ANTIFERROMAGNETIC SPINTRONICS

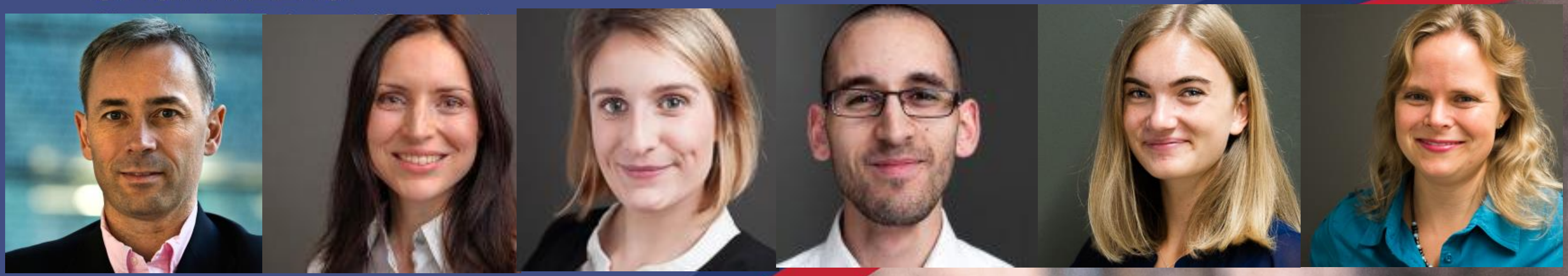
FROM TOPOLOGY TO NEUROMORPHIC COMPUTING

Hideo Ohno   Shunsuke Fukami

Workshop October 7th - 10th, 2019
Schloss Waldthausen, Mainz, Germany

SPICE

ORGANIZERS:

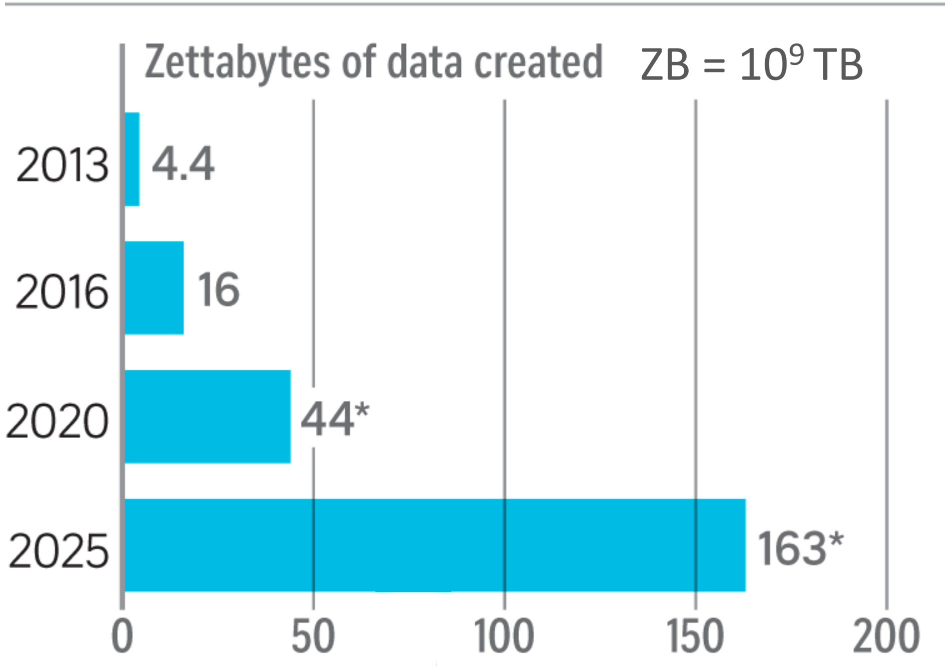


Jairo Sinova   Elena Hilp   Denise Kornbrust   Robert-Andre Vettel   Hjördis Pusch   Karin Everschor-Sitte

Big data storage

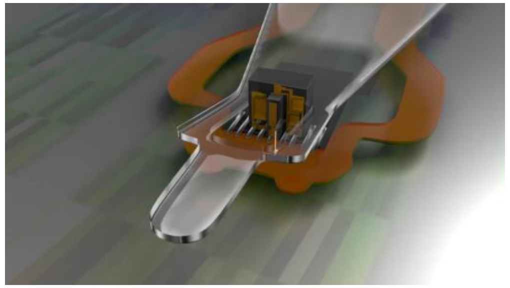
Internet (PC & cloud IT)

Internet of Things (edge IT)



Samsung Flash SSD (30TB)

Sony/IBM tape (330TB)



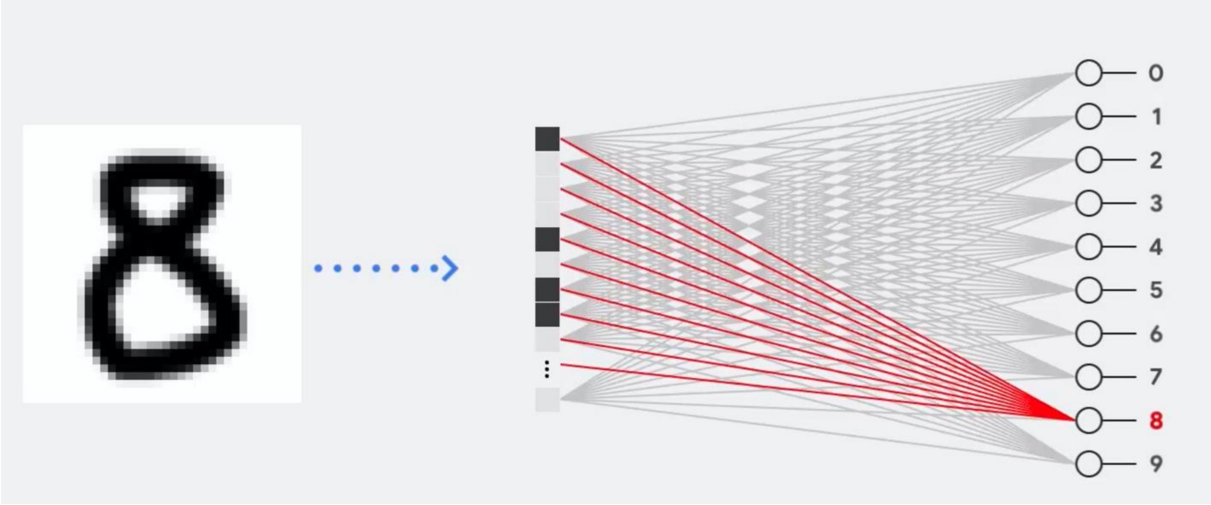
Seagate HDD (16TB)

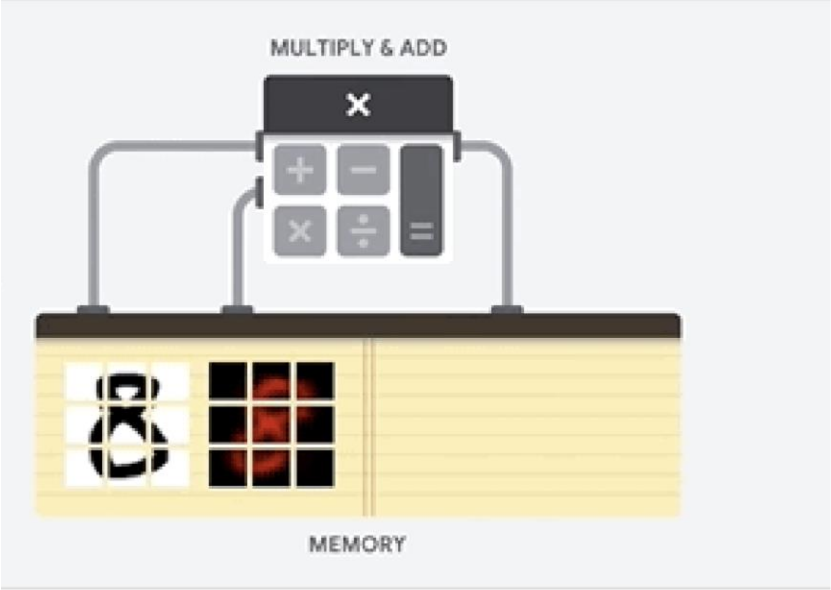
Sony optical disc (3.3TB)

Big data processing: 1. Artificial neural networks

Mass applications – Google Brain (2012 – image recognition, 2016 – language translation)

Synchronous: memory & processor under global clock





$$\Sigma\, x_i \;\bullet\; w_{ij} \;=\; y_j$$

Hebbian learning $\Delta w_{ij} \sim x_i \bullet y_j$

Big data processing: 1. Artificial neural networks

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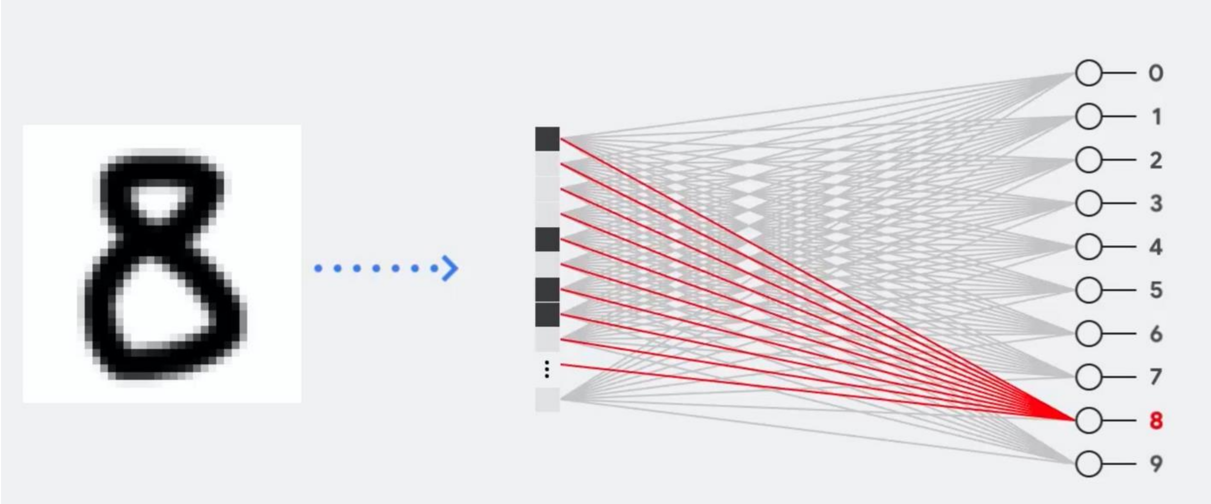
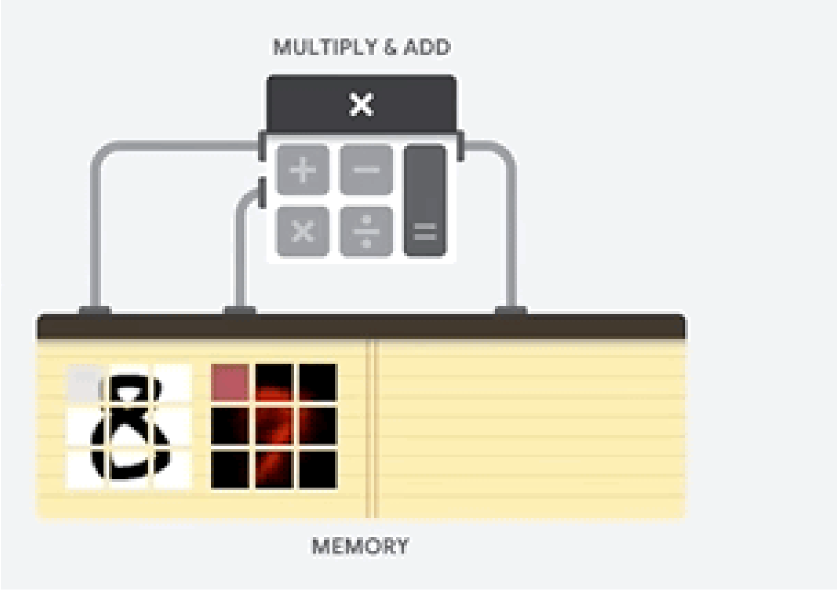




OUTPUT

$$\Sigma\, x_i \;\bullet\; w_{ij} \;=\; y_j$$

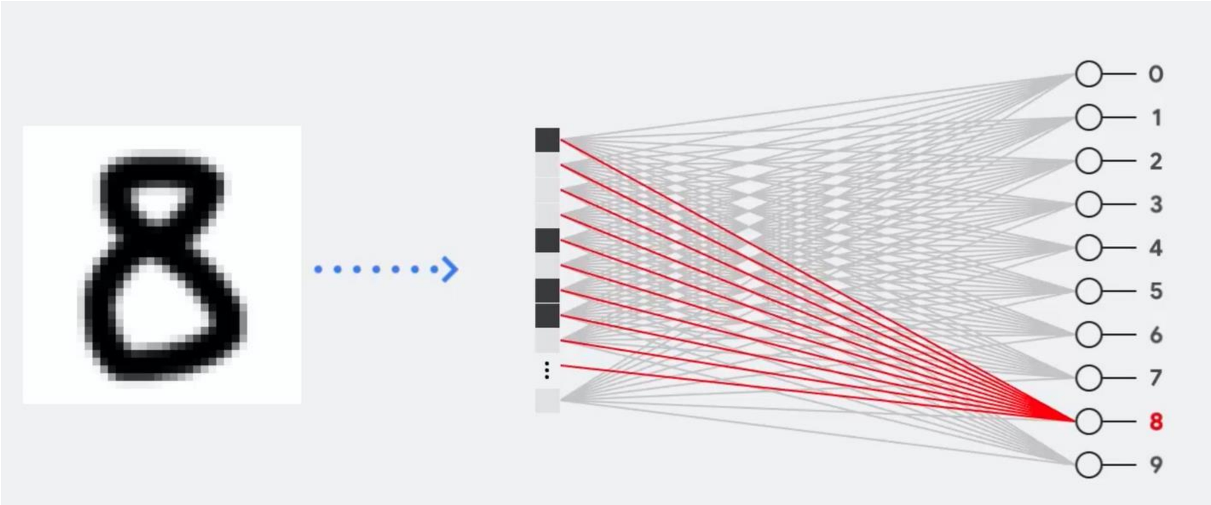
General purpose **CPU** (Intel) a few big cores

