Let’s racap

problem

- **Internet**
- **Internet of Things**
- **Big data**

- **No Moore**
  Speed
  Energy
  CMOS scaling

1. Recording & computers

2. Conventional & neuromorphic computing

3. Non-CMOS devices and materials

5. Physical principles of operation of magnetic devices

do differently

- **von Neumann**
  Revisit the architecture to tackle the bottleneck

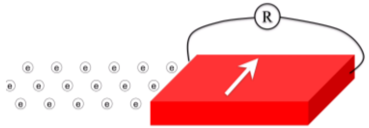
- **Analog to digital**
  Revisit the noise vs. complexity trade-off

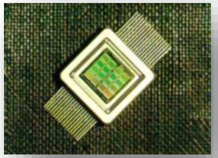
do more

- **Spintronic**
- **Phase-change**
- **....**
  Exploit full potential of non-CMOS devices

- **Optical**
  Explore speed and energy efficiency limits

Anisotropic magnetoresistance





Review: Daughton, Thin Sol. Films '92

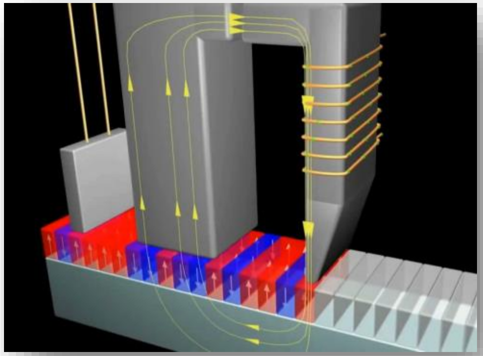
100 kb AMR-MRAM

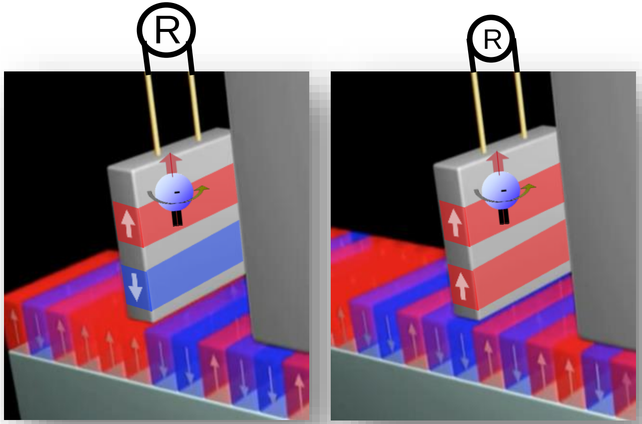
Magnetic RAM

Everspin
MRAM
10ns & 1Gb

Bipolar switching

1988 **Giant magnetoresistance readout: dawn of spintronics**
1998 IBM HDD read-head
2007 Grünberg & Fert Nobel Prize





Review: Chappert, Fert, Van Dau, Nature Mater. 6, 813 (2007)

Tunneling magnetoresistance

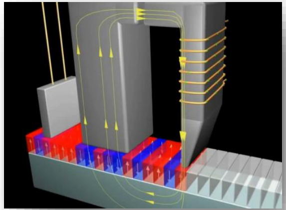
Moodera et al., PRL '95
Miyazaki & Tezuka JMMM '95

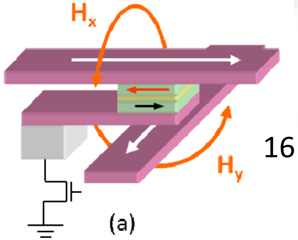
Magnetic RAM

Bipolar switching

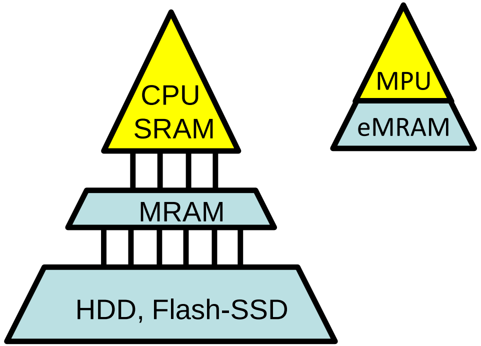
1998 **Spin transfer torque writing**
2018 Everspin STT-MRAM
2013 Slonczewski & Berger Buckley Prize

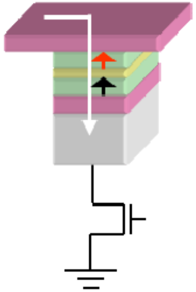
Everspin
MRAM
10ns & 1Gb

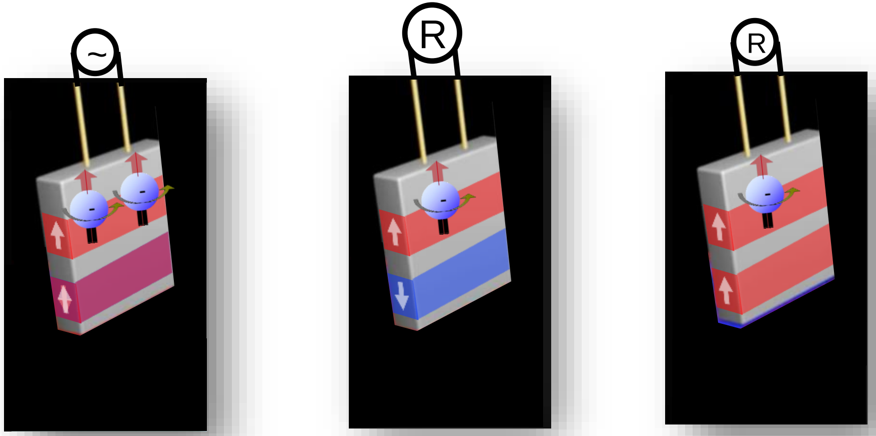




16 Mb TMR-MRAM







Review: Chappert, Fert, Van Dau, Nature Mater. 6, 813 (2007)

Tunneling magnetoresistance

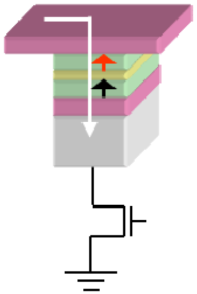
Moodera et al., PRL '95
Miyazaki & Tezuka JMMM '95

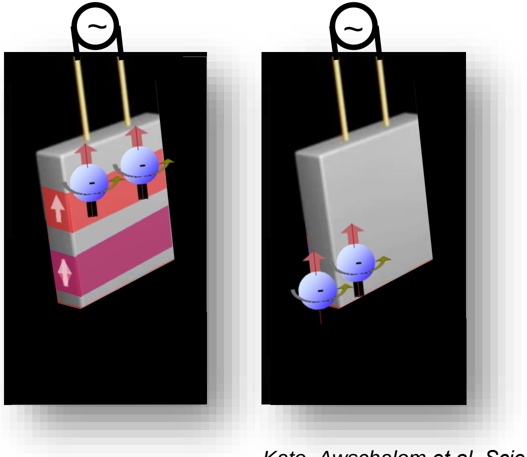
Magnetic RAM

Everspin
MRAM
10ns & 1Gb

Bipolar switching

2004 **Spin Hall effect**





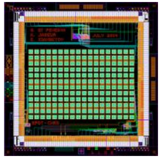
Kato, Awschalom et al. Science ‘04
Wunderlich, Kastner Sinova, TJ arXiv ’04, PRL ‘05
Review: Sinova, TJ et al. RMP ’15

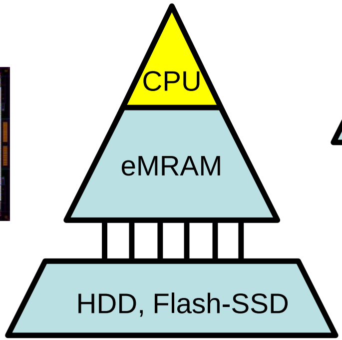
Magnetic RAM

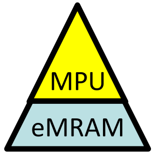
Everspin
MRAM
10ns & 1Gb

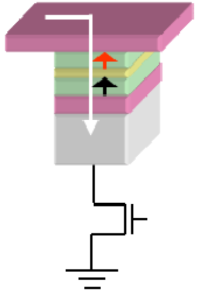
Bipolar switching

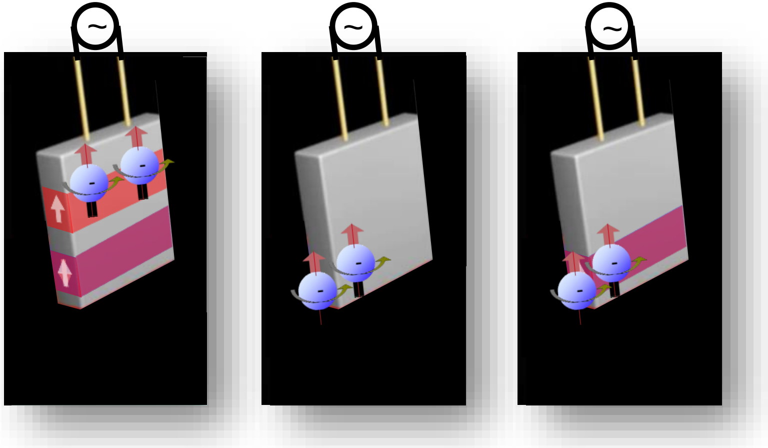
2004 **Spin Hall effect**
2011 **Spin orbit torque**
2016 Experimental chip (SPINTEC)



