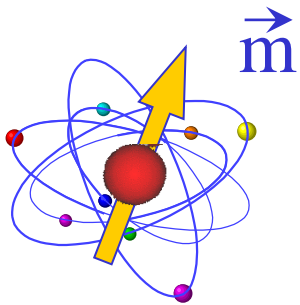## Intra-atomic exchange, electron correlation effects:

LOCAL (ATOMIC) MAGNETIC MOMENTS

$\vec{m}$
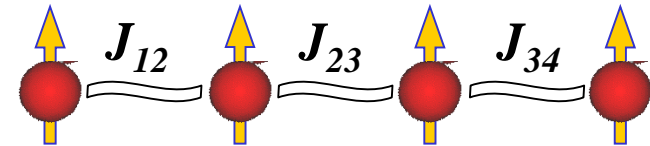
d or *f* electrons

Hund's rules

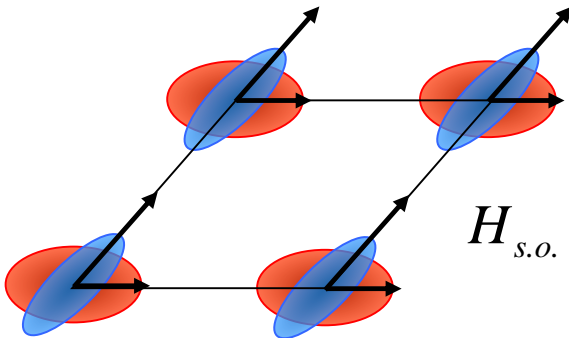## Inter-atomic exchange:

MAGNETIC ORDER

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

J_{12} J_{23} J_{34}

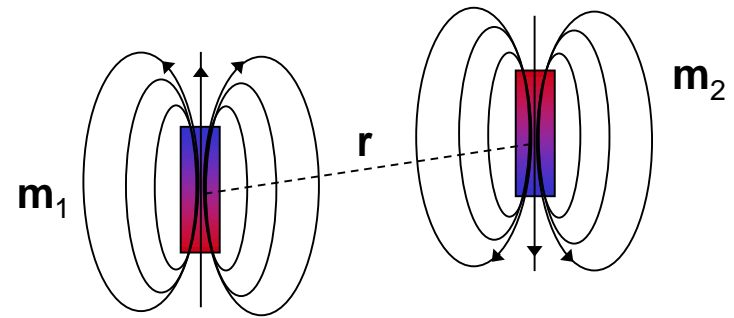## Spin-Orbit Coupling:

MAGNETOCRYSTALLINE ANISOTROPY: K

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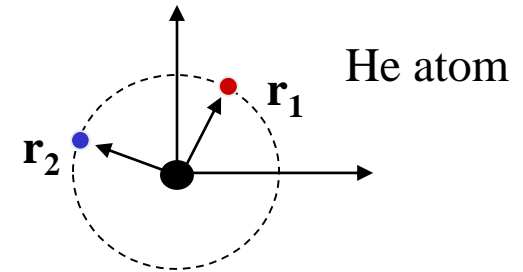$$= \sum \xi \mathbf{s}_i \cdot \mathbf{l}_i$$

Dipolar Interaction:

SHAPE ANISOTROPY

$\mathbf{m}_2$

$\mathbf{m}_1$

r

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

He atom

$$H_{He} = \sum_{i=1}^{2} \frac{p_i^2}{2m} - \frac{1}{4\pi\varepsilon_0} \sum_{i=1}^{2} \frac{Ze^2}{r_i^2} + \frac{1}{4\pi\varepsilon_0} \frac{e^2}{|r_2 - r_1|} = H_0 + H_{e-e}$$

Ground state -> the two electrons occupy the 1s orbital

-> the spatial part of the wavefunction is symmetric (electrons have identical quantum numbers nlm=100)

-> the spin part must be antisymmetric (electrons are fermions)

$$\Psi_{ground} = \Psi_{sym}(r_1, r_2)\chi_{antisym}(s_1, s_2) = \frac{1}{2}[\Psi_{100}(r_1)\Psi_{100}(r_2) + \Psi_{100}(r_1)\Psi_{100}(r_2)][\alpha\beta - \beta\alpha]$$

From the previous Hamiltonian we can calculate the energy of the ground state. Because H_{He} does not contain spin terms, the spin part of the wavefunction only needs to satisfy the antisymmetric condition

Excited state -> one electron occupies the 1s orbital (nlm=100); the second electron is in an excited state nlm

1) the spatial part of the wavefunction is symmetric and the spin part is antisymmetric

$$\Psi_{exci}^{S} = \Psi_{sym}(r_1, r_2)\chi_{antisym}(s_1, s_2) = \frac{1}{2}[\Psi_{100}(r_1)\Psi_{nlm}(r_2) + \Psi_{nlm}(r_1)\Psi_{100}(r_2)][\alpha\beta - \beta\alpha] \quad \text{Singlet S=0}$$

2) the spatial part of the wavefunction is antisymmetric and the spin part is symmetric

$$\Psi_{exci}^{T} = \Psi_{antisym}(r_1, r_2)\chi_{sym}(s_1, s_2) = \frac{1}{2}[\Psi_{100}(r_1)\Psi_{nlm}(r_2) - \Psi_{nlm}(r_1)\Psi_{100}(r_2)]\chi_{sym}(s_1, s_2)$$

Triplet S=1

$$\alpha = \frac{1}{2}; \beta = -\frac{1}{2} \qquad\qquad \chi_{sym}(s_1, s_2) = \alpha\alpha; \beta\beta; \frac{1}{\sqrt{2}}(\alpha\beta + \beta\alpha)$$

The singlet and triplet wavefunctions applied to H_0 give the same energy;
  the H_{e-e} contribution can be calculated with the perturbation theory

$$I = \int\int \left|\Psi_{100}(r_1)\right|^2 \frac{e^2}{4\pi\varepsilon_0 \left|r_1 - r_2\right|} \left|\Psi_{nlm}(r_2)\right|^2 dr_1 dr_2$$

$$J = \int\int \Psi_{100}(r_1)\Psi_{nlm}(r_2) \frac{e^2}{4\pi\varepsilon_0 \left|r_1 - r_2\right|} \Psi_{100}^*(r_2)\Psi_{nlm}^*(r_1) dr_1 dr_2$$

$$E_{e-e}^S = I + J$$

$$E_{e-e}^T = I - J$$

I is the Coulomb integral -> electrostatic repulsion between the electrons ($\Psi(r)^2$ -> ρ electron density)
J is the exchange integral -> energy associated with a change of quantum states between the electrons

Origin of Exchange interaction: -> Coulomb repulsion between electrons
                                  -> total anti-symmetric wave function (Pauli exclusion principle)
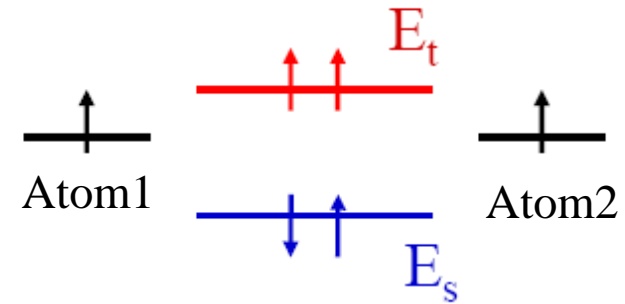
J is positive   -> triplet ground state S=1   -> parallel spins
J is negative   -> singlet ground state S=0   -> antiparallel spins

Note: we get the exchange energy from an Hamiltonian not including spin terms !!!!!
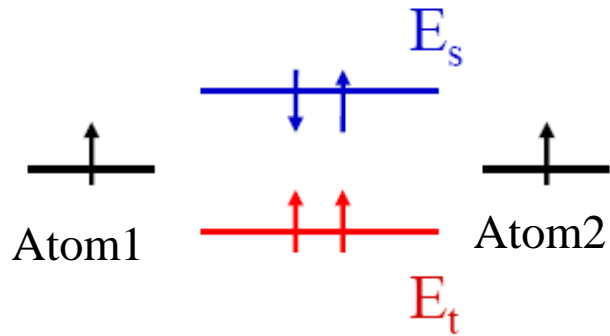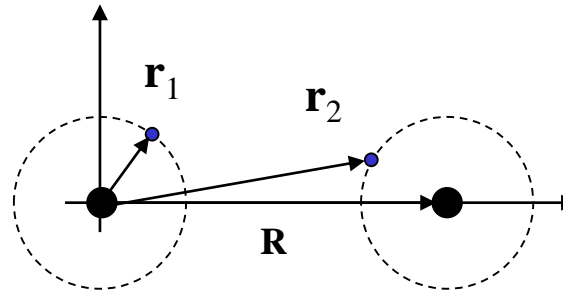
magnetic ground state   nonmagnetic ground state

Hamiltonian $H = H_1 + H_2 + H_{12}$, where

$$
\begin{cases}
H_1 = -\dfrac{\hbar^2}{2m}\Delta_1 - \dfrac{Ze^2}{r_1} \\[2mm]
H_2 = -\dfrac{\hbar^2}{2m}\Delta_2 - \dfrac{Ze^2}{r_2} \\[2mm]
H_{12} = +\dfrac{e^2}{r_{12}}
\end{cases}
$$

$$\psi_1 = \frac{1}{\sqrt{2-2l^2}}\left(\phi_a(r_1)\phi_b(r_2) - \phi_b(r_1)\phi_a(r_2)\right)\left(\alpha(r_1)\alpha(r_2)\right) \text{ triplet}$$

$$\psi_2 = \frac{1}{\sqrt{2-2l^2}}\left(\phi_a(r_1)\phi_b(r_2) - \phi_b(r_1)\phi_a(r_2)\right)\left(\beta(r_1)\beta(r_2)\right) \text{ triplet}$$

$$\psi_3 = \frac{1}{\sqrt{2-2l^2}}\left(\phi_a(r_1)\phi_b(r_2) - \phi_b(r_1)\phi_a(r_2)\right)\frac{1}{\sqrt{2}}\left(\beta(r_1)\alpha(r_2) + \alpha(r_1)\beta(r_2)\right) \text{ triplet}$$

$$\psi_4 = \frac{1}{\sqrt{2+2l^2}}\left(\phi_a(r_1)\phi_b(r_2) + \phi_b(r_1)\phi_a(r_2)\right)\frac{1}{\sqrt{2}}\left(\beta(r_1)\alpha(r_2) - \alpha(r_1)\beta(r_2)\right) \text{ singlet}$$

$$E = \frac{\langle\psi_i|H|\psi_i\rangle}{\langle\psi_i|\psi_i\rangle} = \langle\psi_i|H_1 + H_2 + H_{12}|\psi_i\rangle \qquad \text{N.B.} \quad \langle\psi_i|\psi_i\rangle = 1$$

