The new challenges of spintronics

Spintronics, from Giant Magnetoresistance to magnetic Skyrmions and Topological Insulators

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Outline of the talk

- ❖ A bit of history:

What is Spintronics?

Magnetic resistance MR

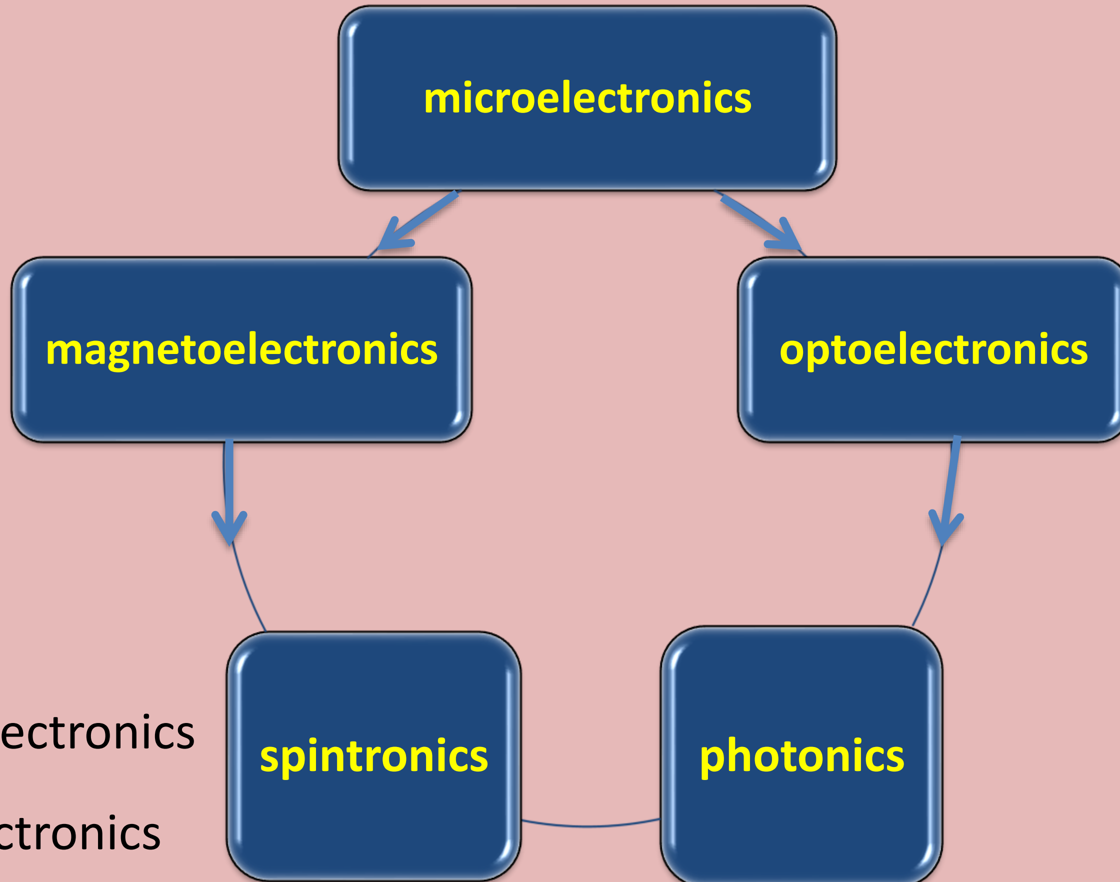
- ❖ SPIN POLARIZED CURRENT
- ❖ EFFECTS WITH SPIN POLARIZED CURRENT: Giant magnetic

  resistance

  Spin-Trans

- ❖ Spin-orbitr

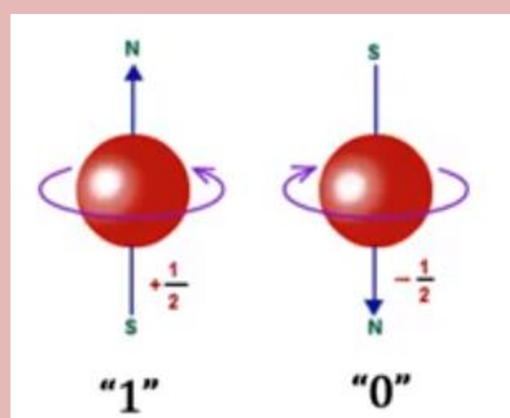
  topologica

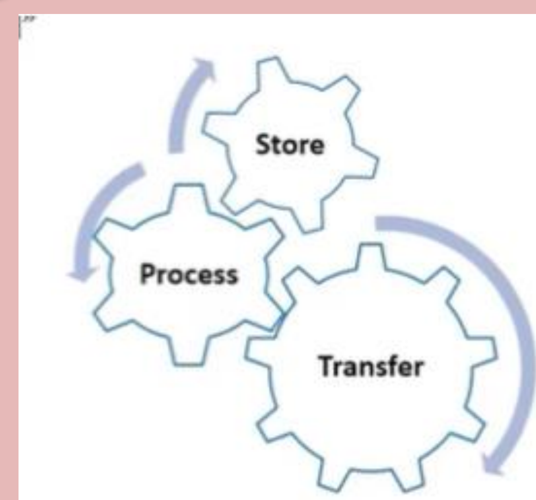


spin transport electronics

spin-based electronics

spin-electronics

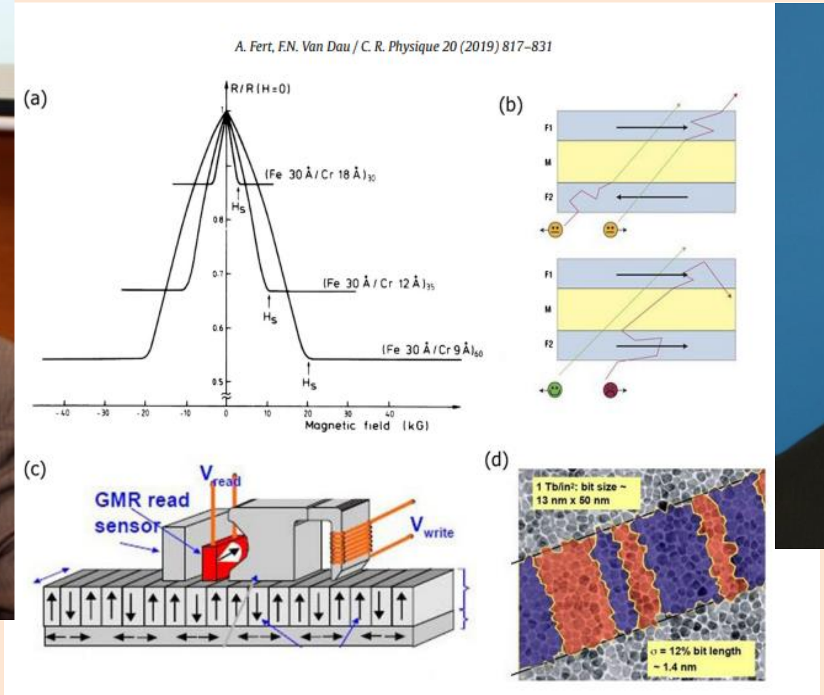




spintronics studies magnetic and magneto-optical interactions in metals and semiconductor structures, as well as quantum magnetic phenomena in nanoscale structures.

GMR

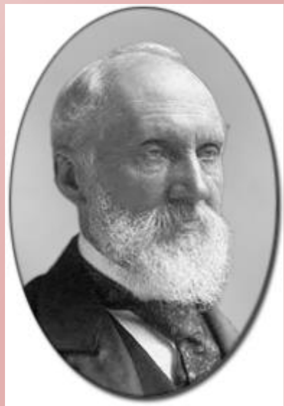
Albert Fert



Peter Andreas Grünberg

It is considered that spintronics started in 1988 with the discovery of the giant magnetic resistance effect. The GMR is the effect that gave rise to the use of nanotechnology.

Let's first understand what magnetoresistance MR means. This term is used when considering electrical resistance in a magnetic field.

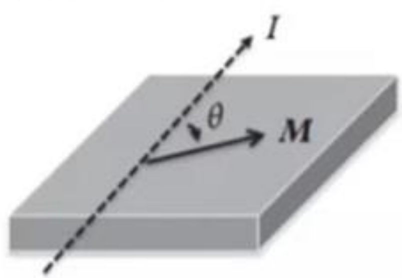


William Thomson
1824-1907

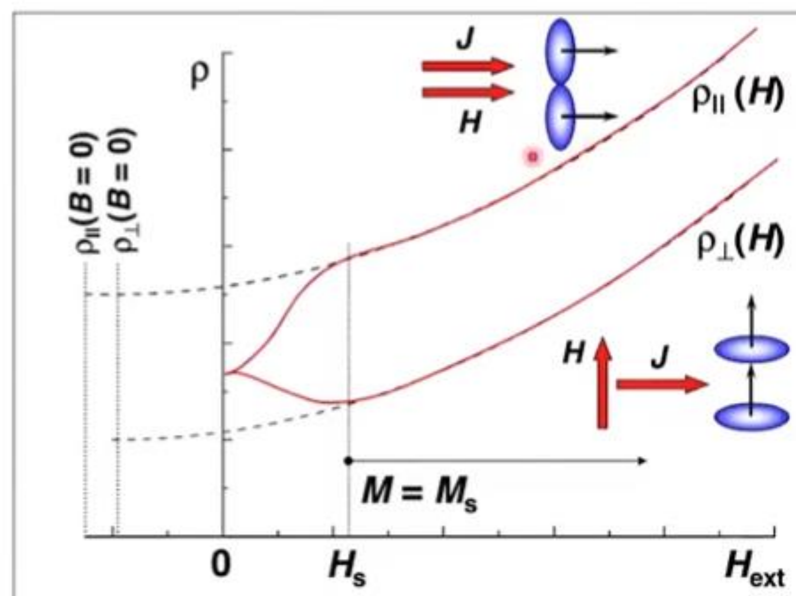
The English physicist Thomson (Lord Kelvin) began to study MR. In 1857, he found how the resistance of iron changes: if an electric current flows in the direction of the magnetic field, the resistance increases, and if it flows perpendicularly, resistance decreases. This effect is called anisotropic magnetoresistance.

