Magnetism basics

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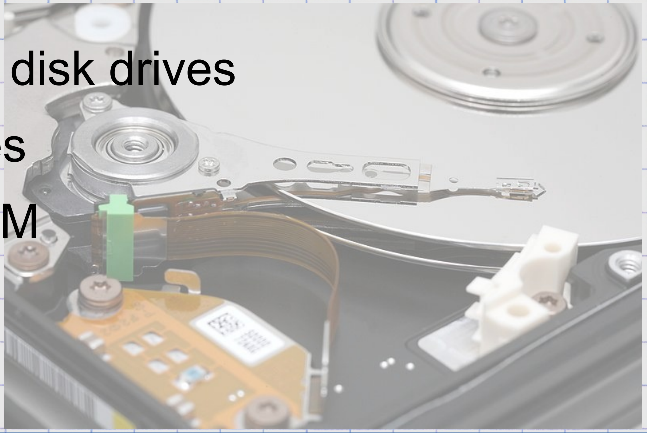
Modern applications of magnetism

Where does 'nano' contribute ?

Materials

- Magnets (→ motors and generators)
- Transformers
- Magnetocaloric

Data storage



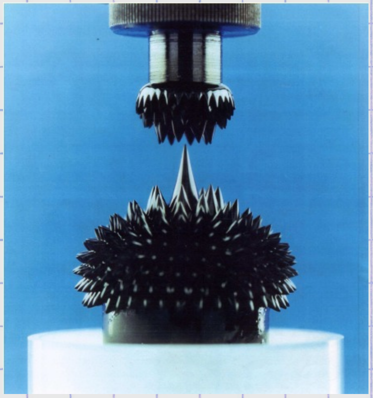
- Hard disk drives
- Tapes
- MRAM

Sensors

- Compass
- Field mapping
- HDD read heads

Nanoparticles

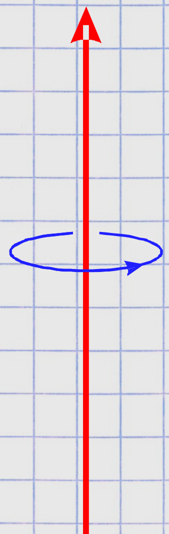
- Ferrofluids
- MRI contrast
- Hyperthermia
- Sorting & tagging



Maxwell equation : $\nabla \times \mathbf{B} = \mu_0 \, \mathbf{j}$

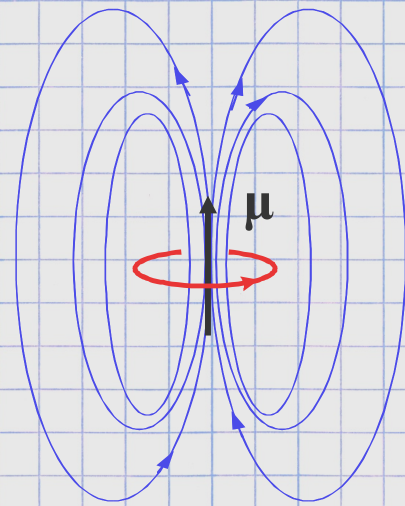
Electric currents produce magnetic fields

Oersted field



$$B_\theta = \frac{\mu_0 I}{2\pi r}$$

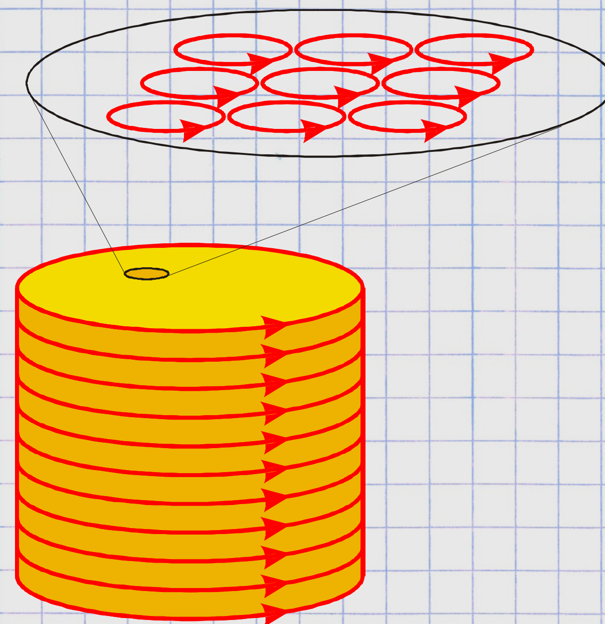
Magnetic dipole



$$\mathbf{B} = \frac{\mu_0}{4\pi r^3} \times \left[\frac{3}{r^2} (\boldsymbol{\mu} \cdot \mathbf{r}) \mathbf{r} - \boldsymbol{\mu} \right]$$

Magnetic dipole $\mathrm{A.m^2}$

Magnetic material



Magnetization $\mathrm{A/m}$

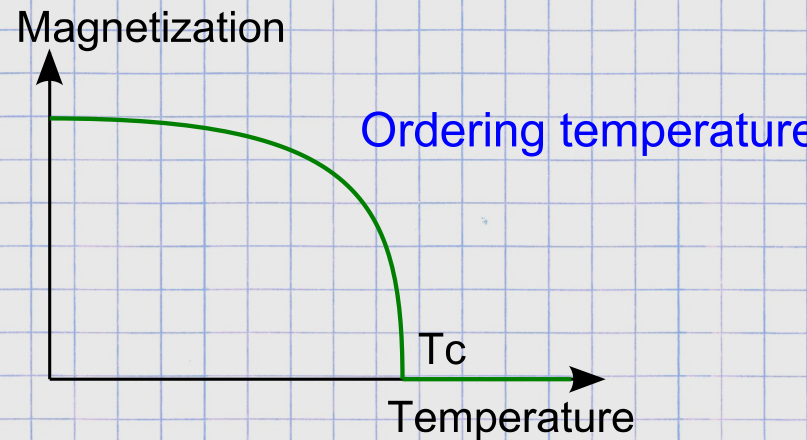
Magnetic moment $\mathrm{A.m^2}$

$\mathbf{B} = \mu_0 (\mathbf{H} + \mathbf{M})$ Induction **B**, Magnetic field **H**, Magnetization **M**

Magnetic ordering

Magnetic exchange
between microscopic moments

$$\mathcal{E} = -2 \sum_{i>j} J_{i,j} \mathbf{S_i} . \mathbf{S_j}$$



Ferromagnet

$J_{i,j} > 0$

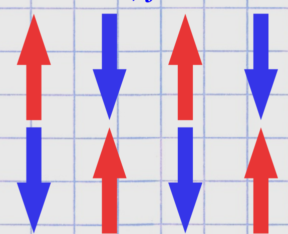
➡ Fe

$T_C = 1043\ \mathrm{K}$

$M_s = 1.73 \times 10^6\ \mathrm{A/m}$

Antiferromagnet

$J_{i,j} < 0$



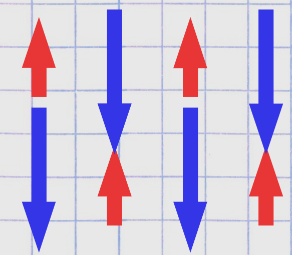
➡ CoO

$T_N = 292\ \mathrm{K}$

$J = 3/2$

Ferrimagnet

$J_{i,j} < 0$



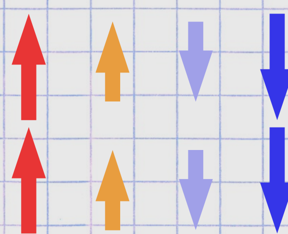
➡ Fe3O4

$T_C = 858\ \mathrm{K}$

$M_s = 480\ \mathrm{kA/m}$

Helical

$J_1, J_2 \ldots$

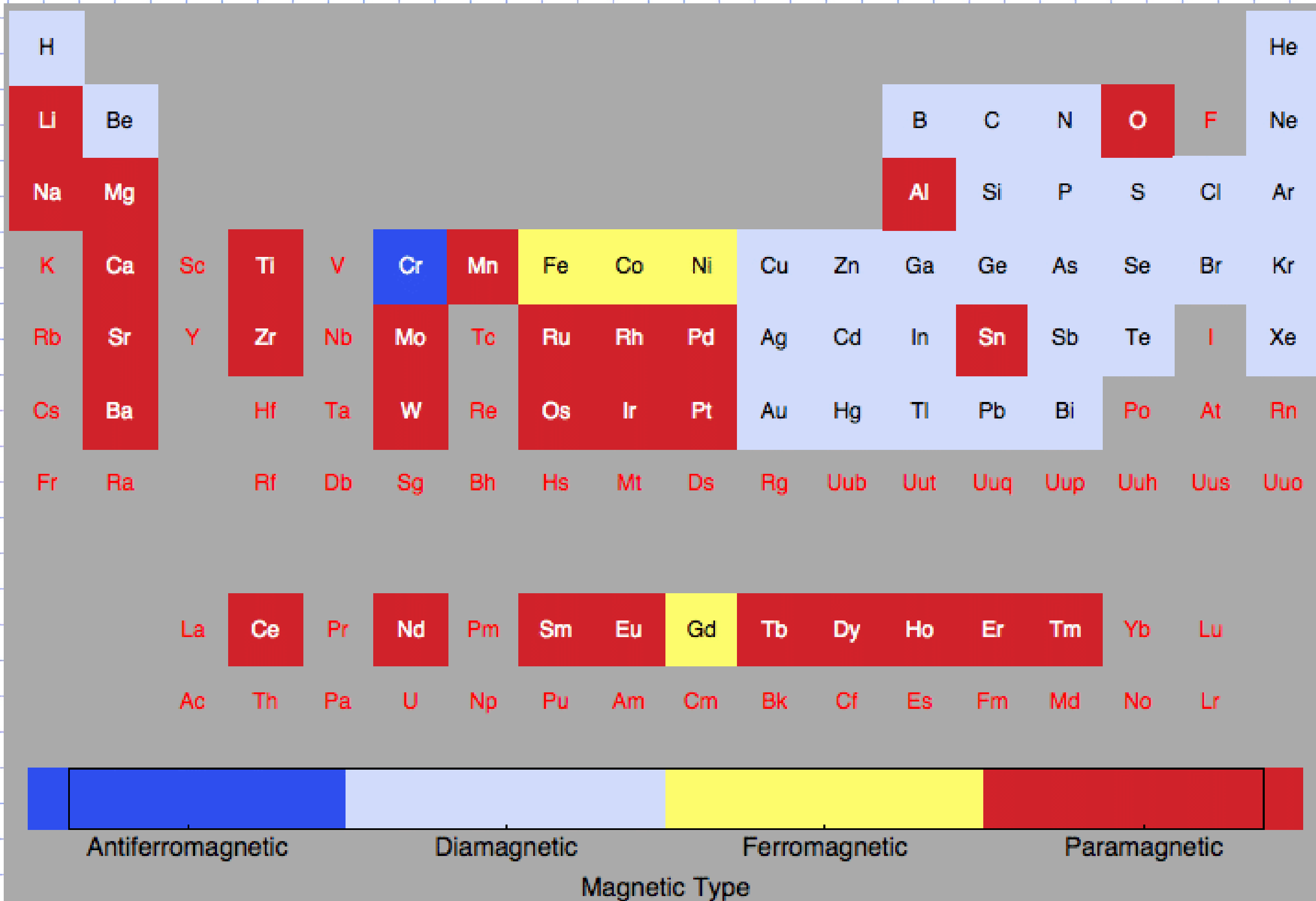


➡ Dy

$T \in 85-179\ \mathrm{K}$

$\mu = 10.4 \mu_B$

Magnetic properties at room temperature, single elements

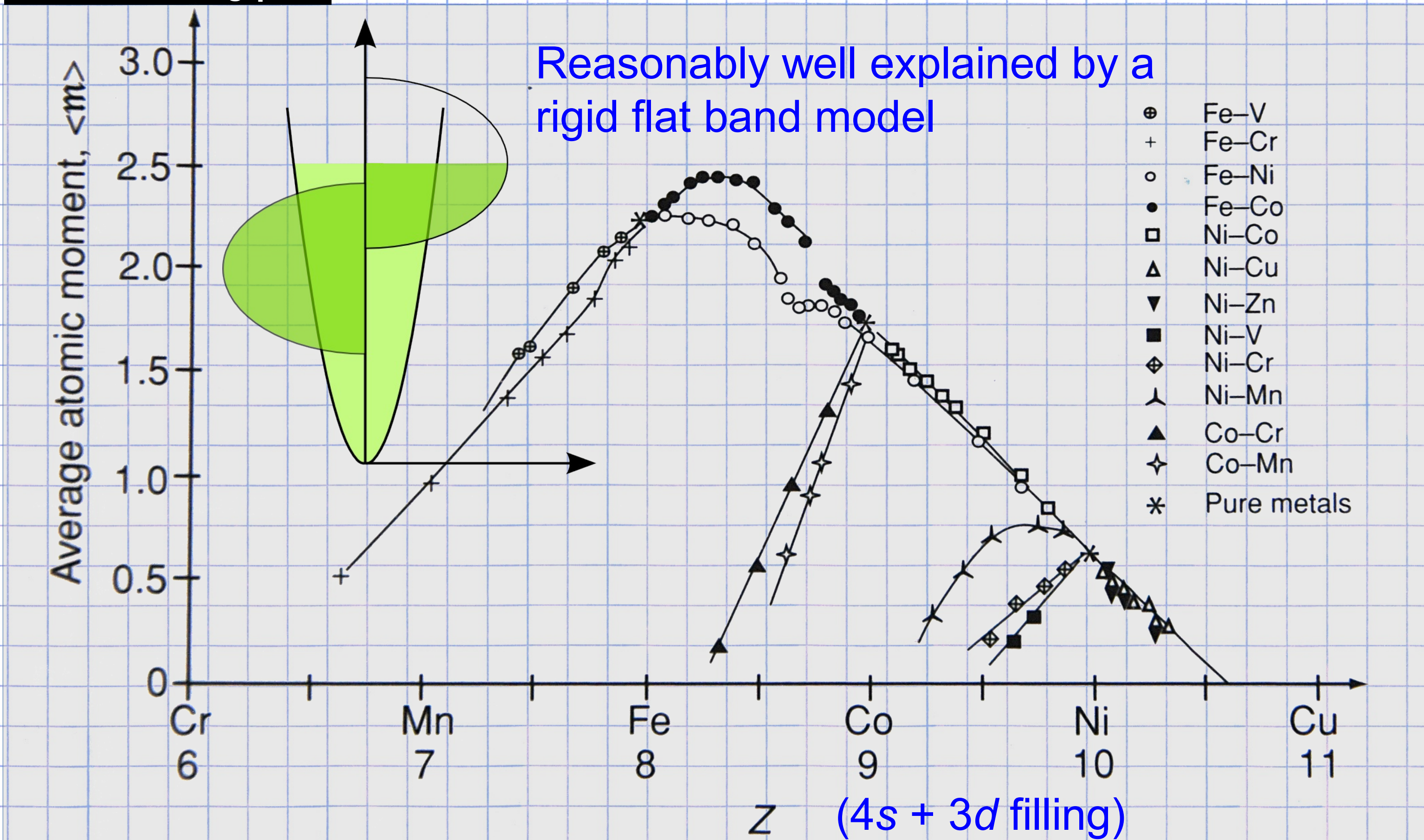


Periodictable.com

FIELDS and MOMENTS – Limited value of magnetic moments (here : 3d alloys)

Do not use Hund's rules to estimate atomic moments

Slater-Pauling plot



From: Coey

- Moment per atom + lattice spacing → Magnetization
- Magnetization is bounded in practice

Material	T_C (K)	M_s (kA/m)	$\mu_0 M_s$ (T)
Fe	1043	1730	2.174
Co	1394	1420	1.784
Ni	631	490	0.616
$Fe_{20}Ni_{80}$ (Permalloy)	850	835	1.050
$Fe_3 0_4$	858	480	0.603
$BaFe_{12}O_{19}$	723	382	0.480
$Nd_2Fe_{14}B$	585	1280	1.608
$SmCo_5$	995	907	1.140
Sm_2Co_{17}	1190	995	1.250
FePt $L1_0$	750	1140	1.433
CoPt $L1_0$	840	796	1.000
Co_3Pt	1100	1100	1.382

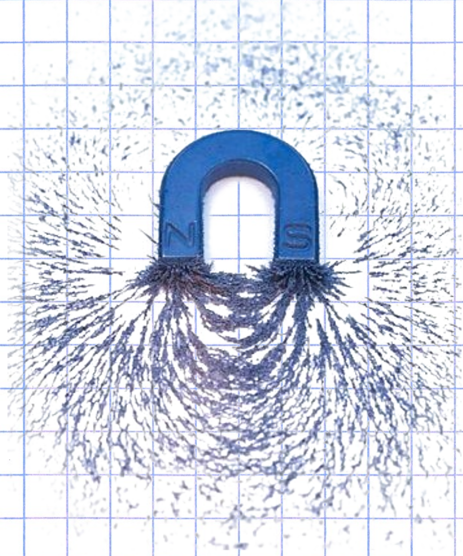
	SI system		cgs-Gauss	
Definitions	Meter	m	Centimeter	cm
	Kilogram	kg	Gram	g
	Second	s	Second	s
	Ampere	A	Ab-Ampere	ab-A = 10A
	$\mathbf{B}=\mu_0(\mathbf{H}+\mathbf{M})$		$\mathbf{B}=\mathbf{H}+4\pi\mathbf{M}$	
	$\mu_0=4\pi\times10^{-7}$ SI		$\mu_0=4\pi$	

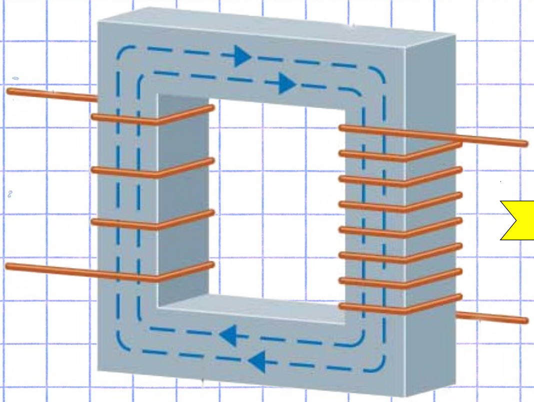
Conversions

		SI		cgs-Gauss	
Field	$\mathbf{H}$	1 A/m	⟷	$4\pi\times10^{-3}$ Oe	(Oersted)
Moment	μ	1 $A.m^2$	⟷	10^3 emu	
Magnetization	$\mathbf{M}$	1 A/m	⟷	10^{-3} emu/cm^3	
Induction	$\mathbf{B}$	1 T	⟷	10^4 G	(Gauss)
Susceptibility	$\chi=M/H$	1	⟷	$1/4\pi$	