$$= \frac{1}{2\pm 2l^2}\iint\left(\phi_a(r_1)\phi_b(r_2) \pm \phi_b(r_1)\phi_a(r_2)\right)^*\left(H_1 + H_2 + H_{12}\right)\left(\phi_a(r_1)\phi_b(r_2) \pm \phi_b(r_1)\phi_a(r_2)\right)d\mathbf{r}_1 d\mathbf{r}_2$$
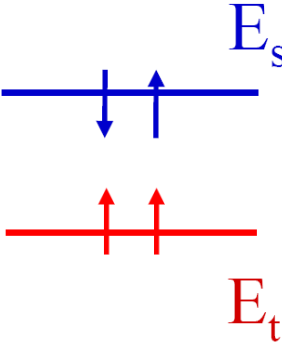
$$= \frac{1}{2\pm 2l^2}\left(I_1 + I_2 + K_{12} \pm J_{12}\right)$$

$$E = \frac{\langle \psi_i \mid H \mid \psi_i \rangle}{\langle \psi_i \mid \psi_i \rangle} = \langle \psi_i \mid H_1 + H_2 + H_{12} \mid \psi_i \rangle \qquad \text{N.B.} \quad \langle \psi_i \mid \psi_i \rangle = 1$$

$$= \frac{1}{2 \pm 2l^2} \iint \left(\phi_a(r_1)\phi_b(r_2) \pm \phi_b(r_1)\phi_a(r_2) \right)^* \left(H_1 + H_2 + H_{12} \right)\left(\phi_a(r_1)\phi_b(r_2) \pm \phi_b(r_1)\phi_a(r_2) \right) d\mathbf{r}_1 d\mathbf{r}_2$$

$$= \frac{1}{2 \pm 2l^2} \left(I_1 + I_2 + K_{12} \pm J_{12} \right)$$

$$I_1 = \underbrace{\int \phi_a^*(r_1)H_1\phi_a(r_1)d\mathbf{r}_1}_{e_1 \text{ on atom } a} + \underbrace{\int \phi_a^*(r_2)H_2\phi_a(r_2)d\mathbf{r}_2}_{e_2 \text{ on atom } a}$$

$$I_2 = \underbrace{\int \phi_b^*(r_2)H_2\phi_b(r_2)d\mathbf{r}_2}_{e_2 \text{ on atom } b} + \underbrace{\int \phi_b^*(r_1)H_1\phi_b(r_1)d\mathbf{r}_1}_{e_1 \text{ on atom } b}$$

$$K_{12} = \underbrace{\iint \phi_a^*(r_1)\phi_b^*(r_2)H_{12}\phi_a(r_1)\phi_b(r_2)d\mathbf{r}_1 d\mathbf{r}_2}_{e_1 - e_2 \text{ interaction, } e_1, e_2 \text{ on different atoms}} + \underbrace{\iint \phi_a^*(r_2)\phi_b^*(r_1)H_{12}\phi_a(r_2)\phi_b(r_1)d\mathbf{r}_1 d\mathbf{r}_2}_{e_1 - e_2 \text{ interaction, } e_1, e_2 \text{ on different atoms}}$$

$$J_{12} = \underbrace{\iint \phi_a^*(r_1)\phi_b^*(r_2)H_{12}\phi_b(r_1)\phi_a(r_2)d\mathbf{r}_1 d\mathbf{r}_2}_{\substack{\text{exchange interaction: } e_1, e_2 \text{ swap from b to a and a to b,} \\ \text{respectively, due to the action of } H_{12}}} + \underbrace{\iint \phi_a^*(r_2)\phi_b^*(r_1)H_{12}\phi_a(r_1)\phi_b(r_2)d\mathbf{r}_1 d\mathbf{r}_2}_{\substack{\text{exchange interaction: } e_1, e_2 \text{ swap from a to b and b to a,} \\ \text{respectively, due to the action of } H_{12}}}$$

$$\Rightarrow \begin{cases} E_s = \dfrac{1}{2+2l^2}\left(I_1 + I_2 + K_{12} + J_{12}\right) \\[3mm] E_t = \dfrac{1}{2-2l^2}\left(I_1 + I_2 + K_{12} - J_{12}\right) \end{cases}$$

E$_s$

E$_t$

$$\Rightarrow E_s - E_t = \frac{1}{4-4l^4}\left[-4l^2\left(I_1 + I_2 + K_{12}\right) + 4J_{12}\right]$$

Ground state depends on the relative strength of J_{12} (always > 0) in respect to $-4l^2(I_1+I_2+K_{12})$

$J_{12} > 4l^2(I_1+I_2+K_{12})$ -> ground state is magnetic (triplet)

$J_{12} < 4l^2(I_1+I_2+K_{12})$ -> ground state is non magnetic (singlet)

Ex: H$_2$ molecule $J_{12} < 0$ -> singlet ground state

The molecule magnetic ground state depends on the interaction between electrons belonging to two different atoms

The Heisenberg Hamiltonian is an effective Hamiltonian extending to larger atoms the electron-electron interaction seen in the He atom

$$H_{Heisenberg} = H_0 + H_{Coulomb} + H_{exchange}$$

$$H_{exchange} = -2\sum_{i<j}^{N} J_{ij} s_i \cdot s_j;$$

$$J_{ij} = \int\int \psi_i(r_i)\psi_j(r_j) \frac{e^2}{4\pi\varepsilon_0 |r_i - r_j|} \psi_i^*(r_j)\psi_j^*(r_i) dr_i dr_j$$

The Heisenberg Hamiltonian is used to describe:
-> coupling of individual spins located on the same atom
(intra-atomic exchange)
-> coupling of atomic spin moments on different atoms
(inter-atomic exchange)
BUT
Intra-atomic (a,c) and inter-atomic (b) exchange have different energies

a),c) -> intra-atomic V_{e-e} in the isolated atom
(Hund's rules) or Stoner band approach

[Stö06]
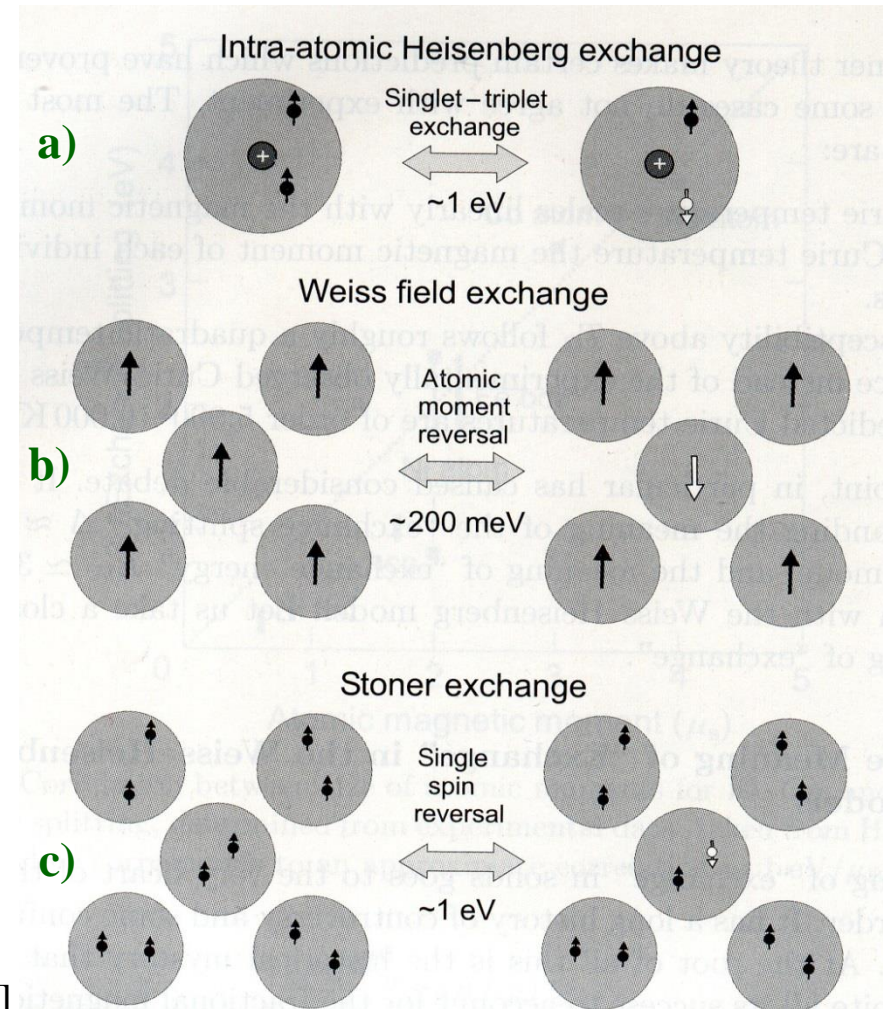
Generalization to N-atoms system:

• **Coulomb interaction + Pauli's principle → The spins of the electrons are correlated**

i.e., there is a magnetic splitting in the energy spectrum of electrons in systems of atoms with open el. shells, true for systems of any size, doesn't tell what type of magnetic coupling

• **The energy spectrum is represented by a model system of pairwise interacting spins**

$$H = -\sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j \qquad \textit{Heisenberg model}$$

$\approx$ correct to 2nd order in the overlap orbitals, cannot be proven rigorously

• **There are many possible exchange-interaction Hamiltonians…**

$$H = -J_z \sum_{i \neq j} S_i^z S_j^z - J_\perp \sum_{i \neq j} \left(S_i^x S_j^x + S_i^y S_j^y \right) \qquad \textit{Anisotropic Heisenberg model and XY model (J$_z$=0)}$$

$$H = -J_z \sum_{i \neq j} S_i^z S_j^z \qquad \textit{Ising model}$$

$$H = -\sum_{i \neq j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j \begin{cases} J > 0 \text{ } \textit{ferromagnetic coupling} \quad \textit{(10-50 meV in Fe, Co, Ni)} \\ J < 0 \text{ } \textit{antiferromagnetic coupling} \quad \textit{(30-100 meV in Mn, Cr;} \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad \textit{20 meV in NiO superexchange)} \end{cases}$$

$J < 0$, depending on formula unit, system dimensions, topology:

• fully compensated AFM

• ferrimagnetism (uncompensated AFM)