General purpose **GPU** (NVIDIA) 2,000 medium cores

Neuromorphic **TPU** (Google) 30,000 small cores

Hebbian learning $\Delta w_{ij} \sim x_i \bullet y_j$

Big data processing: 1. Artificial neural networks

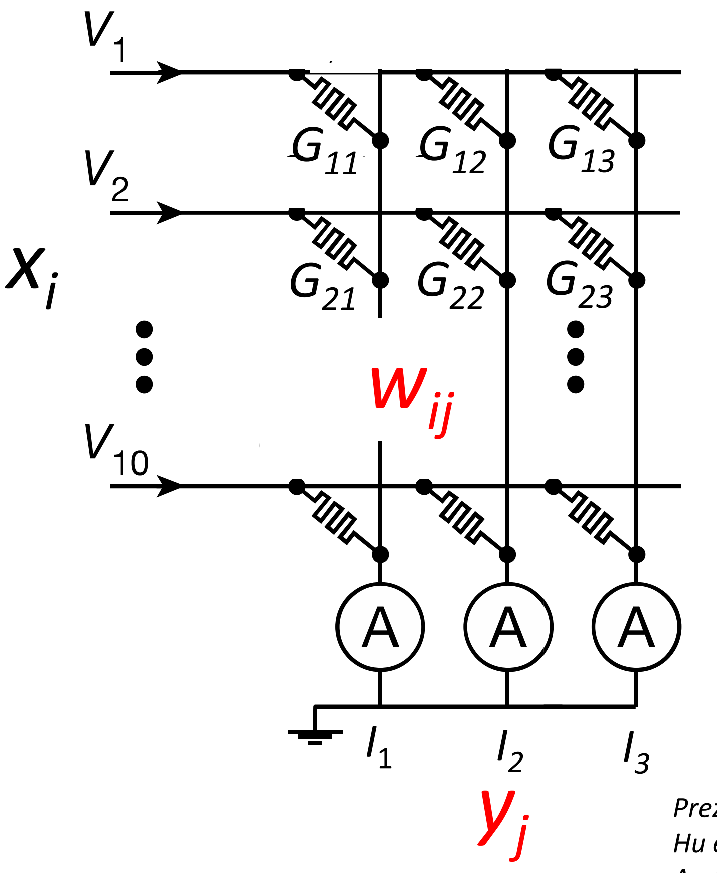


$$\Sigma\, x_i \cdot w_{ij} = y_j$$

Hebbian learning $\Delta w_{ij} \sim x_i \cdot y_j$

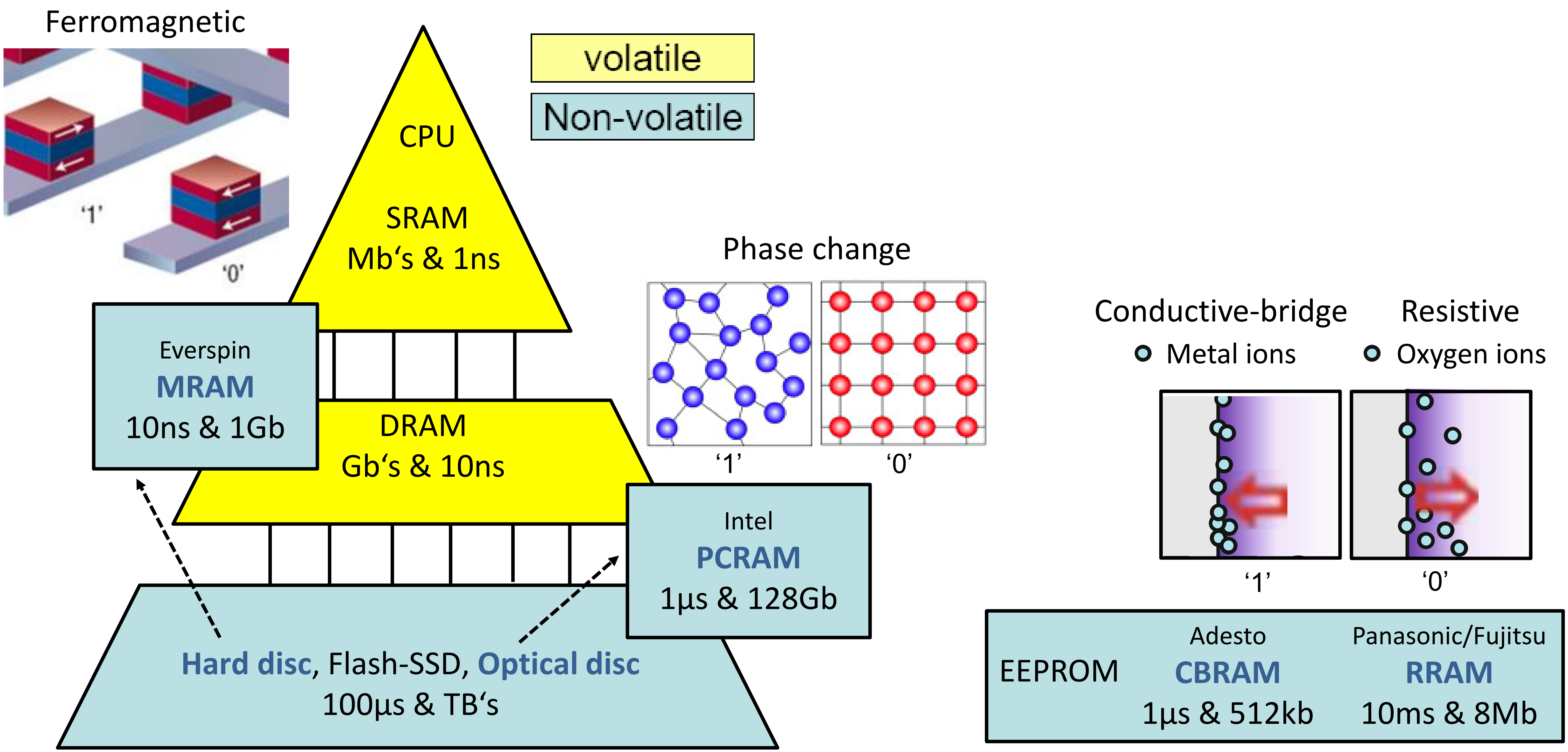
Logic-in-memory

Weighted sum $\rightarrow$ Kirchhoff's rule

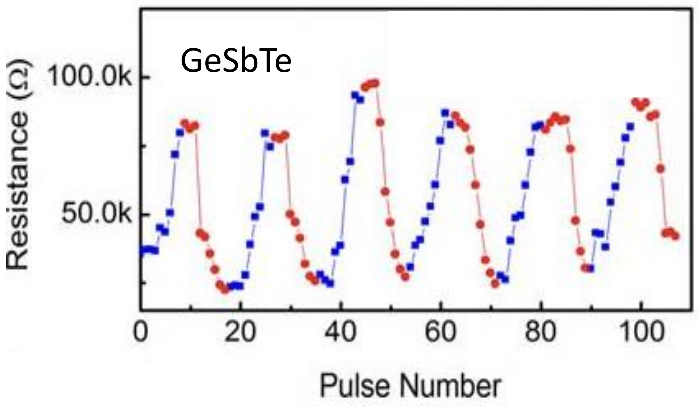


Prezioso et al. Nature 521, 61 (2015)
Hu et al. Nature Elec. 1, 52 (2018)
Ambrogio et al. Nature 558, 60 (2018)

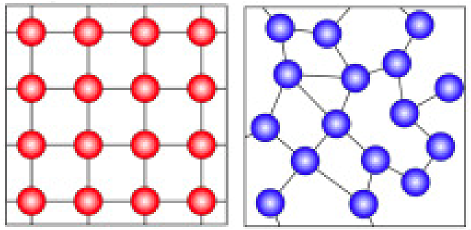
Non-CMOS resistive memories



Non-CMOS multi-level resistive memories: electrical switching

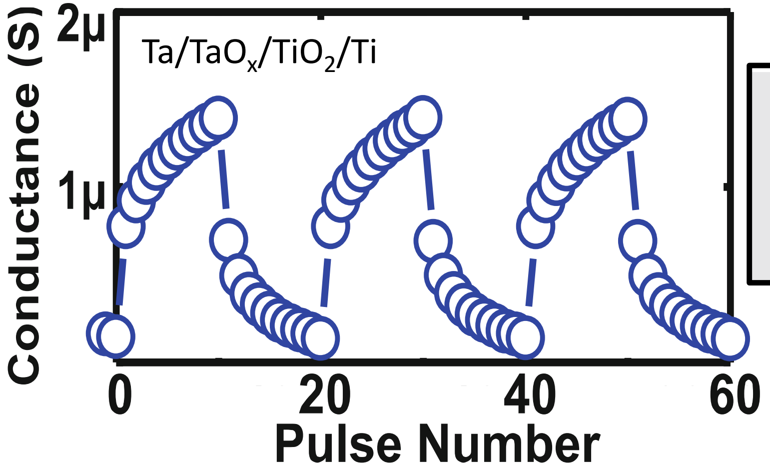


Phase change

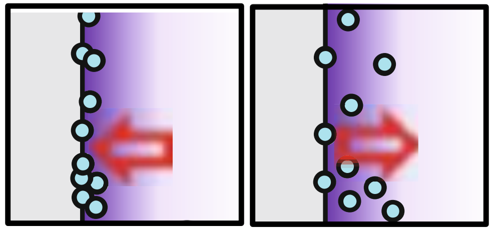


unipolar

Zhong et al. Phys. Stat. Sol. RRL 9, 414 (2015)

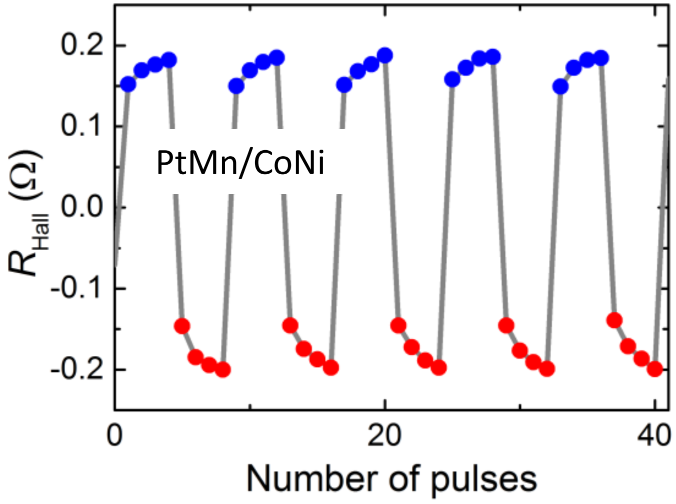


Resistive

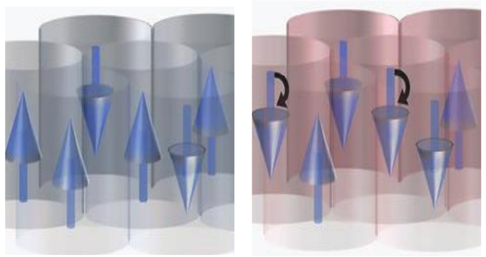


bipolar

Yu (ed.), Neuro-inspired Computing Using Resistive Synaptic Devices, Springer (2017)

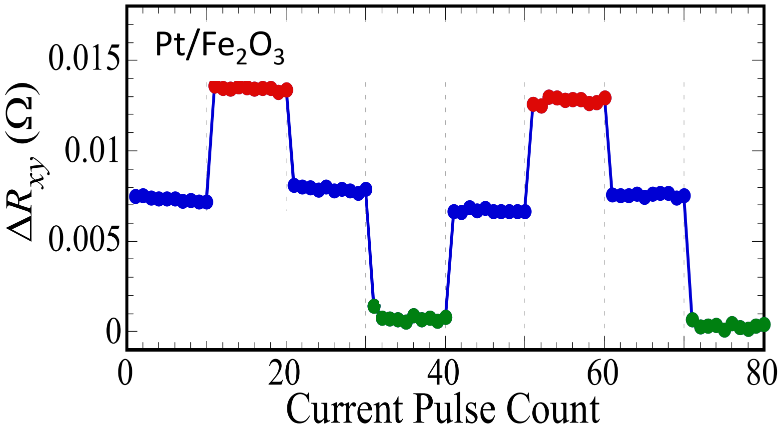


Ferromagnetic

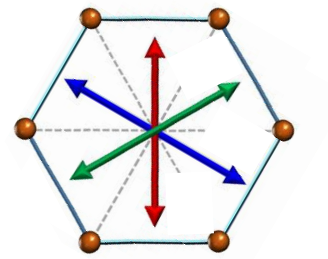


bipolar

Fukami et al. Nature Mater. 15, 535 (2016)