See pratical on units : http://magnetism.eu/esm/2013/abs/fruchart-tutorial.pdf

1. Fields, moments, materials



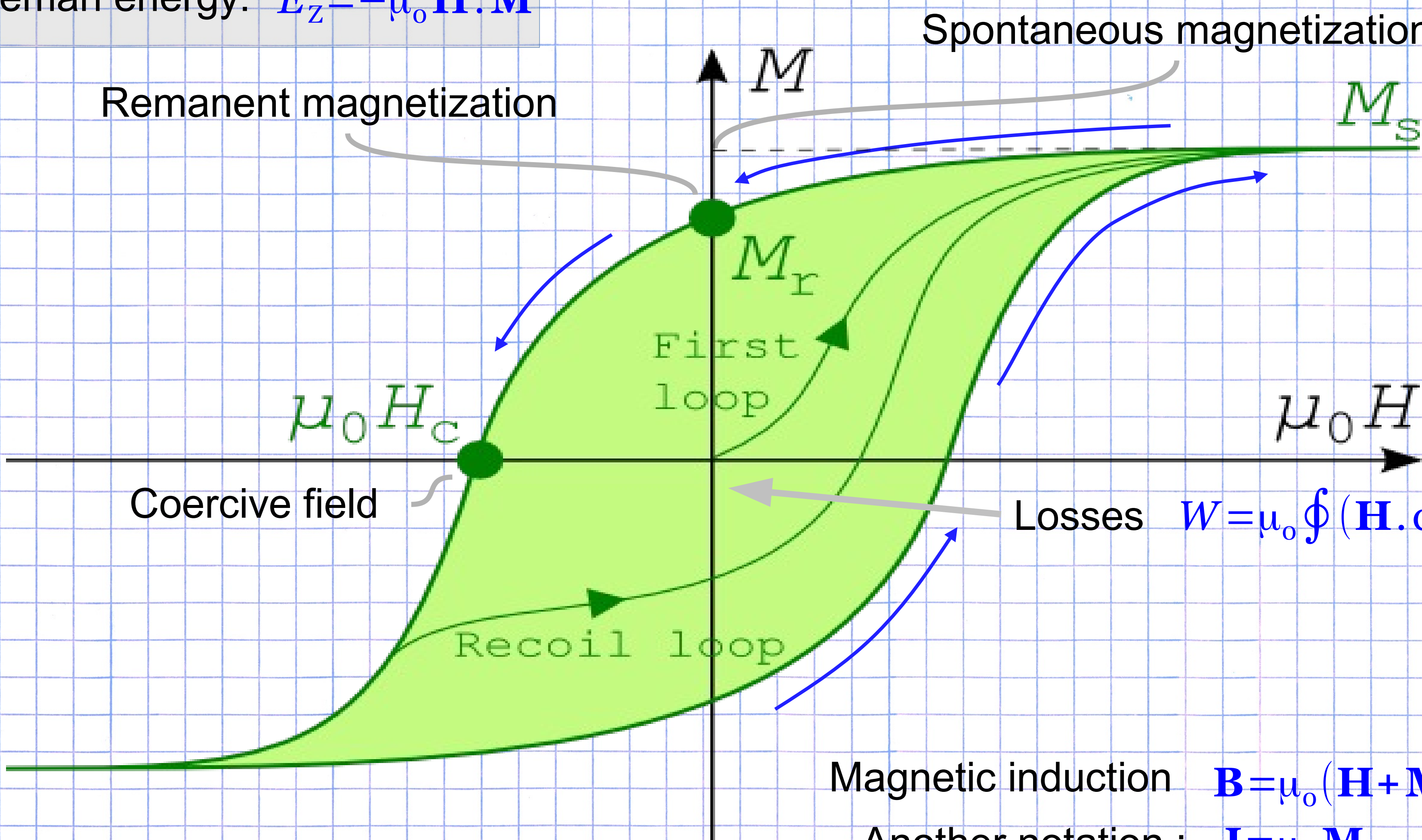


2. Magnetization processes

3. Thin film effects

Manipulation of magnetic materials:
→ Application of a magnetic field

Zeeman energy: $E_Z = -\mu_0 \mathbf{H}.\mathbf{M}$

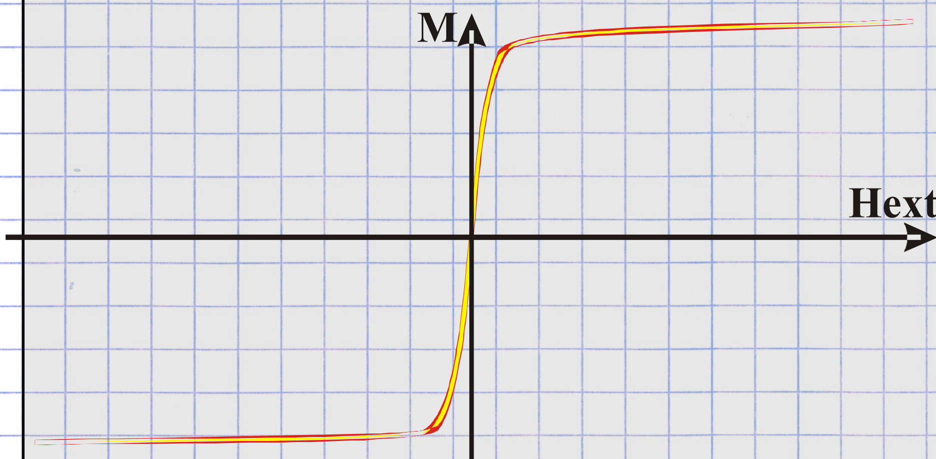


Losses $W = \mu_0 \oint (\mathbf{H}.\mathrm{d}\mathbf{M})$

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

Another notation : $\mathbf{J} = \mu_0 \mathbf{M}$

Soft magnetic materials

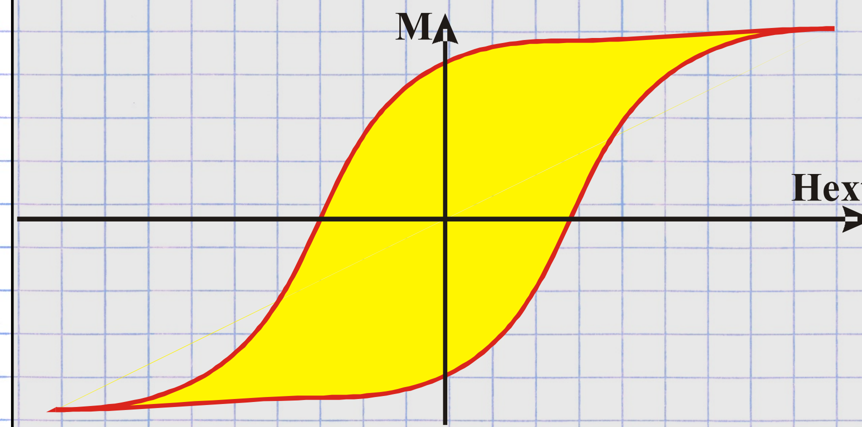


Transformers

Flux guides, sensors

Magnetic shielding

Hard magnetic materials

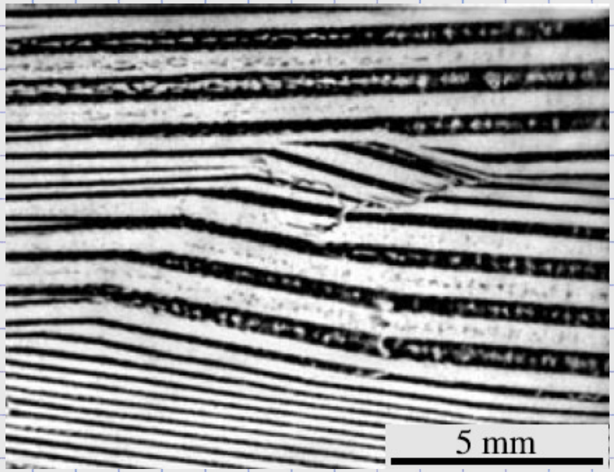


Permanent magnets, motors

Magnetic recording

Bulk material

Numerous and complex magnetic domains

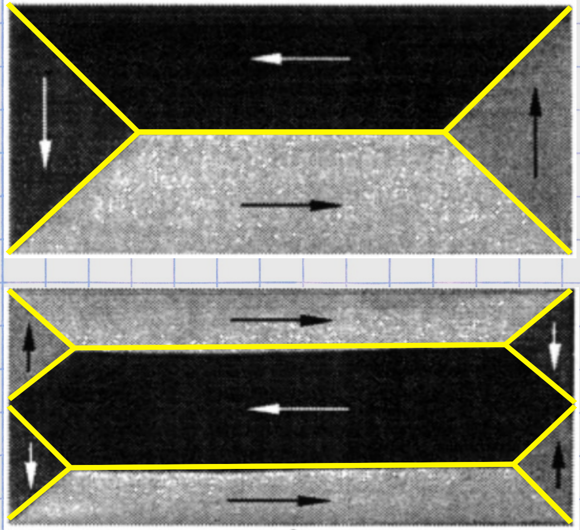


FeSi soft sheet

A. Hubert, *Magnetic domains*

Mesoscopic scale

Small number of domains, simple shape

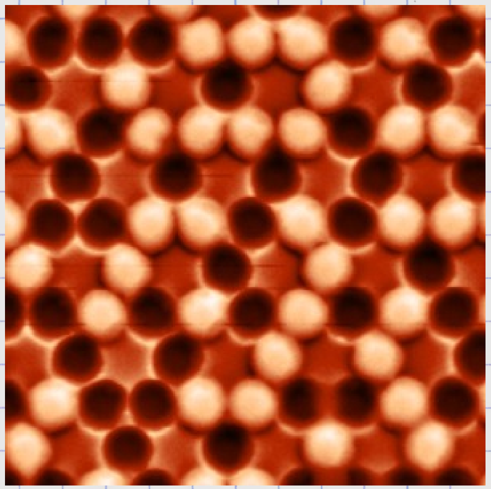


Microfabricated dots
Kerr magnetic imaging

A. Hubert, *Magnetic domains*

Nanometric scale

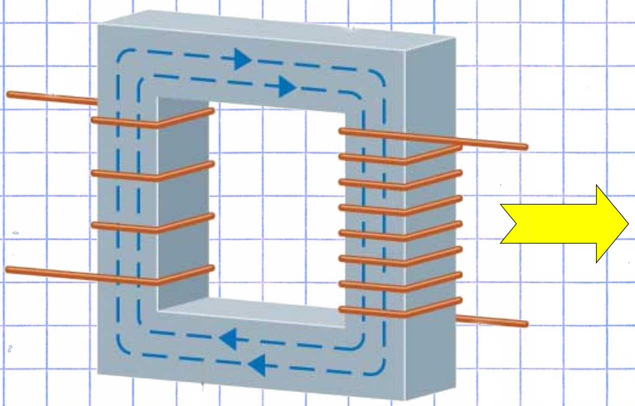
Magnetic single-domain



Nanofabricated dots
MFM

Sample courtesy :
N. Rougemaille, I. Chioar

Nanomagnetism ~ mesoscopic magnetism



II. MAGNETIZATION PROCESSES

Magnetization

Magnetization vector **M** →

May vary over time and space

$$\mathbf{M}=\begin{pmatrix}M_x\\M_y\\M_z\end{pmatrix}=M_\mathrm{s}\begin{pmatrix}m_x\\m_y\\m_z\end{pmatrix}$$

Modulus is constant
(hypothesis in micromagnetism) →

$$m_x^2+m_y^2+m_z^2=1$$

Mean-field approach possible: $M_\mathrm{s}=M_\mathrm{s}(T)$

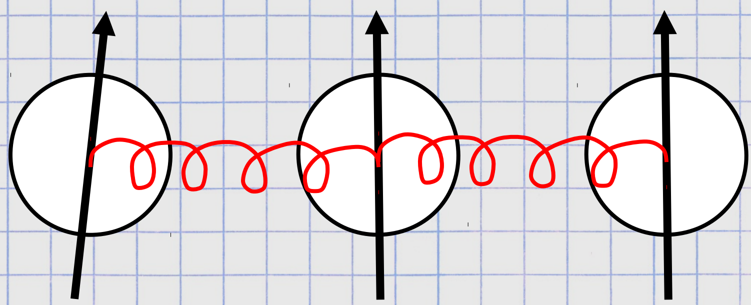
Exchange interaction

Atomistic view : $\mathcal{E}=-2\sum_{i>j}J_{i,j}\mathbf{S_i}.\mathbf{S_j}$ (total energy)

Micromagnetic view : $\mathbf{S_i}.\mathbf{S_j}=S^2\cos\theta_{i,j}\approx S^2(1-\theta_{i,j}^2/2)$

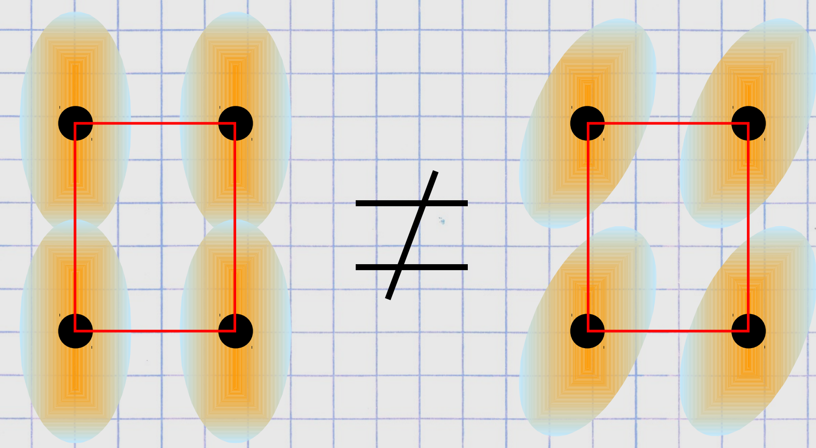
$E=A(\nabla.\mathbf{m})^2$ (energy per unit volume)

Exchange energy



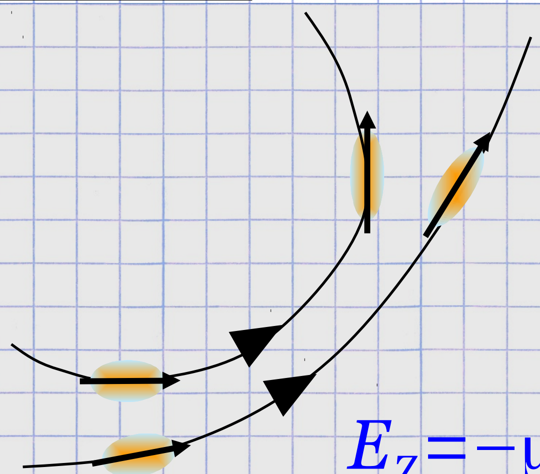
$$E_{\mathrm{ex}} = A(\nabla.\mathbf{m})^2 = A\sum_{i,j}\left(\frac{\partial m_i}{\partial x_j}\right)^2$$

Magnetocrystalline anisotropy energy



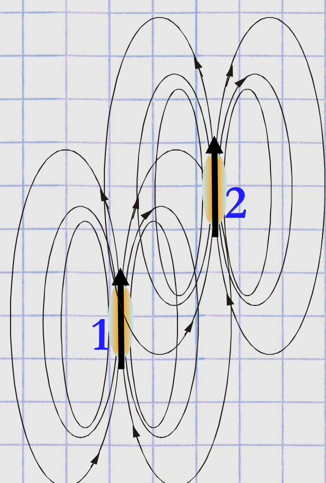
$$E_{\mathrm{mc}} = A f(\theta,\varphi)$$

Zeeman energy



$$E_{\mathrm{Z}} = -\mu_0 \mathbf{M}.H$$

Dipolar energy



$$E_{\mathrm{d}} = -\frac{1}{2}\mu_0 \mathbf{M}.H_{\mathrm{d}}$$

Analogy with electrostatics (synonym : magnetostatic energy)

Maxwell equation → $\operatorname{div}(\mathbf{H}_\mathrm{d}) = -\operatorname{div}(\mathbf{M})$

$$\Rightarrow \mathbf{H}_\mathrm{d}(\mathbf{r}) = -M_\mathrm{s} \iiint_\mathrm{Space} \frac{\operatorname{div}[\mathbf{m}(\mathbf{r}')].(\mathbf{r}-\mathbf{r}')}{4\pi \|\mathbf{r}-\mathbf{r}'\|^3} \mathrm{d}V'$$

To lift the singularity that may arise at boundaries, a volume integration around the boundaries yields:

$$\mathbf{H}_\mathrm{d}(\mathbf{r}) = \iiint \frac{\rho(\mathbf{r}').(\mathbf{r}-\mathbf{r}')}{4\pi \|\mathbf{r}-\mathbf{r}'\|^3} \mathrm{d}V' + \iint \frac{\sigma(\mathbf{r}').(\mathbf{r}-\mathbf{r}')}{4\pi \|\mathbf{r}-\mathbf{r}'\|^3} \mathrm{d}S'$$

Usefull expressions

$$\mathcal{E}_\mathrm{d} = -\frac{1}{2}\mu_0 \iiint_\mathrm{Sample} \mathbf{M}.\mathbf{H}_\mathrm{d} \mathrm{d}V$$

$$\mathcal{E}_\mathrm{d} = \frac{1}{2}\mu_0 \iiint_\mathrm{Space} \mathbf{H}_\mathrm{d}^2 \mathrm{d}V$$

⇨ Dipolar energy is always positive

⇨ Zero energy means a minimum

Magnetic charges

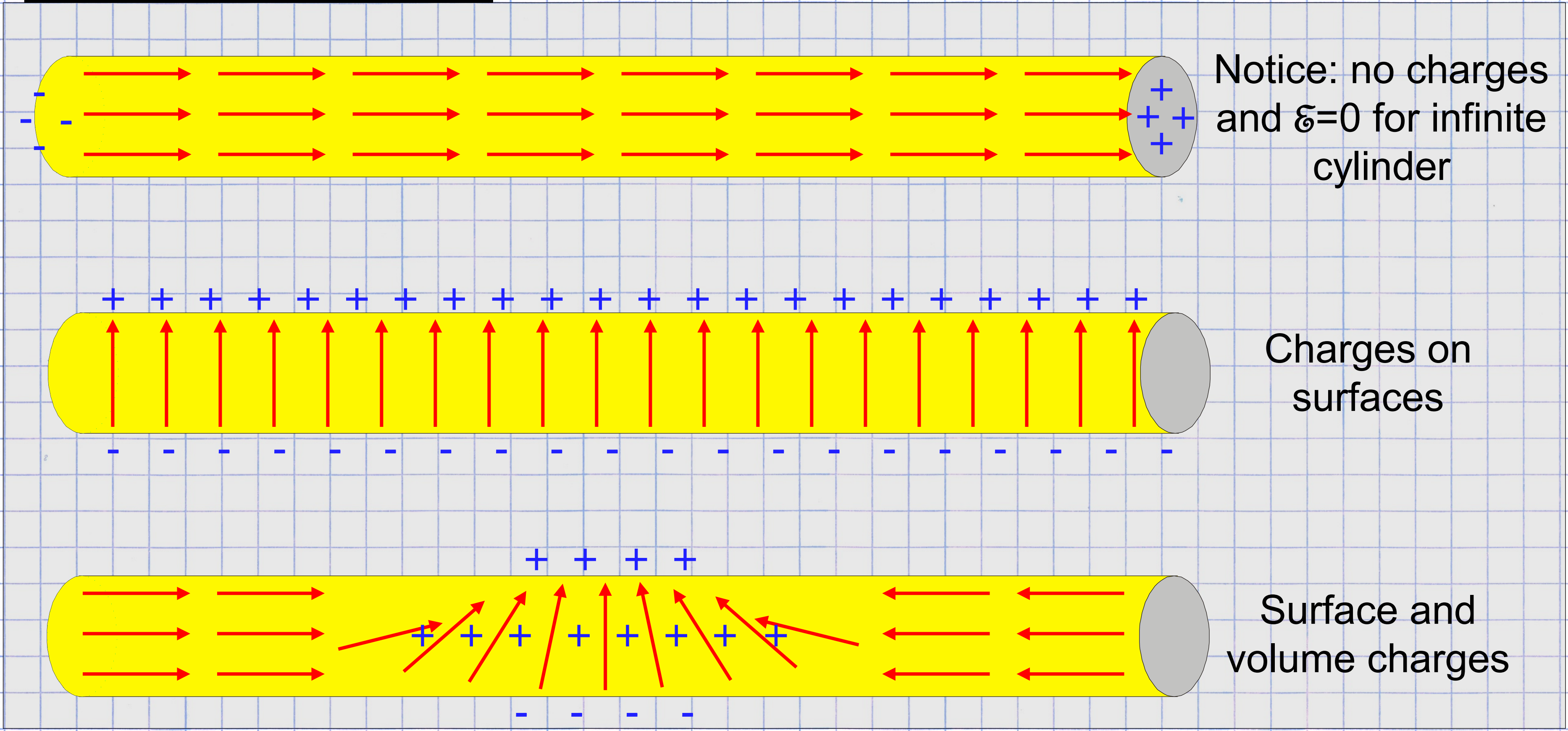
$\rho(\mathbf{r}) = -M_\mathrm{s} \operatorname{div}[\mathbf{m}(\mathbf{r})]$ → volume density of magnetic charges