• frustrated AFM

Cr(100) surface

G-type   C-type   A-type

$H_{exc} \ll kT$

Coupling is destroyed and the net magnetic moment is zero
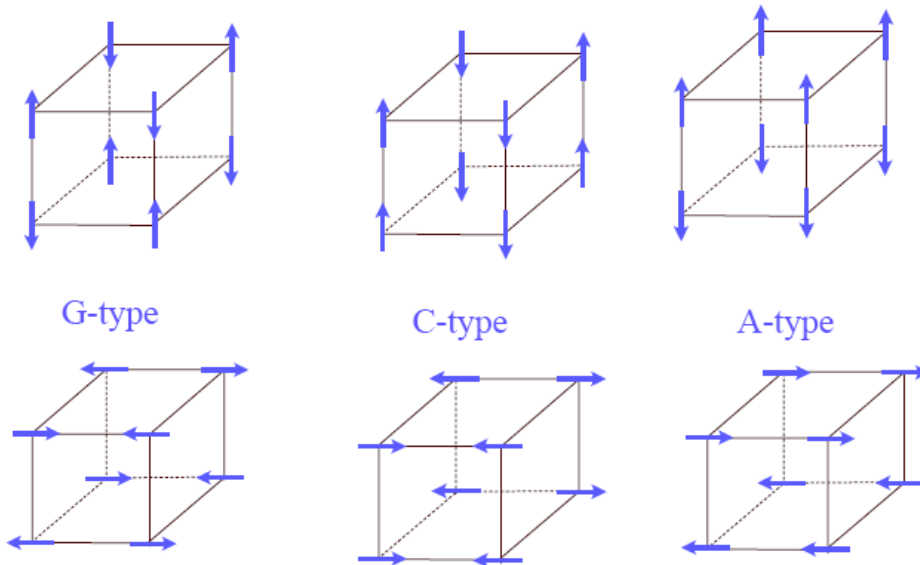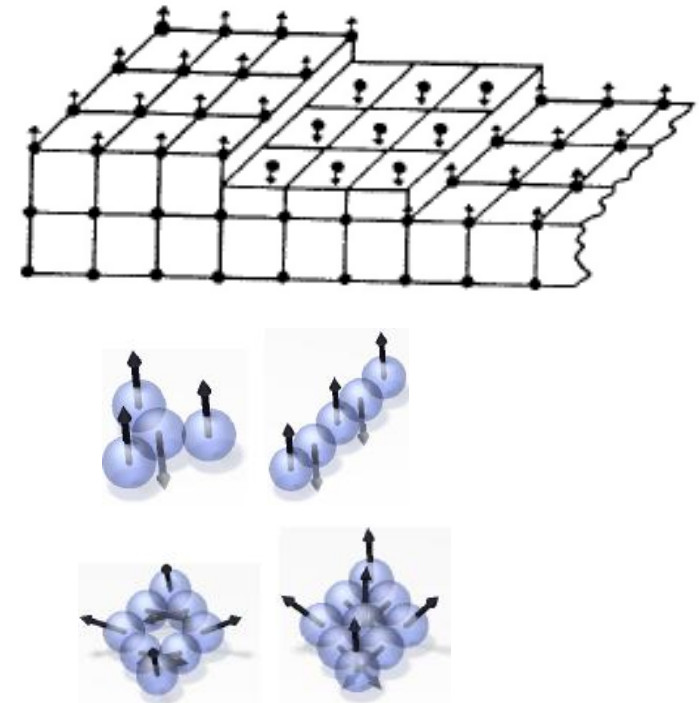
All spins in the grain must be ferromagnetically aligned

exchange energy J coupling spins

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

Domain formation -> magnetic moment is strongly reduced
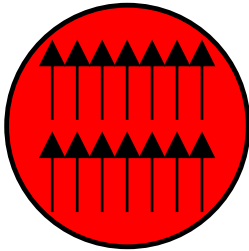
S_i is the atomic spin

Gain in the magnetostatic energy at the expenses of the exchange energy
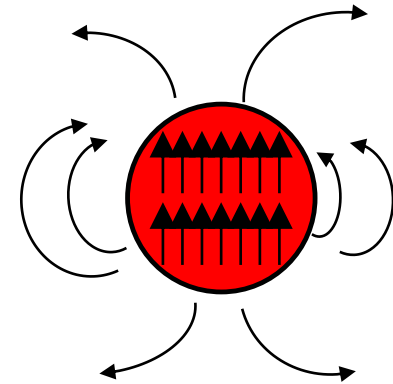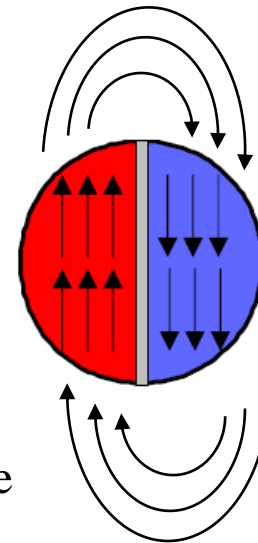
Which is the origin of the aligned atomic spin moments in a ferromagnetic domain (spontaneous magnetization)?

Weiss -> molecular field H_W (or mean field theory) of unknown origin

Heisenberg -> molecular field originating from the interaction of the atomic spin moment with the spin sea of all the other atoms

$$E_i = -2s_i \sum_j J_{ij}s_j = -m_i H_W; \quad H_W = -\frac{2}{g\mu_B}\sum_j J_{ij}s_j$$

Example:
single spin s=1/2 $\Longrightarrow$

Two energy levels: +/- $\mu_B H$ with an occupation probability given by $\exp(+/-\mu_B H/kT)$

$$M(H,T) = M^\uparrow - M_\downarrow = Ng\mu_B\left(\frac{e^x}{e^x+e^{-x}} - \frac{e^{-x}}{e^x+e^{-x}}\right) = N\mu_B \tanh(x); \quad x = \frac{\mu_B H}{k_B T}$$

Sea of spin s=1/2 $\Longrightarrow$ $x = \dfrac{\mu_B(H+\beta M(T))}{k_B T}$ $\qquad$ βM(T) -> molecular field

Curie temperature: temperature at which the spontaneous magnetization (H=0) goes to zero

M(T) ->0 when tanh(x) -> 0
when x-> 0 i.e. tanh(x) = x

$$M(T_c) \approx N\mu_B x = N\mu_B \frac{\mu_B(\beta M(T_c))}{k_B T_C} \implies \qquad T_C = \frac{N\mu_B^2\beta}{k_B} = \mu_B\frac{\beta M(0)}{k_B}$$

The magnetization goes to zero when the thermal energy ($k_B T_C$) equals the energy of a single spin in the molecular field ($gs\mu_B H_W = gs\mu_B\beta M(0)$)

For a general spin value *s* and moment *m=-gμ_Bs*

$$T_C = \frac{2\langle s \rangle^2 J_0}{3k_B}; \quad J_0 = \sum_j J_{ij} = NJ_{01}$$

$$H_W = \frac{2\langle s \rangle^2 J_0}{3\,m}$$

element	$\langle s \rangle^2 J_{01}$ [meV]	N	$N\langle s \rangle^2 J_{01}$ [meV]	$\langle s \rangle^2 J_0$ [meV]	T_C [K]	B_W $[10^3\ T]$
Fe (bcc)	19.5	8	156	183	1414	2.9
Co (fcc)	14.8	12	178	212	1645	4.3
Ni (fcc)	2.8	12	34	51	397	2.9

Neel temperature: is the equivalent to the Curie temperature for an antiferromagnet

A few Neel temperatures

NiO T_N = 525 K
CoO T_N = 290 K
FeO T_N = 298 K

● oxigen

● metal
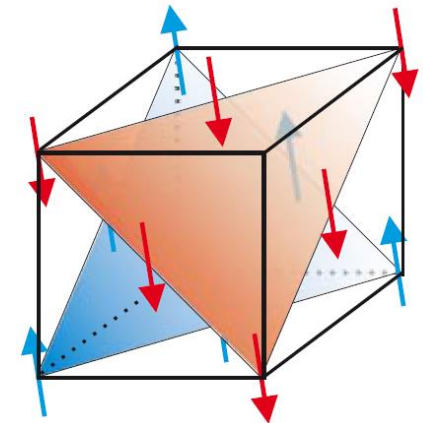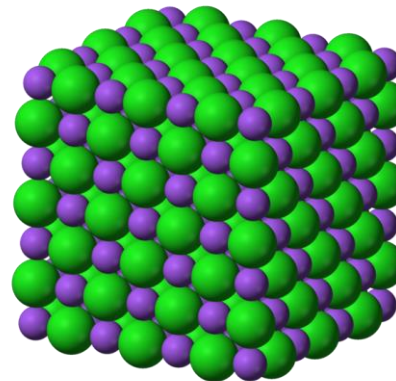
T_C depends on the atomic coordination

$$T_C = \frac{2\langle s \rangle^2 J_0}{3k_B}; \quad J_0 = \sum_j J_{ij} = NJ_{01}$$

J_{ij} as a function of distance

T_c nanostructures < T_c bulk
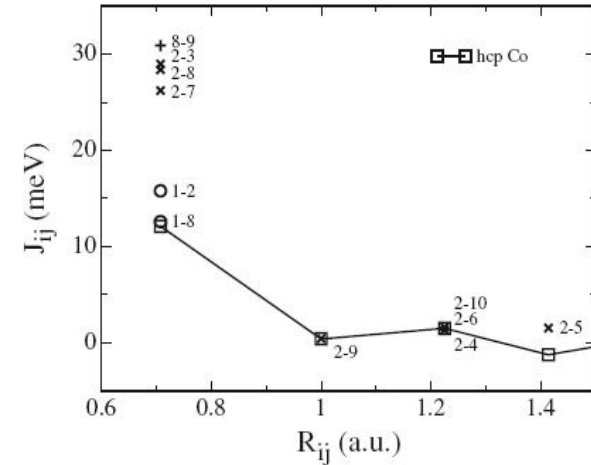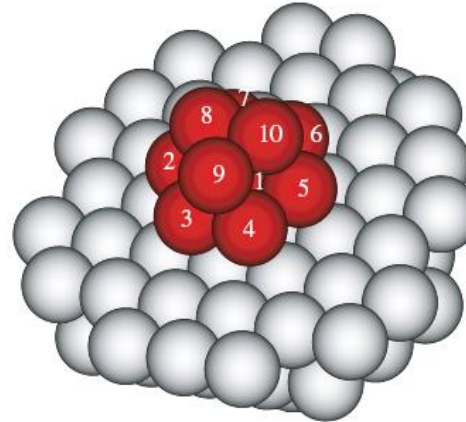
The number of magnetic neighbours (N) is reduced in a thin film

interface: N_i ———

bulk-like: N_b

interface: N_i ———

t layers

$$\overline{N} = \frac{t_b N_b + t_i N_i}{t_b + t_i} = z_b - 2\frac{N_b - N_i}{t}$$

$t = t_b + t_i$

1/t dependence

NANO !
INSTITUT DE PHYSIQUE
DES NANOSTRUCTURES

EPFL
Ecole Polytechnique
Fédérale de Lausanne

Critical Temperatures of Ising Lattice Films

G. A. T. ALLAN

Baker Laboratory, Cornell University, Ithaca, New York 14850

Phys. Rev. B **1**, 352 (1970)

$$T_C(\infty) - T_C(t) = t^{-\lambda}, \qquad \lambda = 1$$

Experiments and finite-size scaling model:

$$\frac{T_C(\infty) - T_C(t)}{T_C(\infty)} = \left(\frac{t}{t_0}\right)^{-\lambda'}, \qquad \lambda' = 1-1.6$$