Antiferromagnetic

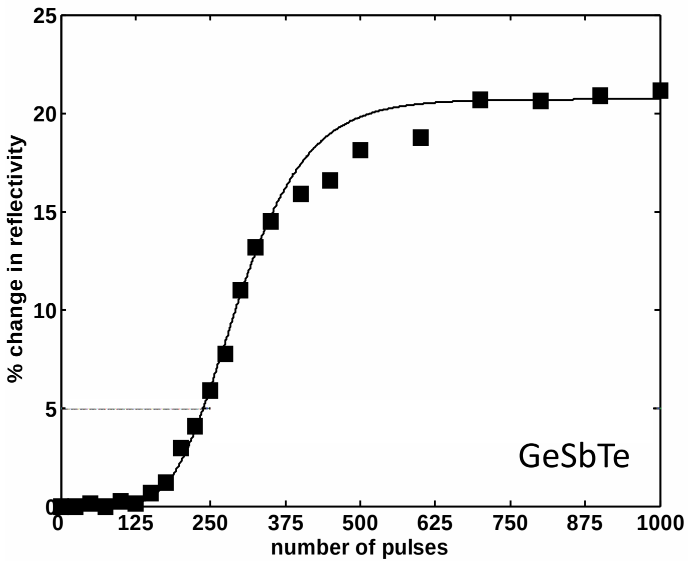


bi(multi)polar

Cheng et al. arXiv:1906.04694

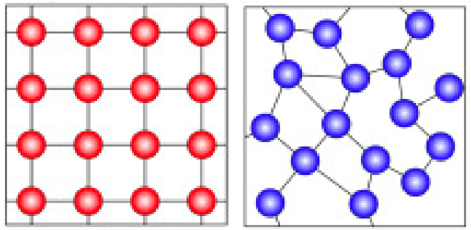
Non-CMOS multi-level resistive memories: optical switching

down to ~100 fs, ~mJ/cm^2 pulses



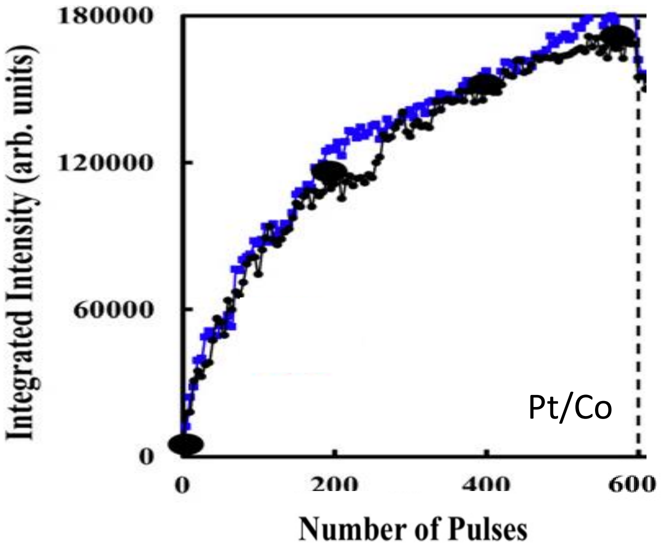
Wright et al. Adv. Mater. 23, 3408 (2011)

Phase change

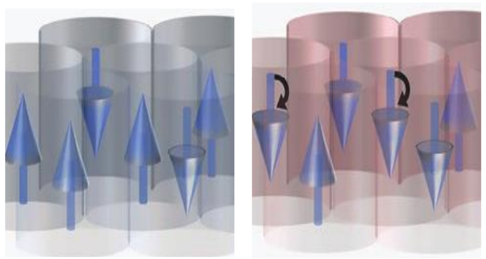


polarization independent

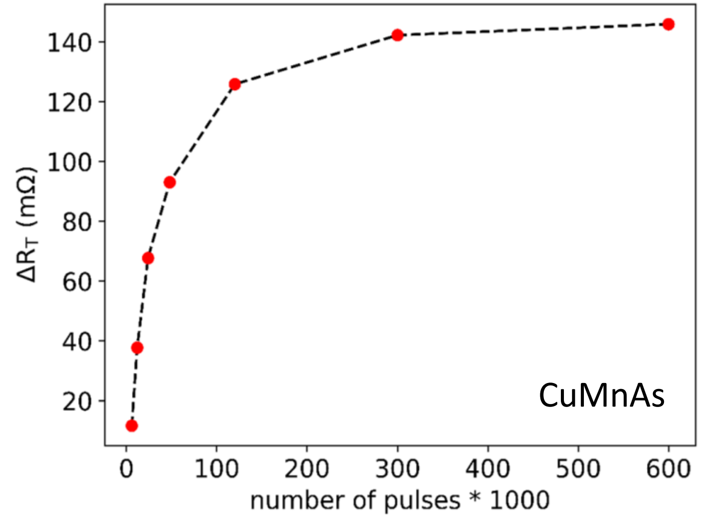
Resistive



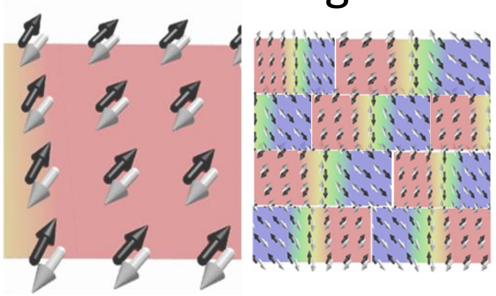
Ferromagnetic



circularly polarized



Antiferromagnetic



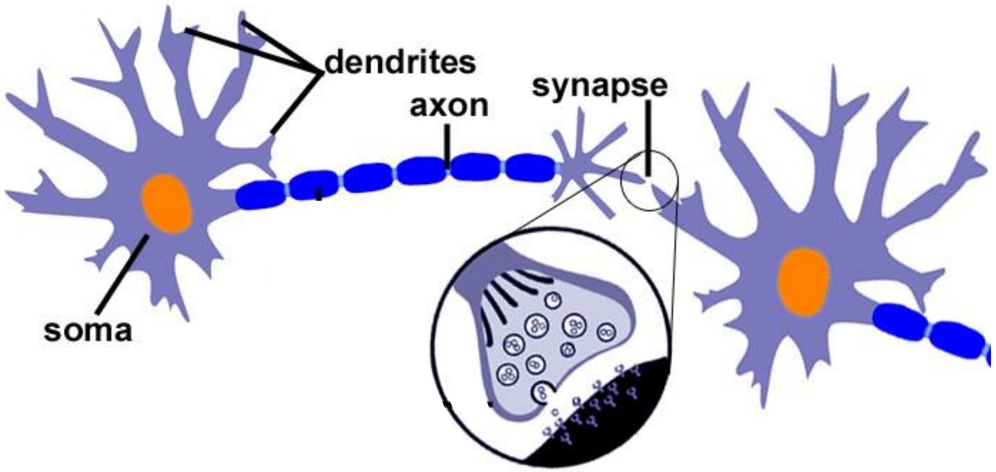
polarization independent

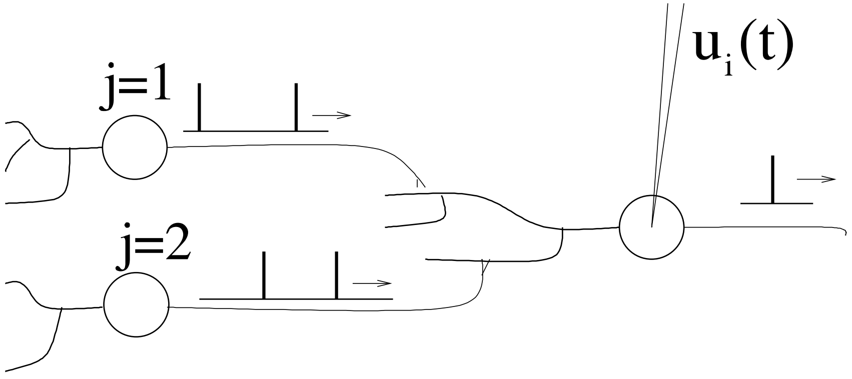
Kaspar et al. arXiv:1909.09071

Chakravarty et al. Appl. Phys. Lett. 114, 192407 (2019), Nemec, Fiebig, Kampfrath, Kimel, Nature Phys. 14, (2018)

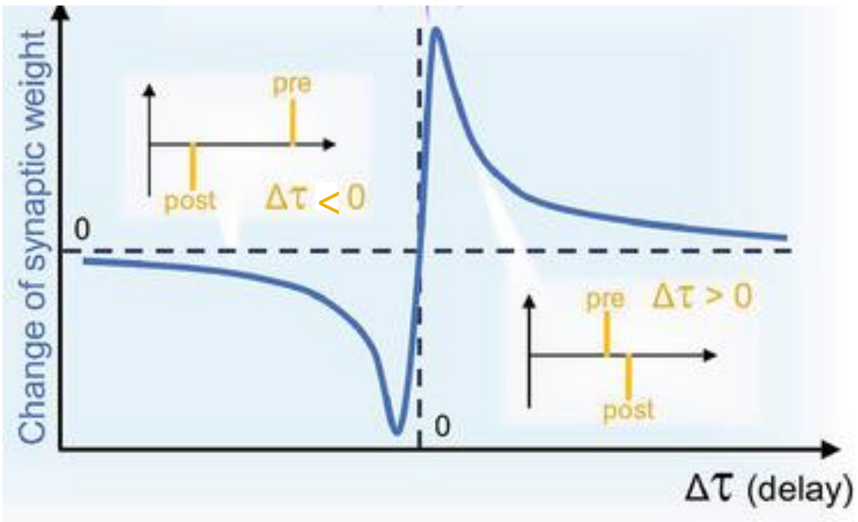
Big data processing: 2. Spiking neural networks

Asynchronous spiking; order/delay between spikes; energy saving



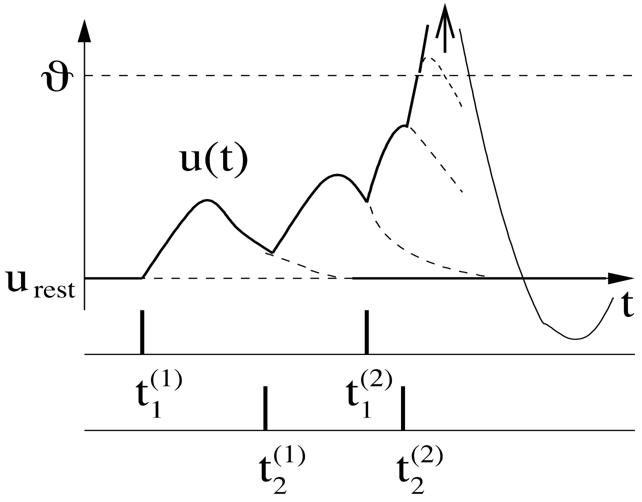


Spiking time dependent plasticity of synapse



Kurenkov et al. Adv. Mater. 31, 1900636 (2019)

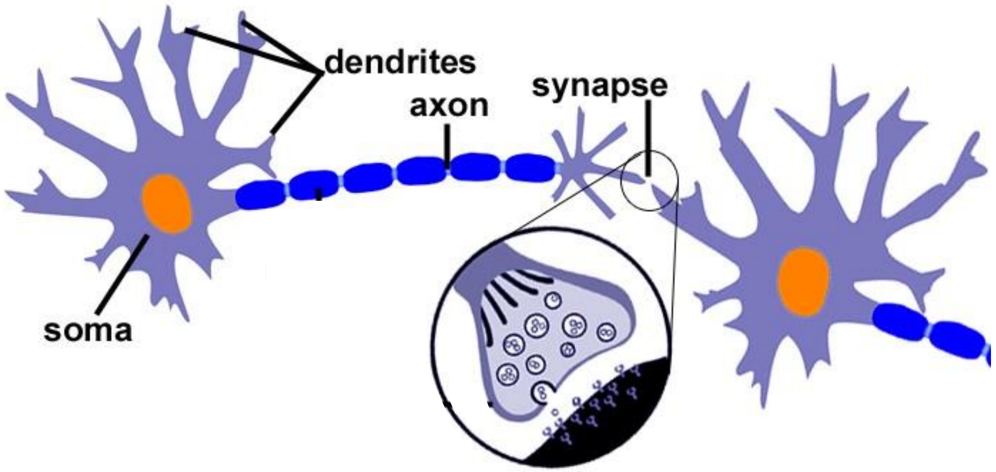
Leaky-sum-and-fire neuron



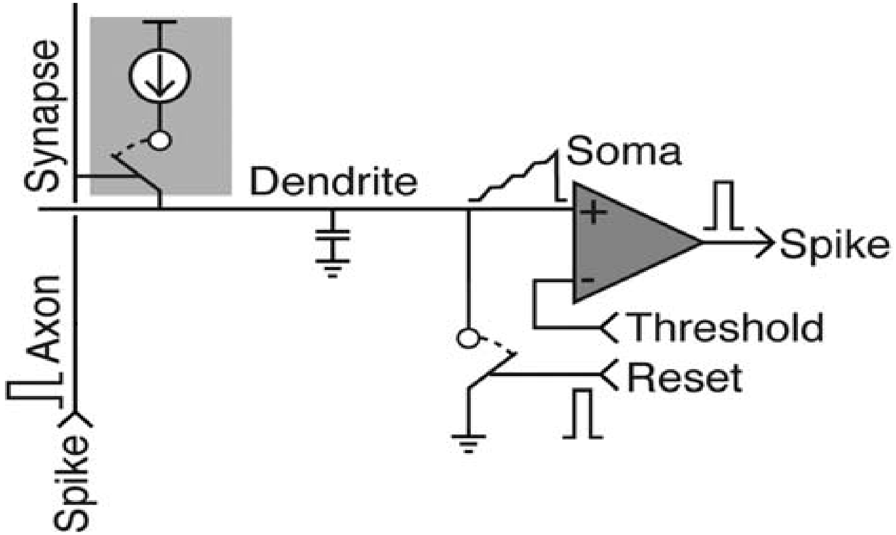
Gerstner & Kistler, Spiking Neuron Models, Cambridge University Press (2002)

