Micromagnetics

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Outline

Stoner

Wohlfarth

Brown

Why micromagnetics ?

Magnetic recording

Strong magnets

What is micromgnetics ?

Energy contribution

Magnetization dynamics

How does it work ?

Finite element method

Can I do it myself ?

Examples

Why do we need micromagnetics ?

An introduction

Permanent magnets

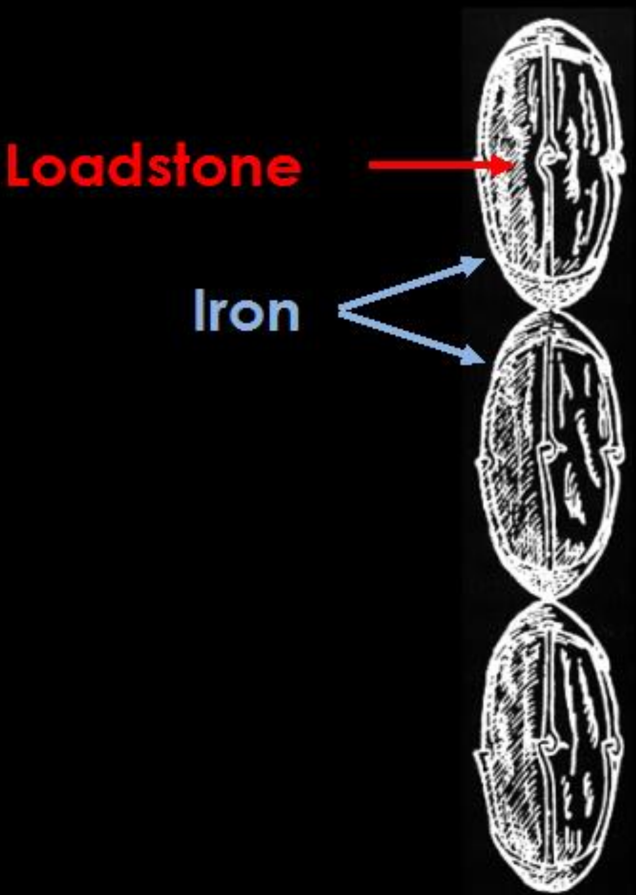

700 kg of NdFeB per MW

1.5 kg NdFeB

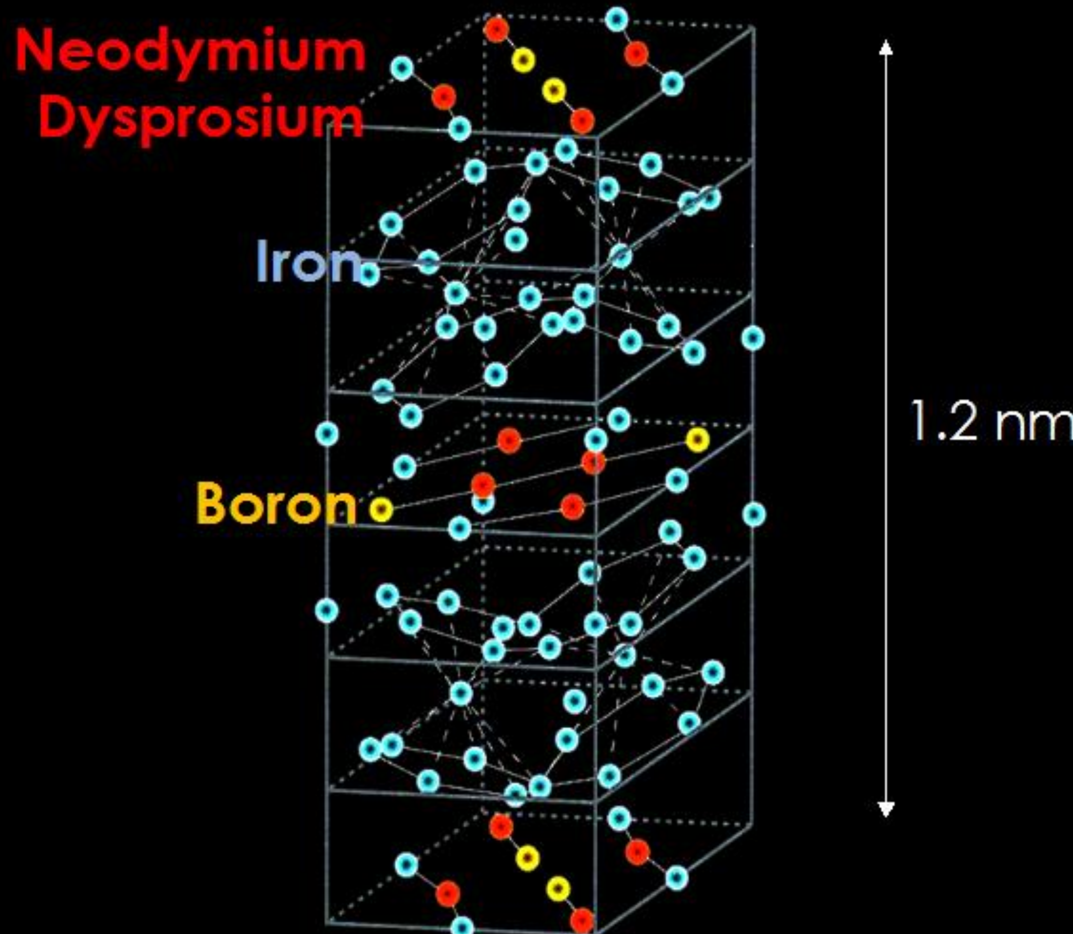
Ancient magnets (1600)

Armed loadstone

Modern magnets (1984)

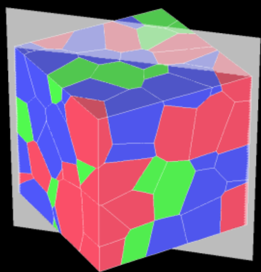


Gilbert's „capped“ loadstone

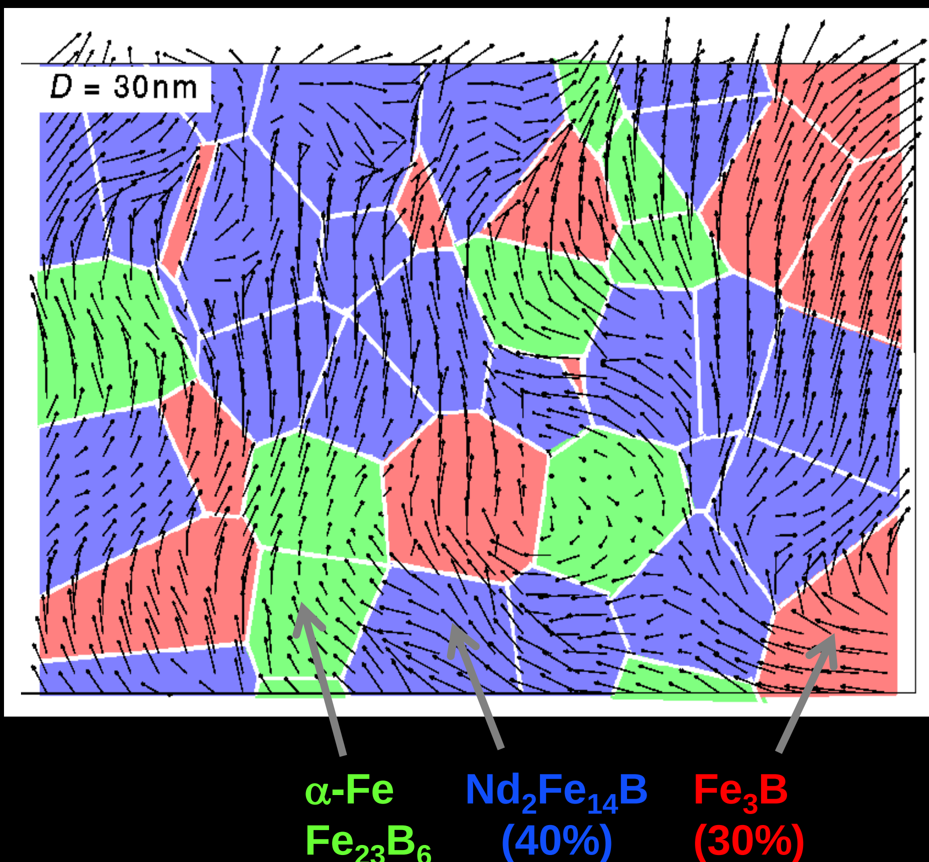


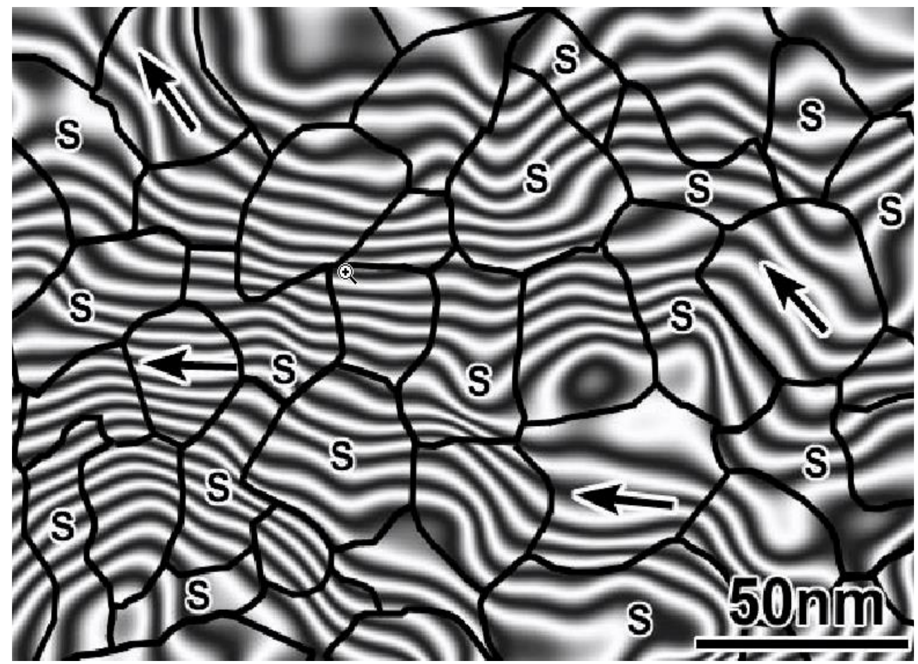
$Nd_2Fe_{14}B$ crystal

Interactions



Electron holography TEM study
Reconstructed phase image
of magnetization structure



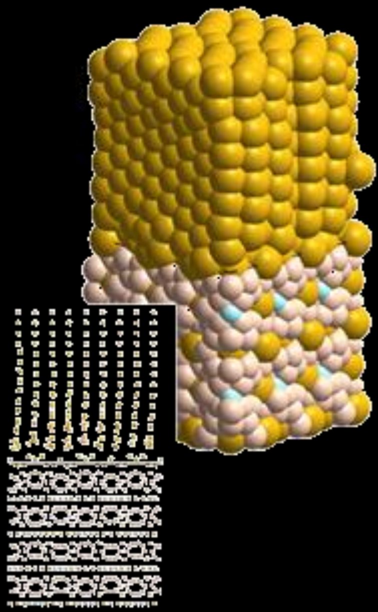


D Shindo et al.YG Park,
ICEM15, Sept. 2002, Durban

Multiscale simulation

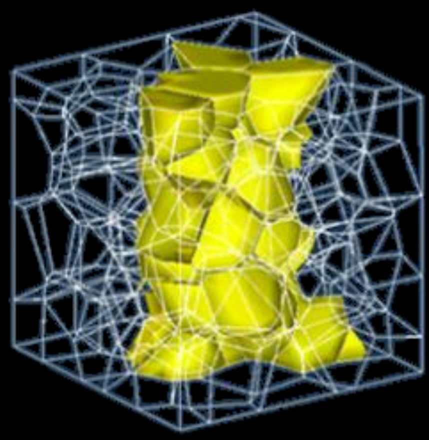
10^{-10} m

Arrangement of atoms



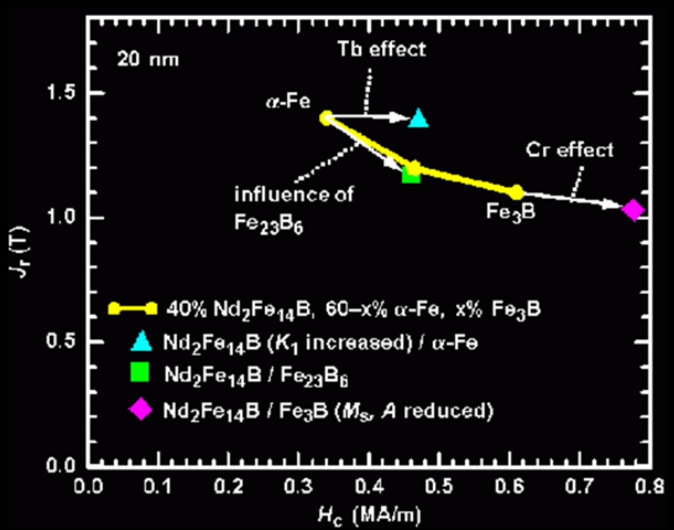
10^{-6} m

Magnetic domains

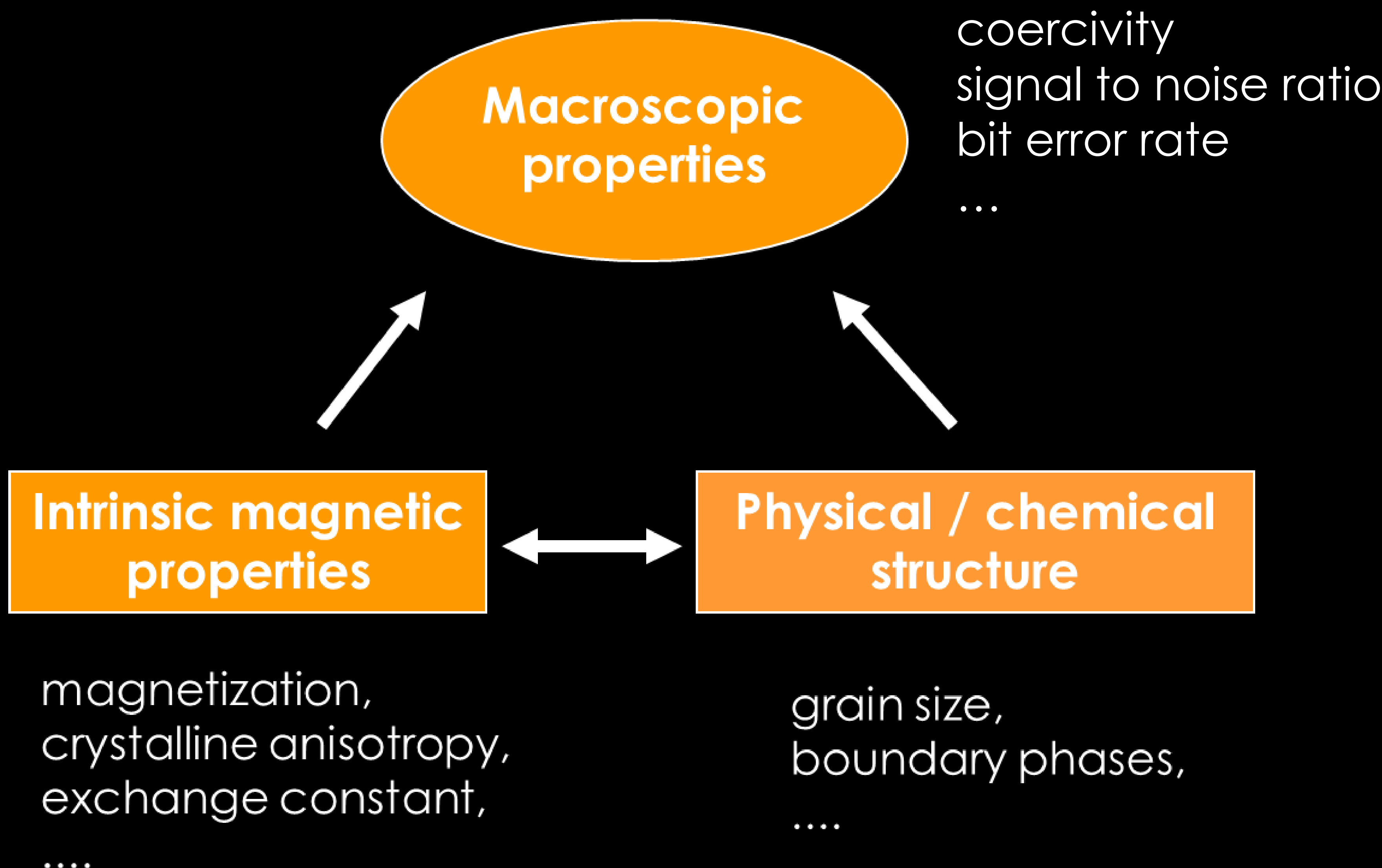


10^{-2} m

Properties as function of chemical composition



→ Design guidelines for magnet development


Macroscopic properties
coercivity
signal to noise ratio
bit error rate
...
Intrinsic magnetic properties
Physical / chemical structure
magnetization,
crystalline anisotropy,
exchange constant,
....
grain size,
boundary phases,
....

Magnetic recording

1956

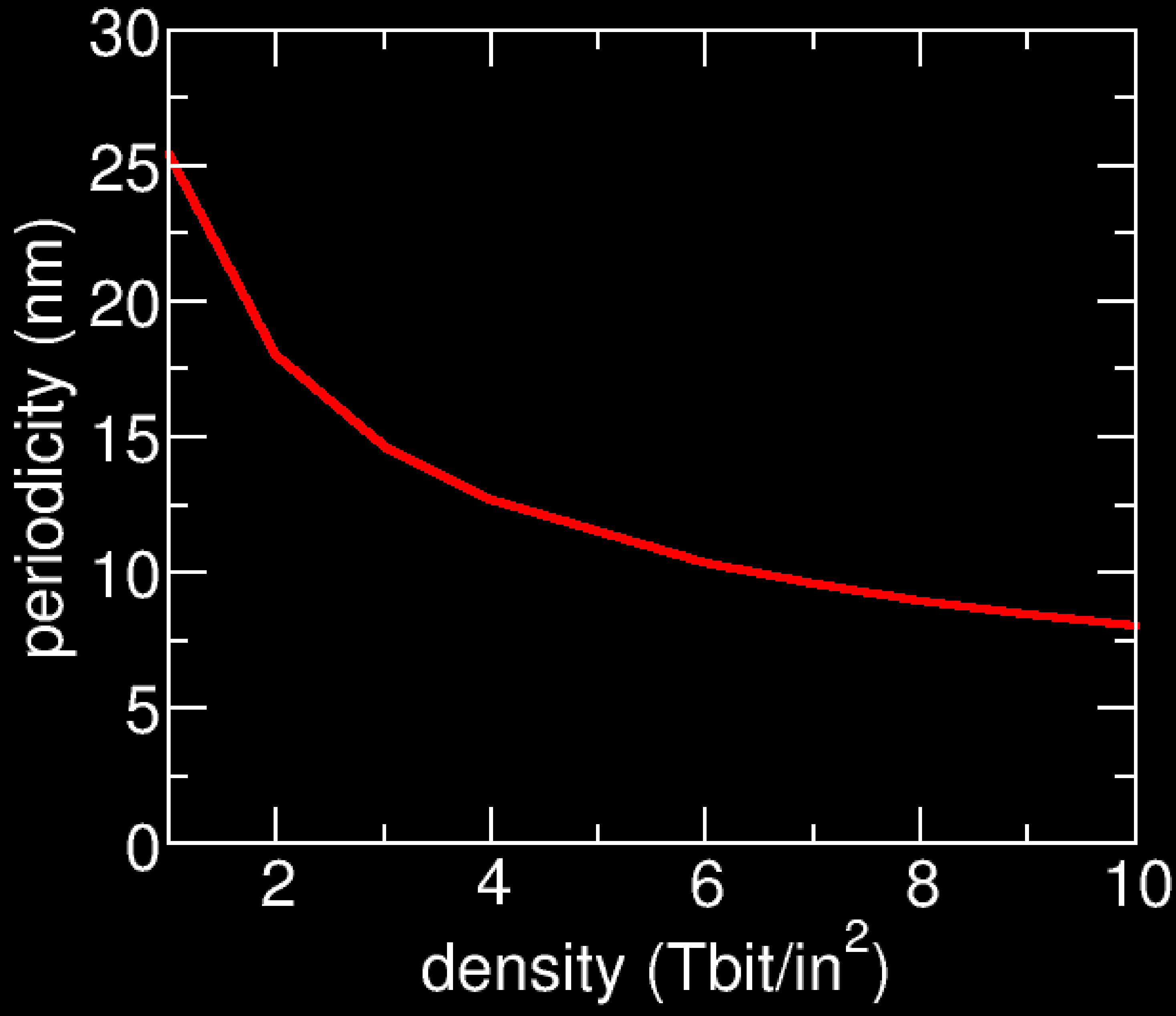
5 MB
971 kg

www.hgst.com

2006

8 GB
13 grams

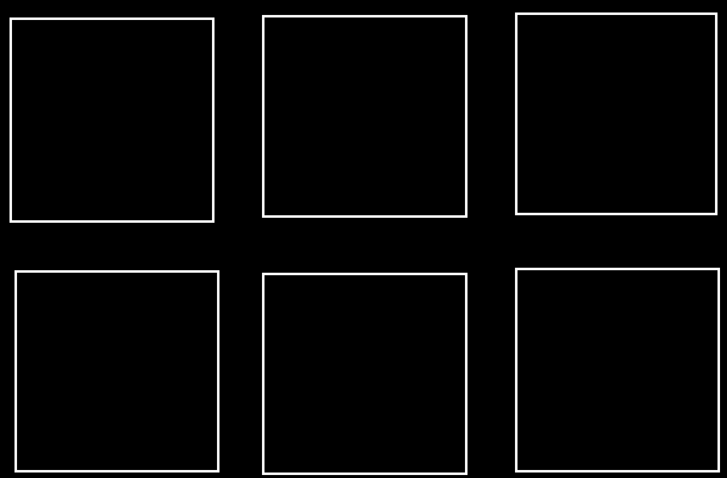
Magnetic media account for 92 % of newly stored information



30
25
20
15
10
5
0
periodicity (nm)
2
4
6
8
10
density (Tbit/in2)

