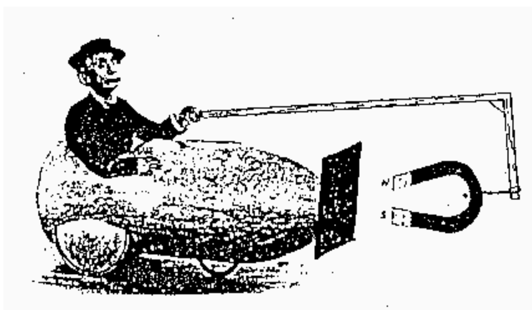
TECHNISCHE UNIVERSITÄT CHEMNITZ

Gastvorlesung „Magnetischen Funktionsmaterialien“ im Rahmen der Vorlesung „Komplexe Materialien“ (Prof. Deibel)

Prof. Dr. Olav Hellwig

7.5.2020

Magnetische Funktionsmaterialien
SS 2020



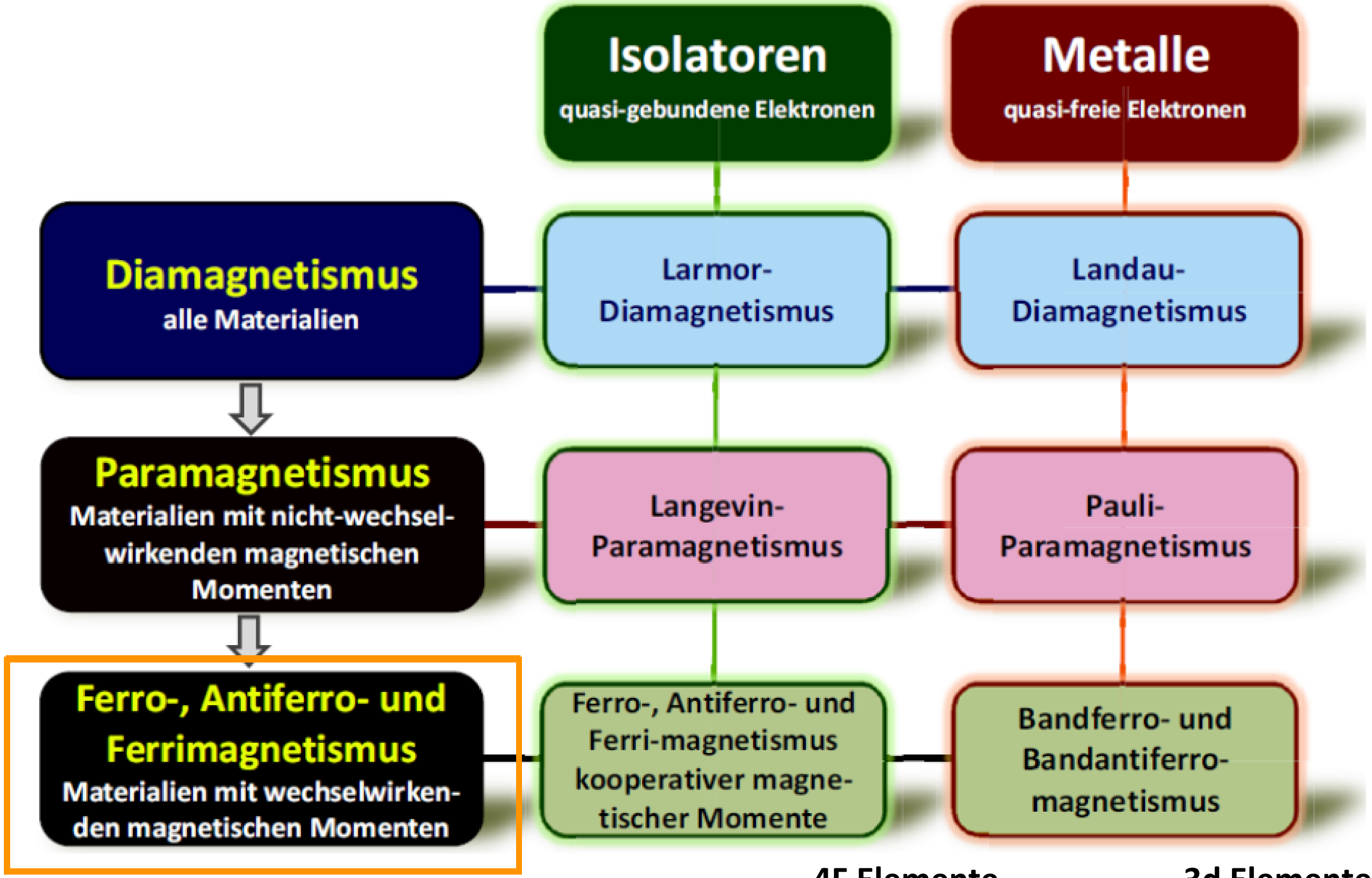
Magnetic Functional Materials • TUC • HZDR

Inhalt

Ferromagnetische (Funktionale) Materialien

- **Einordung und Einleitung**
- **Energien und Energiedichten einer ferromagnetischen Probe**
  - **Austauschwechselwirkung**
  - **Streufeld- oder Demagnetisierungsenergie, Formanisotropie**
  - **Anisotropie (außer Formanisotropie = Demagnetisierungsenergiedichte)**
  - **Zeemann Energie, äußeres Feld**
- **Wechselseitige Konkurrenz verschiedener magnetischer Energieterme**
- **Hysterese-Effekte, Stoner-Wohlfarth Modell,** **Basis für binäre magn. Datenspeicher**
- **Magnetische Funktionsmaterialien zur Datenspeicherung**
  - **Entwicklung der Festplatte: Von magnetischen Mikrosystemen zu Nanosystemen**
  - **GMR (Riesenmagnetwiderstand) und TMR Effekte für empfindlichere Leseköpfe**
  - **Zukünftige Festplattentechnologien**
  - **Neue Effekte in der Nanowelt: Spin tranfer torque in Nanokontakten**
  - **Separation von Ladungs und Spinströmen: Spin orbit torque in Dünnschichtsystemen**
  - **Anwendungen im Magnetic Random Access Memory (MRAM)**
  - **Die Spinwelle als Informationsträger (HZDR-movie)**

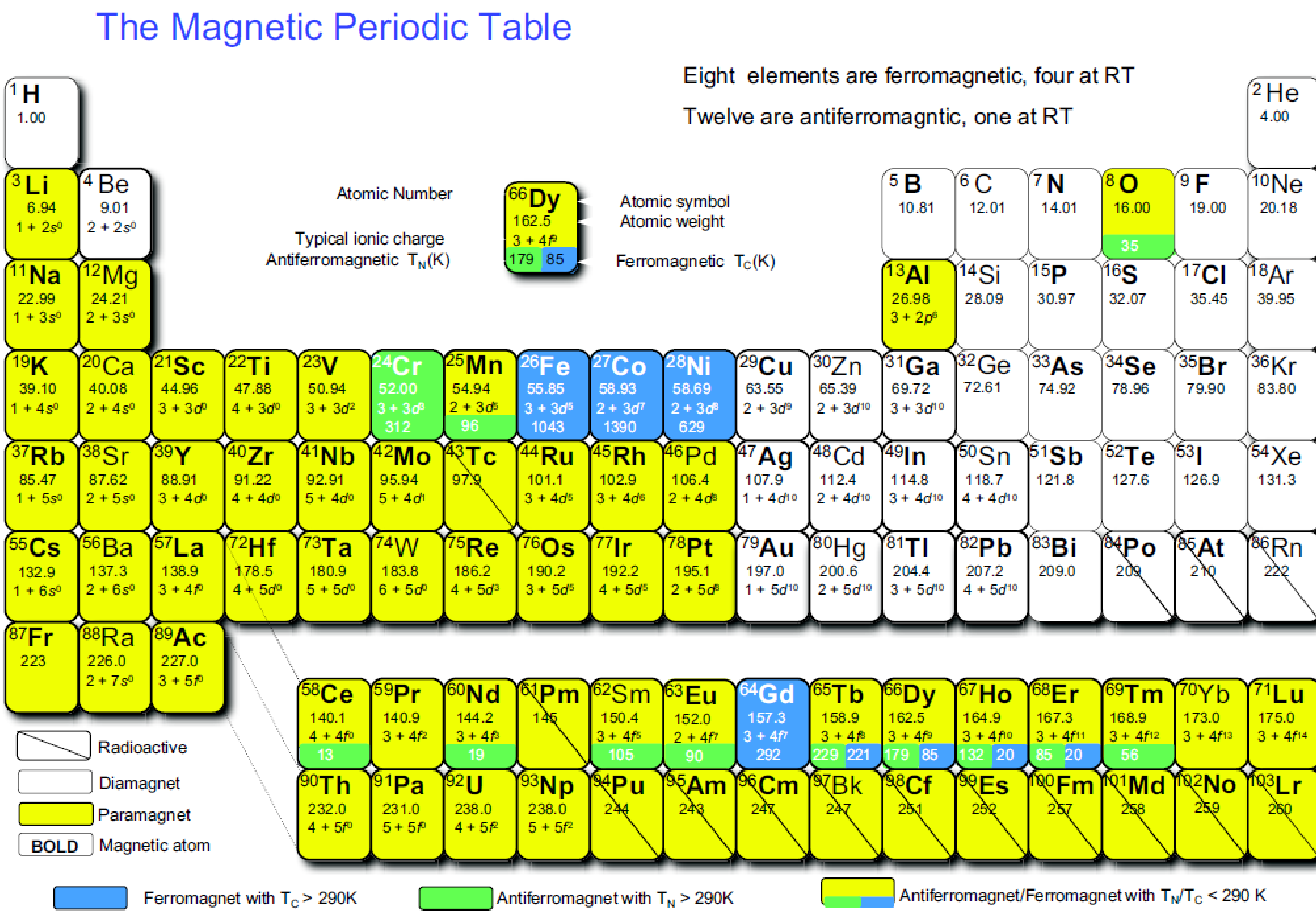
Klassifizierung der mikroskopischen Ursachen unterschiedlicher magnetischer Phänomene



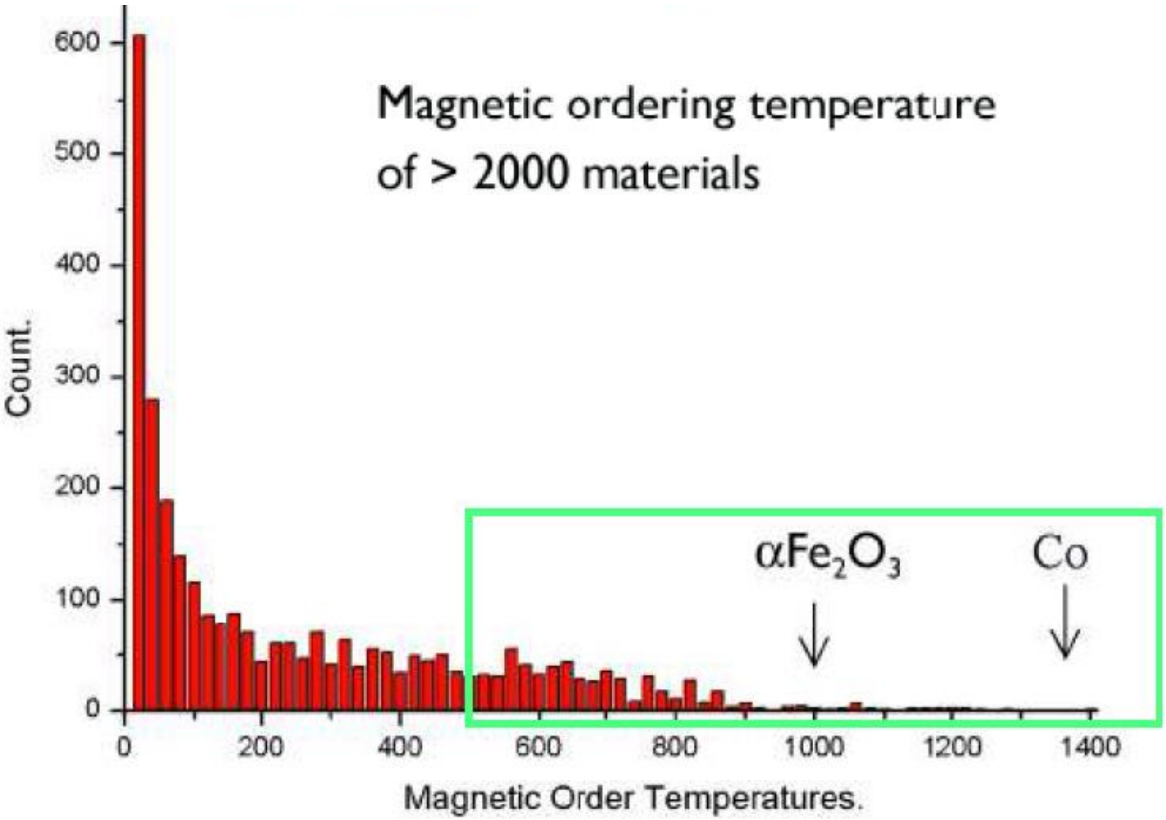
4F Elemente (Gd, Tb, Sm, Nd, …)

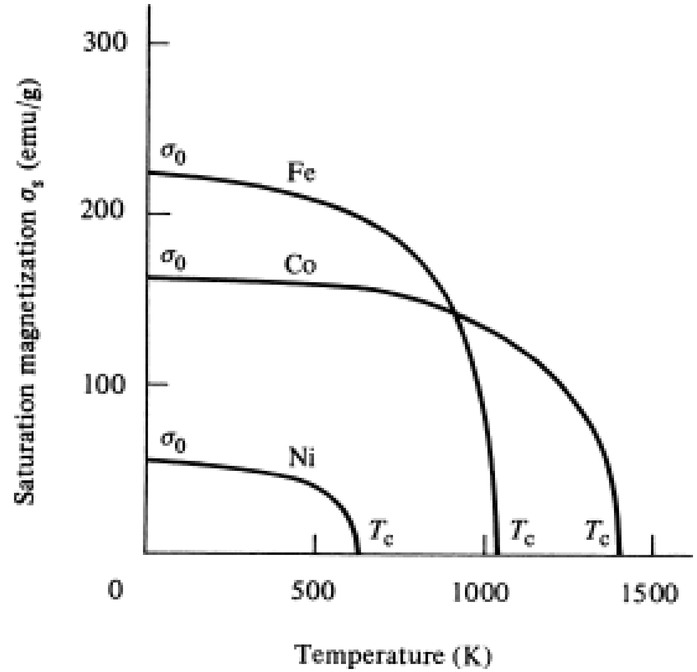
3d Elemente (Fe, Co, Ni)

Magnetic Elements



T_C of magnetic materials





A useful magnetic material needs to be able to operate from -50 C to 120 C.