Big data processing: 2. Spiking neural networks

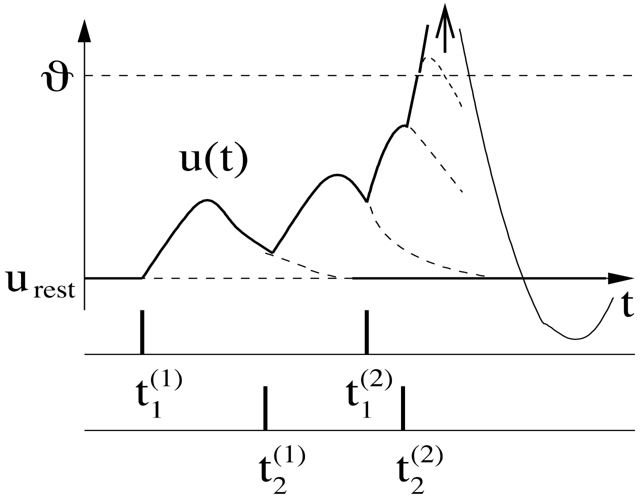
Asynchronous spiking; order/delay between spikes; energy saving



Spiking mixed digital/analog CMOS

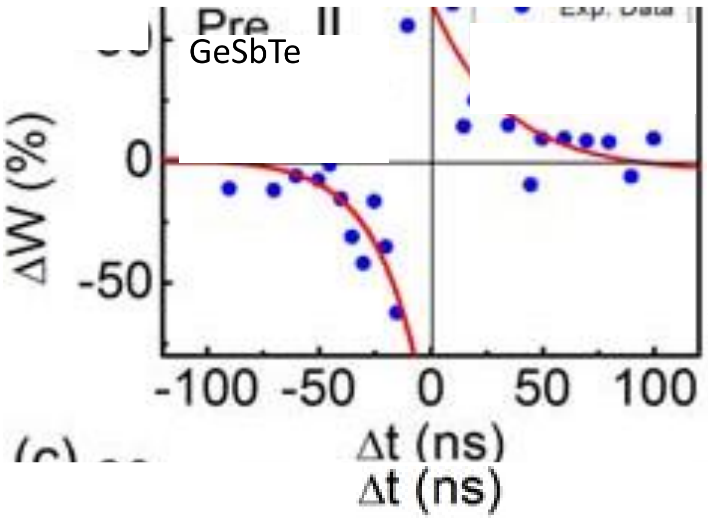


Leaky-sum-and-fire neuron



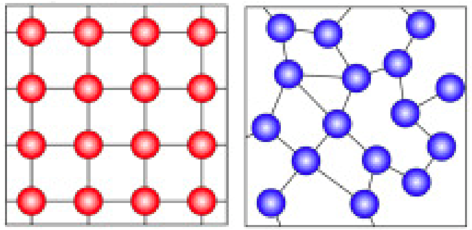
Benjamin et al. Proceedings of the IEEE 102, 699 (2014)

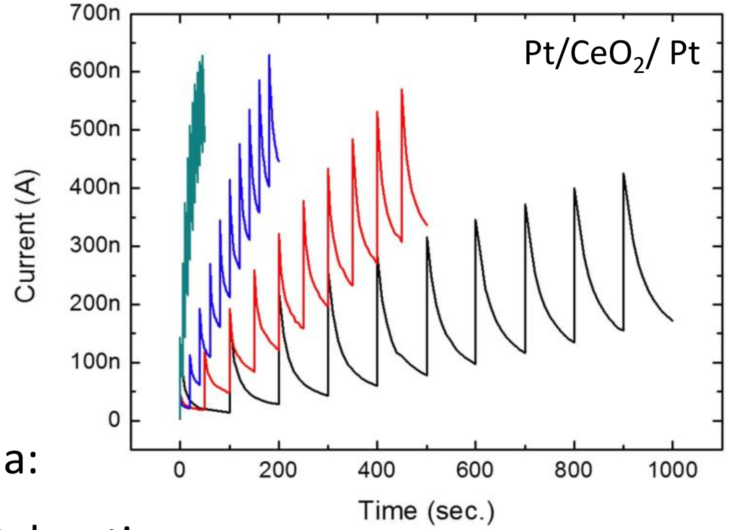
Non-CMOS spiking analog memories



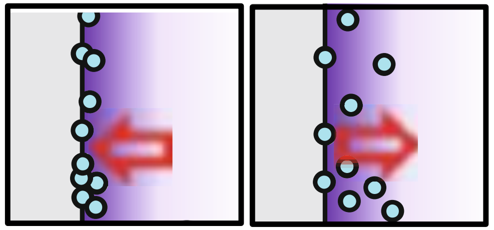
Zhong et al. Phys. Status Solidi RRL 9, 414 (2015)

Phase change





Resistive

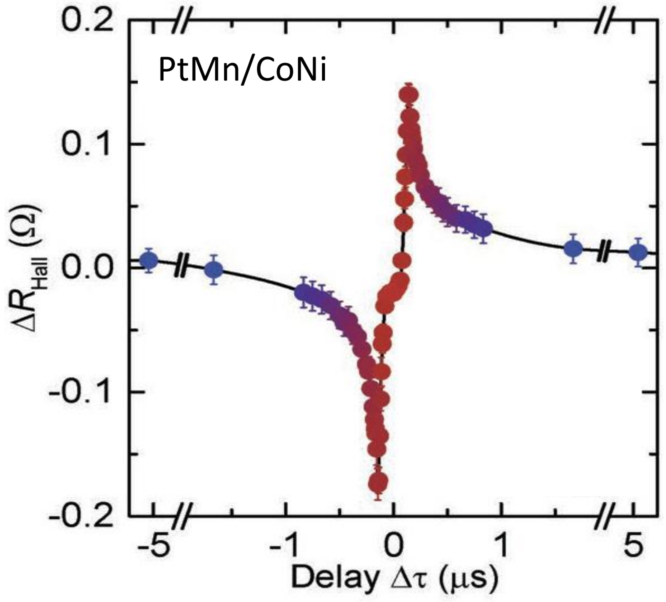


Time dependence via:

Transient heating

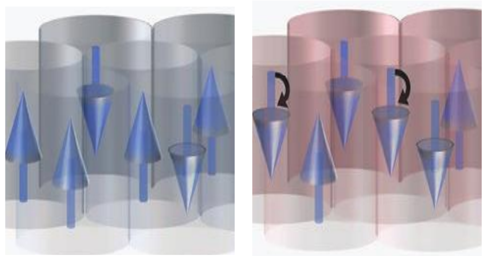
Relaxation

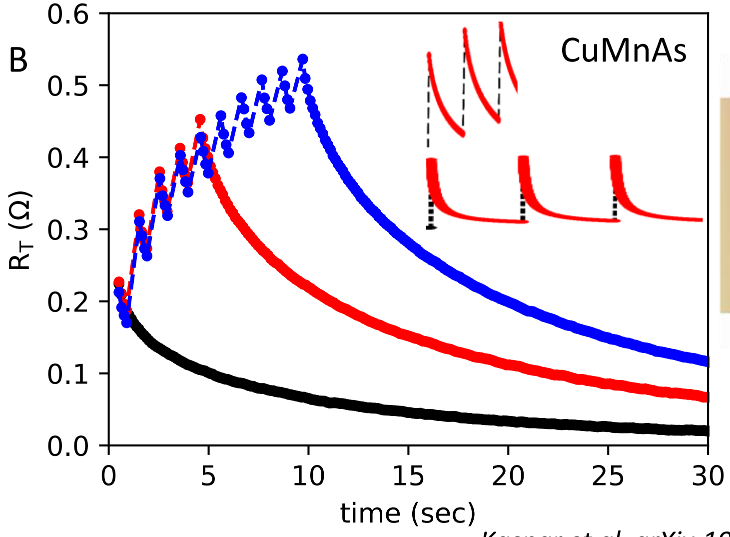
Kim et al. Nanotechnology 29, 265204 (2018)



Kurenkov et al. Adv. Mater. 31, 1900636 (2019)