C. Domb, J. Phys. A **1**, 1296 (1973); Y. Li *et al.* Phys. Rev. Lett. **68**, 1208 (1992); etc.

This model accounts for the decrease of T_C with t down to a critical thickness $t_0 \approx 4$ monolayers.

t is a continuous parameter -> in the ultra thin limit t becomes discrete (number of atomic layers)

Ultra thin limit:
linear decrease

$$\frac{T_C(\infty) - T_C(t)}{T_C(\infty)} = A - (n-1)/2N_0$$

N_o is the spin-spin coupling range (typically a few atomic sites) A takes into account the observation that for n=1 ferromagnetism can exist

R. Zhang *et al.* Phys. Rev. Lett. **86**, 2665 (2001)

Paramagnet

T>T_C

the magnetic moments are randomly oriented due to thermal fluctuations
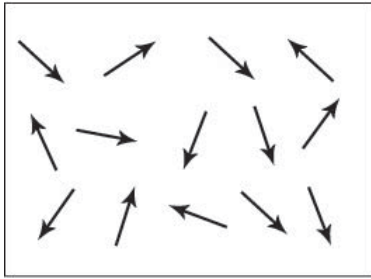
T<T_C

Ferromagnet

unlike the moments in a paramagnet, these moments will remain parallel even when a magnetic field is not applied
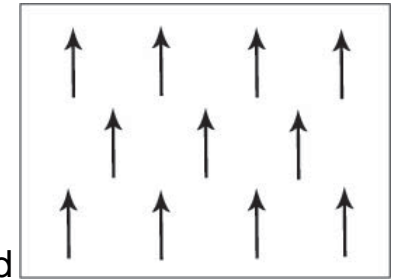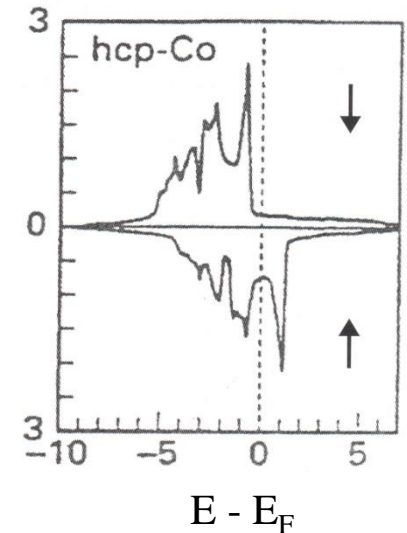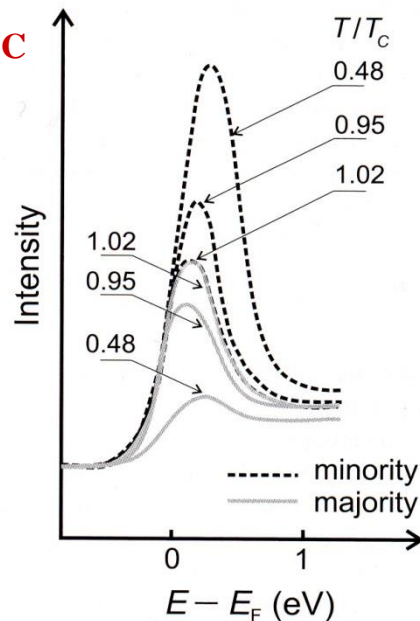
Antiferromagnet

Adjacent magnetic moments from the magnetic ions align anti-parallel to each other without an applied field.
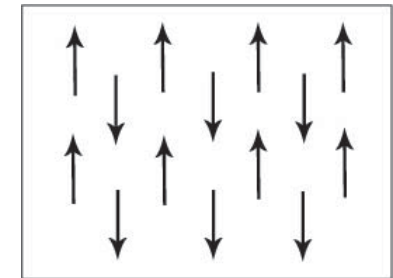
T>T_C

Spin resolved inverse photoemission spectroscopy for 3d bands as a function of temperature for Ni(110)

$T=T_C$ -> spin transition from minority and majority states are equal -> $\Delta=0$

T<T_C

T/T_C

0.48
0.95
1.02

1.02
0.95
0.48

Intensity

------ minority
—— majority

$E - E_F$ (eV)

hcp-Co

$E - E_F$

[Stö06]

Curie (Neel temperature)   ->   magnetic order in a ferromagnetic (antiferromagnetic) nanostructure

Super-exchange   ->   mediated interaction between magnetic atoms

Bias exchange   ->   interaction at the interface of FM – AFM structures

Kondo effect   ->   interaction between a magnetic impurity and the conduction band electrons

RKKY interaction   ->   interaction between magnetic impurities mediated by the conduction band electrons
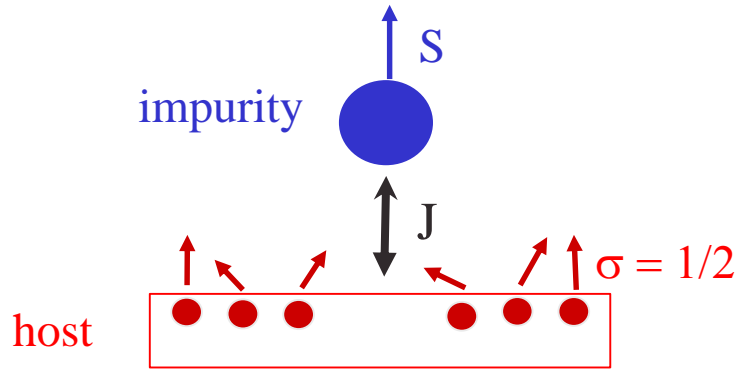
oxigen

metal
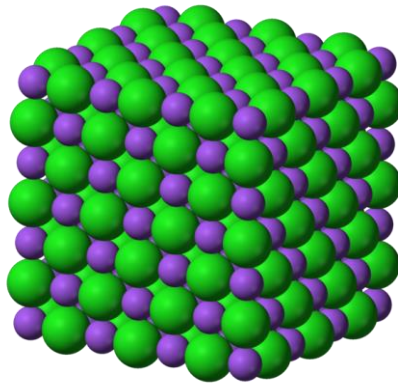
(ex: MnO)

in many materials (oxides), magnetic atoms are
separated by non-magnetic ions (oxygen)

Mn ——— O ——— Mn

d_{z^2} p_z d_{z^2}

↑   ↓
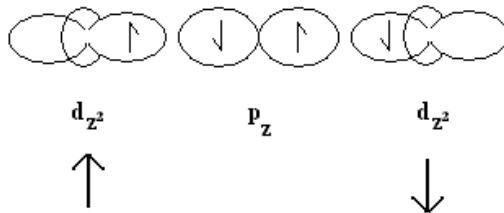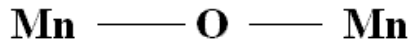
Indirect interactions through oxygen atoms

In the antiferromagnetic configuration, electrons of atoms A and B
can both hybridize with 1 p-electron of Oxygen

energy depends on the relative spin orientation

$J\,S\,\sigma \ll k_B\,T_K$
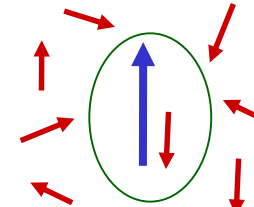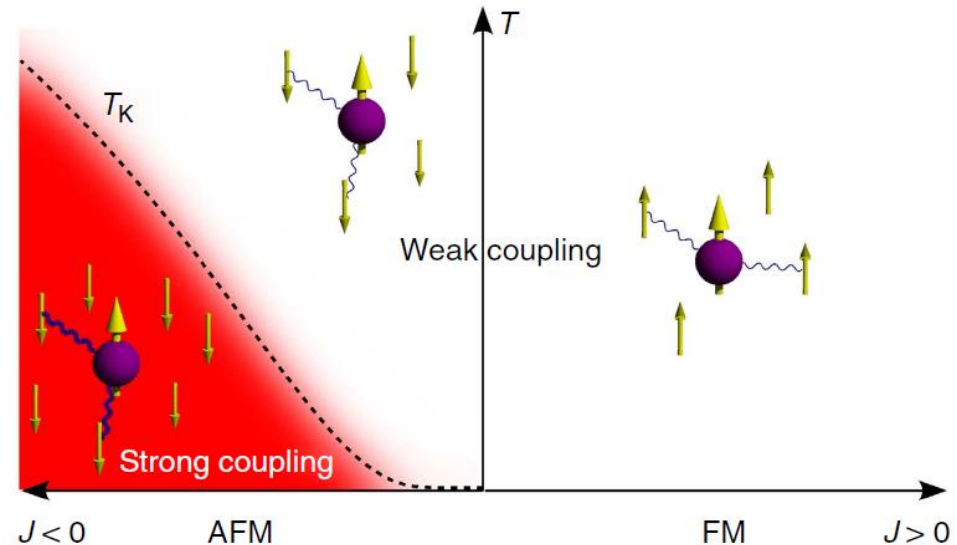
Screening
S - σ

$J\,S\,\sigma \gg k_B\,T_K$
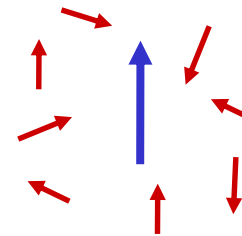
Non screening
S

The Kondo interaction J S σ couples itinerant electrons of the host with spin σ = 1/2 to a magnetic impurity with spin S.

For exchange interaction J < 0, antiferromagnetic (AFM) coupling of the spins of the conduction electrons screens the impurity spin. The ground state at temperatures T below the Kondo temperature T_K is a spin S - σ (red area).

For J > 0, the ferromagnetic (FM) coupling tends to create a cloud of spins aligned parallel to the impurity spin, which becomes asymptotically free at low temperatures.

