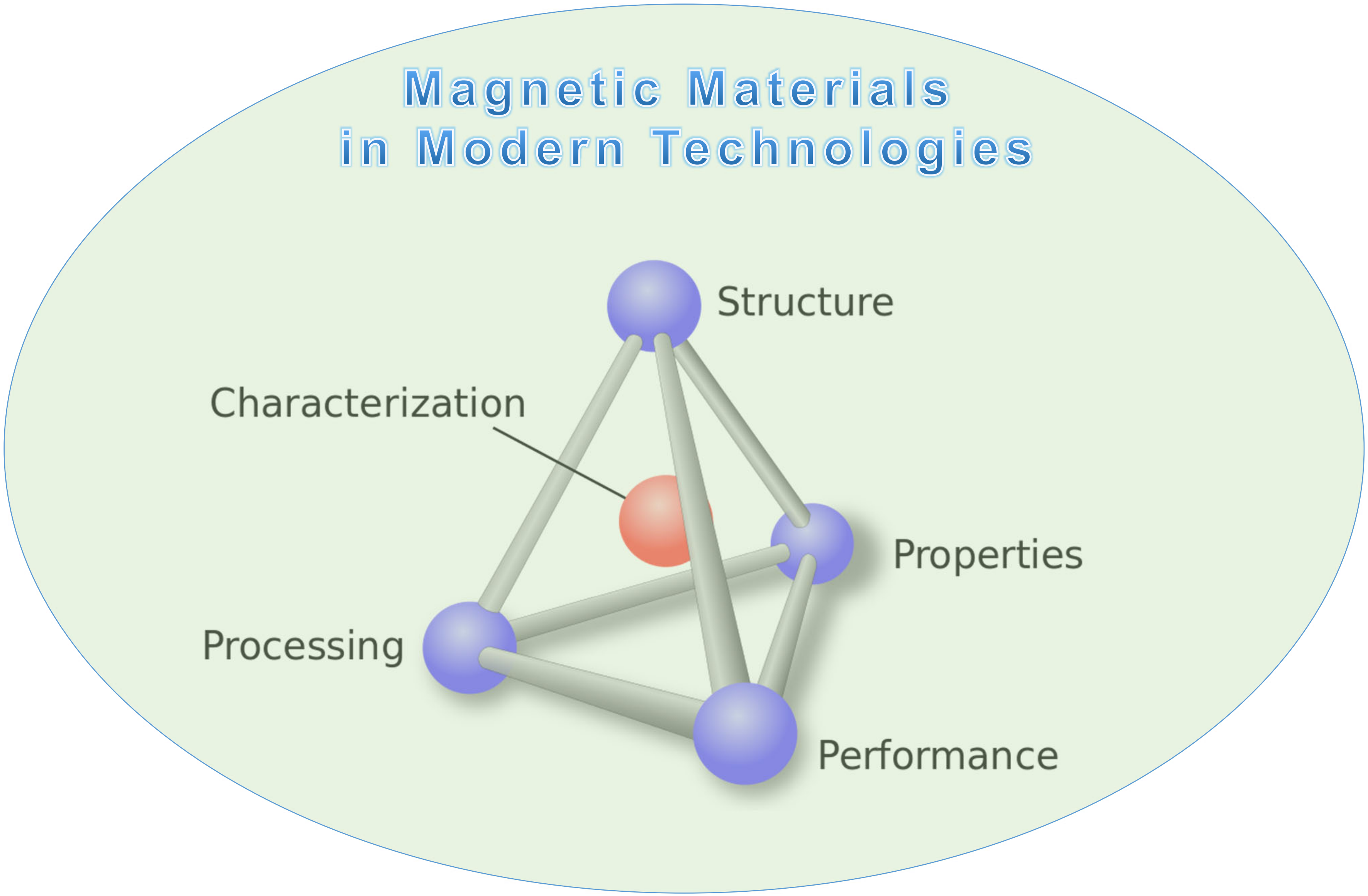


Fig. 1.1. The major classifications of magnetic properties of media. Antiferromagnetism can be viewed as a special case of ferrimagnetism.

Taken from Stancil/Prabhakar

Outline of MSE-432

Aim of MSE-432: Materials Science, not Solid State Physics



Contents

Chapter 1: Exchange interaction: Basic concepts and relation to materials performance
Chapter 2: Hysteretic behavior of magnetization M(H)
Chapter 3: Anisotropy
Chapter 4: (Applications of) Hard magnets
Chapter 5: Magnetic domains and domain walls
Chapter 6: Soft magnets for technical applications
Chapter 7: Magnetoelastic effects – electronic article surveillance
Chapter 8: Magnetic recording
Chapter 9: High-frequency applications (up to about 50 GHz)

Chapters uploaded to MOODLE website before lectures. The main aspects are then addressed and discussed in the following lecture(s) (The corresponding documents might contain more information for the benefit of the interested reader, and thereby stimulate further questions in the lecture).

EPFL

Bibliography

Available at library, eg.
B.D. Cullity, C.D. Graham, Introduction to Magnetic Materials, (2009);
J.D. Coey, Magnetism and Magnetic Materials (2010).
R.C. O'Handley, Modern magnetic materials: principles and applications (2000);
the library provides several copies of the book by
K. Krishnan (Fundamentals and Applications of Magnetic Materials)

Ressources en bibliothèque

- Introduction to Magnetic Materials / Cullity
- Fundamentals and Applications of Magnetic Materials / Krishnan
- Magnetism and Magnetic Materials / Coey
- Modern magnetic materials: principles and applications / O'Handley

Moodle Link

- http://moodle.epfl.ch/course/view.php?id=15219

To monitor the learning outcomes:

We will offer problems and solutions, student's talks (flipped classroom) and own micromagnetic simulations (including data analysis and presentations of simulation results) which will be evaluated during the term