Open questions in applied and fundamental nanomagnetism

Facing societal challenges of the 21st century

nano[front]mag-cm

nuevas fronteras
del nanomagnetismo
fundamental y aplicado

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Slides: http://fruchart.eu/slides

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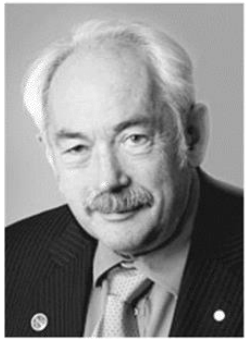
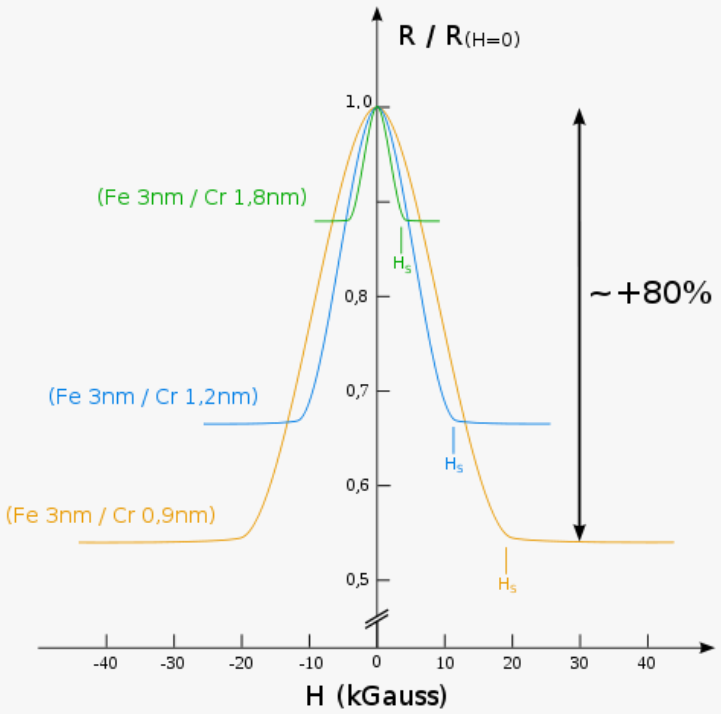
- Decades of nanomagnetism



Giant magneto-resistance



A.Fert et al, PRL (1988);

P.Grunberg et al, patent (1988) +PRB (1989)

The Nobel Prize in Physics 2007

Photo: U. Montan
Albert Fert
Prize share: 1/2

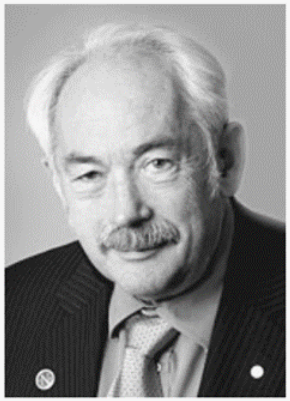
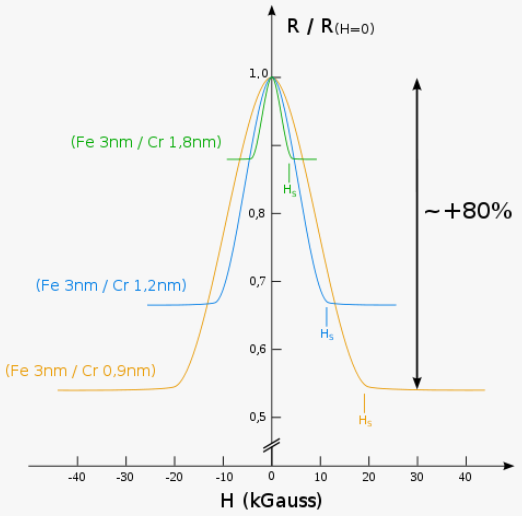


Photo: U. Montan
Peter Grünberg
Prize share: 1/2

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg *"for the discovery of Giant Magnetoresistance"*