The angular dependence of the resistivity is given by:

$$\rho(\theta) = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2\theta$$



where $\rho_\parallel$ and $\rho_\perp$ are resistivities with magnetization parallel and perpendicular to the current, respectively

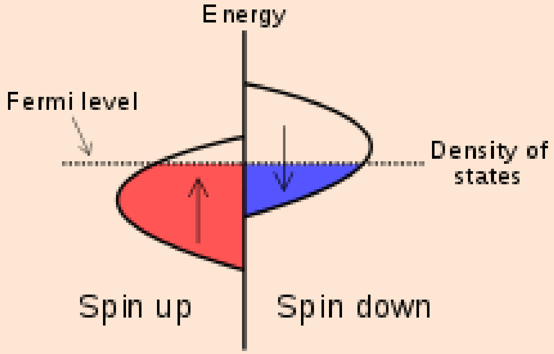


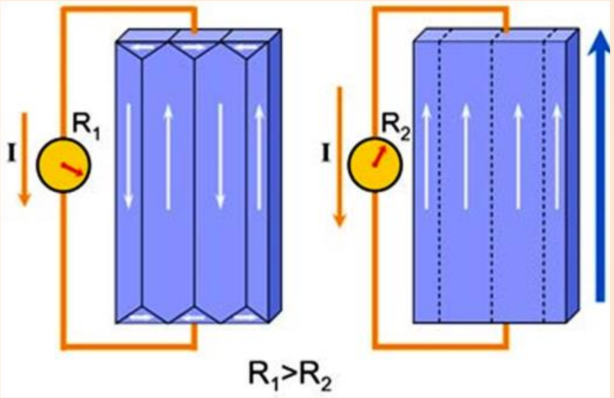
Nevill Mott
1905-1996

The next step in this direction was done by the English physicist Nevill Mott, who received the Nobel Prize in Physics in 1977. He introduced the concept of spin-polarized currents and also predicted that in ferromagnets the current must be polarized.

Edmund Stoner
1899-1968

The reason for the polarization is not determined by the magnetization in the magnetic field, but is explained by the Stoner model.





$$\delta_H = \frac{R(0) - R(H)}{R(H)}$$

This phenomenon cannot be explained without quantum mechanics.

In fact, atoms do not present a barrier to electrons if they are located along a strictly periodic lattice (electron has dual nature wave/particle). When the strictly periodic state is breach, the electrons collide with inhomogeneities.

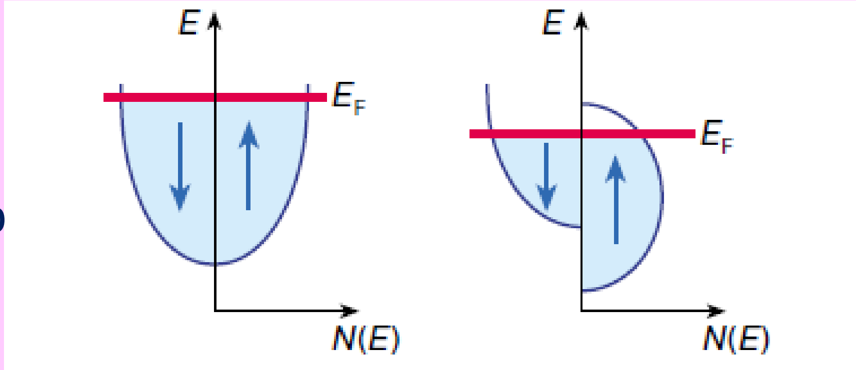
Electric current ⟶ not all electrons can participate - **only electrons with the value of the Fermi energy**

- The scattering of electrons as a result of electron-electron collisions makes a small contribution to the resistance.
- Thermal vibrations of atoms - phonon contribution
- Electrons are scattered by crystal defects and impurities
- In magnets, electrons are additionally scattered by the magnetic lattice of the crystal. It depends on the orientation of the spin with regard to the magnetic moments of the atoms.

$$\rho(T) = \rho_e(\mathrm{T}) + \rho_p(\mathrm{T}) + \rho_i + \rho_M(\mathrm{T})$$

N + = N –

The magnetization is zero and the electrons are not polarized.



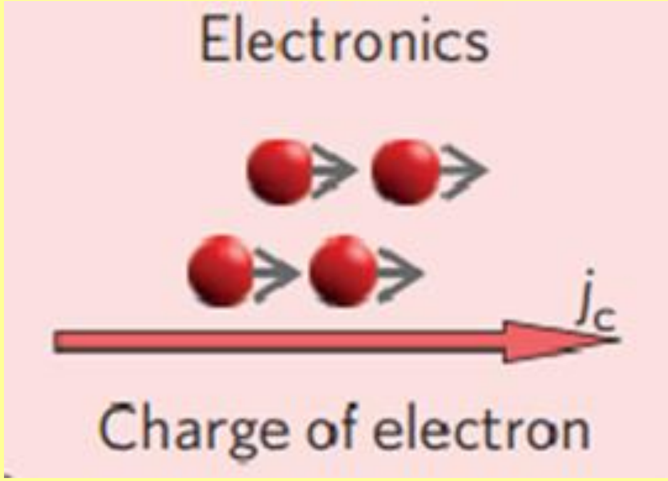
copper cobalt.

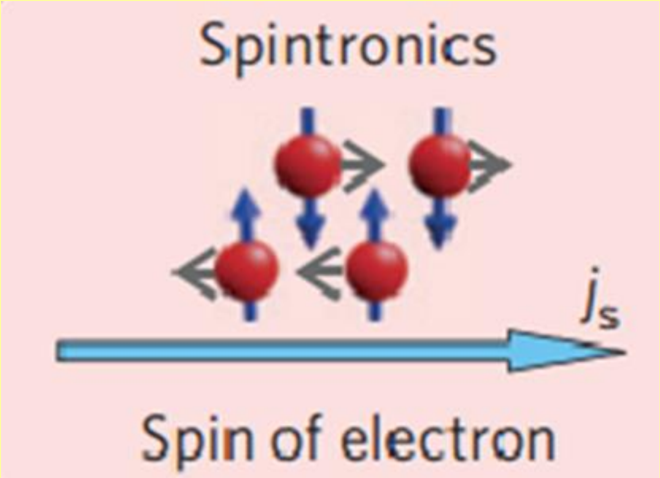
$$M = \mu_B(N_+ - N_-).$$

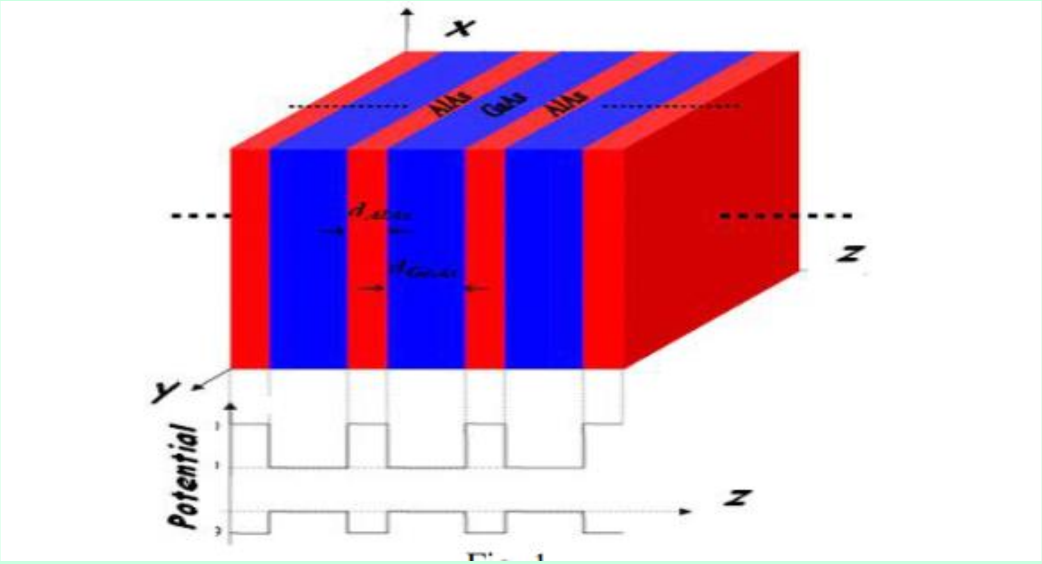
The magnetic field inside the metal acts on the electron and differently influences on the spins both in the direction of the field and against it.

As there is an energy splitting between the “majority spin” and “minority spin” bands, the electrons at the Fermi level, which carry the electrical current, are in different states and exhibit different conduction properties.

Electric current in ferromagnets consists of two different but balanced flows. These two types of electrons experience different resistance from the metal, those that are oriented against the field move more freely than those that are oriented in the direction of the field.







A multilayers structure

Thus, the inner world of ferromagnets is quite rich, but so far there is no way to manipulate the resistance of the sample. Artificial structures are of primary importance here. As it turned out, in such structures we can control not only the magnitude of the magnetization, but also the nature of the magnetic order and, as a consequence, the electrical resistance.