For S = ½ complete screening
For S > 1 under-screening Kondo

Indirect exchange couples moments (in impurities or magnetic layers) over relatively large distances
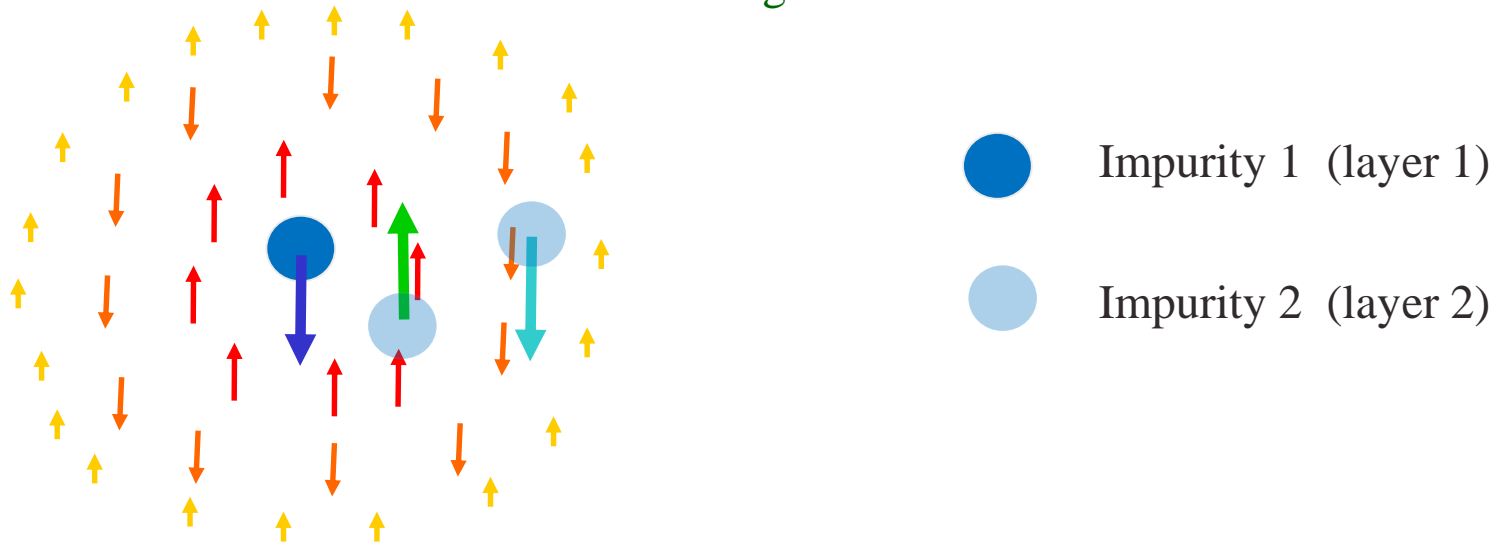
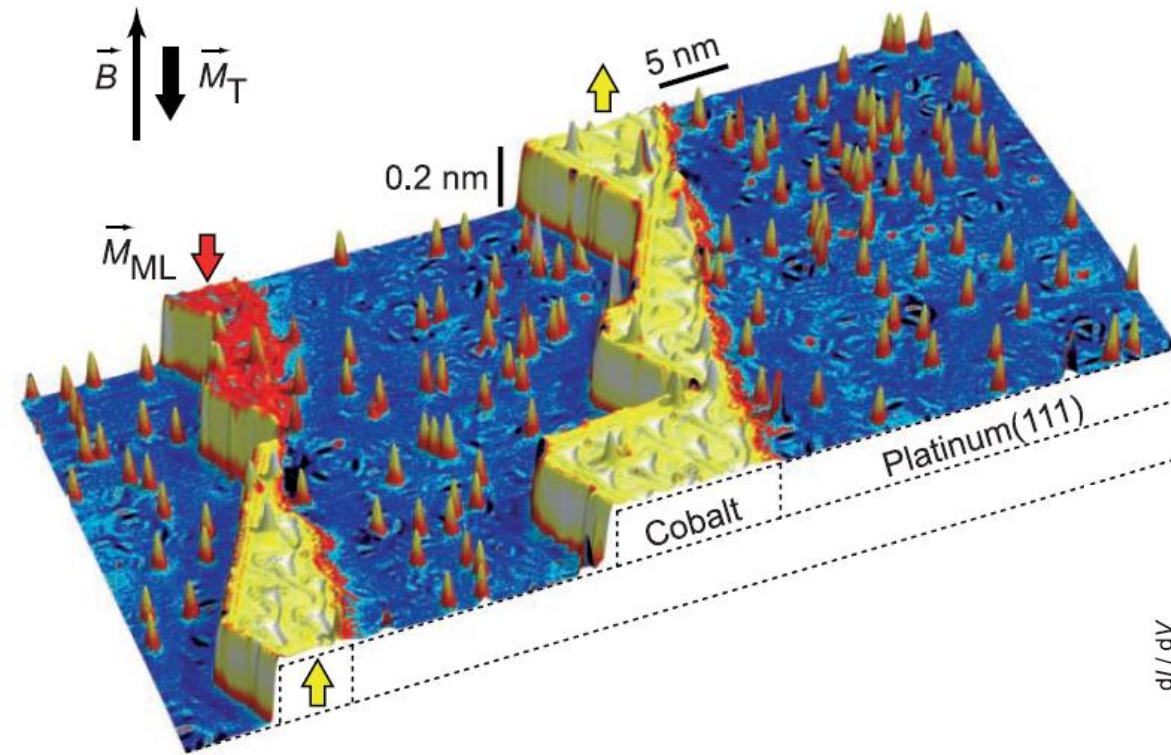

Impurity 1 (layer 1)

Impurity 2 (layer 2)
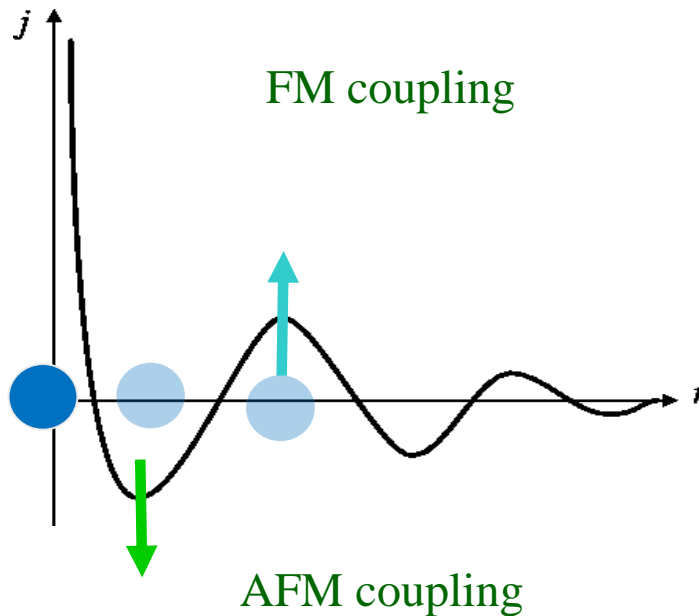
FM coupling

AFM coupling

$J(r) = J_0 \cdot \cos(2 \cdot k_F \cdot r)/(2 \cdot k_F \cdot r)^D$
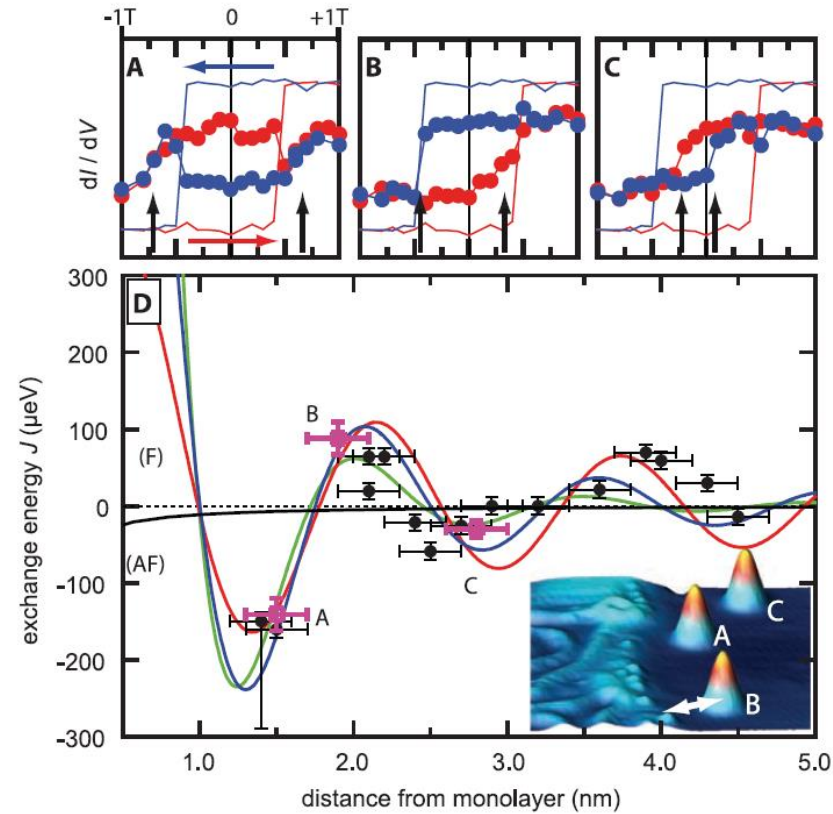
D represent the system dimensionality

$\lambda_F = 2\pi/k_F$ Fermi wave length
(in metal is of the order of a few nm)

$$J(r) = J_0 \cdot \cos(2 \cdot k_F \cdot r)/(2 \cdot k_F \cdot r)$$

$$\lambda_F = 2\pi/k_F \approx 3 \text{ nm}$$

F. Meier, *et al.,* Science, 82, 320 (2008)

Atom-by-atom engineering and magnetometry of tailored nanomagnets

Alexander Ako Khajetoorians[1], Jens Wiebe[1]*, Bruno Chilian[1], Samir Lounis[2], Stefan Blügel[2]
and Roland Wiesendanger[1]

a)   In an external field and above the Néel temperature T_N, antiferromagnetic spins located at the interface with the ferromagnet are aligned, like the ferromagnet, with the external field.

b) Once cooled below T_N, these interface spins keep their orientation and appear "pinned" because they are tightly locked to the spin lattice in the bulk of the antiferromagnet, which is not sensitive to external fields. Consequently these pinned spins produce a constant magnetic field at the interface that causes the hysteresis loop of the ferromagnet to shift.

c) This intuitive picture overestimates the magnitude of the loop shift by orders of magnitude.

$$H_b / H_c \approx W / \xi \approx 2 \text{ eV} / 50 \text{ meV} \approx 30$$

When $T < T_N$ you need several tens of tesla to reverse the AFM coupled spins ("pinning")

