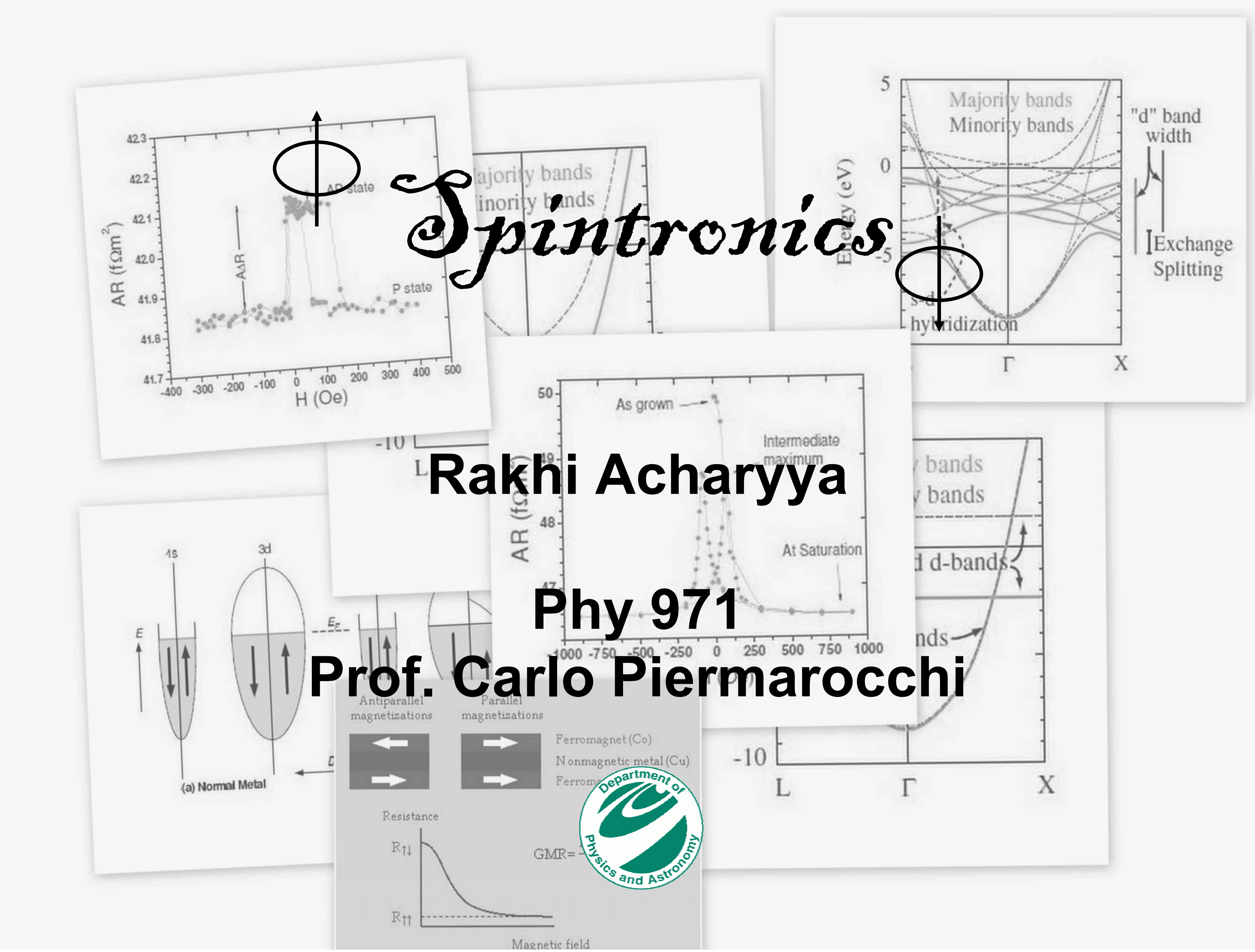

Spintronics

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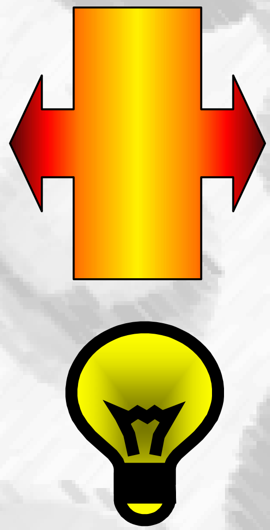
An Introduction

Information technology based on semiconductor and ferromagnetic materials.