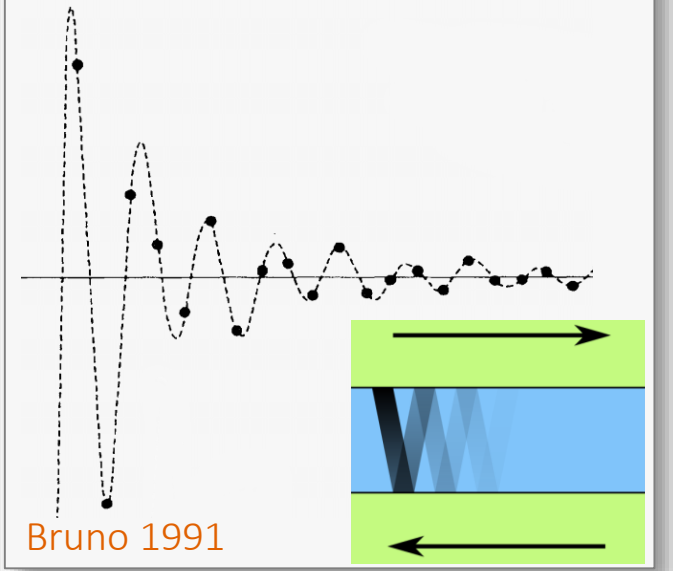
30 years of nanomagnetism & spintronics

Giant magneto-resistance



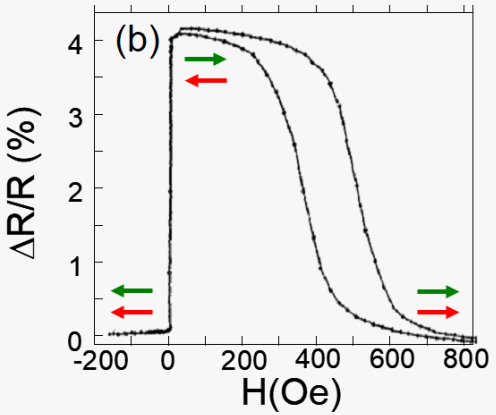
1988

RKKY coupling



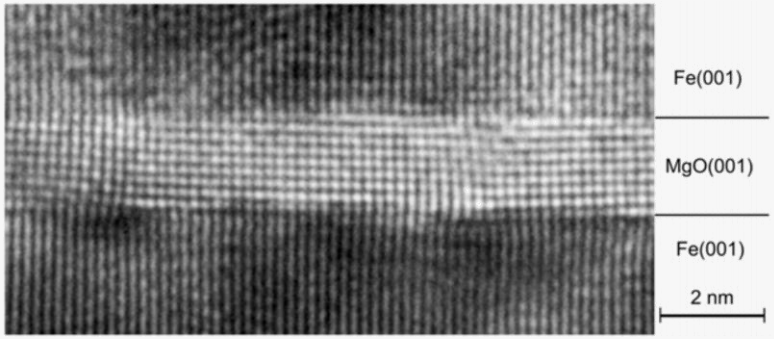
Bruno 1991

Spin-valve concept



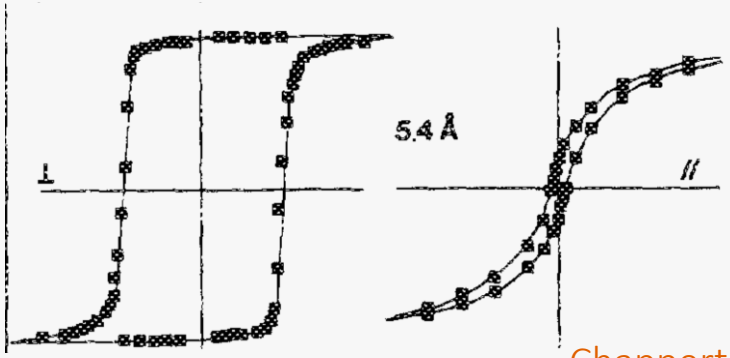
Diény 1991

Tunneling magneto-resistance



Yuasa 2007

Perpendicular magnetic anisotropy

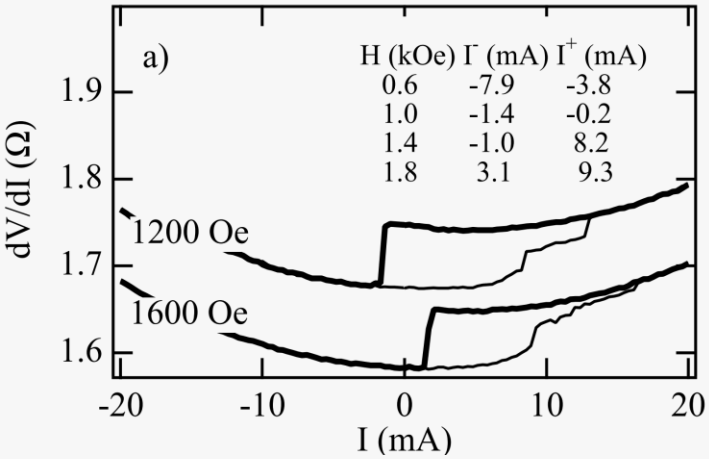


Chappert 1988

30 years of nanomagnetism & spintronics

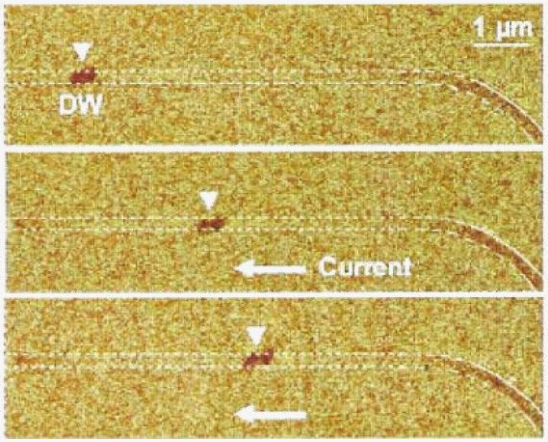
Spin-transfer torque

Magnetization switching



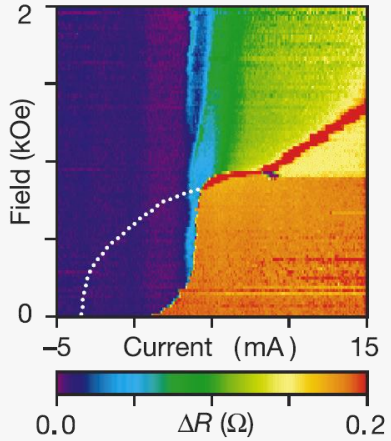
Katine 2000

Domain-wall motion



Yamaguchi 2004

Oscillator



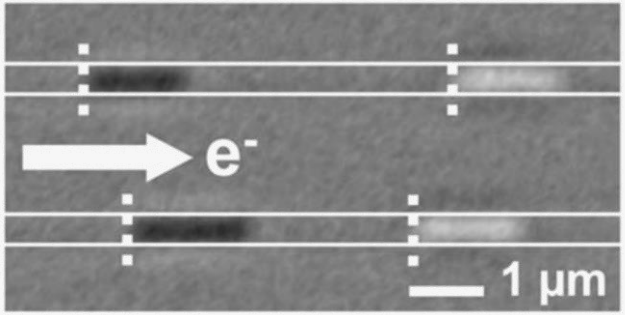
Kiselev 2003

Spin-Hall effect

SHE, ISHE

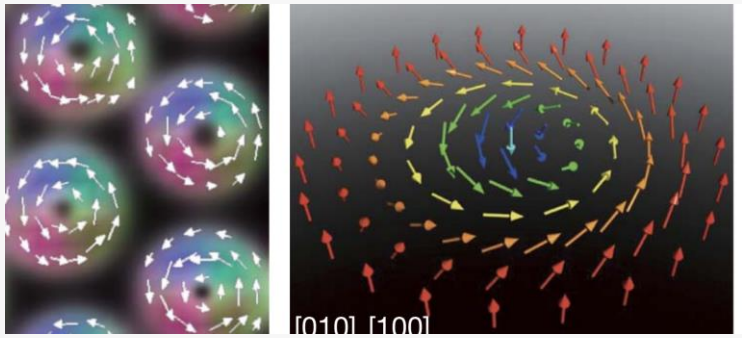
Valenzuela 2011

Domain wall motion



Moore 2008

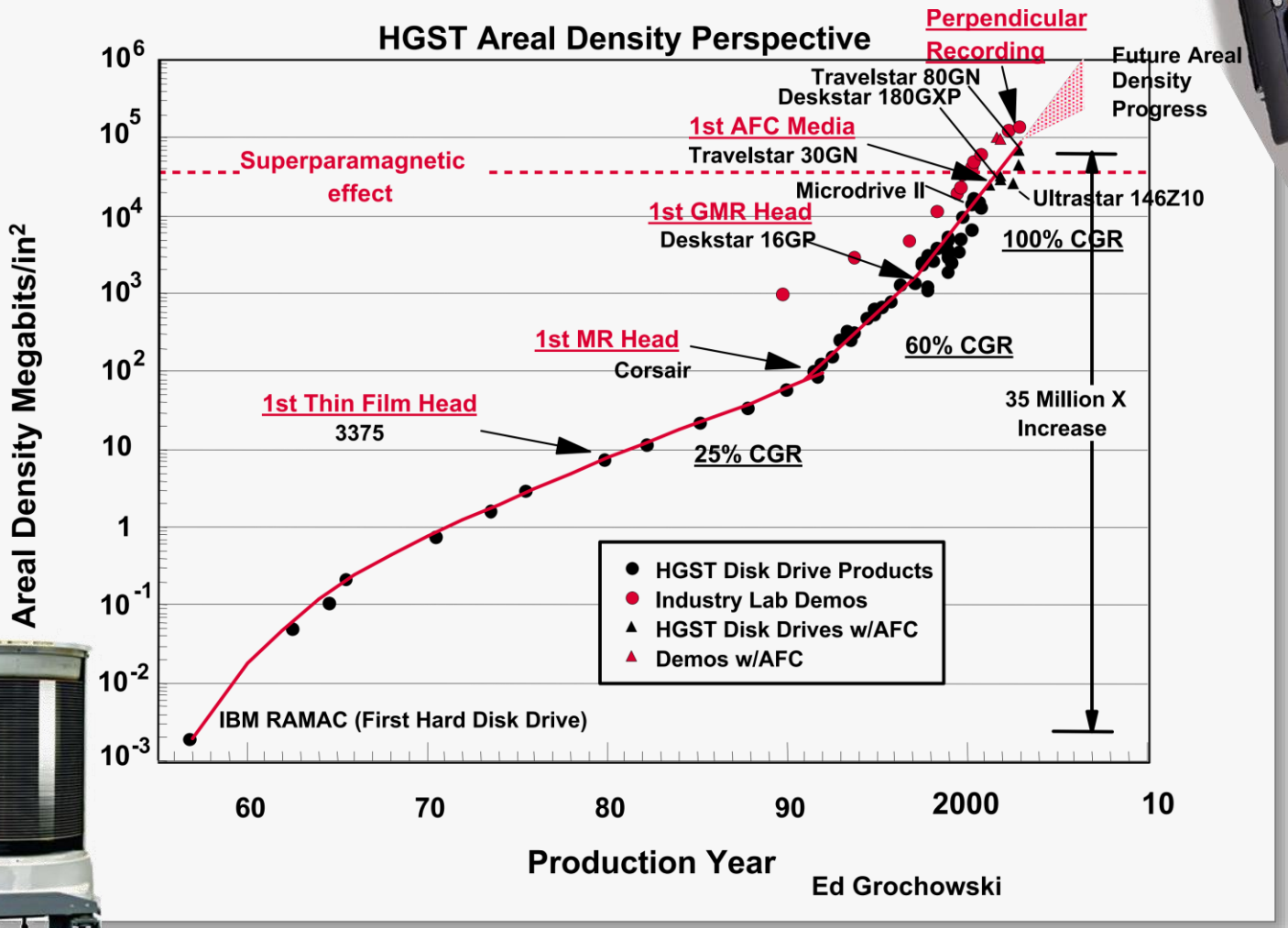
DMI, skyrmions



Tokura 2010

Technology pushing science: HDDs

Hard disk drives



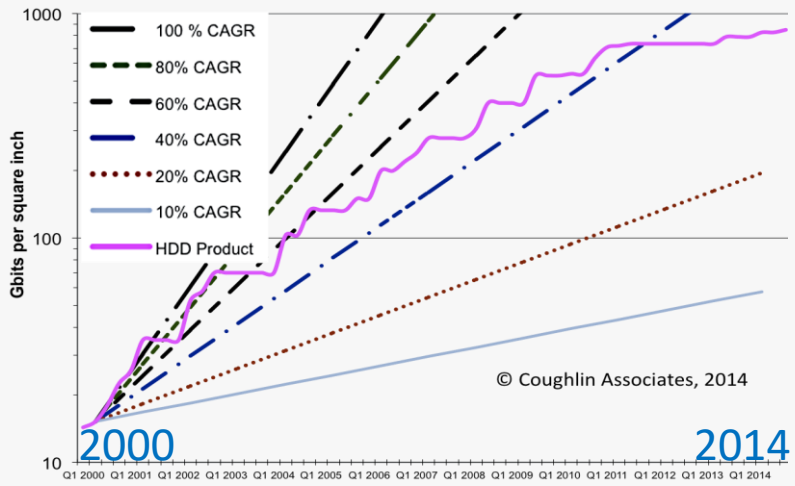
Technology pushing science: HDDs

Steady progress of HDD, however: incremental, keeping the design

1956

Today

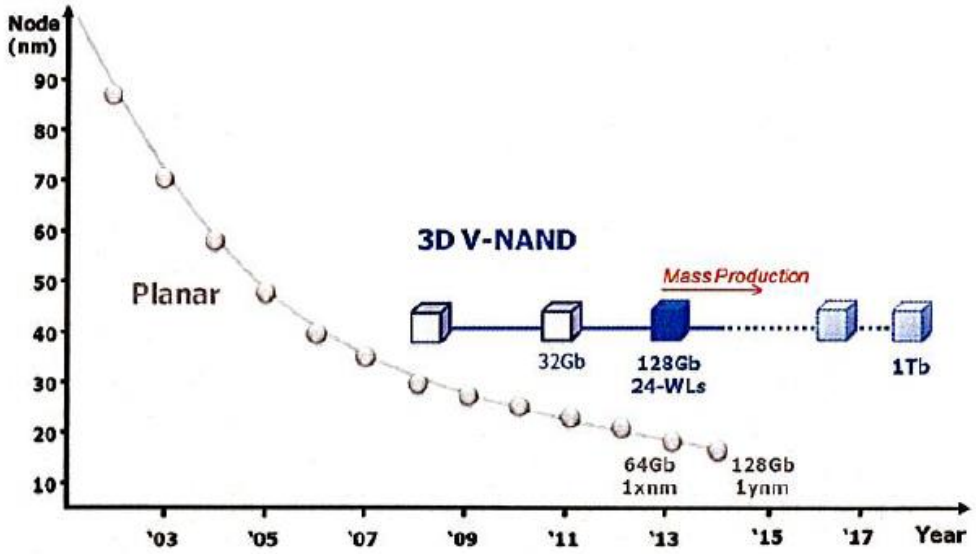
Staggering areal density



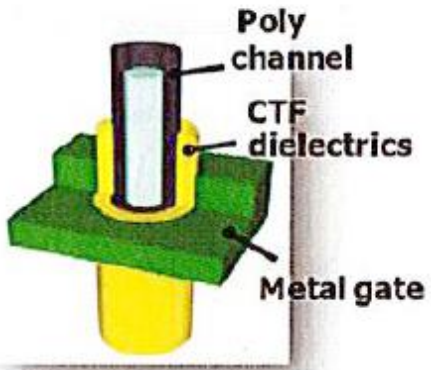
- Increasing fundamental and technological bottlenecks
- Any 2D-based technology is bound to face an end

Technology pushing science: HDDs

Competing technologies go 3D



24-layer 3D NAND Flash



Cross-over in 2016

- **1Gb/mm2 → 600Gb/in2...**
- **Magnetic mass storage may only remain for niche applications**

K. T. Park et al., IEEE J. Sol. State Circuits 50 (1), 204 (2015)

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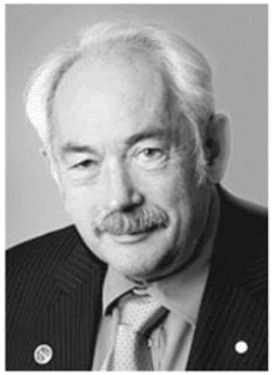
- Decades of nanomagnetism

- Societal challenges

Frontier backgrounds for nanomagnetism

Societal requests and challenges

- Energy consumption – Pollution, global warming
- Communication: more, faster, cheaper
- Intelligent systems: comfort, safer, less energy
- Sustainability: energy, material criticality
- Health

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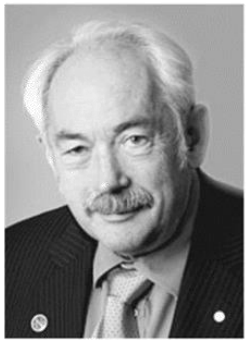
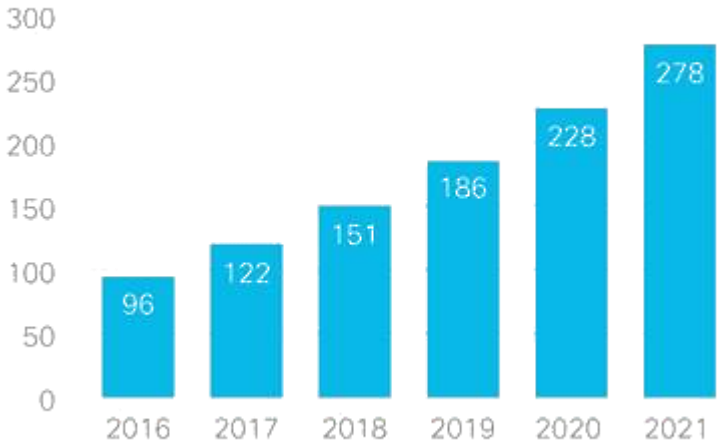


- Societal challenges

- Energy consumption in ICT

Continuous growth of data handling

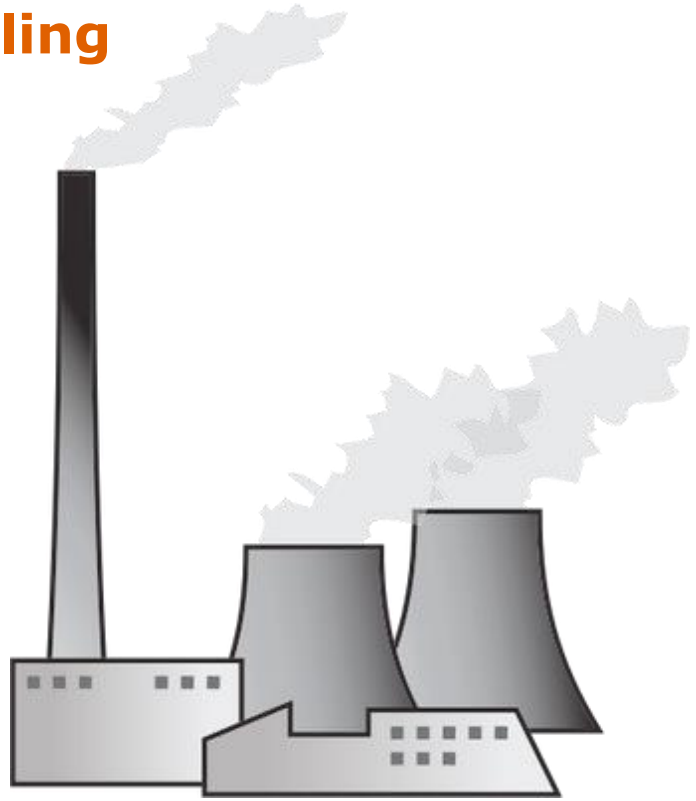


https://www.smartinsights.com

Continuous growth of data handling

1 Farm = Multi-MW operating power

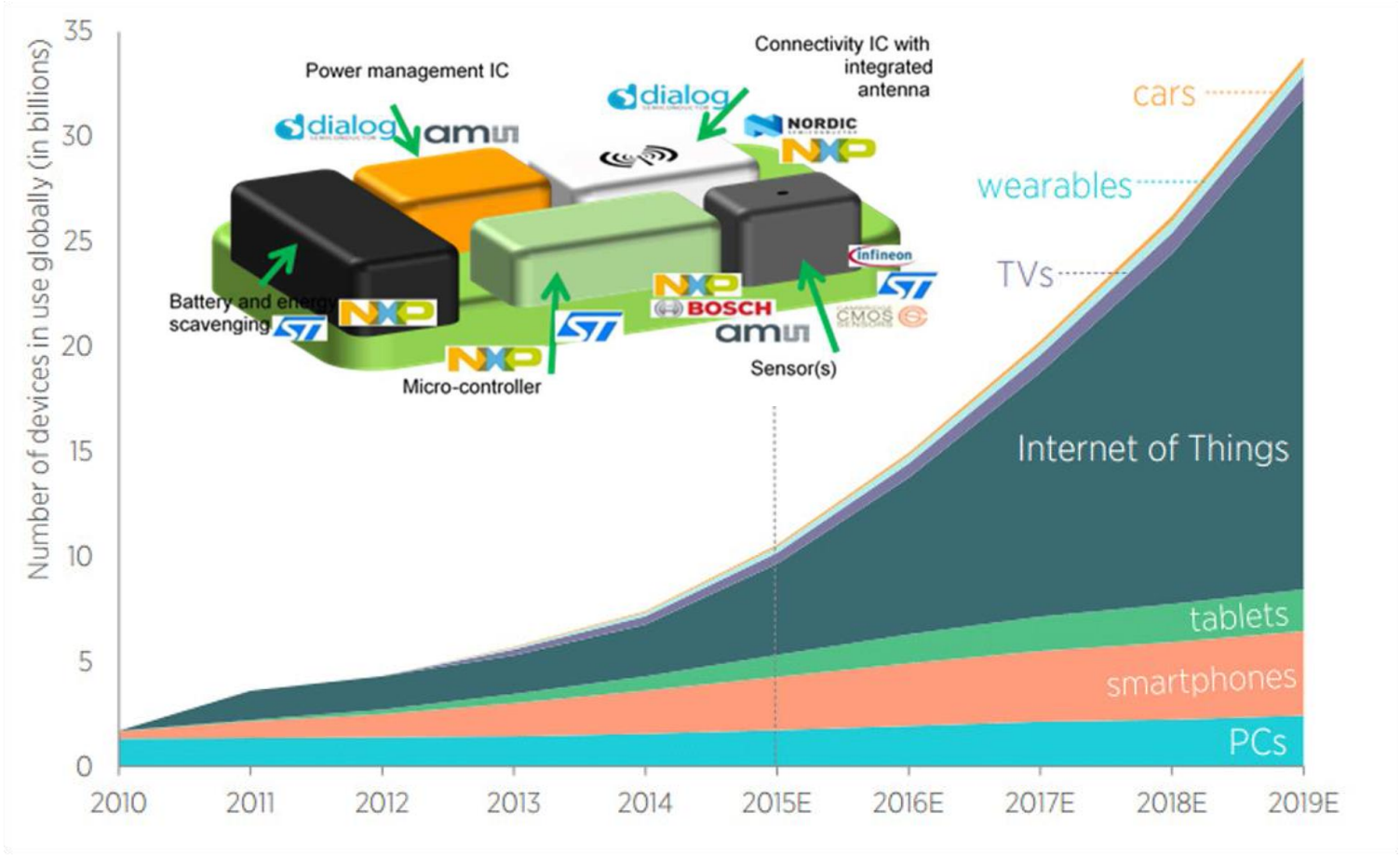
+ Same amount for cooling



Requirements

- Cost
- Environment

Internet of Things: a booming market

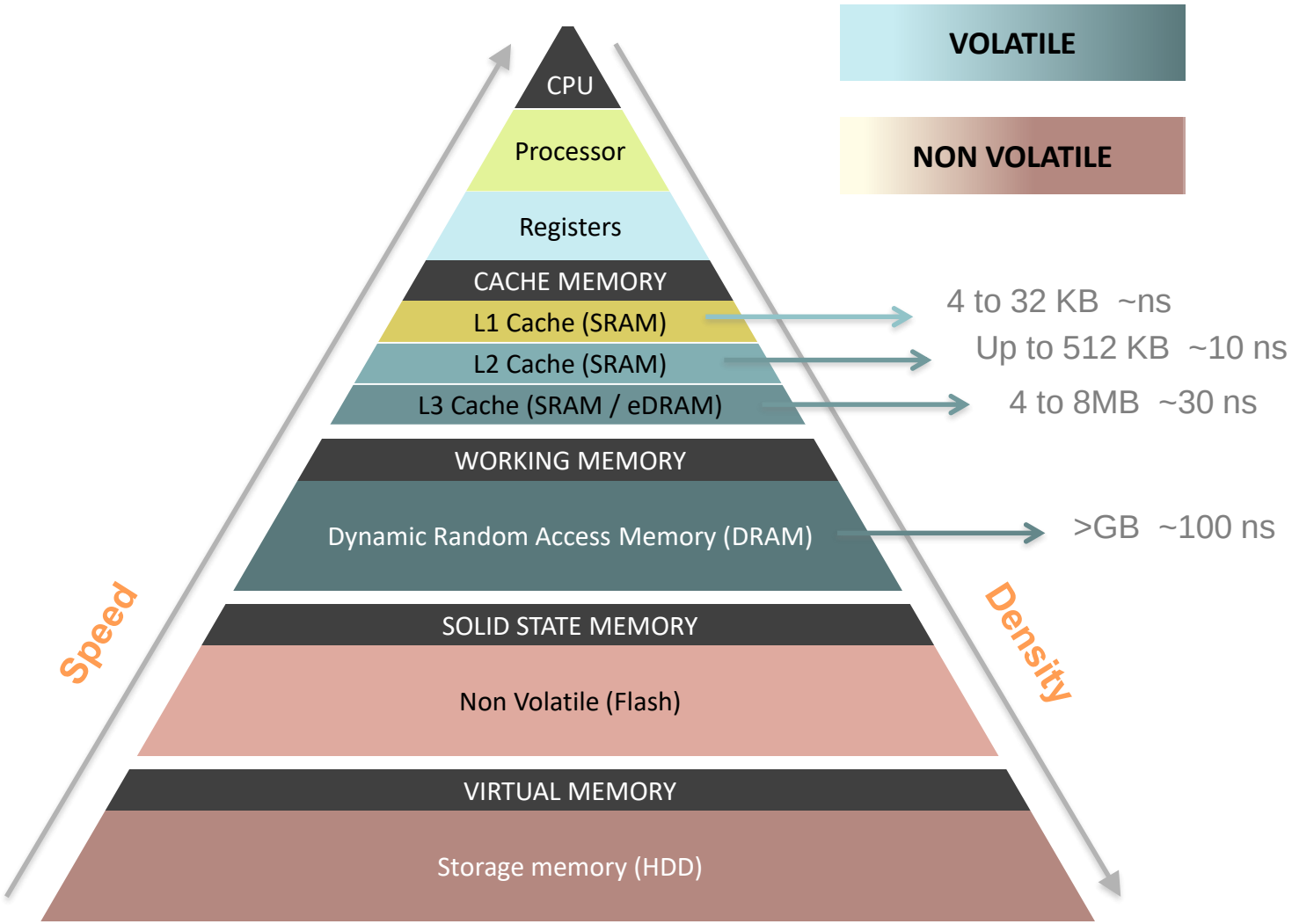


Source: John Greenough, "The Internet of Everything 2015," *Business Insider Intelligence*. Produced by Adam Thierer and Andrea Castillo, Mercatus Center at George Mason University, 2015.