$\sigma(\mathbf{r}) = M_\mathrm{s} \mathbf{m}(\mathbf{r}).\mathbf{n}(\mathbf{r})$ → surface density of magnetic charges

Notice

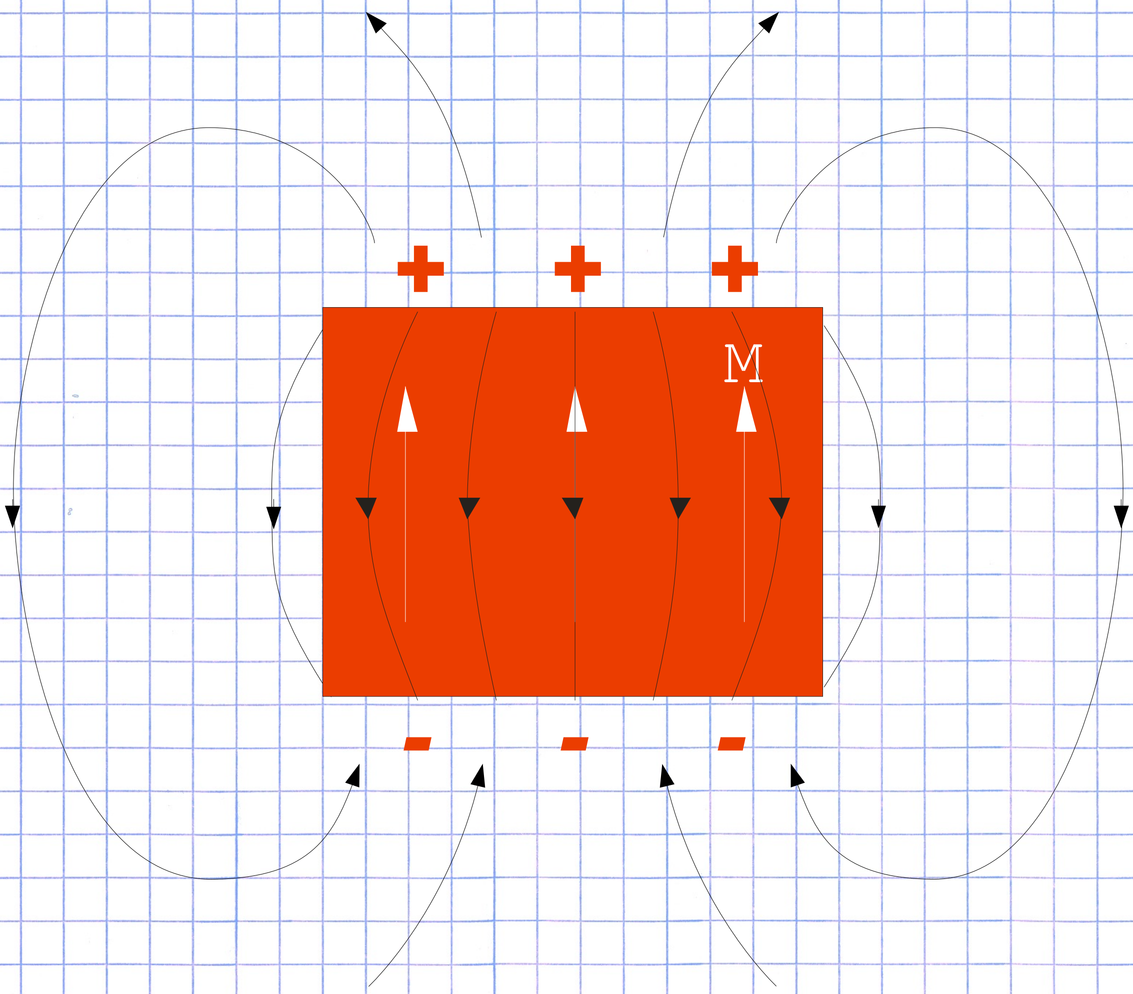
- Hd depends on sample shape, not size
- Synonym : dipolar ↔ magnetostatic

Examples of magnetic charges



Take-away message

➪ Dipolar energy favors alignement of magnetization with longest direction of sample



Names

- Generic names
  - Magnetostatic field
  - Dipolar field
- Within sample
  - Demagnetizing field
- Outside sample
  - Stray field

Principle

Goal : calculate strength of demagnetizing field and energy

Assume uniform magnetization $\mathbf{M}(\mathbf{r}) = \mathbf{M} = M_\mathrm{s}(m_x \mathbf{u}_x + m_y \mathbf{u}_y + m_z \mathbf{u}_z)$

Demagnetizing coefficients

$$\left.\begin{aligned}\langle \mathbf{H}_\mathrm{d}(\mathbf{r})\rangle &= -N_i \mathbf{M} \\ \mathcal{E}_\mathrm{d} &= N_i K_\mathrm{d} V\end{aligned}\right\} \text{along main directions}$$

$K_\mathrm{d} = \frac{1}{2}\mu_0 M_\mathrm{s}^2$ Dipolar constant (J/m³)

$\bar{\bar{\mathbf{N}}}$ Demagnetizing tensor

Notice: Valid for any shape

$N_x + N_y + N_z = 1$

cgs: $\langle \mathbf{H}_\mathrm{d}\rangle = -4\pi\bar{\bar{\mathbf{N}}}.\mathbf{M}$ $\qquad \bar{\bar{\mathbf{D}}} = 4\pi\bar{\bar{\mathbf{N}}}$

Model cases : slabs, cylinders and ellipsoids

(Not easy to prove, mathematics...)

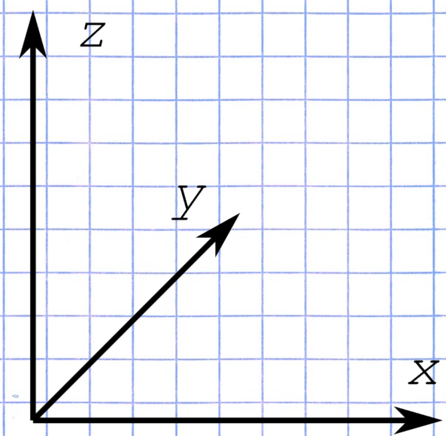
Hd is uniform for surfaces of polynomial boundary with order <=2 $\qquad \mathbf{H}_\mathrm{d} = -N_i \mathbf{M}$

J. C. Maxwell, Clarendon 2, 66-73 (1872)

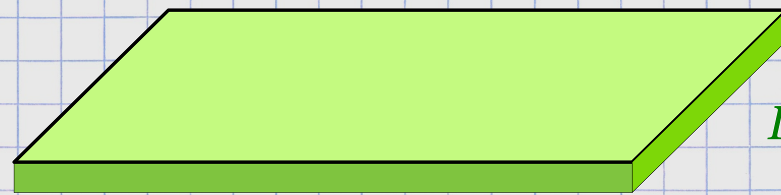
Dipolar energy contributes to magnetic anisotropy with second-order term

Example :

$$\mathcal{E}_\mathrm{d} = VK_\mathrm{d}(N_x m_x^2 + N_y m_y^2) = VK_\mathrm{d}(N_x - N_y)\cos^2\theta$$



Slabs (infinite thin films)

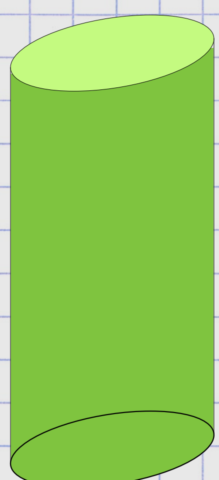


$L_x = L_y = \infty$

$N_x = N_y = 0$

$N_z = 1$

Cylinders (infinite)



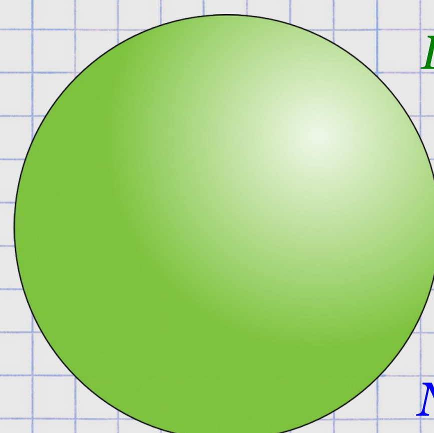
$L_x = L_y = D$

$L_z = \infty$

$N_x = N_y = \frac{1}{2}$

$N_z = 0$

Spheres



$L_x = L_y = L_z = D$

$N_x = N_y = N_z = \frac{1}{3}$

Ellipsoids

$$N_x = \frac{1}{2}abc\int_0^\infty \left[(a^2+\eta)\sqrt{(a^2+\eta)(b^2+\eta)(c^2+\eta)}\right]^{-1} d\eta$$ General ellipsoid: main axes (a,b,c)

$$N_x = \frac{\alpha^2}{1-\alpha^2}\left[\frac{1}{\sqrt{1-\alpha^2}}\operatorname{arsinh}\left(\frac{\sqrt{1-\alpha^2}}{\alpha}\right)-1\right]$$

For prolate revolution ellipsoid: (a,c,c) with $\alpha=c/a<1$

$$N_x = \frac{\alpha^2}{\alpha^2-1}\left[1-\frac{1}{\sqrt{\alpha^2-1}}\arcsin\left(\frac{\sqrt{\alpha^2-1}}{\alpha}\right)\right]$$

For oblate revolution ellipsoid: (a,c,c) with $\alpha=c/a>1$

$$N_y = N_z = \frac{1}{2}(1-N_x)$$

Cylinders

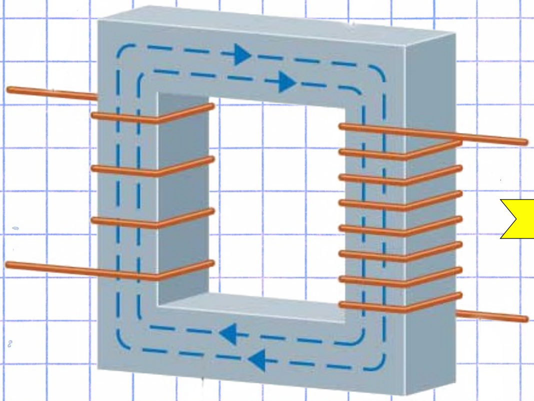
$N_x=0$ $\quad N_y = \frac{c}{b+c}$ $\quad N_z = \frac{b}{b+c}$

For a cylinder with axis along *x*

J. A. Osborn, Phys. Rev. 67, 351 (1945).

For prisms, see: **A. Aharoni, J. Appl. Phys. 83, 3432 (1998)**

More general forms, FFT approach: **M. Beleggia et al., J. Magn. Magn. Mater. 263, L1-9 (2003)**



II. MAGNETIZATION PROCESSES

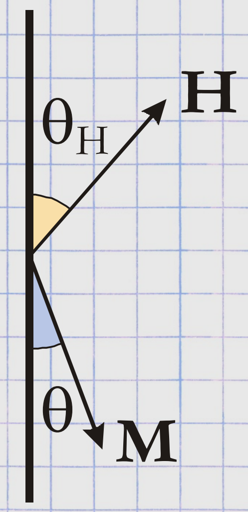
Framework

Approximation: $\partial_{\mathbf{r}}\mathbf{m}=\mathbf{0}$ (uniform magnetization)

(strong!)

$$\mathcal{E}=EV=V\left[K_{\mathrm{eff}}\sin^2\theta-\mu_0 M_S H\cos(\theta-\theta_H)\right]$$

$$K_{\mathrm{eff}}=K_{\mathrm{mc}}+(\Delta N)K_{\mathrm{d}}$$



Dimensionless units:

$$e=\sin^2\theta-2h\cos(\theta-\theta_H)$$

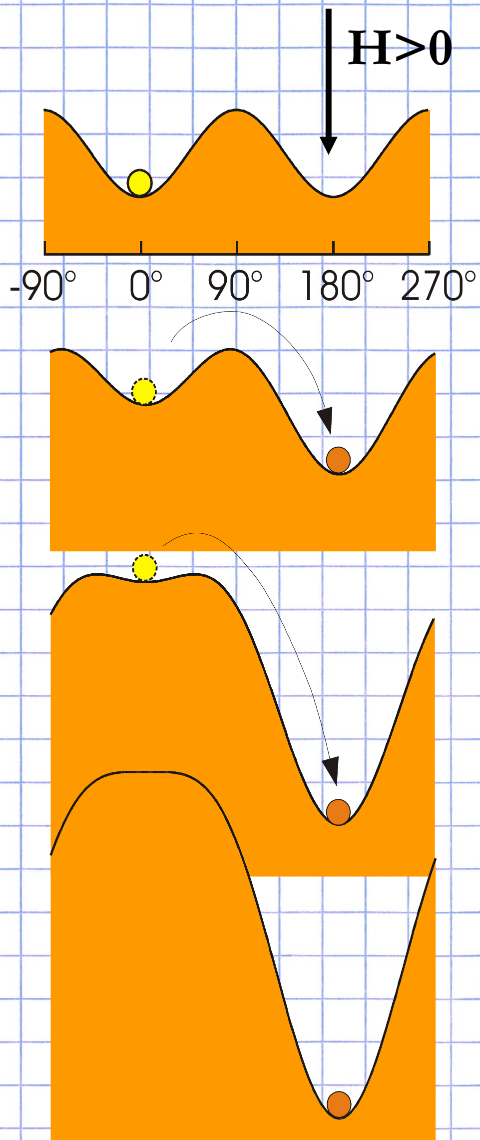
$$e=\mathcal{E}/KV$$
$$h=H/H_a$$
$$H_a=2K/\mu_0 M_S$$

L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)
E. C. Stoner and E. P. Wohlfarth, Phil. Trans. Royal. Soc. London A240, 599 (1948)
IEEE Trans. Magn. 27(4), 3469 (1991) : reprint

Names used

- Uniform rotation / magnetization reversal
- Coherent rotation / magnetization reversal
- Macrospin etc.

Example for $\theta_H = 180°$ ► $e = \sin^2\theta + 2h\cos\theta$



Equilibrium states

$$\partial_\theta e = 2\sin\theta\left(\cos\theta - h\right) \qquad \partial_\theta e = 0 \Rightarrow \left|\begin{array}{l} \cos\theta_m = h \\ \theta \equiv 0\,[\pi] \end{array}\right.$$

Stability

$$\begin{aligned} \partial_{\theta\theta} e &= 2\cos 2\theta - 2h\cos\theta \\ &= 4\cos^2\theta - 2 - 2h\cos\theta \end{aligned}$$

$$\begin{aligned} \partial_{\theta\theta} e(0) &= 2(1-h) \\ \partial_{\theta\theta} e(\theta_m) &= 2(h^2-1) \\ \partial_{\theta\theta} e(\pi) &= 2(1+h) \end{aligned}$$

Energy barrier

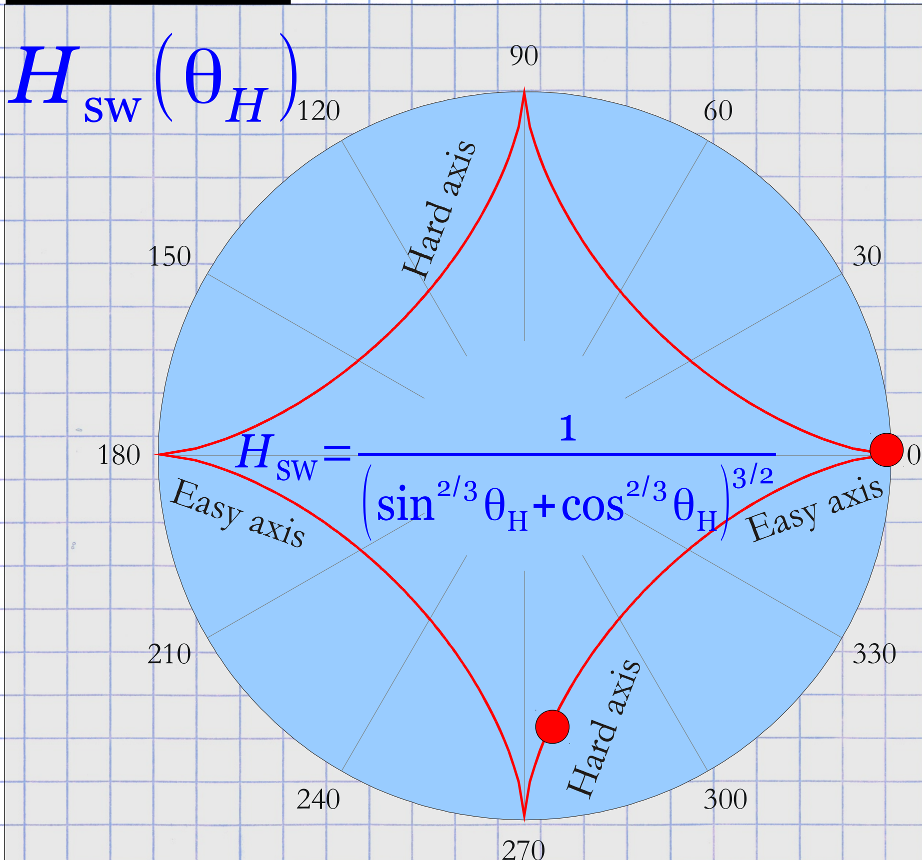
$$\begin{aligned} \Delta e &= e(\theta_{max}) - e(0) \\ &= 1 - h^2 + 2h^2 - 2h \\ &= (1-h)^2 \end{aligned}$$

Switching

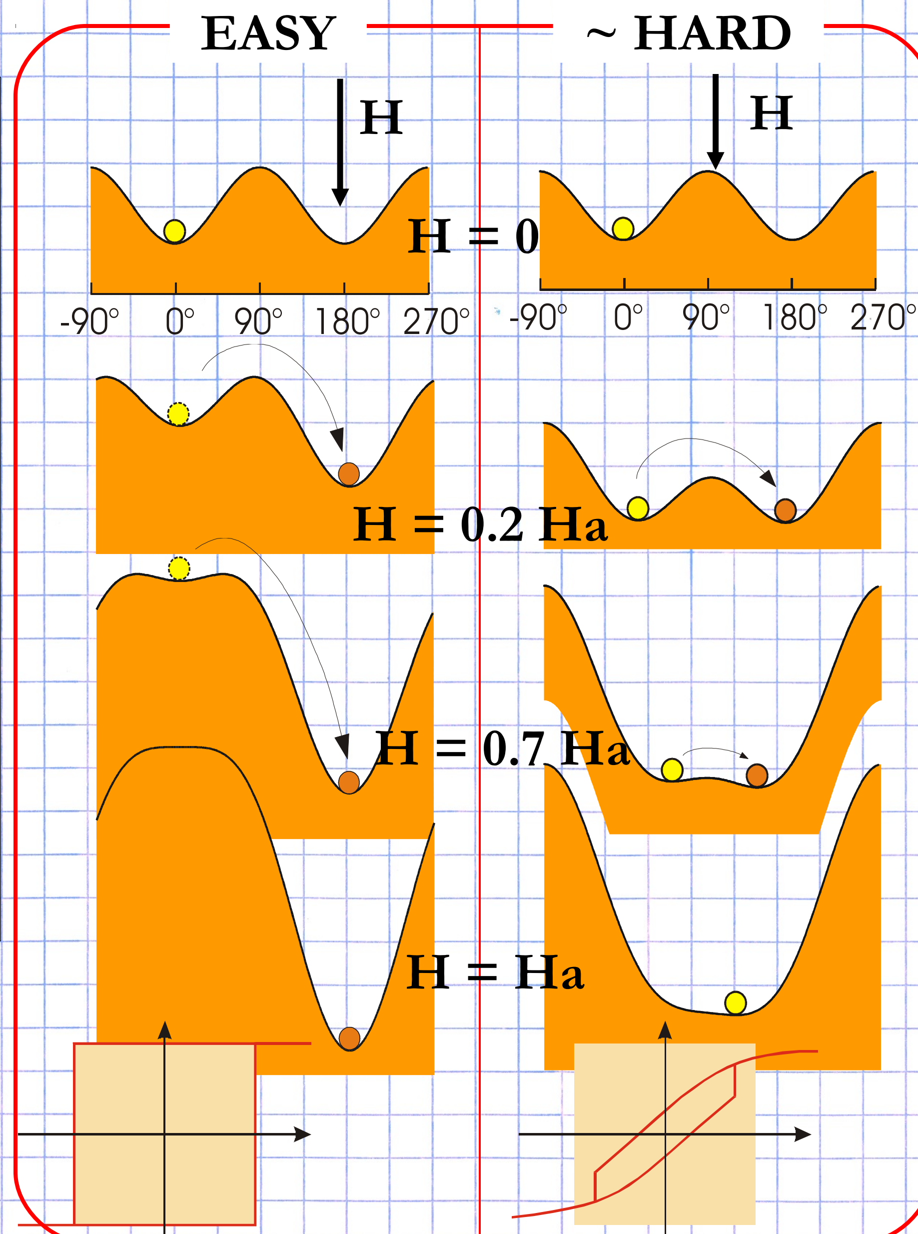
$$\begin{aligned} h &= 1 \\ H &= H_a = 2K/\mu_0 M_s \end{aligned}$$

$(1-h)^\alpha$ with exponent 1.5 in general

'Astroid' curve



- $H_{Sw}(\theta)$ is a <u>one</u> signature of reversal modes



J. C. Slonczewski, Research Memo RM 003.111.224, IBM Research Center (1956)

Switching field = Reversal field

A value of field at which an irreversible (abrupt) jump of magnetization angle occurs.