The Curie temperature needs to be > 500 K

Co has the highest T_C of all magnetic materials

Three ways to approach magnetism

Maxwell's Equations: Phenomenological macroscopic equations

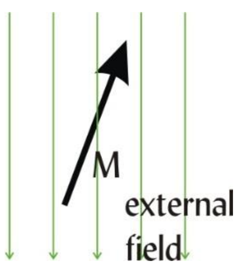
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

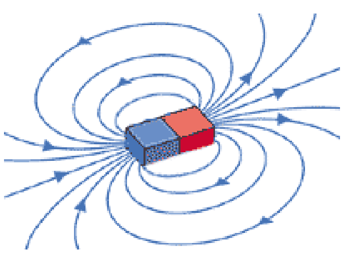
$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J}$$

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

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

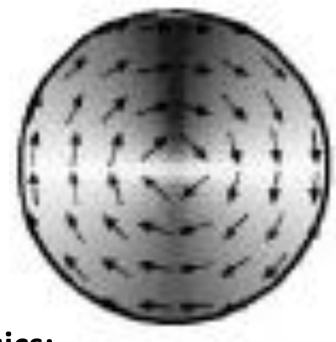
Zeemann





Demagnetization
Stray field
Shape anisotropy

Nanomagnetism:

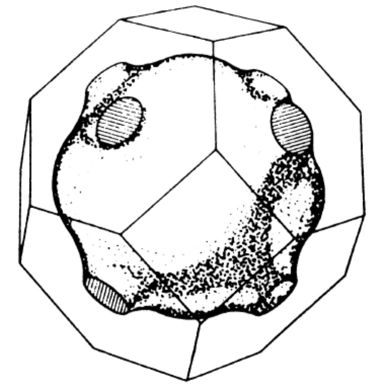


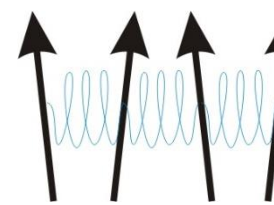
Basics:
- Micromagnetic ground state
- Characteristic length scales
- Exchange length, domain wall width magnetic hardness parameter
- Stoner Wohlfarth theory
- Magnetic field reversal, hysteresis

Applications:
- Hard Disk Drives
- Magnetoresistance
- Spintronics, spin torques
- Magnonics

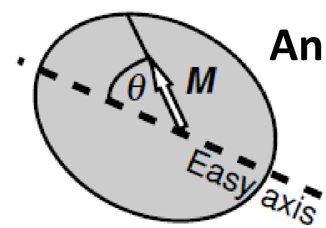
Quantum Mechanics:

$$\nabla^2 \psi + \frac{2m}{\hbar^2}(E - V)\psi = 0$$



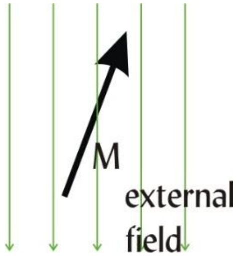


Exchange

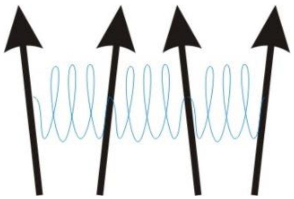


Anisotropy

Micromagnetic Energies determining the magnetic state of a sample



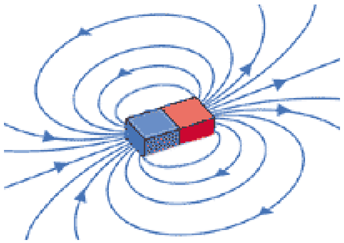
$$E_{external} = -\vec{H} \cdot \vec{M}$$



$$E_{exchange} = A\left(\frac{\partial \theta}{\partial x}\right)^2$$

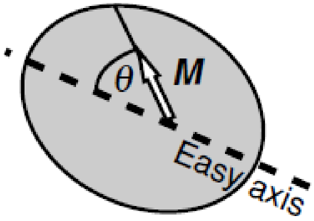
$$E_{total} = \int_{\Omega} (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy}) dV + surface + others$$

$$E_{stray} = -\frac{1}{2} \vec{H}_S \cdot \vec{M}$$

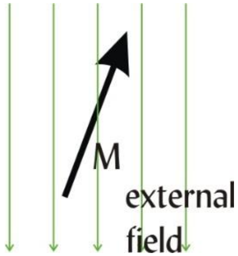


$$E_{anisotropy} = g(\theta)$$

$$= K_U \sin^2 \theta$$



Micromagnetic Energies determining the magnetic state of a sample



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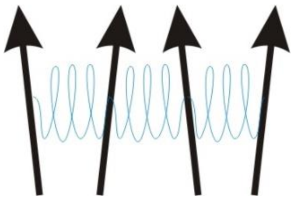

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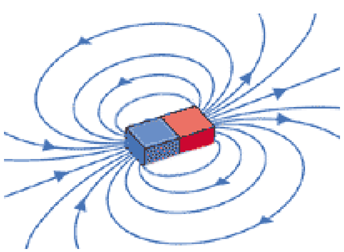
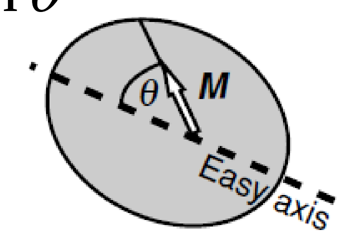


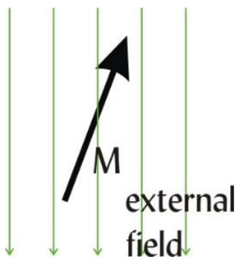
$$E_{anisotropy} = g(\theta)$$

$$= K_U \sin^2\theta$$



How much do these parameters vary across FM materials?

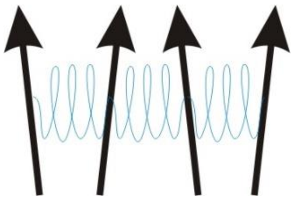
Micromagnetic Energies determining the magnetic state of a sample



$$E_{external} = -\vec{H} \cdot \vec{M}$$

H earth ≈ 50µT=0.00005 T, H electromagnet ≈ 2.5 T
H superconducting ≈ 15 T, H pulsed ≈ 100 T (factor 10^7)

$$E_{exchange} = A\left(\frac{\partial \theta}{\partial x}\right)^2$$

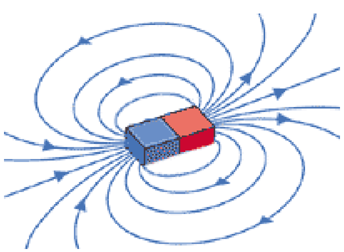


A varies by a factor of less than 10

$$E_{total} = \int_{\Omega} (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy})dV + surface + others$$

M varies by a factor of ~10 (for useful, large M materials)

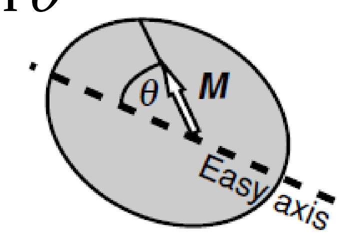
$$E_{stray} = -\frac{1}{2}\vec{H}_S \cdot \vec{M}$$



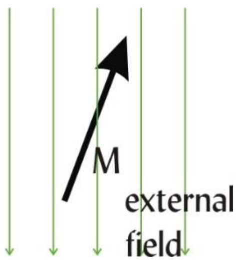
K_u varies by a factor of 100 000 or more …

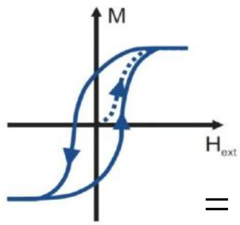
$$E_{anisotropy} = g(\theta)$$

$$= K_U \sin^2\theta$$



Micromagnetic Energies determining the magnetic state of a sample

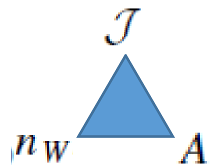




$= - H\,M\cos\theta$

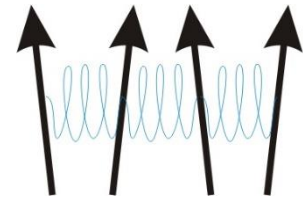
$$E_{external} = -\vec{H}\cdot\vec{M}$$

H earth ≈ 50µT=0.00005 T, H electromagnet ≈ 2.5 T
H superconducting ≈ 15 T, H pulsed ≈ 100 T (factor 10^7)



$$E_{exchange} = A\left(\frac{\partial\theta}{\partial x}\right)^2$$

very short range,
nearest neighbor interactions only



exchange integral

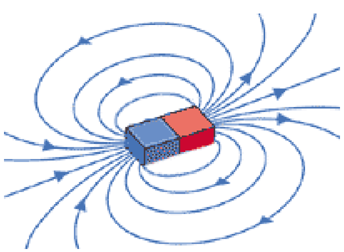
$$\mathcal{H} = -2\sum_{i>j}\mathcal{J}_{ij}\mathbf{S}_i\cdot\mathbf{S}_j$$

***A* varies by a factor of less than 10**

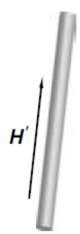
$$E_{total} = \int_\Omega (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy})\,dV + surface + others$$

M varies by a factor of ~10 (for useful, large M materials)

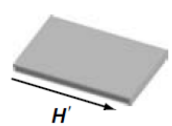
$$E_{stray} = -\frac{1}{2}\vec{H}_S\cdot\vec{M}$$



long range,
everything interacts,
takes most computational
resources in micro-magnetics



$$\begin{pmatrix} ½ & 0 & 0 \\ 0 & ½ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



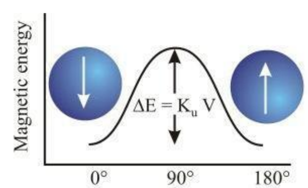
$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

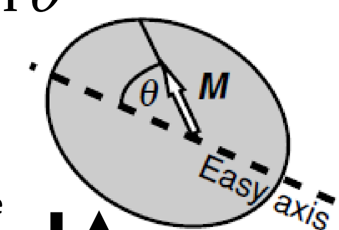
$$E_{magnetostatics} = -\frac{1}{2}\int_{sample}\vec{H}_d\cdot\vec{M}\,dV = -\frac{1}{2}\int_{sample}N\vec{M}^2\,dV = -\frac{1}{2}N\vec{M}^2V$$

K_u varies by a factor of 100 000 or more …

$$E_{anisotropy} = g(\theta)$$

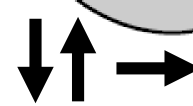
$$= K_U\sin^2\theta$$





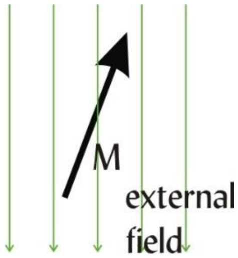
directionally varying energy,
source is often the crystal structure

simplest case = uni-axial



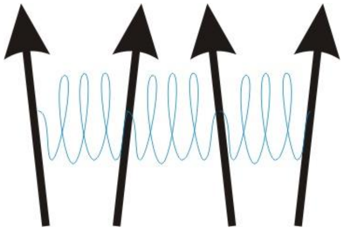
Closer look at Anisotropy energy (biggest knob)
(Exchange and stray field energy should be known ….)

