Nanomagnetism

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Magnetism!

Before

Nanoscience and Nanotechnology

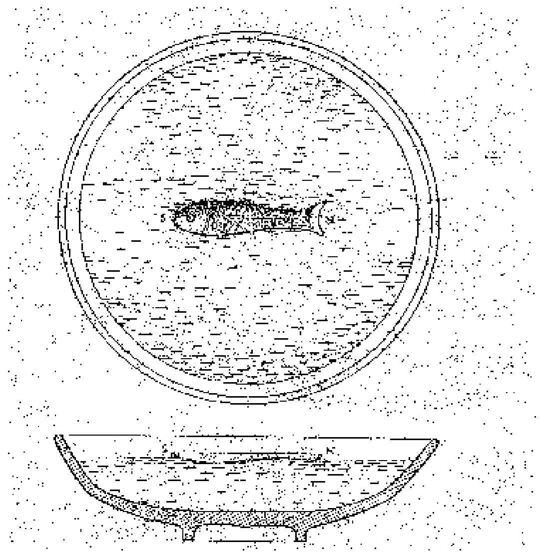
there was

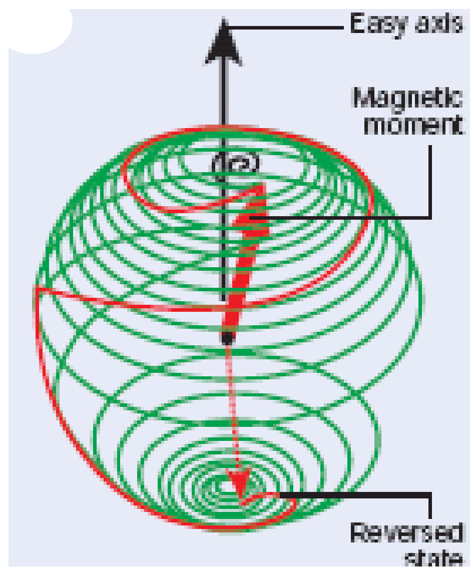
"The nation that controls **magnetism** will control the universe!"

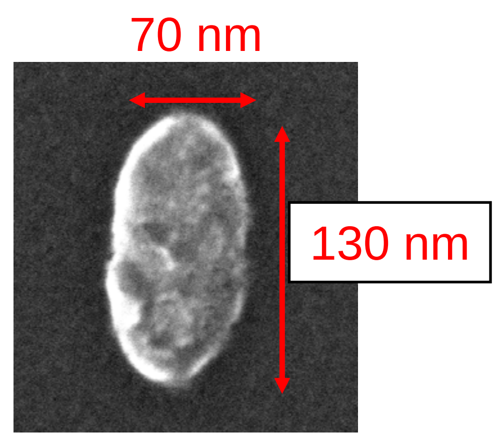
Magneto
Master of Magnetism

Magnetism

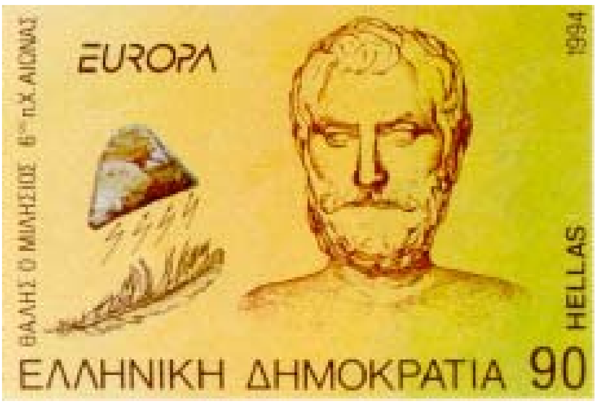
From Lodestones to Nanomagnets and Spin Torque







Lodestone or Loadstone
(Chinese – Loving Stone)



Thales of Miletus is credited with discovering that amber rubbed with wool or fur attracts light bodies such as pieces of dry leaves or bits of straw, and **observing that lodestone attracts iron and other lodestones**.

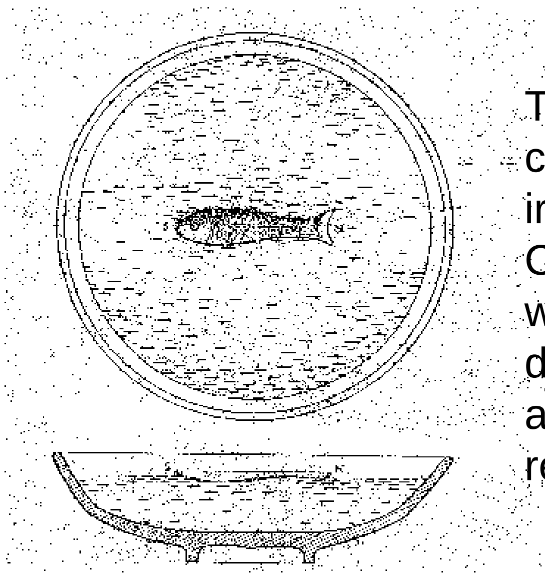
Magnetite A black, isometric, strongly magnetic, opaque mineral of the spinel group, (Fe_3O_4). It constitutes an important ore of iron. Magnetite is a very common and widely distributed accessory mineral in rocks of all kinds

How is magnetite magnetized in nature?

One proposal is that this occurs during lighting strikes when strong fields are generated by the current passing through the mineral.

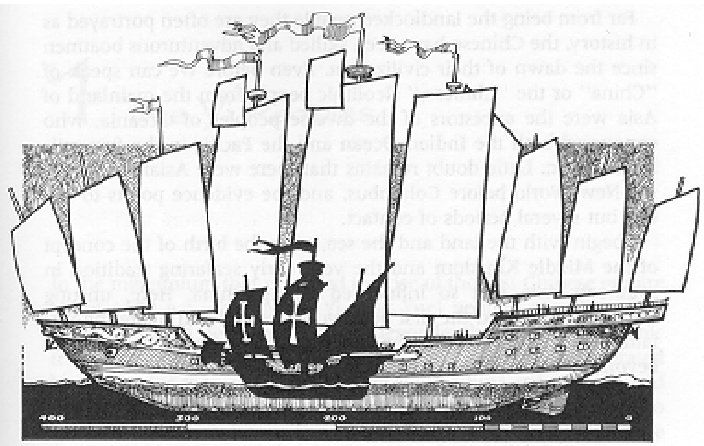
www.phy6.org/earthmag/lodeston.htm

The First Magnetic Technology



This is one of the earliest magnetic compasses: A floating fish-shaped iron leaf, mentioned in the Wu Ching Tsung Yao which was written around 1040. The book describes how iron can be heated and quenched to produce thermo-remanent magnetisation.

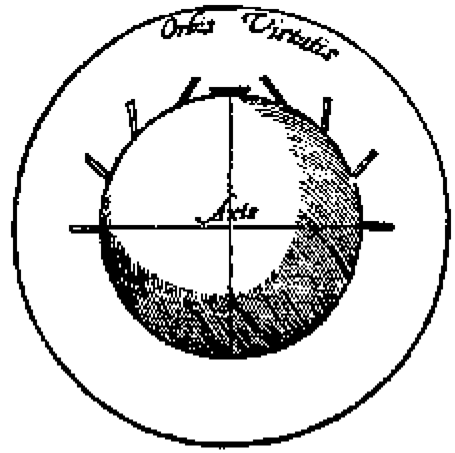
Zheng He



Zheng He's treasure ship (four hundred feet) and Columbus's St. Maria (eighty-five feet).
(Illustration by Jan Adkins, 1993.)