J. Nogués *et al.*, J. Magn. Magn. Mater. **192**, 203 (1999)
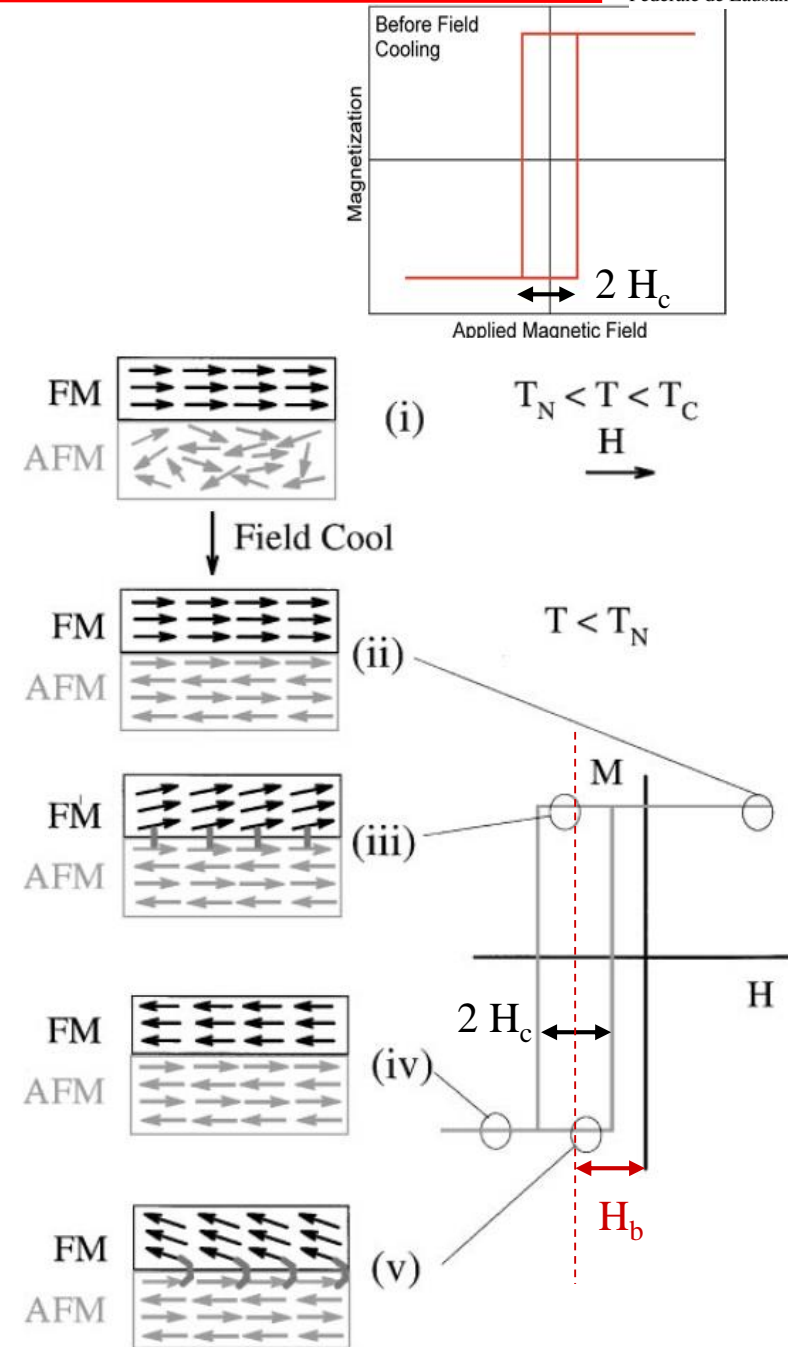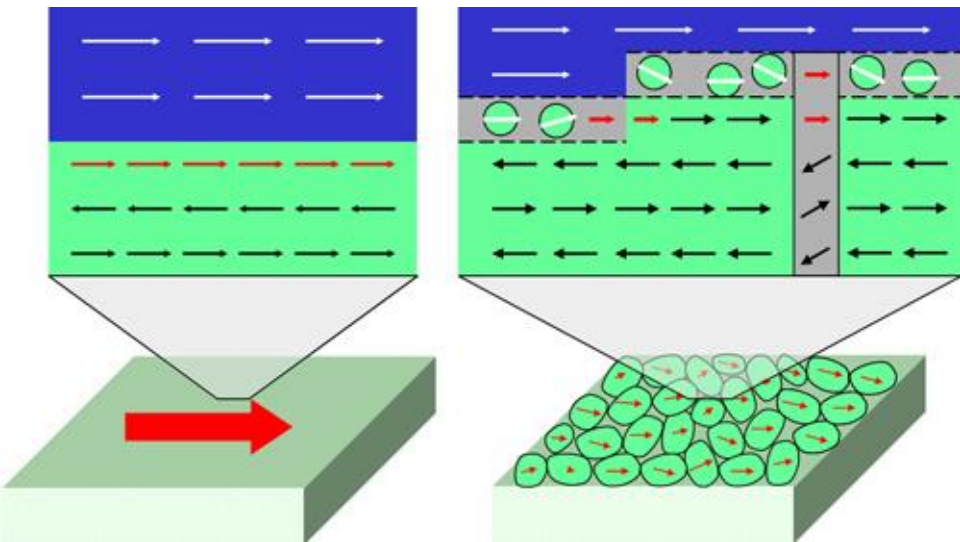
only a small fraction (5%) of interfacial spins is actually pinned, and these cause the horizontal hysteresis loop shifts.

$$H_B = \frac{\sigma}{M_{FM} t_{FM}} = J \frac{S_{AFM} S_{FM}}{a_{AFM}^2 M_{FM} t_{FM}}$$

TABLE I. Effective and corrected interface energies σ calculated from the macroscopic loop shift and the coverage with pinned spins ρ.

	Sample	ρ (ML)	σ_{eff} (mJ/m^2)	σ (mJ/m^2)
A	3 nm Co/NiO	0.04 ± 0.01	0.052 ± 0.005	1.3 ± 0.5
B	2 nm Co/IrMn	0.04 ± 0.01	0.168 ± 0.020	4.1 ± 1.4
C	1 nm CoFe/PtMn	0.03 ± 0.01	0.124 ± 0.014	3.9 ± 1.4
D	2 nm CoFe/PtMn	0.04 ± 0.01	0.188 ± 0.015	4.8 ± 1.7
E	3 nm CoFe/PtMn	0.04 ± 0.01	0.229 ± 0.027	5.7 ± 2.0

H. Ohldag *et al*., Phys. Rev. Lett. **91**, 017203 (2003)
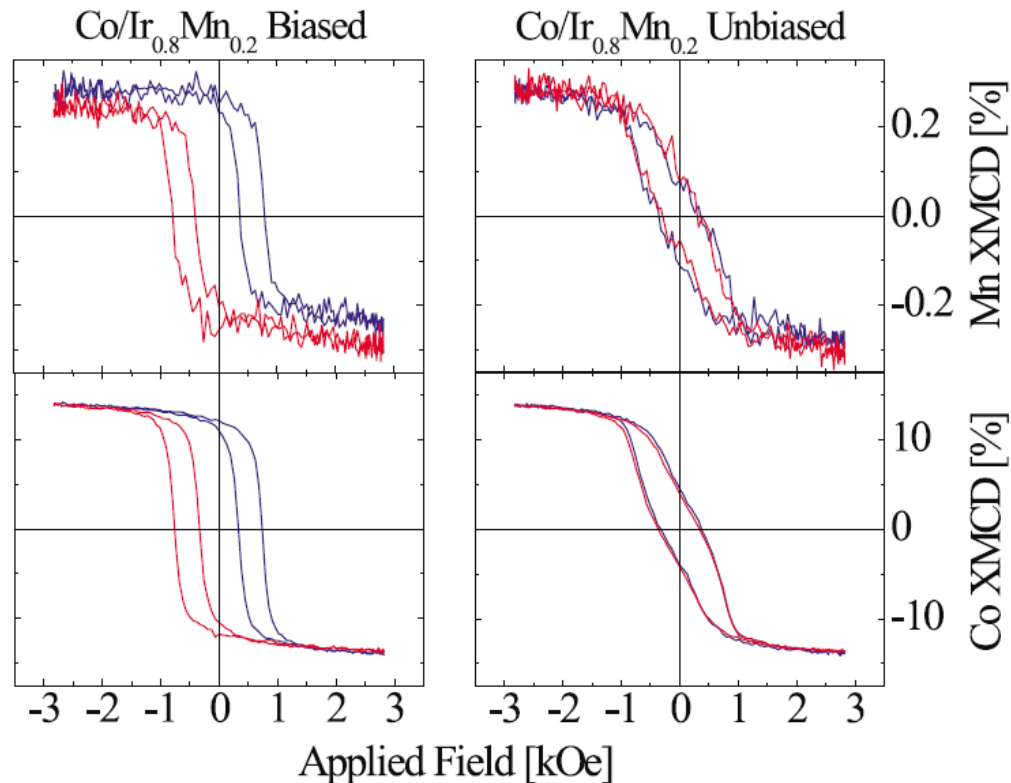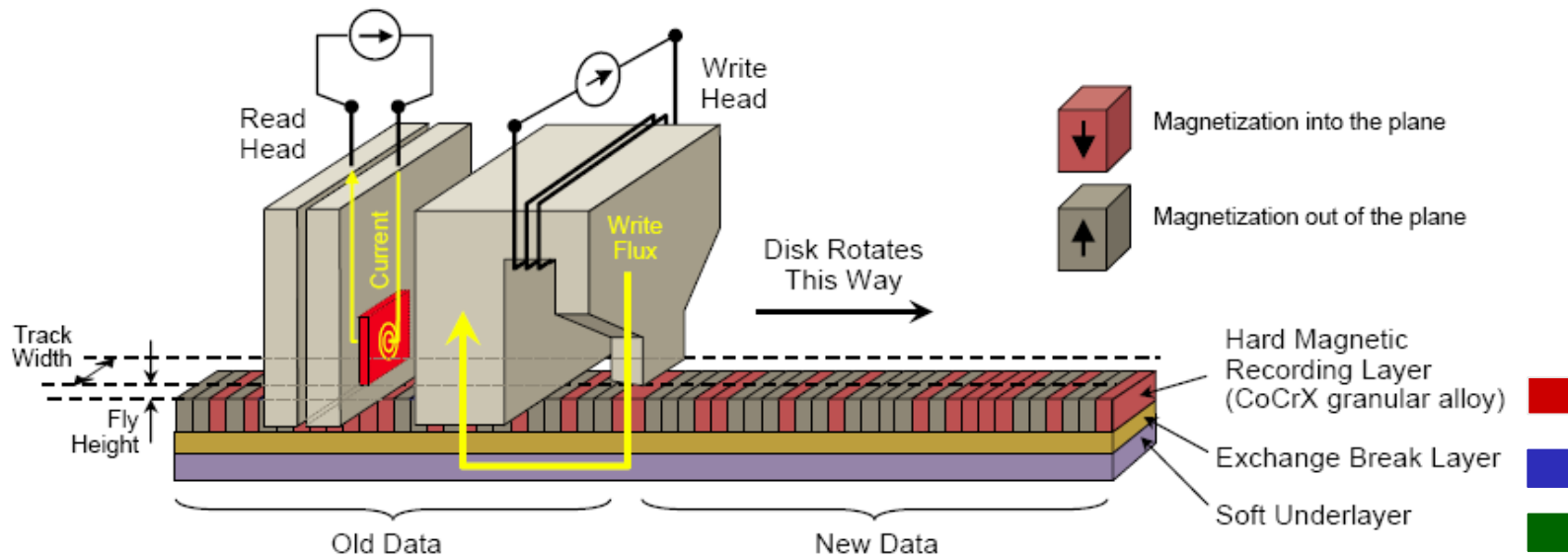
The exchange break layer is need to decouple the recording layer from the soft underlayer (necessary to close the magnetic flux lines)
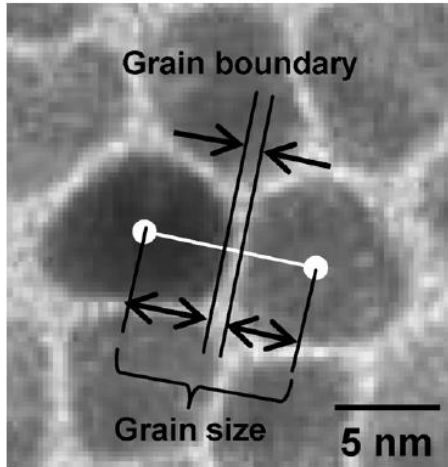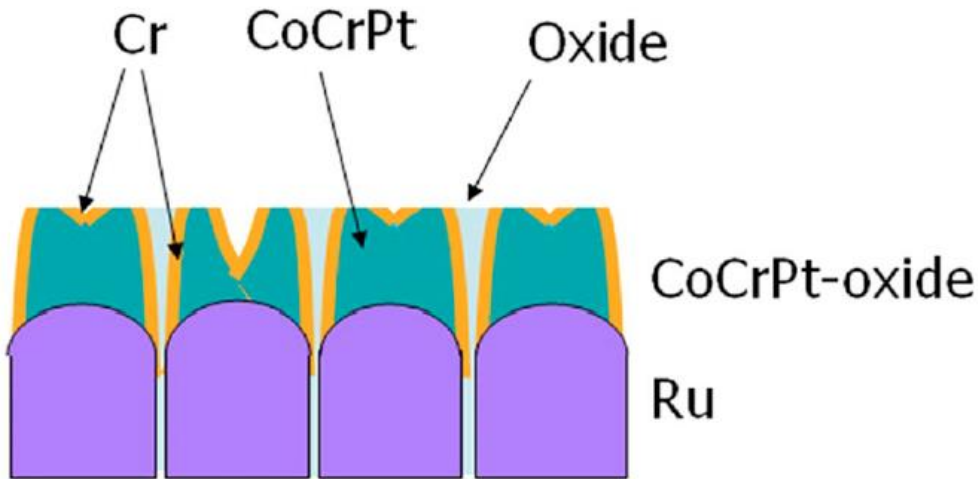
Fig. 1. Plan-view TEM image of CoCrPt-SiO$_2$ with definition of grain size and grain boundary width. White dots in the image show the centroids of each grain.
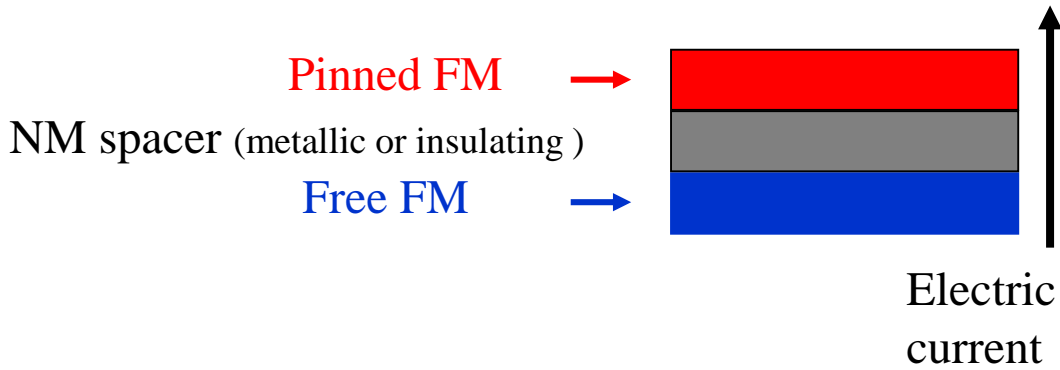
R. Araki, *et al.* IEEE Trans. Magn. **44**, 3496 (2008).