Requirements

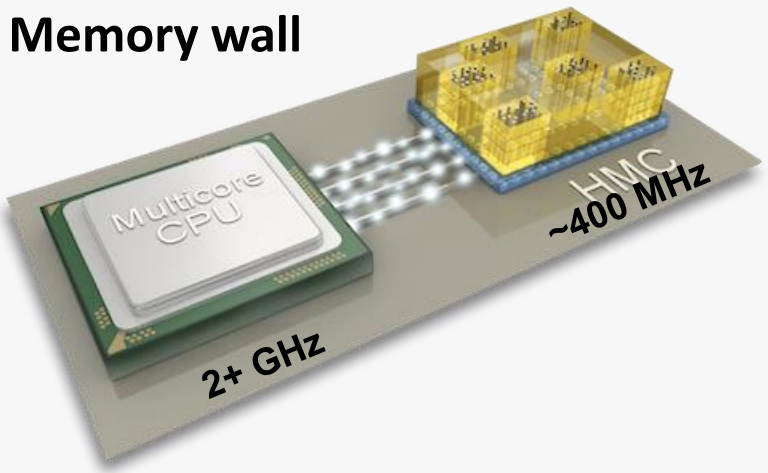
- Cost, weight, material
- Low-power

Memory challenges to address



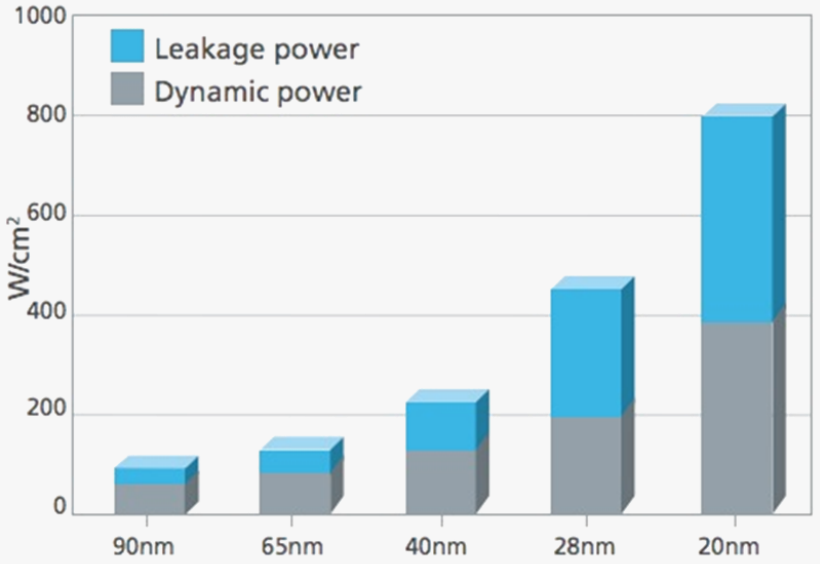
Memory challenges to address

Memory wall



- Logic keeps awaiting data
- Limits speed
- Increases power consumption

SRAM leakage



Challenges

- Embed memory
- (Leakage) power

Why MRAM?

Non-volatile
like Flash
10+ years retention

Dense
like DRAM
$10F^2$, small overheads

Fast
Like SRAM
~10ns in normal mode

High Endurance
like SRAM / DRAM
10^{12} cycles, up to 10^{16}



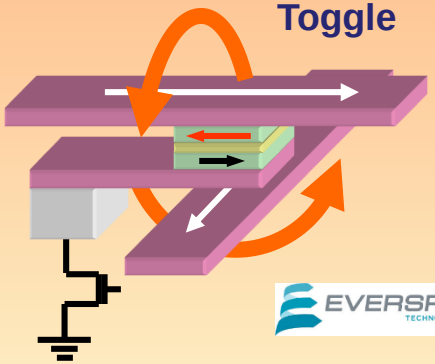
MRAM is not the best but …

- Can replace SRAM at 1/6th of size, zero leakage
- Can replace e-Flash at >105x speed, lower power
- Can replace DRAM (if running out of steam)

Generations of MRAM

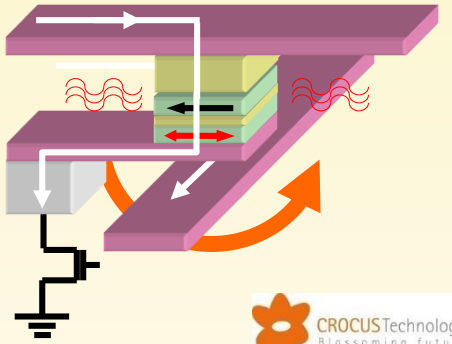
Field-driven

Toggle



EVERSPIN TECHNOLOGIES

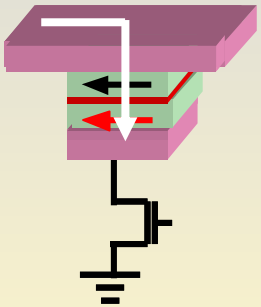
Thermally Assisted (TAS)



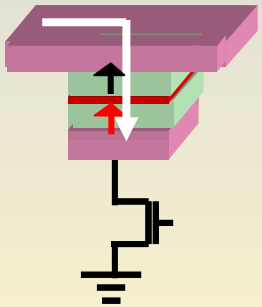
CROCUS Technology
Blossoming future

STT (SPRAM)

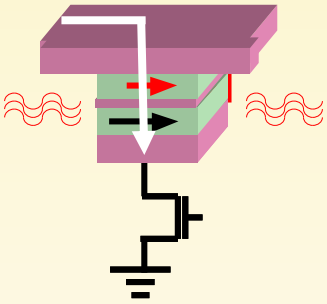
Planar



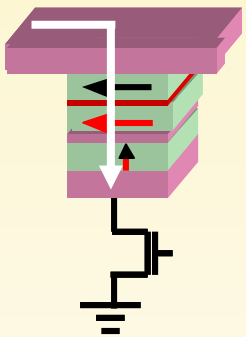
Perpendicular



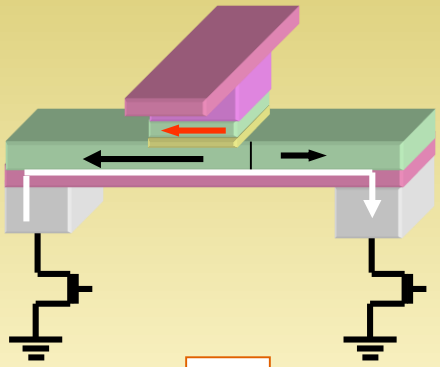
STT-TAS



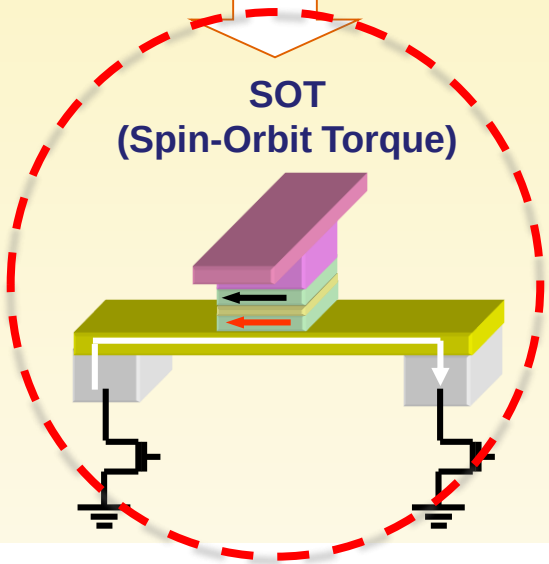
OST (Precessional)



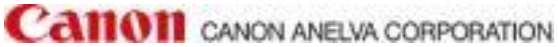
DW motion



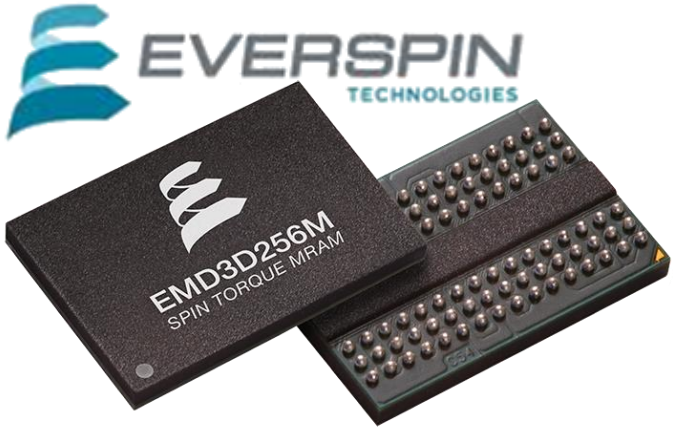
SOT (Spin-Orbit Torque)



MRAM players

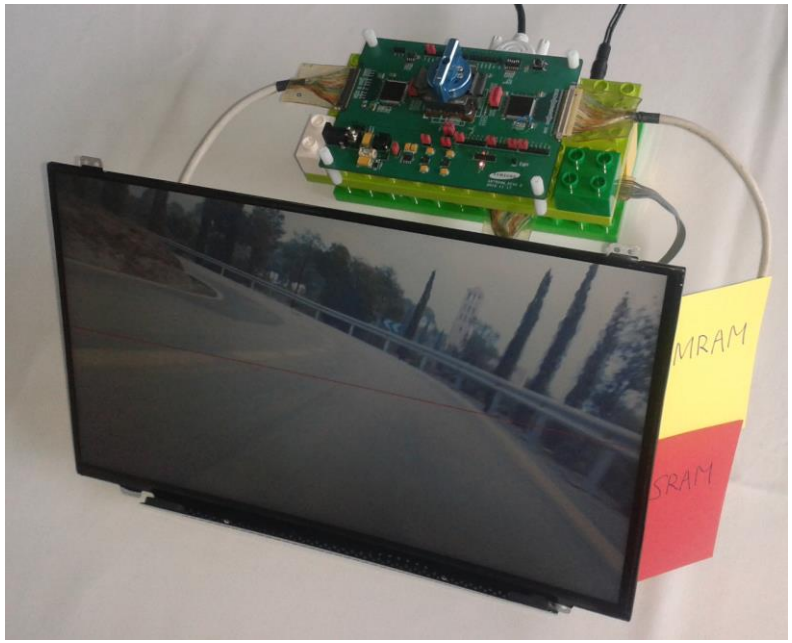


MRAM coming to reality



256Gb in production. 1Tb in the pipes.

SAMSUNG



Demo at the 7th MRAM
Global Innovation Forum (Zurich, June 2016)

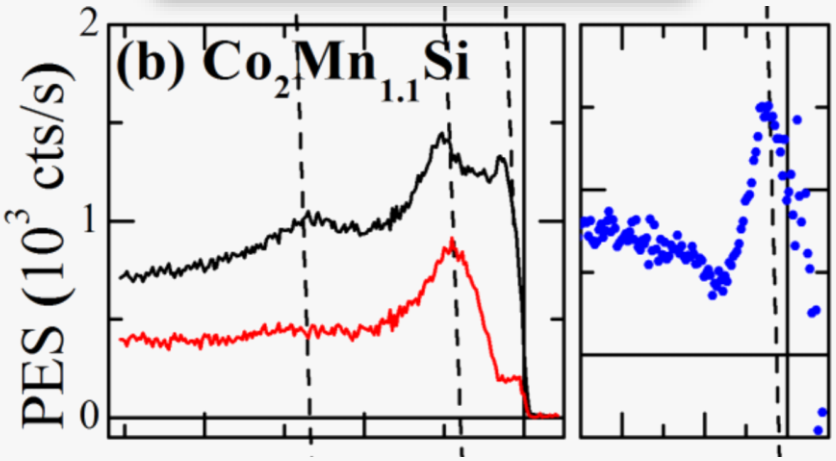
https://www.linkedin.com/company/mram-info/
https://www.mram-info.com

Fundamental frontiers and challenges: efficiency

Efficiency of writing

- Spin-Hall, three-terminal?
- Spin-Hall efficiency, topological insulators?
- Electric field effects
- Low damping: heusler etc.

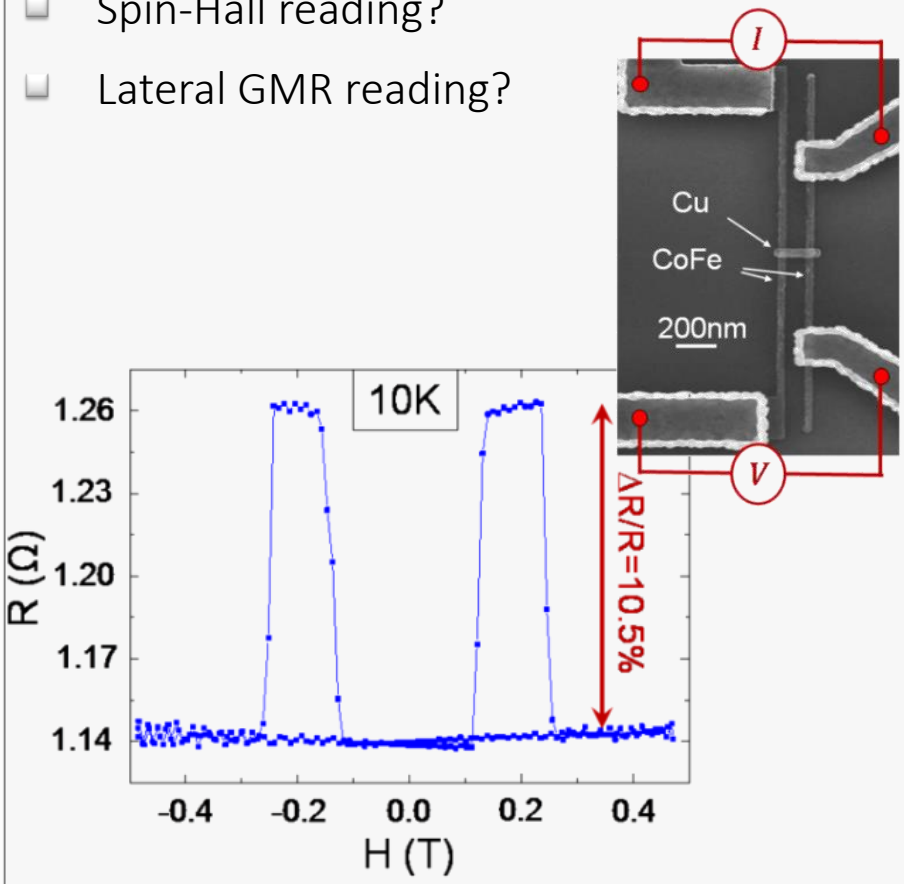
Co2MnSi Heusler alloy
Damping $\alpha < 7 \cdot 10^{-4}$



S. Andrieu et al., PRB93, 094417 (2016)

Efficiency of reading

- Electric field, multiferroics
- Spin-Hall reading?
- Lateral GMR reading?