Let's try to explain this process.

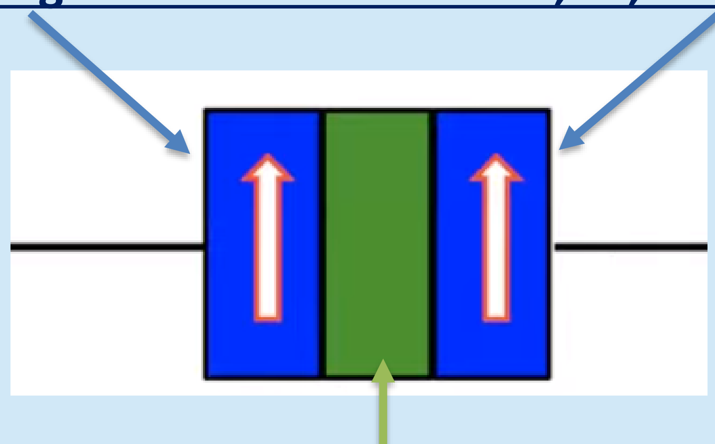
First of all, we need to create a nanoscale device. This is a **sandwich model** of thin layers of metal, a few nanometers thick, it can be called a spin valve.

Two layers of ferromagnetic material: iron-cobalt-nickel, their alloy.

The central part of a non-magnetic material - it can be aluminum, copper or any insulator MgO, AlOx ....

If the central part is non-magnetic, a device is called a spin valve; If it is an insulator, then we have a magnetic tunnel junction (MTJ).

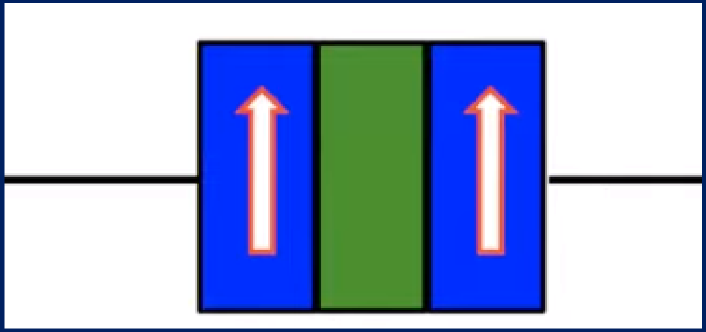
Ferromagnetic material – Fe. Co, Ni, their alloys

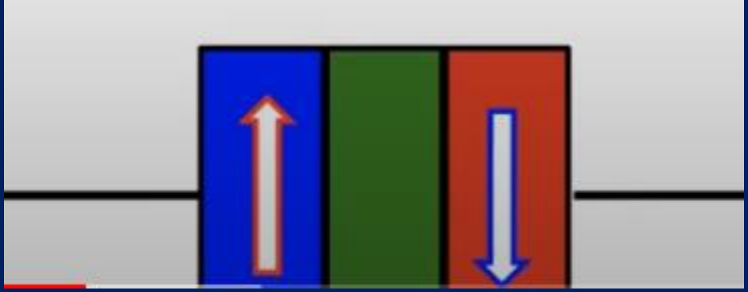


non-magnetic material- Cu,   Al, Au or any insulator MgO, AlOx ....

What is important here?

These ferromagnetic layers can have different directions of magnetization.

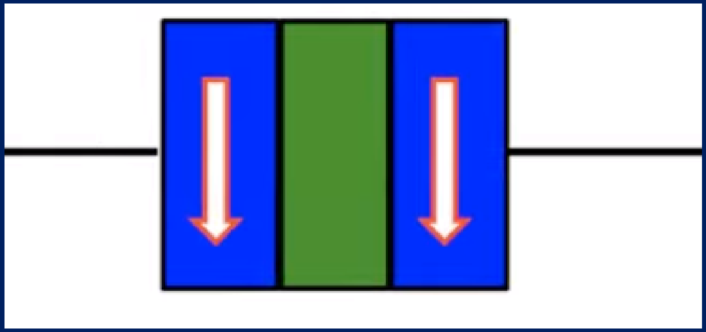


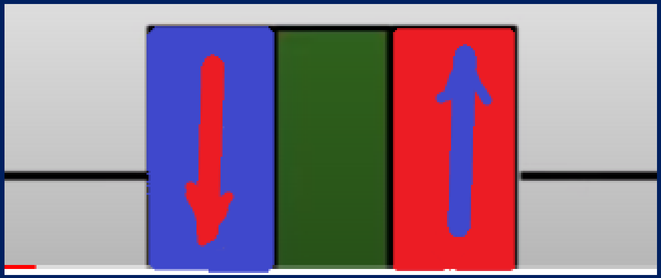


There are 4 configuration forms.

Parallel Configuration - Low resistance.

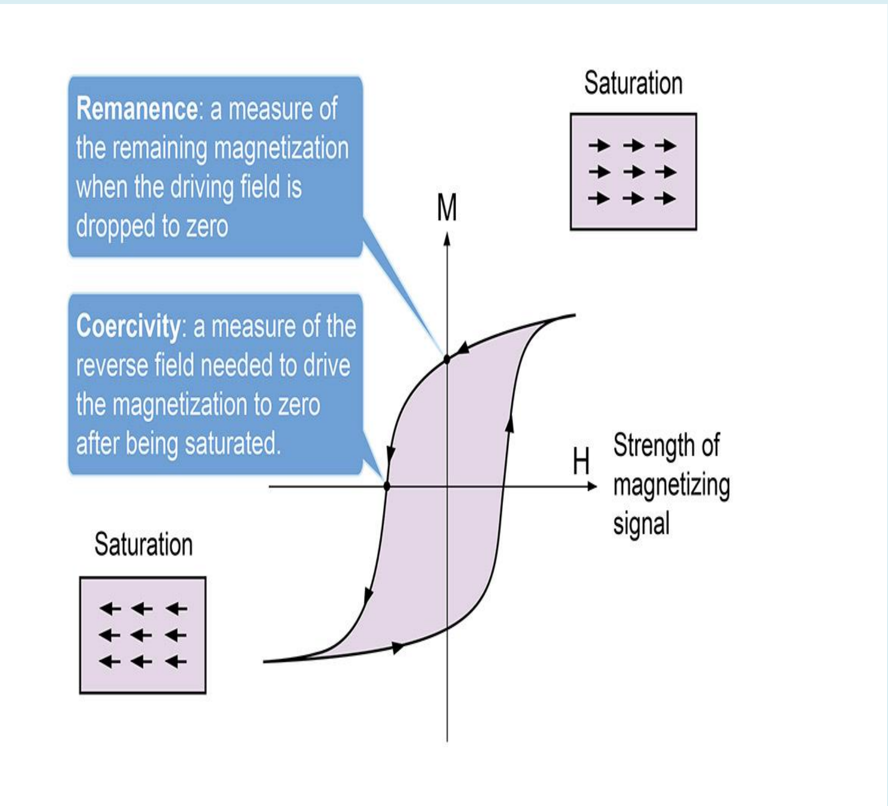
Antiparallel Configuration - High resistance.



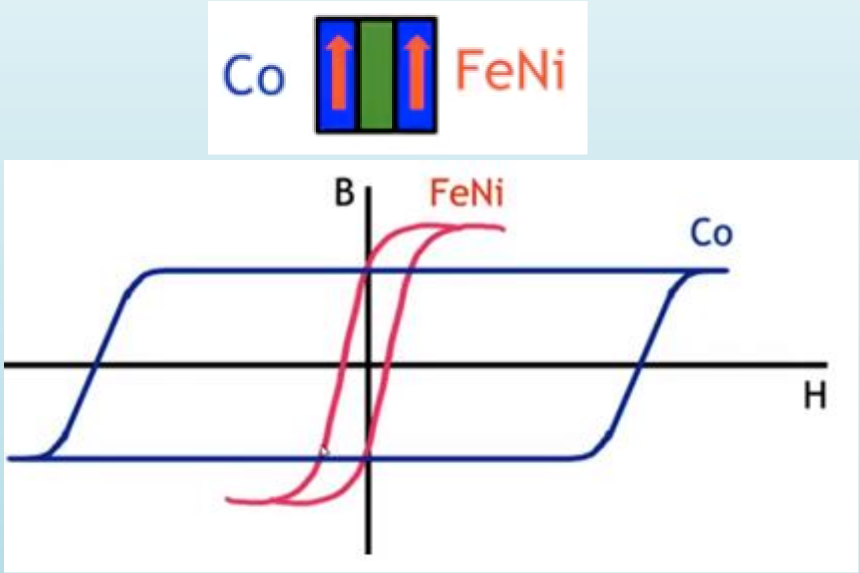


? Why is this configuration important?

There are two different ferromagnetic layers with different coercive force: cobalt - 10 kA/m and permalloy (iron-nickel alloy) - 0.05 kA/m.