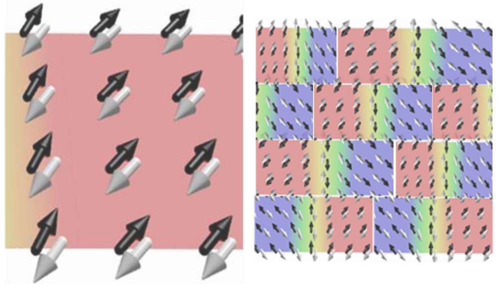
Ferromagnetic



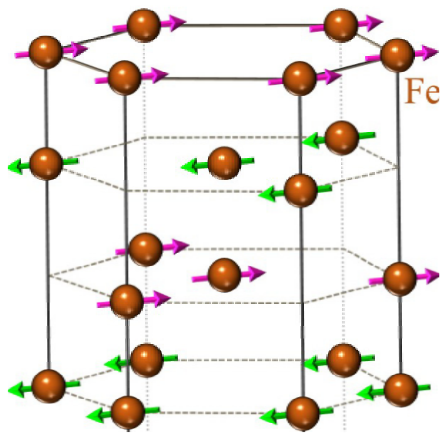


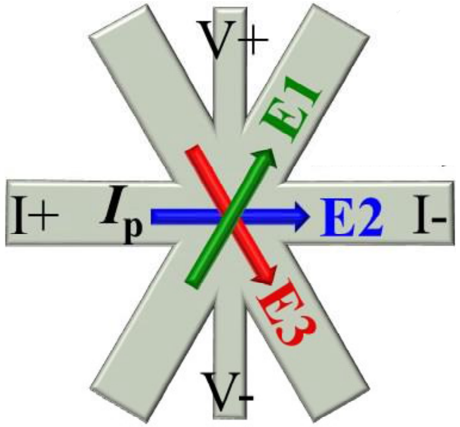
Kaspar et al. arXiv:1909.09071

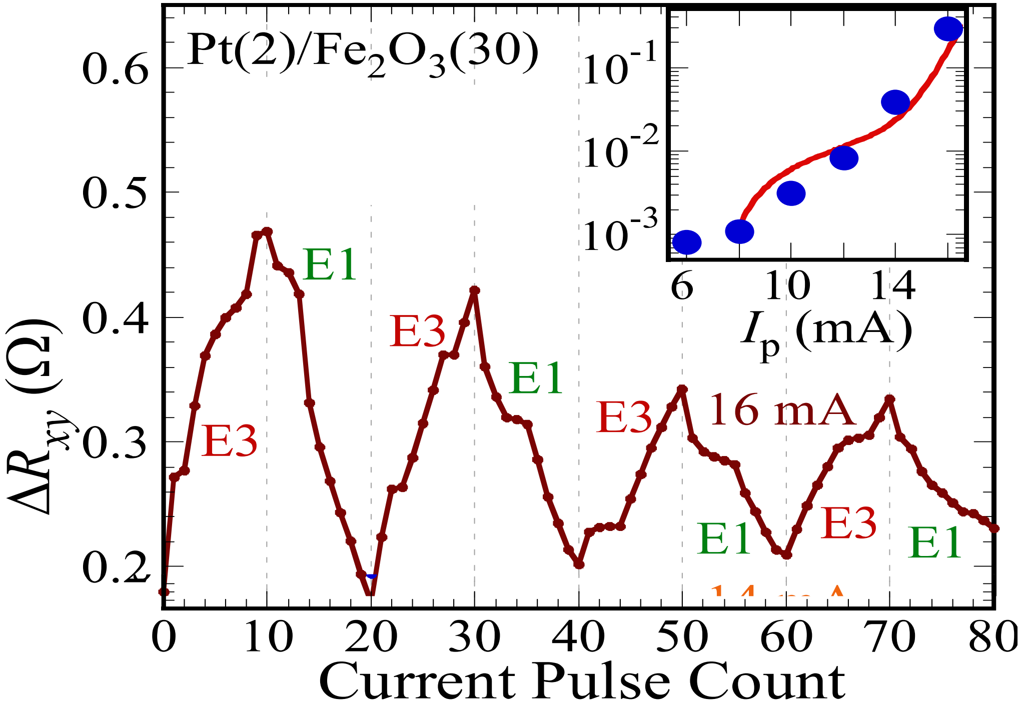
Antiferromagnetic

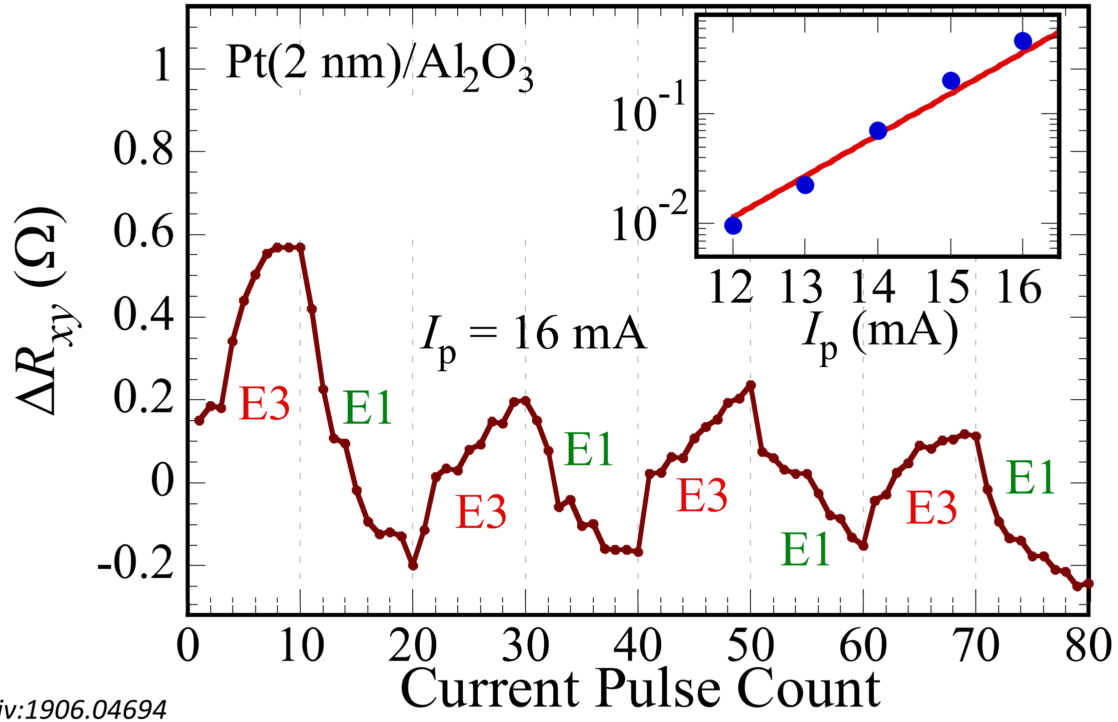


Magnetic vs. non-magnetic origin of resistive switching









Cheng et al. arXiv:1906.04694

Conductivity

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

Linear response:

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

Onsager relations:

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

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

Ordinary

$$T\overleftrightarrow{\sigma^{s}}(\vec{s}) = \overleftrightarrow{\sigma^{s}}(-\vec{s}) = \overleftrightarrow{\sigma^{s}}(\vec{s})$$

Even under time-reversal

Hall

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

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

Hall (pseudo)-vector

$$T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$$

Odd under time-reversal

vector: $P\vec{j} = -\vec{j}$

$$P\vec{E} = -\vec{E}$$

pseudo-vector: $P\vec{h} = \vec{h}$

Hall conductivity

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

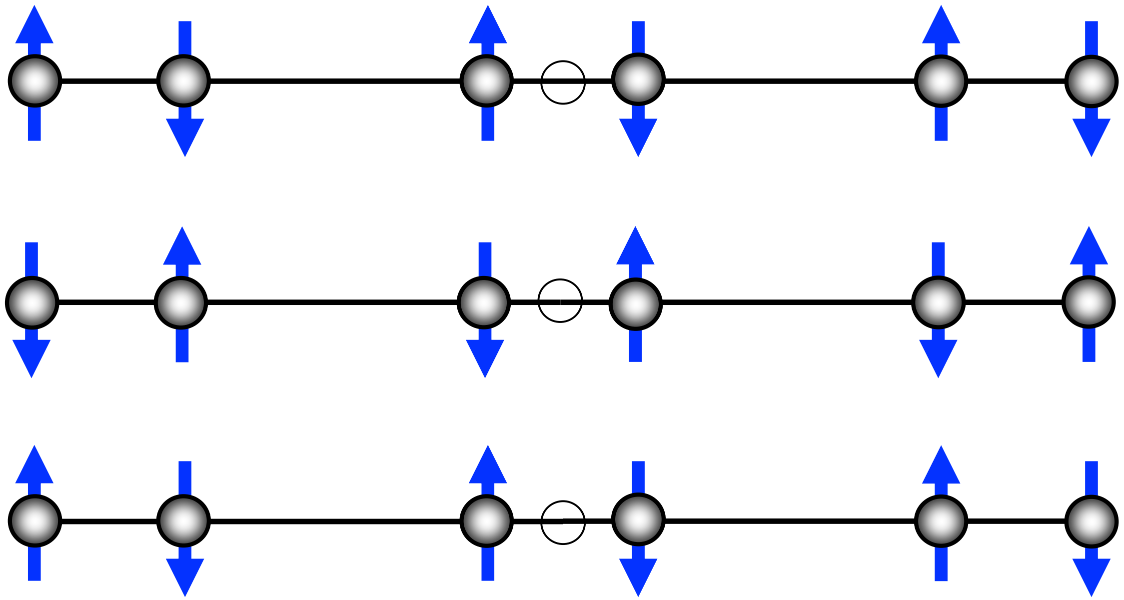
Linear response:

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

Onsager relations:

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

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



$+\vec{h}$

$T\vec{h} = -\vec{h}$

$P(-\vec{h}) = -\vec{h}$

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

$$\cancel{\vec{h} = (\sigma^{\mathrm{a}}_{zy}, \sigma^{\mathrm{a}}_{xz}, \sigma^{\mathrm{a}}_{yx})}$$

~~Hall (pseudo)-vector~~

$$\cancel{T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})}$$

Odd under time-reversal

Ordinary conductivity

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

Linear response:

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

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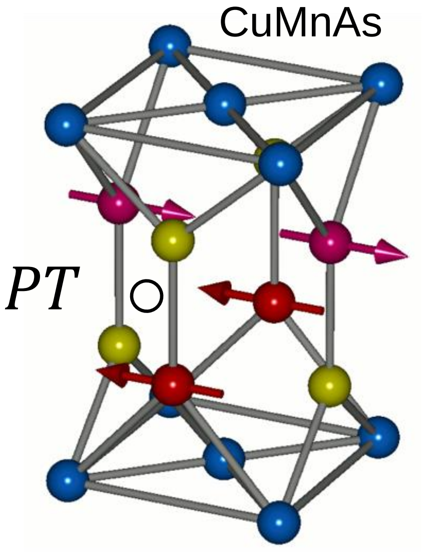
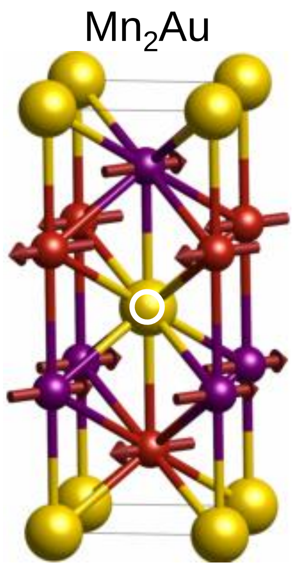
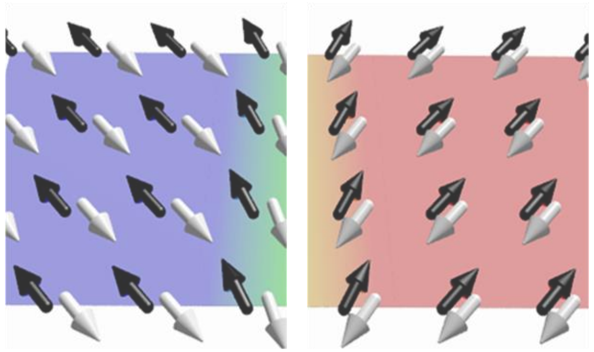
Effective time-reversal symmetry PT



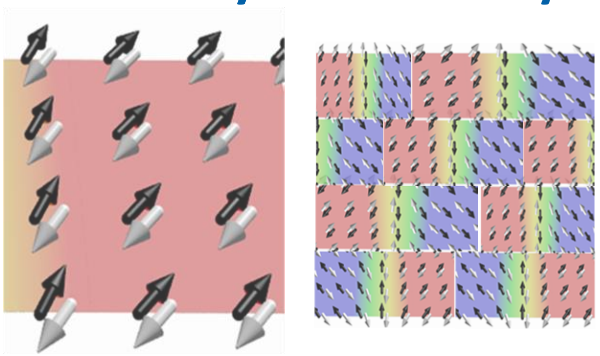


Wadley et al., Science ’16, Bodnar et al., Nature Commun. ’18,
Meinert et al. Phys. Rev. Appl. ’18, Zhou et al. Phys. Rev. Appl. ’18

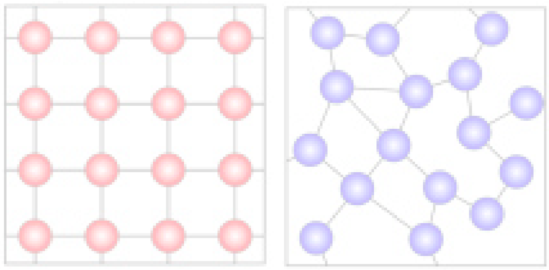
Ordinary conductivity



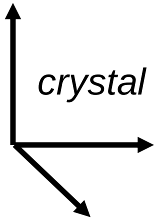
Anistropic magnetoresistance



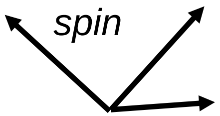
Nano-texture magnetoresistance



Disorder resistance



Weak spin-orbit (Dirac) interaction

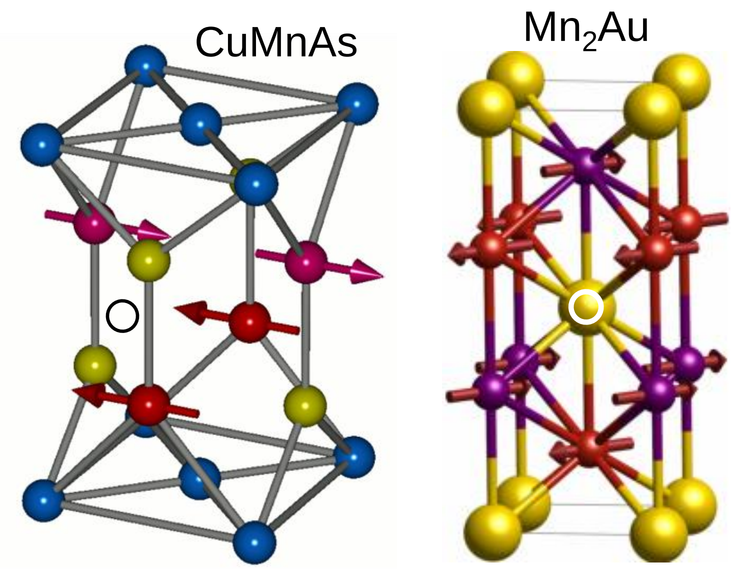


Strong exchange (Coulomb) interaction

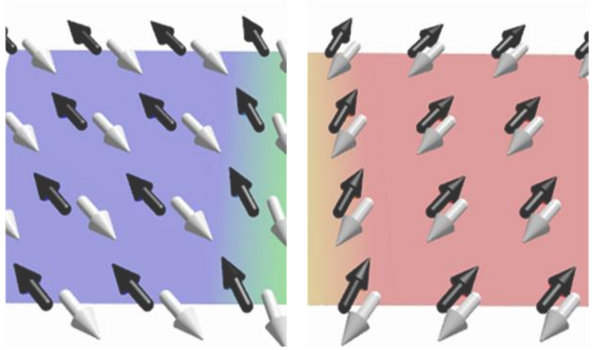
Maca et al. PRB 96, 094406 (2017), Kaspar et al. arXiv:1909.09071

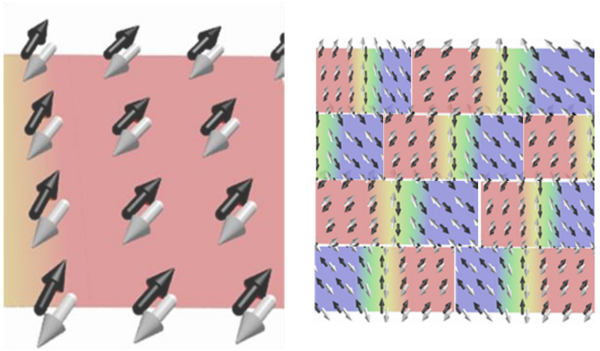
Shick et al. PRB '10, Park et al. Nature Mater '11, Wang et al. Phys. Rev. Lett. '12, Marti, TJ et al. Nature Mater. '14, Moriyama et al. Appl. Phys. Lett. '15

