Magnetization textures and processes

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Email to esm@grenoble.cnrs.fr on Aug.19 2009 18:55

More practicals ahead

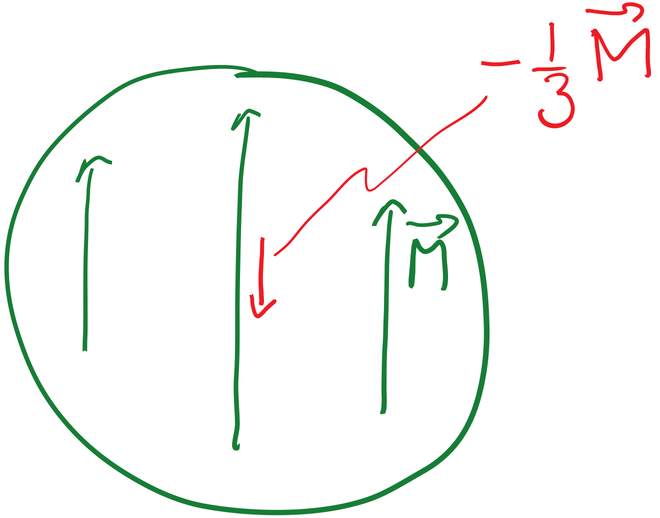
Hi,
I was investigating about magnetism in the human body and I used a speaker with a plug connected to it and then I started touching my body with the plug to hear how it sounds, I realized that when I put the plug in my nipples it made a louder sound which means that the magnetics were bigger in that area, I have asked about this but I get no answer why, there is no coverage about this subject on the internet either, please if you know about this let me know, my theory is that our nipples are our bridge of expulsing magnetics and electric signal to control the energy outside our bodies, hope this helps with some research, thank you...
Xxx YYY

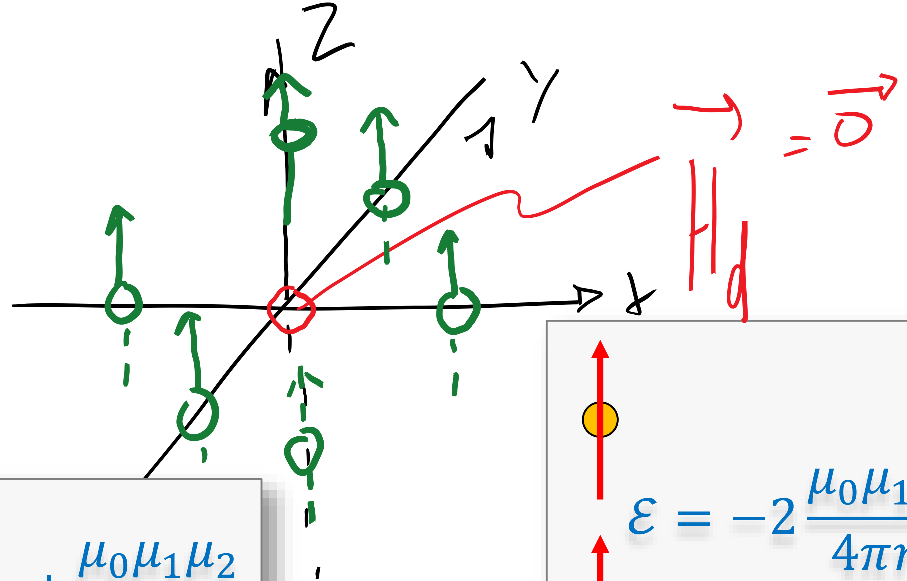
A volunteer to track my mistakes?

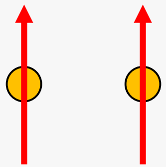
(Please)

Quizz #1

I can prove that demagnetizing field does NOT exist !







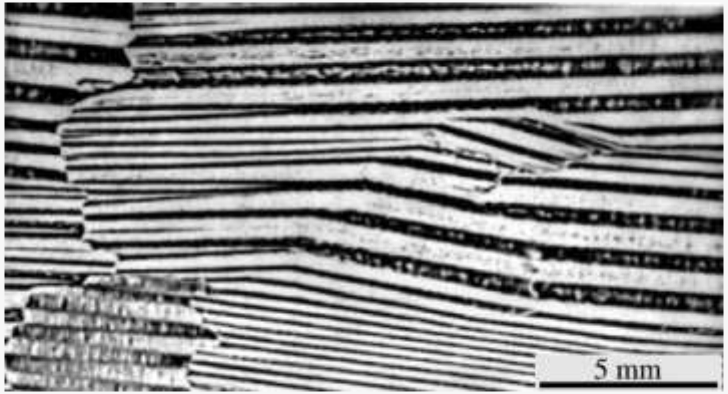
$$\mathcal{E} = +\frac{\mu_0 \mu_1 \mu_2}{4\pi r^3}$$

$$\mathcal{E} = -2\frac{\mu_0 \mu_1 \mu_2}{4\pi r^3}$$

Motivation – Materials

Magnetic domains

- Numerous and complex shape of domains



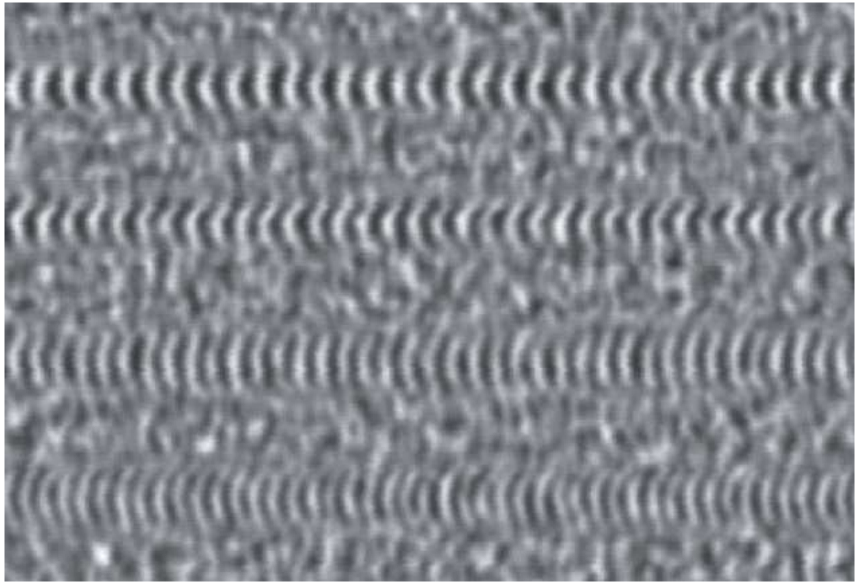
History: Weiss domains

Practical: improve material properties

Motivation – Spintronic devices

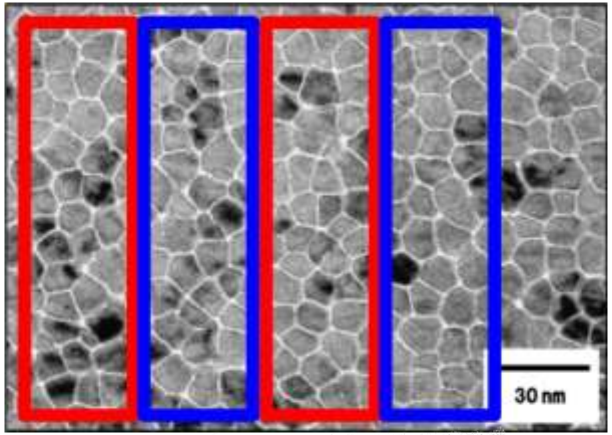
Magnetic bits on hard disk drives

Co-based hard disk media : bits 50nm and below



B. C. Stipe, Nature Photon. 4, 484 (2010)

Underlying microstructure



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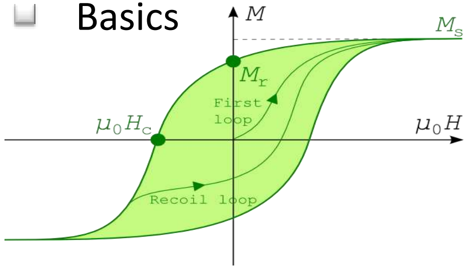
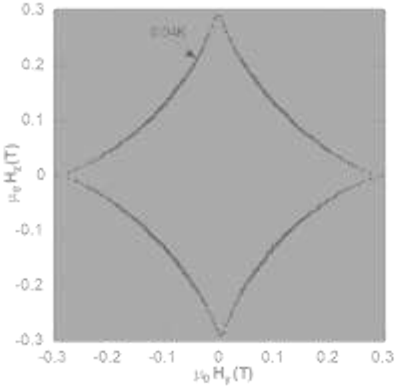
- Motivation

- Basics

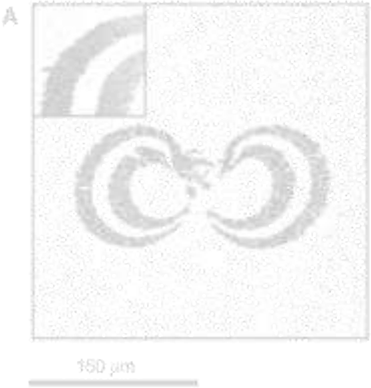


- Statics

- Macrospin switching



- Precessional dynamics

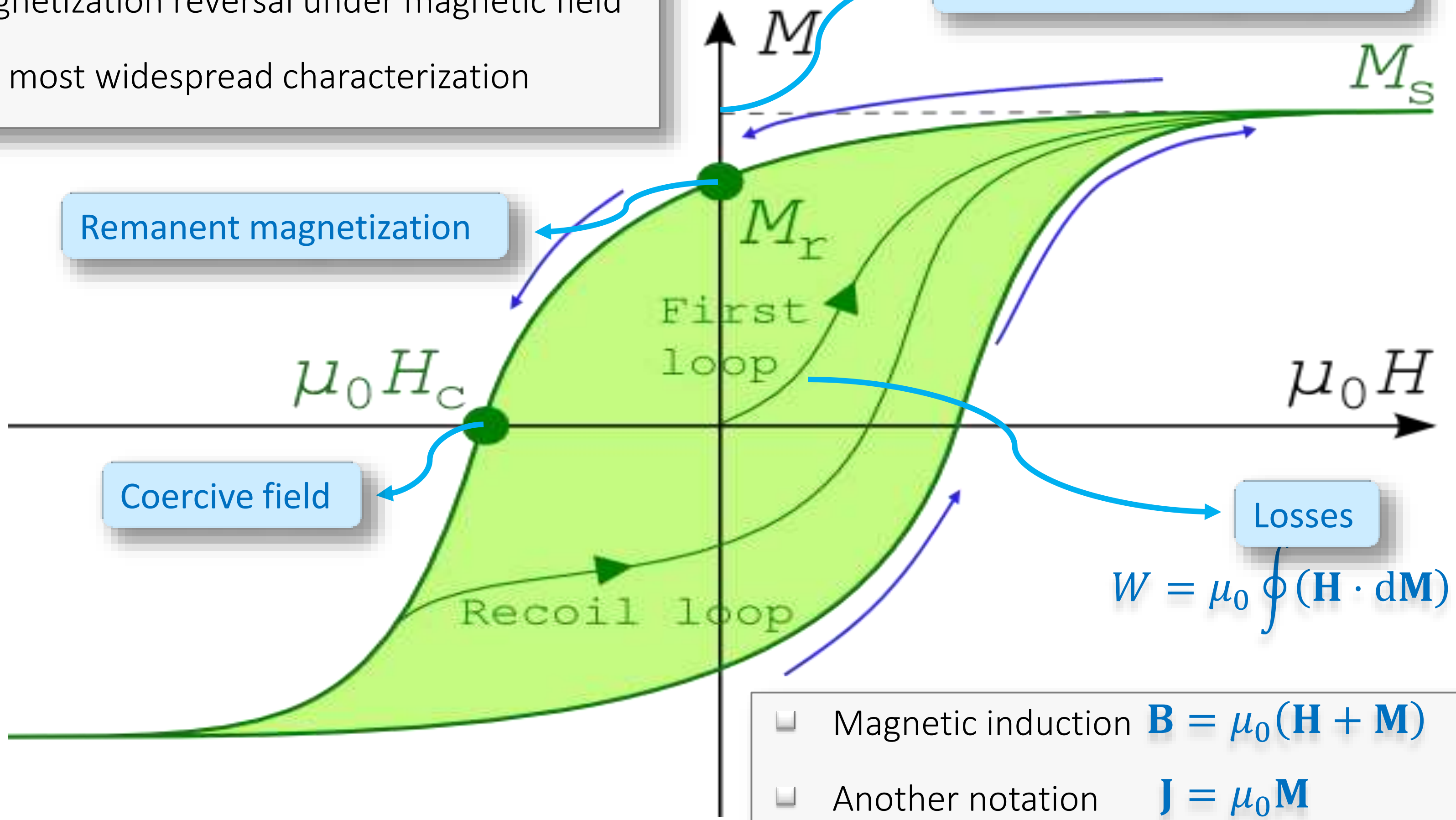


- Extended systems

The hysteresis loop

- Magnetization reversal under magnetic field
- The most widespread characterization

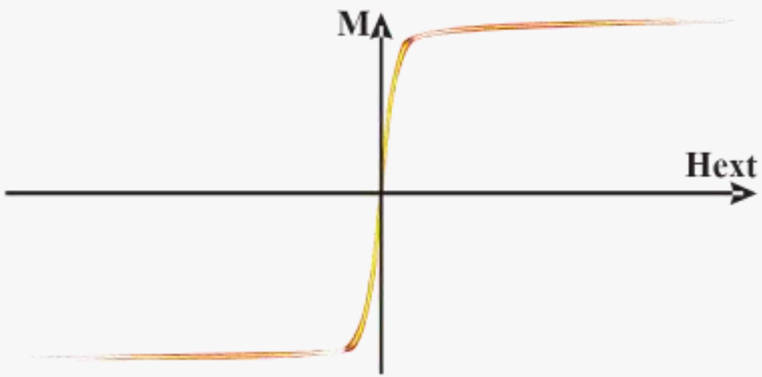
Spontaneous ≠ **S**aturation



- Magnetic induction $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$
- Another notation $\mathbf{J} = \mu_0 \mathbf{M}$

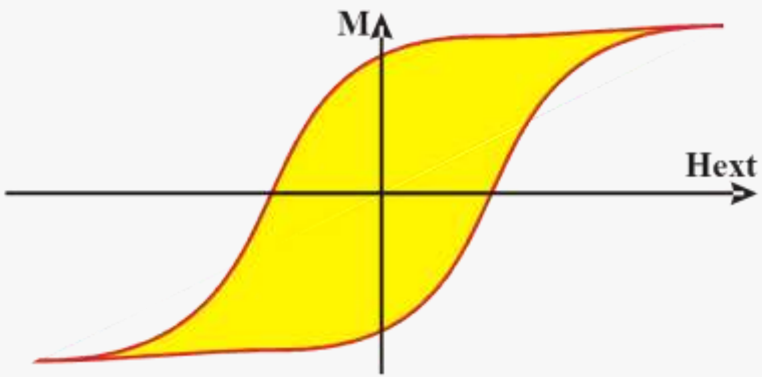
Basics – Soft and hard magnetic materials

Soft magnetic material



- Transformers
- Magnetic shielding, flux guides
- Magnetic sensors

Hard magnetic material



- Magnetic recording
- Permanent magnets

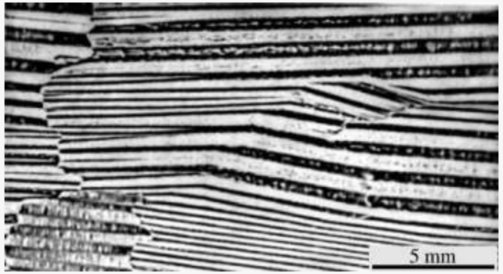
What determines hysteresis loops?

