Nanomagnetism

Nanomagnetism

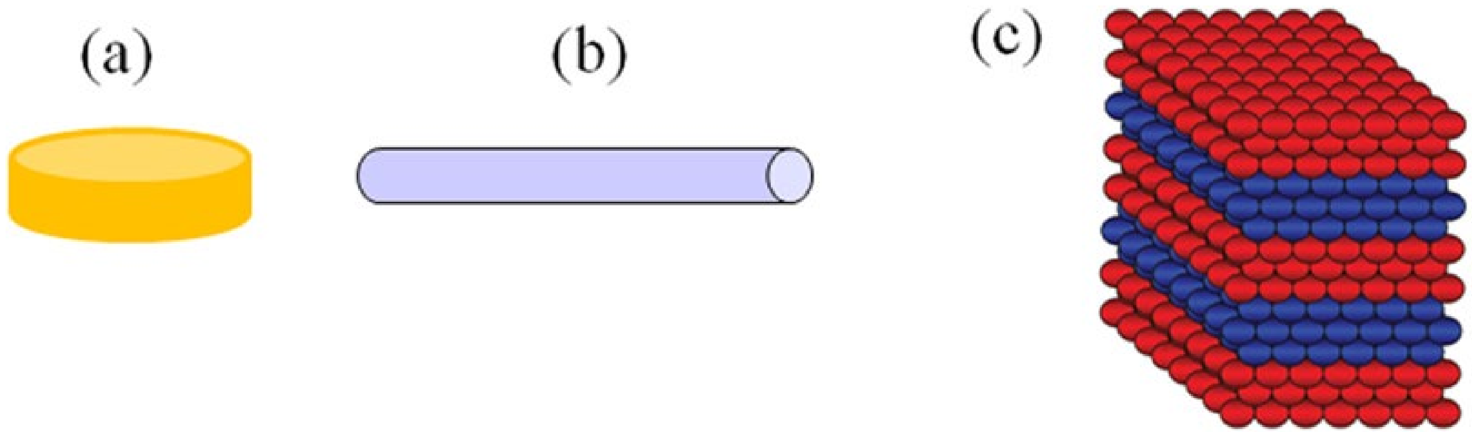
- Atomic magnetism
- Exchange, anistropy, superparamagnetism
- Magnetic storage

Nanoscaled magnetic "objects"

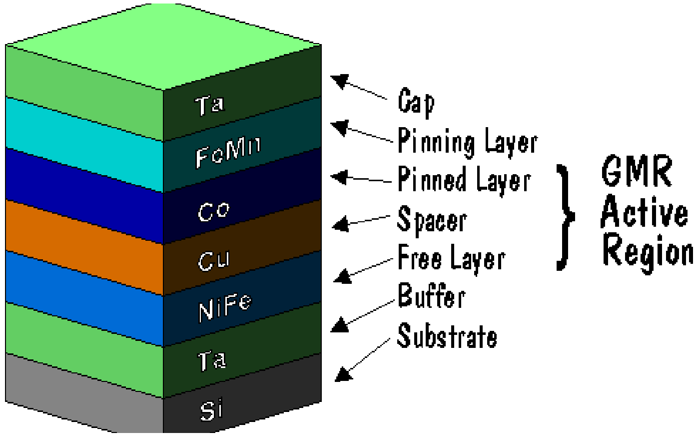
Nanodots Nanoparticles

Nanowires

Ultrathin films and multilayers



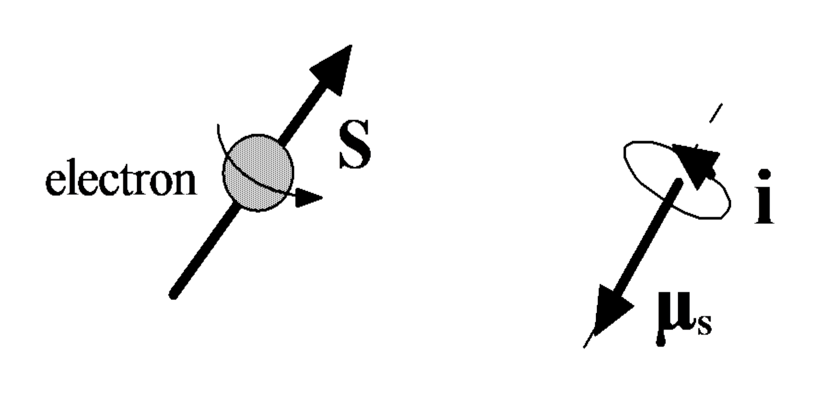
Ultrathin complex multilayers



Microscopic sources of magnetic field

Intrinsic magnetic moment of an electron

$$\mu_S = 2\mu_B\sqrt{s(s+1)} = \mu_B\sqrt{3} \approx \mu_B$$



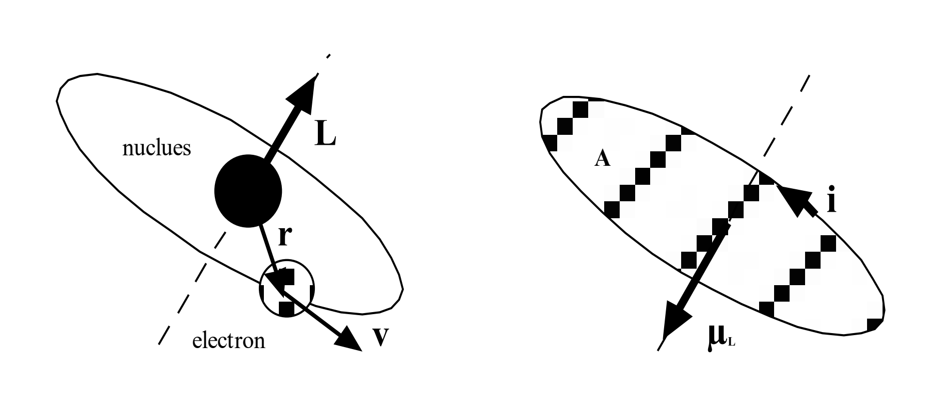
(the classical picture with the electron that rotates about itself is not correct)

$$\mu_B \equiv \frac{e\hbar}{2m_e} \cong 9.3\times10^{-24}\ \text{Am}^2$$

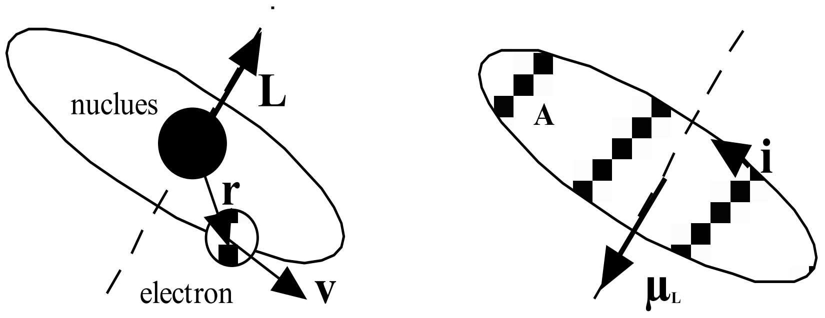
is called *Bohr magneton*.

Orbital magnetic moment of an electron

$$\mu_L = -\frac{e}{2m_e}L \approx \mu_B$$



Orbital magnetic moment of an electron



- Equilibrium between **Coulomb force** and **centrifugal force:**

$$\frac{e}{4\pi\varepsilon_0 r^2} = m_e\frac{v^2}{r} \quad \Rightarrow \quad v = e\sqrt{\frac{1}{4\pi\varepsilon_0 r}\frac{1}{m_e}}$$

- **Orbital angular momentum:**

$$L = rm_e v \qquad \Rightarrow (\text{for} \quad r \sim 10^{-10}\text{m}) \qquad L = e\sqrt{\frac{m_e r}{4\pi\varepsilon_0}} \cong 10^{-34}\ \text{Js} \cong \hbar$$

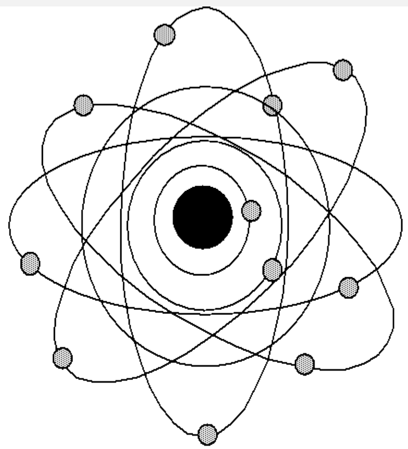
- The **orbital magnetic moment** is then**:**

$$\mu_L = iA = -\left(\frac{ev}{2\pi r}\right)(\pi r^2) = -\frac{ev}{2}r = -\frac{e}{2m_e}L \approx \mu_B$$

Note:

$$i \sim \frac{\mu_B}{A} \sim \frac{\mu_B}{\pi r^2} \sim 0.3\ \text{mA}$$

Magnetic moment of an atom



Questions:

- The **magnetic moment of an atom** with **Z electrons** is the **"sum"** of the magnetic moment of each electron ?
- Yes. We will see how the **"sum"** must be done.

- For an atom with many electrons, the magnetic moment **is much larger** than the Bohr magneton ?
- No. The biggest is only **a few times the Bohr magneton** (because filled shells have zero angular momentum).

- The **magnetic moment of the nucleus** is negligible with respect to that of the electron ?
- Yes. It is at least **1000 times smaller** (because $\mu \propto 1/m$) .

How to compute the total magnetic moment of an atom ?

1. Solve the **Schrödinger equation** for the atomic system (electrons + nucleus)

$$H_{atom}\psi_i = E_i\psi_i$$

H_{atom}: Hamiltonian operator (total energy)

ψ_i: Wavefunction of state i (possible state of the system)

E_i: Energy of state i (possible energy of the system)

Electron kinetic energy	Electron-Nucleus Coulomb interaction	Electron-Electron Coulomb interaction (Exchange)	Spin-Orbit Interaction (Anisotropy)

$$H_{atom} = \sum_{i=1}^{Z}\frac{p_i^2}{2m} - \sum_{i=1}^{Z}\frac{Ze^2}{r_i^2} + \sum_{i<j}^{Z}\frac{e^2}{\left|r_i - r_j\right|^2} + \sum_{i=1}^{Z}(\mathbf{l}_i\cdot\mathbf{s}_i)\xi(r_i)$$

2. Compute the value of the **magnetic moment** for each state of the system

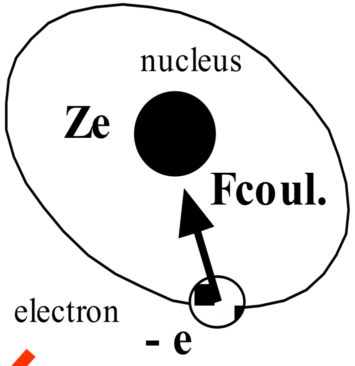
$$\mu_i = \left|\langle\psi_i|\mu|\psi_i\rangle\right|$$

μ: Magnetic moment operator

The hydrogen-like atom

- The "hydrogen-like atom" is an hypothetical atom with:
  - one electron of charge –e
  - one nucleus of charge Ze

with total energy that contains only:
- the kinetic energy of the electron
- the Coulomb interaction electron-nucleus

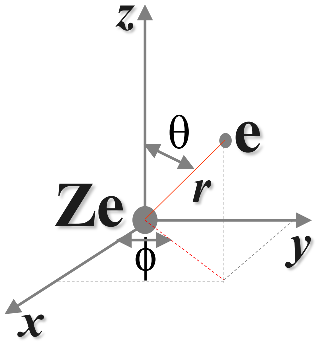


$$H_{atom} = \sum_{i=1}^{Z} \frac{p_i^2}{2m_e} - \sum_{i=1}^{Z} \frac{Ze^2}{4\pi\varepsilon_0 r_i} + \sum_{i<j}^{Z} \frac{e^2}{4\pi\varepsilon_0 |r_i - r_j|} + \sum_{i=1}^{Z} (\mathbf{l}_i \cdot \mathbf{s}_i)\xi(r_i) =$$

$$= \frac{p^2}{2m_e} - \frac{Ze^2}{4\pi\varepsilon_0 r}$$

- **The Hamiltonian operator is:**

$$H = \frac{p^2}{2m_e} - \frac{Ze^2}{4\pi\varepsilon_0 r} \rightarrow H = -\frac{\hbar^2\nabla^2}{2m_e} - \frac{Ze^2}{4\pi\varepsilon_0 r}$$



∇^2 : Laplace operator

EPFL

- An **electron state** is properly described by **4 quantum numbers**:

Principle:

n = 1, 2, 3, 4 ("diameter" of the electron orbit)

Orbital angular momentum:

l = 0, 1, 2, n-1. ("shape" of the electron orbit)

z-component of the orbital angular momentum:

$l_z = -l, -l+1, .., l-1, l$ ("direction" of the electron orbit)

z-component of the spin angular momentum:

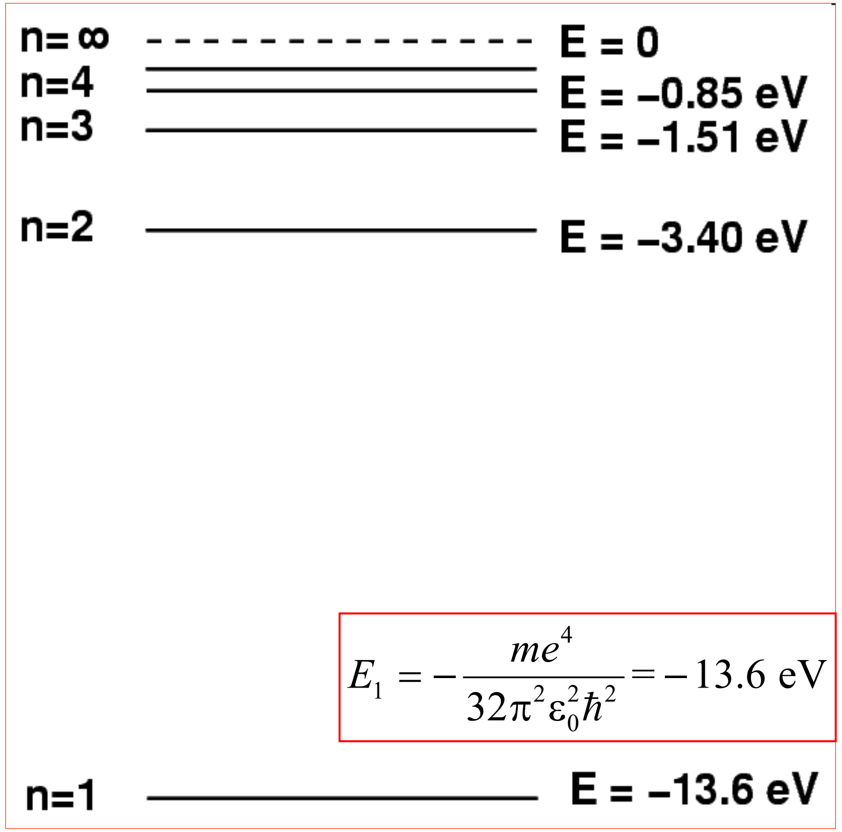
$s_z = \pm 1/2$ (spin orientation of the electron)

Example: Energy levels hydrogen atom

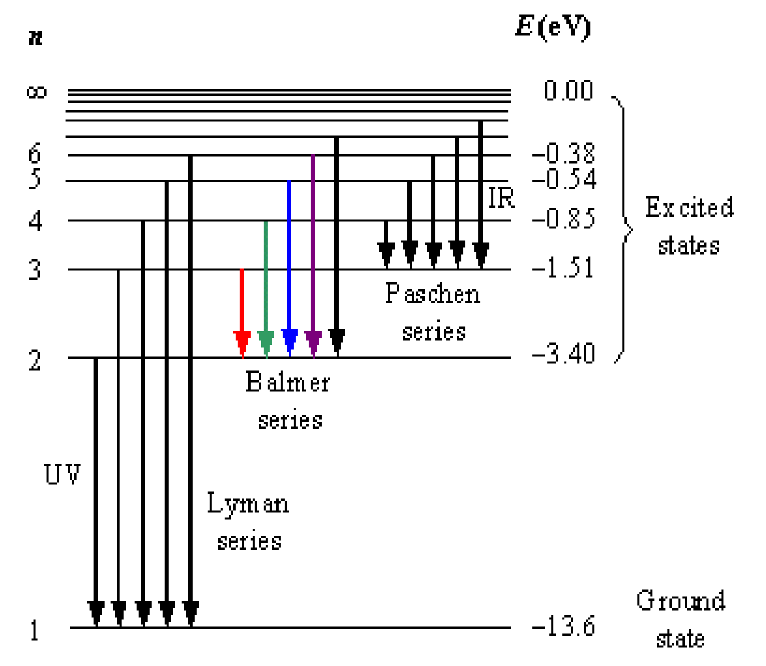
Energy levels for the hydrogen atom (Z=1)

$$Z=1 \Rightarrow \; E_n = -\frac{m_e e^4}{32\pi^2\varepsilon_0^2\hbar^2}\frac{1}{n^2}$$