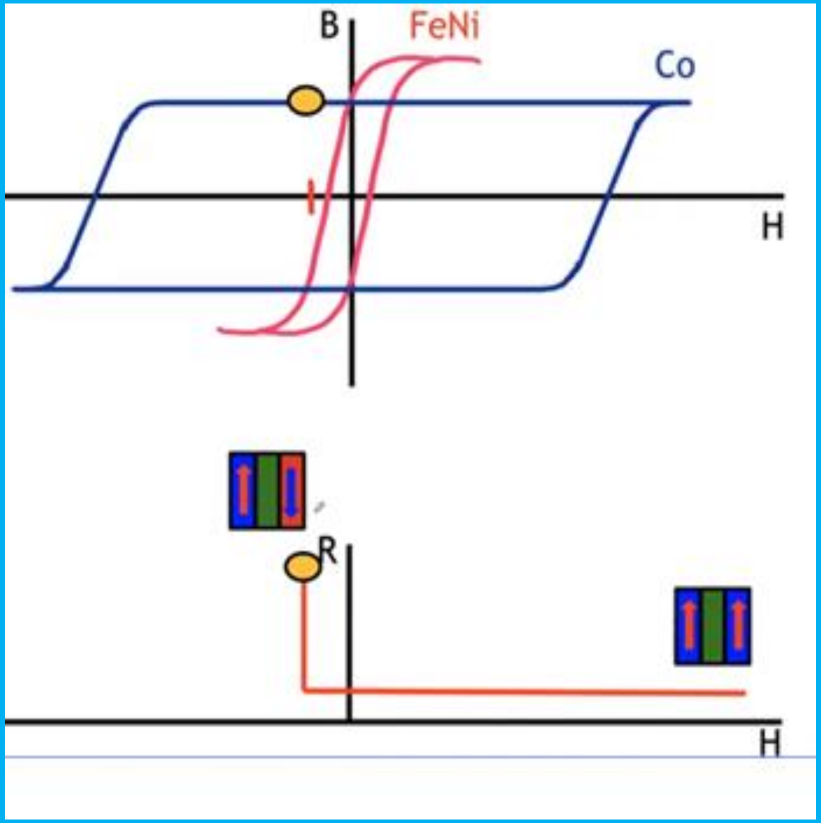


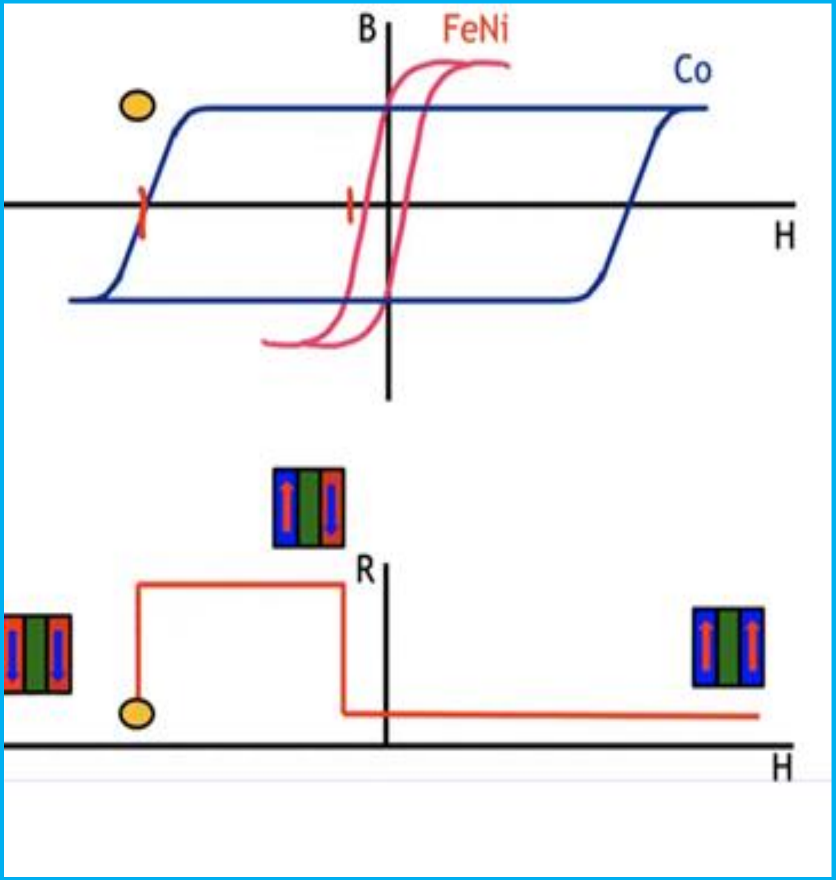
Let's remember the hysteresis

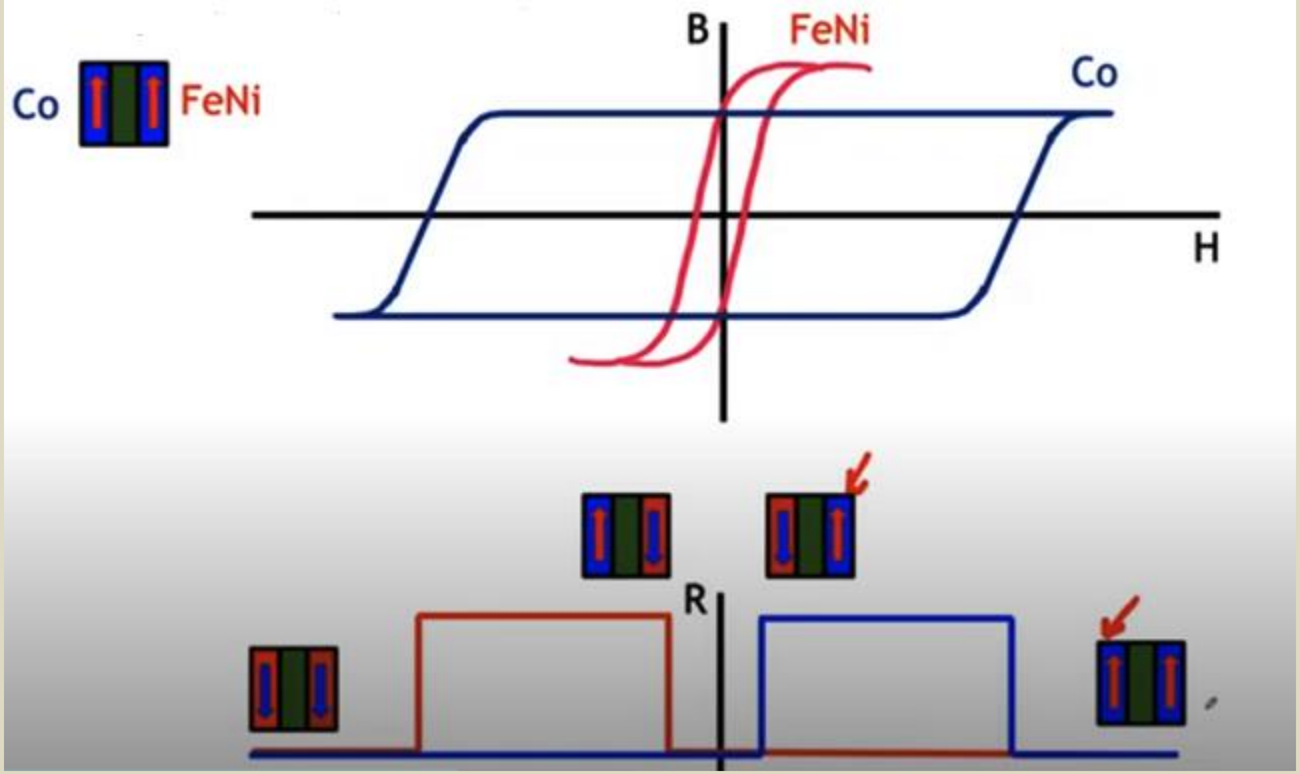


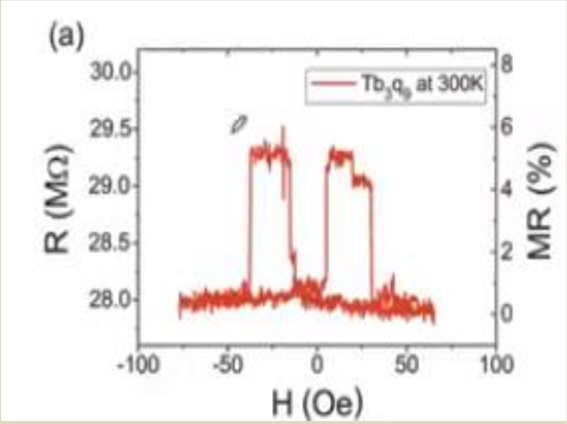
A larger magnetic field is required to magnetize cobalt in the opposite direction, and permalloys change the direction of magnetization very easily.

Let's start the discussion with a parallel configuration.



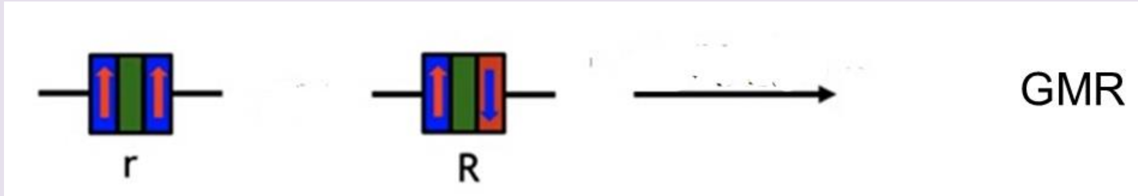


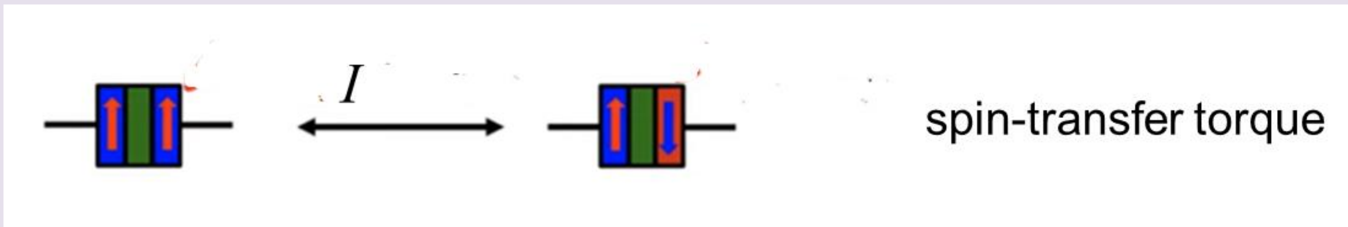

Co
FeNi
B
FeNi
Co
H
R


(a)
R (MΩ)
MR (%)
H (Oe)
30.0
29.5
29.0
28.5
28.0
-100
-50
0
50
100
8
6
4
2
0

We can choose a material that has a lower coercive force, it instantly remagnetizes, and another has a higher coercive force that will never remagnetize at low values of the magnetic field; We will get a counting head for hard drives. Modern counting devices work on this principle, so the amount of memory has increased.