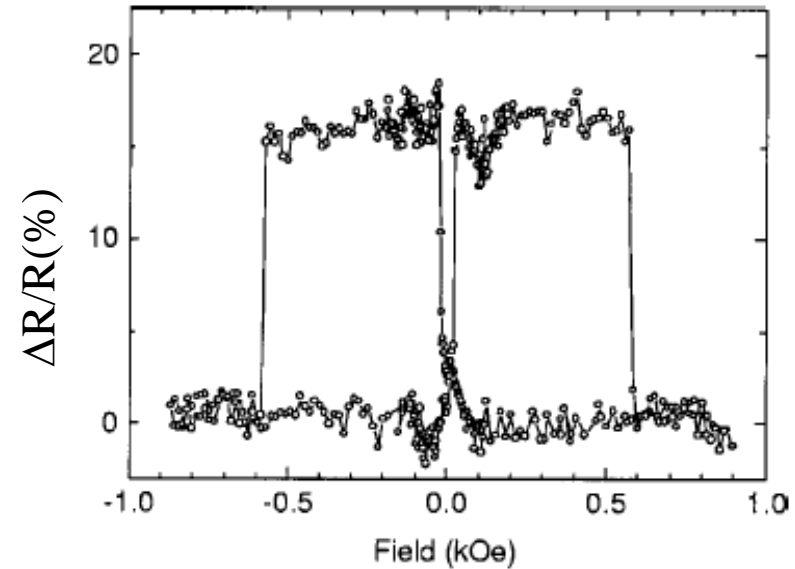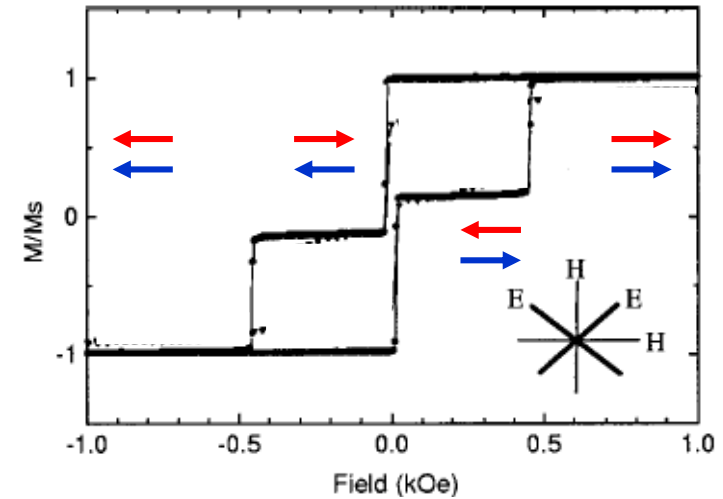D. E. Laughlin, *et al.* J. Appl. Phys. **105**, 07B739 (2009).

The inter-grain exchange interaction is stopped by the oxide layer
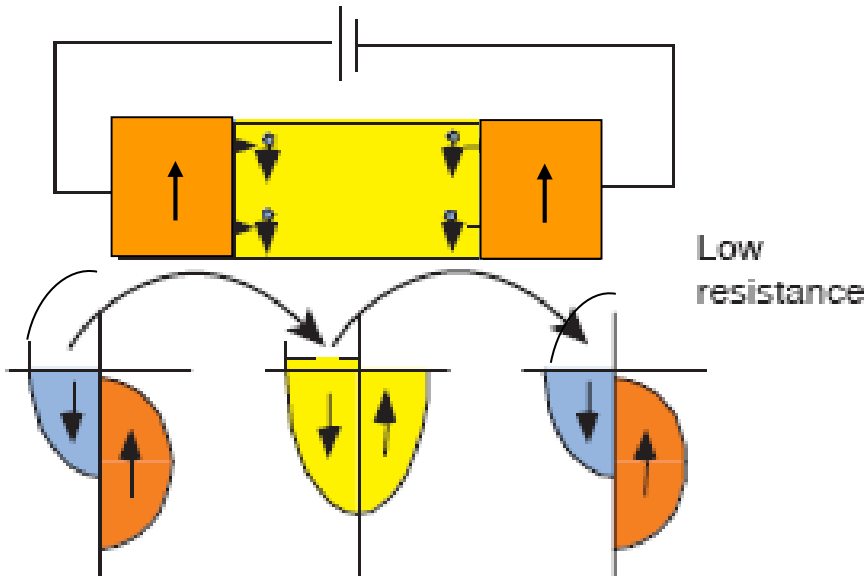

FIG. 3. (Color online) Schematic of a possible mechanism for tooth growth.

Pinned FM →

NM spacer (metallic or insulating)

