Physics of Condensed Matter I

1100-4INZ`PC

Faculty of Physics UW

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inżynieria nanostruktur

Ćwiczenia

Ćwiczenia środowe odrabiamy:
28.10 i 4.11 – 16:00-17:00 (prośba o ustalenie z prowadzacymi Termodynamikę)

Od przyszłego tygodnia 2 grupy

1. 37 Maciej Ściesiek (parzyste nr. indeksu)
2. 25 Aneta Drabińska (nieparzyste nr. indeksu)

Magnetic field and spin

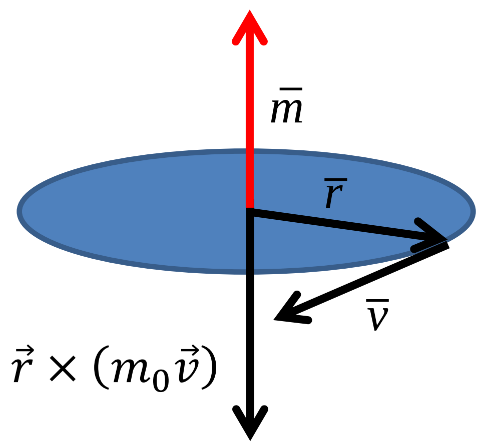
Magnetic field:

$$H' = -\vec{m}\vec{B}$$

Here $\vec{m}$ is the magnetic moment

clasically:

$$|\vec{m}| = \left|I\vec{S}\right| = \frac{e}{T}\pi r^2 = \frac{e}{2\pi r/v}\pi r^2 = \frac{e}{2} rv \quad [\mathrm{Am}^2]$$

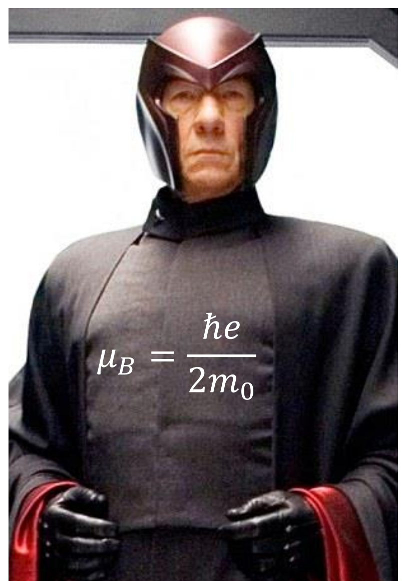


thus: $\vec{m} = -\frac{e}{2m_0}\vec{L} = -\frac{\mu_B}{\hbar}\vec{L}$

$$\vec{L} = \vec{r} \times (m_0\vec{v})$$

Bohr magneton $\mu_B = \frac{\hbar e}{2m_0}$

$\mu_B = 9{,}274009994(57)\times 10^{-24}$ J/T



$$H' = -\vec{m}\vec{B} = \frac{\mu_B}{\hbar}\hat{L}\vec{B}$$

$$\hat{L} = \left(\hat{L}_x, \hat{L}_y, \hat{L}_z\right)$$

Magnetic field and spin

Spin, spin-orbit interaction

Spin operators $\hat{S}_x, \hat{S}_y, \hat{S}_z, \hat{S}^2$

$$H' = \frac{\mu_B}{\hbar}(\hat{L} + g\hat{S})\vec{B}$$

g-factor for the agreement with experiments

$$\mu_B = \frac{\hbar e}{2m_0}$$

Total angular momentum operator $\hat{J} = \hat{L} + \hat{S}$, the base $|j, m_j\rangle$

Total magnetic moment $\widehat{M} = \widehat{M}_L + \widehat{M}_S = -g_L \frac{\mu_B}{\hbar}\hat{L} - g_S \frac{\mu_B}{\hbar}\hat{S}$

(g_L =1, g_S =2)

$\widehat{M} \neq \hat{J}$ - magnetic anomaly of spin

Magnetic field and spin

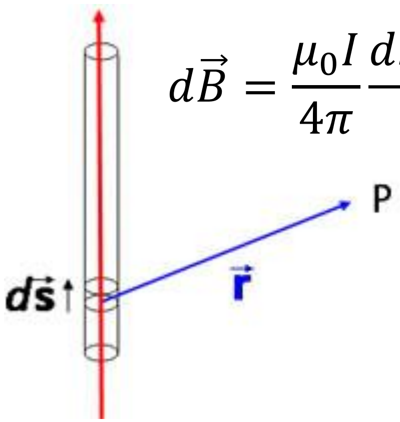
Spin-orbit interaction $\widehat{H}_{SO} = \frac{\lambda}{\hbar^2}\hat{L}\hat{S}$ with the base $|n, l, s, m_l, m_s\rangle$

For s-states $\hat{L} = 0 \Rightarrow \hat{L}\hat{S} = 0$

Total angular momentum operator $\hat{J} = \hat{L} + \hat{S}$, the base $|j, m_j\rangle$

$$H' = -\vec{\mu}_S \vec{B}_L$$

Biot-Savart law – magnetic field of en electron of angular momentum L



$$d\vec{B} = \frac{\mu_0 I}{4\pi}\frac{d\vec{s} \times \vec{r}}{|r|^3}$$

Orbiting charge: $v\, d\vec{s} = \vec{v}\, ds$ $\qquad I = \frac{Zqv}{2\pi a_B}$

Classically

$$\vec{B}_L = \frac{Ze\mu_0}{4\pi m_e}\frac{1}{r^3}\vec{L}$$

Electron in the external field $\vec{B}_L$

http://www.chem.ox.ac.uk/teaching/Physics%20for%20CHemists/Magnetism/Field.html

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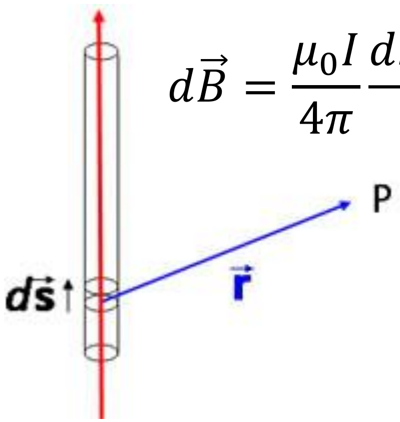

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Quantum

$$\vec{B}_L = \frac{1}{2}\frac{Ze\mu_0}{4\pi m_e}\frac{1}{r^3}\vec{L} \qquad \vec{\mu}_S = g_S \frac{\mu_B}{\hbar}\hat{S}$$

Thomas factor from relativistic calculations

http://www.st-andrews.ac.uk/~dc43/PH4021/Lectures%2011-13%20SPIN-ORBIT%20INTERACTION.pdf

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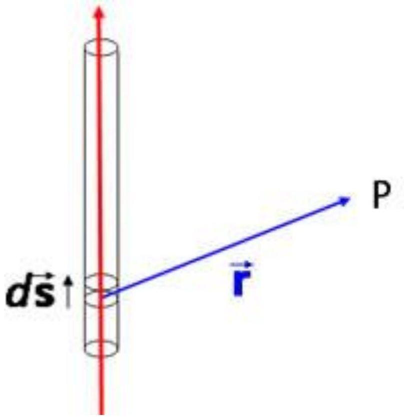

$$H' = \frac{e}{m_e}\hat{S}\cdot\vec{B}_L = \frac{Ze^2\mu_0}{8\pi m_e^2}\frac{1}{r^3}\hat{S}\cdot\hat{L} = \frac{\lambda}{\hbar^2}\hat{L}\hat{S}$$

(<u>Note</u>: sometimes convenction is $H' = \lambda\hat{l}\hat{s}$)

$$H_{SO} = \frac{1}{2}\left(\frac{Ze^2}{4\pi\epsilon_0}\right)\left(\frac{g_s}{2m^2c^2}\right)\frac{\hat{L}\hat{S}}{r^3}$$

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fine-structure constant α

$$\lambda = \frac{Ze^2\mu_0\hbar^2}{8\pi m_e^2}\left\langle\frac{1}{r^3}\right\rangle = \frac{Z\hbar^3\alpha}{2m_e^2\, c}\left\langle\frac{1}{r^3}\right\rangle$$

$$\alpha = \frac{e^2}{4\pi\varepsilon_0\hbar c} \approx \frac{1}{137.037}$$

$Ry = hcR_\infty$

$R_\infty = \frac{m_e e^4}{8\varepsilon_0^2 h^3 c}$

$R_\infty = 1{,}097 \times 10^7$ m^{-1}

$$E_{SO} = \int \psi^* H_{SO}\psi\, dV = \frac{Z}{2(137)^2}\int \psi^* \frac{\hat{L}\hat{S}}{r^3}\,\psi\, dV$$

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$$\left\langle\frac{1}{r^3}\right\rangle = uff \ldots ufff \ldots ufffff \ldots = \frac{Z^3}{n^3 a_B^3}\frac{1}{l\left(l+\frac{1}{2}\right)(l+1)}$$

$$\langle\hat{L}\hat{S}\rangle = \frac{\hbar^2}{2}[j(j+1) - l(l+1) - s(s+1)]$$

e.g. for ψ_{210} we get $\left\langle\frac{1}{r^3}\right\rangle = \frac{1}{24}\left(\frac{Z}{a_0}\right)^3$ and for general n (principal quantum number)

$$E_{SO} = \frac{Z^4}{2(137)^2 a_0^3 n^3}\left(\frac{j(j+1) - l(l+1) - s(s+1)}{2l(l+1/2)(l+1)}\right)$$

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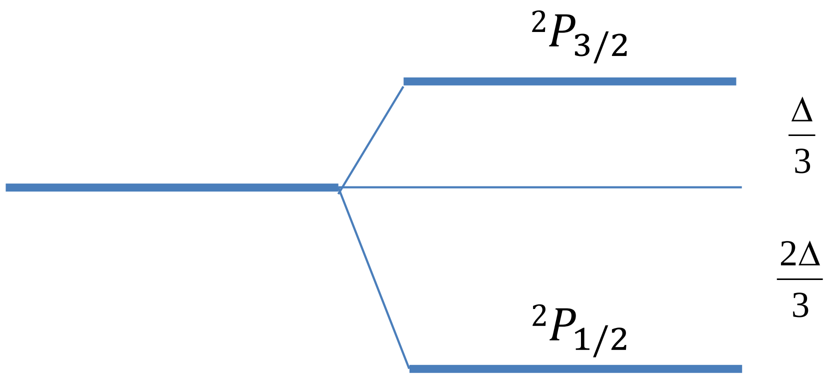
$\hat{L} = 1;\ \hat{S} = \frac{1}{2}$



the base: $|n, l, s, j, m_j\rangle$

shortly: $|j, m_j\rangle$

Fine structure

The fine structure means the splitting of the spectral lines of atoms due to electron spin and relativistic corrections to the Schrödinger equation. We got corrections to the value of energy levels.

- Kinetic energy relativistic correction
- Spin-orbit coupling
- Darwin term

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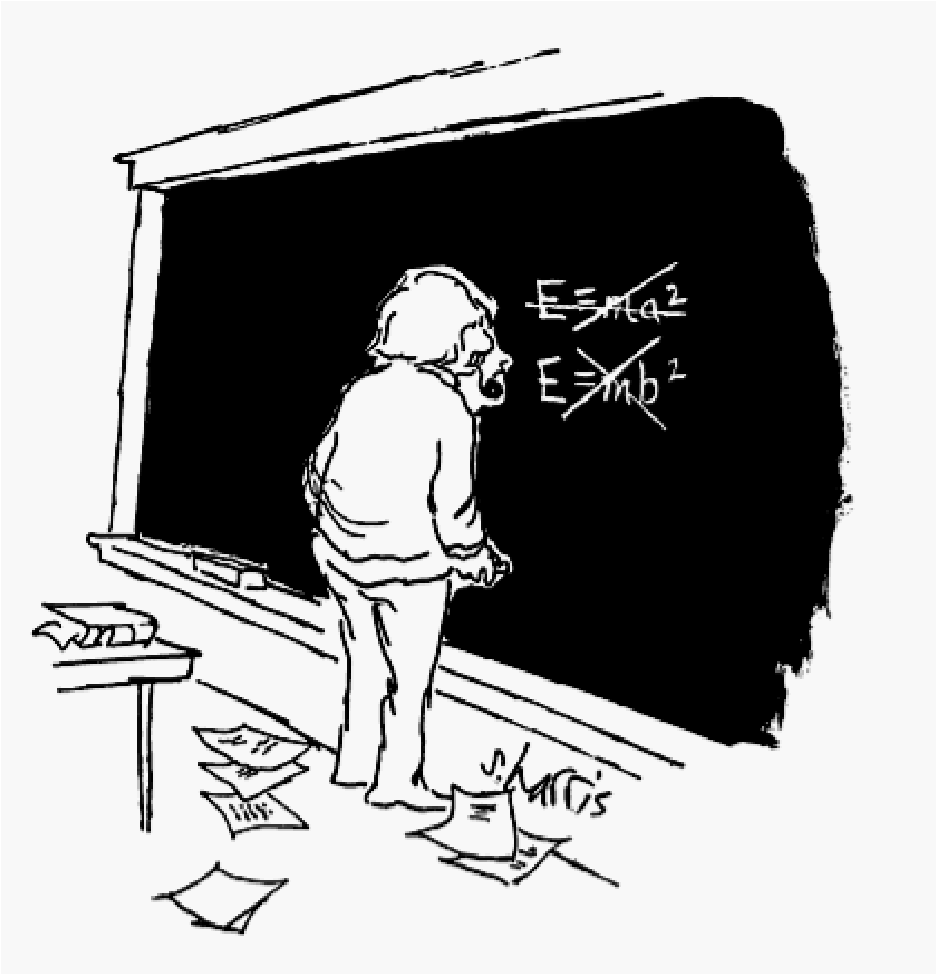

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- Kinetic energy relativistic correction

$$E = \sqrt{\vec{p}^2 c^2 + m_0^2 c^4}$$

The correct description of the atom requires taking into account the relativistic effects which lead to the Dirac Hamiltonian.

The square root can be expanded into a series:

$$E = m_0 c^2 \left(1 + \frac{p^2}{2m_0^2 c^2} - \frac{p^4}{8m_0^4 c^4} + \cdots \right) = m_0 c^2 + \frac{p^2}{2m_0} - \frac{p^4}{8m_0^3 c^2} + \cdots$$

thus kinetic energy can be expressed as $E_K = E - m_0 c^2 = \frac{p^2}{2m_0} - \frac{p^4}{8m_0^3 c^2} + \cdots$

and the Hamiltonian is:

$$i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}, t) = \left[-\frac{\hbar^2}{2m} \nabla^2 + \mathrm{V}(\vec{r}) - \frac{\hbar^4}{8m_0^3 c^2} \nabla^4 \right] \Psi(\vec{r}, t)$$

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Using perturbation theory one can find correction due to the **relativistic mass change** for each principal quantum number and corresponding energy E_n.
For instance the electron speed of $1s$ in gold ^{79}Au $v = 53\%\ c$!

$$m = \frac{m_0}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$\Delta E_n' = -\frac{E_n^2}{2mc^2}\left[\frac{4n}{l+\frac{1}{2}} - 3\right] = -\frac{\alpha^2 Z^2}{2n^4}E_n\left[\frac{n}{l+\frac{1}{2}} - \frac{3}{4}\right]$$

$$\alpha = \frac{e^2}{4\pi\epsilon_0\,\hbar c} \approx \frac{1}{137}$$

$$E_n = -\frac{mc^2\alpha^2}{2}\frac{Z^2}{n^2}$$

Correction from this perturbation:

- Small for light atoms
- Rapidly decreases with the principal quantum number n
- Significant for large Z

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$$= \frac{1}{2}\left(\frac{Ze^2}{4\pi\epsilon_0}\right)\left(\frac{g_s}{2m^2c^2}\right)\frac{\hat{L}\hat{S}}{r^3}$$

e.g. for ψ_{210} we get $\left\langle \frac{1}{r^3} \right\rangle = \frac{1}{24}\left(\frac{Z}{a_0}\right)^3$ and for general n (principal quantum number)

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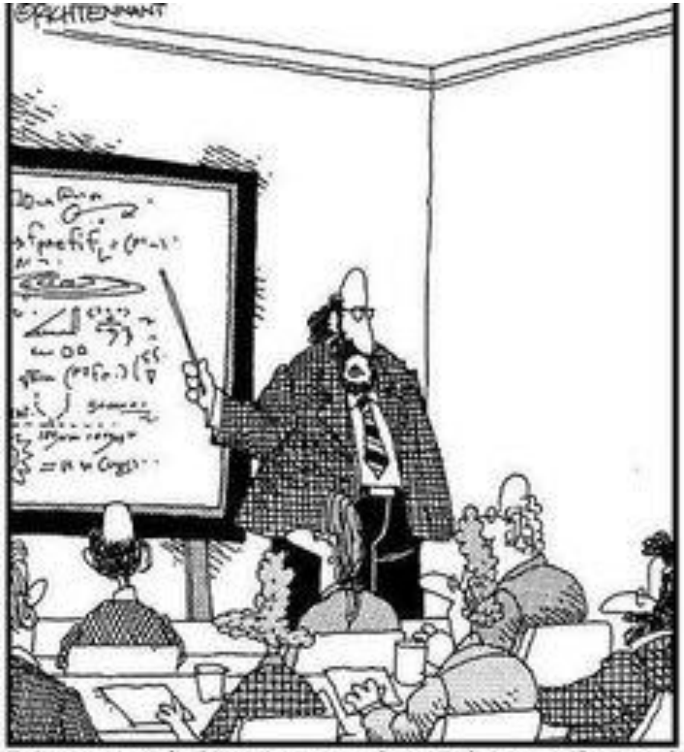
Darwin term is the non-relativistic expansion of the Dirac equation:

$$\left[\beta mc^2 + c\left(\sum_{n}^{3} \alpha_n p_n\right)\right]\psi(\vec{r},t) = i\hbar\frac{\partial\psi(\vec{r},t)}{\partial t}$$

Negative E solutiuons to the equation → antimatter



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

https://pl.wikibooks.org/wiki/Mechanika_kwantowa/Relatywistyczna_teoria_kwant%C3%B3w_Diraca

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$$\alpha_x = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

$$\beta = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} \qquad \alpha_y = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \end{pmatrix} \qquad \alpha_z = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

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$$H_{Darwin} = \frac{\hbar^2}{8m^2c^2} 4\pi \left(\frac{Ze^2}{4\pi\epsilon_0}\right) \delta(\vec{r}\,)$$

$$\langle H_{Darwin} \rangle = \frac{\hbar^2}{8m^2c^2} 4\pi \left(\frac{Ze^2}{4\pi\epsilon_0}\right) |\psi(\vec{r} = 0)|^2$$

Only for s-orbit, because: $\psi(\vec{r} = 0) = 0$ for $l > 0$

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$$E_{SO} = \frac{Z^4}{2(137)^2 a_0^3 n^3}\left(\frac{j(j+1) - l(l+1) - s(s+1)}{2l(l+1/2)(l+1)}\right)$$

$$E_{Darwin} = \frac{\hbar^2}{8m^2c^2} 4\pi \left(\frac{Ze^2}{4\pi\epsilon_0}\right) |\psi(\vec{r}=0)|^2 = \frac{1}{2} mc^2 \frac{(Z\alpha)^4}{n^3}$$