Information processing and computation using electron charge…



Information stored on magnetic high density hard disks using electron spins…

Spintronics

aims to simultaneously exploit both charge and spin of the electrons in the same device!

Spin Transport Electronics ≡ Spintronics

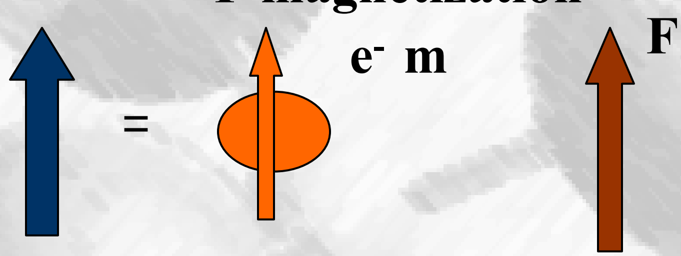
based on spin angular momentum of electrons or ‘spins’
Electronics is based on electronic charge.

Spin angular momentum of electron is given as

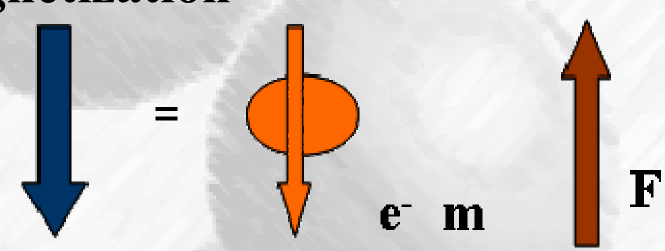
$$\langle m_z \rangle = -\frac{e}{2m_e}\langle s_z \rangle$$

