Magnetism, nano and applications

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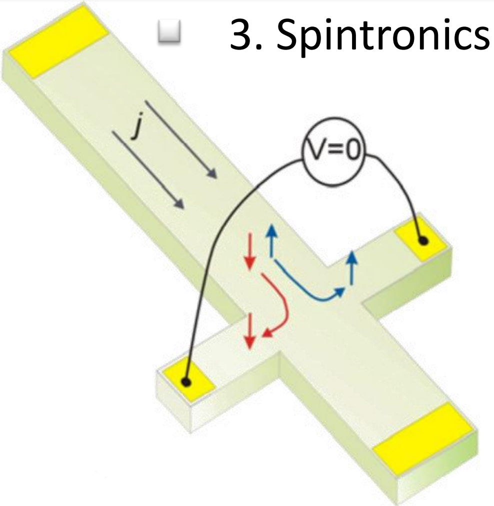
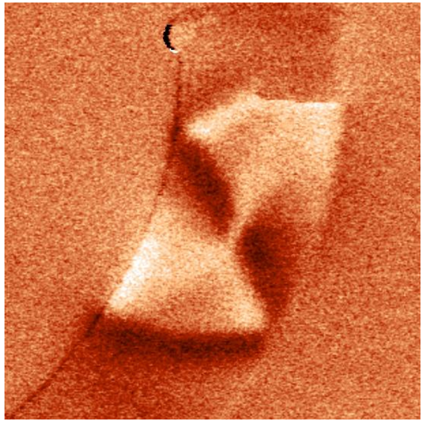
General outline

- 1. Magnetism basics

- 3. Spintronics



- 2. Magnetism and nano-objects

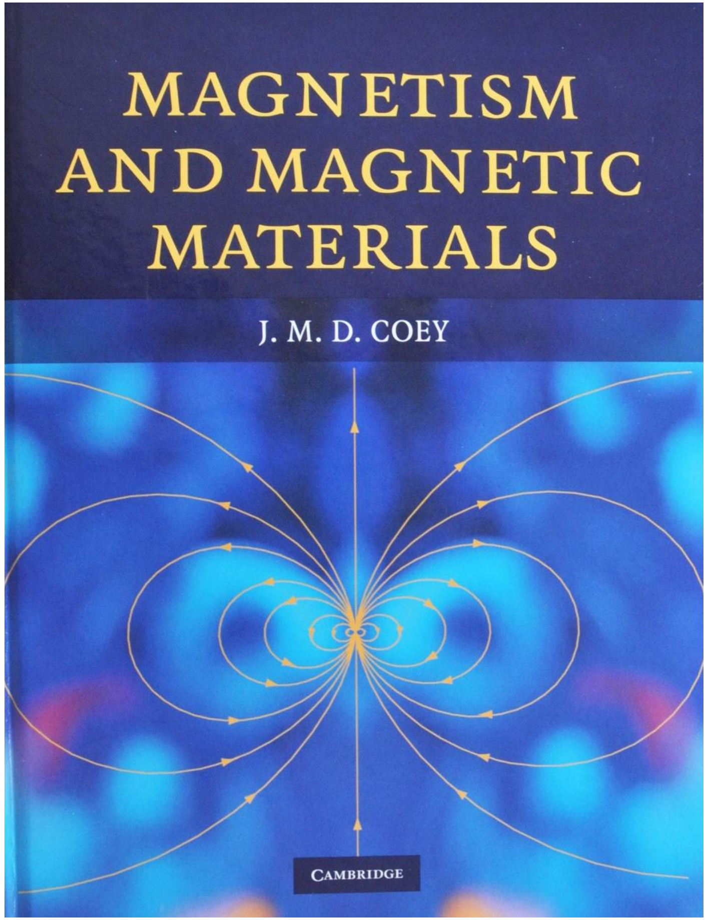


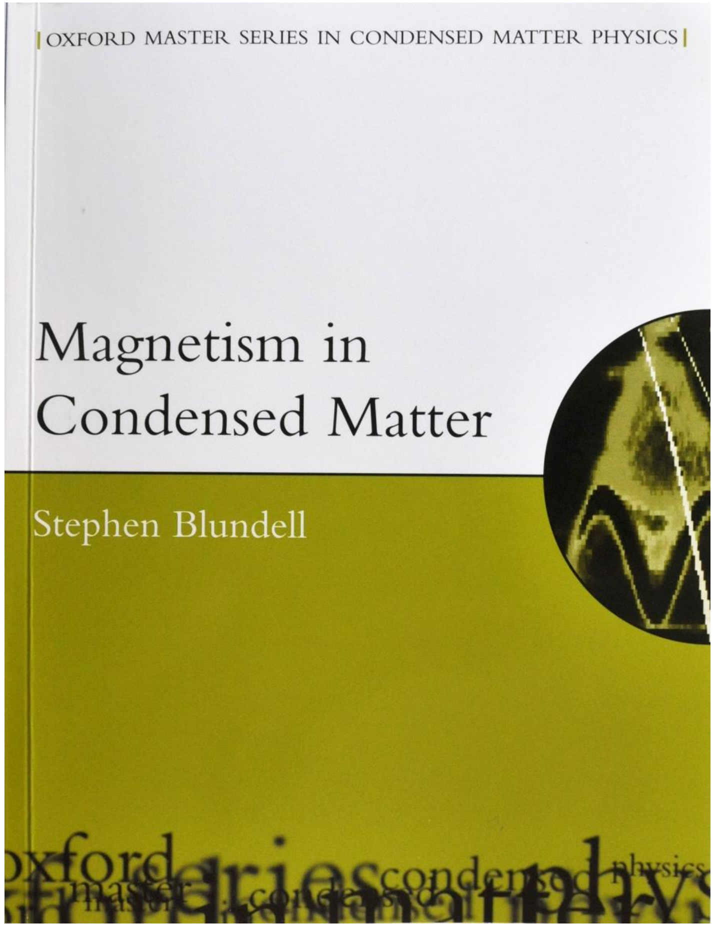
- 4. Applications of nano-magnetism

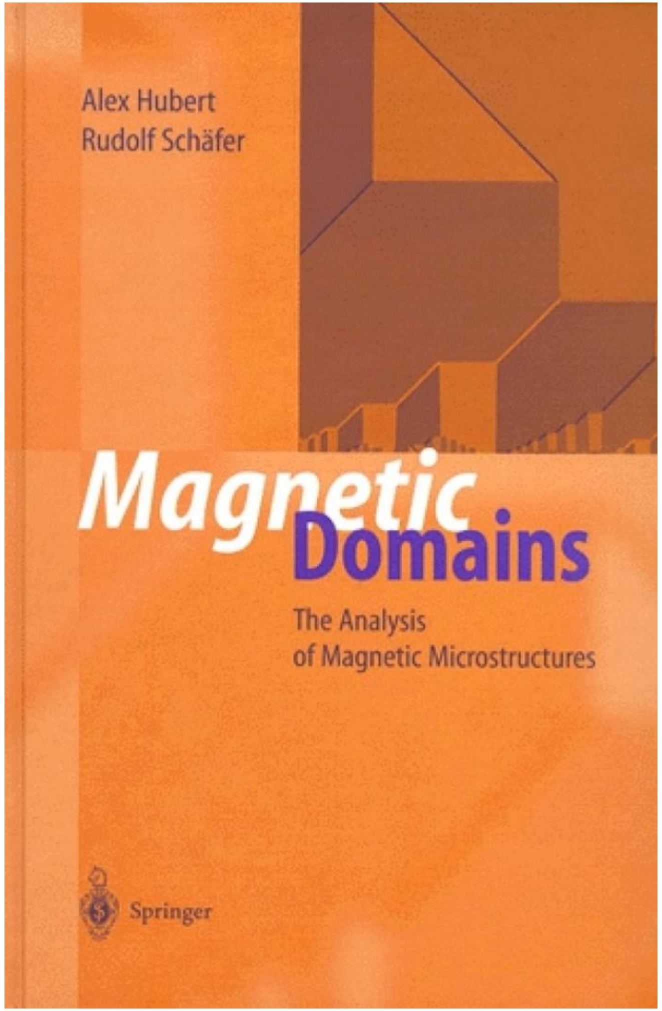
I. MAGNETISM BASICS – Outline

- Fields, moments, units
- Magnetism in matter: moments, exchange, ordering, anisotropy
- Domains and domain walls
- Quasistatic magnetization processes
- Precessional dynamics

Some references







Some references

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magnetism.eu/esm/repository-topics.html

MAGNETISM.eu
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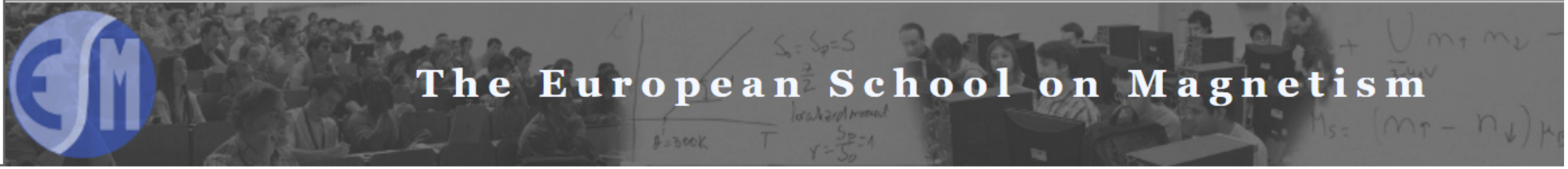


ESM repository | Home | Search | By topics | By authors

The lectures of all ESM schools since 2003 are ordered here in terms of topics. Those pertaining to several topics are listed several times. The topics are:

Topics

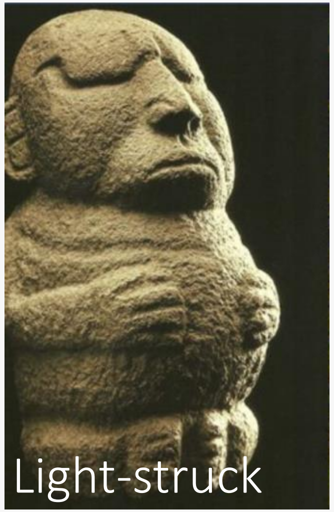
- Units, fields and moments
- Exchange, magnetic ordering, magnetic anisotropy
- Temperature effects and excitations
- Correlated systems
- Transport
- Magnetization processes
- Simulations
- Materials
- Nanoparticles, microstructures etc
- Nanomagnetism and spintronics
- Techniques
- Applications and interdisciplinary magnetism
- Industry perspectives
- Open sessions

Magnetic field and moments

- **[2020]** Origin of magnetism (spin and orbital momentum, atoms and ions, paramagnetism and diamagnetism): **STEPHEN BLUNDELL**, *Oxford, UK* [**Slides** | **Recording**]
- **[2020]** Fields, moments, units: **OLIVIER FRUCHART**, *Grenoble, France* [**Slides** | **Recording**]
- **[2019]** Fields, moments, units: **OLIVIER FRUCHART**, *Grenoble, France* [**Abstract** | **Slides**]
- **[2019]** Magnetism of atoms, Hund's rules, spin-orbit in atoms: **VIRGINIE SIMONET**, *Grenoble, France* [**Abstract**]
- **[2018]** Units in Magnetism (practical): **OLIVIER FRUCHART**, *Grenoble, France* [**Questions** | **Answers**]
- **[2018]** Magnetism of atoms and ions: **JANUSZ ADAMOWSKI**, *Kraków, Poland* [**Abstract** | **Slides**]
- **[2018]** Fields, Moments, Units, Magnetostatics: **RICHARD EVANS**, *York, UK* [**Abstract** | **Slides**]
- **[2017]** Fields, Units, Magnetostatics: **LAURENT RANNO**, *Grenoble, France* [**Abstract** | **Slides**]
- **[2017]** Magnetism of atoms and ions: **WULF WULFHEKEL**, *Karlsruhe, Germany* [**Abstract** | **Slides**]
- **[2017]** Units in Magnetism (practical): **OLIVIER FRUCHART**, *Grenoble, France* [**Questions** | **Answers**]
- **[2015]** Units in Magnetism (practical): **OLIVIER FRUCHART**, *Grenoble, France* [**Questions** | **Answers**]

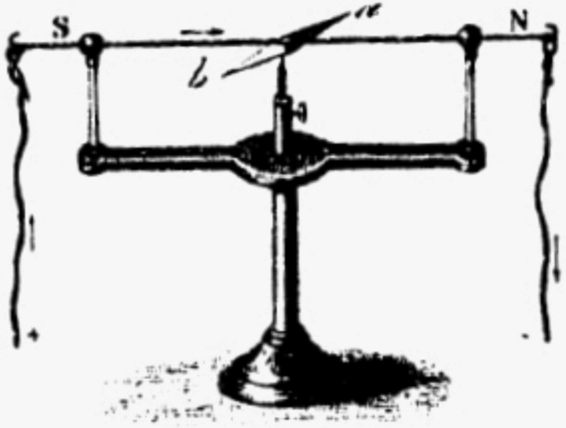
Century-old facts

- Magnetic materials (rocks)



- Magnetic field of the earth

Œrsted experiment in 1820



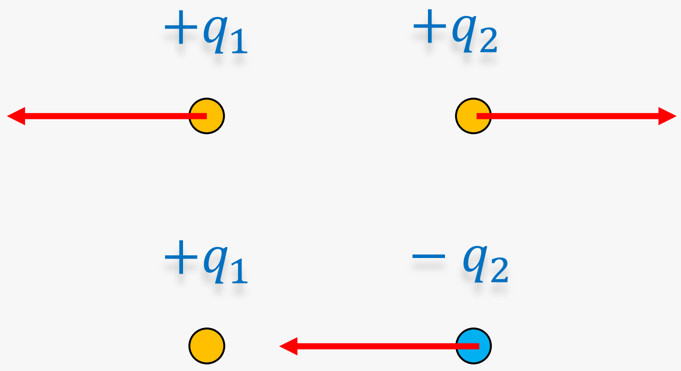
Hans-Christian Oersted, 1777–1851.

→ Birth of electromagnetism

The electric charge and the electric field

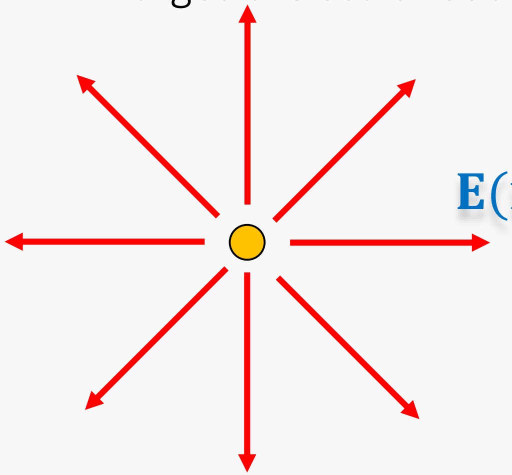
Facts: force between charges

$$\mathbf{F}_{1\to 2} = \frac{q_1 q_2}{4\pi\epsilon_0 r_{12}^2}\,\mathbf{u}_{12}$$



Modeling by the Physicist

- Electric field $\mathbf{E}_{1\to 2}$ $\qquad \mathbf{F}_{1\to 2} = \mathrm{q}_2\mathbf{E}_{1\to 2}$
- Charges are scalar sources of electric field

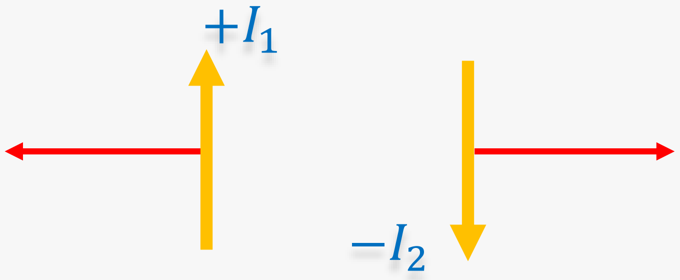


$$\mathbf{E}(\mathbf{r}) = \frac{q}{4\pi\epsilon_0 r^2}\,\mathbf{u}$$

The electric current and the magnetic induction field

Facts: force between charge currents

$$\delta \mathbf{F}_{1\to 2} = \mu_0 \frac{I_1 I_2[\delta \boldsymbol{\ell}_2 \times (\delta \boldsymbol{\ell}_1 \times \mathbf{u}_{12})]}{4\pi r_{12}^2}$$

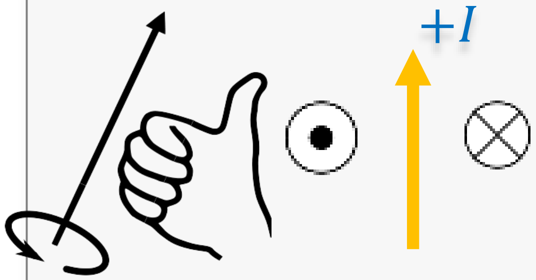


<u>Note</u>: former definition of the Ampère:

The force between two infinite wires 1m apart with current 1A is $2\times 10^{-7}\ \mathrm{N/m}$

Modeling by the Physicist

- Magnetic induction field: Biot & Savart law



$$\delta \mathbf{B} = \frac{\mu_0 I \delta \boldsymbol{\ell} \times \mathbf{u}}{4\pi r^2}$$

- Retrieve the force (Laplace)

$$\delta \mathbf{F}_2 = I_2 \delta \boldsymbol{\ell} \times \mathbf{B}(\mathbf{r}_2)$$

$$\Rightarrow \quad \mathbf{F} = q\ \mathbf{v} \times \mathbf{B}$$

- Magnetic induction field defined through Lorentz Force

Maxwell equations (in vacuum)

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$ → Gauss theorem

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$ → Faraday law of induction

$$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{j} + \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$$ → Ampère theorem

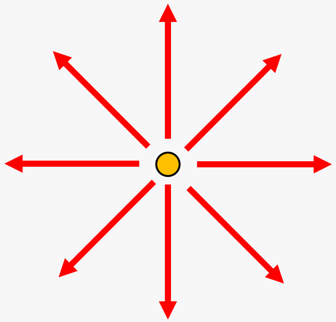
$$\nabla \cdot \mathbf{B} = 0$$ → B is divergence free (no magnetic poles)

The electric charge and the electric field

Macroscopic level: Gauss theroem

- Ostogradski theorem

$$\iiint_{\mathcal{V}} \nabla \cdot \mathbf{E}\, \mathrm{d}\mathcal{V} = \oiint_{\partial\mathcal{V}} \mathbf{E} \cdot \mathbf{n}\, \mathrm{d}\mathcal{S}$$



$$\Rightarrow \frac{Q}{\epsilon_0} = \iiint_{\mathcal{V}} \frac{\rho}{\epsilon_0}\, \mathrm{d}\mathcal{V} = \oiint_{\partial\mathcal{V}} \mathbf{E} \cdot \mathbf{n}\, \mathrm{d}\mathcal{S}$$

Microscopic level: Maxwell equation

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\rho = \frac{\delta Q}{\delta \mathcal{V}}$$ Volume density of electric charge

- Q is the scalar source of **E**

Link

$$\nabla \cdot \mathbf{E} = \frac{\partial E_x}{\partial x} + \ldots = \frac{E_x(x+\delta x) - E_x(x)}{\delta x} + \cdots$$

The electric current and the magnetic induction field

Macroscopic level: Ampere theorem

- Stokes theorem

$$\iint_{\mathcal{S}} (\boldsymbol{\nabla} \times \mathbf{B}) \cdot \mathbf{n} \, \mathrm{d}\mathcal{S} = \oint_{\partial\mathcal{S}} \mathbf{B} \cdot \mathrm{d}\boldsymbol{\ell}$$

$$\Rightarrow \quad I = \mu_0 \iint_{\mathcal{S}} (\mathbf{j} \cdot \mathbf{n}) \, \mathrm{d}\mathcal{S} = \oint_{\partial\mathcal{S}} \mathbf{B} \cdot \mathrm{d}\boldsymbol{\ell}$$

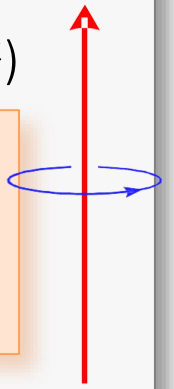
Microscopic level: Maxwell equation

$$\boldsymbol{\nabla} \times \mathbf{B} = \mu_0 \mathbf{j}$$

j: Volume density of current (A/m^2)

- j is the vectorial source of curl of B

Unit for B: tesla (T)



Link

$$\boldsymbol{\nabla} \times \mathbf{B} = \begin{pmatrix} \cdots \\ \cdots \\ \dfrac{\partial B_y}{\partial x} - \dfrac{\partial B_x}{\partial y} \end{pmatrix} = \begin{pmatrix} \cdots \\ \cdots \\ \dfrac{B_y(x+\delta x) - B_y(x)}{\delta x} - \dfrac{B_x(y+\delta y) - B_x(y)}{\partial y} \end{pmatrix}$$

Units

C'NANO

Definitions

	SI system		cgs-Gauss	
	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

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

Problems with cgs-Gauss

- The quantity for charge current is missing

  No check for homogeneity

  Mix of units in spintronics

- Inconsistent definition of H

  Dimensionless quantities are effected: demag factors, susceptibility etc.

- More in the practical on units: http://magnetism.eu/esm/repository-authors.html#F

Units

Definitions

	S.I.		cgs-Gauss	
	Meter	m	Centimeter	cm
	Kilogram	kg	Gram	g
	Second	s	Second	s
	Ampere	A	Ab-Ampere	ab-A = 10 A

$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$ (S.I.) $\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$ (cgs-Gauss)

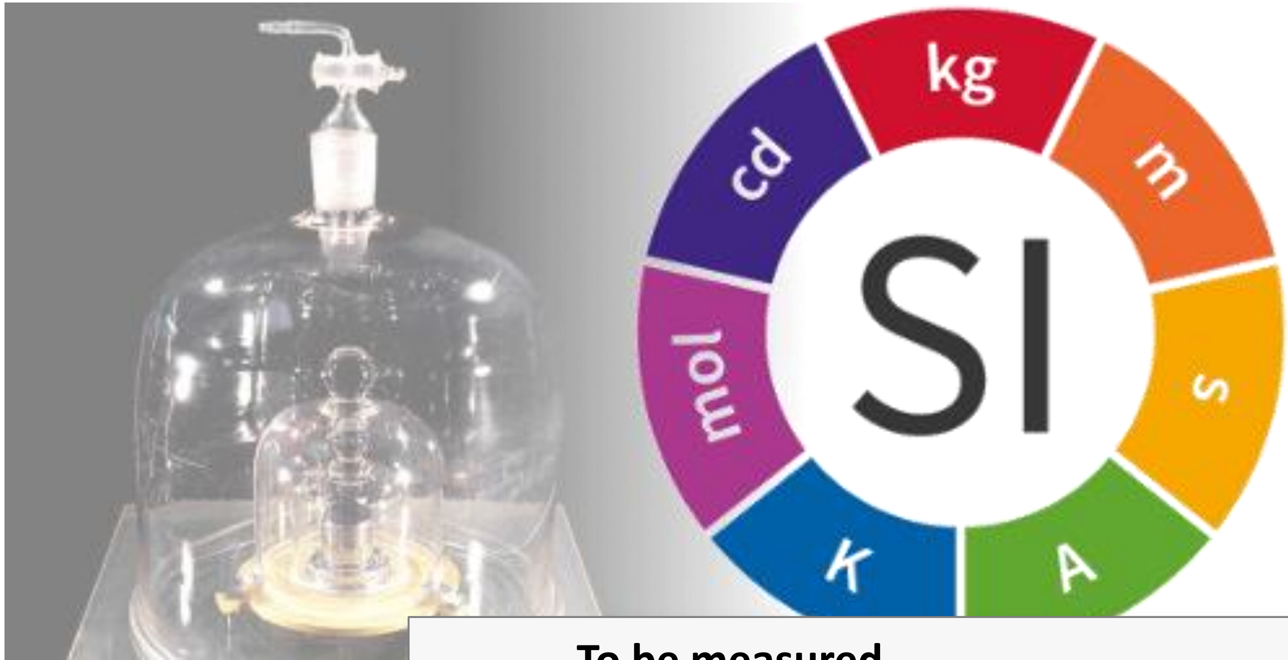
$\mu_0 = 4\pi \times 10^{-7}$ S.I. $"\mu_0" = 4\pi.$

Conversion

Field	$\mathbf{H}$	$1\ \mathrm{A/m}$	⟷	$4\pi \times 10^{-3}\ \mathrm{Oe}$	Oersted
Moment	$\boldsymbol{\mu}$	$1\ \mathrm{A \cdot m^2}$	⟷	$10^3\ \mathrm{emu}$	
Magnetization	$\mathbf{M}$	$1\ \mathrm{A/m}$	⟷	$10^{-3}\ \mathrm{emu/cm^3}$	Electromagnetic Unit
Induction	$\mathbf{B}$	$1\ \mathrm{T}$	⟷	$10^4\ \mathrm{G}$	Gauss
Susceptibility	$\chi = M/H$	1		$1/4\pi$ ⟷	

Tutorial on units
Questions: http://magnetism.eu/esm/2018/abs/fruchart-practical-abs1.pdf
Answers: http://magnetism.eu/esm/2018/abs/fruchart-practical-answers1.pdf

Quantum revolution in SI units in 2019



To be measured

- Magnetic permeability of vacuum

$$\mu_0 \neq 4\pi \times 10^{-7}\ \mathrm{S.I.}$$

$$\mu_0 = 4\pi[1 + 2.0(2.3)\cdot 10^{-10}] \times 10^{-7}\ \mathrm{S.I.}$$

Define quantities

- Times
- Length
- Mass
- Electric charge

Fixed values

- Speed of light -> Define meter
- Planck constant -> Defines kg
- Charge of the electron

R. B. Goldfarb, IEEE Trans. Magn. MAG. 8, 1-3 (2017); R. B. Goldfarb, IEEE Mag. Lett. 9, 1205905 (2018)
S. Schlamminger, Redefining the kilogram and other SI units, IOP Physics World Discovery (2018)

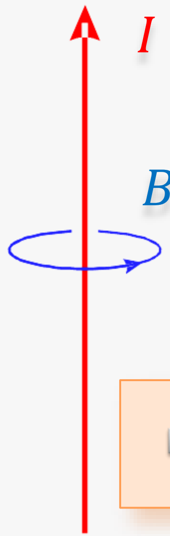
The magnetic point dipole

Biot and Savart

$$\delta\mathbf{B} = \frac{\mu_0 I \delta\boldsymbol{\ell} \times \mathbf{u}}{4\pi r^2}$$

- Note: $1/r^2$ decay

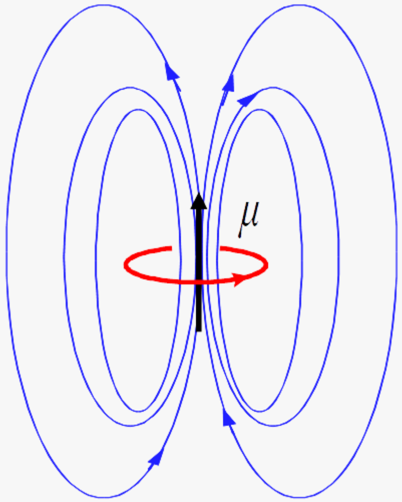
Ampere theorem and Œrsted field



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

- Note: $1/r$ decay

The magnetic point dipole



- Simple loop

$$\boldsymbol{\mu} = I\mathcal{S}\,\mathbf{n}$$ **Unit**: $\mathrm{A}\cdot\mathrm{m}^2$

- General definition

$$\boldsymbol{\mu} = \frac{1}{2}\iiint_{\mathcal{V}} \mathbf{r}\times\mathbf{j}(\mathbf{r})\,\mathrm{d}\mathcal{V}$$

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

- Note: $1/r^3$ decay

$$\mathbf{B} = \frac{\mu_0}{4\pi r^3}(2\mu\cos\theta\,\mathbf{u}_r + \mu\sin\theta\,\mathbf{u}_\theta)$$

The magnetic point dipole in a magnetic induction field

Energy

$\mathcal{E} = -\boldsymbol{\mu} \cdot \mathbf{B}$ Zeeman energy (J)

Demonstration

- Work to compensate Lenz law during rise of **B**
- Integrate torque from Laplace force while flipping dipole in **B**

Force

$\mathbf{F} = \boldsymbol{\mu} \cdot (\overline{\overline{\nabla \mathbf{B}}})$

- Valid only for fixed dipole
- No force in uniform magnetic induction field

Torque

$$\boldsymbol{\Gamma} = \oint \mathbf{r} \times I(\mathrm{d}\boldsymbol{\ell} \times \mathbf{B}) = \boldsymbol{\mu} \times \mathbf{B}$$

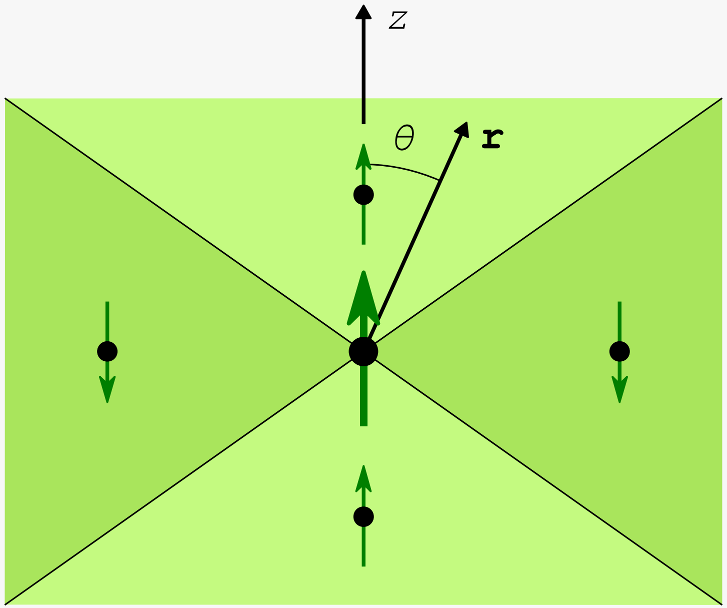
- Inducing precession of dipole around the field
- It is energy-conservative, as expected from Laplace (Lorentz) force

Two interacting magnetic point dipoles

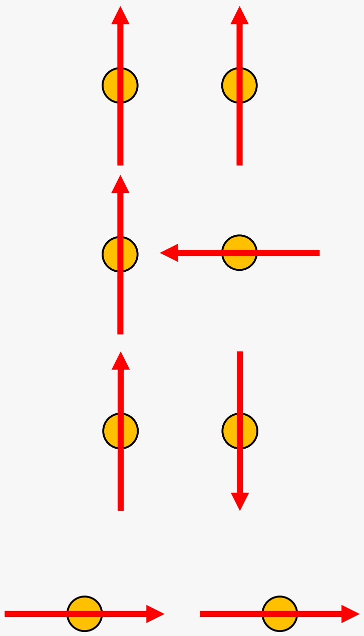
Energy

$$\mathcal{E} = -\frac{\mu_0}{4\pi r^3}\left[\frac{3}{r^2}(\boldsymbol{\mu}_1 \cdot \mathbf{r})(\boldsymbol{\mu}_2 \cdot \mathbf{r}) - \boldsymbol{\mu}_1 \cdot \boldsymbol{\mu}_2\right]$$

- The dipole-dipole interaction is anisotropic



Examples



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

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

$$\mathcal{E} = 0$$

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

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

Magnetization

Definition

- Volume density of magnetic point dipoles

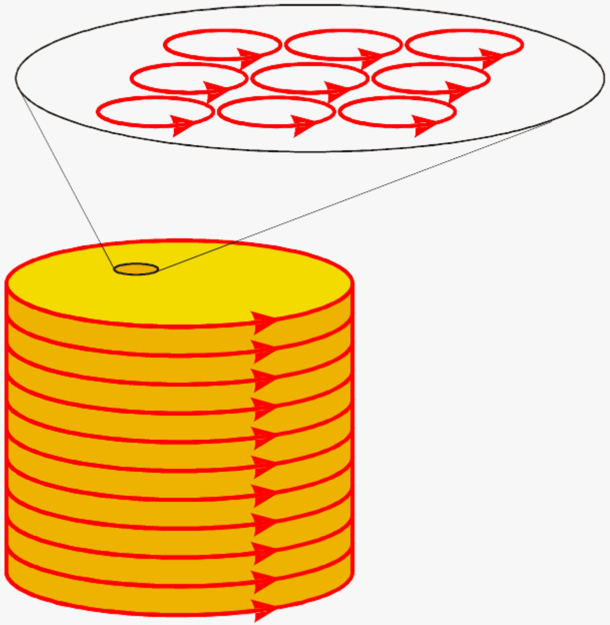
$$\mathbf{M} = \frac{\delta \boldsymbol{\mu}}{\delta \mathcal{V}} \qquad \mathrm{A/m}$$

- Total magnetic moment of a body

$$\boldsymbol{\mathcal{M}} = \int_{\mathcal{V}} \mathbf{M}\, \mathrm{d}\mathcal{V} \qquad \mathrm{A \cdot m^2}$$

- Applies to: ferromagnets, paramagnets, diamagnets etc.
- Must be defined at a length scale much larger than atoms
- Is the basis for the micromagnetic theory

Equivalence with surface currents



- Name: Amperian description of magnetism
- Surface current equals magnetization $\mathrm{A/m}$

Free currents and bound currents

Back to Maxwell equations

- Consider separately real charge current, $\mathbf{j}_\mathrm{c}$ from fictitious currents of magnetic dipoles $\mathbf{j}_\mathrm{m}$

$$\boldsymbol{\nabla}\times\mathbf{B}=\mu_0(\mathbf{j}_\mathrm{c}+\mathbf{j}_\mathrm{m})$$

The magnetic field H

- One has: $\boldsymbol{\nabla}\times\left(\dfrac{\mathbf{B}}{\mu_0}-\mathbf{M}\right)=\mathbf{j}_\mathrm{c}$

- By definition: $\mathbf{H}=\dfrac{\mathbf{B}}{\mu_0}-\mathbf{M}$ A/m

$$\boldsymbol{\nabla}\times\mathbf{H}=\mathbf{j}_\mathrm{c}$$

- Outside matter, $\mathbf{B}$ and $\mu_0\mathbf{H}$ coincide and have exactly the same meaning.