Spintronics turned out to be the simplest way to create the most sensitive magnetic field sensor.

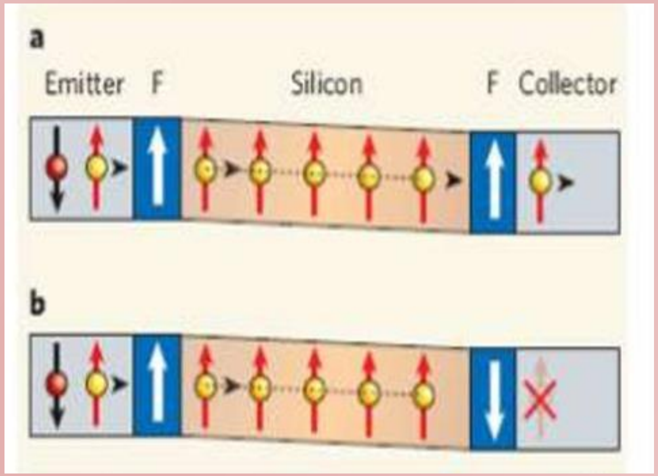




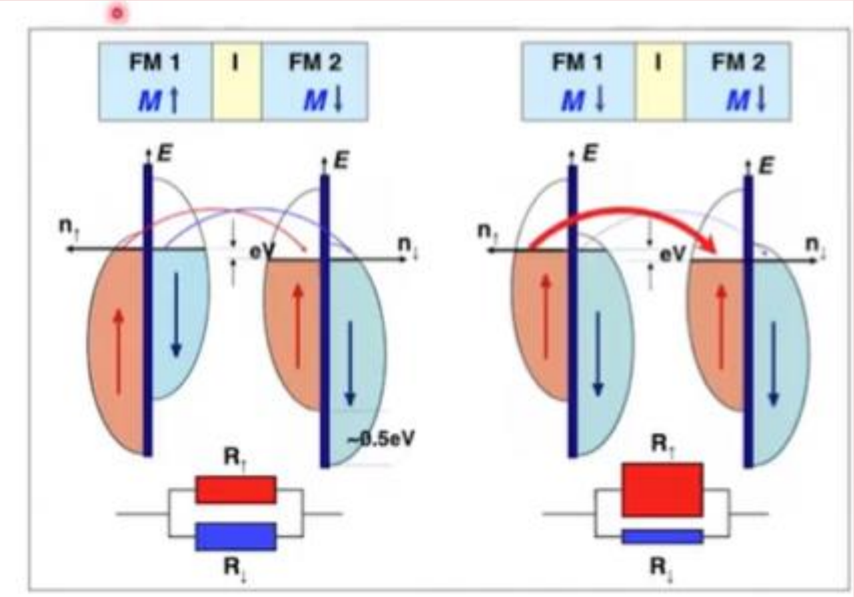
What does it mean?

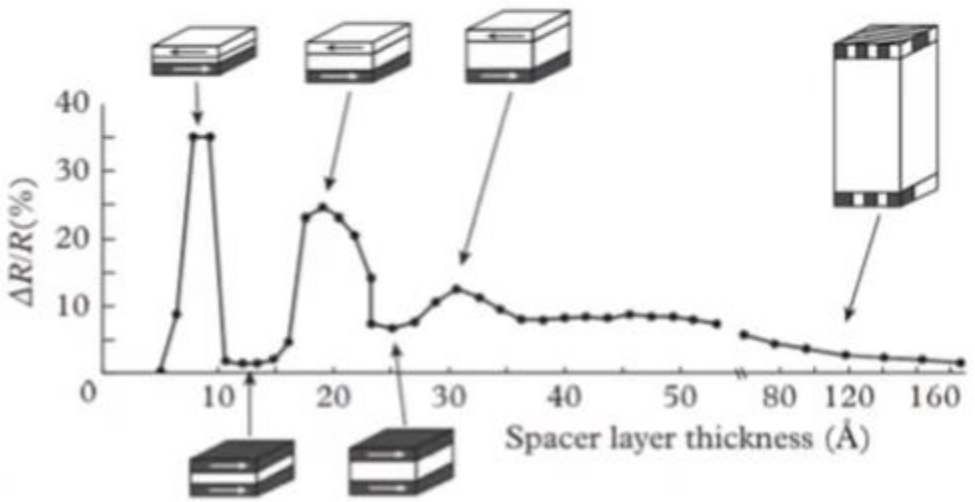
That we can store information in the form of RAM. Because when we want to read information, we measure the resistance, and when we want to write it, we increase the current a little (μA or less). It's a brilliant design compared to conventional RAM because once something is written, it persists even when the power is turned off. Switching is faster than charging a capacitor

Spin injection



Tunnel magnetoresistance



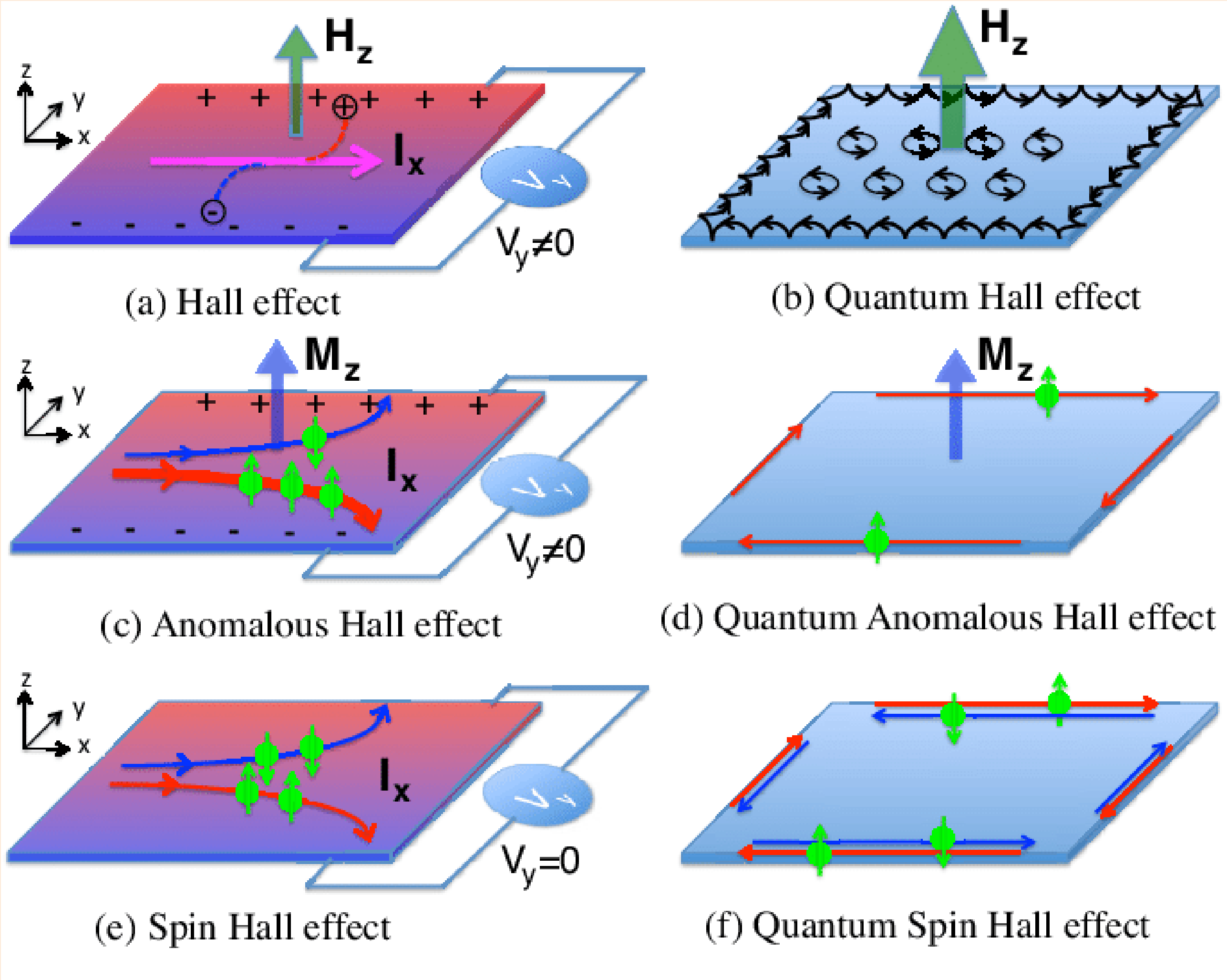


40
30
20
10
0
ΔR/R(%)
10
20
30
40
50
80
120
160
Spacer layer thickness (Å)

Classical spintronic devices use the exchange interaction between conduction electron spins and local spins in magnetic materials or to manipulate nanomagnets by spin transfer. A novel direction of spintronics –**spin-orbitronics -** exploits the Spin-Orbit Coupling (SOC) in nonmagnetic materials. This opens the way to spin devices made of only nonmagnetic materials and operated without magnetic fields.