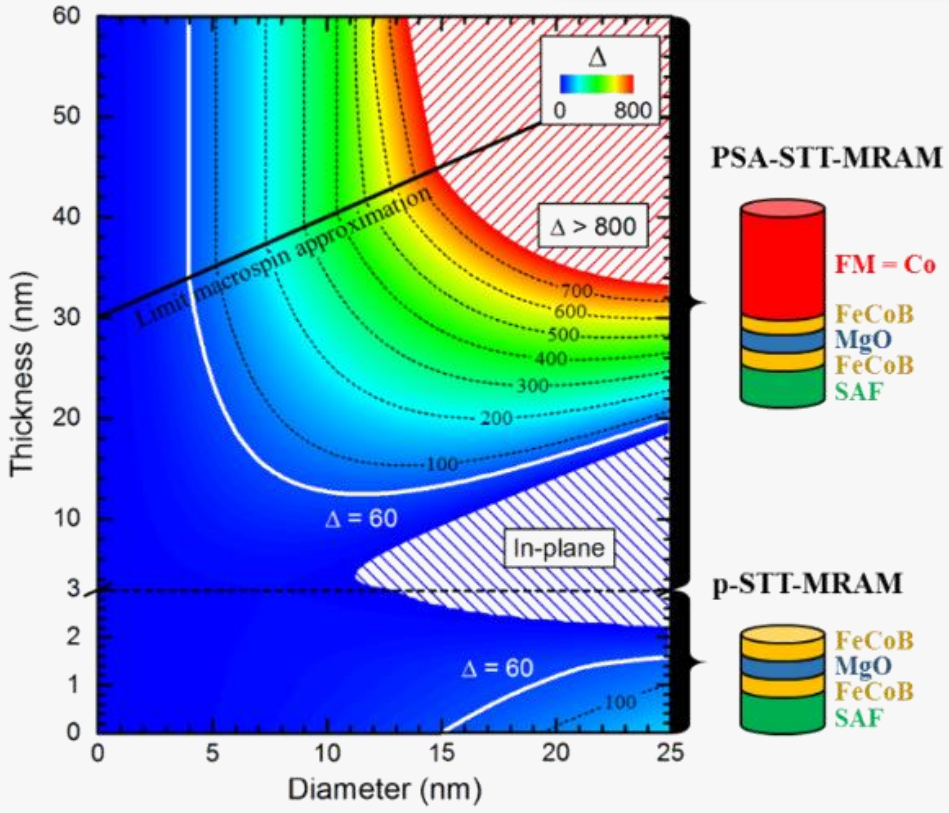
G. Zahnd, Sci. Rep. 7.1 9553 (2017)

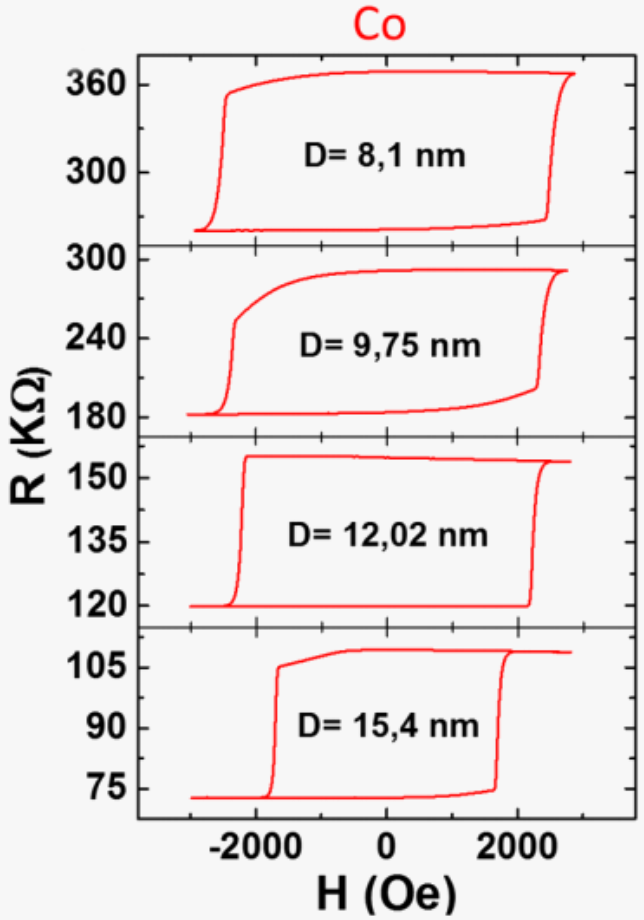
Fundamental frontiers and challenges: size

Bit size & retention

- 3D design
- Patterning challenges

PSA STT-MRAM
Perpendicular Shape Anisotropy





arXiv:1803.02663 (SPINTEC)

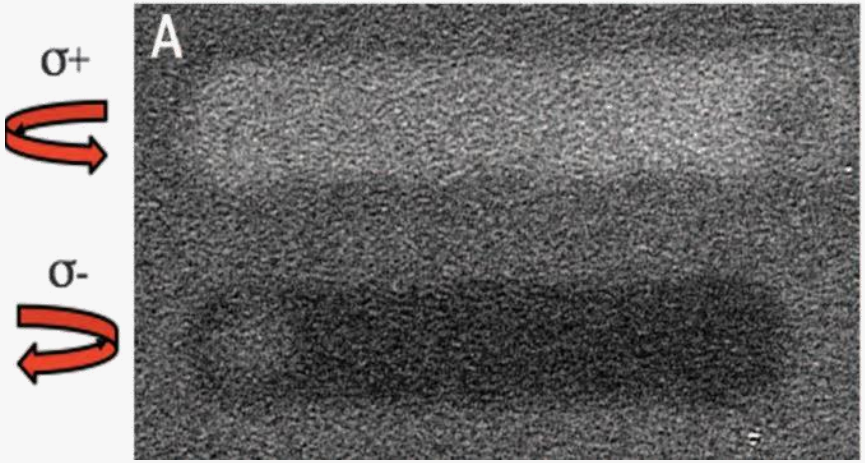
Watanabe et al, Nat.Com. 9, 663 (2018)

Fundamental frontiers and challenges : time

Fast optical switching

$Gd_{22}Fe_{74.6}Co_{3.4}$
λ=800nm, 40fs

C. D. Stanciu, PRL99, 047601 (2007)



C. H. Lambert, Science 345, 1337 (2014)

Physics

- Three-temperature model
- Superdiffusive hot electrons
- Multiphysics and multiscale modeling

Technology

- All-optical or not?
- One shot or stochastic?
- Material versatility?

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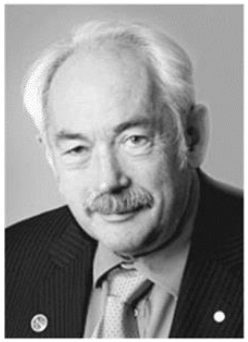
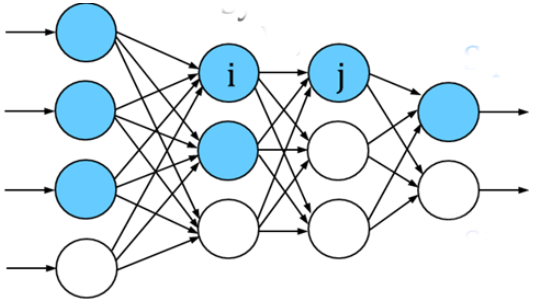


- Societal challenges

- Energy consumption in ICT

- Neuromorphic computing



New computing scheme: neuromorphic

Brain

20 W

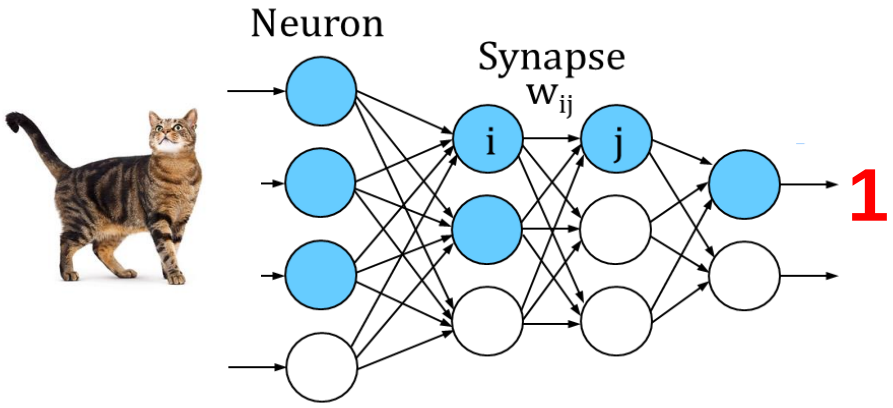
- Low power
- Non-linear, stochastic

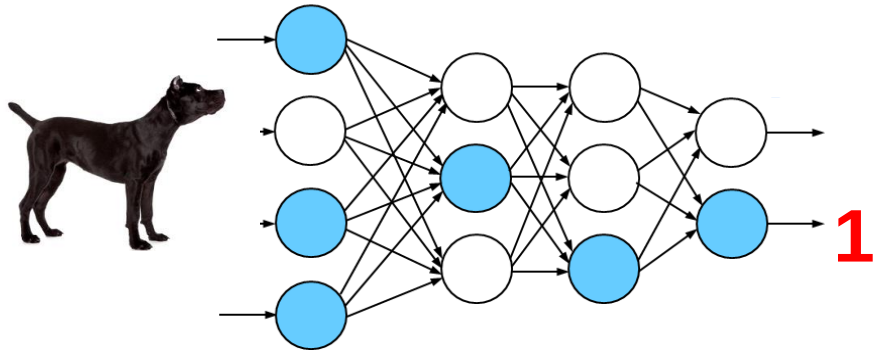
High-performance computing

10 MW

- High power
- Deterministic

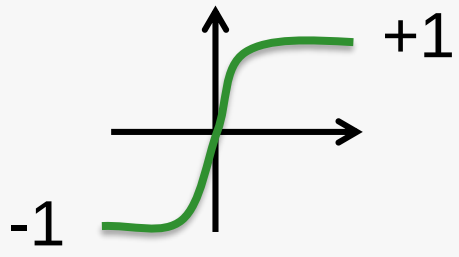
How do neurons and synapses work?





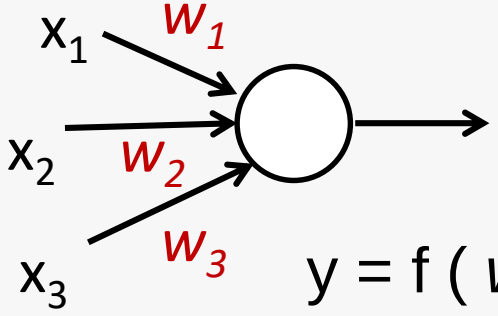
Neurons

- Non-linear



Synapses

- Analog valves (weighs w)



$$y = f (w_1 x_1 + w_2 x_2 + w_3 x_3)$$

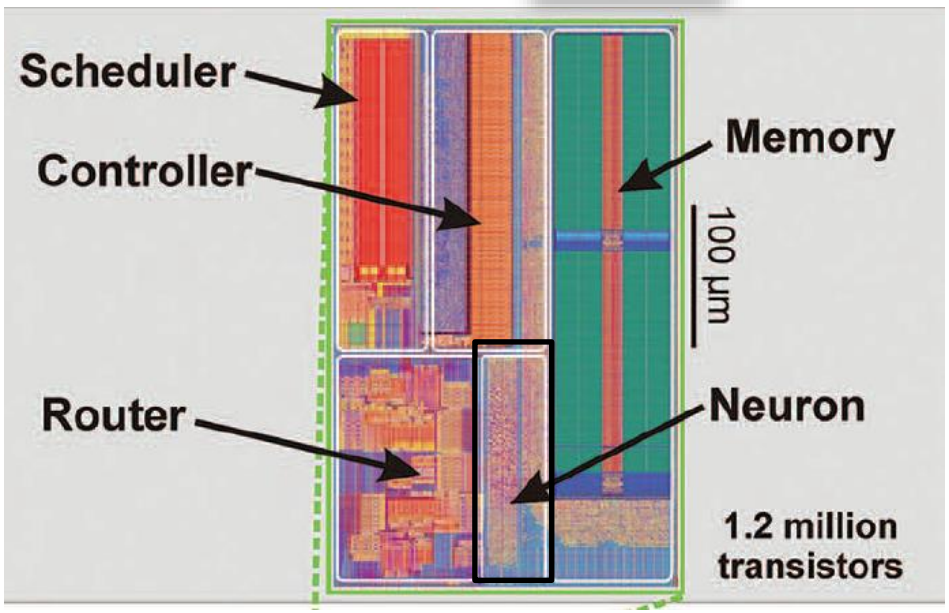
- **Ingredients for neural networks: non-linearity, memory and plasticity**

CMOS emulated circuits

- A transistor is nanoscale but it is just a switch
- CMOS does not provide memory (volatile)

CMOS neuron 10-100 µm

CMOS synapse 10 µm



Merolla et al, Science 345, 668 (2014)