NOTE: The experimental values for the hydrogen atom energy differ from these theoretical values by less than 0.0001 eV.



$$E_1 = -\frac{me^4}{32\pi^2\varepsilon_0^2\hbar^2} = -13.6 \text{ eV}$$

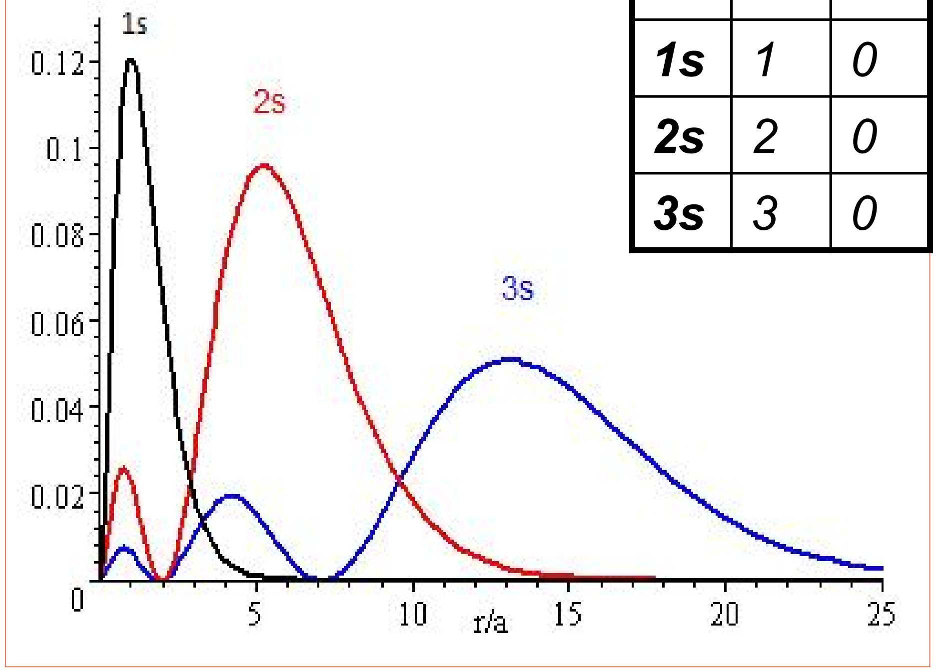


Energy levels of the hydrogen atom with some of the transitions between them that give rise to the spectral lines indicated.

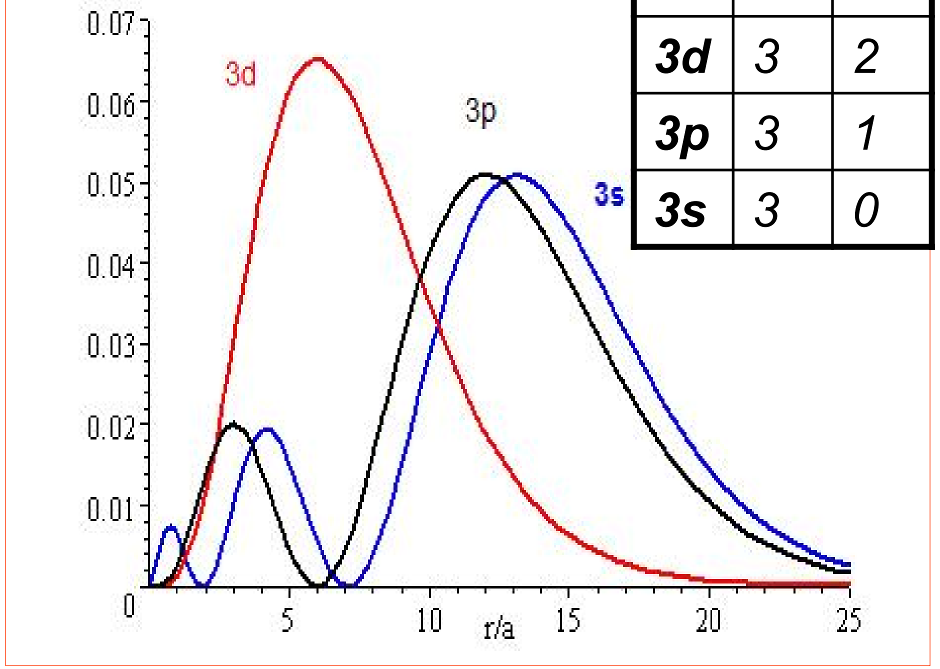
Distribution of probability of presence of an electron

Radial distribution of probability of presence of an electron

$$D(r) = r^2 dr \int_0^{\pi} \sin\theta\, d\theta \int_0^{2\pi} \left|\psi\left(r,\theta,\varphi\right)\right| d\varphi$$

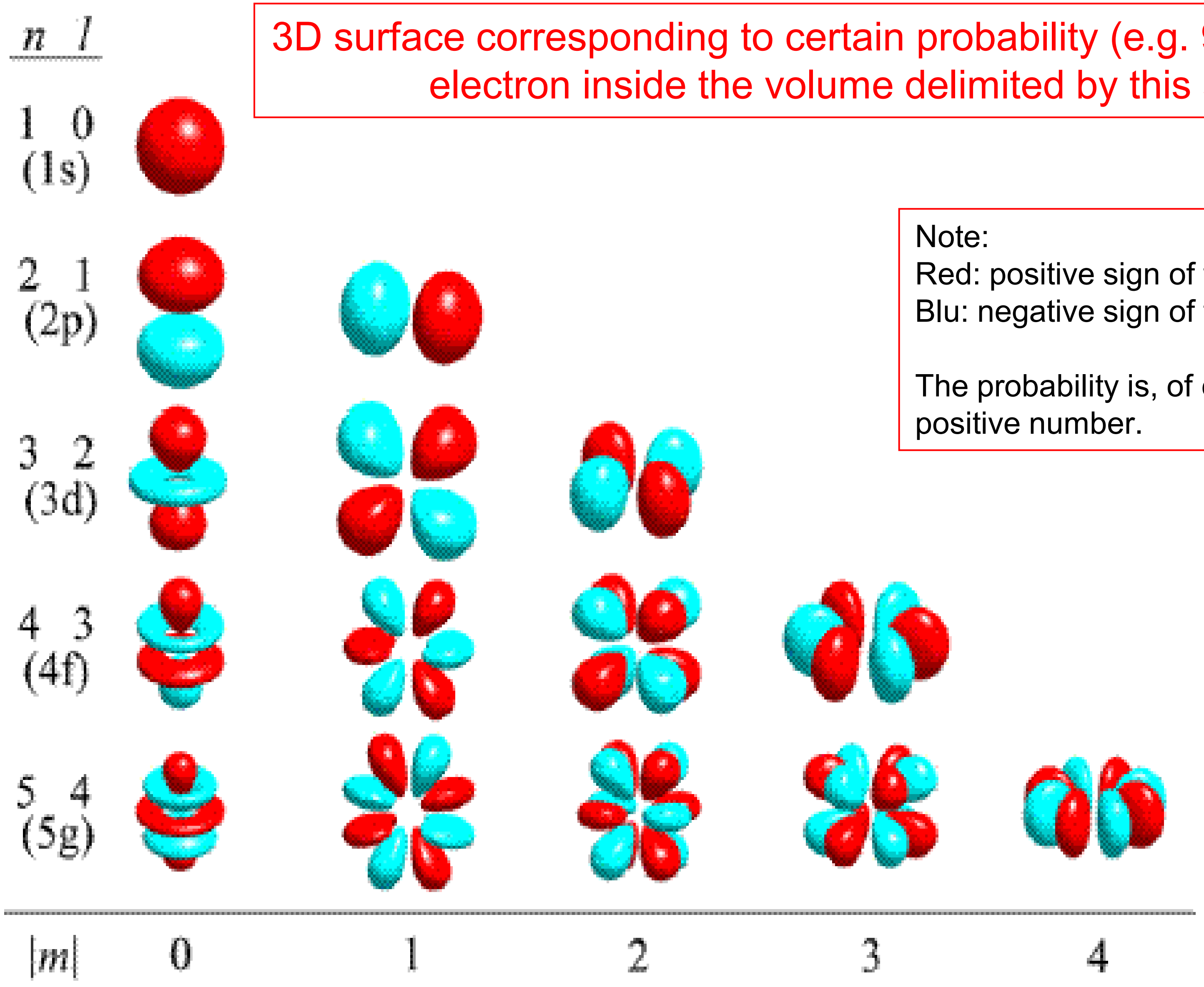


	n	*l*
1s	*1*	*0*
2s	*2*	*0*
3s	*3*	*0*



	n	*l*
3d	*3*	*2*
3p	*3*	*1*
3s	*3*	*0*

3D surface corresponding to certain probability (e.g. 90%) to find the electron inside the volume delimited by this surface



Note:
Red: positive sign of the wavefunction
Blu: negative sign of the wavefunction

The probability is, of course, always a positive number.

The real atom

The **hydrogen-like atom:**
- one electron with charge -e
- one nucleus with charge +Ze

$$H = \frac{p^2}{2m_e} - \frac{Ze^2}{4\pi\varepsilon_0 r}$$

The **real atom**:
- Z electrons, each with charge -e
- one nucleus with charge +Ze
- electrons are interacting with each other
- the orbital and the spin angular momentum of the electrons are interacting

$$H = \sum_{i=1}^{Z} \frac{p_i^2}{2m_e} - \sum_{i=1}^{Z} \frac{Ze^2}{4\pi\varepsilon_0 r_i} + \sum_{i<j}^{Z} \frac{e^2}{4\pi\varepsilon_0 \left| r_i - r_j \right|} + \sum_{i=1}^{Z} (\mathbf{l}_i \cdot \mathbf{s}_i)\xi(r_i)$$

$$H=\sum_{i=1}^{Z}\frac{p_i^2}{2m_e}-\sum_{i=1}^{Z}\frac{Ze^2}{4\pi\varepsilon_0 r_i}+\sum_{i<j}^{Z}\frac{e^2}{4\pi\varepsilon_0\left|r_i-r_j\right|}+\sum_{i=1}^{Z}(\mathbf{l}_i\cdot\mathbf{s}_i)\xi(r_i)$$

Solving the Schrodinger equation for the real atom Hamiltonian is very difficult.

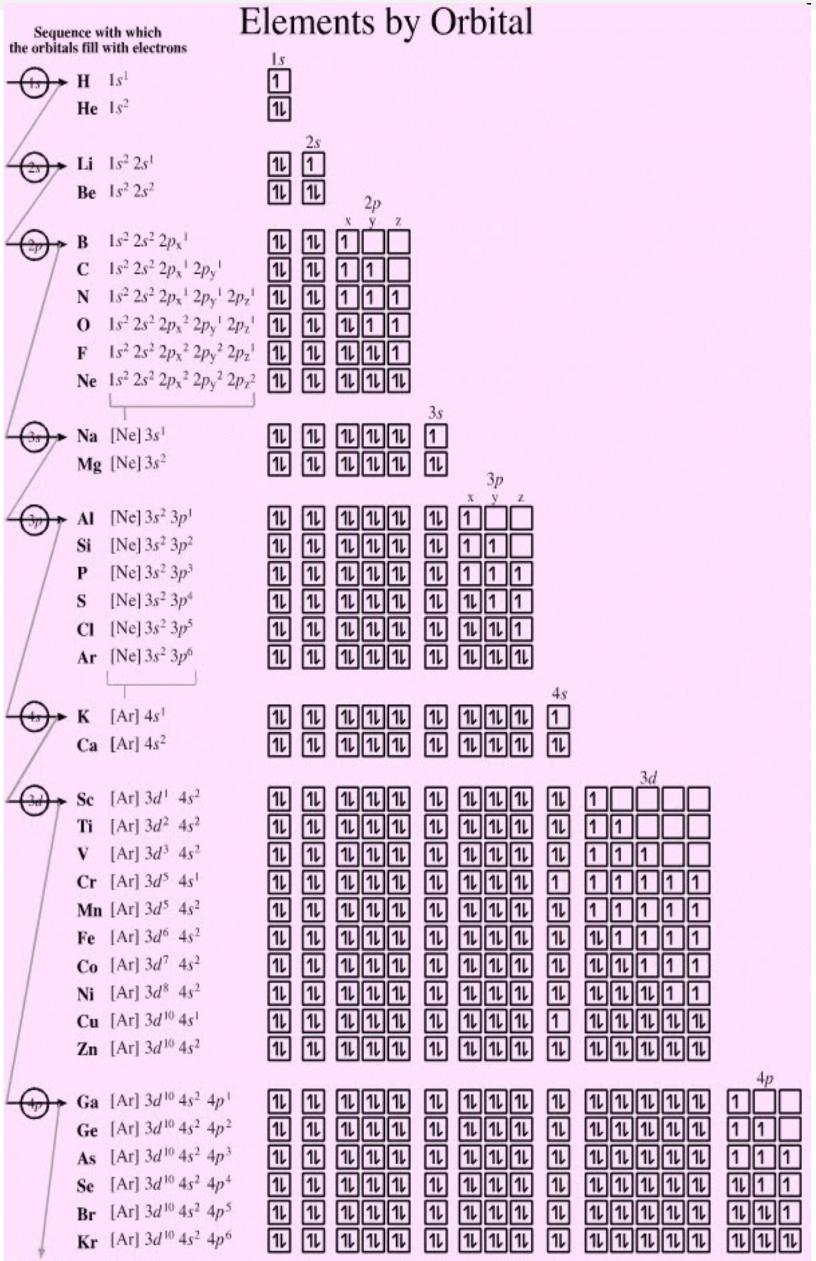
It is easier to:
1)Assume that **the hydrogen-like atom** gives the possible (states, wavefunctions, orbitals) also for the real atom.
2)Introduce some **ad-hoc rules** to describe the way the possible hydrogen-like orbitals are filled with the Z electrons of the real atom.

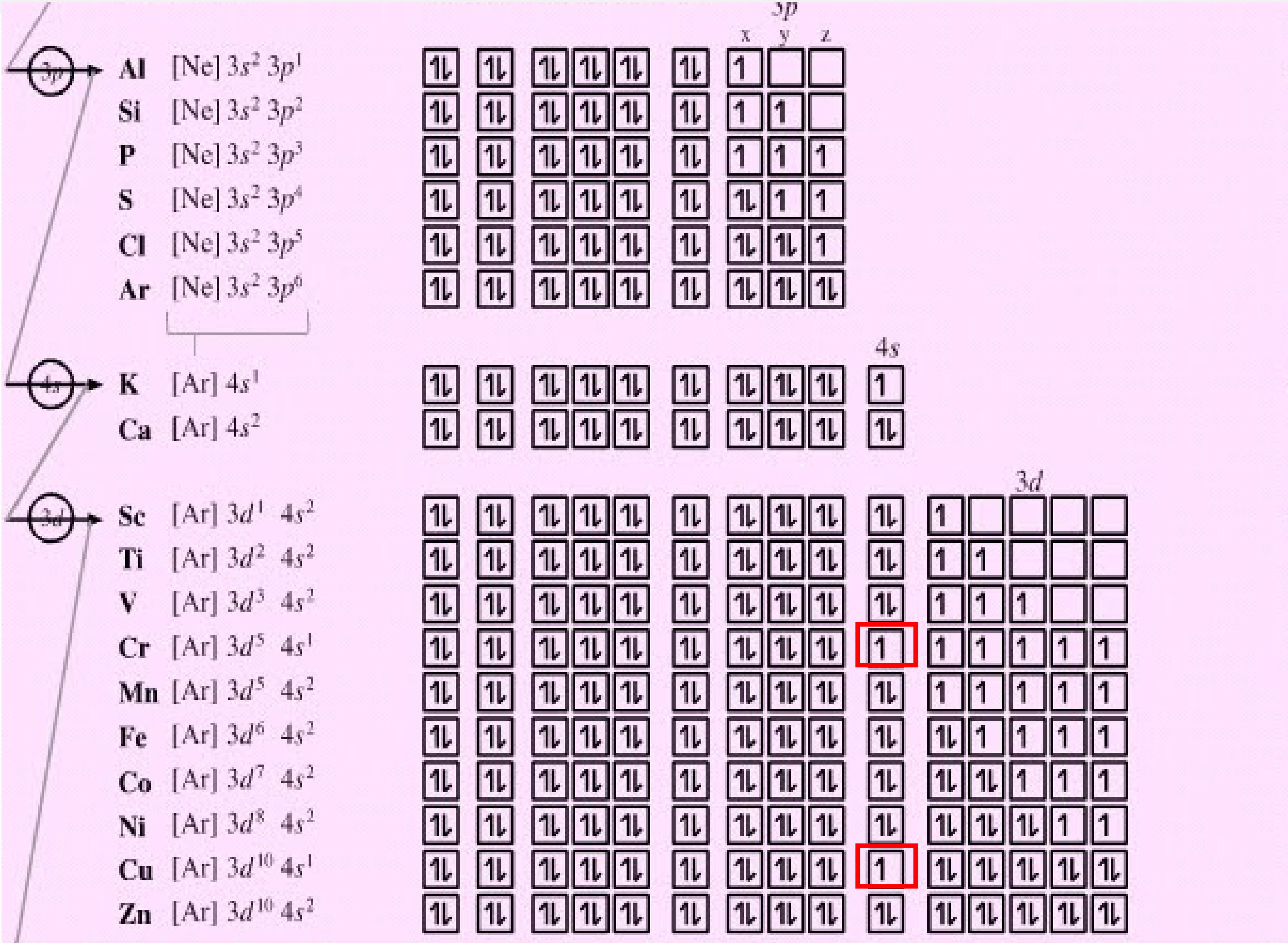
This approx. approach (i.e., hydrogen-like atom orbitals + rules) allows to explain most of the physical, chemical, optical, … properties of the real atoms without solving the complex Hamiltonian of the real atoms.