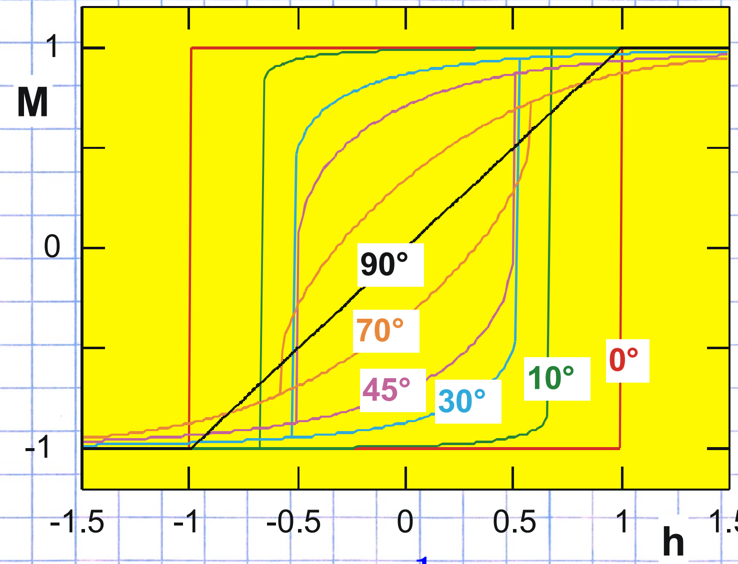
Can be measured only in single particles.

Coercive field

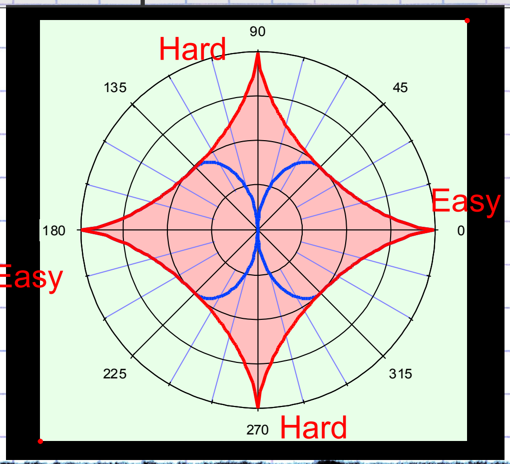
The value of field at which **M.H=0** $(\theta=\theta_H\pm\pi/2)$

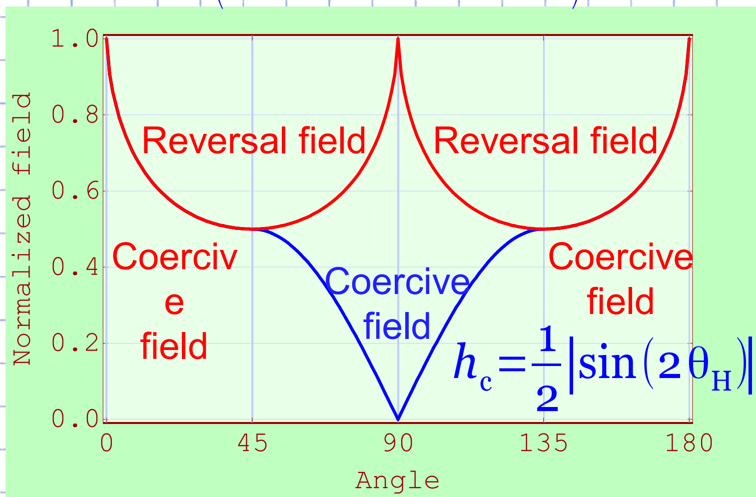
A quantity that can be measured in real materials (large number of 'particles').

May be or may not be a measure of the mean switching field at the microscopic level



$$H_{SW}=\frac{1}{\left(\sin^{2/3}\theta_H+\cos^{2/3}\theta_H\right)^{3/2}}$$



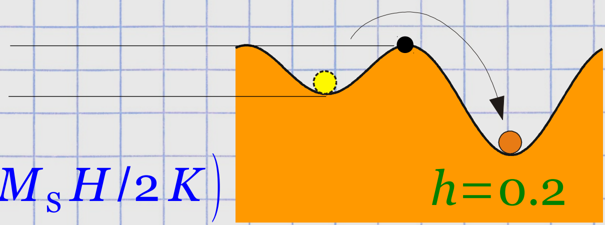


Barrier height

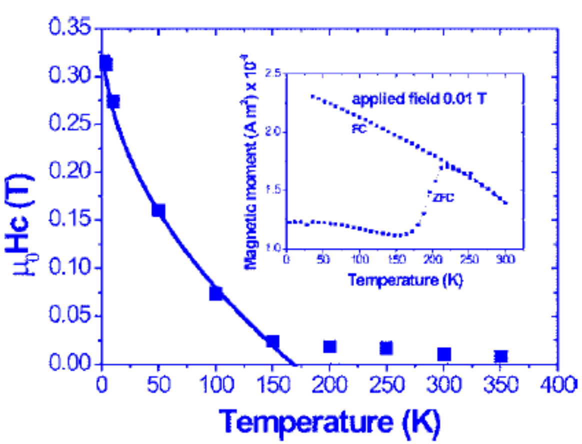
$$\Delta e = e(\theta_{max}) - e(0) = (1-h)^2$$

Δe

$$(h = \mu_0 M_S H / 2K)$$



J. Appl. Phys. **99**, 08Q514 (2006)



Thermal activation

Brown, Phys.Rev.130, 1677 (1963)

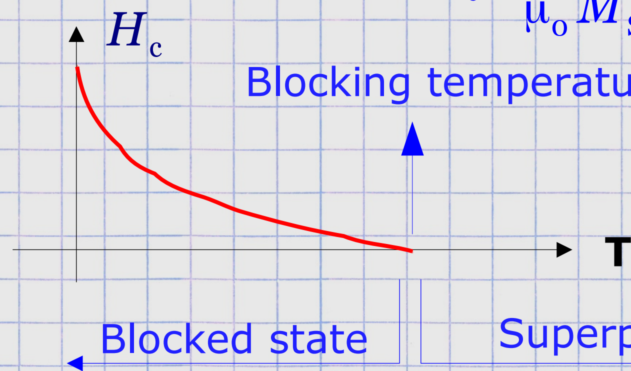
$$\tau = \tau_0 \exp\left(\frac{\Delta \mathcal{E}}{k_B T}\right) \Rightarrow \Delta \mathcal{E} = k_B T \ln(\tau/\tau_0)$$

$$\tau_0 \approx 10^{-10}\ \mathrm{s}$$

Lab measurement: $\tau \approx 1\ \mathrm{s} \Rightarrow \Delta \mathcal{E} \approx 25 k_B T$

$$\Rightarrow H_c = \frac{2K}{\mu_0 M_S}\left(1 - \sqrt{\frac{25 k_B T}{KV}}\right)$$

Blocking temperature $T_b \simeq KV / 25 k_B$



E. F. Kneller, J. Wijn (ed.) Handbuch der Physik XIII/2: Ferromagnetismus, Springer, 438 (1966)

M. P. Sharrock, J. Appl. Phys. 76, 6413-6418 (1994)

Notice, for magnetic recording : $\tau \approx 10^9\ \mathrm{s}$ $\quad KV_b \approx 40-60\, k_B T$

Formalism

C. P. Bean & J. D. Livingston, J. Appl. Phys. 30, S120 (1959)

Energy

$$E = KV\ f(\theta,\varphi) - \mu_0 \mu H$$

Partition function

$$Z = \sum \exp(-\beta E)$$

Average moment

$$\langle\mu\rangle = \frac{1}{\beta\mu_0 Z}\frac{\partial Z}{\partial H}$$

Isotropic case

$$Z = \int_{-\mathcal{M}}^{\mathcal{M}} \exp(-\beta E)\,\mathrm{d}\mu$$

Note: equivalent to integration over solid angle

$$\langle\mu\rangle = \mathcal{M}\left[\coth(x) - \frac{1}{x}\right]$$

Langevin function

Note:

Use the moment M of the particule, not spin ½ .

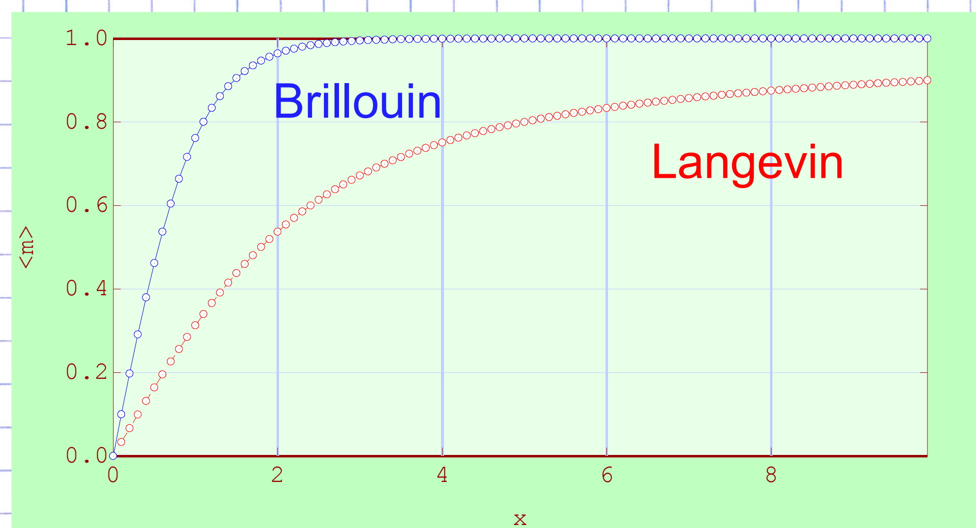
$$x = \beta\mu_0 \mathcal{M} H$$

Infinite anisotropy

$$Z = \exp(\beta\mu_0 \mathcal{M} H) + \exp(-\beta\mu_0 \mathcal{M} H)$$

$$\langle\mu\rangle = \mathcal{M} \tanh(x)$$

Brillouin ½ function



Material	T_C (K)	M_s (kA/m)	$\mu_0 M_s$ (T)	K (kJ/m^3)
Fe	1043	1730	2.174	48
Co	1394	1420	1.784	530
Ni	631	490	0.616	-4.5
$Fe_{20}Ni_{80}$ (Permalloy)	850	835	1.050	≈ 0
$Fe_3 0_4$	858	480	0.603	-13
$BaFe_{12}O_{19}$	723	382	0.480	250
$Nd_2Fe_{14}B$	585	1280	1.608	4900
$SmCo_5$	995	907	1.140	17000
Sm_2Co_{17}	1190	995	1.250	3300
FePt $L1_0$	750	1140	1.433	6600
CoPt $L1_0$	840	796	1.000	4900
Co_3Pt	1100	1100	1.382	2000

MRAM : anisotropy comes from shape or interfaces (see later) → materials with high anisotropy not wanted → Fe20Ni80, CoFe(B) etc. Avoid pure Co, Fe (bcc)

Other effects not discussed : magneto-elastic anisotropy → avoid pure Ni

Basics of precessional switching

Demonstration: 1999

Magnetization dynamics:

Landau-Lifshitz-Gilbert equation:

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = -|\gamma_0|\,\mathbf{m}\times\mathbf{H} + \alpha\,\mathbf{m}\times\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t}$$

γ_0 Gyromagnetic ratio

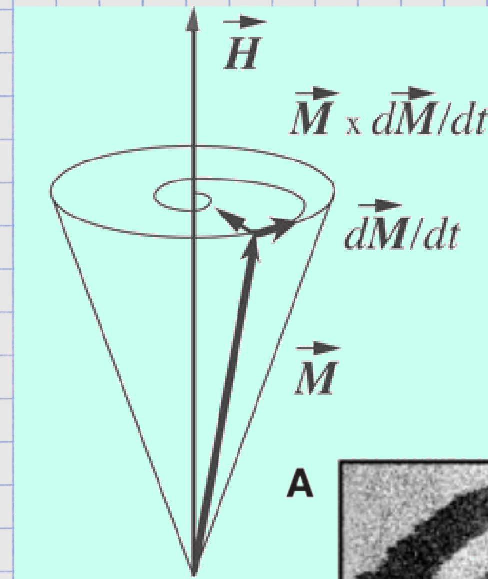
$\gamma_0 = \mu_0\gamma$ $\qquad \gamma = -g_J\dfrac{e}{2m_e} < 0$

$\gamma_{\mathrm{spin}}/2\pi \approx 28\ \mathrm{GHz/T}$

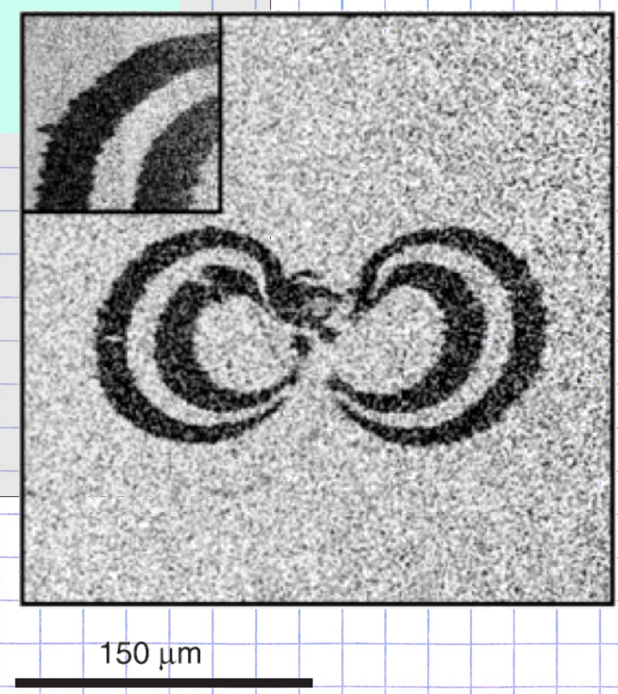
H_{eff} Effective field (including applied)

$$H_{\mathrm{eff}} = -\frac{1}{\mu_0 M_s}\frac{\partial E_{\mathrm{mag}}}{\partial \mathbf{m}}$$

α Damping coefficient $\alpha = 10^{-1} - 10^{-3}$

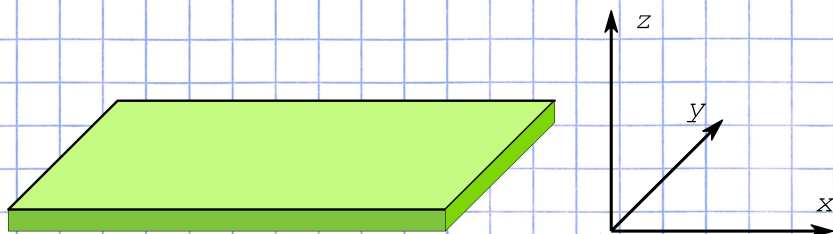


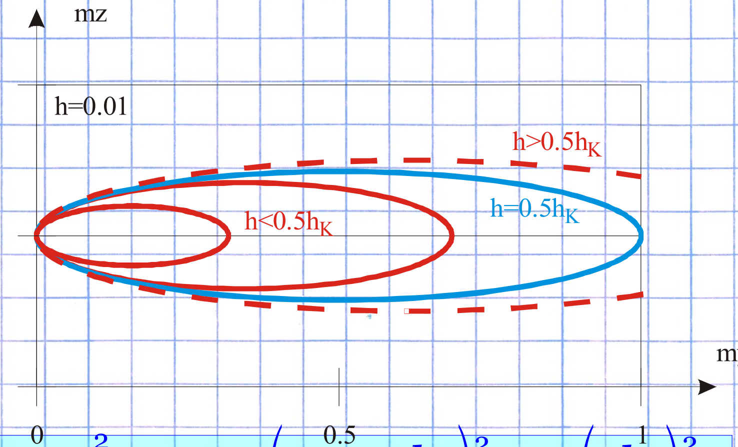
A



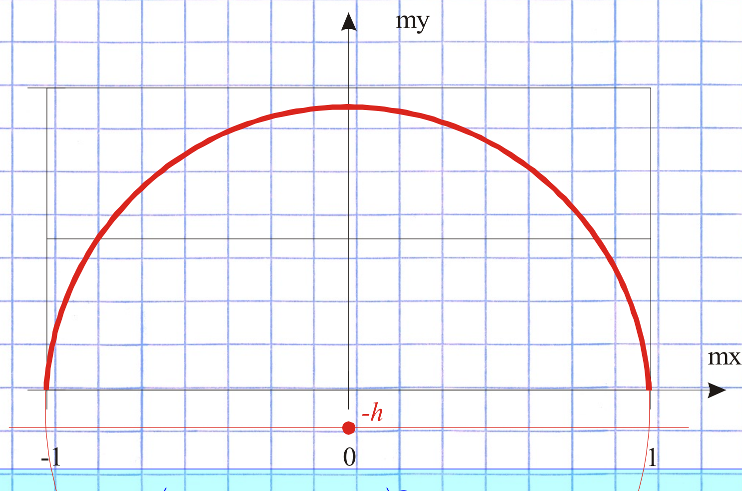
C. Back et al., Science 285, 864 (1999)