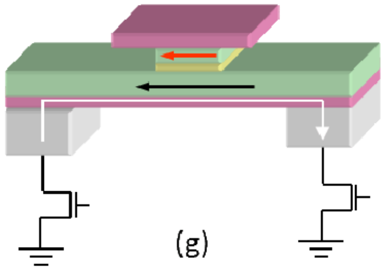








Kato, Awschalom et al. Science '04
Wunderlich, Kastner Sinova, TJ arXiv '04, PRL '05
Review: Sinova, TJ et al. RMP '15



Miron et al. Nature '11, Liu et al. Science '12
Review: Manchon, TJ et al. RMP'19

Spin, Zeeman coupling, and spin-orbit coupling

Relativistic QM: Dirac equation

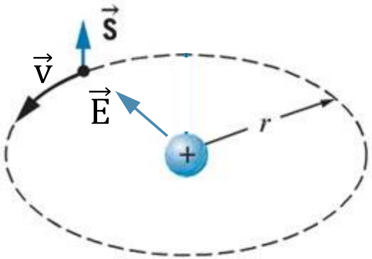
$$i\hbar\frac{\partial\phi(\mathbf{r},t)}{\partial t} = c\left(\frac{\hbar}{i}\boldsymbol{\nabla} - e\mathbf{A}\right)\cdot\boldsymbol{\sigma}\lambda(\mathbf{r},t) + \left(V(\mathbf{r}) + mc^2\right)\phi(\mathbf{r},t)$$

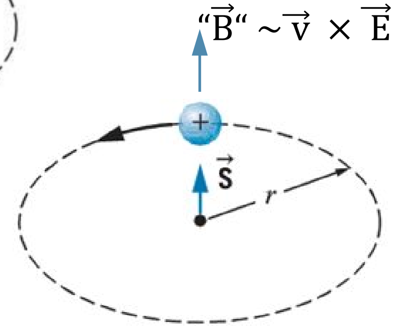
$$i\hbar\frac{\partial\lambda(\mathbf{r},t)}{\partial t} = c\left(\frac{\hbar}{i}\boldsymbol{\nabla} - e\mathbf{A}\right)\cdot\boldsymbol{\sigma}\phi(\mathbf{r},t) + \left(V(\mathbf{r}) - mc^2\right)\lambda(\mathbf{r},t)$$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\mathbf{B} = \boldsymbol{\nabla}\times\mathbf{A} \qquad \mathbf{S} = \frac{\hbar}{2}\boldsymbol{\sigma}$$

Classical E&M: Maxwell's equations





Spin-orbit = "Zeeman" felt in electron's frame of reference

Weak relativistic limit $\cdots \sim 1/c^2$

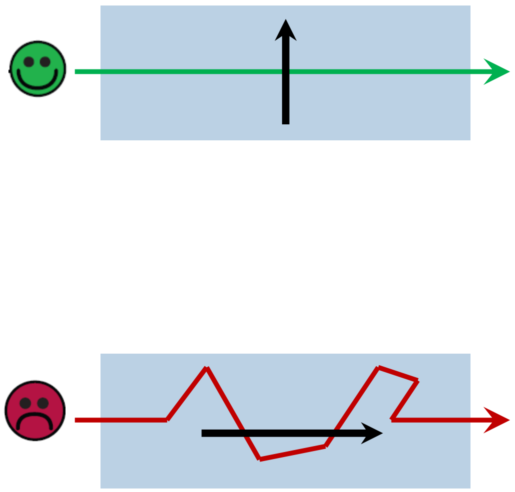
$$i\hbar\frac{\partial\phi\mathbf{r},t)}{\partial t} = \left(\underbrace{\frac{1}{2m}\left(\frac{\hbar}{i}\boldsymbol{\nabla} - e\mathbf{A}\right)^2 + V(\mathbf{r})}_{\text{Schrödinger}} + \underbrace{\frac{g_s\mu_B}{\hbar}\mathbf{S}\cdot\mathbf{B}}_{\text{Zeeman}} + \underbrace{\frac{e}{2mc^2}\mathbf{S}\cdot(\mathbf{v}\times\mathbf{E})}_{\text{Spin-orbit}}\right)\phi(\mathbf{r},t)$$

Magnetoresistive readout

~1% anisotropic magnetoresistance

Kelvin, 1857

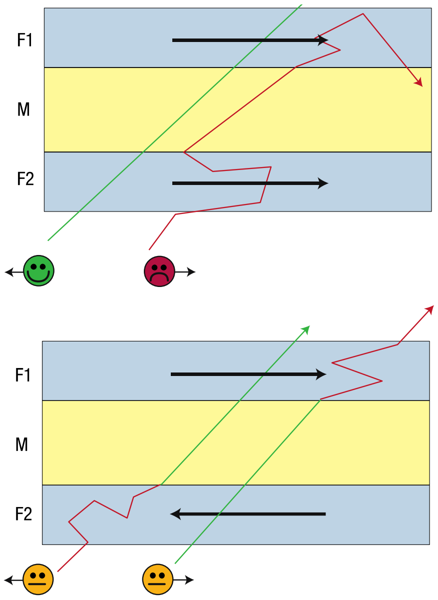
Relativistic:
spin-orbit scattering



~10% tunneling magnetoresistance

Grunberg, Fert 1988

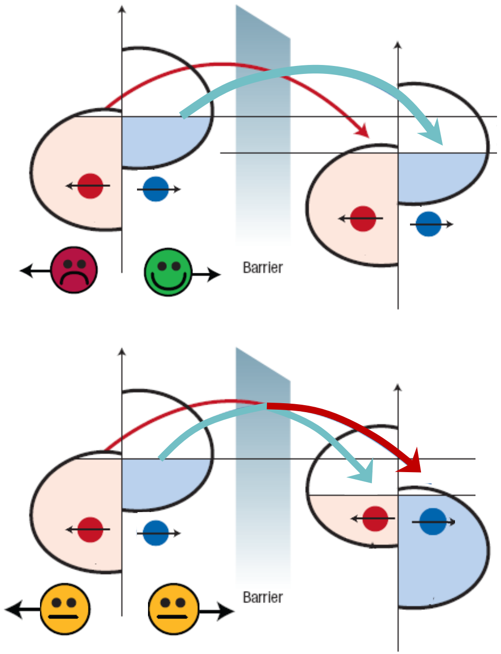
Non-relativistic:
Majority and miniroty spin scattering



~100% tunneling magnetoresistance

Moodera, Miyazaki, Tezuka 1995

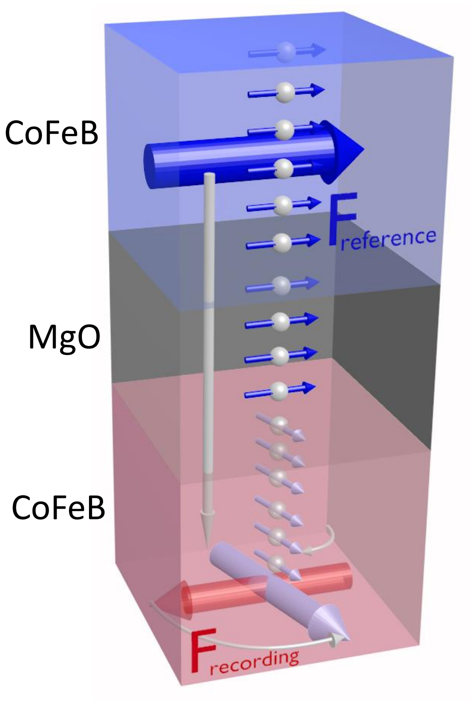
Non-relativistic:
Majority and minority density of states

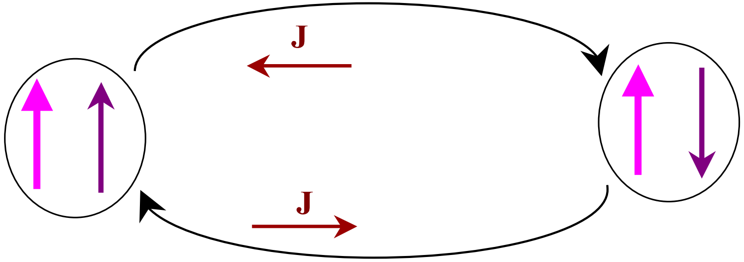


Review: Chappert, Fert, Van Dau, Nature Mater. 6, 813 (2007)

Writing by non-relativistic spin-transfer torque

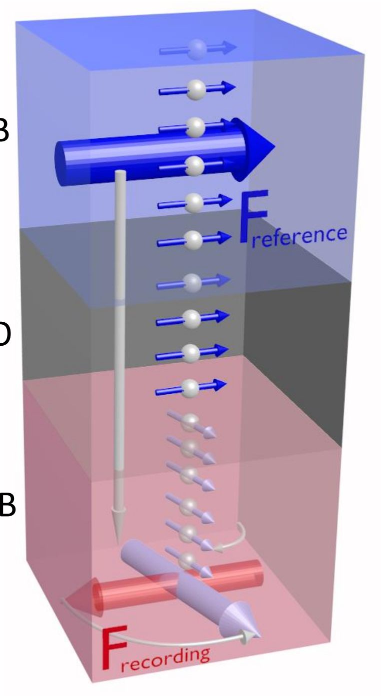
Transfer from carrier spin angular momentum to magnetization angular momentum





Slonczewski, JMMM '96, Berger, PRB '96
Review: Ralph & Stiles, JMMM '08

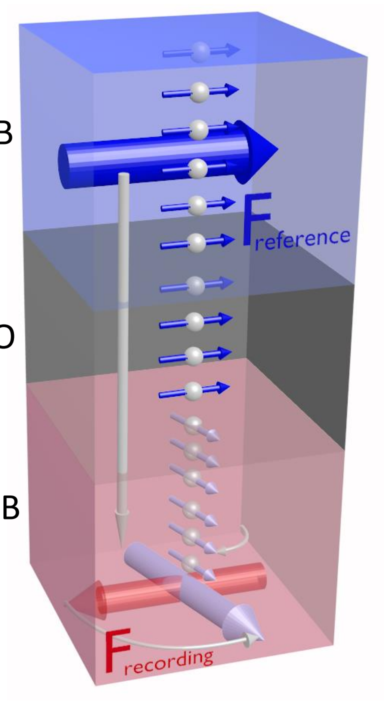
Writing by non-relativistic spin-transfer torque