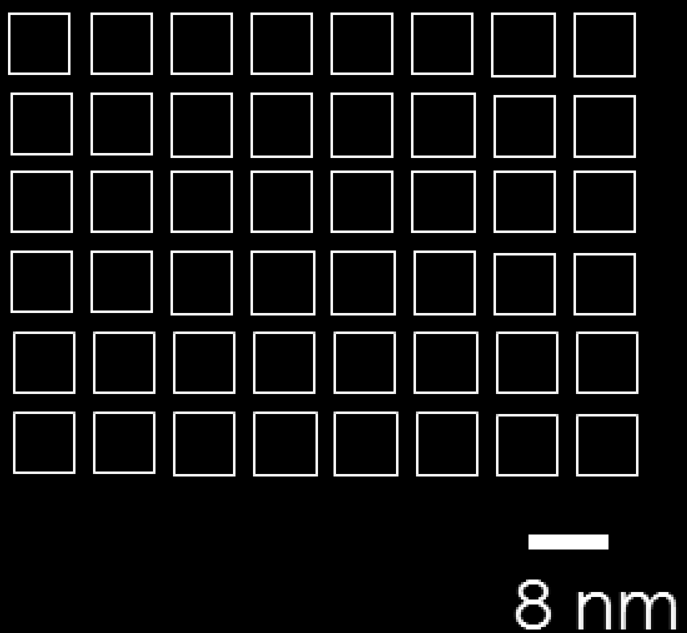
1 Tbit/in²

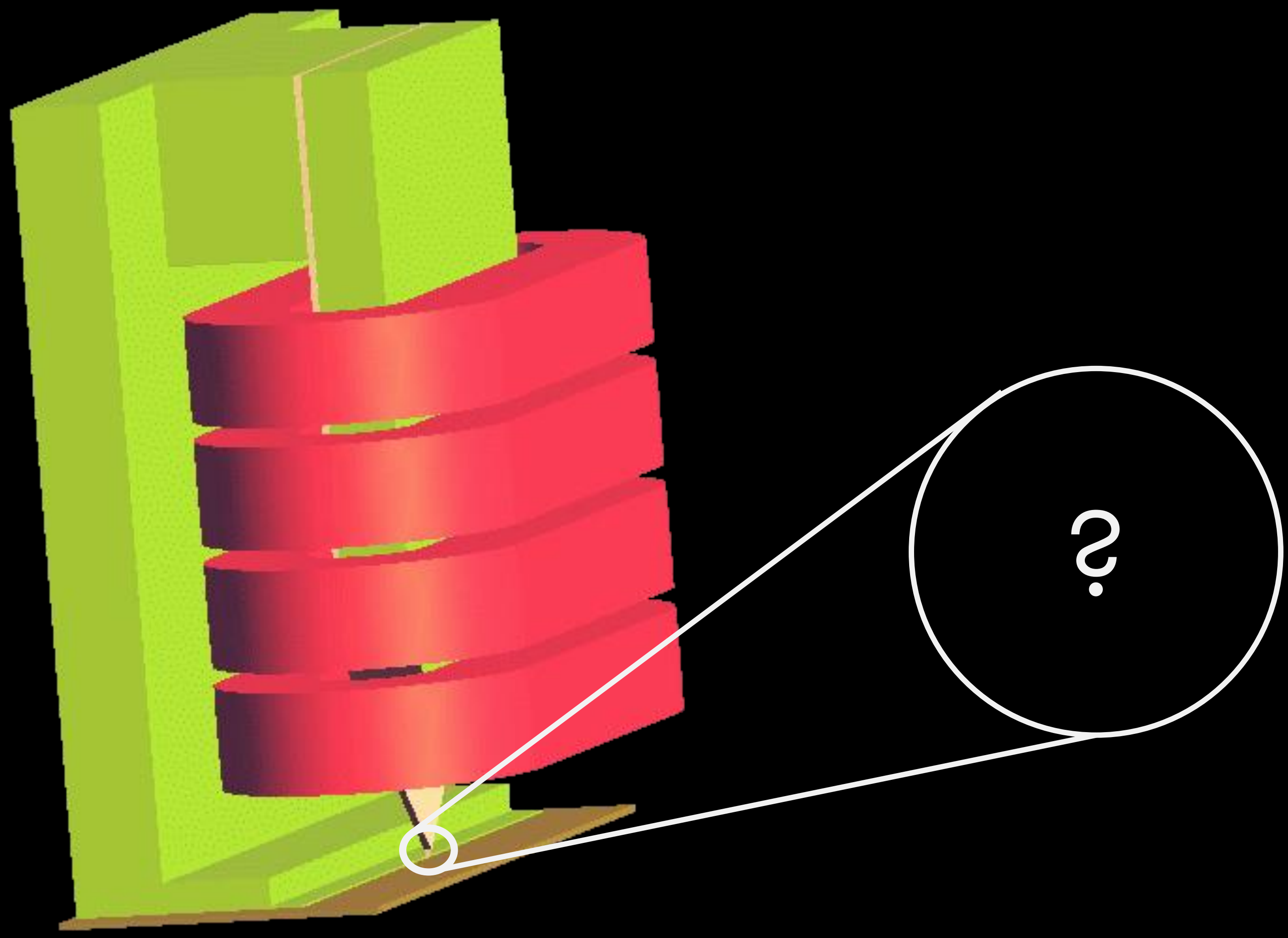
25 nm periodicity
20 nm islands

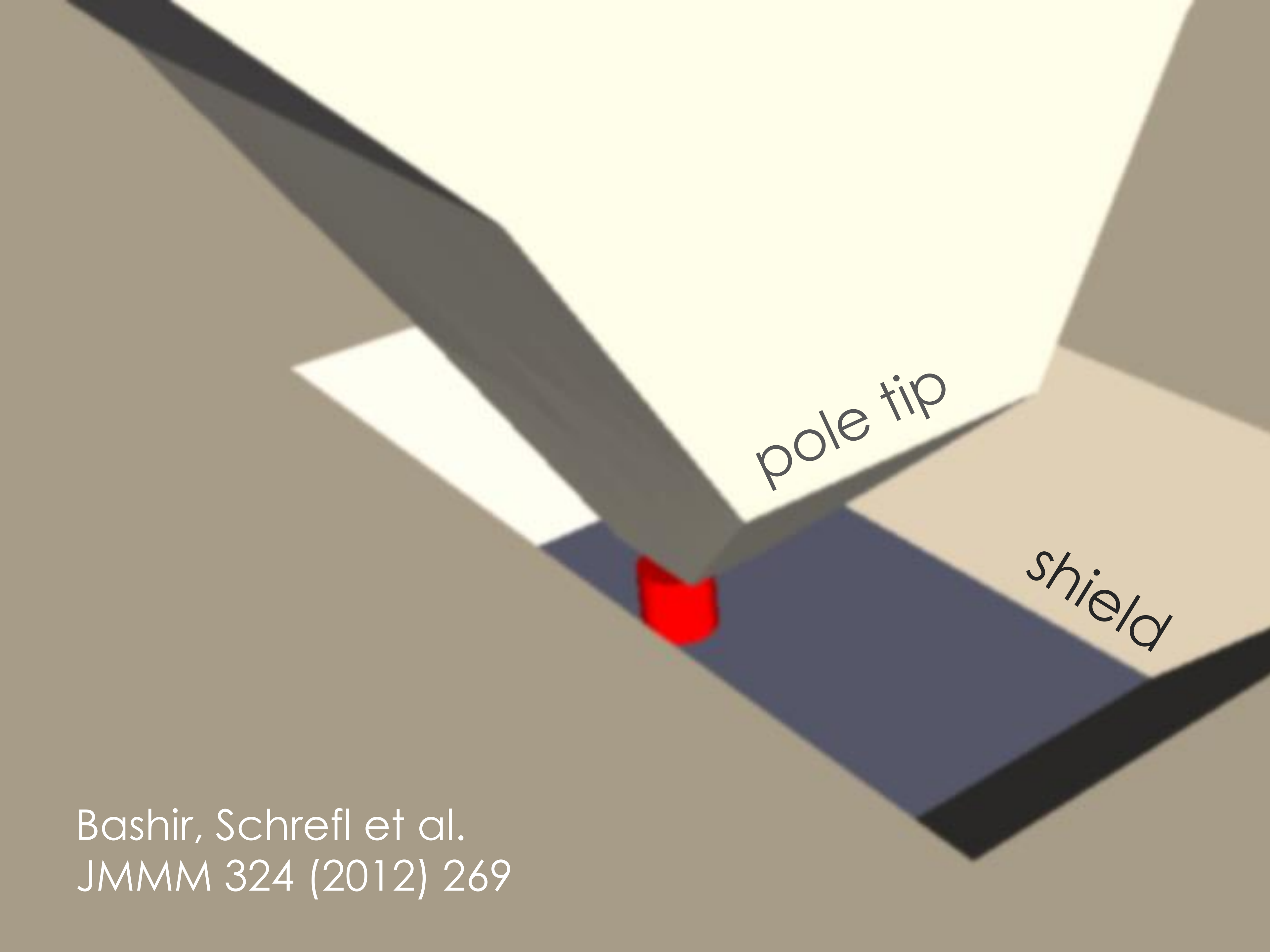


10 Tbit/in²

8 nm periodicity
6 nm islands







Bashir, Schrefl et al.
JMMM 324 (2012) 269

EC Stoner

EP Wohlfarth

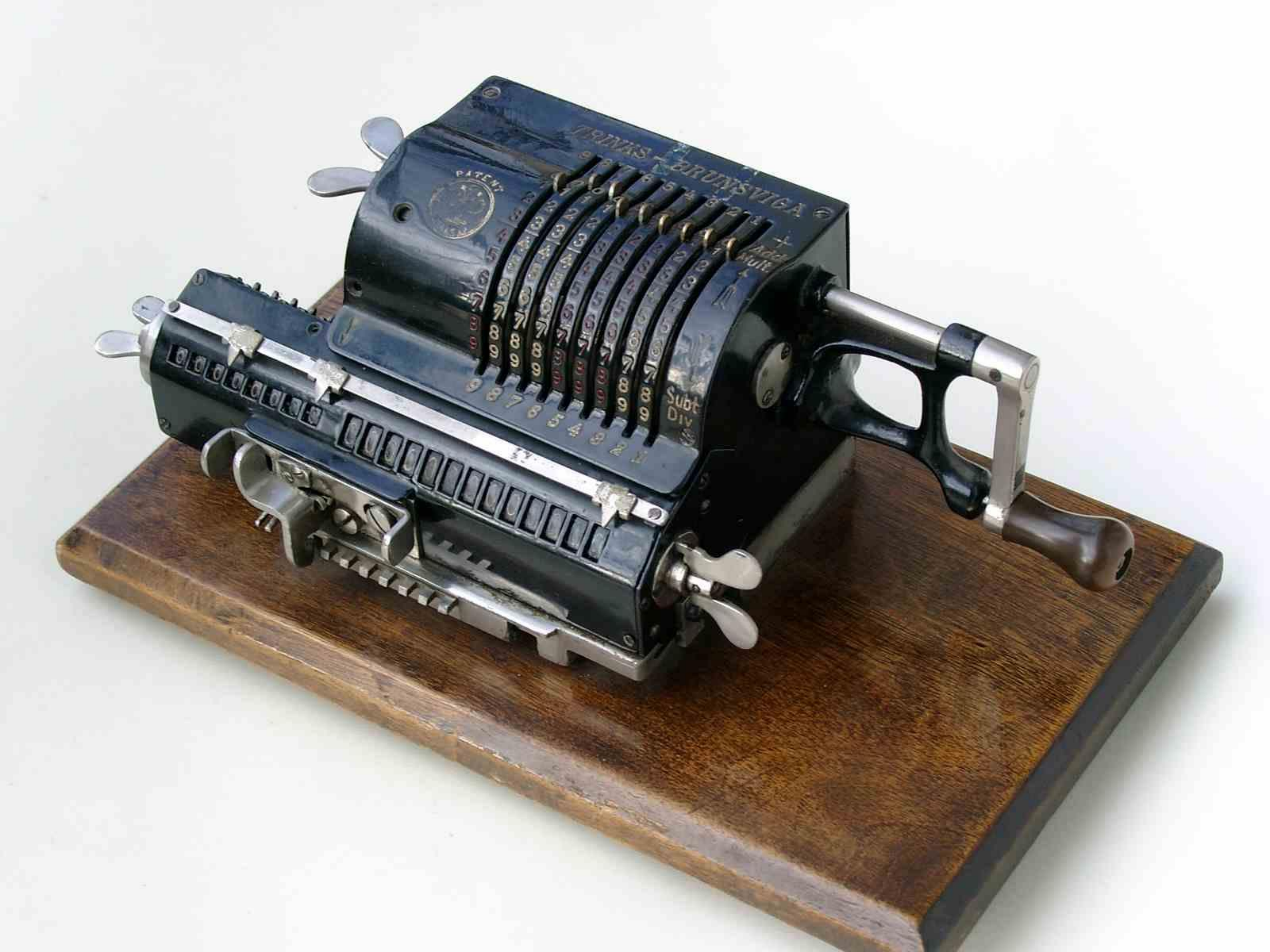
A MECHANISM OF MAGNETIC HYSTERESIS IN HETEROGENEOUS ALLOYS

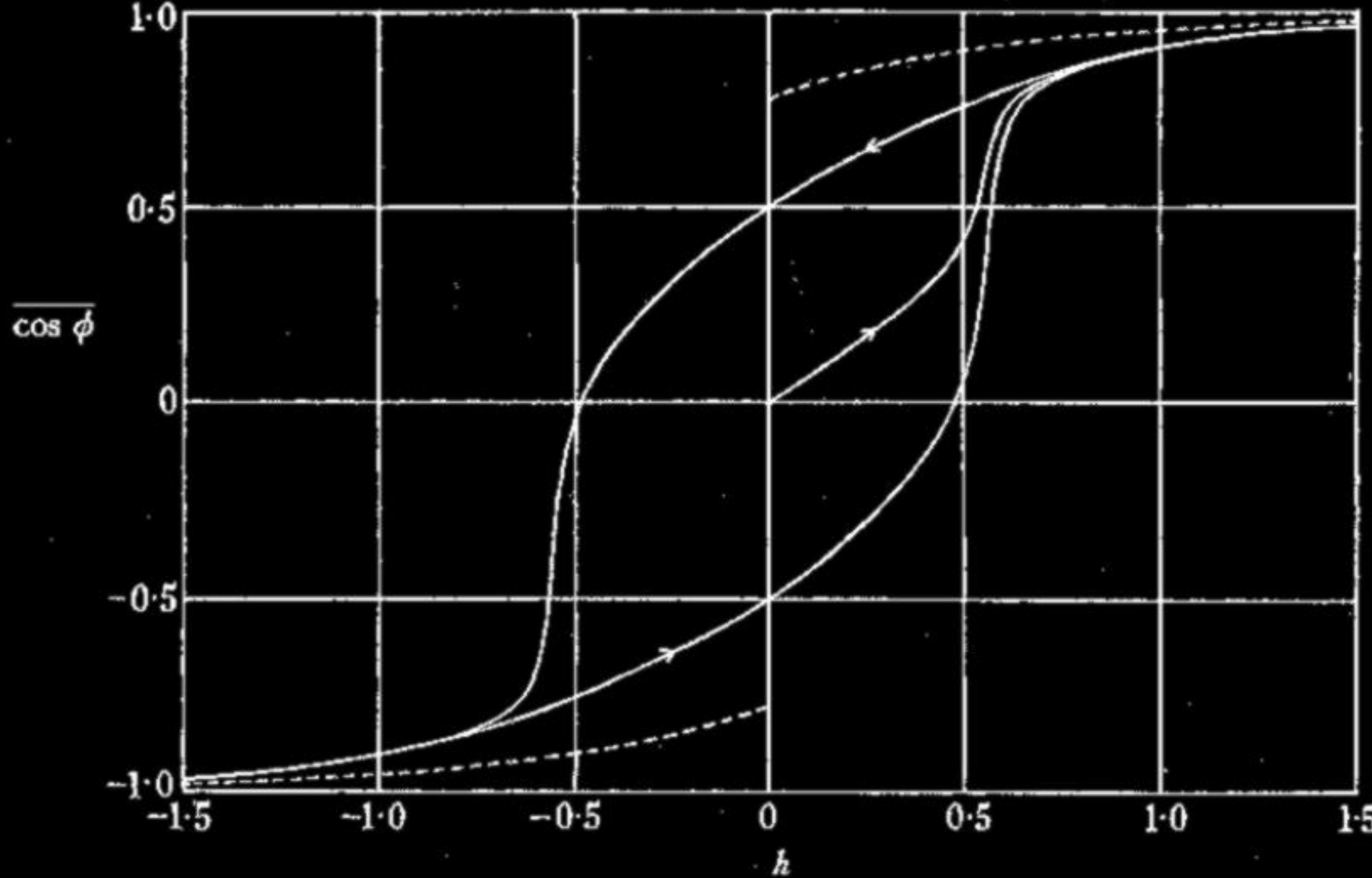
By E. C. STONER, F.R.S. and E. P. WOHLFARTH

Physics Department, University of Leeds

(*Received 24 July 1947*)

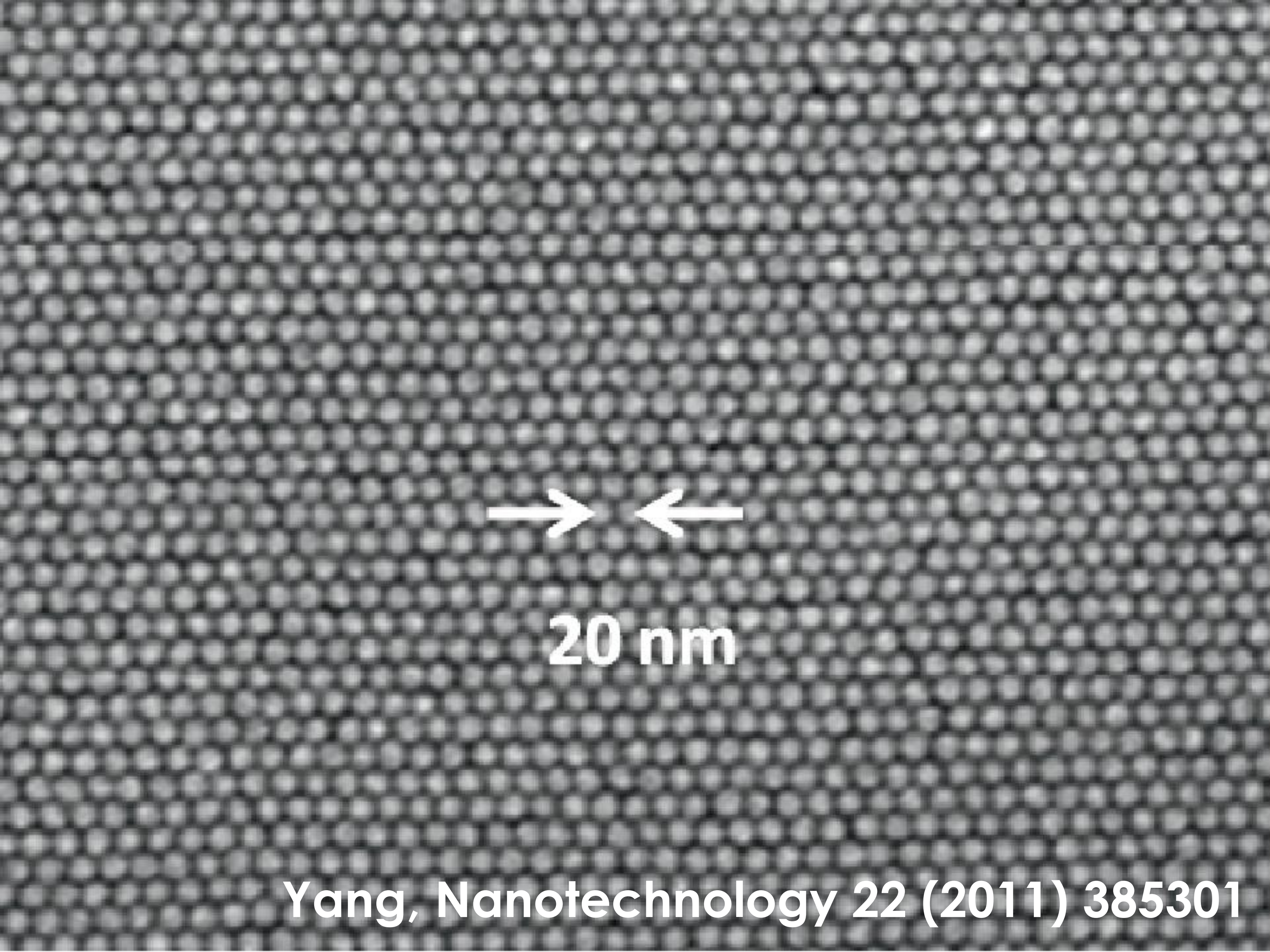
Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, Vol. 240, No. 826. (May 4, 1948), pp. 599-642.


TRINKS-BRUNSVIGA
PATENT
Add
Mult
Subt
Div



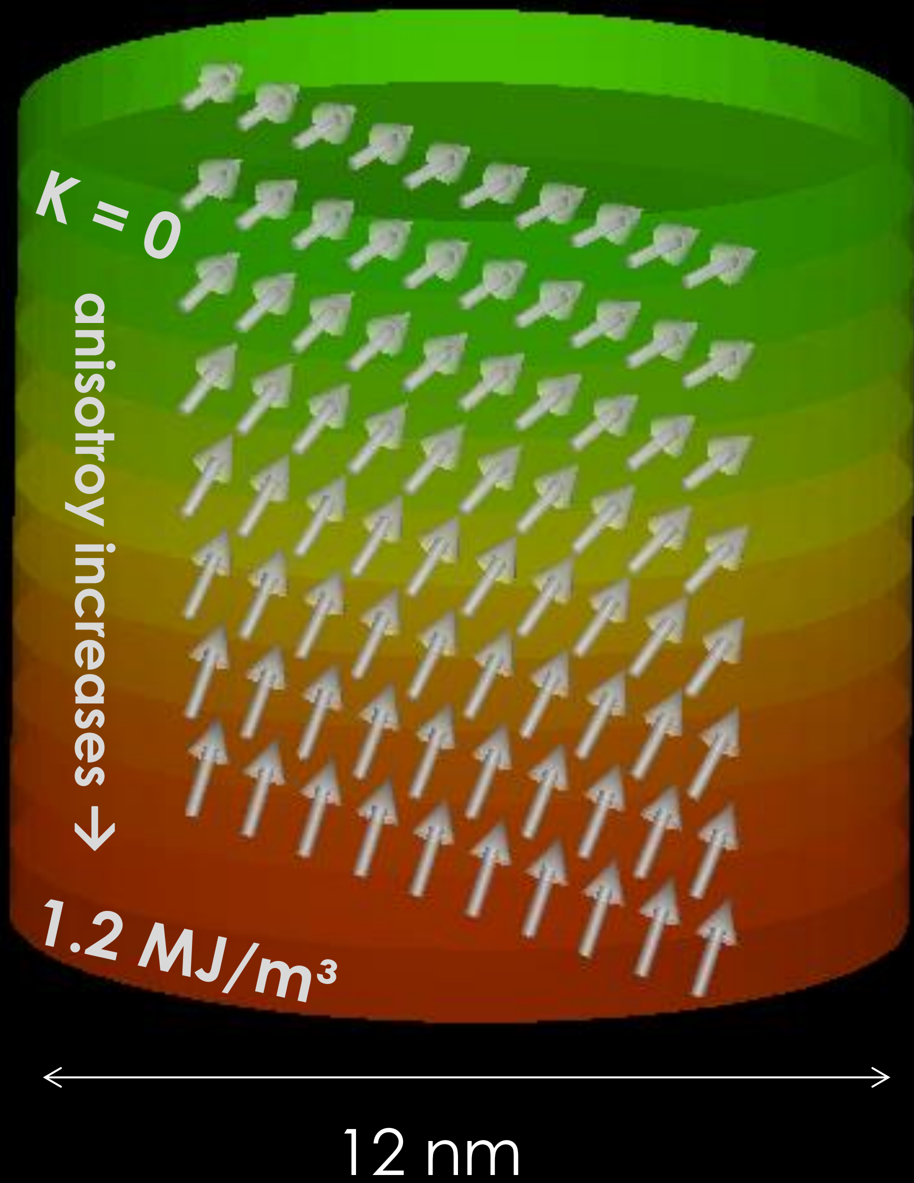
1·0
0·5
0
−0·5
−1·0
$\overline{\cos\phi}$
−1·5
−1·0
−0·5
0
0·5
1·0
1·5
h

The size must be below
a critical value,
depending on shape,
such that the particle
constitutes a single domain, in which
boundary formation is precluded.



Yang, Nanotechnology 22 (2011) 385301

exchange spring



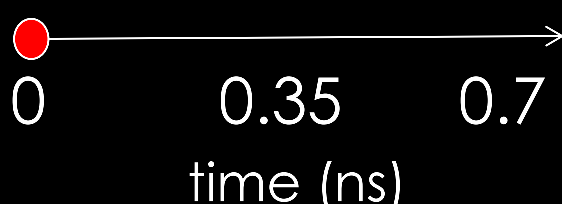
At this value, namely

$$H_0 = \tfrac{1}{2}(d\gamma/dx)_{\text{max.}}/I_0,$$

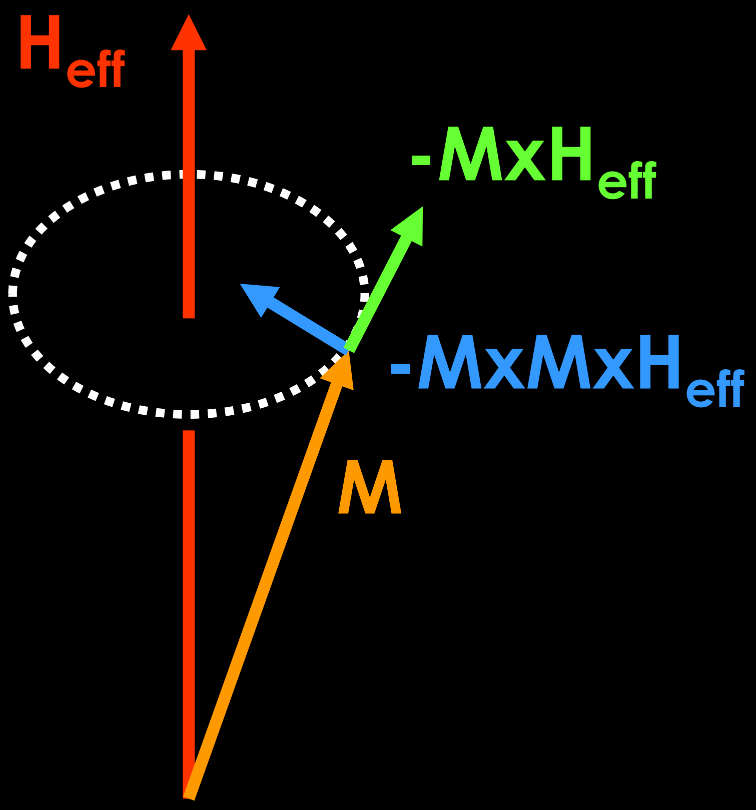
the boundary will move spontaneously

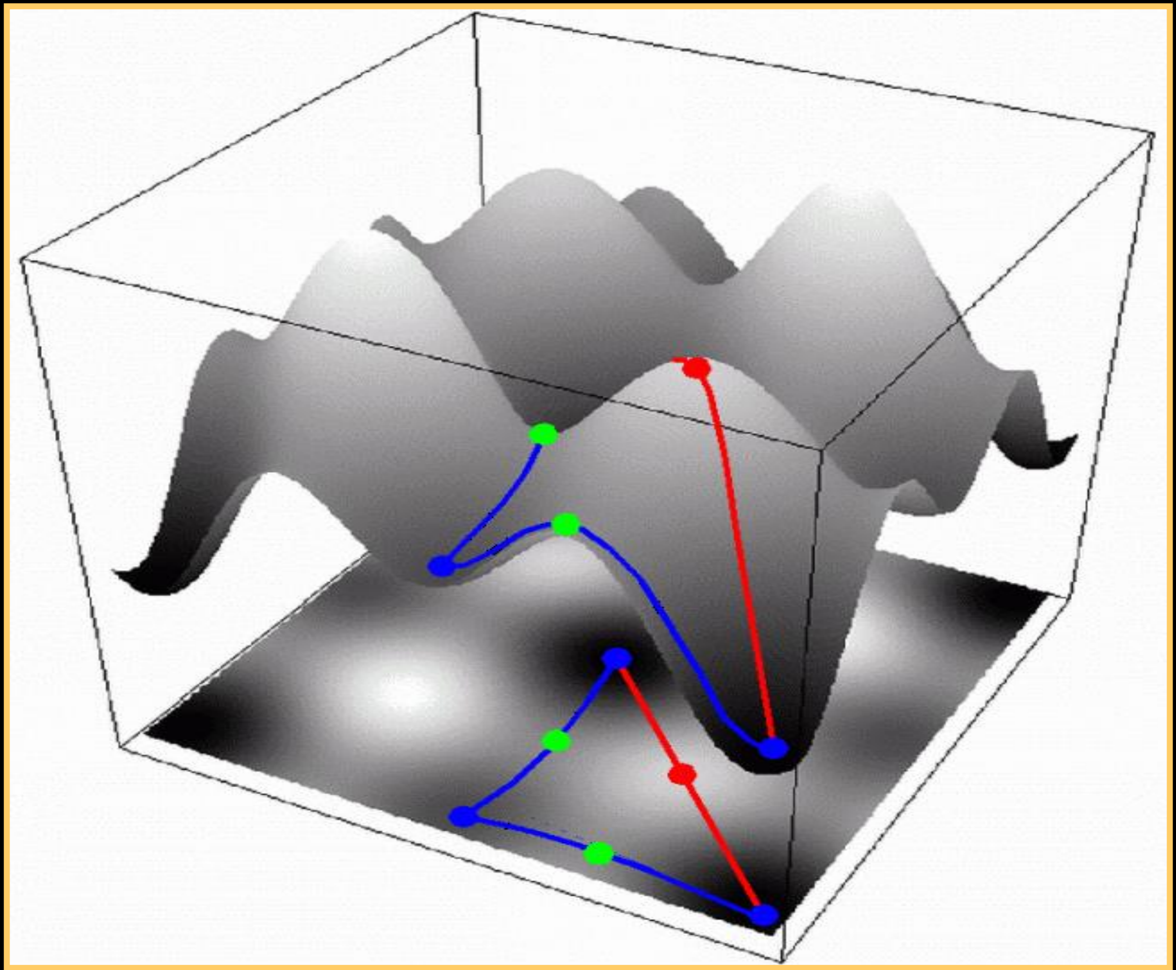
EC Stoner, EP Wohlfarth,
Phil. Trans. Roy. Soc. A240 (1948) 599

switching in the write field



$$\frac{1+\alpha^2}{|\gamma|}\frac{d\mathbf{M}}{dt} = -\mathbf{M}\times\mathbf{H}_{eff} - \frac{\alpha}{M_s}\mathbf{M}\times\mathbf{M}\times\mathbf{H}_{eff}$$





elastic band method

- saddle points

Dittrich et al, JMMM 250 (2002) 12
Henkelman et al, J Chem Phys113 (2000) 22

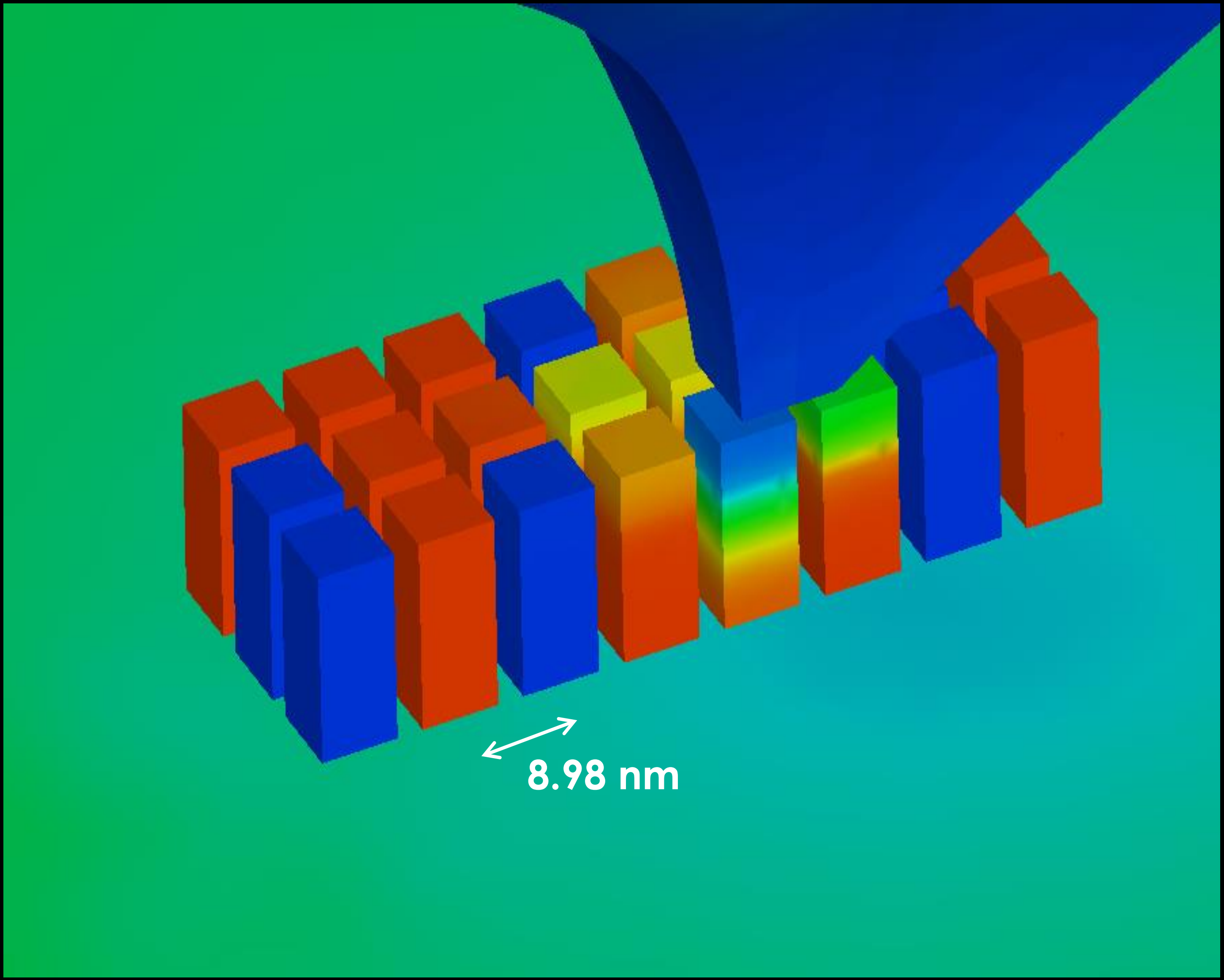
thermal switching

energy barrier: 128 $k_B T$

pol tip
antiferro-
magnetically
coupled

bit
patterned
islands
soft/hard
magnetic

soft
under
layer



pol tip
antiferro-
magnetically
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soft/hard
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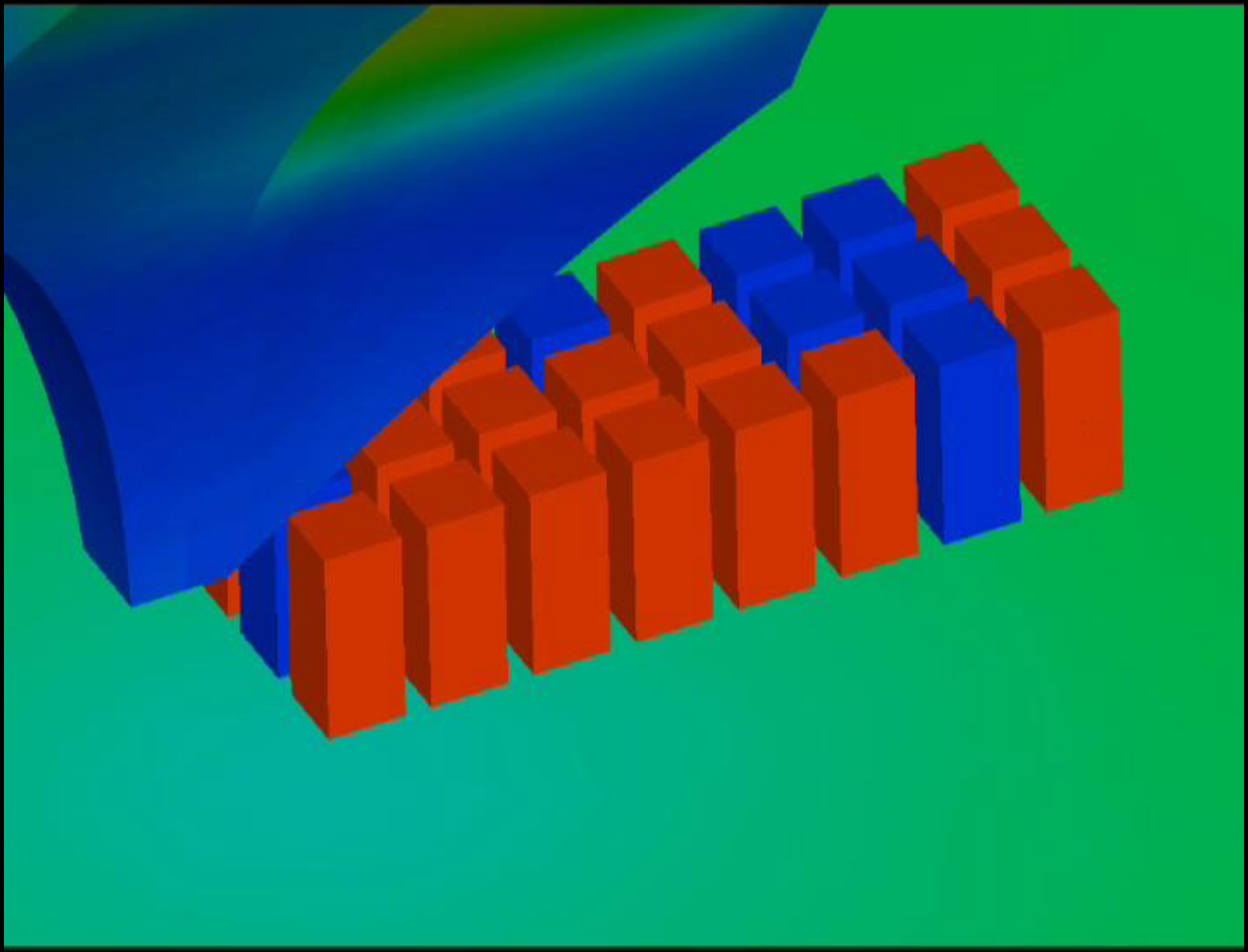
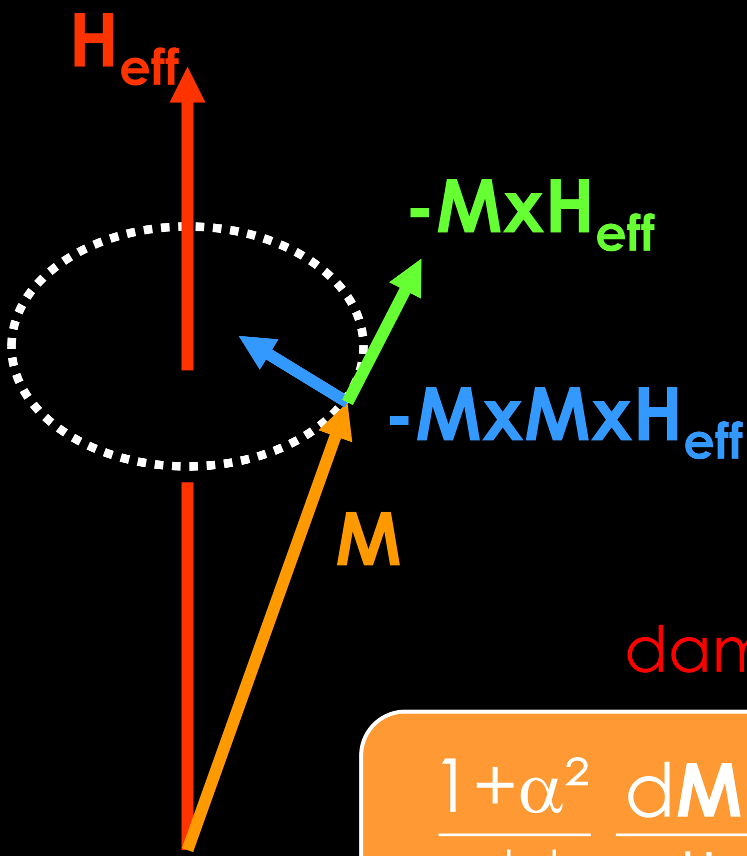
soft
under
layer