EPFL

The RULES

Pauli Exclusion Principle	Each orbital contains a **maximum of two electrons** which must be of opposite spin.
Build-up Principle	Electrons fill **lower energy orbitals first.**
Hund's Rule	**No pairing up.** Only when all the orbitals are half filled will pairing-up occur.
Madelung's Rule	Orbitals fill to **minimize *n* + *l*.** For identical *n*+*l*, **minimization** of *n*.





3p
x y z
Al [Ne] $3s^2$ $3p^1$
Si [Ne] $3s^2$ $3p^2$
P [Ne] $3s^2$ $3p^3$
S [Ne] $3s^2$ $3p^4$
Cl [Ne] $3s^2$ $3p^5$
Ar [Ne] $3s^2$ $3p^6$
4s
K [Ar] $4s^1$
Ca [Ar] $4s^2$
3d
Sc [Ar] $3d^1$ $4s^2$
Ti [Ar] $3d^2$ $4s^2$
V [Ar] $3d^3$ $4s^2$
Cr [Ar] $3d^5$ $4s^1$
Mn [Ar] $3d^5$ $4s^2$
Fe [Ar] $3d^6$ $4s^2$
Co [Ar] $3d^7$ $4s^2$
Ni [Ar] $3d^8$ $4s^2$
Cu [Ar] $3d^{10}$ $4s^1$
Zn [Ar] $3d^{10}$ $4s^2$

There are three angular momentum operators:

- **total** angular momentum (usually denoted **J**),
- **orbital** angular momentum (usually denoted **L**),
- **spin** angular momentum (usually denoted **S**).

Total angular momentum **J** for a closed system is conserved.
(Closed system: no mass transferred in or out of the system boundaries, heat and work can be exchanged across the boundary of the system).

L and **S** are *not* generally conserved.
(Spin–orbit interaction allows angular momentum to transfer back and forth between **L** and **S**, with the total **J** remaining constant).

The orbital angular momentum operator $\mathbf{L}$ is defined as (same as classical mechanics):

$$\mathbf{L} = \mathbf{r} \times \mathbf{p}$$

where $\mathbf{r}$ is the position operator and $\mathbf{p}$ is the momentum operator.

Since $\mathbf{p} = -i\hbar\nabla \Rightarrow \boxed{\mathbf{L} = -i\hbar\mathbf{r} \times \nabla}$ where $\nabla = \frac{\partial}{\partial x}\hat{\mathbf{x}} + \frac{\partial}{\partial x}\hat{\mathbf{y}} + \frac{\partial}{\partial z}\hat{\mathbf{z}}$

The spin angular momentum operator $\mathbf{S}$ is an intrinsic property of many particles, with no classical equivalent.

The total angular momentum operator is $\mathbf{J} = \mathbf{L} + \mathbf{S}$.

Russel-Saunders Rule

The total angular momentum of the atom or ion is given by
(valid more accurately for light atoms where the spin-orbit coupling is weaker than spin-spin and orbit-orbit couplings):

$$\mathbf{J} = \mathbf{L} + \mathbf{S} = \sum_{i=1}^{Z} \mathbf{L}_i + \sum_{i=1}^{Z} \mathbf{S}_i$$

Hund Rules

1) The spin vectors $\mathbf{S}_i$ are arranged to <u>maximize</u> total spin **S**
Physical interpretation: minimization of the exchange energy

$$E_{exc} = -J\mathbf{S}_i \cdot \mathbf{S}_j$$

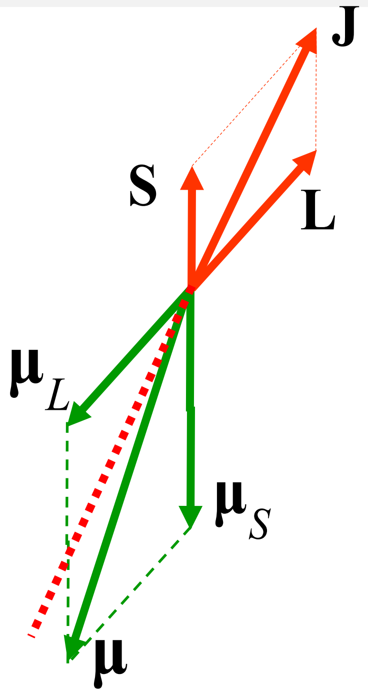
2) The orbital vectors $\mathbf{L}_i$ are arranged to <u>maximize</u> total momentum **L**
Physical interpretation: electrons with the same sign of angular momentum can more easily «avoid» each other because they precess in the same direction.

3) If a «shell», specified by (n,l), is:

Less than half filled: $\mathrm{J} = |\mathrm{L} - \mathrm{S}|$ More than half filled: $\mathrm{J} = |\mathrm{L} + \mathrm{S}|$

Physical interpretation: minimization of the spin-orbit coupling. This rule is often not valid (ok pour rare-earths but not for transition metals)

In general: $\boldsymbol{\mu} \neq -\mu_B \mathbf{J}$ (with $\mathbf{J} = \mathbf{L} + \mathbf{S}$)



Total orbital magnetic moment: $\boldsymbol{\mu}_L \equiv \mu_B g_L \mathbf{L} = -\mu_B \mathbf{L}$

Total spin magnetic moment: $\boldsymbol{\mu}_S \equiv \mu_B g_S \mathbf{S} \cong -\mu_B 2\mathbf{S}$

Total magnetic moment: $\boldsymbol{\mu} = \boldsymbol{\mu}_L + \boldsymbol{\mu}_S = -\mu_B (\mathbf{L} + 2\mathbf{S})$

Case 1: J=0 and **zero** partially filled shells $\Rightarrow$ $\boldsymbol{\mu} = 0$

Case 2: $J \neq 0$ and **one** partially filled shells $\Rightarrow$ $\boldsymbol{\mu} \neq 0$

$$\mu = \mu_B g_J \sqrt{J(J+1)} \qquad g_J \cong \frac{3}{2} + \frac{S(S+1) - L(L+1)}{2J(J+1)}$$

Case 3: J=0 and **one** partially filled shells $\Rightarrow$ $\boldsymbol{\mu} \neq 0$ (complex case)

Ground state of a 3d^5 ion (Mn^{2+})

+2	+1	0	-1	-2
↑	↑	↑	↑	↑

$L = 0,\ S = 5/2,\ J = 5/2$

$m_L = L\ \mu_B = 0\ \mu_B$,

$m_S = g_e\ S\ \mu_B = 5\ \mu_B$,

$m_{at} = g\ J\ \mu_B = 5\ \mu_B$

Ground state of a 3d^7 ion (Co^{2+})

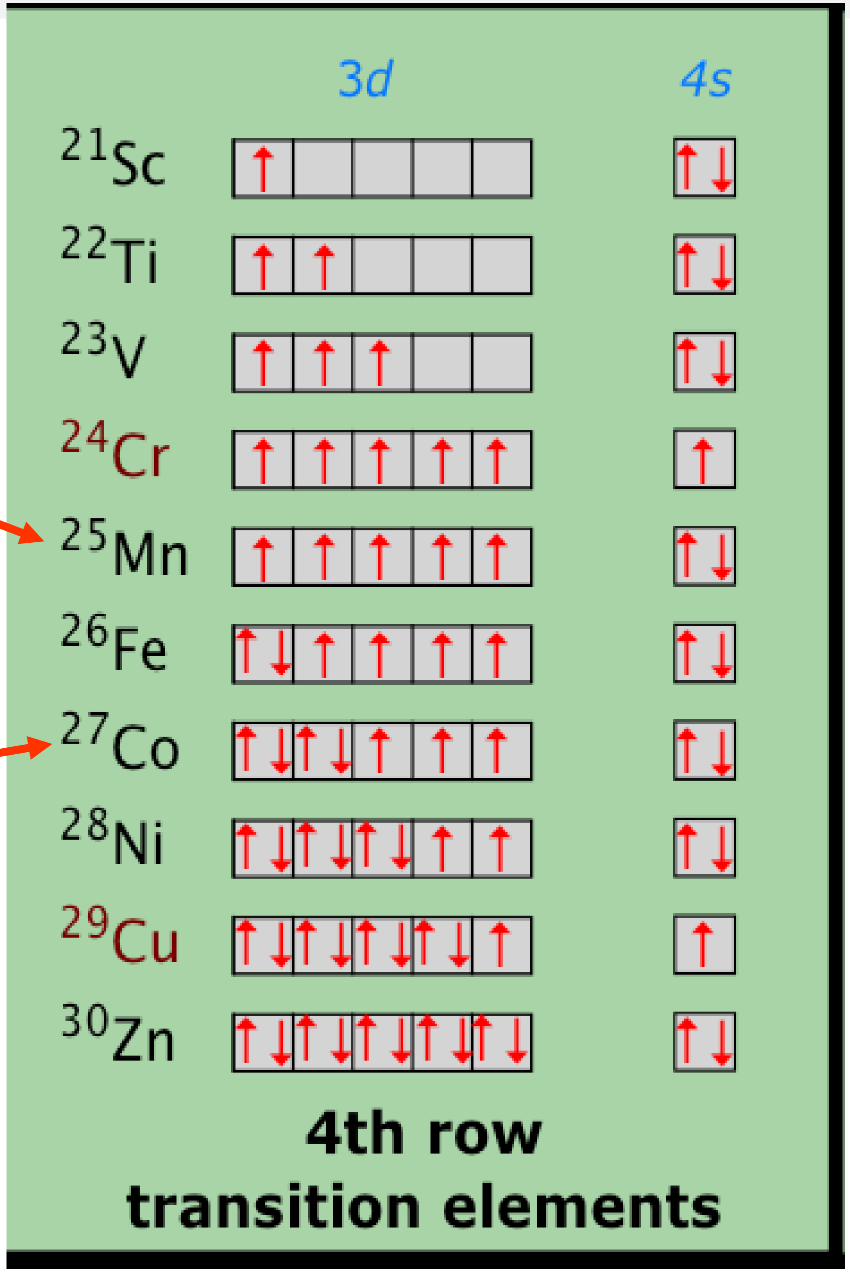
+2	+1	0	-1	-2
↑↓	↑↓	↑	↑	↑

$L = 3,\ S = 3/2,\ J = 9/2$

$m_L = L\ \mu_B = 3\ \mu_B$,

$m_S = g_e\ S\ \mu_B = 3\ \mu_B$,

$m_{at} = g\ J\ \mu_B = 6\ \mu_B$



Transition metal ions

		J	Exp.		$g_J\sqrt{J(J+1)}$		$2\sqrt{S(S+1)}$
Ti^{3+}	3d × 1	3/2	1.80	≠	1.55		1.73
V^{3+}	3d × 2	2	2.80	≠	1.63		2.83
Cr^{3+}	3d × 3	3/2	3.84	≠	0.77		3.87
Cr^{2+} Mn^{3+}	3d × 4	0	4.82	≠	0	→	4.90
Mn^{2+} Fe^{3+}	3d × 5	5/2	5.88		5.92	L = 0	5.92
Fe^{2+} Co^{3+}	3d × 6	4	5.53	≠	6.70		4.90
Co^{2+}	3d × 7	9/2	4.96	≠	6.54		3.87
Ni^{2+}	3d × 8	4	2.82	≠	5.59		2.83
Cu^{2+}	3d × 9	5/2	1.95	≠	3.55		1.73

??

The magnetic moment of an ion or atom predicted by the **hydrogen-like atom model plus simple rules** is often not very accurate (especially for transition metal ions)

Rare earths ions

ion	shell	m_l							S	L	J	term
		+3	+2	+1	0	-1	-2	-3				
La^{3+}	$4f^0$								0	0	0	$^1S_0$
Ce^{3+}	$4f^1$	↓							$\frac{1}{2}$	3	$\frac{5}{2}$	$^2F_{5/2}$
Pr^{3+}	$4f^2$	↓	↓						1	5	4	$^3H_4$
Nd^{3+}	$4f^3$	↓	↓	↓					$\frac{3}{2}$	6	$\frac{9}{2}$	$^4I_{9/2}$
Pm^{3+}	$4f^4$	↓	↓	↓	↓				2	6	4	$^5I_4$
Sm^{3+}	$4f^5$	↓	↓	↓	↓	↓			$\frac{5}{2}$	5	$\frac{5}{2}$	$^6I_{5/2}$
Eu^{3+}	$4f^6$	↓	↓	↓	↓	↓	↓		3	3	0	$^7F_0$
Gd^{3+}	$4f^7$	↓	↓	↓	↓	↓	↓	↓	$\frac{7}{2}$	0	$\frac{7}{2}$	$^8S_{7/2}$
Tb^{3+}	$4f^8$	↓↑	↑	↑	↑	↑	↑	↑	3	3	6	$^7F_6$
Dy^{3+}	$4f^9$	↓↑	↓↑	↑	↑	↑	↑	↑	$\frac{5}{2}$	5	$\frac{15}{2}$	$^6H_{15/2}$
Ho^{3+}	$4f^{10}$	↓↑	↓↑	↓↑	↑	↑	↑	↑	2	6	8	$^5I_8$
Er^{3+}	$4f^{11}$	↓↑	↓↑	↓↑	↓↑	↑	↑	↑	$\frac{3}{2}$	6	$\frac{15}{2}$	$^4I_{15/2}$
Tm^{3+}	$4f^{12}$	↓↑	↓↑	↓↑	↓↑	↓↑	↑	↑	1	5	6	$^3H_6$
Yb^{3+}	$4f^{13}$	↓↑	↓↑	↓↑	↓↑	↓↑	↓↑	↑	$\frac{1}{2}$	3	$\frac{7}{2}$	$^2F_{7/2}$
Lu^{3+}	$4f^{14}$	↓↑	↓↑	↓↑	↓↑	↓↑	↓↑	↓↑	0	0	0	$^1S_0$

		J	Exp.	$g_J\sqrt{J(J+1)}$	g_J	$g_J J$
Ce^{3+}	4f × 1	5/2	2.4	2.54	6/7	$\simeq$ 2.0 μ_B
Pr^{3+}	4f × 2	4	3.5	3.58	4/5	$\simeq$ 3.0 μ_B
Nd^{3+}	4f × 3	9/2	3.5	3.62	8/11	$\simeq$ 3.0 μ_B
Pm^{3+}	4f × 4	4	-	$\neq$ 2.68		$\simeq$ 0 μ_B
Sm^{3+}	4f × 5	5/2 → 1	1.5	$\neq$ 0.845	~ 1	$\simeq$ 1.0 μ_B
Eu^{3+}	4f × 6	0 → 3	3.4	$\neq$ 0	~ 1	$\simeq$ 3.0 μ_B
Gd^{3+}	4f × 7	7/2	8.0	7.94	2	= 7.0 μ_B
Tb^{3+}	4f × 8	6	9.5	9.72	3/2	= 9.0 μ_B
Dy^{3+}	4f × 9	15/2	10.6	10.63	4/3	= 10.0 μ_B
Ho^{3+}	4f × 10	8	10.4	10.60	5/4	= 10.0 μ_B
Er^{3+}	4f × 11	15/2	9.5	9.59	6/5	= 9.0 μ_B
Tm^{3+}	4f × 12	6	7.3	7.55	7/6	= 7.0 μ_B
Yb^{3+}	4f × 13	7/2	4.5	4.54	8/7	= 4.0 μ_B