- Material composition and crystal structure
- Microstructure

Basics – Domains, from bulk to nano

Bulk material

Numerous and complex shape of domains

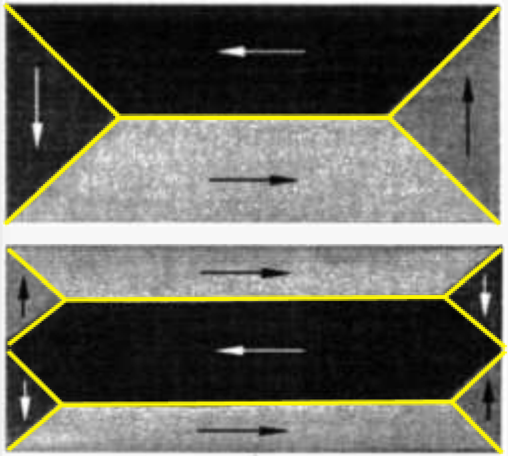


FeSi soft magnetic sheet

A. Hubert, Magnetic domains

Mesoscopic scale

Small number of domains, simple shape

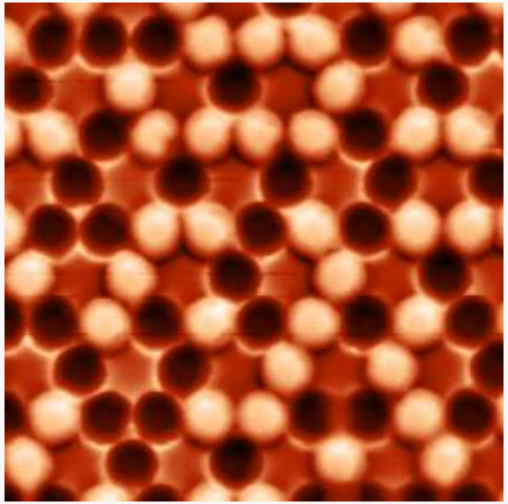


Microfabricated elements
Kerr microscopy

A. Hubert, Magnetic domains

Nanoscopic scale

Magnetic single domain



Nanofabricated dots
MFM

Sample courtesy:
I. Chioar, N.Rougemaille

- Nanomagnetism ≈ Mesomagnetism

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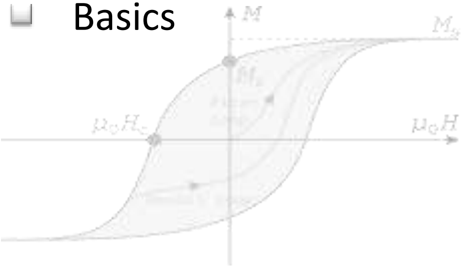
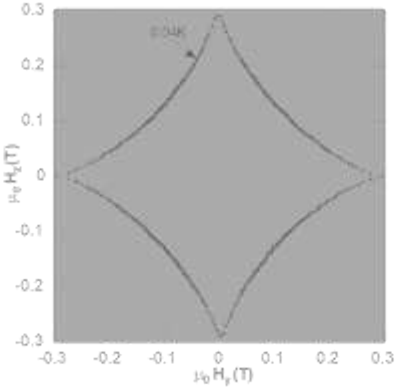
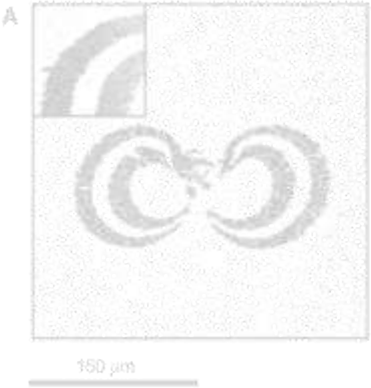


- Statics

- Macrospin switching



- Precessional dynamics



- Extended systems

THE EUROPEAN SCHOOL ON MAGNETISM

Magnetization

Magnetization vector **M**

- Continuous function
- May vary over time and space
- Modulus is constant and uniform (hypothesis in micromagnetism)

$$\mathbf{M}(\mathbf{r}) = \begin{pmatrix} M_x \\ M_y \\ M_z \end{pmatrix} = M_s \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix}$$

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

Mean field approach is possible: $M_s = M_s(T)$

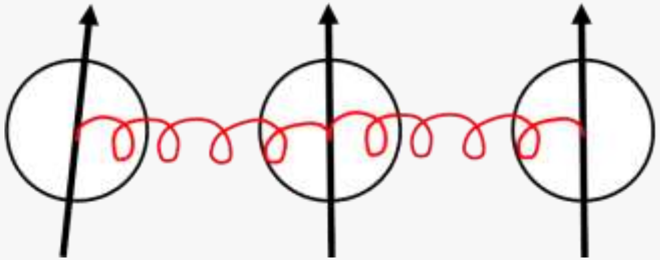
Exchange interaction

- Atomistic view $\mathcal{E} = -\sum_{i \neq j} J_{i,j} \mathbf{S}_i \cdot \mathbf{S}_j$ (total energy, J)
- Micromagnetic view $\mathbf{S}_i \cdot \mathbf{S}_j = S^2 \cos(\theta_{i,j}) \approx S^2 \left(1 - \frac{\theta_{i,j}^2}{2}\right)$

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

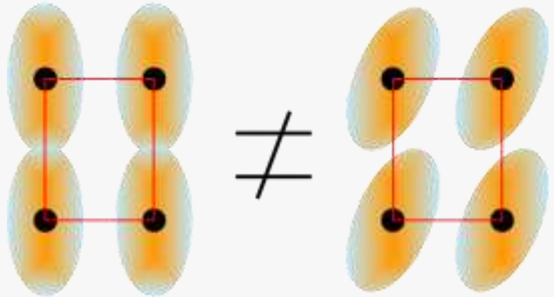
Statics – The various types of magnetic energy

Exchange energy



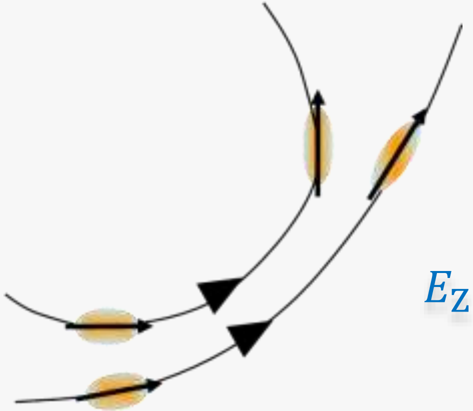
$$E_{\mathrm{ex}} = A(\nabla \cdot \mathrm{m})^2 = A\sum_{i,j}\left(\frac{\partial m_i}{\partial x_j}\right)^2$$

Magnetocrystalline anisotropy energy



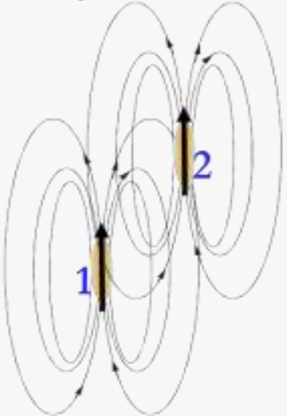
$$E_{\mathrm{mc}} = K\, f(\theta,\varphi)$$

Zeeman energy (→ enthalpy)



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

Magnetostatic energy



$$E_{\mathrm{d}} = -\frac{1}{2}\mu_0 \mathbf{M}\cdot\mathbf{H}_{\mathrm{d}}$$

Statics – Dipolar energy

Analogy with electrostatics

Maxwell equation → $\boldsymbol{\nabla}\cdot\mathbf{H}_\mathrm{d} = -\boldsymbol{\nabla}\cdot\mathbf{M}$

$$\mathbf{H}_\mathrm{d}(\mathbf{r}) = -M_\mathrm{s}\iiint_{\mathcal{V}'}\frac{[\boldsymbol{\nabla}\cdot\mathbf{m}(\mathbf{r}')]\,(\mathbf{r}-\mathbf{r}')}{4\pi\,|\mathbf{r}-\mathbf{r}'|^3}\,\mathrm{d}\mathcal{V}'$$

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

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

Magnetic charges

$\rho(\mathbf{r}) = -M_\mathrm{s}\,\boldsymbol{\nabla}\cdot\mathbf{m}(\mathbf{r})$ → volume density of magnetic charges

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

Usefull expressions

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

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

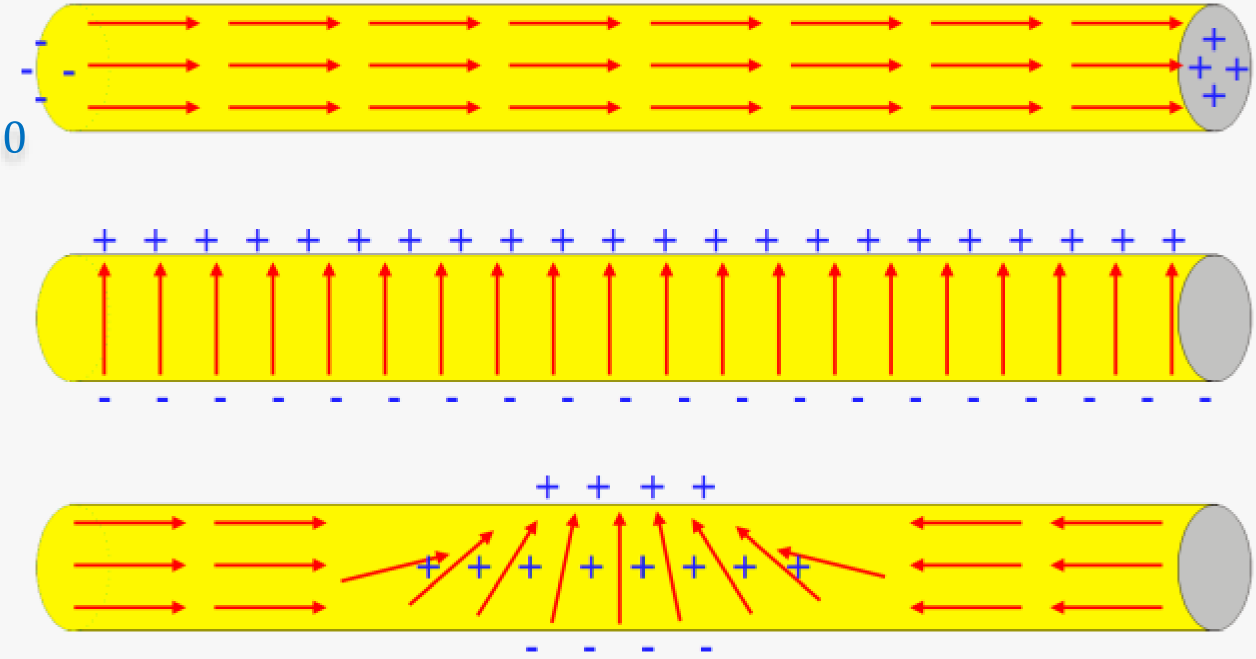
- Always positive
- Zero means minimum

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

Statics – Magnetic charges

Examples of magnetic charges

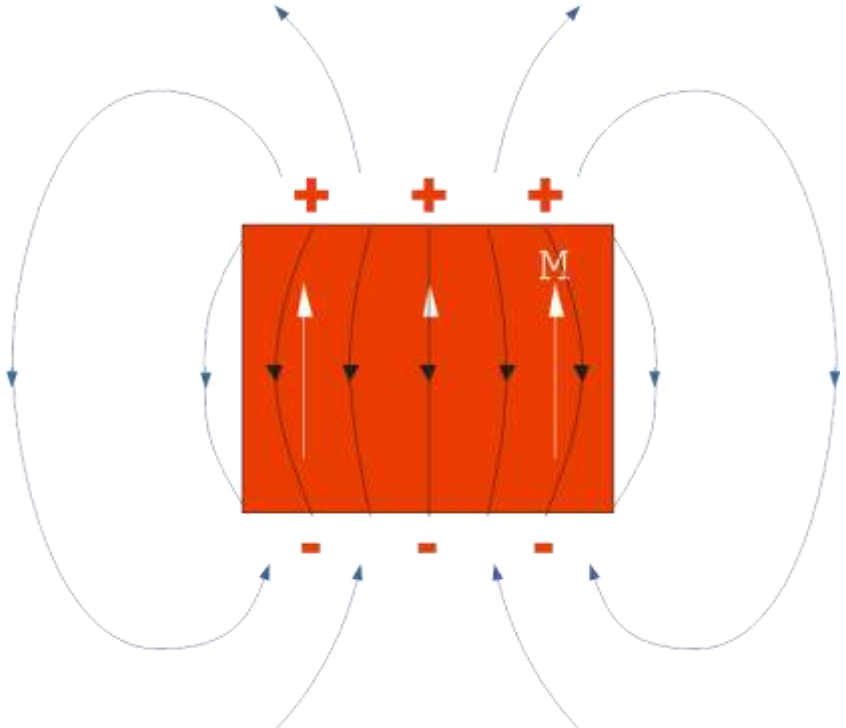
- Note for infinite cylinder:
  no charge $\mathcal{E} = 0$
- Charges on side surfaces
- Surface and volume charges