Energies determining the magnetic state of a sample



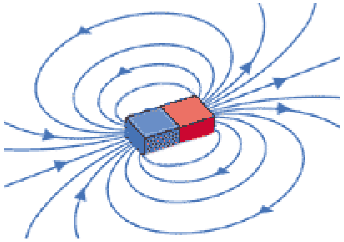
$$E_{external} = -\vec{H} \cdot \vec{M}$$

$$E_{exchange} = A\left(\frac{\partial \theta}{\partial x}\right)^2$$



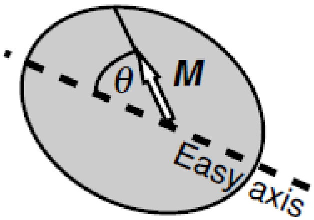
$$E_{total} = \int_{\Omega} (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy}) dV + surface + others$$

$$E_{stray} = -\frac{1}{2}\vec{H}_S \cdot \vec{M}$$



$$E_{anisotropy} = g(\theta)$$

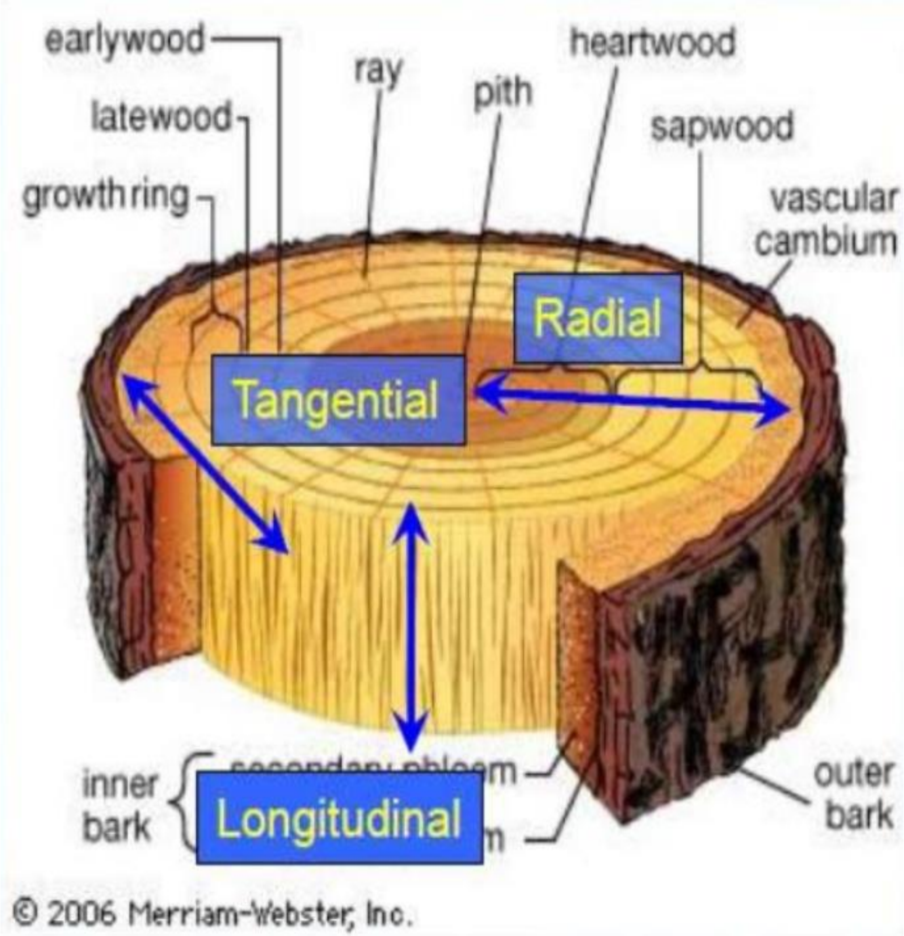
$$= K_U \sin^2\theta$$

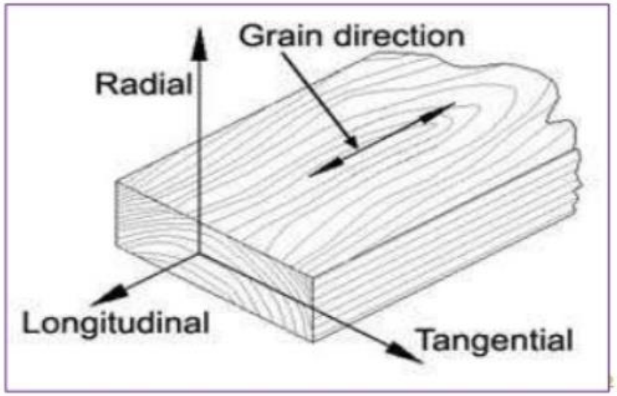


What popular anisotropic materials do you know? → wood

Anisotropy of wood

The dimensional changes in wood are unequal along the three structural directions (longitudinal, tangential and radial).

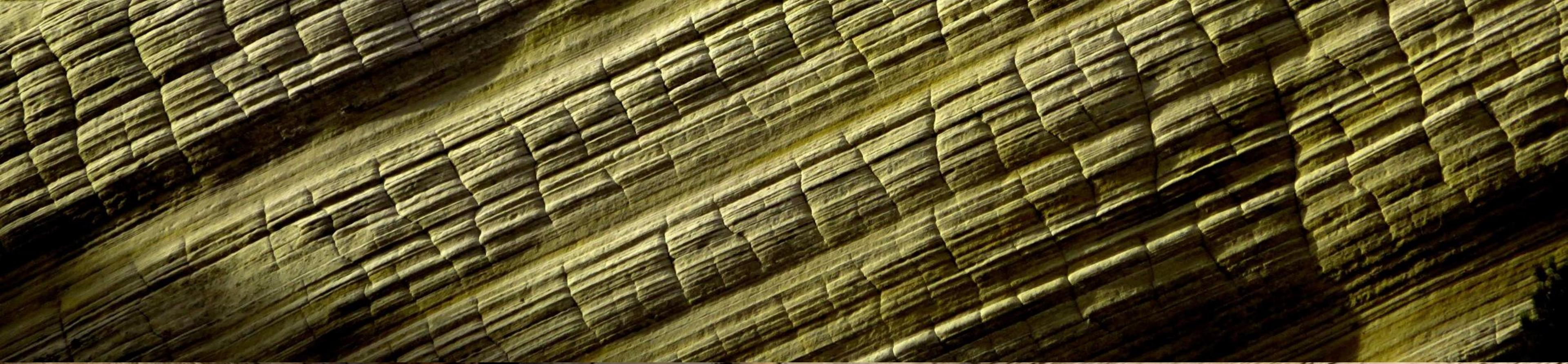




Other examples:

- snow flakes
- icicles
- thin films
- nanotubes
- gaphene
- Crystals in general

➔ Magnetic anisotropy …

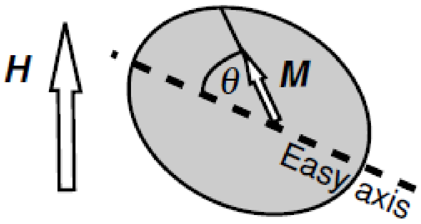


Magnetic Anisotropy

The direction of magnetization ***M*(*r*)** in a macoscopic ferromagnetic domain lies along one or several easy axes.

$$E_a = K_1 \sin^2\theta$$

(uniaxial anisotropy, leading term, simplest case)



Magnetization is not necessarily parallel to applied field, unless *H* is applied in an easy direction.

Symmetry:

- Uniaxial (magnetic recording)
- Cubic (Fe, Ni)
- Hexagonal (Co)
- Teragonal (FePt)
- more complex symmetries

Types of magnetic anisotropy:

- Magneto-crystalline
- Shape
- Surface, interface (➔ MLs)
- Magneto-elastic, strain
- other …

will see this later in the Stoner-Wohlfarth model …

Anisotropy limits the coercivity available in hard magnets
Anisotropy leads to unwanted coercivity in soft magnets

Magneto-crystalline anisotropy energy

Experimental observation: single-crystalline magnetic materials have magnetic “easy and “hard” axes

Physical origin:

- spin-orbit coupling <u>and</u>
- low symmetry crystal field, resulting in asymmetric charge distribution

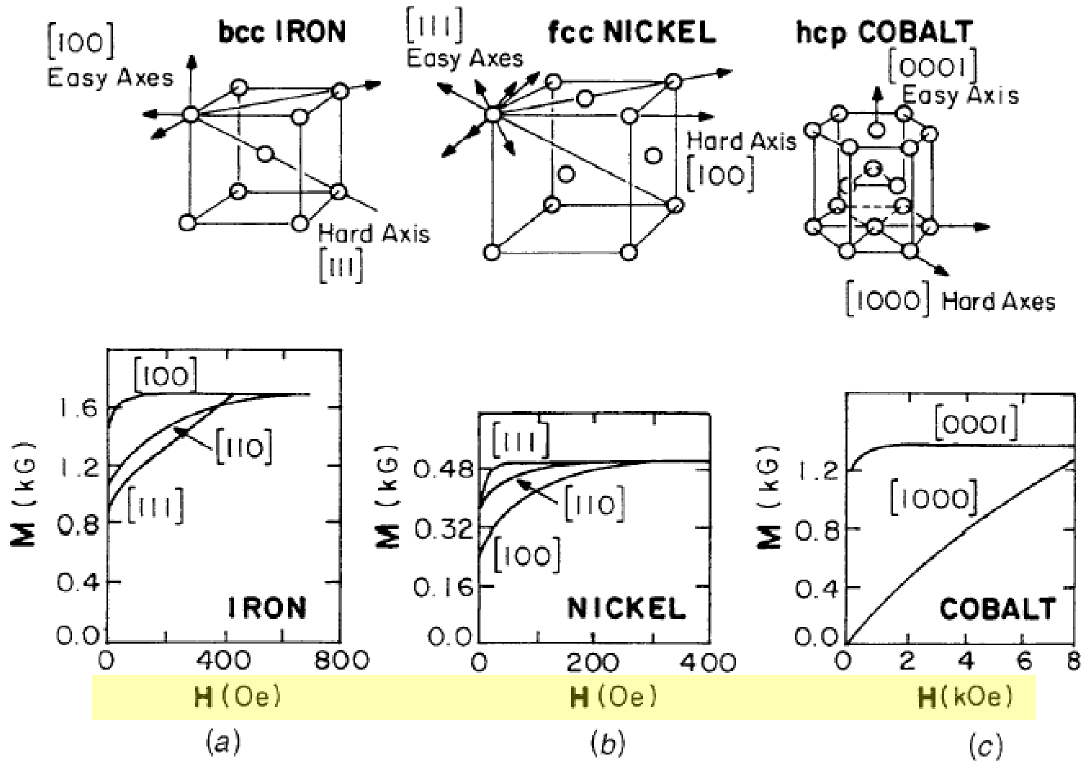
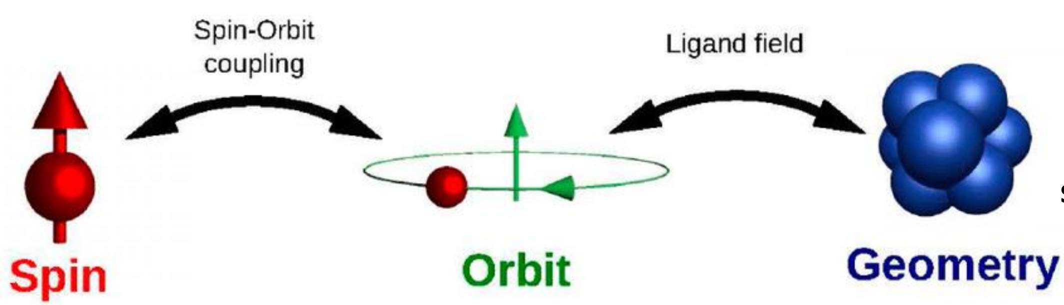


Figure 6.1 Crystal structure showing easy and hard magnetization directions for Fe(a), Ni(b), and Co(c), above. Respective magnetization curves, below.

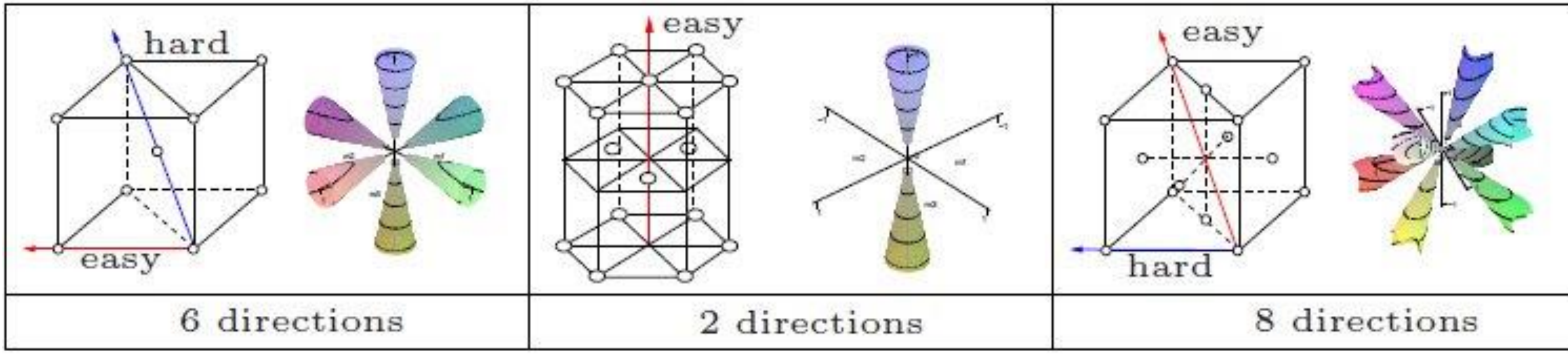


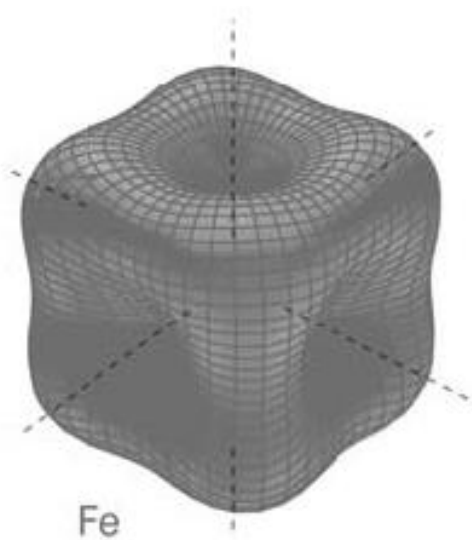
Anisotropy reflects the crystal symmetry