Columbus

The Study of Magnetism Begins the Age of Scientific Research

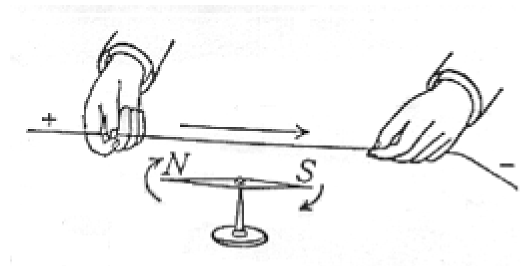


William Gilbert wrote *De Magnete*, arguably the first modern scientific research text, with experimental results and interpretation, in 1600. The book starts with a resolve to strip away all myth from the subject and reason from observation:

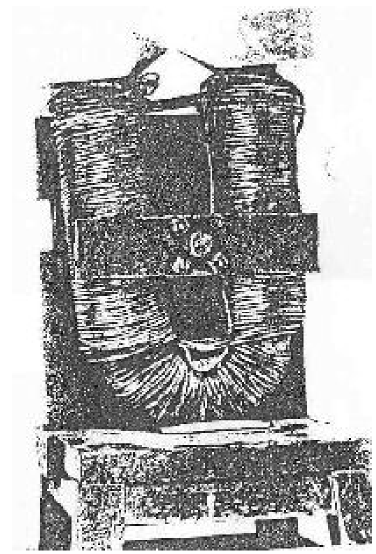
"In follies and fables do philosophers of the vulgar sort take delight; and with such like do they cram readers a-hungered for things obtruse, and every ignorant gaper for nonsense. ***But when the nature of the lodestone shall have been by our labours and experiments tested****, then will the hidden and recondite but real causes of this great effect be brought forward, proven , demonstrated...and* ***the foundations of a grand magnetic science being laid will appear anew, so that high intellect may no more be deluded by vain opinions"***

Uniting Electricity and Magnetism

1820 -Oersted discovers that electrical currents create magnetic fields



1831 – Faraday discovers that changing magnetic fields create electric fields – Faraday induction



Two results:

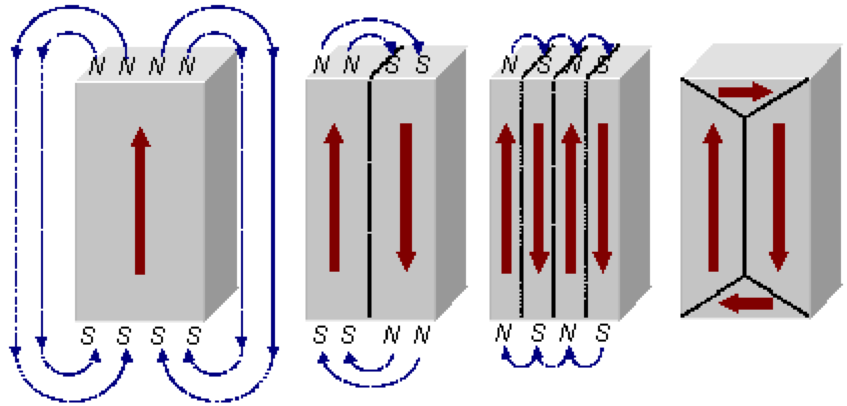
The development of a fundamental understanding of electromagnetism.

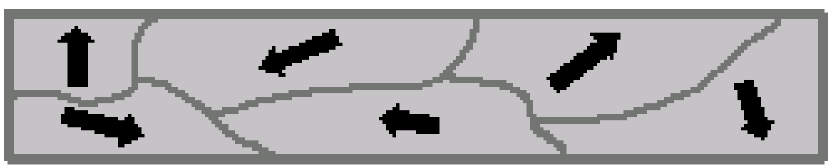
Strong technological need for better magnetic materials and stronger magnets.

Ferromagnetic Domains

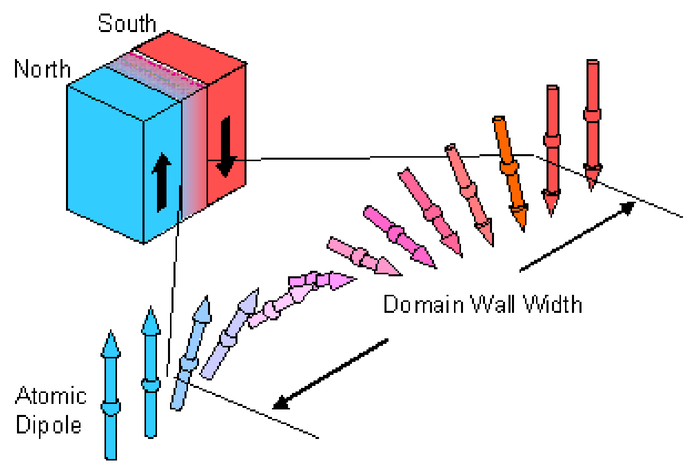
The magnetic energy of a ferromagnet is reduced via the formation of domains

Ideal – single crystal behavior of a magnetically "soft" material



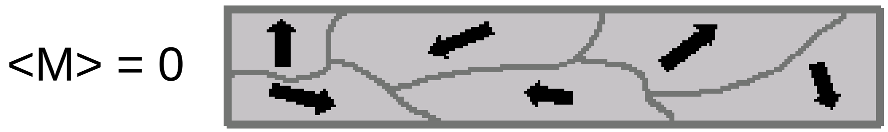


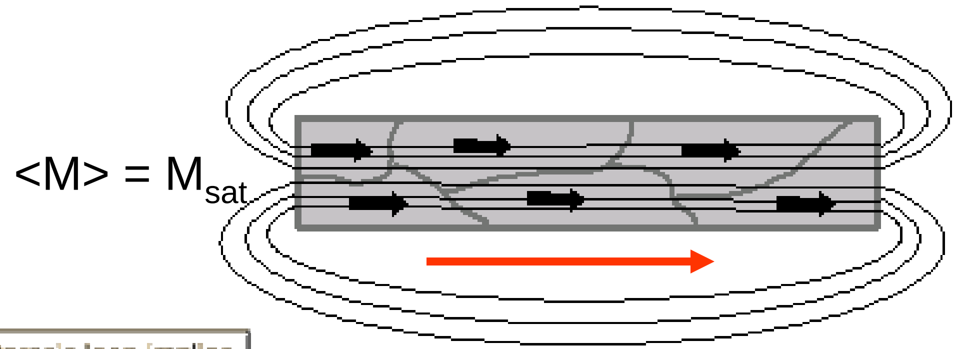
More typically, in polycrystalline ferromagnets domains are irregular in form and not perfectly matched



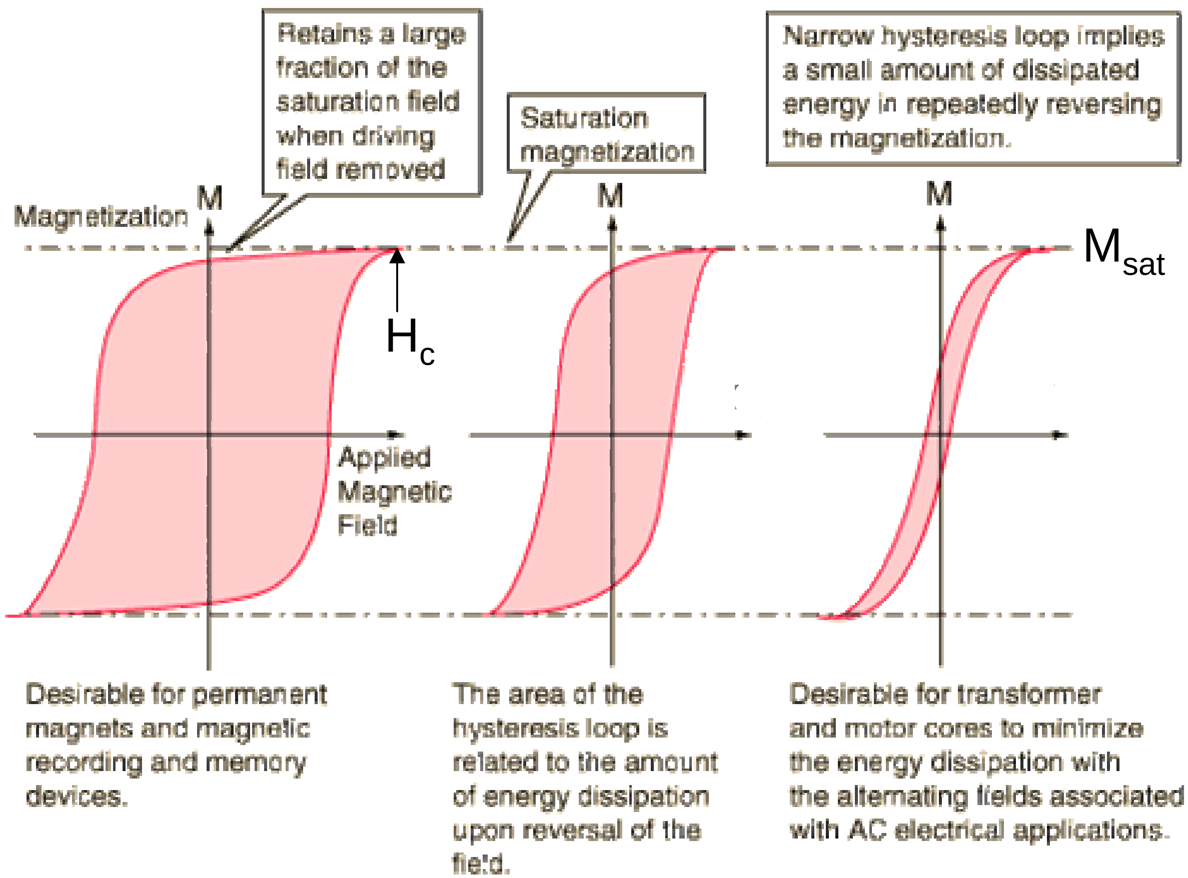
Domain size set by energy cost of forming **domain walls** balanced by the energy reduction by formation of domains
Domain wall thickness ~ 10 – 1000+ nm.