Take-away message

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

Statics – Dipolar fields



Vocabulary

- Generic names

  Magnetostatic field
  Dipolar field

- Inside material

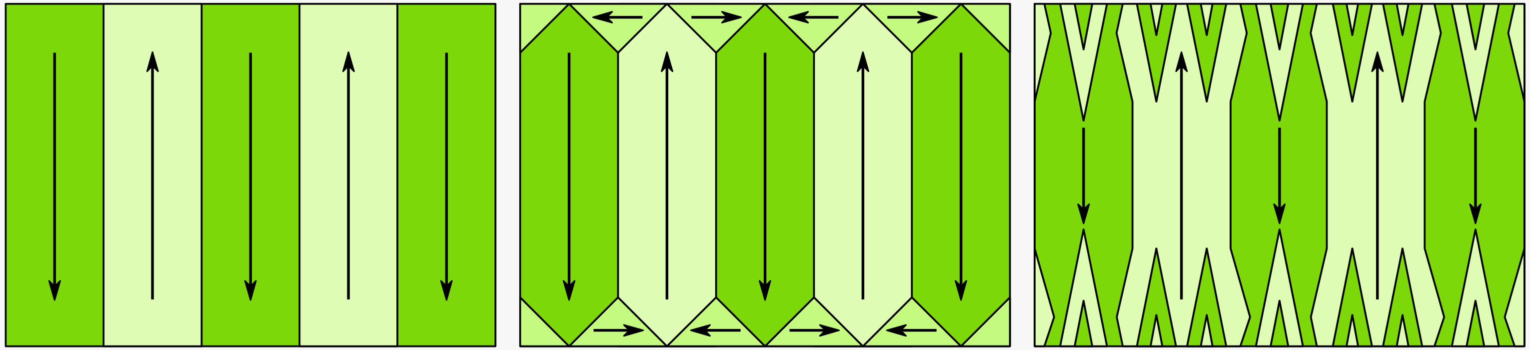
  Demagnetizing field

- Oustide material

  Stray field

Films with easy axis out-of-the-plane: Kittel domains

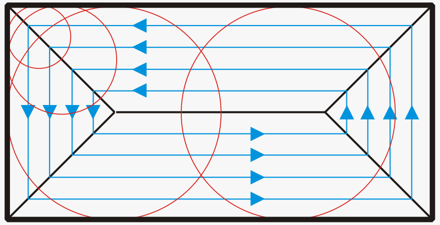
Principle: compromise between gain in dipolar energy, and cost in wall energy

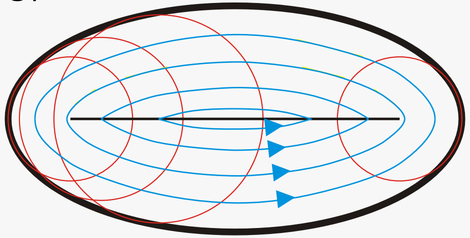


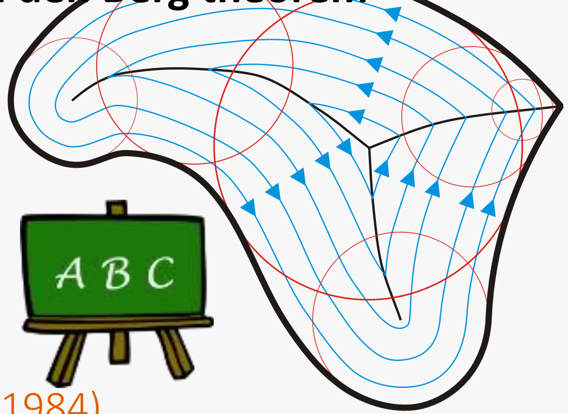
C. Kittel, Physical theory of ferromagnetic domains, Rev. Mod. Phys. 21, 541 (1949)

Nanostructures with in-plane magnetization – Van den Berg theorem

Principle: Reduce dipolar energy to zero







H. A. M. van den Berg, J. Magn. Magn. Mater. 44, 207 (1984)

Statics – Magnetic length scales

The dipolar exchange length

When: anisotropy and exchange compete

$$E = A\left(\frac{\partial m_i}{\partial x_j}\right)^2 + K_\mathrm{d}\sin^2\theta$$

Exchange: $\mathrm{J/m}$ — Dipolar: $\mathrm{J/m^3}$

$$K_\mathrm{d} = \frac{1}{2}\mu_0 M_\mathrm{s}^2$$

$$\boxed{\Delta_\mathrm{d} = \sqrt{A/K_\mathrm{d}} = \sqrt{2A/\mu_0 M_\mathrm{s}^2}}$$

$$\Delta_\mathrm{d} \simeq 3 - 10\ \mathrm{nm}$$

Critical single-domain size, relevant for small particles made of soft magnetic materials

Often called: exchange length

The anisotropy exchange length

When: anisotropy and exchange compete

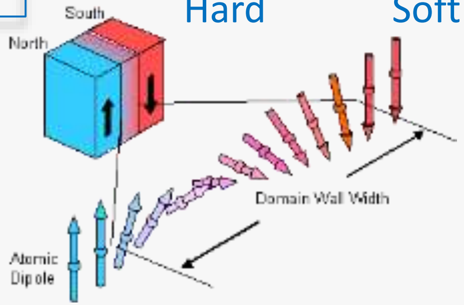
$$E = A\left(\frac{\partial m_i}{\partial x_j}\right)^2 + K\sin^2\theta$$

Exchange: $\mathrm{J/m}$ — Anisotropy: $\mathrm{J/m^3}$

$$\boxed{\Delta_\mathrm{u} = \sqrt{A/K}}$$

$$\Delta_\mathrm{u} \simeq 1\ \mathrm{nm} \rightarrow 100\ \mathrm{nm}$$

Hard — Soft

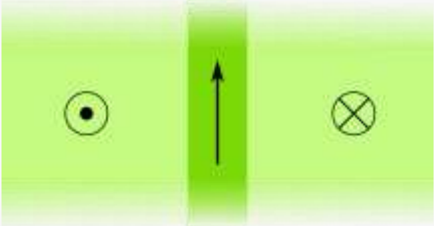


Sometimes called: Bloch parameter, or wall width

Note: Other length scales can be defined, e.g. with magnetic field

Statics – Domain walls and dimensionality

Bloch wall in the bulk (2D)

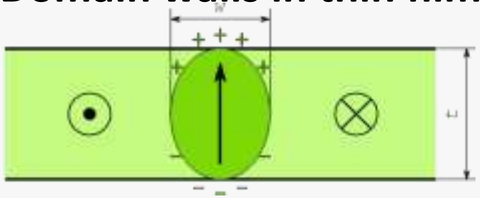


- No magnetostatic energy
- Width $\Delta_u = \sqrt{A/K}$
- Energy $\gamma_W = 4\sqrt{AK}$

Other angles & anisotropy

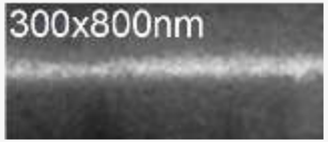
F. Bloch, Z. Phys. 74, 295 (1932)

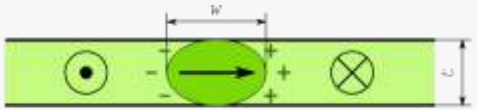
Domain walls in thin films (towards 1D)



Bloch wall

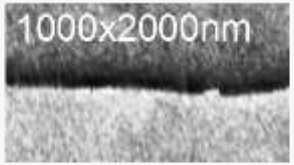
$t \gtrsim w$





Néel wall

$t \lesssim w$



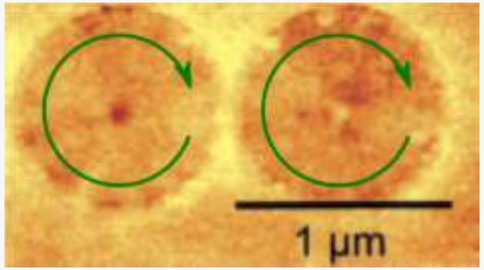
- Implies magnetostatic energy
- No exact analytic solution

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

Constrained walls (eg in strips)

Permalloy (15nm)
Strip width 500nm

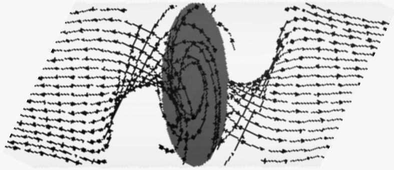
Vortex (1D → 0D)



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

Bloch point (0D)

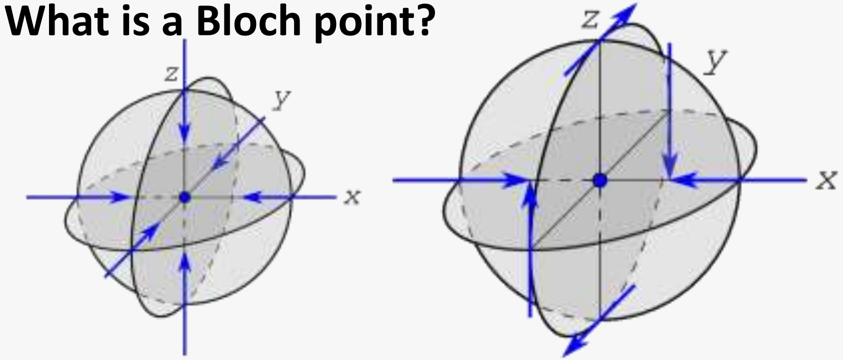
- Point with vanishing magnetization



W. Döring, JAP 39, 1006 (1968)

Statics – Walls and topology (Bloch point)

What is a Bloch point?

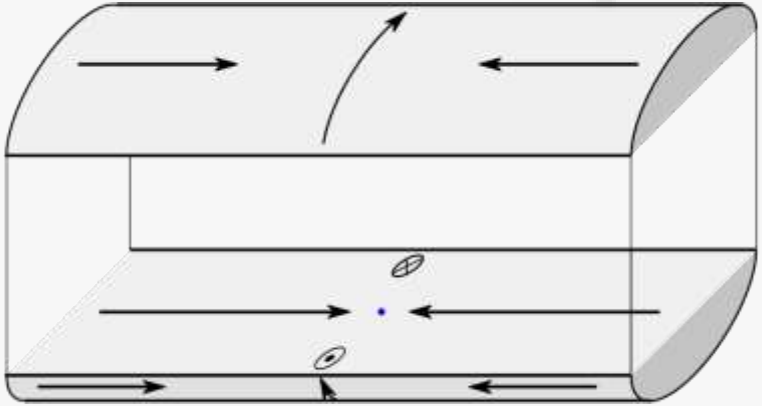


A magnetization texture with local cancellation of the magnetization vector

R. Feldkeller,
Z. Angew. Physik 19, 530 (1965)

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

Bloch-point wall, theory $D \gtrsim 7\Delta_{\mathrm{d}}^2$



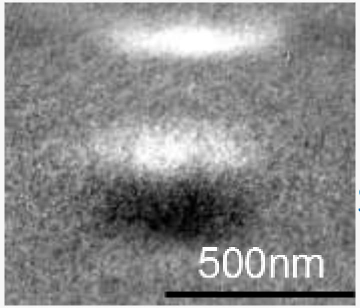
H. Forster et al., J. Appl. Phys. 91, 6914 (2002)

A. Thiaville, Y Nakatani, Spin dynamics in confined magnetic structures III, 101, 161-206 (2006)

Bloch-point wall, experiments

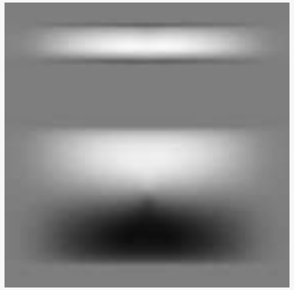
Experiment

Simulation



WIRE

SHADOW



Shadow XMCD-PEEM

S. Da-Col et al., PRB (R) 89, 180405, (2014)

The Dzyaloshinskii-Moriya interaction

- Usual magnetic exchange

$$\mathcal{E}_{i,j} = -J_{i,j}\mathbf{S}_i \cdot \mathbf{S}_j$$

Promotes ferromagnetism (or antiferromagnetism)

- The DM interaction

$$\mathcal{E}_{\mathrm{DMI}} = -\mathbf{d}_{i,j} \cdot (\mathbf{S}_i \times \mathbf{S}_j)$$

Requires: loss of inversion symmetry

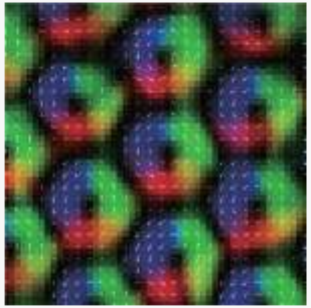
Promotes spirals and cycloids

I. Dzyaloshiinsky, J. of Phys. Chem. Solids 4, 241 (1958)

T. Moriya, Phys. Rev. 120, 91 (1960)

A.Fert and P.M.Levy, PRL 44, 1538 (1980)