Spin-orbit coupling can also be used to create new types of topological magnetic objects as the magnetic **skyrmions** or the **Dzyaloshinskii-Moriya domain walls.**

Members of the Hall family

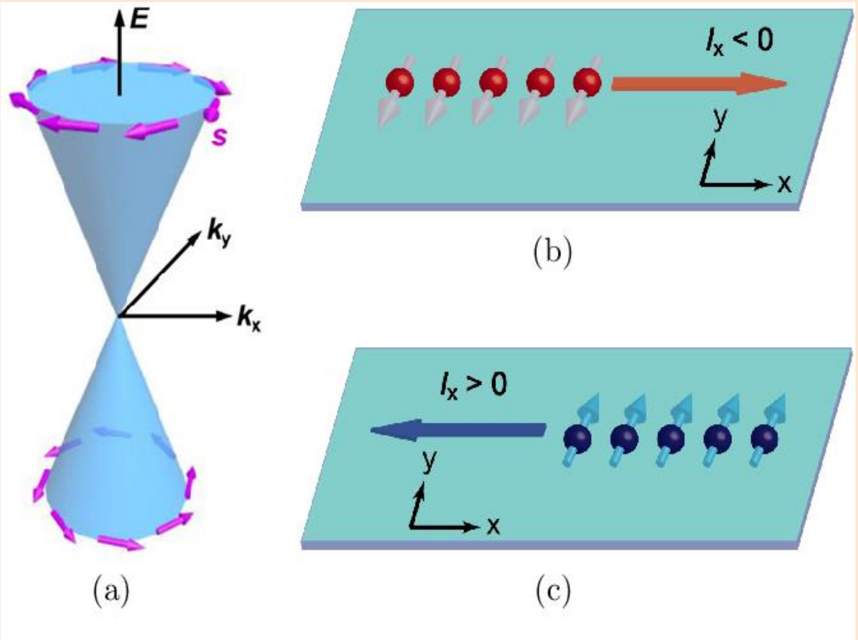


The spin Hall effect is a transport phenomenon consisting of the appearance of spin accumulation on the lateral surfaces of a sample carrying electric current.

New – Photo-induced Hall effect

Spintronics Based on Topological Insulators

A topological insulator is a material that behaves as an insulator in its interior but whose surface contains conducting states, meaning that electrons can only move along the surface of the material. Topological insulators have non-trivial symmetry-protected topological order. What is special about topological insulators is that their surface states are symmetry-protected Dirac fermions by particle number conservation and time-reversal symmetry.



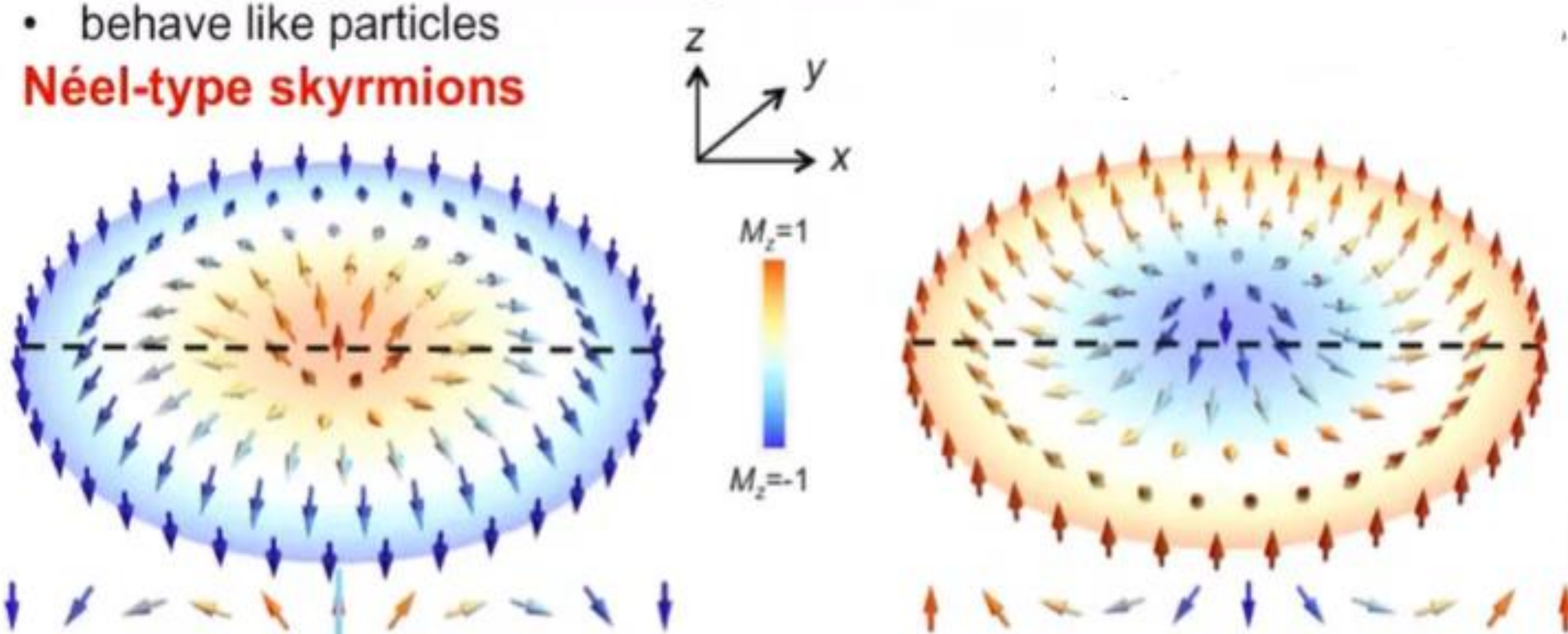
Magnetic skyrmions: topological phases of matter

Magnetic skyrmions:

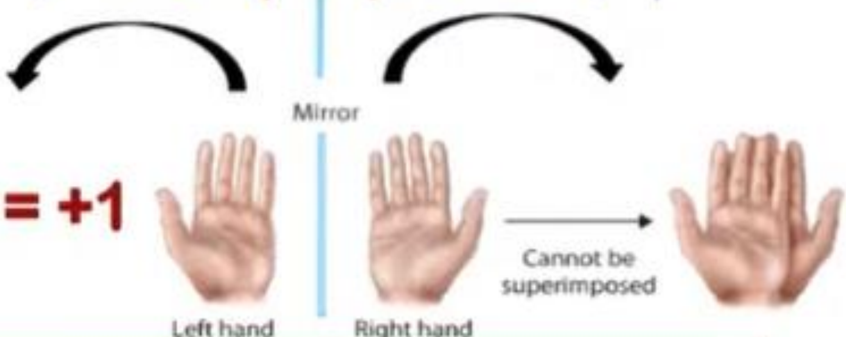
- topologically protected chiral spin textures
- behave like particles