The dipolar field

Maxwell equation $\boldsymbol{\nabla}\cdot\mathbf{B}=\mathbf{0}\rightarrow\boldsymbol{\nabla}\cdot\mathbf{H}_\mathrm{d}=-\boldsymbol{\nabla}\cdot\mathbf{M}$

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

Magnetic charges

The singularity that arises at boundaries can be renormalized as surface 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

Stray field and demagnetizing field

Vocabulary

- Generic names

  Magnetostatic field

  Dipolar field

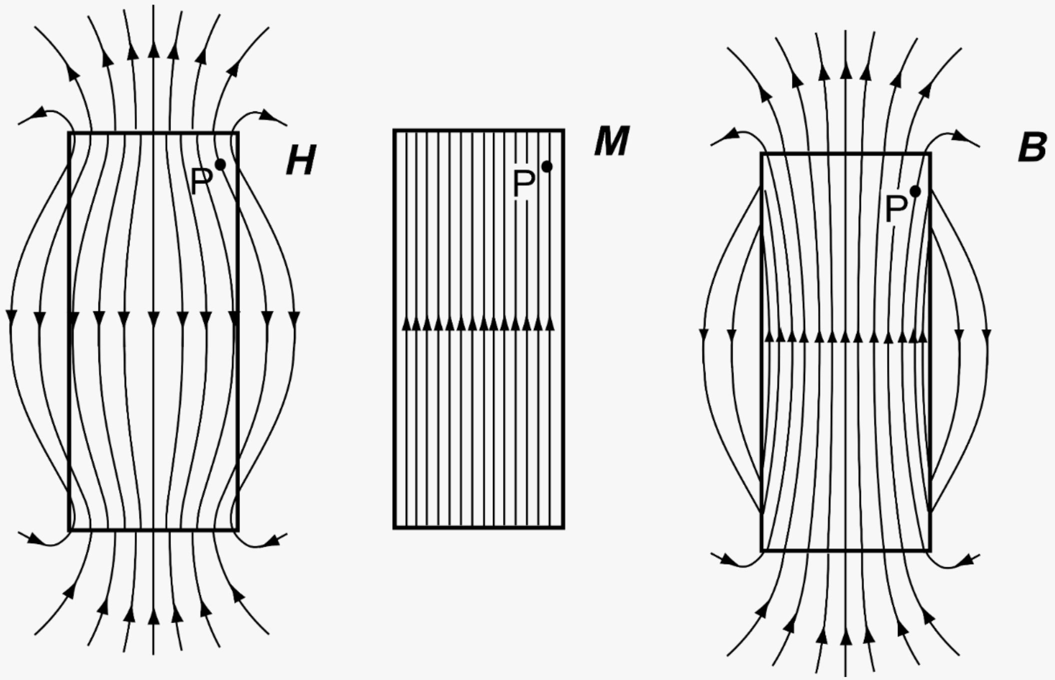
- Inside material

  Demagnetizing field

- Outside material

  Stray field

Example Permanent magnet (uniformly-magnetized)



- Surface charges

$$\sigma(\mathbf{r}) = M_s \mathbf{m}(\mathbf{r}) \cdot \mathbf{n}(\mathbf{r})$$

- Dipolar field

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

Illustration from: M. Coey's book

Dipolar energy and demagnetizing tensor

Dipolar energy

- Zeeman energy of microscopic volume
  $$\delta\mathcal{E}_\mathrm{Z} = -\mu_0 \mathbf{M}\delta\mathcal{V} \cdot \mathbf{H}_\mathrm{ext}$$
- Elementary volume of a macroscopic system creating its own dipolar field
  $$E_\mathrm{d} = \delta\mathcal{E}_\mathrm{d}/\delta\mathcal{V} = -\frac{1}{2}\mu_0 \mathbf{M} \cdot \mathbf{H}_\mathrm{d}$$
- Total dipolar energy of macroscopic body
  $$\mathcal{E}_\mathrm{d} = -\frac{1}{2}\mu_0 \iiint_\mathcal{V} \mathbf{M} \cdot \mathbf{H}_\mathrm{d}\, \mathrm{d}\mathcal{V}$$
  $$\mathcal{E}_\mathrm{d} = \frac{1}{2}\mu_0 \iiint_\mathcal{V} \mathbf{H}_\mathrm{d}^2\, \mathrm{d}\mathcal{V}$$

- Always positive. Zero means minimum

Size considerations

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

- Unchanged if all lengths are scaled: homothetic. NB: the following is a solid angle:
  $$\mathrm{d}\boldsymbol{\Omega} = \frac{(\mathbf{r}-\mathbf{r}')\mathrm{d}\mathcal{S}'}{|\mathbf{r}-\mathbf{r}'|^3}$$

- H_d does not depend on the size of the body
- Said to be a long-range interaction

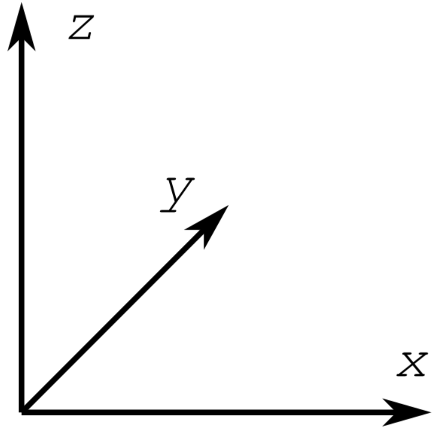
Demagnetizing tensor

$$\langle \mathbf{H}_\mathrm{d}(\mathbf{r}) \rangle = -M_\mathrm{s}\, \overline{\overline{\mathbf{N}}} \cdot \mathbf{m}$$

Applies to uniform magnetization

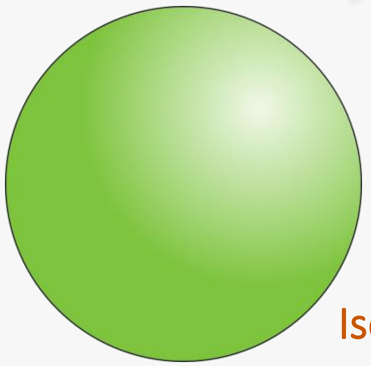
- Along main directions $\langle H_{\mathrm{d},i}(\mathbf{r}) \rangle = -N_i M_\mathrm{s}$

Demagnetizing coefficient (examples)



Sphere

$L_x = L_y = L_z = D$



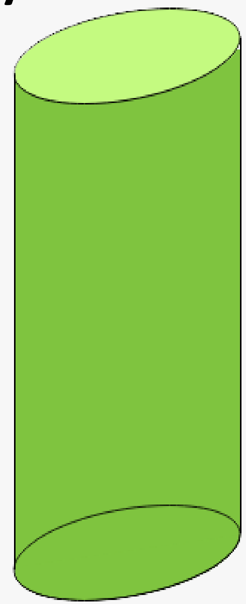
$N_x = N_y = N_z = \frac{1}{3}$

Isotropic

Cylinder

$L_x = L_y = D$

$L_z = \infty$



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

$N_z = 0$

Favors **axial magnetization**

Slab (thin film)

$L_x = L_y = \infty$

$N_x = N_y = 0$

$N_z = 1$

Favors in-plane magnetization

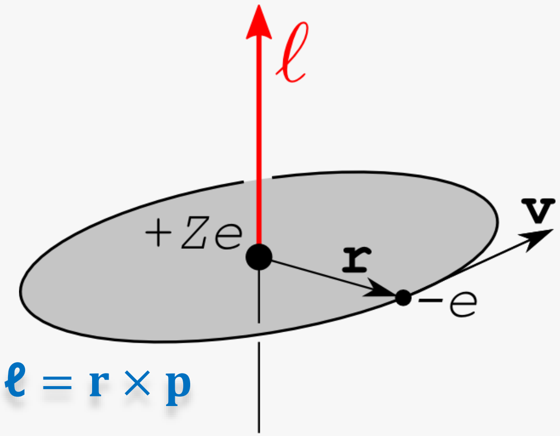
Take-away message

Dipolar energy favors alignment of magnetization with longest direction of sample

Moments

Angular momentum

Classical view: electron orbiting around the nucleus



$\boldsymbol{\ell} = \mathbf{r} \times \mathbf{p}$

➡ $\ell = m_\mathrm{e} r v$

Niels Bohr postulate: is quantized

$$\ell = m_\mathrm{e} r v \in \hbar\mathbb{N}$$

$$\hbar = \frac{\mathrm{h}}{2\pi} = 1.0546 \times 10^{-34}\ \mathrm{J \cdot s}$$

Orbital magnetic moment

Results from angular momentum

$$\boldsymbol{\mu} = \frac{1}{2} \iiint \mathbf{r} \times \mathbf{j}(\mathbf{r}) \mathrm{d}\mathbf{r} = I\boldsymbol{\mathcal{S}}$$

$$\mu = \pi r^2 I = -erv/2 \qquad \mathrm{A \cdot m^2}$$

Gyromagnetic ratio γ

Magnetic moment associated with angular momentum: $\boldsymbol{\mu} = \gamma \boldsymbol{\ell}$

For the orbital motion of electrons: $\gamma = -\dfrac{e}{2m_\mathrm{e}}$

Bohr magneton μ_B

Quantum for magnetic moments, resulting from the quantization of angular momentum

$$\mu_\mathrm{B} = \gamma\hbar \qquad \mu_\mathrm{B} = 9.274 \times 10^{-24}\ \mathrm{A \cdot m^2}$$

Moments

Spin magnetic moment

- Spin = intrinsically-quantized angular momentum
- Electrons are fermions (half-integer spin)

$$s = \pm \frac{1}{2}$$

- Angular momentum $s\hbar = \pm \frac{\hbar}{2}$
- Magnetic moment (Dirac equation, not classical)

$$\gamma = -\frac{e}{m_\mathrm{e}}$$

→ Electrons carry a spin magnetic moment $\approx 1\ \mu_\mathrm{B}$

Gyromagnetic ratio γ

- Magnetic moment associated with angular momentum $\boldsymbol{\mu} = \gamma \boldsymbol{\ell}$
- Orbital motion of electrons $\gamma \approx -\frac{e}{2m_\mathrm{e}}$
- Spin of electrons $\gamma \approx -\frac{e}{m_\mathrm{e}}$

Bohr magneton μ_B

- Quantum for magnetic moment, resulting from the quantization of angular momentum

$\mu_\mathrm{B} = \gamma \hbar$ $\qquad$ $\mu_\mathrm{B} = 9.274 \times 10^{-24}\ \mathrm{A \cdot m^2}$

Landé factor $\frac{|\boldsymbol{\mu}|}{\mu_\mathrm{B}} = g \frac{|\boldsymbol{\ell}|}{\hbar}$

- Orbital moment $g = 1$
- Electron spin $g \approx 2$

Magnetic exchange

Physics

- Spin + space wave function must be antisymmetric
- Coulomb repulsion
- Pauli exclusion

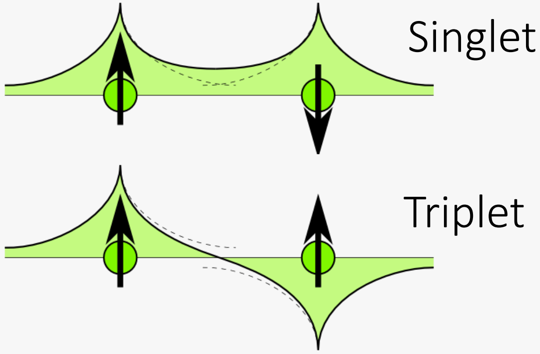
May be viewed as interatomic Hund's rules

Hamiltonian

$$\mathcal{H} = -2J_{1,2}\mathbf{S}_1 \cdot \mathbf{S}_2$$

$J_{1,2}$ Exchange integral

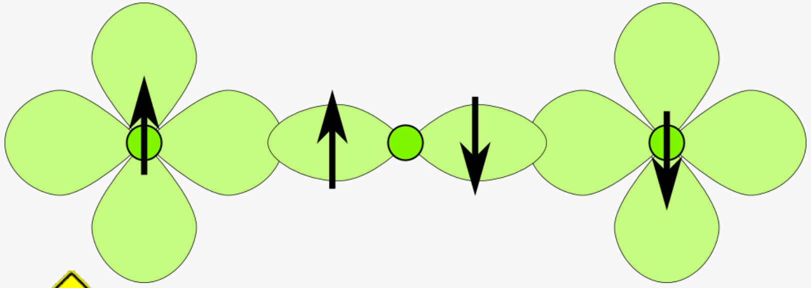
Direct exchange



Molecules → Singlet

Metals ⟶ Ferro/Antiferro

Superexchange



Bond-length and – orientation dependent

Often: π ⟶ Antiferro; π /2 ⟶ ferro

Indirect exchange

Conduction electrons

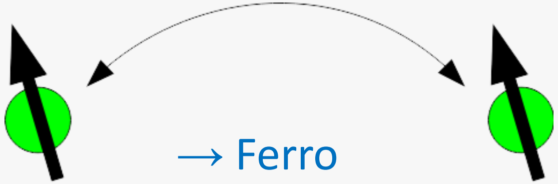
⟶ Ferro

RKKY, rare-earth (4f), GaMnAs (3d)

Double exchange

Mixed-valence states

e- hopping



⟶ Ferro

Mn^{3+} ($3d^4$) Mn^{4+} ($3d^3$)

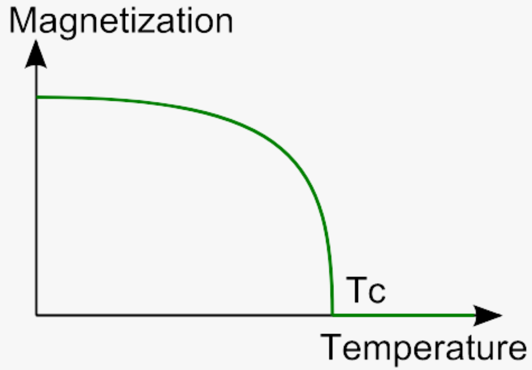
Example: $(La_{0.7}Ca_{0.3})MnO_3$

Magnetic ordering

Magnetic ordering

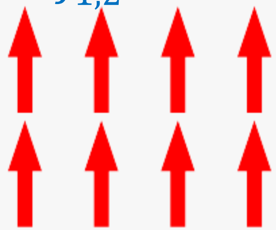
Magnetic exchange between microscopic moments:

$$\mathcal{E} = -2\sum_{i<j} J_{1,2}\mathbf{S}_i \cdot \mathbf{S}_j$$



Ferromagnetism

$J_{1,2} > 0$



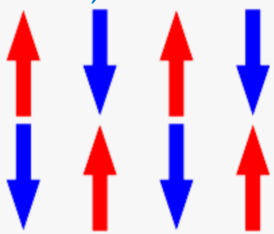
Fe

$T_\mathrm{C} = 1043\ \mathrm{K}$

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

Antiferromagnetism

$J_{1,2} < 0$



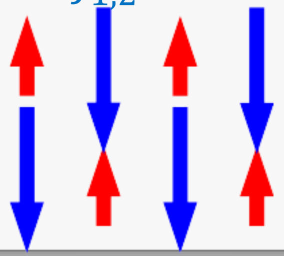
CoO

$T_N = 292\ \mathrm{K}$

$J = 3/2$

Ferrimagnetism

$J_{1,2} < 0$



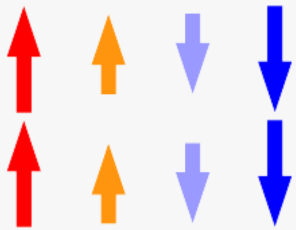
Fe_3O_4

$T_\mathrm{C} = 858\ \mathrm{K}$

$M_\mathrm{s} = 480\ \mathrm{kA/m}$

Helimagnetism

$J_1\ , J_2\ \dots$



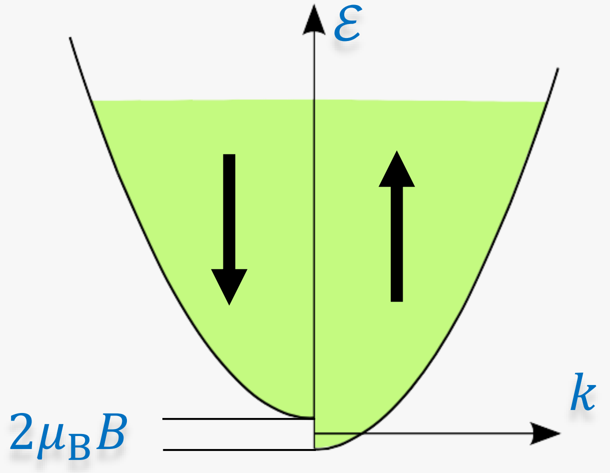
Dy

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

$\mu = 10.4\ \mu_\mathrm{B}$

Magnetic exchange (band magnetism)

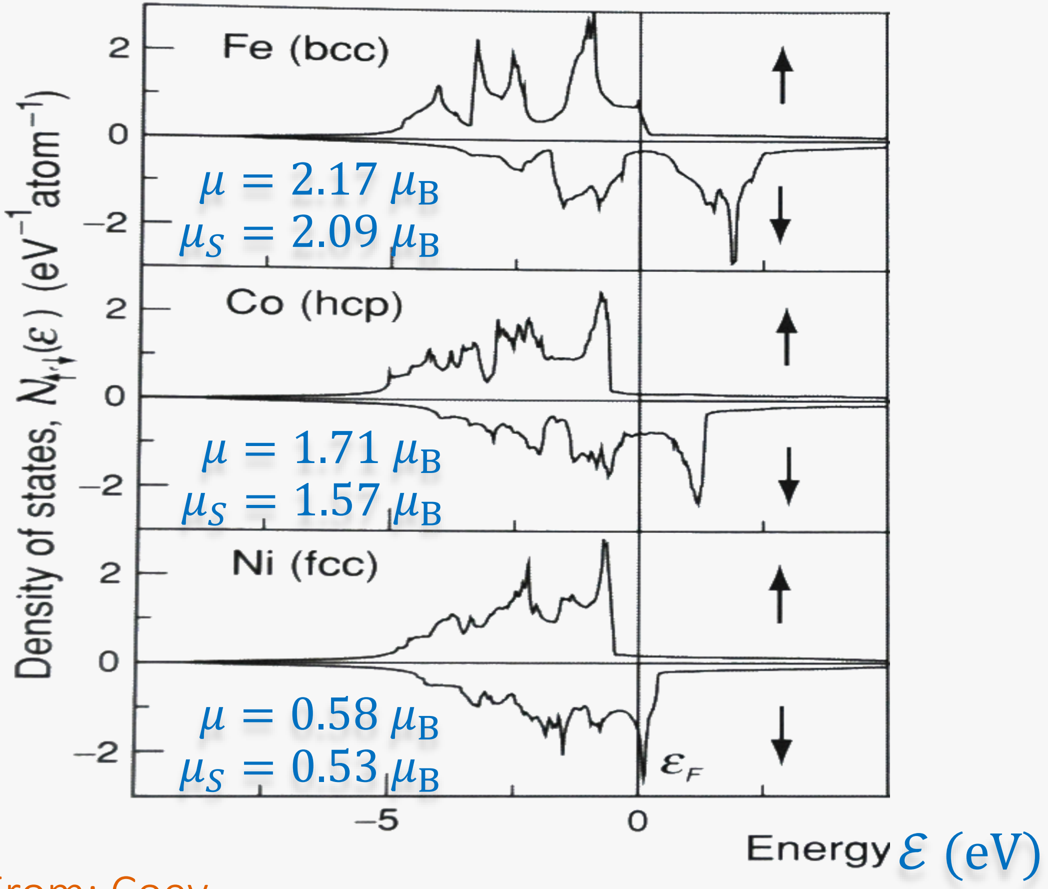
Stoner criterium



- Cost in kinetic energy
- Gain in Coulomb interaction

Criterion for ordering: $I\rho_{\uparrow,\downarrow}(\mathcal{E}_F)>1$

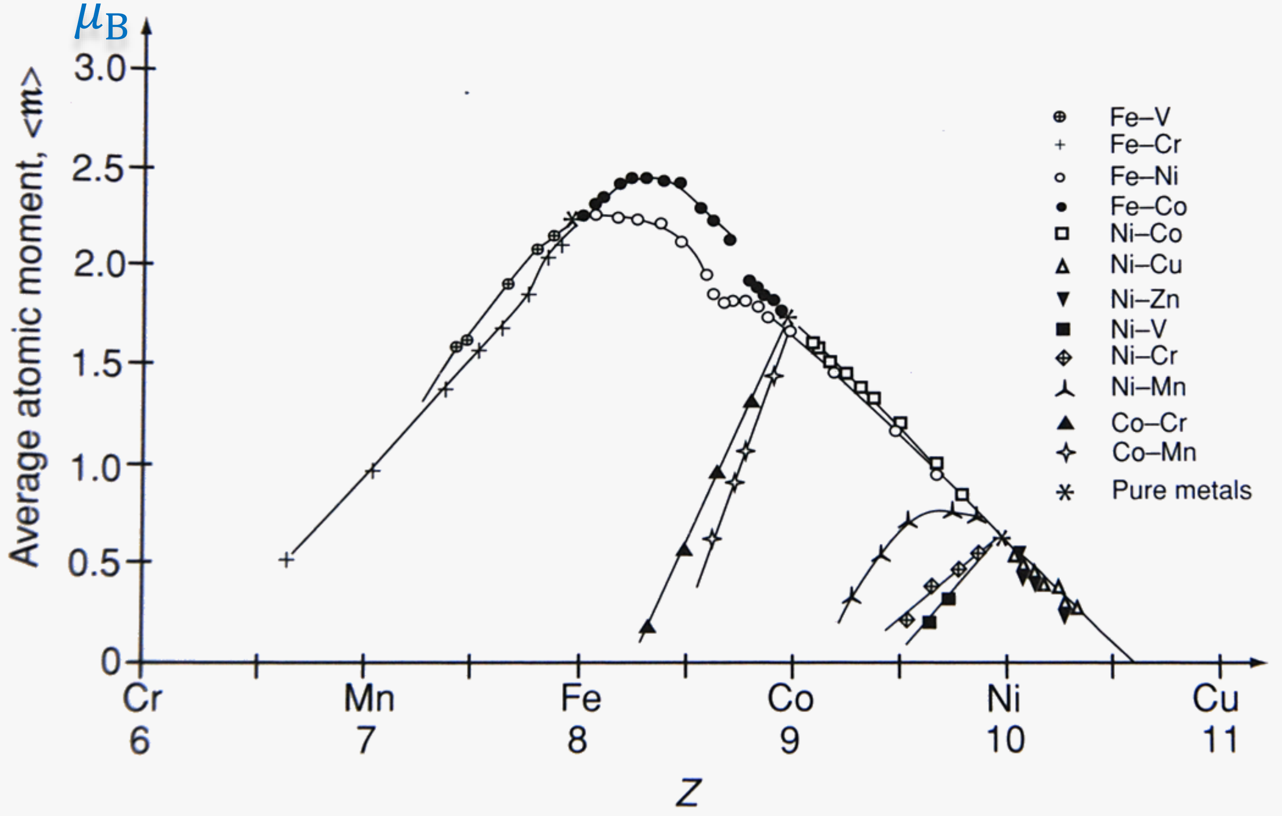
Spin-polarized band structure



From: Coey

Magnetic exchange (band magnetism)

Slater-Pauling curve Magnetic moment per atom versus 3d band filling

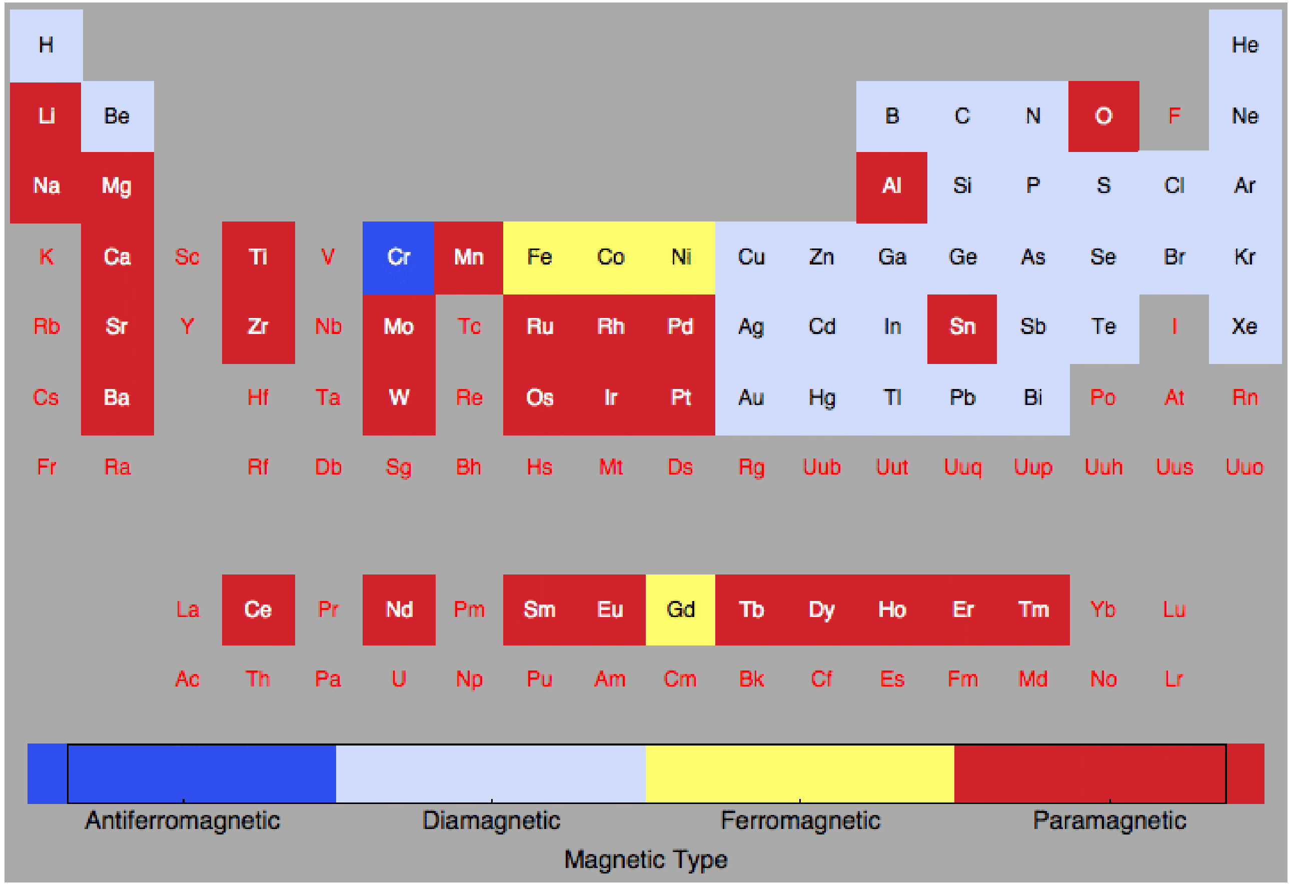


- Moment per atom is lower than for atomic species
- Reasonably well explained by a rigid flat band model
- Illustrates the transfer from 4s to 3d electrons

From: Coey

Magnetic ordering

Magnetic properties at room temperature, single elements



periodic table.com

Magnetic anisotropy

Underlying physics

- Crystal electric field (CEF): Coulomb interaction between electronic orbitals and the crystal environment $\mathcal{H}_{\mathrm{CEF}}$
- Spin-orbit coupling S and L $\mathcal{H}_{\mathrm{SO}}$

	$\mathcal{H}_{\mathrm{CEF}}$	$\mathcal{H}_{\mathrm{SO}}$
3d	$1-10\ \mathrm{eV}$	$10-100\ \mathrm{meV}$
4f	$25\ \mathrm{meV}$	$100-500\ \mathrm{meV}$

Phenomenology

- Angular dependence of the energy of a magnetic material
- Applies to all orders: ferromagnets, antiferromagnets etc.
- Group theory predict terms in expansions:

Cubic

$$E_{\mathrm{mc}} = K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^3 + \alpha_3^2\alpha_1^2) + K_2\alpha_1^2\alpha_2^2\alpha_3^2 + \cdots$$

Hexagonal

$$E_{\mathrm{mc}} = K_1 \sin^2\theta + K_2 \sin^4\theta + K_3 \sin^6\theta + K_3' \sin^6\theta \sin^6\phi + \cdots$$

Numbers

- Low symmetry favors high anisotropy
- Large range of values in known materials

Crucial importance for applications

- Compass, spintronic-based magnetic sensors
- Magnetic recording, including tapes, hard-disk drives, magnetic random access memories

Magneto-elastic anisotropy

C'NANO

Phenomenology

- Dependence of magnetic anisotropy on strain
- Can be viewed as the strain-derive of magneto-crystalline anisotropy
- Source of
  - Magnetostriction: direction of magnetization induces strain
  - Inverse magnetostriction: strain tends to orient magnetization along specific directions
- Example: polycrystalline sample under uniaxial strain

$$E_{\mathrm{mel}} = -\lambda_{\mathrm{S}} \frac{E}{2}(3\cos^2\theta - 1)\epsilon - \frac{1}{2}E\epsilon^2 + \cdots$$

E Young modulus

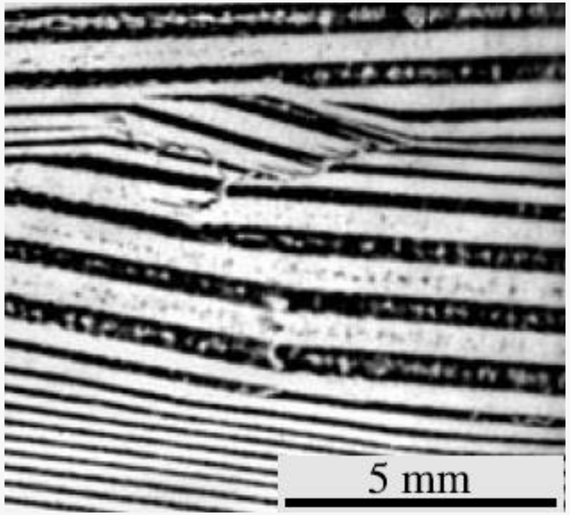
Impact

- **Order of magnitude** of Lambda: 10^{-6}
- **Contributes to coercivity** in low-anisotropy materials
- Underpins effects such as **Invar**
- Magnetostriction is used in **actuators**

The origin of magnetic domains

Historical background

- **Puzzle from the early days** of magnetism: some materials may be magnetized under applied field, however “loose” their magnetization when the field is removed
- **Postulate from Weiss**: existence of magnetic domains, i.e., large (3D) regions with each uniform magnetization
- **Magnetic domain walls** are the narrow (2D: planes) regions separating neighboring domains

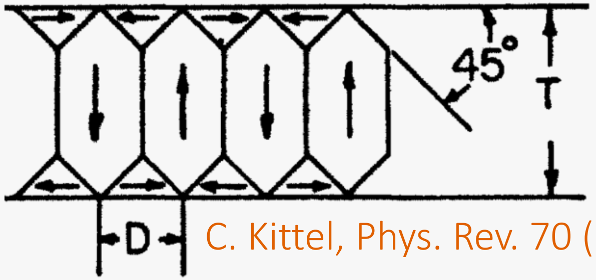


FeSi sheet (transformer)

A. Hubert, magnetic domains

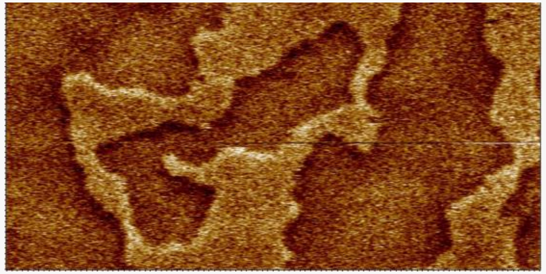
Origin of domains

- **Minimization of energy:** closure of magnetic flux to decrease dipolar energy, at the expense of energy in the domain walls (exchange, anisotropy…)



C. Kittel, Phys. Rev. 70 (11&12), 965 (1946)

- **Magnetic history:** magnetic domains along various directions may form through the ordering transition or following a partial magnetization process, persisting even though leaving the system not in the ground state