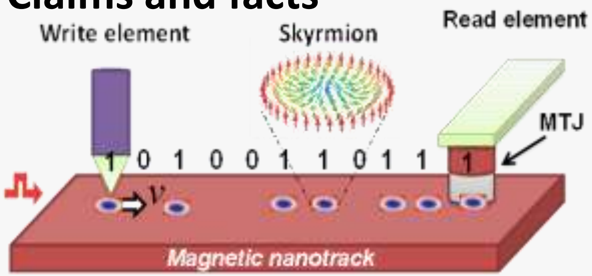
Magnetic skyrmions

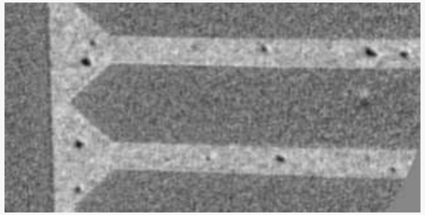


90 nm Bulk FeCoSi

Lorentz microscopy

Claims and facts

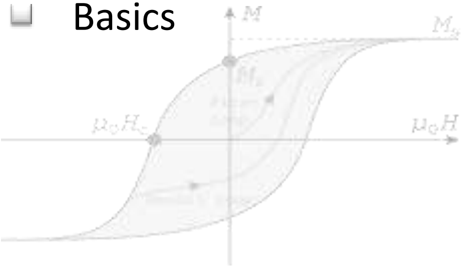




O. Boulle et al., Nat. Nanotech., 11, 449 (2016)

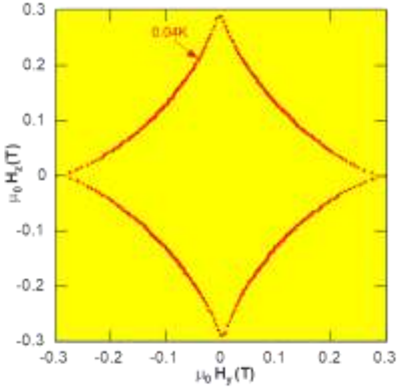
- Motivation

- Basics

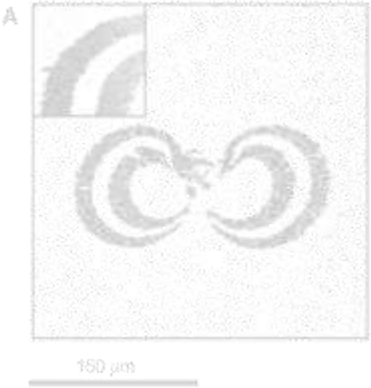


- Statics

- Macrospin switching



- Precessional dynamics

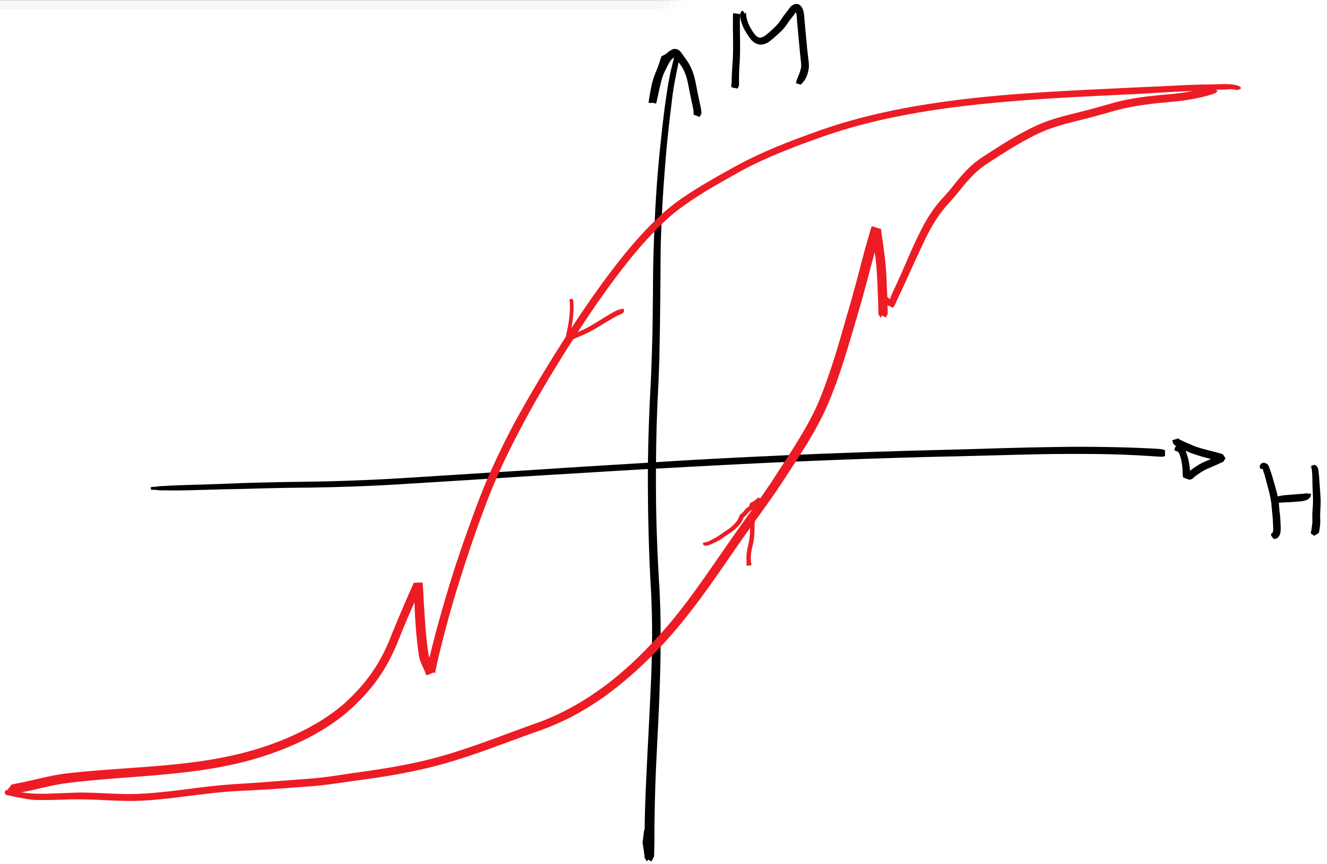


- Extended systems

THE EUROPEAN SCHOOL ON MAGNETISM

Quizz #2

Is such a hysteresis loop possible ?



Macrospins – Stoner-Wohlfarth

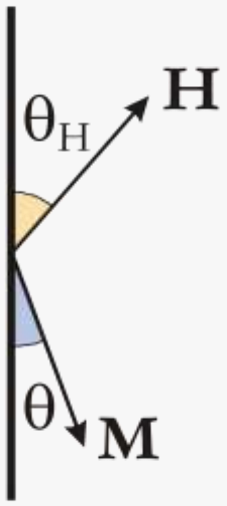
Framework: uniform magnetization

- Drastic, unsuitable in most cases
- Remember: demagnetization field may not be uniform

$$\mathcal{E} = E\mathcal{V}$$

$$= \mathcal{V}[K_{\text{eff}} \sin^2\theta - \mu_0 M_s H \cos(\theta - \theta_H)]$$

- Anisotropy: $K_{\text{eff}} = K_{\text{mc}} + (\Delta N)K_{\text{d}}$



Names used

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

Dimensionless units

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

$$e = \mathcal{E}/(K\mathcal{V})$$

$$h = H/H_{\text{a}}$$

$$H_{\text{a}} = 2K/(\mu_0 M_s)$$

L. Néel, Compte rendu Acad. Sciences 224, 1550 (1947)

E. C. Stoner and E. P. Wohlfarth,

Phil. Trans. Royal. Soc. London A240, 599 (1948)

Reprint: IEEE Trans. Magn. 27(4), 3469 (1991)

Example: $\theta_H = \pi$ ➡ $e = \sin^2\theta + 2h\cos\theta$

Equilibrium positions

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

$\cos\theta_{\mathrm{m}} = h$

$\theta \equiv 0\ [\pi]$

Stability

$\partial_{\theta\theta} e = 4\cos^2\theta - 2h\cos\theta - 2$

$\partial_{\theta\theta} e(0) = 2(1-h)$

$\partial_{\theta\theta} e(\theta_{\mathrm{m}}) = 2(h^2-1)$

$\partial_{\theta\theta} e(\pi) = 2(1+h)$

Switching field

- Vanishing of local minimum
- Is abrupt

$h_{\mathrm{sw}} = 1$

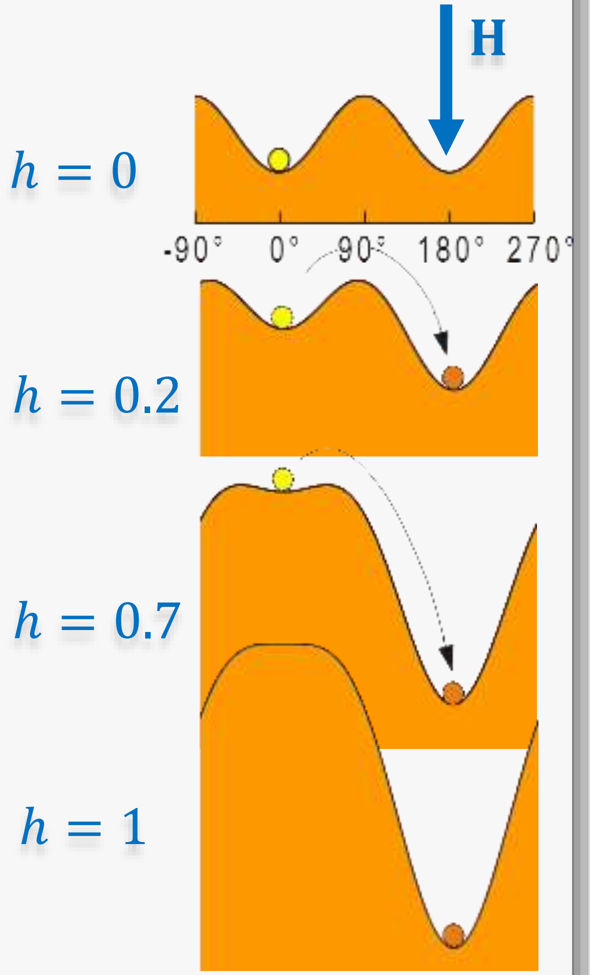
➡ $H = H_{\mathrm{a}} = 2K/(\mu_0 M_{\mathrm{s}})$

Energy barrier

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

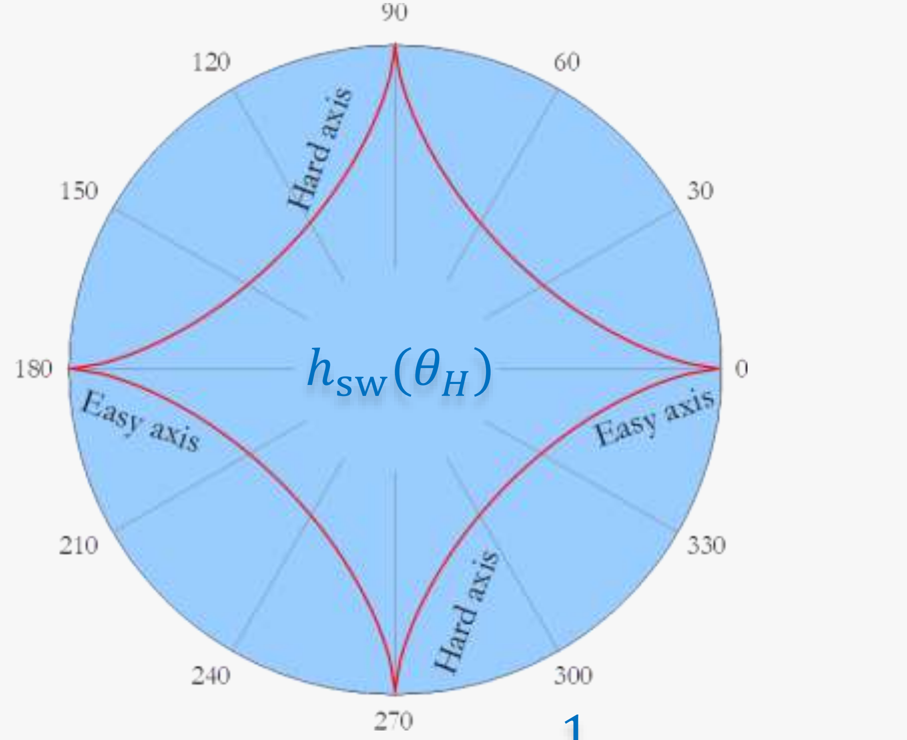
$\Delta e \sim (1-h)^{1.5}$ In general (breaking of symmetry)

Energy lanscape



Macrospins – Stoner-Wohlfarth

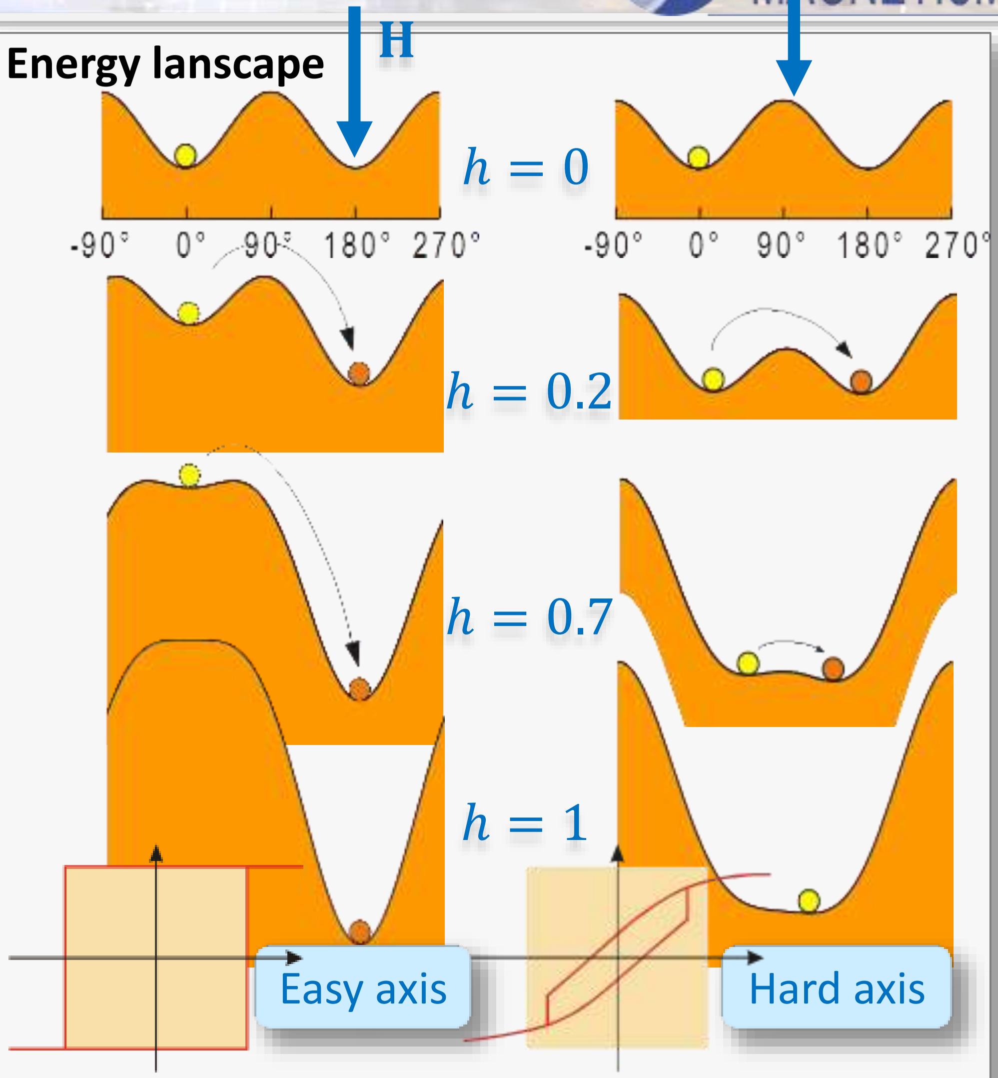
Stoner-Wohlfarth astroid: switching field



$$h_{sw}(\theta_H) = \frac{1}{(\sin^{2/3}\theta_H + \cos^{2/3}\theta_H)^{3/2}}$$

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

Energy lanscape



Macrospins – Switching vs coercive field

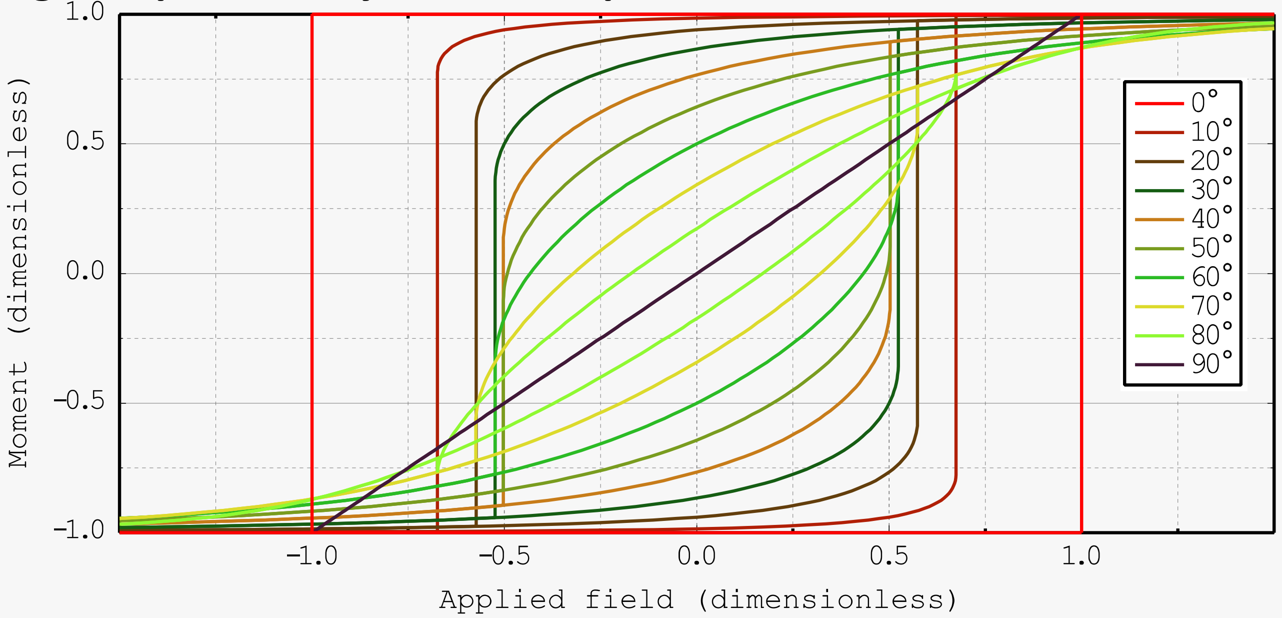
Switching field H_{sw}

- A value of field at which an irreversible (abrupt) jump of magnetization angle occurs.
- Can be measured only in single particles.