Free FM →

Electric current

$$\Delta R / R = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}$$

Available states with the same spin:
Low resistance

1

Low resistance

0
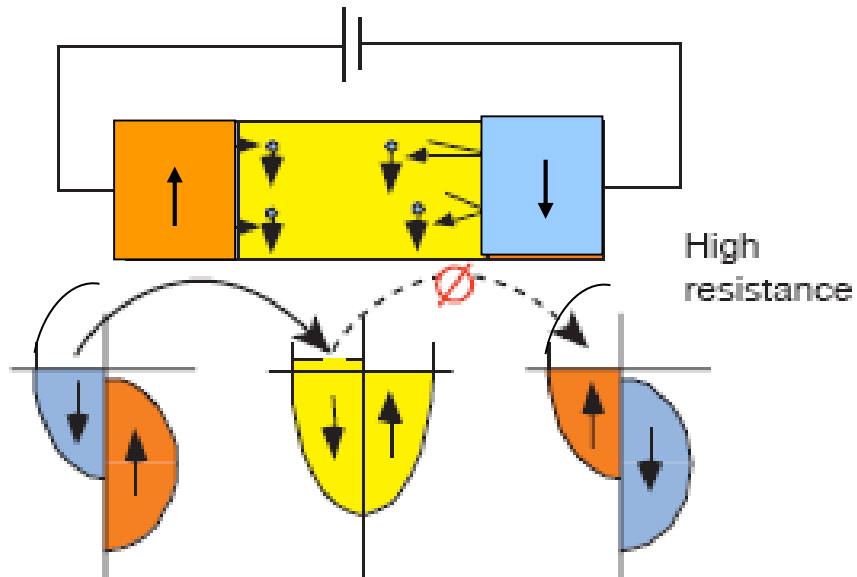
High resistance

Absence of states with the same spin:
High resistance

Electric current

Pinned layer

Free layer

H_E

AFM ←

Pinned FM ←

Free FM ←

J. Appl. Phys. **69**, 4774 (1991)
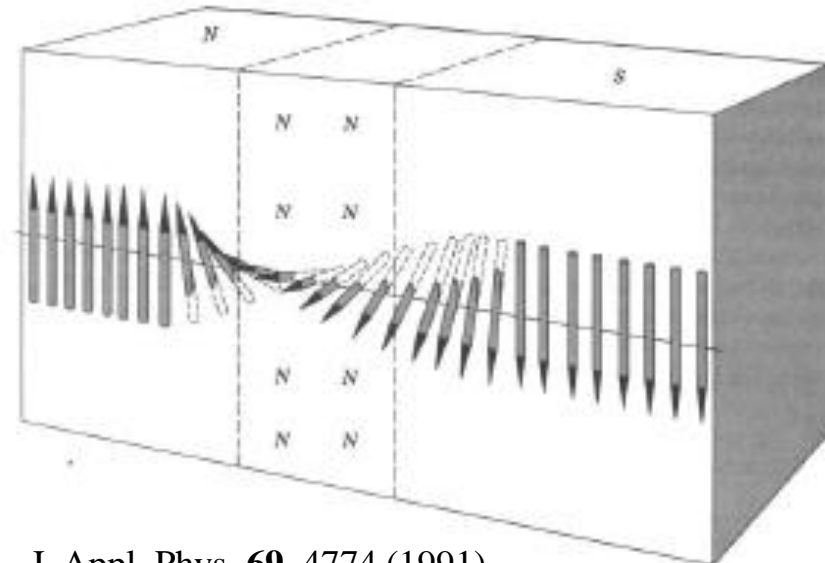
Ecole Polytechnique
Fédérale de Lausanne
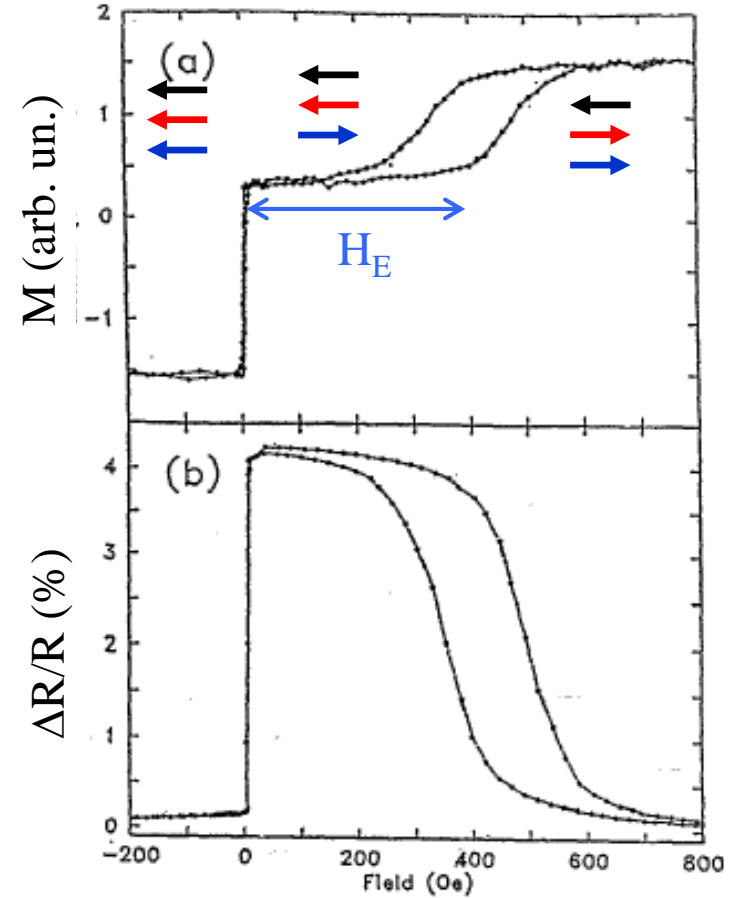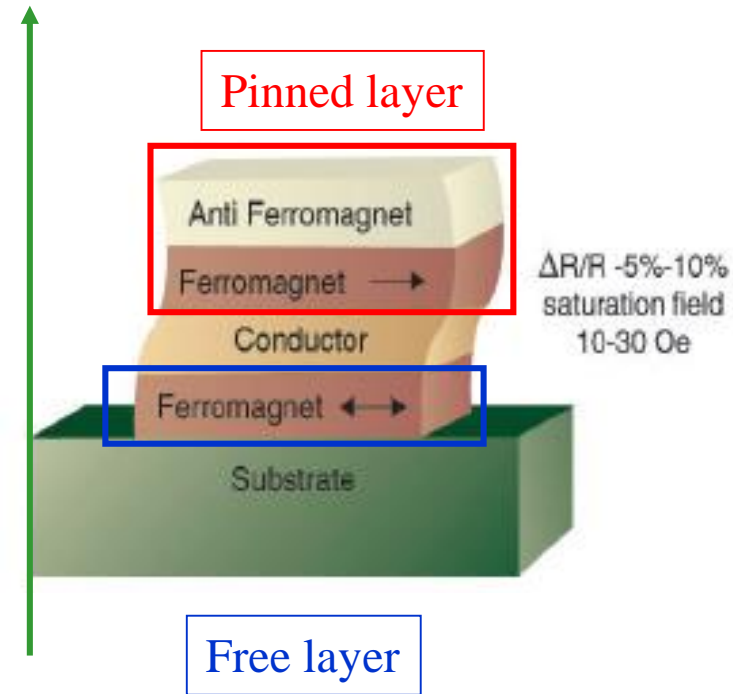
The atom spins are coupled together

In non magnetic materials $H_{ex} = J\, S_i\, S_j = 0$

Inter-atomic exchange:

MAGNETIC ORDER

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

J_{12} J_{23} J_{34}

Domain wall between two pinned ferromagnetic materials with opposite orientation of the magnetization

Without the spacer two (negative) scenarios depending on the strength of the exchange force in respect to the pinning force:
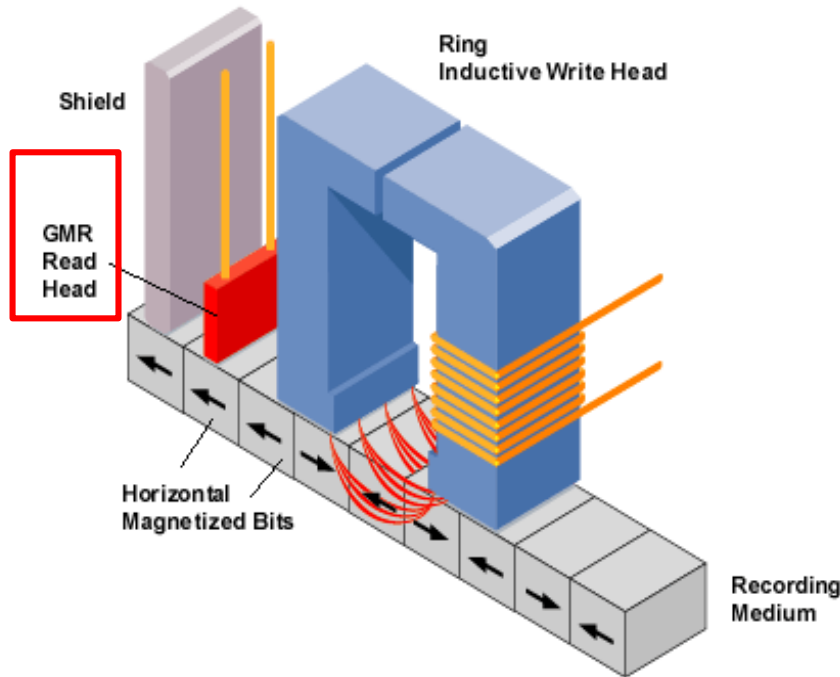
a) The free layer magnetization always aligns parallel to the magnetization of the pinned layer

b) A domain wall forms which produces the spin current depolarization

J. Appl. Phys. **69**, 4774 (1991)

Magnetic random access memory (MRAM)

Ferromagnetic (FM) - nonmagnetic (NM) - ferromagnetic (FM) junction

Science **282**, 1660 (1998); Nat. mater. **6**, 813 (2007)
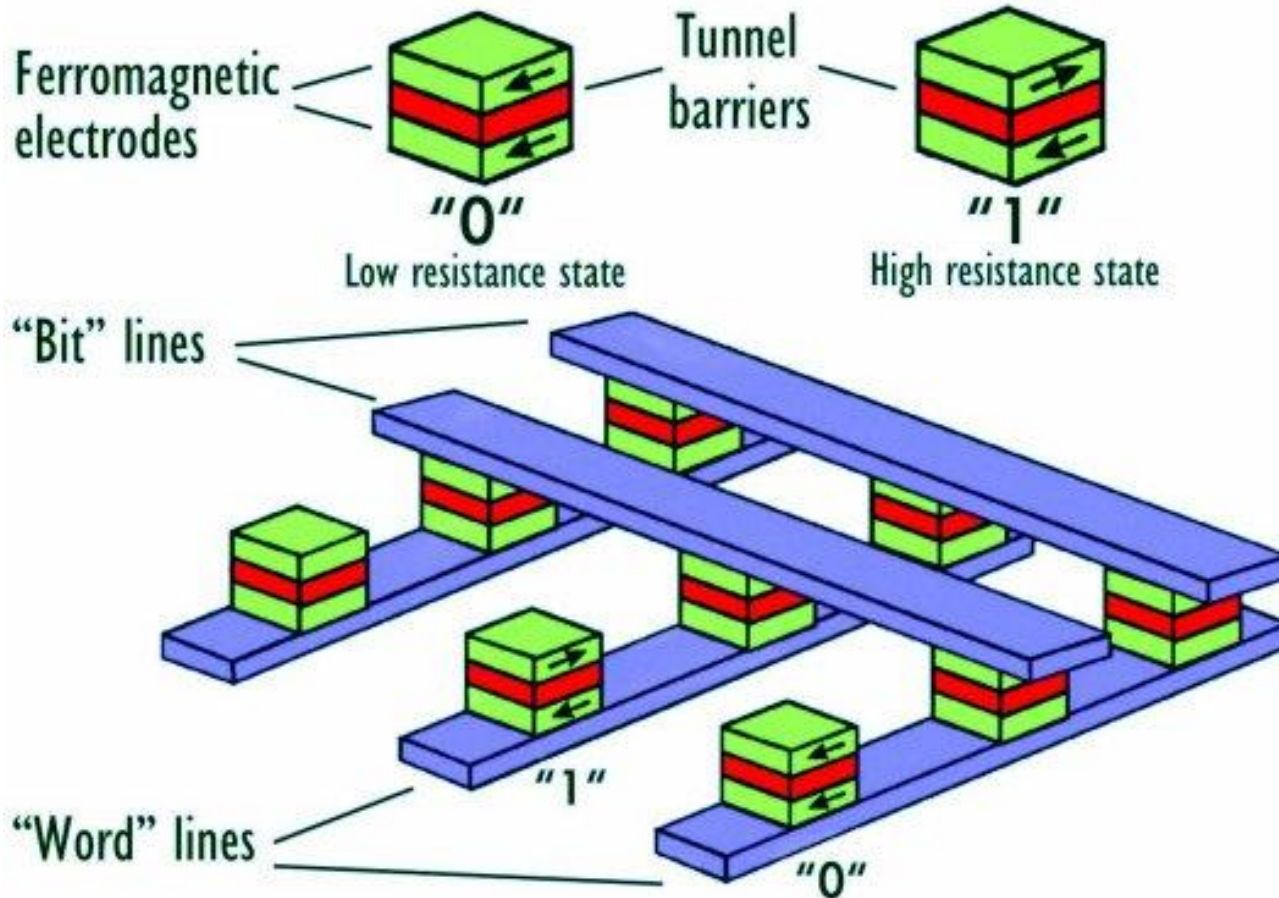
Reading-writing head in HDD

Reading:
the bit stray field defines the magnetization
direction of the free layer