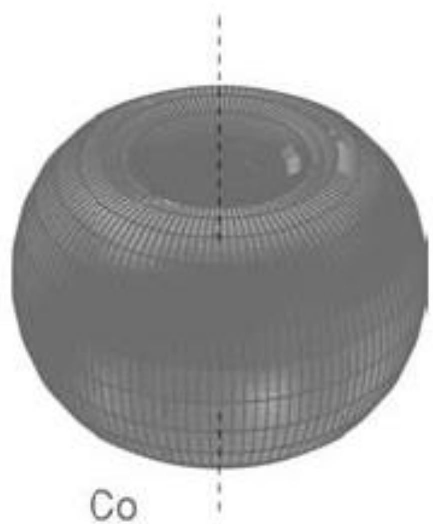
 Examples: Fe, Co, Ni

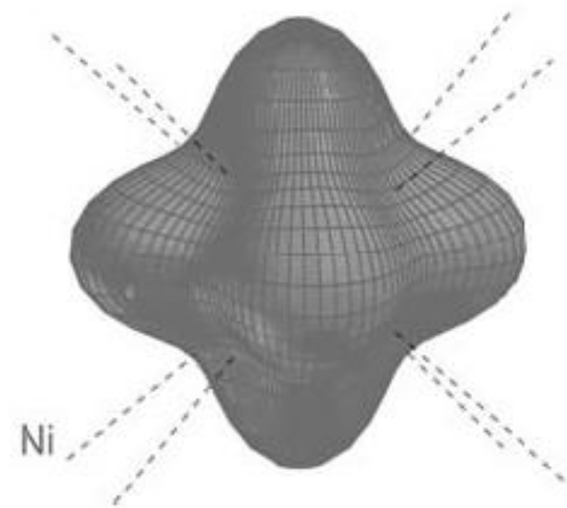
Anisotropy

Fe bulk **Co bulk** **Ni bulk**







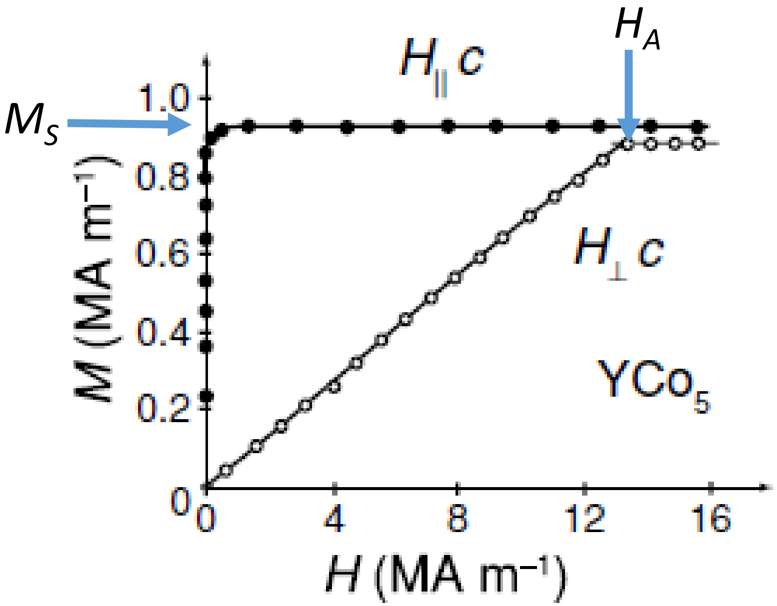


Magneto-crystalline anisotropy energy

To move M from one direction into another direction an external magnetic field B_0 has to do work against the magneto-crystalline anisotropy:

$$E = \int \vec{B}_0 \, \mathrm{d}\vec{M}$$

The magnetic anisotropy energy is defined as the difference of the free energy between different directions of M at constant temperature:



(cgs)

$$K_U = \frac{1}{2} H_A M_S$$

for uniform magnetization
(single domain objects)

(SI)

$$K_U = \frac{\mu_0}{2} H_A M_S$$

The magnetic easy axis is usually used as a reference direction.

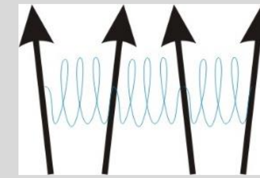
Magneto-crystalline anisotropy energy

(across all magnetic materials)

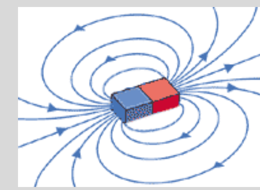
Table 7.1. Domain wall parameters for some ferromagnetic materials

	M_s stray/demag $(\mathrm{MA\ m^{-1}})$	A exchange $(\mathrm{pJ\ m^{-1}})$	K_1 anisotropy $(\mathrm{kJ\ m^{-3}})$
$Ni_{80}Fe_{20}$	0.84	10	0.15
Fe	1.71	21	48
Co	1.44	31	410
CoPt	0.81	10	4900
$Nd_2Fe_{14}B$	1.28	8	4900
$SmCo_5$	0.86	12	17 200
CrO_2	0.39	4	25
Fe_3O_4	0.48	7	−13
$BaFe_{12}O_{19}$	0.38	6	330
	magnetization	exchange stiffness	anisotropy (energy density)
Variation across materials	less than 5	less than 10	up to 100 000

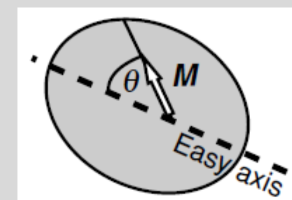
$$E_{exchange} = A\left(\frac{\partial\theta}{\partial x}\right)^2$$



$$E_{stray} = -\frac{1}{2}\vec{H}_S \cdot \vec{M}$$



$$E_{anisotropy} = g(\theta) = K_U \sin^2\theta$$



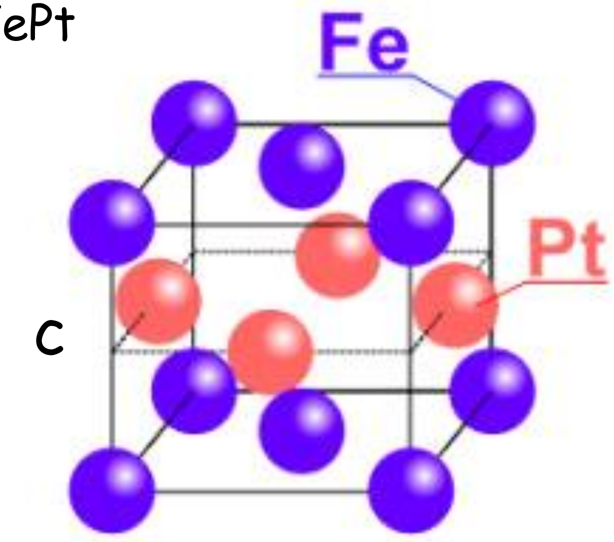
$$E_{magnetostatics} = -\frac{1}{2}\int_{sample} \vec{H}_d \cdot \vec{M} dV = -\frac{1}{2}\int_{sample} N\vec{M}^2 dV = -\frac{1}{2} N\vec{M}^2 V$$

largest variations in anisotropy

Magneto-crystalline anisotropy energy

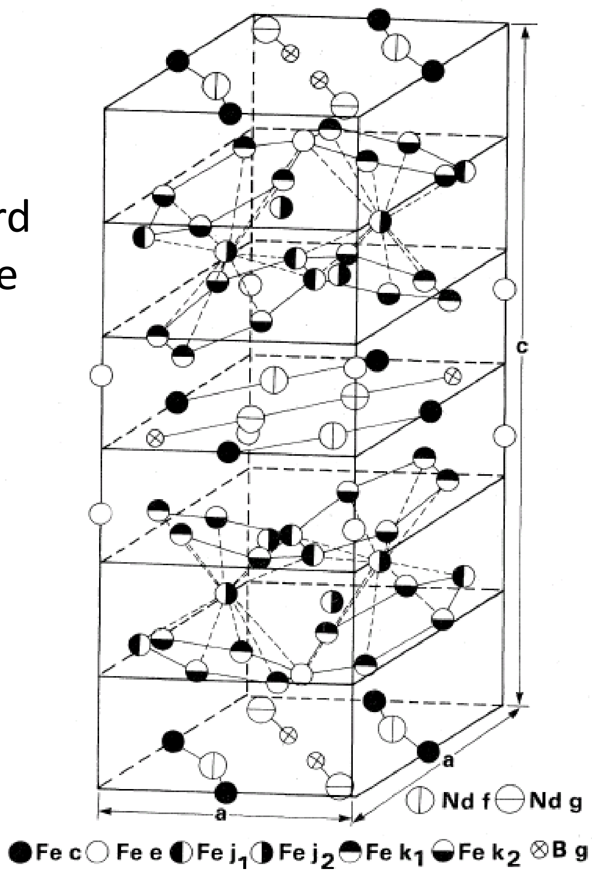
Simple hard magnetic structure

FePt



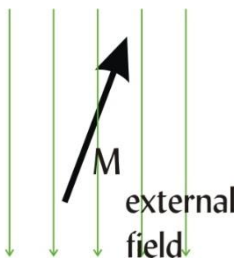
$Nd_2Fe_{14}B$

More complex hard magnetic structure



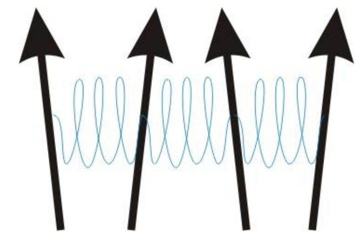
Alloy system	Material	K_1 (10^7erg/cm^3)	M_S (emu/cm^3)	H_K (kOe)	T_C (K)
Co-alloys	CoPtCr	0.20	298	13.7	—
$L1_0$ phases	FePt	6.6–10	1140	116	750
Rare-earth	$Fe_{14}Nd_2B$	4.6	1270	73	585
Transition metals	$SmCo_5$	11–20	910	240–400	1000

Energies determining the magnetic state of a sample



$$E_{external} = -\vec{H} \cdot \vec{M}$$

$$E_{exchange} = A\left(\frac{\partial \theta}{\partial x}\right)^2$$

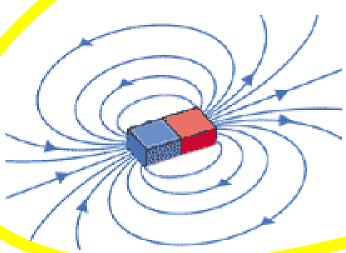


$$E_{total} = \int_{\Omega} (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy})dV + surface + others$$

originates from macroscopic dipole-dipole interaction

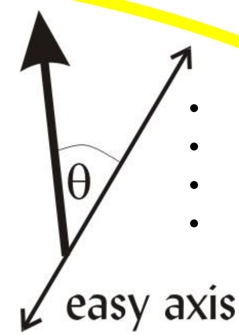
originates from spin-orbit interaction in conjunction with the crystal field, i.e. from microscopic (electronic and atomic) dipole-dipole interactions

$$E_{stray} = -\frac{1}{2}\vec{H}_S \cdot \vec{M}$$



$$E_{anisotropy} = g(\theta)$$

$$= K_U \sin^2\theta$$



- Magneto-crystalline
- Magneto-elastic
- Surface (mix: ex+intr)
- etc.

demag energy
stray field energy
➔ (sample) shape anisotropy

extrinsic anisotropy

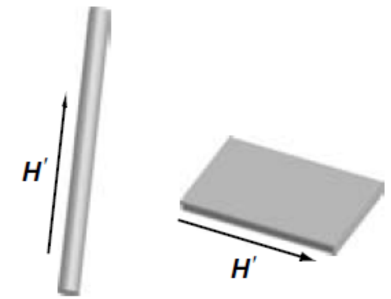
Crystalline and induced anisotropies

Intrinsic/mixed anisotropy

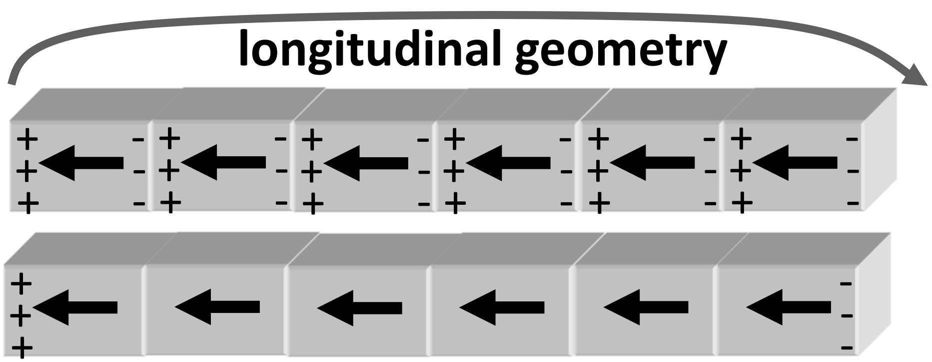
Magnetic hardness parameter or quality factor

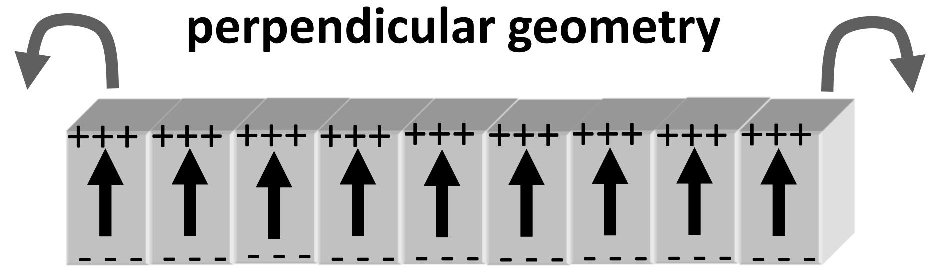
The magnetic hardness parameter is the dimensionless ratio of anisotropy to stray field (or dipole) energy:

$$\kappa = \sqrt{|K_1| / \mu_0 M_s^2}$$



It should be greater than 1 for a permanent magnet and much less than 1 for a good temporary magnet.