MgO\Co[1nm)\Pt

Magnetic Force Microscopy, 5 x 2.5 µm

Micromagnetism formalism

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: $M_s = M_s(T)$

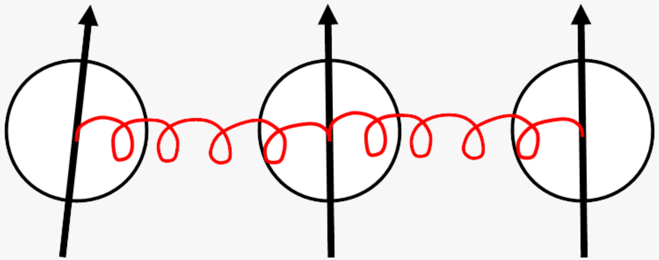
Exchange interaction

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

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

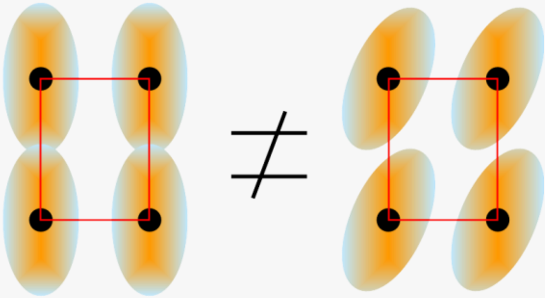
The various types of magnetic energy

Exchange energy



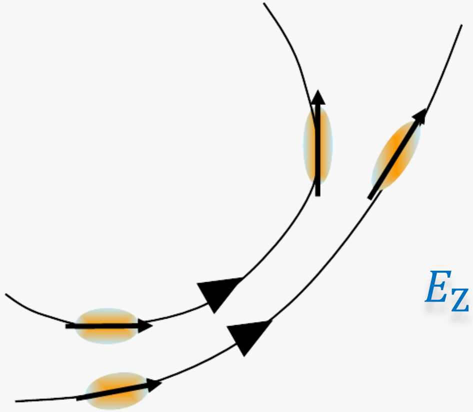
$$E_{\mathrm{ex}} = A(\boldsymbol{\nabla}\cdot\mathrm{m})^2 = A\sum_{i,j}\left(\frac{\partial m_i}{\partial x_j}\right)^2$$

Magnetocrystalline anisotropy energy



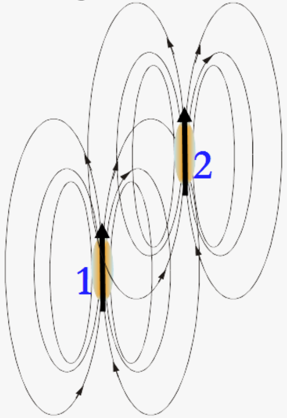
$$E_{\mathrm{mc}} = K\, f(\theta,\varphi)$$

Zeeman energy (→ enthalpy)



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

Magnetostatic energy



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

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: $\mathrm{J/m^3}$

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

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

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

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

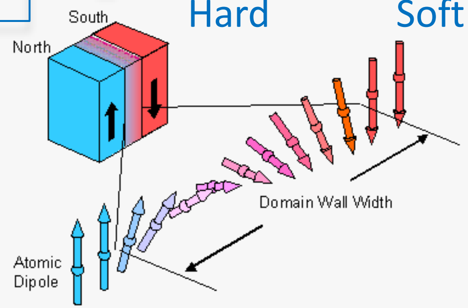
$$E = A\left(\frac{\partial m_i}{\partial x_j}\right)^2 + K\sin^2\theta$$

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

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

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

Hard → Soft



Sometimes called: Bloch parameter, or wall width

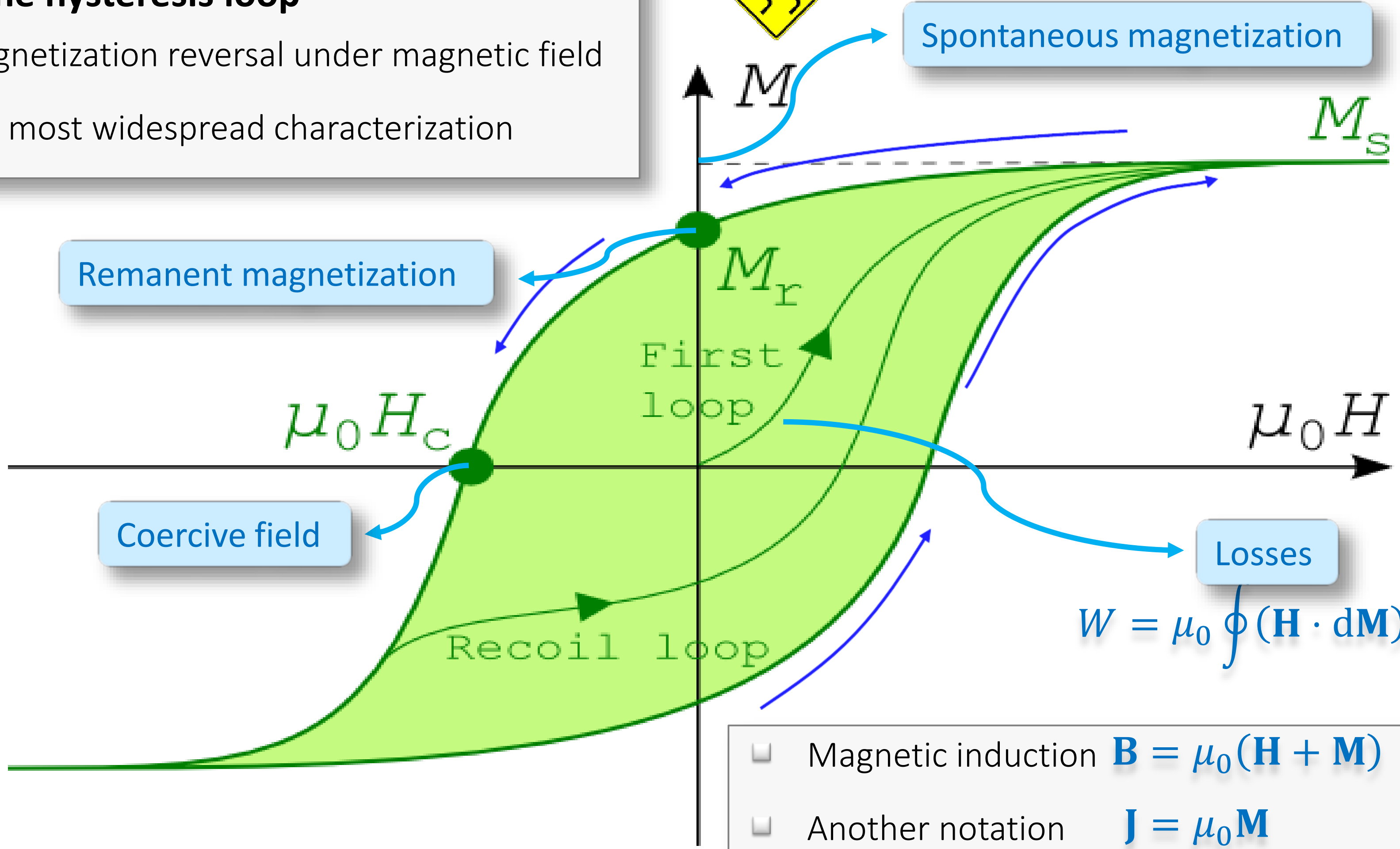
Note: Other length scales can be defined, e.g. with magnetic field

The hysteresis loop

The hysteresis loop

- Magnetization reversal under magnetic field
- The most widespread characterization

Spontaneous ≠ Saturation



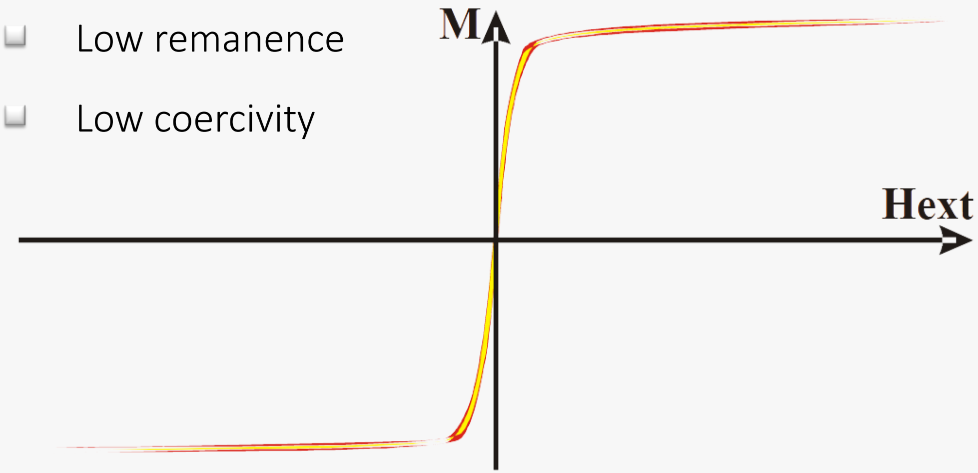
$$W = \mu_0 \oint (\mathbf{H} \cdot \mathrm{d}\mathbf{M})$$

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

The hysteresis loop

Soft-magnetic materials

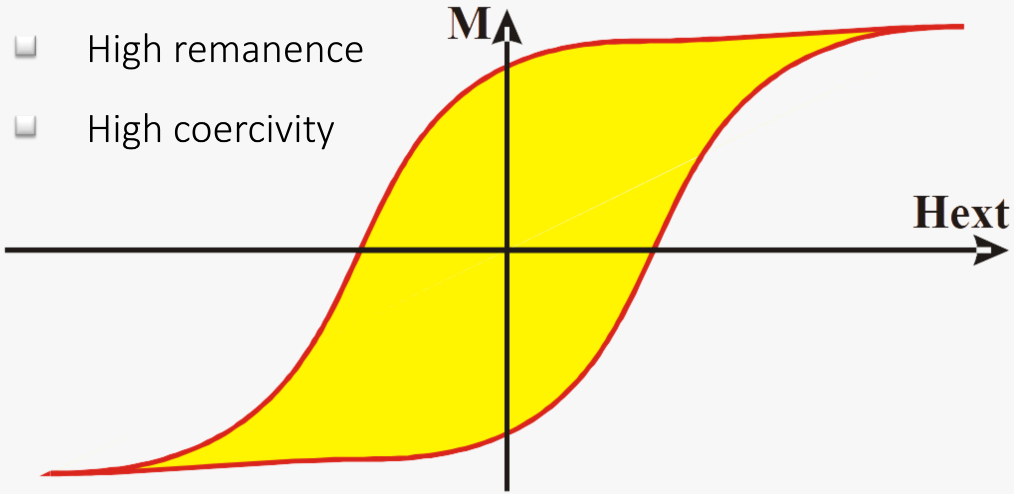
- Low remanence
- Low coercivity



Applications
- Transformers
- Flux guides, sensors
- Magnetic shielding

Hard-magnetic materials

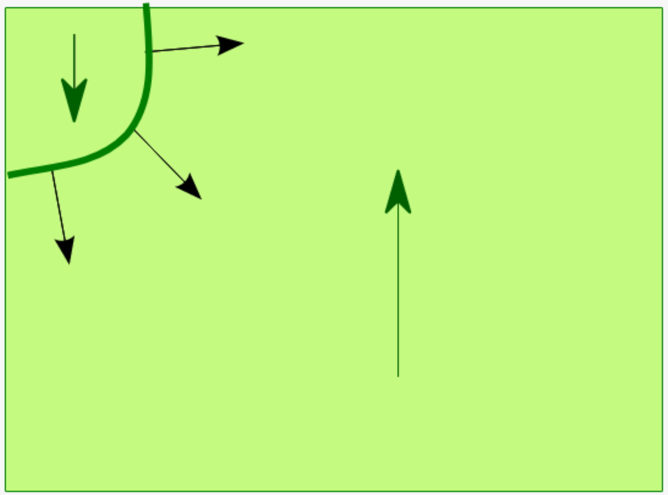
- High remanence
- High coercivity



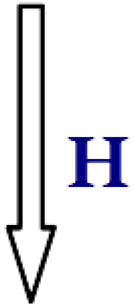
Applications
- Permanent magnets,
- Motors and generators
- Magnetic recording

Nucleation – Propagation mechanisms

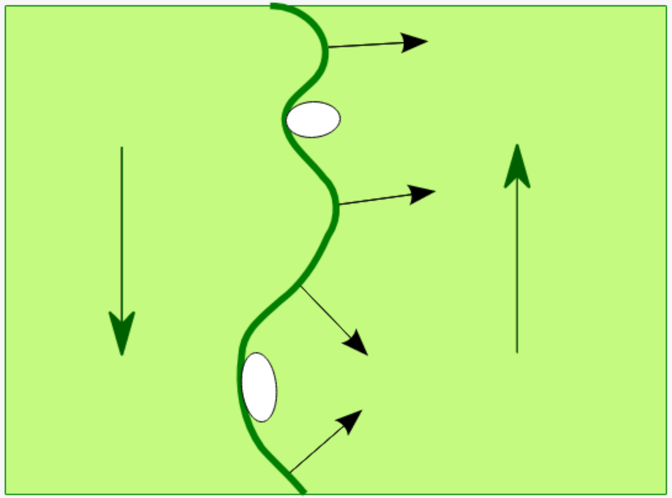
Coercivity determined by nucleation



- Concept of nucleation volume
- Physics has some similarity with that of the Stoner-Wohlfarth model for small particles



Coercivity determined by propagation

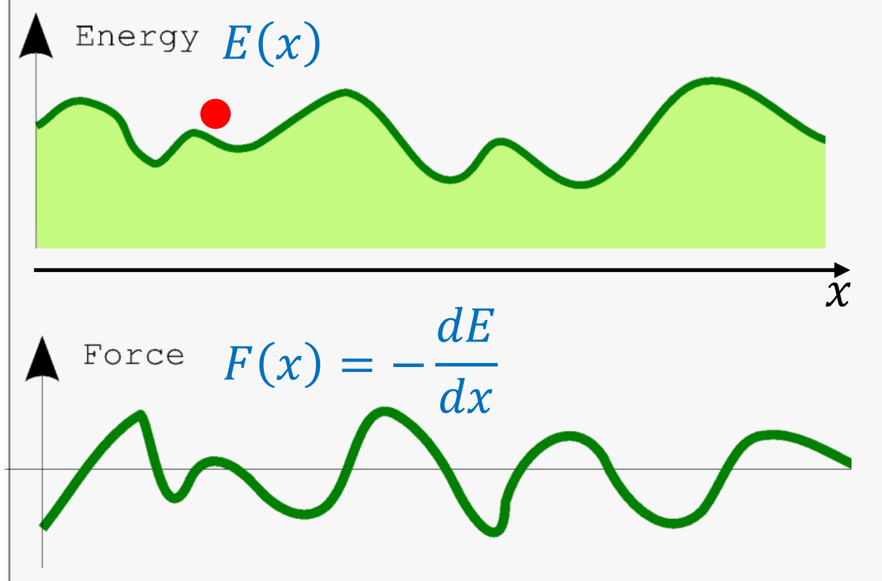


- Physics of surface/string in heterogeneous landscape
- Modeling necessary

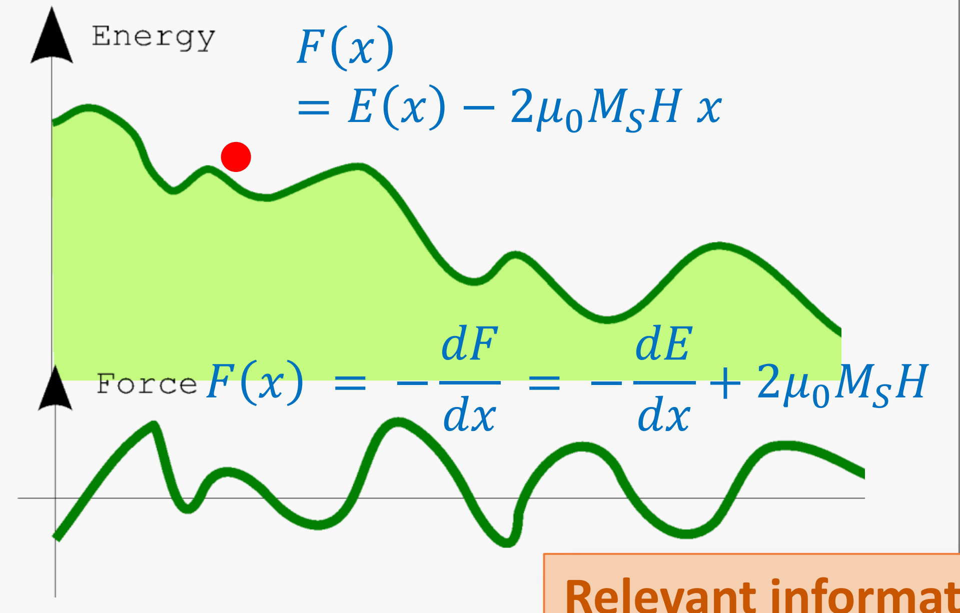
Pinning of domain walls

Example : domain wall to be moved along a 1d system

Without applied field



With applied field



E. Kondorski, On the nature of coercive force and irreversible changes in magnetisation, Phys. Z. Sowjetunion 11, 597 (1937)

Relevant information

- Microstructure
- Chemical composition
- Crystal structure

The Stoner-Wohlfarth model

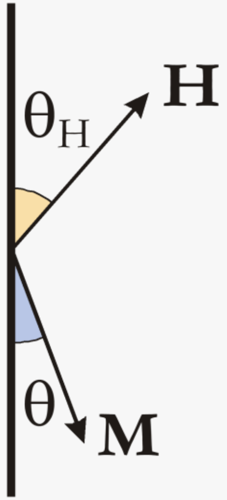
Framework: uniform magnetization

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

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

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

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



Names used

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

Dimensionless units

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

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

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

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

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)

The Stoner-Wohlfarth model

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

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

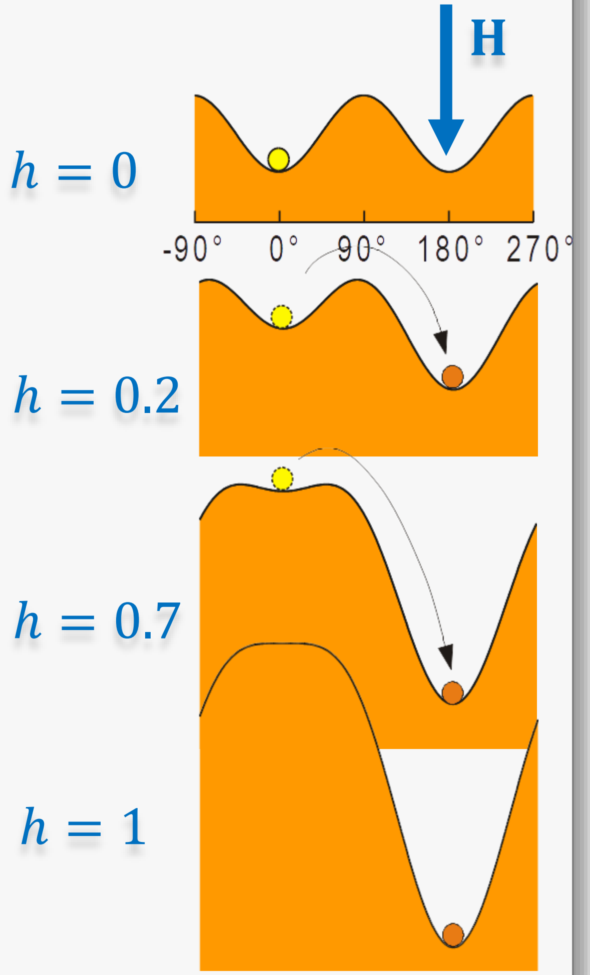
→ $H = H_{\mathrm{a}} = 2K/(\mu_0 M_{\mathrm{s}})$

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 landscape



The Landau-Lifshitz-Gilbert equation

LLG equation

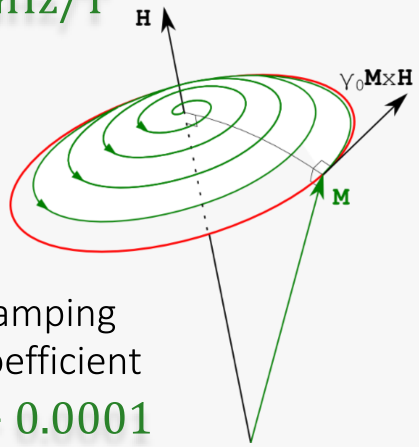
- Describes: precessional dynamics of magnetic moments
- Applies to magnetization, with phenomenological damping

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

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

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

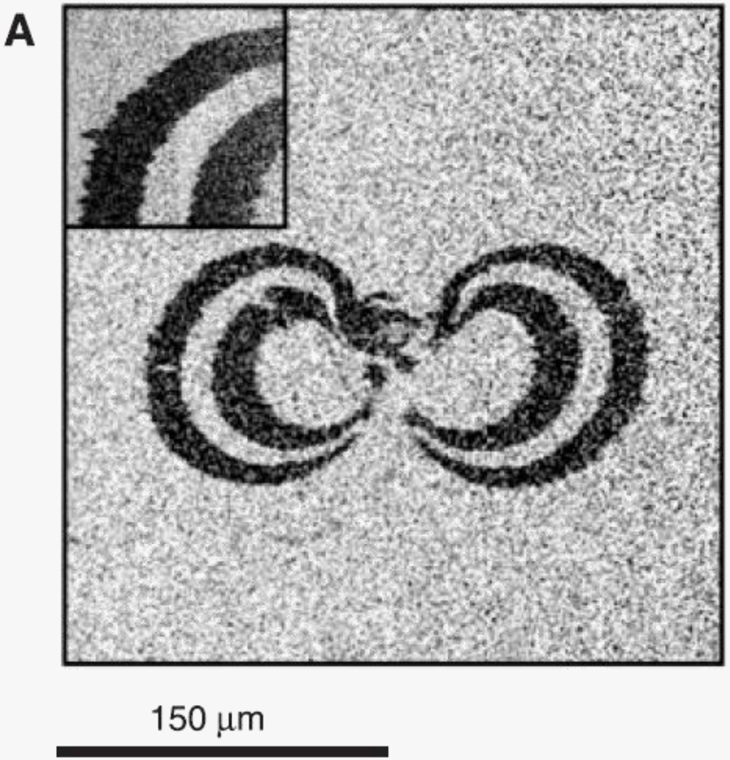
Larmor precession



$\alpha > 0$ Damping coefficient

$\alpha = 0.1 - 0.0001$

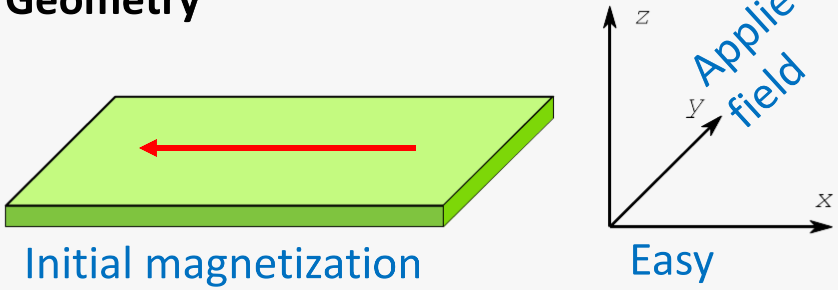
Pioneering experiment of precessional magnetization reversal



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

Precessional trajectories

Geometry

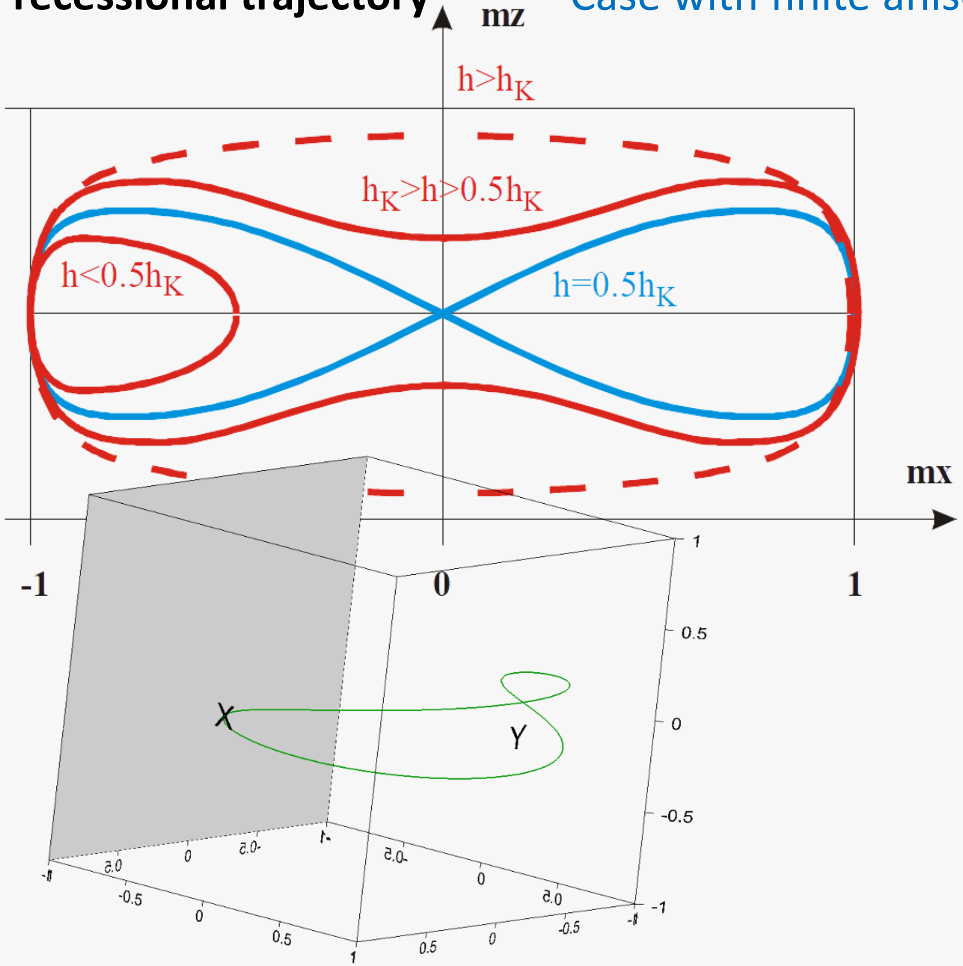


$$\frac{d\mathbf{m}}{dt} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \text{damping}$$

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

Precessional trajectory

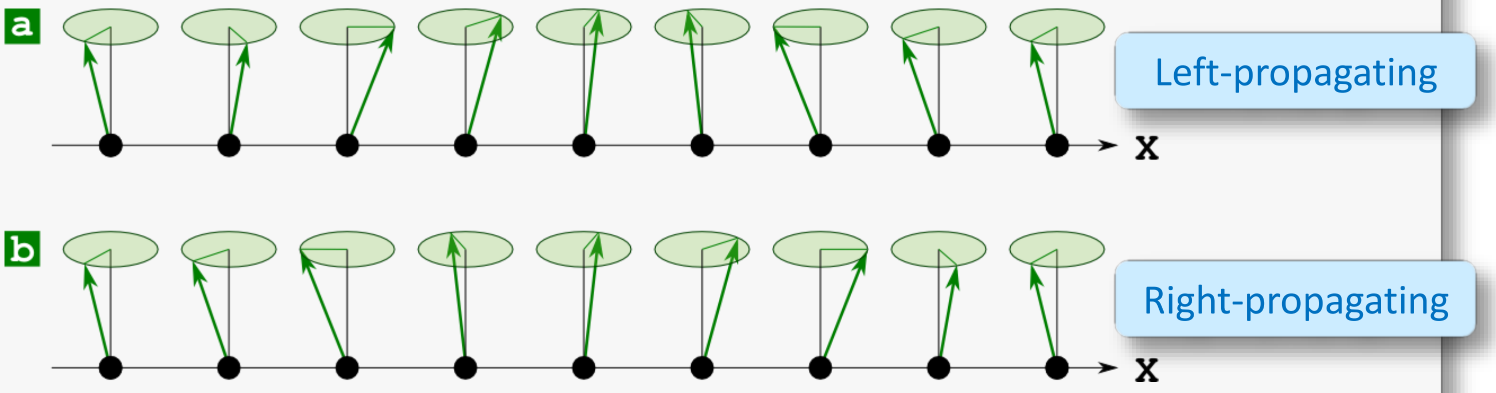
Case with finite anisotropy



Spin waves

Propagating Larmor precession

- **Physics**: exchange promotes propagation
- Spin waves have an angular frequency ω and a vector for propagation
- **There exist various geometries**, related to the direction of $\mathbf{M}$ versus $\mathbf{k}$, and the geometry of the system (thin film etc.)



Dispersion curve

- **Physics**: exchange implies additional energy, and thus higher frequency

$$\omega(k) = \omega_0 + Dk^2$$

D Spin-wave stiffness coefficient

- **Dipolar energy**: depending on the spin-wave geometry, dipolar energy provides additional contributions to D, possibly with a negative value.

Situations for spin waves

- **Thermally-excited** → Contributes to the decay of magnetization with temperature
- **Magnonics:** excited on purpose using a radio-frequency field or a spin-polarized current.

II. NANO-MAGNETISM – Outline

- Interfacial effects
- Thermal effects and superparamagnetism
- Domains and magnetization processes
- Microscopies for magnetism

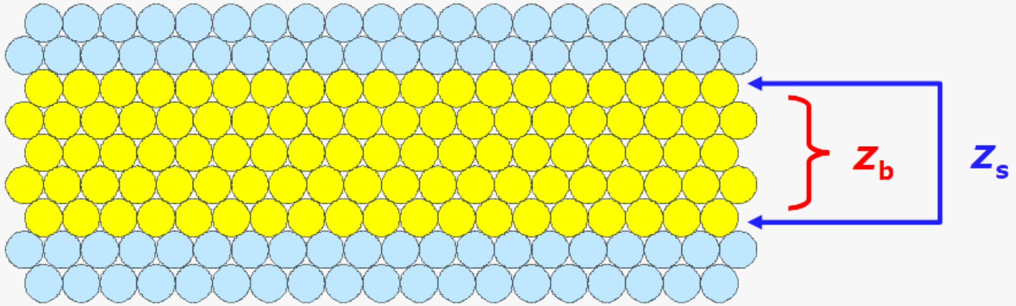
Ordering temperature (theory)

A bit 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)
  N. D. Mermin, H. Wagner, PRL17, 1133 (1966)
- **Onsager (1944) + Yang (1951)**. 2D Ising model: Tc>0K

→ Magnetic anisotropy promotes ordering

Naïve views: mean field



$$T_C = \frac{\mu_0 z n_{W,1} n g_J^2 \mu_B^2 J(J+1)}{3k_B}$$

N atomic layers → $\langle z \rangle = z_b - \frac{2(z_b - z_s)}{N}$

nearest neighbors

→ $\Delta T_C(t) \sim 1/t$

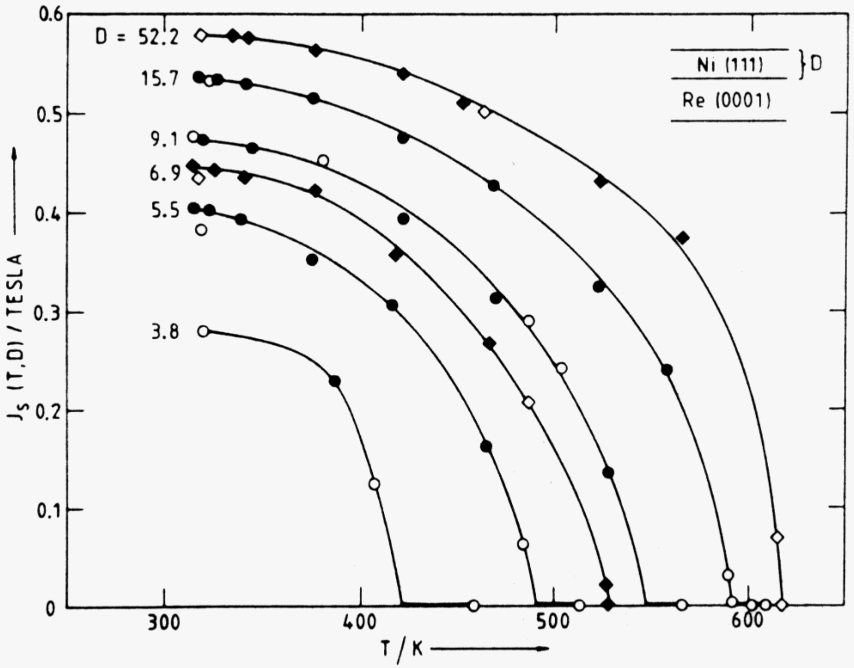
Confirmed by a more robust layer-dependent mean-field theory

G.A.T. Allan, PRB1, 352 (1970)

Ordering temperature (experiments)

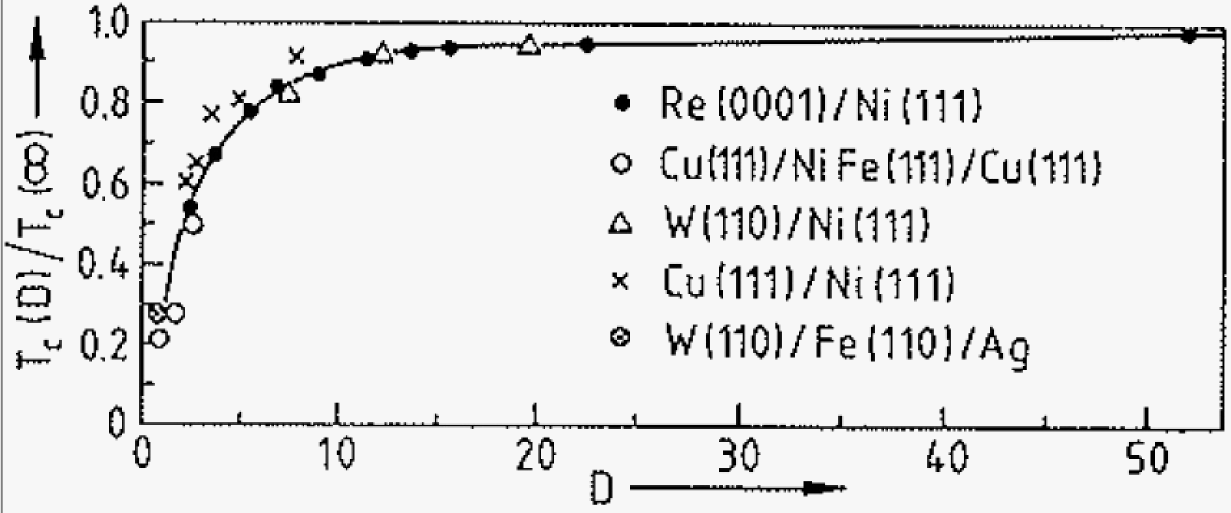
Qualitative

Ni(111)/Re(0001)