Magnetization trajectories

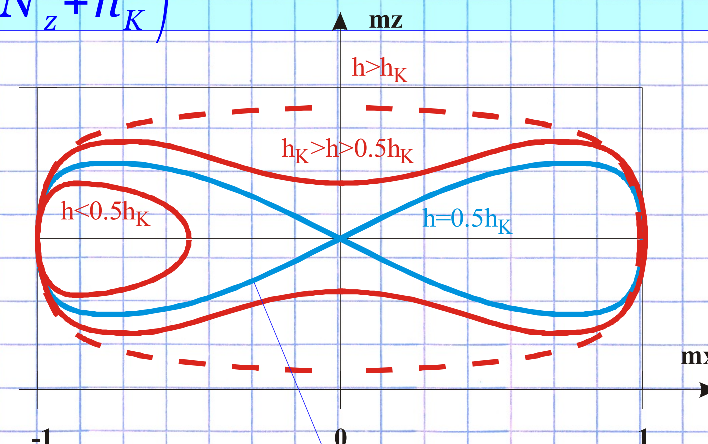




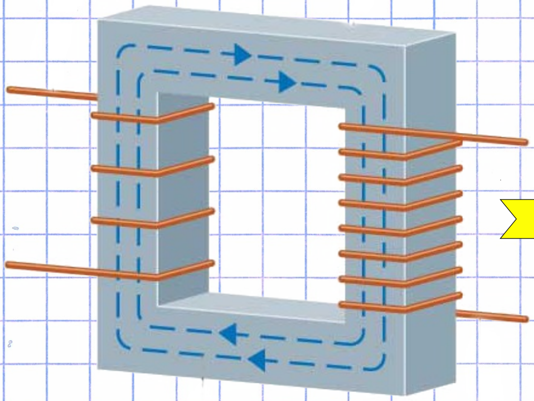
$$\frac{m_z^2}{\left(\frac{h_K}{N_z+h_K}\right)} + \left(m_y - \frac{h}{h_K}\right)^2 = \left(\frac{h}{h_K}\right)^2$$



$$m_x^2 + \frac{\left(m_y + h/N_z\right)^2}{1+h_K/N_z} = 1 + \frac{h^2}{N_z\left(N_z+h_K\right)}$$

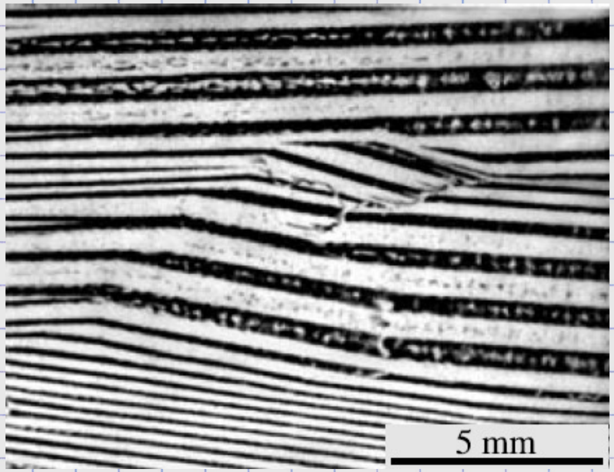


$$\omega \approx 0.847\,\gamma_0 \sqrt{M_s\left(H-H_K\right)/2}$$



Bulk material

Numerous and complex magnetic domains

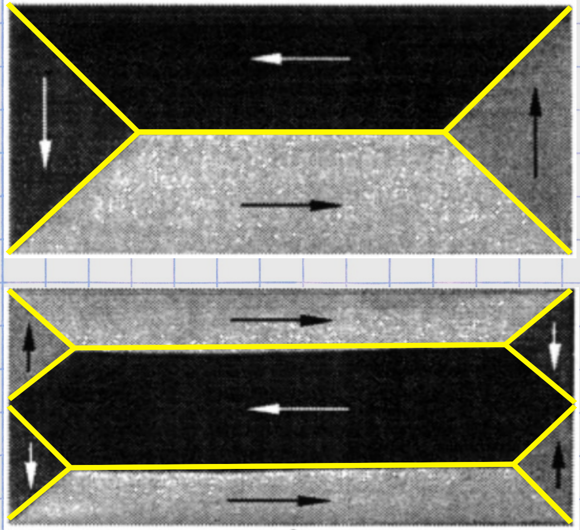


FeSi soft sheet

A. Hubert, *Magnetic domains*

Mesoscopic scale

Small number of domains, simple shape

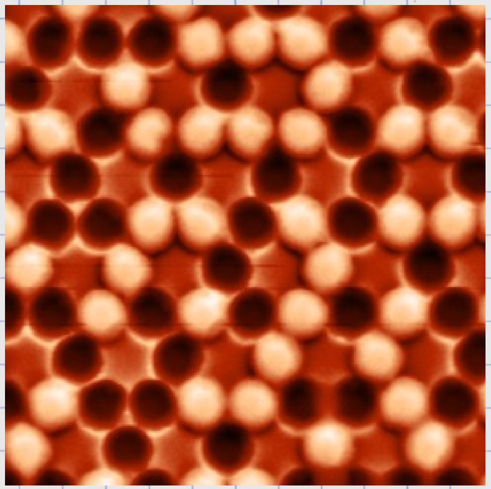


Microfabricated dots
Kerr magnetic imaging

A. Hubert, *Magnetic domains*

Nanometric scale

Magnetic single-domain



Nanofabricated dots
MFM

Sample courtesy :
N. Rougemaille, I. Chioar

Anisotropy exchange length

$$E = A(\partial_x \theta)^2 + K \sin^2\theta$$

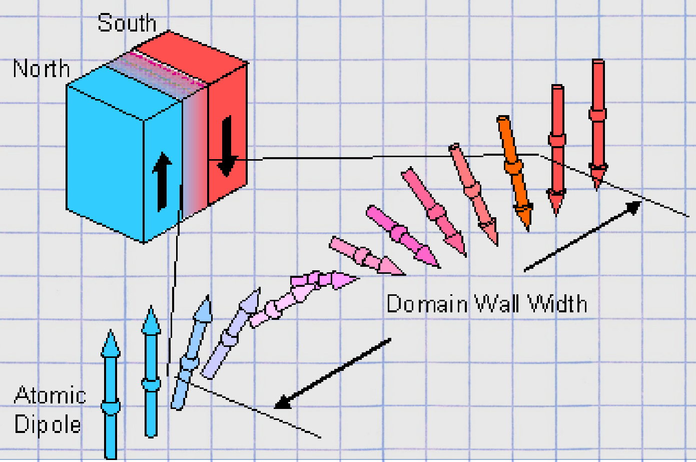
Exchange → $\mathrm{J/m}$

Anisotropy → $\mathrm{J/m^3}$

Anisotropy exchange length: $\Delta_u = \sqrt{A/K}$

$\Delta_u \approx 1\ \mathrm{nm}$ → $\Delta_u \geq 100\ \mathrm{nm}$

Hard — Soft



Often called *Bloch parameter* or *domain-wall width*

Dipolar exchange length

$$E = A(\partial_x \theta)^2 + K_d \sin^2\theta$$

Exchange → $\mathrm{J/m}$

Dipolar energy → $\mathrm{J/m^3}$

$$K_d = \frac{1}{2}\mu_0 M_s^2$$

Dipolar exchange length:

$$\Delta_d = \sqrt{A/K_d}$$
$$= \sqrt{2A/\mu_0 M_s^2}$$

$\Delta_d \approx 3-10\ \mathrm{nm}$

Single-domain critical size relevant for nanoparticules made of soft magnetic material

Often called *Exchange length*

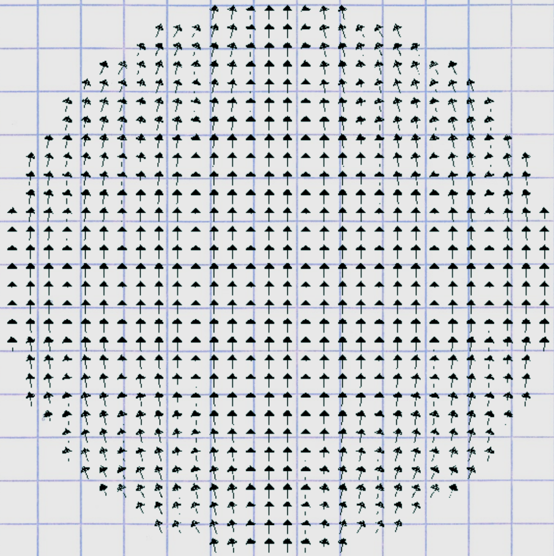
Notice:

Other length scales: with field etc.

Geometry

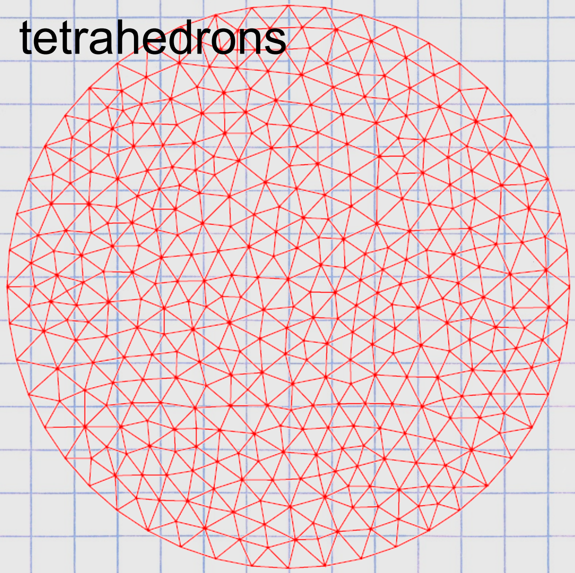
Finite differences

Cells = prisms



Finite elements

Cells = tetrahedrons



Constraints

- Cell size smaller than magnetic length scales
- Time step <1ps
- Limiting step : calculation of dipolar field

Features

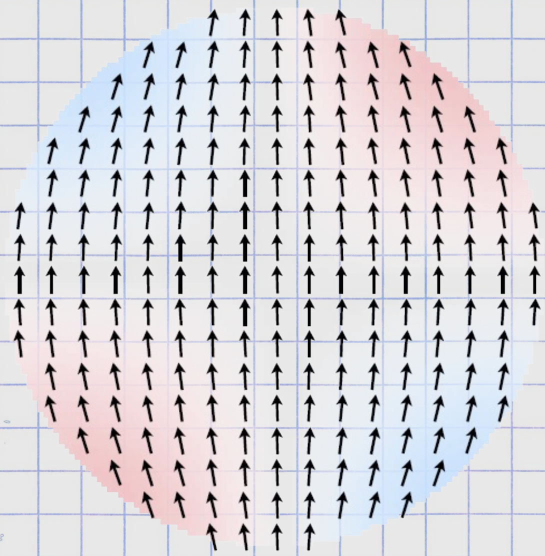
- Map of magnetization
- Magnetization dynamics
- Coupling with transport : still imperfect
- Long time & temperature : difficult

Some codes

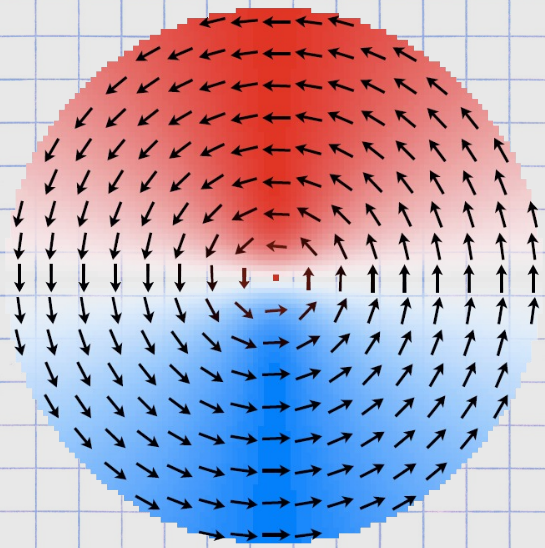
- Proprietary
- FD : OOMMF (soon on GPU), Mumax, Micromagus, GPMagnet ...
- FE : LLG micromagnetics simulator, Magpar, Nmag ...

http://magnetism.eu/links/tools.html

Flat disk ('dot')

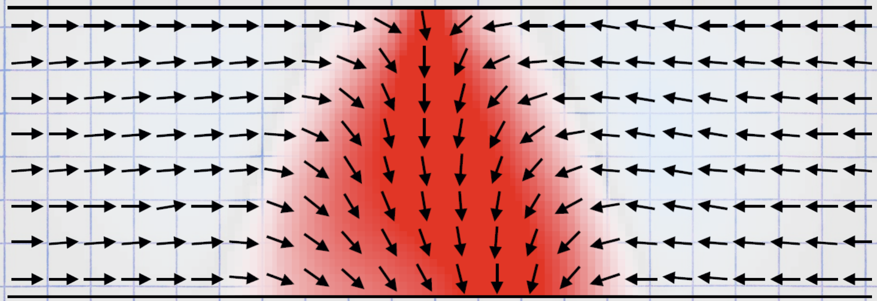


Near single-domain



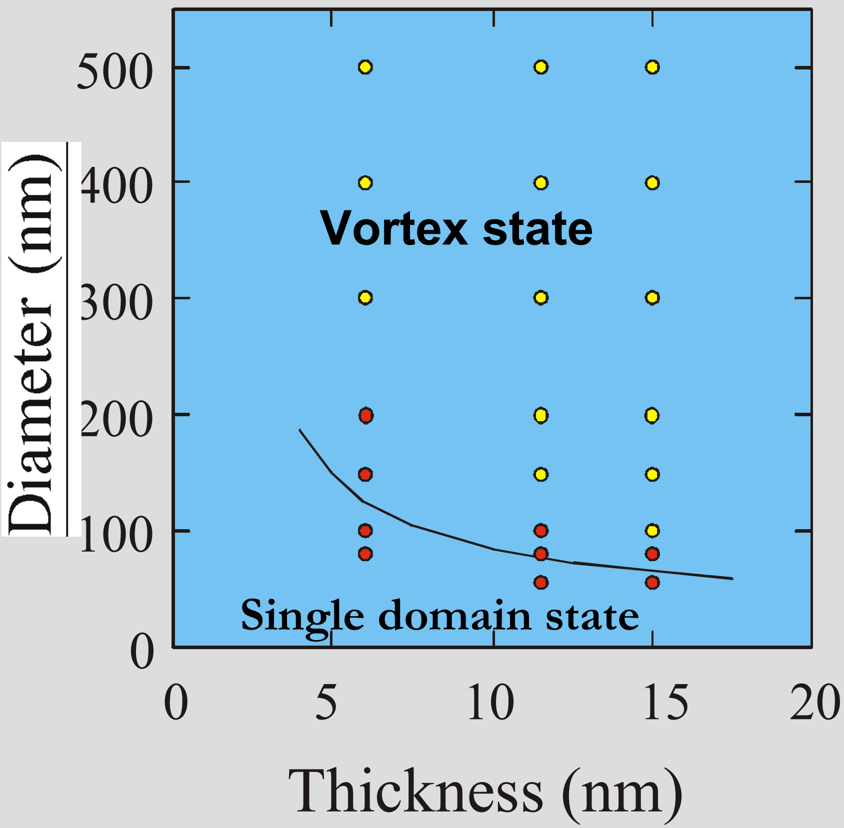
Vortex state (flux closure)

Strip (one-dimensional track)



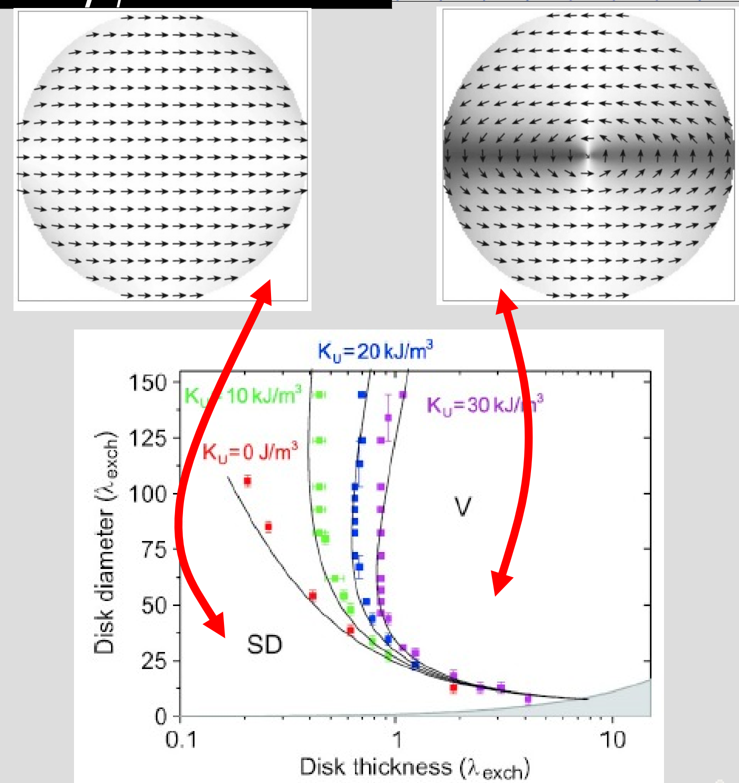
'Transverse' domain wall

Experiments



R.P. Cowburn, J.Phys.D:Appl.Phys.33, R1–R16 (2000)

Theory / Simulation



P.-O. Jubert & R. Allenspach, PRB 70, 144402/1-5 (2004)

Zero-field cross-over

$$t\,D \approx 20\,\Delta_d^2$$

- Vortex state (flux-closure) dominates at large thickness and/or diameter
- The size limit for single-domain is much larger than the exchange length
- Experimentally the vortex may be difficult to reach close to the transition (hysteresis)

MAGNETIZATION PROCESSES – Range of dipolar field

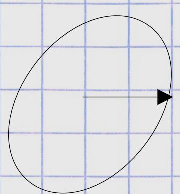
Upper bound for dipolar fields in 2D

Estimation of an upper range of dipolar field in a 2D system

$$\left\|\mathbf{H}_\mathrm{d}(R)\right\| \leqslant \int_\mathrm{o}^{R} \frac{2\pi r}{r^3}\,\mathrm{d}r$$

Integration

Local dipole $1/r^3$



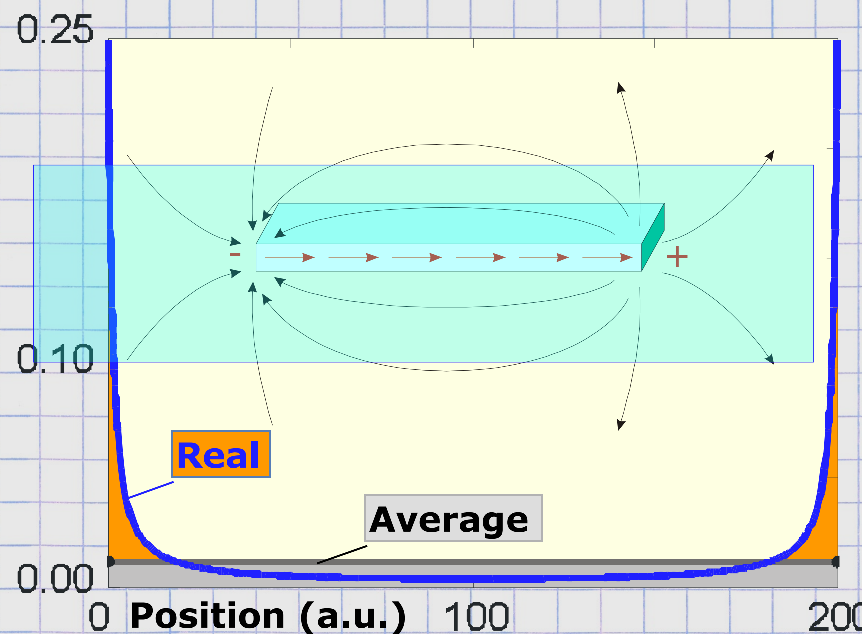
R

$$\left\|\mathbf{H}_\mathrm{d}(R)\right\| = \mathrm{Cte} + \mathcal{O}(1/R)$$

Convergence with finite radius (typically thickness)

Non-homogeneity of dipolar fields in 2D

Example: flat strip with thickness/height = 0.0125



⇛ Dipolar fields are weak and short-ranged in 2D or even lower-dimensionality systems

⇛ Dipolar fields can be highly non-homogeneous in anisotropic systems like 2D

⇛ Consequences on dot’s non-homogenous state, magnetization reversal, collective effects etc.