From atoms to solids

$$H_{total} = H_{Zeeman} + H_{Exchange} + H_{Anisotropy} + H_{Dipolar}$$

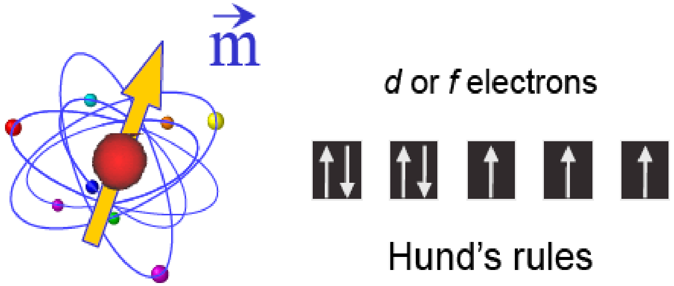
$$H_{total} = \mu_0 \mathbf{H} \sum_i \mathbf{m}_i - \sum_{i<j} J_{ij} \mathbf{m}_i \cdot \mathbf{m}_j - \sum_i k_i (\mathbf{m}_i \cdot \mathbf{e}_i)^2 - \frac{\mu_0}{8\pi} \sum_{i,j\neq i} \left[\frac{3(\mathbf{m}_i \cdot \mathbf{r}_{ij})(\mathbf{m}_j \cdot \mathbf{r}_{ij})}{r_{ij}^5} - \frac{(\mathbf{m}_i \cdot \mathbf{m}_j)}{r_{ij}^3} \right]$$

$\mathbf{H}$: applied magnetic field

$\mathbf{m}_i$: magnetic moment of atom i

Intra-atomic exchange,
electron correlation effects:

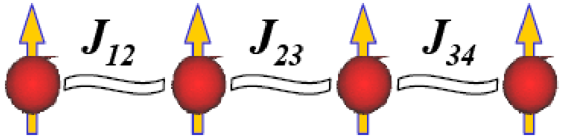
LOCAL (ATOMIC) MAGNETIC MOMENTS



Inter-atomic exchange:

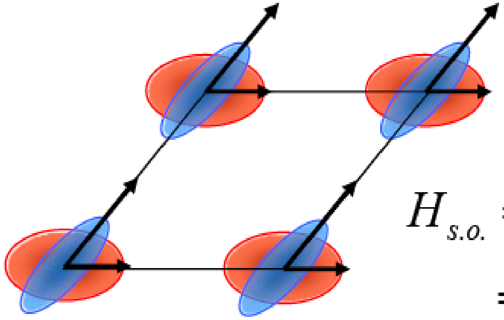
MAGNETIC ORDER

$$H_{exc} = -\sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$



Spin-Orbit Coupling:

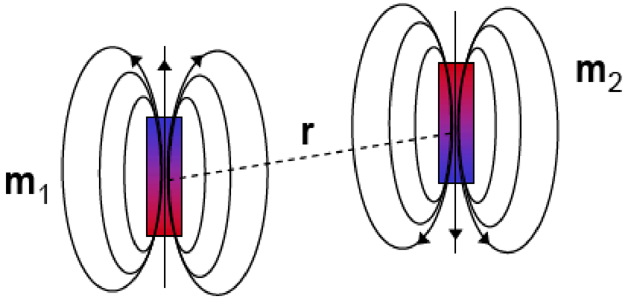
MAGNETOCRYSTALLINE ANISOTROPY: K



$$H_{s.o.} = \lambda \mathrm{L} \cdot \mathbf{S} = \sum \xi \, \mathbf{s}_i \cdot \mathrm{l}_i$$

Dipolar Interaction:

SHAPE ANISOTROPY



$$H_{dip} = \frac{\mathbf{m}_1 \cdot \mathbf{m}_2}{r^3} - 3\frac{(\mathbf{m}_1 \cdot \mathbf{r})(\mathbf{m}_2 \cdot \mathbf{r})}{r^5}$$

EPFL

$$\mathbf{M} = \chi \mathbf{H}$$

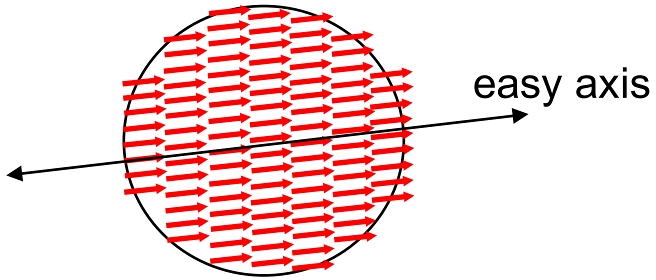
Type	Typical values	Physical Origin
Diamagnetism	$\chi \approx -10^{-6}$	Non-interacting «induced» atomic magnetic dipoles
Paramagnetism	$\chi \approx +(10^{-5} \div 10^{-3})$	Orientation of non-interacting «permanent» atomic magnetic dipoles
Superparamagnetism	$\chi \approx +10^{-2}$	Orientation of non-interacting «permanent» large (many atoms) magnetic dipoles
Ferromagnetism	$\chi = +\left(0 \div 10^{6}\right)$	Orientation + coupling + anisotropy of «permanent» atomic magnetic dipoles

Superparamagnetism

Superparamagnetism appears in ferromagnetic or ferrimagnetic single magnetic domain nanoparticles, having a diameter below 3 to 50 nm, depending on the materials.

In a single nanoparticle:

1) The atomic magnetic moment are alligned in the same direction due to the exchange interaction.
2) Usually there are two stable orientations, antiparallel to each other and separated by an energy barrier, along the so called easy axis of the nanoparticle. This energy barrier is called magnetic anisotropy energy.



At any temperature *T*>0, there is a finite probability for the magnetization to flip and reverse its direction.

The mean time between two flips, called the Néel relaxation time, is:

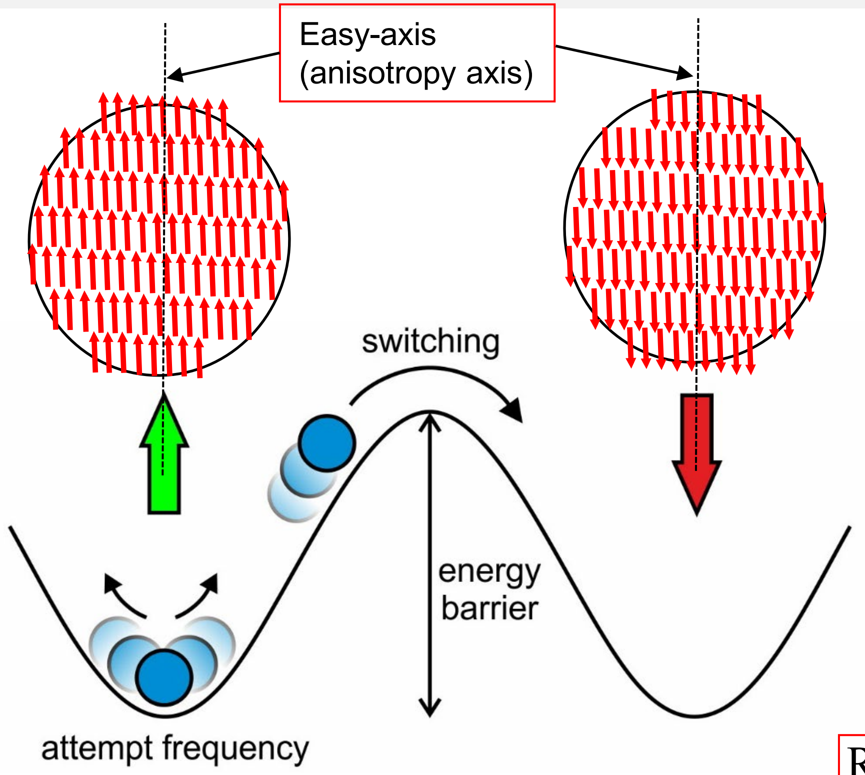
$$\tau_N = \tau_0 \exp\left(\frac{KV}{k_B T}\right)$$

τ_N : average time that it takes for the nanoparticle's magnetization to randomly flip due to thermal fluctuations.

τ_0 : is a characteristic time of the material, called the *attempt time* (typically: 10^{-9} to 10^{-10} s).

K: nanoparticle's magnetic anisotropy energy density $\qquad$ V : particle volume

τ_N is the range from **nanoseconds** to **millions of years**, depending on V, T, and K



$KV << kT \Rightarrow$

Magnetization flips direction often ($\tau_N \cong \tau_0$) $\Rightarrow$

Information cannot be stored

$KV >> kT \Rightarrow$

Magnetization flips direction rarely ($\tau_N \to \infty$) $\Rightarrow$

Information can be stored

Relaxation time (average time to jump from one minumum to the other):

$$\tau_N = \tau_0 \exp\left(\frac{KV}{kT}\right)$$

Assuming $\tau_0 \cong 0.1$ ns we have that:

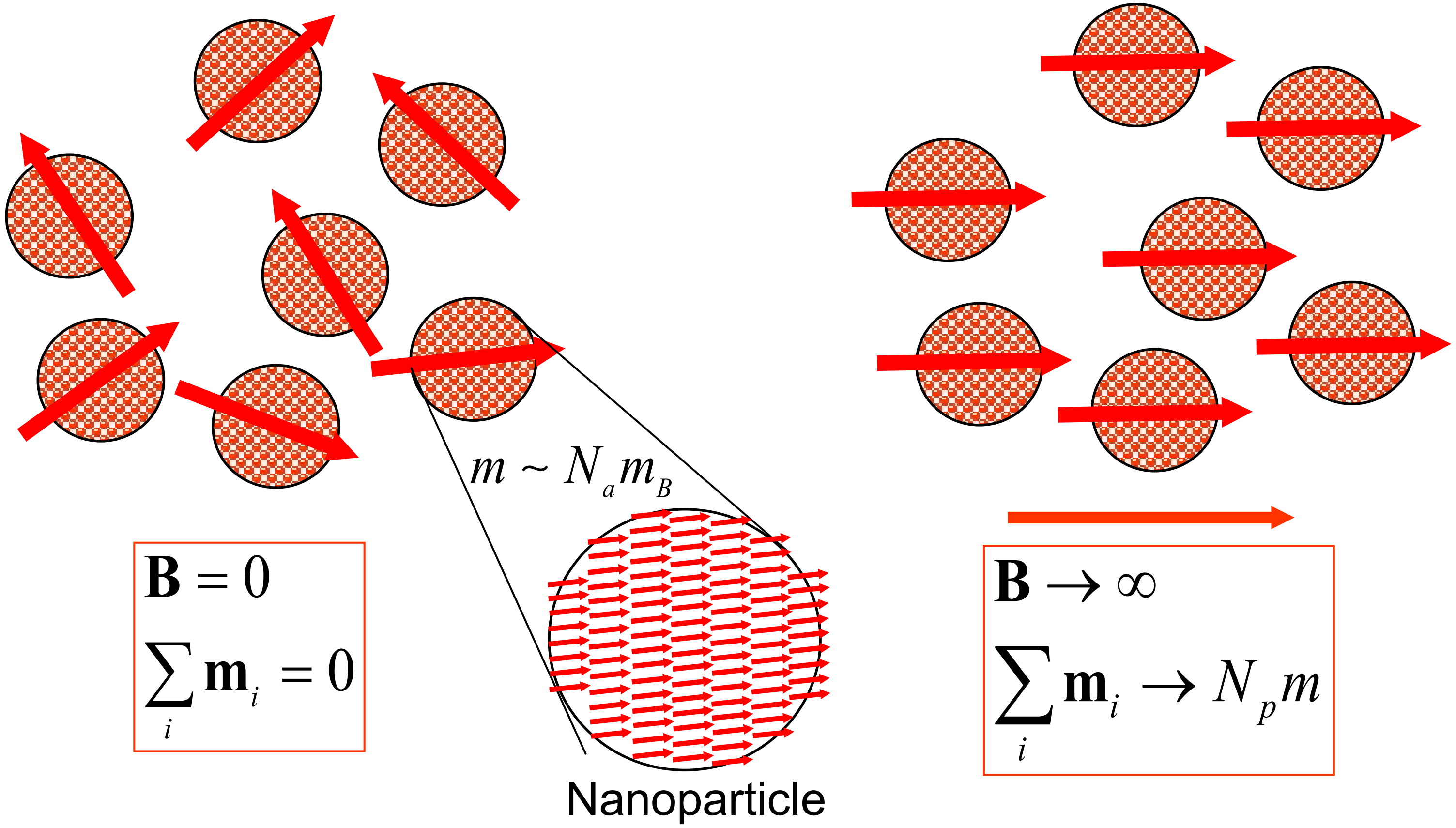
$KV = 43\ kT \Rightarrow \tau \cong 15$ years

$KV = 40\ kT \Rightarrow \tau \cong 9$ months

$KV = 23\ kT \Rightarrow \tau \cong 1$ s

Behaviour of an ensemble of N_p superparamagnetic nanoparticules each with N_a atoms inside:

Ensemble of nanoparticles in B=0 | Ensemble of nanoparticles in large B

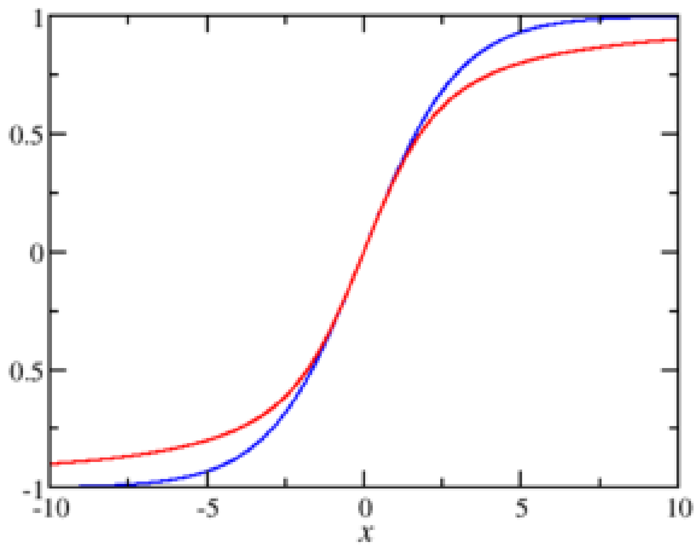


Inside each nanoparticle the N_a atoms have their magnetic moments all alligned in the same direction due to the exchange interaction. Each nanoparticle has a magnetic moment **m** of about $N_a\mu_B$

An external magnetic field tends to “orient” the magnetic moment of the nanoparticle in the direction of the magnetic field.

In an **ensemble of paramagnetic atoms**: each atom is interacting with the external magnetic field but the interaction with the other atoms is negligible. The effective magnetic moment is the one of a single atom (about 1 μ_B).

In an **ensemble of superparamagnetic nanoparticles:** inside each nanoparticle the atoms are strongly coupled by the exchange interaction and, hence, interact globally with the external magnetic field. The effective magnetic moment is about $N_a\mu_B$, where N_a is the number of atoms in the nanoparticle.



Langevin function (red line), compared with tanh(x/3)(blue line).