R. Bergholz and U. Gradmann, J. Magn. Magn. Mater. 45, 389 (1984)

Quantitative, master curve

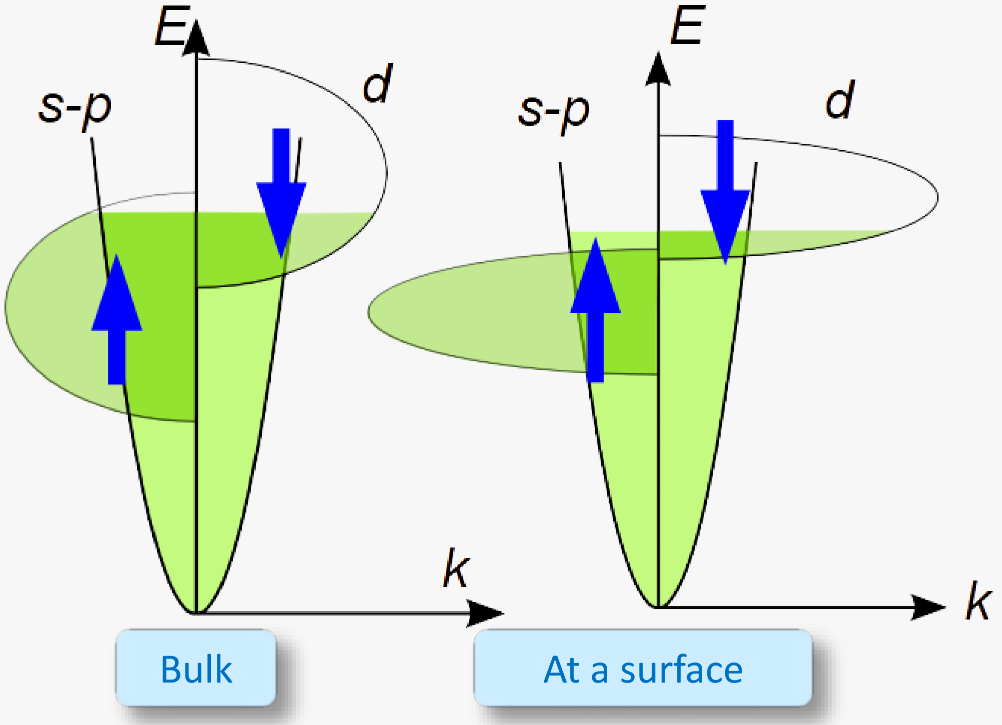


- Curie temperature well fitted by molecular field $\Delta T_C(t) \sim 1/t$

- Ordering temperature decreases with thickness
- Very significant below ≈ 1nm

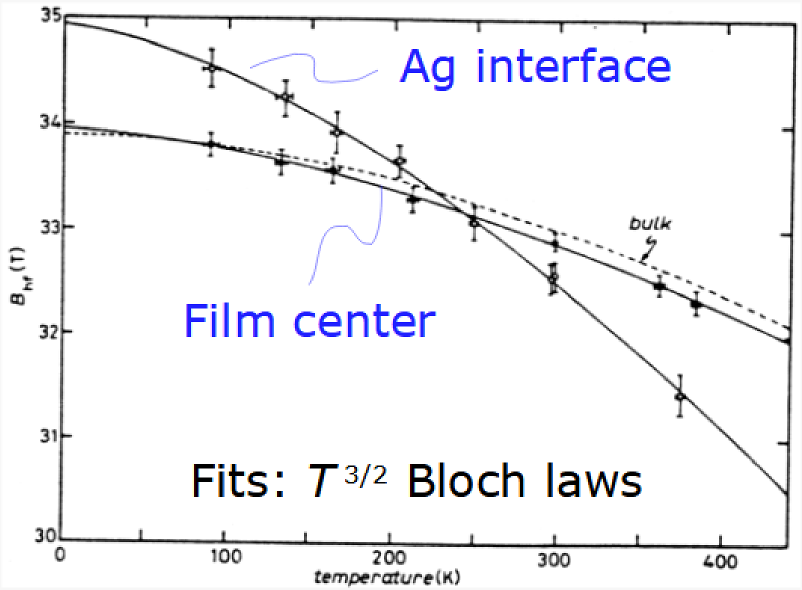
Magnetic moment

Simple picture: band narrowing at surfaces



In practice

Ag/Fe(110)/W(110)

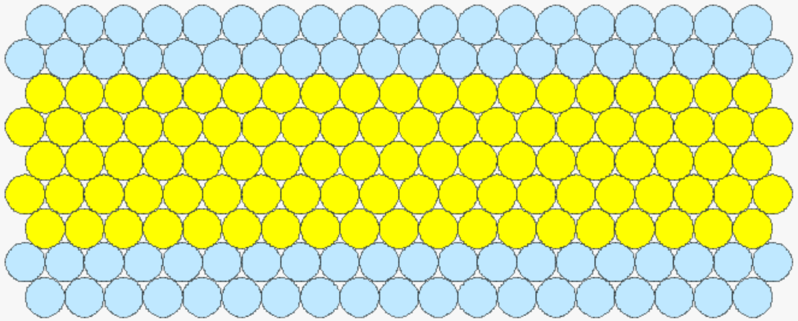


U. Gradmann et. al.

- Surface moments are usually 20-30% larger than in the bulk
- However, decay faster with temperature

Interfacial magnetic anisotropy

Simple picture: interfacial magnetic anisotropy



- Breaking of symmetry for surface/interface atoms
- Brings a correction to magnetocrystalline anisotropy

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

L. Néel, J. Phys. Radium 15, 15 (1954),
Superficial magnetic anisotropy and orientational superstructures

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.

Visionary !!!

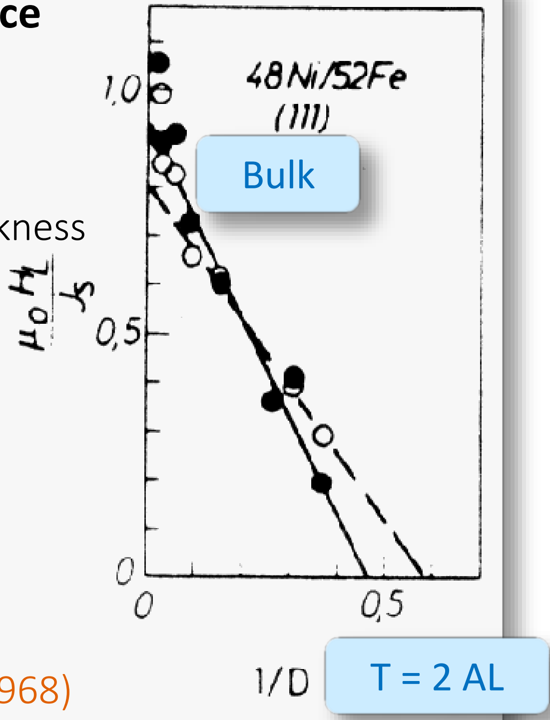
First Experimental evidence

- Total anisotropy energy

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

- Anisotropy per unit thickness

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



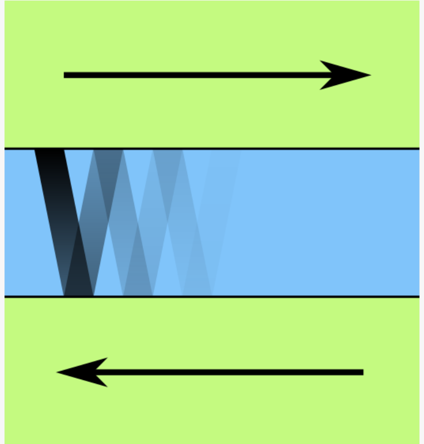
U. Gradmann and J. Müller,
Phys. Status Solidi 27, 313 (1968)

Figures

- Magnitude around $1\ \mathrm{mJ/m^2}$
- 80's & 90's: in contact with high spin-orbit materials (Au, Pt …)
- Since: Al_2O_3, MgO, graphene…

Interlayer exchange coupling

Spin-dependent quantum confinement



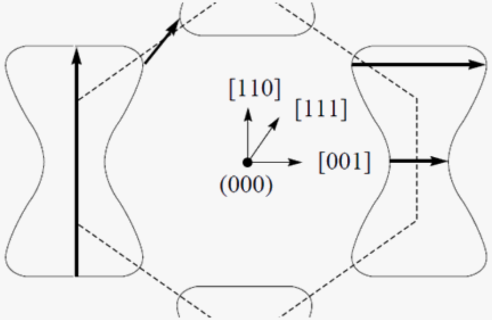
- Forth & back phase shift

$$\Delta\varphi = qt + \varphi_A + \varphi_B$$

- Spin dependence:

$$r_A, \varphi_A, r_B, \varphi_B$$

Oscillating constructive and destructive interferences with spacer thickness



Cu Fermi surface

- Importance of nesting
- Depends on crystal direction

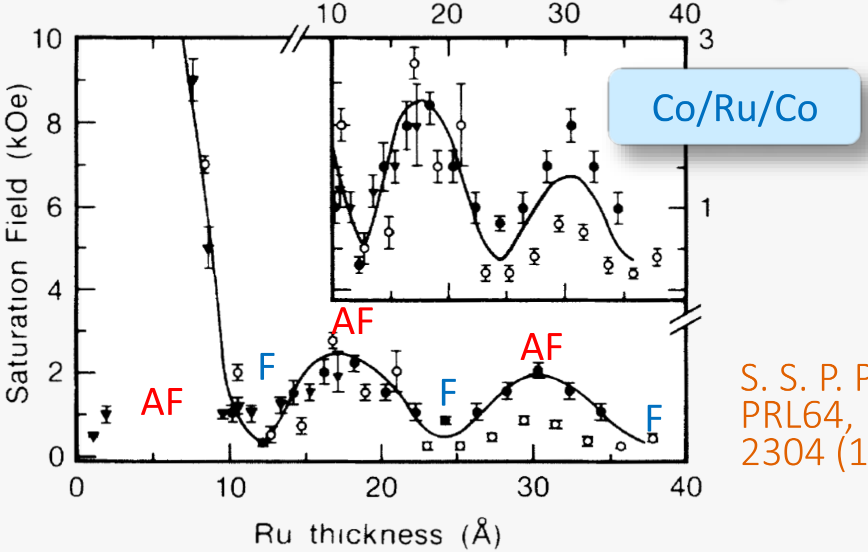
P. Bruno, J. Phys. Condens. Matter 11, 9403 (1999)

Coupling strength

$E_s(t) = J(t)\cos\theta$ with unit: $\mathrm{J/m^2}$

$$\theta = \langle \mathbf{m}_1, \mathbf{m}_2 \rangle$$

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

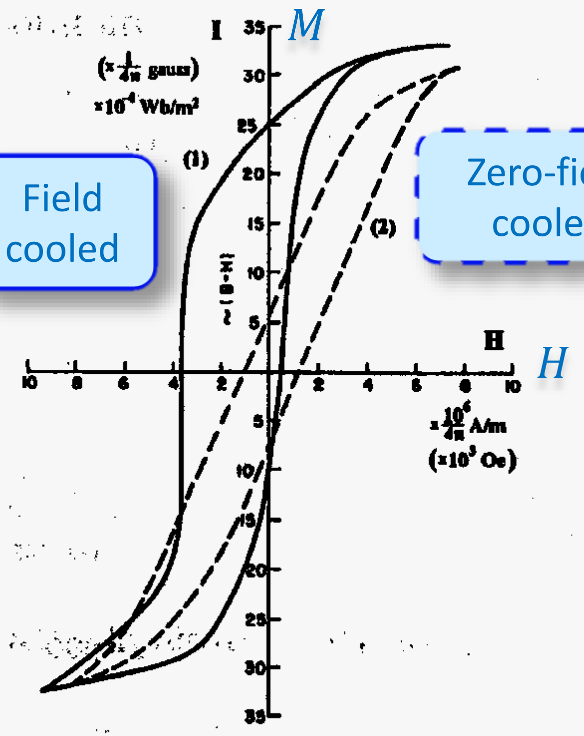


S. S. P. Parkin et al., PRL64, 2304 (1990)

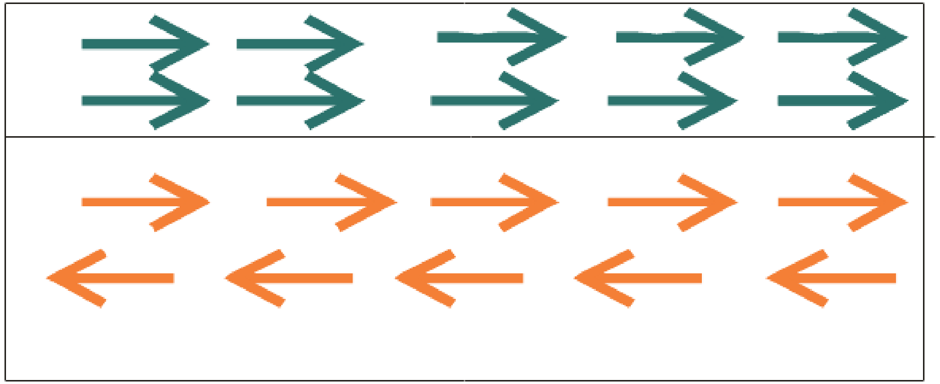
- RKKY = Ruderman-Kittel-Kasuya-Yoshida
- A function quantum effect at room temperature !
- Crucial to couple magnetic layers in stacks

Exchange bias

Seminal invertigation



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



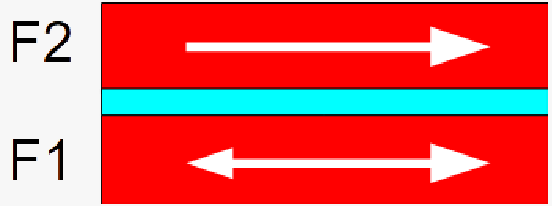
- Field-shift of hysteresis loop
- Increase of coercivity
- Crucial to design reference layer in memories

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)

Synthetic antiferromagnets and spin valves

RKKY Synthetic Ferrimagnets (SyF) – Basics



- Crude phenomenology

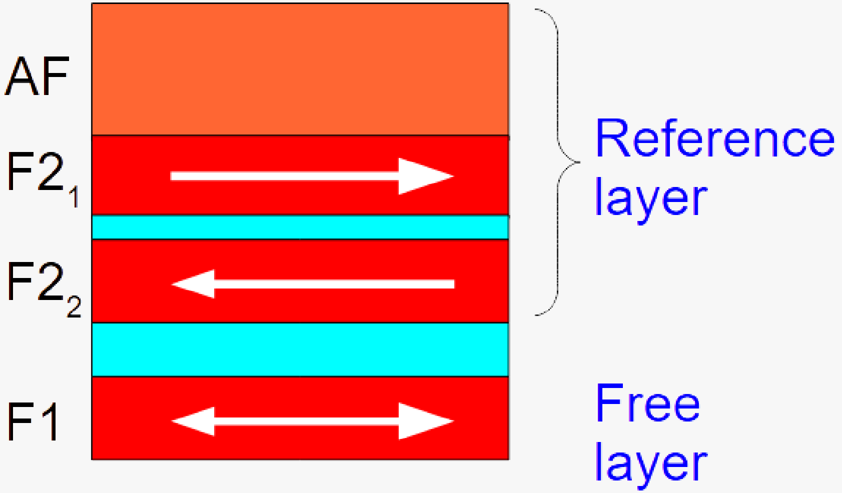
$$M = \frac{|e_1 M_1 - e_2 M_2|}{e_1 + e_2} \qquad K = \frac{e_1 K_1 + e_2 K_2}{e_1 + e_2}$$

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

- Enhances coercivity
- Reduces cross-talk in dense arrays

Spin valves

- “Free” and reference layers



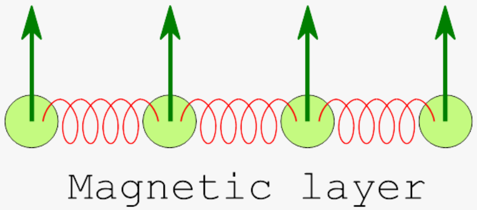
B. Diény et al., J. Magn. Magn. Mater. 93, 101 (1991)

- Spin-valves are key elements in magneto-resistive devices (sensors, memories)
- Control Ru thickness within the Angström !

Chirality

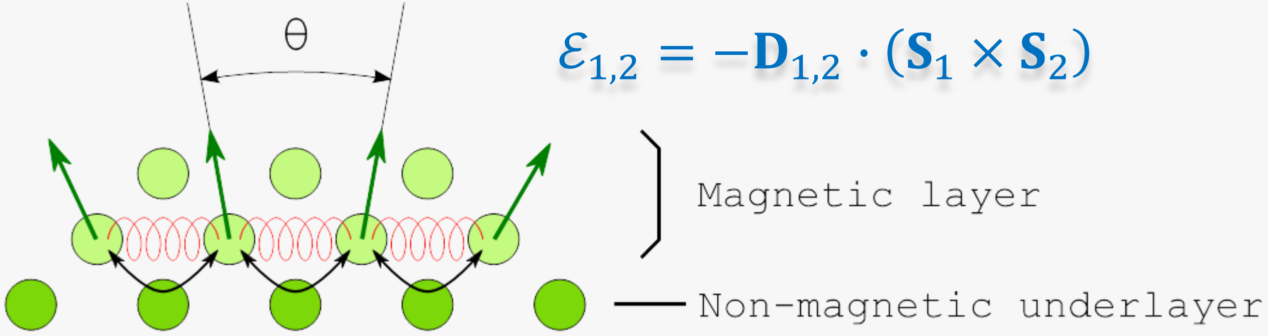
Magnetic exchange

$$\mathcal{E}_{1,2} = -J_{1,2}\,\mathbf{S}_1 \cdot \mathbf{S}_2$$

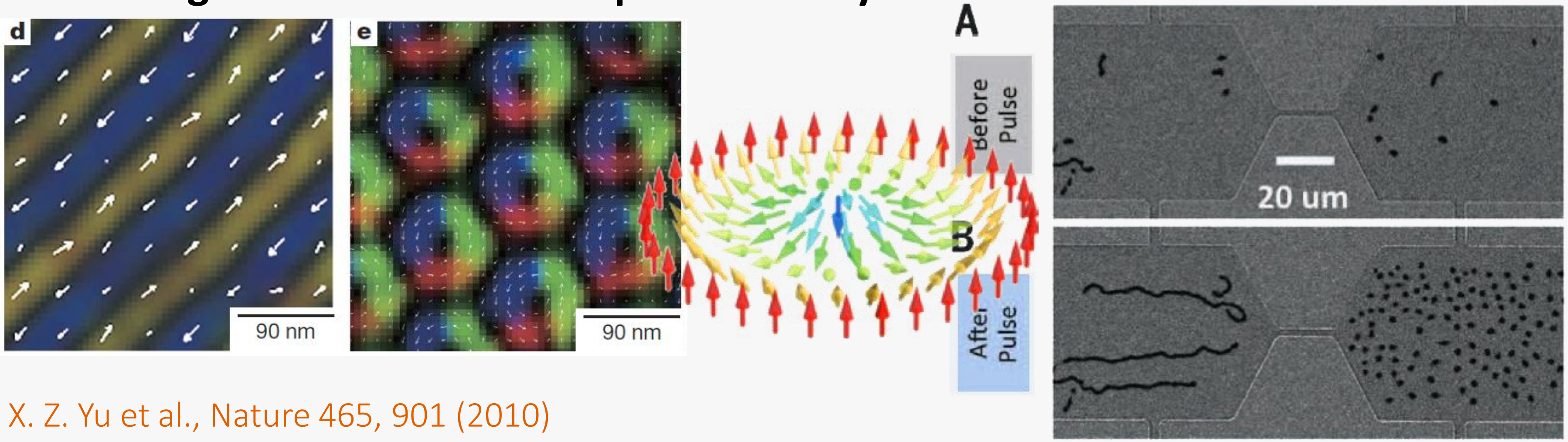


The Dzyaloshiinski-Moriha interaction (DMI)

$$\mathcal{E}_{1,2} = -\mathbf{D}_{1,2} \cdot (\mathbf{S}_1 \times \mathbf{S}_2)$$



Chiral magnetization textures: spirals and skyrmions



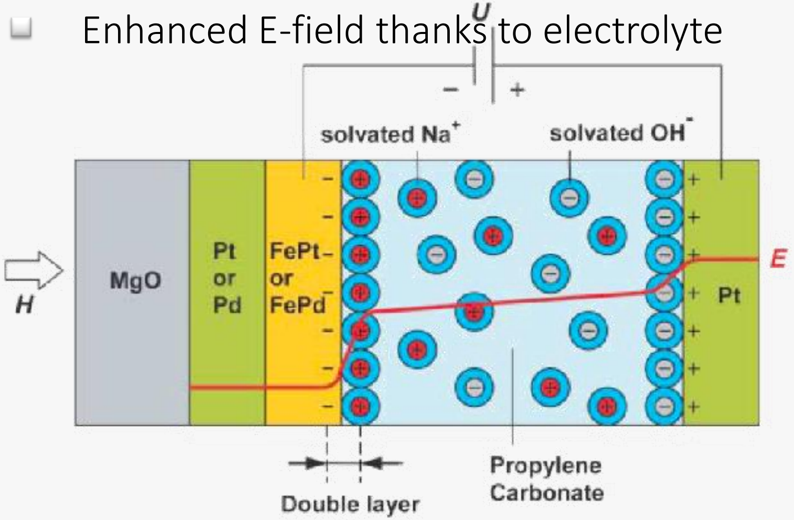
X. Z. Yu et al., Nature 465, 901 (2010)

W. Jiang et al., Science 349, 283 (2015)

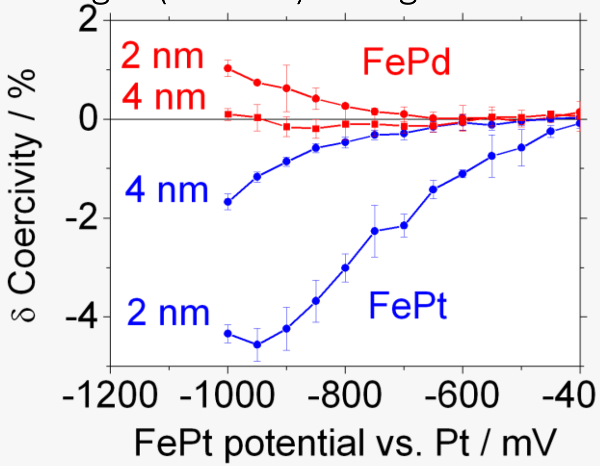
Voltage control of magnetization in metals

Seminal report

- Enhanced E-field thanks to electrolyte



- Slight (relative) change of coercivity



- Effect not expected for metals, due to short screening length
- Relative change of coercivity is weak as coercivity is large

M. Weisheit et al., Science 315, 349 (2007)

Developments

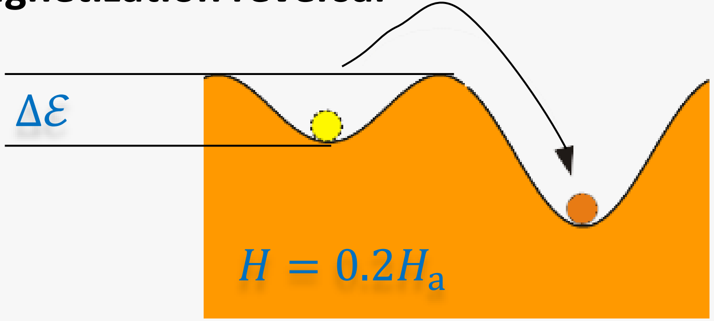
- Precessional switching with pulse of E-field
  Y. Shiota et al., Nature Mater.11, 39 (2012)
- Ferromagnetic resonance with ac E-field
  T. Nozaki et al., Nature Phys. 8, 491 (2012)
- Inversion of sign of DMI and skyrmions chirality
  R. Kumar et al., arXiv: 2009.13136 (2020)

Motivations for technology

- Drastically reduce Joule heating (only capacitance current)
- Gateable functionality

The blocking temperature

Energy barrier preventing magnetization reversal



$$\Delta\mathcal{E} = K\mathcal{V}\left(1 - \frac{H}{H_a}\right)^2$$

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)

Thermal activation

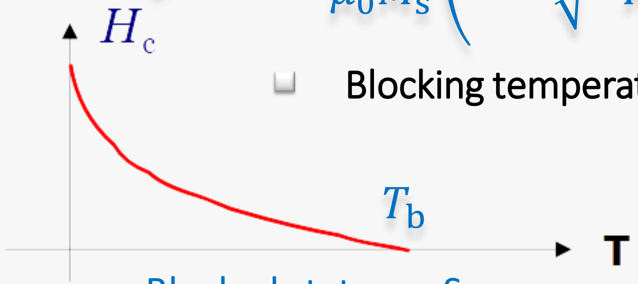
Brown, Phys.Rev.130, 1677 (1963)

- Waiting time (Arrhenius law) $\tau = \tau_0 \exp\left(\frac{\Delta\mathcal{E}}{k_\mathrm{B}T}\right)$

⇒ $\Delta\mathcal{E} = k_\mathrm{B}T \ln\left(\frac{\tau}{\tau_0}\right)$

- Lab measurement: $\tau \approx 1\ \mathrm{s}$ ⇒ $\Delta\mathcal{E} \approx 25 k_\mathrm{B}T$

⇒ $H_\mathrm{c} = \frac{2K}{\mu_0 M_\mathrm{s}}\left(1 - \sqrt{\frac{25 k_\mathrm{B}T}{K\mathcal{V}}}\right)$



- Blocking temperature: $T_\mathrm{b} \approx \frac{K\mathcal{V}}{25 k_\mathrm{B}}$

- Coercivity and remanence are lost at small size
- Incentive to enhance magnetic anisotropy

The case of magnetic recording or memory

$\tau \approx 10^9\ \mathrm{s}$ ⇒ $K\mathcal{V}_\mathrm{b} \approx 40-60\, k_\mathrm{B}T$

Modeling superparamagnetism

Formalism

- Energy

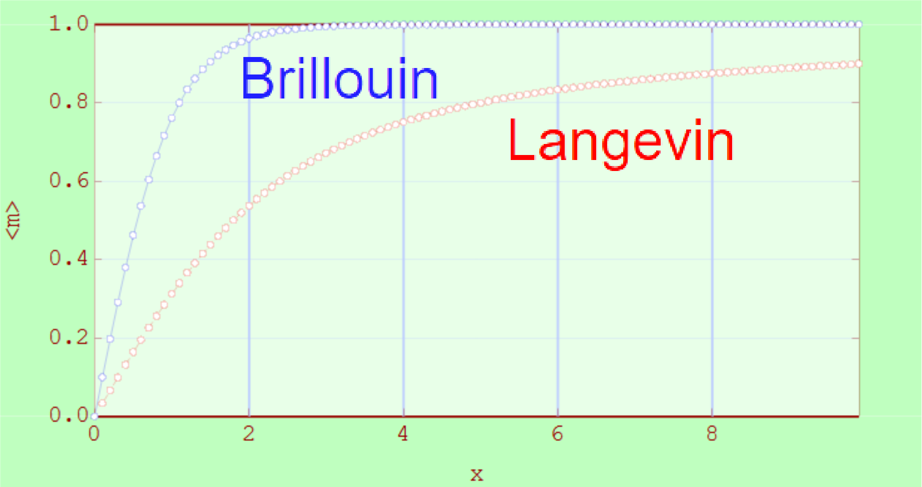
$$\mathcal{E} = K\mathcal{V}\mathrm{f}(\theta,\phi) - \mu_0\mu H$$

- Partition function

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

- Average moment

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



- Fit M(H) curve to extract magnetization (and hence the volume) of nanoparticles
- Beware of anisotropy strength and distribution in fits !

Isotropic case

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

Note: equivalent to integrate on solid angle

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

Langevin function

Note: refers to the moment of the particle, not a spin ½

Highly anisotropic case

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

Note: only two states are populated, ‘up’ and ‘down’

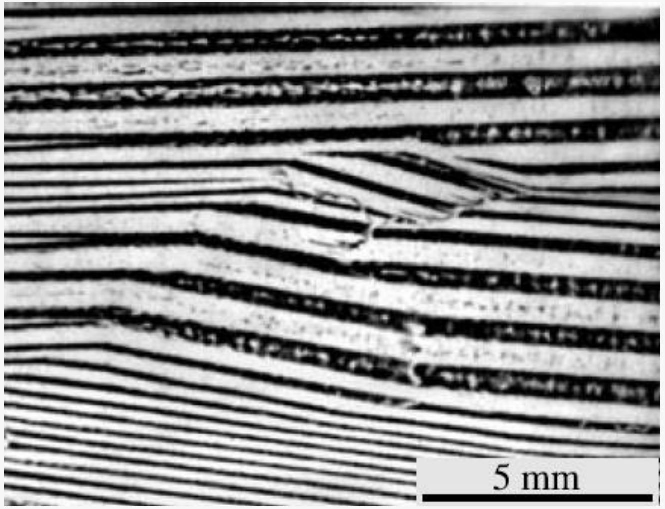
$$\langle\mu\rangle = \mathcal{M}\tanh(x)$$

Brillouin ½ function

Magnetic domains

Bulk materials

Numerous and complex magnetic domains

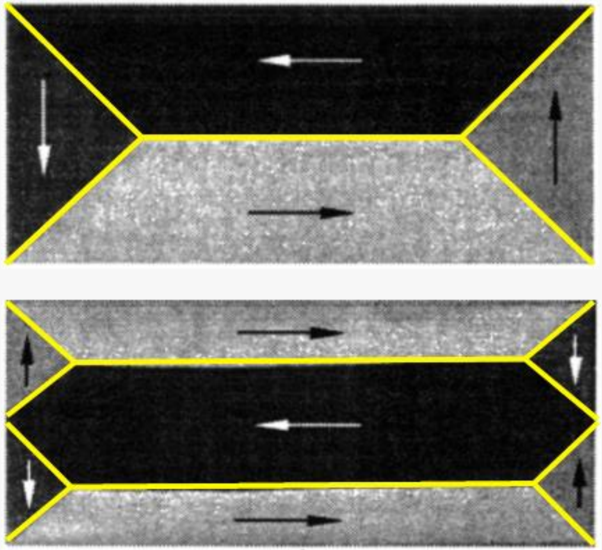


FeSi sheet (transformer)

A. Hubert, magnetic domains

Mesoscopic scale

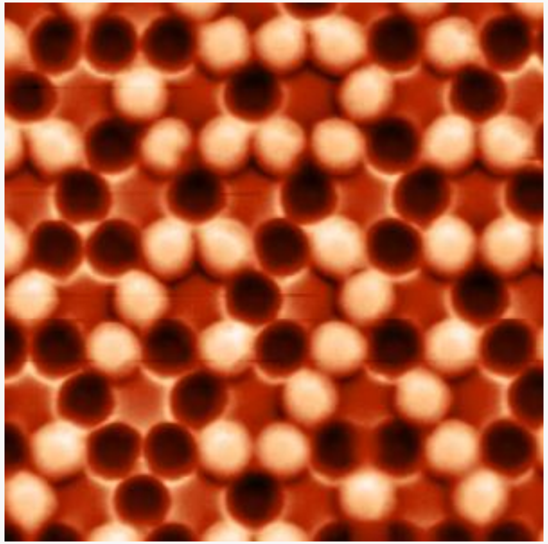
Small number of domains, simple shape



Microfabricated dots,
Kerr magnetic imaging
A. Hubert, magnetic domains

Nanometric scale

Magnetic single domain



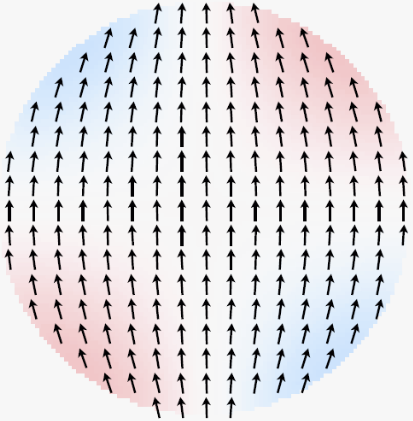
Microfabricated dots,
magnetic force microscopy
Sample courtesy: I. Chioar

Micromagnetic softwares

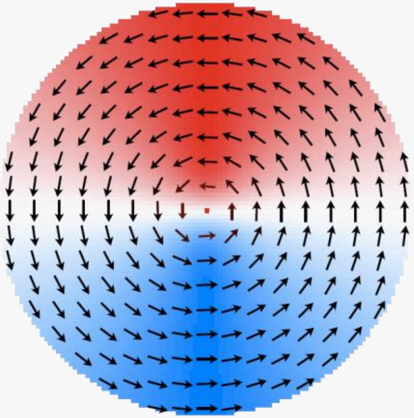
Principle

- Subdivides a system in small prisms or tetrahedrons
- Considers all energies
- Solves the Landau-Lifshitz equation