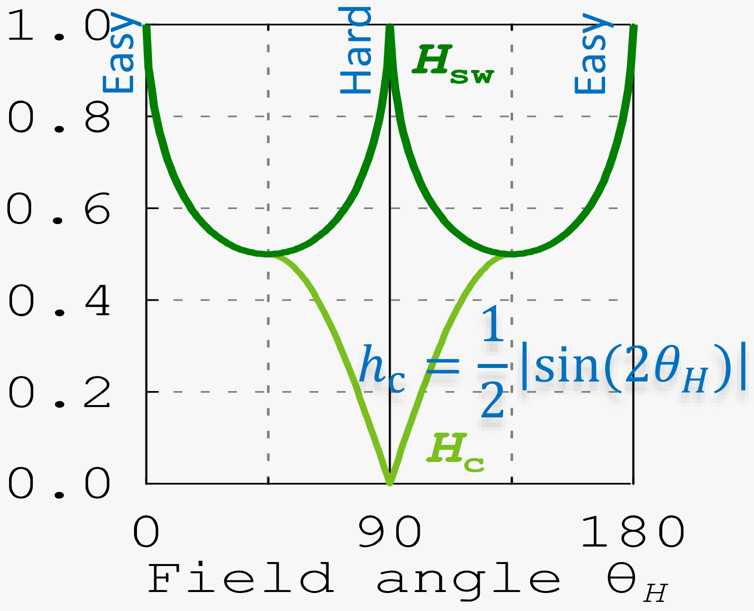
Coercive field H_c

- The field at which $\mathbf{H} \cdot \mathbf{M} = 0$
- Measurable in materials (large number of 'particles').
- May or may not be a measure of the mean switching field at the microscopic level

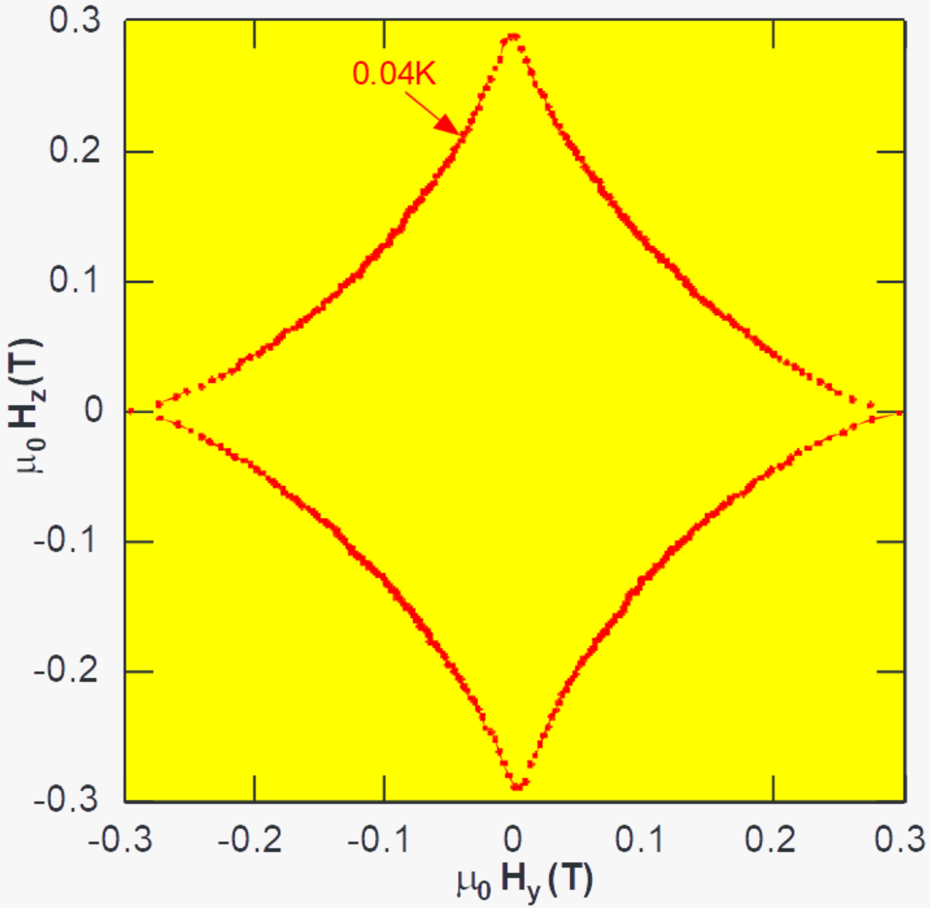
Angle-dependent hysteresis loops



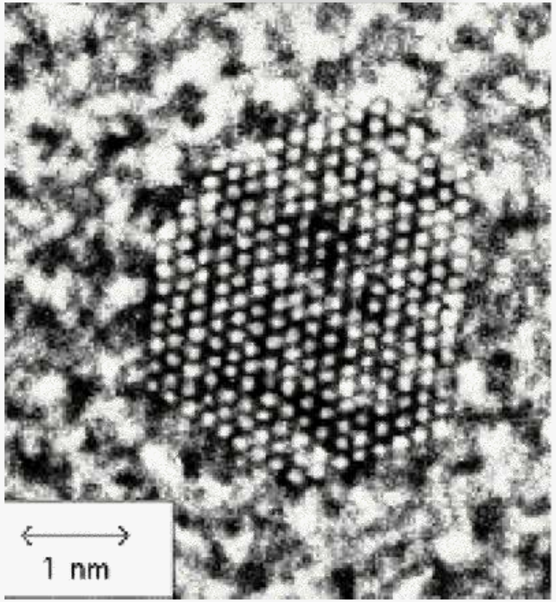
Switching versus coercive field

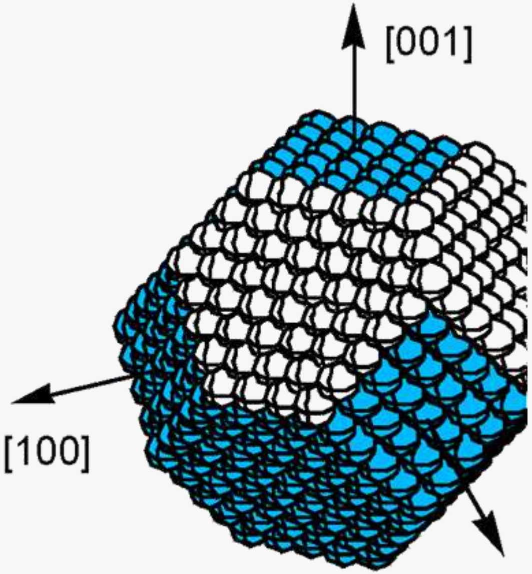


First experimental evidence



Co cluster





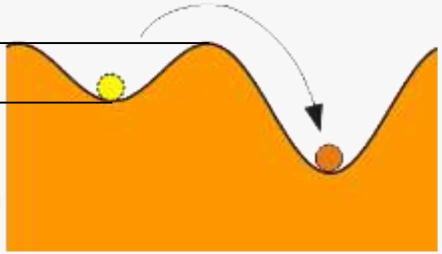
W. Wernsdorfer et al., Phys. Rev. Lett. 78, 1791 (1997)

Macrospins – Thermal activation

Barrier height (reminder)

$$\Delta e = (1 - h)^2$$

$$h = \left(\frac{\mu_0 M_s}{2K}\right) H$$



Thermal activation

- Mean waiting time to switch with excitations

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

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

$\tau_0 \approx 10^{-10}$ s Inverse attempt frequency

- Barrier height preventing spontaneous switching in time τ

$$\Delta\mathcal{E} = k_B T \ln(\tau/\tau_0)$$

Lab time scale 1 s $\Rightarrow$ $\Delta\mathcal{E} = 25 k_B T$

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

Sharrock law

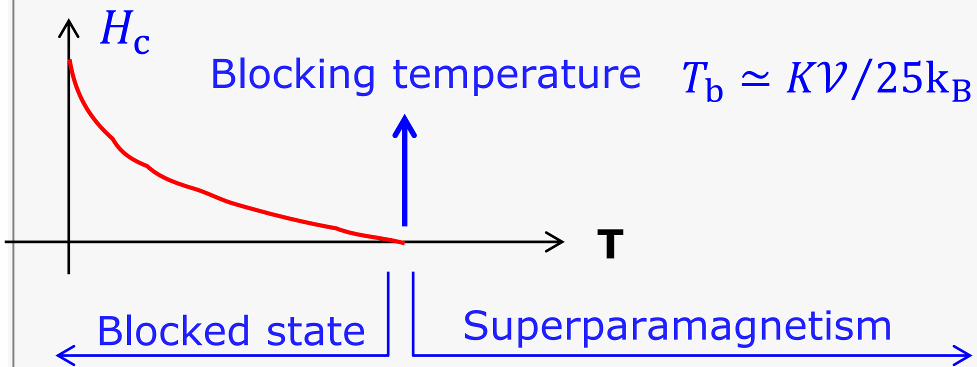
M. P. Sharrock, J. Appl. Phys. 76, 6413-6418 (1994)

≃ 10 years

40 to 60 $k_B T$
for magnetic recording

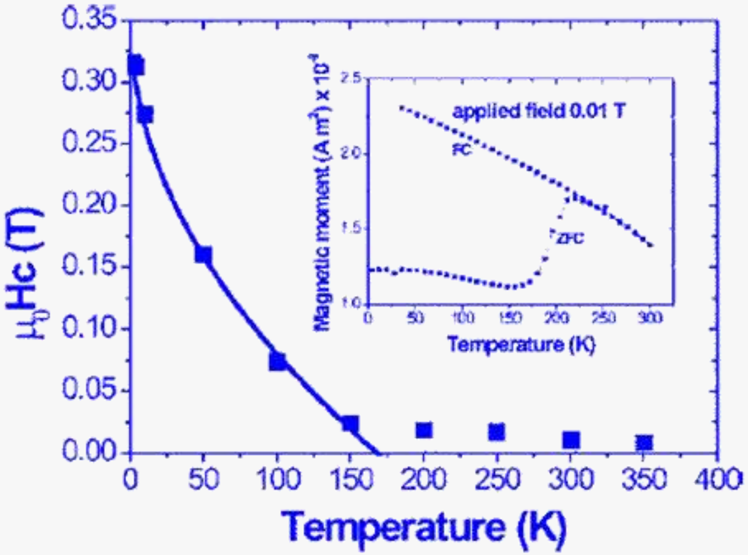
Superparamagnetism

Thermally-induced loss of all coercivity



Example

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



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

Macrospins – Thermal activation

Superparamagnetism – Formalism

- Energy

$$\mathcal{E} = KVf(\theta,\phi) - \mu_0\,\boldsymbol{\mu}\cdot\mathbf{H}$$

- Partition function

$$Z = \sum \exp(-\beta\mathcal{E})$$

- Average moment

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

Isotropic case

$$Z = \int_{-\mathcal{M}}^{\mathcal{M}} \exp(\beta\mu_0\mu H)\,\mathrm{d}\mu$$

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

Langevin function

Consider total moment, not with spin ½

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

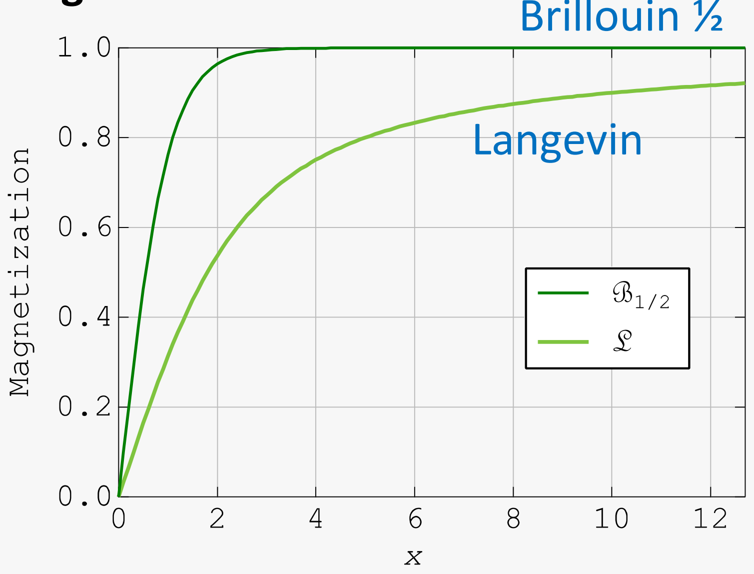
Infinite anisotropy

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

$$\Rightarrow \langle\mu\rangle = \mathcal{M}\,\mathrm{th}(x)$$

Brillouin ½ function

Langevin versus Brillouin



REVIEW : S. Bedanta & W. Kleemann, Supermagnetism, J. Phys. D: Appl. Phys., 013001 (2009)

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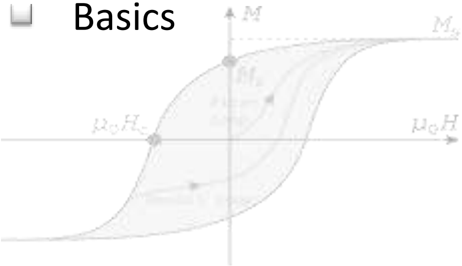
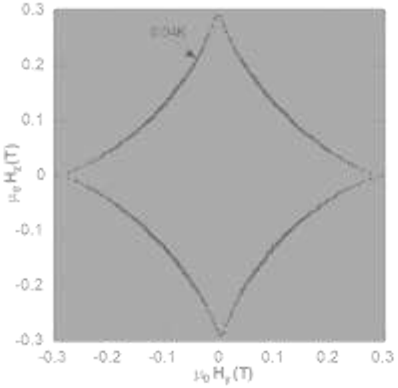
- Motivation