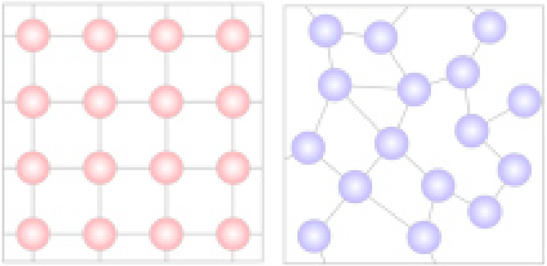
Wadley et al., Science '16, Bodnar et al., Nature Commun. '18, Meinert et al. Phys. Rev. Appl. '18, Zhou et al. Phys. Rev. Appl. '18



Ordinary conductivity



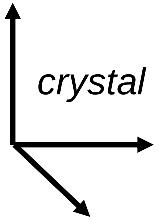




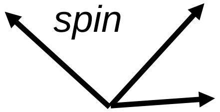
Anistropic magnetoresistance

Nano-texture magnetoresistance

Disorder resistance



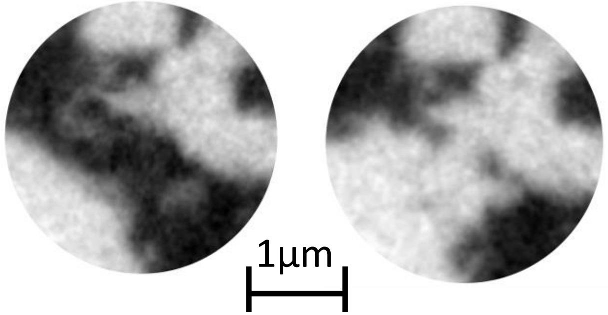
Weak spin-orbit (Dirac) interaction

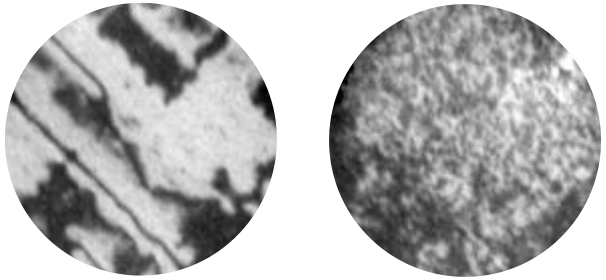


Strong exchange (Coulomb) interaction

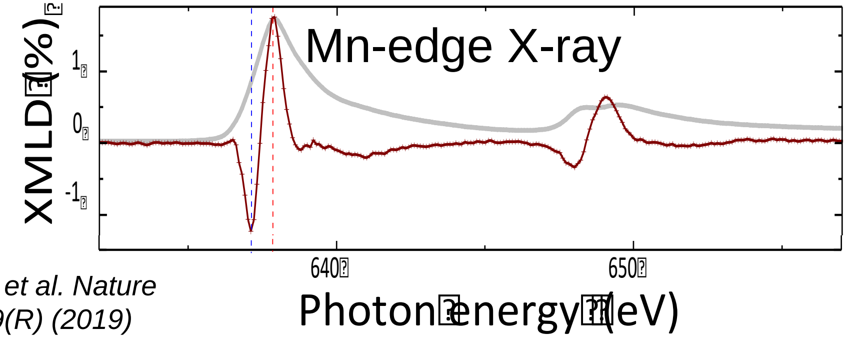
Maca et al. PRB 96, 094406 (2017), Kaspar et al. arXiv:1909.09071

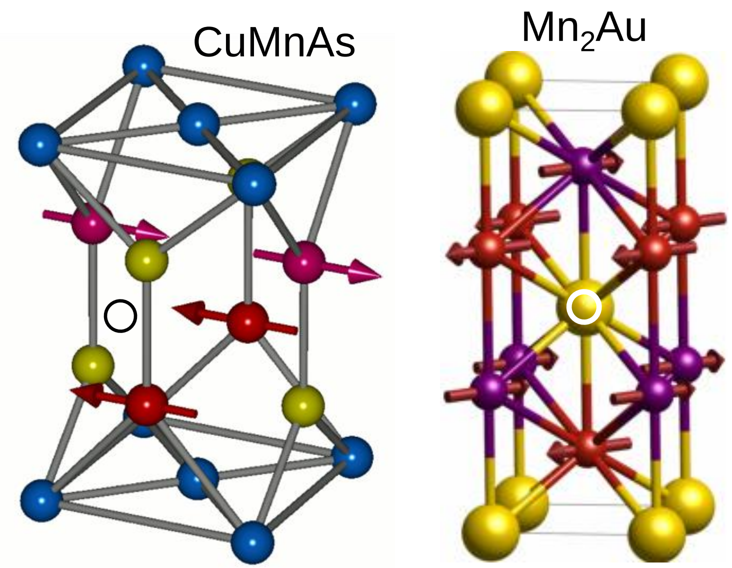
Imaging





Linear dichroism





Grzybowski et al. PRL 118, 057701 (2017), Wadley et al. Nature Nano 13, 362 (2018), Bodnar et al. PRB 99, 140409(R) (2019)

Hall conductivity

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

Linear response:

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

Onsager relations:

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

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

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

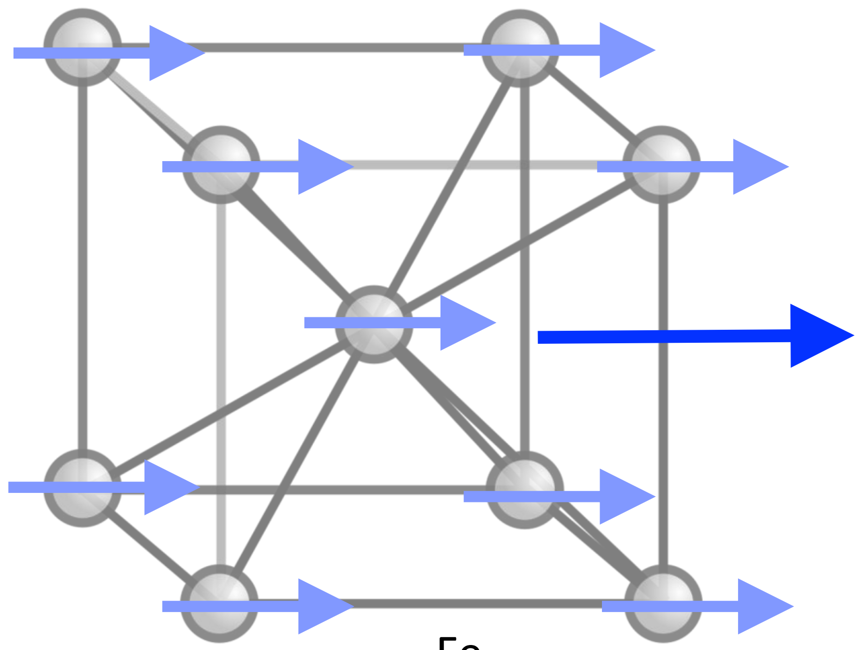
$$\vec{h} = (\sigma^{\mathrm{a}}_{zy}, \sigma^{\mathrm{a}}_{xz}, \sigma^{\mathrm{a}}_{yx})$$

Hall (pseudo)-vector

$$T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$$

Odd under time-reversal

Hall conductivity



Net ferromagnetic (pseudo)-vector

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

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

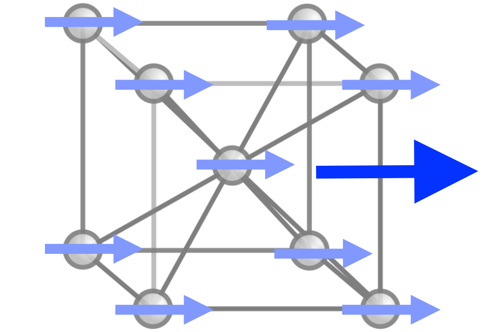
Hall (pseudo)-vector

$$T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$$

Odd under time-reversal

Suzuki et al. Phys. Rev. B 95, 094406 (2017)
Zelezny et al. PRL 119, 187204 (2017)

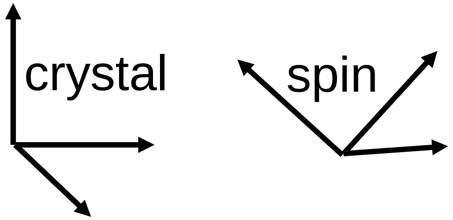
Hall conductivity

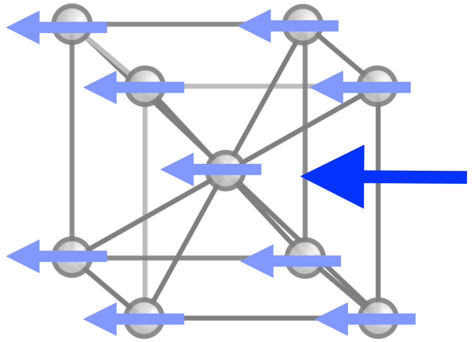


$+\vec{h}$

No spin-orbit coupling

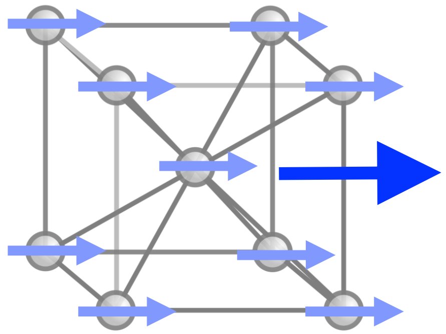
$\vec{h}$ invariant under pure spin rotation R_{φ}^{s}





$T\vec{h} = -\vec{h}$

Net ferromagnetic (pseudo)-vector



$R_{\pi}^{s}(-\vec{h}) = -\vec{h}$

Effective time-reversal symmetry $R_{\pi}^{s}T$

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

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

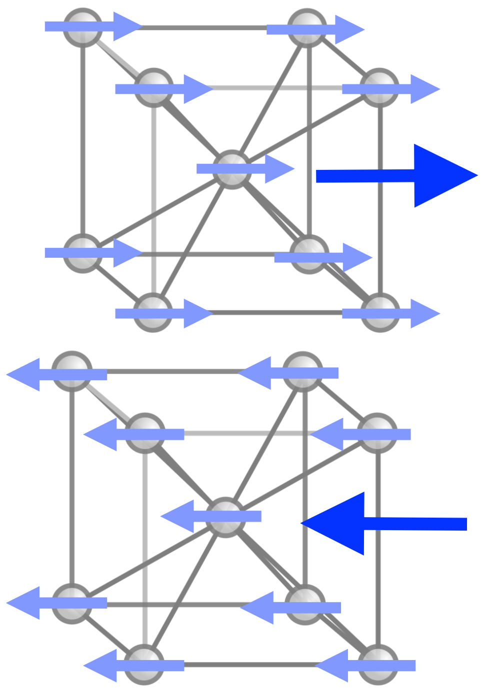
Hall (pseudo)-vector

$$T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$$

Odd under time-reversal

Suzuki et al. Phys. Rev. B 95, 094406 (2017)
Zelezny et al. PRL 119, 187204 (2017)

Hall conductivity



$+\vec{h}$

$T\vec{h} = -\vec{h}$

Spin-orbit coupling

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

Net ferromagnetic (pseudo)-vector

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

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

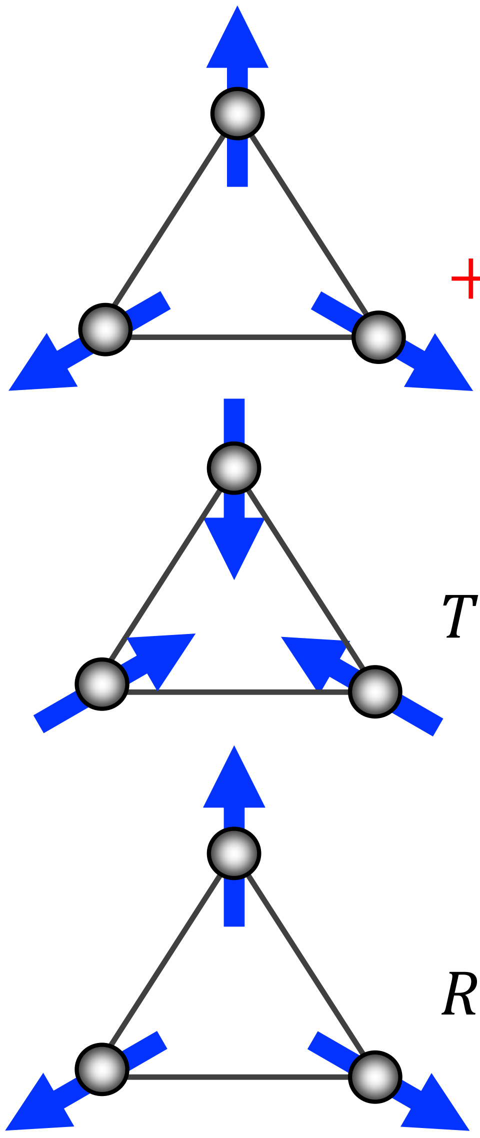
Hall (pseudo)-vector

$$T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$$

Odd under time-reversal

Suzuki et al. Phys. Rev. B 95, 094406 (2017)
Zelezny et al. PRL 119, 187204 (2017)