Magnetization Dynamics



Gyromagnetic precession

M rotates around $\mathbf{H}_{\mathrm{eff}}$

Dissipative term

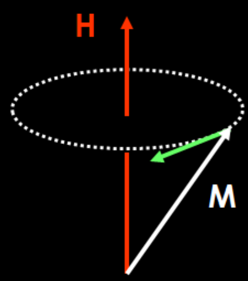
“force“ proportional to generalized velocity

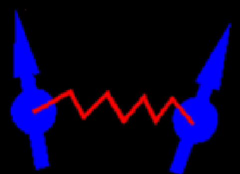
damping parameter

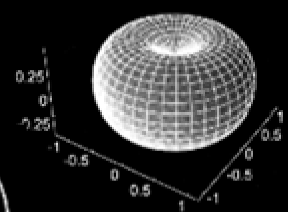
$$\frac{1+\alpha^2}{|\gamma|}\frac{d\mathbf{M}}{dt} = -\mathbf{M}\mathrm{x}\mathbf{H}_{\mathrm{eff}} - \frac{\alpha}{M_s}\mathbf{M}\mathrm{x}\mathbf{M}\mathrm{x}\mathbf{H}_{\mathrm{eff}}$$

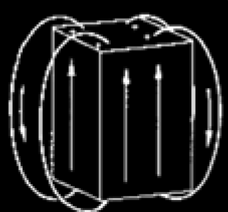
Micromagnetic basics

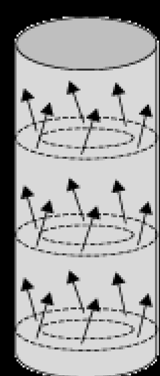
Micromagnetic basics











Torque
Forces on the magnetic moment

Energies
Micromagnetic energy contributions

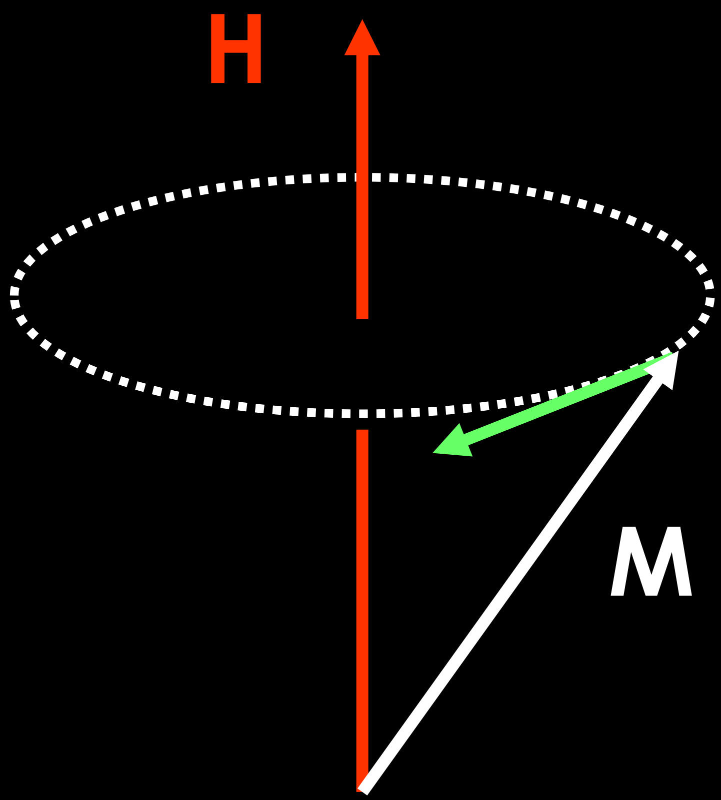
Deviation from equilibrium
Reversal modes

Micromagnetics, Domains, and Resonance

William Fuller Brown, Jr.
Department of Electrical Engineering, University of Minnesota, Minneapolis 14, Minnesota

JOURNAL OF APPLIED PHYSICS
SUPPLEMENT TO VOL. 30, NO. 4
APRIL, 1959

Search for equilibrium

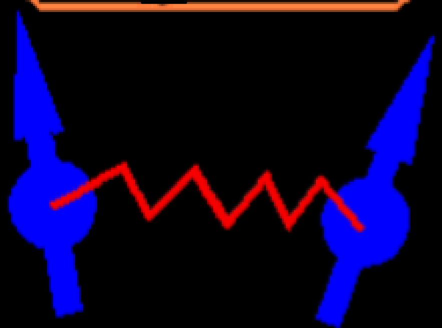


Torque $\mathbf{M} \times \mathbf{H}$

$|\mathbf{M}| = M_s$

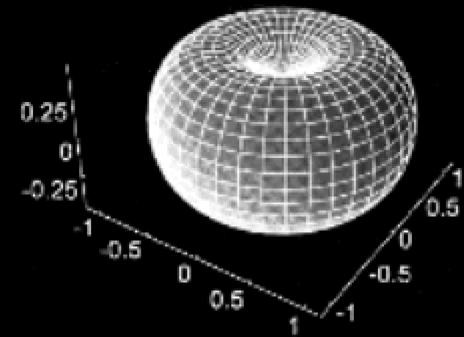
→ Magnetization can only rotate forces on **M** are torques

exchange



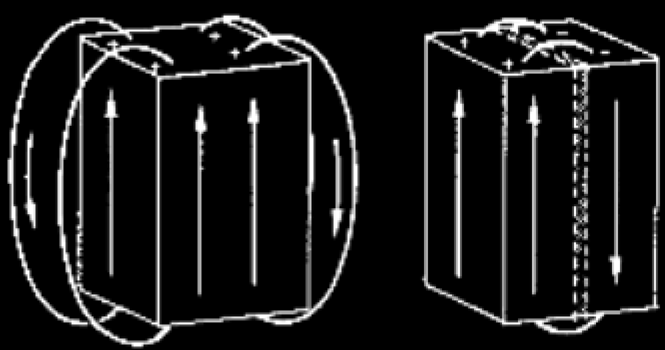
⇨ parallel spins

anisotropy



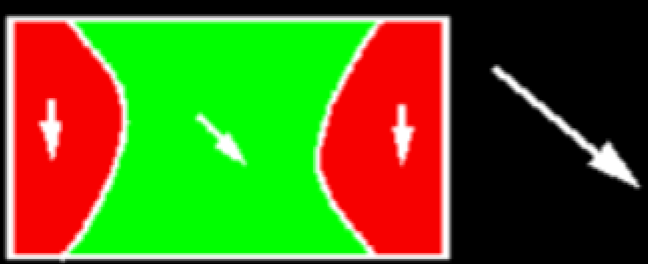
⇨ easy directions

magnetostatic



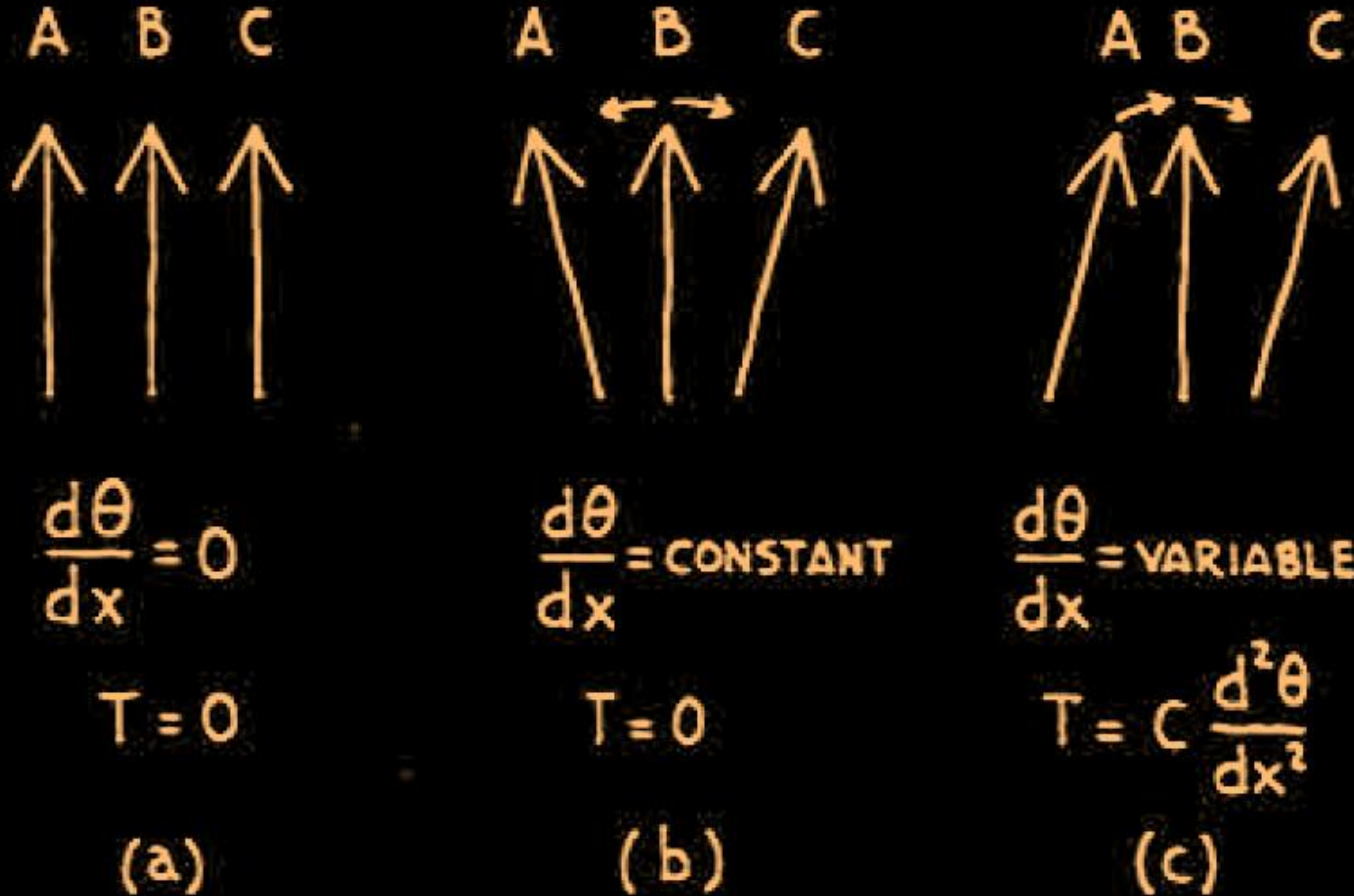
⇨ domains

external field



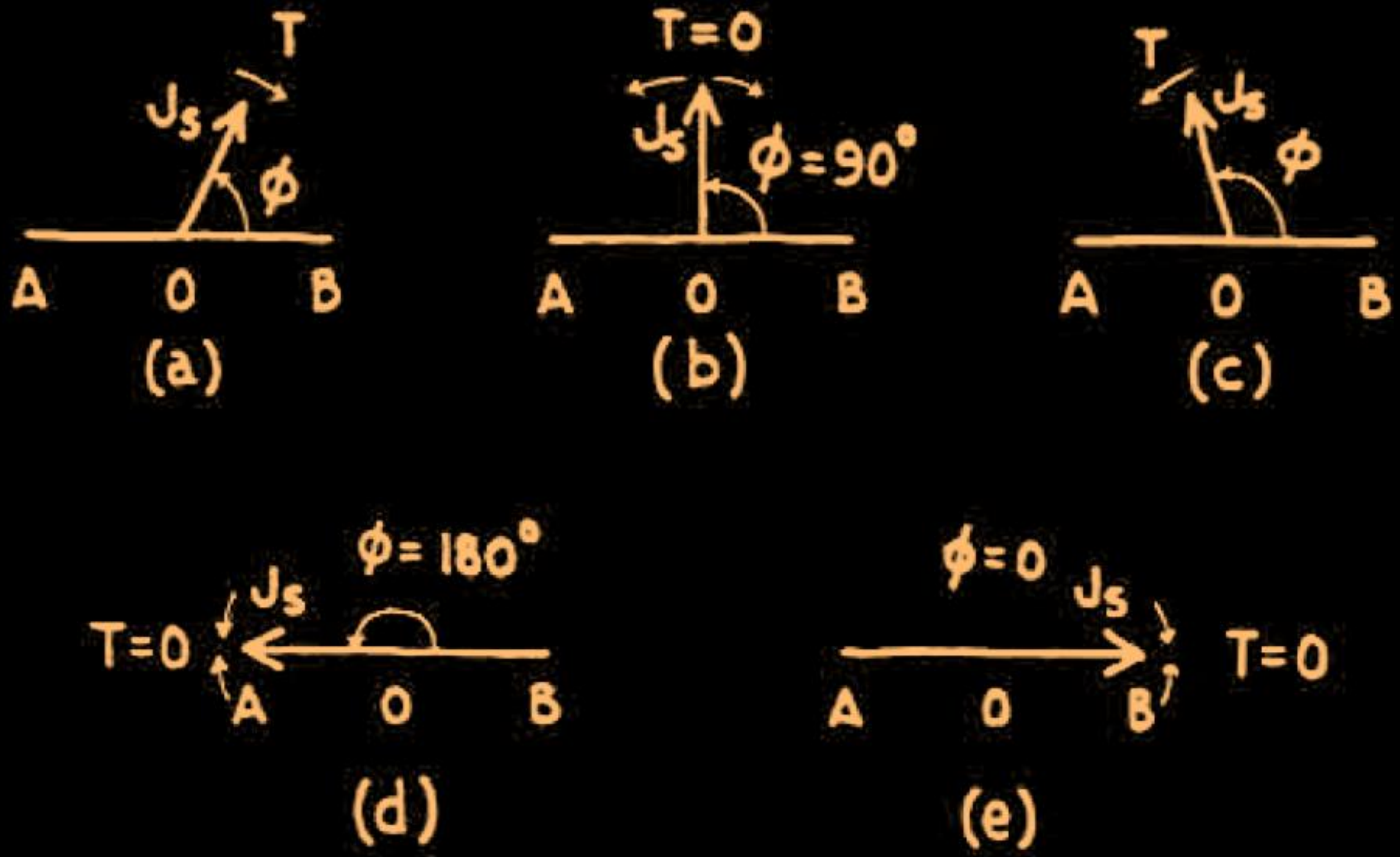
⇨ rotation

Exchange



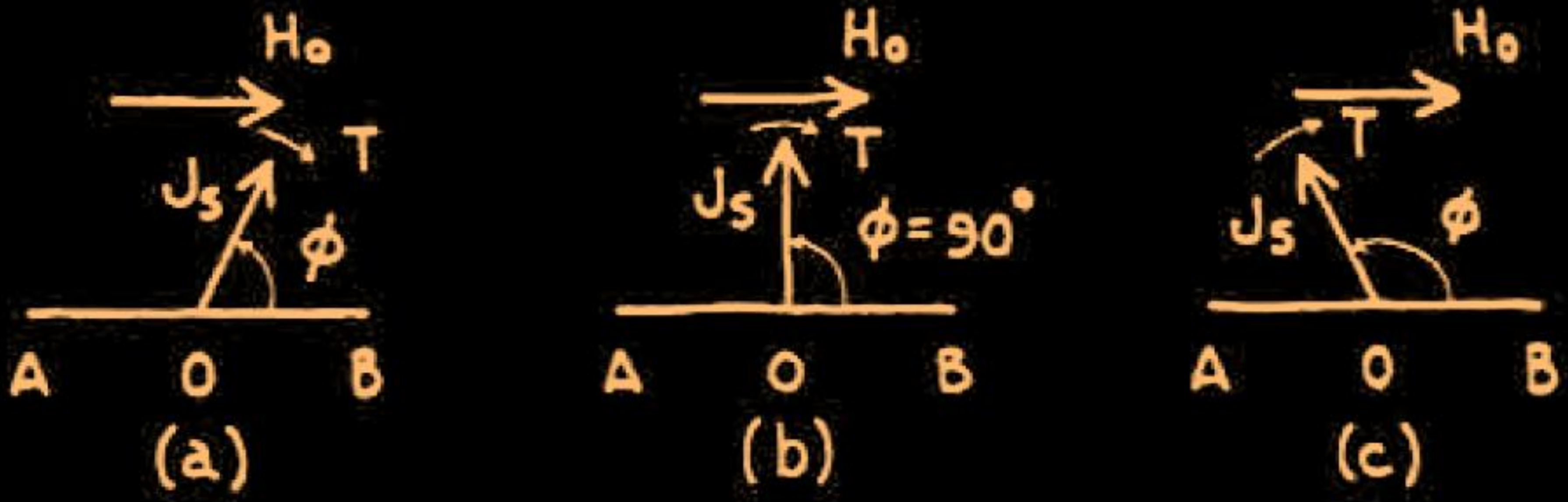
A B C
$\frac{d\theta}{dx} = 0$
T = 0
(a)
A B C
$\frac{d\theta}{dx}$ = CONSTANT
T = 0
(b)
A B C
$\frac{d\theta}{dx}$ = VARIABLE
$T = C\frac{d^2\theta}{dx^2}$
(c)