Ferromagnets – Hard and Soft





$H > H_c$, coercive field



Hard **Soft**

If after $H > H_c$
$\langle M \rangle = M_{sat}$ for $H << H_c$,
hard ferromagnet

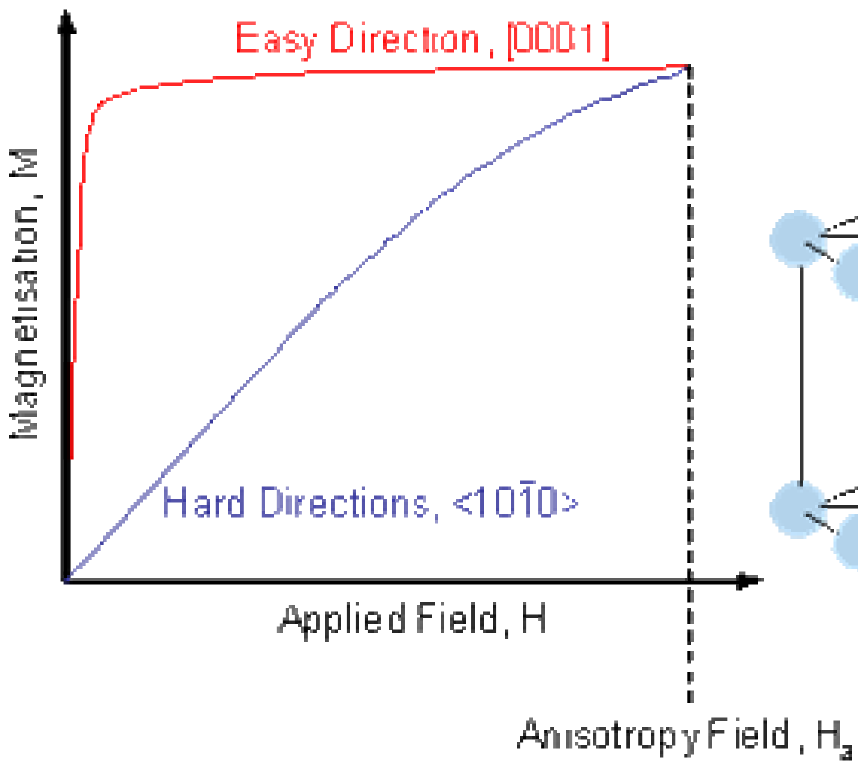
If after $H > H_c$
$\langle M \rangle << M_{sat}$ for $H << H_c$,
soft ferromagnet

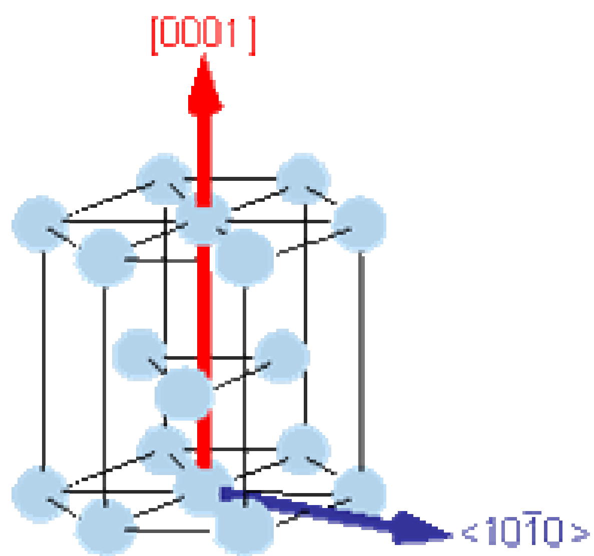
How to obtain a hard ferromagnet?

Use **magnetic anisotropy** and optimal grain (micro-crystallite) size

Grain size should be small enough that only one domain fits readily into a grain, but not too small, i.e. **between 10 and 100 nm**.

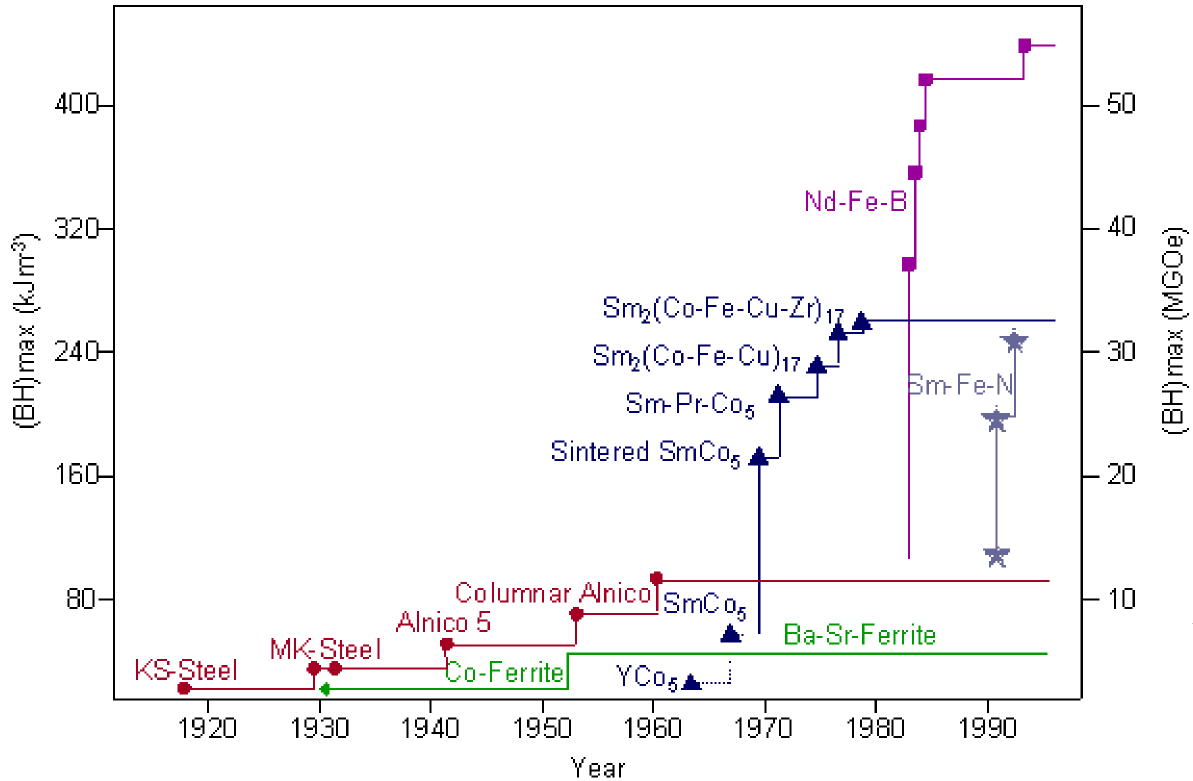
magnetic anisotropy – crystalline anisotropy





Magnetic anisotropy and crystal structure of Co

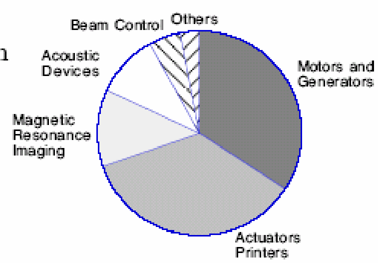
Development of Hard Ferromagnets



A lodestone magnet from the 1750's and typical ferrite and rare earth used in modern appliances. Each of these contain about 1J of magnetic energy.