- Basics

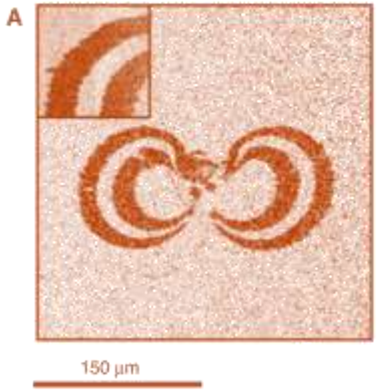


- Statics

- Macrospin switching



- Precessional dynamics



- Extended systems

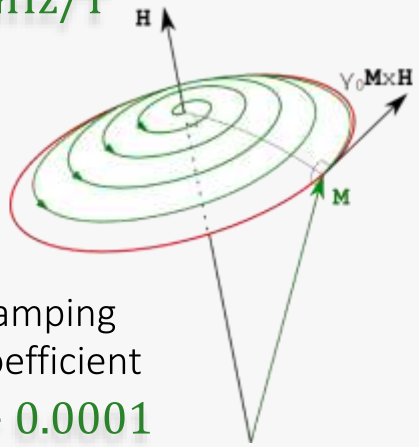
LLG equation

- Describes: precessional dynamics of magnetic moments
- Applies to magnetization, with phenomenological damping

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

$\gamma_0 = \mu_0\gamma < 0$ Gyromagnetic ratio

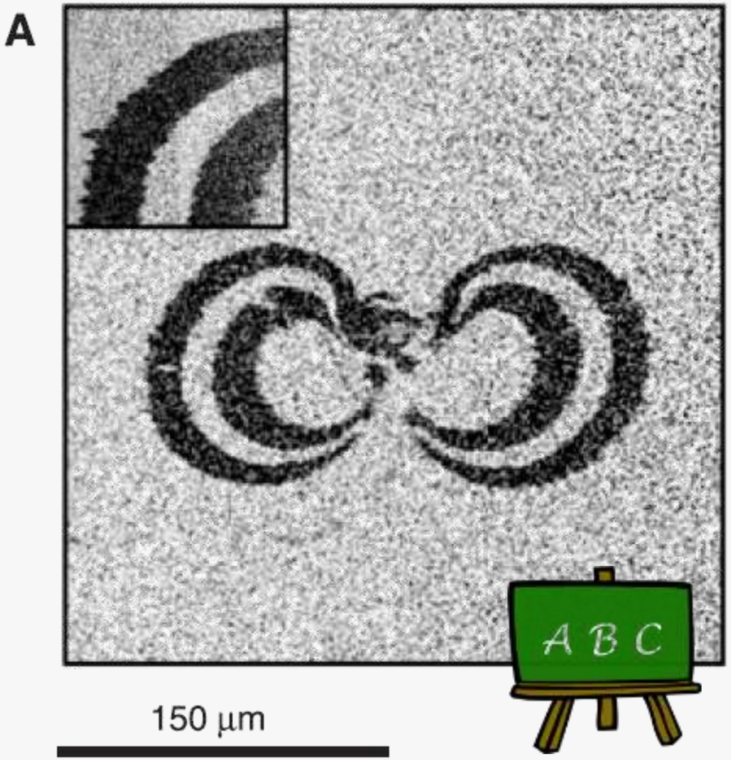
$\gamma_s = 28\ \mathrm{GHz/T}$



$\alpha > 0$ Damping coefficient

$\alpha = 0.1 - 0.0001$

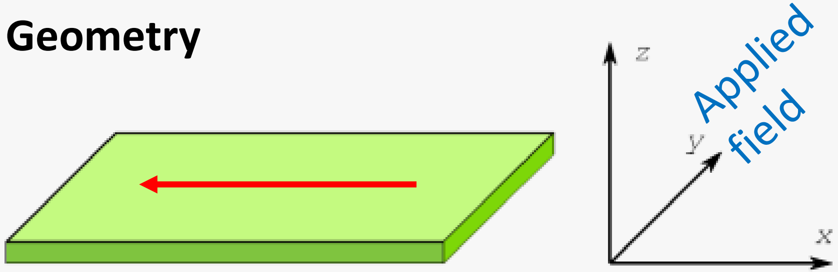
Pioneering experiment of precessional magnetization reversal



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

Precessional dynamics – Trajectories

Geometry



Initial magnetization

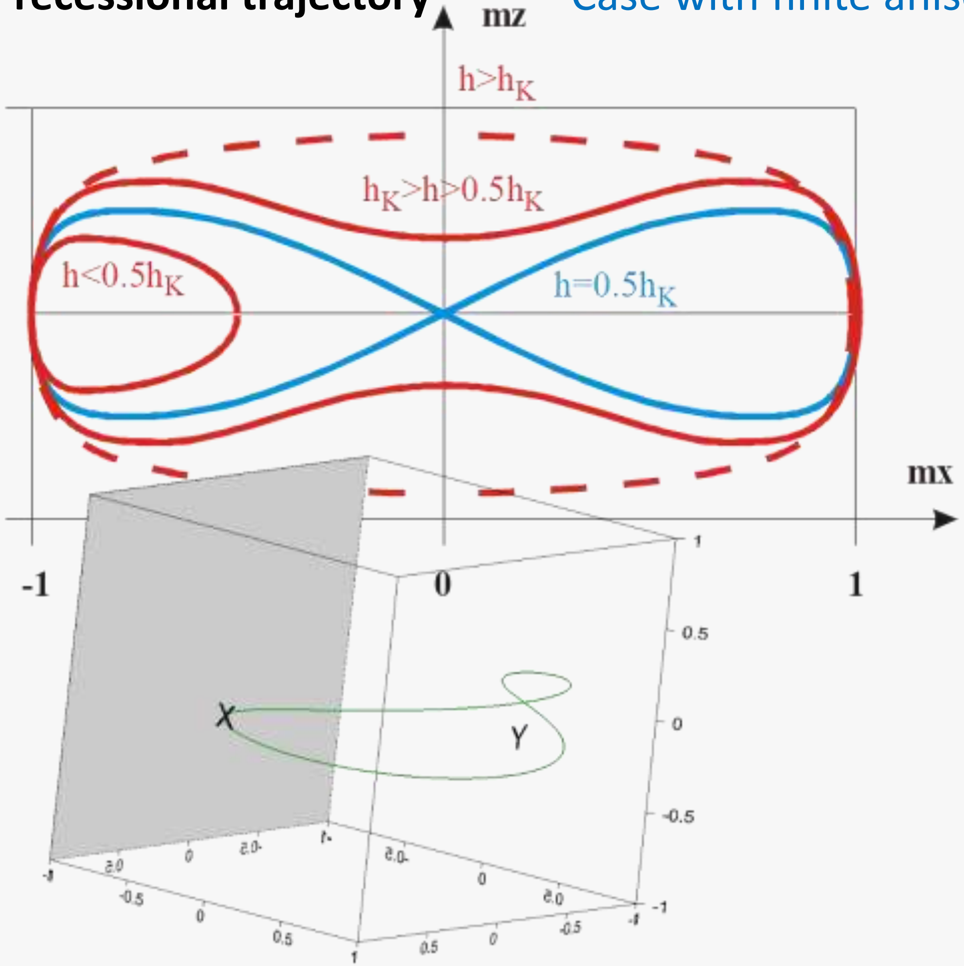
Easy

$$\frac{d\mathbf{m}}{dt} = -|\gamma_0|\mathbf{m} \times \mathbf{H} + \text{damping}$$

- Precession around its own demagnetizing field
- Threshold for switching is half the Stoner-Wohlfarth one

Precessional trajectory

Case with finite anisotropy

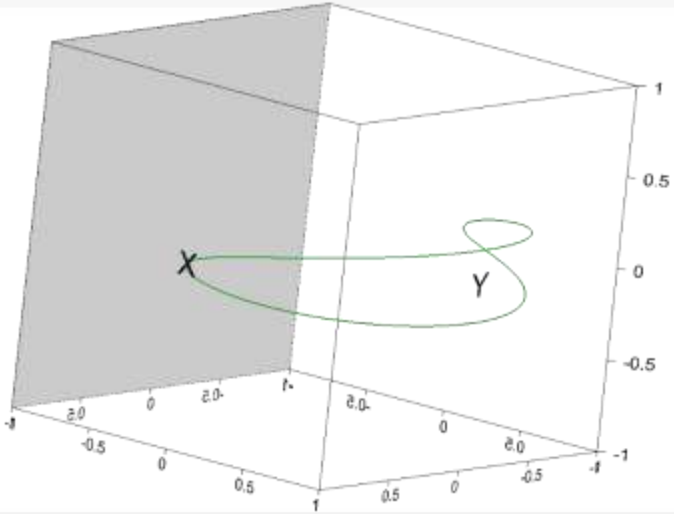


Precessional dynamics – Energy considerations

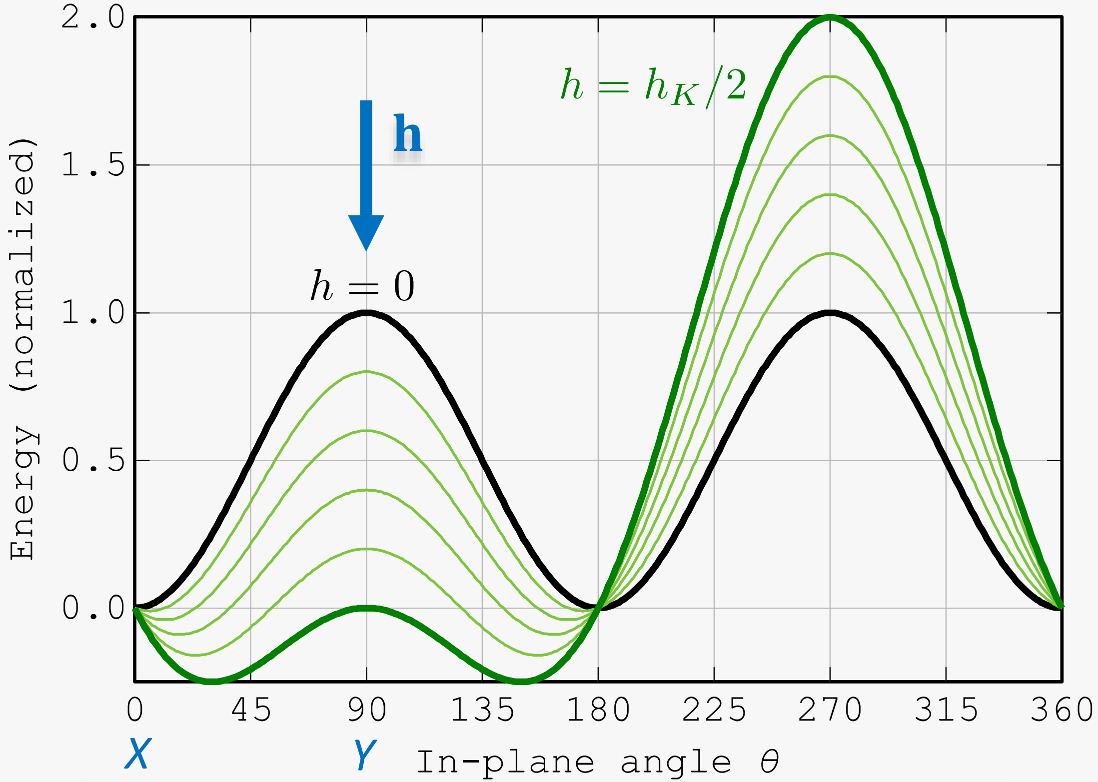
Stoner-Wohlfarth versus precessional switching

- Stoner-Wohlfarth: slow field variation; system remains quasistatically at local minimum
- Precessional: short time scale; system may follow iso-energy lines in case of moderate damping

Precession period: $\dfrac{2\pi}{|\gamma|} = 35 \;\; \mathrm{ps} \cdot \mathrm{T}$

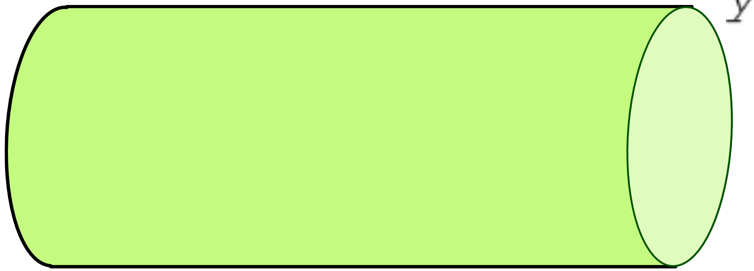


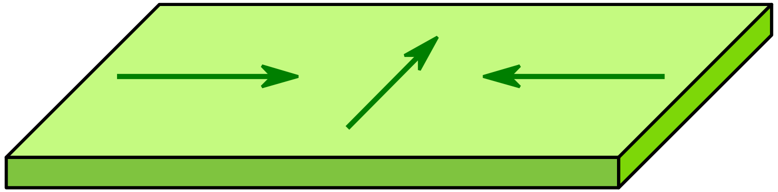
Energy landscape

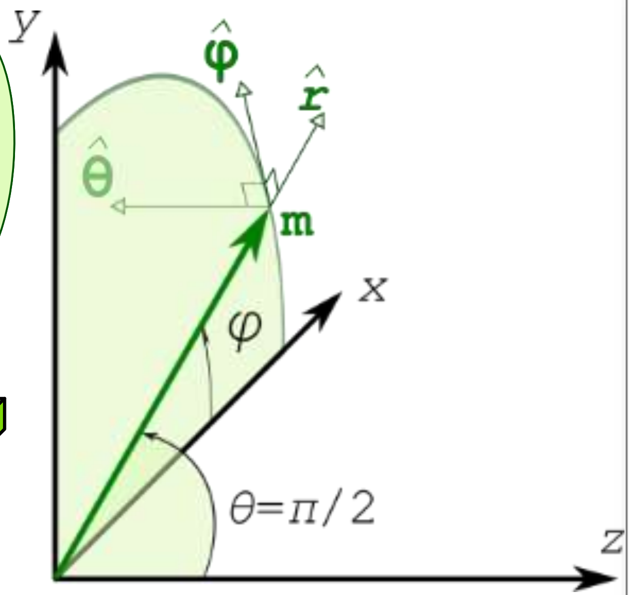


- In practice, difficult to control (backswitching due to distributions)