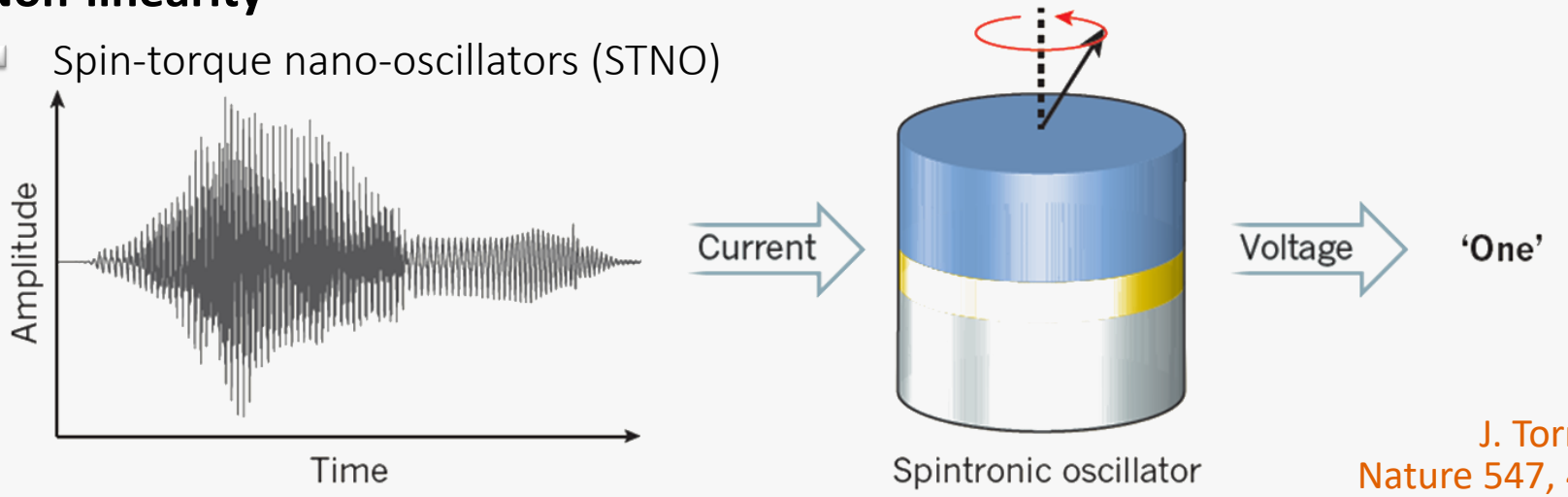
Brainscales 20 wafer machine.
4M neurons, 1B synapses

- **May neurons and synapses be produced as hardware components ?**

Assets of spintronics for neuromorphic computing

Non-linearity

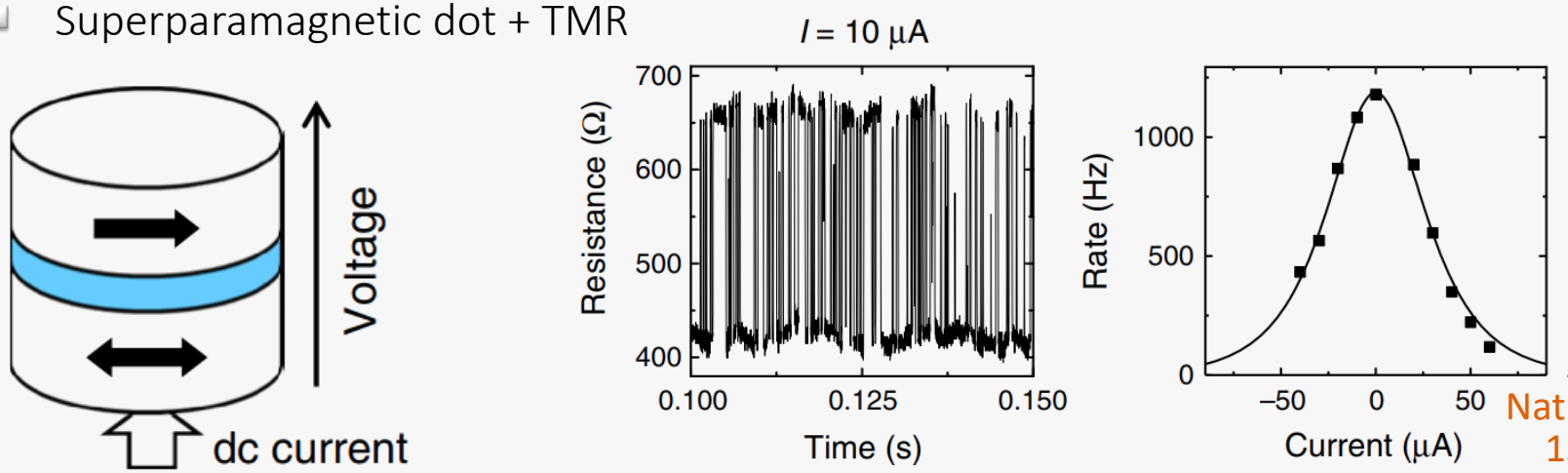
- Spin-torque nano-oscillators (STNO)



J. Torrejon et al, Nature 547, 428 (2017)

Stochasticity

- Superparamagnetic dot + TMR



A. Mizrahi, Nat. Comm. 9, 1533 (2018)

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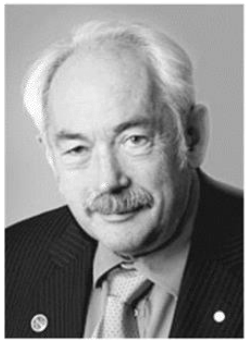
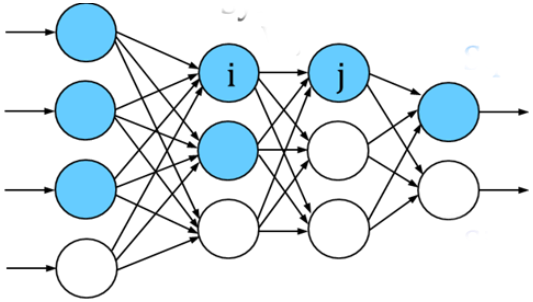
- Decades of nanomagnetism

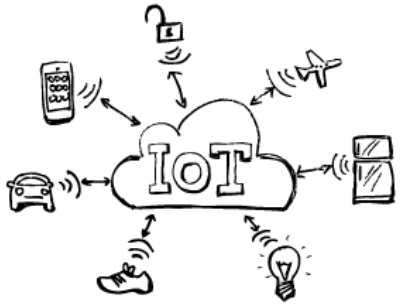
- Societal challenges

- Energy consumption in ICT

- Neuromorphic computing



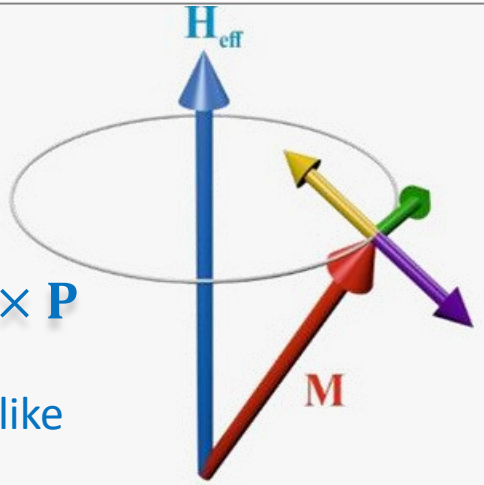
- Wireless communication



Current-driven precession of magnetization

$$\frac{d\mathbf{m}}{dt} = -|\gamma_0|\mathbf{m}\times\mathbf{H} + \alpha\mathbf{m}\times\frac{d\mathbf{m}}{dt} + |\gamma_0|a_j\mathbf{m}\times(\mathbf{m}\times\mathbf{P}) + b_j\mathbf{m}\times\mathbf{P}$$

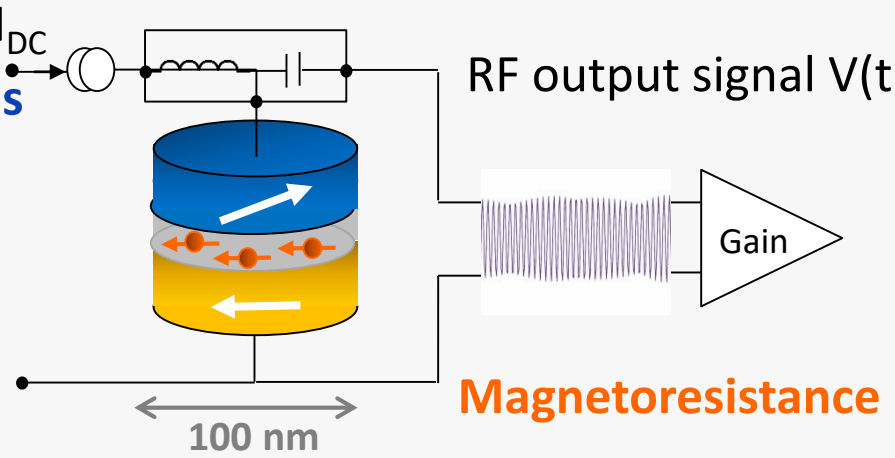
Damping-like Field-like



Implementation in spin-torque nano-oscillators (STNO)

Steady state oscillations

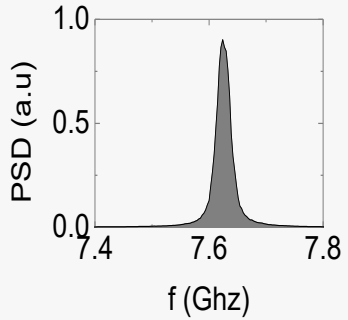
Spin momentum transfer



RF output signal V(t)

Gain

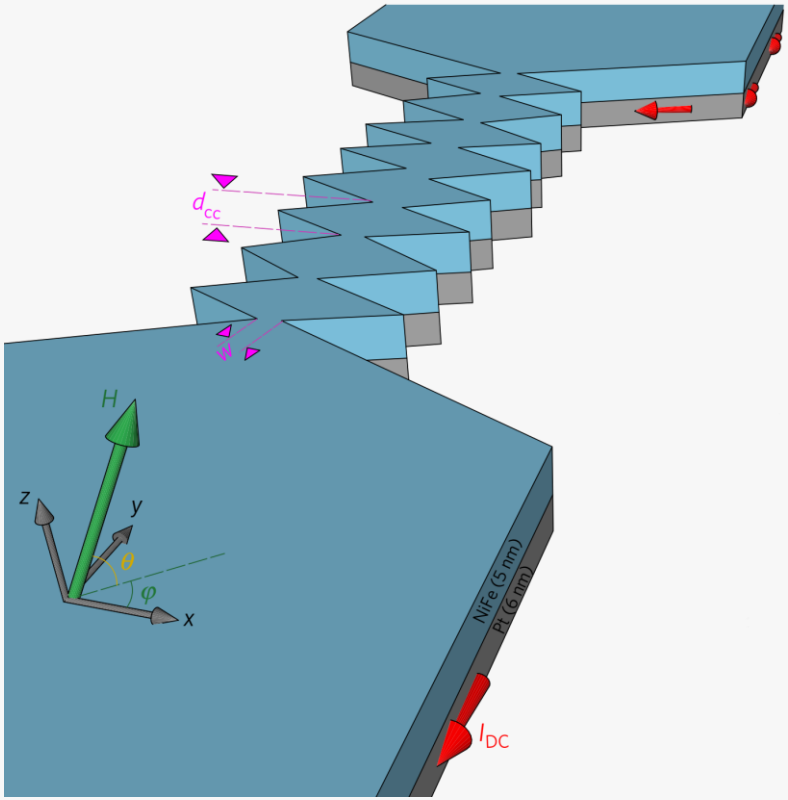
Magnetoresistance



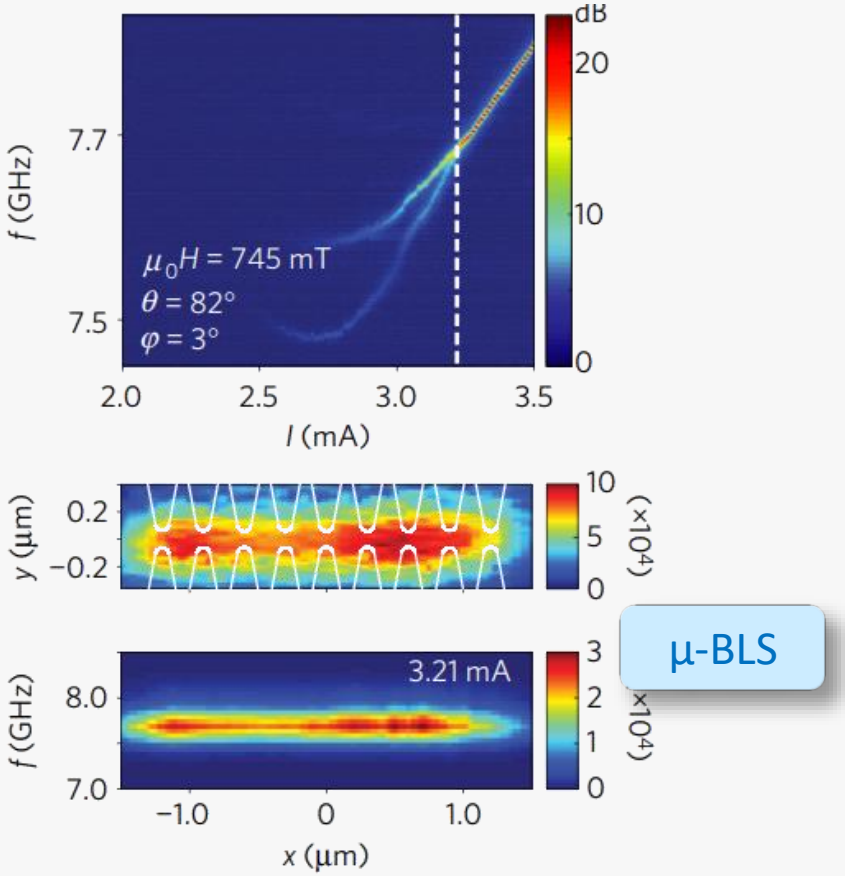
Challenge: synchronization

Goal: increase power, increase frequency and phase coherence

Mutual synchronization



Spin-Hall Nano-Oscillator (SHNO)

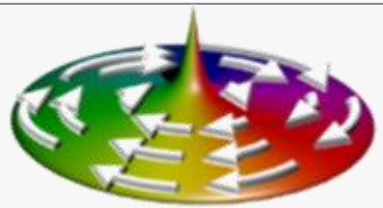


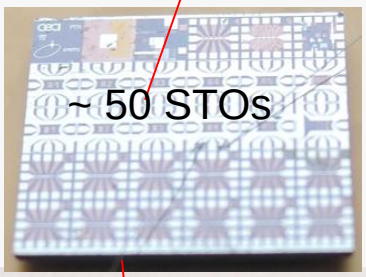
A. A. Awad, Nat. Phys. 13, 292 (2016)