Permanent Magnets

- Why permanent magnets
  - No resistive losses
- What's it worth
  - US $ 11.5 Billion in 2000



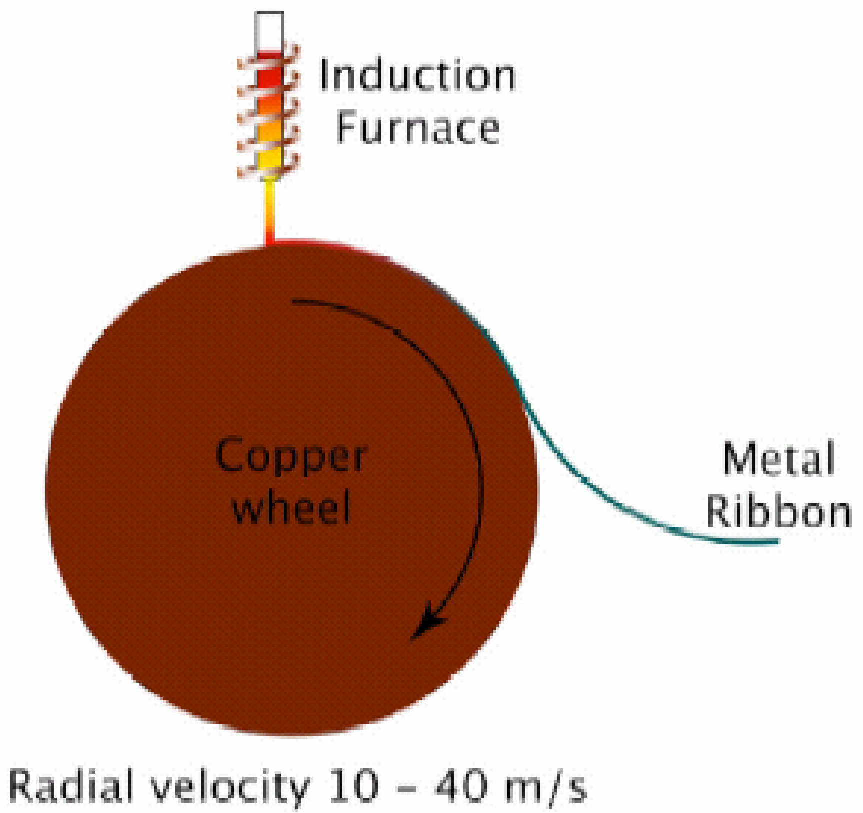
The number of magnets in the family car has increased from one in the 1950's to over thirty today.

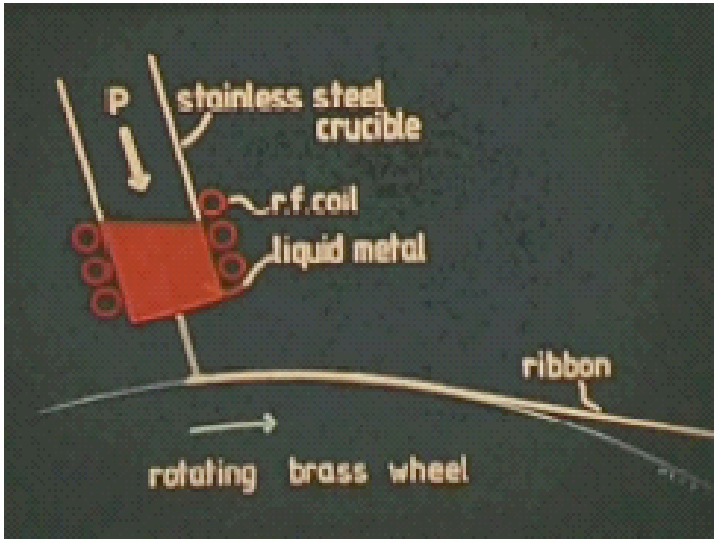
Over 30g of magnets are produced annually for each person on Earth.

Production of NdFeB Magnets
General Motors – 1980's

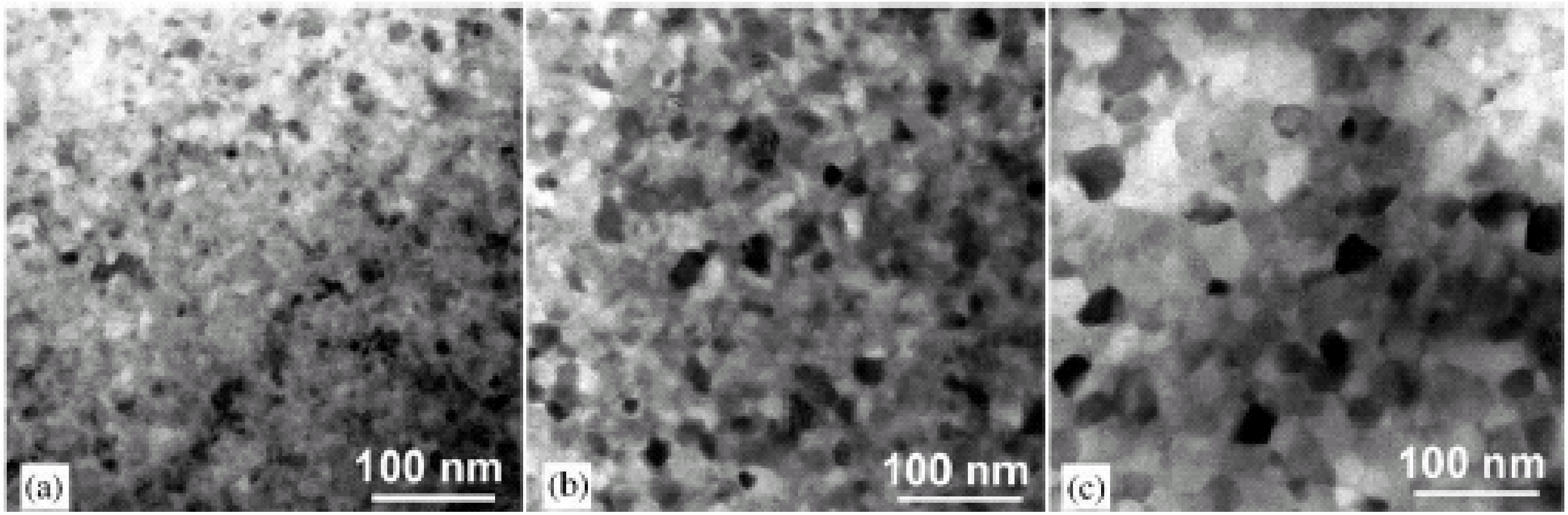
Currently the highest energy density ($M_{sat}H_c$) magnetic material known
The crystal structure and components combine to yield high M_{sat}
The grain size has to be just right to get the highest possible H_c