- topologically protected non-linear vector fields

Néel-type skyrmions

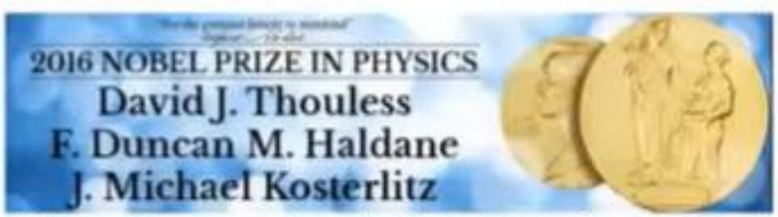


***Q* = -1**

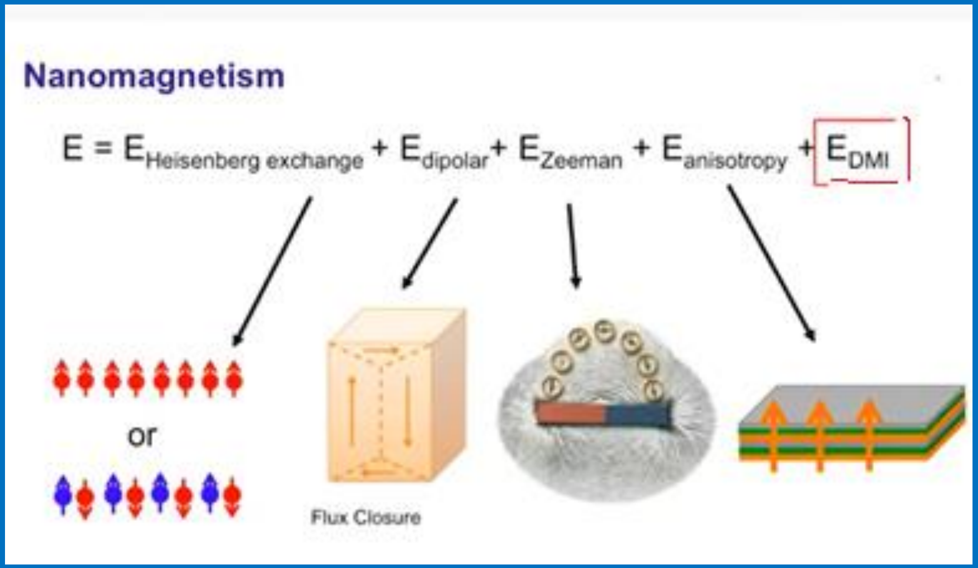


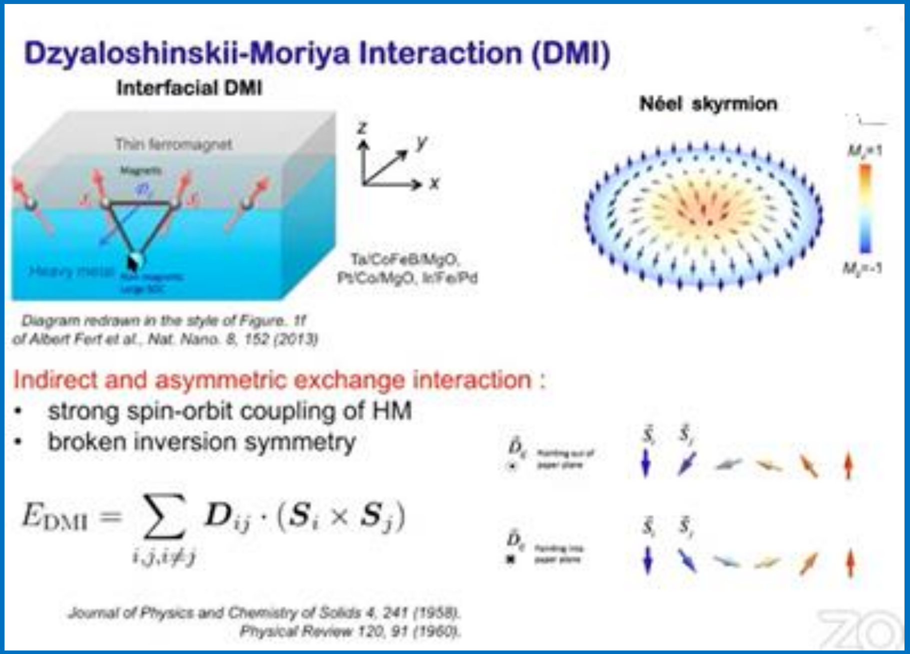
***Q* = +1**

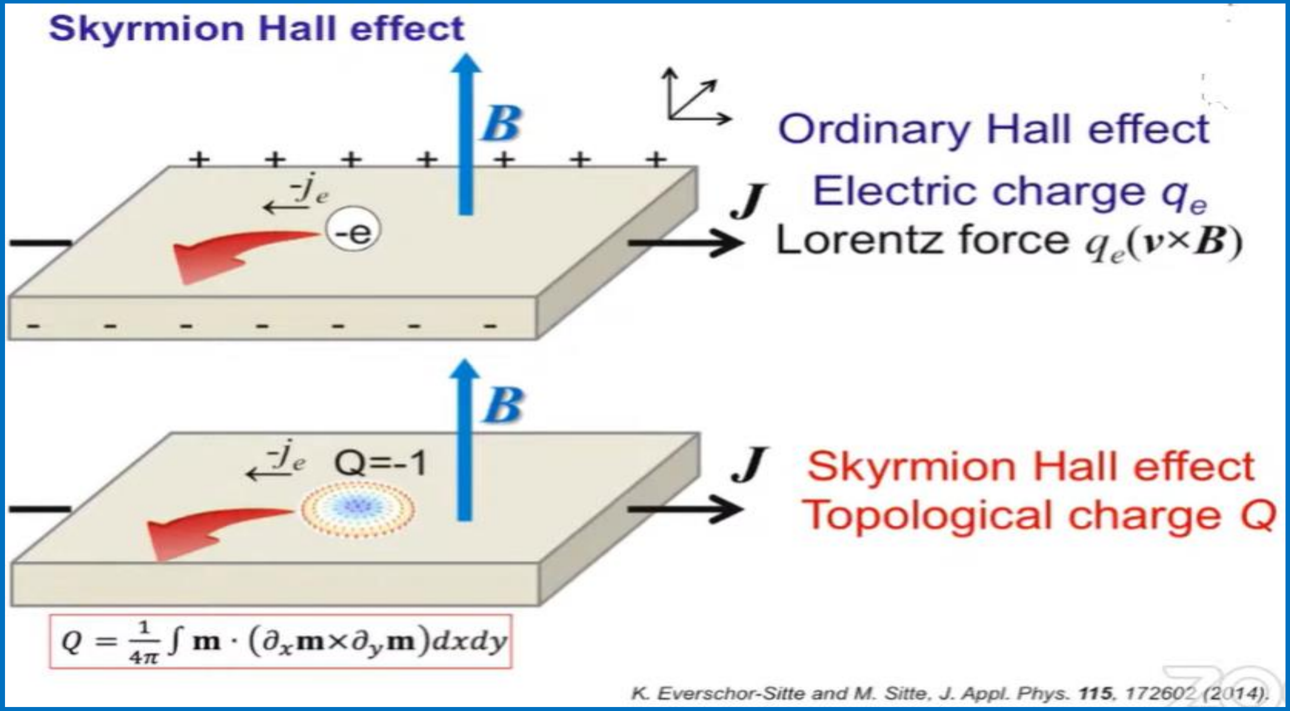
$$Q = \frac{1}{4\pi}\int \mathbf{m}\cdot\left(\partial_x\mathbf{m}\times\partial_y\mathbf{m}\right)dxdy$$

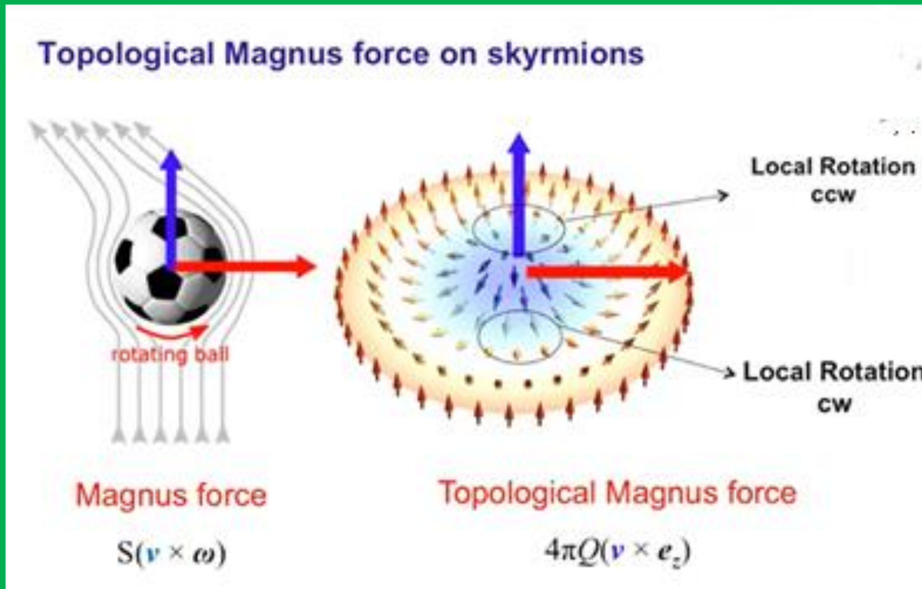


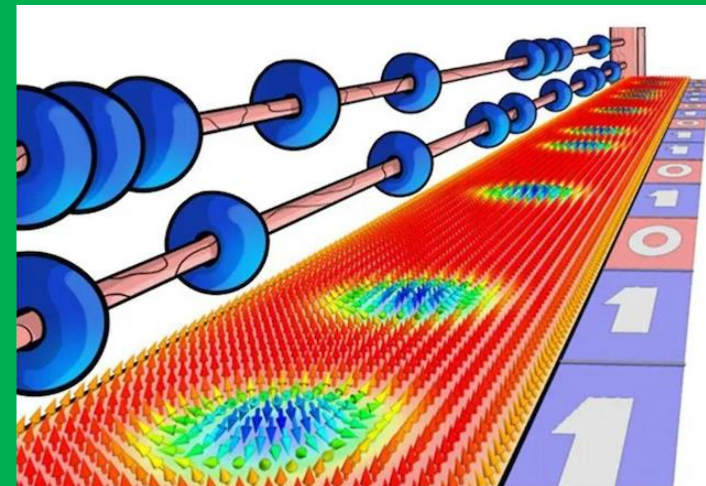
"for theoretical discoveries of topological phase transitions and topological phases of matter"


Nanomagnetism
E = E_Heisenberg exchange + E_dipolar + E_Zeeman + E_anisotropy + E_DMI
or
Flux Closure


Dzyaloshinskii-Moriya Interaction (DMI)
Interfacial DMI
Thin ferromagnet
Heavy metal
Ta/CoFeB/MgO,
Pt/Co/MgO, Ir/Fe/Pd
Néel skyrmion
Diagram redrawn in the style of Figure. 1f
of Albert Fert et al., Nat. Nano. 8, 152 (2013)
Indirect and asymmetric exchange interaction :
• strong spin-orbit coupling of HM
• broken inversion symmetry
$E_{\mathrm{DMI}} = \sum_{i,j,i\neq j} \boldsymbol{D}_{ij} \cdot (\boldsymbol{S}_i \times \boldsymbol{S}_j)$
Journal of Physics and Chemistry of Solids 4, 241 (1958).
Physical Review 120, 91 (1960).


Skyrmion Hall effect
B
-e
J
Ordinary Hall effect
Electric charge q_e
Lorentz force $q_e(\boldsymbol{v}\times\boldsymbol{B})$
Q=-1
Skyrmion Hall effect
Topological charge Q
$Q = \frac{1}{4\pi}\int \mathbf{m}\cdot(\partial_x\mathbf{m}\times\partial_y\mathbf{m})dxdy$
K. Everschor-Sitte and M. Sitte, J. Appl. Phys. 115, 172602 (2014).