Total effect (Hydrogen atom):

$$\Delta E_n' = -\frac{\alpha^2 Z^2}{n^2} E_n \left[\frac{n}{j+\frac{1}{2}} - \frac{3}{4}\right]$$

http://www.tcm.phy.cam.ac.uk/~bds10/aqp/lec12-14_compressed.pdf

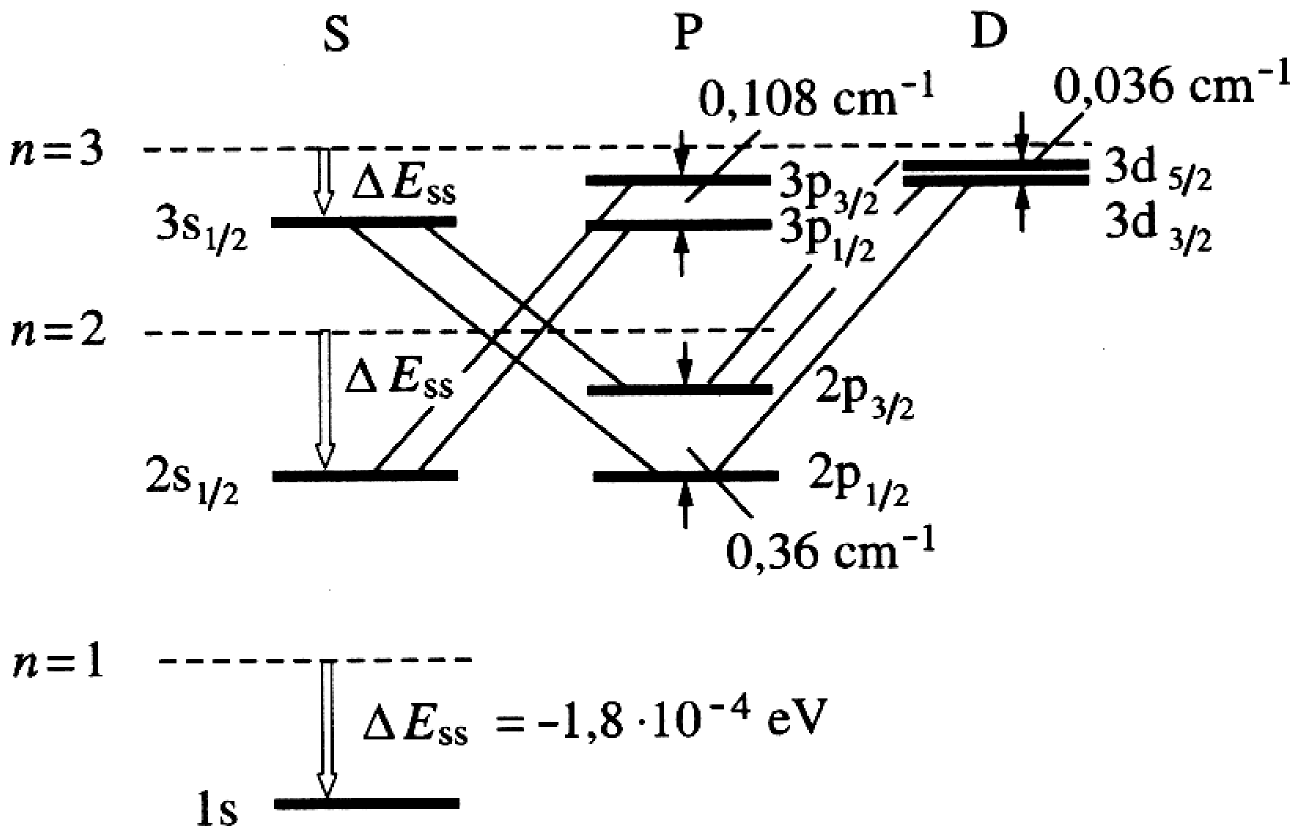
Fine structure

Paul Dirac calculations:

Bohr

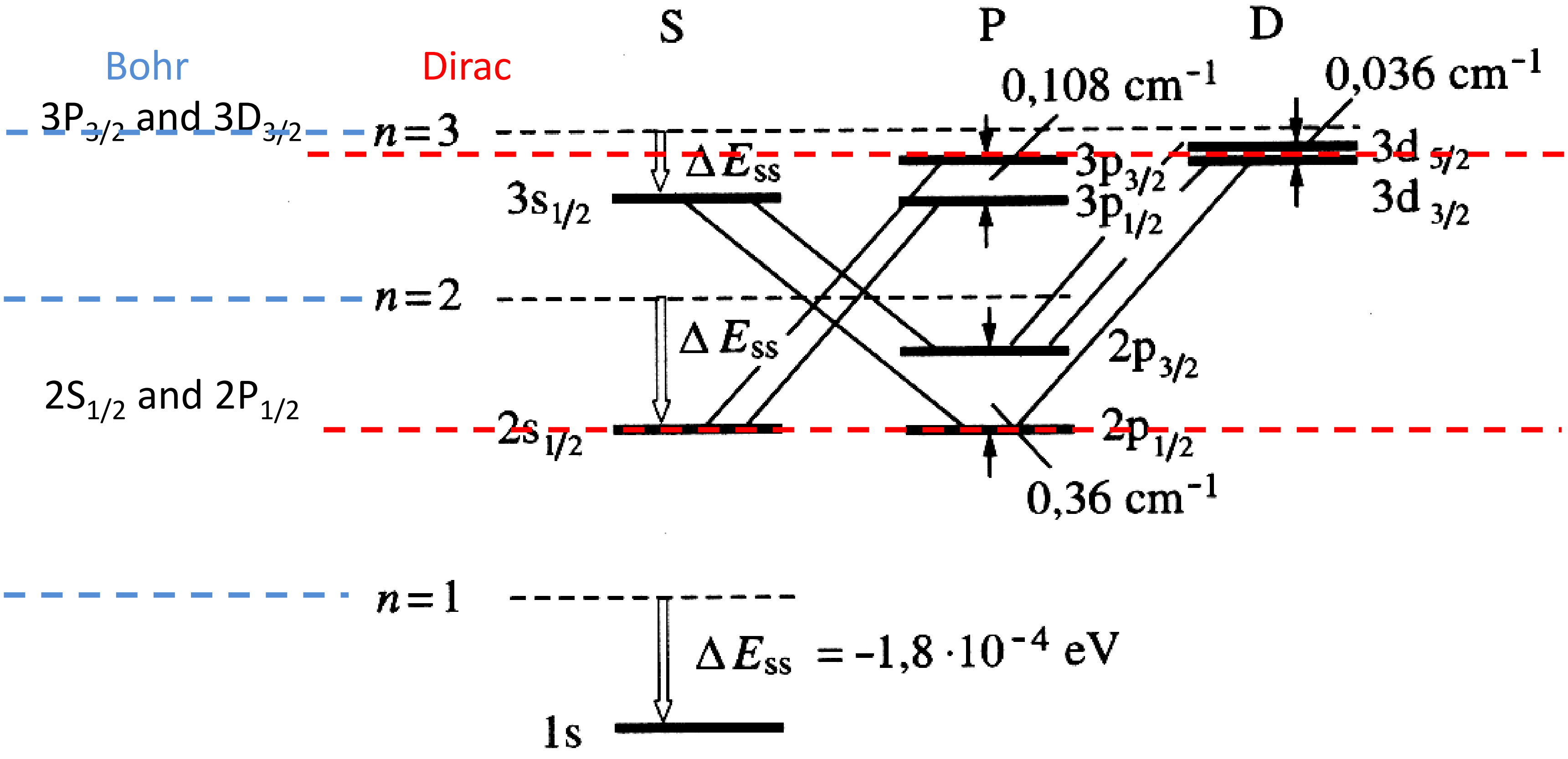
$3P_{3/2}$ and $3D_{3/2}$

$2S_{1/2}$ and $2P_{1/2}$



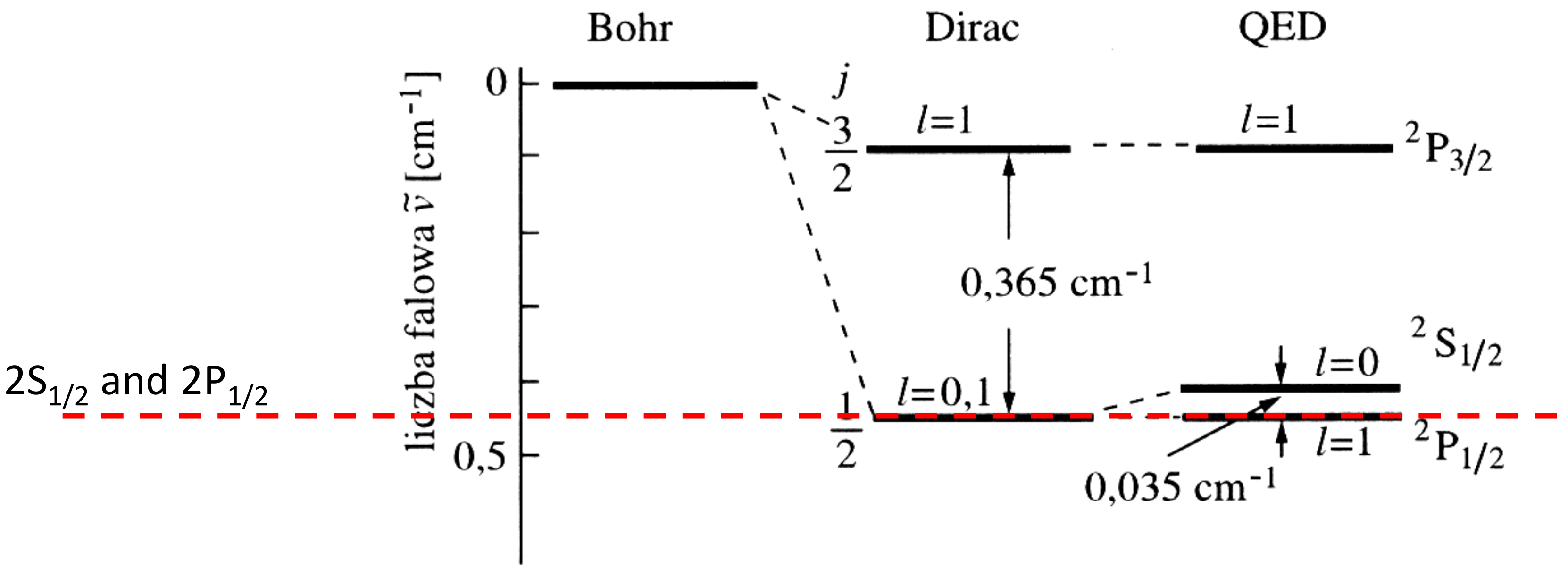
Fine structure

Paul Dirac (Nobel 1933) calculations:

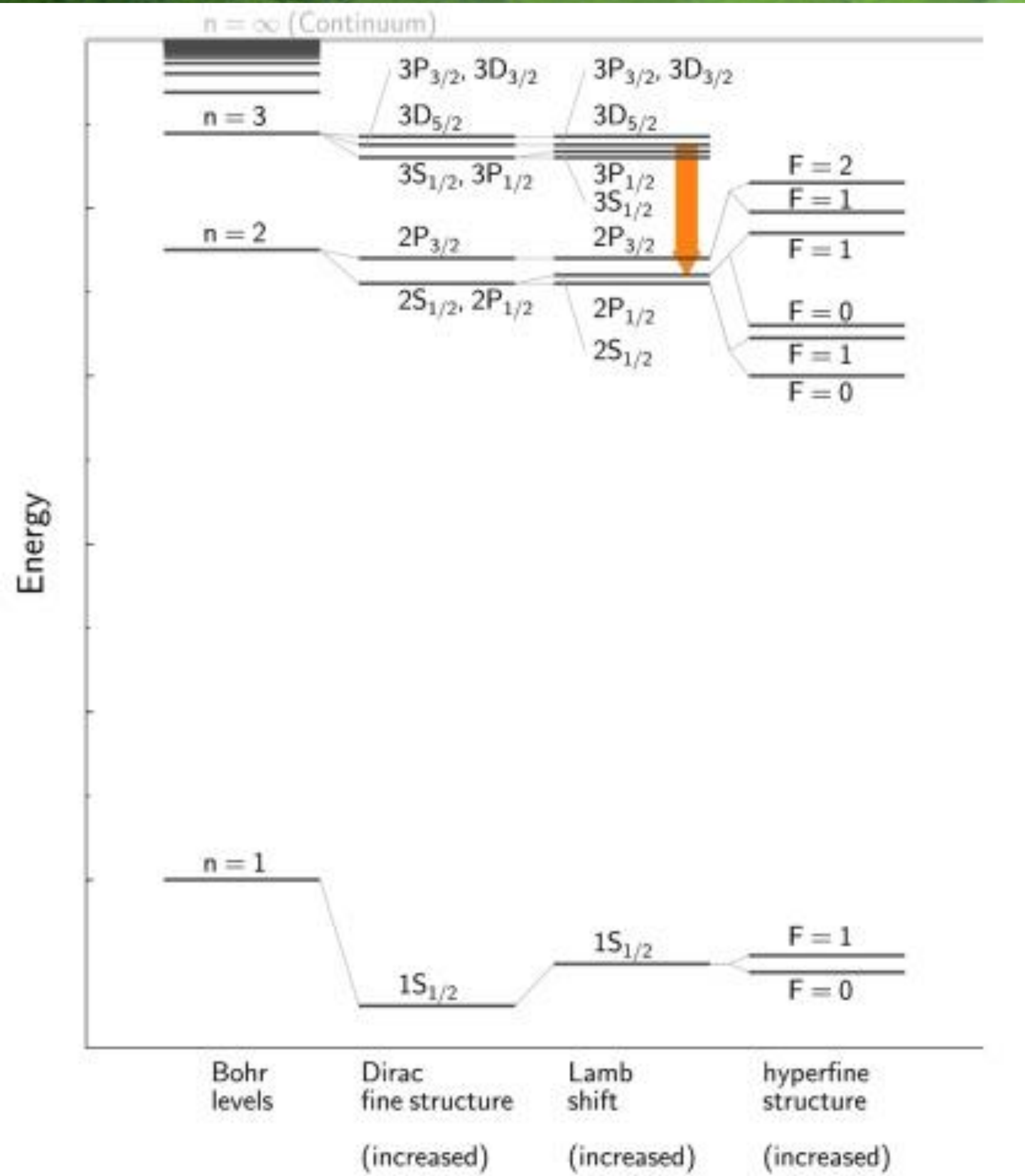


Fine structure

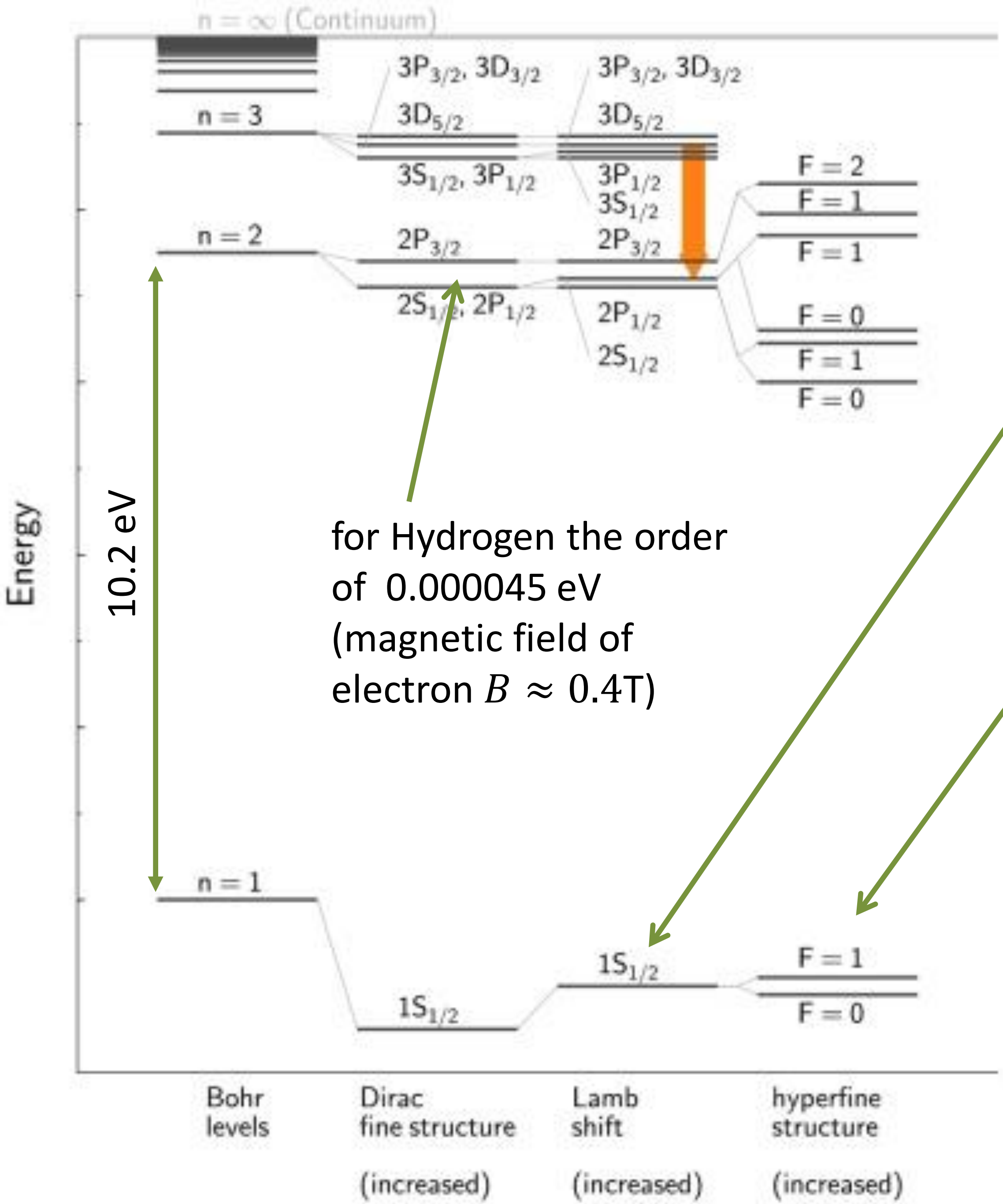
Willis Lamb (Nobel 1955) calculations:



QED – Quantum ElectroDynamics – Lamb shift due to the interaction of the atom with virtual photons emitted and absorbed by it. In quantum electrodynamics the electromagnetic field is quantized and therefore its lowest state cannot be zero ($E_{min} = \frac{\hbar\omega}{2}$), which perturbs Coulomb potential.



http://backreaction.blogspot.com/2007/12/hydrogen-spectrum-and-its-fine.html

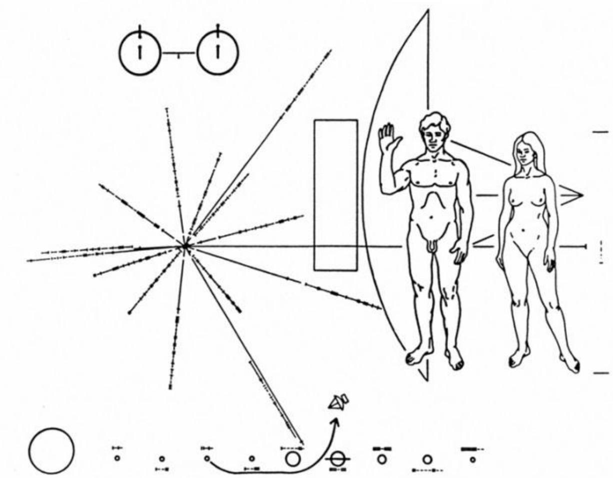


10.2 eV

for Hydrogen the order of 0.000045 eV (magnetic field of electron $B \approx 0.4$T)

Lamb shift – (Willis Lamb) QED
size of the proton!
(hydrogen vs muonic hydrogen)
[about 1 GHz]

Hyperfine interaction: interaction with nuclear moment
[21 cm (1420 MHz) for atomic H]



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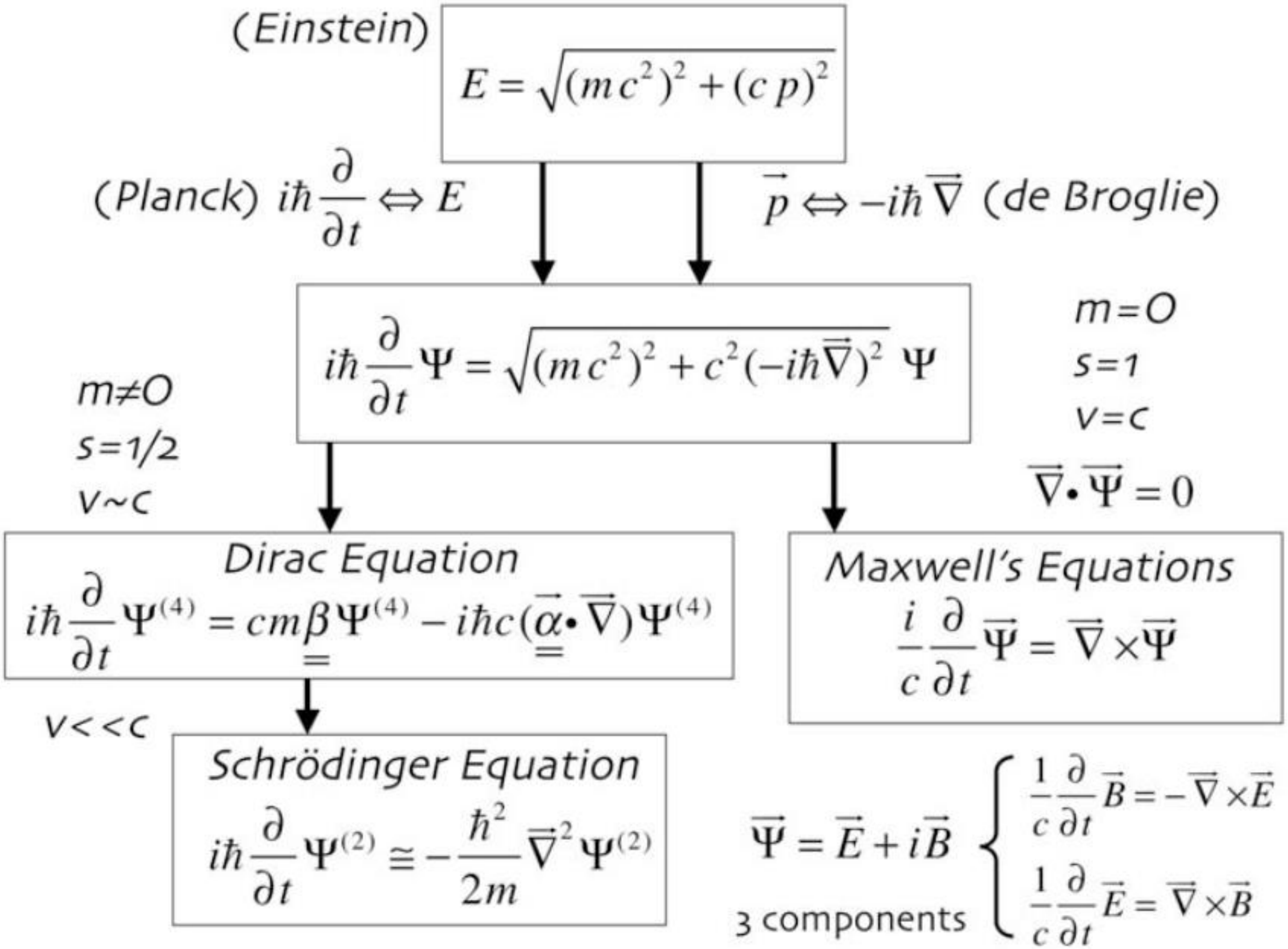

Fig.1 Flow chart for derivations of electron and photon wave equations, m = rest mass, s = spin, v = velocity.