Configurational anisotropy: deviations from single-domain

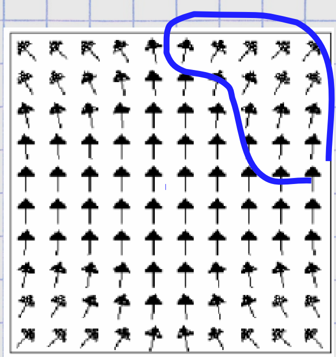
Strictly speaking, 'shape anisotropy' is of second order:

$$E_\mathrm{d}=\frac{1}{2}\mu_0\left(N_x M_x^2 + N_y M_y^2 + N_z M_z^2\right)$$

2D: $\mathcal{E}_\mathrm{d}=V K_\mathrm{d}\sin^2\theta$

In real samples magnetization is never perfectly uniform: competition between exchange and dipolar

Num.Calc. (100nm)



Flower state

$c/a > 2.7$

Leaf state

$c/a < 2.7$

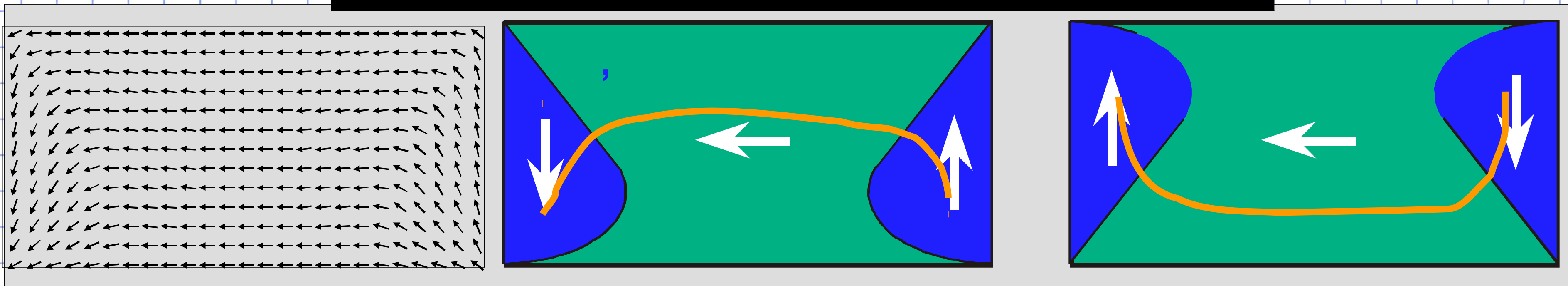
Configurational anisotropy may be used to stabilize configurations against switching

Higher-order contributions to magnetic anisotropy

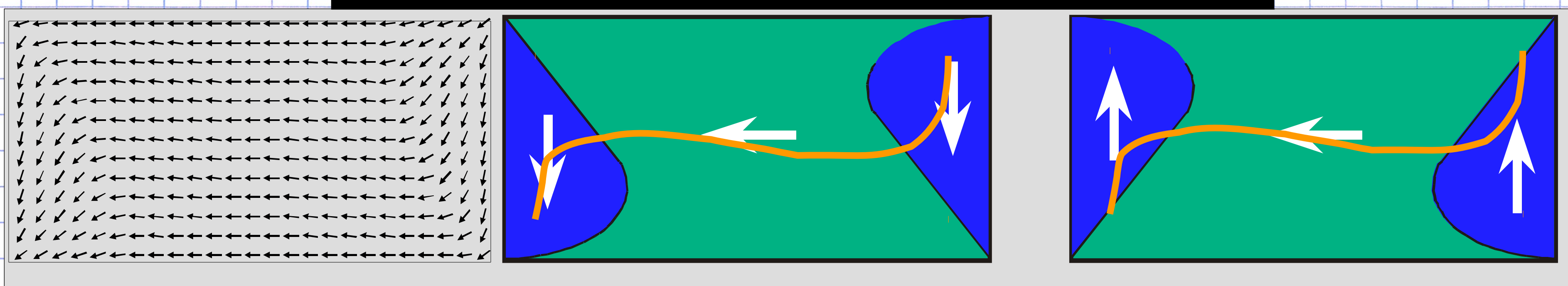
M. A. Schabes et al., JAP 64, 1347 (1988)

R.P. Cowburn et al., APL 72, 2041 (1998)

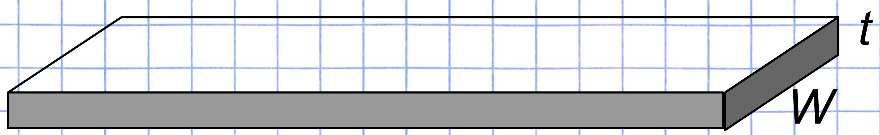
‘C’ state



‘S’ state



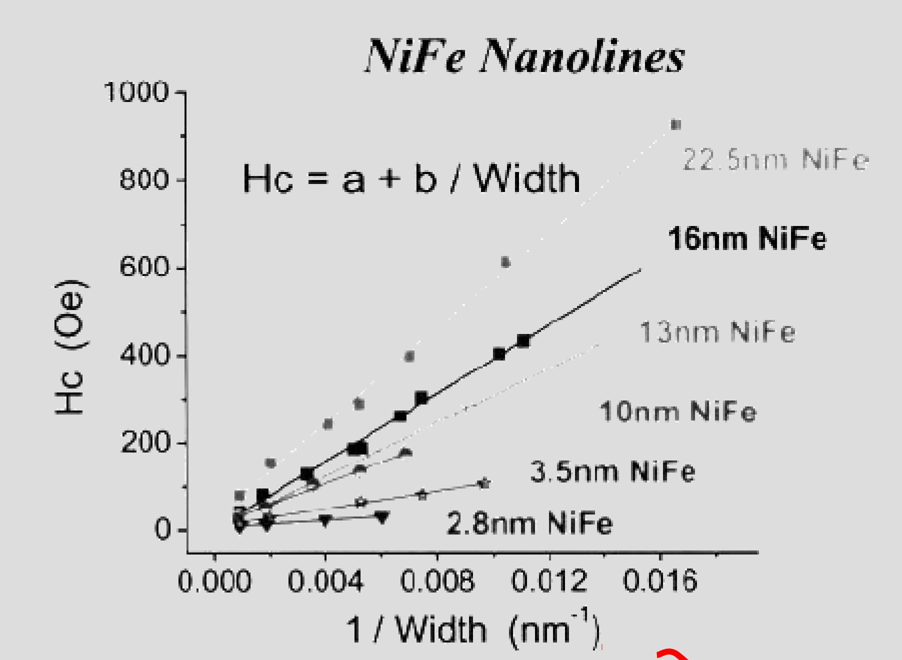
- At least 8 nearly-equivalent ground-states for a rectangular dot
- Issue for the reproductibility of magnetization reversal



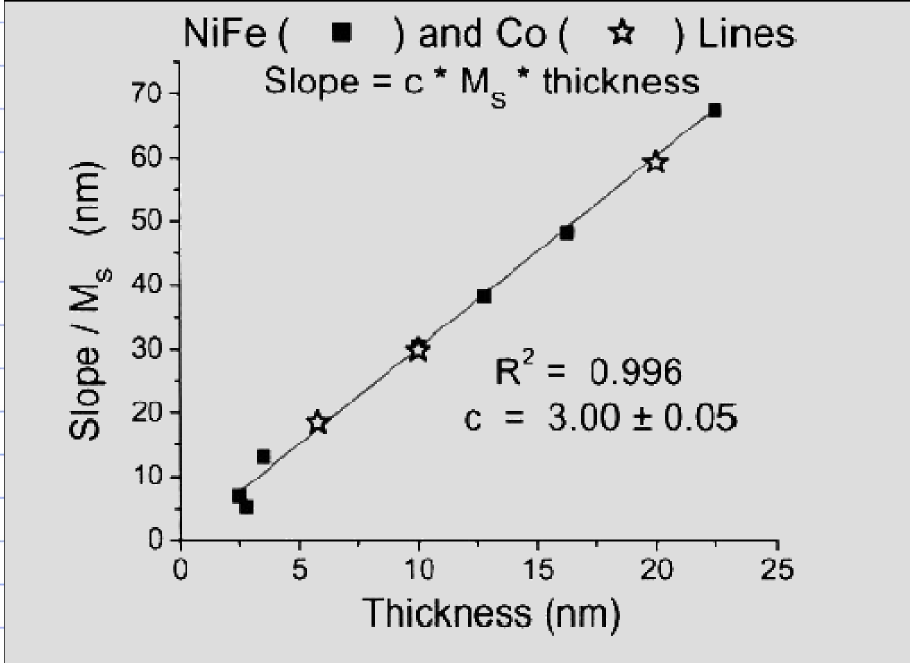
Hypotheses ⇨ Soft magnetic material

⇨ Not too small neither too large nanostructures

Hc ~1/Width



Hc ~Ms * Thickness



$$H_c \approx a + 3 M_s \frac{t}{W}$$

~Lateral demagnetizing coefficient of the strip

W. C. Uhlig & J. Shi,
Appl. Phys. Lett. 84, 759 (2004)

Magnetization is pinned at sharp ends

Experiments **Permalloy** (soft)

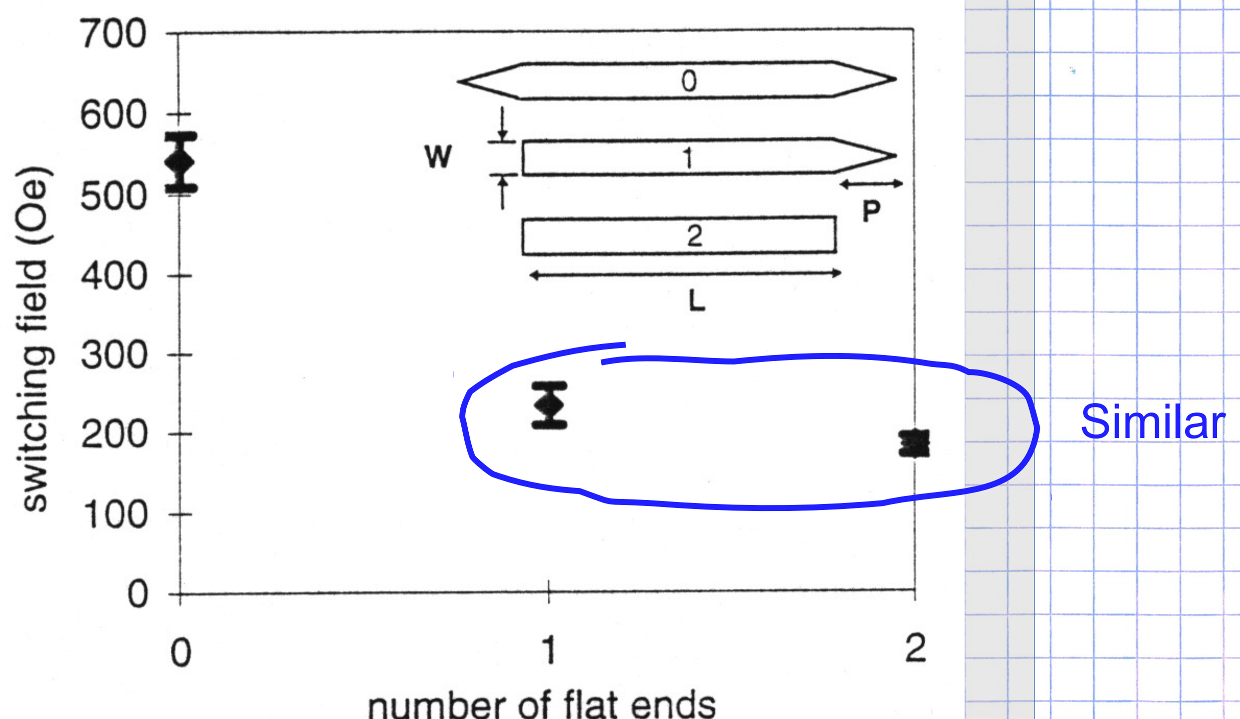
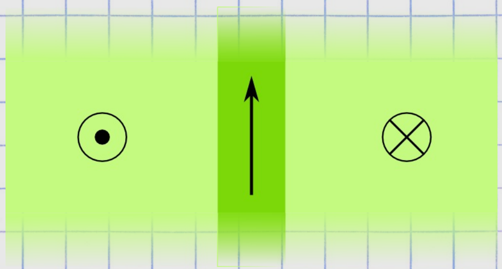


Fig. 8 Dependence of switching field of acicular elements on the number of flat ends. Element geometry is also shown: $L=2.5\,\mu m$, $W=200$ nm, $P=500$ nm.

K.J. Kirk et al., J. Magn. Soc. Jap., 21 (7), (1997)

Bloch domain wall in the bulk (2D)

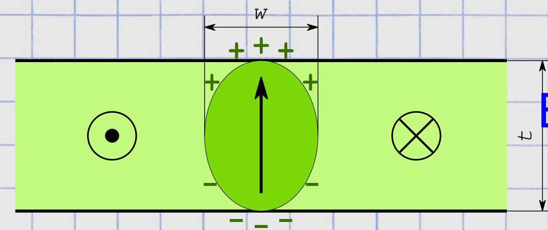


- No magnetostatic energy
- Width $\Delta_u = \sqrt{A/K}$
- Areal energy $\gamma_W = 4\sqrt{AK}$

Other angles & anisotropy

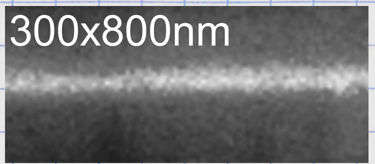
F. Bloch, Z. Phys. 74, 295 (1932)

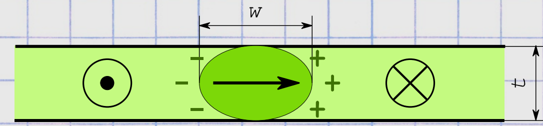
Domain walls in thin films (2D → 1D)



Bloch wall

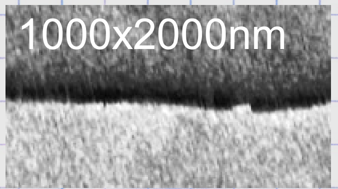
$t \gtrsim w$





Néel wall

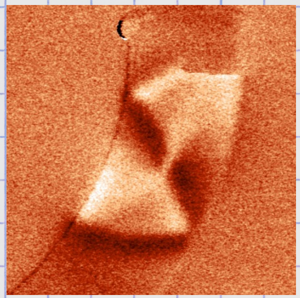
$t \lesssim w$



- Contains magnetostatic energy
- No exact analytics

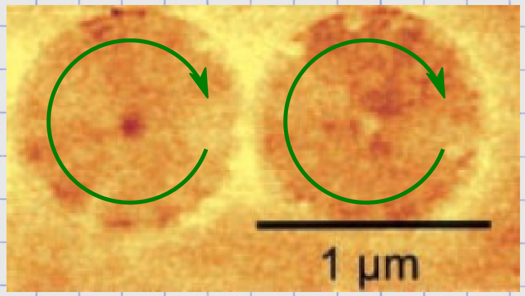
L. Néel, C. R. Acad. Sciences 241, 533 (1956)

Constrained walls (eg : in stripes)



Permalloy (15nm)
Strip 500nm

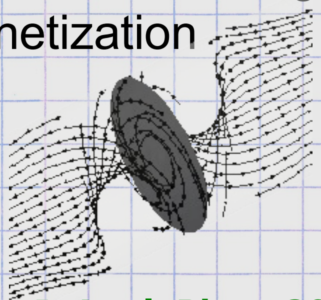
Magnetic vortex (1D → 0D)



T. Shinjo et al.,
Science 289, 930 (2000)

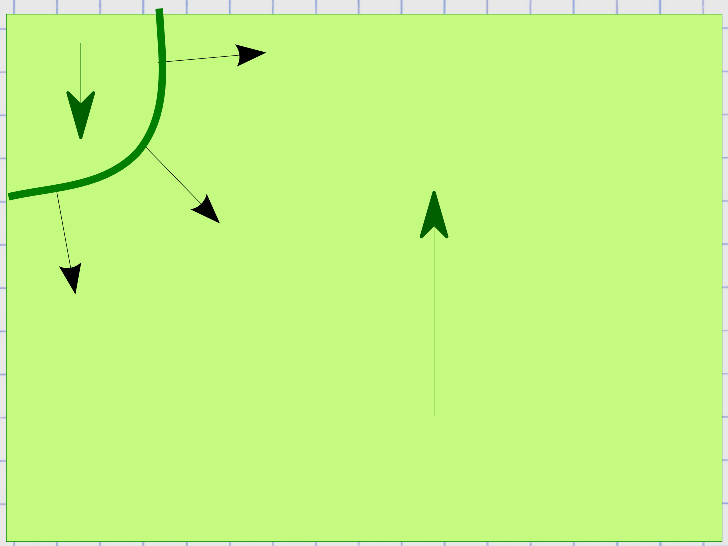
Bloch point (0D)

- Point with vanishing magnetization



W. Döring, J. Appl. Phys. 39, 1006 (1968)

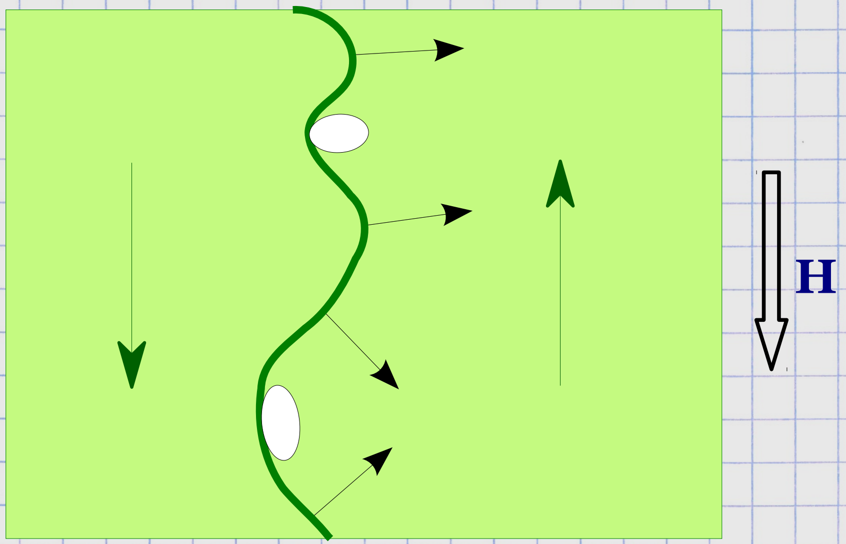
Coercivity determined by nucleation



⇨ Physics has some similarity with that of grains

⇨ Concept of nucleation volume

Coercivity determined by propagation



⇨ Physics of surface/string in heterogeneous landscape

⇨ Modeling necessary

Towards superparamagnetism

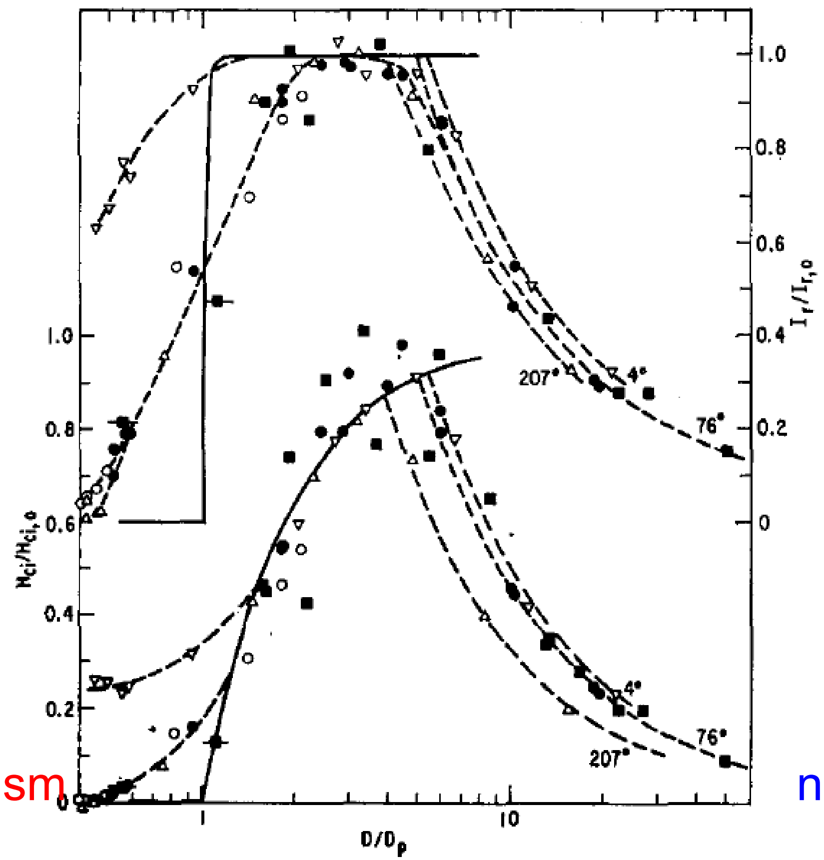
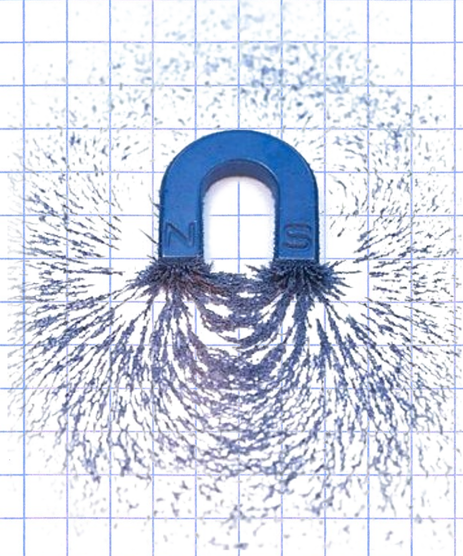
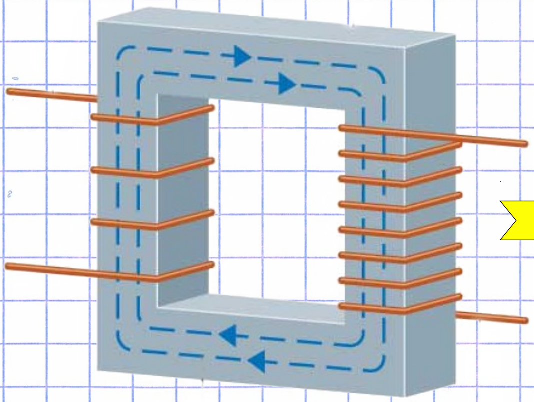


FIG. 1. Particle size dependence of essentially spherical, randomly oriented, iron particles. Calculated curve given by solid line. Diameters $D=\hat{d}_v$. Data at 76°K obtained from electron microscopic examination ■, calculated from I_r/I_s vs temperature O, and from smoothed data of H_{ci} vs D ●.