Anisotropy



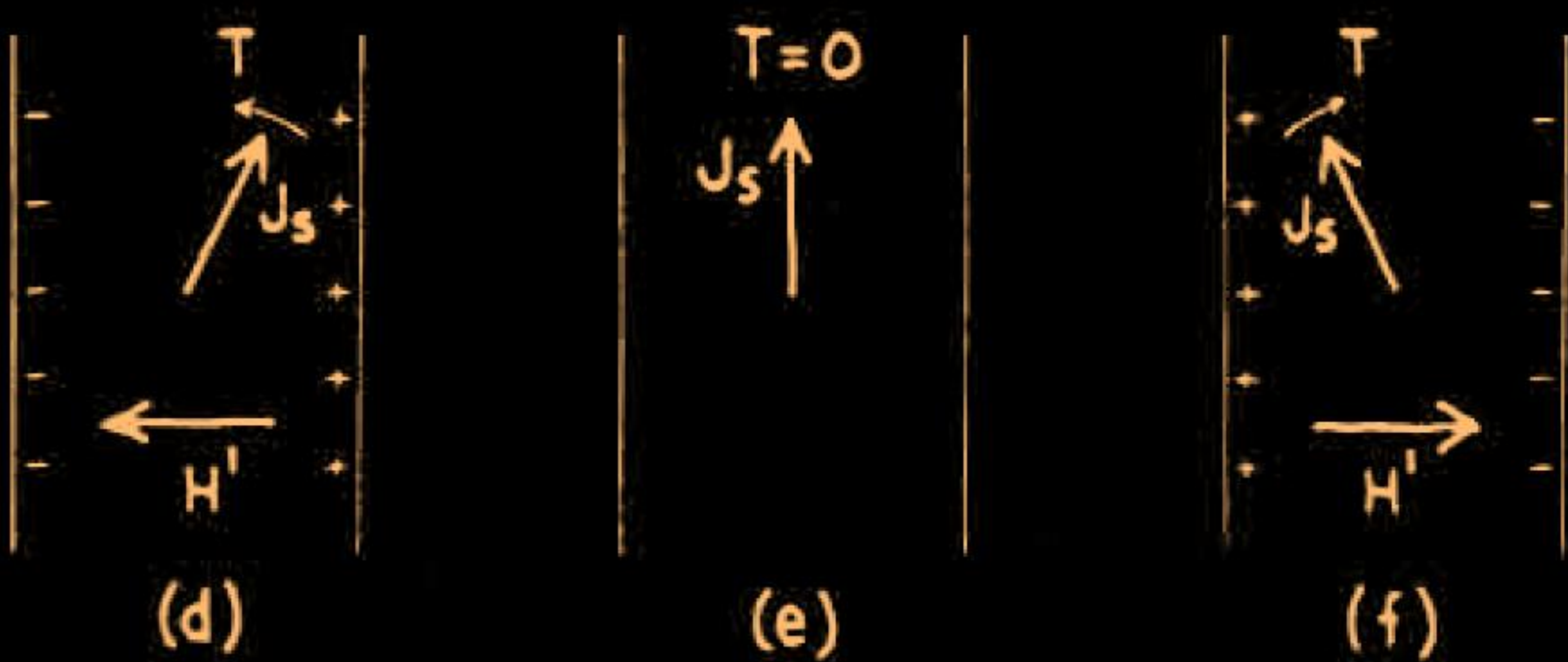
$$T_2 = -K \sin 2\phi.$$

External magnetic forces



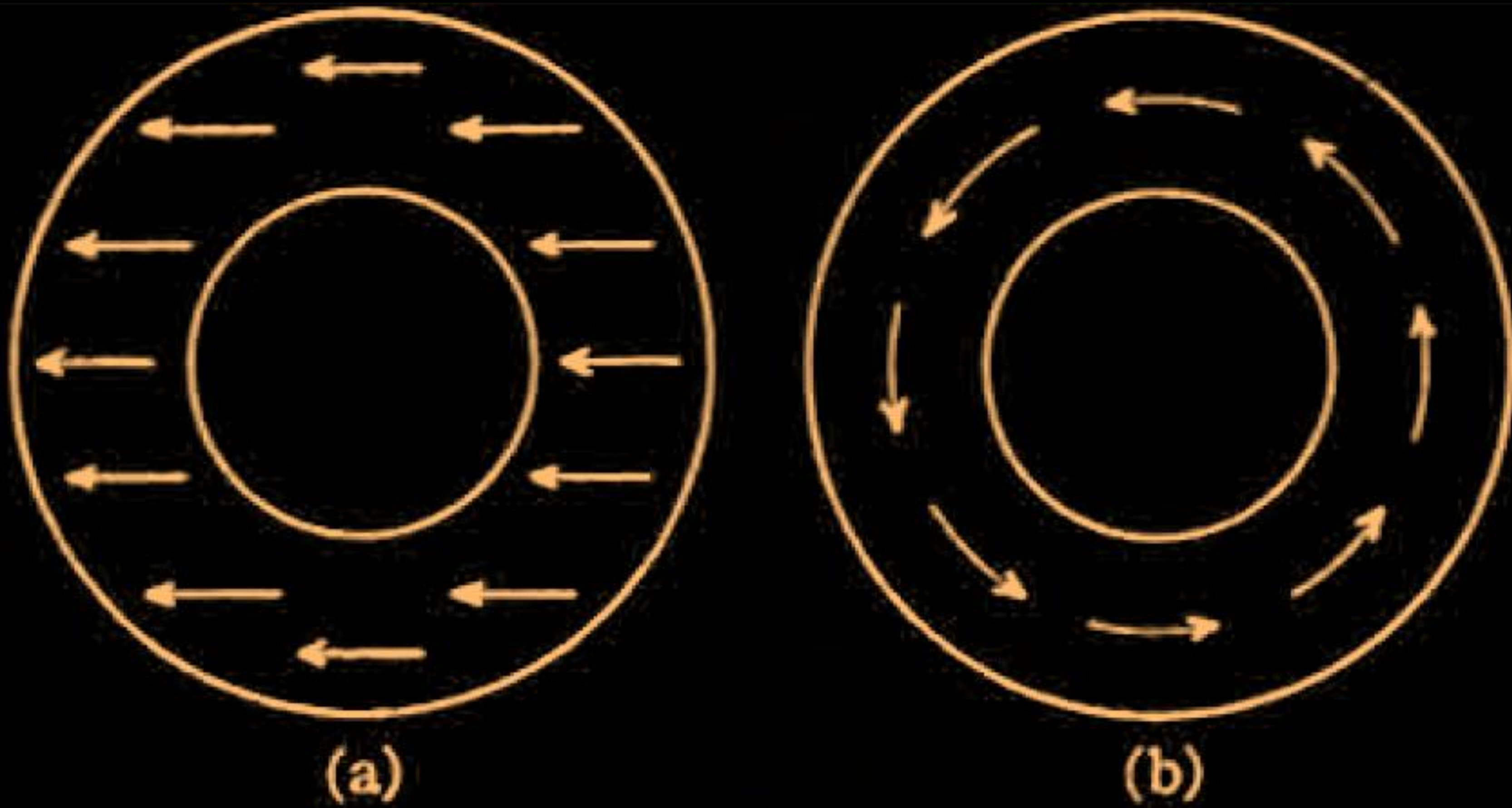
$$T_3 = -J_s H_0 \sin\phi.$$

Internal magnetic forces

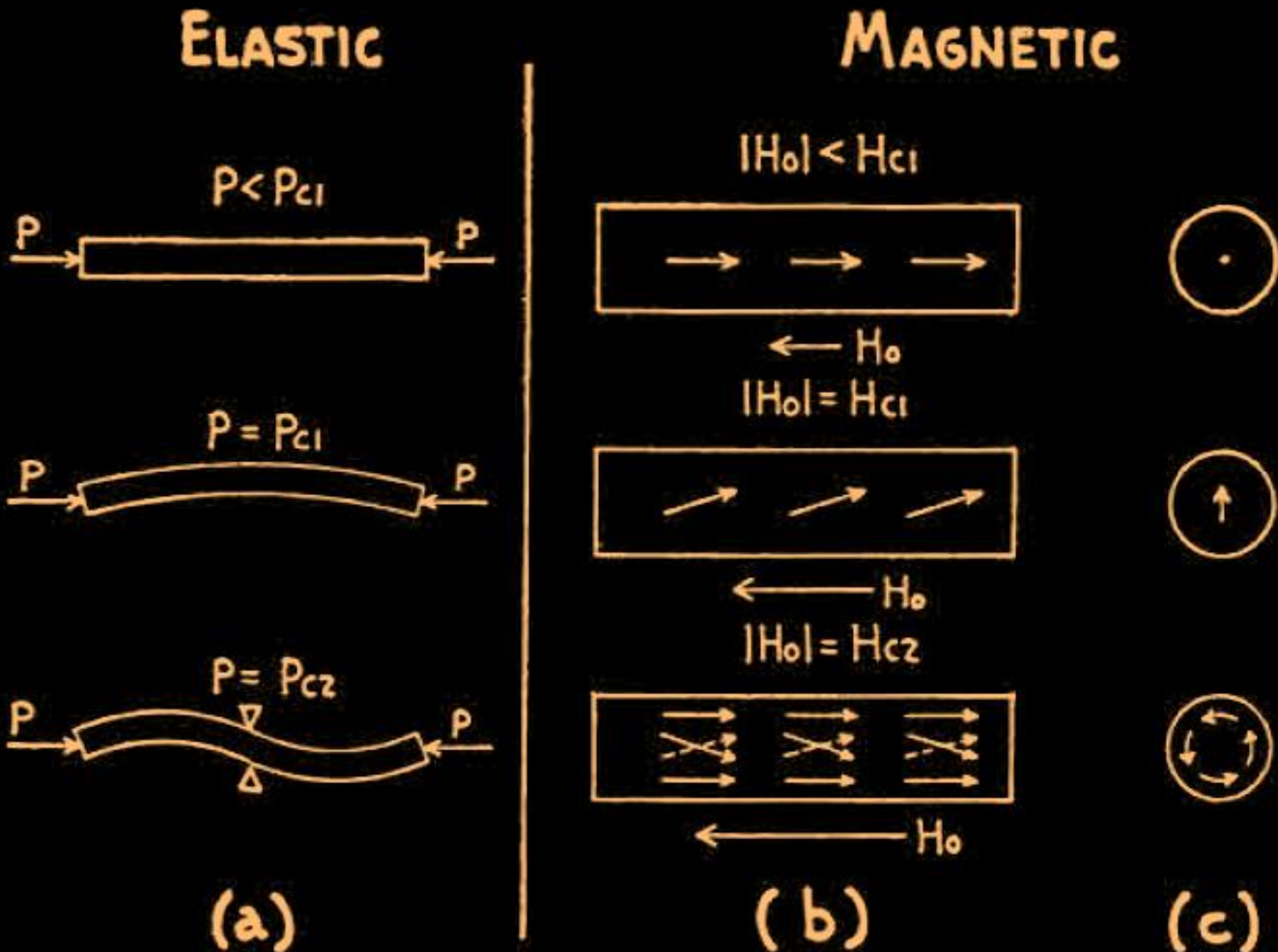


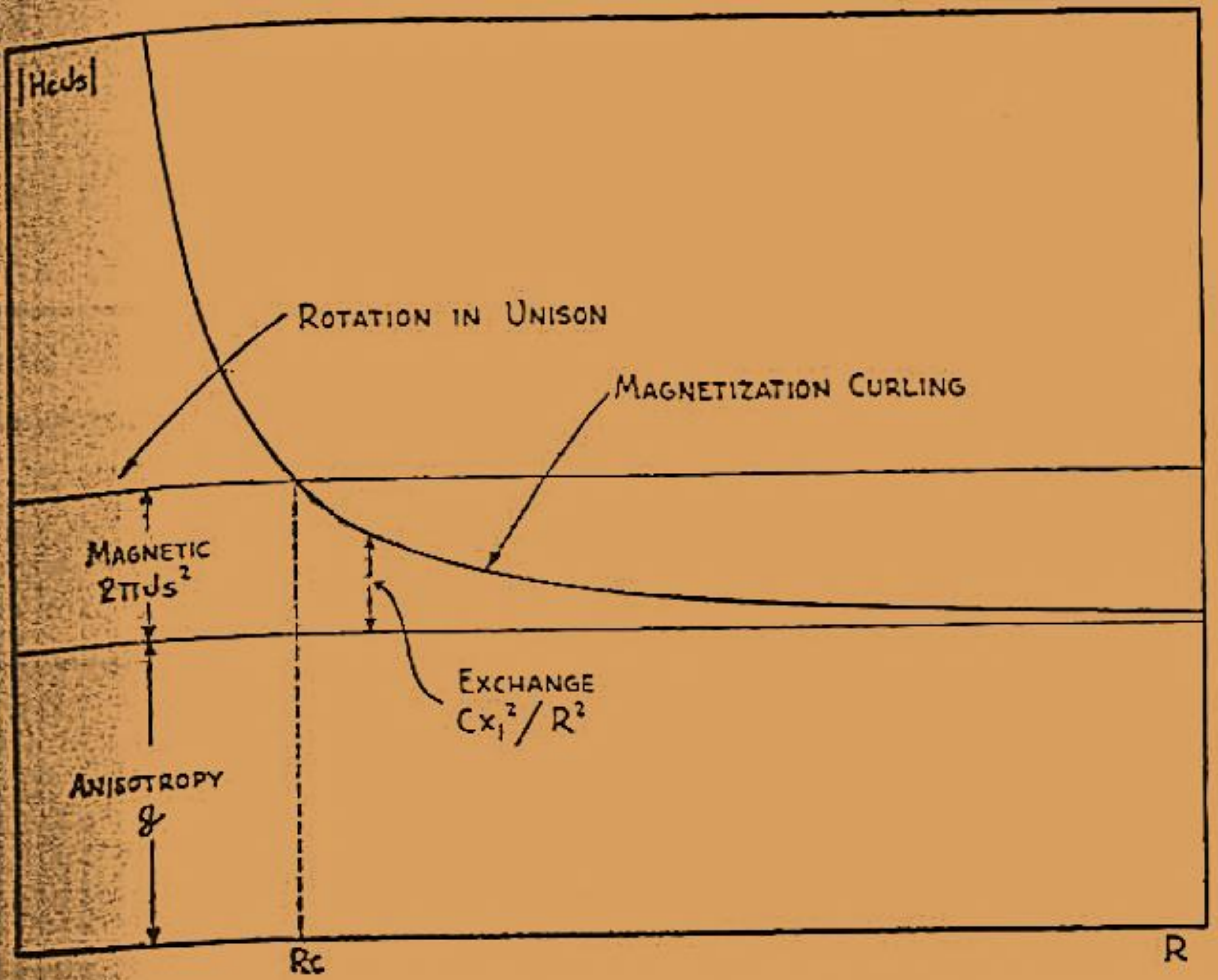
$$(8\pi)^{-1}\int H'^2 dv \rightarrow \min$$

Internal magnetic forces



→ non-uniform magnetic states


ELASTIC
MAGNETIC
P < Pc1
P
P
P = Pc1
P
P
P = Pc2
P
P
|Ho| < Hc1
Ho
|Ho| = Hc1
Ho
|Ho| = Hc2
Ho
(a)
(b)
(c)



|HcJs|
Rotation in Unison
Magnetization Curling
Magnetic
$2\pi J_s^2$
Exchange
Cx_1^2/R^2
Anisotropy
g
Rc
R

I have always been grateful to the editors for the promptness with which they rejected it that enabled me to send it to the Physical Review

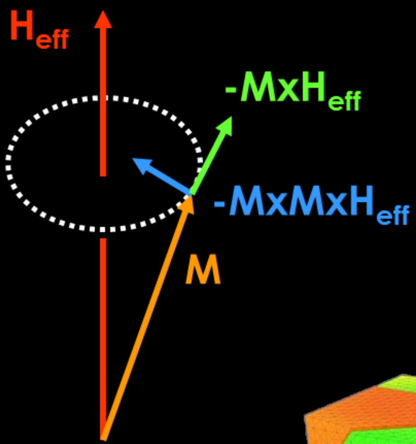
WF Brown, Domains, micromagnetics, and beyond: Reminiscences and assessments, J Appl Phys 49 (1978) 1937

… numerical integration by use of high-speed computers. This method is laborious, but it needs to be applied …

WF Brown, J Appl Phys 30 (1959) S62

Numerical micromagnetics

Numerical micromagnetics



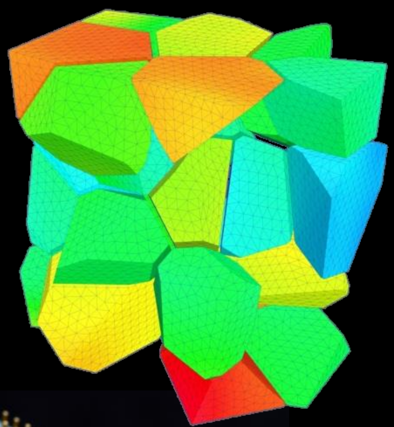
Basic equations

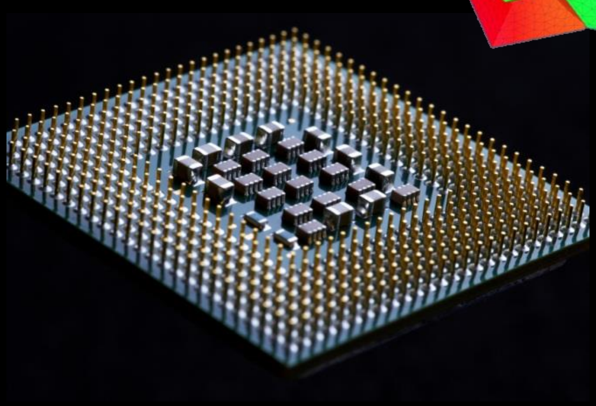
Magnetization dynamics

Demagnetizing field

Integral approach

Finite elements



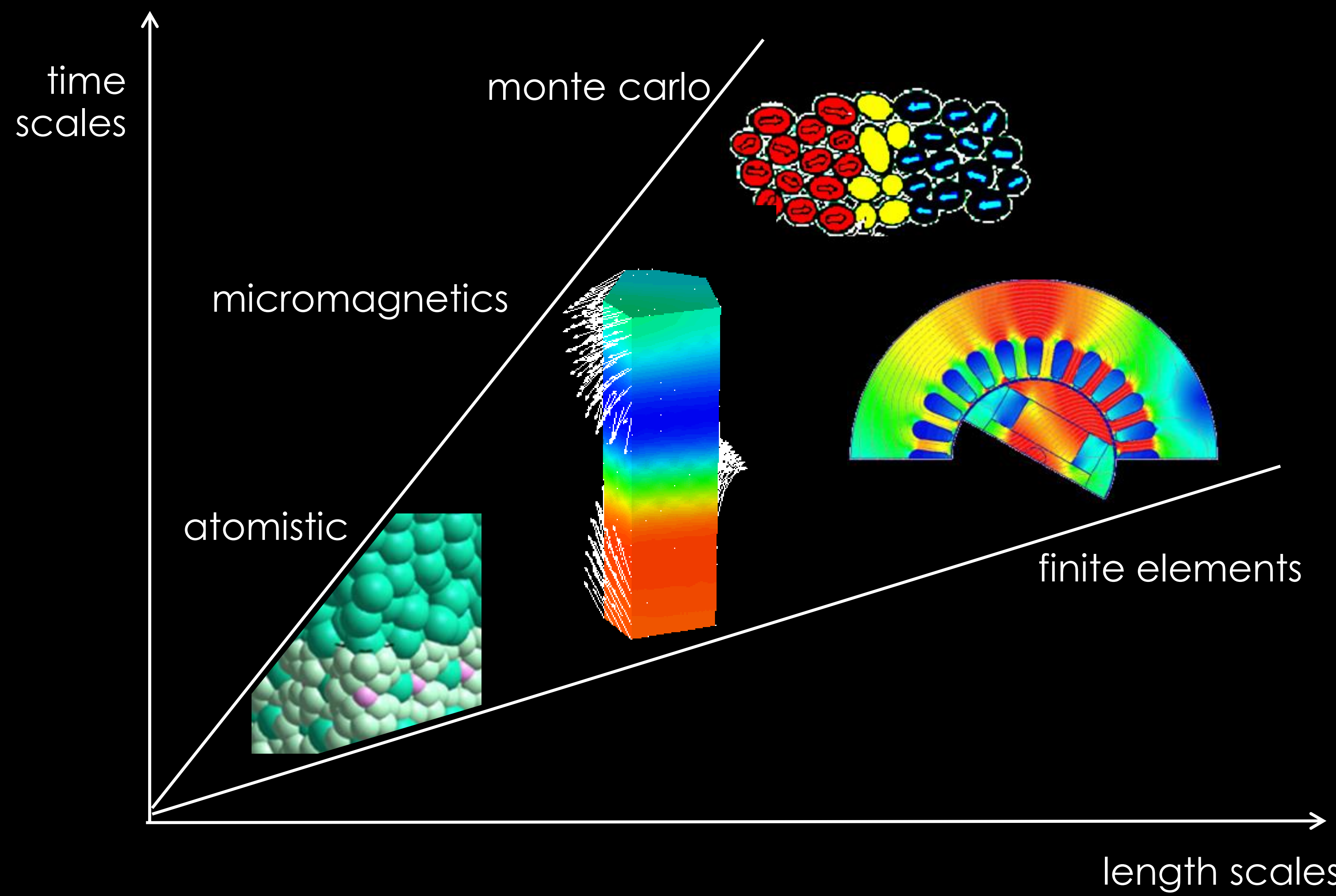


Numerics

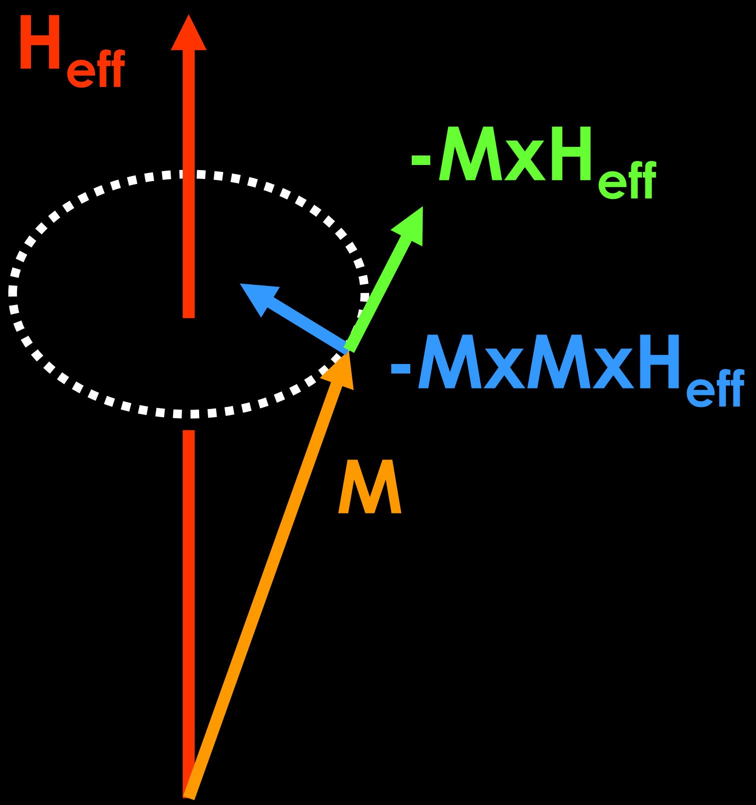
Sparse linear algebra

Computer hardware

Computational magnetism



$$\frac{1+\alpha^2}{|\gamma|}\frac{d\mathbf{M}}{dt} = -\mathbf{M}\times\mathbf{H}_{\text{eff}} - \frac{\alpha}{M_s}\mathbf{M}\times\mathbf{M}\times\mathbf{H}_{\text{eff}}$$



Partial differential equations

$$\frac{1+\alpha^2}{|\gamma|}\frac{d\mathbf{M}}{dt} = -\mathbf{M}\mathrm{x}\mathbf{H}_{eff} - \frac{\alpha}{M_s}\mathbf{M}\mathrm{x}\mathbf{M}\mathrm{x}\mathbf{H}_{eff} \qquad (1)$$

$$\mathbf{H_{eff}} = \frac{A}{{M_s}^2}(\nabla^2\mathbf{M}) + f(\mathbf{M}) - \nabla U + \mathbf{H}_{ext} \qquad (2)$$

$$\nabla^2 U = \nabla \cdot \mathbf{M} \qquad U \sim \frac{1}{r} \quad \text{for } r \rightarrow \infty \qquad (3)$$

Partial differential equations

$$\frac{1+\alpha^2}{|\gamma|}\frac{d\mathbf{M}}{dt} = -\mathbf{M}\times\mathbf{H}_{eff} - \frac{\alpha}{M_s}\mathbf{M}\times\mathbf{M}\times\mathbf{H}_{eff} \qquad (1)$$

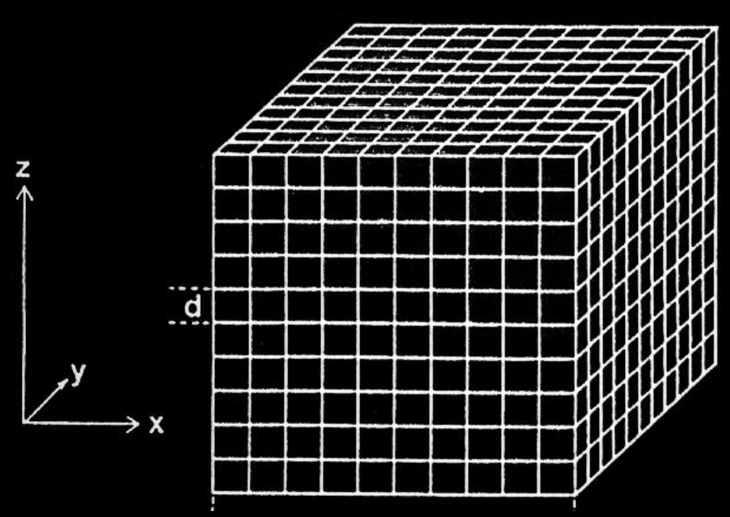
exchange, anisotropy

$$\mathbf{H}_{\mathbf{eff}} = A(\nabla^2\mathbf{M}) - \nabla U + K(\mathbf{k}\cdot\mathbf{u})\mathbf{k} + \mathbf{H}_{ext} \qquad (2)$$

magneto-static, external

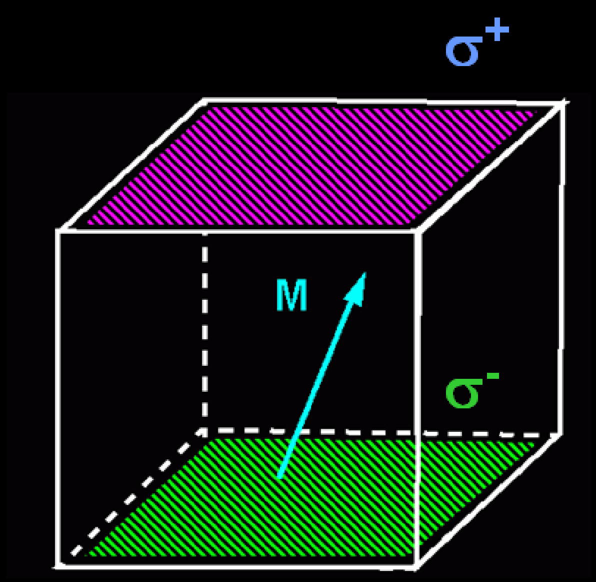
$$\nabla^2 U = \nabla\cdot\mathbf{M} \qquad U \sim \frac{1}{r} \quad \text{for } r \to \infty \qquad (3)$$

Integral approach



divide particles
into cubic cells

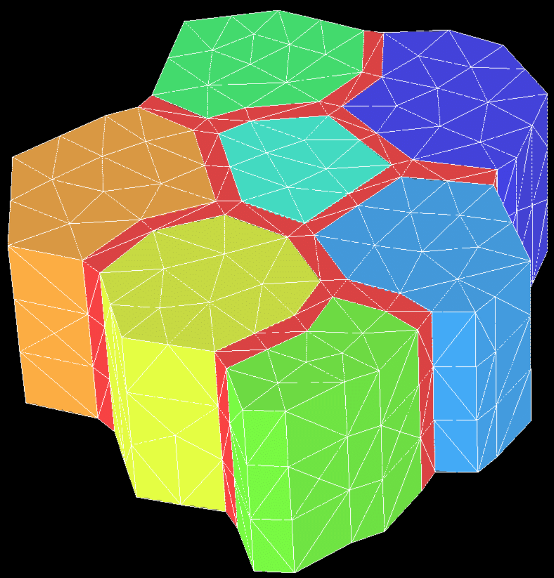
rigid magnetic moment
within each cell



sum over charge
sheets (FFT) to obtain the
magnetostatic field

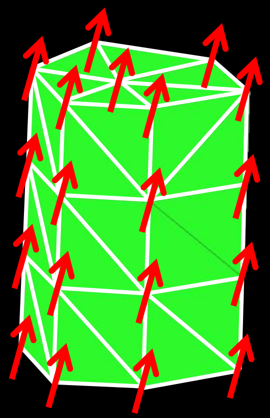
"one" LLG equation
per cell

Finite element approach



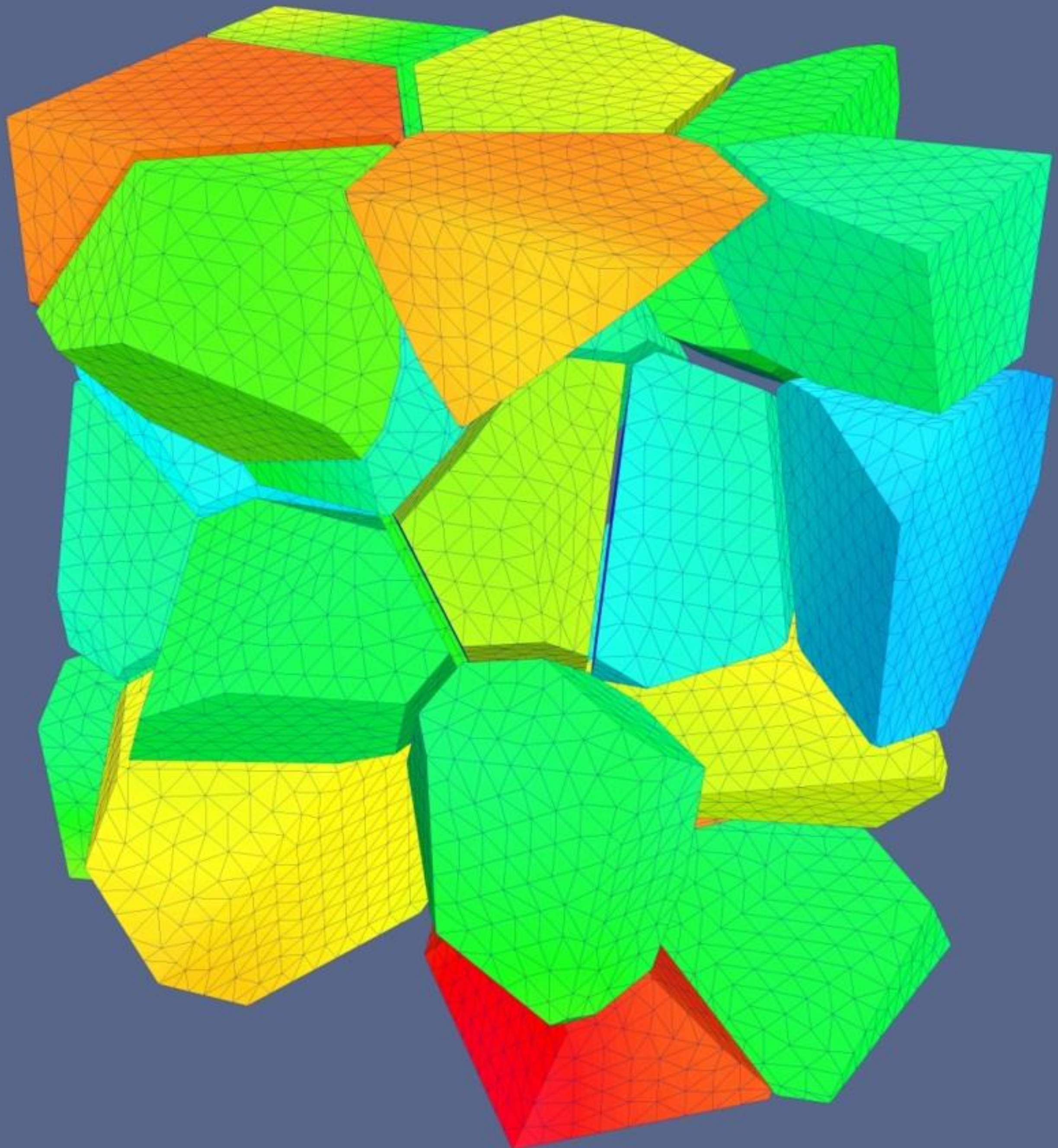
divide particles into finite elements (tetrahedrons)

Interpolate **M**, U within the elements



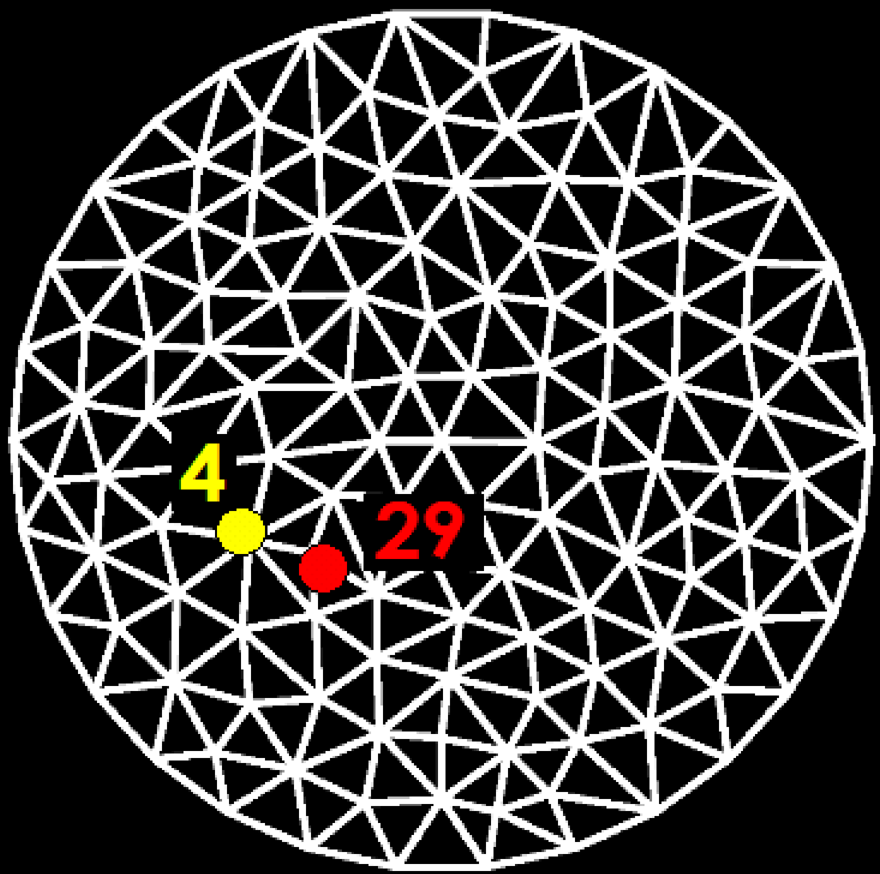
solve partial differential equation for the **magnetic potential**

