New trends in spintronics

Pavel Baláž

Charles University, Department of Condensed Matter Physics, **Group of Theoretical Physics**

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What is spintronics ?

Spintronics: electronics with spins

- electron has spin: internal momentum
- in magnetic field and inside magnetic materials electron's spin can have just two possible values:
  up $\uparrow$ or down $\downarrow$

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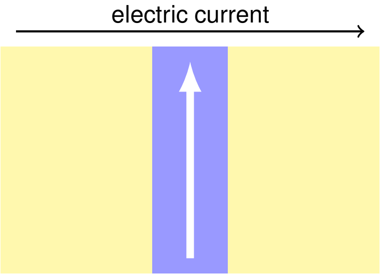

$N_\uparrow = N_\downarrow$

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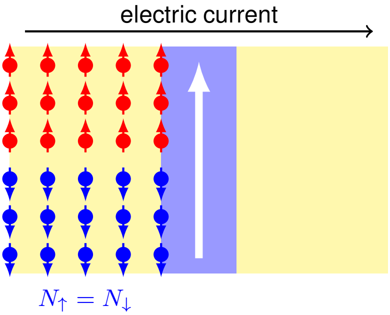

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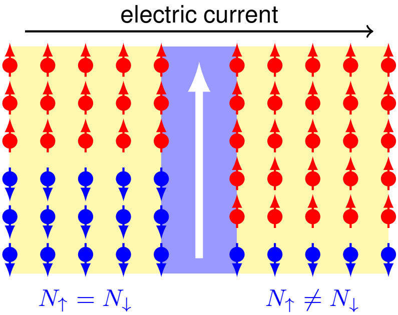

Breakthrough in magnetic memories: Giant Magnetoresistance

Peter Grünberg and Albert Fert
Nobel Prize in Physics, 2007

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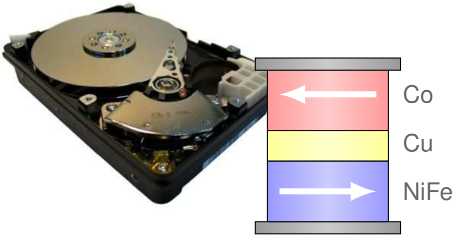

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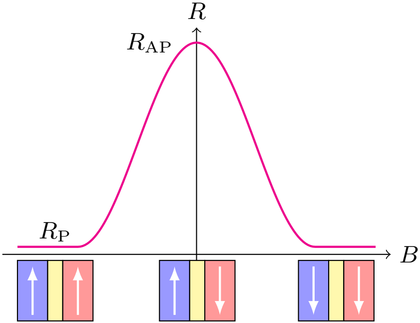

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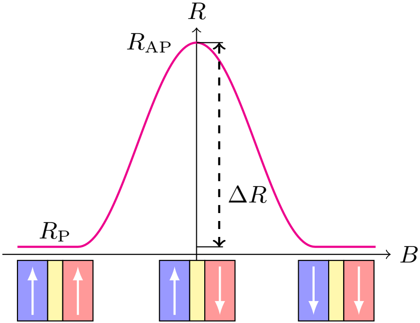

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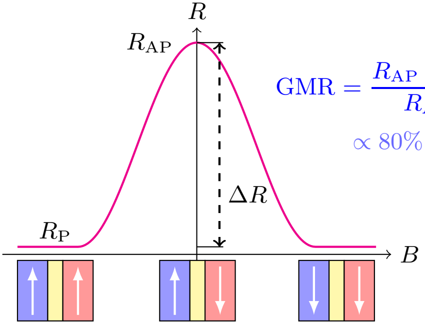


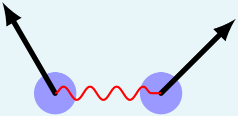
$$\mathrm{GMR} = \frac{R_{\mathrm{AP}} - R_{\mathrm{P}}}{R_{\mathrm{AP}}}$$

$\propto 80\%$

Spin current interacts with magnetic moments

Exchange interaction

$$E_{\text{exch}} = J\, \boldsymbol{S}_1 \cdot \boldsymbol{S}_2$$



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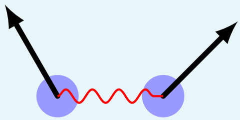
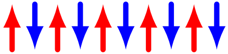