Alternative definition: magnetic Q-factor

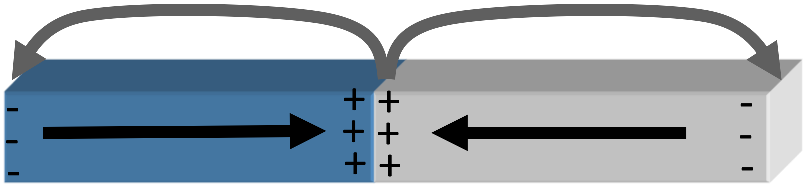
shape anisotropy of a thin film

Magnetization of thin films. $Q = -K_u/K_d$ where $K_d = (1/2)\mu_0 M_s^2$

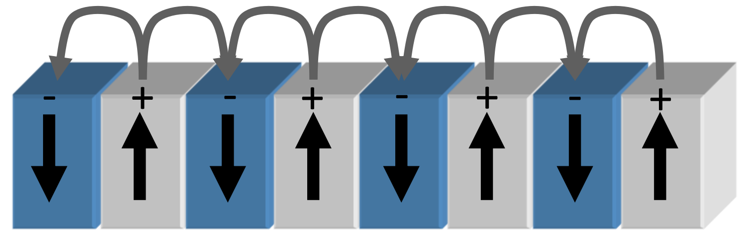
If Q>1 then the anisotropy K_1 is large enough to pull the magnetization out-of-the-plane in a thin fim geometry

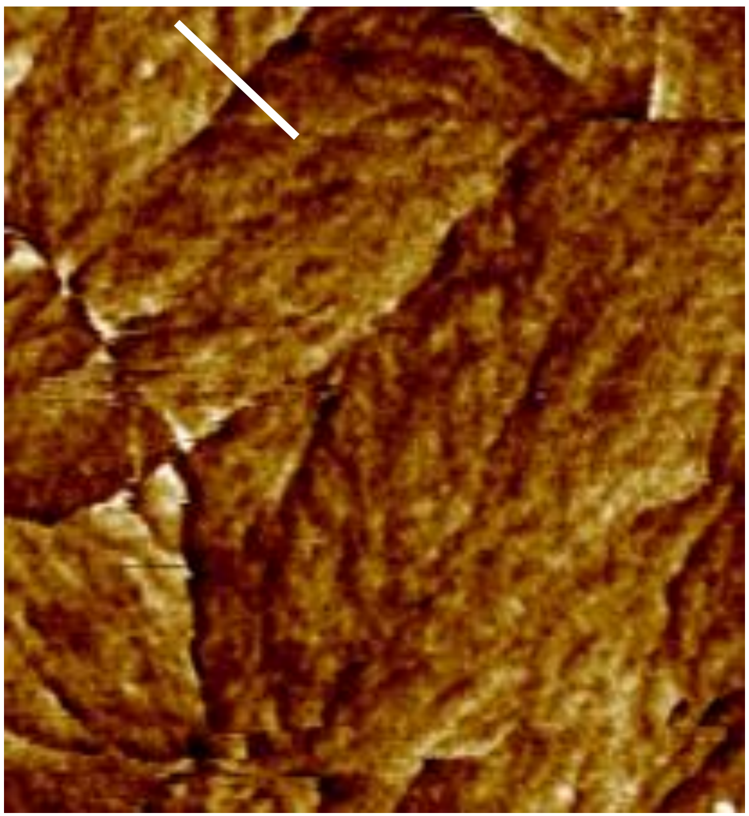
Mostly used: demagnetization factor of a thin film

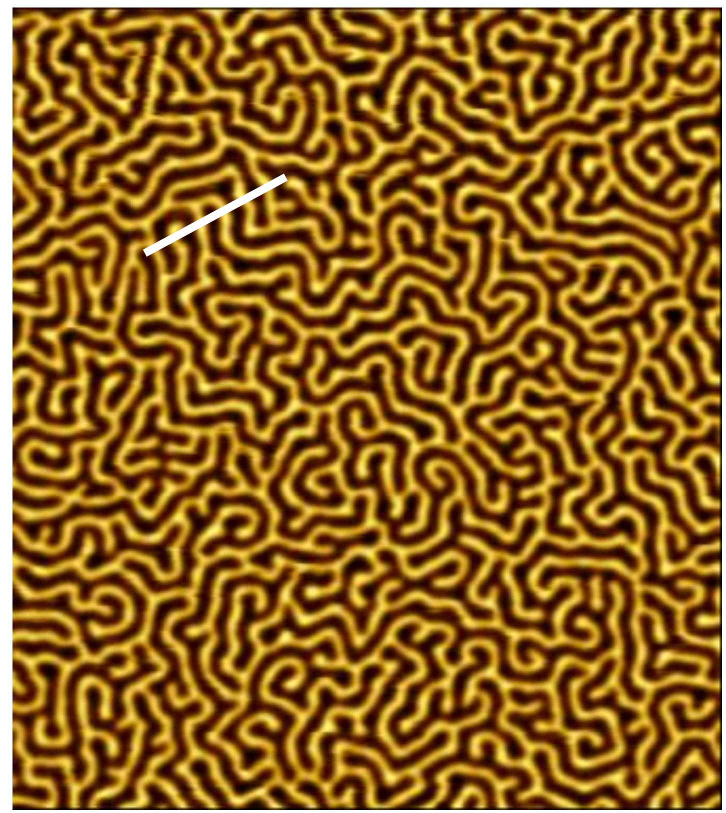
longitudinal geometry



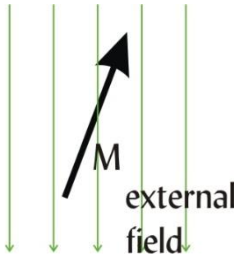
perpendicular geometry





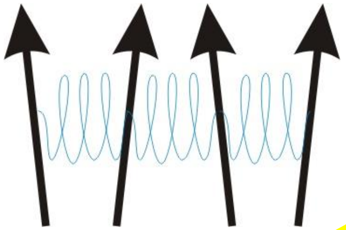


Energies determining the magnetic state of a sample



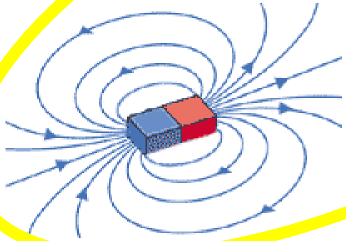
$$E_{external} = -\vec{H} \cdot \vec{M}$$

$$E_{exchange} = A\left(\frac{\partial\theta}{\partial x}\right)^2$$



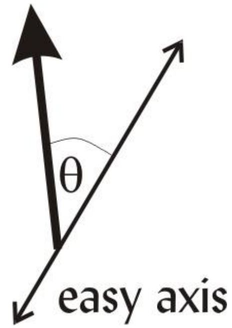
$$E_{total} = \int_{\Omega} (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy})dV + surface + others$$

$$E_{stray} = -\frac{1}{2}\vec{H}_S \cdot \vec{M}$$



$$E_{anisotropy} = g(\theta)$$

$$= K_U \sin^2\theta$$



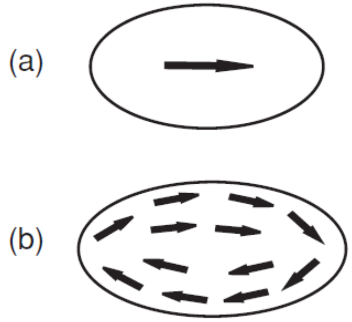
$$E_{magnetostatics} = -\frac{1}{2}\int_{sample} \vec{H}_d \cdot \vec{M} dV = -\frac{1}{2}\int_{sample} N\vec{M}^2 dV = -\frac{1}{2} N\vec{M}^2 V$$

Exchange length = measure for relative strength

Exchange length

Exchange length is the distance over which the magnetization is expected to be able to respond.

Competition between exchange energy and stray field energy is characterized by the exchange length



Stable ferromagnetic configurations in a soft spheroidal particle:
(a) without and (b) with the effect of the demagnetizing field.

Film shape anisotropy energy $E_{shape\ (or\ stray)} = 1/2\mu_0 M^2$

$$l \sim \frac{\partial x}{\partial \theta}$$ length to tilt Θ against shape anisotropy

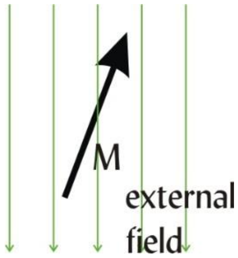
$$E_{exchange} = A\left(\frac{\partial \theta}{\partial x}\right)^2 = \frac{A}{l^2} = E_{stray} = 1/2\mu_0 M^2$$

$$l_{ex} = \sqrt{\frac{A}{\mu_0 M_s^2}}$$

factor ½ is sometimes skipped

	l_{ex} (nm)
$Ni_{80}Fe_{20}$	3.4
Fe	2.4
Co	3.4
CoPt	3.5
$Nd_2Fe_{14}B$	1.9
$SmCo_5$	3.6
CrO_2	4.4
Fe_3O_4	4.9
$BaFe_{12}O_{19}$	5.8

Energies determining the magnetic state of a sample



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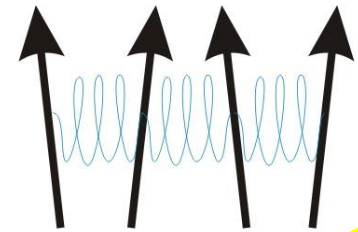
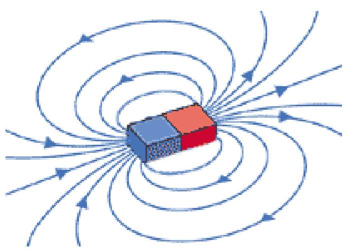


$$E_{total} = \int_{\Omega} (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy})dV + surface + others$$

$$E_{stray} = -\frac{1}{2}\vec{H}_S \cdot \vec{M}$$



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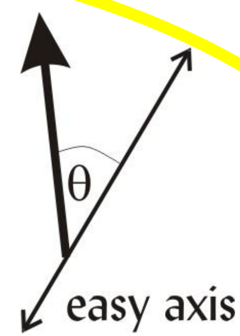
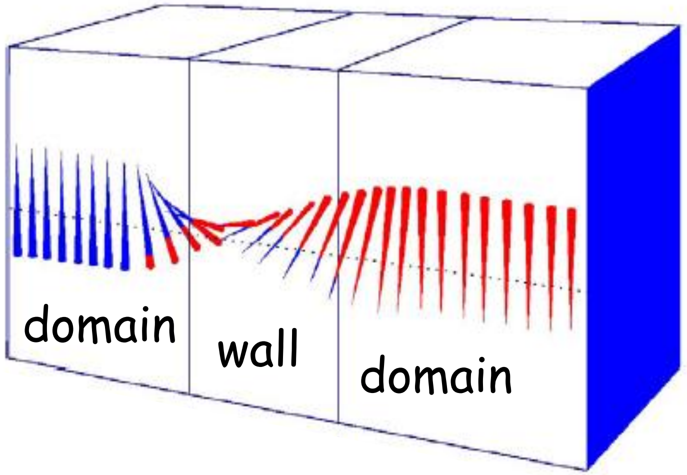


Domain wall width and energy

walls $\sigma_w = exchange + anisotropy$

$$= \int_{-\infty}^{\infty} A\left(\frac{\partial\theta}{\partial x}\right)^2 + K\sin^2(\theta)dx$$

How do we define where the domain wall ends?



Minimize the energy (exchange+anisotropy),
No demag energy included in the domain wall

$$\theta(x) = \arctan\left[\sinh(\pi x/\delta_w)\right] + \pi/2$$

$$\sigma_w = 4\sqrt{AK} \quad and \quad \delta_w = \pi\sqrt{A/K}$$

domain wall energy density — domain wall width

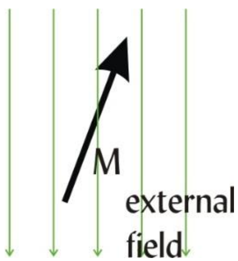
anisotropy K (energy density) up to 100 000

exchange stiffness A less than 10

The domain wall does not have a precisely defined width, since the direction of magnetization only approaches the easy axis asymptotically. Anisotropy of some sort is necessary for finite domain wall width.

Stray field or demagnetization energy triggers domain formation ➔ domain wall formation
Exchange wants infinitely thick DW, anisotropy wants infinitely thin DW ➔ compromise

Energies determining the magnetic state of a sample



$$E_{external} = -\vec{H} \cdot \vec{M}$$

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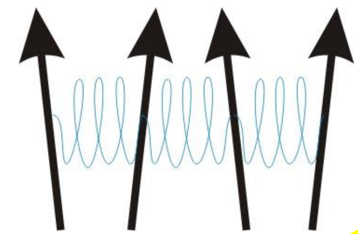
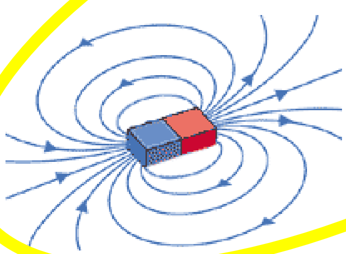


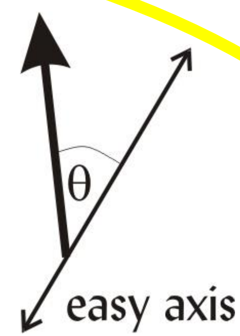
$$E_{total} = \int_{\Omega} (E_{external} + E_{stray} + E_{exchange} + E_{anisotropy})dV + surface + others$$

$$E_{stray} = -\frac{1}{2}\vec{H}_S \cdot \vec{M}$$



$$E_{anisotropy} = g(\theta)$$

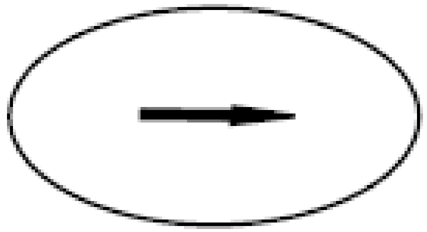
$$= K_U \sin^2\theta$$



Energy competition and micromagnetic states …

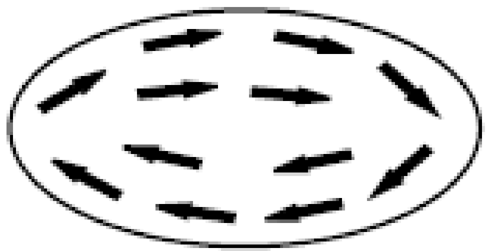
exchange dominates

(a)



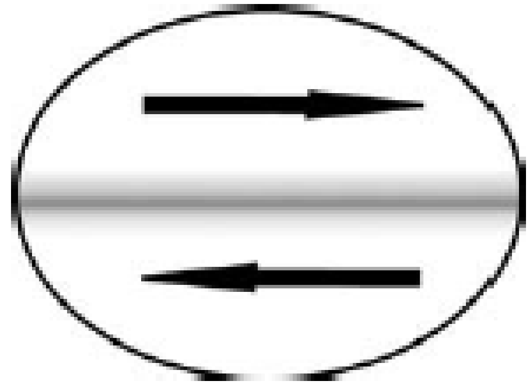
stray fields start to compete

(b)



Stable ferromagnetic configurations in a soft spheroidal particle: (a) without and (b) with the effect of the demagnetizing field.

stray fields and anisotropy start to compete with exchange



A ferromagnetic domain state resulting from the interplay of uniaxial anisotropy and demagnetizing field. The domain wall is the shaded region.