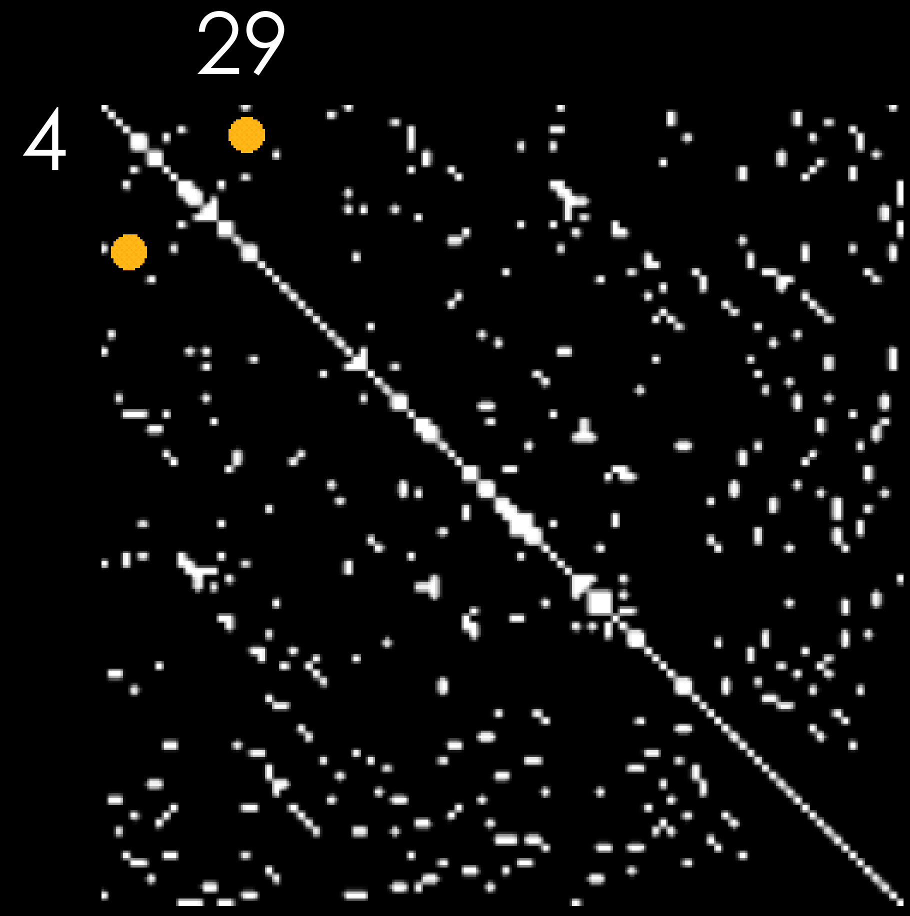
energy as a function of **M**(**r**)
⇨ effective field
⇨ magnetic moment



sparse
matrix
algebra

sparse matrix



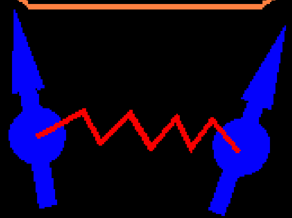


From Uniform to multidomain states

Four easy examples

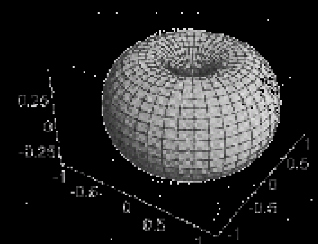
Example 1: Simple particle reversal

exchange



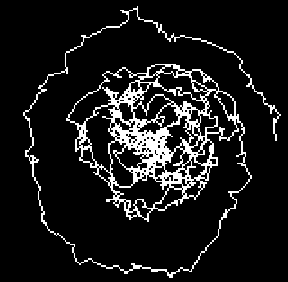
⇨ parallel spins

anisotropy



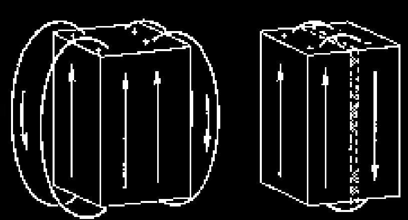
⇨ easy directions

thermal activation



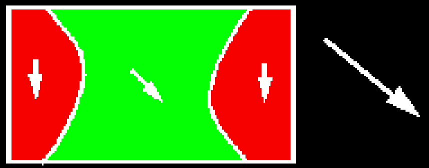
⇨ fluctuations

magnetostatic



⇨ domains

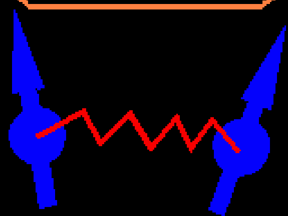
external field



⇨ rotation

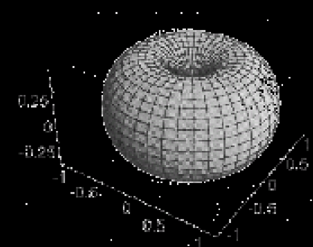
Example 1: Simple particle reversal

exchange



⇨ parallel spins

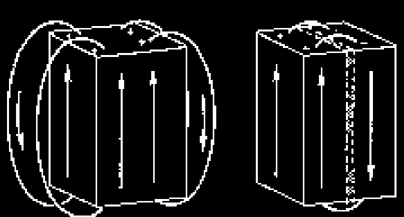
anisotropy



⇨ easy directions

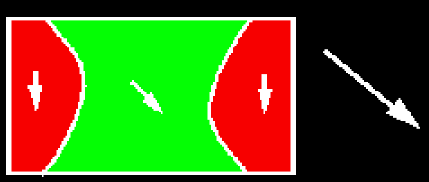
Very hard material:
Neglect
thermal activation

magnetostatic

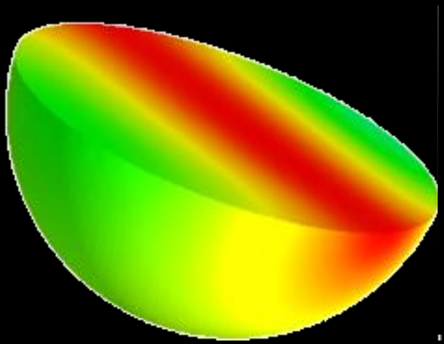


⇨ domains

external field

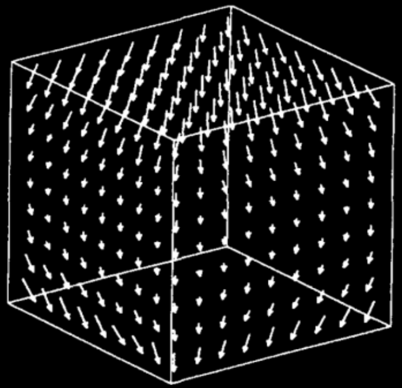


⇨ rotation



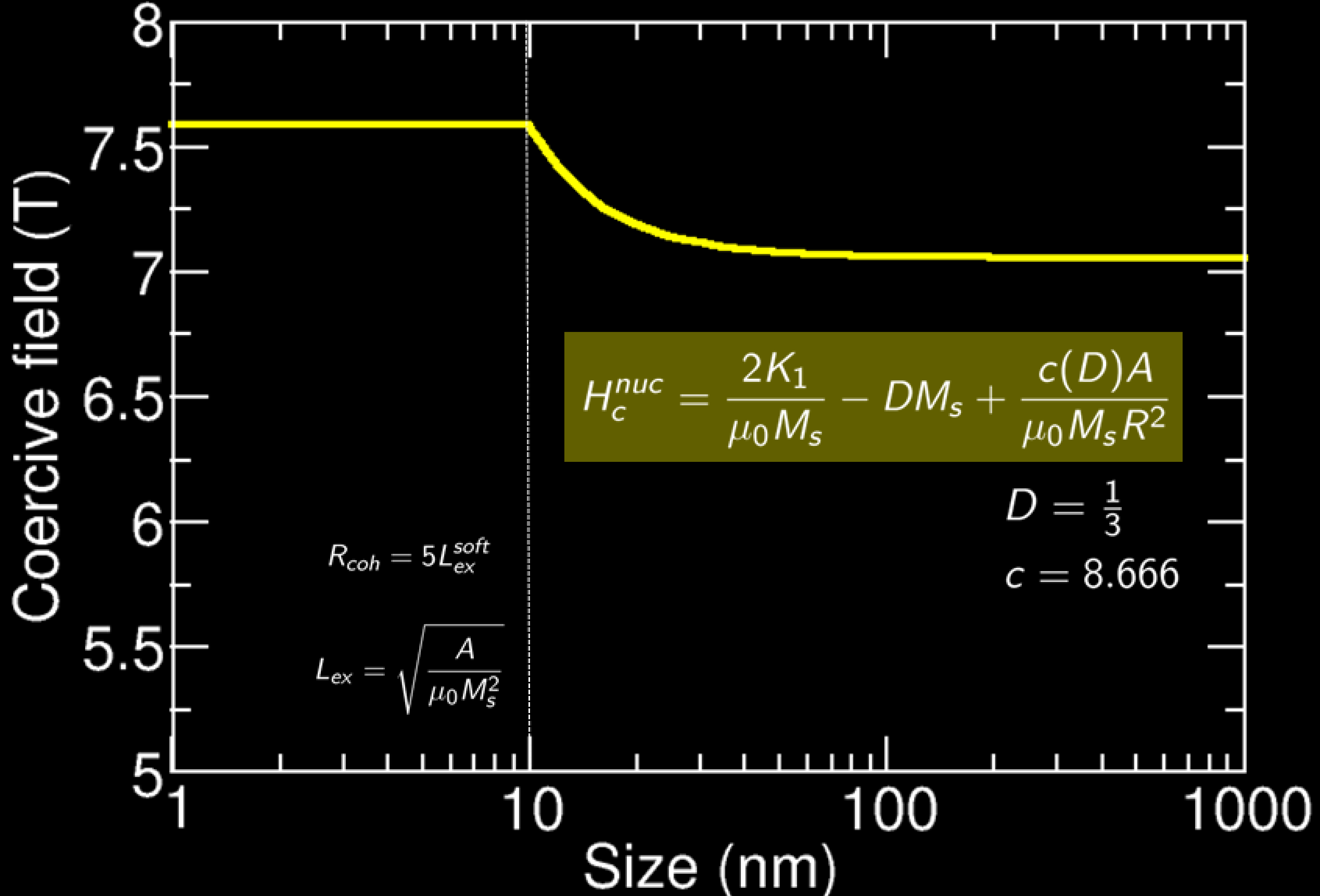
Sphere

Reversal modes

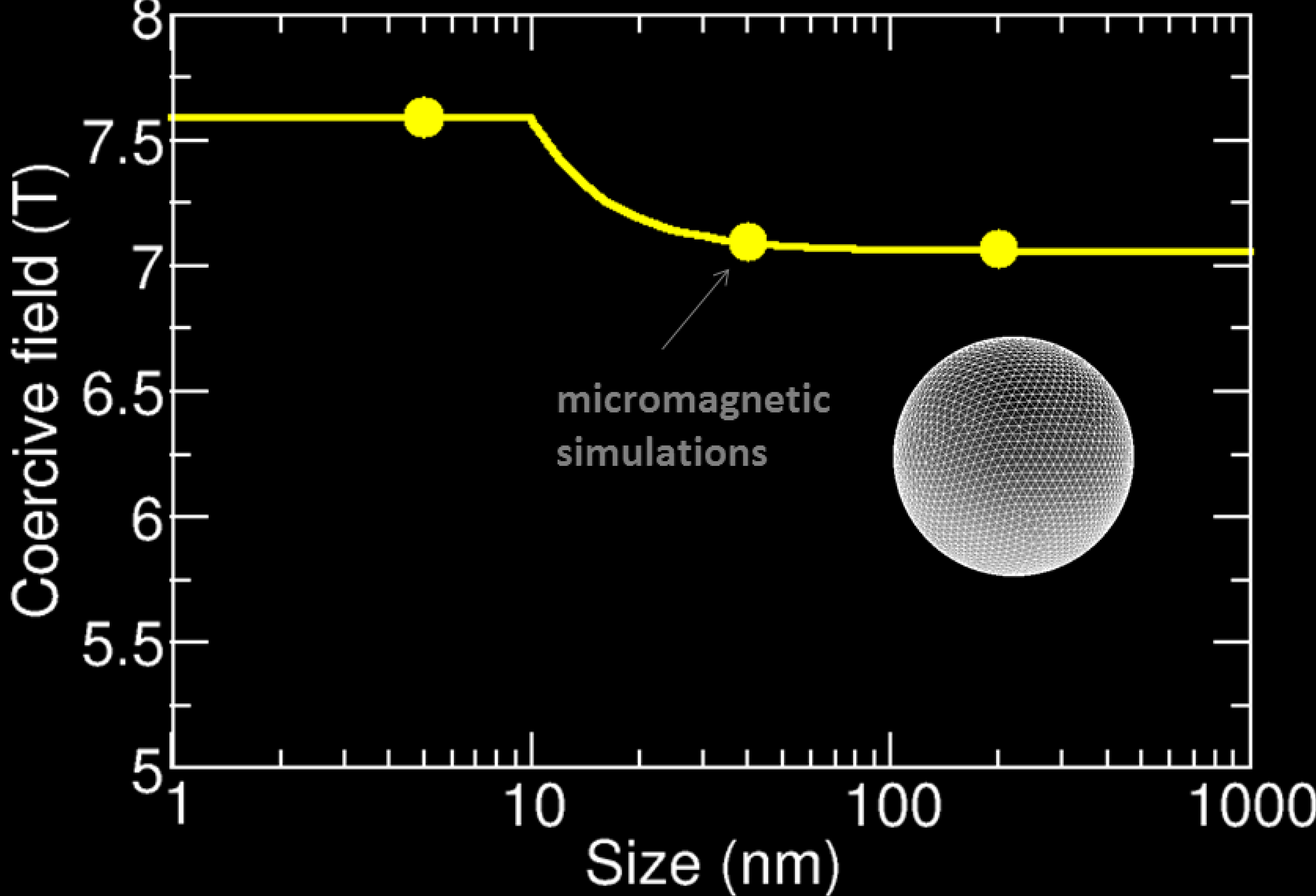


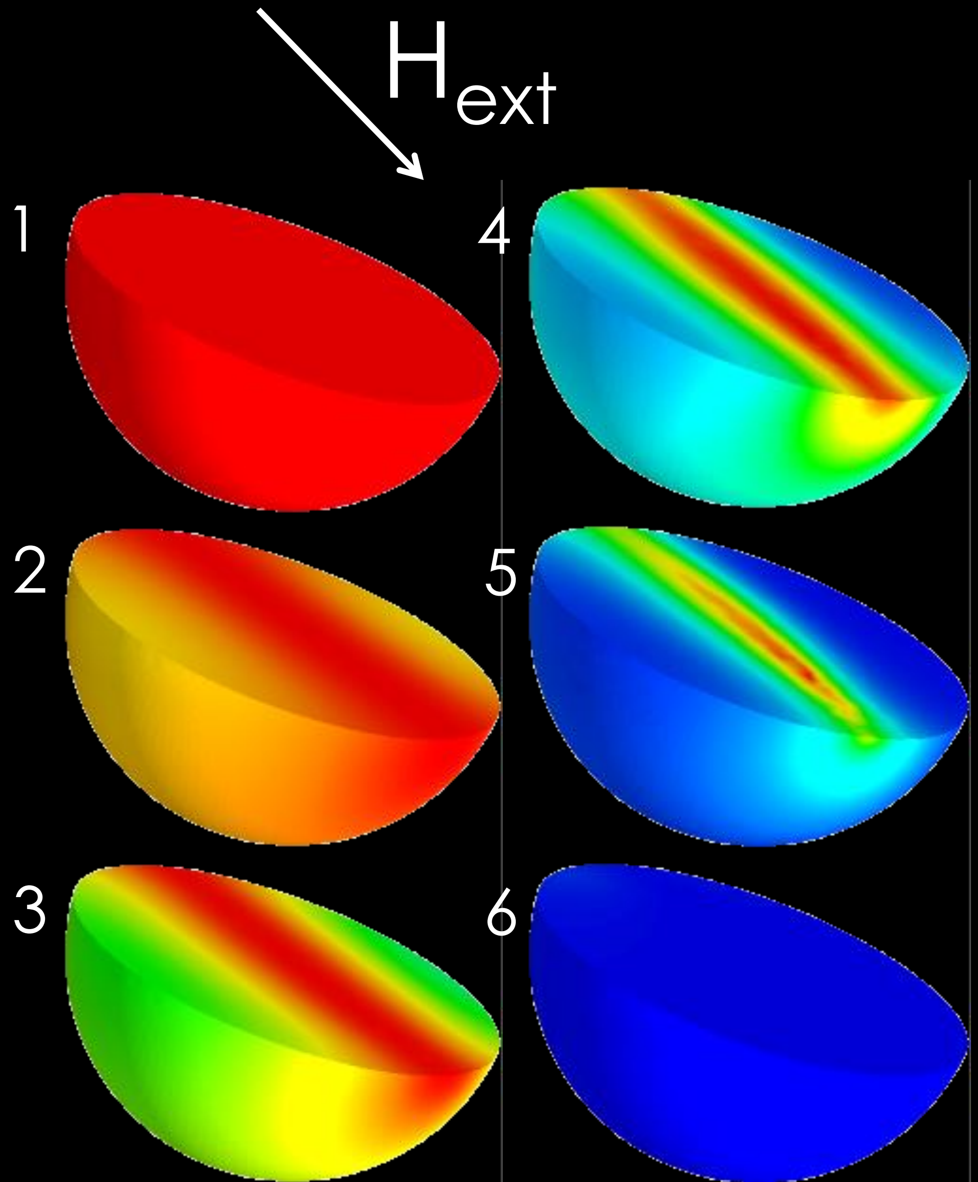
Cube

Size dependence of coercive field

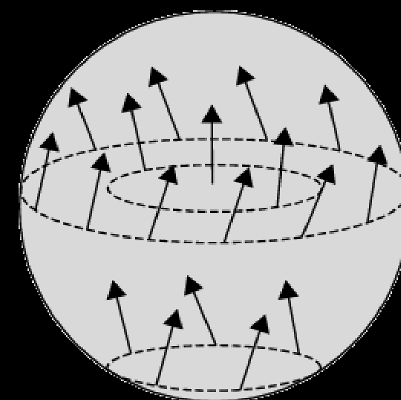


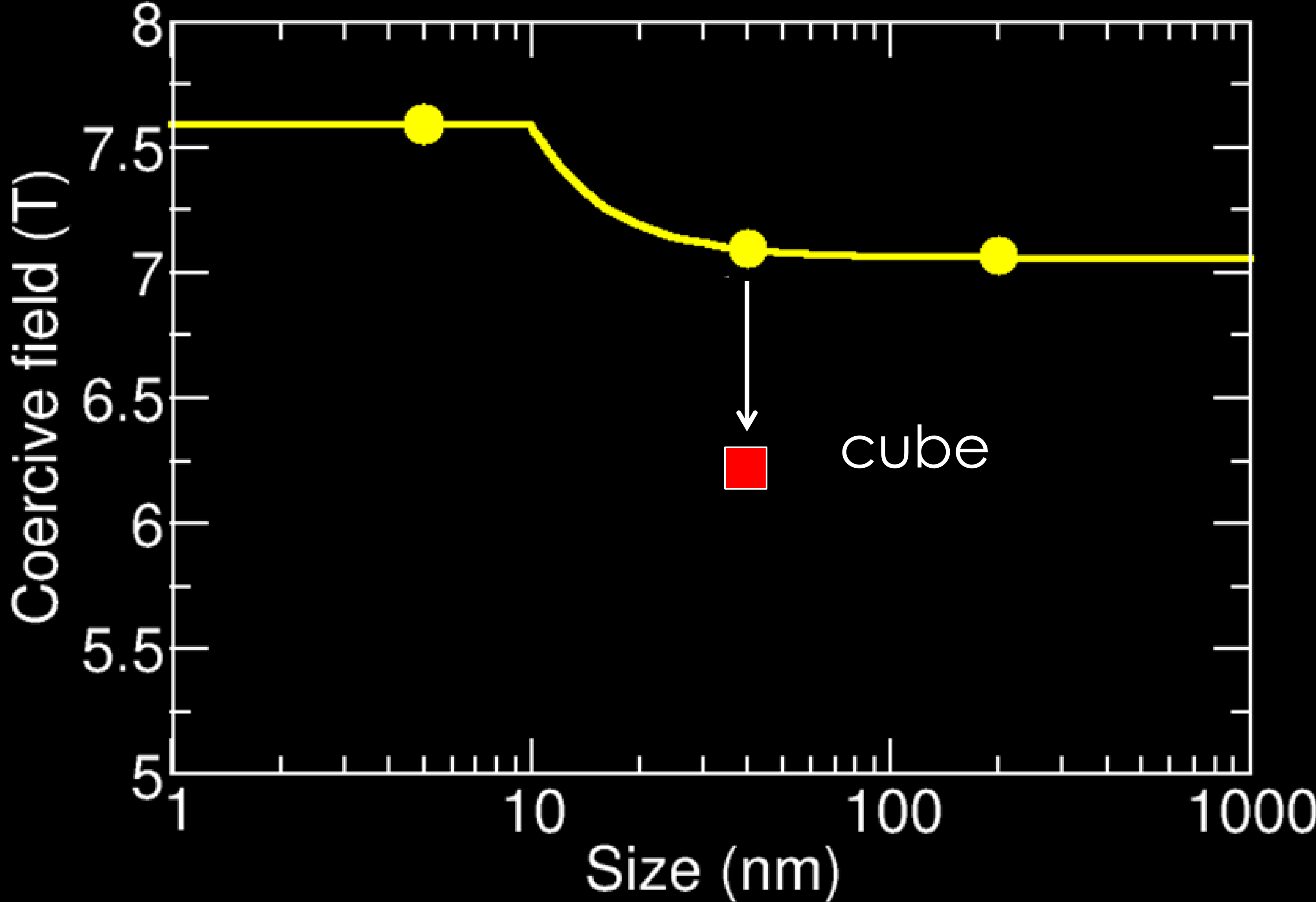
R Skomski, Simple models of magnetism, Oxford University Press, 2008


8
7.5
7
6.5
6
5.5
5
Coercive field (T)
1
10
100
1000
Size (nm)
micromagnetic
simulations



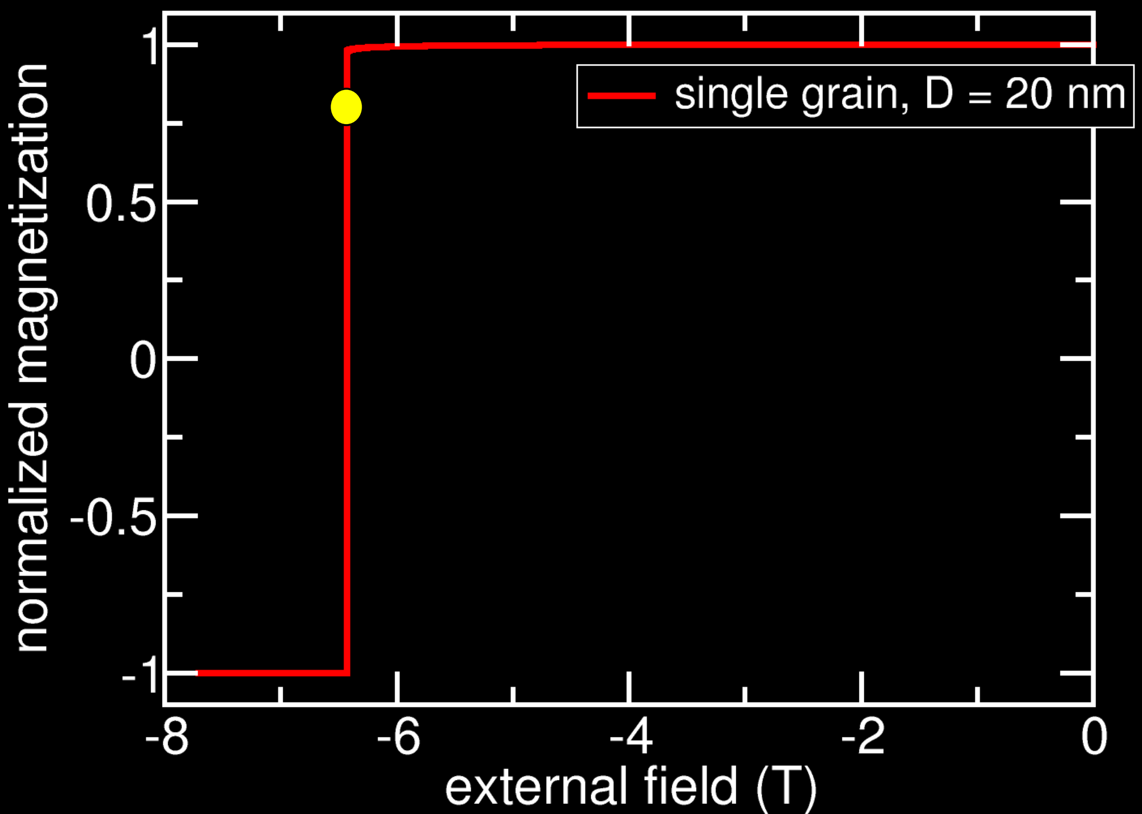
Reversal by curling

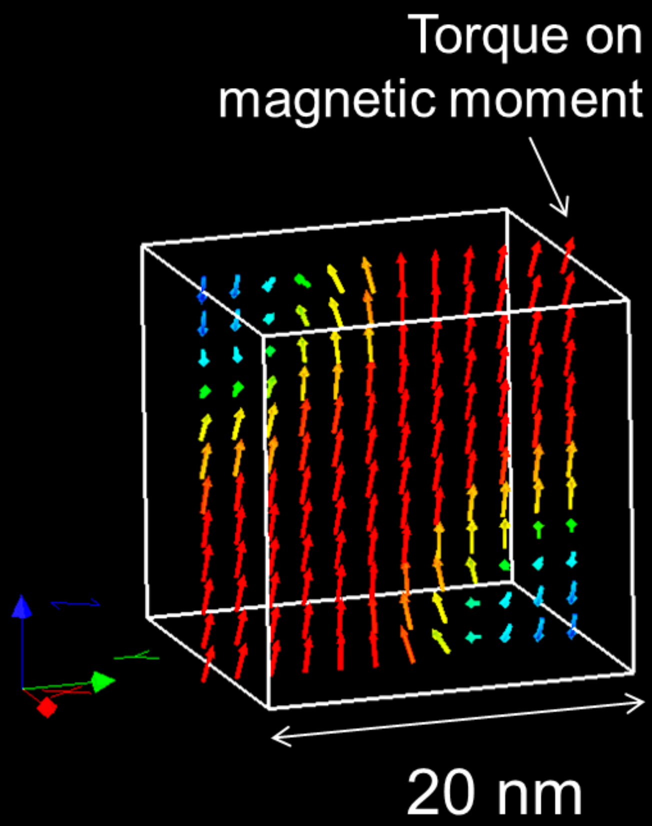




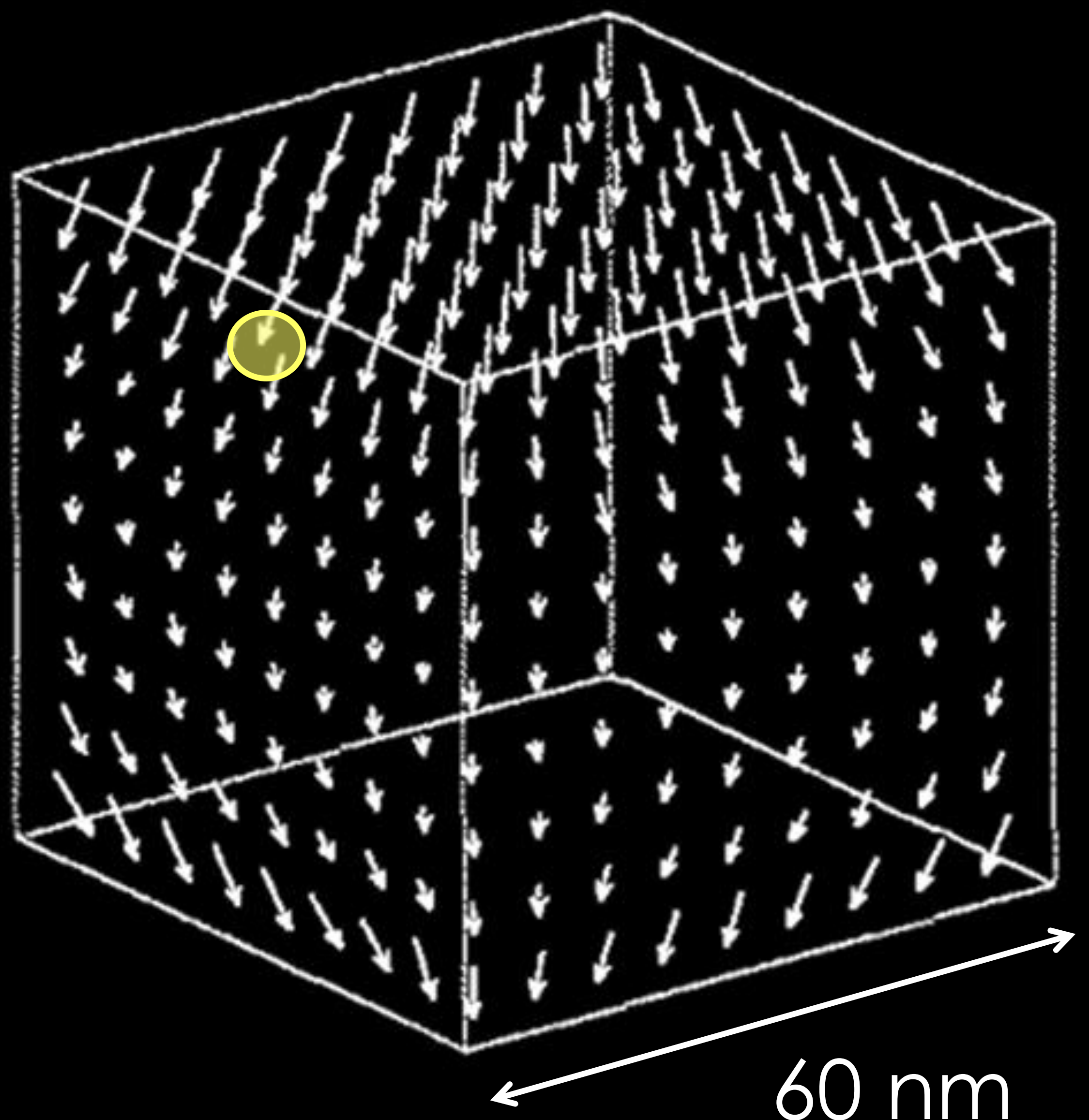
8
7.5
7
6.5
6
5.5
5
1
10
100
1000
Coercive field (T)
Size (nm)
cube