- spin angular momentum transfer $\vec{p}_{curr} \sim J$
- spin precession $\frac{d\vec{s}}{dt} = \frac{d\langle\vec{\sigma}\rangle}{dt} = \frac{1}{i\hbar}\langle[\vec{\sigma}, H_{ex}]\rangle$ $\quad H_{ex} = J_{ex}\vec{M}\cdot\vec{\sigma}$ $\quad \tau_{ex} = \frac{\hbar}{J_{ex}M}$
- spin decay t_s

Slonczewski, JMMM '96, Berger, PRB '96
Review: Ralph & Stiles, JMMM '08

Writing by non-relativistic spin-transfer torque



- spin angular momentum transfer $\vec{p}_{curr} \sim J$

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- spin decay t_s

$$t_s << t_{ex} : \; 0 = \frac{d\vec{s}}{dt} = \vec{p}_{curr} - \frac{\vec{s}}{\tau_s}$$

$$t_s >> t_{ex} : \; 0 = \frac{d\vec{s}}{dt} = \vec{p}_{curr} + \frac{J_{ex}}{\hbar}\vec{s}\times\vec{M}$$

Field-like torque $\vec{T} = \frac{d\vec{M}}{dt} = \frac{J_{ex}}{\hbar}\vec{M}\times\vec{s}$ Antidamping-like torque

$$\vec{T} = \frac{\tau_s}{\tau_{ex}}\vec{M}\times\vec{p}_{curr}$$

$$J_{crit} \sim H_{aniso}$$

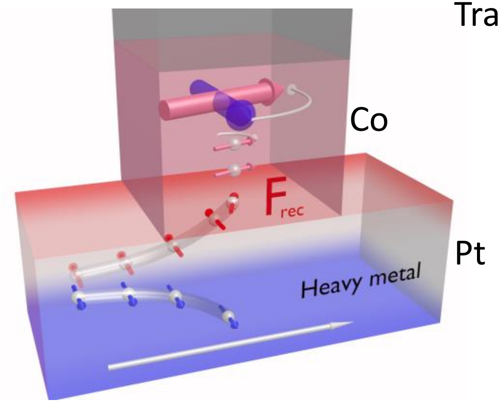
$$\vec{T} = \vec{M}\times[\vec{p}_{curr}\times\vec{M}]$$

$$J_{crit} \sim a_{Gilbert}H_{aniso}$$

Slonczewski, JMMM '96, Berger, PRB '96
Review: Ralph & Stiles, JMMM '08

Writing by relativistic spin-orbit torque

Transfer from carrier linear momentum to spin angular momentum

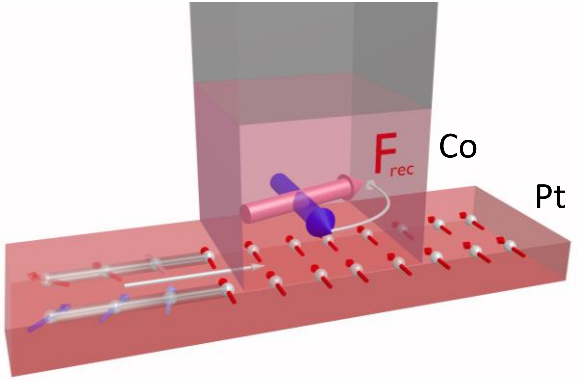


Spin Hall effect

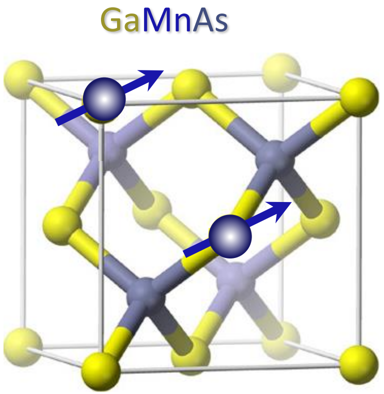
Kato, Awschalom et al. Science '04, Wunderlich, Kastner Sinova, TJ arXiv '04, PRL '05, Silov et al. APL '04, Ganichev et al. arXiv '04, Bernevig & Vafek, PRB '05, Manchon & Zhang, PRB '08, Chernyshev et al. Nature Phys.'09, Miron et al. Nature '11, Liu et al. Science '12

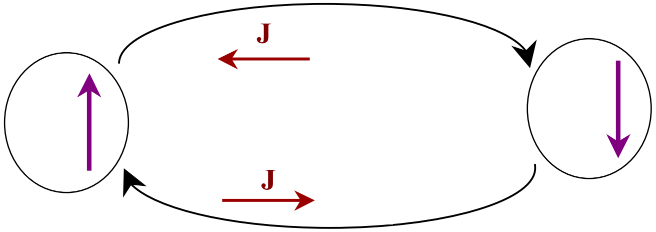
Reviews: TJ et al. RMP '14
Sinova, TJ et al. RMP '15
Manchon, TJ et al. RMP '19

Spin-orbit coupling & broken inversion symmetry



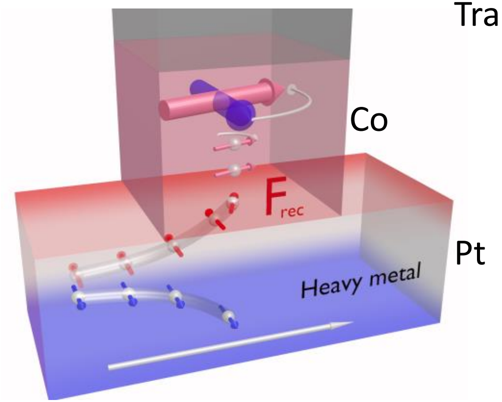
Inverse spin galvanic (Edelstein) effect





Writing by relativistic spin-orbit torque

Transfer from carrier linear momentum to spin angular momentum



Spin Hall effect

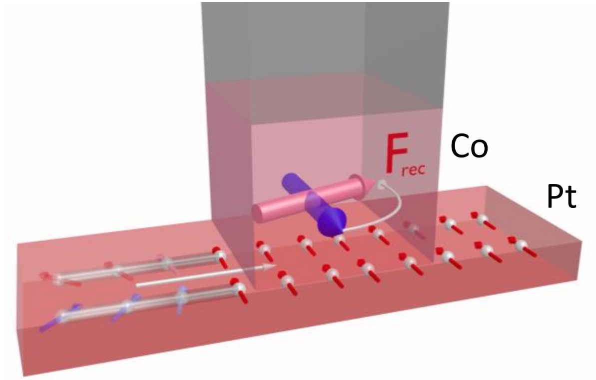
$$\frac{d\vec{s}}{dt} = \frac{d\langle\vec{\sigma}\rangle}{dt} = \frac{1}{ih}\langle[\vec{\sigma},(H_{ex} + H_{so}])\rangle$$

$$\frac{d\vec{s}}{dt} = 0 \Longrightarrow \frac{J_{ex}}{h}\vec{M} \times \vec{s} = \frac{1}{ih}\langle[\vec{\sigma}, H_{so}]\rangle$$

$$\vec{T} = \frac{d\vec{M}}{dt} = \frac{J_{ex}}{h}\vec{M} \times \vec{s} = \frac{1}{ih}\langle[\vec{\sigma}, H_{so}]\rangle$$

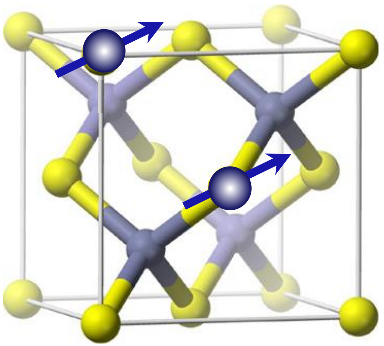
Reviews: TJ et al. RMP '14
Sinova, TJ et al. RMP '15
Manchon, TJ et al. RMP '19

$$H_{SO} = \underbrace{\frac{e}{2mc^2}\boldsymbol{S} \cdot (\mathbf{v} \times \mathbf{E})}_{\text{Spin-orbit coupling}}$$



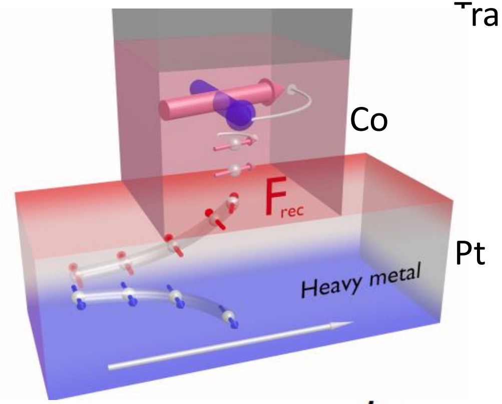
Inverse spin galvanic (Edelstein) effect