The Maxwell wave function of the photon M. G. Raymer and Brian J. Smith, SPIE conf. Optics and Photonics 2005

Multi-electron atom

Term symbol $^{2S+1}L_J$

an abbreviated description of the angular momentum quantum numbers in a multi-electron atom

Total wavefunction must be antisymmetric (under interchange of any pair of particle)

$$\psi(\vec{r}, S_z) = \psi(\vec{r})\chi(S_z)$$

Orbital part **Spin part**

Multi-electron wavefunction:

$$\psi(\vec{r}_1, \dots, \vec{r}_N, \vec{S}_1, \dots, \vec{S}_N) = \psi(\vec{r}_1, \dots, \vec{r}_N)\chi(\vec{S}_1, \dots, \vec{S}_N)$$

Antisymmetric wavefunction + Pauli exclusion principle + Coulomb interaction =

Exchange interaction

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Hund's rules (soon!)

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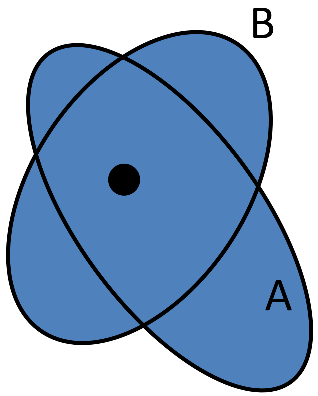
$\Psi = \Psi_{orbital} \times \Psi_{spin}$ Antisymmetric!

Example:



Two electrons localized on one centrum

$$\mathcal{H}(1,2) = H_0(1) + H_0(2) + \frac{e^2}{r_{12}}$$

Exchange interaction

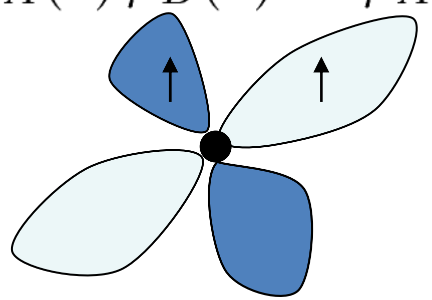
Antisymmetric wavefunction + Pauli exclusion principle + Coulomb interaction =

Exchange interaction

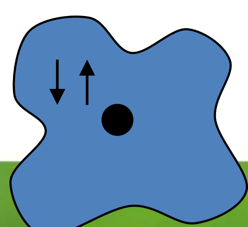
$\Psi = \Psi_{orbital} \times \Psi_{spin}$ <u>Antisymmetric!</u>

Hund's rules, $E_T < E_S$

$$\frac{1}{\sqrt{2}}[\varphi_A(1)\varphi_B(2) - \varphi_A(2)\varphi_B(1)] \times \begin{bmatrix} \chi_\uparrow(1)\chi_\uparrow(2) \\ \frac{1}{\sqrt{2}}[\chi_\uparrow(1)\chi_\downarrow(2) + \chi_\downarrow(1)\chi_\uparrow(2)] \\ \chi_\downarrow(1)\chi_\downarrow(2) \end{bmatrix}$$



$$\frac{1}{\sqrt{2}}[\varphi_A(1)\varphi_B(2) + \varphi_A(2)\varphi_B(1)] \; \frac{1}{\sqrt{2}}[\chi_\uparrow(1)\chi_\downarrow(2) - \chi_\downarrow(1)\chi_\uparrow(2)]$$

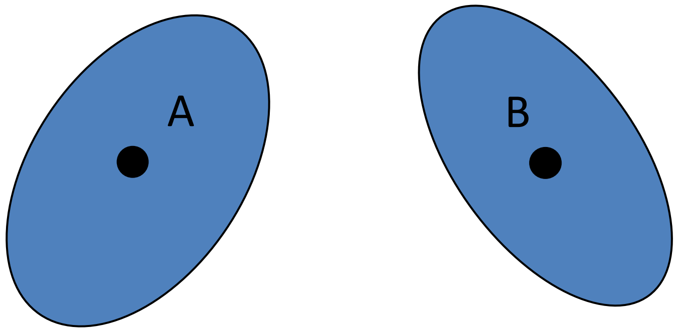


Exchange interaction

Antisymmetric wavefunction + Pauli exclusion principle + Coulomb interaction = Exchange interaction

$$\Psi = \Psi_{orbital} \times \Psi_{spin}$$ Antisymmetric!

Example:



Two electrons localized on two centres

$$\mathcal{H}(1,2) = H_0^A(1) + H_0^B(2) + \frac{e^2}{r_{12}}$$

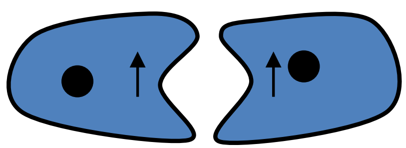
Exchange interaction

Antisymmetric wavefunction + Pauli exclusion principle + Coulomb interaction =

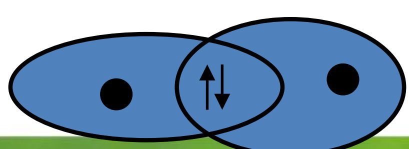
Exchange interaction

$$\Psi = \Psi_{orbital} \times \Psi_{spin}$$

$$\frac{1}{\sqrt{2}}\left[\varphi_A(1)\varphi_B(2) - \varphi_A(2)\varphi_B(1)\right] \times \begin{bmatrix} \chi_\uparrow(1)\chi_\uparrow(2) \\ \frac{1}{\sqrt{2}}\left[\chi_\uparrow(1)\chi_\downarrow(2) + \chi_\downarrow(1)\chi_\uparrow(2)\right] \\ \chi_\downarrow(1)\chi_\downarrow(2) \end{bmatrix}$$



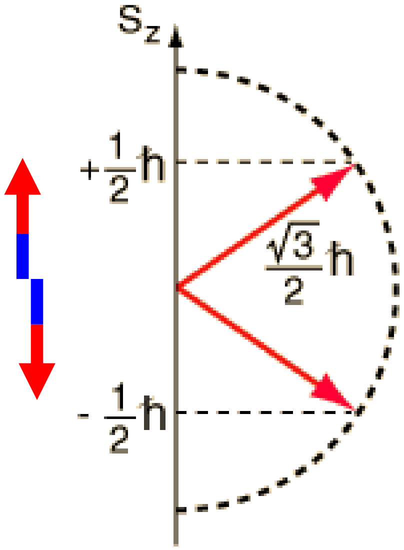
$$\frac{1}{\sqrt{2}}\left[\varphi_A(1)\varphi_B(2) + \varphi_A(2)\varphi_B(1)\right] \; \frac{1}{\sqrt{2}}\left[\chi_\uparrow(1)\chi_\downarrow(2) - \chi_\downarrow(1)\chi_\uparrow(2)\right]$$

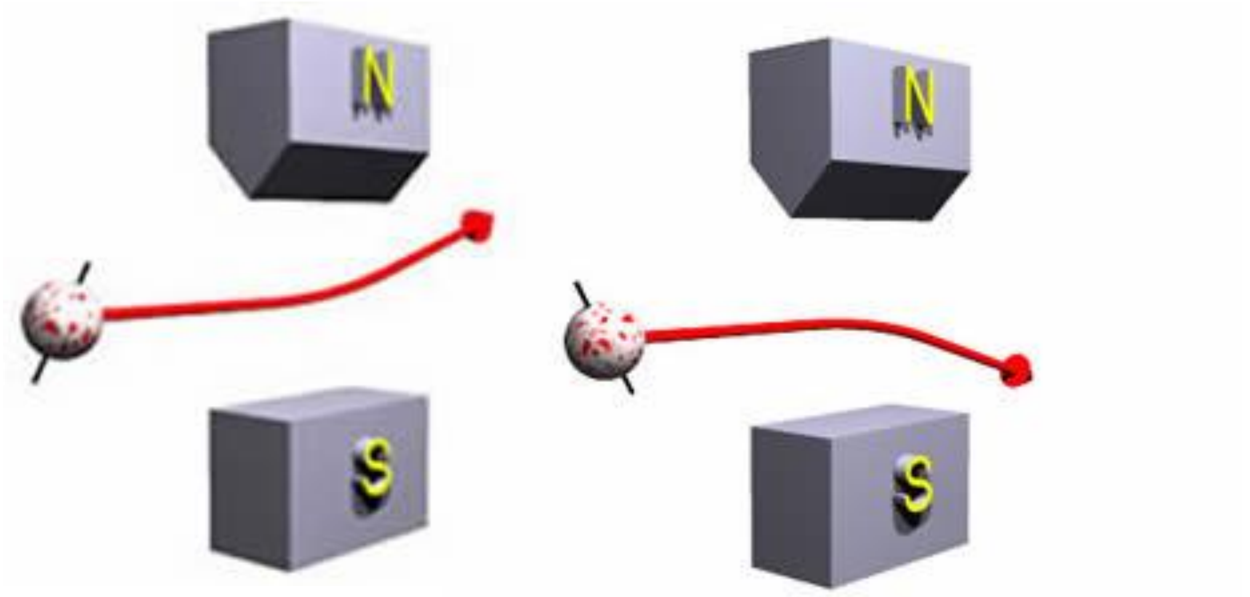


Chemical bonds, $E_S < E_T$

Thank you for your attention

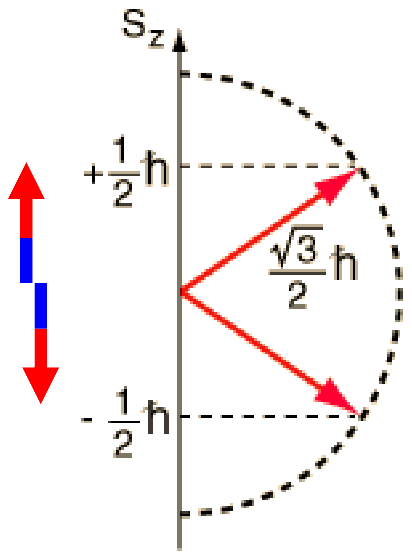
What is the „spin”?

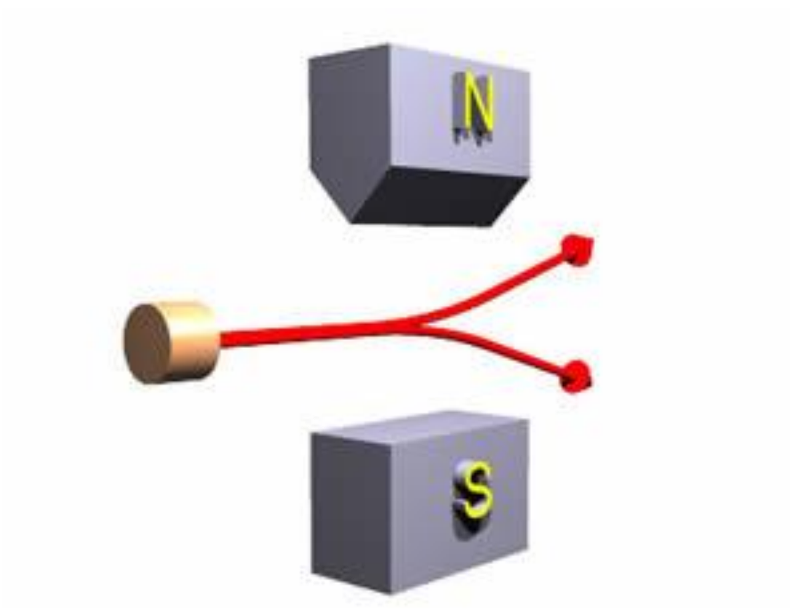




http://www.upscale.utoronto.ca/GeneralInterest/Harrison/SternGerlach/SternGerlach.html

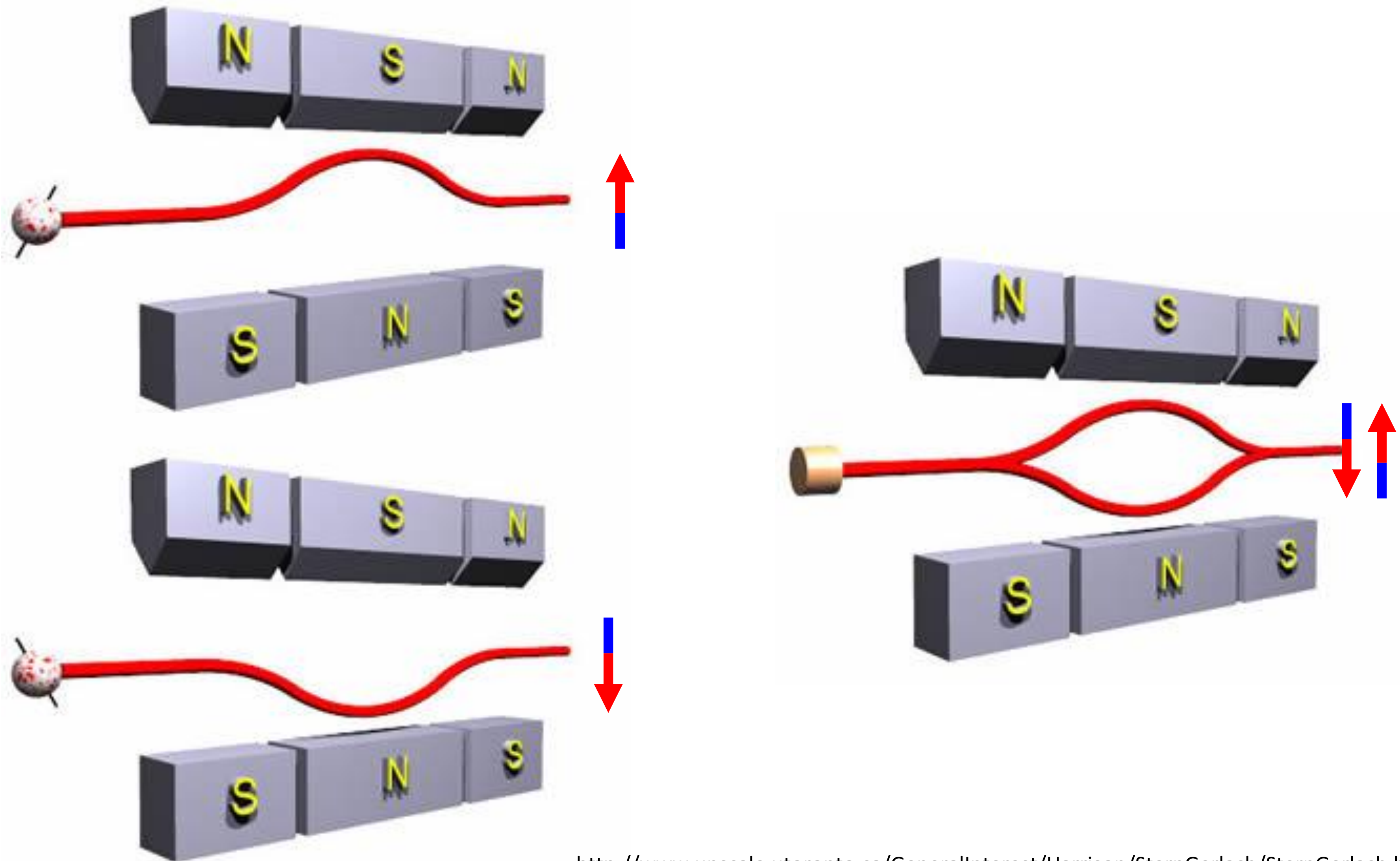
What is the „spin”?





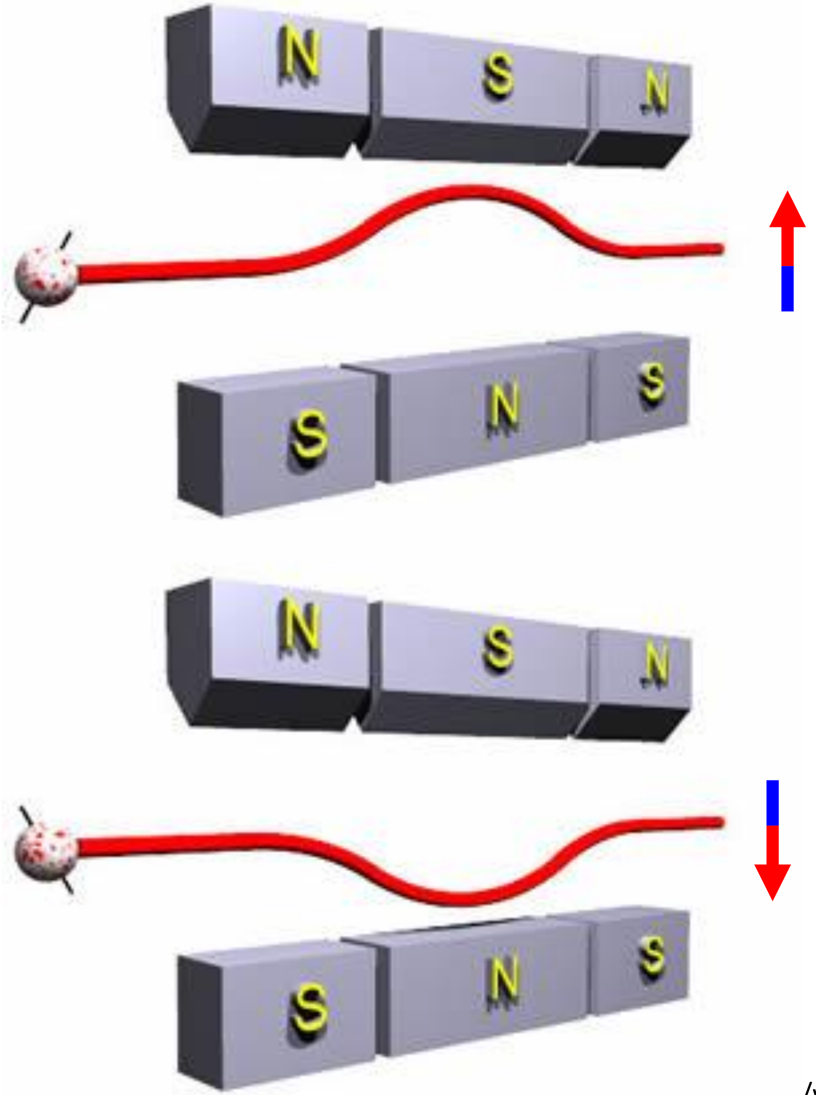
http://www.upscale.utoronto.ca/GeneralInterest/Harrison/SternGerlach/SternGerlach.html

What is the „spin”?

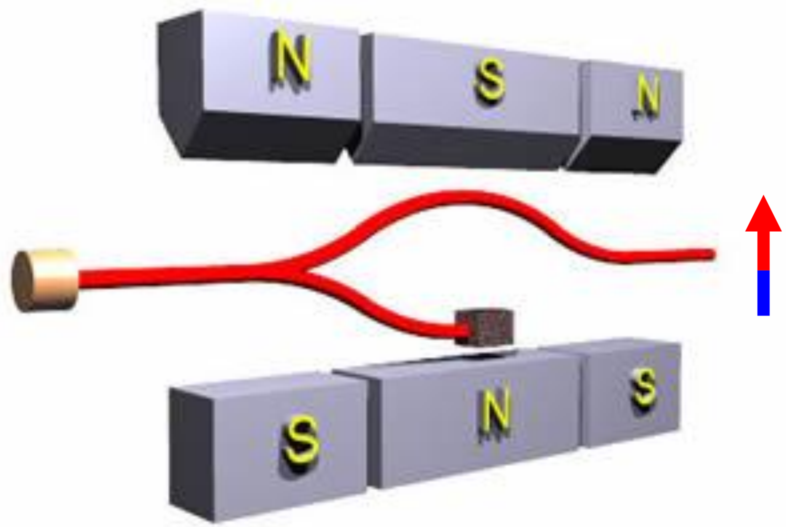


http://www.upscale.utoronto.ca/GeneralInterest/Harrison/SternGerlach/SternGerlach.html

What is the „spin”?