Flat disk

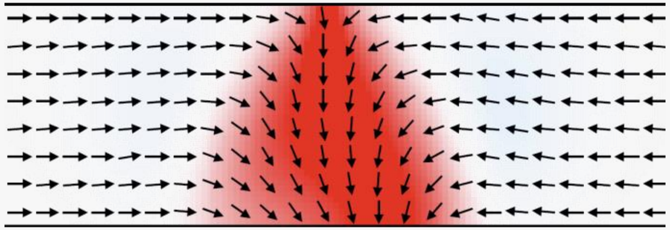


Near single-domain



Vortex state

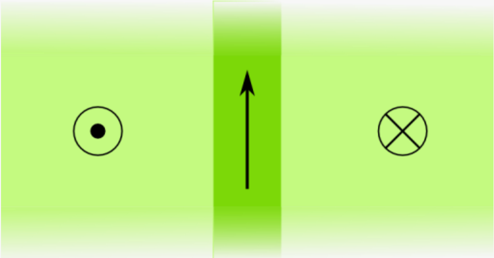
Domain wall in a flat strip



Transverse domain wall

Magnetic domains walls

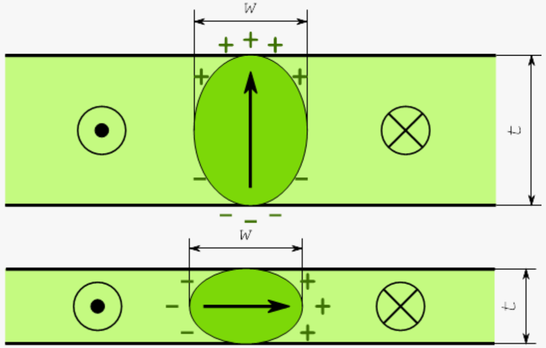
Bloch wall in the bulk (2D)



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

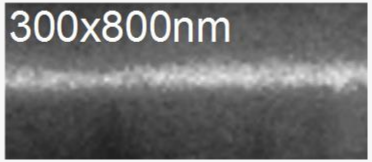
F. Bloch, Z. Phys. 74, 295 (1932)

Domain walls in thin films (towards 1D)



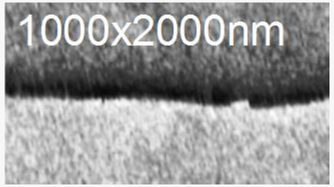
Bloch wall

$t \gtrsim w$



Néel wall

$t \lesssim w$

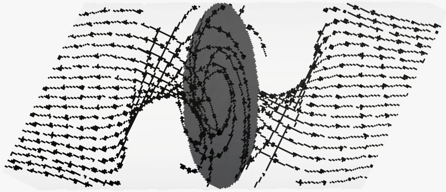


- Implies magnetostatic energy
- No exact analytic solution

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

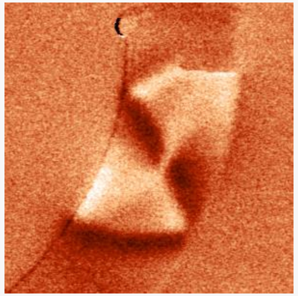
Bloch point (0D)

- Point with vanishing magnetization



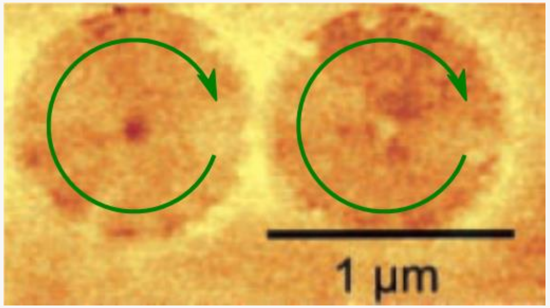
W. Döring, JAP 39, 1006 (1968)

Constrained walls (eg in strips)



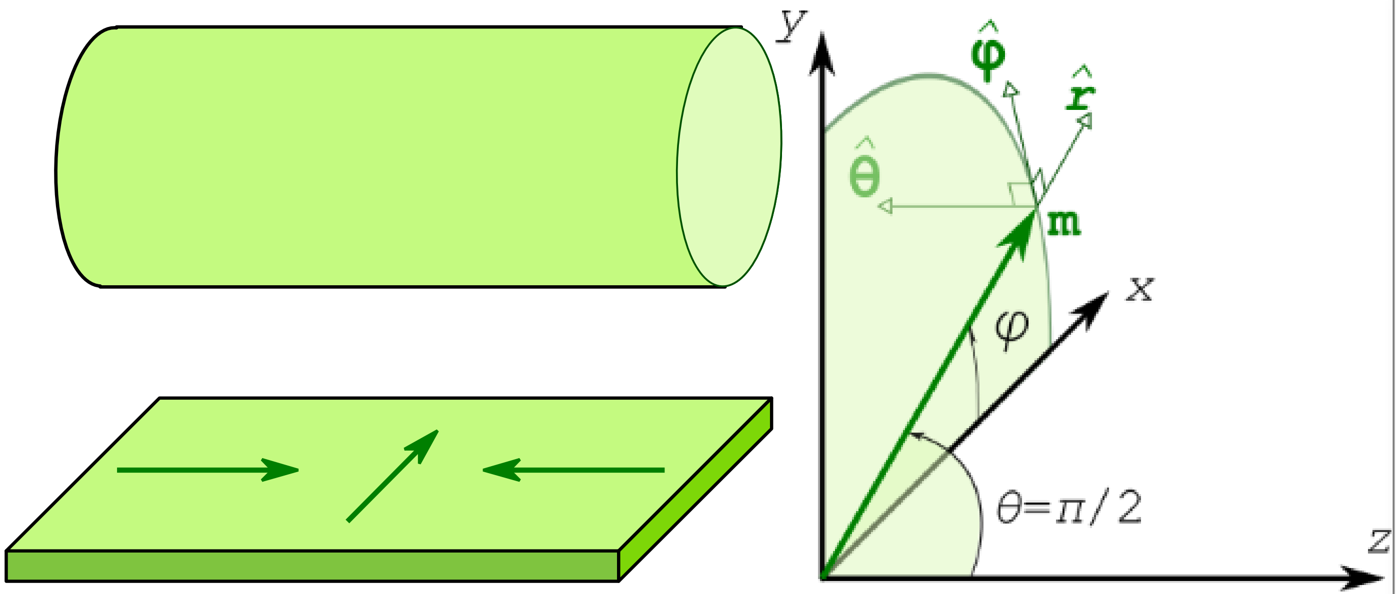
Permalloy (15nm)
Strip width 500nm

Vortex (1D → 0D)



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

Domain-wall motion



Precessional dynamics under magnetic field

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

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

Wall speed

$$v = \alpha|\gamma_0|\Delta H$$

$$v = |\gamma_0|\Delta H/\alpha$$

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

Criteria for magnetic microscopies

Versatility

- Samples made with lithography or ex situ OK ?
- Need for sample preparation ?
- Compatible with various environments ? (temperature, field etc.)

Speed of acquisition

- Sample preparation needed ?
- How much time for one image ?

Access

- Large-scale instrument or in-lab ?
- Expensive or cheap ?

Measured quantity

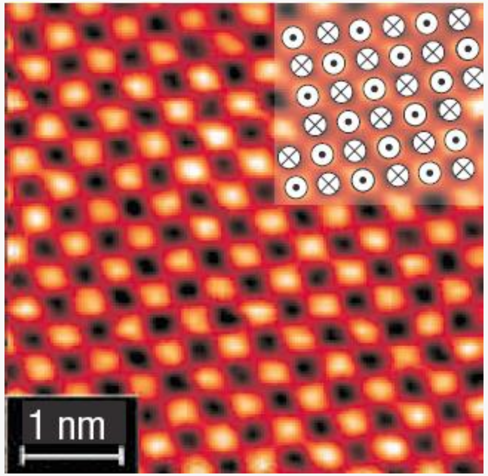
- Surface or volume technique ?
- Sensitivity ?
- Magnetization, stray field, other ?

- No universal technique
- Many criteria to be balanced

Scanning probe

Spin-polarized STM

Fe(1ML)/W(001)

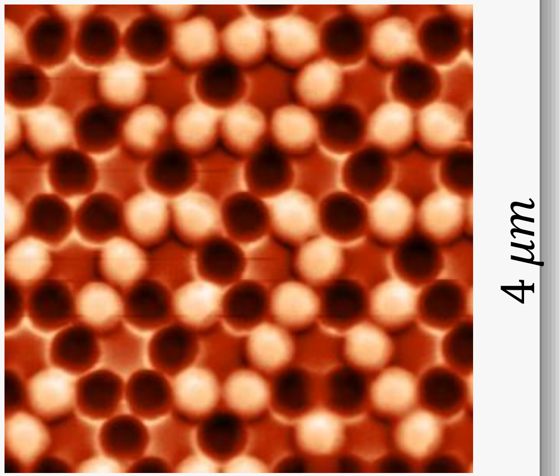


Antiferromagnetic domain

M. Bode et al., Nat. Mater. 5, 477-481 (2006)

Magn. Force Microscopy

Array of dots

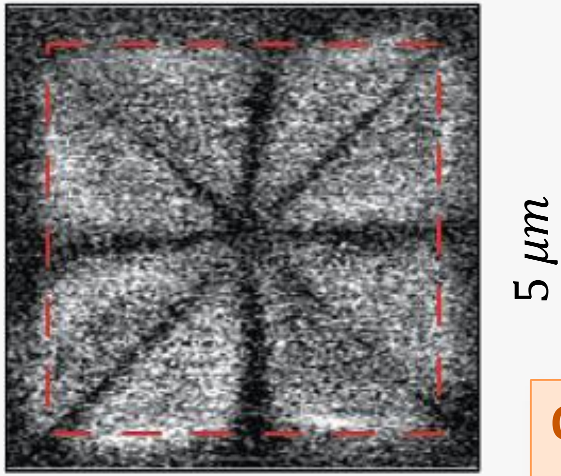


Up-and-down 'single-domains'

Sample courtesy:
N. Rougemaille, I. Chioar

NV center microscopy

Square Fe20Ni80 dot



Signature of flux-closure

L. Rondin et al., Nat. Comm. 4, 2279 (2013)

Overview

- Large variety
- Rather slow

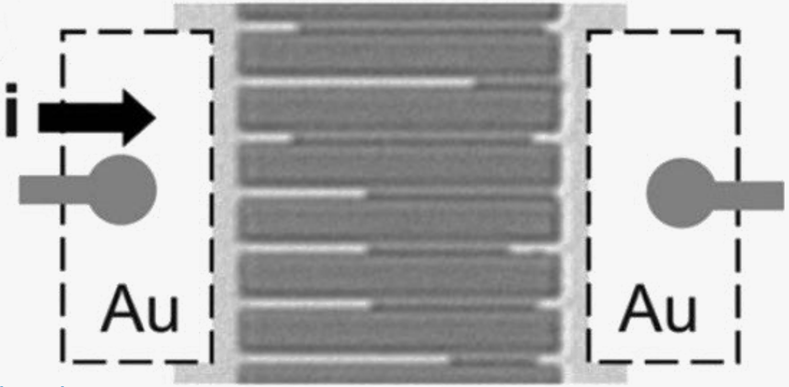
REVIEW :
R. Wiesendanger, Rev. Mod. Phys. 81, 1495 (2009)

REVIEW : R. Proksch et al., Modern techniques for characterizing magnetic materials, Springer, p.411 (2005)

Optical

Magneto-optical

- Polarization of light versus magnetic body
- Kerr : reflection geometry
- Faraday : transmission geometry

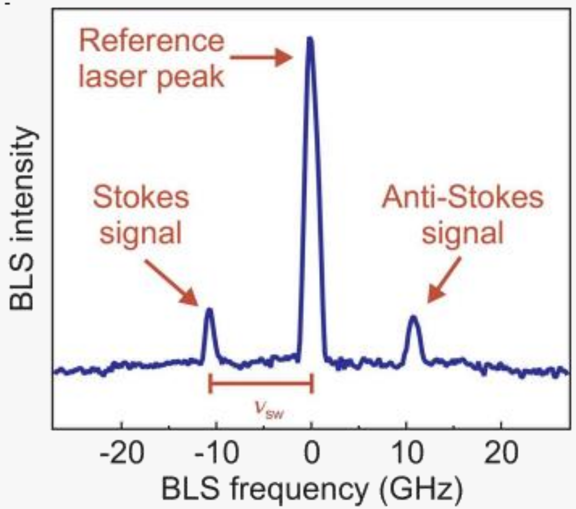


Pt/Co/AlOx patterns with perpendicular magnetization

T. A. Moore et al., Appl. Phys. Lett 93, 262504 (2008)

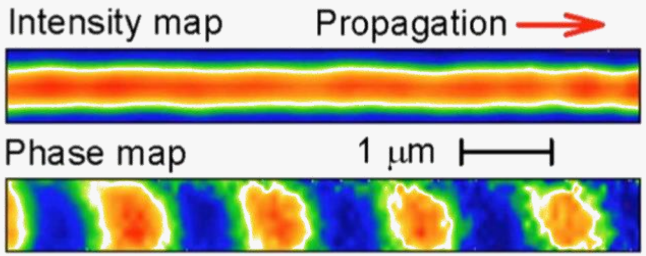
- Quick (full field)
- Compatible with time resolution
- Limited spatial resolution

Brillouin light scattering



- **Principle**: spectroscopy of the emission and absorption of spin waves
- **Implementation**: large-field or focused, scanning for microscopy

T. Sebastian et al., Front. Phys. 3, 35 (2015)

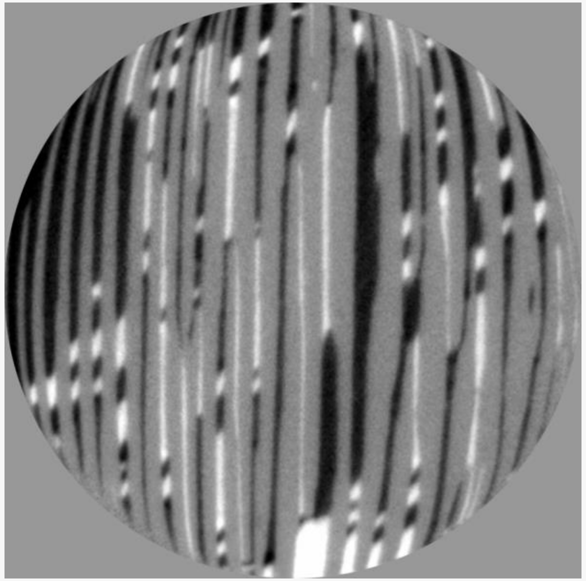


V. E. Demidov et al., Appl Phys Lett. 95, 262509 (2009)

Intensity- and phase-resolved map of spin waves propagation along a Fe20Ni80 nanostrip

Electron-based

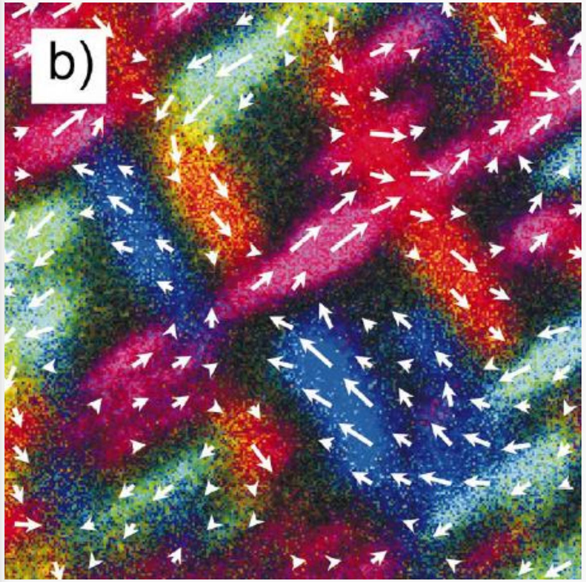
SPLEEM
Spin-Polarized Low Energy Electron Microscopy



Stripes of Fe/W(110)

REVIEW:
N. Rougemaille et al., Eur. Phys. J. Appl. Phys. 50, 20101 (2010)

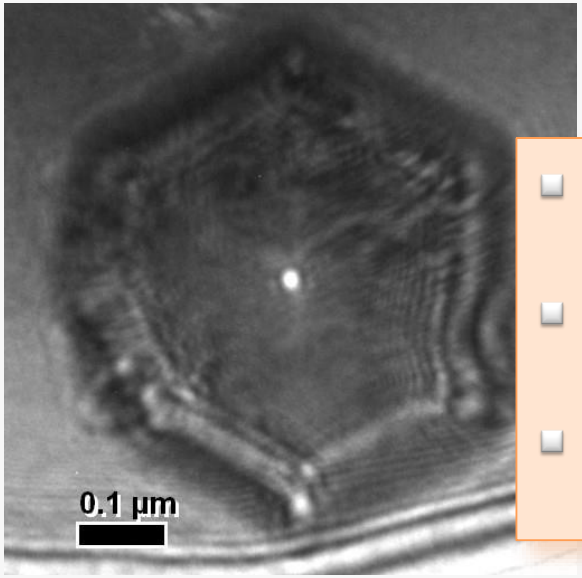
SEMPA
Scanning Electron Microsc. with Polarization Analysis



Maze of Fe/W(001) 1.5 μm

W. Wulfhekel et al., Phys. Rev. B 68, 144416/1-9 (2003)

Lorentz, holography etc.
TEM - based



Self-assembled Co/W(110)

O. Fruchart et al., J. Phys. Condens. Matter 25, 496002 (2013)

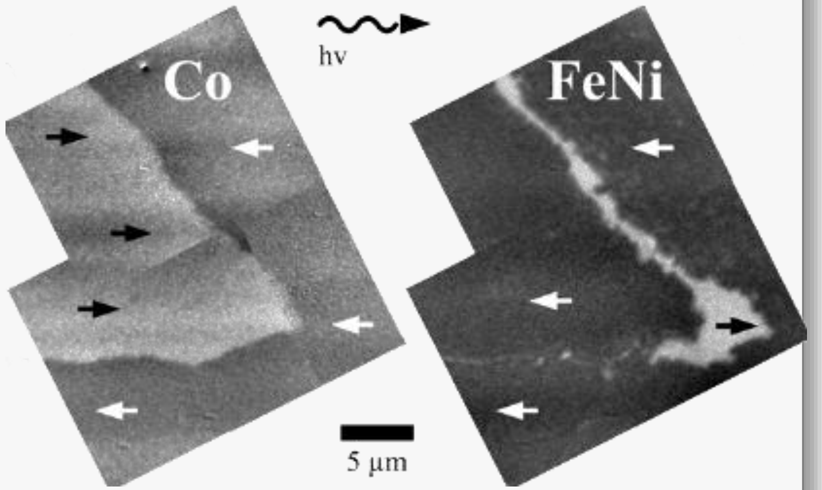
- Requires sample preparation
- Good spatial resolution
- Some information about structure

Synchrotron-based

XMCD-PEEM

X-ray Magnetic Circular Dichroism

Photo-Emission Electron Microsc.



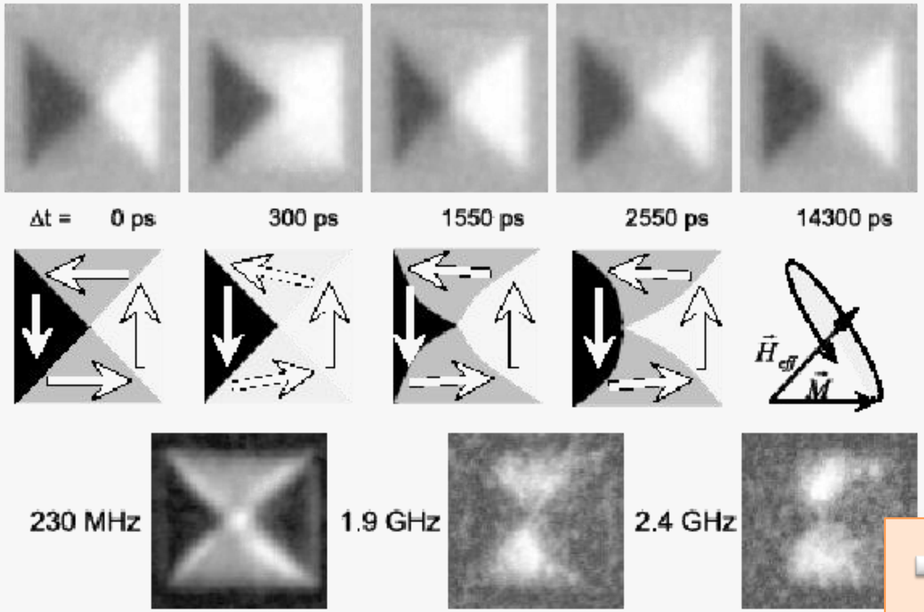
Co\Cu\FeNi trilayer

→ elemental resolution

J. Vogel et al., J. Phys. : Condens. Matter 19, 476204 (2007)

TXM

Transmission X-ray Microscopy



FeNi 6µm square dot → time resolution

J. Raabe et al., Phys. Rev. Lett. 94, 217204 (2005)

- Elemental sensitivity
- Compatible with time resolution
- Rather versatile

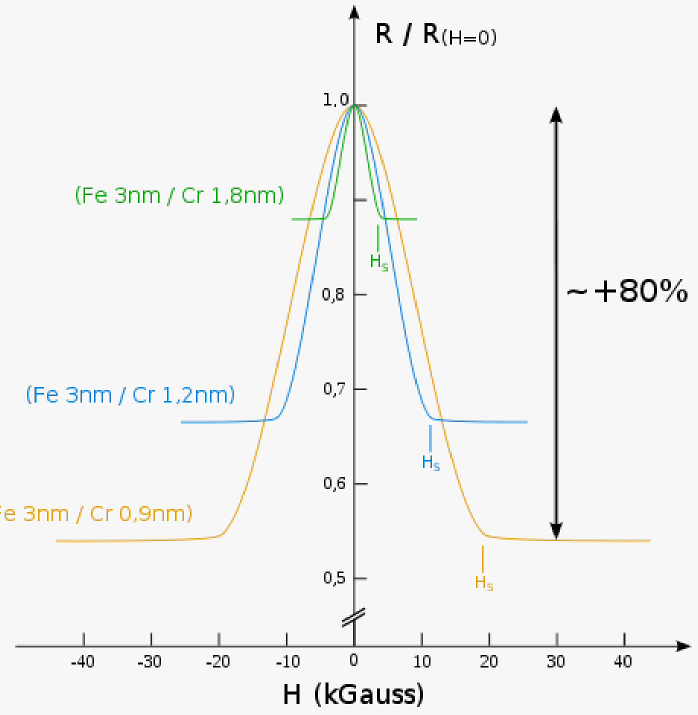
Others : holography, scattering, ptychography

III. SPINTRONICS – Outline

- Introduction
- Magnetoresistance effects
- Spin-transfer effects
- Spin-orbitronics

The discovery of giant magneto-resistance

Giant magneto-resistance



A.Fert et al, PRL (1988);

P.Grunberg et al, patent (1988) +PRB (1989)

The Nobel Prize in Physics 2007

Photo: U. Montan

Albert Fert

Prize share: 1/2

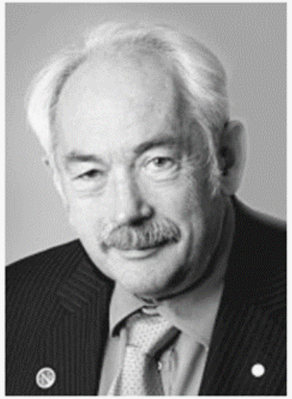


Photo: U. Montan

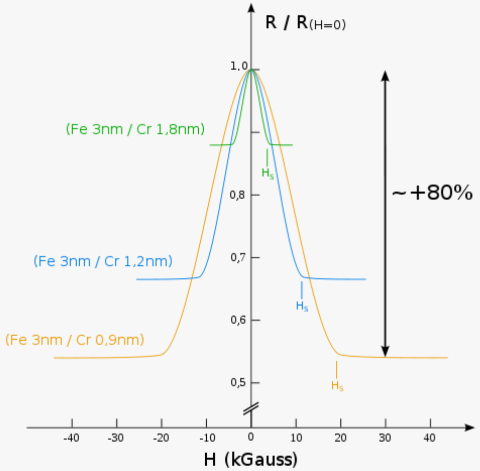
Peter Grünberg

Prize share: 1/2

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg *"for the discovery of Giant Magnetoresistance"*

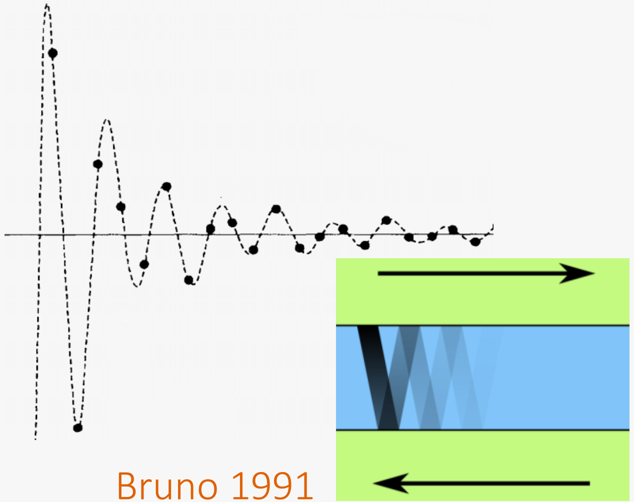
A wealth of fundamental new effects

Giant magneto-resistance



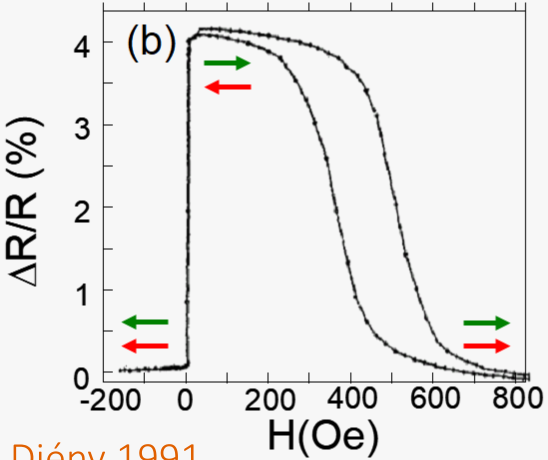
1988

RKKY coupling



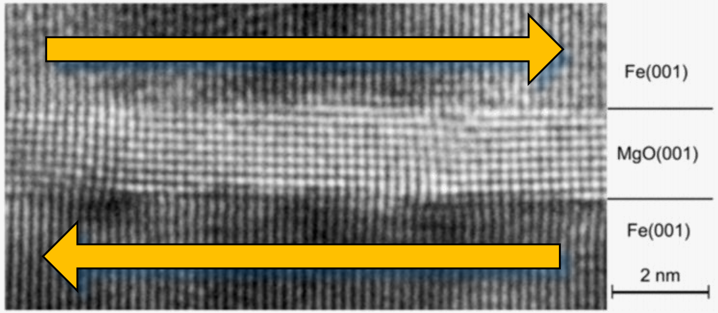
Bruno 1991

Spin-valve concept



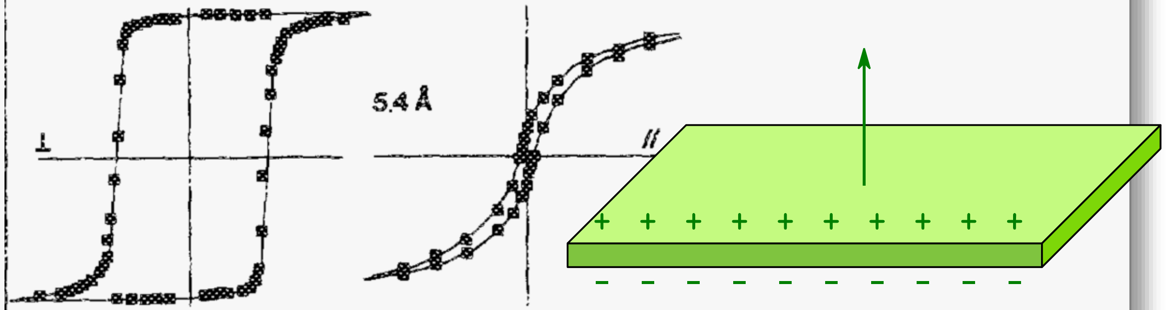
Diény 1991

Tunneling magneto-resistance



Moodera 1995 (Yuasa 2007)

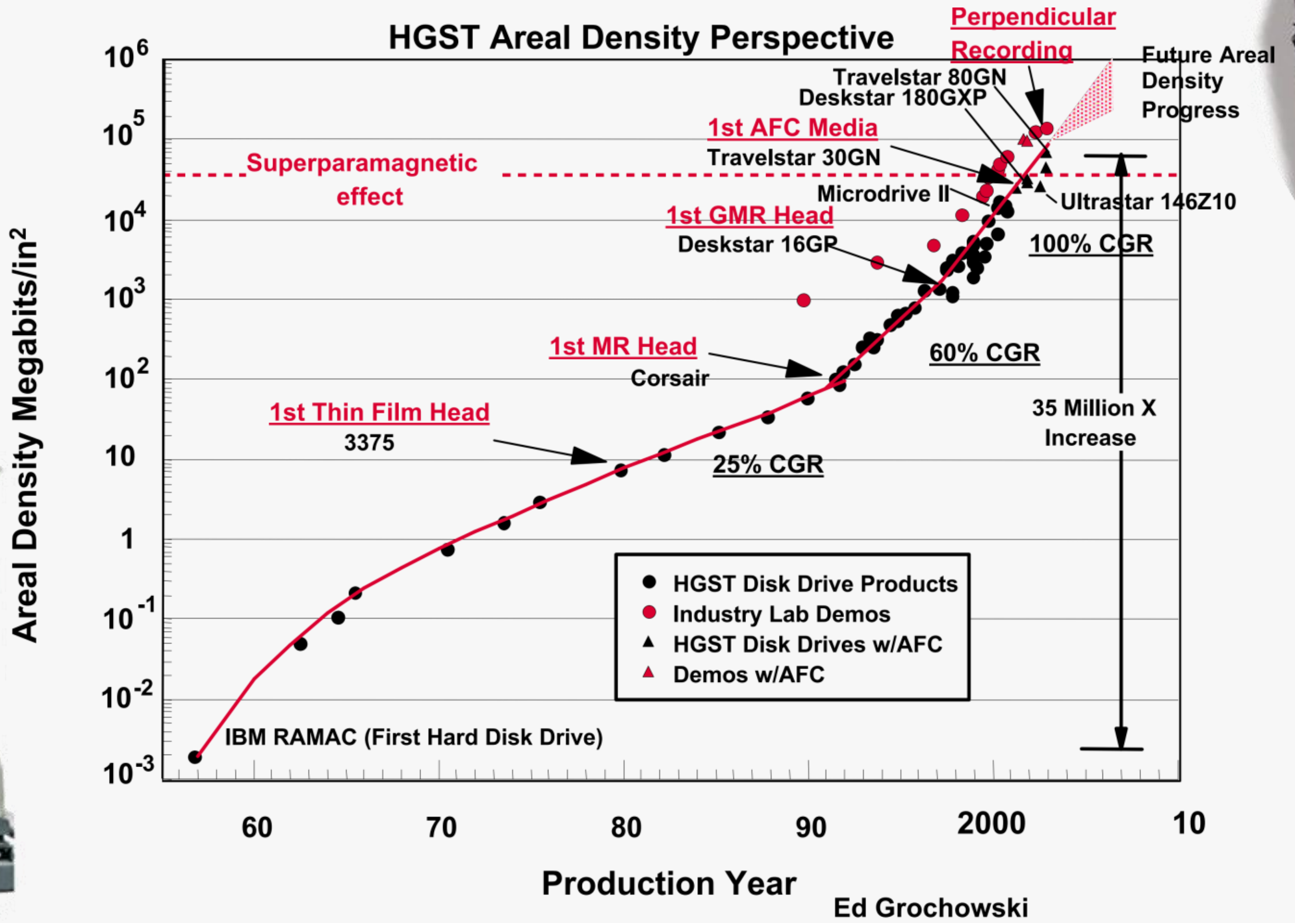
Perpendicular magnetic anisotropy



Chappert 1988

The golden area of the hard-disk drive

Technology pushing science: hard disk drives



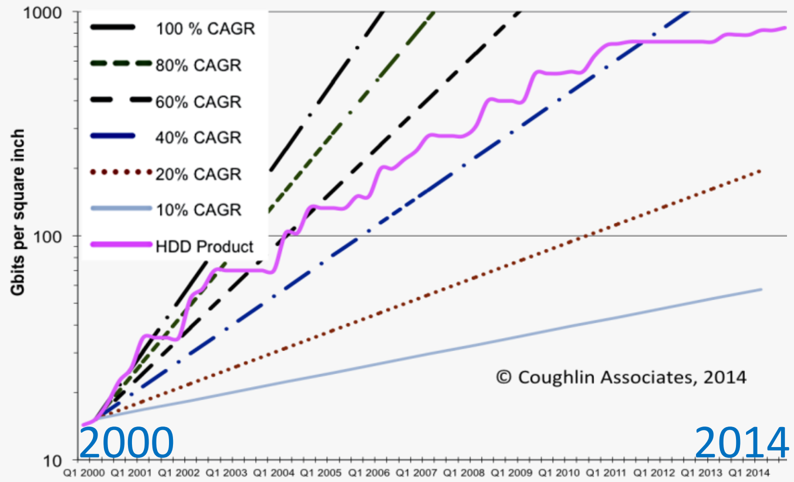
Hard-disk drive progress is coming to an end

Steady progress of HDD, however: incremental, keeping the design

1956

Today

Staggering areal density

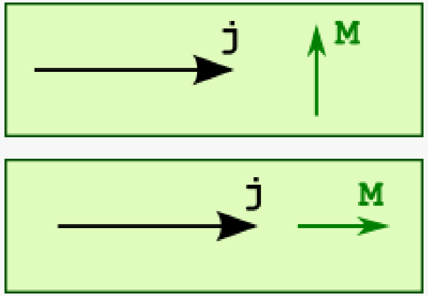


- **Increasing fundamental and technological bottlenecks**
- **Any 2D-based technology is bound to face an end**
- **Hard-disk drive driving force of magnetism has come to an end**