GaMnAs



Writing by relativistic spin-orbit torque

Transfer from carrier linear momentum to spin angular momentum



Spin Hall effect

Reviews: TJ et al. RMP '14
Sinova, TJ et al. RMP '15
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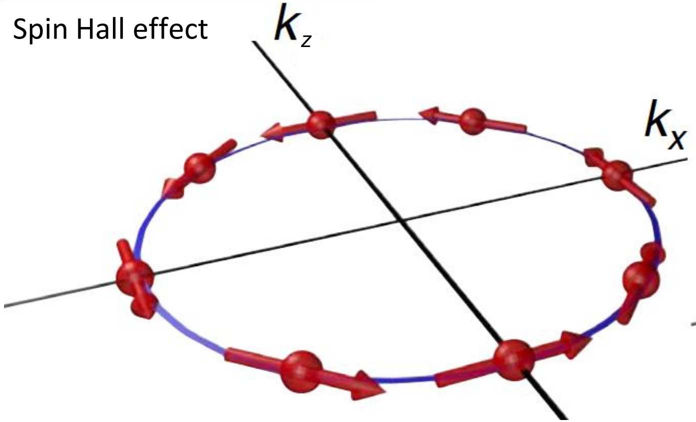
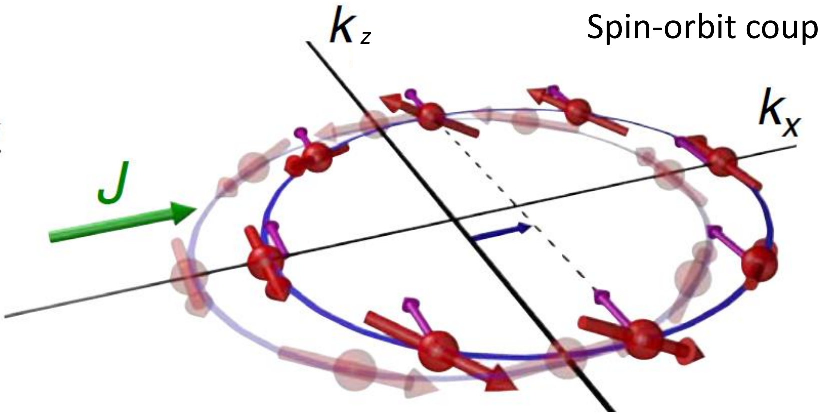
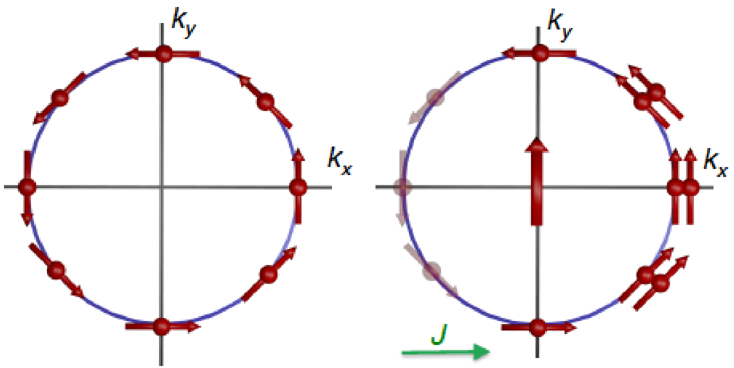




Writing by relativistic spin-orbit torque

Transfer from carrier linear momentum to spin angular momentum



Reviews: TJ et al. RMP ’14
Sinova, TJ et al. RMP ’15
Manchon, TJ et al. RMP ‘19

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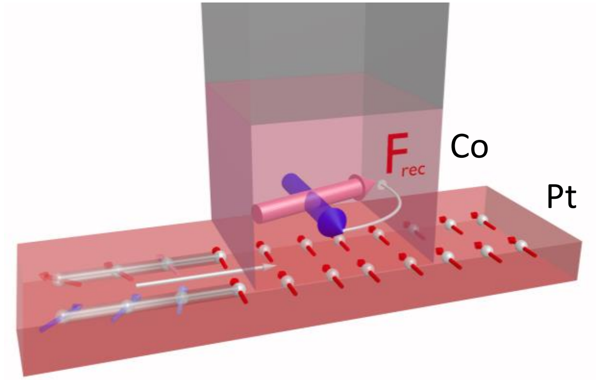

Inverse spin galvanic (Edelstein) effect

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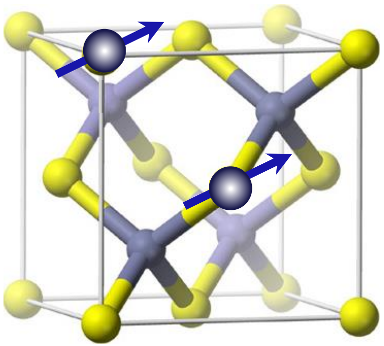
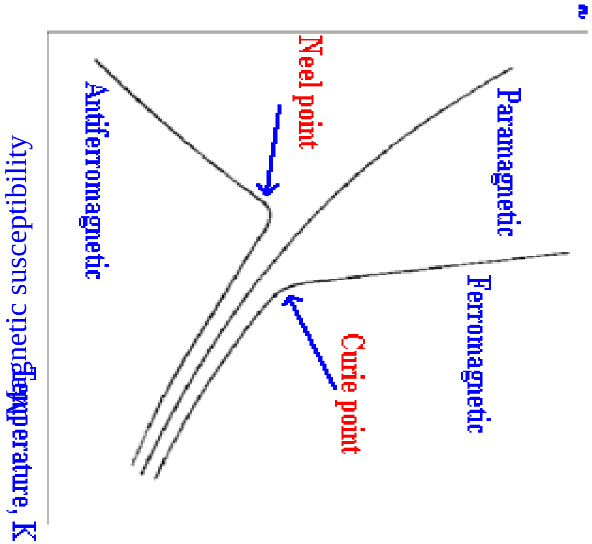
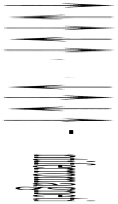


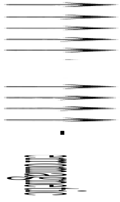
Antiferromagnets



Louis Néel 1930's

Tape recorder 1930's





Paramagnetic no spontaneous order of spins

Ferromagnetic exchange, global Weiss molecular field

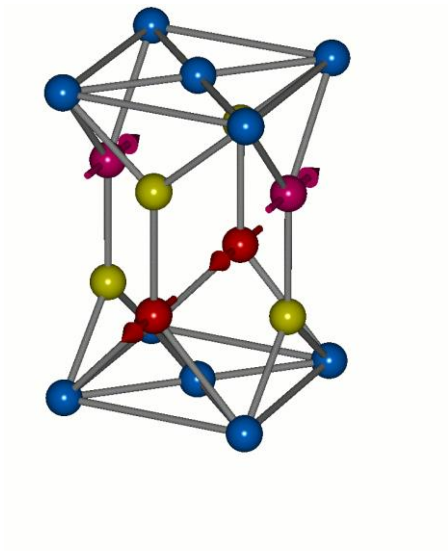
Antiferromagnetic exchange, local Néel molecular field

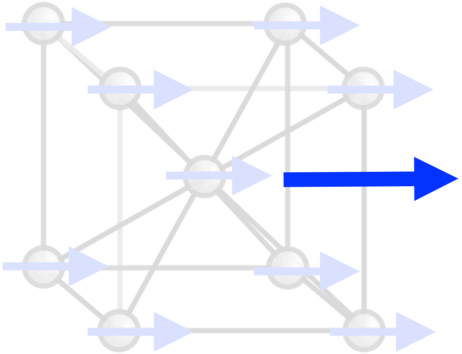
Antiferromagnets

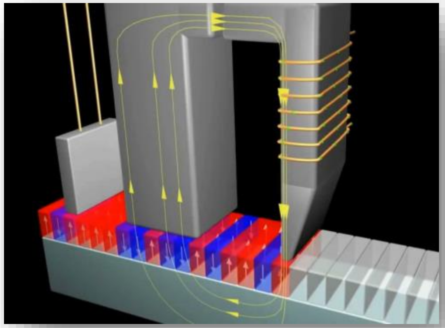
Louis Néel 1930‘s

AFs: Néel local molecular field, **M**=0

FMs: Weiss global molecular field, **M**





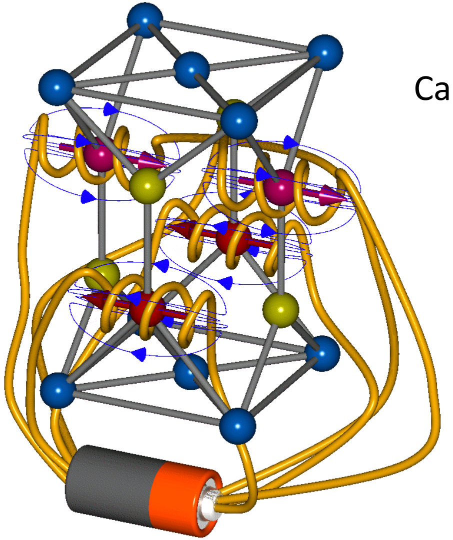


Antiferromagnets

AFs: Néel local molecular field, **M**=0

Néel's Nobel Lecture 1970

"Antiferromagnets are interesting and useless"