Hall conductivity



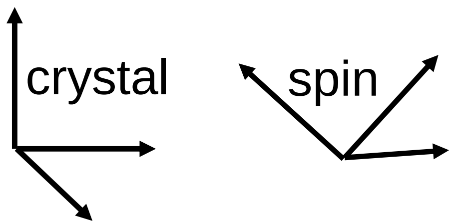
$+\vec{h}$

$T\vec{h} = -\vec{h}$

$R^s_\pi(-\vec{h}) = -\vec{h}$

No spin-orbit coupling

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



No (or negligible) net ferromagnetic moment

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

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

Hall (pseudo)-vector

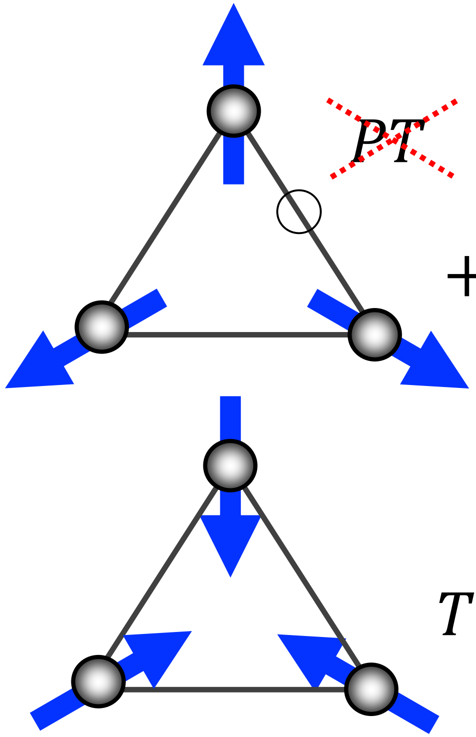
$T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$

Odd under time-reversal

Effective time-reversal symmetry $R^s_\pi T$

Suzuki et al. Phys. Rev. B 95, 094406 (2017)
Zelezny et al. PRL 119, 187204 (2017)

Hall conductivity



$\cancel{PT}$

$+\vec{h}$

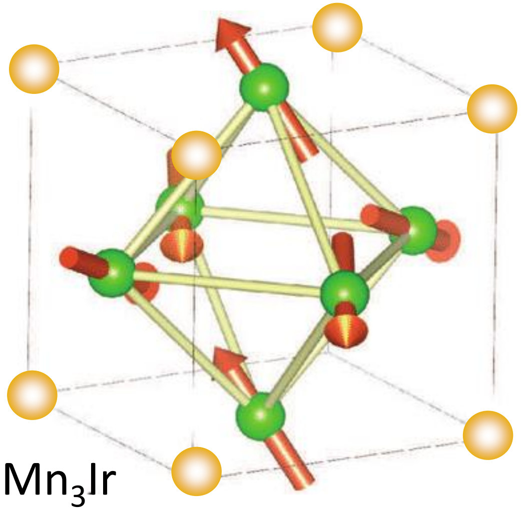
$T\vec{h} = -\vec{h}$

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_{φ}^{s}

No (or negligible) net ferromagnetic moment



Mn_3Ir

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

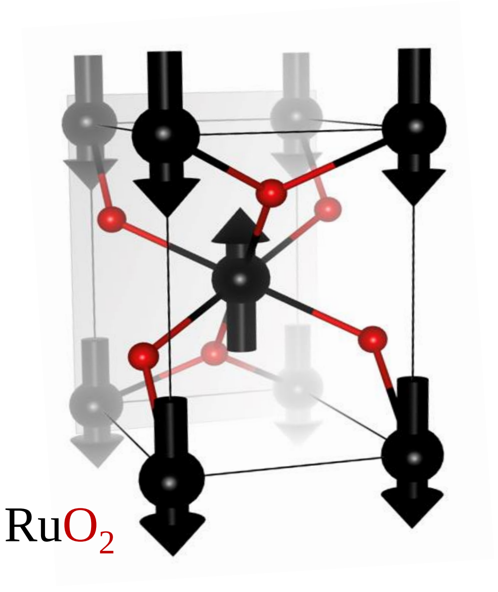
$$\vec{h} = (\sigma_{zy}^{\mathrm{a}}, \sigma_{xz}^{\mathrm{a}}, \sigma_{yx}^{\mathrm{a}})$$

Hall (pseudo)-vector

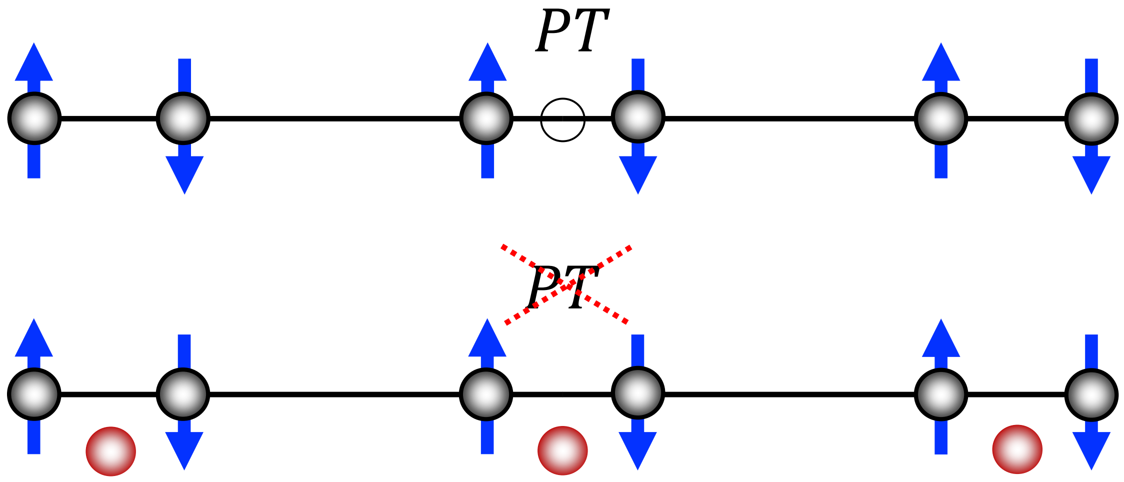
$$T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$$

Odd under time-reversal

Hall conductivity



Šmejkal et al. arXiv:1901.00445



Spin-orbit coupling

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

No (or negligible) net ferromagnetic moment

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

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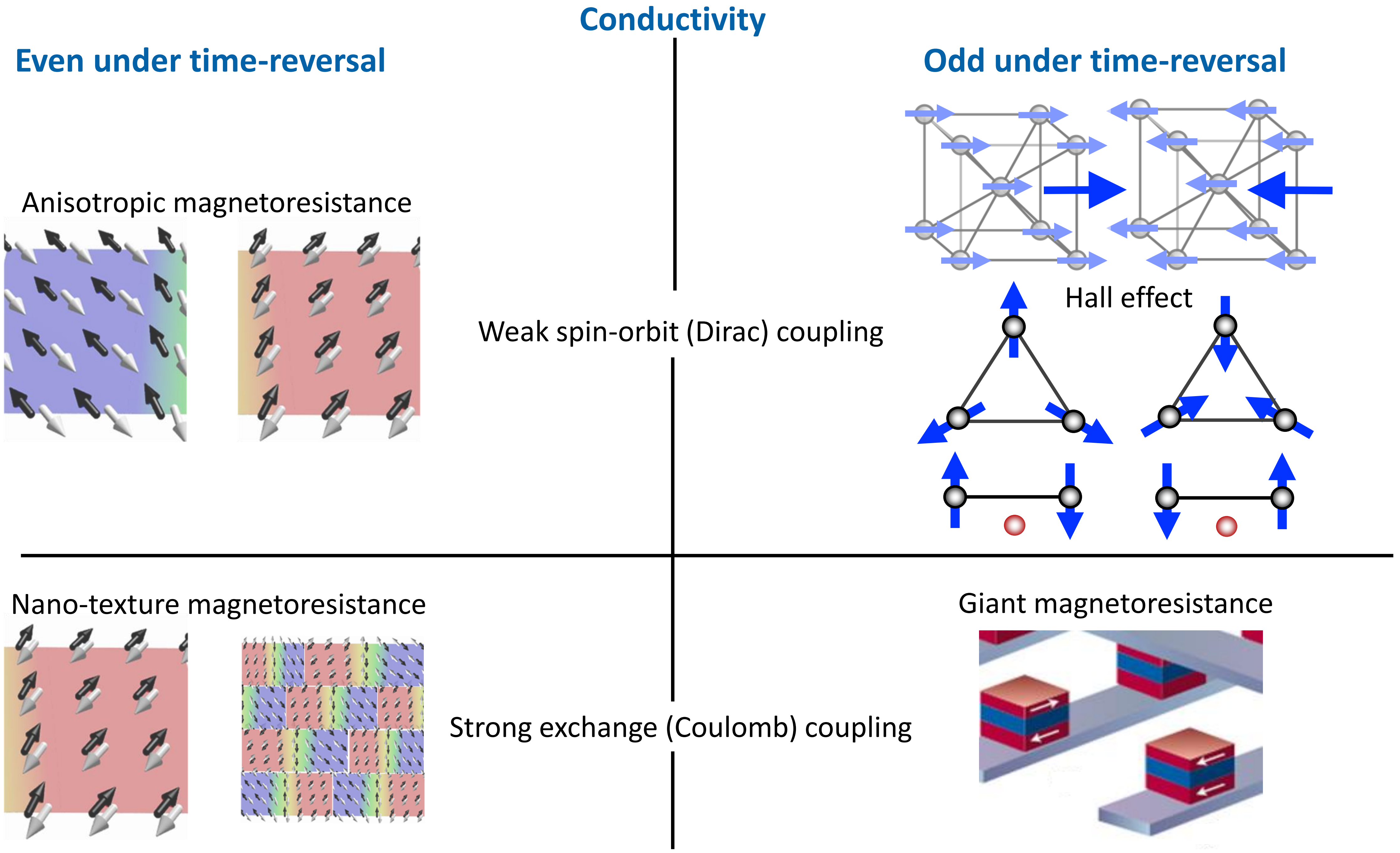
Hall (pseudo)-vector

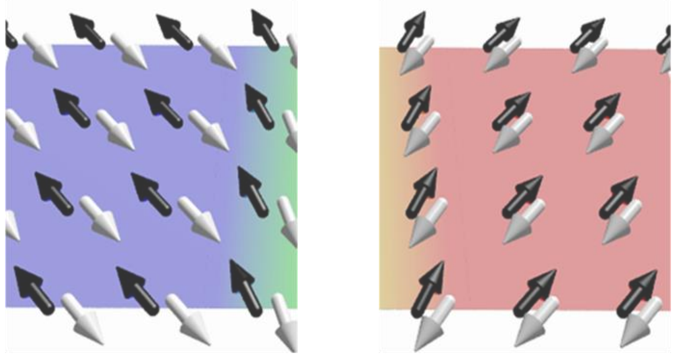
$$T\vec{h}(\vec{s}) = \vec{h}(-\vec{s}) = -\vec{h}(\vec{s})$$

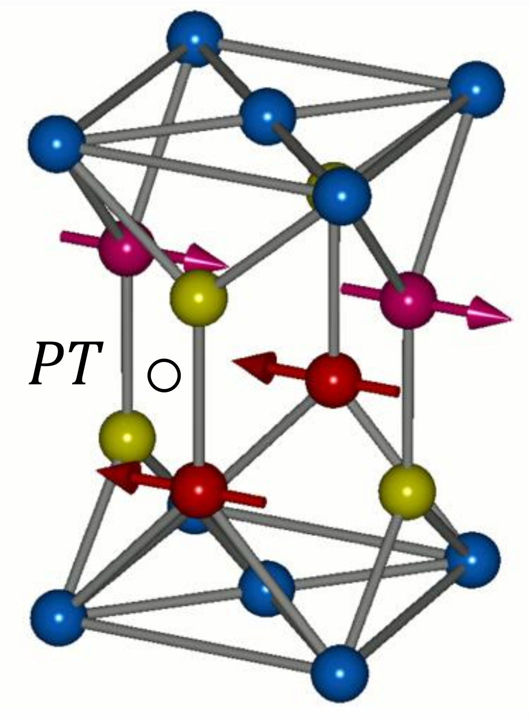
Odd under time-reversal


Conductivity
Even under time-reversal
Odd under time-reversal
Anisotropic magnetoresistance
Hall effect
Weak spin-orbit (Dirac) coupling
Nano-texture magnetoresistance
Giant magnetoresistance
Strong exchange (Coulomb) coupling