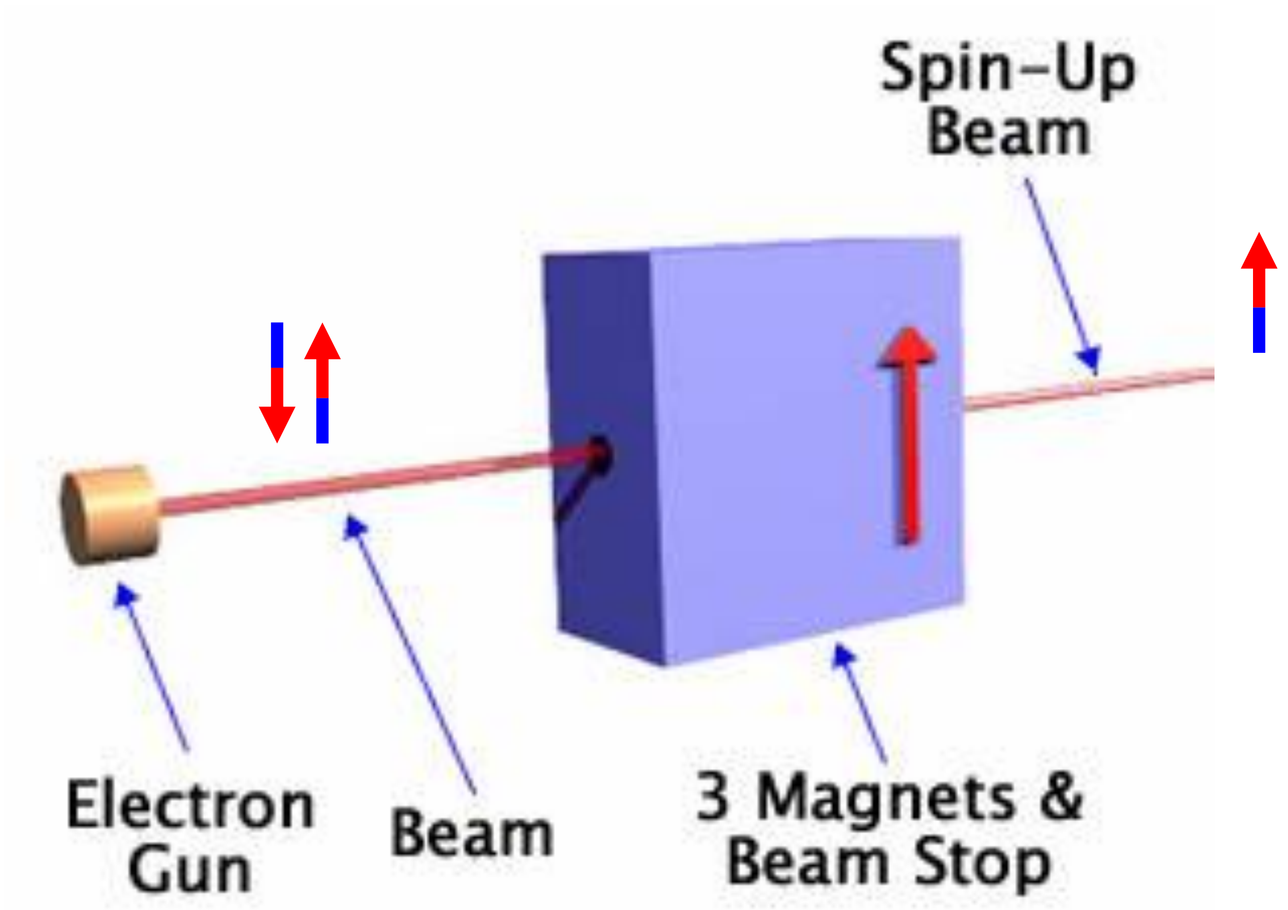


Spin filter!



/www.upscale.utoronto.ca/GeneralInterest/Harrison/SternGerlach/SternGerlach.html

Spin-filter



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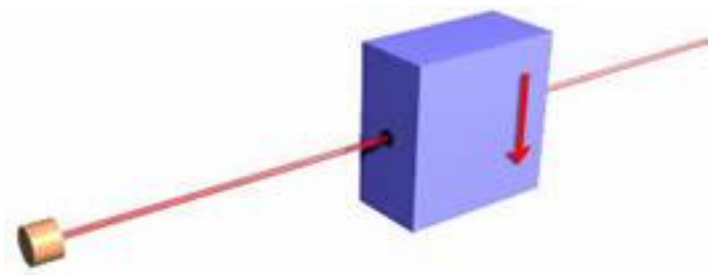
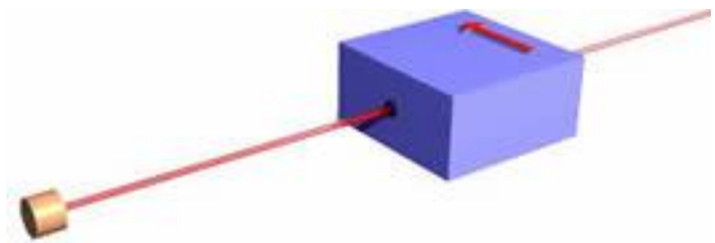
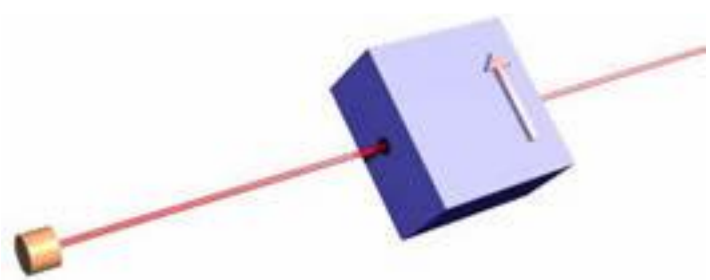
Spin-filter







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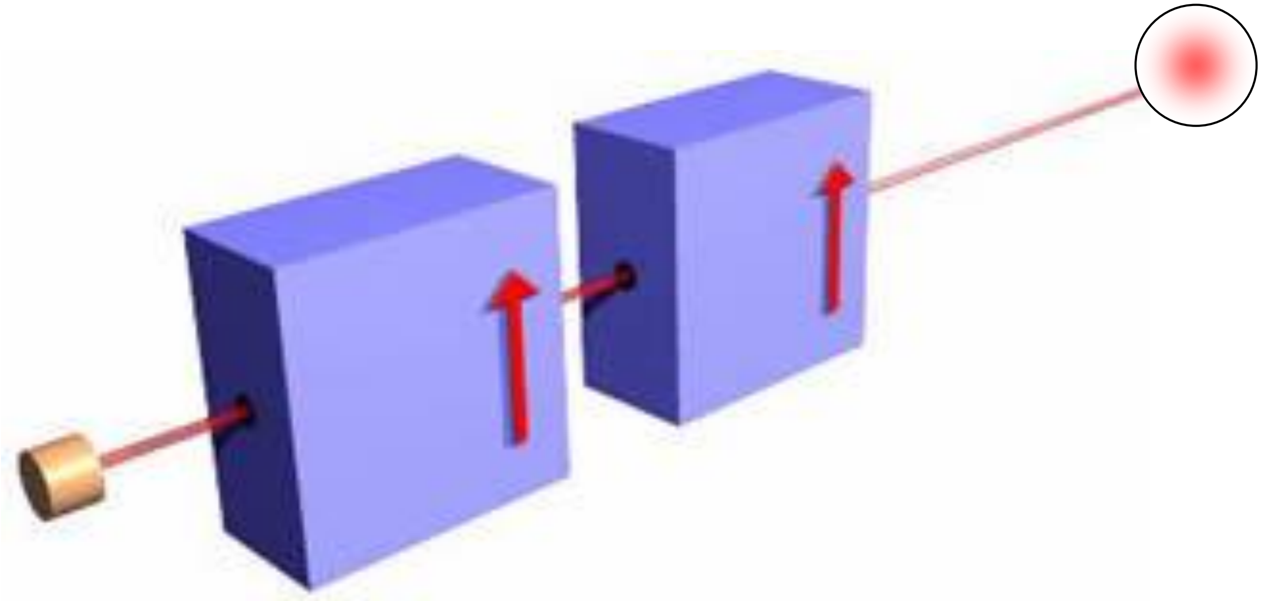
Spin-filter



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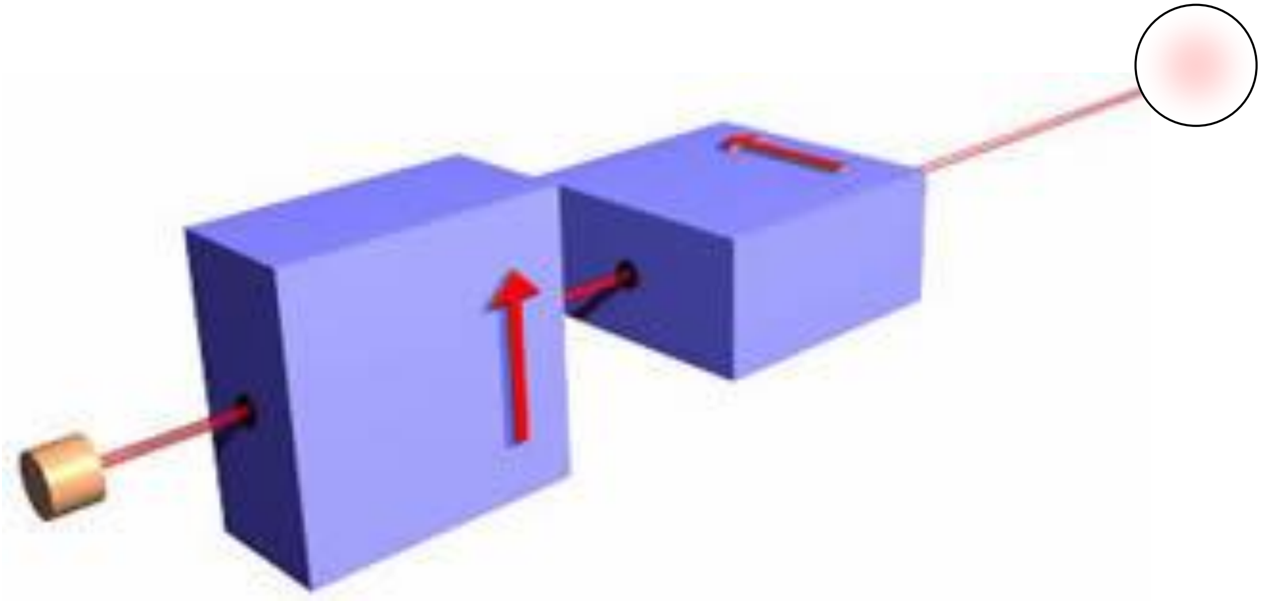
Spin-filter



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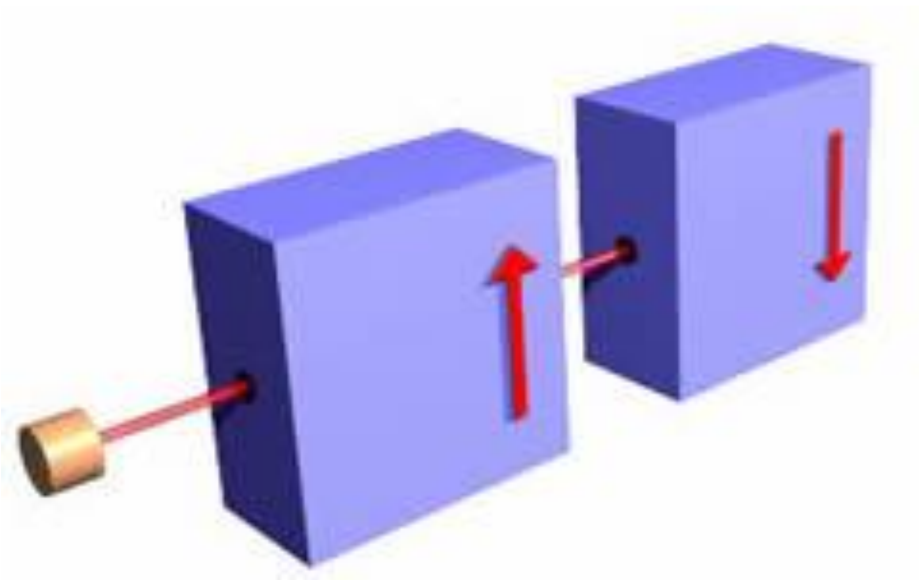
Spin-filter



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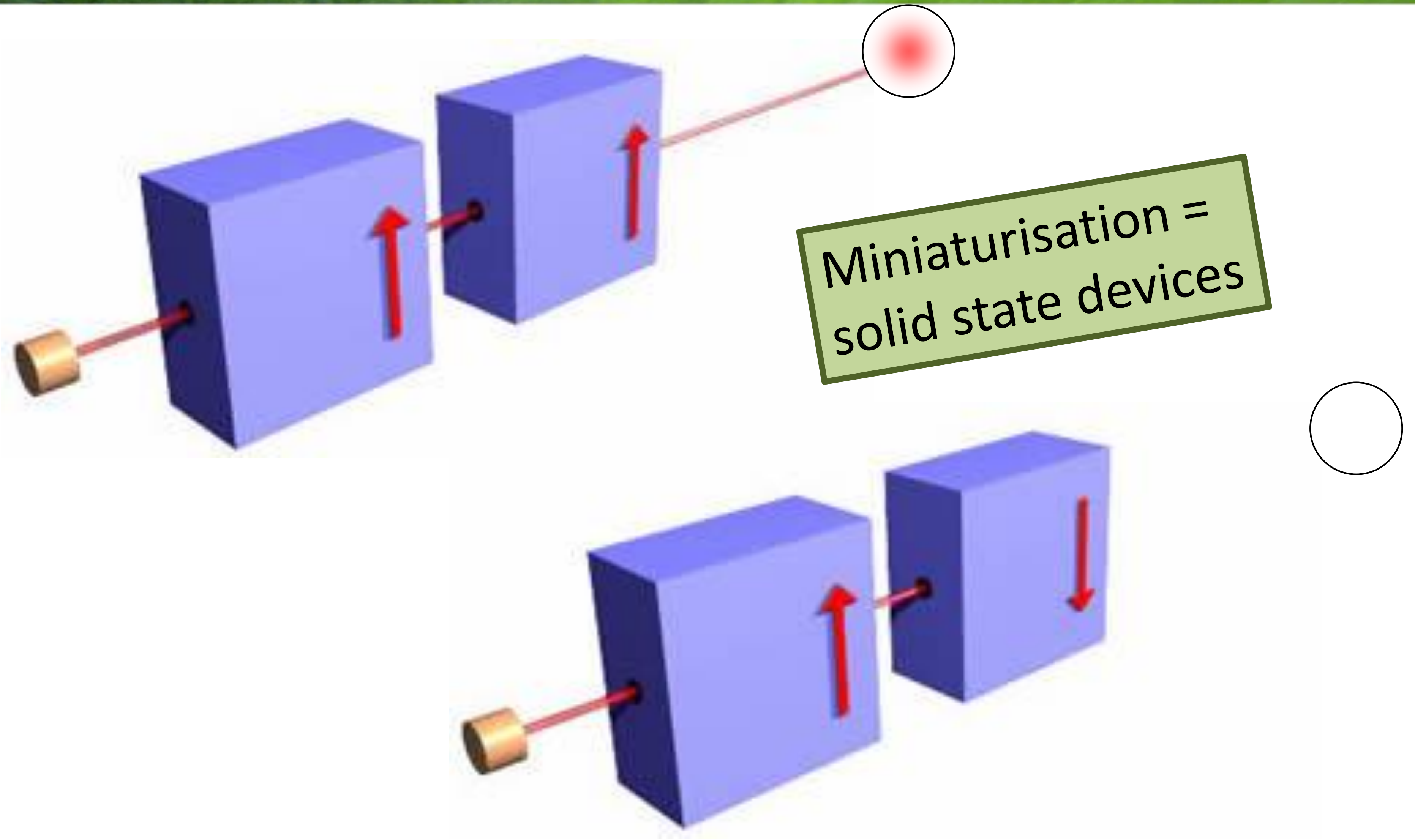
Spin-filter



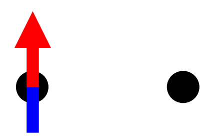
Miniaturisation = solid state devices

http://www.upscale.utoronto.ca/GeneralInterest/Harrison/SternGerlach/SternGerlach.html

Spintronics

S. Harris

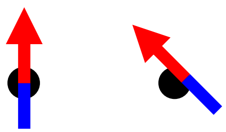
Magnet



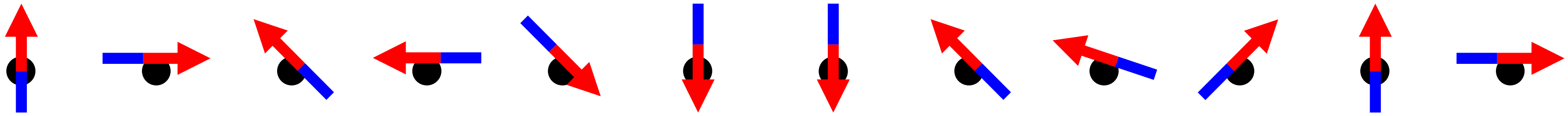
A crystal:

Magnet

PARA

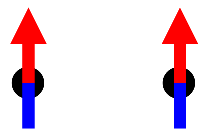


Magnetization M in the absence of magnetic field $M = 0$

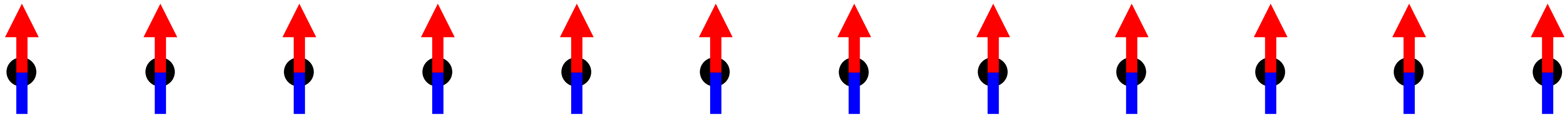


Magnet

FERRO

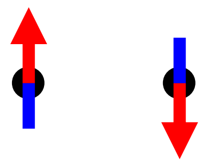


Magnetization M in the absence of magnetic field $M > 0$

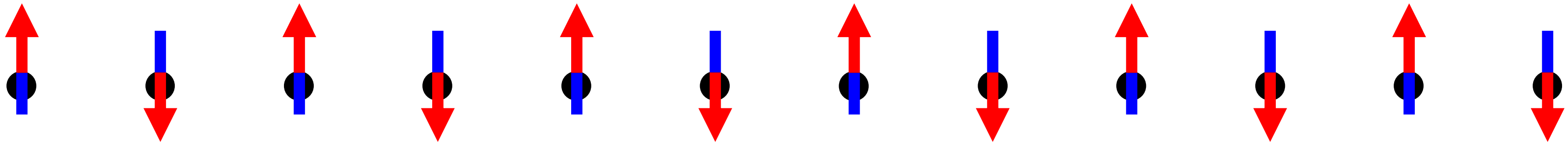


Magnet

ANTYFERRO

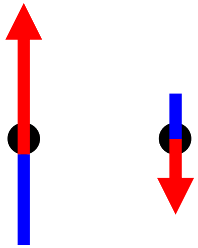


Magnetization M in the absence of magnetic field $M = 0$

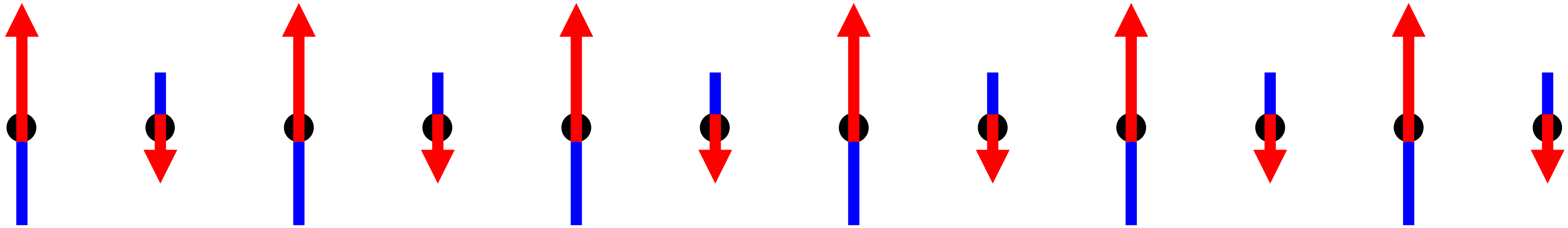


Magnet

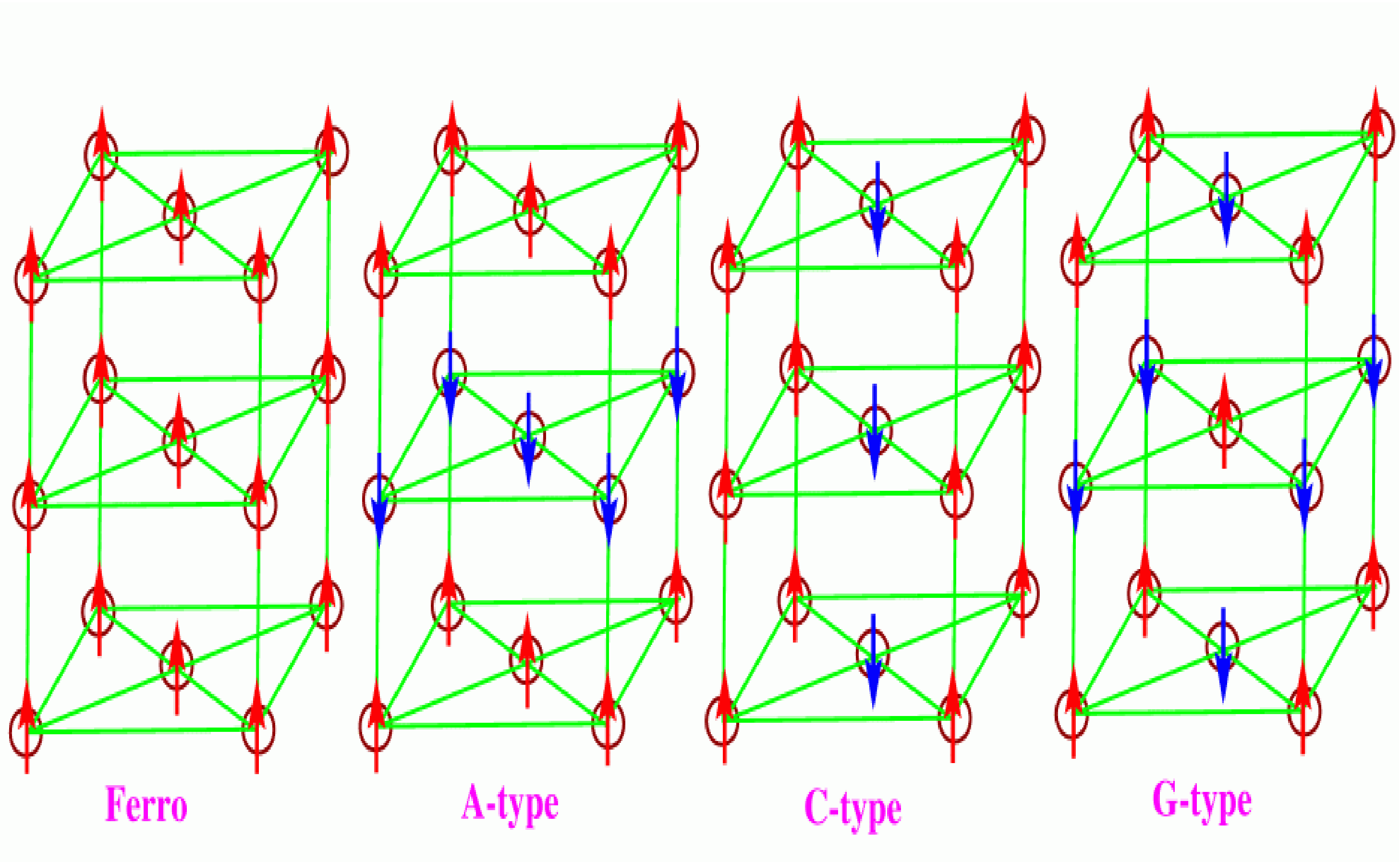
FERRI



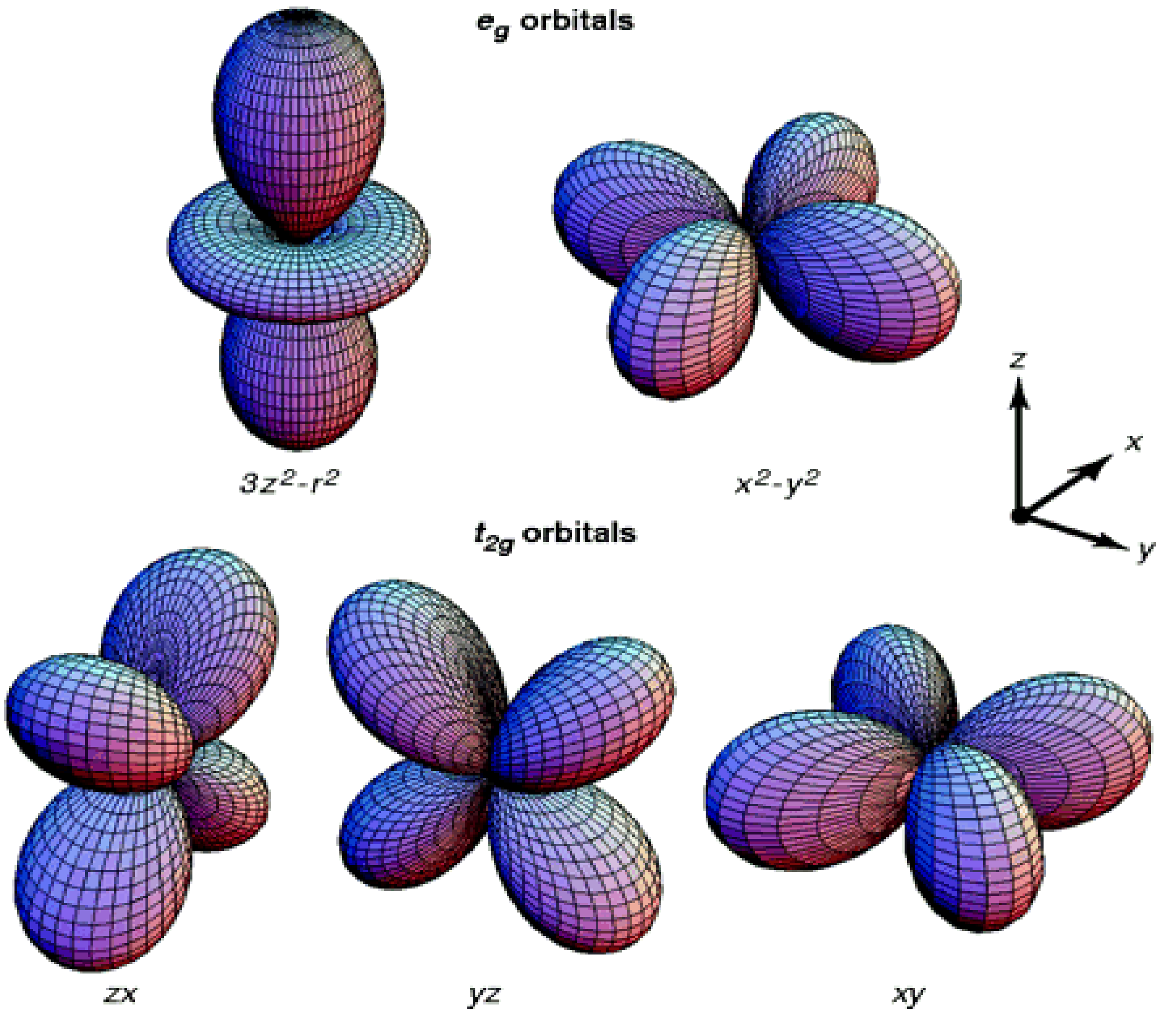
Magnetization M in the absence of magnetic field $M > 0$



Magnet

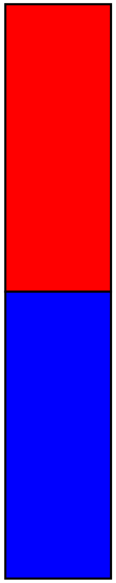


Magnet



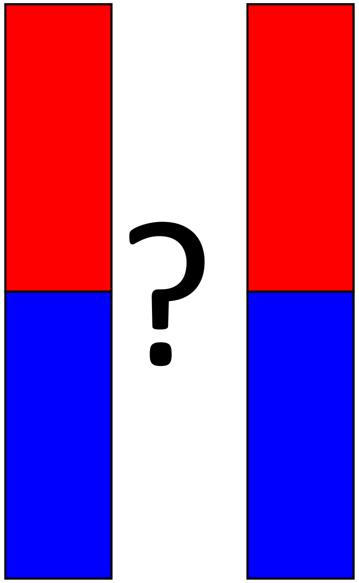
Lubna SHAH; Department of physics; University of Delaware

Magnet



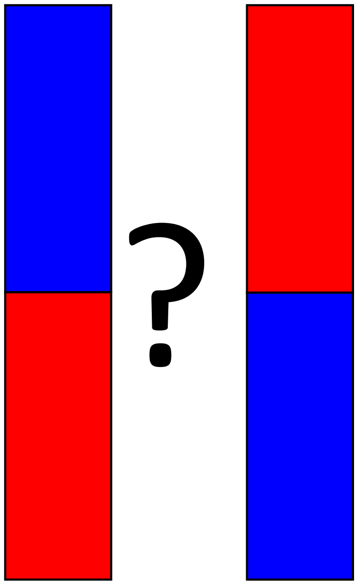
Magnet

FERRO?

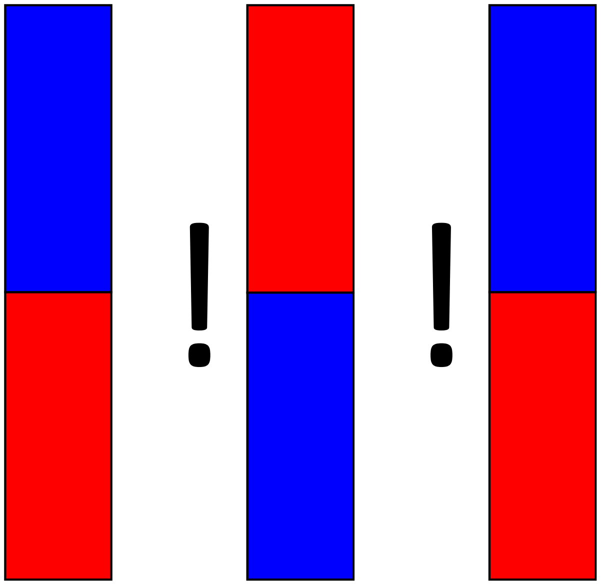


Magnet

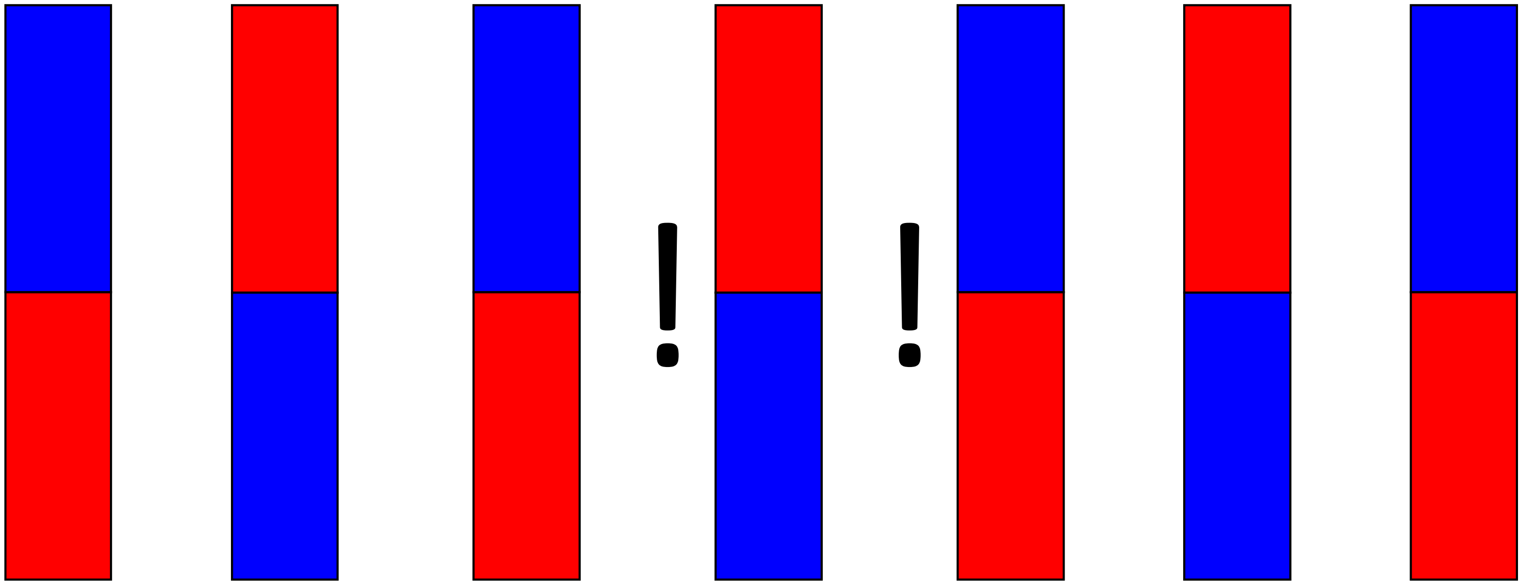
ANTI - FERRO?



Magnet

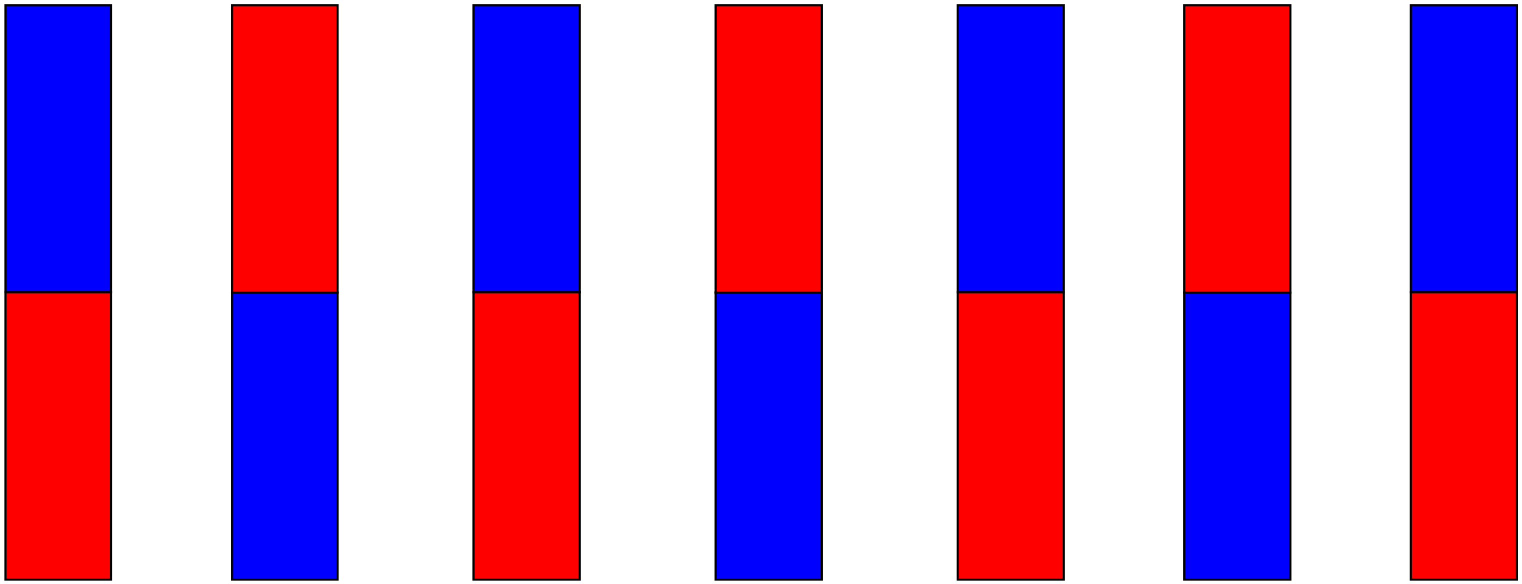


Magnet



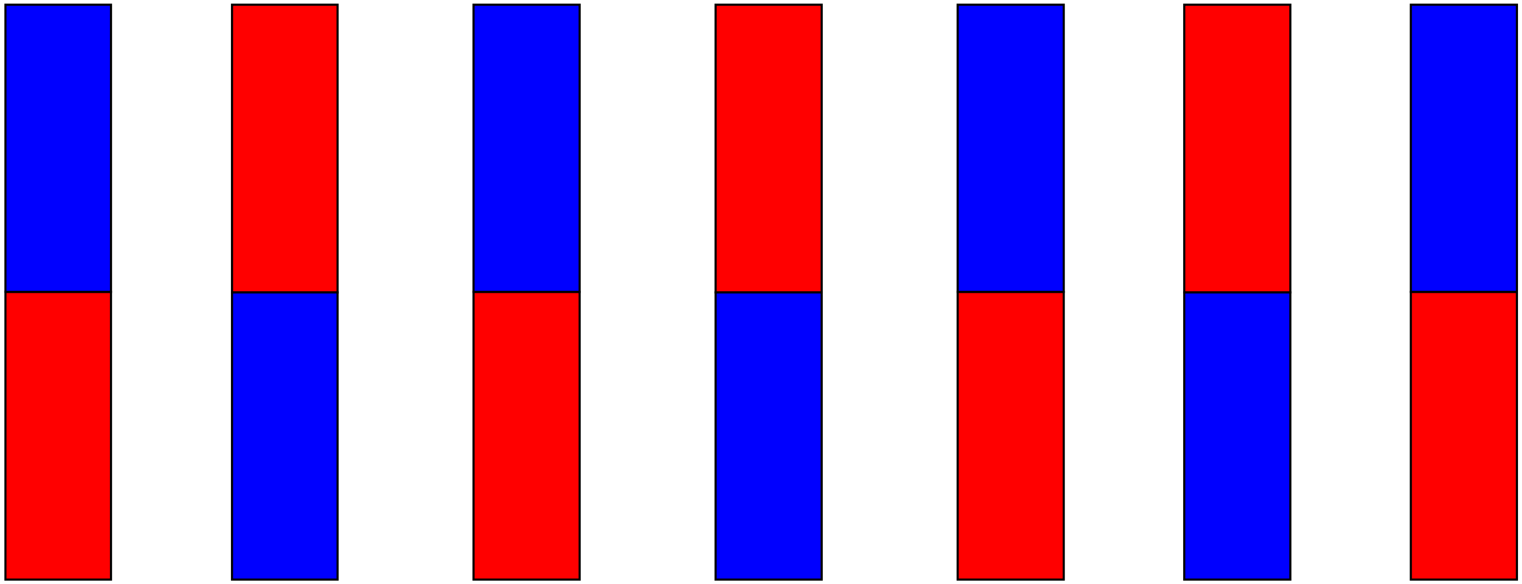
Antiferromagnetic ordering is more preferable

Magnet



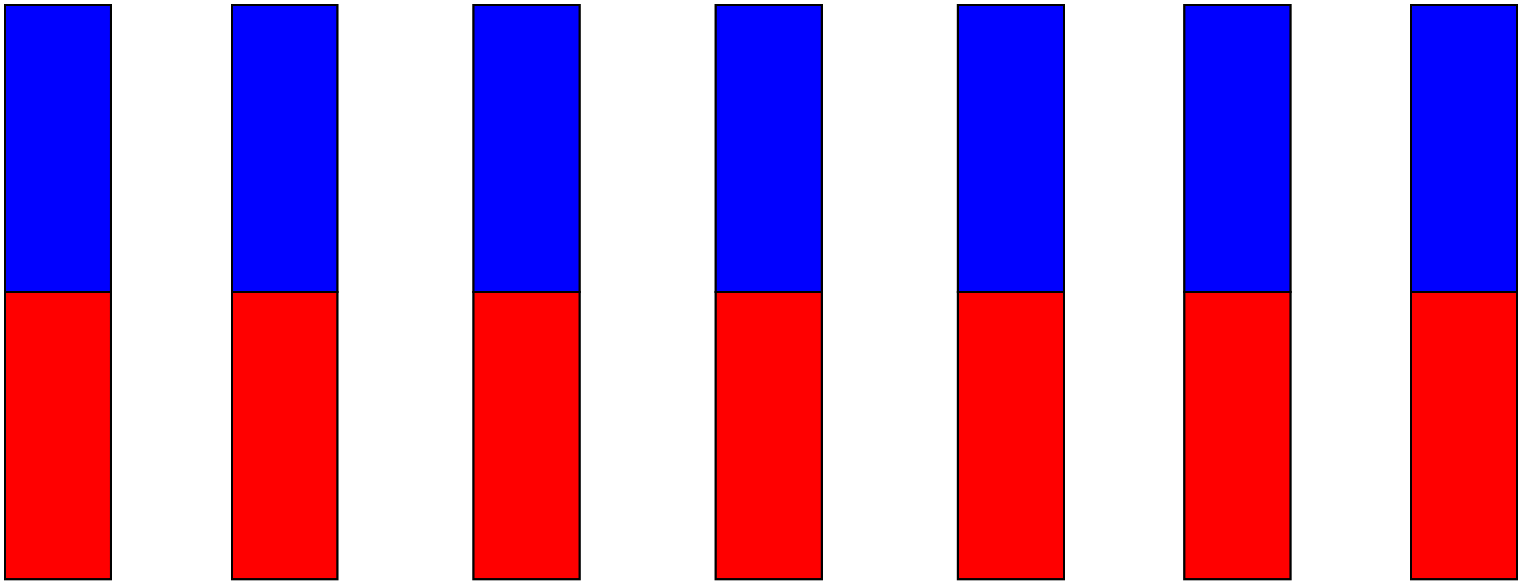
Why there are magnets?