Magneto-crystalline anisotropy energy

(across all magnetic materials)

Table 7.1. Domain wall parameters for some ferromagnetic materials

	M_s stray/demag ($MA\ m^{-1}$)	A exchange ($pJ\ m^{-1}$)	K_1 anisotropy ($kJ\ m^{-3}$)	δ_w (nm)	γ_w ($mJ\ m^{-2}$)	κ	l_{ex} (nm)
$Ni_{80}Fe_{20}$	0.84	10	0.15	2000	0.01	0.01	3.4
Fe	1.71	21	48	64	4.1	0.12	2.4
Co	1.44	31	410	24	14.3	0.45	3.4
CoPt	0.81	10	4900	4.5	28.0	2.47	3.5
$Nd_2Fe_{14}B$	1.28	8	4900	3.9	25	1.54	1.9
$SmCo_5$	0.86	12	17 200	2.6	57.5	4.30	3.6
CrO_2	0.39	4	25	44.4	1.1	0.36	4.4
Fe_3O_4	0.48	7	−13	72.8	1.2	0.21	4.9
$BaFe_{12}O_{19}$	0.38	6	330	13.6	5.6	1.35	5.8
	magnetization	exchange stiffness	anisotropy (energy density)	domain wall width	domain wall energy	hardness parameter	exchange length
Variation across materials	less than 5	less than 10	up to 100 000	up to 1000	up to 6000	up to 500	~ factor 3

largest variations in anisotropy

Magneto-crystalline anisotropy energy

(across all magnetic materials)

Table 7.1. Domain wall parameters for some ferromagnetic materials

	M_s stray/demag (MA m^{-1})	A exchange (pJ m^{-1})	K_1 anisotropy (kJ m^{-3})	δ_w exchange vs anisotropy (nm)	γ_w (mJ m^{-2})	κ anisotropy vs stray fields	l_{ex} exchange vs stray (nm)
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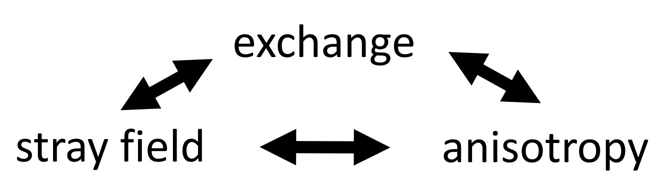
	magnetization	exchange stiffness	anisotropy (energy density)	domain wall width	domain wall energy	hardness parameter	exchange length
Variation across materials	less than 5	less than 10	up to 100 000	up to 1000	up to 6000	up to 500	~ factor 3
				$\delta_w = \pi\sqrt{A/K}$	$\gamma_w = 4\sqrt{AK}$	$\kappa = \sqrt{\lvert K_1\rvert / \mu_0 M_s^2}$	$l \approx \sqrt{A}/M$

factor 1000!

largest variations in anisotropy

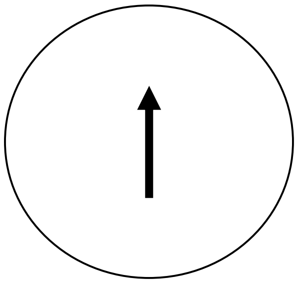
stray field energy =
shape anisotropy energy



Single domain particle size

Assume a magnetic sphere of radius R, moment M, uniaxial anisotropy K and exchange parameter A.
What is the critical radius to form a single domain. For simplicity we will assume the magneto-static energy is zero for the domain state.

Single domain



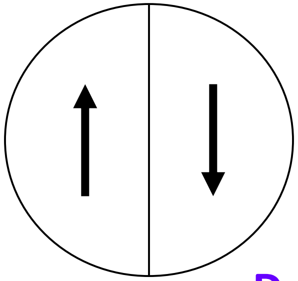
- H_K does not allow for any tilt
- only demag energy

Demag energy

$$E = \frac{1}{2} H_d M V = \frac{1}{2} \frac{4\pi}{3} M^2 \frac{4\pi}{3} R^3 = \frac{8\pi^2}{9} M^2 R^3$$

we used $H_d = 4\pi N M = \frac{4\pi}{3} M, N_{sphere} = \frac{1}{3}$

Domain formation



- H_K does not allow for any tilt
- only domain wall energy

Domain wall energy

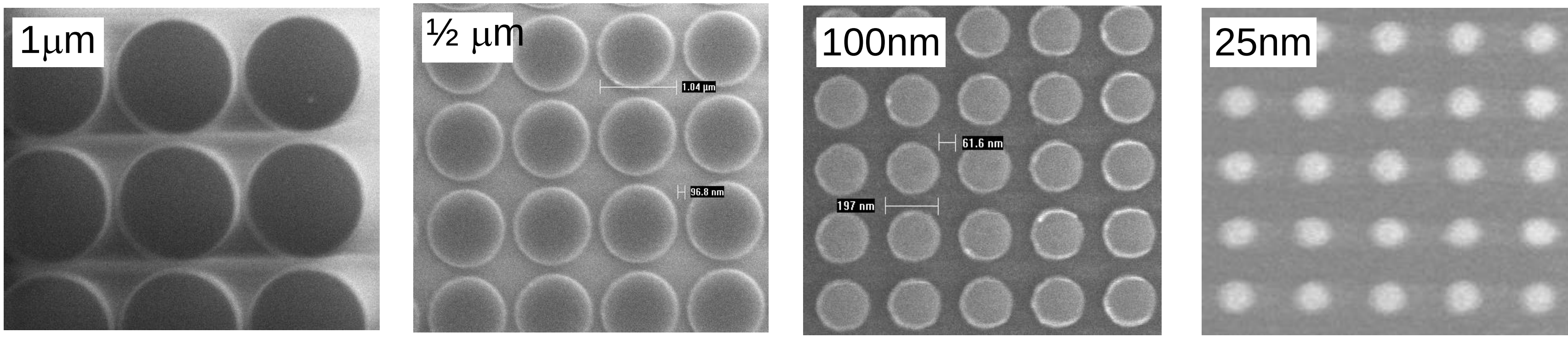
$$E \approx 4\sqrt{AK}\pi R^2$$

These energies are equal ➔ $R = \frac{9\sqrt{AK}}{2\pi M^2}$

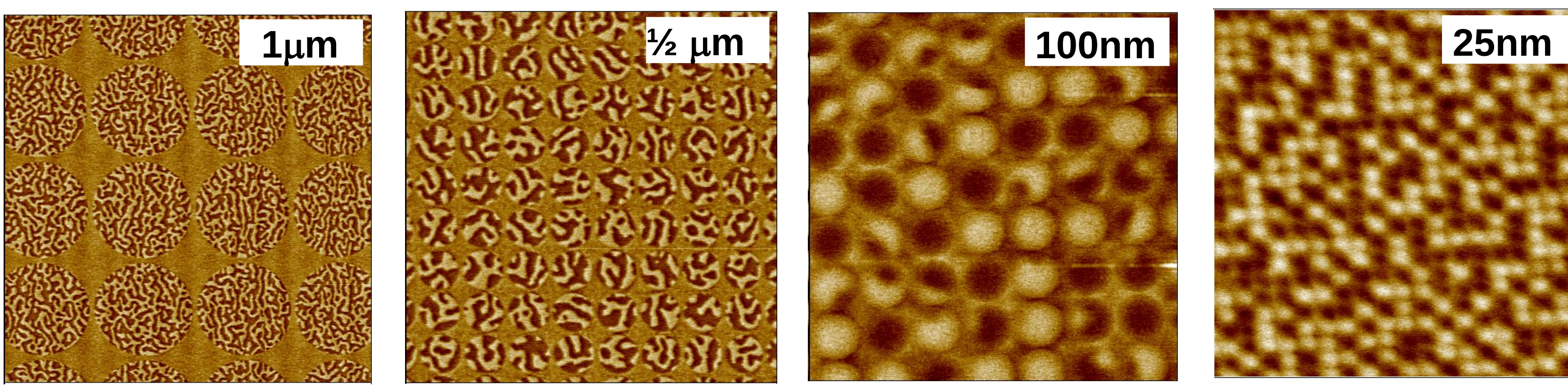
Use typical parameters for magnetic recording media,
e.g. A = 10^{-6} erg/cm = 10^{-11} J/m, M=1000 emu/cc, K=5×10^{6} ergs/cc gives R=32 nm

Single domain experiments

- Studied islands with variable sizes, radius ranging from 5μm – 50 nm

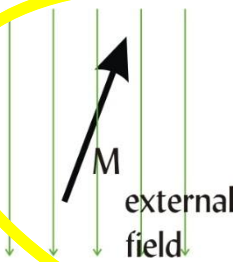


- Single domain behavior is found in islands with a radius ~50nm.



MFM images of islands in demagnetized states

Energies determining the magnetic state of a sample



$$E_{external} = -\vec{H} \cdot \vec{M}$$

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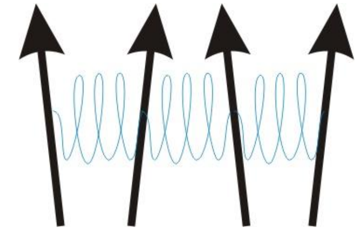

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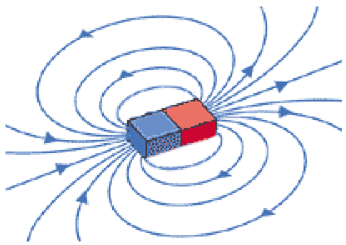
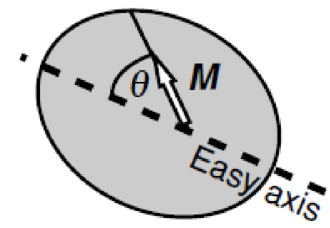


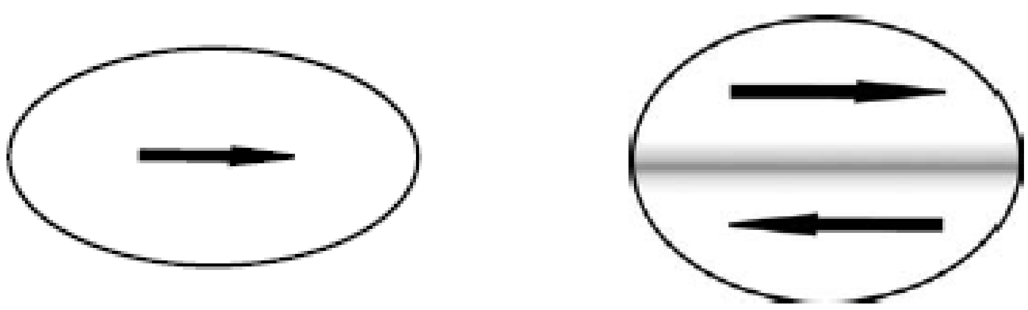
$$E_{anisotropy} = g(\theta)$$

$$= K_U \sin^2\theta$$



Reversal mechanisms

- Assume a small particle, such that the magnetism stays uniform, i.e. the particle is too small to support a domain wall, i.e. particle is smaller or of similar length scale than the typical domain wall width …
- Treat the magnetization as a single spin known as a macro-spin, this type of model was used in a previous lecture, when we talked about micro-magnetic modeling using computer models …



	δ_w (nm)
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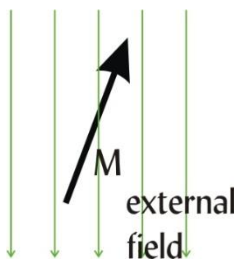
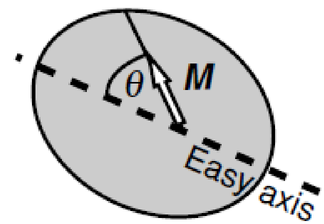
CoPt	4.5
$Nd_2Fe_{14}B$	3.9
$SmCo_5$	2.6
CrO_2	44.4
Fe_3O_4	72.8
$BaFe_{12}O_{19}$	13.6

Stoner-Wohlfarth-Model

Simplest possible reversal: Consider only Zeeman and anisotropy energy
Simplest analytical model that exhibits hysteresis, Stoner-Wohlfarth-Model