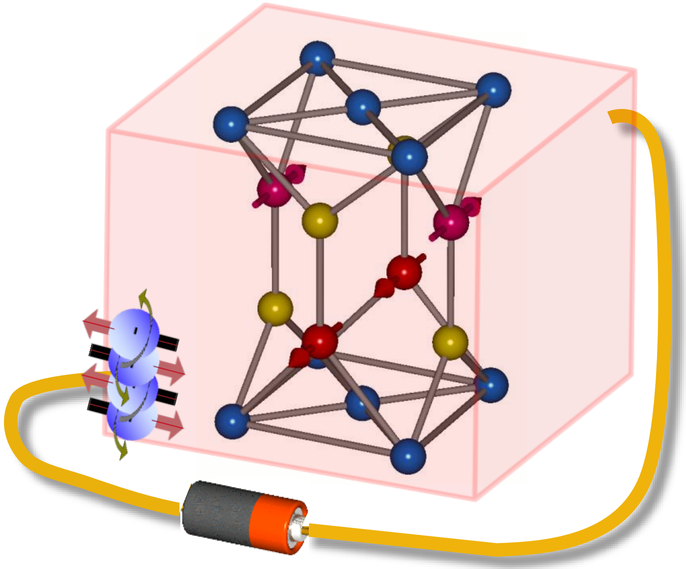


Can't write and read

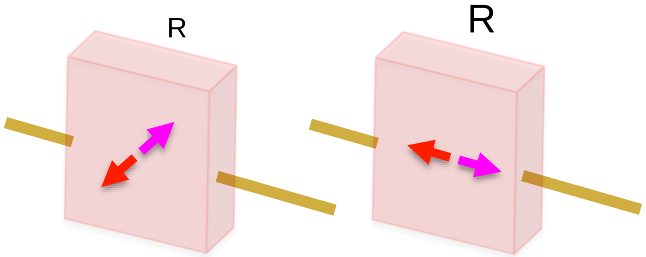
Writing in antiferromagnets by relativistic spin-orbit torque

Transfer from carrier linear momentum and spin angular momentum

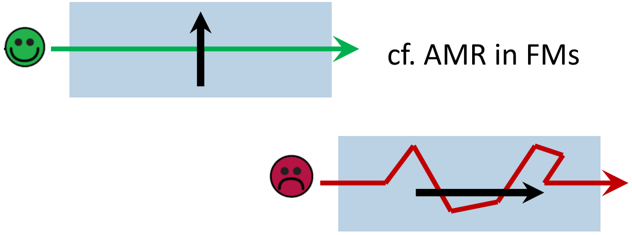
Spin-orbit coupling & local inversion asymmetry



Anisotropic magnetoresistance readout



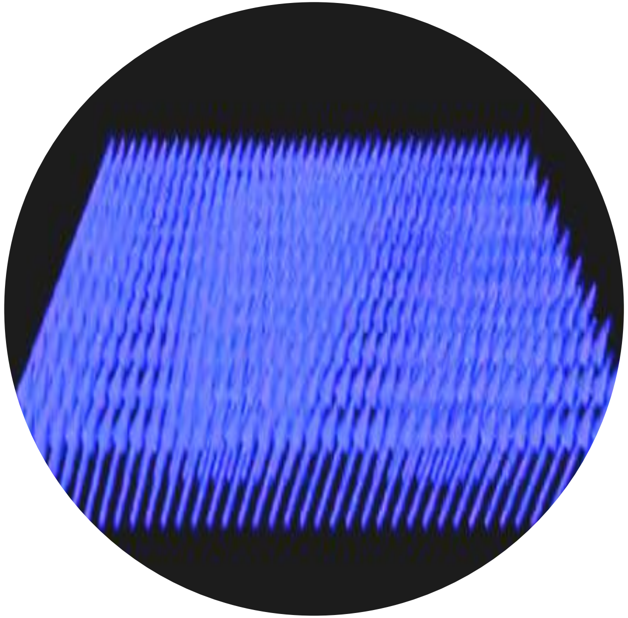
Wadley, TJ et al., Science '16
Review: TJ et al. Nature Nanotech '16



cf. AMR in FMs

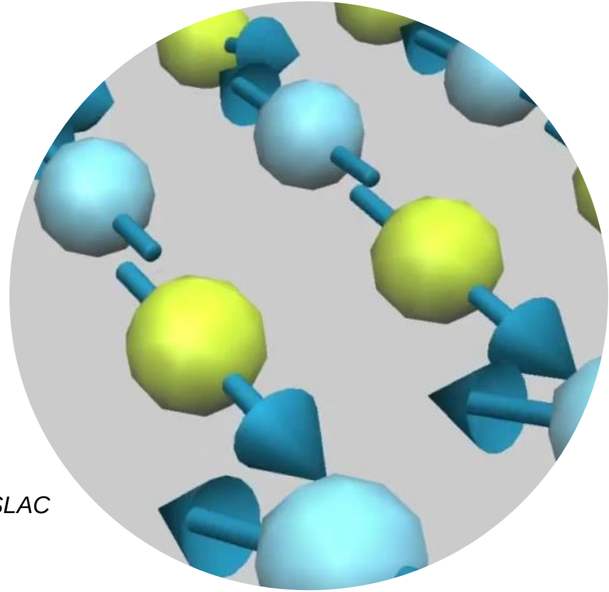
Kittel PR '51

Writing speed: magnetic resonance frequency threshold



Ferromagnetic resonance ~GHz

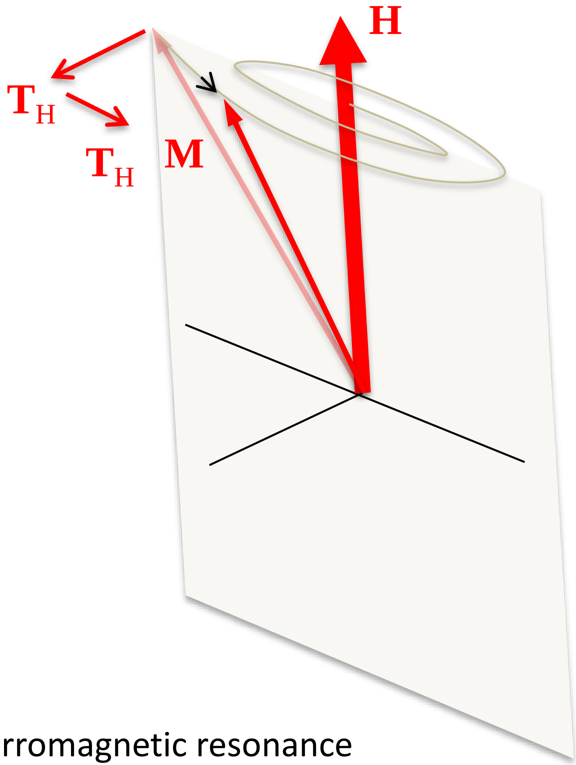
Youtube channel: SLAC



Antiferromagnetic resonance ~THz

Kittel PR '51

Writing speed: magnetic resonance frequency threshold

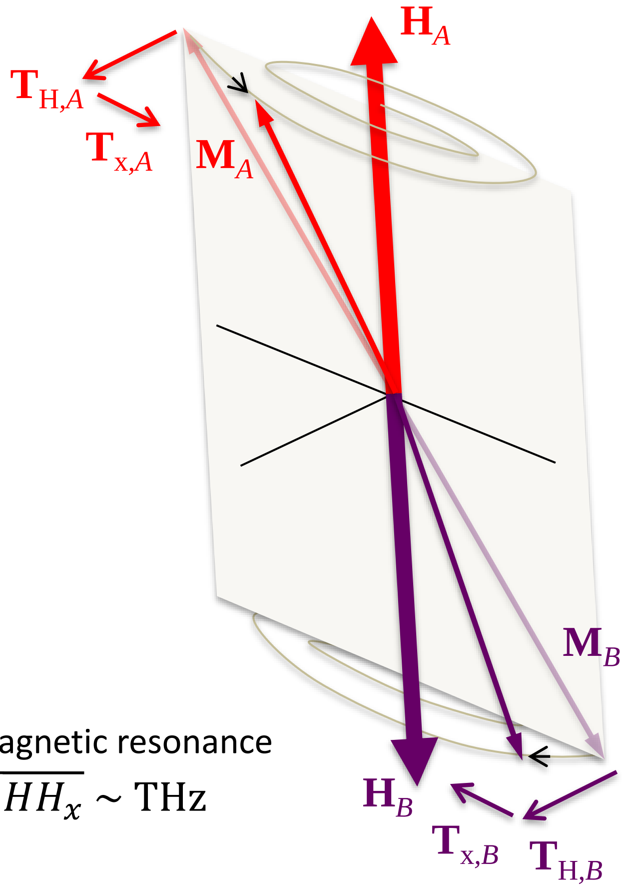


H: external + anisotropy field

$\mathbf{T}_{\mathrm{H}} = \mathbf{M} \times \mathbf{H}$

H$_{\mathrm{x}}$: exchange field

$\mathbf{T}_{\mathrm{x}} = \mathbf{M} \times \mathbf{H}_{\mathrm{x}}$



Ferromagnetic resonance

$f \sim H \sim \mathrm{GHz}$

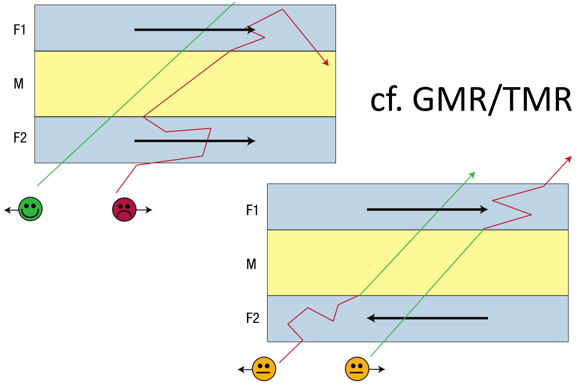
Antiferromagnetic resonance

$f \sim \sqrt{H H_x} \sim \mathrm{THz}$

Magnetoresistive readout in antiferromagnets

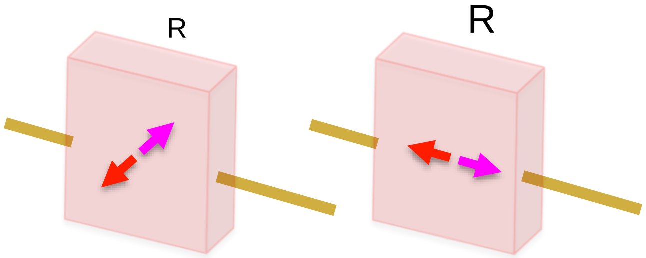
Giant/tunneling magnetoresistance

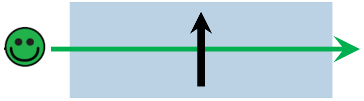
in antiferromagnet ??