Melt Spinning





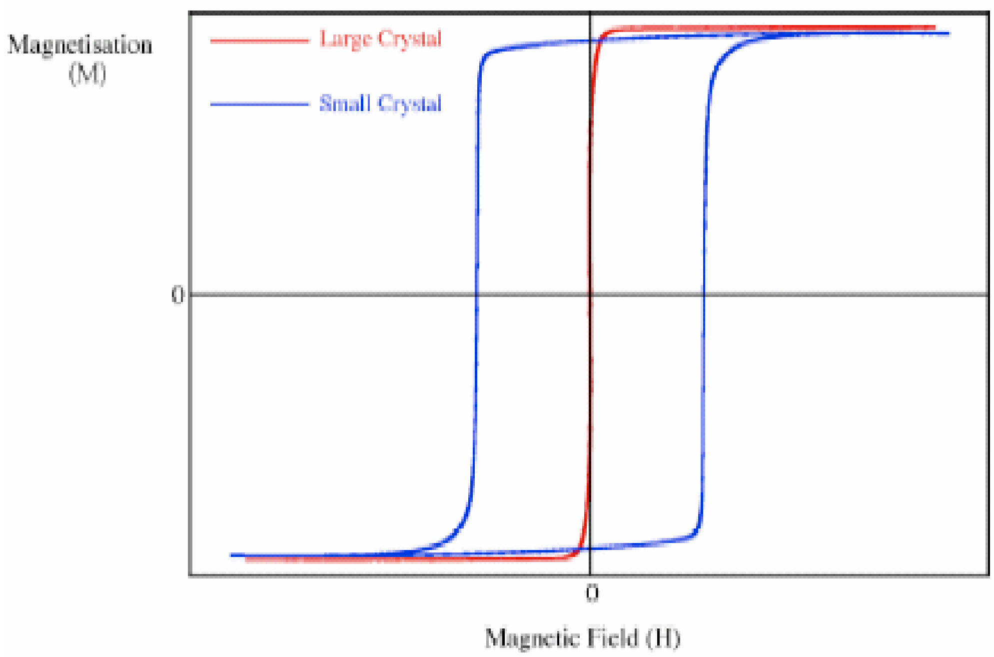
Getting the grain size right



Electron microscope image of NdFeBNb ferromagnet with different grain sizes made by spin quenching.

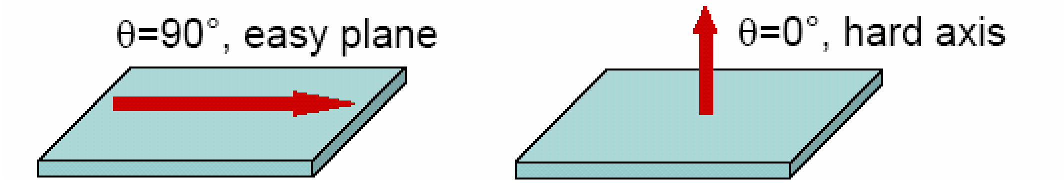
Which material is the hard ferromagnet?

Which one is the soft ferromagnet?



Shape Anisotropy and Magnetic Memory

Shape anisotropy for ferromagnetic thin films, often restricts domains to lie in-plane



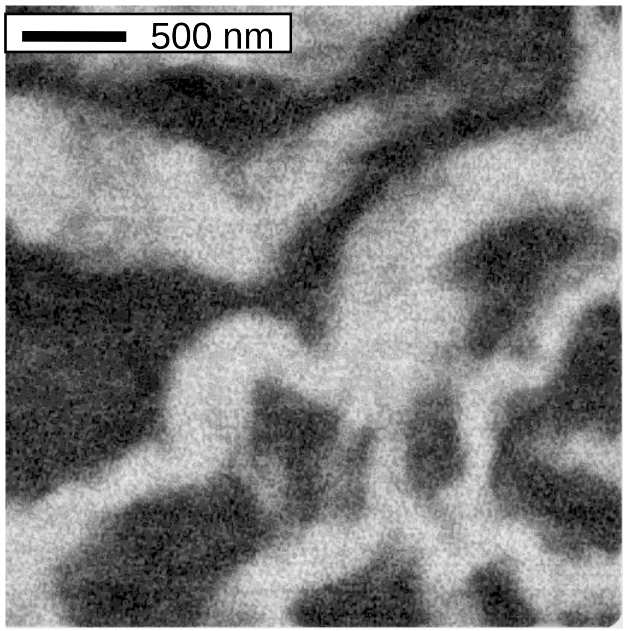
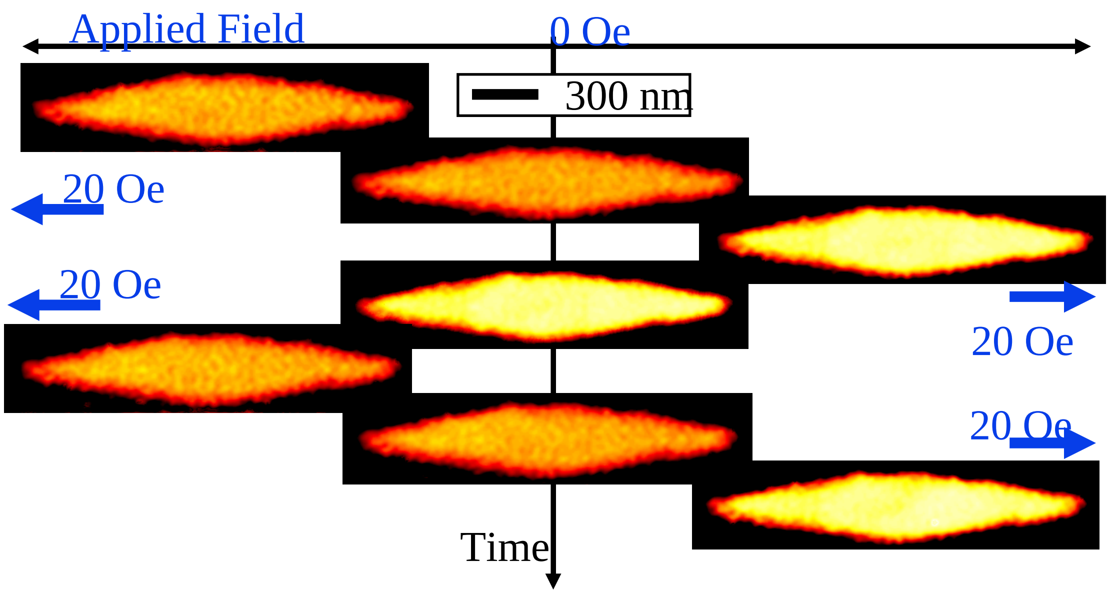


Image of in-plane domain structure of a 3 nm thick NiFe (permalloy) film

In patterned films domains lie in elongated direction

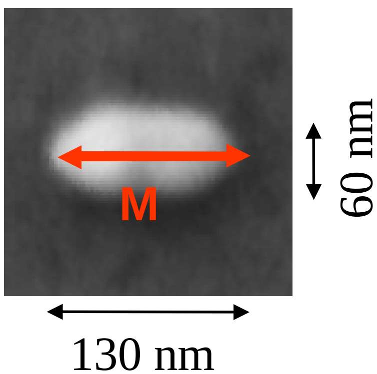


Single domain switching behavior of **patterned** NiFe thin film nanomagnet

Nanomagnets and the Super-Paramagnetic Limit

How small is too small?

If a magnetic domain, either a patterned ferromagnetic structure or single ferromagnet grain is too small, it becomes **super-paramagnetic** despite its anisotropy.
Then, due to random thermal energy, Brownian energy, the domain will fluctuate randomly between its possible, preferential, directions.



electron microscope image of thin film NiFe nanomagnet

Magnetic energy required to flip domain $E_{mag} = \frac{1}{2} M_{sat} H_c \, Vol$

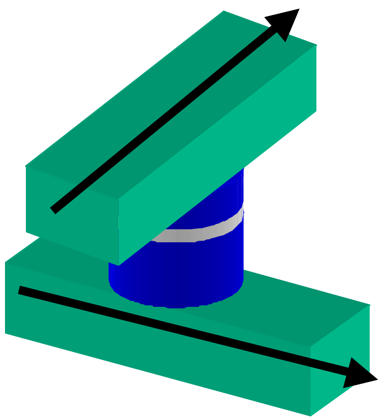
Average rate of flipping $\Gamma = \tau_0^{-1} e^{-E_{mag}/k_B T}$

$\tau = \Gamma^{-1}$ = mean lifetime or time spent in one of the possible magnetic states.
τ_0^{-1} = rate the magnet attempts to flip ~ 10^9 /sec

For data storage we require τ > 10 years.
As Vol becomes smaller, H_c must become larger.
Challenge for nanoscale magnetic memory

A New Approach for Magnetic Memory

Current approach to MRAM:
MTJs switched with magnetic field.
As nanomagnets get **smaller**,need
more current - **bigger** wires.
Also have “half-select” problem