Anisotropic magnetoresistance (AMR)

Physics

- Anisotropic Magneto-Resistance is a bulk effect
- Scattering due to spin-orbit and/or impurities



$\rho_\perp$

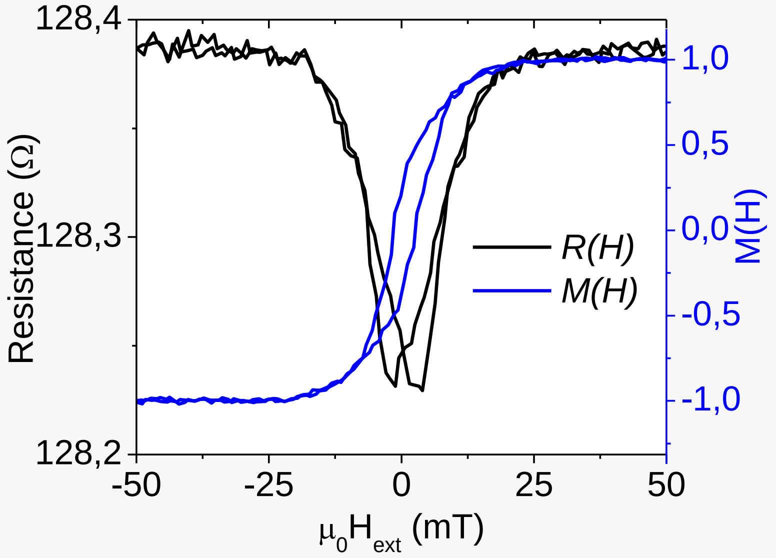
$\rho_\parallel$

$$\rho = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2(\langle \mathbf{j}, \mathbf{M} \rangle)$$

Features

- Magnitude of $\Delta\rho$ is at most a few percent
- Sensitive to the direction however not the sign of magnetization
- Used in: standard magnetic sensors, HDD read heads in the 1980's

Example



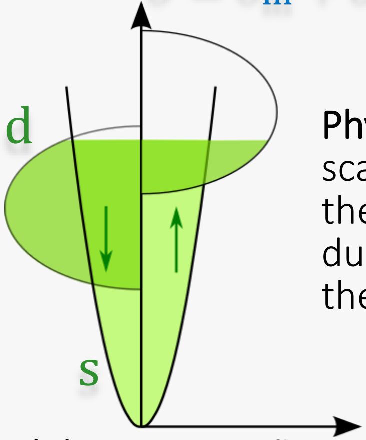
CoNiB single nanotube with azimuthal magnetization, field applied along the tube axis

Giant magnetoresistance (GMR)

Two-current model

Mott 1930

- **Model**: electrons with spin up and down contribute to two independent conduction channels $\sigma = \sigma_{\mathrm{m}} + \sigma_{\mathrm{M}}$

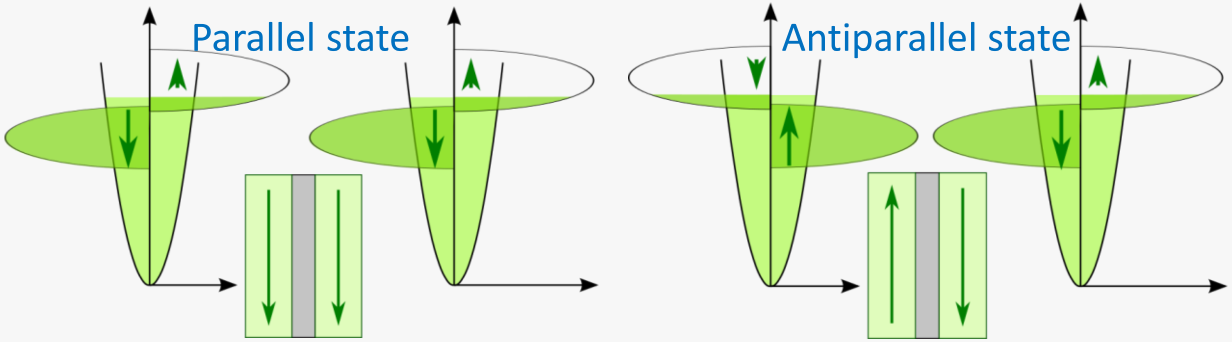


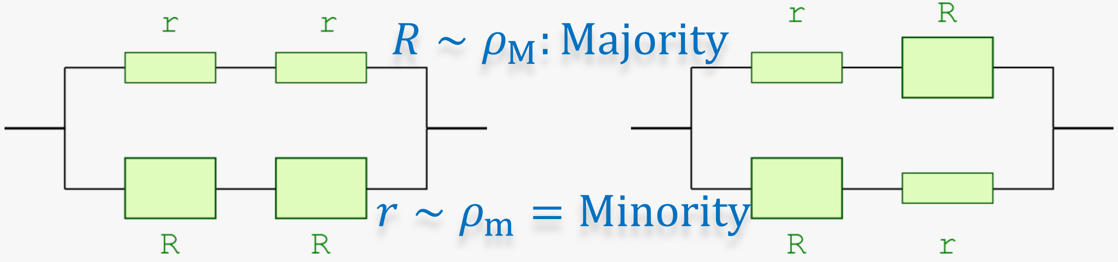
Physics: the s-d scattering is different in the two spin channels, due to the splitting of the d bands.

- **Validity**: no spin-flip, rather low temperature (no magnons and phonons)
- **Define**: asymmetry of resistivity $\alpha = \dfrac{\rho_{\mathrm{m}}}{\rho_{\mathrm{M}}} = \dfrac{\sigma_{\mathrm{M}}}{\sigma_{\mathrm{m}}}$

$$\rho = \frac{1}{\sigma} = \frac{\rho_{\mathrm{M}}\rho_{\mathrm{m}}}{\rho_{\mathrm{M}} + \rho_{\mathrm{m}}} = \frac{\alpha}{1+\alpha^2}$$

Handwaving model for GMR





$R \sim \rho_{\mathrm{M}}$: Majority

$r \sim \rho_{\mathrm{m}}$ = Minority

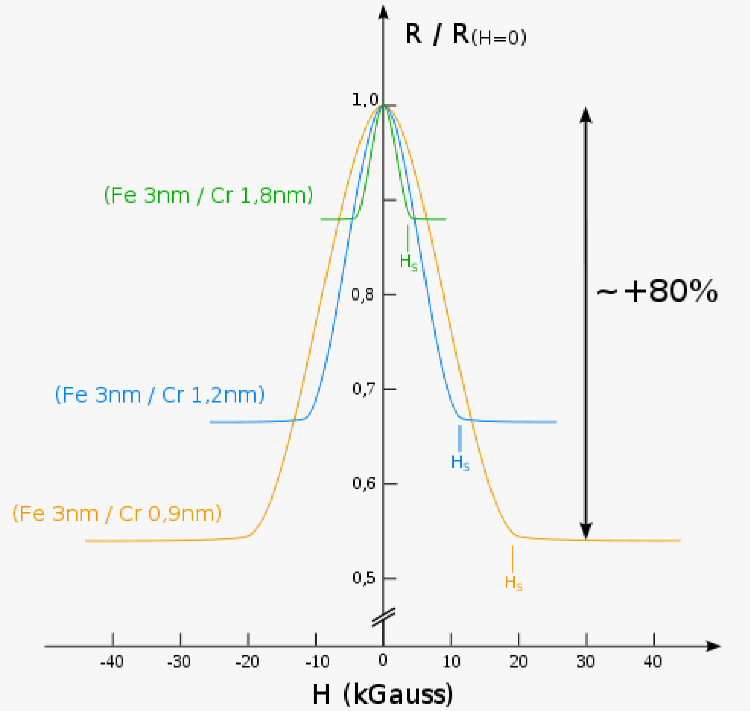
$$R_{\mathrm{P}} = \frac{2rR}{r+R}$$

$$R_{\mathrm{AP}} = \frac{r+R}{2}$$

$$\mathrm{GMR} = \frac{R_{\mathrm{AP}} - R_{\mathrm{P}}}{R_{\mathrm{P}}} = \frac{(\alpha-1)^2}{4\alpha}$$

Giant magnetoresistance (GMR)

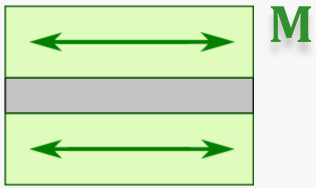
Example (Seminal, 1986)



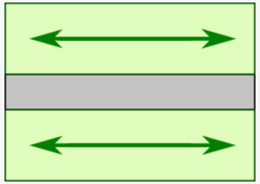
A.Fert et al, PRL (1988);

P.Grunberg et al, patent (1988) +PRB (1989)

Facts



- **Current-In-Plane (cip)**: mean free path → A few nanometers
- **Current-Perpendicular-to-Plane (cpp)**: spin diffusion length → Hundreds of nanometers up to micrometers
- Magnitude: a few tens of percent (larger in cpp)

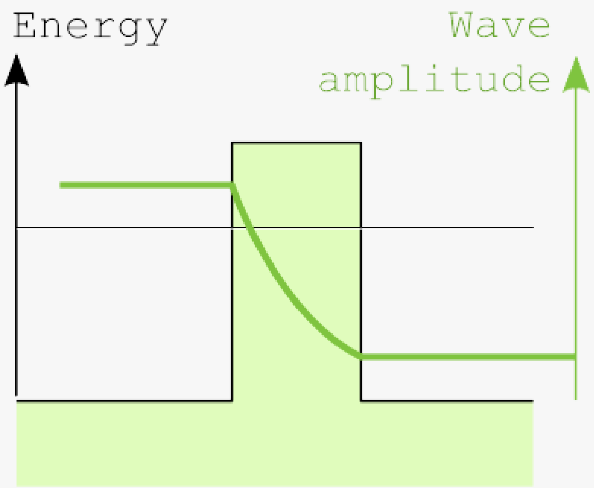


Spin accumulation

- Electrons with minority spin accumulate in front of a ferromagnetic layer (cpp geometry)
- May be modeled by spin-dependent potential and diffusion equations
- Possible implementation of lateral spin valves and GMR

Tunnel magnetoresistance (TMR)

Tunneling transport

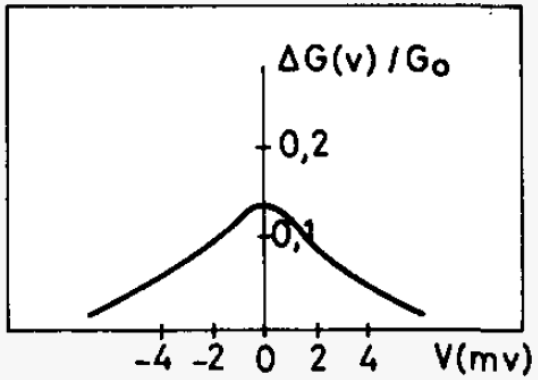


- Exponential decay of wave functions in the barrier

- Used in high sensitivity sensors, memory reading, HDD head…
- TMR should be bound to circa 50 % (3d ferromagnets)

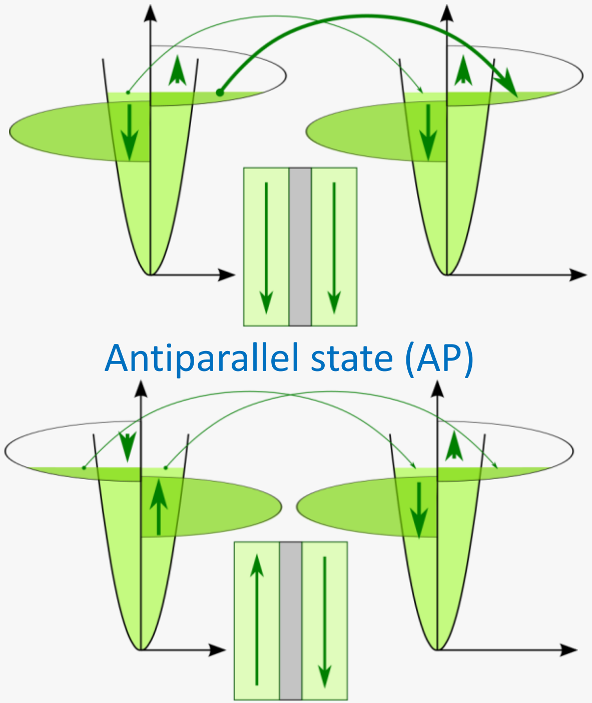
Tunneling Magneto-resistance

- Discovery at 4K in Fe/Ga/Fe thin-film stacks
  M. Julliere, Phys. Lett. 54A, 3, 225 (1975)
- Revival at 300K in F / Al_2O_3 / F stacks
  J. S. Moodera, Phys. Rev. Lett. 74, 3273 (1995)



Parallel state (P)

Antiparallel state (AP)



- Define polarization at the Fermi level

$$P = \frac{D_{\mathrm{Maj}} - D_{\mathrm{Min}}}{D_{\mathrm{Maj}} + D_{\mathrm{Min}}}$$

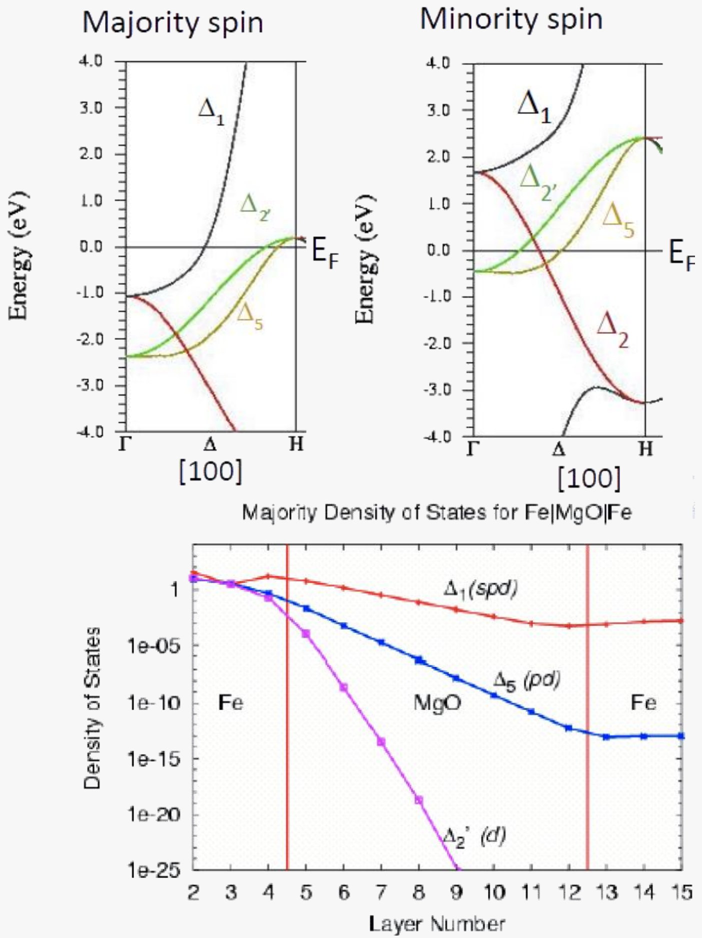
- Define the TMR ratio

$$\mathrm{TMR} = \frac{R_{\mathrm{AP}} - R_{\mathrm{P}}}{R_{\mathrm{P}}} = \frac{2P^2}{1 - P^2}$$

Need to name differently spins up/down, versus minority/majority

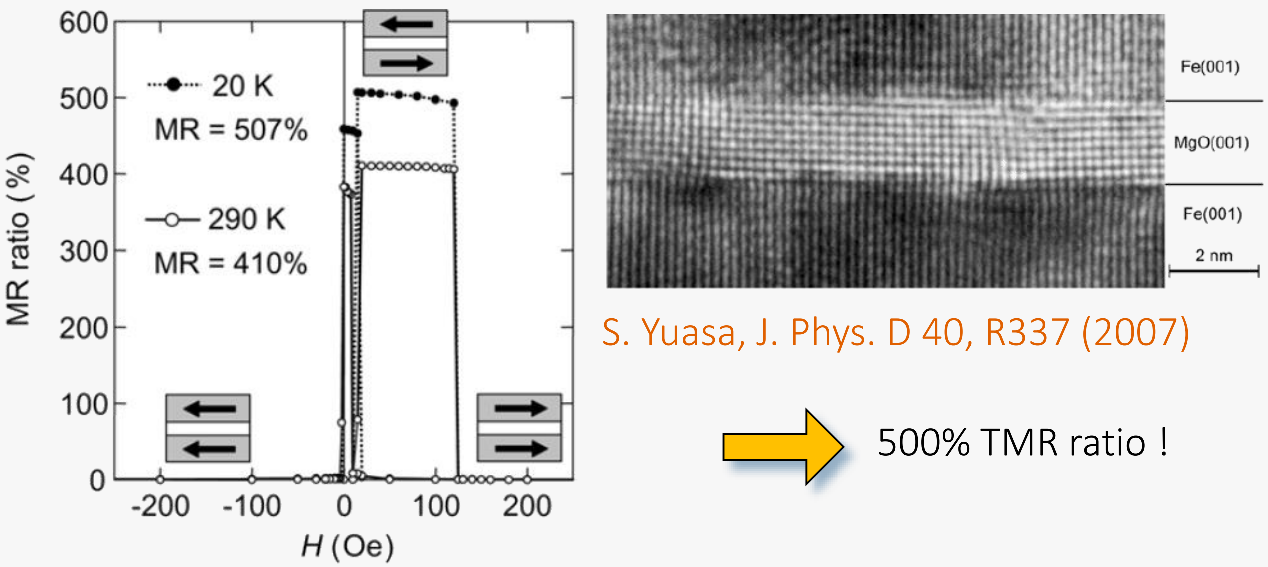
Tunnel magneto-resistance (TMR)

Prediction of spin filtering for Fe/MgO/Fe



F. Butler et. al., Phys. Rev. B 63, 220403 (2001)

Realization of spin filtering for MgO(001) barriers



S. Yuasa, J. Phys. D 40, R337 (2007)

500% TMR ratio !

- Not a transistor, yet enough to discriminate On/Off states
- Magnetic Tunnel Junctions (MTJs) are the key building block of solid-state magnetic memories

Spin-transfer torque: theoretical prediction

$$P_{\text{trans}} = P\frac{J}{|e|}\mu_{\text{B}}$$

$$\frac{\mathrm{d}\mathbf{m}_2}{\mathrm{d}t} = -|\gamma_0|\mathbf{m}_2 \times \mathbf{H}_{\text{eff}} + \alpha\mathbf{m}_2 \times \frac{\mathrm{d}\mathbf{m}_2}{\mathrm{d}t} - \frac{P_{\text{trans}}}{M_2}\mathbf{m}_2 \times (\mathbf{m}_2 \times \mathbf{m}_1)$$

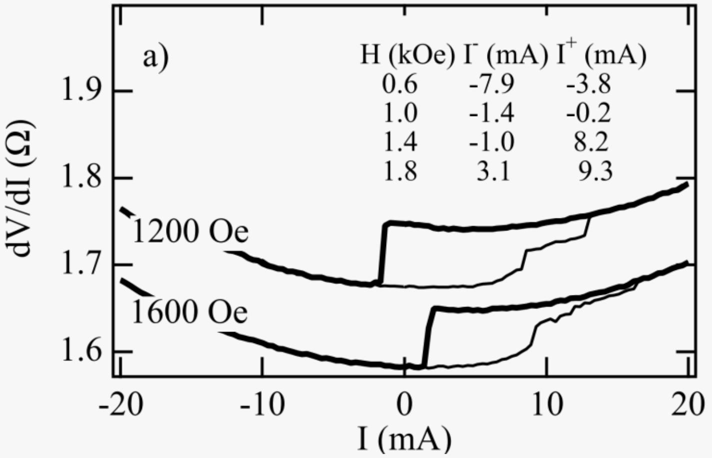
J. C. Slonczewski, J. Magn. Magn. Mater. 159, L1-7(1996)

- Can be viewed as the reverse effect of Giant Magnetoresistance

Experimental confirmation

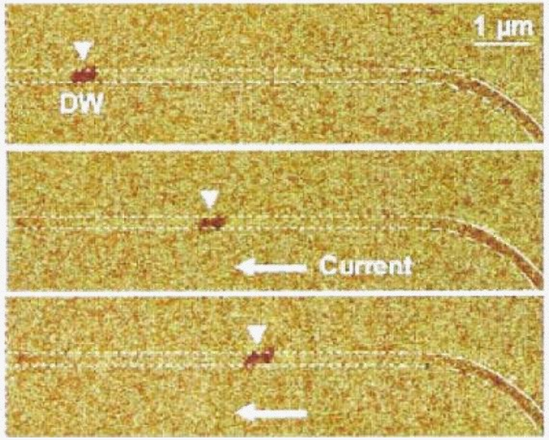
Spin-transfer torque: experiments

Magnetization switching



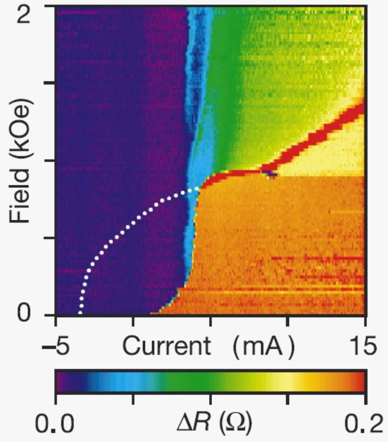
Katine 2000

Domain-wall motion



Yamaguchi 2004

Oscillator



Kiselev 2003

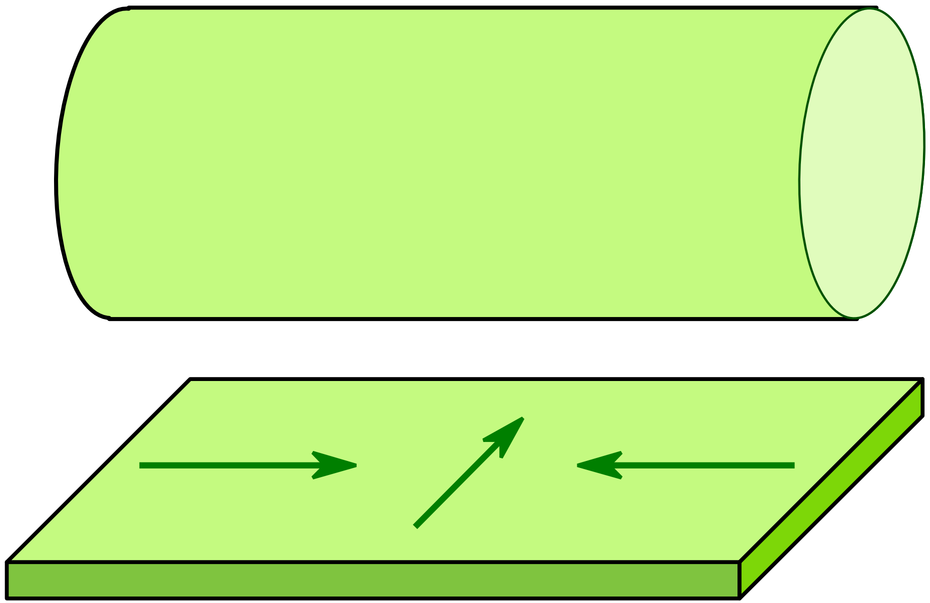
New physics deeply rooted in condensed matter magnetism!

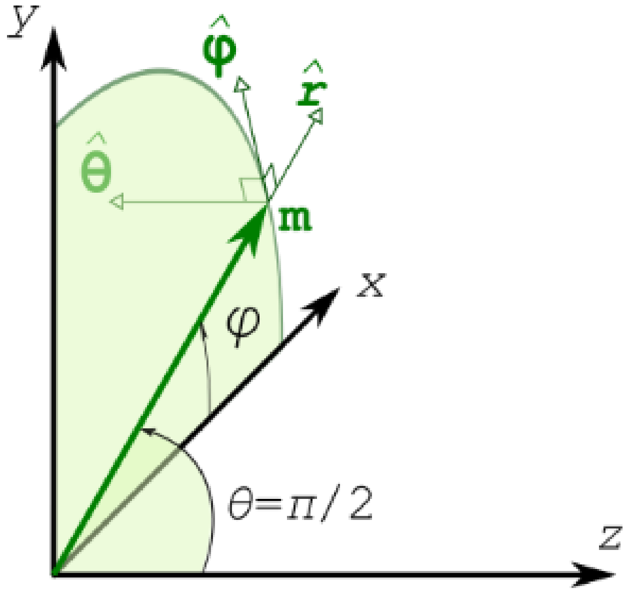
- Magnetization switching with charge current
- Domain-wall motion with charge current
- Precessional dynamics with charge current

A booster for applications

- Simplifies architectures
- Scalable to smaller nodes
- Robust writing

Formulation for continuous magnetization fields





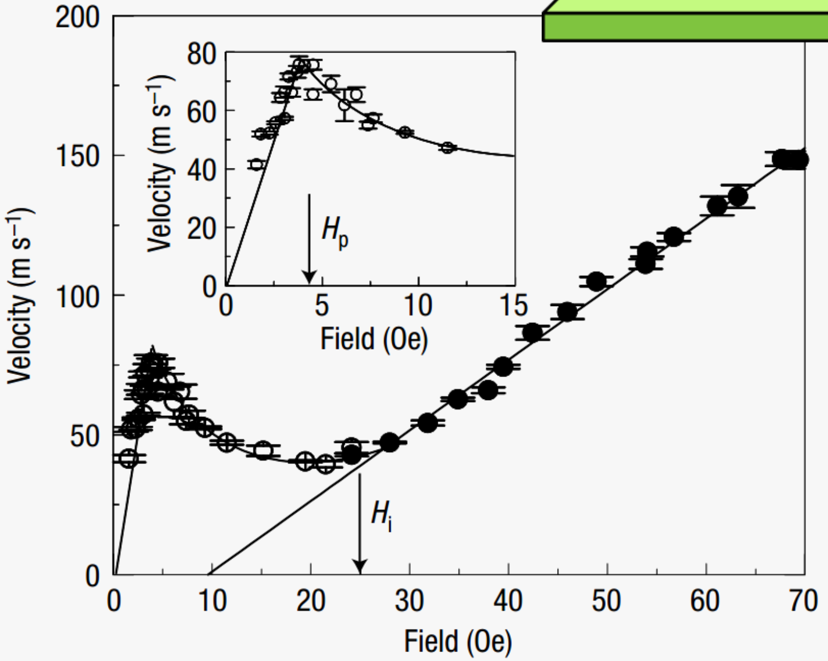
Precessional dynamics under current

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

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

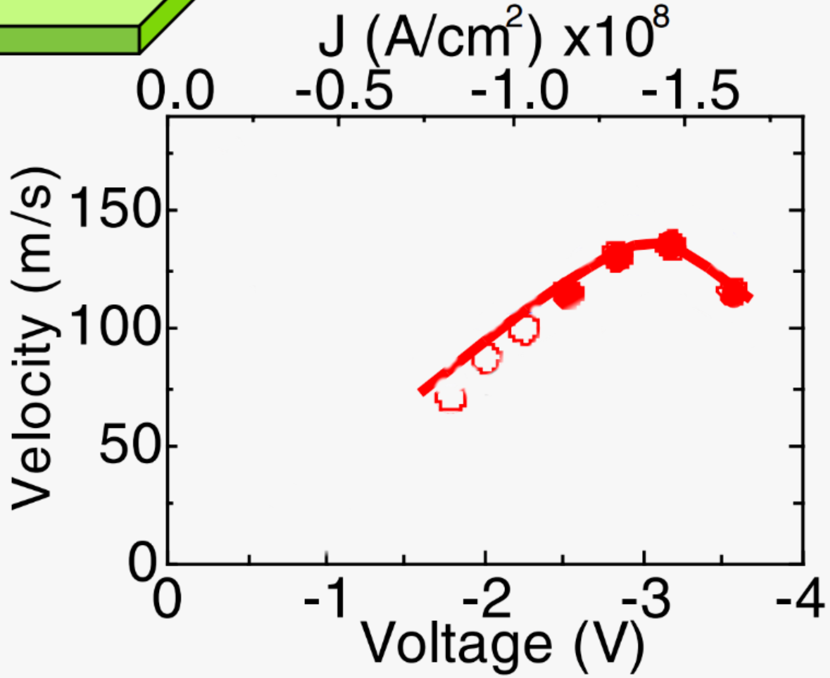
Domain wall motion under STT

Field-driven case



G. S. D. Beach et al., Nat. Mater 4, 741 (2005)

Current-driven case



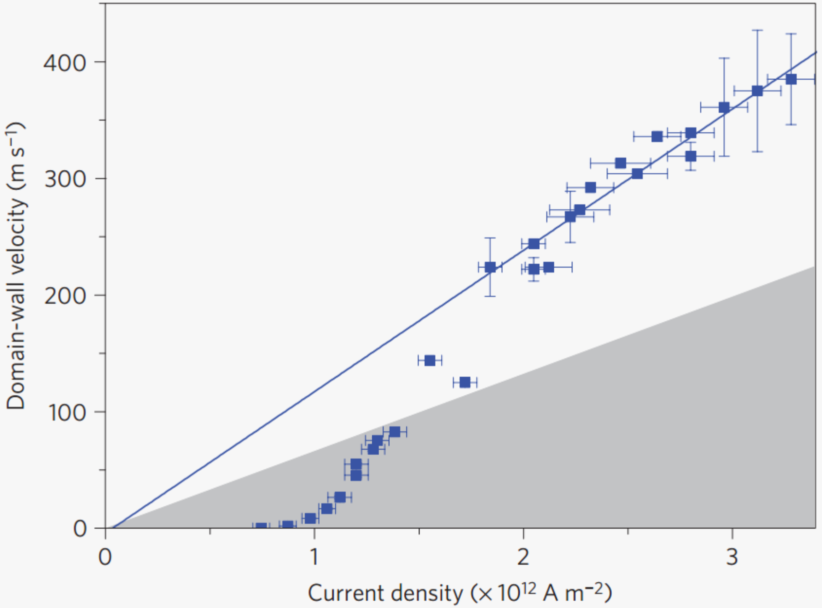
M. Hayashi et al., PRL 98, 037204 (2007)

- **Physics: dynamic transformation of domain walls**
- **Average speed does not exceed much 100 m/s**

Domain wall motion (enhanced)

C'NANO

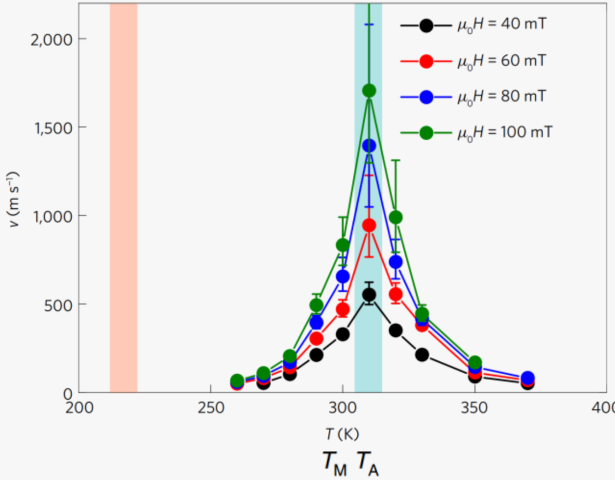
Dzyaloshinskii-Moriya interaction + Spin-Hall currents



I.. M. Miron et al., Nat. Mater. 10, 419 (2011)

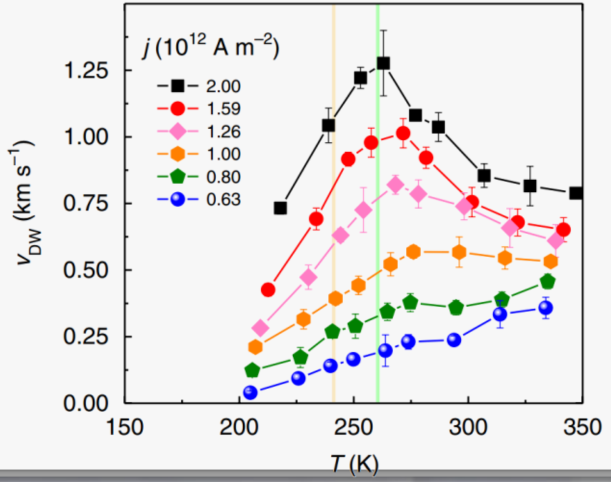
A. Thiaville et al., EPL100, 57002 (2012)

Ferrimagnetic materials



Kim et al., Nat. Mater. 16, 1187 (2017)