Electrons traveling through a Ferromagnet

e^- moment parallel to F magnetization



e^- moment antiparallel to F magnetization

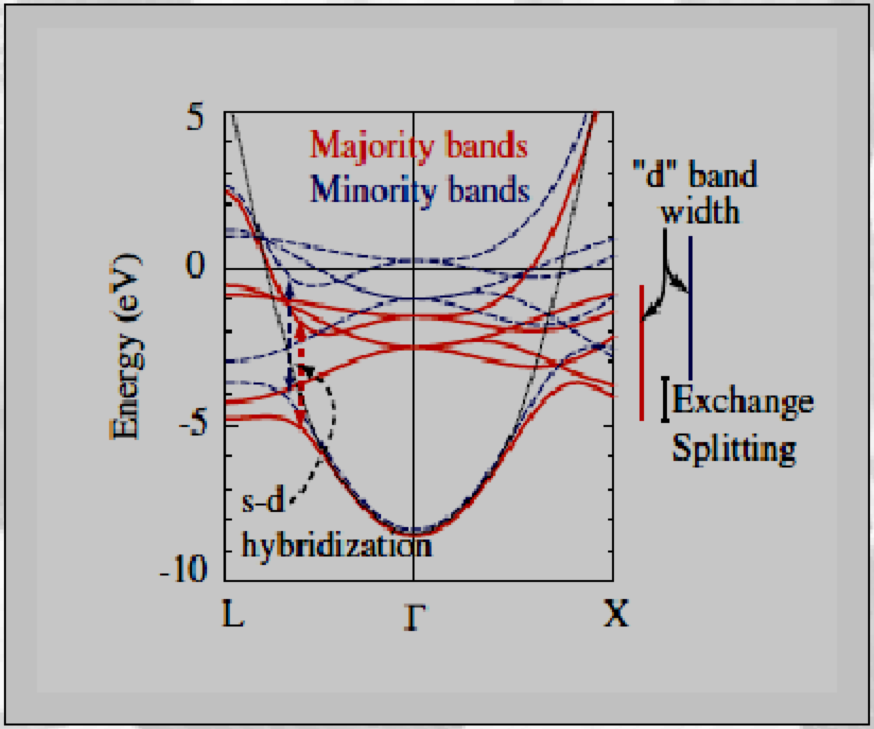


Models describing F metals

LSDA predicts properties of transition metal ferromagnets,ie,magnetic moment

- ❑**electron density**
- ❑**spin density**

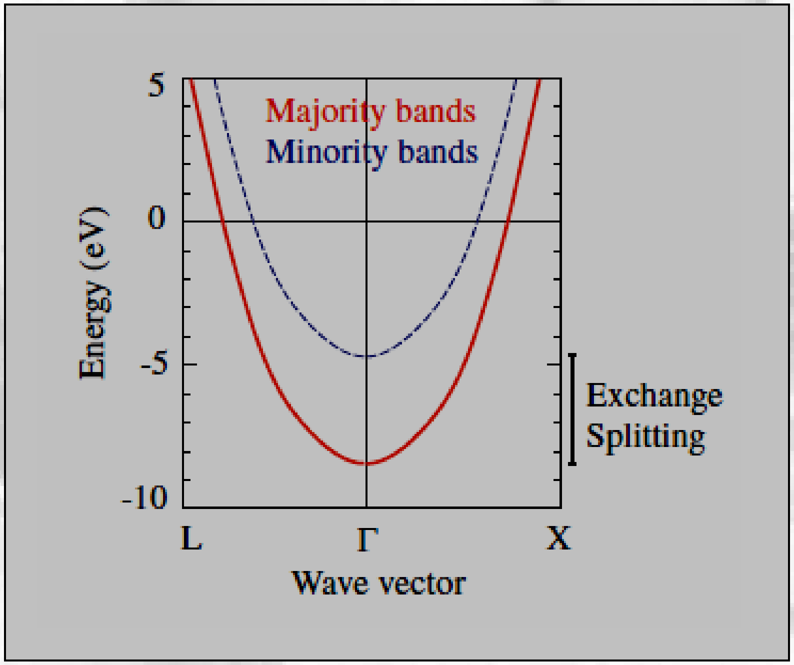
} **degrees of freedom**



Simplified Models

Stoner Model

- ❑Electron bands for spin ↑ and ↓ have relative shift in energy due to *Exchange* interaction.
- ❑Both have free electron dispersion, "equation"