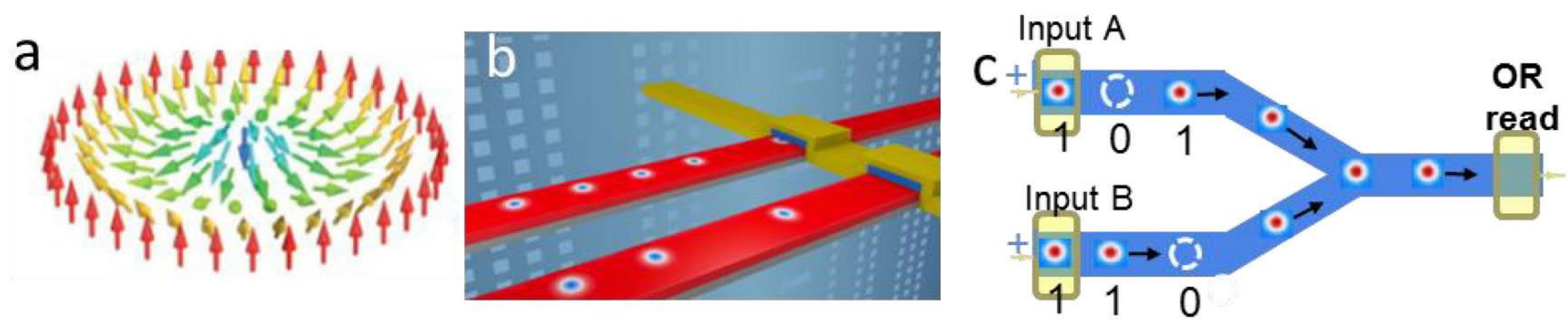
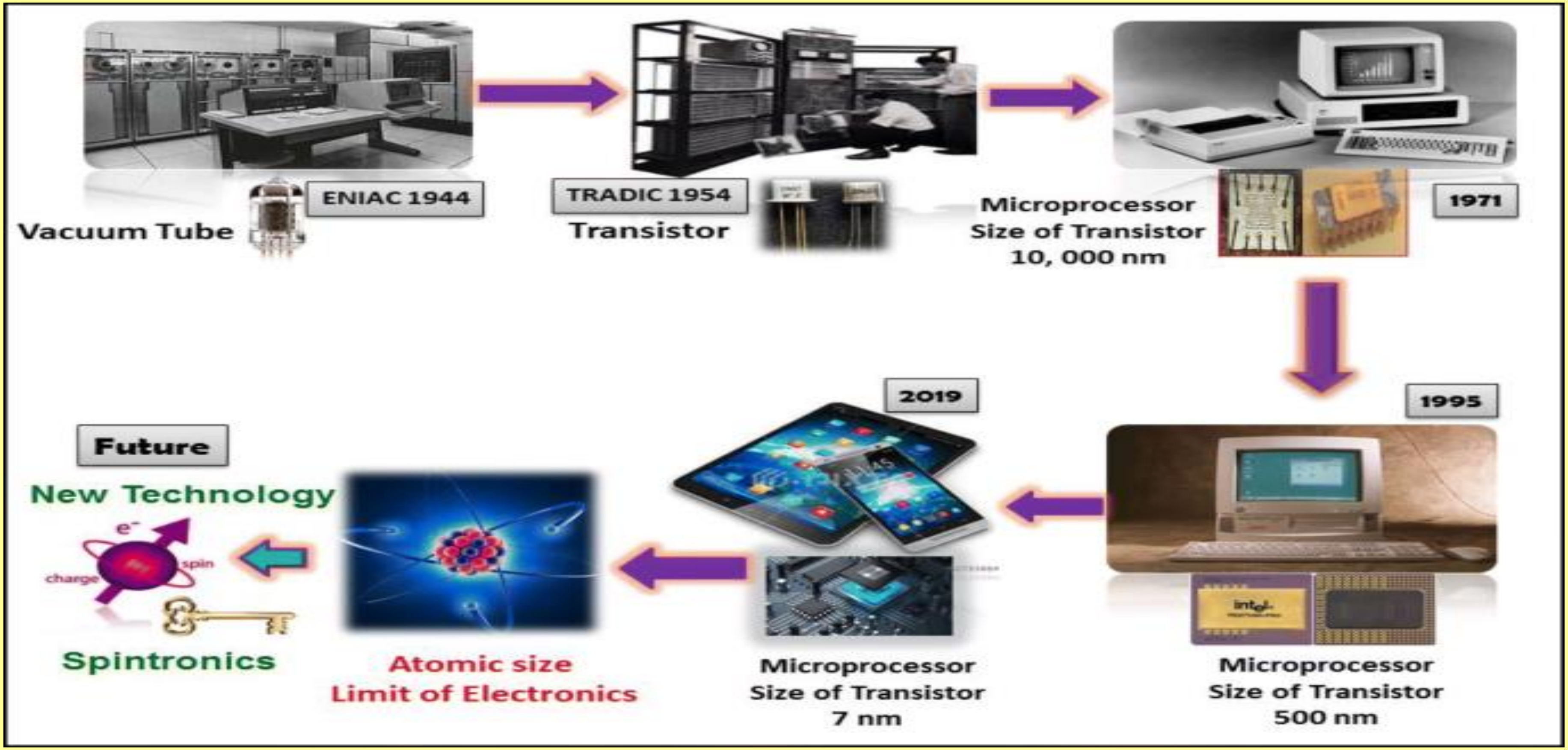
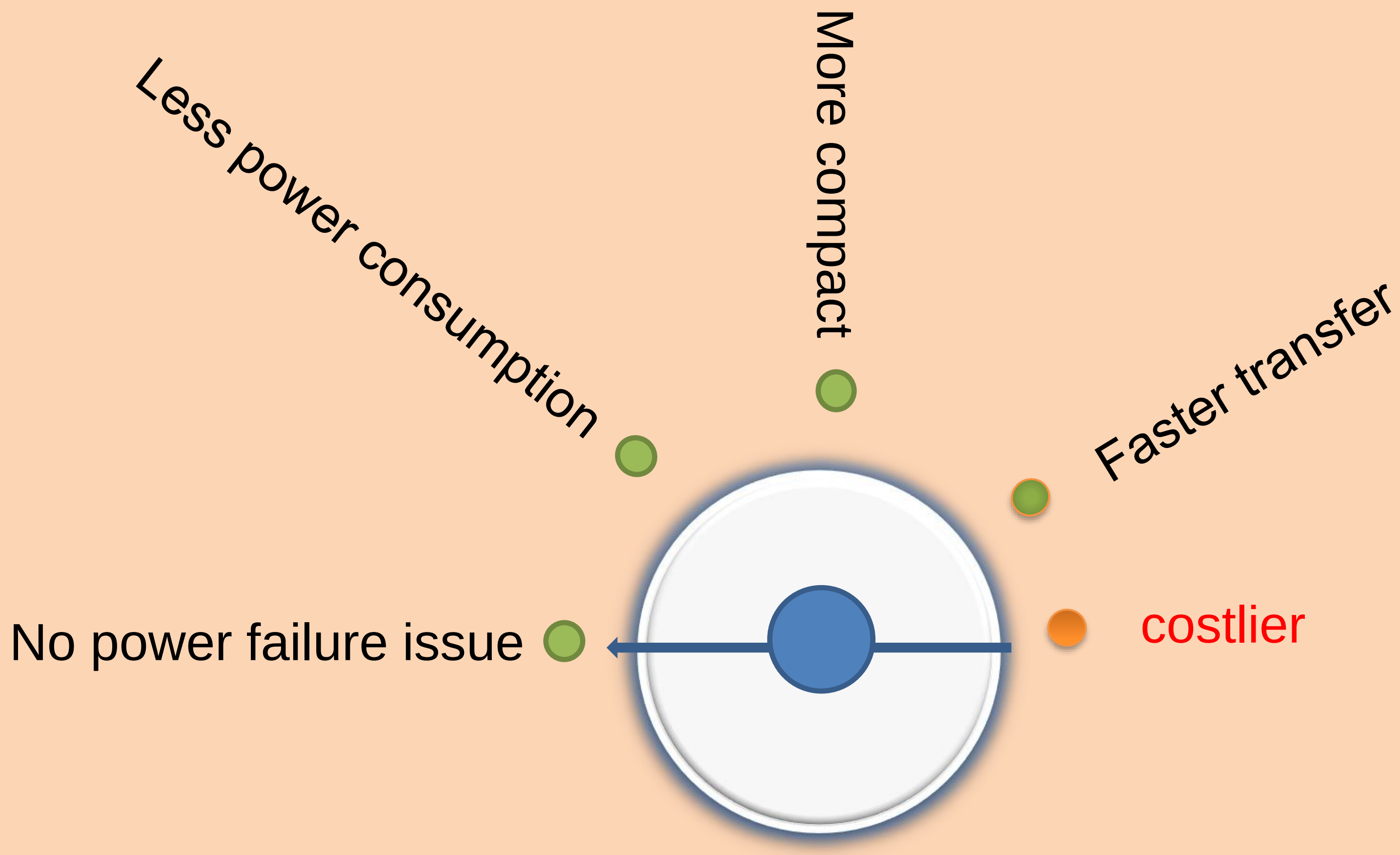


Figure 1 a. Schematic representation of a magnetic skyrmions [1]. b Magnetic shift register based on magnetic skyrmions, c. Logic gate based on the manipulation of magnetic skyrmions.

No doubt that Spintronics brings new challenges to the researchers across the globe. This is a new paradigm of electronic and magnetic devices built on the charge and spin of the electrons. Modern engineering and technological advances give us hope that this would be a very optimistic technology in the upcoming days.



Comparison between electronics and spintronics



Thank you for your attention!

I hope you find this lecture useful.