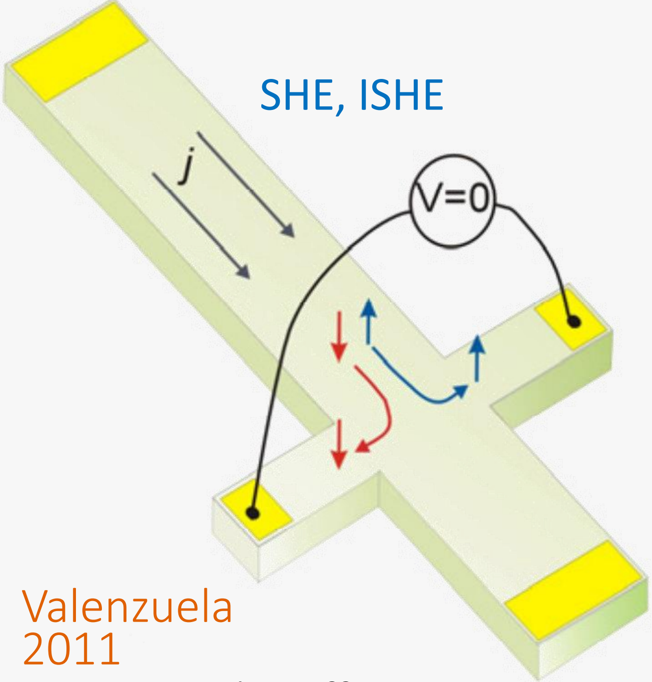
Field-driven



Current-driven

The spin-Hall effect

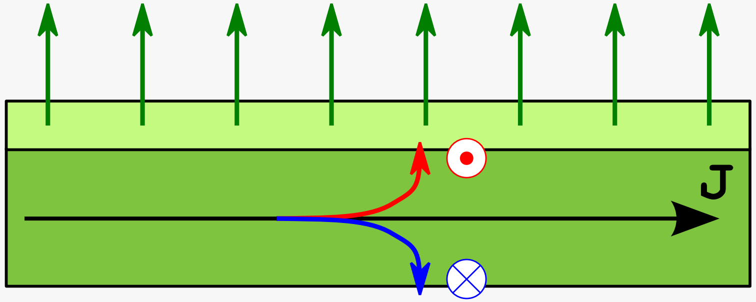
Spin-Hall effect: physics



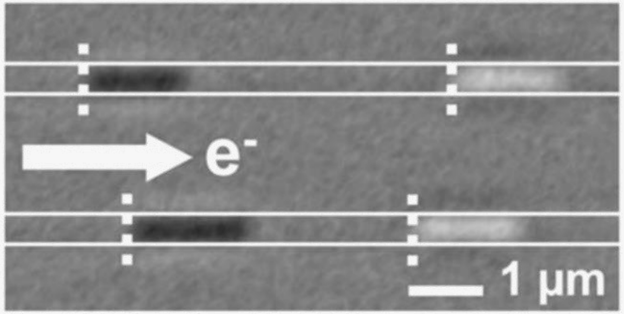
Valenzuela 2011

- Spin-orbit effect
- Analogous to Mott detectors
- Generate pure spin currents from non-magnetic materials

Spin-Hall effect: drive magnetization dynamics



Domain wall motion, magnetization switching …



Moore 2008

- New physics,
- Increased efficiency
- New materials…
- Requires chiral walls or a bias field

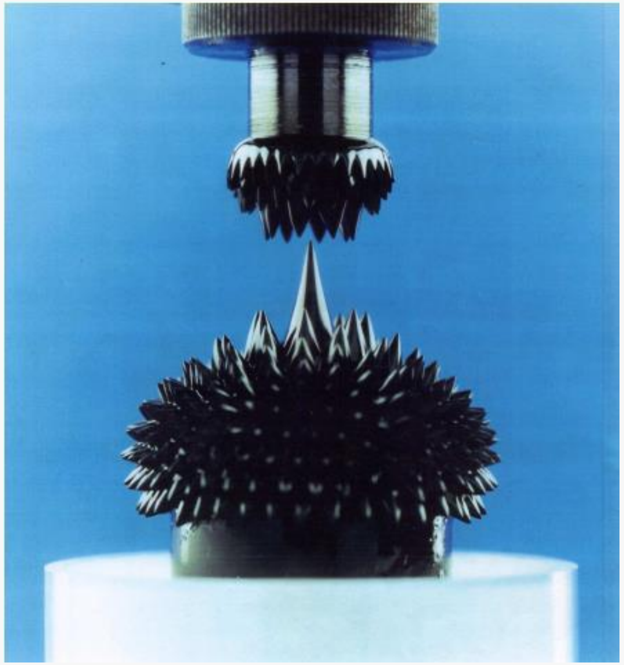
- Microstructures for hard/soft magnetic materials
- Nanoparticules : materials, ferrofluids and beads
- Magnetic sensors
- Memories and logics

Ferrofluids

Principle

Surfactant-coated nanoparticles, preferably superparamagnetic

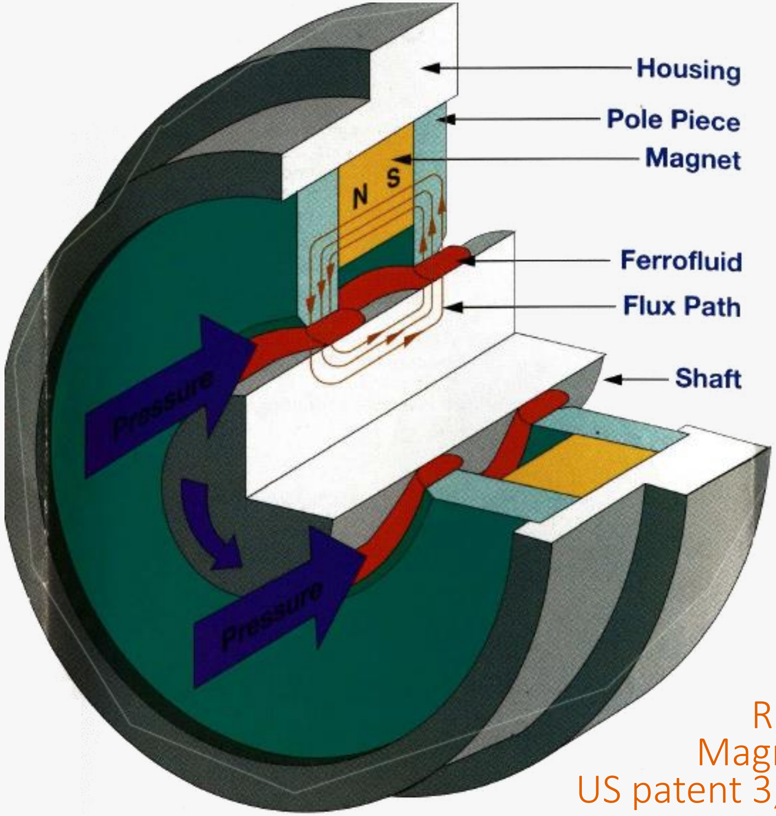
- Avoid agglomeration of the particles
- Fluid and polarizable



http://magnetism.eu/esm/2007-cluj/slides/vekas-slides.pdf

Example of use

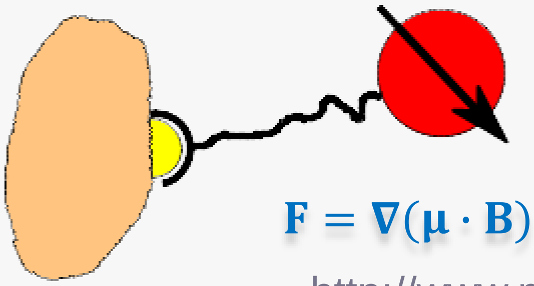
Seals for rotating parts



R. E. Rosensweig, Magnetic fluid seals, US patent 3,260,584 (1971)

C'Nano

Cell sorting

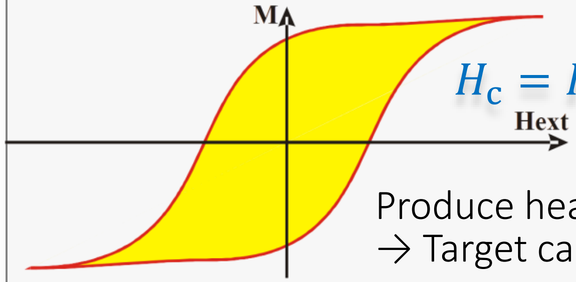


$$\mathbf{F} = \nabla(\boldsymbol{\mu} \cdot \mathbf{B})$$

MagIA diagnostics

http://www.magia-diagnostics.com/

Hyperthermia

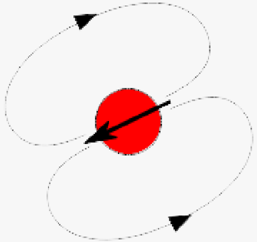


$$H_c = H_{c,0}\left(1 - \sqrt{\frac{\ln\left(\frac{\tau}{\tau_0}\right) k_B T}{K\mathcal{V}}}\right)$$

Produce heat by ac magnetic field
→ Target cancer cells etc.

MRI contrast agent

Principle: local extinction of MRI contrast due to the stray field of the magnetic nanoparticles



Beads = coated nanoparticles, preferably superparamagnetic
→ Avoid agglomeration of the particles

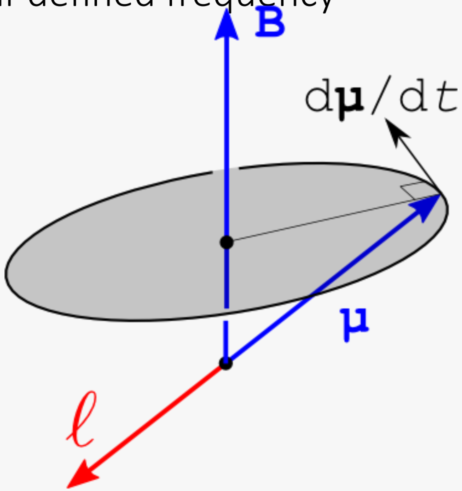
RAM (radar absorbing materials)

Principle: Absorbs energy at a well-defined frequency (ferromagnetic resonance)

$$\frac{\mathrm{d}\boldsymbol{\mu}}{\mathrm{d}t} = \mu_0 \gamma \boldsymbol{\mu} \times \mathbf{H}$$

$$\gamma = -g_J \frac{e}{2m_\mathrm{e}} < 0$$

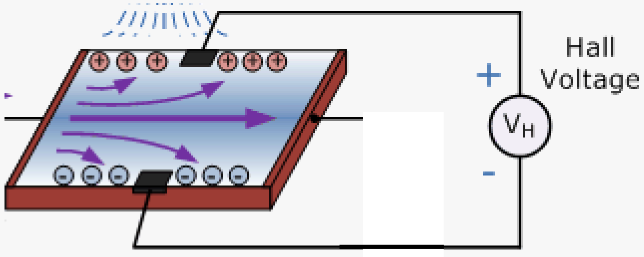
$$\frac{\gamma_\mathrm{s}}{2\pi} \approx 28\ \mathrm{GHz/T}$$



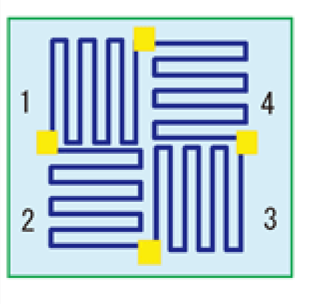
Field versus flux sensor

Magnetic-field sensors: Hall & magneto-resistive

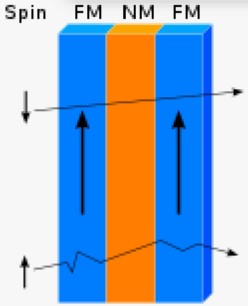
Sensor size may be scaled down



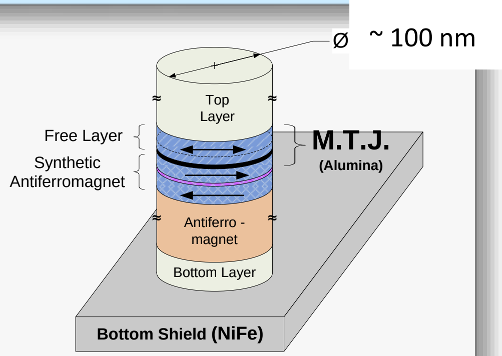
Hall effect



AMR



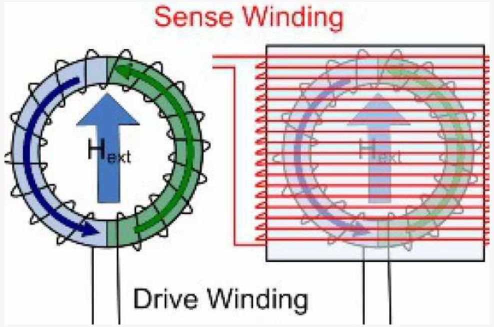
GMR



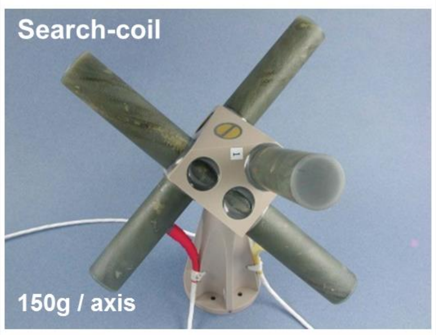
TMR

Flux sensors: inductive or SQUIDs

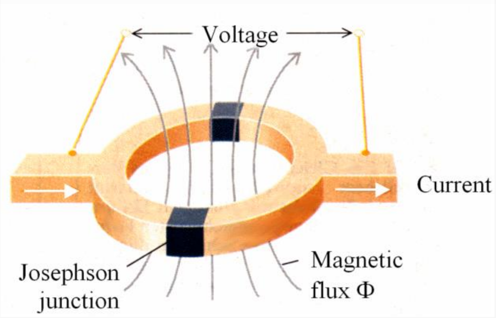
Field sensitivity proportional to size → The larger, the better



Flux gate

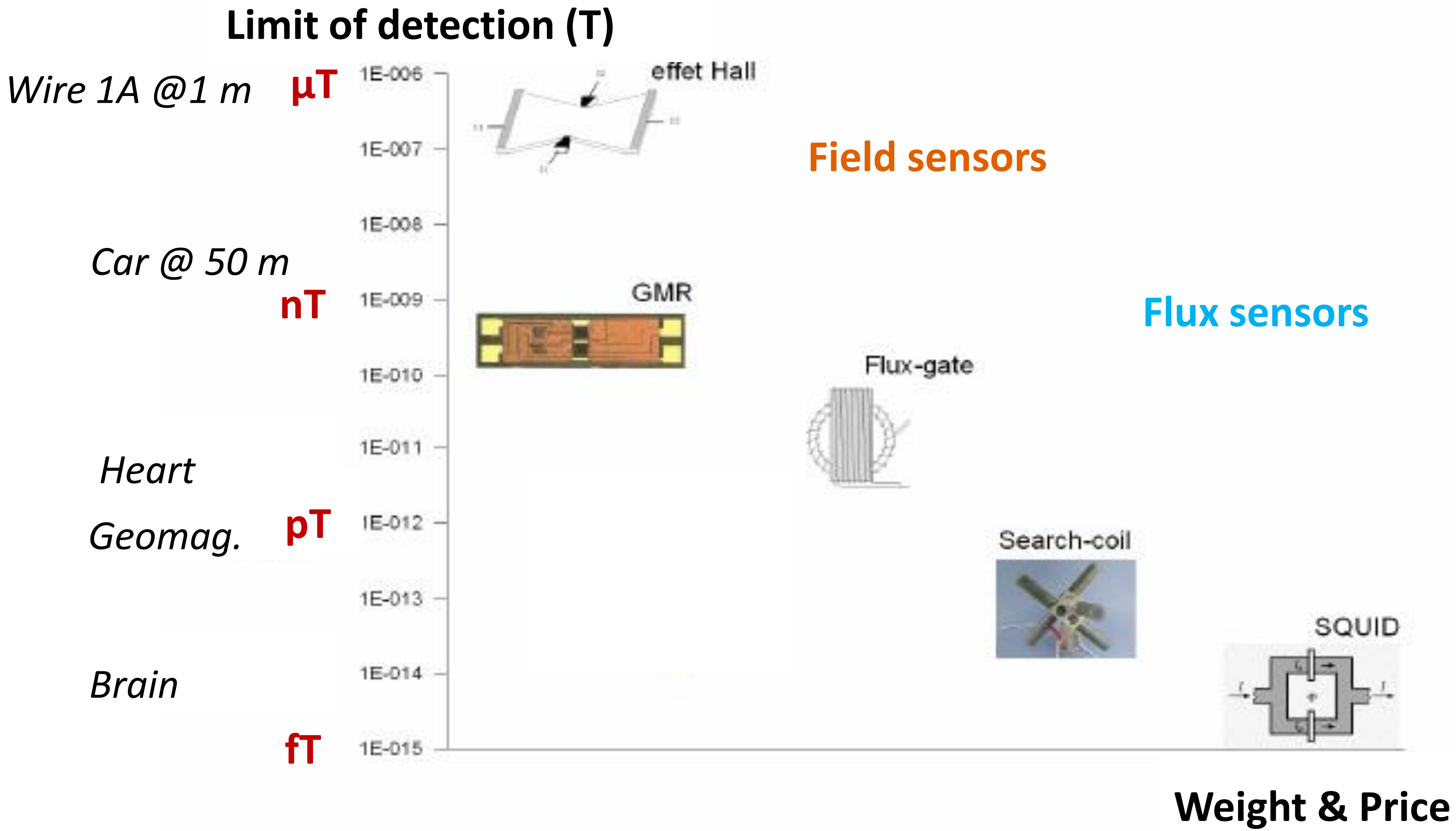


Search coil



SQUID

Detectivity



Sensor characteristics

Ranges

Field, dynamical & frequency range

Linearity

Bias free layers

Temperature stability

Use bridges etc.

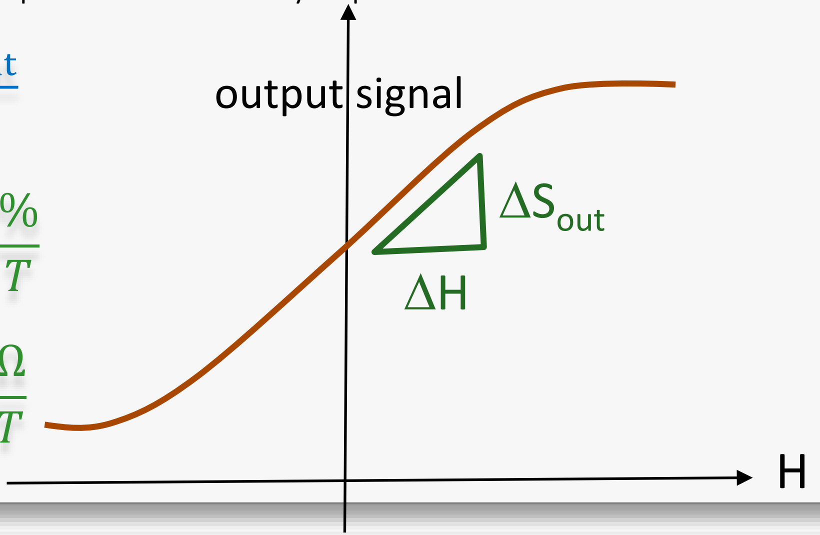
Sensitivity

Output signal slope normalized by input bias

$$s = \frac{1}{S_{\mathrm{in}}} \frac{\mathrm{d}S_{\mathrm{out}}}{\mathrm{d}H}$$

Unit: $\frac{V}{V \cdot T} \sim \frac{\%}{T}$

or: $\frac{V}{A \cdot T} \sim \frac{\Omega}{T}$



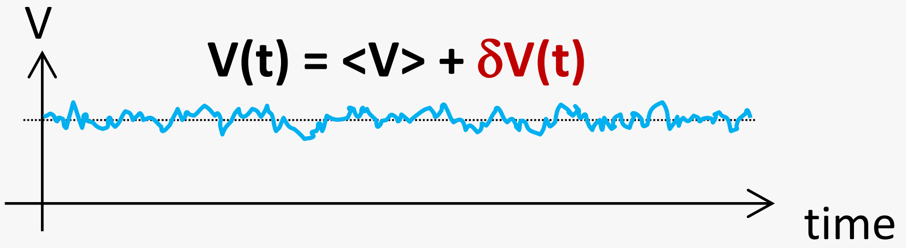
Noise

Depends on the frequency and on the bandwidth

→ noise @ f_0 in V^2/Hz *or* $V/\sqrt{Hz}$

Operation frequency

Bandwidth



Detectivity

Related to the smallest field that can be detected.

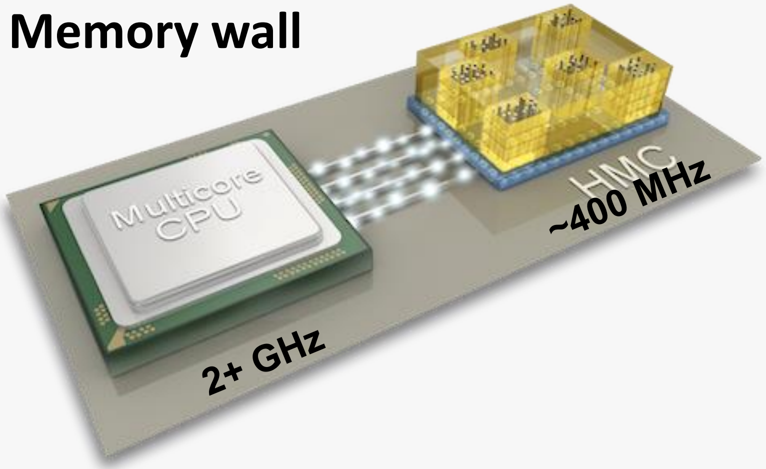
The smallest detectable field corresponds to Signal/Noise=1

Detectivity= $\frac{noise\ (\frac{V}{\sqrt{Hz}})}{\frac{dV}{dH}\ (\frac{V}{T})}$ *in* T/√Hz given @ f0

(Often called sensor noise BUT combines noise & sensitivity)

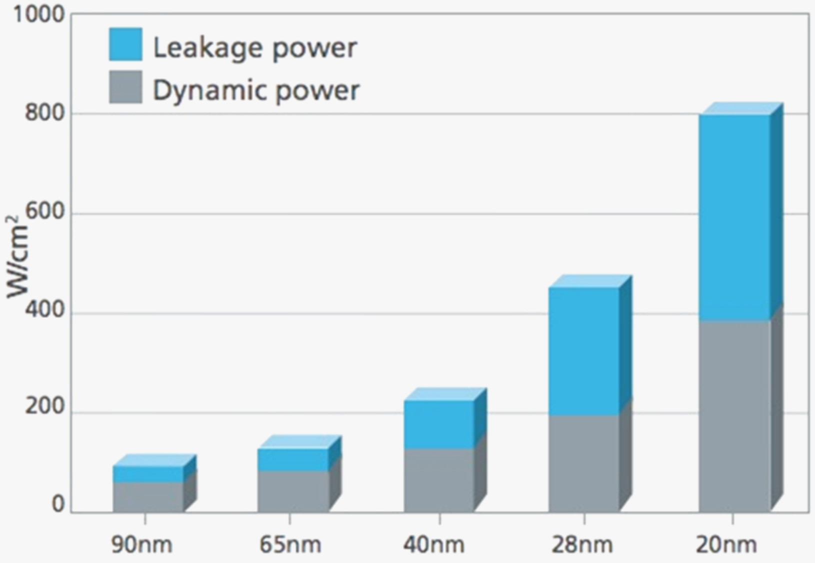
Magnetic Random Access Memory

Memory wall



- Logic keeps awaiting data
- Limits speed
- Increases power consumption

SRAM leakage

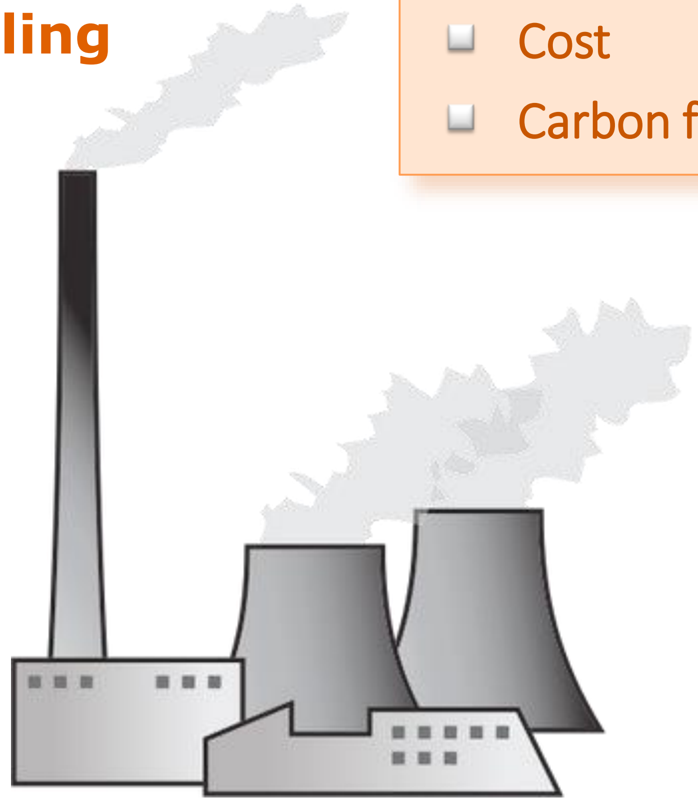


Challenges

- Embed memory
- (Leakage) power

1 Farm = Multi-MW operating power
+ Same amount for cooling

Impact
- Cost
- Carbon footprint

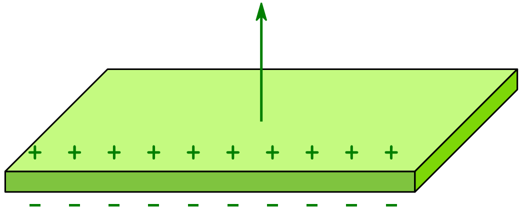


Magnetic Random Access Memory

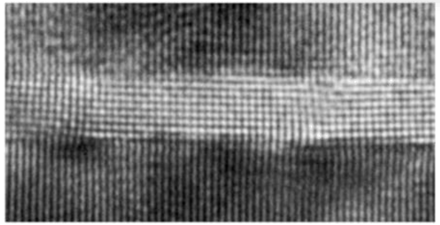
Solid-state magnetic cells

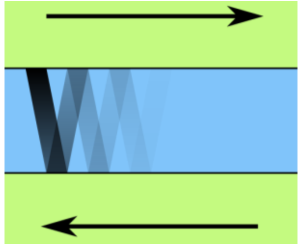
- Magnetic field sensors
- Magnetic memory bit (MRAM)

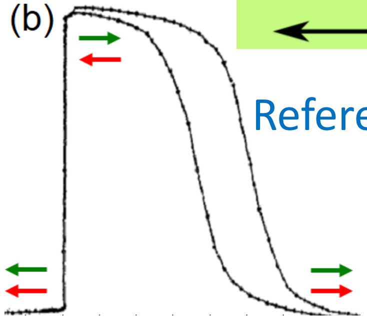
Enhance stability



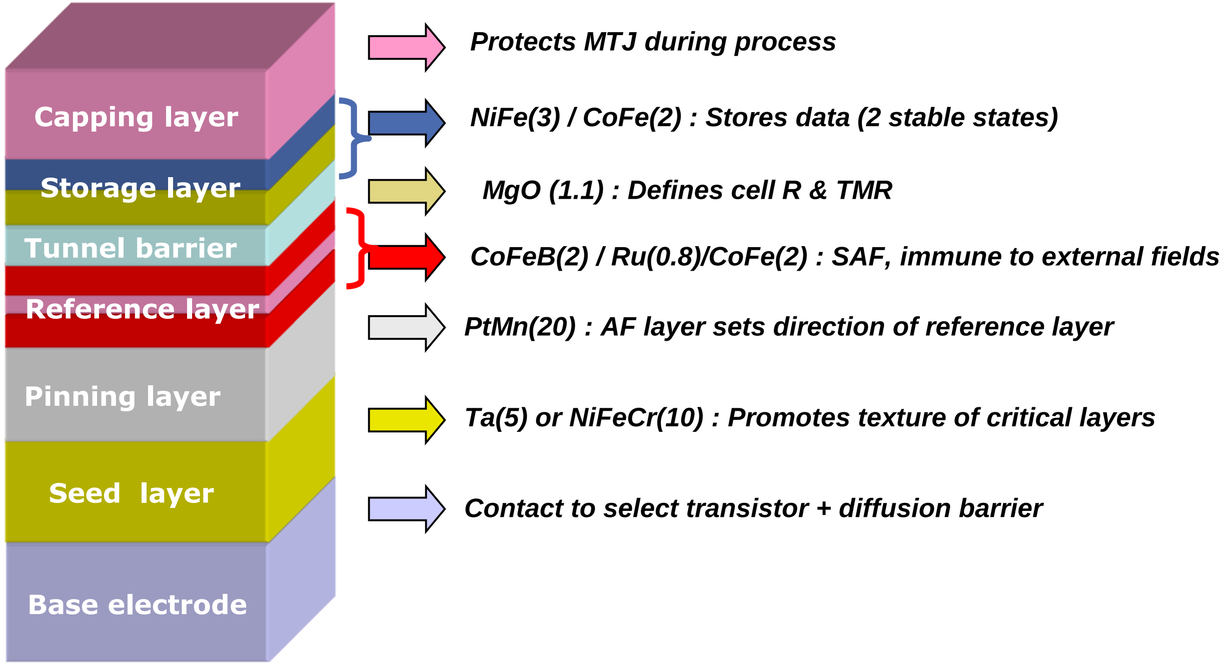
Read







Reference



Magnetic Random Access Memory

Non-volatile
like Flash
10+ years retention

Dense
like DRAM
$10F^2$, small overheads

Fast
Like SRAM
~10ns in normal mode

High Endurance
like SRAM / DRAM
10^{12} cycles, up to 10^{16}

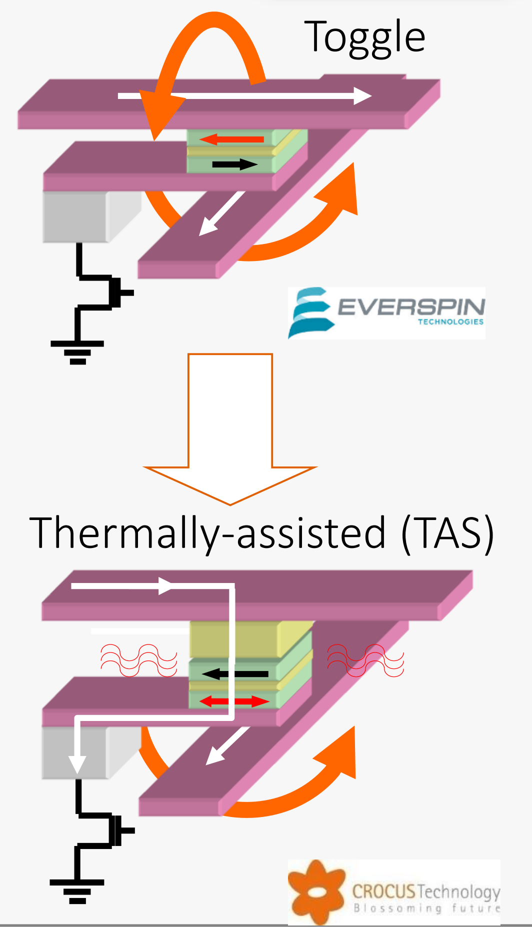
MRAM is not the best but …

- Can replace SRAM at 1/6th of size, zero leakage
- Can replace e-Flash at $>10^5$x speed, lower power
- Could replace DRAM (if running out of steam)

Magnetic Random Access Memory

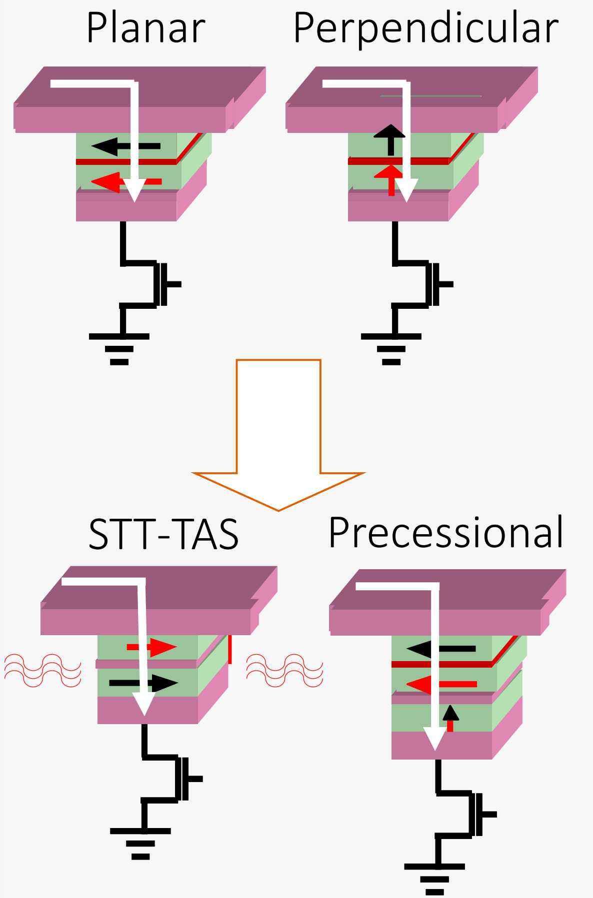
Field driven

→ 2010



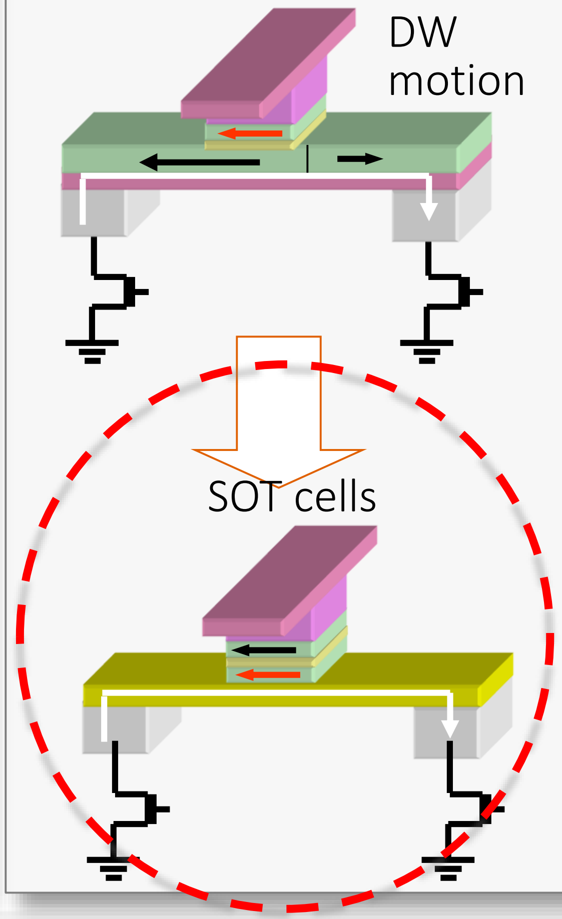
STT

2010 - Now



SOT (spin-orbit torque)

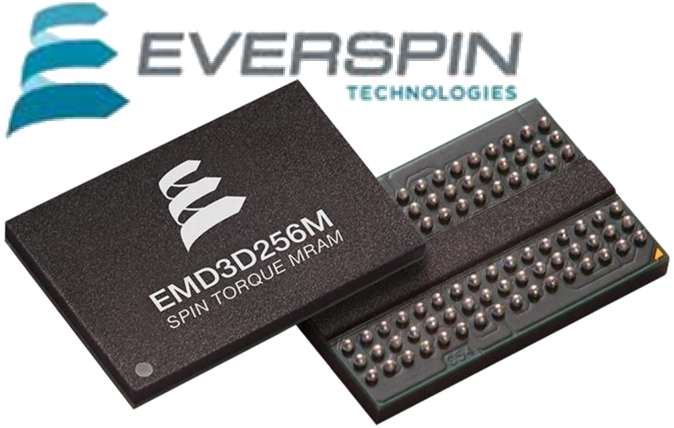
R & D



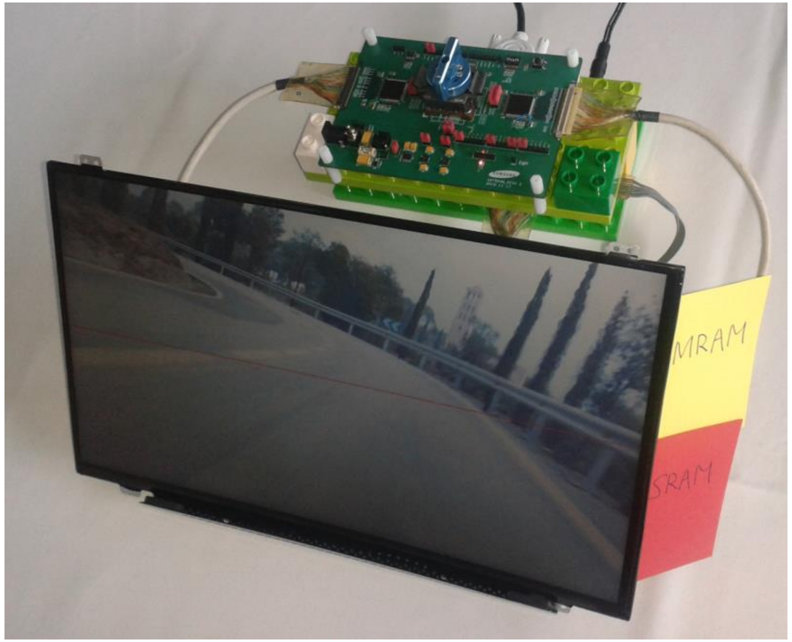
Spintronics enters the ITRS roadmap in 2015

Spintronics enters the ITRS roadmap in 2015

SAMSUNG



1Gb in production.