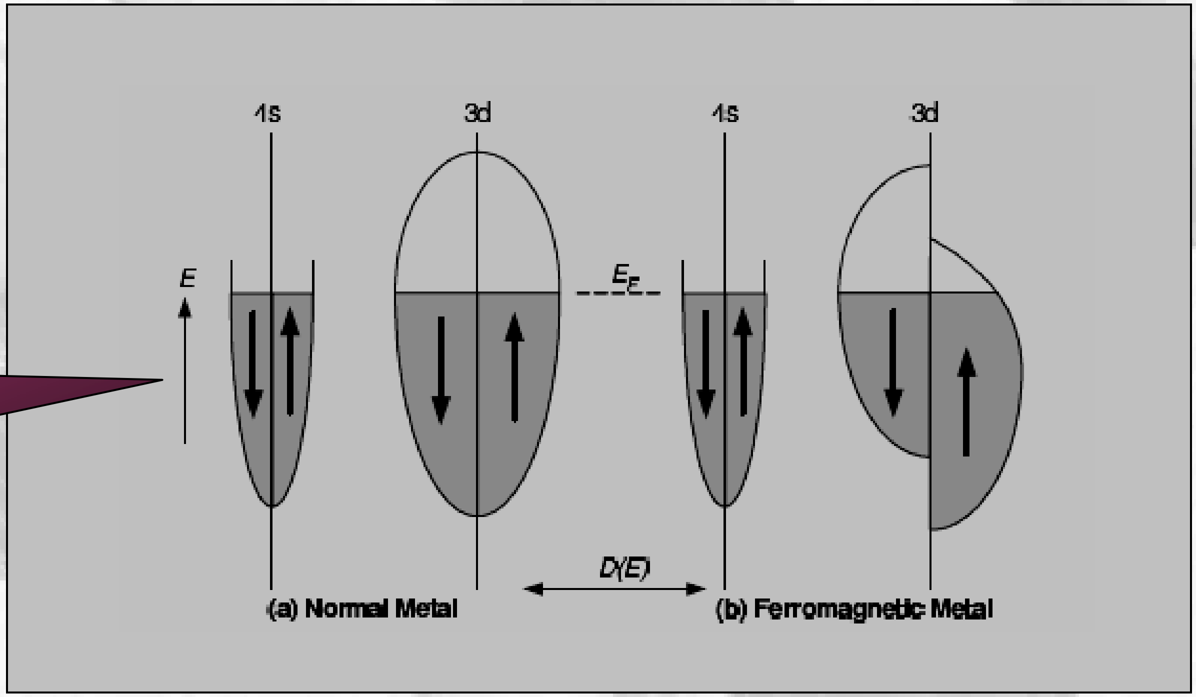


s-d model

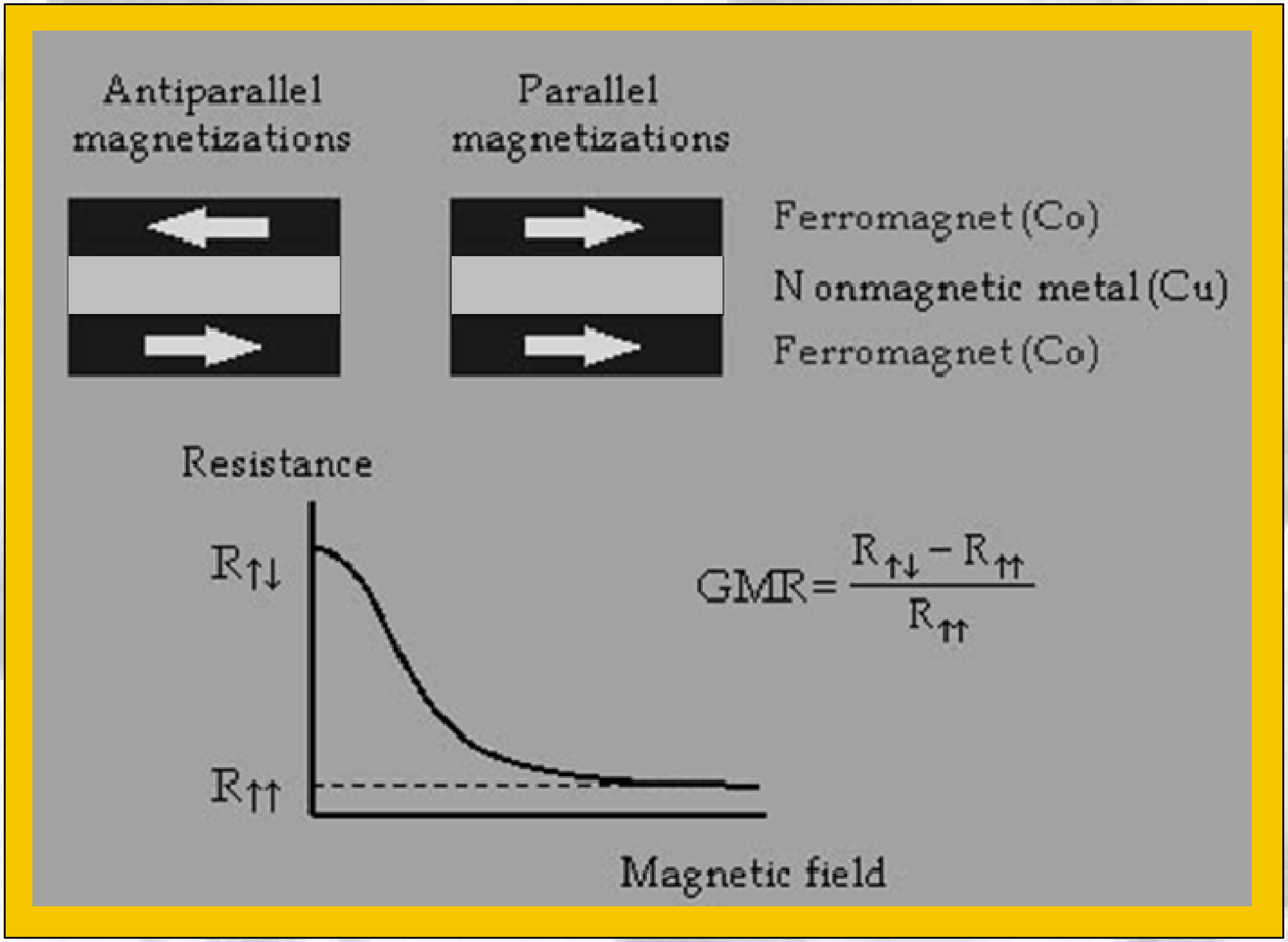
Mott's s-d model (1936)

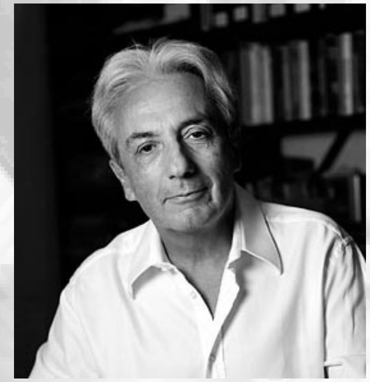
- two spin states carry current in parallel
- s↑ can scatter to s↑ or d↑
- s↓ can scatter to s↓
  or d↓
- d band density of states near ε_F for down moment channel > density of states for up moment channel
- $\rho^{\uparrow} < \rho^{\downarrow}$