The "volume averaged" magnetization of an **ensemble of superparamagnetic nanoparticles** is

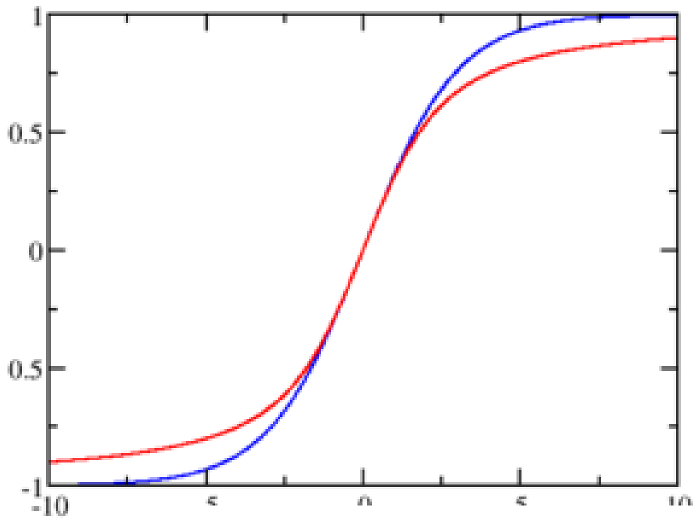
$$M = \frac{N_p}{V} m L\left(\frac{mB}{kT}\right) = \frac{N_p}{V} m \left(\frac{1}{\tanh\left(\frac{mB}{kT}\right)} - \frac{kT}{mB} \right)$$

m: is the magnetic moment of a single nanoparticle ($m \cong N_a \mu_B$)

N_p: Number of nanoparticles in the ensemble

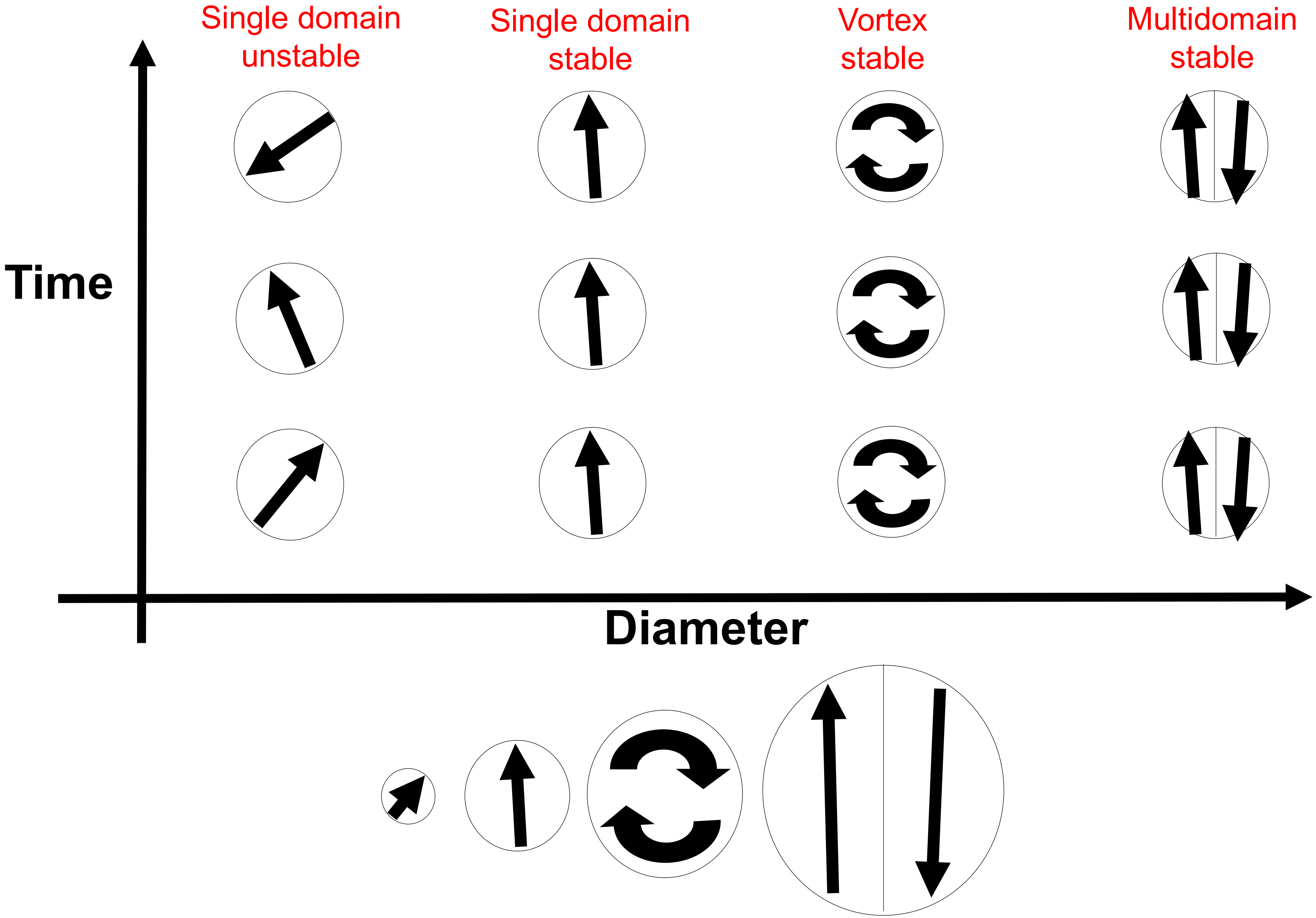
V: Volume of the ensemble

$L(x) = \frac{1}{\tanh(x)} - \frac{1}{x}$: Langevin function



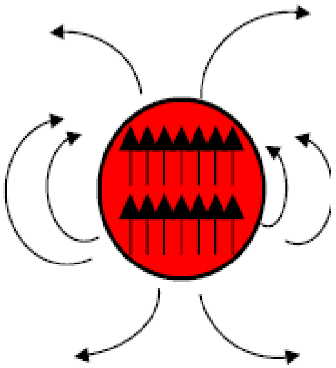
Langevin function (red line), compared with tanh(x/3)(blue line).

Nano and microdots magnetism



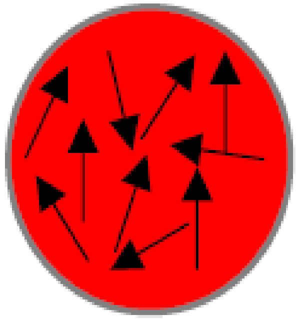
exchange energy J coupling spins

$$H_{exc} = -\sum J_{ij}\mathbf{S}_i \cdot \mathbf{S}_j$$



Temperature increase

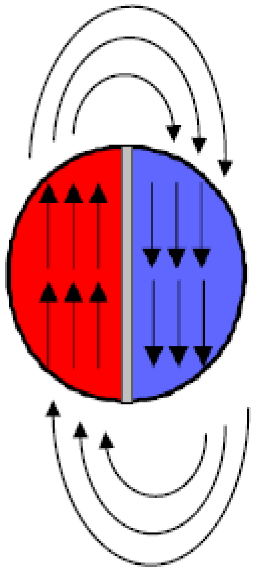
$H_{exc} \ll kT$



Coupling is destroyed and the net magnetic moment is zero

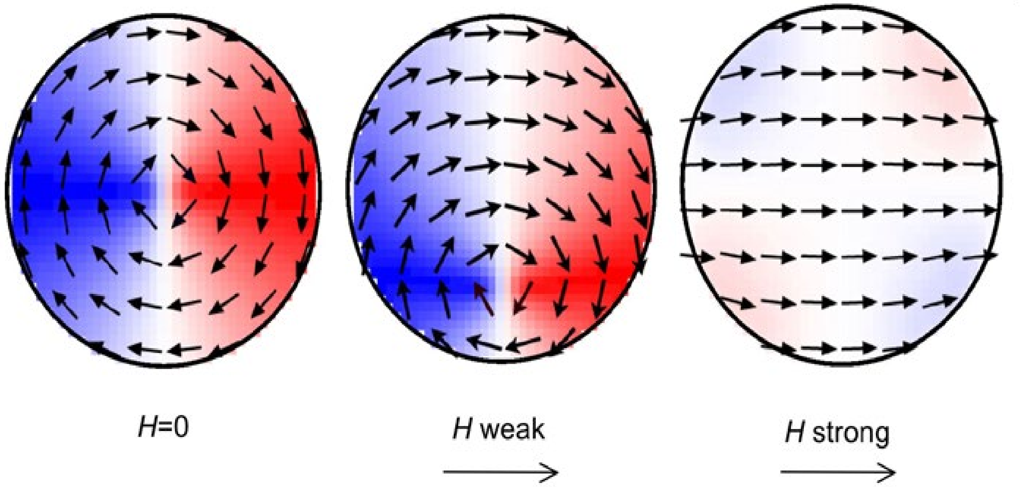
Size increase

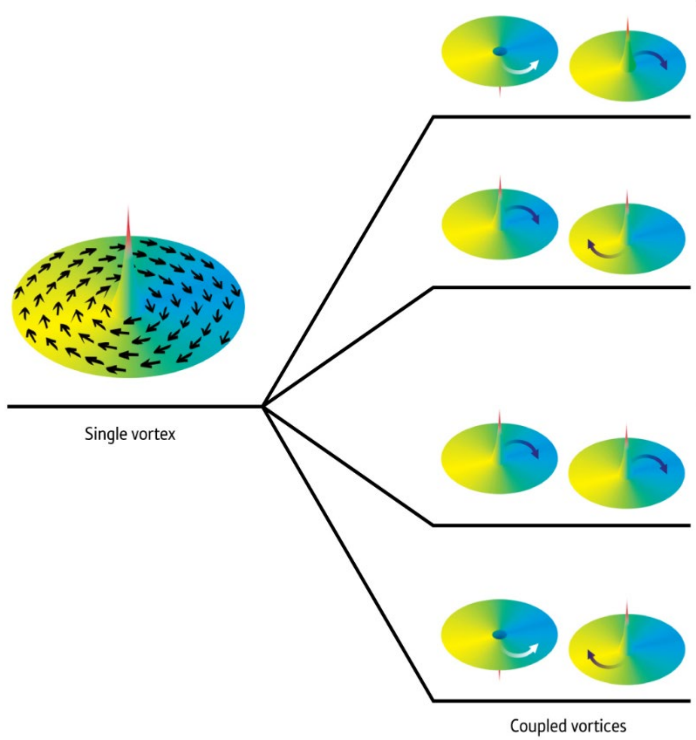
Domain formation -> magnetic moment is strongly reduced

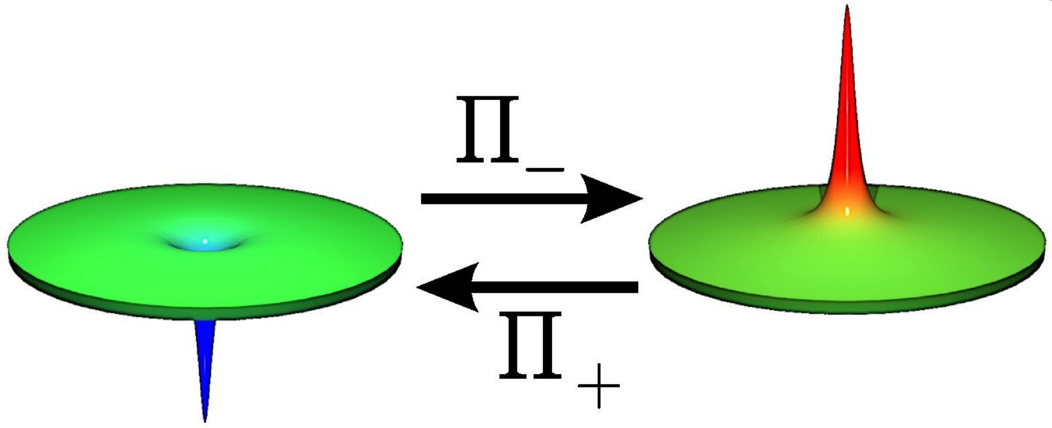


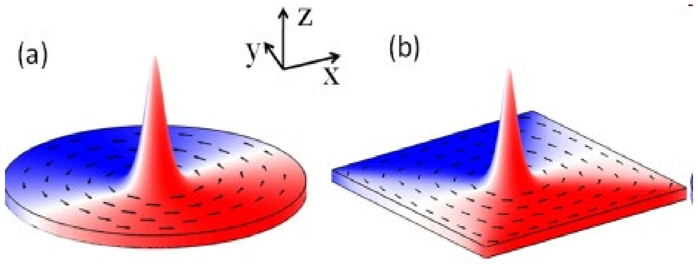
Gain in the magnetostatic energy at the expenses of the exchange energy