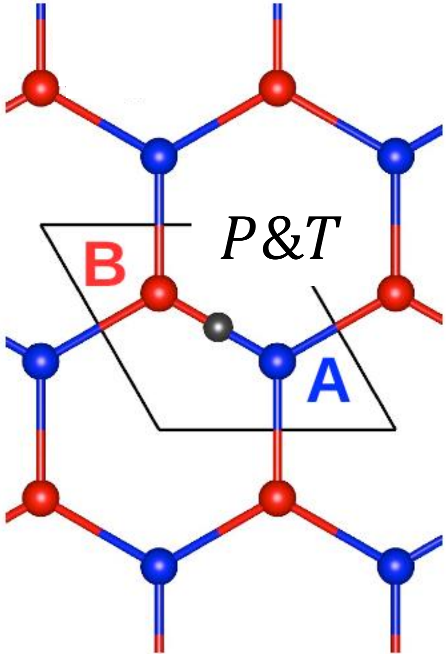
Even under time-reversal

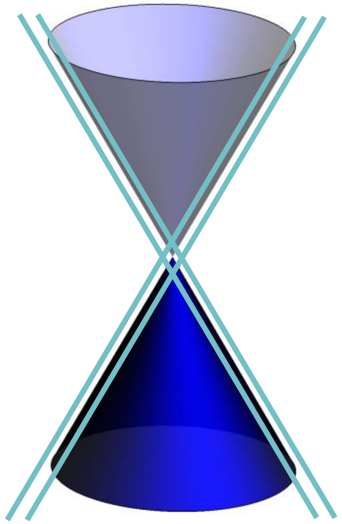
Anisotropic magnetoresistance





Topological Dirac semimetal





No magnetism in graphene

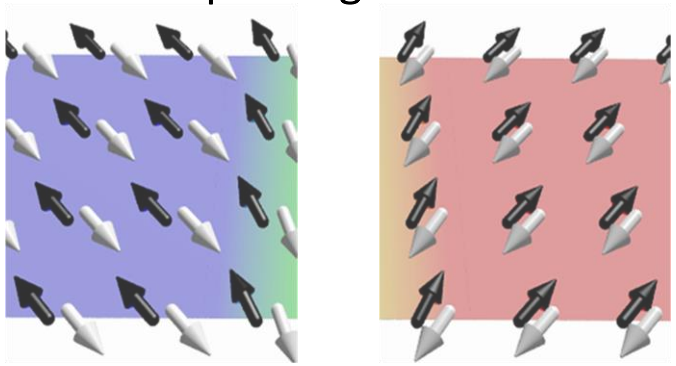
No PT symmetry in ferromagnets

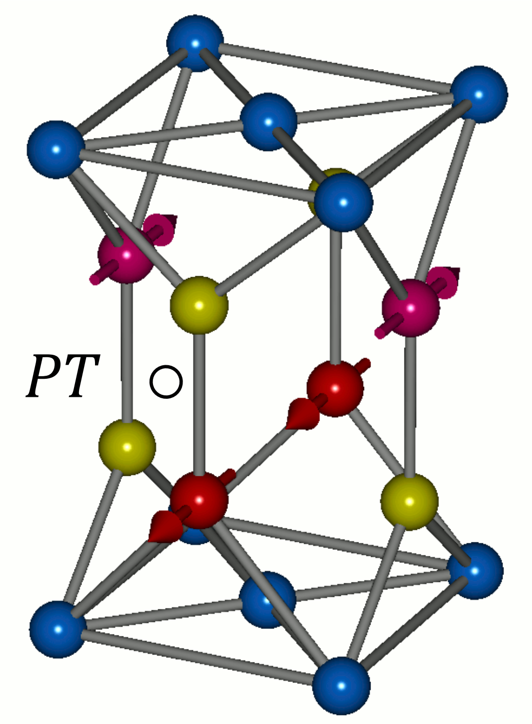
Smejkal, Mokrousov, Yan, MacDonald, Nature Phys. 14, 242 (2018)

Tang et al. Nature Phys. 12, 1100 (2016)
Smejkal et al. PRL 118, 106402 (2017)

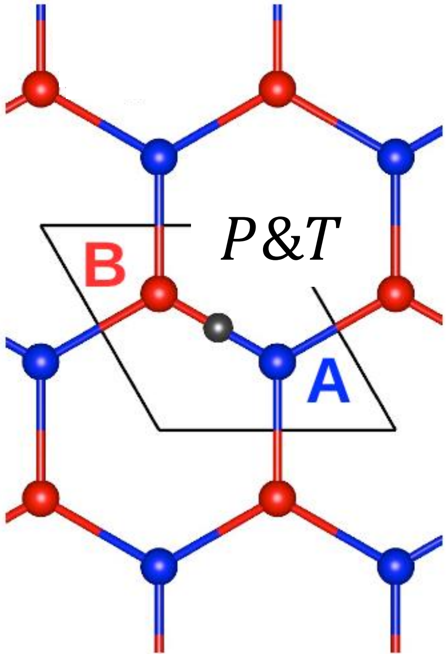
Even under time-reversal

Anisotropic magnetoresistance





Topological Dirac semimetal



No magnetism in graphene

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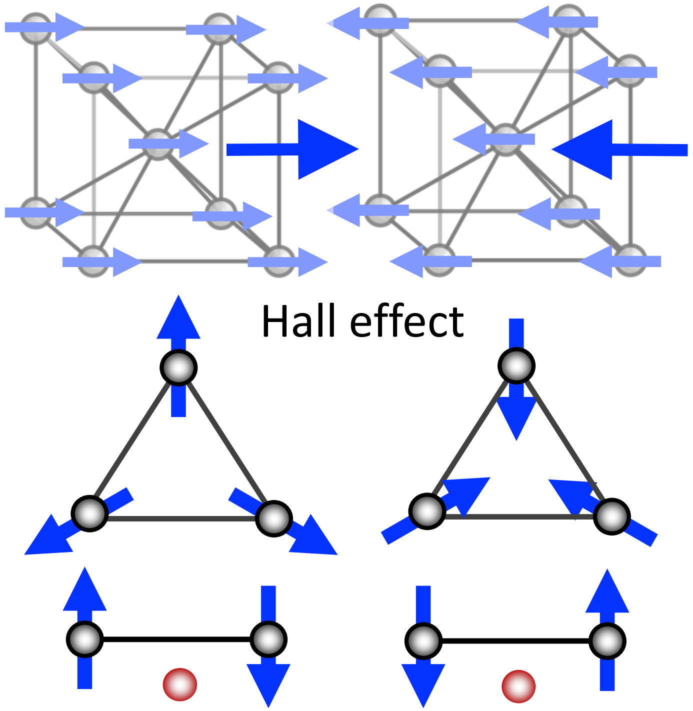
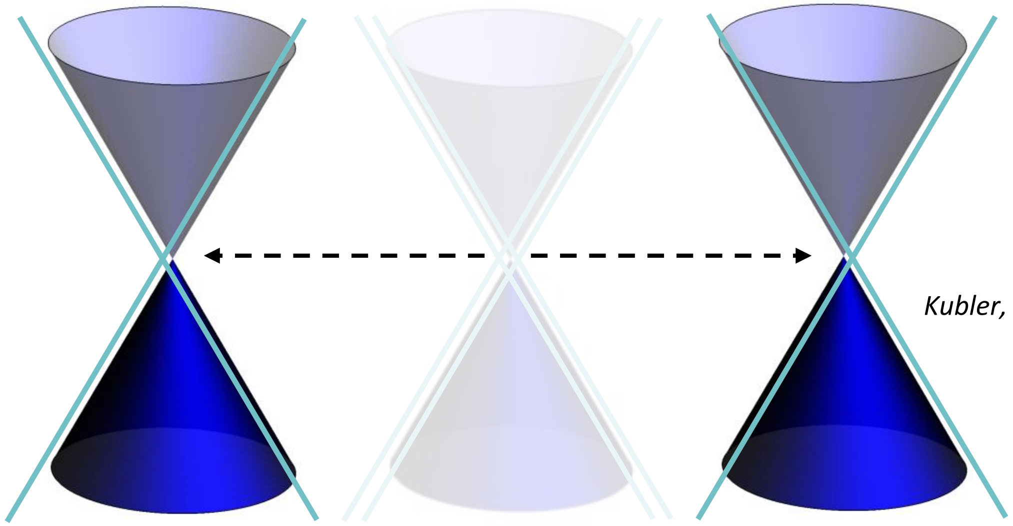
Odd under time-reversal

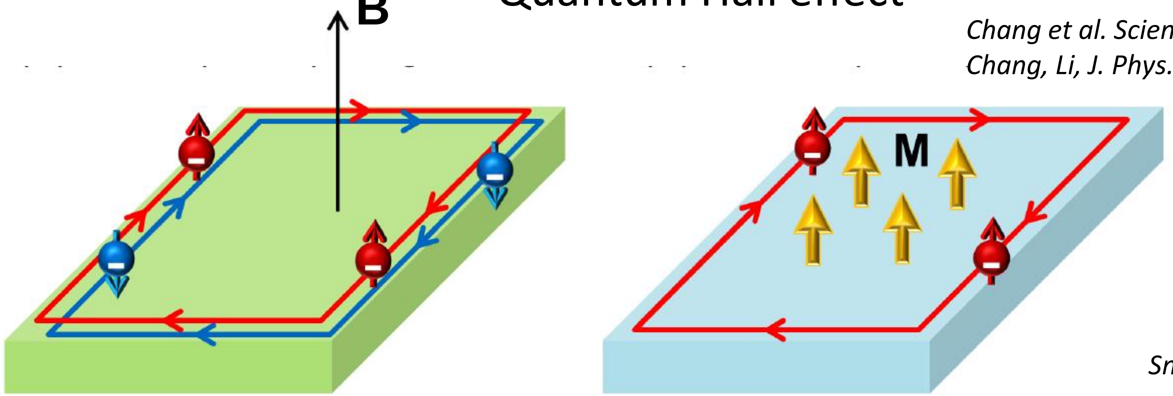


Topological Weyl semimetal



Kubler, Felser Europhys. Lett. 108, 67001 (2014)

Quantum Hall effect

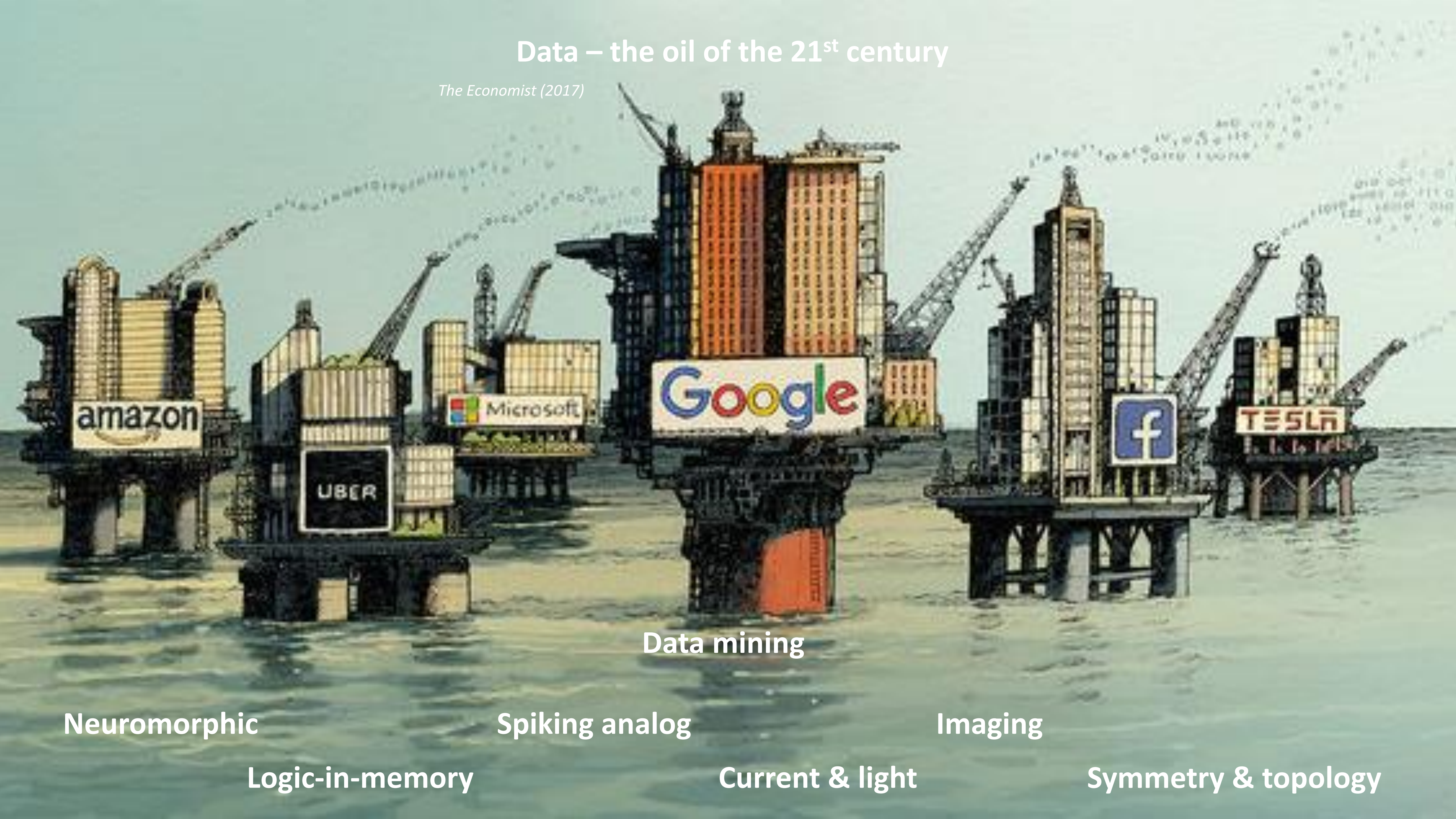


Chang et al. Science 340, 167 (2013)
Chang, Li, J. Phys.: Condens. Matter 28 123002 (2016)

Smejkal, Mokrousov, Yan, MacDonald, Nature Phys. 14, 242 (2018)

Data – the oil of the 21st century

The Economist (2017)



Data mining

Neuromorphic

Spiking analog

Imaging

Logic-in-memory

Current & light

Symmetry & topology

Non-CMOS storage & memory