Magnet



Why there are magnets?

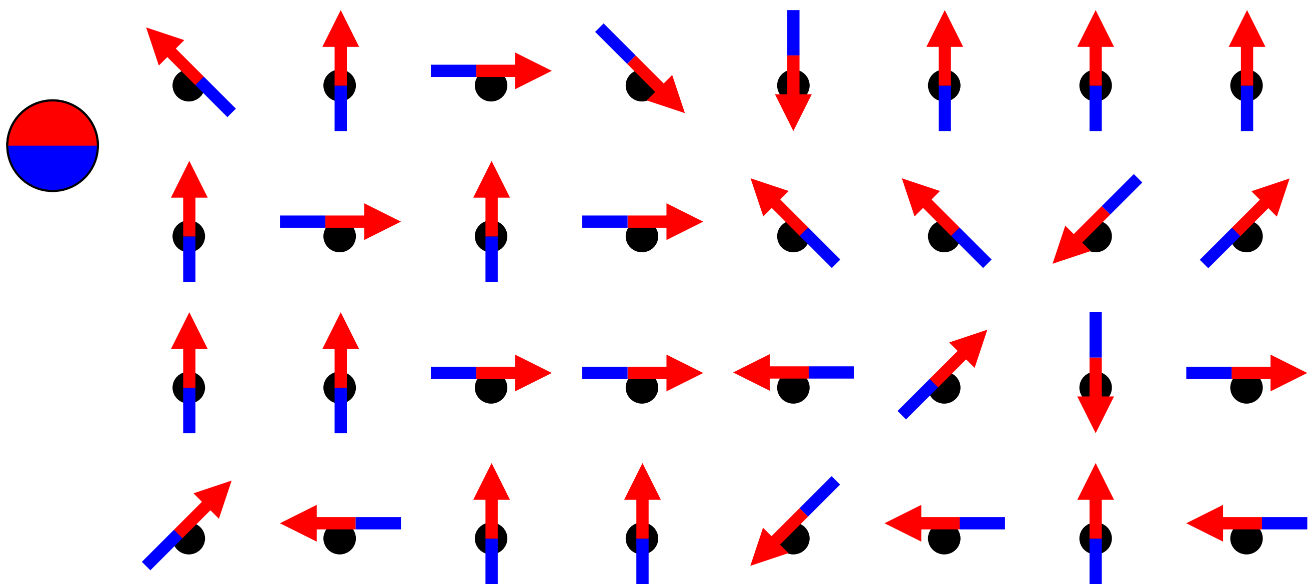
Magnet

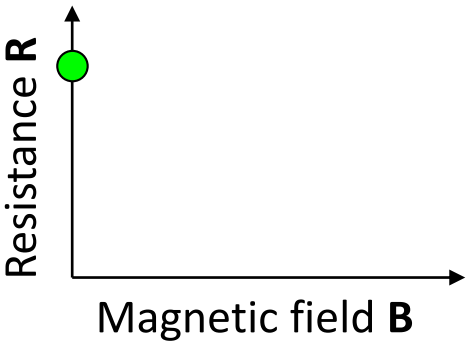


Why there are magnets?

Magnetoresistance

External magnetic field B = 0 T

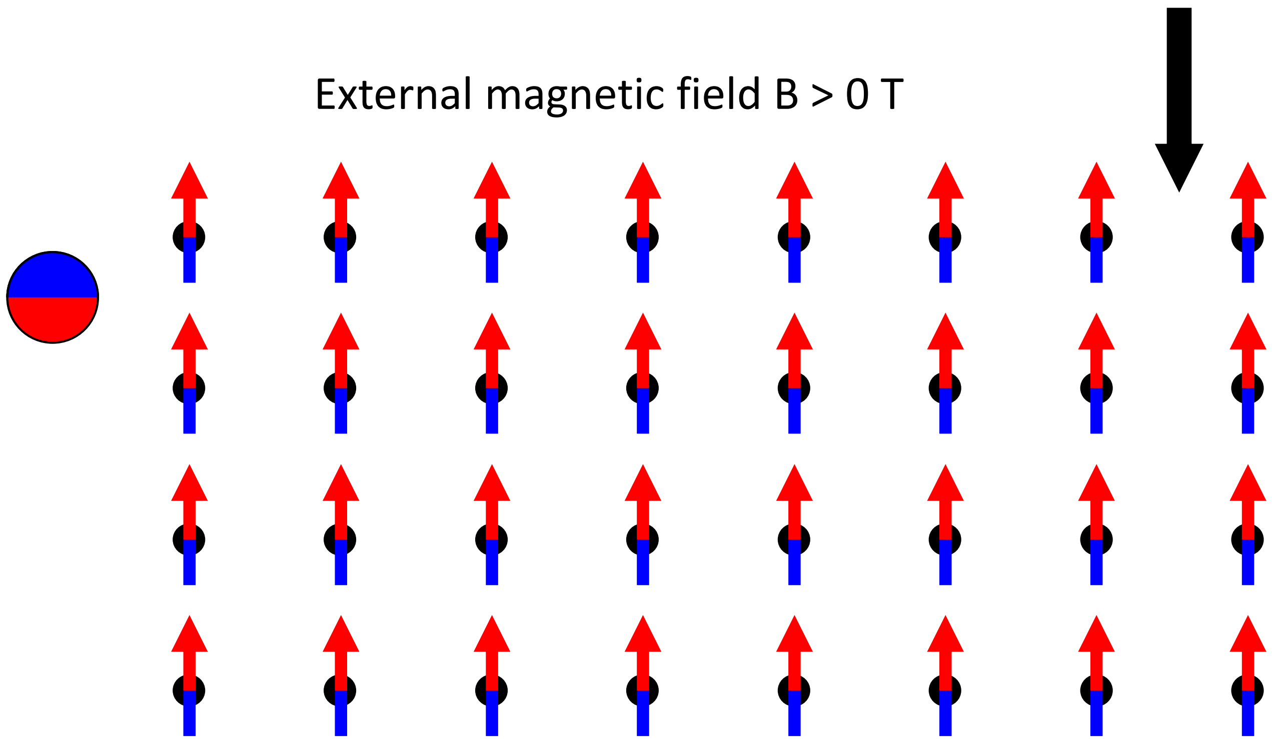


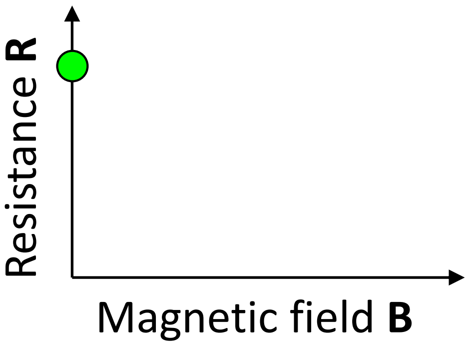


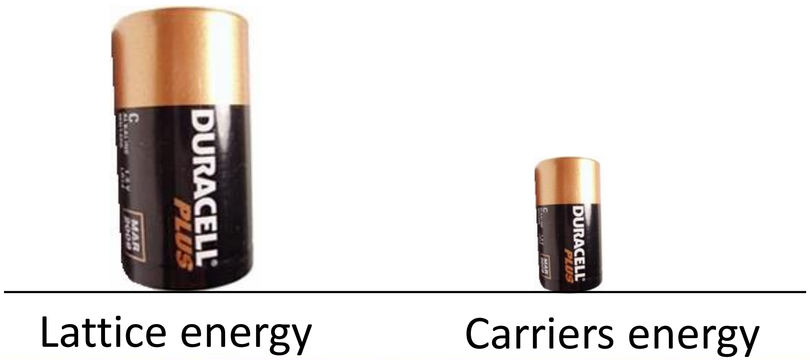
Lattice energy

Carriers energy

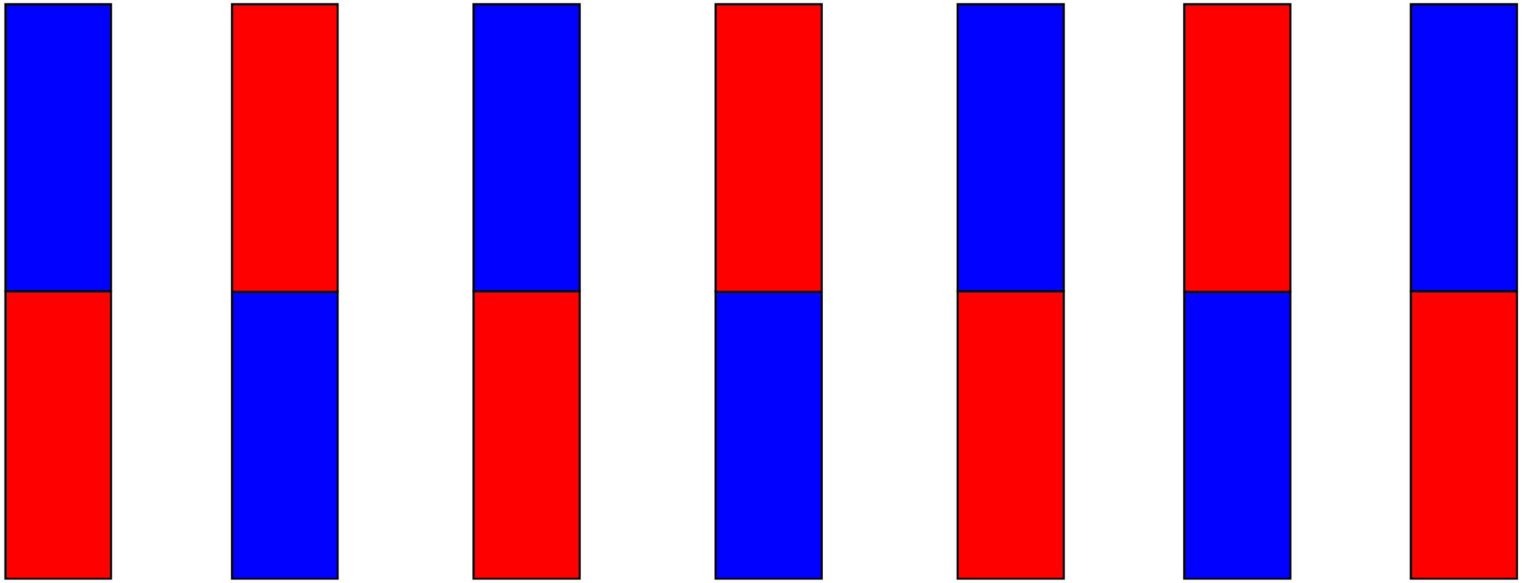
Magnetoresistance





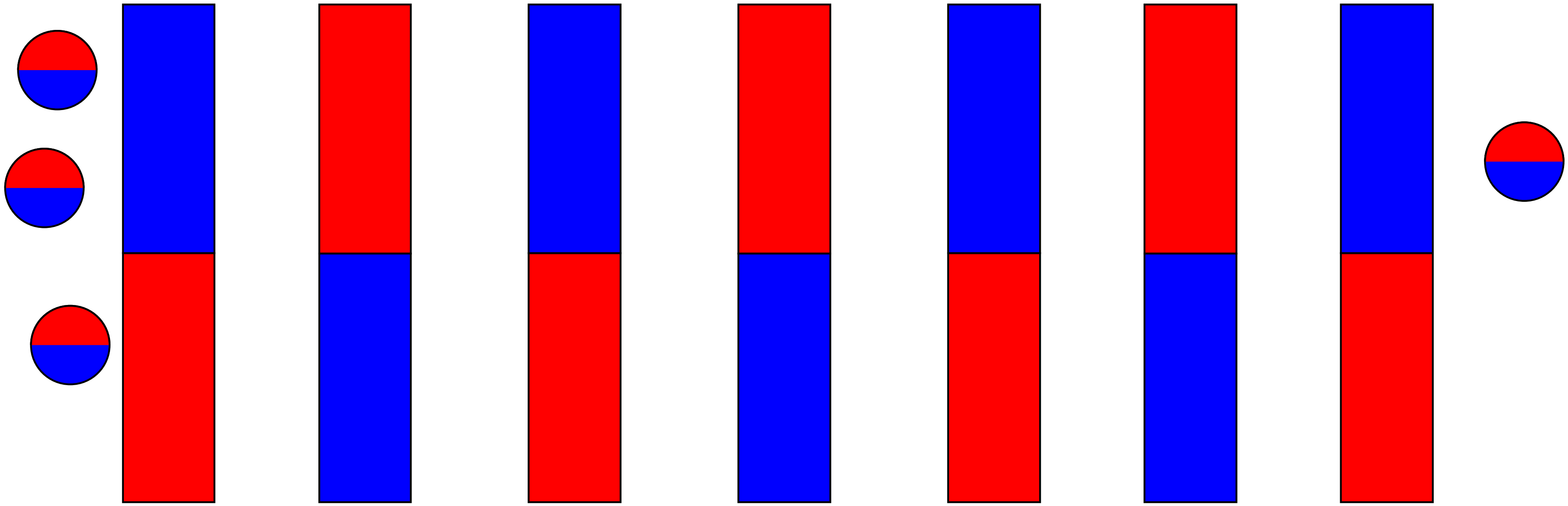


Magnet



Why there are magnets?

Magnet



Carriers!!!

Spintronics

Magnetoresistance $\Delta R/R$ ~ few %

Spintronics

Magnetoresistance $\Delta R/R$ ~ few %

Gigantyczny magnetoopór

(Giant Magnetoresistance – GMR) 1988

$\Delta R/R$ ~ 20 %

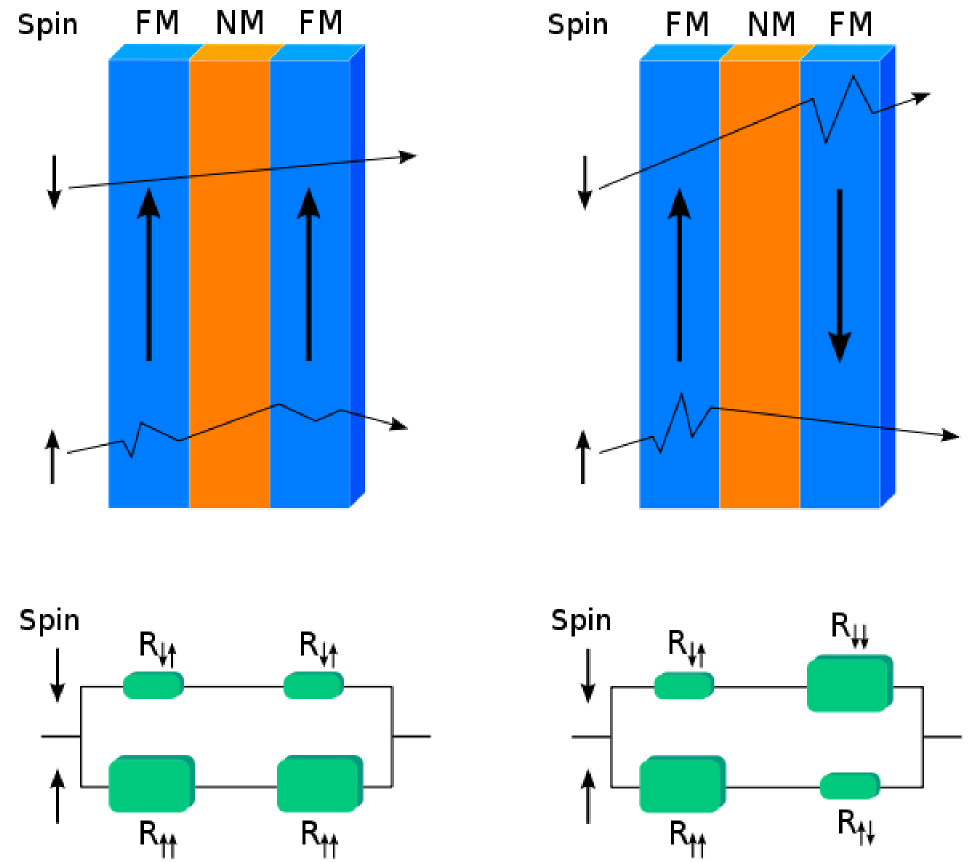
Spintronics

Magnetoresistance ΔR/R ~ few %

Gigantyczny magnetoopór

(Giant Magnetoresistance – GMR) 1988

ΔR/R ~ 20 %



Wikipedia

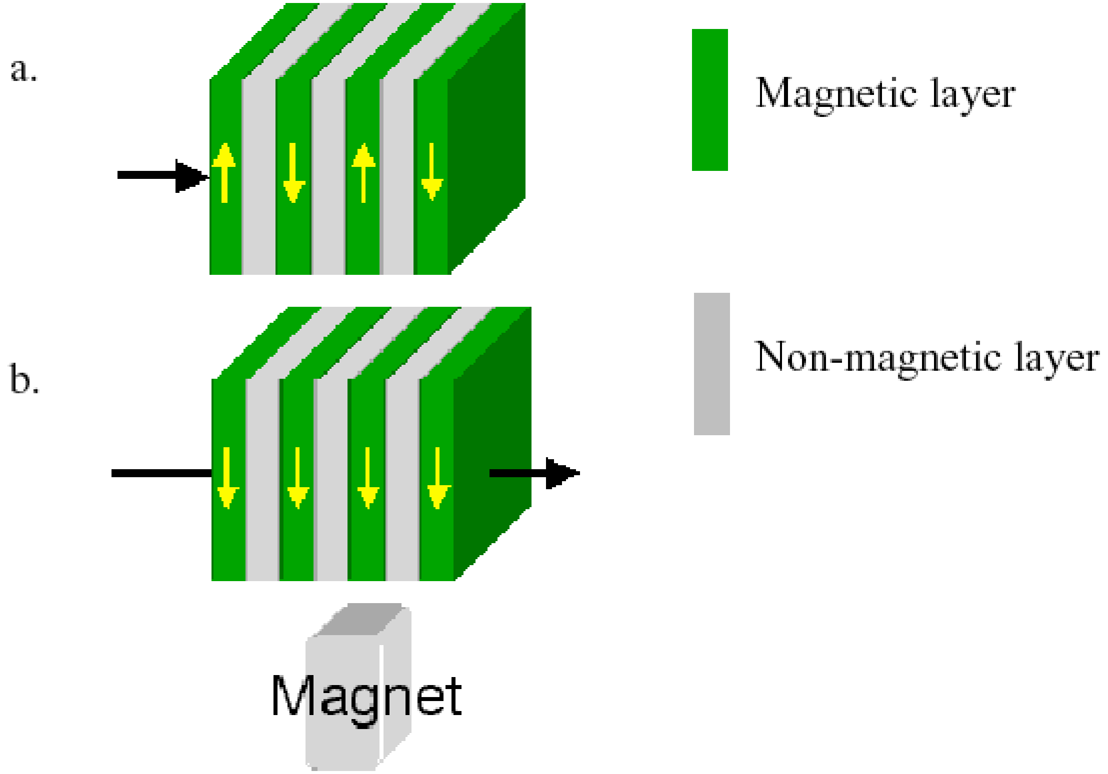
Spintronics

Magnetoresistance ΔR/R ~ few %

Gigantyczny magnetoopór

(Giant Magnetoresistance – GMR) 1988

ΔR/R ~ 20 %



Spintronics

Magnetoresistance $\Delta R/R$ ~ few %

Gigantyczny magnetoopór

(Giant Magnetoresistance – GMR) 1988

$\Delta R/R$ ~ 20 %

Kolosalny magnetoopór

(Colossal Magnetoresistance – CMR) 1993 $\Delta R/R$ ~ several orders of magnitude!