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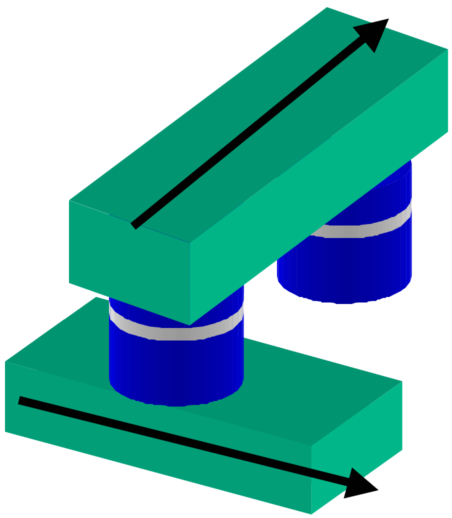
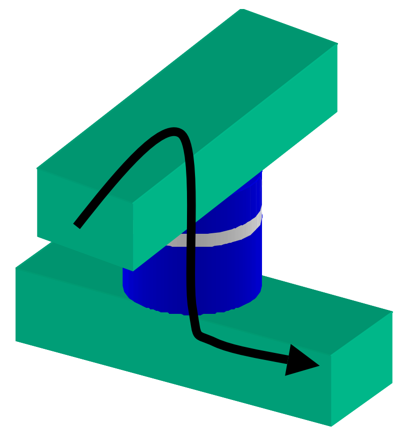


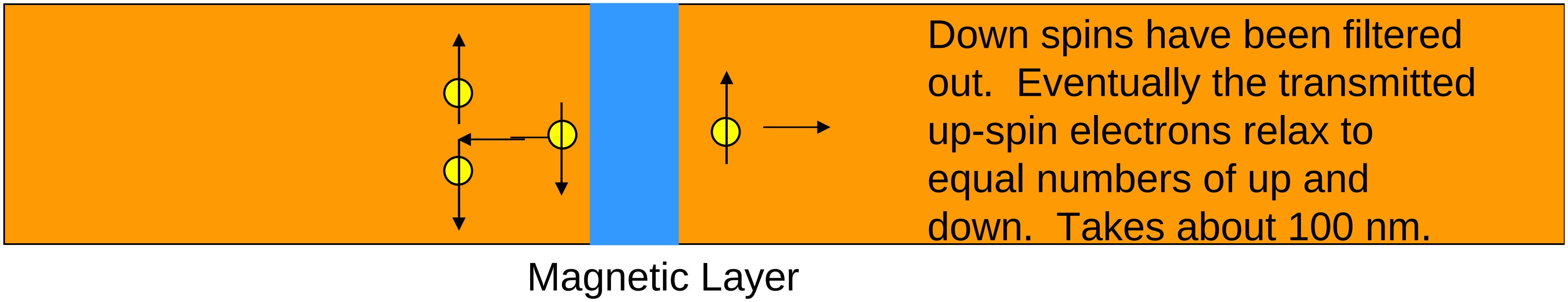
Possible future MRAM:
nanomagnets switched with ***spin polarized*** current

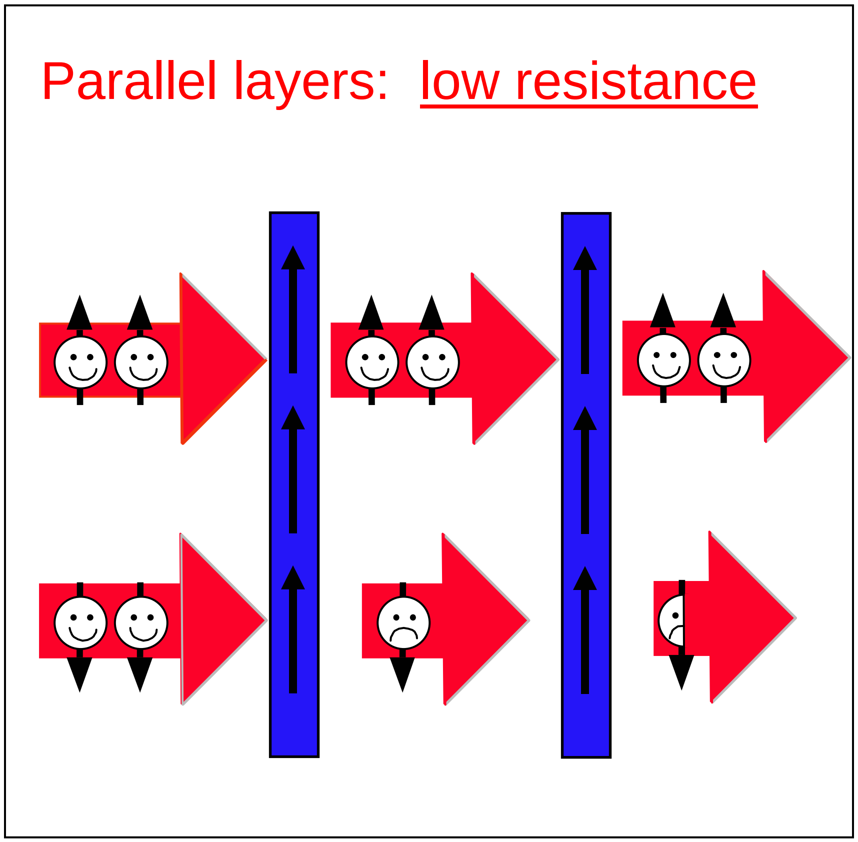


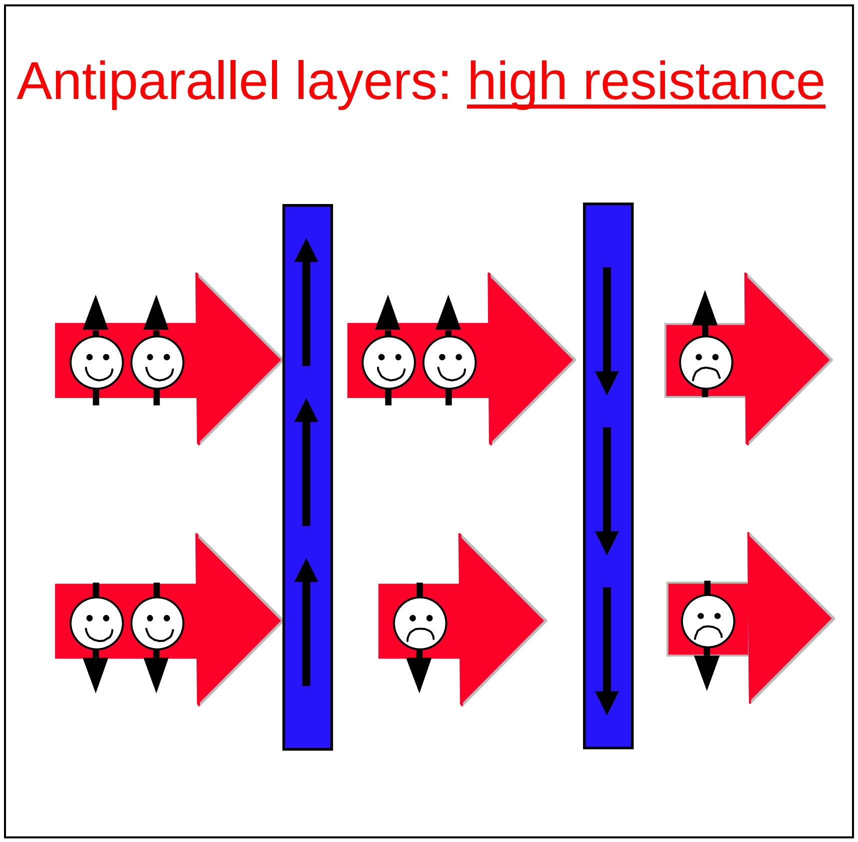
New discovery: **Predicted** in 1996 by IBM scientist, John Slonczewski