Switching of a cube

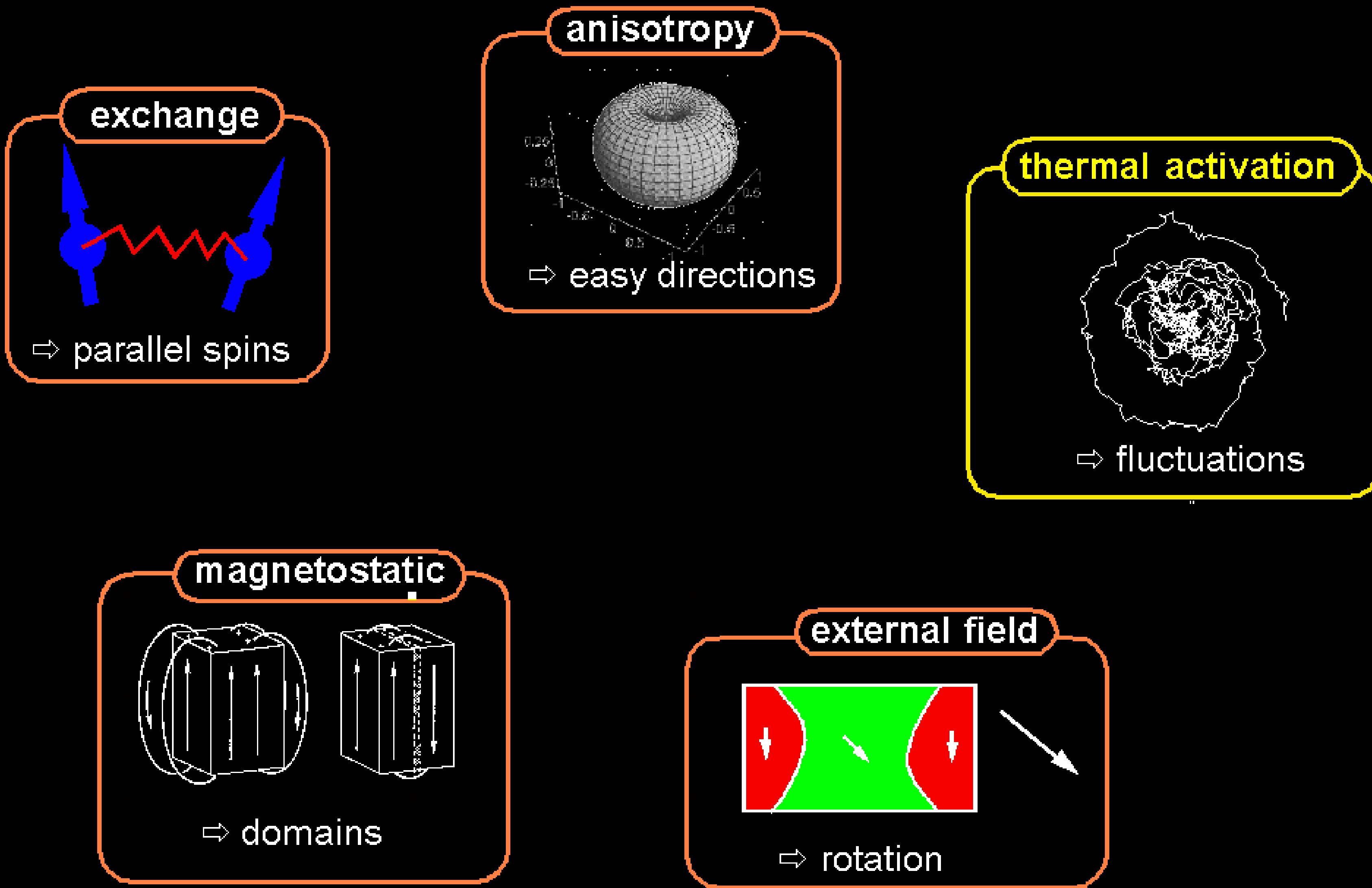




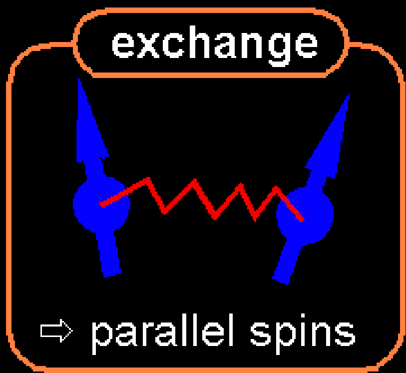
Demagnetizing field



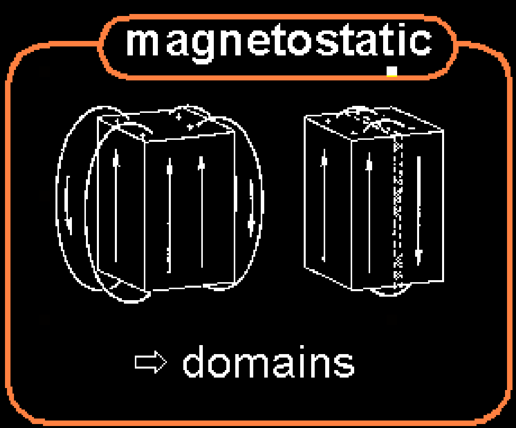
Example 2: Configurational anisotropy

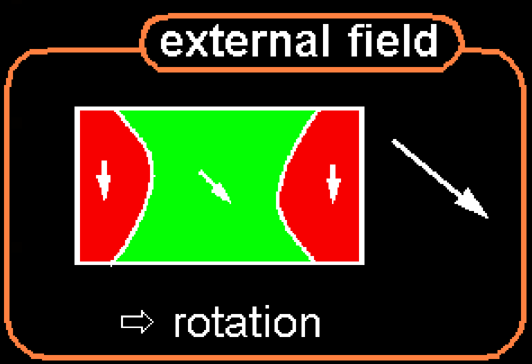


Example 2: Configurational anisotropy

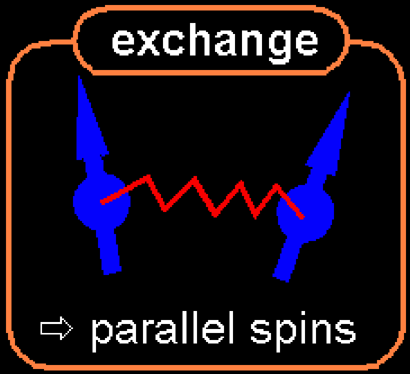


Soft magnet:
no cyrstalline anisotropy

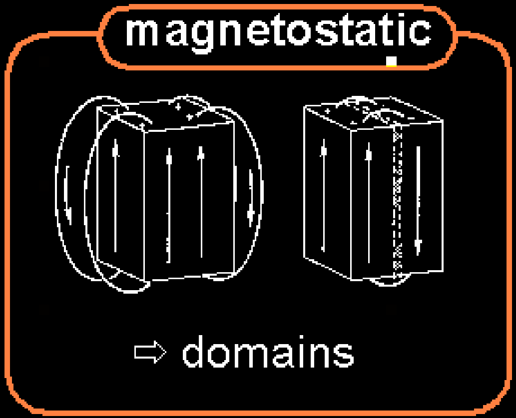




Example 2: Configurational anisotropy



Soft magnet:
no cyrstalline anisotropy

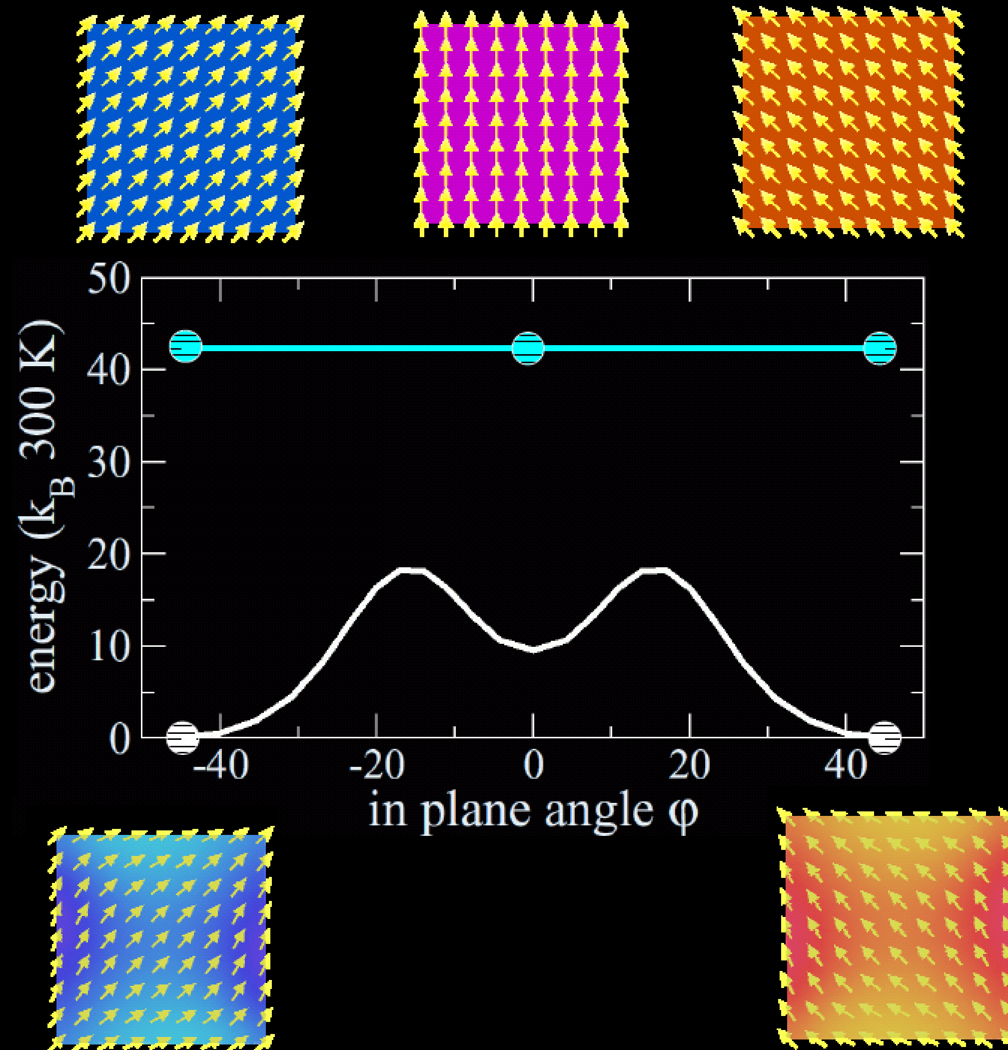


No external field

Example 2: Configurational anisotropy

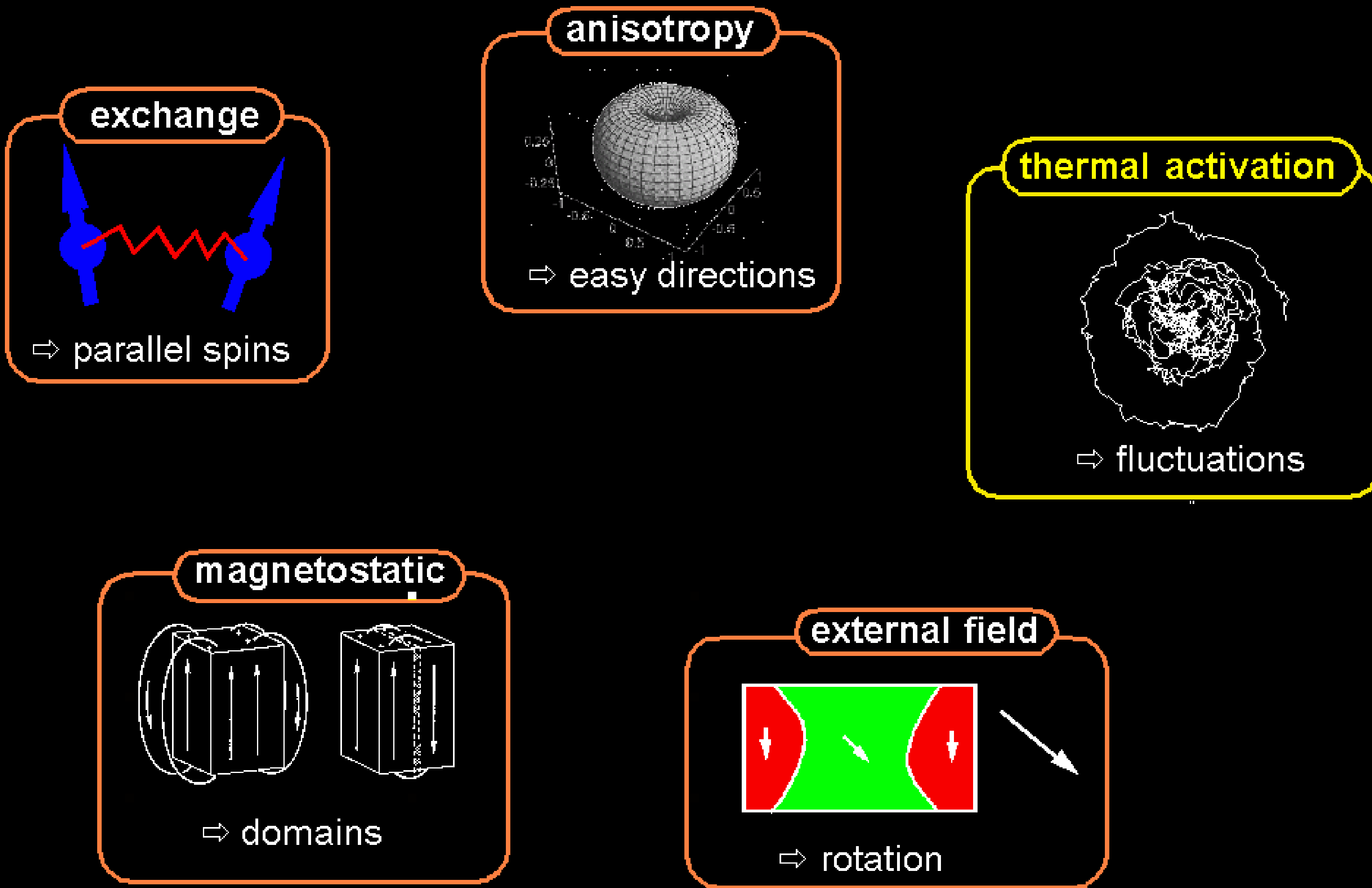
Permalloy (NiFe)
100 x 100 x 5 nm^3

If uniformly magnetized
all directions have
the same energy



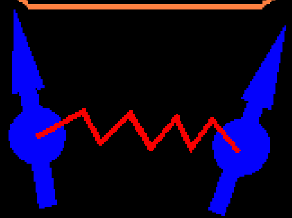
R Dittrich et al, J Appl Phys, 93 (2003) 7891.
R Cowburn, et al. J Appl Phys, 87 (2000) 7067.

Example 3: Domain walls



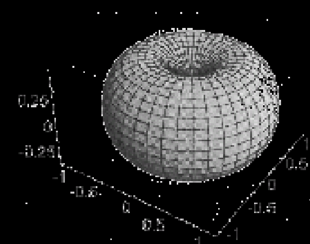
Example 3: Domain walls

exchange



⇨ parallel spins

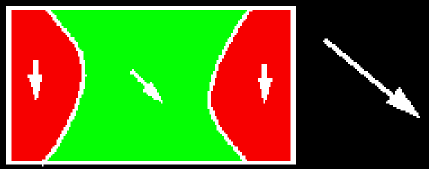
anisotropy



⇨ easy directions

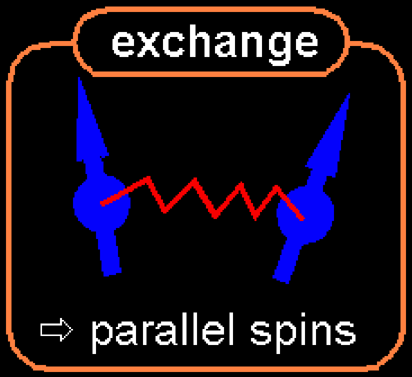
Anisotropy field larger than magnetostatic field

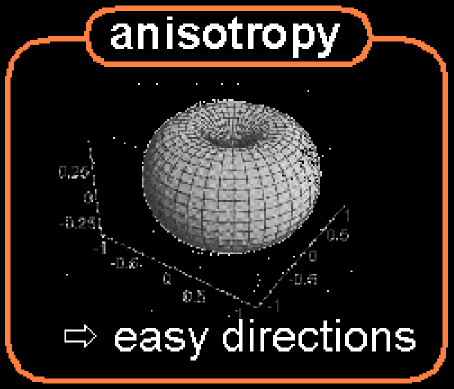
external field



⇨ rotation

Example 3: Domain walls





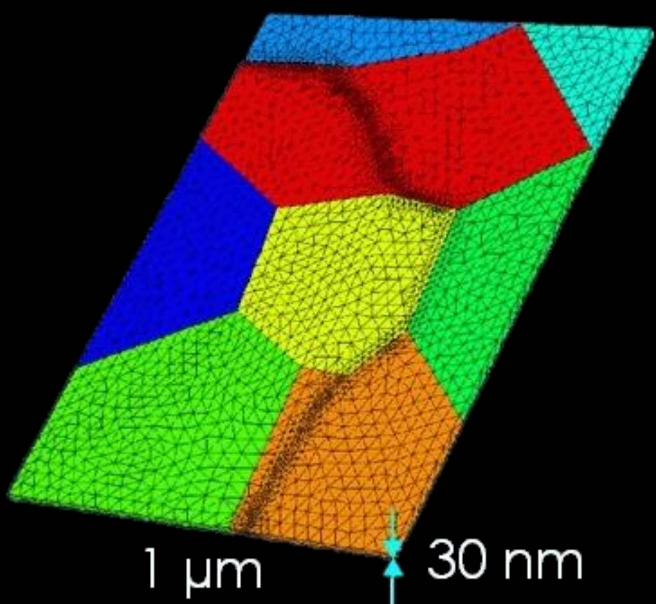
Anisotropy field larger than magnetostatic field

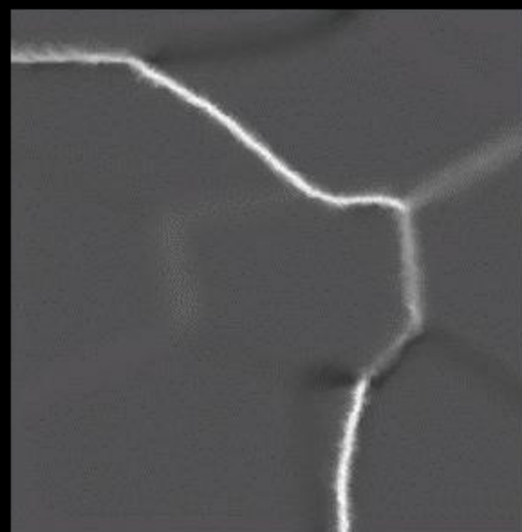
No external field

Domain walls and grains

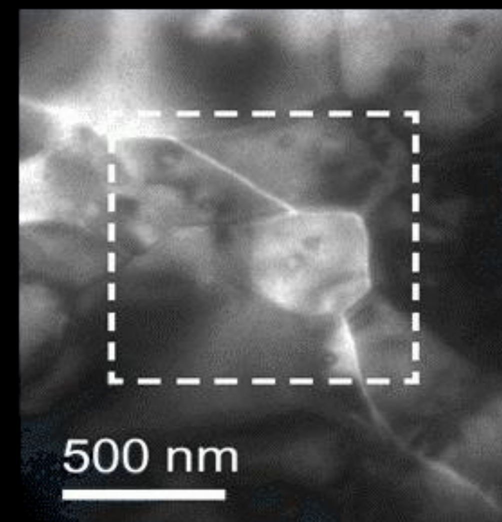
thin $Nd_2Fe_{14}B$ specimen

P Thompson et al.
J. Phys. D 30 (1997) 1854



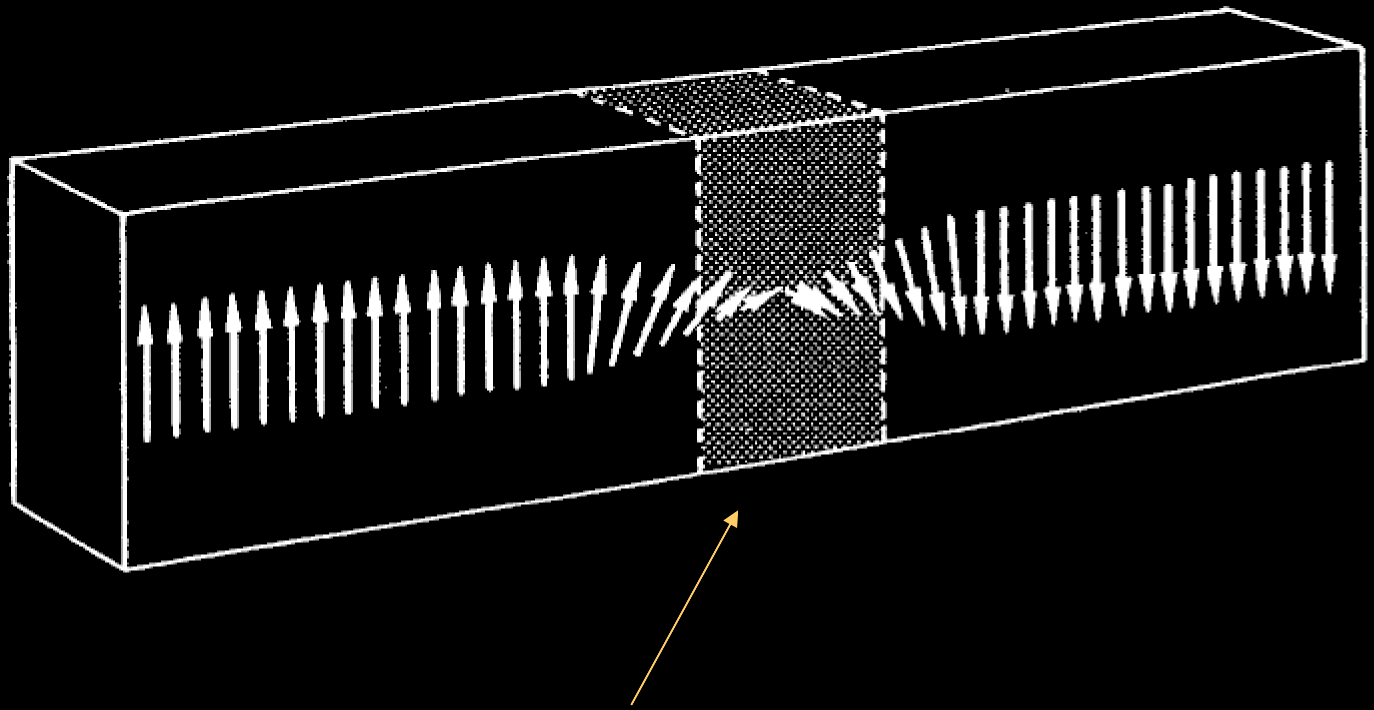


simulation



Fresnel image

Example 3: Domain walls



What is the energy of the domain wall ?

Example 3: Domain walls

$$E_{ex} = \int A \cdot \left(\nabla \varphi\right)^2 \cdot dx$$

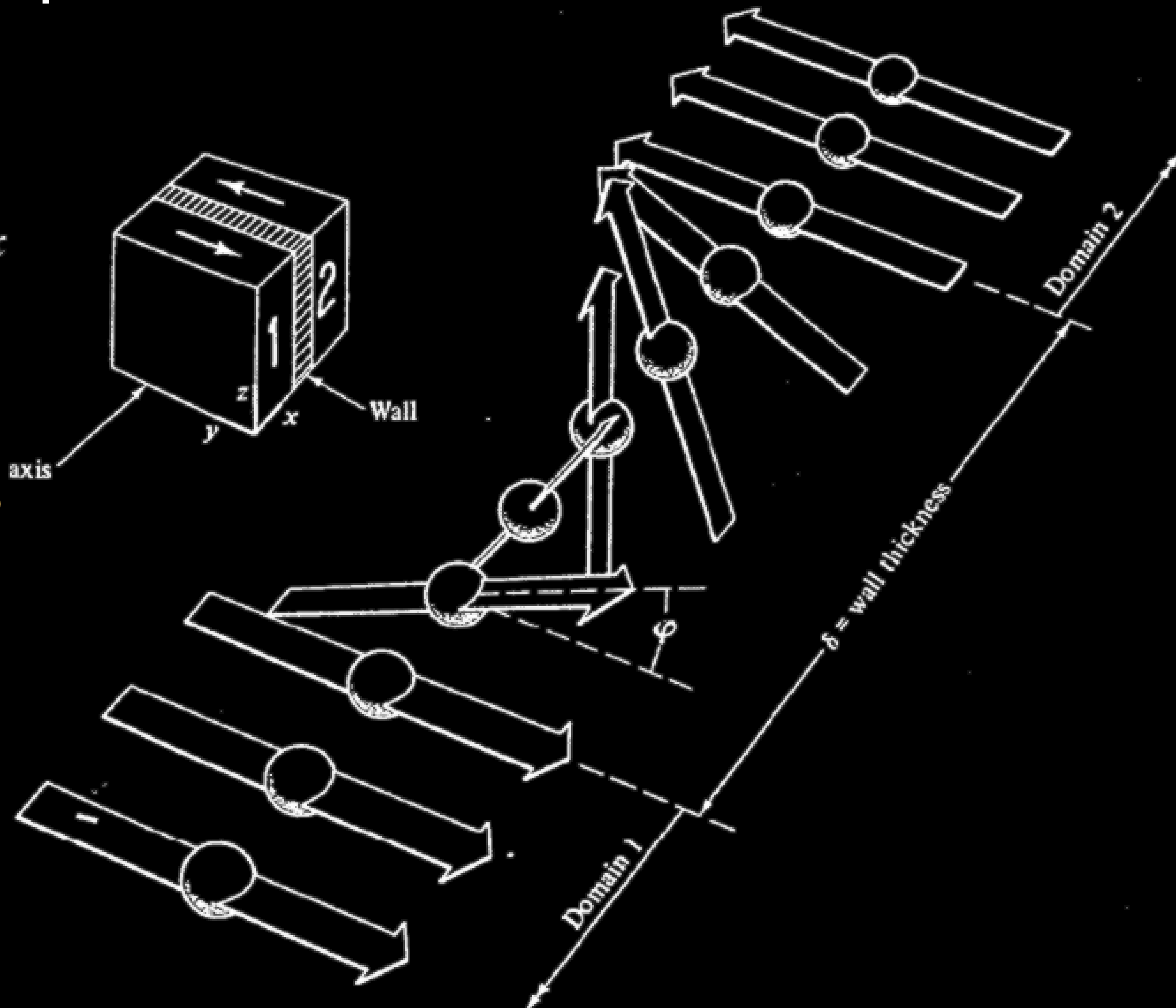
$$E_{ani} = \int K_1 \cdot \sin^2 \varphi \cdot dx$$

wall is not moving
torque MxH is zero

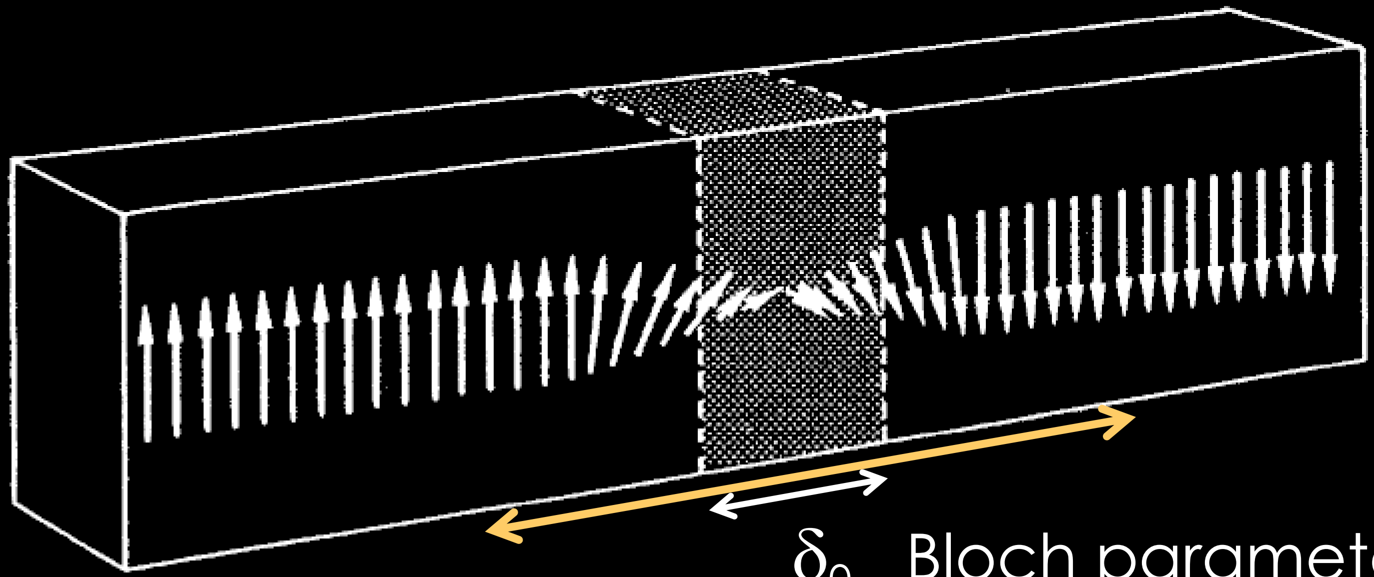
$$\frac{\partial E_{tot}}{\partial x_0} = 0 \quad \Rightarrow$$

$$\cos\varphi = -\tanh\left(-\frac{x}{\delta_0}\right)$$

$$\delta_0 = \sqrt{\frac{A}{K_1}}$$



Example 3: Domain walls



δ_0 Bloch parameter

$\pi\delta_0$ domain wall width

$$\gamma = 4 \cdot \sqrt{A \cdot K_1}$$ domain wall energy

Some numbers

Material	$\mu_0 M_s$ (T)	A (pJ m^{-1})	K_1 (MJ m^{-3})	δ (nm)
Fe	2.15	8.3	0.05	40
Co	1.76	10.3	0.53	14
Ni	0.61	3.4	−0.005	82
$BaFe_{12}O_{19}$	0.47	6.1	0.33	14
$SmCo_5$	1.07	22.0	17	3.6
$Nd_2Fe_{14}B$	1.61	7.7	4.9	3.9

Skomski, Nanomagnetics,
J. Phys.: Condens. Matter 15 (2003) R841–R896

Domain wall width is characteristic length scales

Characteristic length scales

Non-uniform magnetization
confined in regions smaller than
the domain wall width $\pi\delta_0$