- short range interaction
- acts between atomic spins

$J > 0$

$J < 0$



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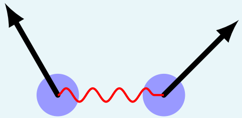

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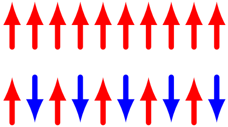
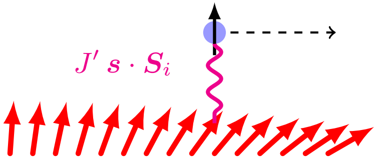


- exchange interaction acts also between conduction and localized spins



- spin current transfers angular momentum between localized atomic spins
- result: magnetization will move
- spin transfer torque

How can we use this ?

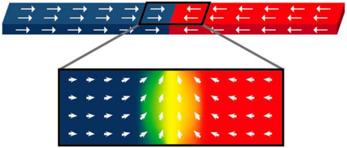
Magnetic domain walls in nanowires

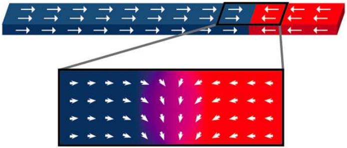
Topological defect

boundary between
two distinct phases

- TD is a discontinuity that cannot be removed
- TD is topologically protected
- TDs can be used for storing information and computation

Magnetic domain walls in nanowires





Source: Physics 1, 17 (2008)

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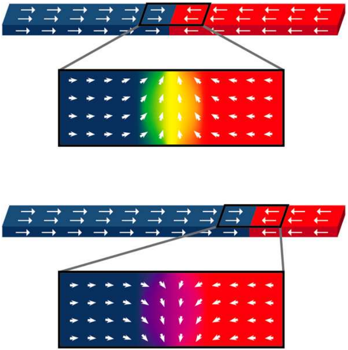

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Topological defect

boundary between two distinct phases

- TD is a discontinuity that cannot be removed
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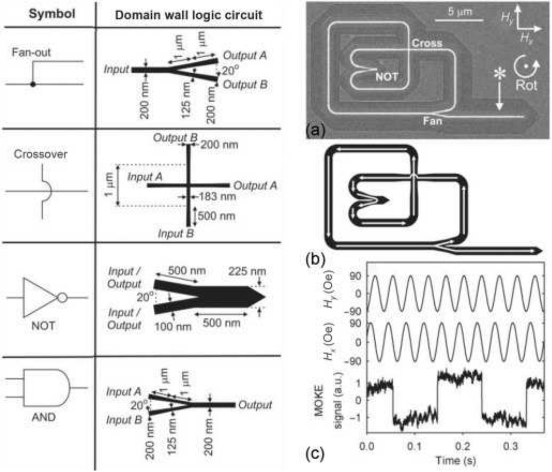
- TDs can be used for storing information and computation

- domain wall contains noncollinear magnetizations
- Spin transfer torque is possible

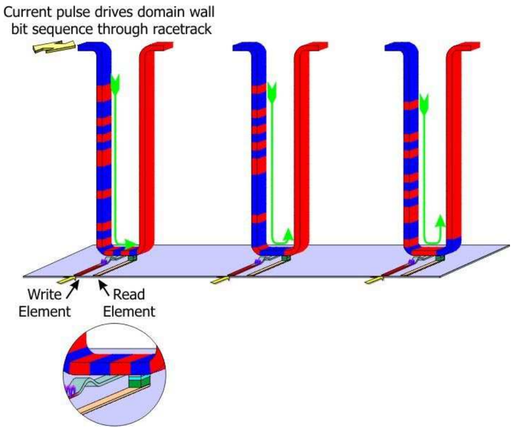
Domain wall logic



Source: Handbook of Surface Science **5**, 335-370 (2015)

Domain wall racetrack memory

3D magnetic memory



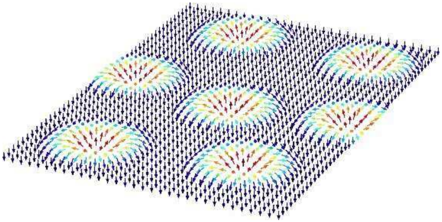
Source: Physics World

Skyrmions

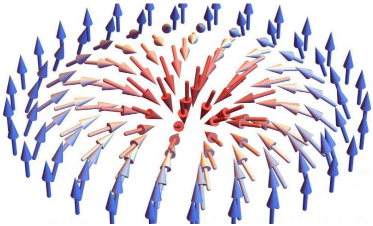
Dzialoshinkii–Moriya interaction

$$E_{\mathrm{DMI}} = \boldsymbol{D} \cdot (\boldsymbol{S}_1 \times \boldsymbol{S}_2)$$