Demo at the 7th MRAM (STT MRAM) Global Innovation Forum (Zurich, June 2016)

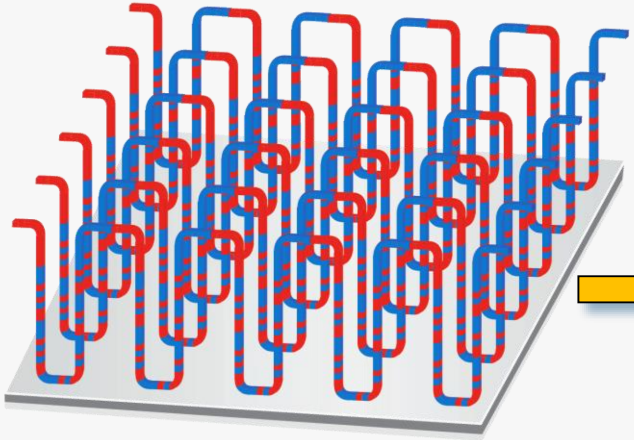
https://www.linkedin.com/company/mram-info/
https://www.mram-info.com

Magnetic Random Access Memory – Players in the field

Everspin Technologies
NEC
intel
TDK
Avalanche Technology
IBM
Global Foundries
Spin Transfer Technologies
tsmc
Renesas – Everywhere you imagine.
Micron
Crocus Technology – Blossoming future
Samsung
Sony
Fujitsu
antaios
TowerJazz
Grandis
TEL
Qualcomm
Toshiba
Hprobe
Keysight Technologies
Singulus
Applied Materials
hynix
Canon – Canon Anelva Corporation
Capres A/S – Copenhagen Applied Research

Storing information with domain walls?

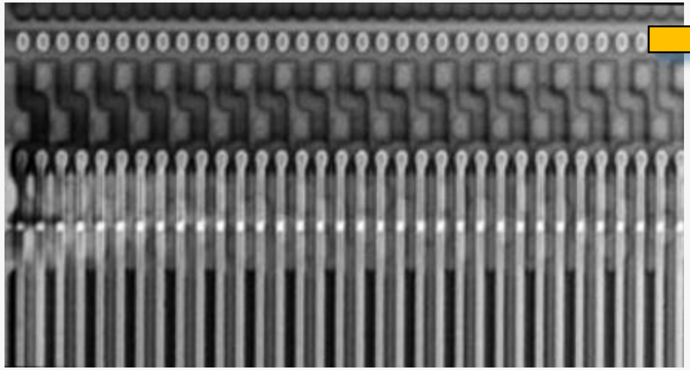
Proposal for a 3D race-track memory



S. S. P. Parkin, Science 320, 190 (2008)
Scientific American 76 (2009)
+ patents (IBM)

Playground for fundamental research, too many challenges for devices

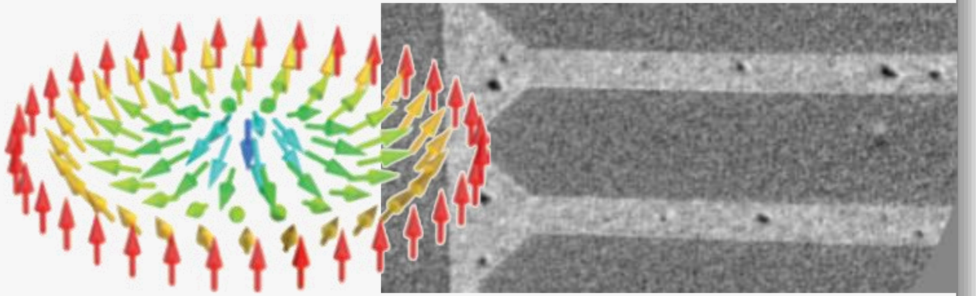
2D demonstrators only



L. Thomas et al., IEEE Intern. Electr. Dev. Meeting (2011)

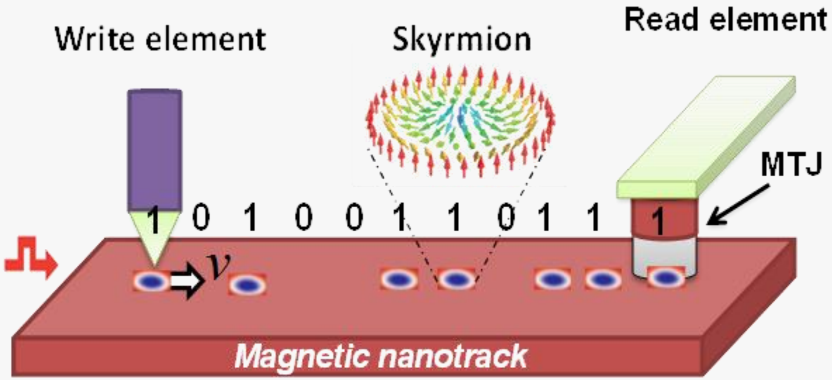
Science is now clear, however lack reproducibility and not dense enough for devices

Magnetic skyrmions



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

Claims



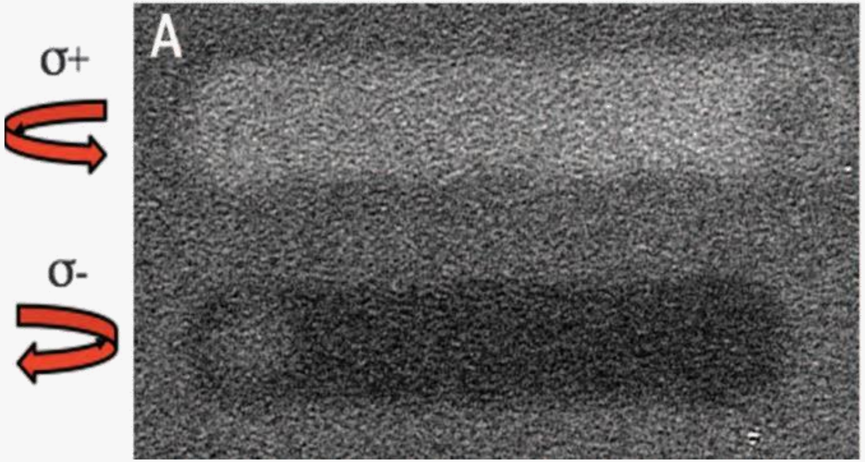
Pinning and stochastic (temperature) effects remain too strong for devices

New concepts for memories

Fast all-optical switching

$Gd_{22}Fe_{74.6}Co_{3.4}$
λ=800nm, 40fs

C. D. Stanciu, PRL99, 047601 (2007)



C. H. Lambert, Science 345, 1337 (2014)

Physics

- Three-temperature model
- Superdiffusive hot electrons
- Multiphysics and multiscale modeling

Technology

- All-optical or not?
- One shot or stochastic?
- Material versatility?

Neuromorphic computing

Brain

20 W

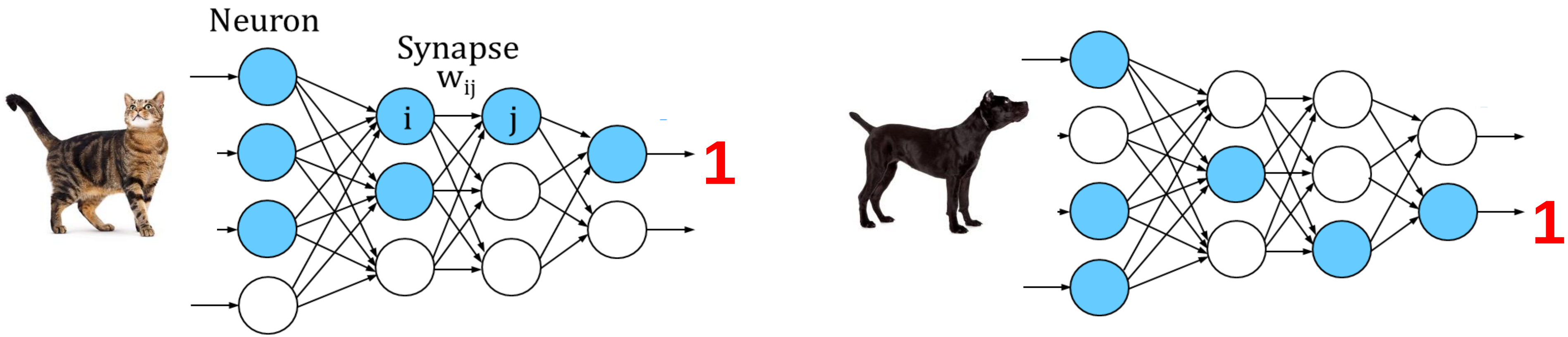
- Low power
- Non-linear, stochastic

High-performance computing

10 MW

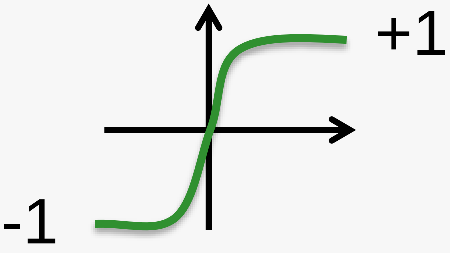
- High power
- Deterministic

Neuromorphic computing



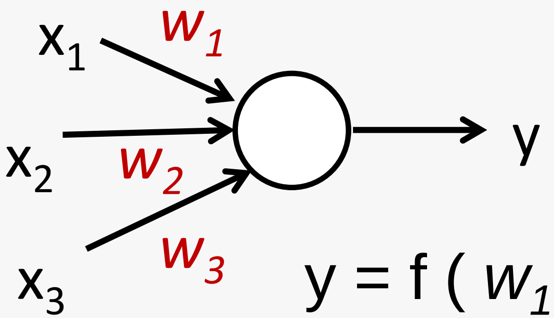
Neurons

- Non-linear



Synapses

- Analog valves (weighs w)



$$y = f\,(\,w_1\,x_1 + w_2\,x_2 + w_3\,x_3)$$

- **Ingredients for neural networks: non-linearity, memory and plasticity**

Neuromorphic computing

Assets of spintronics hardware components for artificial Intelligence (AI)

- Intrinsically hysteretic and non-linear
- Much lower power and footprint than dedicated CMOS AI

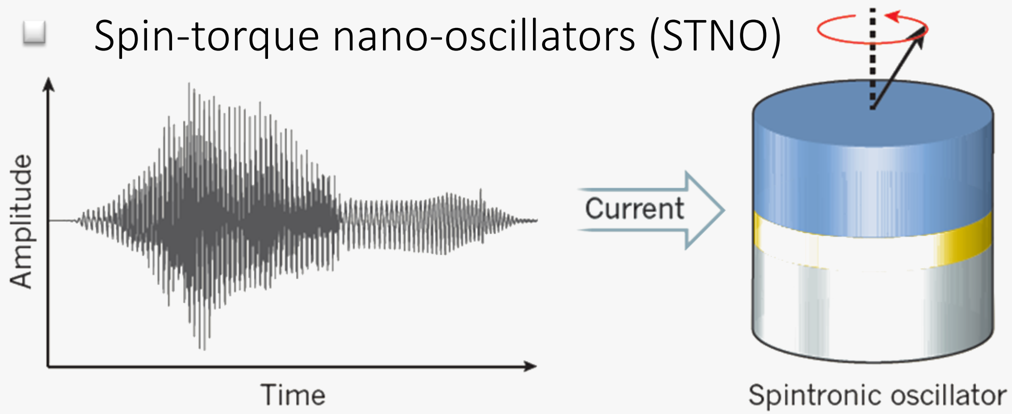
NB: weakness = small gain

Real neurone spiking

Rossant et al., Frontiers in Neuroscience 5, 9 (2011)

Non-linearity

- Spin-torque nano-oscillators (STNO)

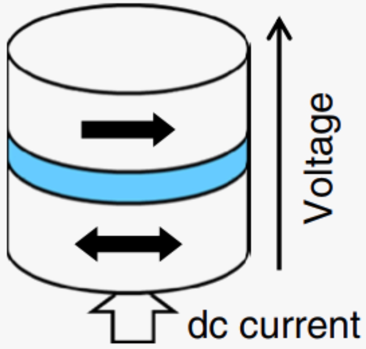


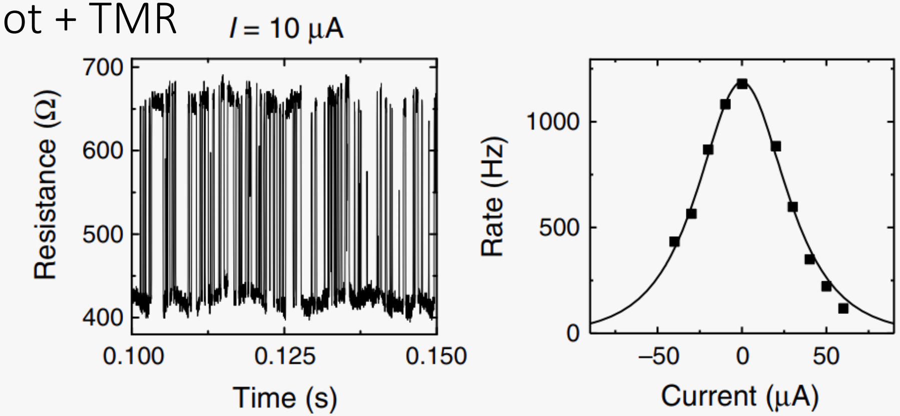
J. Torrejon et al, Nature 547, 428 (2017)

Stochasticity

A. Mizrahi, Nat. Comm. 9, 1533 (2018)

- Superparamagnetic dot + TMR





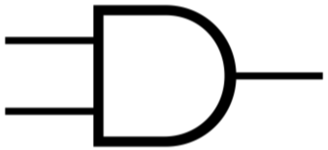
Neuromorphic computing – Stochastic computing

Superparamagnetic tunnel junction
+ precharge-sense amplifiers
→ stochastic bitstreams

$p = 0.2$

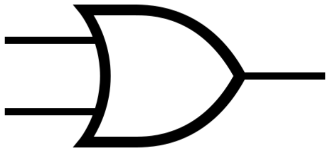
observed = 0.19

AND gates – multiplication of bitstreams
→ synaptic weights



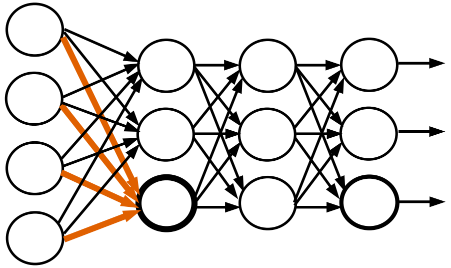
  1001010100 (0.5)
x 1010001110 (0.4)
= 1000000100 (0.2)

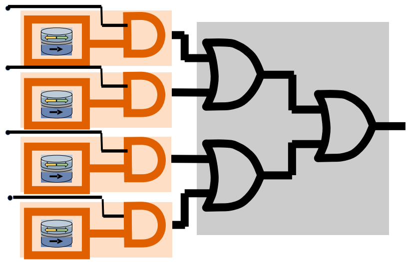
OR gates – non-linear summation
→ neuron activation



  1001010100 (0.4)
+ 1010001110 (0.5)
= 1011011110 (0.7)

Implement deep neural network with all information encoded in stochastic bitstreams



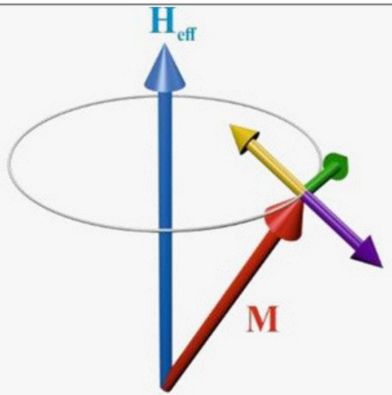


Short-distance low-power wireless communication

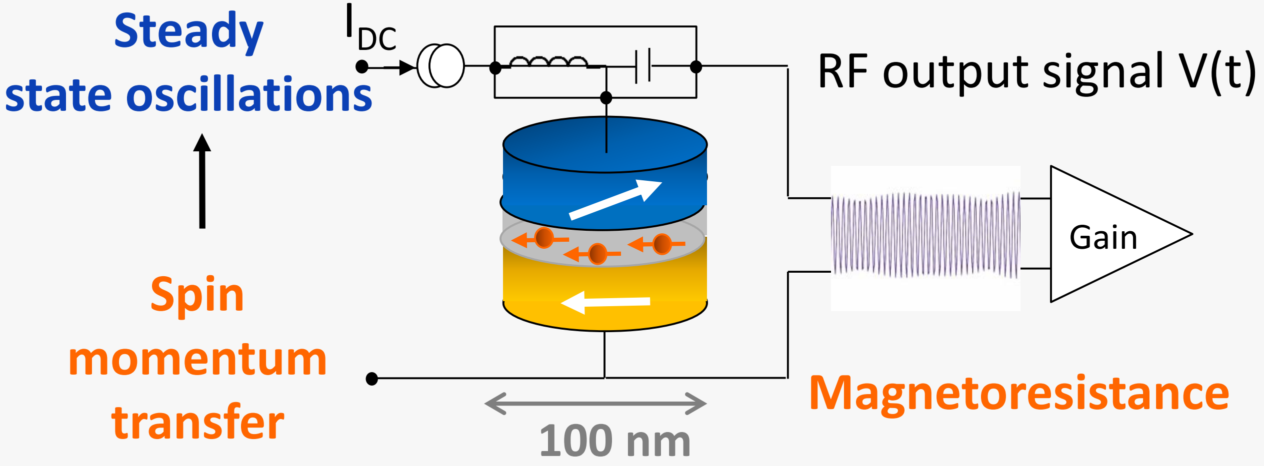
Current-driven precession of magnetization

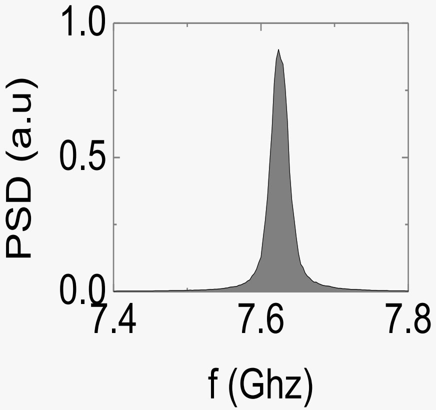
$$\frac{d\mathbf{m}}{dt} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{d\mathbf{m}}{dt} + |\gamma_0|a_j\mathbf{m}\times(\mathbf{m}\times\mathbf{P}) + b_j\mathbf{m}\times\mathbf{P}$$

Damping-like Field-like



Implementation in spin-torque nano-oscillators (STNO)

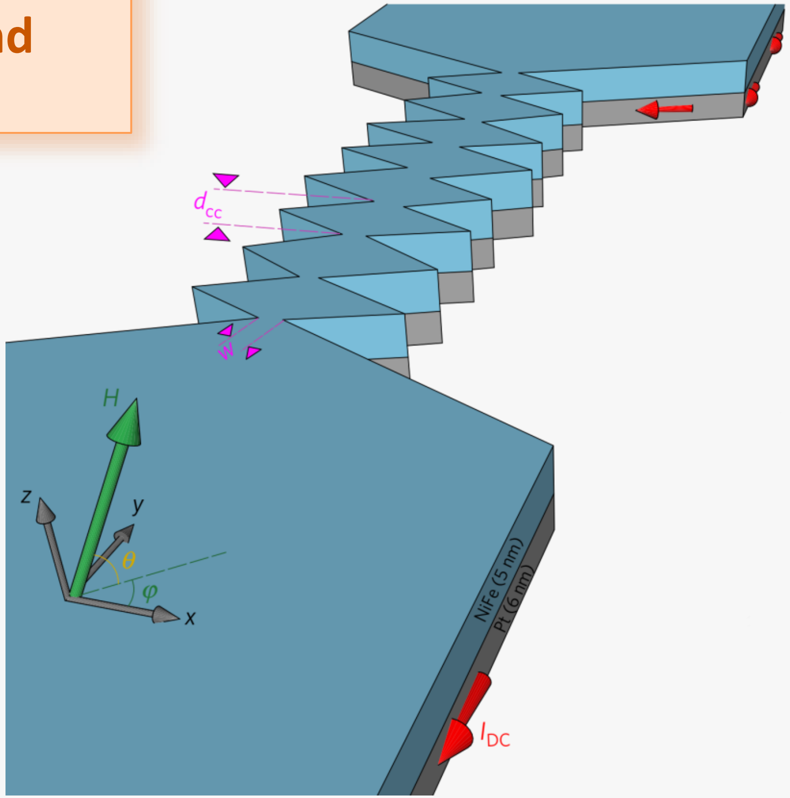




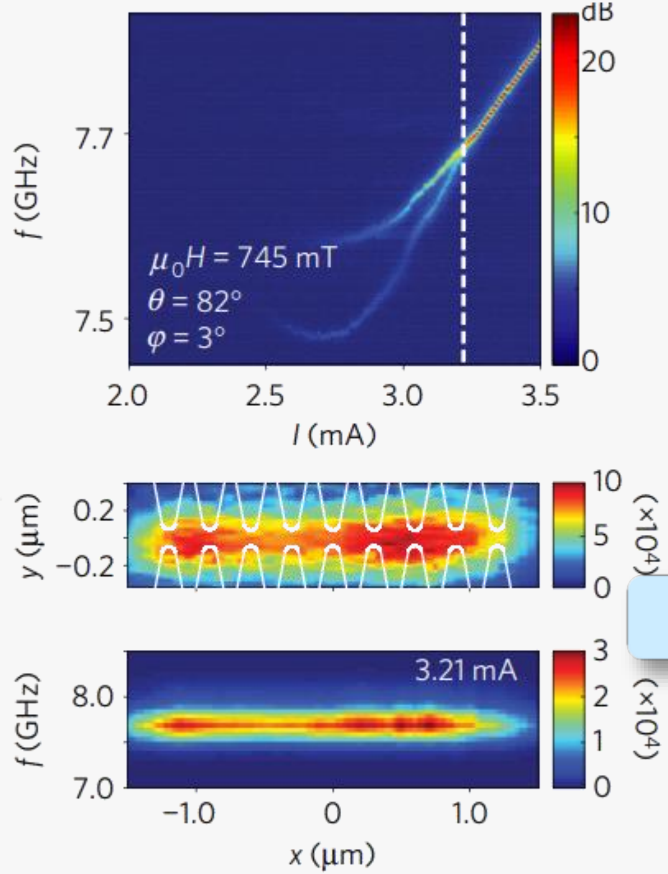
Short-distance low-power wireless communication

Challenge: increase power, increase frequency and phase coherence

Mutual synchronization



Spin-Hall Nano-Oscillator (SHNO)

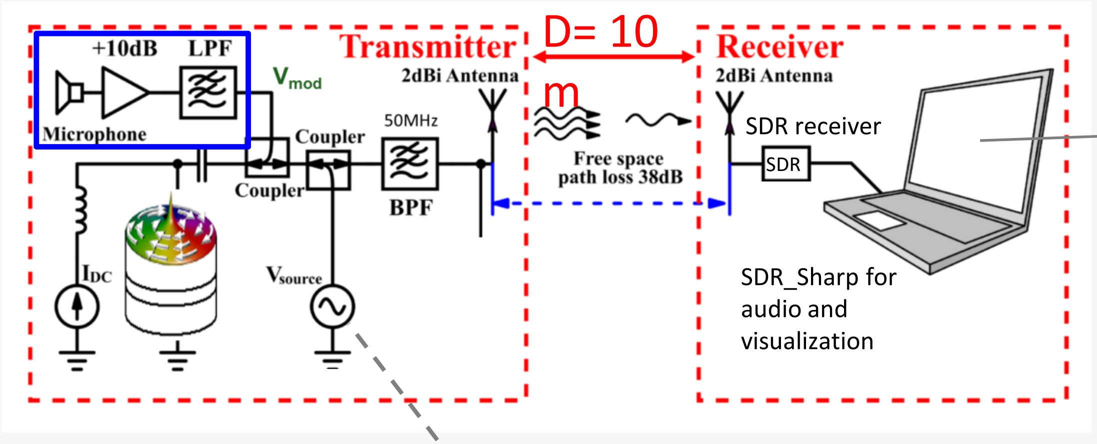


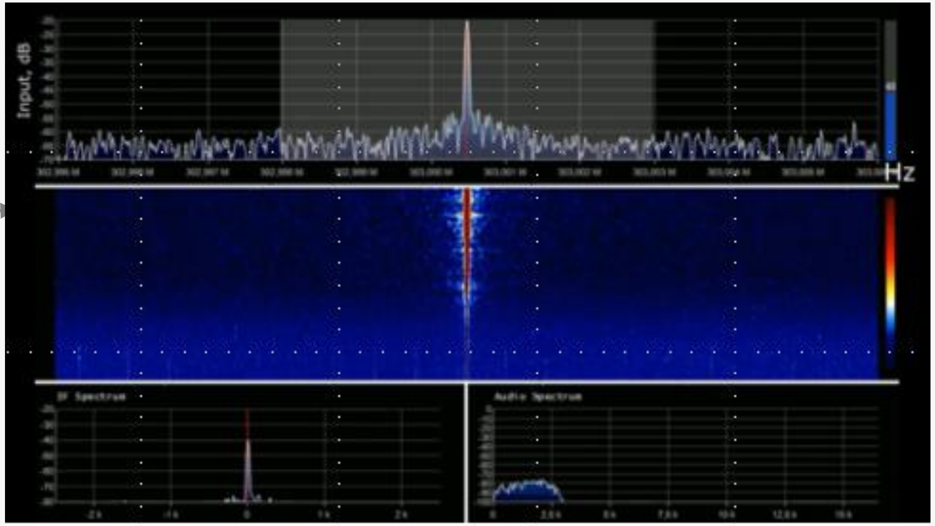
µ-BLS

A. A. Awad, Nat. Phys. 13, 292 (2016)

Short-distance low-power wireless communication

Phase modulation





$P_{STNO} = 0.25 \mu W$ << 1mW

Commercial Signal Generator

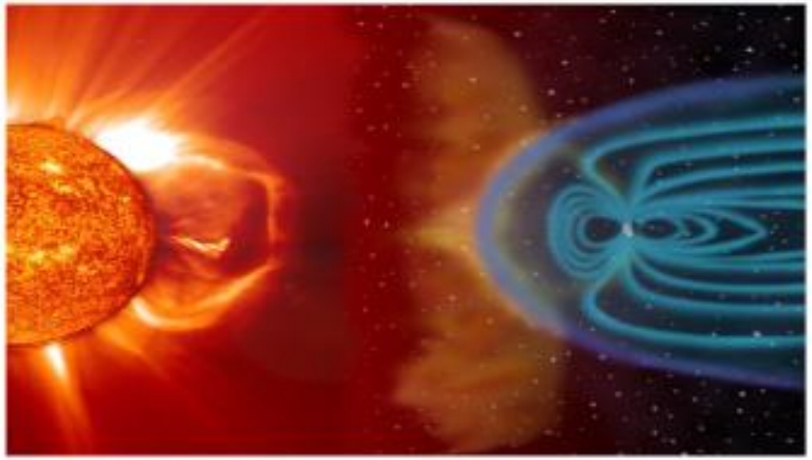
A. Litvinenko arxiv:1905.02443

Other device opportunities

- Fast spectrum analyzer
- Wake-up receivers

Radiaiton hardness

Space applications



- Solar particles
- Cosmic rays

Nuclear industry

- Accidents
- Decommissioning

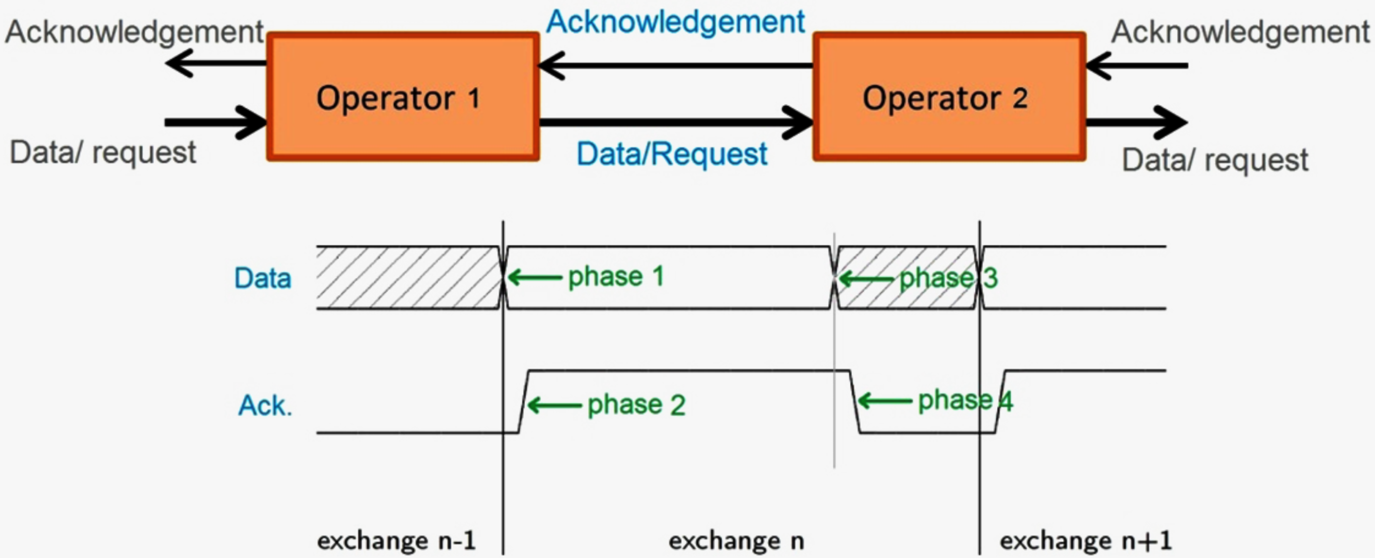
Consequences of radiation

- SSE: Single-Event Effects (digital damage)
- TID: Total Ionizing Dose

Radiation hardness

MRAM and asynchronous communication

- Combine DRAM and MRAM
- In case of SEE, refresh DRAM with MRAM content
- Redundancy reduced, cost lowered



Many thanks for a few slides borrowed from…

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