Effective pinning if
defect size = domain wall width $\pi\delta_0$

Characteristic length scales

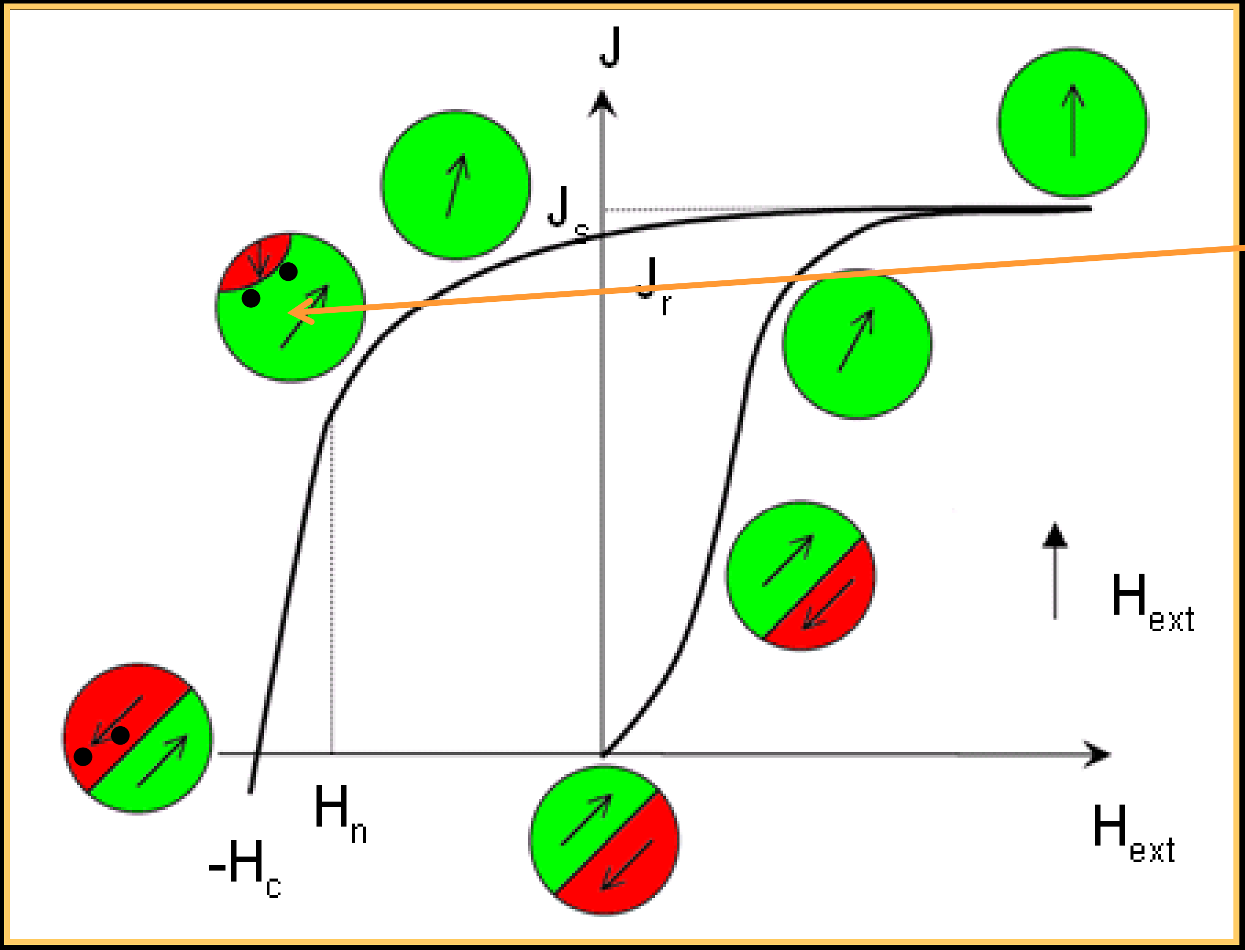
Characteristic length
interplay between the two most important micromagnetic energy contributions

Hard magnets	exchange + anisotropy	$\delta_0 = \sqrt{\frac{A}{K}}$
Soft magnets	exchange + magnetostatic	$l_{ex} = \sqrt{\frac{A}{\mu_0 M_s^2}}$

exchange length

Replace K with $\mu_0 M_s^2$

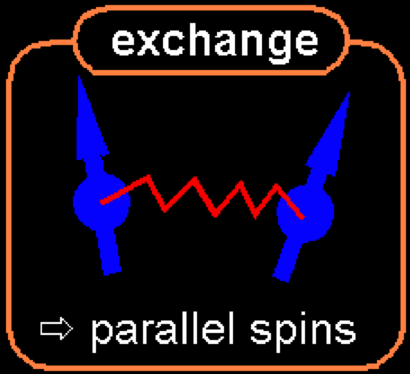
Pinning type permanent magnets



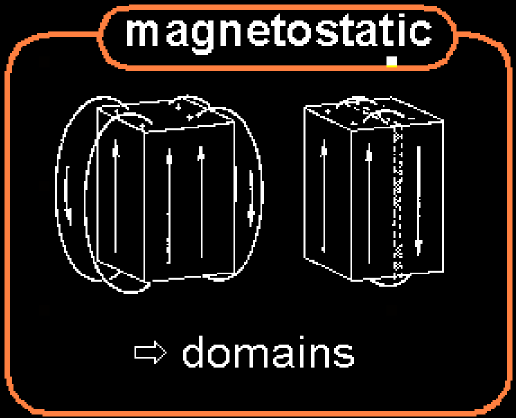
if domain walls cannot move

magnet remains stable

Example 4: Magnetic domains



No magnetocrystalline anisotropy

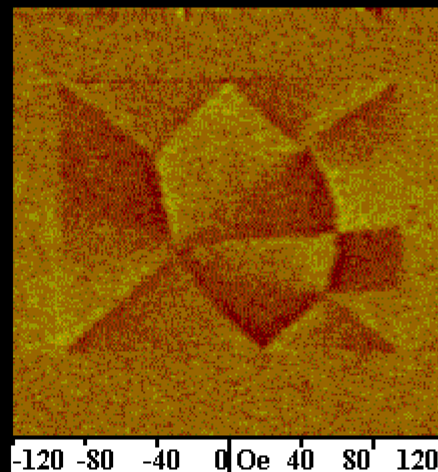


No external field

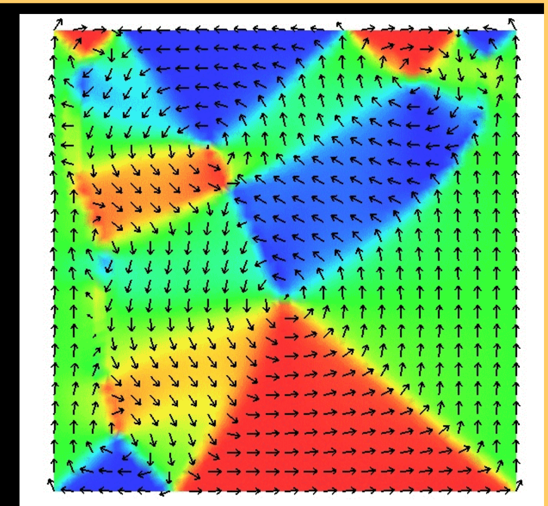
Element size

Micro elements (L > 1μm)

closure domains

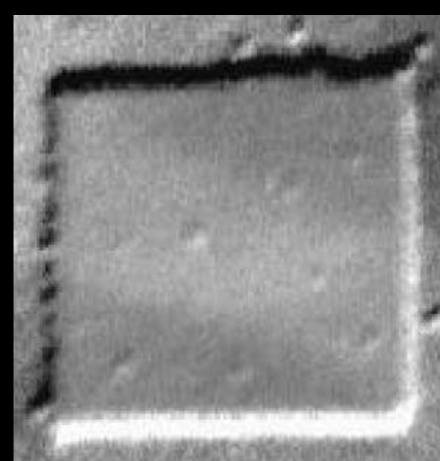


RD Gomez et al.

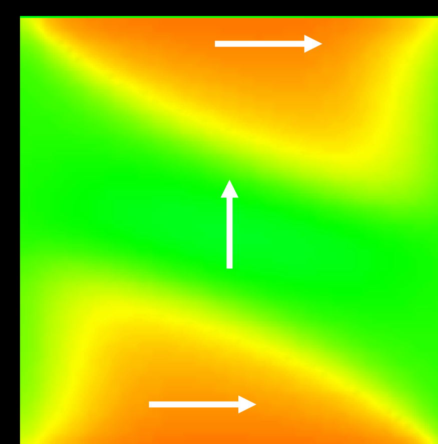


Nano elements (L < 1μm)

one domain
+
end domains

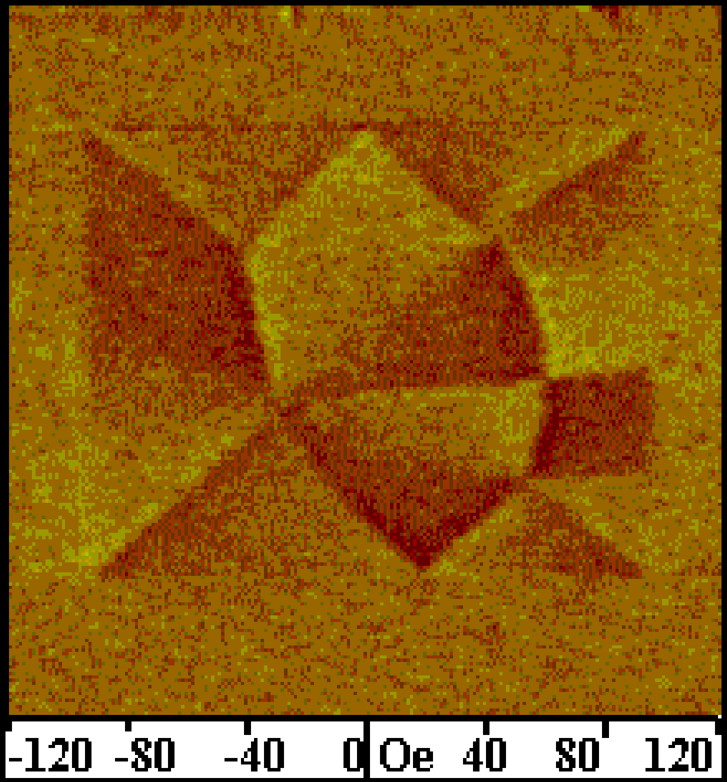


JN Chapman et al.

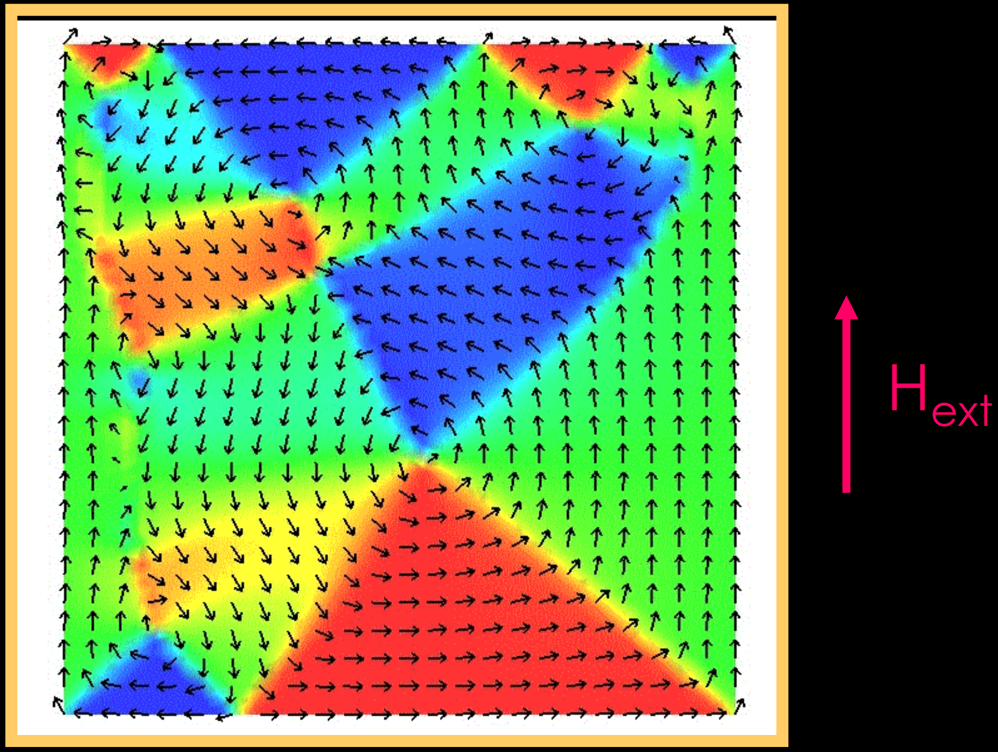


Thin film elements

Large elements >1 μm



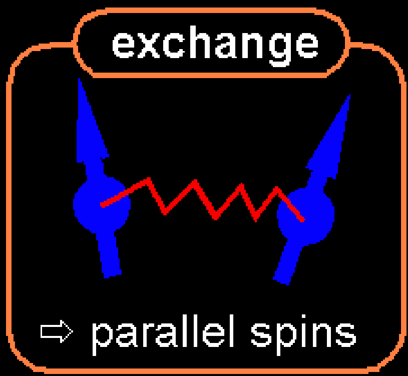
Magnetic force microscopy
Gomez et al.



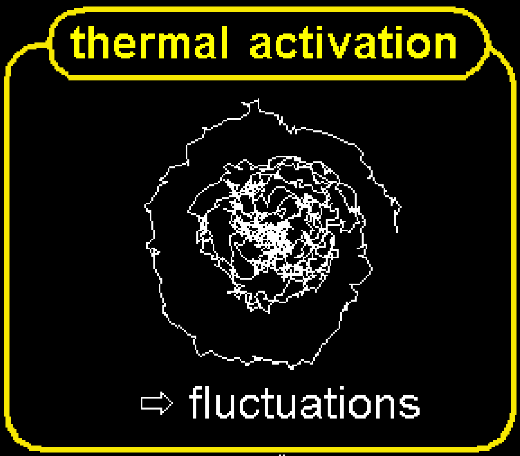
Micromagnetic simulation

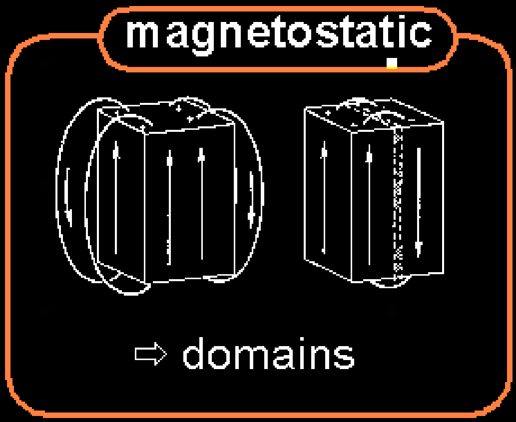
Thermal effects
Stochastic dynamics and energy barriers

Example 5: End domains



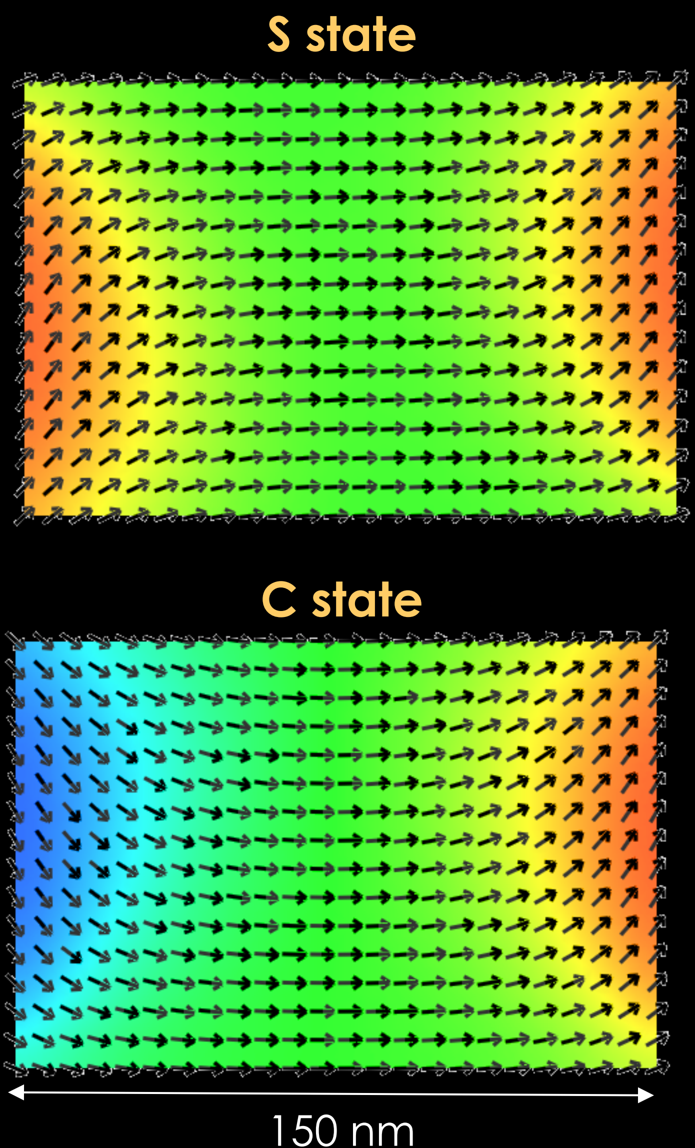
No magnetocrystalline anisotropy

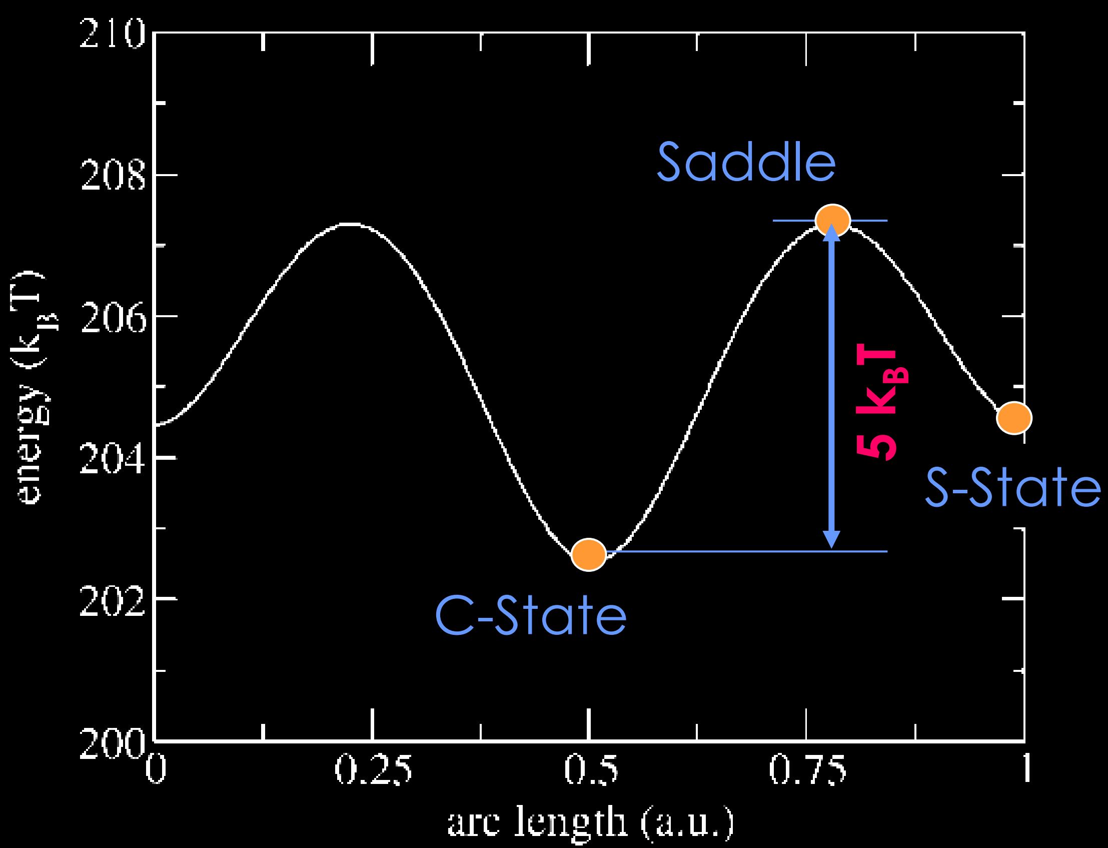




No external field

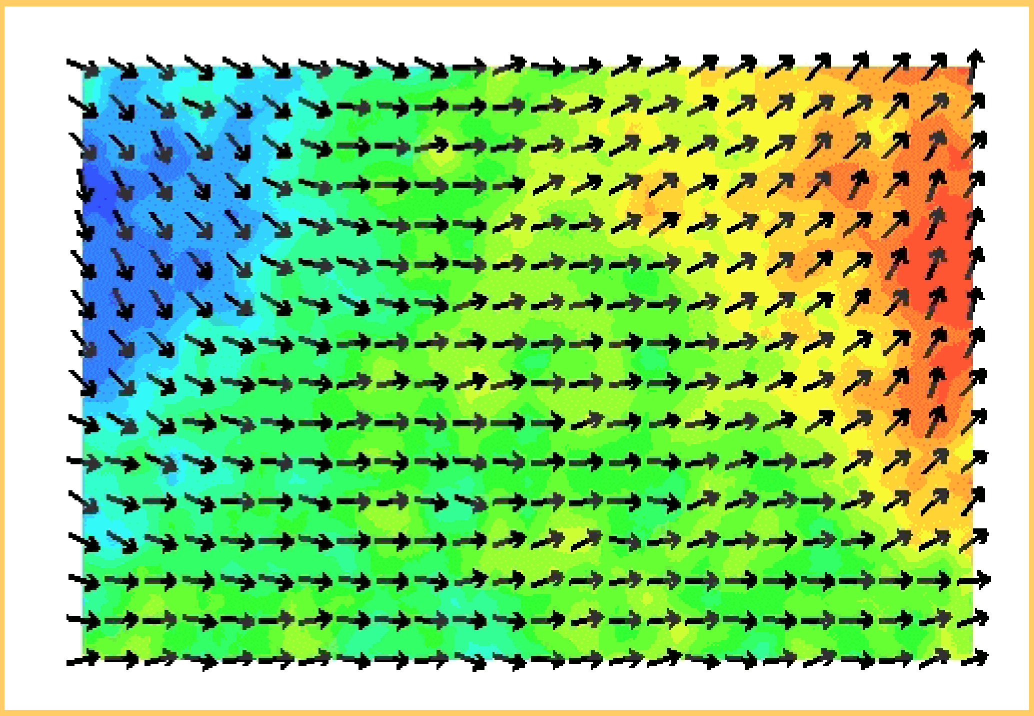
Example 5: End domains





End domain configurations

C-state to S-state transition



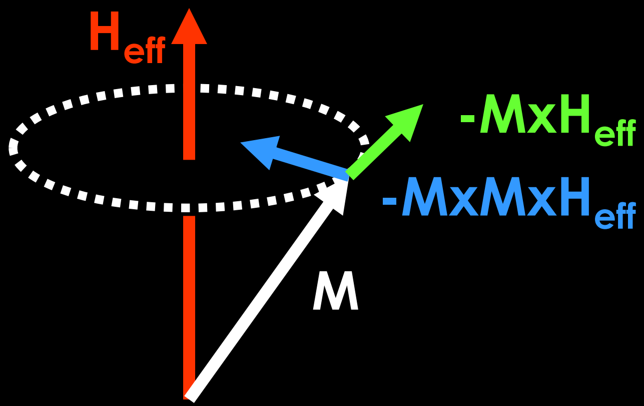
Mag Noise
Switching of end domains

Relaxation time
about 5 ns
$\tau = (1/f_0)\ \exp(E_b/k_B T)$

Thermal effects

Equation of motion

- Gyromagnetic precession
- Damping
- Stochastic field

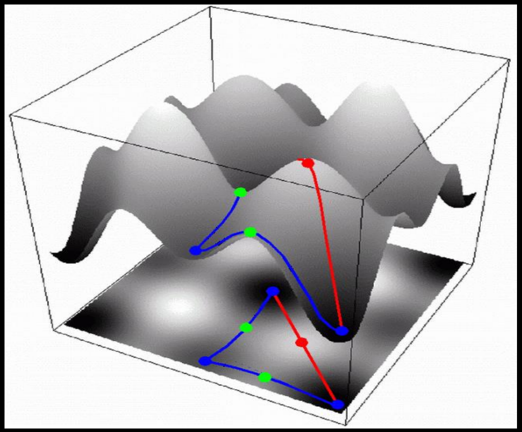


$\mathbf{M} = \mathbf{M}$(time, temperature)

nanoseconds

Path finding method

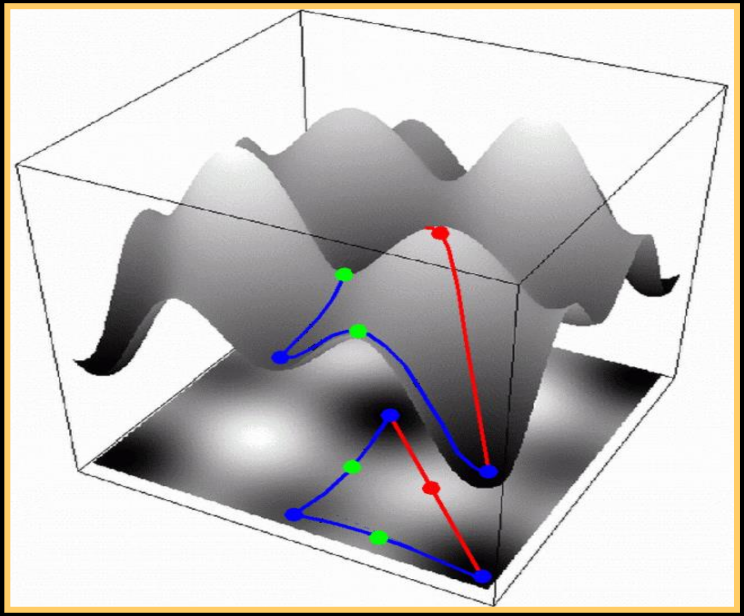
- Energy landscape
- Find a path between two local minima



$\tau = f_0^{-1} \exp(E_{barrier}/k_B T)$

years

Elastic band method



Initial guess
Straight line in configuration space

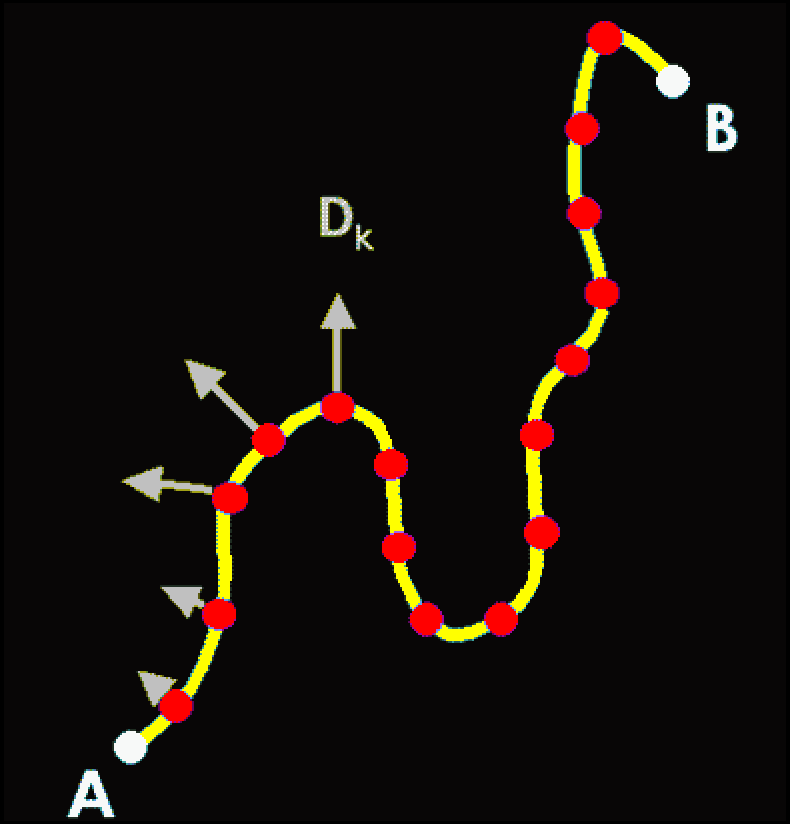
Minimum energy path
Highest transition probability at zero temperature

Energy barrier
MEP connects two minima over the lowest saddle point

- minima
- maxima
- saddle points

R Dittrich, T Schrefl, D Suess, W Scholz, H Forster, J Fidler, J. Magn. Mater. 250 (2002) 12.
G Henkelman, BP Uberuaga, H Jonsson, J. Chem. Phys.113 (2000) 22.