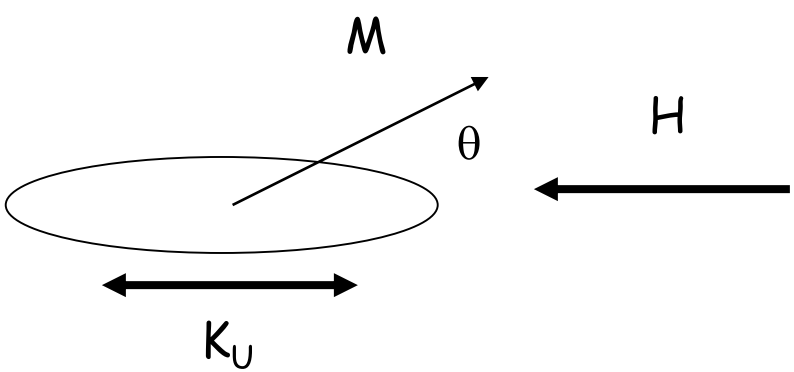




$$E_{external} = -\vec{H} \cdot \vec{M}$$

$$E_{anisotropy} = g(\theta)$$

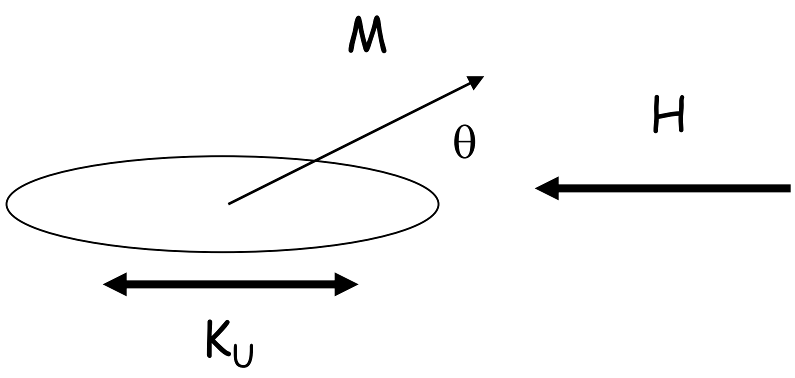
$$= K_U \sin^2\theta$$

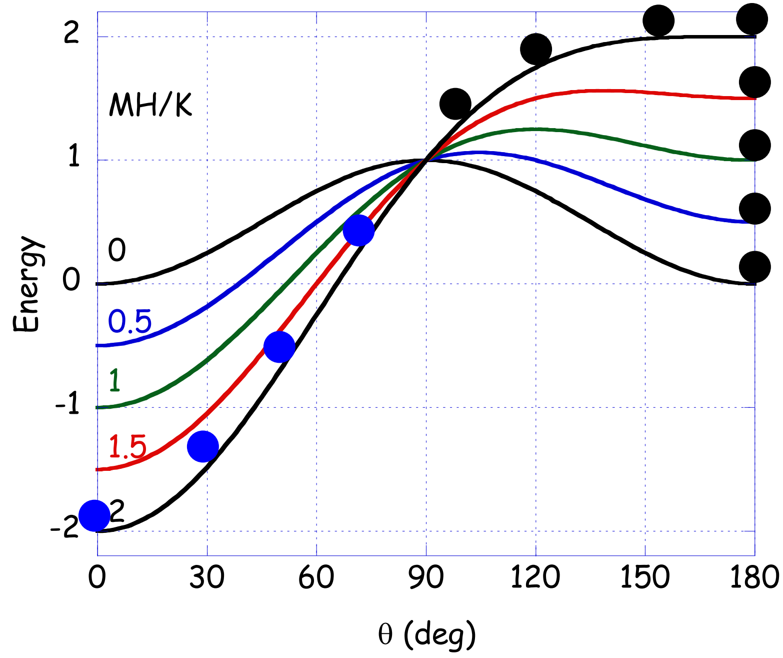


$$E = -MH\cos\theta + K\sin^2\theta$$

H term is uni-directional, K term is uniaxial

Stoner-Wohlfarth-Model





$$E = -MH\cos\theta + K\sin^2\theta$$

$$\partial E / \partial\theta = \sin\theta(MH + 2K\cos\theta) = 0$$

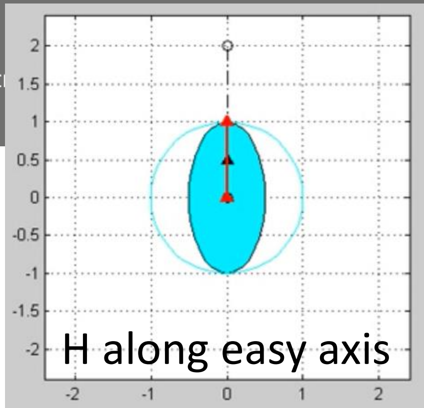
$$\partial^2 E / \partial\theta^2 = MH\cos\theta + 2K\cos(2\theta) > 0$$

$$H_C = 2K / M$$

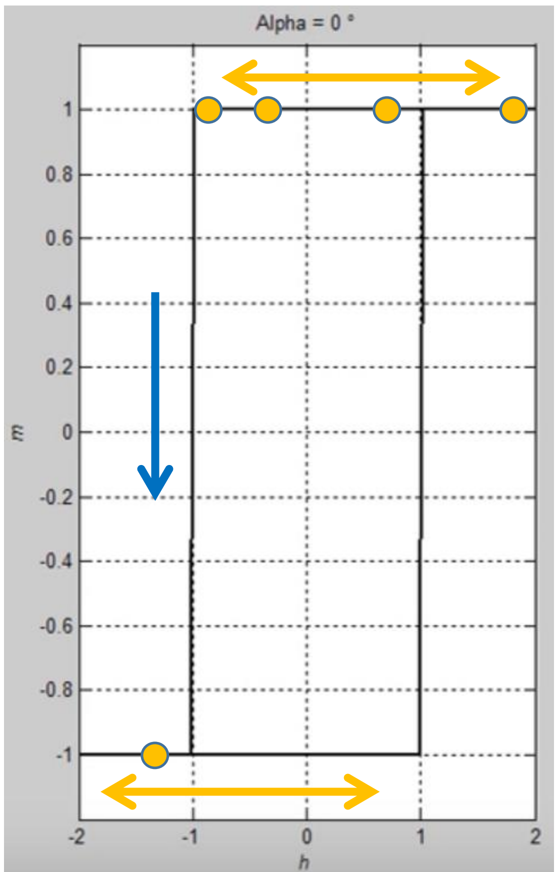
minima stay for all fields
at 0 and 180 degrees
Particle switches at $2K_U/M$

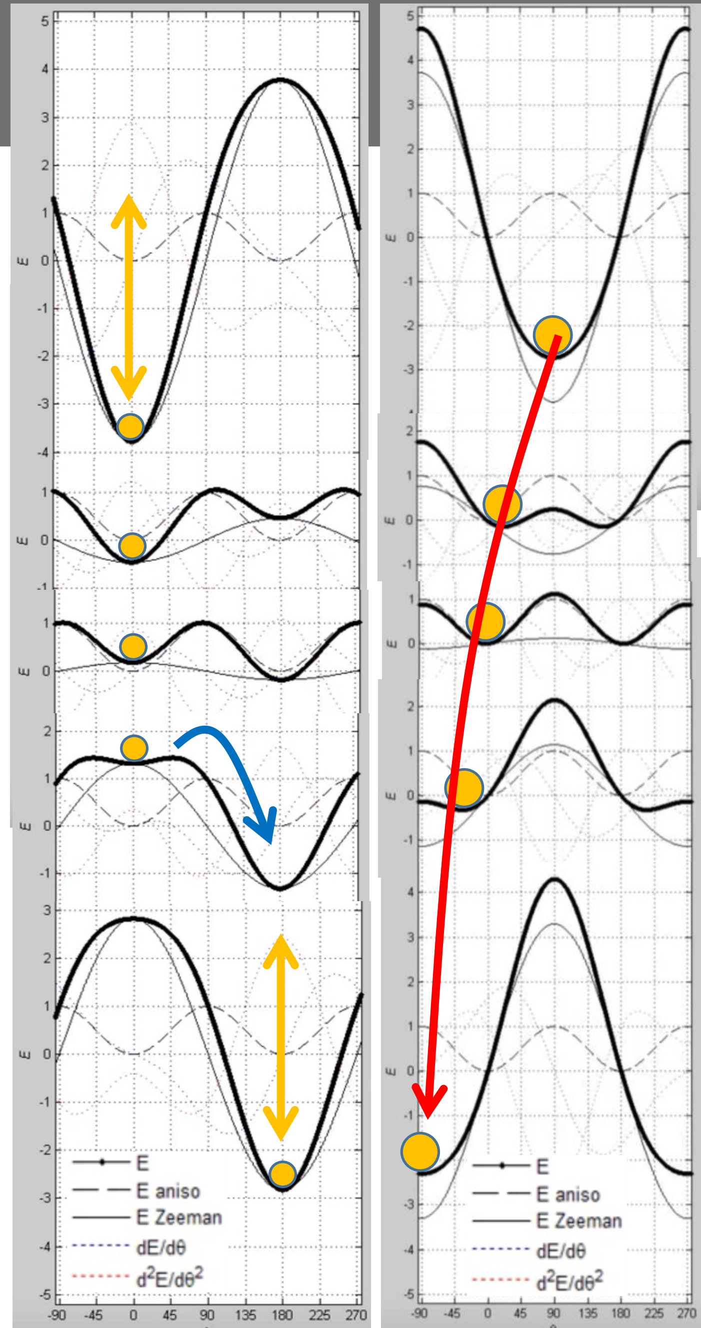
show easy axis Stoner-Wohlfahrth movie

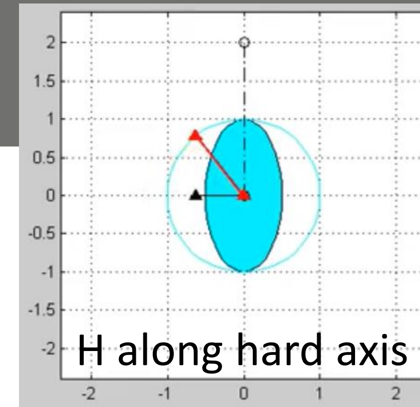
In zero field the magnetic anisotropy term is minimized when the magnetization is aligned with the easy axis. In a large field, the magnetization is pointed towards the field.



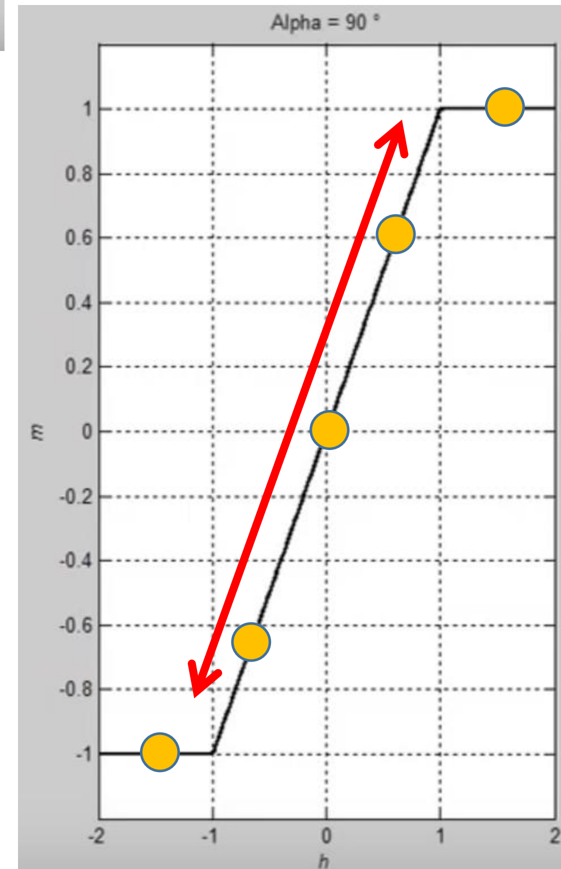
https://www.youtube.com/watch?v=7HNGCJJ5i5A





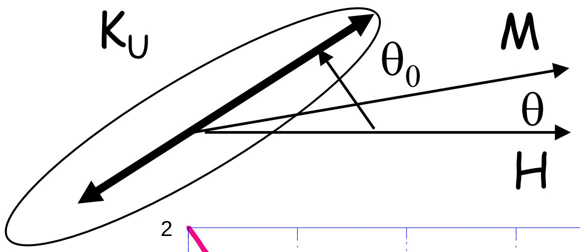


https://www.youtube.com/watch?v=oN-12IsK6Ik



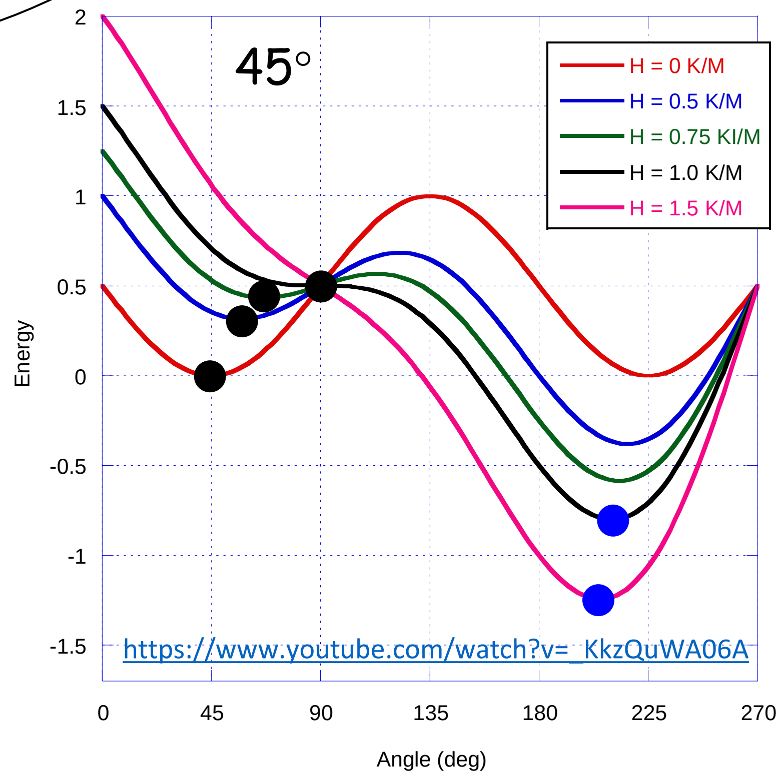
Stoner-Wohlfarth-Model

Up to know: H along easy or hard direction, now arbitrary directions for Stoner-Wohlfarth-Model