Actually observed in 1992 at Cornell but not understood until later

Giant Magnetoresistance as a Spin Filtering Effect



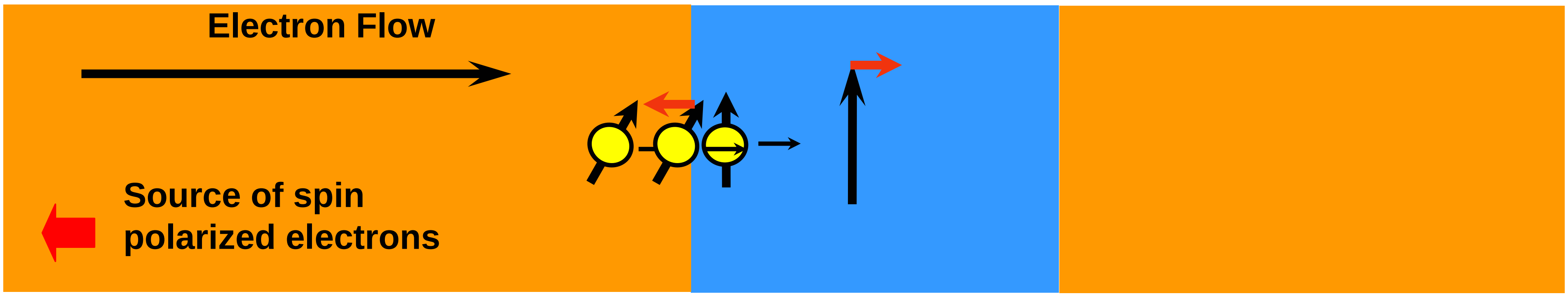




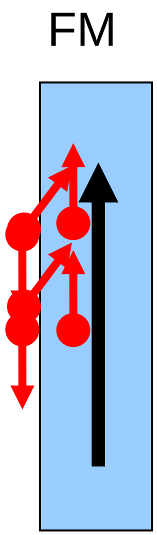
<u>Spin Transfer</u> – Something Even Newer in Nanomagnetism

Spin filtering of polarized electrons that are <u>not parallel</u> to a magnet can be viewed as the ferromagnet exerting a torque ← on the spin of the electron. <u>A quantum physics effect</u>.

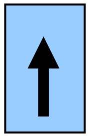
By <u>Newton's third law</u> there must also be a reaction torque → on the ferromagnet



The Spin Transfer Effect



- spin of electron

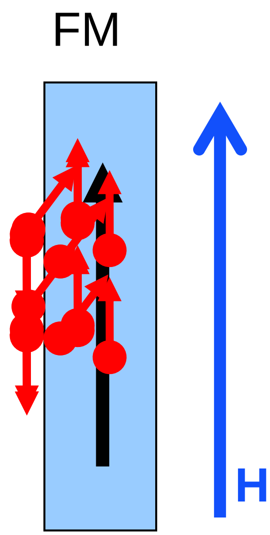


- local moment of ferromagnet

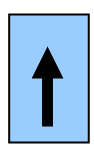
The Spin Transfer Effect

If the amplitude of the spin-polarized current is high enough the result is the excitation of the nanomagnet

- *reversal of the nanomagnet moment in low field,*
- *steady state precession of the moment in high field. .*

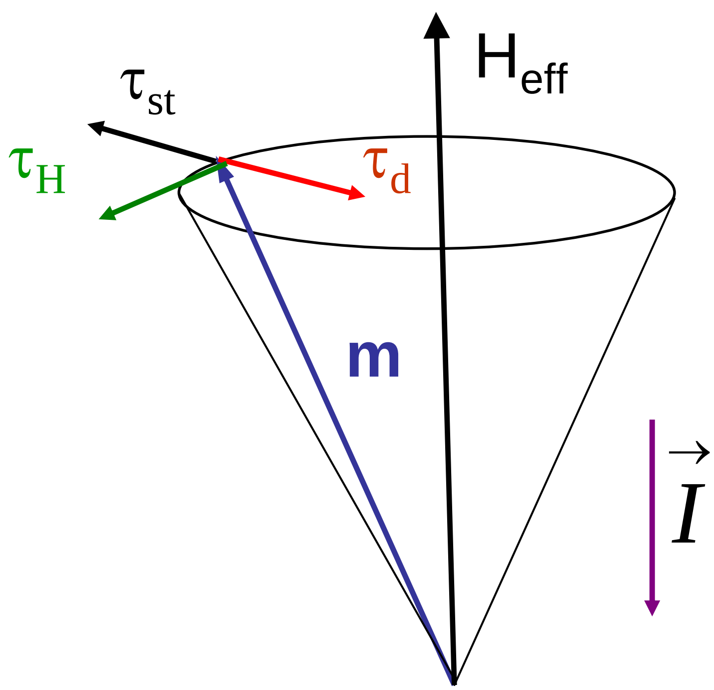


 *- spin of electron*

 *- local moment of ferromagnet*

Spin-Torque Driven Nanomagnet Dynamics

Gyroscopic motion of magnet



Spin-Torque Driven Nanomagnet Dynamics

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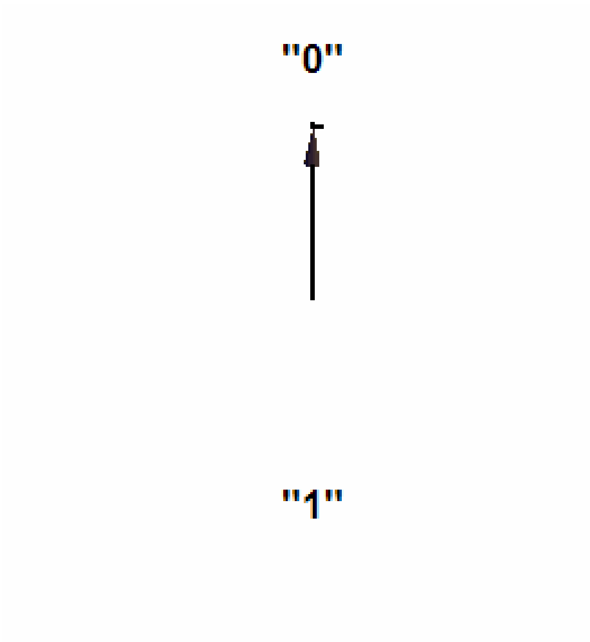
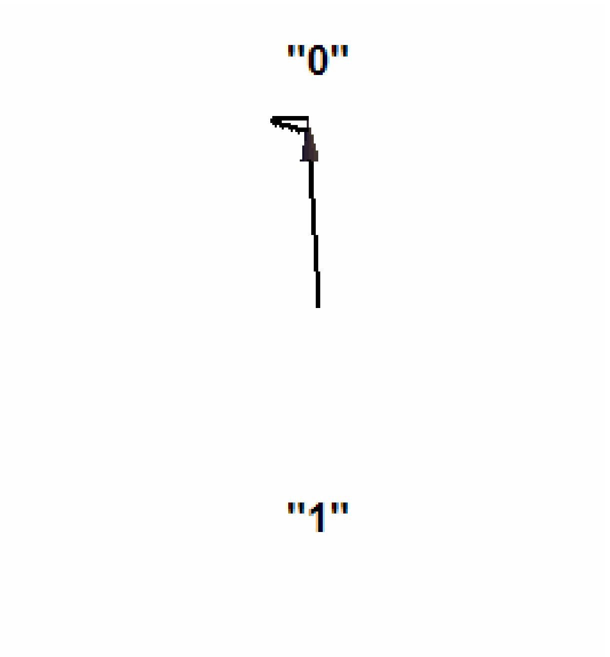