Precessional dynamics – Motion of domain walls



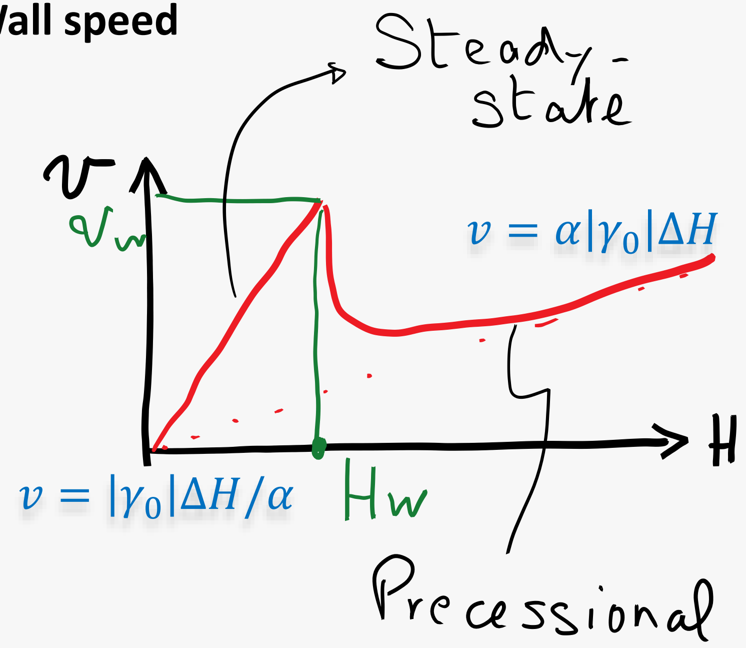




Precessional dynamics under magnetic field

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

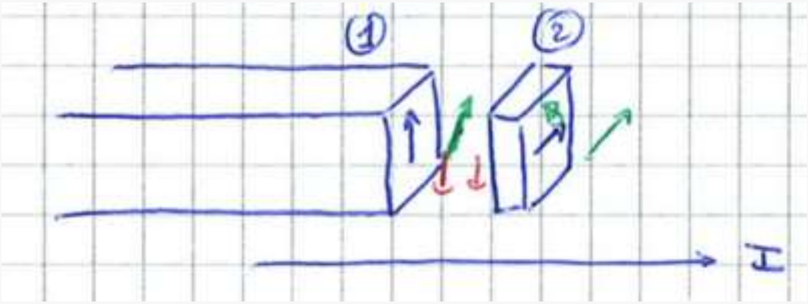
Wall speed



- Walker field $H_\mathrm{W} = \alpha M_\mathrm{s}/2$ $\approx$ few mT
- Walker speed $v = |\gamma_0| M_s \Delta/2$ $\approx$ few 10's of m/s, to km/s

A. Thiaville, Y. Nakatani, Domain-wall dynamics in nanowires and nanostrips, in *Spin dynamics in confined magnetic structures {III}*, Springer (2006)

Macrospins (1d model)



$$\frac{\mathrm{d}\mathbf{M}_2}{\mathrm{d}t} = -|\gamma_0|\mathbf{M}_2 \times \mathbf{H}_{\mathrm{eff}} + \alpha \frac{\mathbf{M}_2}{M_{\mathrm{s},2}} \times \frac{\mathrm{d}\mathbf{M}_2}{\mathrm{d}t} - P_{\mathrm{trans}}\mathbf{M}_2 \times (\mathbf{M}_2 \times \mathbf{M}_1)$$

$$P_{\mathrm{trans}} \sim P\frac{J}{|e|}$$

Number of spin-polarized electrons per unit time

J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1 (1996)
L. Berger, Phys. Rev. B 54, 9353 (1996)

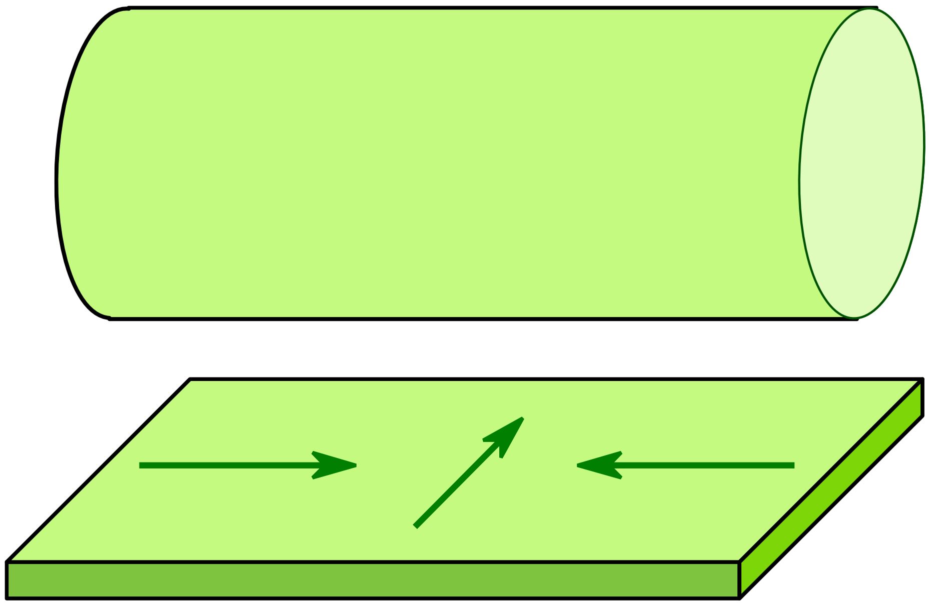
Magnetization texture (domain wall etc.)

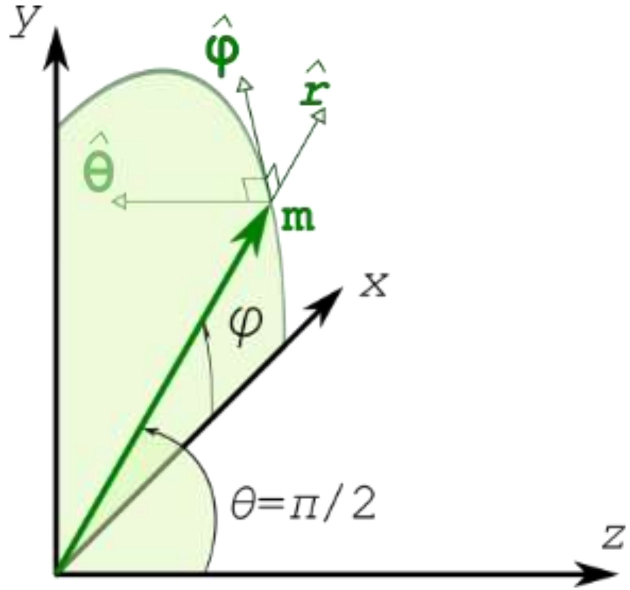
Transfer   Field-like

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = -|\gamma_0|\mathbf{m} \times \mathbf{H} + \alpha\mathbf{m} \times \frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} - (\mathbf{u}\cdot\boldsymbol{\nabla})\mathbf{m} + \beta\mathbf{m} \times [(\mathbf{u}\cdot\boldsymbol{\nabla})\mathbf{m}]$$

A. Thiaville, Y. Nakatani, Micromagnetic simulation of domain wall dynamics in nanostrips, in *Nanomagnetism and Spintronics*, Elsevier (2009)

Precessional dynamics – Motion of domain walls





Reflects spin-polarized current.

Precessional dynamics under current

$$\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{\mathrm{d}\mathbf{m}}{\mathrm{d}t} \underbrace{-(\mathbf{u}\cdot\boldsymbol{\nabla})\mathbf{m}}_{\text{Adiabatic}} + \underbrace{\beta\mathbf{m}\times[(\mathbf{u}\cdot\boldsymbol{\nabla})\mathbf{m}]}_{\text{Non-adiabatic}}$$

Adiabatic

Non-adiabatic

A. Thiaville, Y. Nakatani, Micromagnetic simulation of domain wall dynamics in nanostrips, in *Nanomagnetism and Spintronics*, Elsevier (2009)

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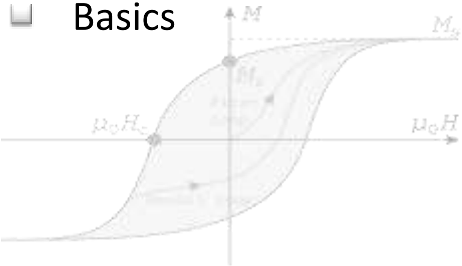
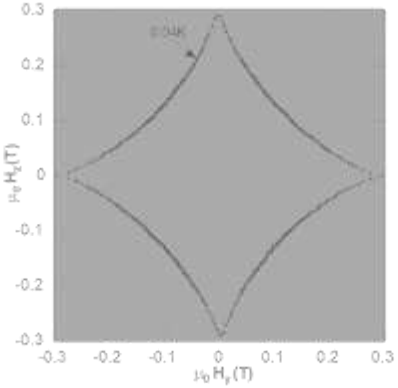
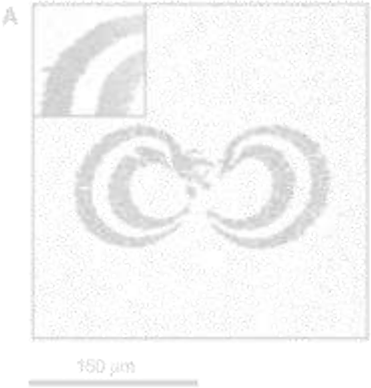


- Statics

- Macrospin switching



- Precessional dynamics



- Extended systems

Switching – Extended systems

Brown paradox

In most (extended systems): $H_c \ll \dfrac{2K}{\mu_0 M_s}$

(Micromagnetic) modeling

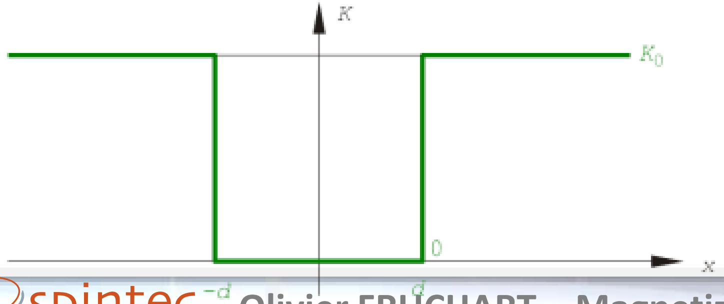
Exhibit analytic, nevertheless realistic models for magnetization reversal

PHYSICAL REVIEW VOLUME 119, NUMBER 1 JULY 1, 1960

Reduction in Coercive Force Caused by a Certain Type of Imperfection

A. AHARONI
Department of Electronics, The Weizmann Institute of Science, Rehovot, Israel
(Received February 1, 1960)

As a first approach to the study of the dependence of the coercive force on imperfections in materials which have high magnetocrystalline anisotropy, the following one-dimensional model is treated. A material which is infinite in all directions has an infinite slab of finite width in which the anisotropy is 0. The coercive force is calculated as a function of the slab width. It is found that for relatively small widths there is a considerable reduction in the coercive force with respect to perfect material, but reduction saturates rapidly so that it is never by more than a factor of 4.



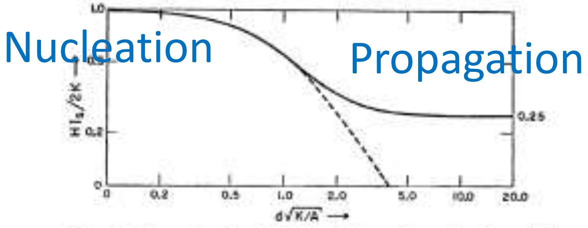
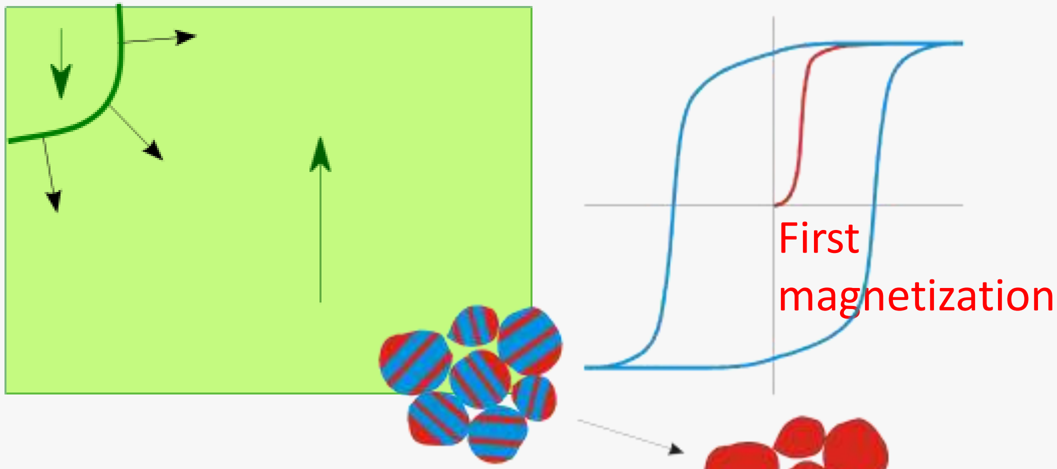
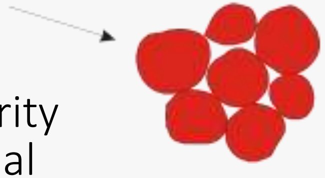


FIG. 1. The nucleation field (dashed) and coercive force (full curve) in terms of the coercive force of perfect material, $HI_s/2K$, as functions of the defect size, d.