Towards nucleation-propagation and multidomain

E. F. Kneller & F. E. Luborsky,
Particle size dependence of coercivity and remanence of single-domain particles,
J. Appl. Phys. 34, 656 (1963)





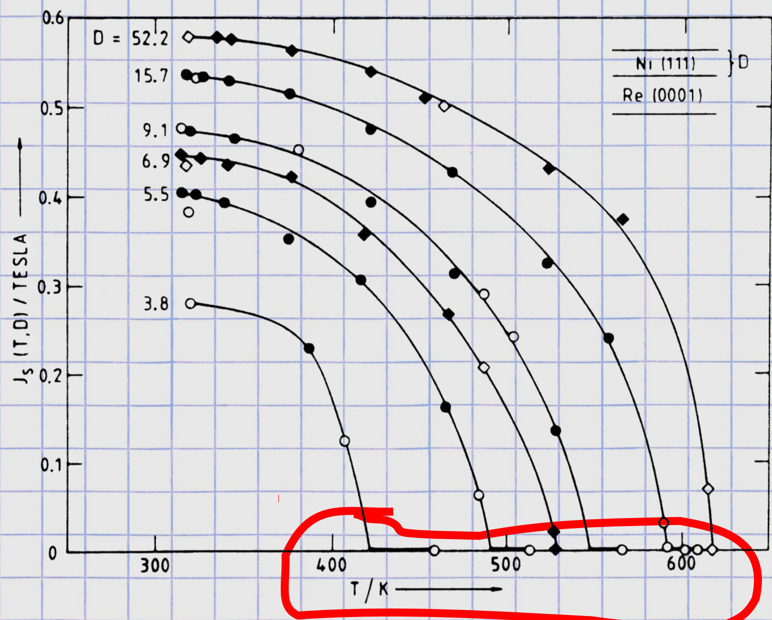
Elements of theory

- Ising (1925). No magnetic order at T>0K in 1D Ising chain.
- Bloch (1930). No magnetic order at T>0K in 2D Heisenberg.
  (spin-waves; isotropic Heisenberg)
- → N. D. Mermin, H. Wagner, PRL17, 1133 (1966)
- Onsager (1944) + Yang (1951).
  2D Ising model: Tc>0K

Magnetic anisotropy stabilizes ordering

Experiments

Ni(111)/Re(0001)



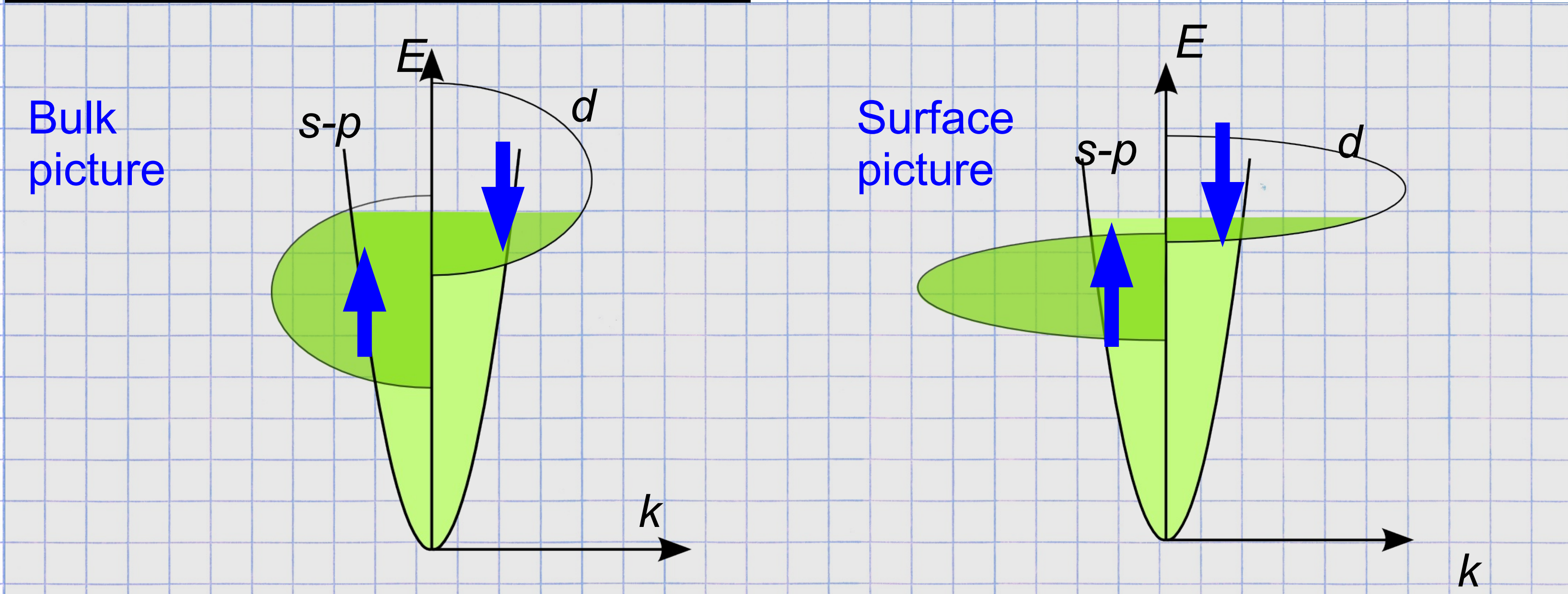
R. Bergholz and U. Gradmann, JMMM45, 389 (1984)

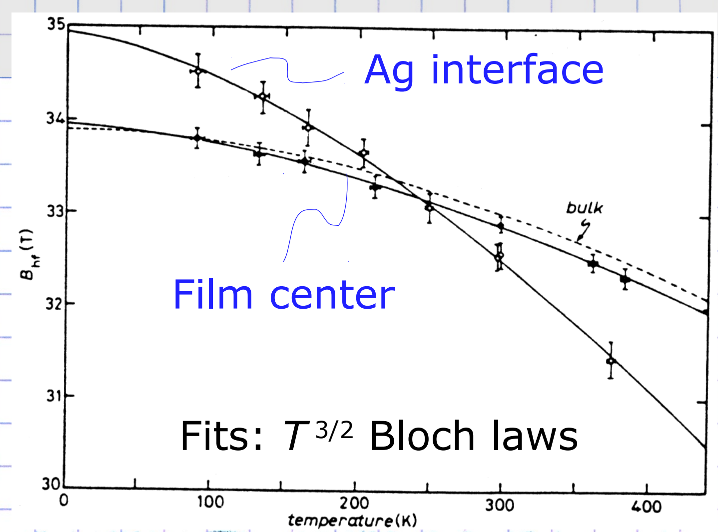
Tc interpreted with molecular field

Noticeable below ≈ 1nm

Enhanced moment at surfaces

Simple picture: band narrowing at surfaces





Ag/Fe(110)/W(110)

U. Gradmann et al.

In practice:

20-30 %, however

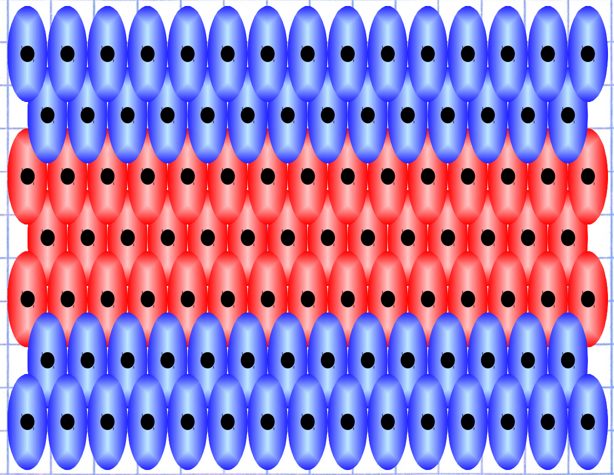
decays faster with

temperature

Surface anisotropy

L. Néel, J. Phys. Radium 15, 15 (1954)

« Superficial magnetic anisotropy and orientational superstructures »



Overview

Breaking of symmetry for surface/interface atoms

Correction to the magneto-crystalline energy

$$E_s = K_{s,1}\cos^2\theta + K_{s,2}\cos^4\theta + \ldots$$

« This surface energy, of the order of 0.1 to 1 erg/cm2, is liable to play a significant role in the properties of ferromagnetic materials spread in elements of dimensions smaller than 100Å »

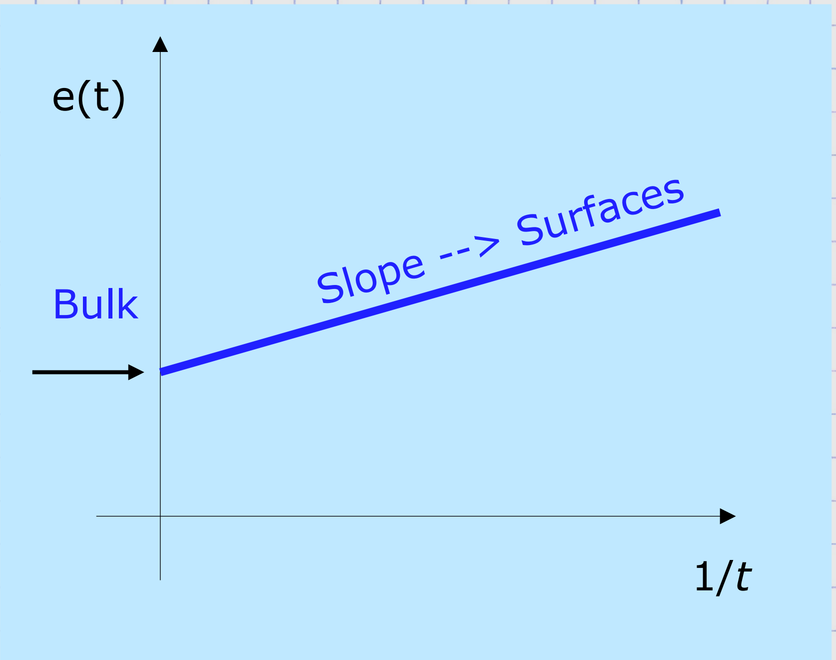
Pair model of Néel:

- Ks estimated from magneto-elastic constants
- Does not depend on interface material
- Yields order of magnitude only: correct value from experiments or calculations (precision !)

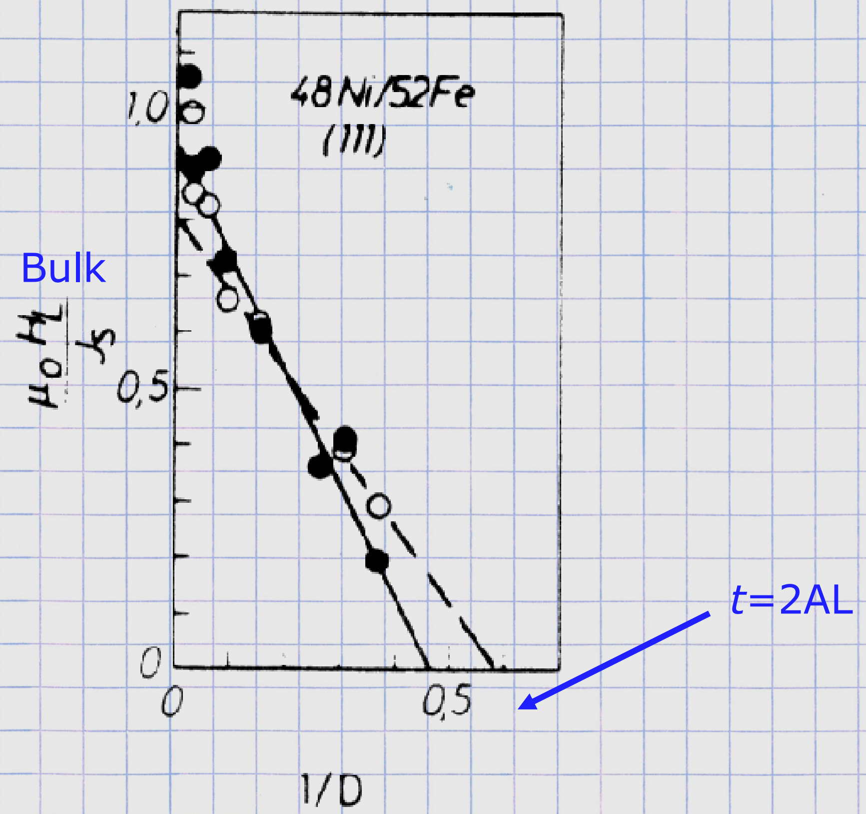
History of surface anisotropy : 1/t plot

$$\mathcal{E}(t)=K_V t+2K_s$$

$$\Rightarrow \quad E(t)=K_V+\frac{2K_s}{t}$$



First example of perpendicular anisotropy



U. Gradmann and J. Müller, Phys. Status Solidi 27, 313 (1968)

What use ?

- ⇨ Well-defined anisotropy
→ do not need exact elliptic shape, better for down-scaling
- ⇨ High magnitude of anisotropy
→ better stability
- ⇨ Provides out-of-plane polarizer for spintronics
- ⇨ Etc.

Materials

- ⇨ 'Bulk-like magnetoelasticiv : Co/Ni, NiPd etc.
- ⇨ Interface : 3d + heavy elements for large spin-orbit coupling : Co/Au, Co/Pt, Co/Pd
- ⇨ Interface (more recent)
  - 3d / oxydes (Mg0, Al2O3)
  - 3d / graphene

Figures

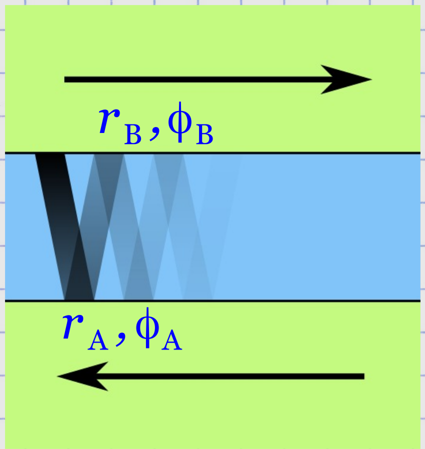
- ⇨ Interfaces 3d / heavy interfaces : up to 1-2nm
- ⇨ Interfaces 3d / oxide & graphene : up to 3-4nm
- ⇨ Multilayers : tens of nanometers

M. T. Johnson et al., Magnetic anisotropy in metallic multilayers, Rev. Prog. Phys. 59, 1409 (1996)

U. Gradmann, Magnetism in ultrathin transition metal films, in Handbook of Magnetism, K. H. J. Buschow (ed.), Elsevier Science Publishers, (1993)