Magnetic domains in nanodots

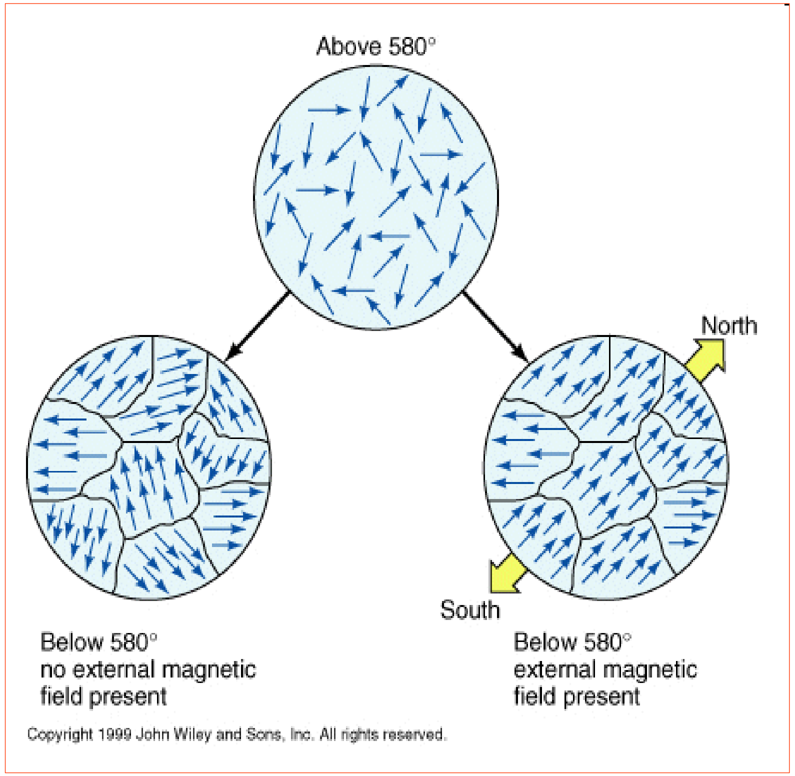


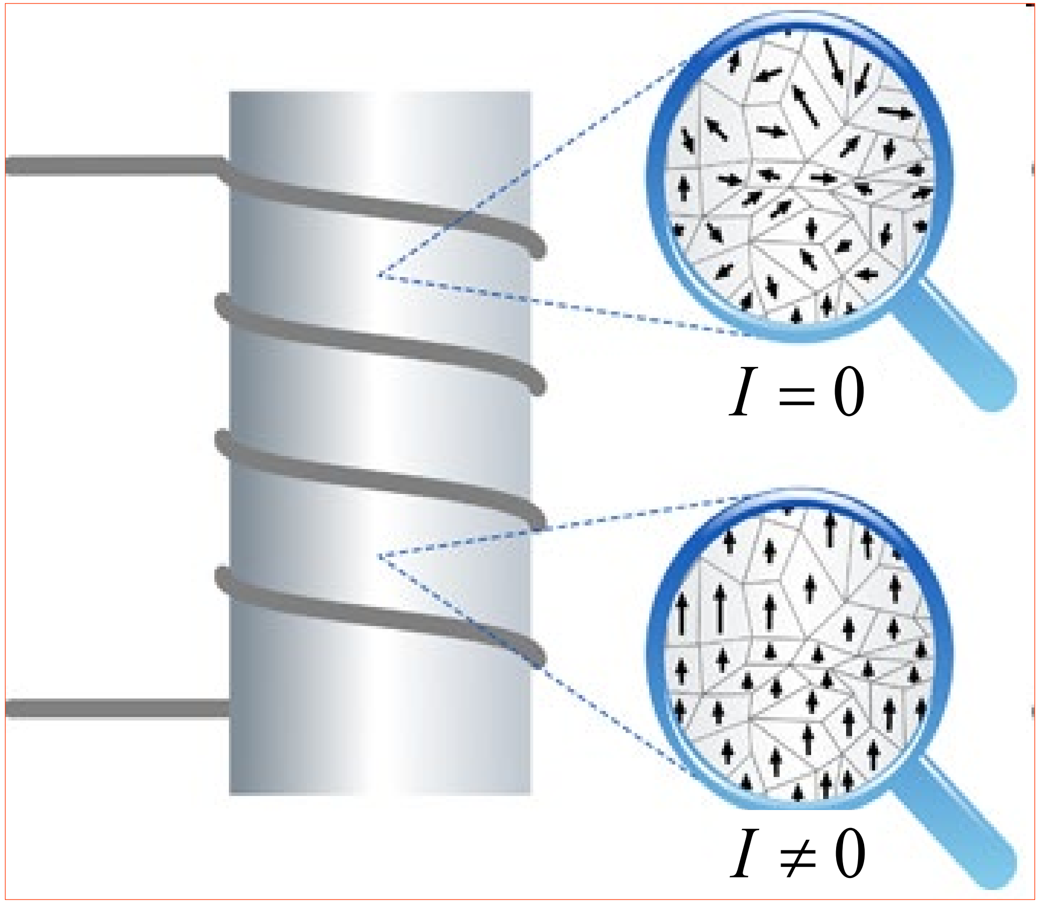




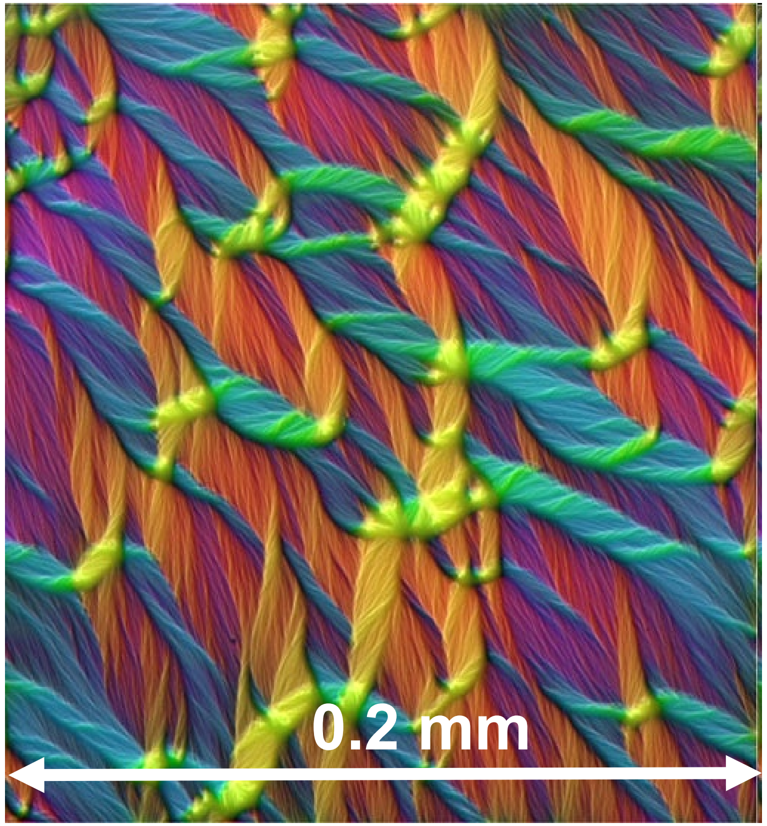


Magnetic domains in large particles

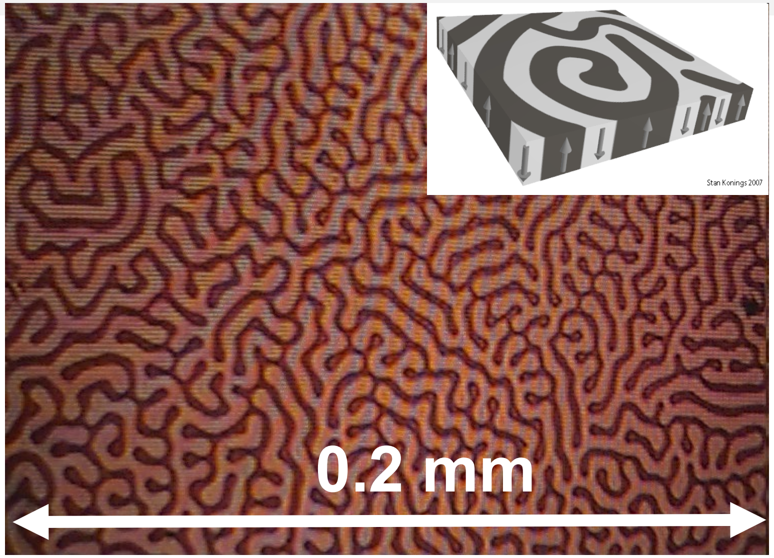




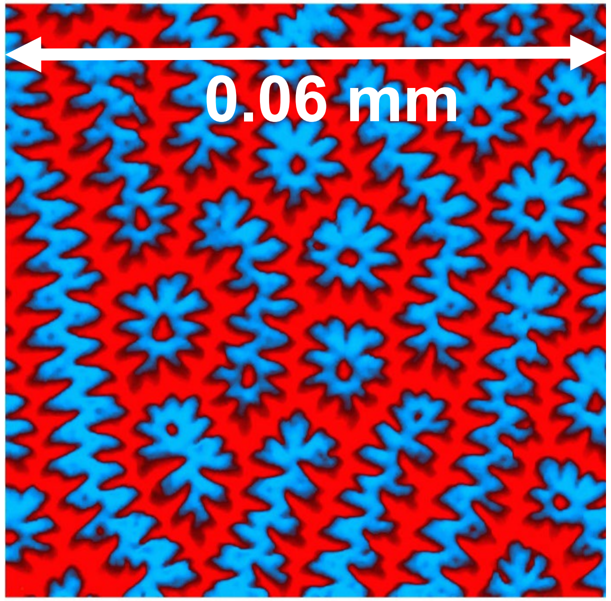
Magnetic domains in thin films



Co thin film (20 nm)
(color scale=magnetization direction)

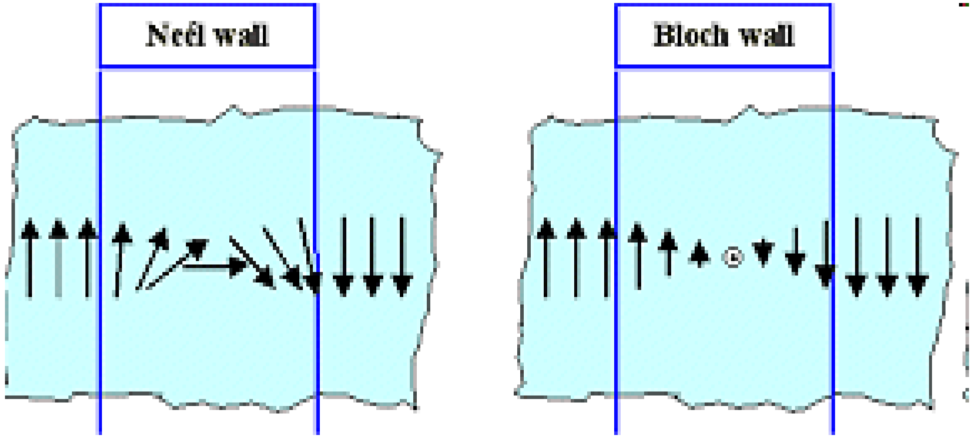


$Bi_{0.6}Tm_{2.4}Ga_{1.15}Fe_{3.85}O_{12}$ (8 μm)

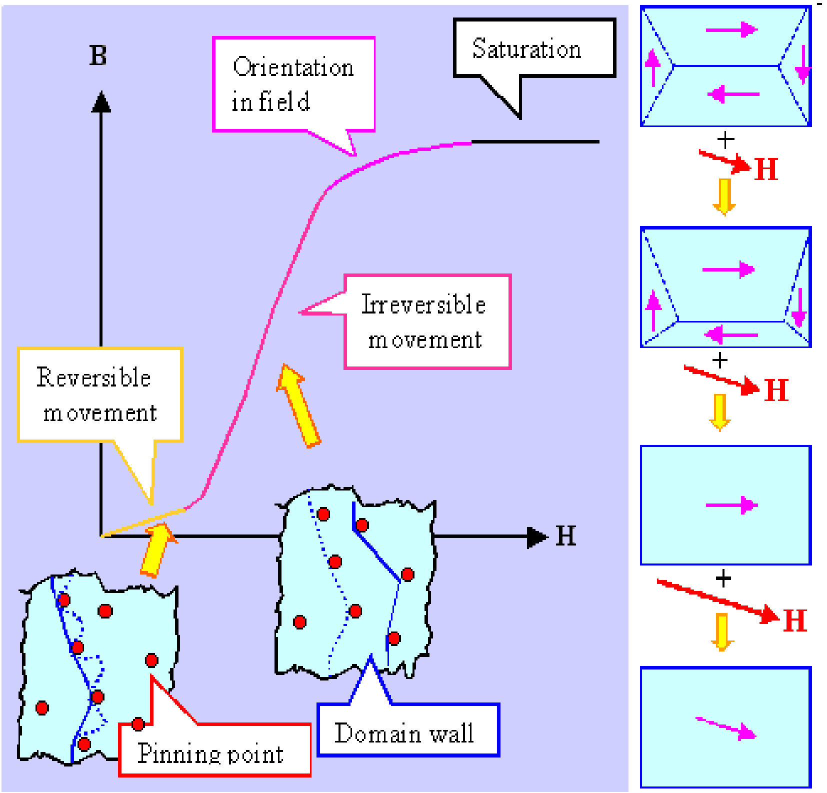


$Y_3Fe_5O_{12}$ (8 μm)

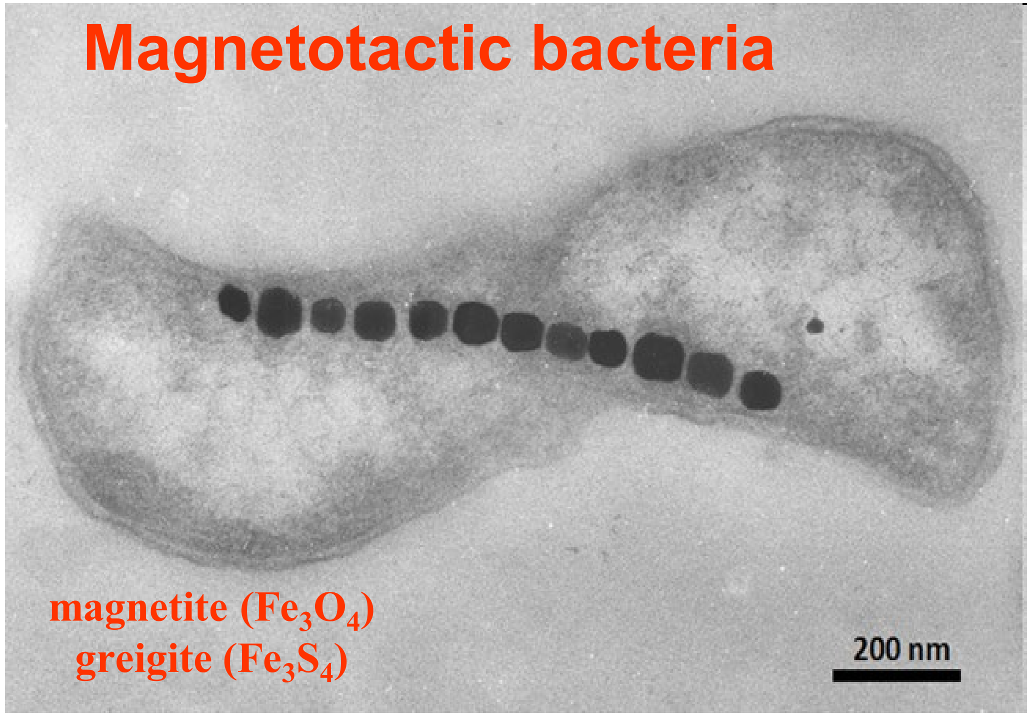
Magnetic domains, domains wall, typical lenghts

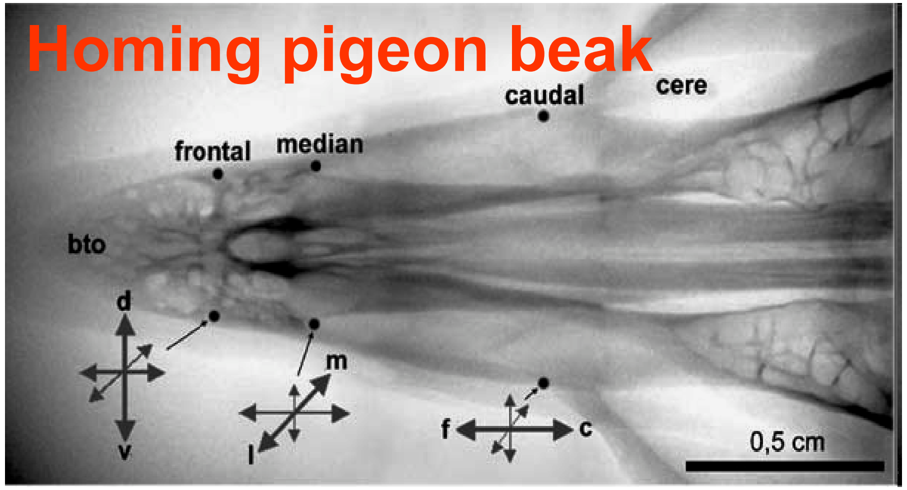


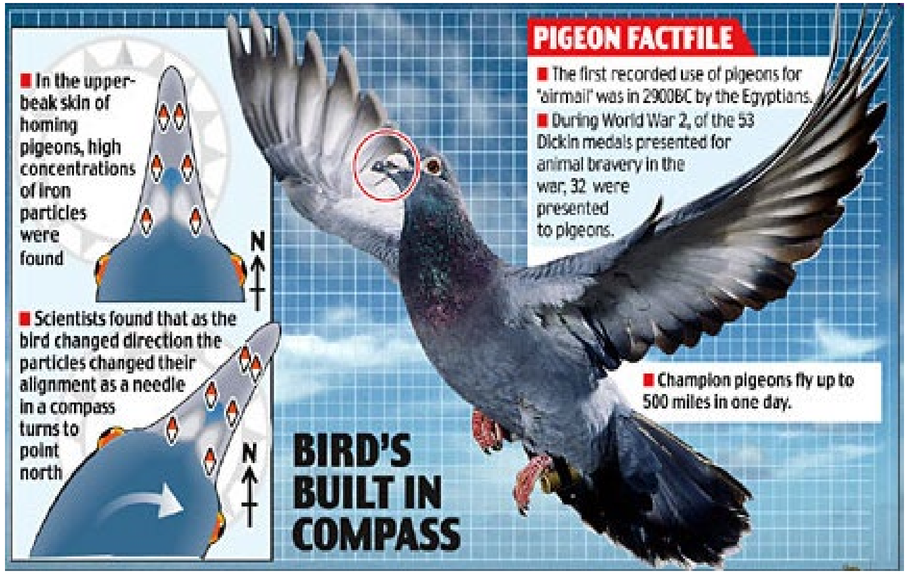
Length	Typ. Value (nm)
Interatomic distance	0.2
Domain size	~ 10- 10^4
Domain wall width	~ 1- ~ 10^2
Critical superparamagnetic diameter	~ 1- ~ 10^2



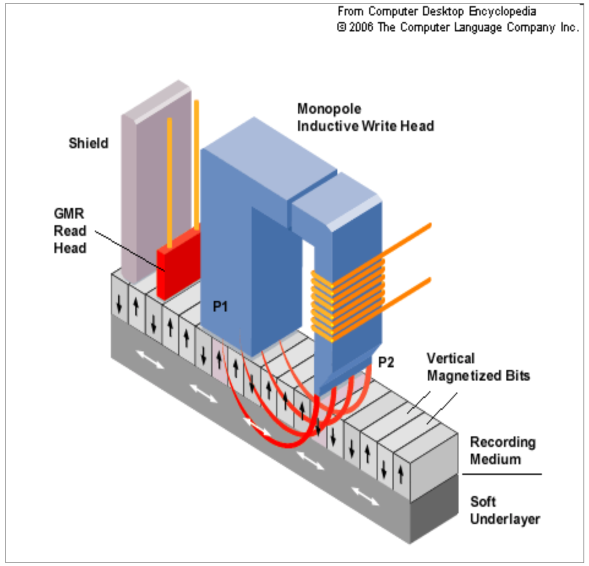
Nanomagnetism in animals

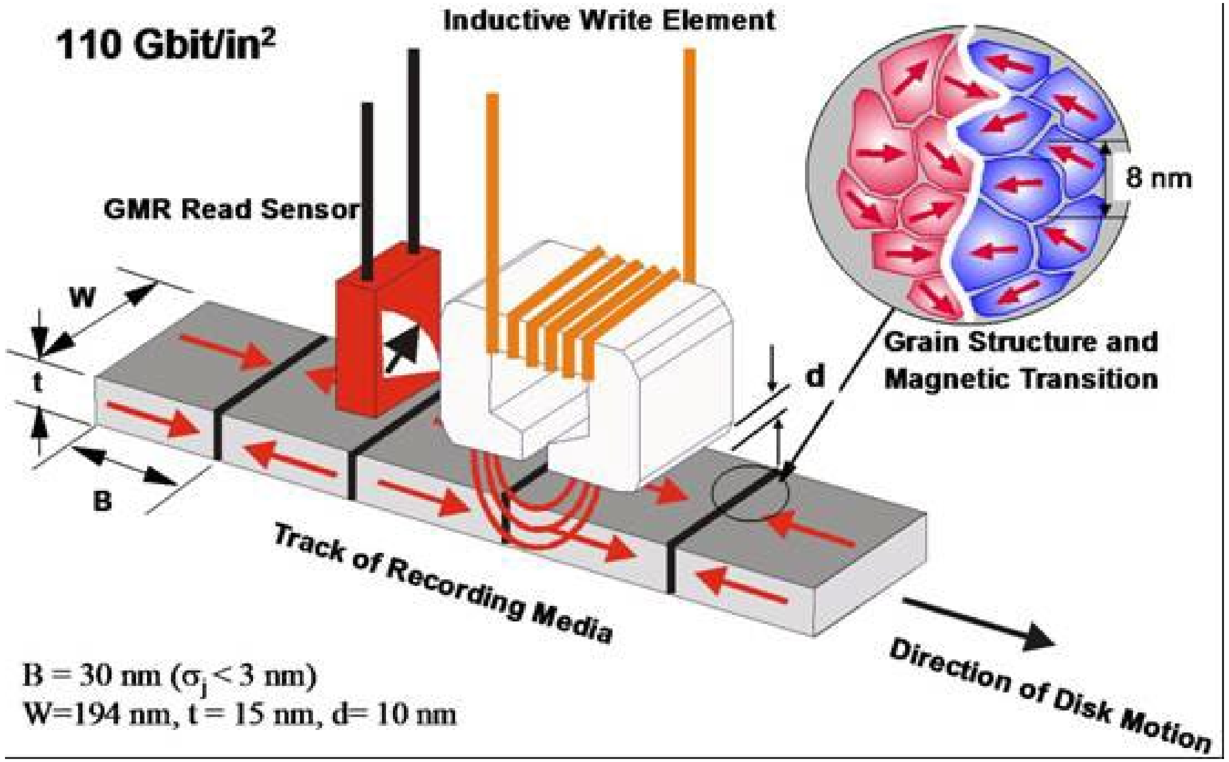






Applications of nanomagnetism: Magnetic data storage





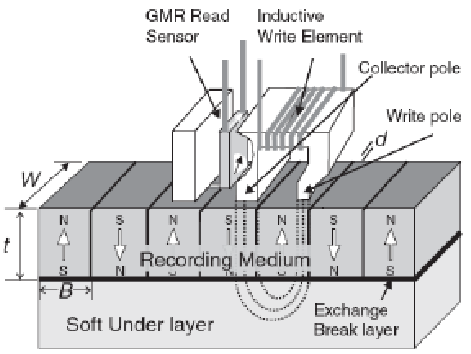
Present: several particles (grains) per bit