2006

Seagate 60GB 1.8-inch Hard Drive

Hitachi 1.0-inch 6GB Micro Drive

Toshiba 60GB 1.8-inch Hard Drive


cingular
9:41 AM
SMS
Text
Calendar
Photos
Camera
Calculator
Stocks
Maps
Weather
Notes
Clock
Settings


Industrial pqi
TURBO+
2.5" SATA
Solid State Disk
256GB

2009


Prt Sc
Sys Rq
Insert
Delete
Backspace
Home
Page Up
Enter
Page Down
End
8GB
ExpressCard SSD
ExpressCard

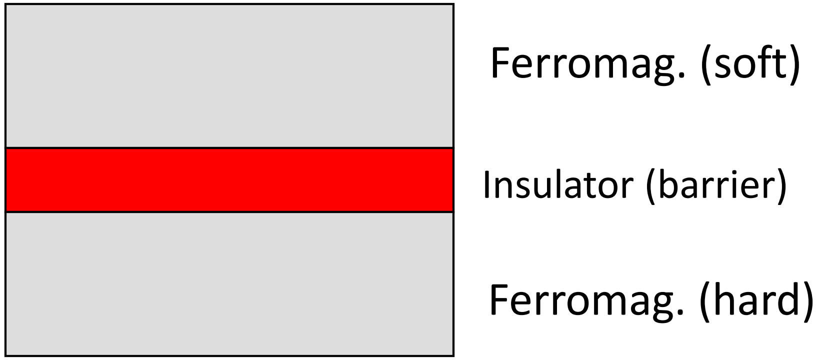

Windows CE .net

HTC Desire Z

1TB

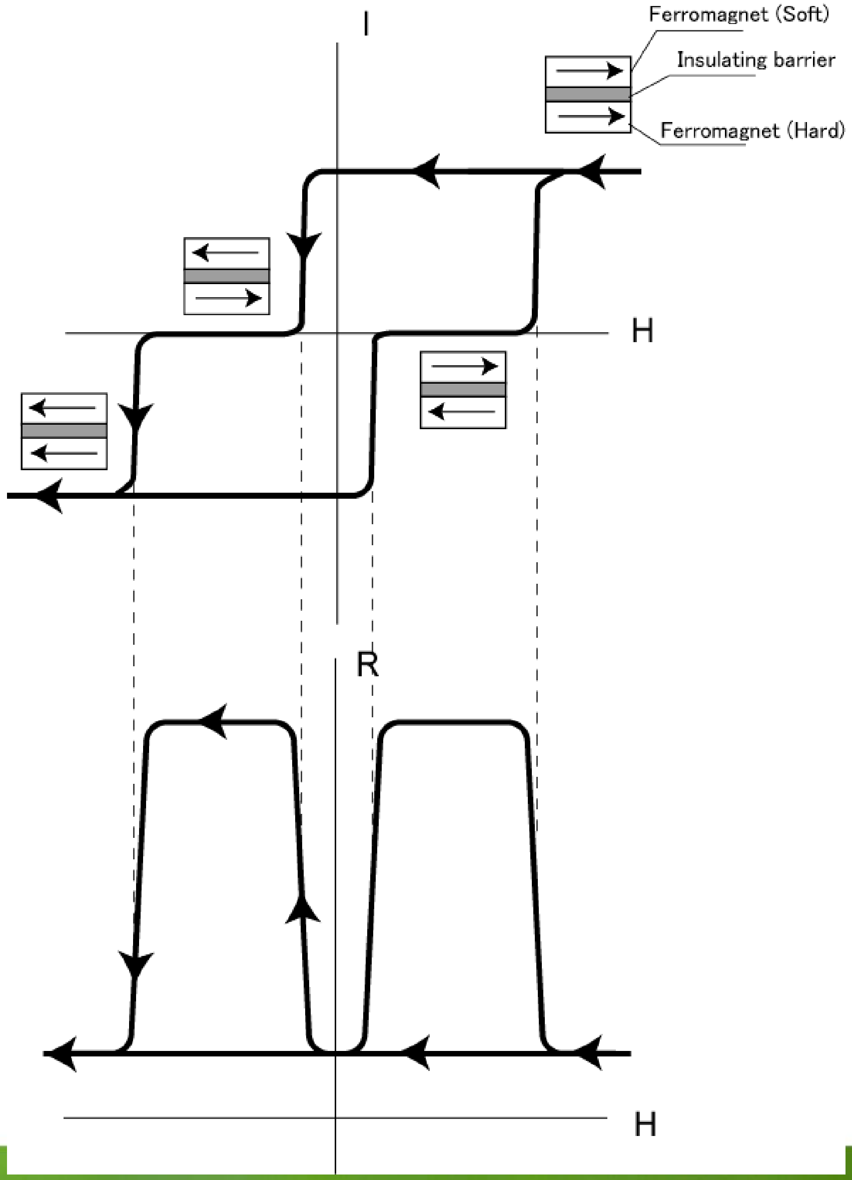
2011

Magnetic tunnel junction (MTJ)



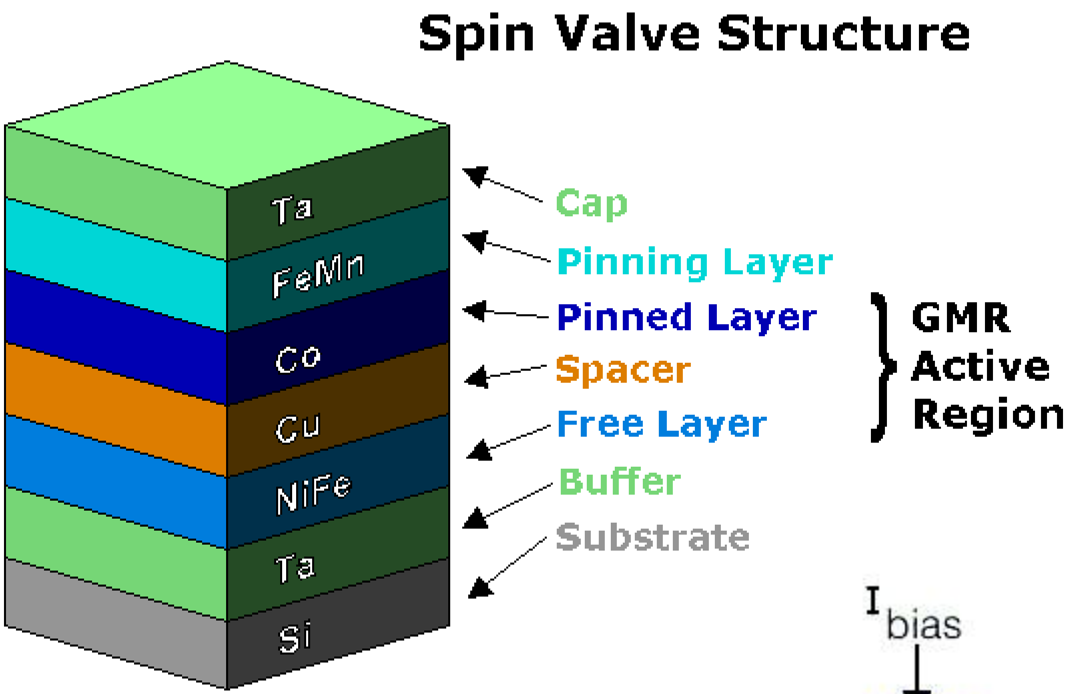
Ferromag.
Co, Py, FeCo, etc.
Barrier
Al2O3, MgO, etc.

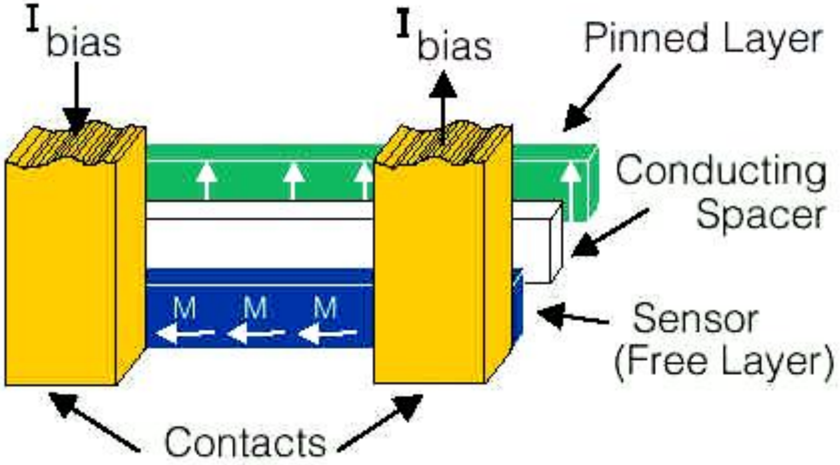
$$TMR(\%)=(R_{AP}-R_{P})/R_{P} *100$$



Takahiro Moriyama http://www.ece.udel.edu/~appelbau/spintronics/

Spintronics



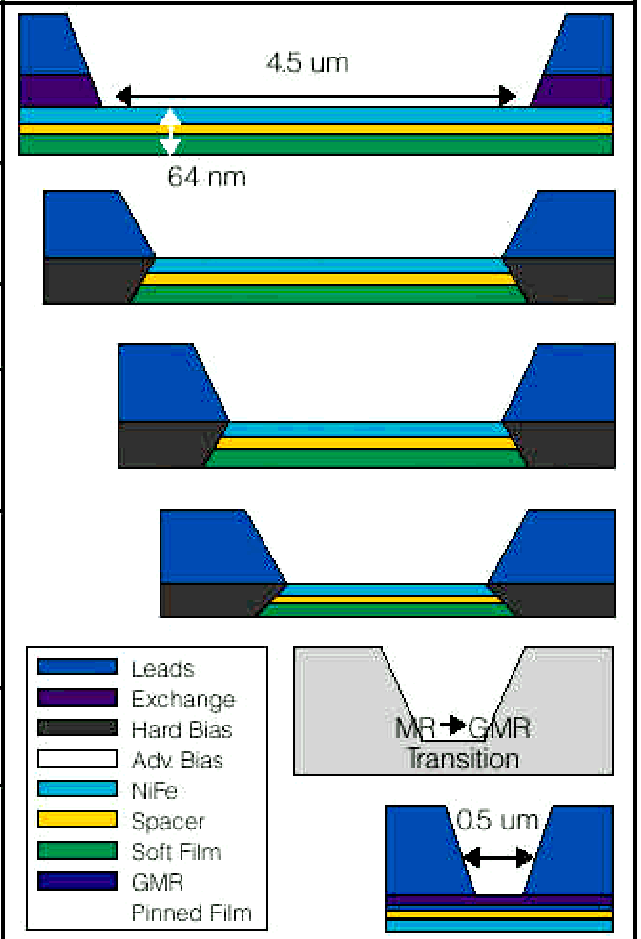


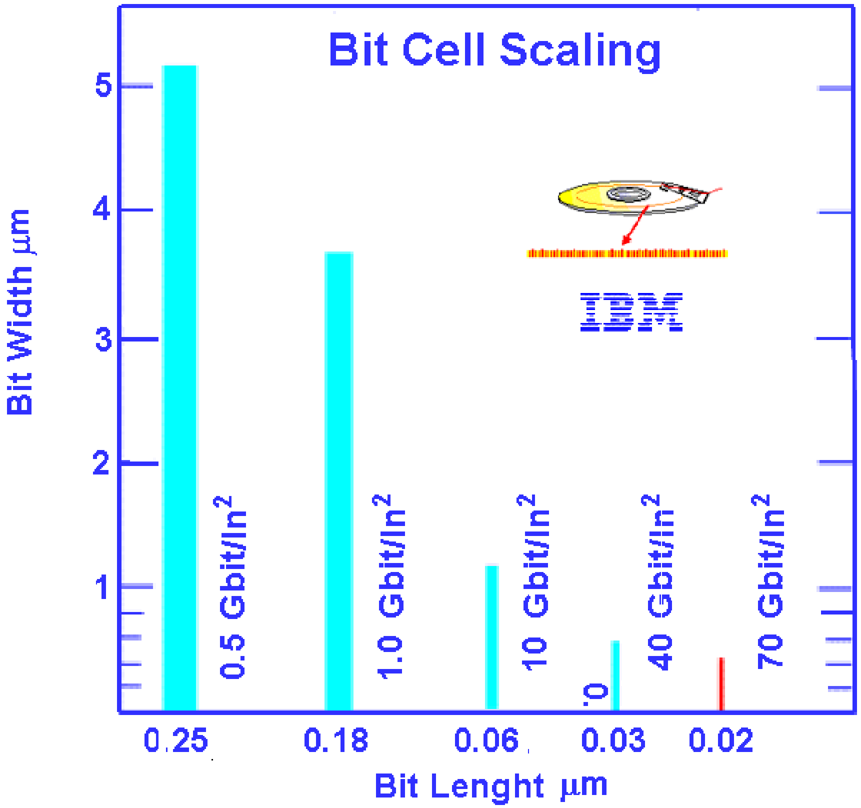
gmr_pc.exe

http://www.ing.unitn.it/~colombo/hard_disks/Magnetic_Heads_003.html

Spintronics

Year	Areal Density Gbits/in²	MR Element
1991	0.132	
1992	0.260	
1993	0.354	
1994	0.578	
1995	0.829	
	0.923	
1996	1.32	
1997	1.45	
	2.64	
1998	3.0-5.0	
2000	10.0	

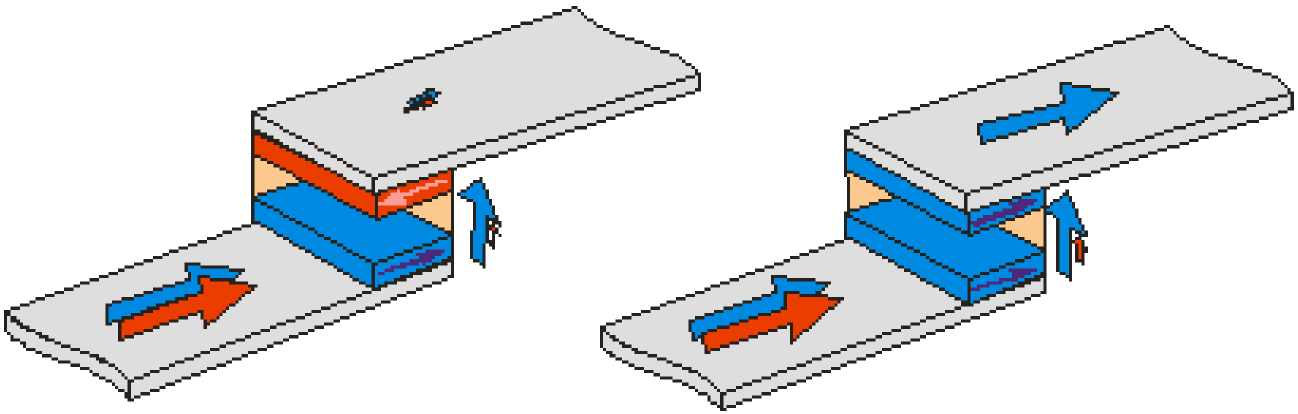




MTJ

insulating space layer

current perpendicular to plane

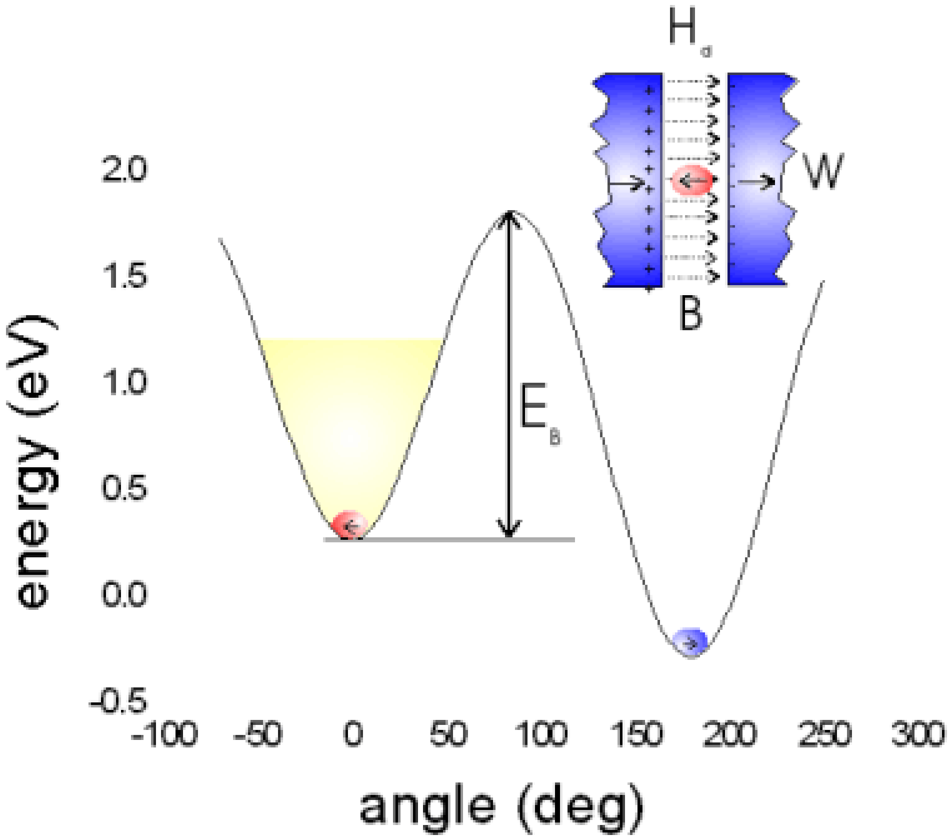


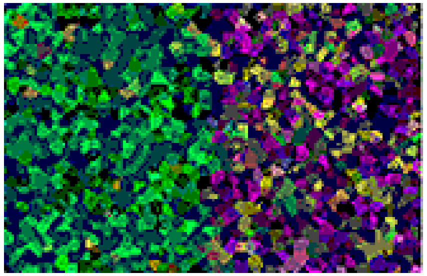
first ferromagnetic electrode acts as spin filter