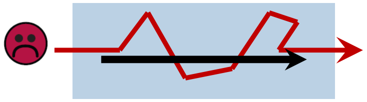
cf. GMR/TMR in FMs

Anisotropic magnetoresistance readout





cf. AMR in FMs



Magneto-transport

$$\vec{j} = \overleftrightarrow{\sigma}\,\vec{E}$$

Spatially averaged:

Invariant under translation $t\overleftrightarrow{\sigma} = \overleftrightarrow{\sigma}$

Linear response:

Invariant under inversion $P\overleftrightarrow{\sigma} = \overleftrightarrow{\sigma}$

Onsager relations:

$\sigma_{ij}(\vec{s}) = \sigma_{ji}(-\vec{s})$

$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} = \underbrace{\begin{bmatrix} \sigma^{\mathrm{s}}_{xx} & \sigma^{\mathrm{s}}_{xy} & \sigma^{\mathrm{s}}_{xz} \\ \sigma^{\mathrm{s}}_{xy} & \sigma^{\mathrm{s}}_{yy} & \sigma^{\mathrm{s}}_{yz} \\ \sigma^{\mathrm{s}}_{xz} & \sigma^{\mathrm{s}}_{yz} & \sigma^{\mathrm{s}}_{zz} \end{bmatrix}} + \underbrace{\begin{bmatrix} 0 & \sigma^{\mathrm{a}}_{xy} & \sigma^{\mathrm{a}}_{xz} \\ -\sigma^{\mathrm{a}}_{xy} & 0 & \sigma^{\mathrm{a}}_{yz} \\ -\sigma^{\mathrm{a}}_{xz} & -\sigma^{\mathrm{a}}_{yz} & 0 \end{bmatrix}}$$

Anisotropic magnetoresistance

Invariant under time (spin)-reversal $T\overleftrightarrow{\sigma^{s}}(\vec{s}) = \overleftrightarrow{\sigma^{s}}(-\vec{s}) = \overleftrightarrow{\sigma^{s}}(\vec{s})$

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

Hall (pseudo)-vector $\vec{h} = (\sigma^{\mathrm{a}}_{zy}, \sigma^{\mathrm{a}}_{xz}, \sigma^{\mathrm{a}}_{yx})$

Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Magneto-transport – spontaneous Hall effect

$$\vec{j} = \overleftrightarrow{\sigma}\,\vec{E}$$

Spatially averaged:

Invariant under translation $t\overleftrightarrow{\sigma} = \overleftrightarrow{\sigma}$

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Anisotropic magnetoresistance

Spontaneous Hall effect

Invariant under time (spin)-reversal $T\overleftrightarrow{\sigma^{\mathrm{s}}}(\vec{s}) = \overleftrightarrow{\sigma^{\mathrm{s}}}(-\vec{s}) = \overleftrightarrow{\sigma^{\mathrm{s}}}(\vec{s})$

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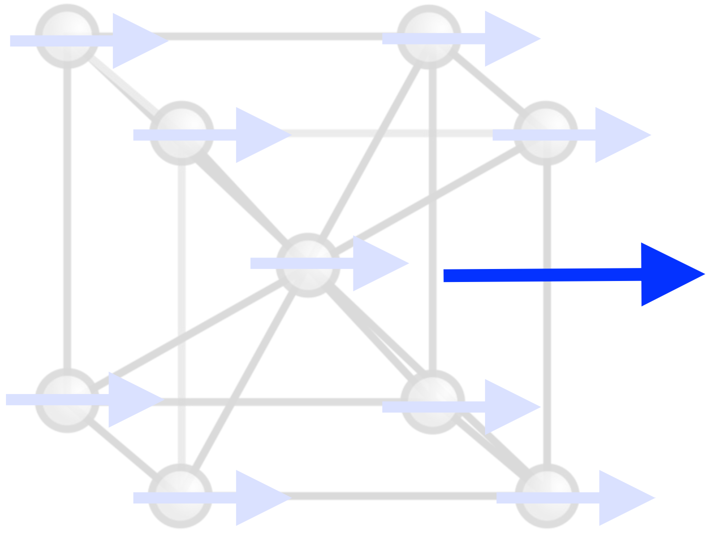
Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Magneto-transport – spontaneous Hall effect

Neumann's principle (1885): A physical property cannot have lower symmetry than the crystal



Net ferromagnetic (pseudo)-vector

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

Hall (pseudo)-vector $\vec{h} = (\sigma_{zy}^{\mathrm{a}}, \sigma_{xz}^{\mathrm{a}}, \sigma_{yx}^{\mathrm{a}})$

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Suzuki et al. Phys. Rev. B 95, 094406 (2017)

Magneto-transport – spontaneous Hall effect

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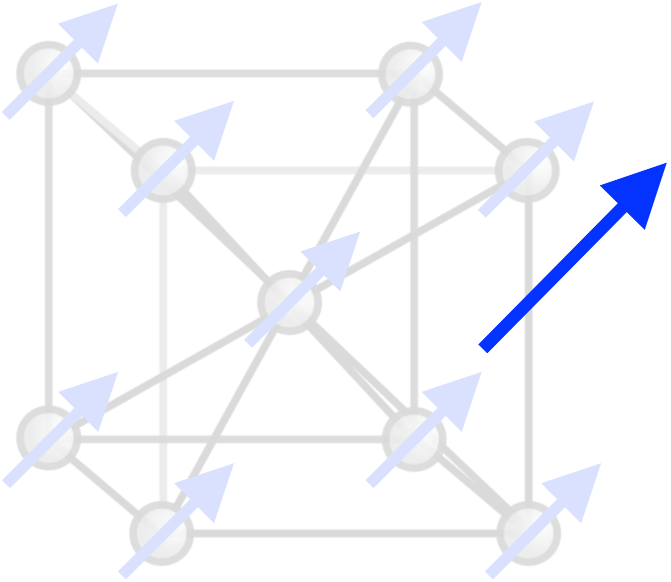
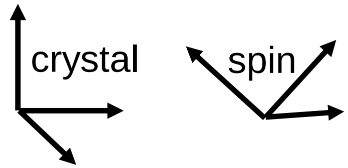


No spin-orbit coupling:

$\vec{h}$ invariant under pure spin rotation R_{φ}^{s}



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Spontaneous Hall effect

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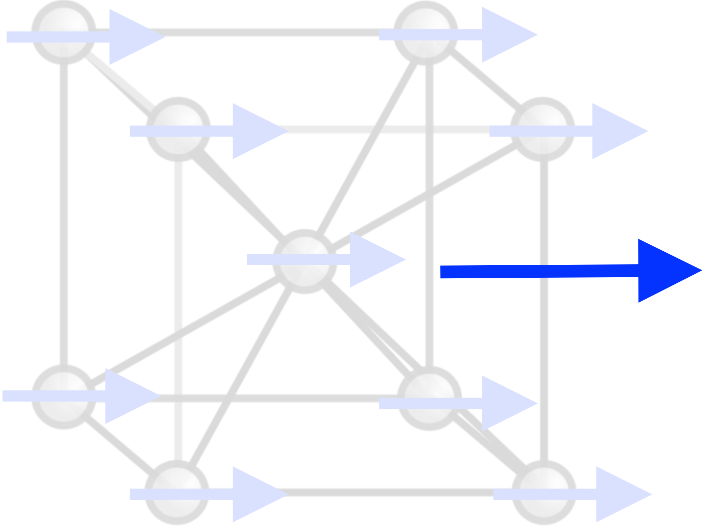

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Spontaneous Hall effect

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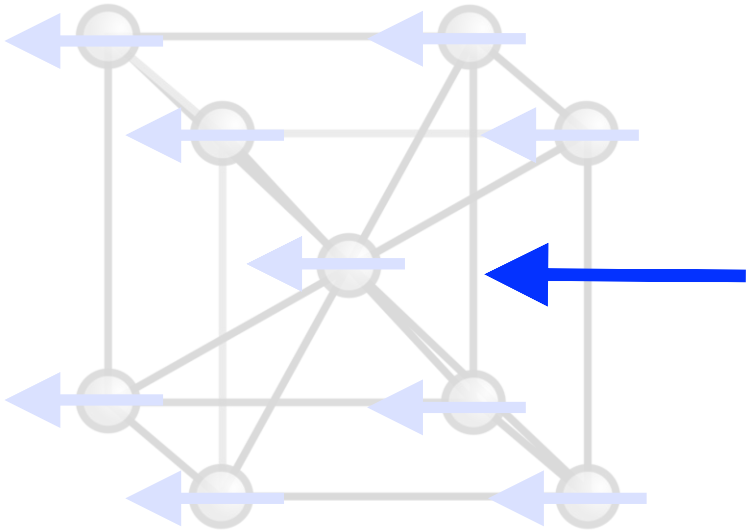

No spin-orbit coupling:

$\vec{h}$ invariant under pure spin rotation R_φ^s

R_π^s

Net ferromagnetic (pseudo)-vector

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

Hall (pseudo)-vector $\vec{h} = (\sigma_{zy}^{\mathrm{a}}, \sigma_{xz}^{\mathrm{a}}, \sigma_{yx}^{\mathrm{a}})$

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Suzuki et al. Phys. Rev. B 95, 094406 (2017)