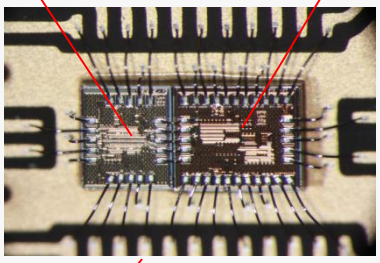
Challenge: synchronization

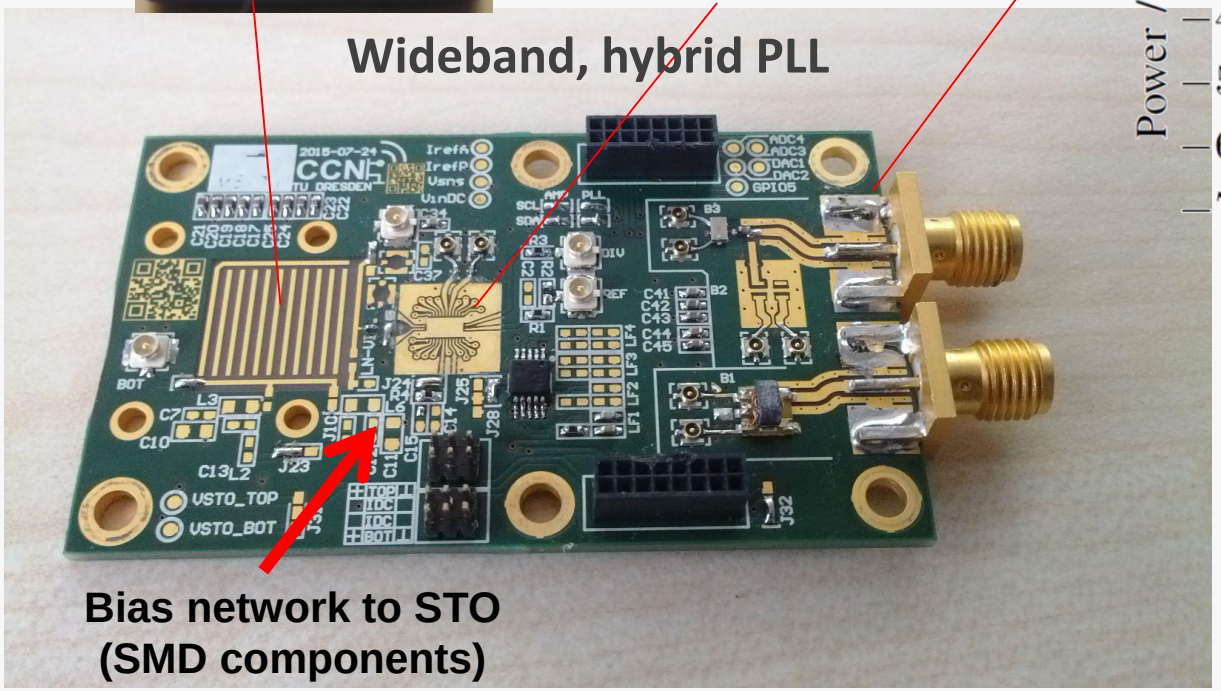
External synchronization through PLL

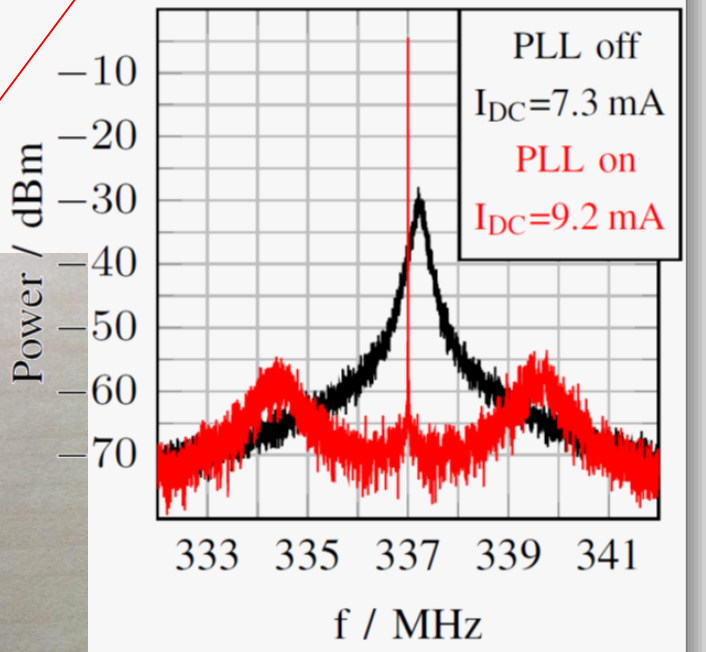
PLL = STO chip + Amp-IC + PLL-IC + PCB card











M. Kreissig, AIP Adv. 7, 056653 (2017)

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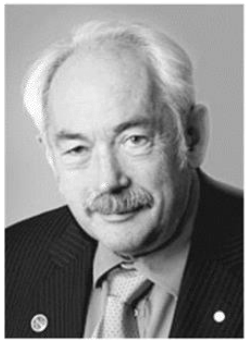

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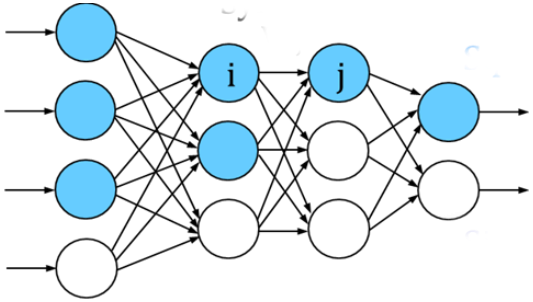
- Energy consumption in ICT

- Neuromorphic computing



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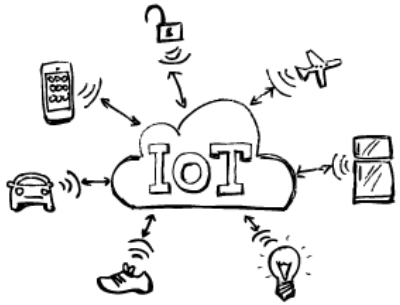
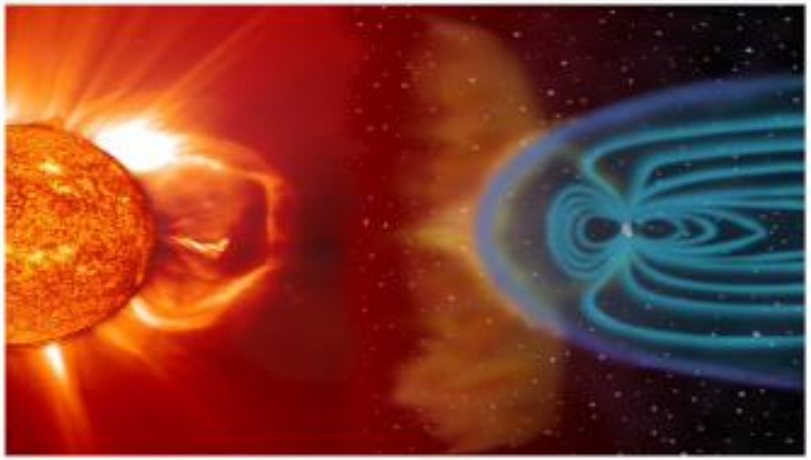


- Radiation hardness

Radiation hardness

Space applications



- Solar particles
- Cosmic rays

Nuclear industry

- Accidents
- Decommissioning

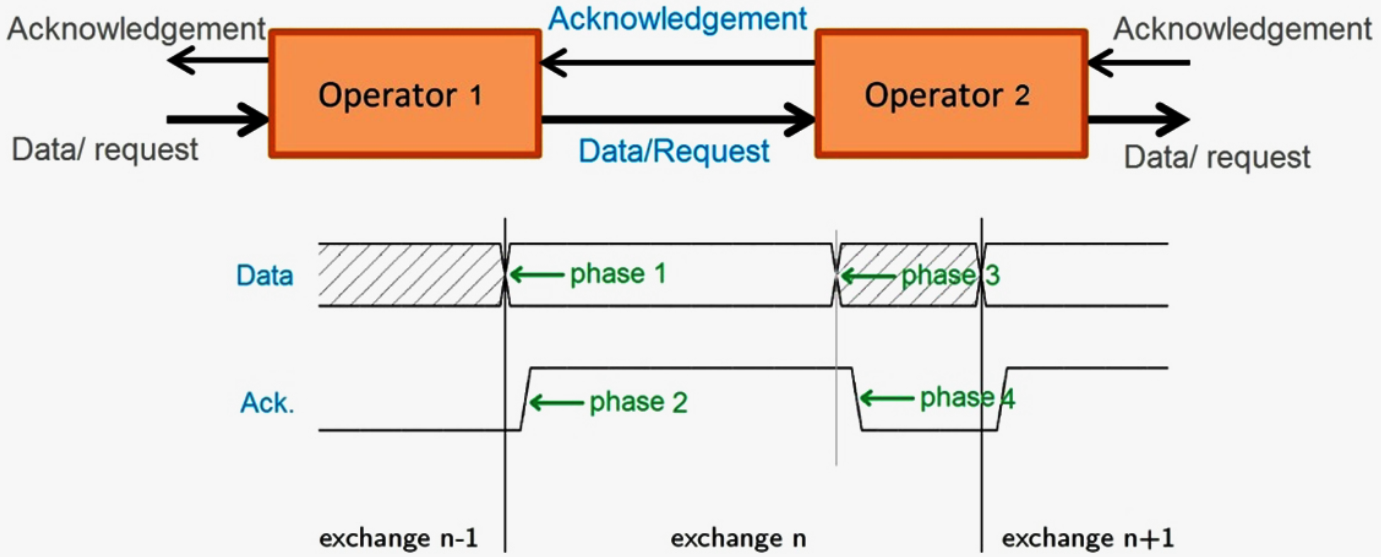
Consequences

- SSE: Single-Event Effects (digital damage)
- TID: Total Ionizing Dose

Assets of spintronics for radiation hardness

MRAM and asynchronous communication

- Combine DRAM and MRAM
- In case of SEE, refresh DRAM with MRAM content
- Redundancy reduced, cost lowered

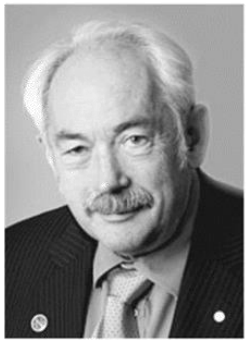


Context

- Spintronics hardware and IC design experts

Table of content

- Decades of nanomagnetism

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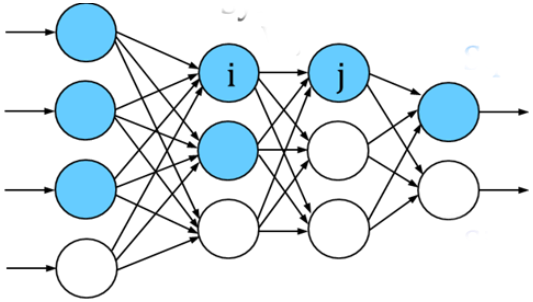

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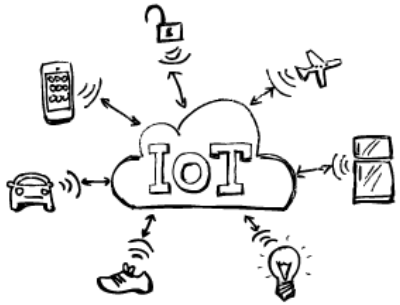
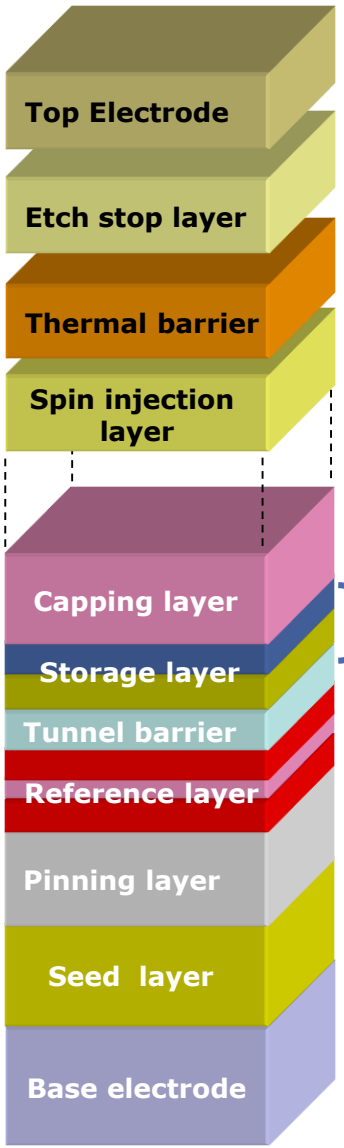


- Radiation hardness

- Material criticality

Materials for spintronics



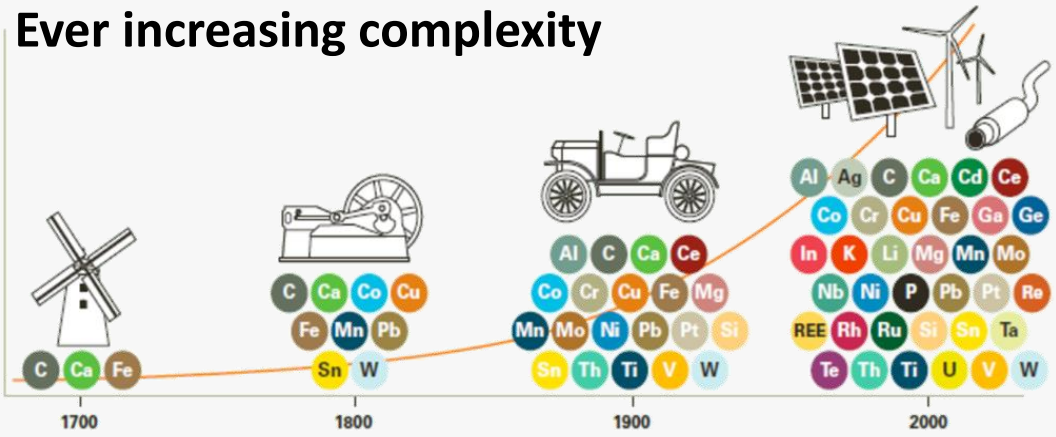
Spintronics requires an increasing number of materials and elements in stacks

- Price
- Material criticality

- *Protects MTJ during process*
- *NiFe(3) / CoFe(2) : Stores data (2 stable states)*
- *MgO (1.1) : Defines cell R & TMR*
- *CoFeB(2) / Ru(0.8)/CoFe(2) : SAF, immune to external fields*
- *PtMn(20) : AF layer sets direction of reference layer*
- *Ta(5) or NiFeCr(10) : Promotes texture of critical layers*
- *Contact to select transistor + diffusion barrier*