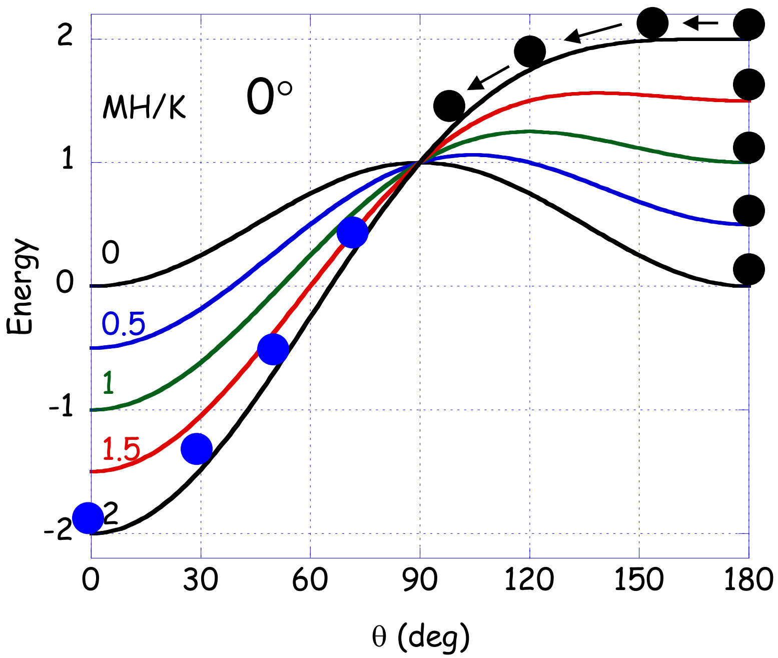


$$E = -MH\cos\theta + K\sin^2(\theta - \theta_0)$$

Field at an angle with the anisotropy axis θ_0



https://www.youtube.com/watch?v=_KkzQuWA06A



minima moves from 45° half way towards hard axis (90°)

Particle switches at K_U/M, not at $2K_U/M$

Easiest way to switch a SW-particle is at 45°

Stoner-Wohlfarth-Model at arbitrary angles

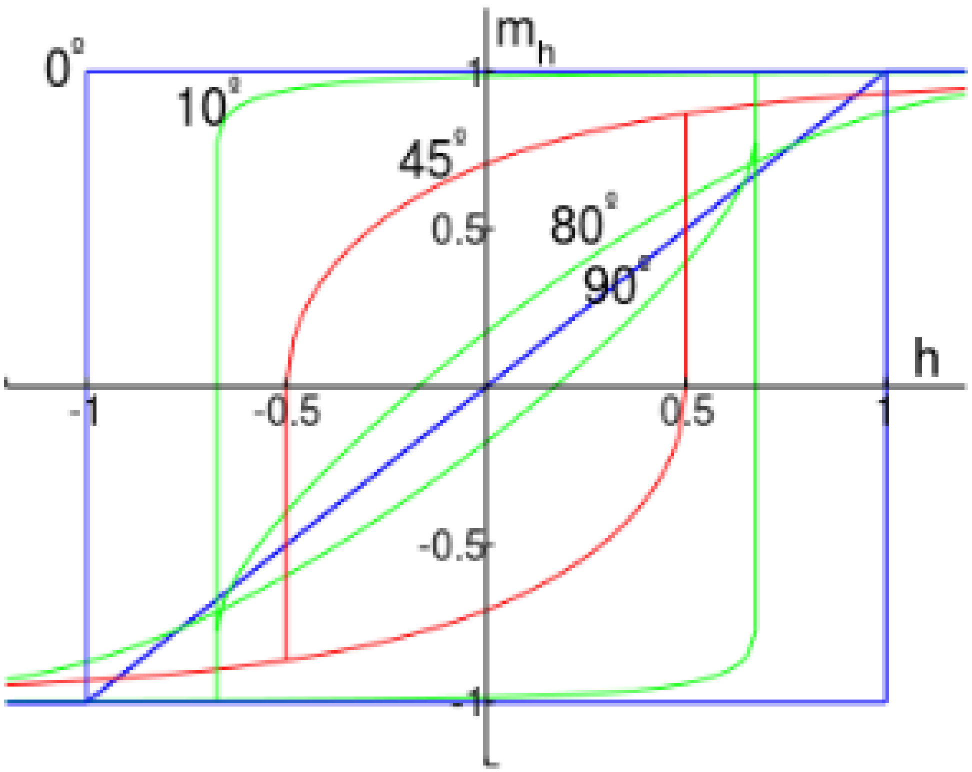


Figure 3. Some hysteresis loops predicted by the Stoner–Wolhfarth model for different angles between the field and easy axis.

https://www.youtube.com/watch?v=_KkzQuWA06A

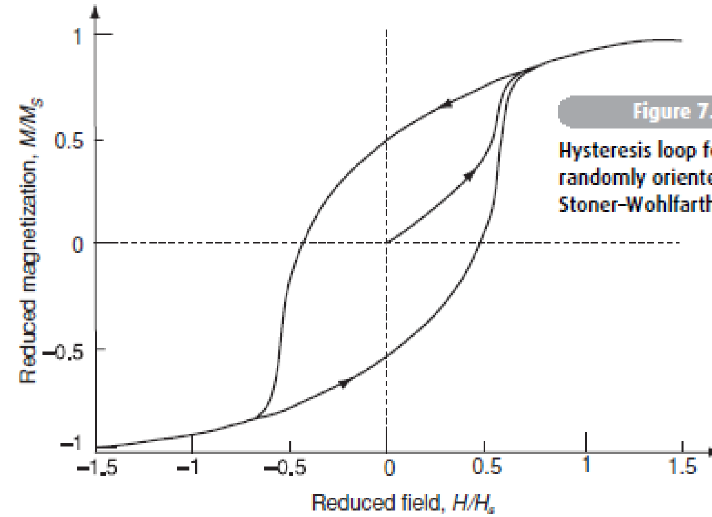
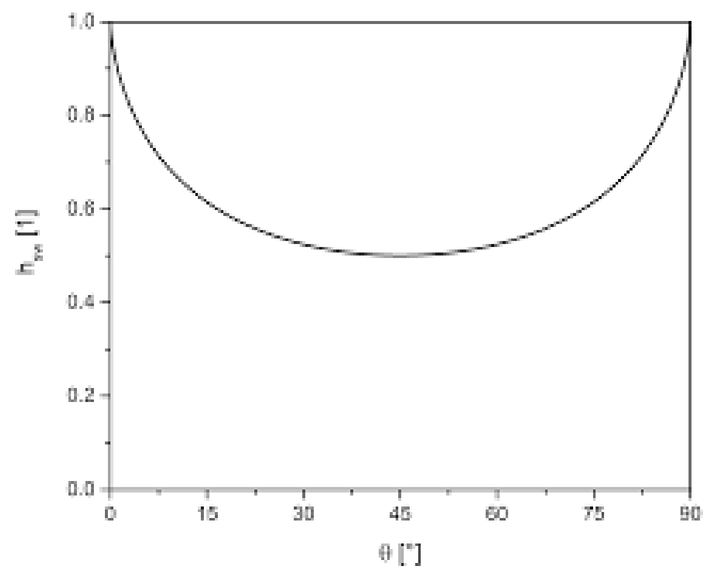
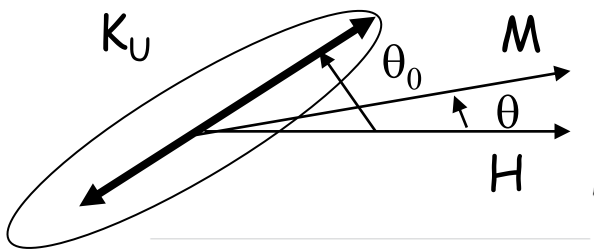


Figure 7.12
Hysteresis loop for a randomly oriented array of Stoner–Wohlfarth particles.

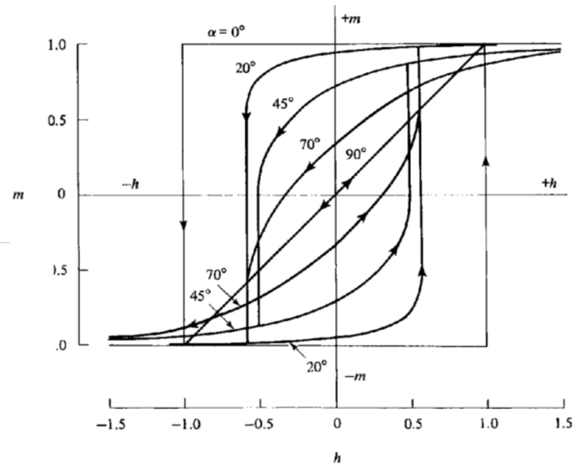


Reversal movies for 0,15,30,45,60,75, 85 and 90 degrees

Stoner-Wohlfarth reversal movies for various angles plot single particle illustration, hysteresis loop, energy landscape



An energy landscape with metastable minima gives rise to remanence and coercivity.



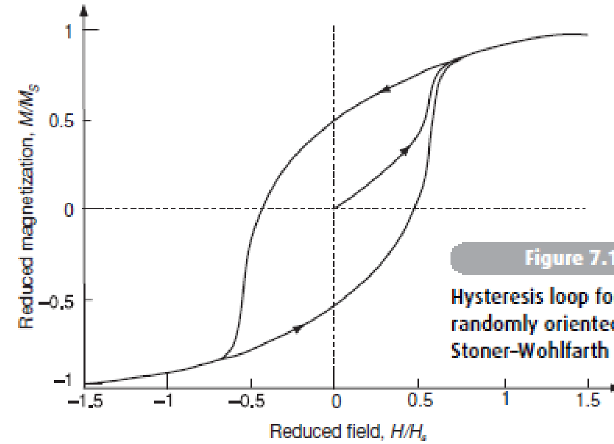
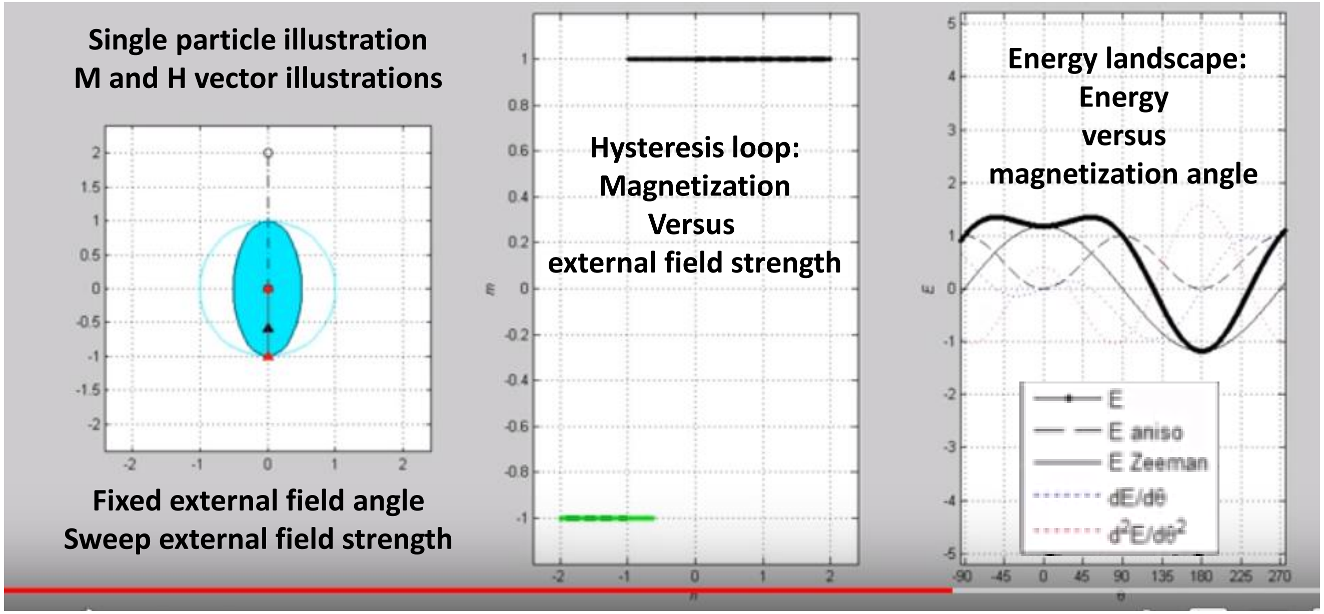
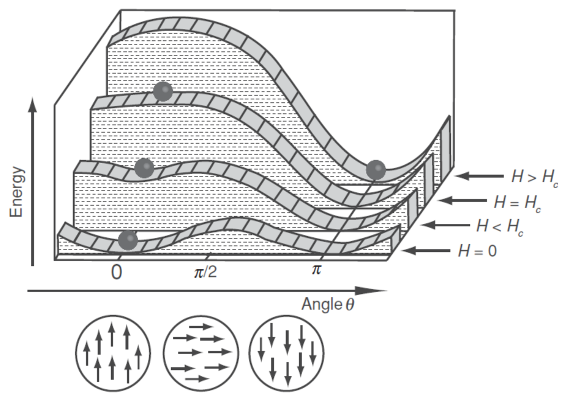


Figure 7.12 Hysteresis loop for a randomly oriented array of Stoner-Wohlfarth particles.





https://www.youtube.com/watch?v=_KkzQuWA06A

Reversal movies for 0,15,30,45,60,75, 85 and 90 degrees

Ferromagnetische (Funktionale) Materialien

- Einordung und Einleitung
- Energien und Energiedichten einer ferromagnetischen Probe
  - Austauschwechselwirkung
  - Streufeld- oder Demagnetisierungsenergie, Formanisotropie
  - Anisotropie (außer Formanisotropie = Demagnetisierungsenergiedichte)
  - Zeemann Energie, äußeres Feld
- Wechselseitige Konkurrenz verschiedener magnetischer Energieterme
- Hysterese-Effekte, Stoner-Wohlfarth Modell, Basis für binäre magn. Datenspeicher
- **Magnetische Funktionsmaterialien zur Datenspeicherung**
  - **Entwicklung der Festplatte: Von magnetischen Mikrosystemen zu Nanosystemen**
  - **GMR (Riesenmagnetwiderstand) und TMR Effekte für empfindlichere Leseköpfe**
  - **Zukünftige Festplattentechnologien**
  - **Neue Effekte in der Nanowelt: Spin tranfer torque in Nanokontakten**
  - **Separation von Ladungs und Spinströmen: Spin orbit torque in Dünnschichtsystemen**
  - **Anwendungen im Magnetic Random Access Memory (MRAM)**
  - **Die Spinwelle als Informationsträger (HZDR-movie)**