Skyrmion lattice

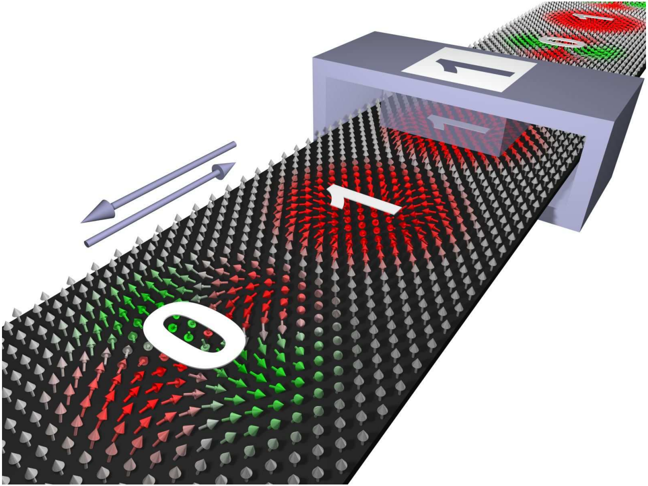


Source: nanowerk.com



Source: Phys.org

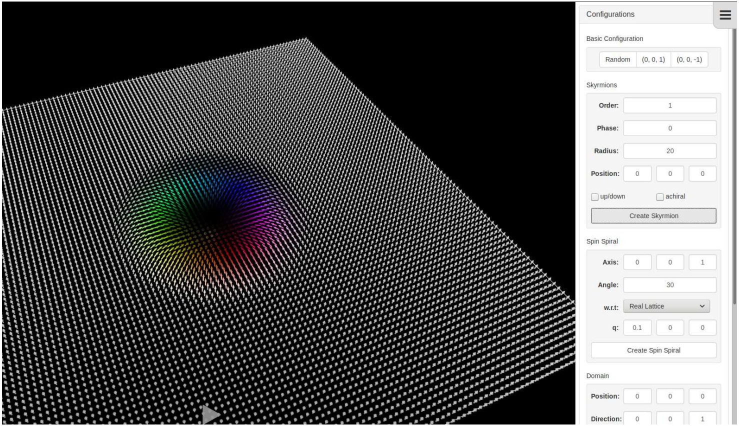
Skyrmionic racetrack memory



Source: Forschungszentrum Jülich

Online web simulator: atomistic spin dynamics

spirit-code.github.io/web.html



Antiferromagnetic spintronics

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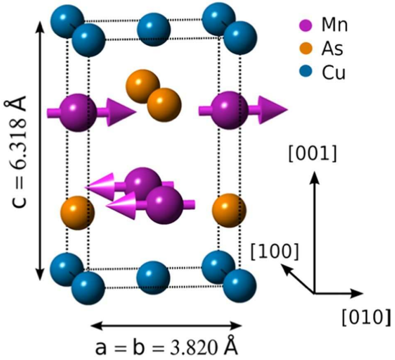
Antiferromagnetic spintronics

Antiferromagnets **do not seem to have any applications** *despite of being extremely interesting from a theoretical viewpoint* (Louis Néel, 1970)

- AFMs have internal magnetic ordering but zero total magnetization
- they have very strong internal exchange interactions
- they are robust against external magnetic fields
- standard spin transfer torque does not work

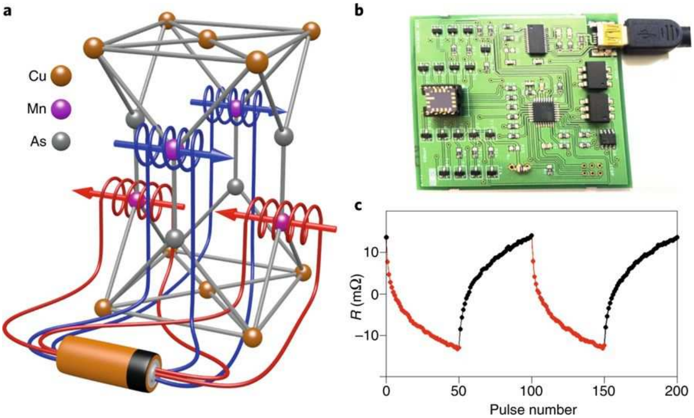
CuMnAs



Source: Scientific Reports **5**, 17079 (2015)