Elastic band method



Images intermediate states between A and B

Springs between subsequent images to enforce continuity

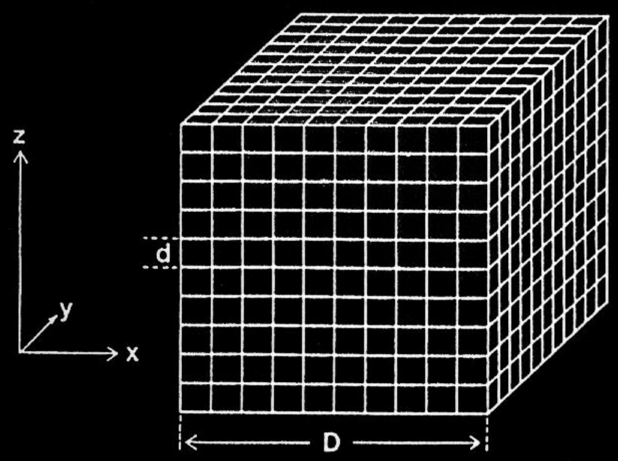
Force on each image due to potential energy and spring

Minimum energy path
Components of the force that is normal to the path are zero

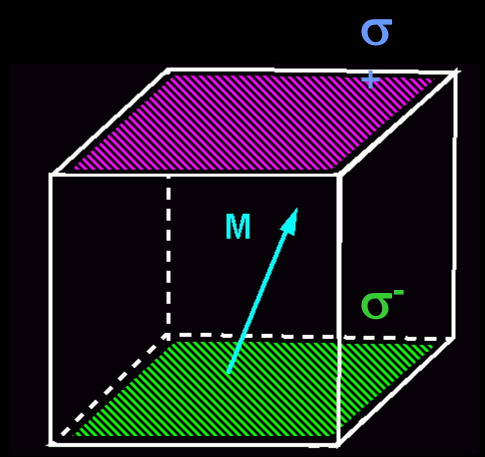
Open source micromagnetics

An example using MAGPAR

Integral approach



- divide particles into cubic cells
- rigid magnetic moment within each cell



- sum over charge sheets to obtain the **magnetostatic field** (FFT)
- “one” LLG equation per cell

Magnetostatics (Integral)

Field sources

$$\rho(\boldsymbol{r}) = -\mathrm{div}\boldsymbol{M}\ (\boldsymbol{r})$$ volume charges

$$\sigma(\boldsymbol{r}\ ) = \boldsymbol{M}\ (\boldsymbol{r}\ ) \cdot \boldsymbol{n}$$ surface charges

Magnetic field

$$U(\boldsymbol{r}) = \frac{1}{4\pi} \int_{V_0} \frac{\rho(\boldsymbol{r}')}{|\,\boldsymbol{r} - \boldsymbol{r}'\,|} \mathrm{d}^3\boldsymbol{r}' + \frac{1}{4\pi} \int_S \frac{\boldsymbol{\sigma}(\boldsymbol{r}')\cdot \mathrm{d}\boldsymbol{f}'}{|\,\boldsymbol{r} - \boldsymbol{r}'\,|}$$

$$\boldsymbol{H}_\mathrm{d}(\boldsymbol{r}) = -\nabla U(\boldsymbol{r})$$

magnetic scalar potential

Magnetostatics (FEM)

Partial differential equation

$$\nabla^2 U(\boldsymbol{r}) = \nabla \cdot \boldsymbol{M}(\boldsymbol{r}) \qquad \text{for } \boldsymbol{r} \in \Omega_{\text{in}} \qquad (1)$$

$$\nabla^2 U(\boldsymbol{r}) = 0 \qquad \text{for } \boldsymbol{r} \in \Omega_{\text{ext}} \qquad (2)$$

Boundary condition

normal component of B field is continuous $\qquad B = \mu_0 (H + M)$

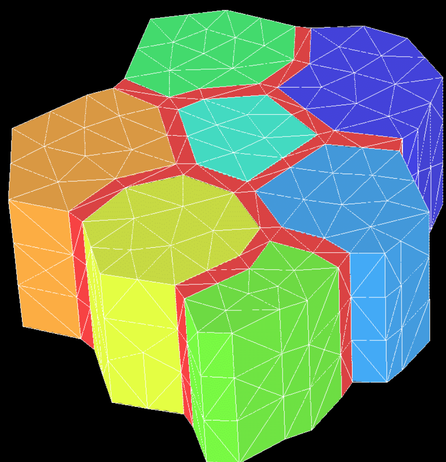
$$\mu_0(-\nabla U^{\text{in}} + \boldsymbol{M}) \cdot \boldsymbol{n} = \mu_0(-\nabla U^{\text{ext}} + 0) \cdot \boldsymbol{n}$$

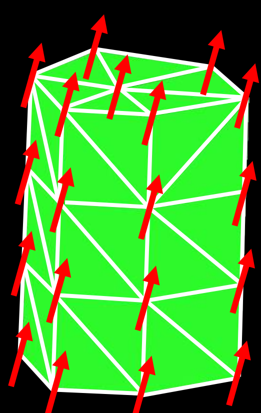
$$\boldsymbol{M} \cdot \boldsymbol{n} = (\nabla U^{\text{in}} - \nabla U^{\text{ext}}) \cdot \boldsymbol{n}$$

$$(\nabla U^{\text{in}} - \nabla U^{\text{ext}}) \cdot \boldsymbol{n} = \sigma \qquad (3)$$

→ **Solve (1), (2), and (3) using standard numerical methods (finite elements, finite differences)**

Finite element micromagnetics





subdivide grains into tetrahedrons

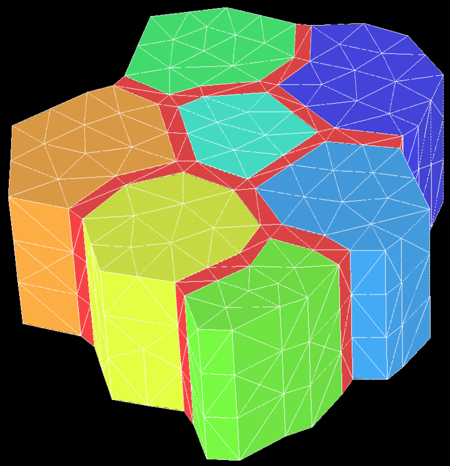
Interpolate magnetization and the magnetic scalar potential

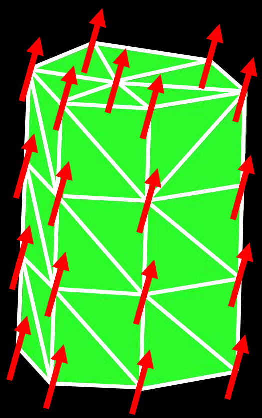
calculate Gibbs free energy for each element

define a magnetic moment and a effective field at each node

solve a system of ordinary differential equations

Finite element micromagnetics





subdivide grains into tetrahedrons

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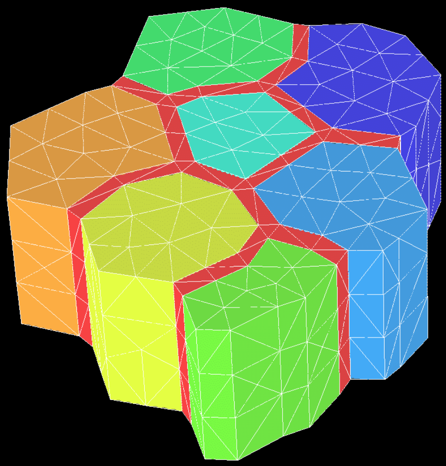
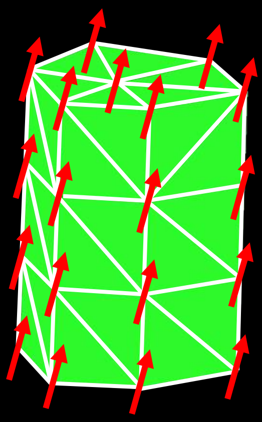
Finite element micromagnetics





subdivide grains into tetrahedrons

Interpolate magnetization and the magnetic scalar potential

calculate Gibbs free energy for each element

define a magnetic moment and a effective field at each node

solve a system of ordinary differential equations

$$\frac{1+\alpha^2}{|\gamma|}\frac{d\mathbf{M}}{dt} = -\mathbf{M}\times\mathbf{H}_{\mathrm{eff}} - \frac{\alpha}{M_s}\mathbf{M}\times\mathbf{M}\times\mathbf{H}_{\mathrm{eff}}$$

Open source micromagnetics

Software	Developer	method	download
OMMF	NIST	Finite difference	math.nist.gov/oommf/
MAGPAR	TU Vienna	Finite elements	http://www.magpar.net/
NMAG	University of Southampton	Finite elements	nmag.soton.ac.uk/nmag/

Open source package “magpar”

magpar is a finite element micromagnetics package which combines several unique features:

Applicability to a variety of static and dynamic micromagnetic problems including uniaxial/cubic anisotropy, exchange, magnetostatic interactions and external fields

Flexibility of the finite element method concerning the geometry and accuracy by using unstructured graded meshes

Availability due to its design based on free, open source software packages

Portability to different hardware platforms, which range from simple PCs to massively parallel supercomputers

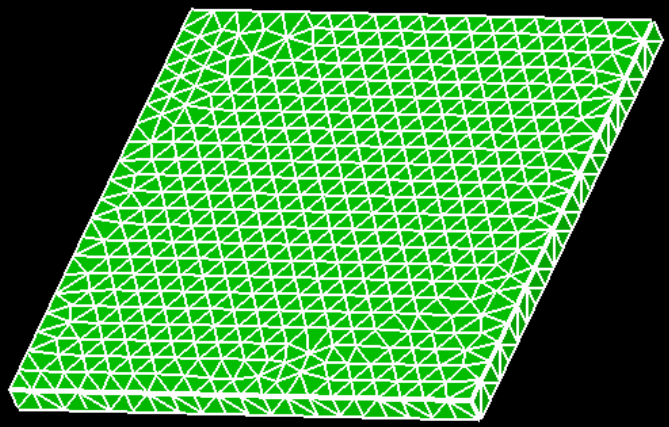
Scalability due to its highly optimized design and efficient libraries

magpar is distributed under the terms of the GNU General Public License
Website: http://http://www.magpar.net/

MAGPAR input files (1)

Geometry (finite element mesh)

- Mesh import (see **Preprocessing**)
  - **MSC.Patran** neutral file
  - AVS **project.inp, project.out: finite element mesh** file
  - **Gmsh** , **GiD** meshes



Mesh of the magpar thin film example

MAGPAR input files (2)

Magnetic material parameters

project.krn: material properties

For each grain (or part of the model with distinct property id) this file contains a line defining its material properties:

```
  theta phi   K1        K2       Js    A         alpha psi    # parameter
  (rad) (rad) (J/m^3)   (J/m^3)  (T)   (J/m)     (1)   (rad)  # units
```

- **theta** and **phi:** direction of the uniaxial magnetocrystalline anisotropy axis in spherical coordinates (rad); theta measured from the z-axis, phi measured from the x-axis in the x-y-plane
- **K1:** first magnetocrystalline anisotropy constant (J/m^3)
- **K2:** second magnetocrystalline anisotropy constant (J/m^3)
- **Js:** saturation polarization (Tesla)
- **A:** exchange constant (J/m)
- **alpha:** Gilbert damping constant (dimensionless)
- **psi:** third Euler angle for cubic anisotropy (assume cubic anisotropy if defined; i.e. valid floating point value). For uniaxial anisotropy set to "uni" (or some other string, which does not represent a valid floating point number).

The grain with property id 1 is assigned the properties in line 1, the grain with property id 2 is assigned the properties in line 2, etc.

MAGPAR input files (3)

Simulation parameters

allopt.txt: simulation parameters

All simulation parameters can be set in the configuration file **allopt.txt** . The example files and the default configuration file **allopt.txt** in the $MAGPAR_HOME/src/cube subdirectory are thoroughly documented. Any option defined in this file can be overridden by an environment variable or command line option (cf. PETSc manual chapter 14 - Other PETSc Features). This useful feature is used in example **mumag3: mumag standard problem #3** .

Additional PETSc internal logging/info/diagnostic options, which may slow down the simulations (!), are given in **allopt_log.txt** .

Output files
Simulation time
External field
Solver parameters
….

MAGPAR Thin film example

Calculate equilibrium magnetic state of a thin film

- download magpar and thin film example
- copy everything into one directory
- edit the simulation parameters (allopt.txt)
- start the simulations
- look at the results

MAG program parameters

allopt.txt particle size

```
##### scaling parameters
# size scaling of finite element mesh (unit: m)
-size 1e-6

##### dimensionless Landau-Lifshitz-Gilbert damping constant
# define for every grain together with material parameters in *.krn
```

change to 100 nm

Initial magnetization

allopt.txt particle size

```
##### initial magnetization
#  negative values: select abs(init_mag), but reverse the magnetization
#  0: magnetization from inp (set file number by -inp below)
#  1: Mx=1
#  2: My=1
#  3: Mz=1
#  4: Mx=My=Mz=sqrt(1/3)=0.57735027
#  5: artificial flower state, center: x=y=z=init_magparm
#  6: set magnetization in x-z plane to theta=init_magpar (from z-axis)
#  7: vortex state: core radius = init_magparm, center in (x=0,y=0)
#  8: random magnetization
#  9: Bloch wall: center at x = init_magparm, width=x/10
# 10: M // anisotropy axes
-init_mag 3
```

Change to 1 (parallel x axis)

Time integration

allopt.txt minimization method

```
##### minimization method
# 0: PVODE (LLG time integration) or
# 1: TAO (energy minimization)
# -mode 0
```

set to time integration

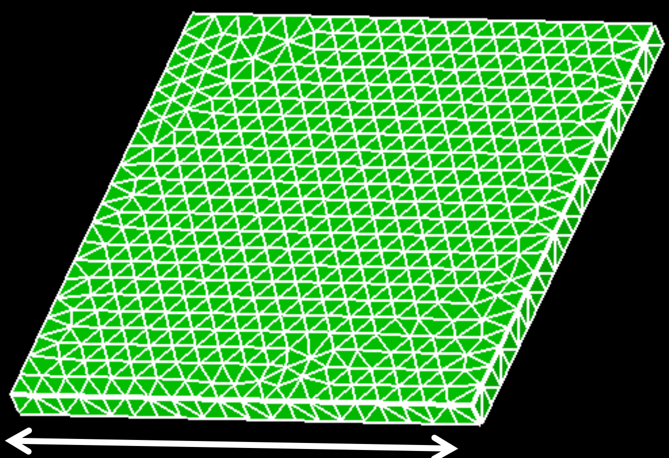
Check mesh size

Finite element size

should be smaller than the exchange length

Exhange length

5 nm for NiFe (permalloy)



1 unit

in mesh generator program

20 elements

100 nm / 20 = 5 nm   OK

Refine the mesh

If initial mesh size > exchange length

allopt.txt Refine the finite element mesh

```
##### regular mesh refinement
# number of regular refinement steps
# (every step generates 8x as many elements and about 8x as many nodes!!!)
-refine 0
```

Give the number of refinement steps

MAG program parameters

allopt.txt   simulation time

```
#########################################################################
# LLG time integration

#Time step options ----------------------------------------------------
#   -ts_max_steps <5000>: Maximum number of time steps (TSSetDuration)
#ignored
#   -ts_init_time <0>: Initial time (TSSetInitialTime) (unit: ns)
-ts_init_time 0.0
#   -ts_max_time <5>: Time to run to (TSSetDuration) (unit: ns)
-ts_max_time -1e99
#   -ts_dt <0.020944>: Initial time step (TSSetInitialTimeStep)
```

change to 5 ns

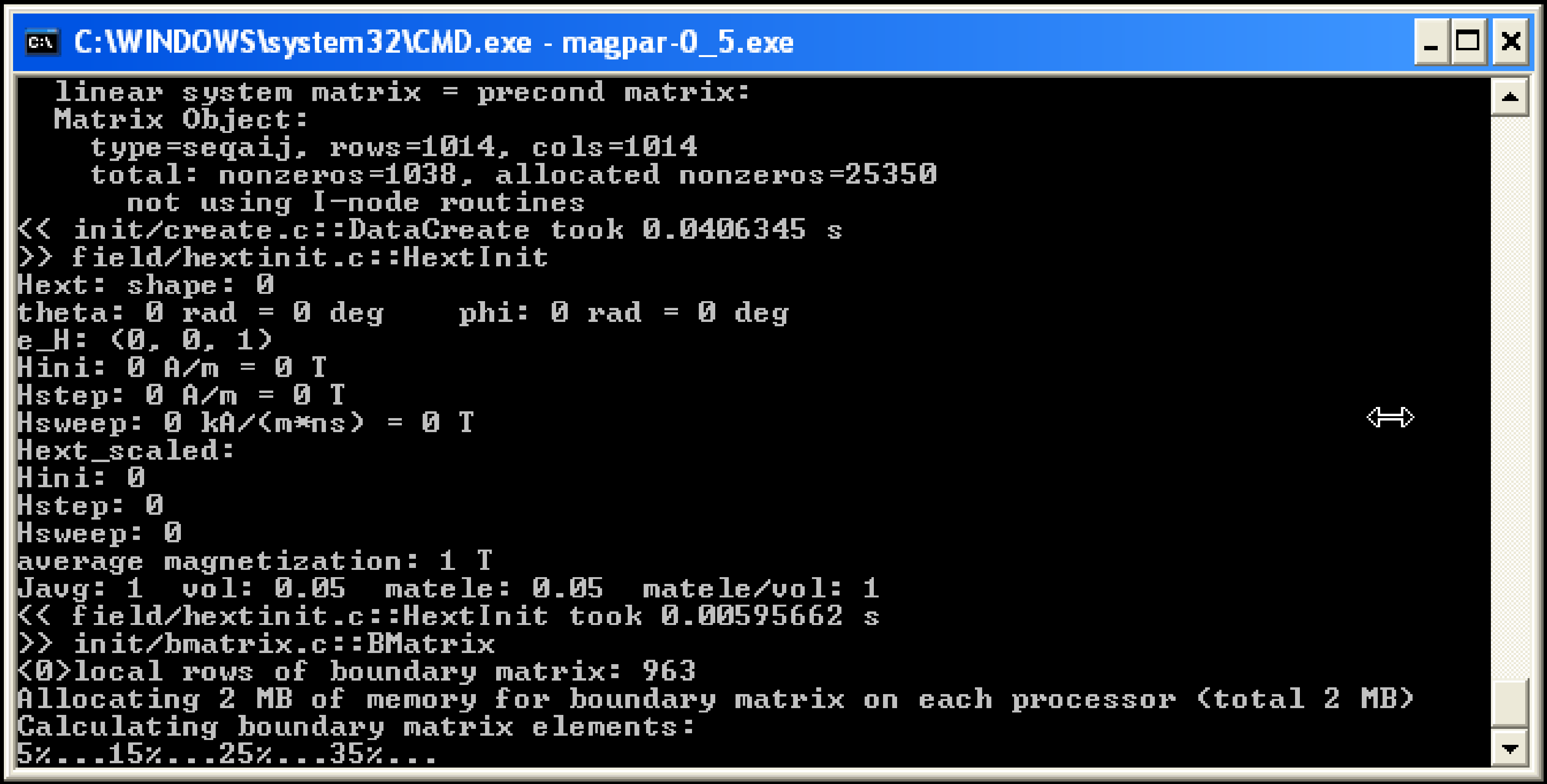
MAGPAR program parameters

allopt.txt   magpar 0.7 parameters

```
##################################################################
# magpar configuration file: allopt.txt
##################################################################

-simName thinfilm

-size 100.e-9            # set length scaling factor to microns
-init_mag 1              # initial magnetization in x-direction
-mode 0                  # solve LLG equation
-ts_max_time 5           # run problem for 5 ns

-slice_n 0,0,1           # slice plane for png files: x-y-plane
-slice_p 0,0,0.025
```

You need to add these 4 parameters

Run the program

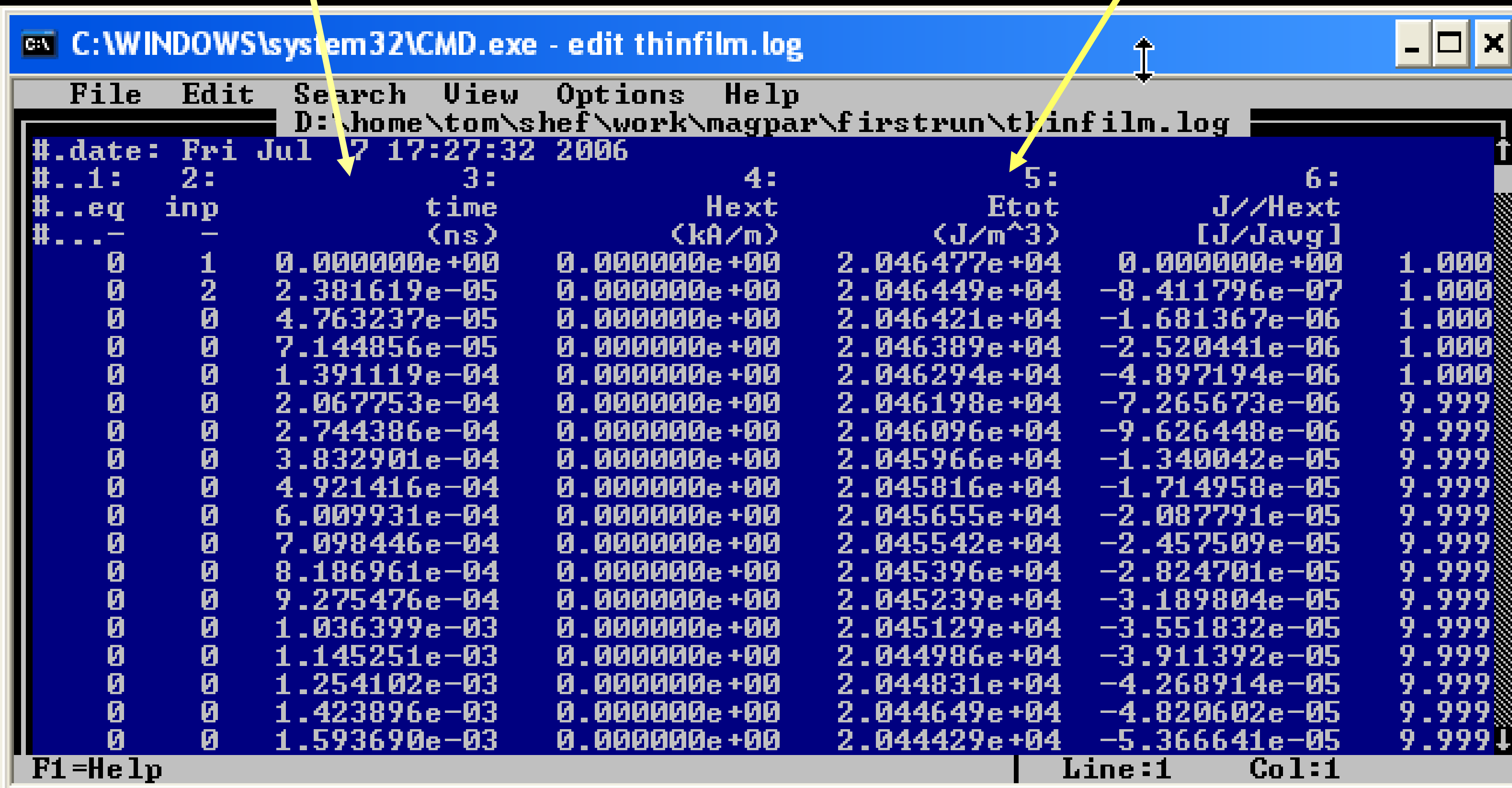


Start magpar.exe from a DOS command line

Look at the results

Time

Total energy



C:\WINDOWS\system32\CMD.exe - edit thinfilm.log

File Edit Search View Options Help

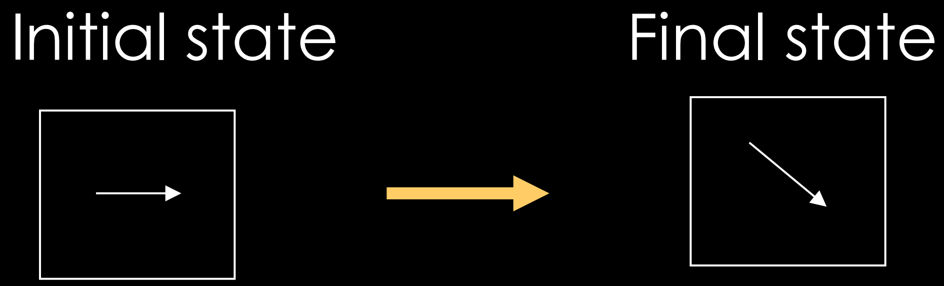
D:\home\tom\shef\work\magpar\firstrun\thinfilm.log

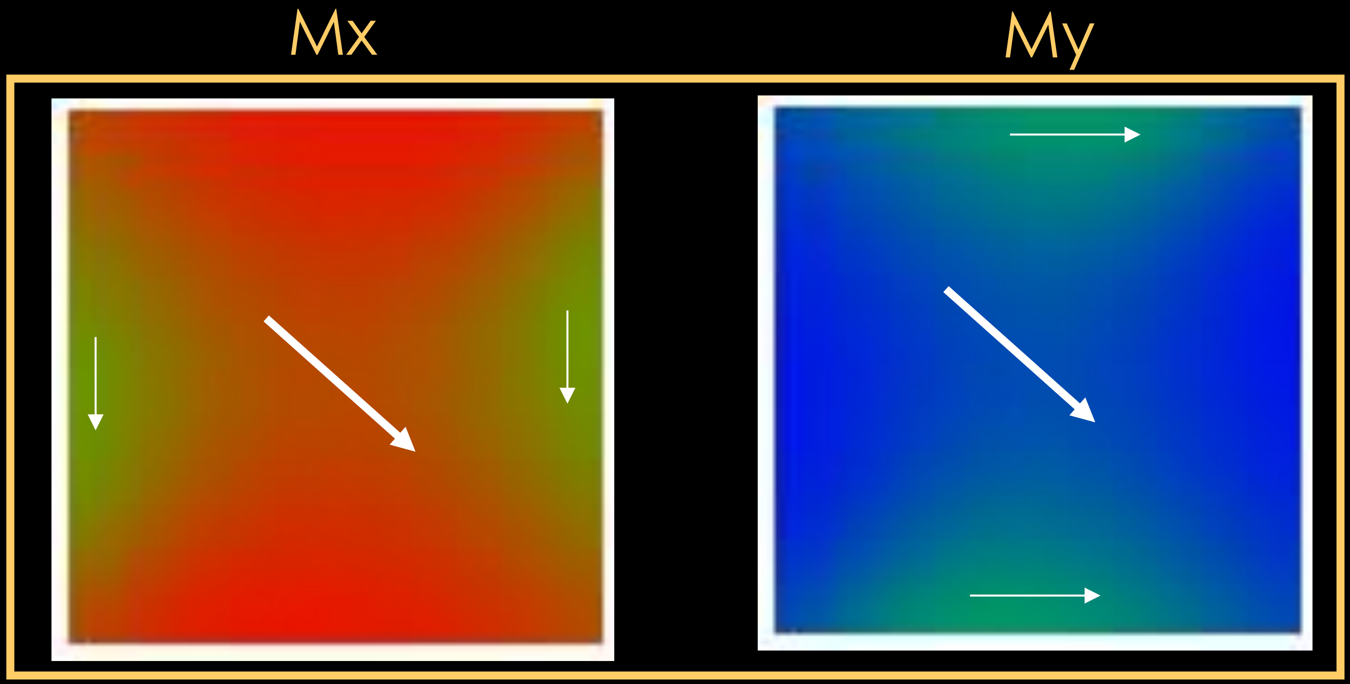
#.date: Fri Jul 7 17:27:32 2006

#..1:	2:	3:	4:	5:	6:	
#..eq	inp	time	Hext	Etot	J//Hext	
#...-	-	(ns)	(kA/m)	(J/m^3)	[J/Javg]	
0	1	0.000000e+00	0.000000e+00	2.046477e+04	0.000000e+00	1.000
0	2	2.381619e-05	0.000000e+00	2.046449e+04	-8.411796e-07	1.000
0	0	4.763237e-05	0.000000e+00	2.046421e+04	-1.681367e-06	1.000
0	0	7.144856e-05	0.000000e+00	2.046389e+04	-2.520441e-06	1.000
0	0	1.391119e-04	0.000000e+00	2.046294e+04	-4.897194e-06	1.000
0	0	2.067753e-04	0.000000e+00	2.046198e+04	-7.265673e-06	9.999
0	0	2.744386e-04	0.000000e+00	2.046096e+04	-9.626448e-06	9.999
0	0	3.832901e-04	0.000000e+00	2.045966e+04	-1.340042e-05	9.999
0	0	4.921416e-04	0.000000e+00	2.045816e+04	-1.714958e-05	9.999
0	0	6.009931e-04	0.000000e+00	2.045655e+04	-2.087791e-05	9.999
0	0	7.098446e-04	0.000000e+00	2.045542e+04	-2.457509e-05	9.999
0	0	8.186961e-04	0.000000e+00	2.045396e+04	-2.824701e-05	9.999
0	0	9.275476e-04	0.000000e+00	2.045239e+04	-3.189804e-05	9.999
0	0	1.036399e-03	0.000000e+00	2.045129e+04	-3.551832e-05	9.999
0	0	1.145251e-03	0.000000e+00	2.044986e+04	-3.911392e-05	9.999
0	0	1.254102e-03	0.000000e+00	2.044831e+04	-4.268914e-05	9.999
0	0	1.423896e-03	0.000000e+00	2.044649e+04	-4.820602e-05	9.999
0	0	1.593690e-03	0.000000e+00	2.044429e+04	-5.366641e-05	9.999

F1=Help Line:1 Col:1

Magnetization patterns





Summary

Micromagnetics
Effects of size, shape, granular structure
Dynamics and reversal modes

Energy contributions
From Stoner-Wohlfarth theory to multi-domain magnetization dynamics

Thermal effects
Stochastic dynmmics (short times)
Energy barriers (long times)

Solution techniques
Integral approach (regular structures)
Finite element approach (irregular structures)

Literature

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- D. Suess, J. Fidler and T. Schrefl, Micromagnetic simulation of magnetic materials, in Handbook of Magnetic Materials, edited by K.H.J. Buschow, (2006), Elsevier Vol. 16, pp. 41-125
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