Material criticality: context

Ever increasing complexity



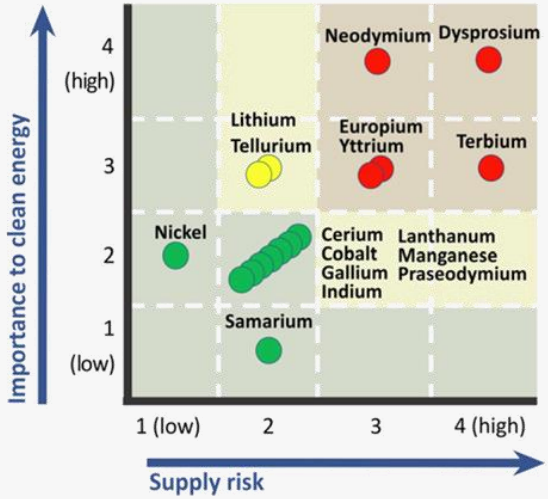
© Fraunhofer IWKS, Armin Reller

Criticality

- Geopolitical
- Limited resources
- Environmental regulations
- Ethics
- Cost

Quantifying criticality

Mid-term (2015-2025) criticality matrix

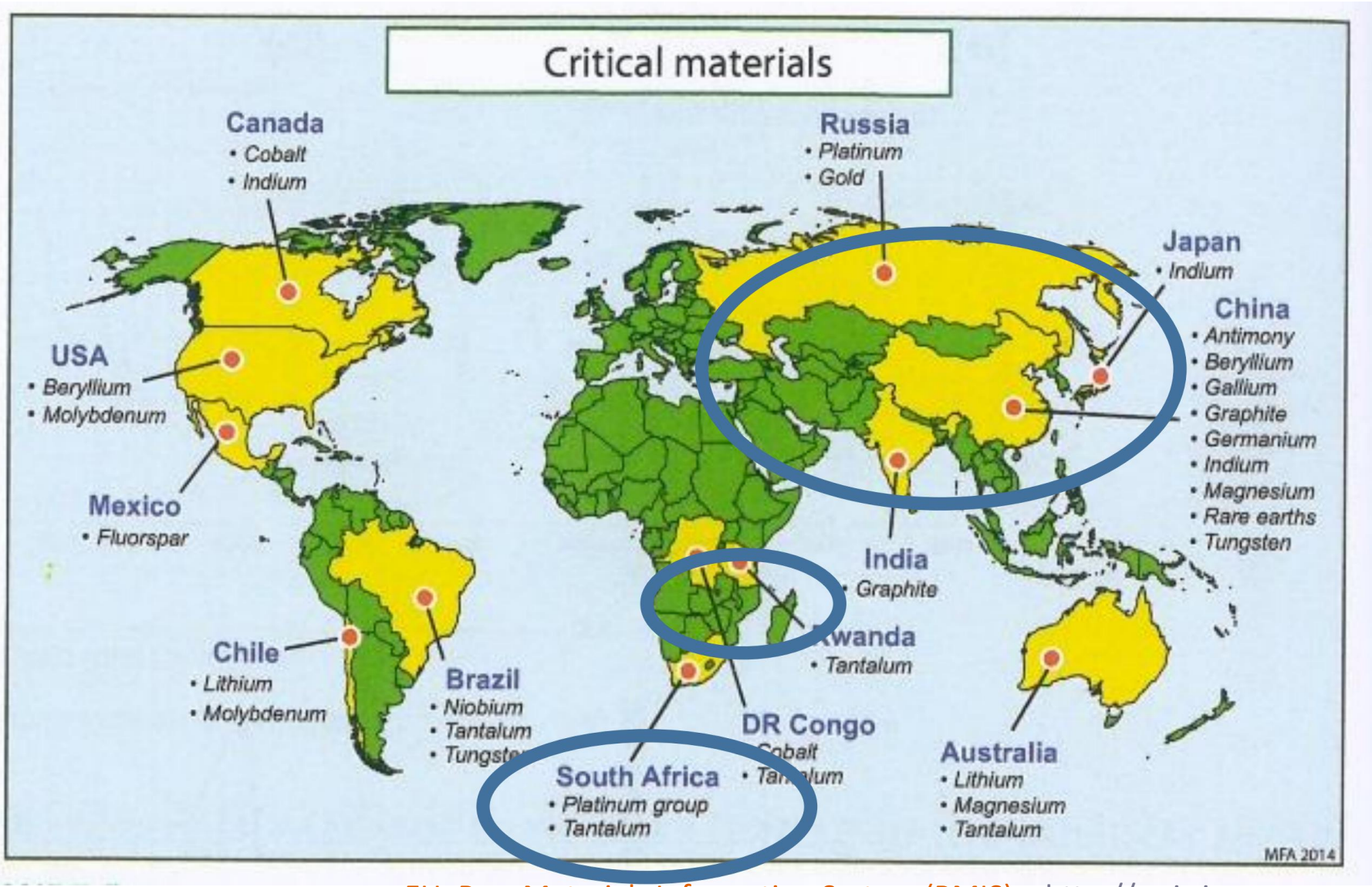


Critical
Near-Critical
Not Critical

Actions

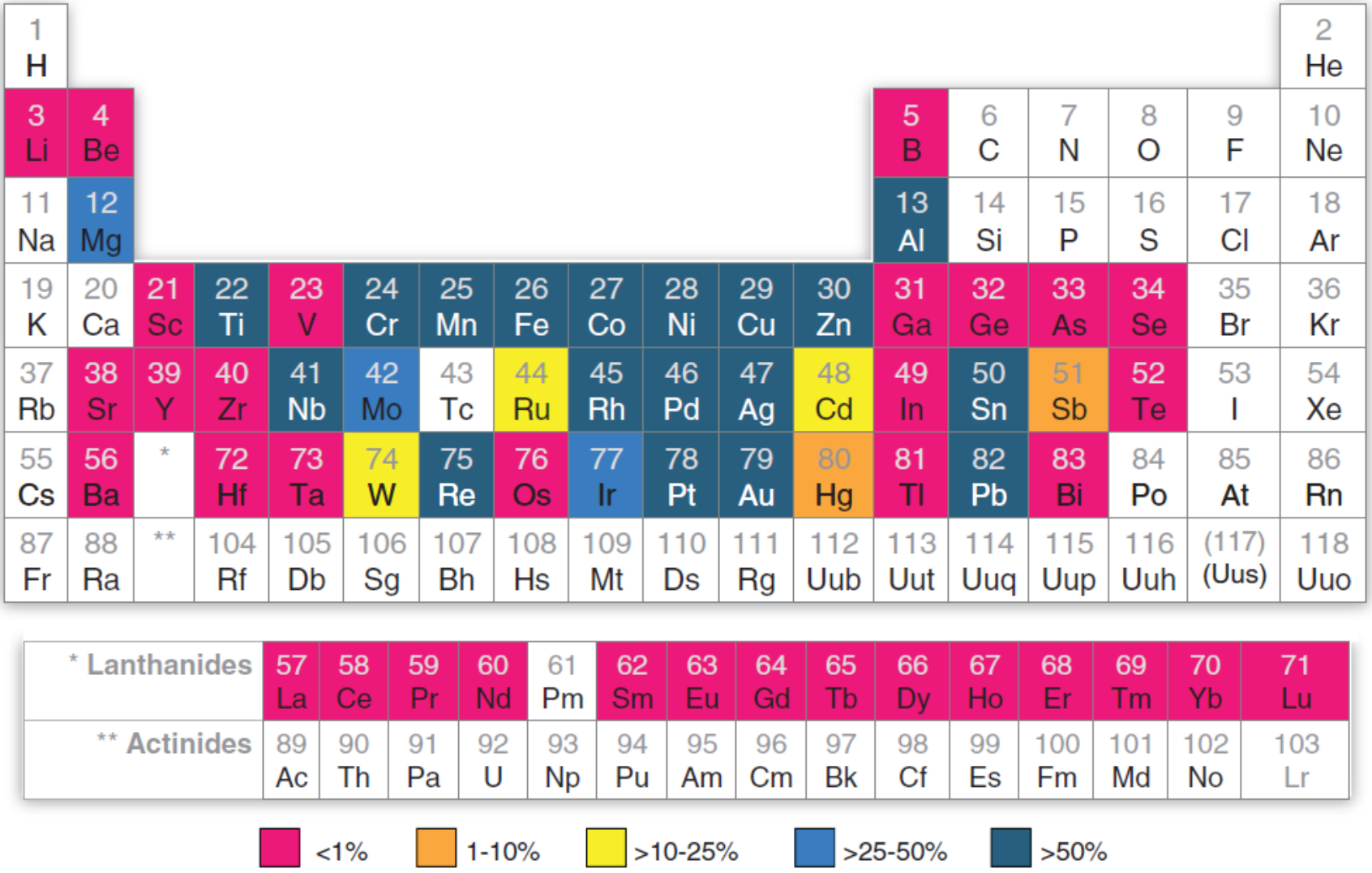
- Replace
- Reduce
- Reuse

Material criticality: mining



EU: Raw Materials Information System (RMIS) – http://rmis.jrc.ec.europa.eu

Material criticality: recycling



T. E. Graedel et al., J. Ind. Ecol. 15, 355 (2011)

Material criticality in spintronics

Reference layers

- Antiferromagnets
  - PtMn, IrMn
- Synthetic antiferromagnets
  - Ru, Ir

Writing

- Spin-Hall effect
  - Pt, W …
- Dzyaloshiinski-Moriya
  - Pt, Ir, W …

Perpendicular magnetic anisotropy

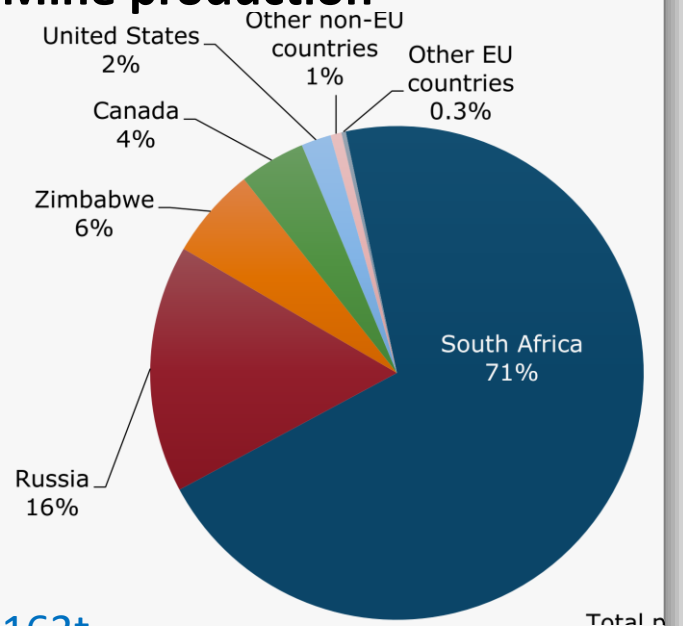
- Interfacial anisotropy
  - Pt, Pd…

Note

- Often related to high spin-orbit
- Heavy (and rare) elements

Material criticality in spintronics: case of Pt

Mine production



163t

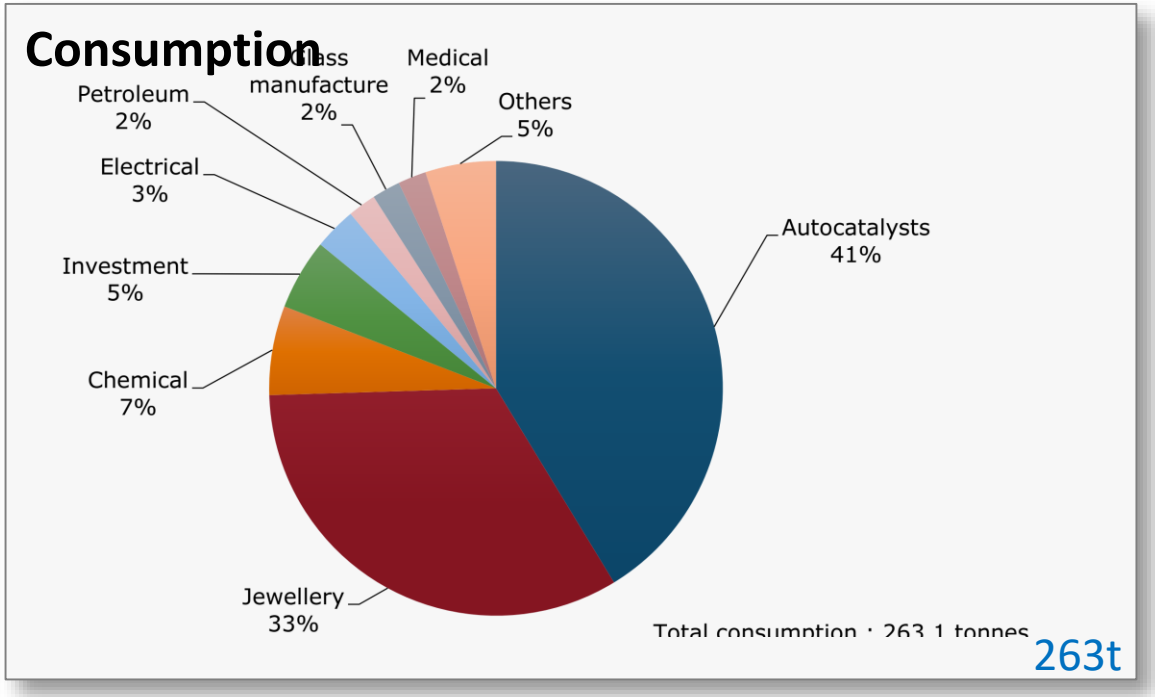
Price

Study on the review of the list of Critical Raw Materials

European Commission

Critical Raw Materials Factsheets

Consumption



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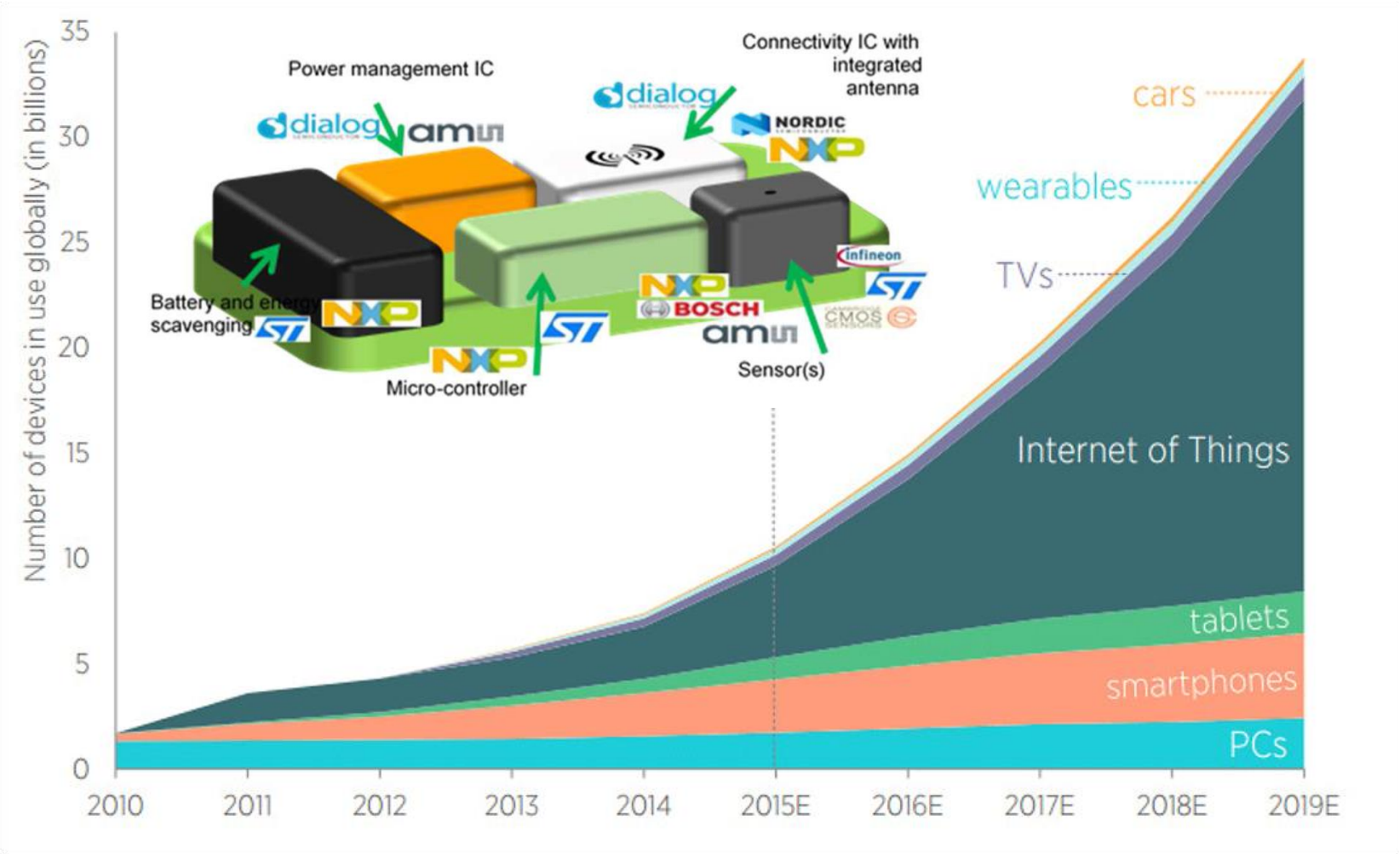
Raw Materials Information System (RMIS) – http://rmis.jrc.ec.europa.eu

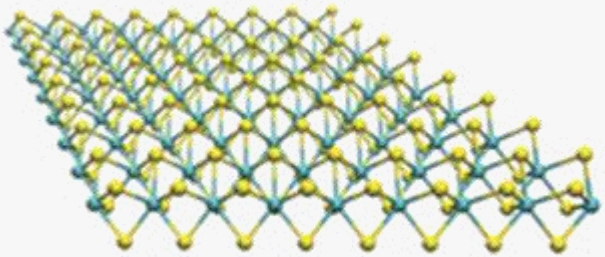
Serious issue for massive production



Source: John Greenough, "The Internet of Everything 2015," *Business Insider Intelligence*. Produced by Adam Thierer and Andrea Castillo, Mercatus Center at George Mason University, 2015.