Antiferromagnetic spintronics

staggered spin-orbit fields



Source: Nature Physics **14**, 200–203 (2018)

Neuromorphic computing

Source: freepik.com

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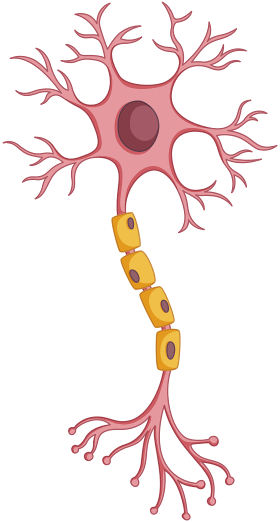


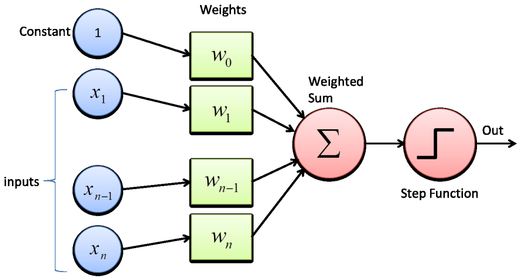
Neuromorphic computing

- high density
- low power
- massively parallel

Source: freepik.com

Artificial neural network

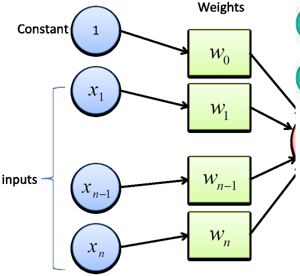
Perceptron (formal neuron)

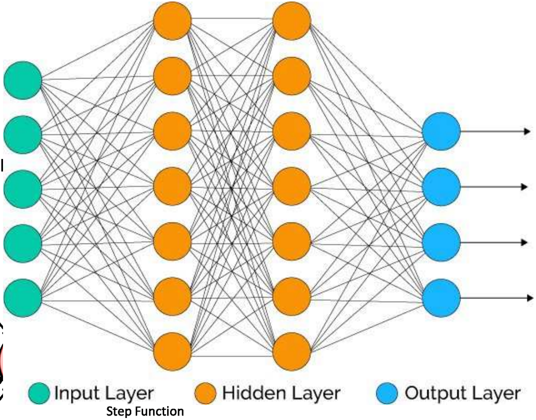


Source: towardsdatascience.com, medium.com

Artificial neural network

Perceptron (fo





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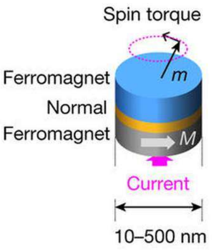
Spin torque oscillator



Source: Nature.com

- J. Torrejon *et al.*, Nature **547**, 428–431 (2017)
- M. Romera *et al.*, Nature **563**, 230–234 (2018)

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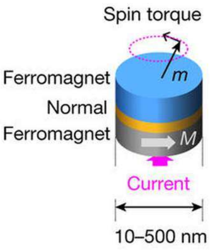

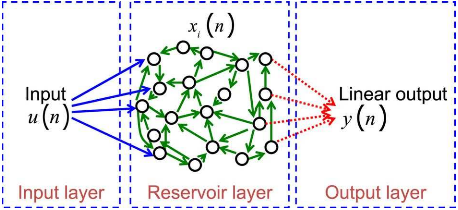

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Multiscale approach in our research group

Material research

doc. I. **Turek**, Dr. K. **Carva**,
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- density functional theory
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- Monte Carlo simulations
- Magnetization dynamics
- Topological defects
- Machine learning

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Micromagnetic simulations

Dr. P. **Baláž**

- modelling of real devices
- spin torque oscillators
- spin-toque magnetization dynamics
- laser-induced magnetization dynamics

Thank you for your attention!

Pavel Baláž

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