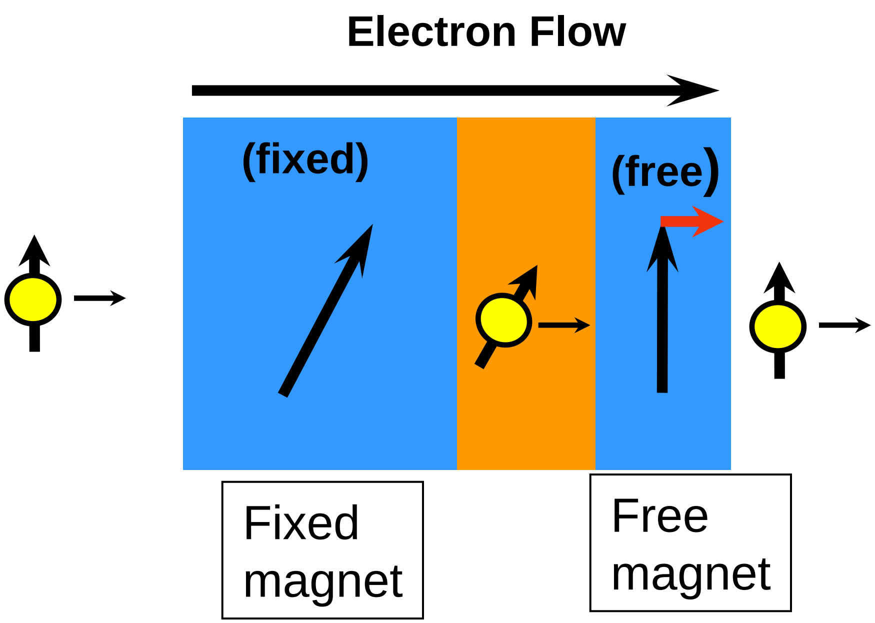


No applied magnetic field

Strong applied magnetic field
Microwave oscillations
1 – 80 GHz

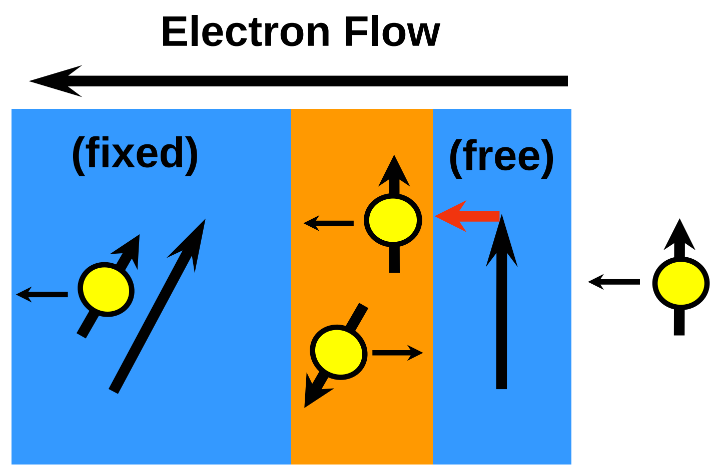
Reversible Spin Transfer Switching of Nanomagnets

How it works



Fixed layer is larger or otherwise pinned so that spin transfer from the current does not excite it

Right-going electrons exert torque on free layer favoring **parallel alignment**

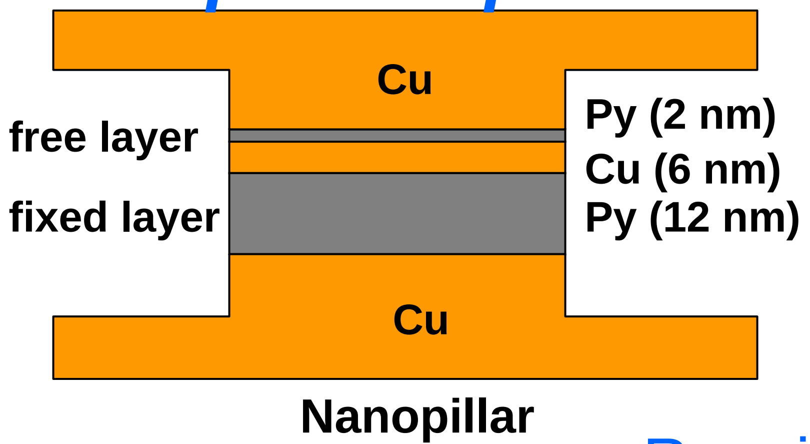


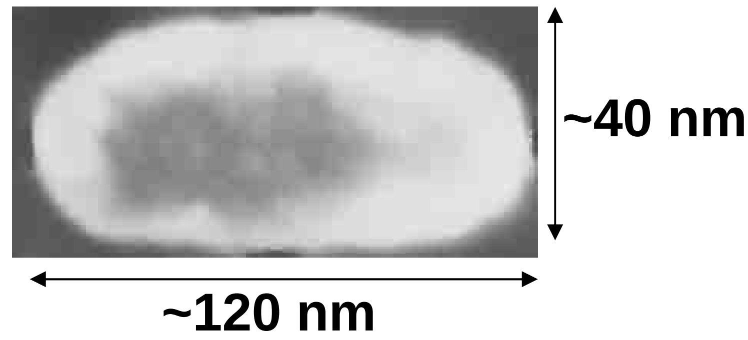
Left-going electrons are partially **reflected** back by fixed layer

Reflected electrons exert **opposite torque** on free layer

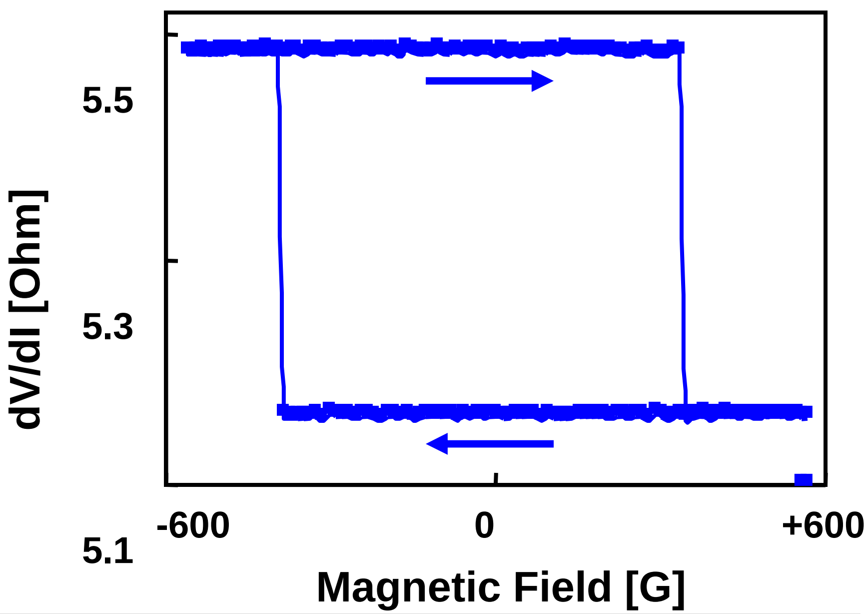
=> **anti-parallel alignment** is favored

Spin Torque Driven Magnetic Reversal

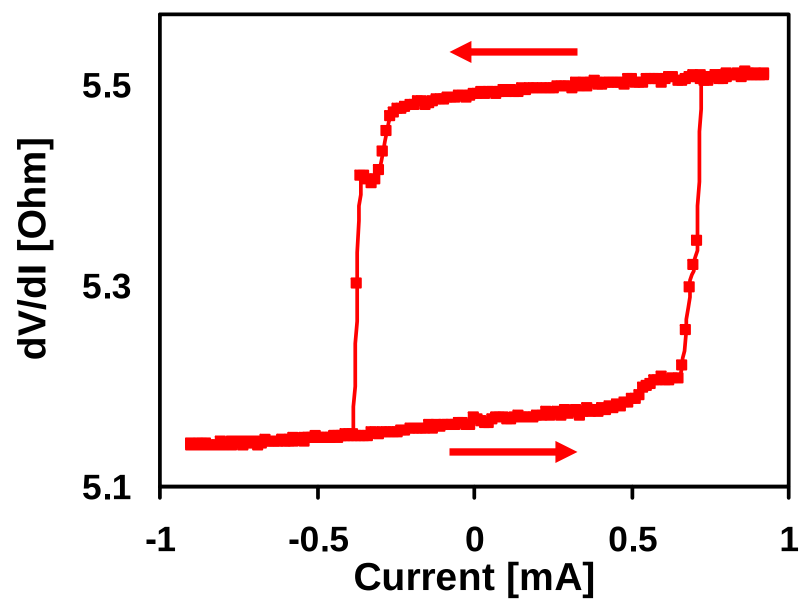




Requires nanoscale magnets



Flipping the thin (free) layer with a magnet



Flipping the thin (free) layer with current

Future Applications of Spin Torque Effects in Nanomagnets

Scalable nanoscale memory

Universal replacement for Si memory in computers

Fast (1 ns), low-power and non-volatile – instant on computers

Nanoscale microwave sources

Communications and signal processing applications

At the nanoscale, new spin phenomena become accessible and some physics challenges, such as thermal fluctuations, become far more important.

Our objective is:

To understand and hence better control nanoscale spin and magnetic phenomena,

To overcome the physics and materials challenges to make them useful in technology and beneficial for society .