Replace, Reduce

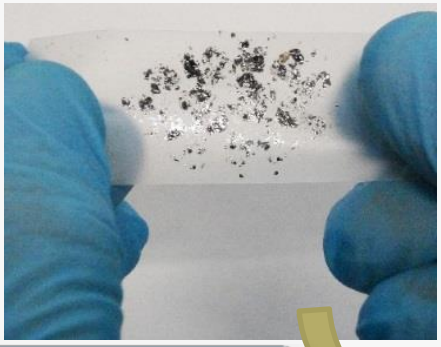
2D materials

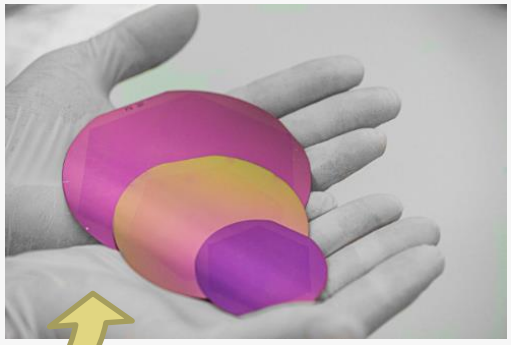


2D materials: graphene, WSe_2, $MoSe_2$, MoS_2

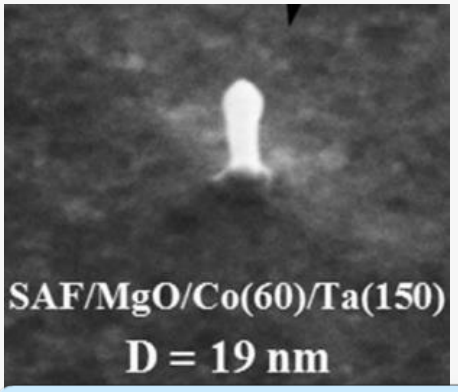
Anisotropy, interconversion, RKKY

Need for upscaled production



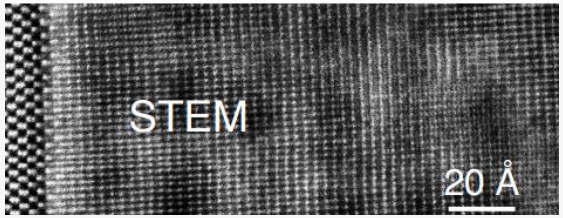


3D structures



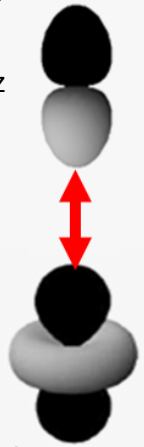
Anisotropy, stacks on wafer

Heusler alloys



Antiferromagnets, anisotropy, polarizers

Oxide interfaces



Anisotropy

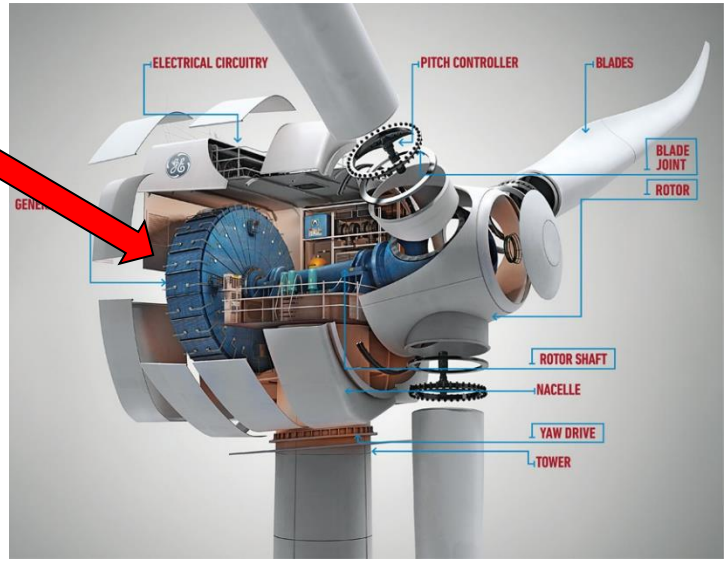
B. Diény, M. Chshiev, Rev. Mod. Phys. (2017)

Material criticality: magnets for energy

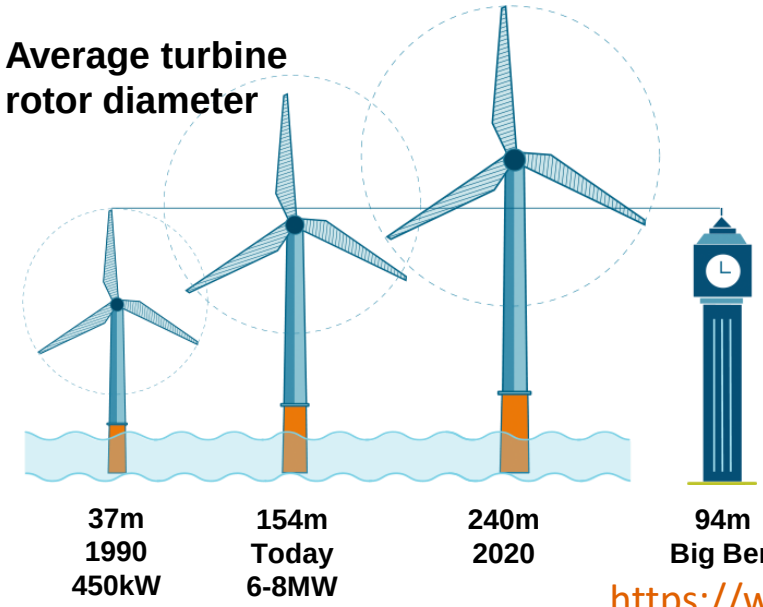
(image Renault)

per 1 MW windpower

- **+/- 600 kg Nd-Dy-Fe-B**
- 4% Dy = 24 kg
- 28% Nd = 168 kg



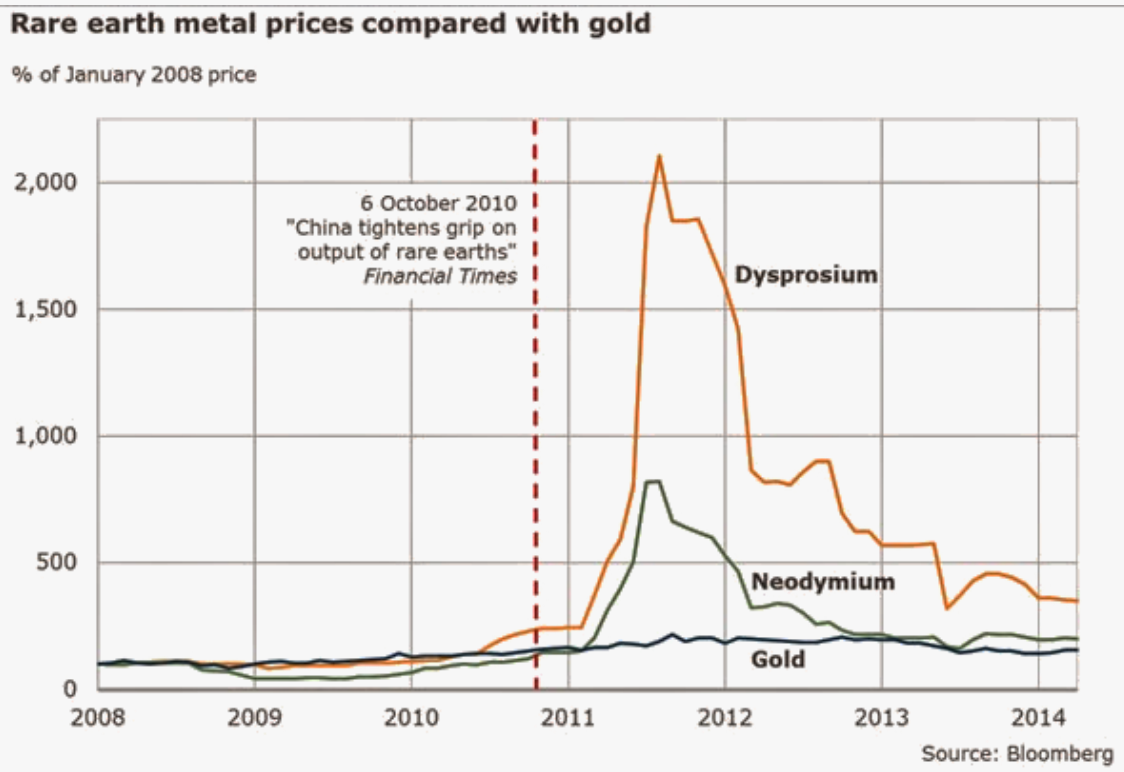
(image General Electric, Data: US DOE)



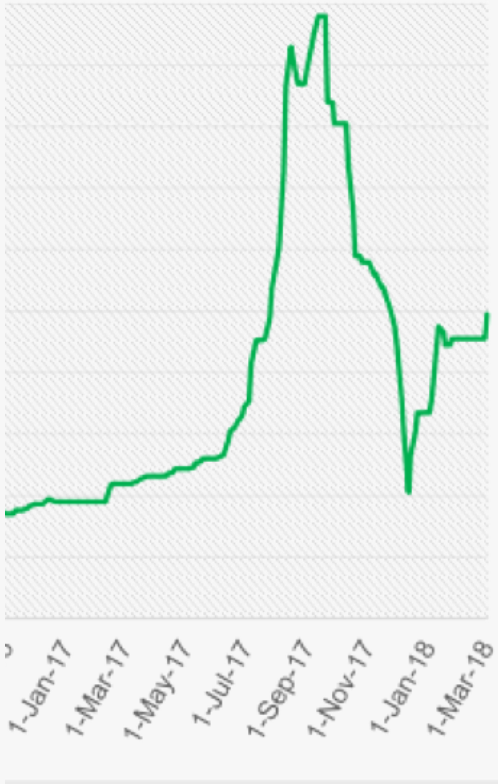
https://www.siemens.com/global/en/home/markets/wind/offshore.html

Material criticality: rare earth

China triggers the 2011 crisis



Never safe again…



Impact on permanent magnets

- Markets: wind mills, electric cars, magnetic refrigeration…
- New material research programs launched: materials and microstructure

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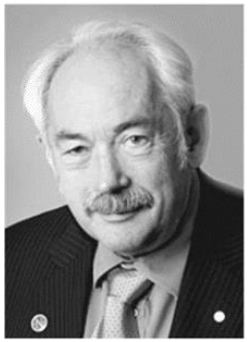

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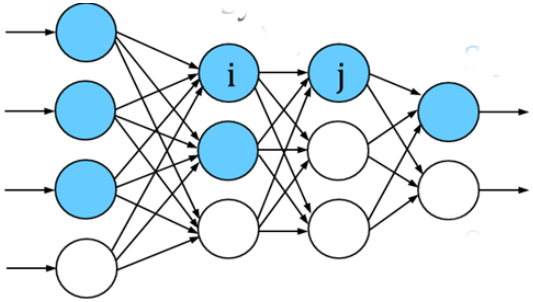

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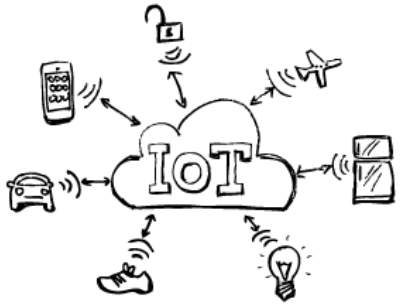


- Radiation hardness

- Material criticality

- Research and society

Research and society

Higher education

A few (conflicting?) requests

- Deep knowledge
- Interdisciplinarity
- Awareness to innovation

The EUROPEAN MAGNETISM ASSOCIATION

The European School on Magnetism

The European School on Magnetism (ESM) is a biyearly event organized by the European Magnetism Association. The mission of ESM is higher education of young European scientist in the field of Magnetism, while promoting networking and create effective links between academics and the industry.

Presentation

http://magnetism.eu/school

Broad public dissemination

- Acceptance of science as facts, not belief
- Educate
- Motivate careers for science

fête de la Science

comunidad de madrid semana de la ciencia

Research and society

Publications

- Open: economic model?
- Evaluation of work and individuals

arXiv.org

SciPost

No publisher, scientific editors, peer review, open reviews and replies

Other aspects

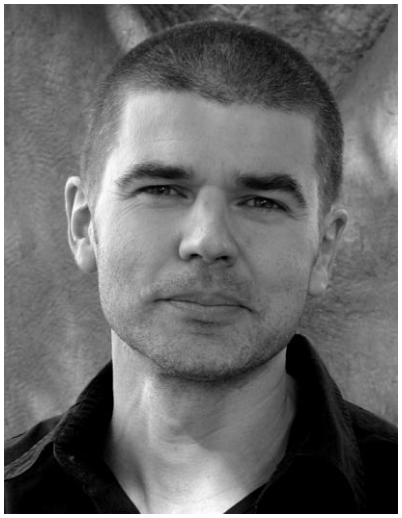
- Various equalities
- Distant working
- (…)

Special thanks for sharing material

Bernard DIENY
Grenoble

Ursula EBELS
Grenoble

Julie GROLLIER
Paris



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Slides: http://fruchart.eu/slides