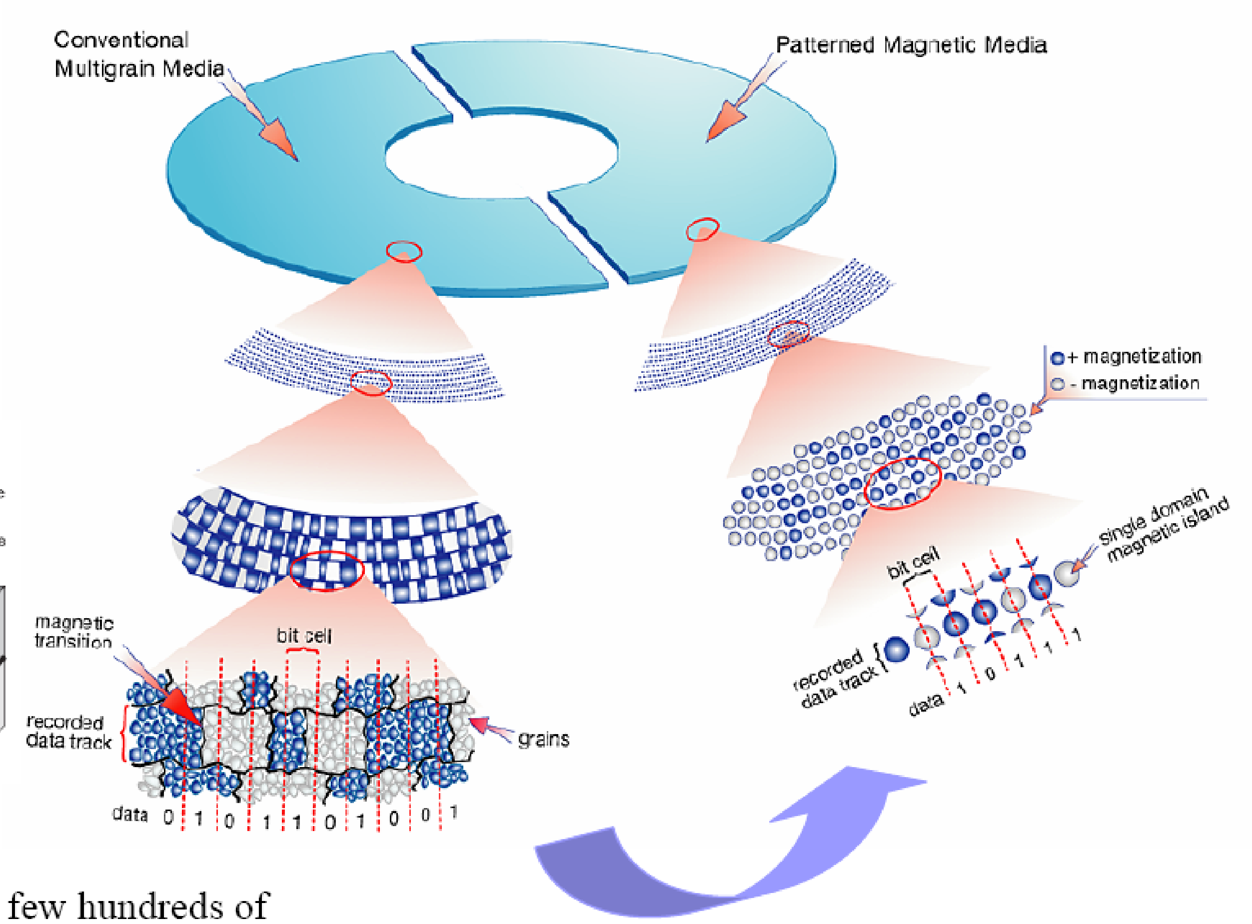
Future: single particle/single atom per bit ?

Conventional Media vs. Patterned Media

HITACHI
Inspire the Next

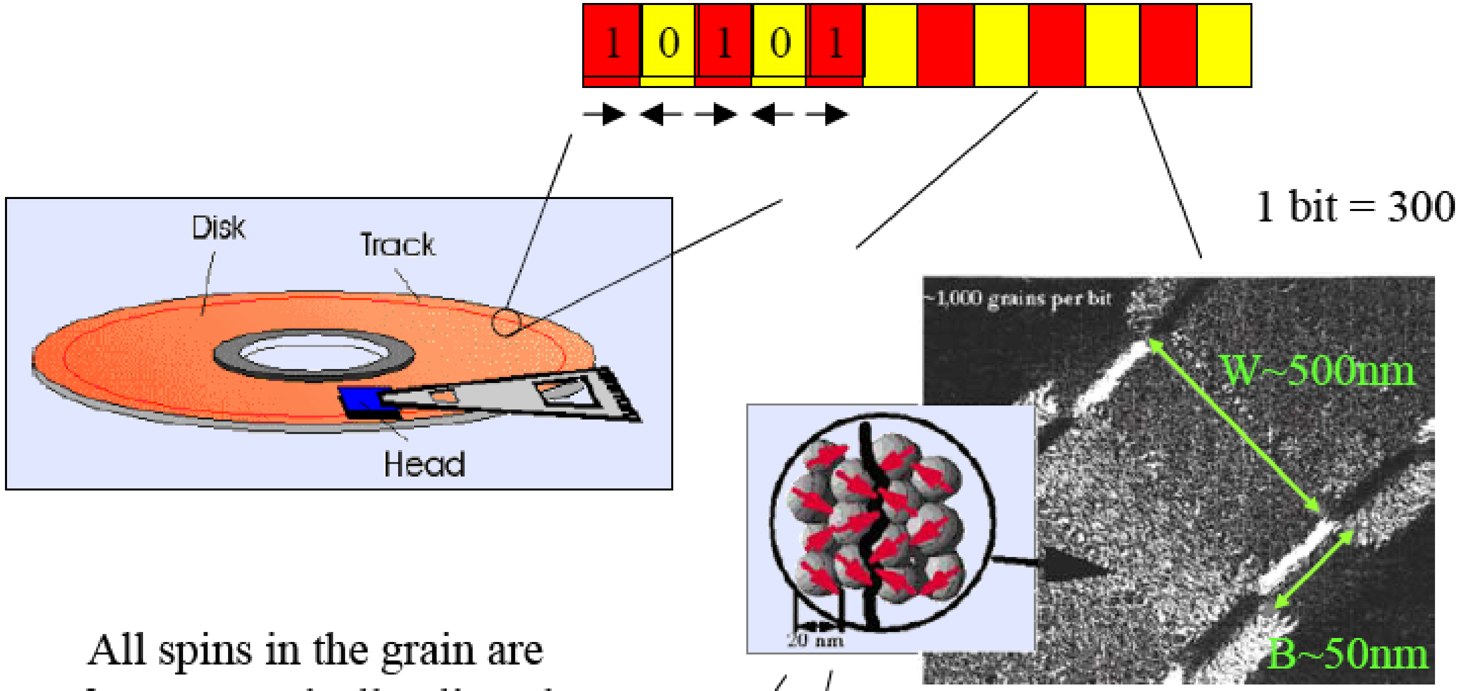
Writing-reading head





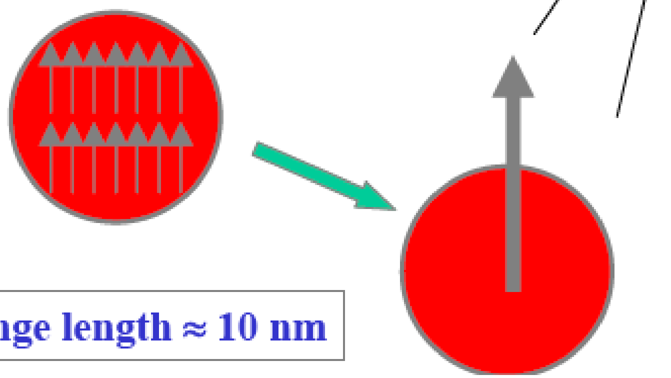
Each bit is made of a few hundreds of grains. The bit size and shape is defined during writing by the head

The future: single particle per bit



1 bit = 300 grains

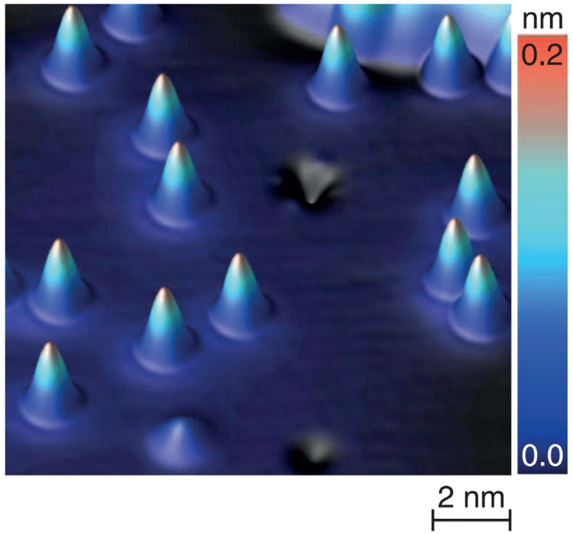
All spins in the grain are ferromagnetically aligned

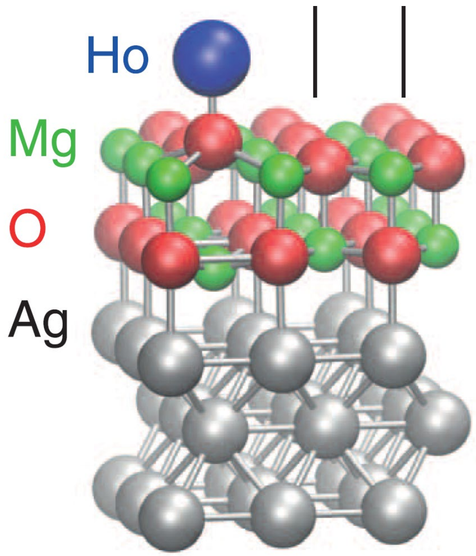


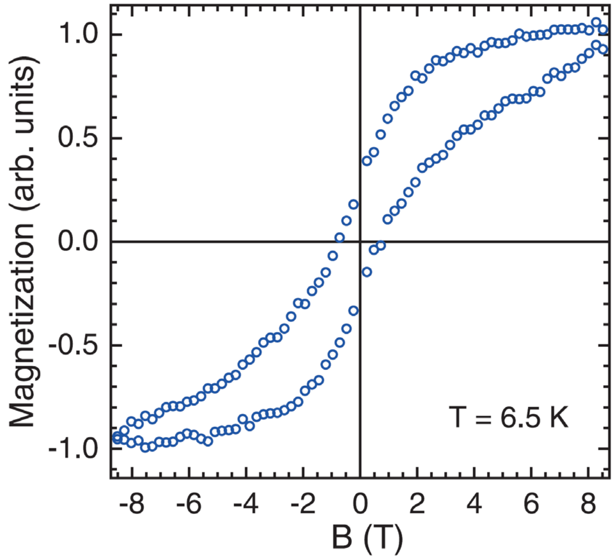
Exchange length ≈ 10 nm

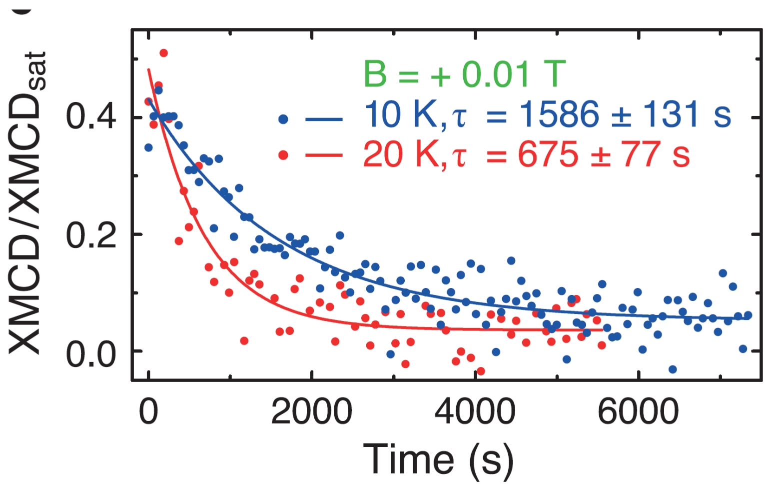
The grain (particle) can be described as a single macrospin $\mu = \Sigma_i \mu_i$