Switching – Extended systems

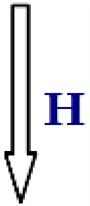
Nucleation-limited coercivity



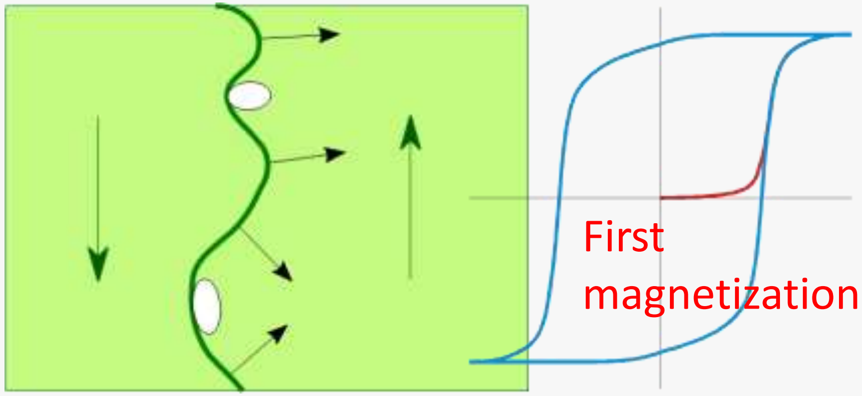


- Physics has some similarity with macrospins (thermal activation etc.)
- Concept of nucleation volume

Ex: $Nd_2Fe_{14}B$ coarse-grained magnets



Propagation-limited coercitivy



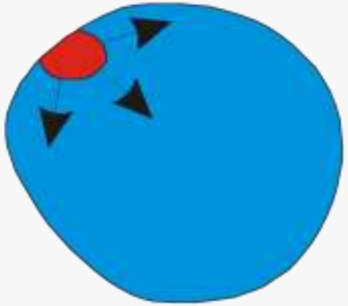
- Physics of surface/string in a disordered landscape
- See in thin films: creep, Fatuzzo-Raquet model
  M. Labrune et al., J. Magn. Magn. Mater. 80, 211 (1989)

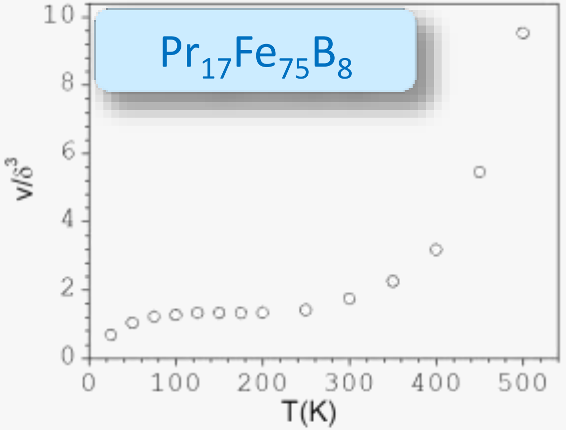
Ex: Sm_2Co_{17} magnets

Switching – Extended systems

Activation volume

- Also called: nucleation volume
- Should be considered if system is larger than the characteristic length scale
- Use for: estimate $H_c(T)$, long-time relaxation, dimensionality
- Size similar to wall width δ





Courtesy D. Givord

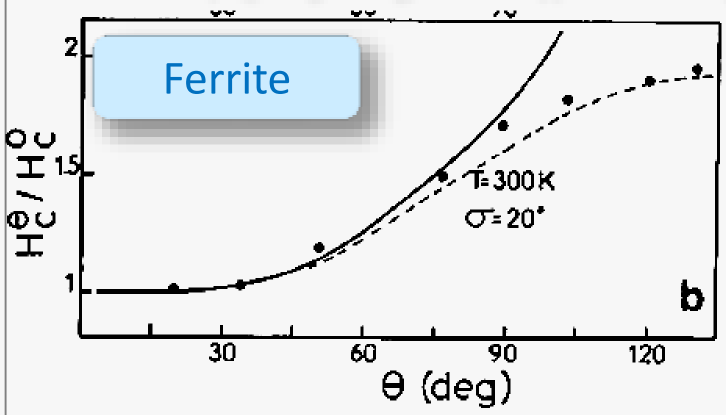
REVIEW: D. Givord et al., JMMM258, 1 (2003)

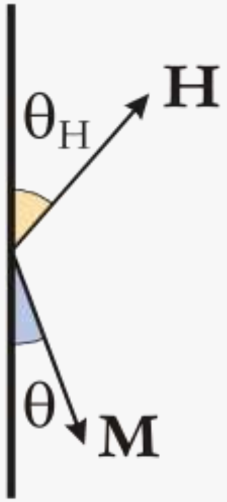
1/cos(ϑ) law, Becker-Kondorski model

E. J. Kondorsky, J. Exp. Theor. Fiz. 10, 420 (1940)

- Assumes:
  coercivity << anisotropy field
- Energy barriers overcome by Zeeman + thermal energy

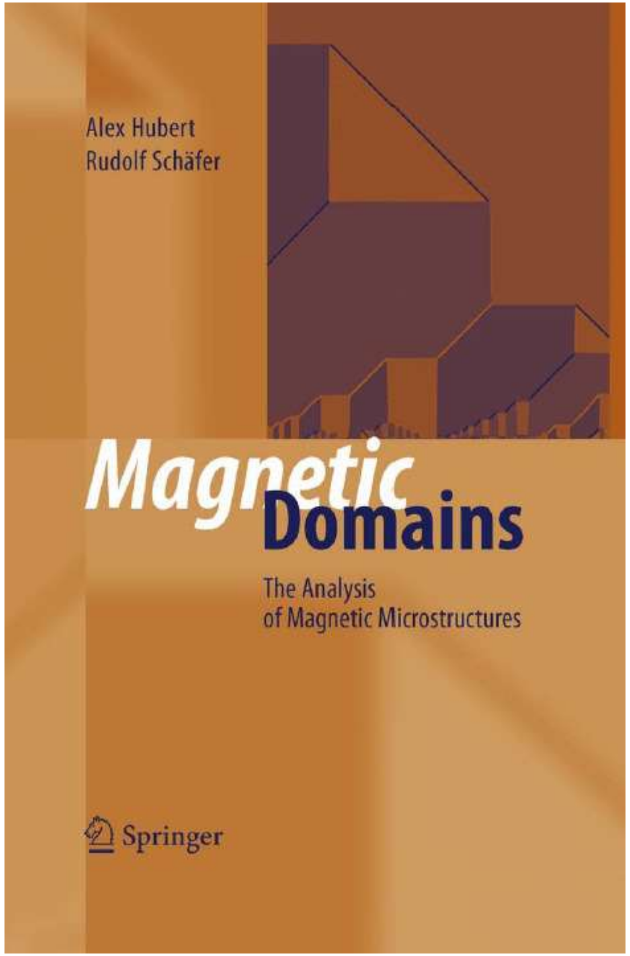
$$\Delta E = -\mu_0 M_s H v_a \cos\theta_H + 25 k_B T$$

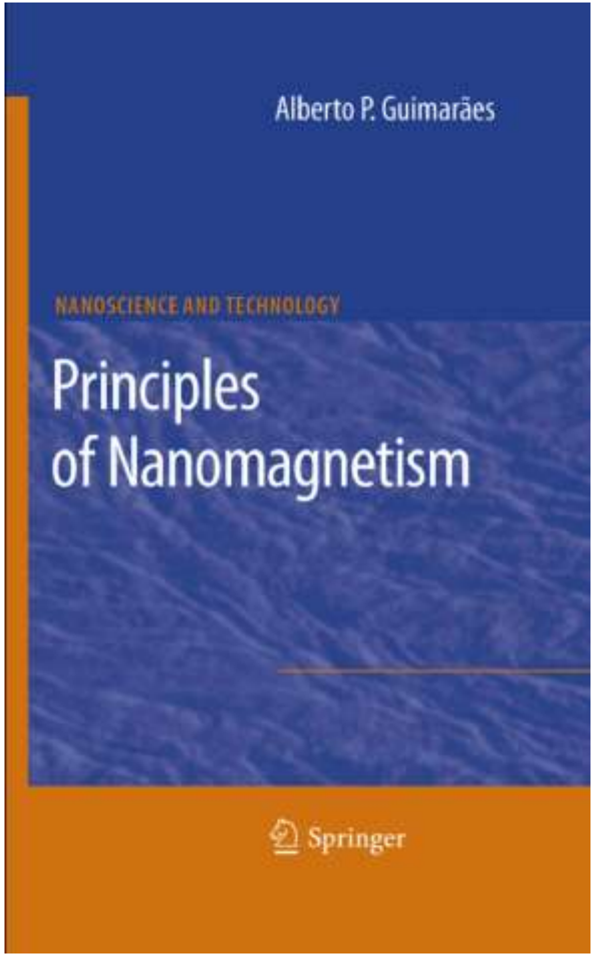


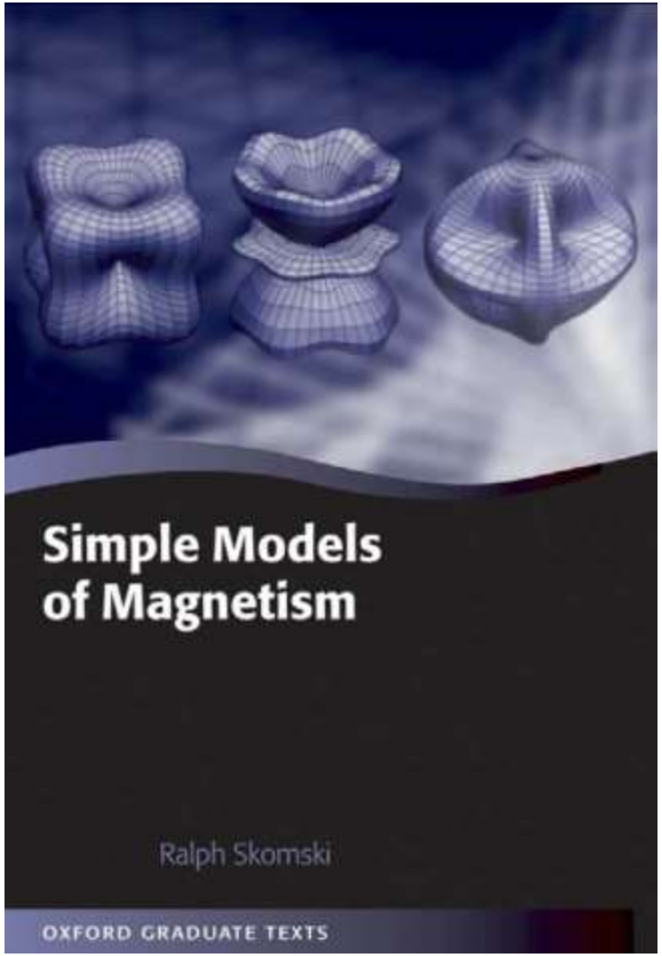


D. Givord et al., JMMM72, 247 (1988)

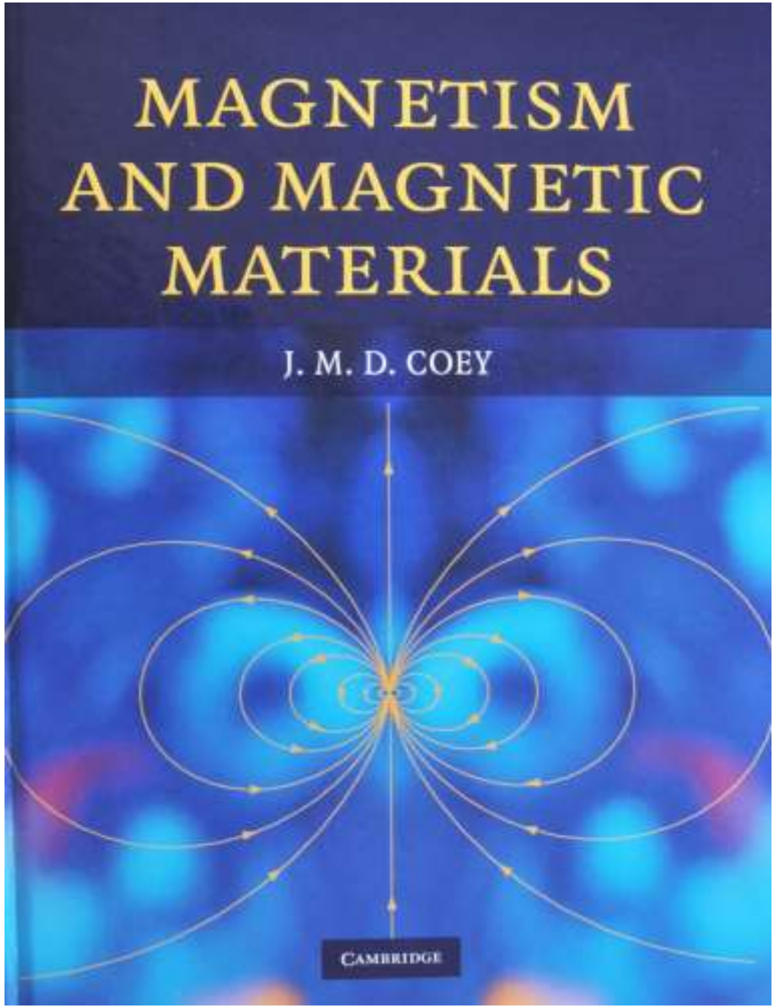
Books (nanomagnetism)

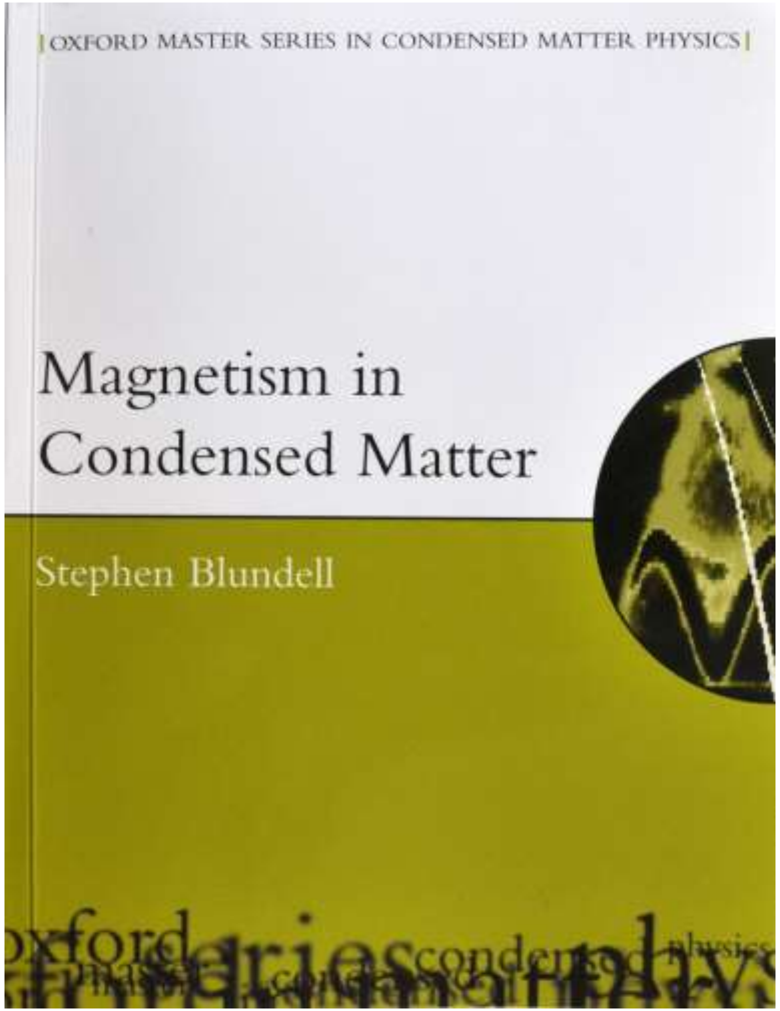






Books (nanomagnetism)





More extensive slides on: http://magnetism.eu/esm/repository-authors.html#F

2013, 2009, 2007

Lecture notes from undergraduate lectures, plus various slides on magnetization reversal:
http://fruchart.eu/olivier/slides/

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Thank you for your attention !

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