The physics

Spin-dependent quantum confinement in the spacer layer



Forth & back phase shift

$$\Delta\phi = qt + \phi_A + \phi_B$$

Spin-independent

$$q = k^+ - k^-$$

Spin-dependent

$$r_A, \phi_A, r_B, \phi_B$$

⇨ Constructive or destructive interferences depending on spacer thickness

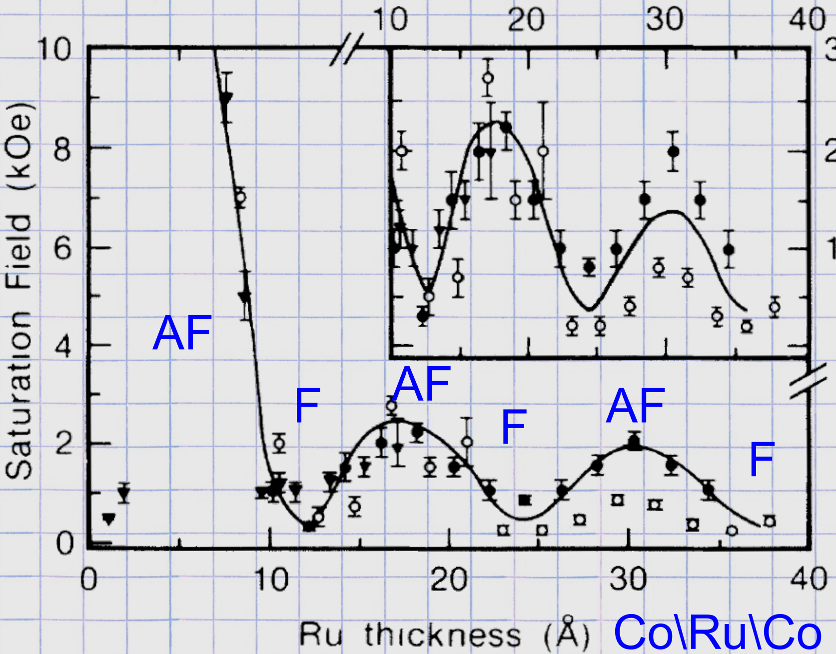
Illustration

Coupling strength:

$$E_S = J(t)\cos\theta \quad \text{in } J/m^2$$

$$\theta = \langle m_1, m_2 \rangle$$

with: $$J(t) = \frac{A}{t^2}\sin(q_\alpha t + \Psi)$$



S. S. P. Parkin et al., PRL64, 2304 (1990)

P. Bruno, J. Phys. Condens. Matter 11, 9403 (1999)

Ti		**V**		**Cr**		**Mn**		**Fe**		**Co**		**Ni**		**Cu**	
No Coupling		9	3	7	7			Ferro-Magnet		Ferro-Magnet		Ferro-Magnet		8	3
		0.1	9	.24	18									0.3	10
2.89		2.62		2.50		2.24		2.48		2.50		2.49		2.56	
Zr		**Nb**		**Mo**		**Tc**		**Ru**		**Rh**		**Pd**		**Ag**	
No Coupling		9.5	2.5	5.2	3			3	3	7.9	3	No Coupling		No Coupling	
		.02	*	.12	11			5	11	1.6	9				
3.17		2.86		2.72		2.71		2.65		2.69		2.75		2.89	
Hf		**Ta**		**W**		**Re**		**Os**		**Ir**		**Pt**		**Au**	
No Coupling		7	2	5.5	3	4.2	3.5			4	3	No Coupling		No Coupling	
		.01	*	.03	*	.41	10			1.85	9				
3.13		2.86		2.74		2.74		2.68		2.71		2.77		2.88	

fcc bcc
hcp complex cubic

Element	
A_1 (Å)	ΔA_1 (Å)
J_1 (erg/cm²)	P (Å)
r_{ws} (Å)	

$$J(t)=\frac{A}{t^2}\sin\left(\frac{2\pi t}{P}+\Psi\right)$$

Illustration of coupling strength

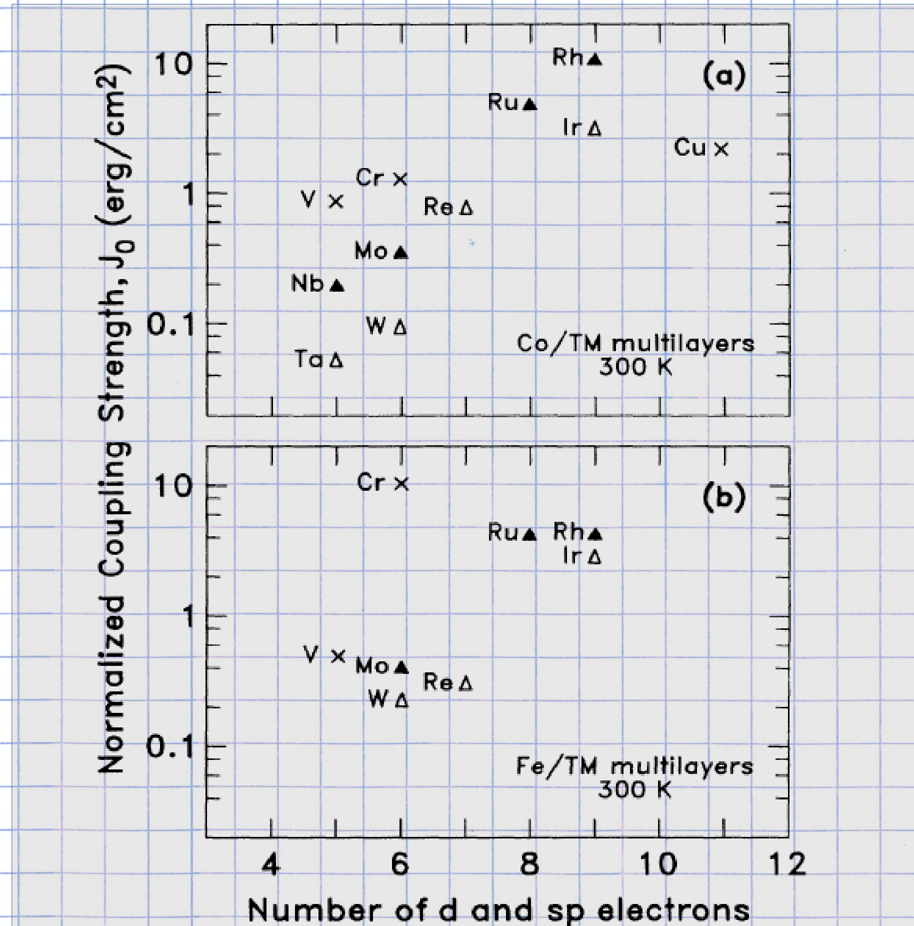


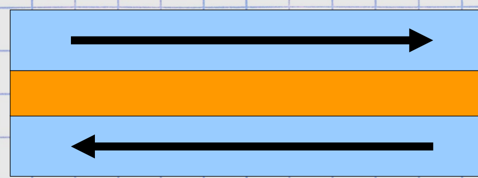
FIG. 3. Dependence of the normalized exchange coupling constant on the 3*d*, 4*d* and 5*d* transition metals in (a) Co/TM and (b) Fe/TM multilayers.

Note: $J(t)$ extrapolated for t=3Å

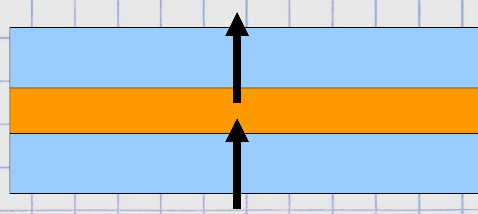
S. S. P. Parkin, Phys. Rev. Lett. 67, 3598 (1991)

Stacked dots : dipolar coupling

In-plane magnetization



Out-of-plane magnetization



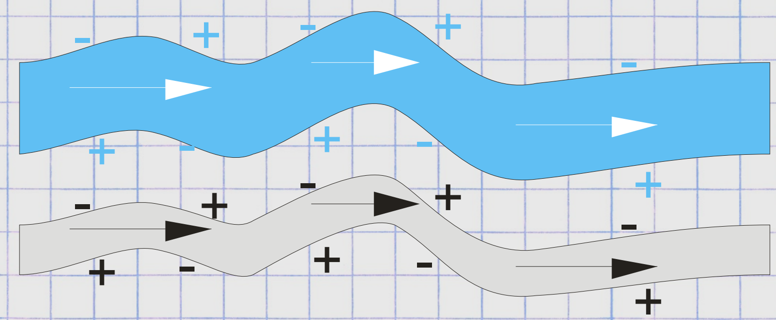
Hint:

An upper bound for the dipolar coupling is the self demagnetizing field

Notice: similar situation as for RKKY coupling

Stacked dots : orange-peel coupling

In-plane magnetization



Always parallel coupling

L. Néel, C. R. Acad. Sci. 255, 1676 (1962)
(valid only for thick films)

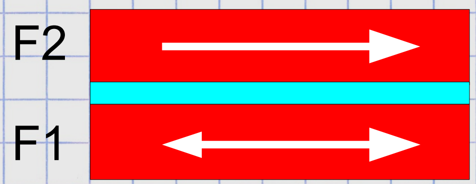
J. C. S. Kools et al., J. Appl. Phys. 85, 4466 (1999)
(valid for any films)

Out-of-plane magnetization

May be parallel or antiparallel

J. Moritz et al., Europhys. Lett. 65, 123 (2004)

Synthetic Ferrimagnets (SyF) – Crude description



Hypothesis:

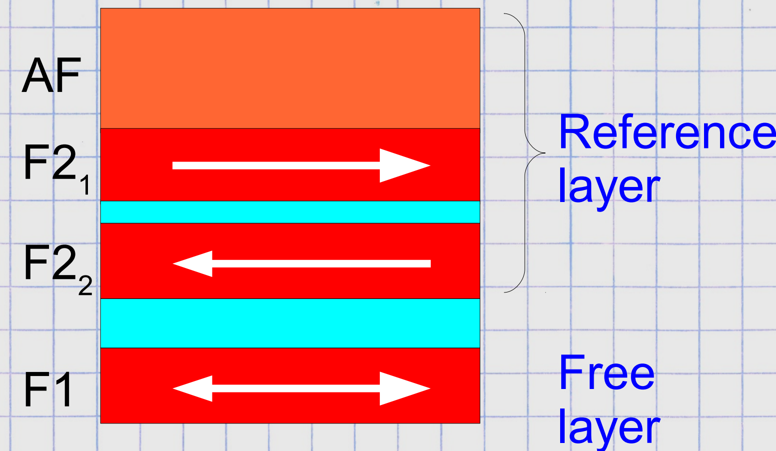
- ⇨ Two layers rigidly coupled
- ⇨ Reversal modes unchanged
- ⇨ Neglect dipolar coupling

$$M = \frac{|e_1 M_1 - e_2 M_2|}{e_1 + e_2} \qquad K = \frac{e_1 K_1 + e_2 K_2}{e_1 + e_2}$$

$$H_c \approx \frac{e_1 M_1 H_{c,1} + e_2 M_2 H_{c,2}}{|e_1 M_1 - e_2 M_2|}$$

What use?

- ⇨ Increase coercivity of layers
- ⇨ Decrease intra- and inter- dot dipolar coupling

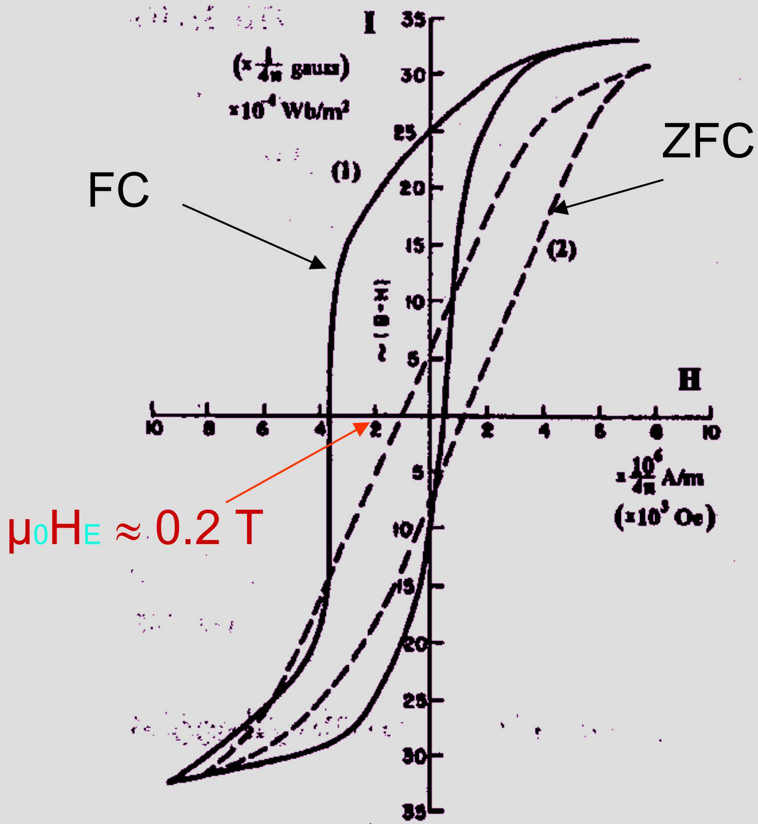


Practical aspects

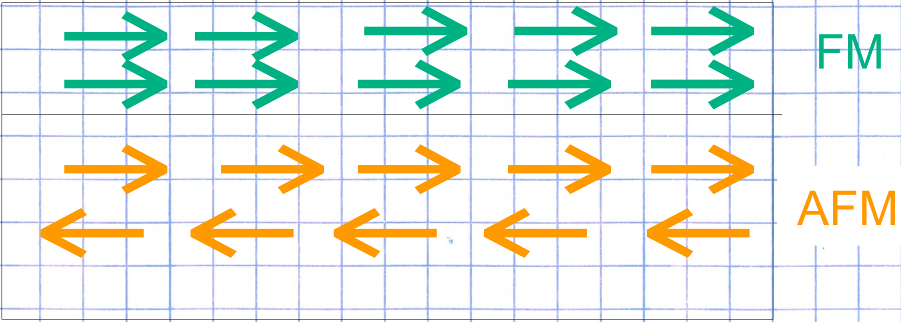
- ⇨ Ru spacer layer (largest effect)
- ⇨ Control thickness within a few Angströms !

Seminal studies

Oxidized Co nanoparticles



Meiklejohn and Bean,
Phys. Rev. 102, 1413 (1956),
Phys. Rev. 105, 904, (1957)



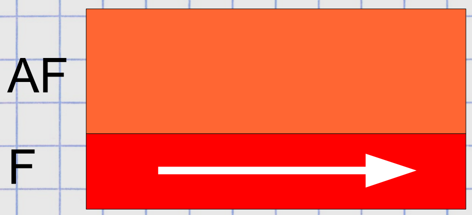
Field-cooled hysteresis loops

- Shift in field
- Increase coercivity

Exchange bias
J. Nogués and Ivan K. Schuller
J. Magn. Magn. Mater. 192 (1999) 203

Exchange anisotropy—a review
A E Berkowitz and K Takano
J. Magn. Magn. Mater. 200 (1999)

Increase coercivity of layers

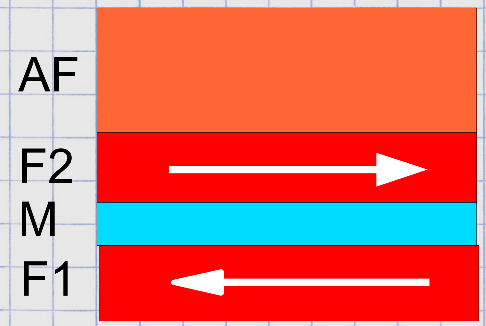


Crude approximation for thin layers:

$$H_{\mathrm{F-AF}} \approx H_{\mathrm{F}} \left(1 + \frac{K_{\mathrm{AF}} t_{\mathrm{AF}}}{K_{\mathrm{F}} t_{\mathrm{F}}} \right)$$

Application

Concept of spin-valve in magneto-resistive elements

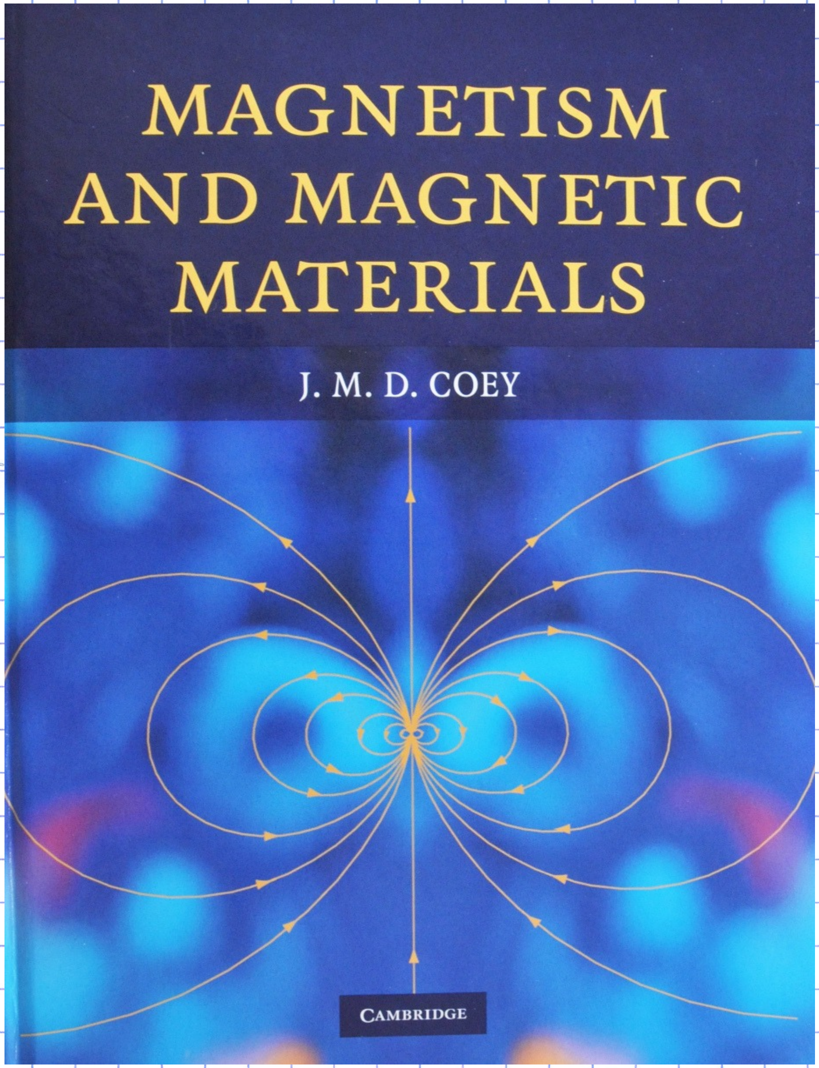


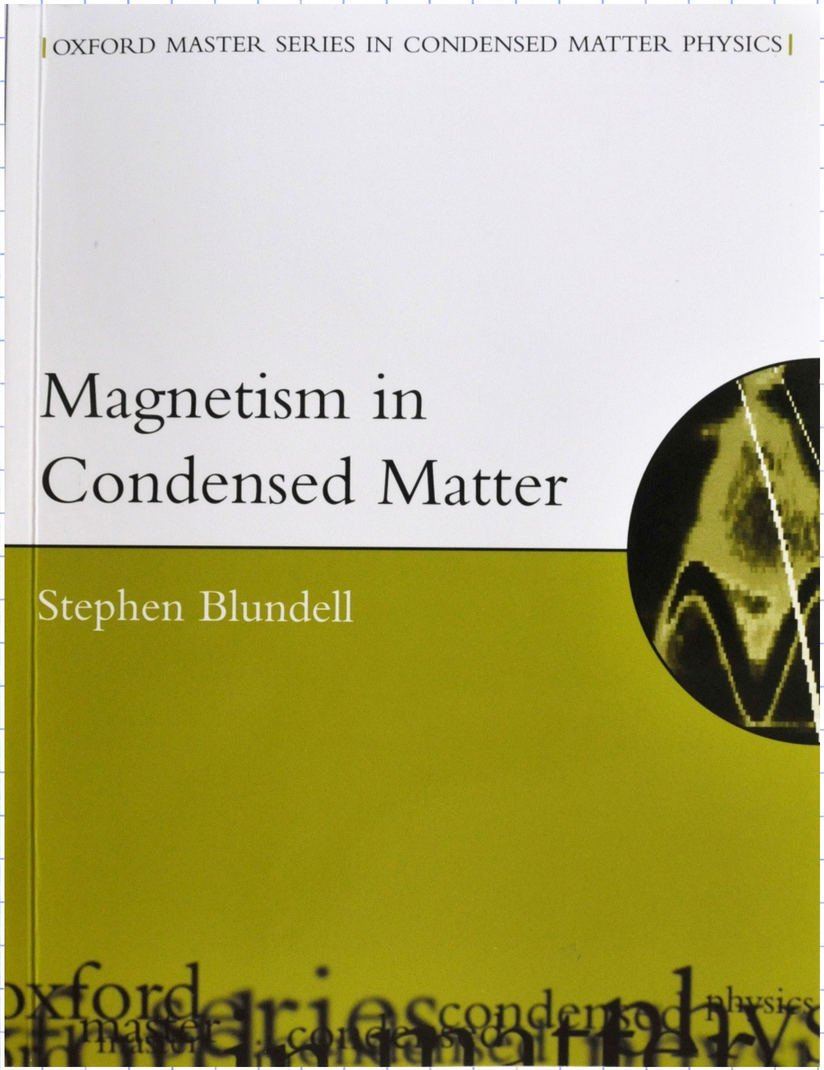
B. Diény et al., Phys. Rev. B 43, 1297 (1991)

⇨ Sensors

⇨ Memory cells

⇨ Etc.





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[4] O. Fruchart, A. Thiaville, Magnetism in reduced dimensions,
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http://perso.neel.cnrs.fr/olivier.fruchart/slides/
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P. Poulopoulos et al., K. Baberschke, Magnetism in thin films, J. Phys.: Condens. Matter 11, 9495 (1999)

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Perpendicular anisotropy

M. T. Johnson et al., Magnetic anisotropy in metallic multilayers, Rep. Prog. Phys. 59, 1409 (1996)

Exchange-bias

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Magneto-elasticity in thin films

D. Sander, The correlation between mechanical stress and magnetic anisotropy in ultrathin films, Rep. Prog. Phys. 62, 809 (1999)

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P. Bruno, Theory of interlayer exchange interactions in magnetic multilayers, J. Phys.: Condens. Matter 11, 9403 (1999)