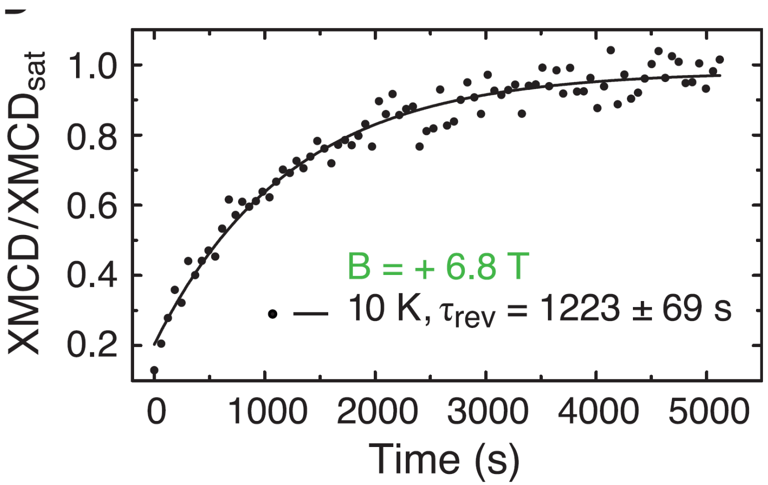
Magnetic «remanence» in single atoms





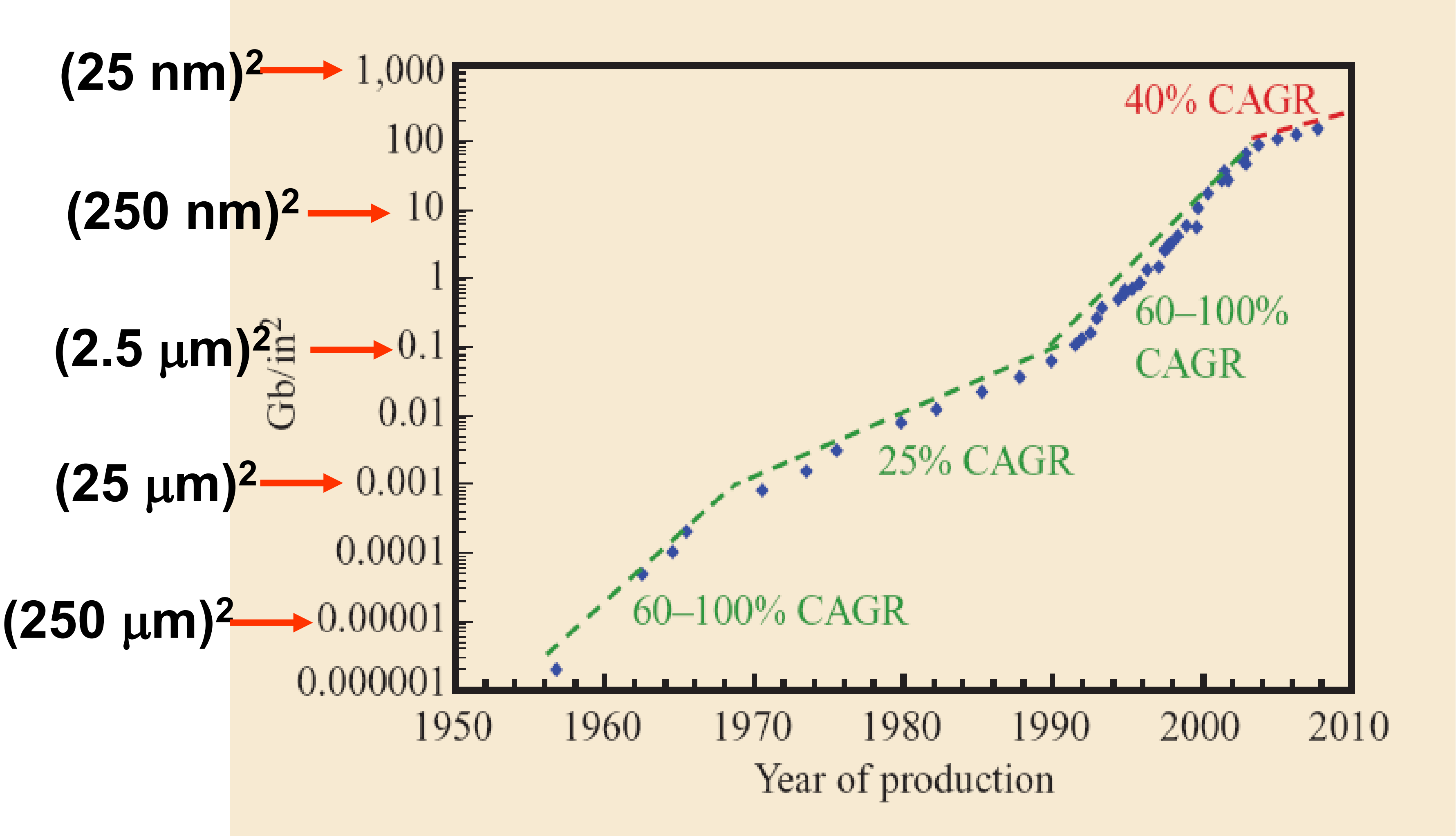






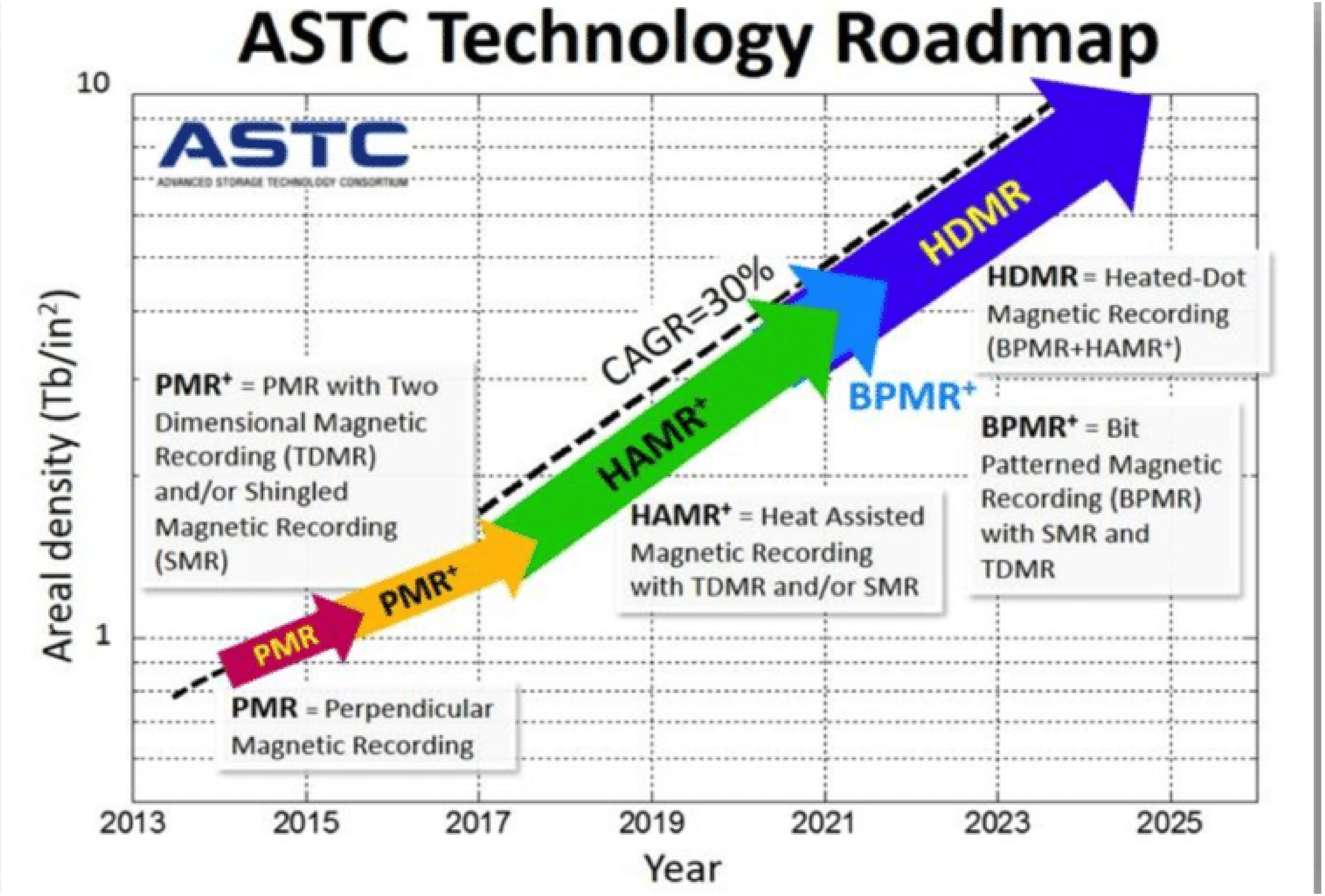
F. Donati et al., Science 352, 318 (2016)

Magnetic data storage

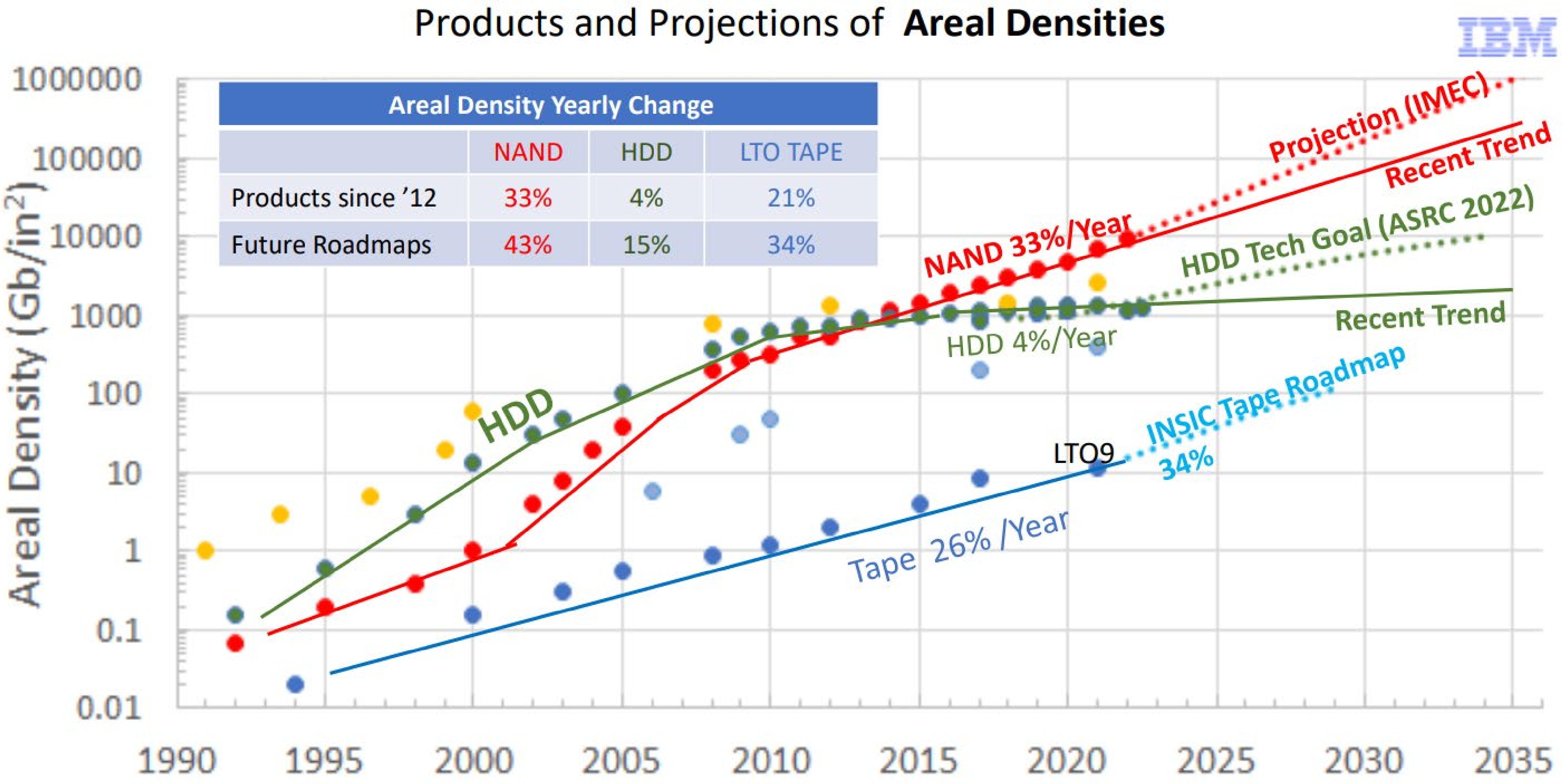


2012: 1 Tbit/inch^2,
i.e., 1 bit on (25 nm)^2

2024: 1.5 Tbit/inch^2


ASTC Technology Roadmap
ASTC
ADVANCED STORAGE TECHNOLOGY CONSORTIUM
10
1
Areal density (Tb/in²)
2013
2015
2017
2019
2021
2023
2025
Year
CAGR=30%
PMR
PMR⁺
HAMR⁺
BPMR⁺
HDMR
PMR⁺ = PMR with Two Dimensional Magnetic Recording (TDMR) and/or Shingled Magnetic Recording (SMR)
PMR = Perpendicular Magnetic Recording
HAMR⁺ = Heat Assisted Magnetic Recording with TDMR and/or SMR
BPMR⁺ = Bit Patterned Magnetic Recording (BPMR) with SMR and TDMR
HDMR = Heated-Dot Magnetic Recording (BPMR+HAMR⁺)

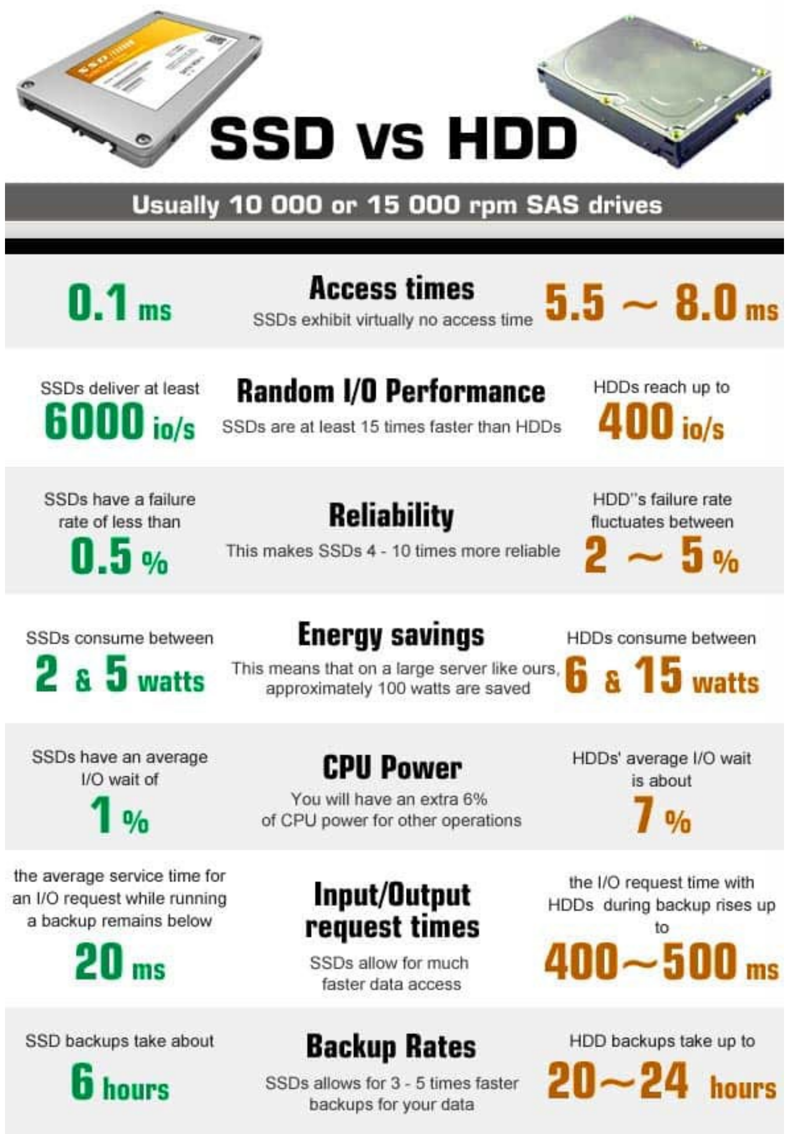
Data storage: overview

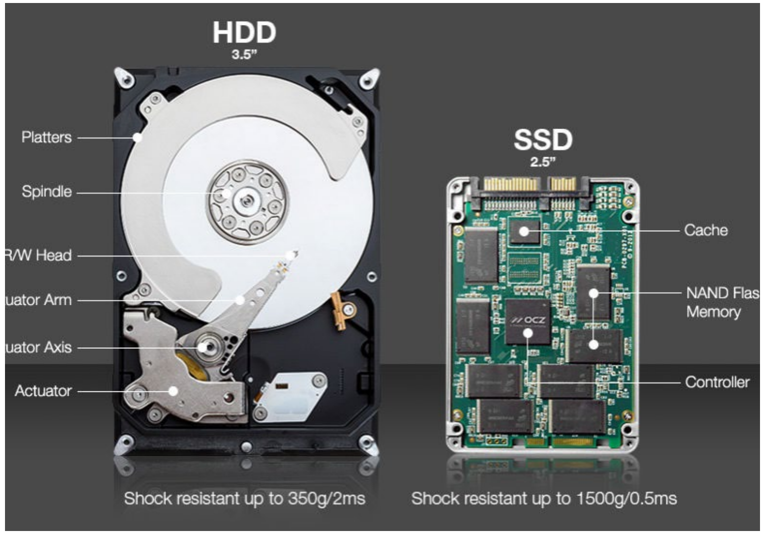


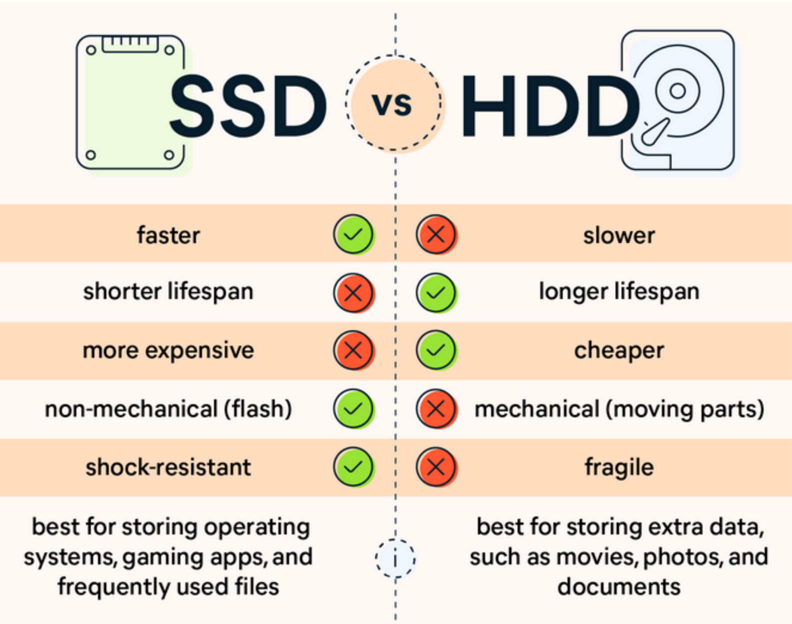
Areal Density Yearly Change			
	NAND	HDD	LTO TAPE
Products since ’12	33%	4%	21%
Future Roadmaps	43%	15%	34%

HDD (Hard disk drive): magnetic storage device with spinning disks coated with a magnetic materials.
NAND (Flash memory): trapped electrons inside an insulated gate within a MOSFET transistor. Used in SSD, USB flash drives,….
LTO (Linear tape-open): magnetic tape storage technology. Used for data backup and archiving.

Drives competition







Magnetic RAM

MRAM (magnetoresistive RAM):
A new approach to magnetic data storage