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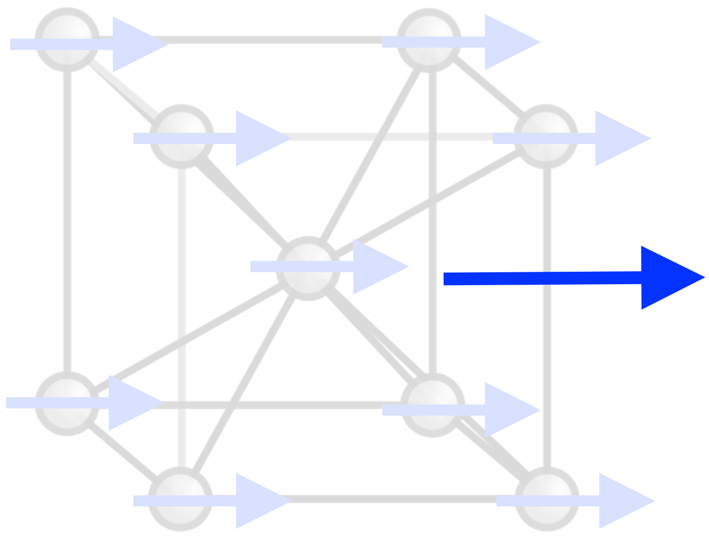
Neumann's principle (1885): A physical property cannot have lower symmetry than the crystal



No spin-orbit coupling:

$\vec{h}$ invariant under pure spin rotation R_{φ}^{s}

$R_{\pi}^{s}T$ – crystal symmetry in **coplanar FM** → **not allowed**

Net ferromagnetic (pseudo)-vector

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

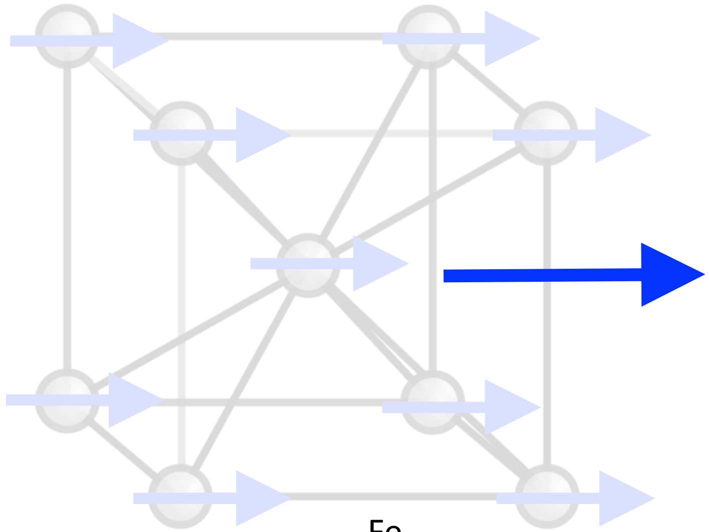
Hall (pseudo)-vector $\vec{h} = (\sigma_{zy}^{\mathrm{a}}, \sigma_{xz}^{\mathrm{a}}, \sigma_{yx}^{\mathrm{a}})$

Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Suzuki et al. Phys. Rev. B 95, 094406 (2017)

Magneto-transport – spontaneous Hall effect

Neumann's principle (1885): A physical property cannot have lower symmetry than the crystal



Edwin Hall 1881
Karplus and Luttinger, Phys. Rev. 95, 1154 (1954)

Spin-orbit coupling:
$\vec{h}$ not invariant under pure spin rotation R_{φ}^{s}

coplanar FM → **always allowed**

Net ferromagnetic (pseudo)-vector

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

Hall (pseudo)-vector $\vec{h} = (\sigma_{zy}^{\mathrm{a}}, \sigma_{xz}^{\mathrm{a}}, \sigma_{yx}^{\mathrm{a}})$

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Suzuki et al. Phys. Rev. B 95, 094406 (2017)

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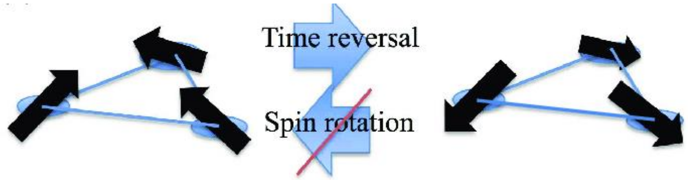
Neumann's principle (1885): A physical property cannot have lower symmetry than the crystal



$Nd_2Mo_2O_7$

Taguchi et al. Science 291, 2573 (2001)

No spin-orbit coupling:

$\vec{h}$ invariant under pure spin rotation R_{φ}^{s}

$R_{\pi}^{s}T$ – crystal symmetry broken in **non-coplanar FM** → **always allowed**

Net ferromagnetic (pseudo)-vector

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

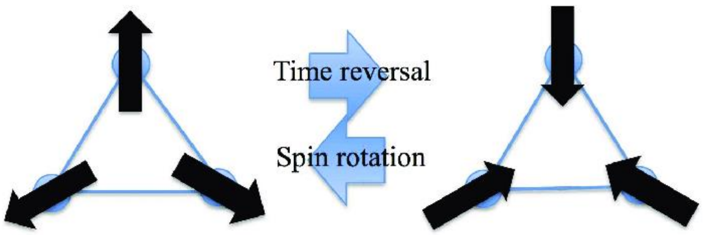
Hall (pseudo)-vector $\vec{h} = (\sigma_{zy}^{\mathrm{a}}, \sigma_{xz}^{\mathrm{a}}, \sigma_{yx}^{\mathrm{a}})$

Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Suzuki et al. Phys. Rev. B 95, 094406 (2017)

Magneto-transport – spontaneous Hall effect

Neumann's principle (1885): A physical property cannot have lower symmetry than the crystal



No spin-orbit coupling:

$\vec{h}$ invariant under pure spin rotation R_φ^s

$R_\pi^s T$ – crystal symmetry in **3-sublattice AF** → **not allowed**

No net ferromagnetic (pseudo)-vector

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

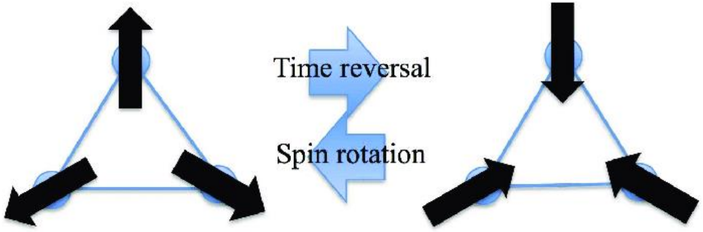
Hall (pseudo)-vector $\vec{h} = (\sigma_{zy}^{\mathrm{a}}, \sigma_{xz}^{\mathrm{a}}, \sigma_{yx}^{\mathrm{a}})$

Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Suzuki et al. Phys. Rev. B 95, 094406 (2017)

Magneto-transport – spontaneous Hall effect

Neumann's principle (1885): A physical property cannot have lower symmetry than the crystal



Mn_3Sb

Chen, Niu, MacDonald, PRL '14
Nakatsuji, Kiyohara, Higo, Nature '15
Nayak et al. Science Adv. '16

Spin-orbit coupling:

$\vec{h}$ not invariant under pure spin rotation R^s_φ

3-sublattice AF → **can be allowed**

No net ferromagnetic (pseudo)-vector

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

Hall (pseudo)-vector $\vec{h} = (\sigma^{\mathrm{a}}_{zy}, \sigma^{\mathrm{a}}_{xz}, \sigma^{\mathrm{a}}_{yx})$

Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Suzuki et al. Phys. Rev. B 95, 094406 (2017)

Magneto-transport – spontaneous Hall effect

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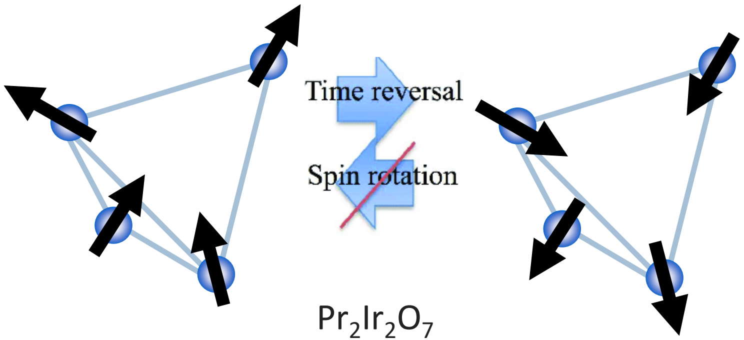


$Pr_2Ir_2O_7$

No spin-orbit coupling:

$\vec{h}$ invariant under pure spin rotation R^s_φ

$R^s_\pi T$ – crystal symmetry broken in **4-sublattice non-coplanar AF**

$\rightarrow$ **can be allowed**

No net ferromagnetic (pseudo)-vector

Suzuki et al. Phys. Rev. B 95, 094406 (2017)
Machida et al., Nature 463, 210 (2010)

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

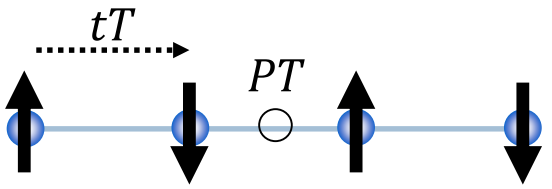
Hall (pseudo)-vector $\vec{h} = (\sigma^{\mathrm{a}}_{zy}, \sigma^{\mathrm{a}}_{xz}, \sigma^{\mathrm{a}}_{yx})$

Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Suzuki et al. Phys. Rev. B 95, 094406 (2017)

Magneto-transport – spontaneous Hall effect

Neumann's principle (1885): A physical property cannot have lower symmetry than the crystal



$\vec{j} = \overleftrightarrow{\sigma}\,\vec{E}$

Spatially averaged:

Invariant under translation $t\overleftrightarrow{\sigma} = \overleftrightarrow{\sigma}$

Linear response:

Invariant under inversion $P\overleftrightarrow{\sigma} = \overleftrightarrow{\sigma}$

Spin-orbit coupling:

$\vec{h}$ not invariant under pure spin rotation R_{φ}^{s}

tT & PT – crystal symmetries in **2-sublattice AF** → **not allowed**

No net ferromagnetic (pseudo)-vector

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

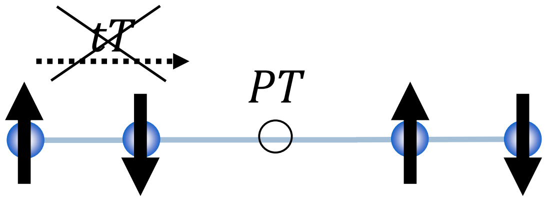
Hall (pseudo)-vector $\vec{h} = (\sigma_{zy}^{a}, \sigma_{xz}^{a}, \sigma_{yx}^{a})$

Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Šmejkal, TJ et al. arXiv (2019)

Magneto-transport – spontaneous Hall effect

Neumann's principle (1885): A physical property cannot have lower symmetry than the crystal



$\vec{j} = \overleftrightarrow{\sigma}\,\vec{E}$

Spatially averaged:

Invariant under translation $t\overleftrightarrow{\sigma} = \overleftrightarrow{\sigma}$

Linear response:

Invariant under inversion $P\overleftrightarrow{\sigma} = \overleftrightarrow{\sigma}$

Spin-orbit coupling:

$\vec{h}$ not invariant under pure spin rotation R_{φ}^{s}

PT – crystal symmetry in **2-sublattice AF** $\rightarrow$ **not allowed**

No net ferromagnetic (pseudo)-vector

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

Hall (pseudo)-vector $\vec{h} = (\sigma_{zy}^{\mathrm{a}}, \sigma_{xz}^{\mathrm{a}}, \sigma_{yx}^{\mathrm{a}})$

Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

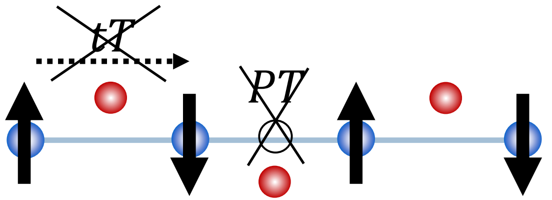
Šmejkal, TJ et al. arXiv (2019)

Magneto-transport – spontaneous Hall effect

Neumann's principle (1885): A physical property cannot have lower symmetry than the crystal

Spin-orbit coupling:

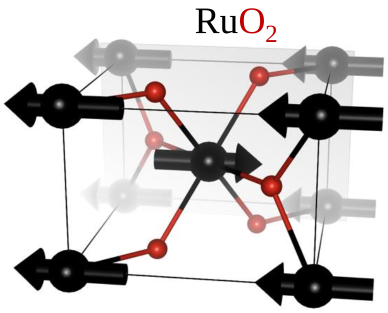
$\vec{h}$ not invariant under pure spin rotation R^s_φ



tT & PT – crystal symmetries broken in **2-sublattice AF**

→ **can be allowed**

No net ferromagnetic (pseudo)-vector



10% out of 600 magnetic structures
from Bilbao MAGNDATA database

Spontaneous Hall effect

$$\overrightarrow{j_H} = \vec{h} \times \vec{E}$$

Hall (pseudo)-vector $\vec{h} = (\sigma^a_{zy}, \sigma^a_{xz}, \sigma^a_{yx})$

Odd under time (spin)-reversal $T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Šmejkal, TJ et al. arXiv (2019)

Magneto-transport – anisotropic magnetoresistance

$$\vec{j} = \overleftrightarrow{\sigma}\vec{E}$$

Spatially averaged:

Invariant under translation $t\overleftrightarrow{\sigma} = \overleftrightarrow{\sigma}$

Linear response:

Invariant under inversion $P\overleftrightarrow{\sigma} = \overleftrightarrow{\sigma}$

Onsager relations:

$\sigma_{ij}(\vec{s}) = \sigma_{ji}(-\vec{s})$

$$\begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} = \underbrace{\begin{bmatrix} \sigma^{\mathrm{s}}_{xx} & \sigma^{\mathrm{s}}_{xy} & \sigma^{\mathrm{s}}_{xz} \\ \sigma^{\mathrm{s}}_{xy} & \sigma^{\mathrm{s}}_{yy} & \sigma^{\mathrm{s}}_{yz} \\ \sigma^{\mathrm{s}}_{xz} & \sigma^{\mathrm{s}}_{yz} & \sigma^{\mathrm{s}}_{zz} \end{bmatrix}} + \underbrace{\begin{bmatrix} 0 & \sigma^{\mathrm{a}}_{xy} & \sigma^{\mathrm{a}}_{xz} \\ -\sigma^{\mathrm{a}}_{xy} & 0 & \sigma^{\mathrm{a}}_{yz} \\ -\sigma^{\mathrm{a}}_{xz} & -\sigma^{\mathrm{a}}_{yz} & 0 \end{bmatrix}}$$

Anisotropic magnetoresistance

Spontaneous Hall effect

Invariant under time (spin)-reversal $T\overleftrightarrow{\sigma^{s}}(\vec{s}) = \overleftrightarrow{\sigma^{s}}(-\vec{s}) = \overleftrightarrow{\sigma^{s}}(\vec{s})$

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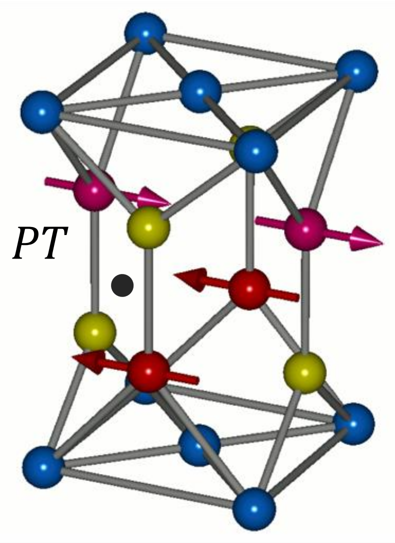
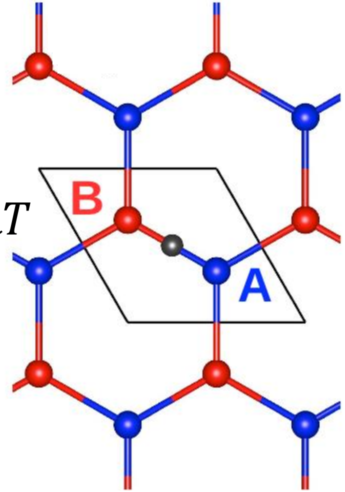
Magneto-transport – anisotropic magnetoresistance

PT

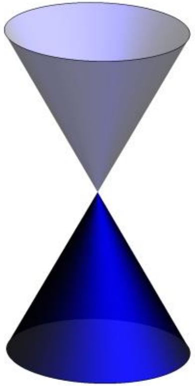


PT does not exist in FMs

$P\&T$



cf. graphene



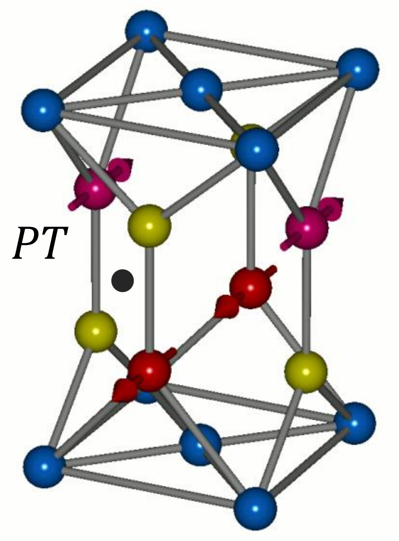
Dirac cone

Šmejkal, TJ et al PRL ’17

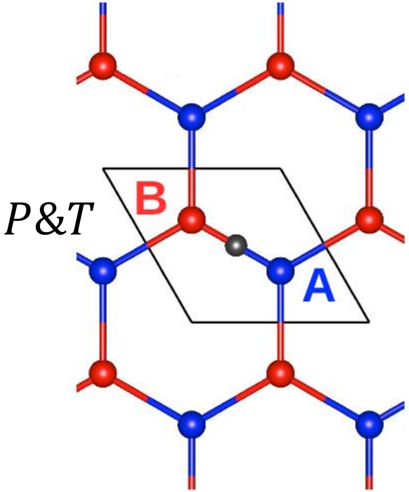
Magneto-transport – anisotropic magnetoresistance

Large AMR ⟷ metal-insulator transition

spin-orbit topological band structure



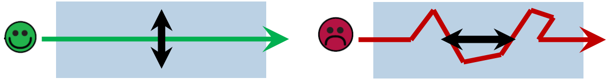
PT does not exist in FMs



cf. graphene

Dirac cone

cf. weak AMR: spin-orbit scattering



Šmejkal, TJ et al PRL ’17

Let's racap

- **Internet**
- **Internet of Things**
- **Big data**

- **No Moore**
  Speed
  Energy
  CMOS scaling

problem

1. Recording & computers

2. Conventional & neuromorphic computing

3. Non-CMOS devices and materials

5. Physical principles of operation of magnetic devices

do differently

- **von Neumann**
  Revisit the architecture to tackle the bottleneck

- **Analog to digital**
  Revisit the noise vs. complexity trade-off

do more

- **Spintronic**
- **Phase-change**
- **....**
  Exploit full potential of non-CMOS devices

- **Optical**
  Explore speed and energy efficiency limits