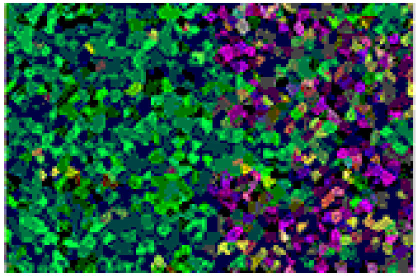
second FM layer acts as spin detector

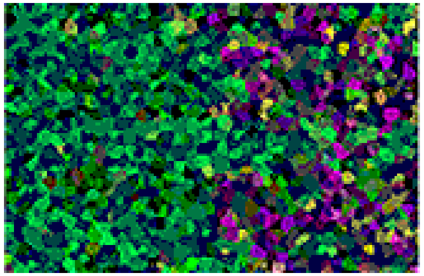
Spintronika

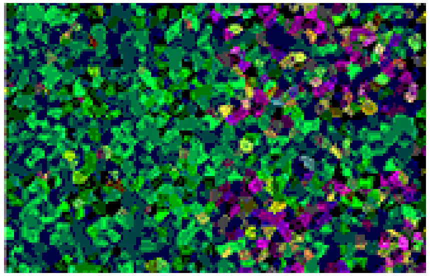
Limit Superparamagnetyczny







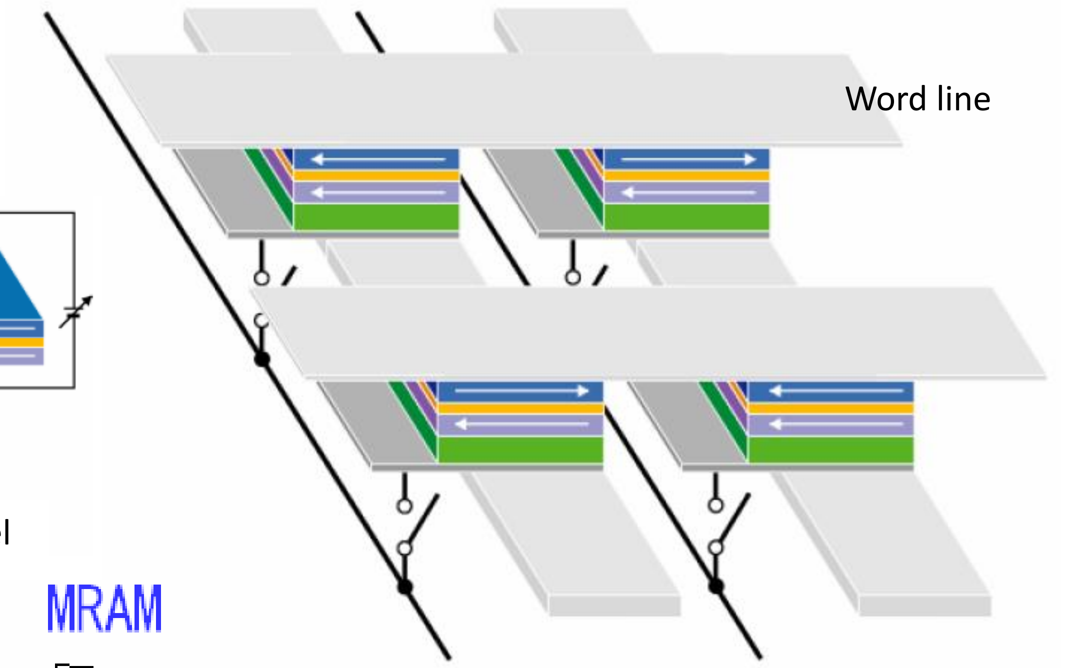


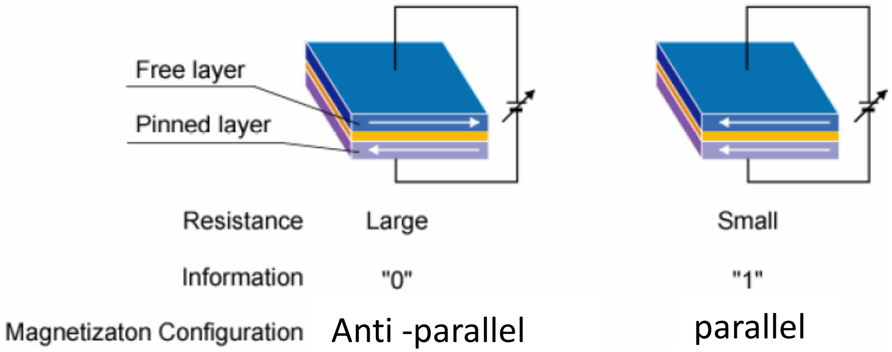


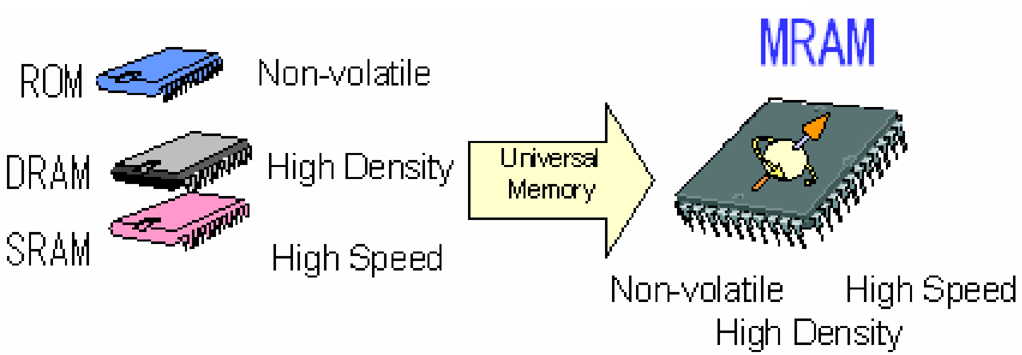
$$E_k = K_u V \sin^2(\vartheta)$$

http://www.ing.unitn.it/~colombo/hard_disks/Magnetic_Heads_003.html

MRAM architecture

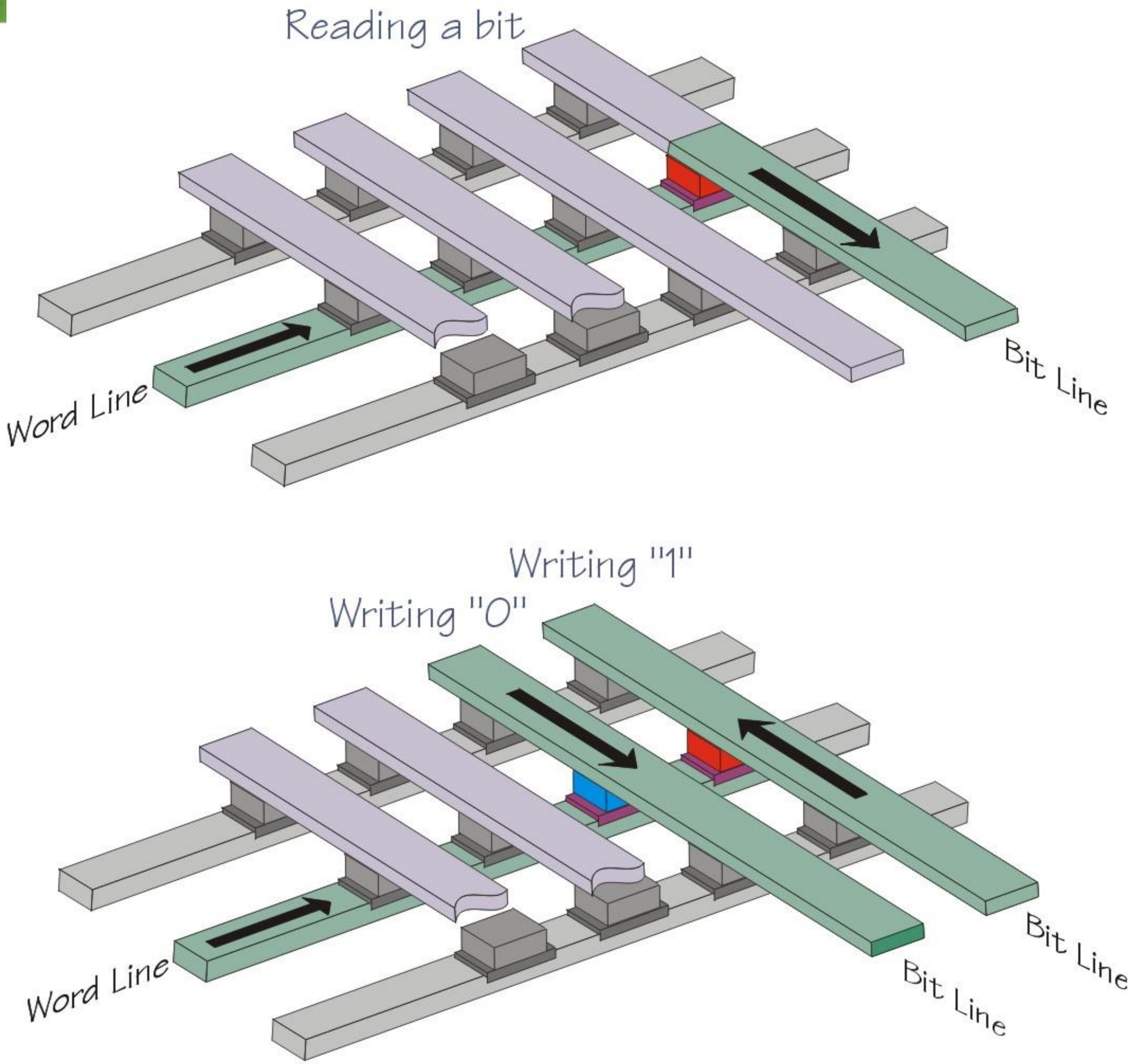






Takahiro Moriyama http://www.ece.udel.edu/~appelbau/spintronics/

Spintronics



MTJ MagRAM promises
- density of DRAM
- speed of SRAM
- non-volatility

http://www.research.ibm.com/resources/news/20001207_mramimages.shtml

Spintronics

Zalety MRAM

	DRAM	MRAM	Flash EEPROM	FeRAM
Trwałość zapisu	Nie	TAK	TAK	TAK
Czas zapisu	50ns	10 to 50ns	1us or longer	30 to 200ns
Czas odczytu	50ns	10ns to 1us	20 to 120ns	30 to 200ns
Metoda odczytu	Destructive	Non-Destructive	Destructive	Non-Destructive
Rewrite cycle	10^{15}	10^{15}	10^{5}	10^{12} to 10^{15}
Pobór prądu	100mA	10mA	10 to 100mA	10mA
Prąd uśpienia	100uA	1uA or lower	1uA or lower	1uA or lower

DRAM: Dynamic Random Access Memory
Flash EEPROM: Electrically Erasable Programmable Read-Only Memory
FeRAM: Ferroelectric RAM

MRAM pokonuje DRAM !!

Takahiro Moriyama http://www.ece.udel.edu/~appelbau/spintronics/

Spintronics

Magnetoresistance $\Delta R/R$ ~ few %

Gigantyczny magnetoopór

(Giant Magnetoresistance – GMR) 1988

$\Delta R/R$ ~ 20 %

Kolosalny magnetoopór

(Colossal Magnetoresistance – CMR) 1993 $\Delta R/R$ ~ several orders of magnitude!

Collosal magnetoresistance

VOLUME 71, NUMBER 14 PHYSICAL REVIEW LETTERS 4 OCTOBER 1993

Giant Negative Magnetoresistance in Perovskitelike $La_{2/3}Ba_{1/3}MnO_x$ Ferromagnetic Films

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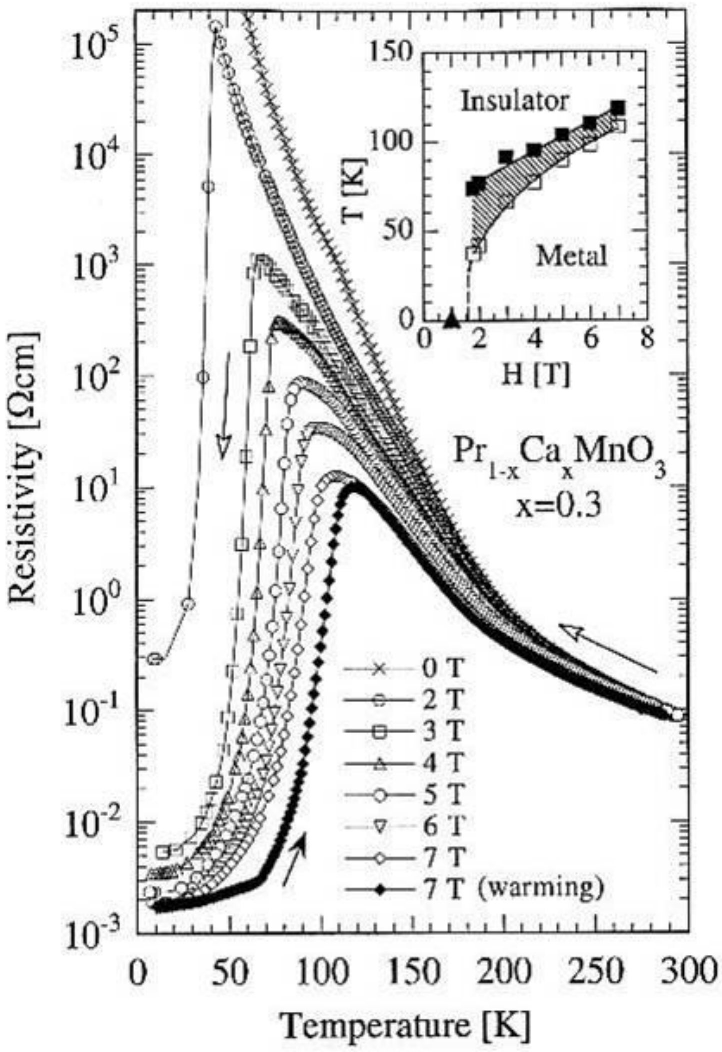
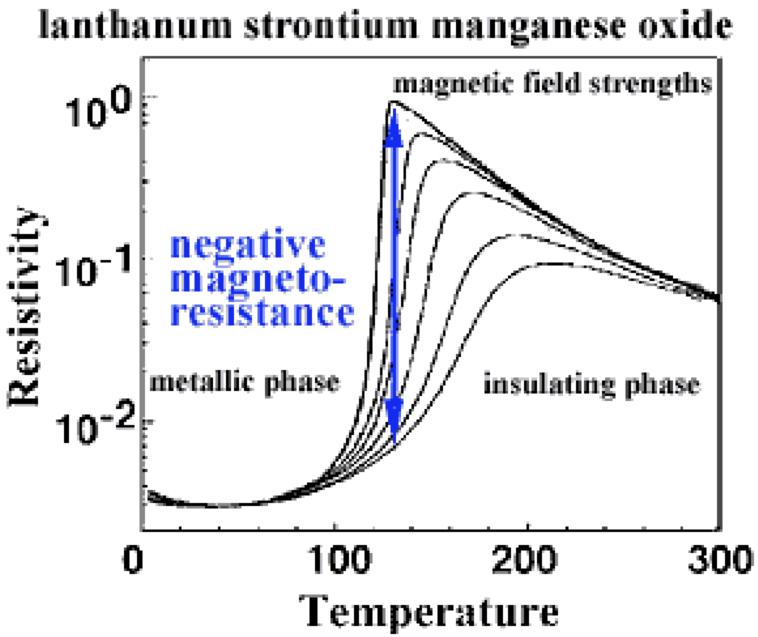
(Received 14 May 1993)

At room temperature a large magnetoresistance, $\Delta R/R(H=0)$, of 60% has been observed in thin magnetic films of perovskitelike La-Ba-Mn-O. The films were grown epitaxially on $SrTiO_3$ substrates by off-axis laser deposition. In the as-deposited state, the Curie temperature and the saturation magnetization were considerably lower compared to bulk samples, but were increased by a subsequent heat treatment. The samples show a drop in the resistivity at the magnetic transition, and the existence of magnetic polarons seems to dominate the electric transport in this region.

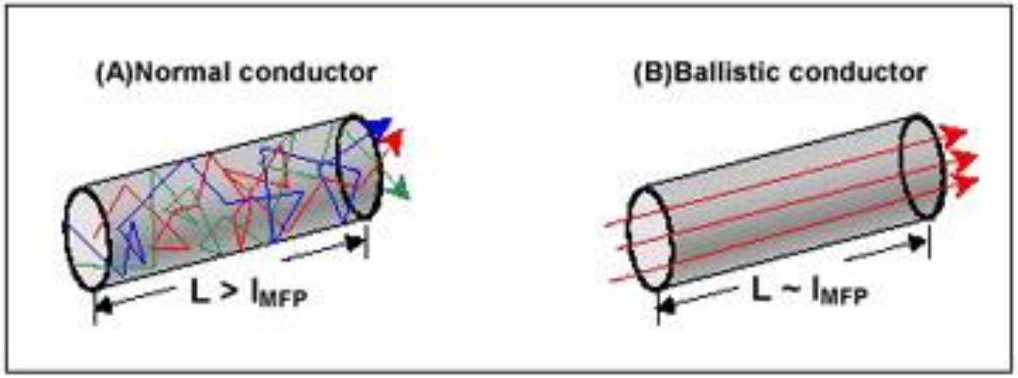
JIN S, TIEFEL TH, MCCORMACK M, FASTNACHT RA, RAMESH R, CHEN LH *et al.* Thousandfold change in resistivity in magnetoresistive La-Ca-Mn-O films. *Science* **264**, 413−415 (1994)

Collosal magnetoresistance





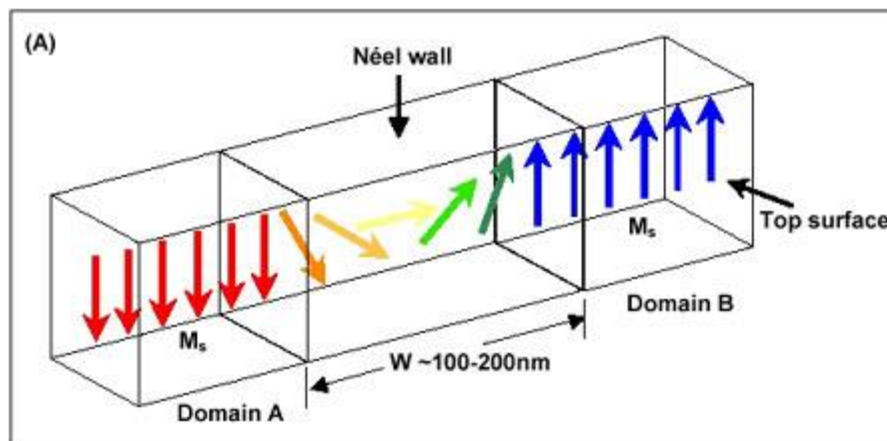
Ballistic magnetoresistance



In normal conductors, the conductor length is larger than the electron mean free path and motion is zigzag, figure (A) above.

For electrons passing through a nanocontact, the nanocontact length is comparable to or less than electron mean free path and motion is ballistic, figure (B) above.

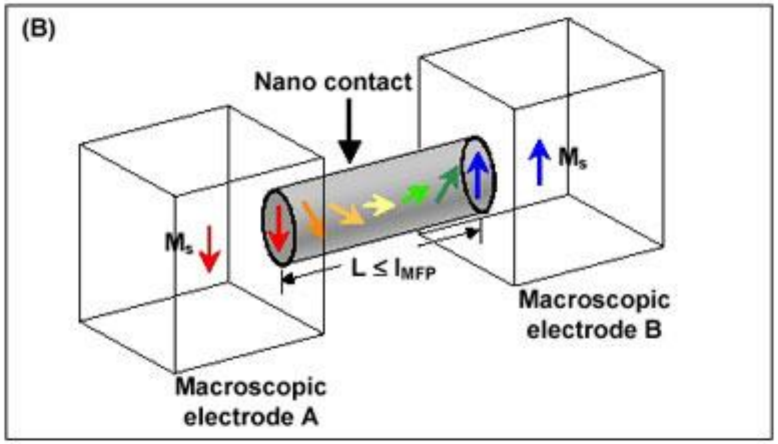
Ballistic Magnetoresistance



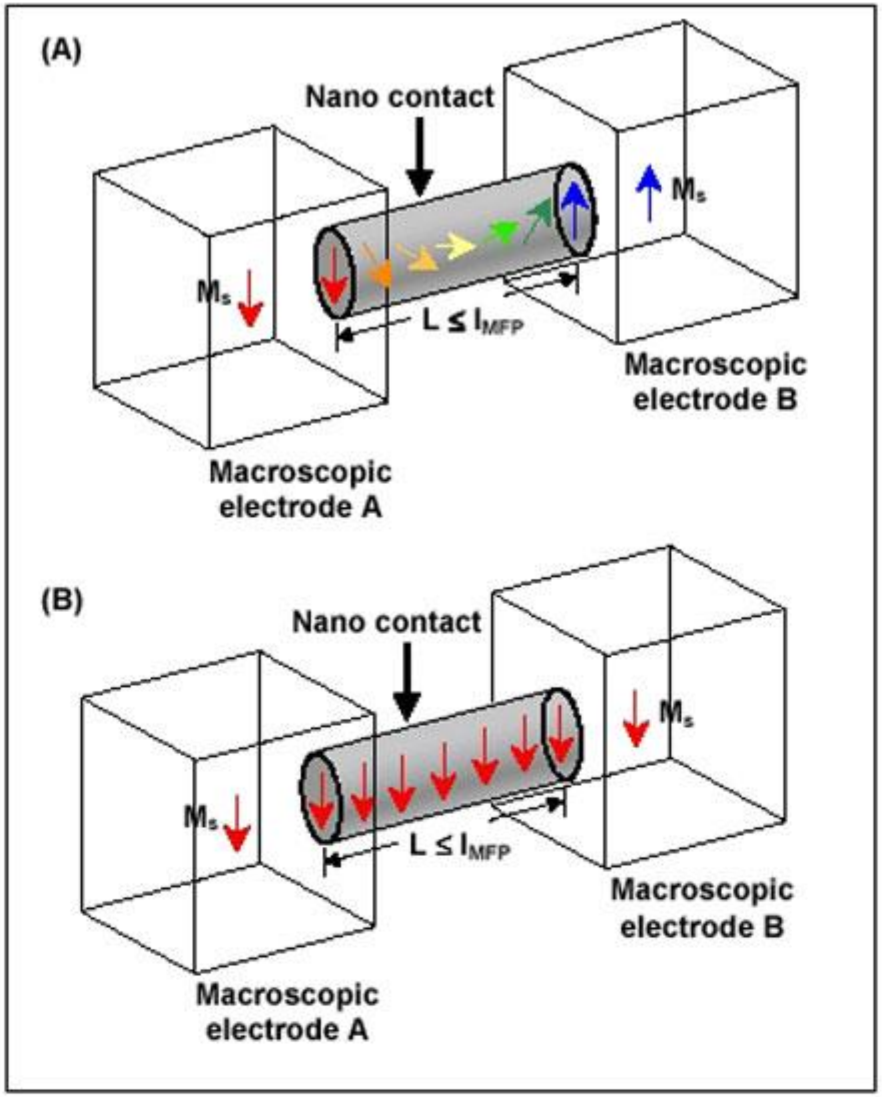
Néel wall in a thin film separates two domains of opposite magnetization. Wall width "W" is several hundred nanometers and BMR effect is negligible.

http://www.aip.org/png/2002/155.htm

Ballistic magnetoresistance



Wall width within a nanocontact separating two macroscopic electrodes of opposite magnetization. Wall width is in the nanometer range and electrons passing through the nanocontact experiences a huge scattering moment.



(A) Magnetization across nanocontact opposite in direction, giving rise to high resistance state.
(B) Magnetization across nanocontact parallel in direction, giving rise to low resistance state.
Transition from state A to state B by applied magnetic field - BMR effect.

http://www.aip.org/png/2002/155.htm