In N metals, *d* band DOS are equal at ε_F
$\rho_{\uparrow} = \rho_{\downarrow}$



Giant Magnetoresistance, GMR

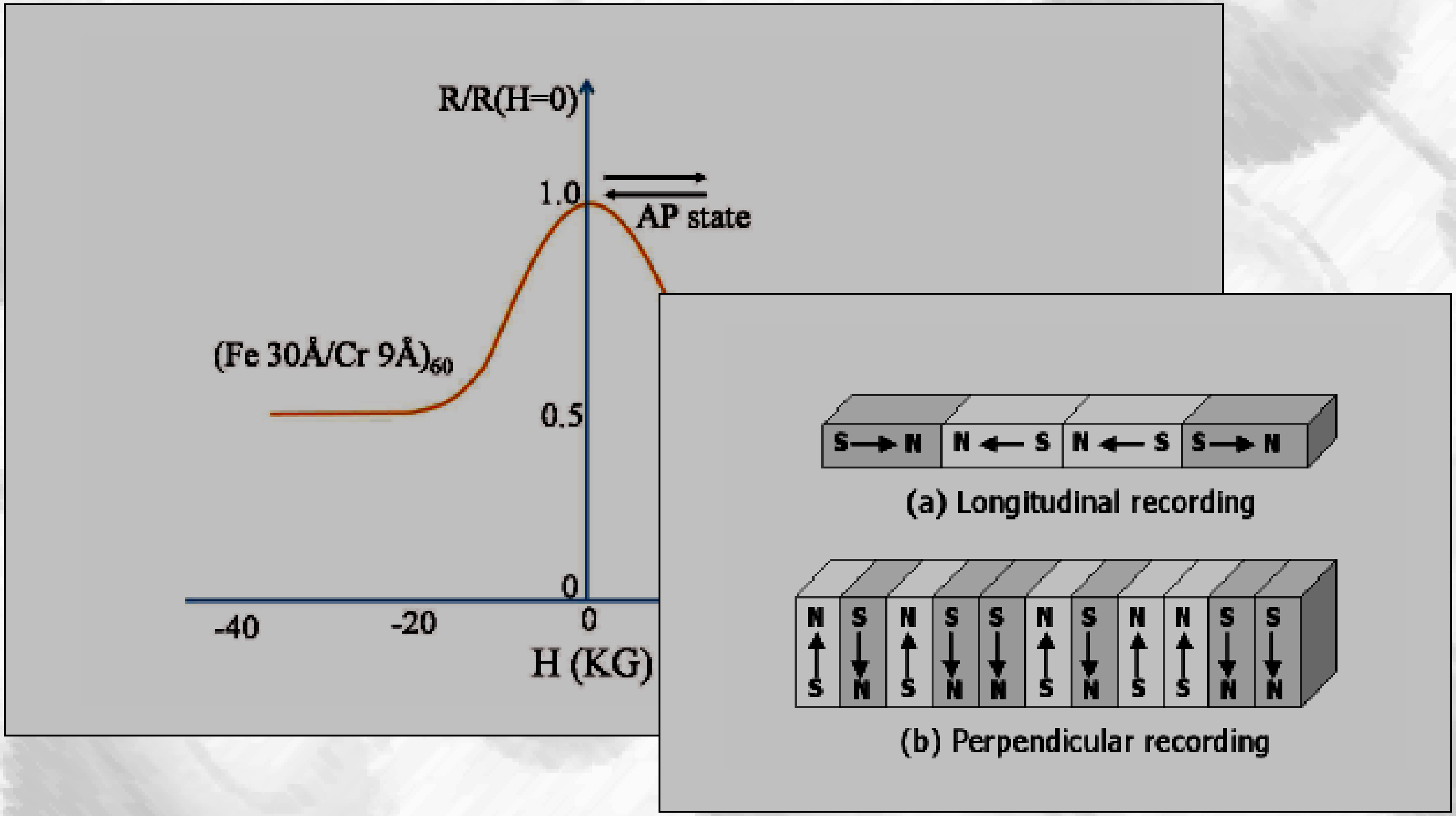




Fert

2007

Grünberg



Fe/Cr multilayers

As Prepared state has moments of Fe antiferromagnetically aligned.

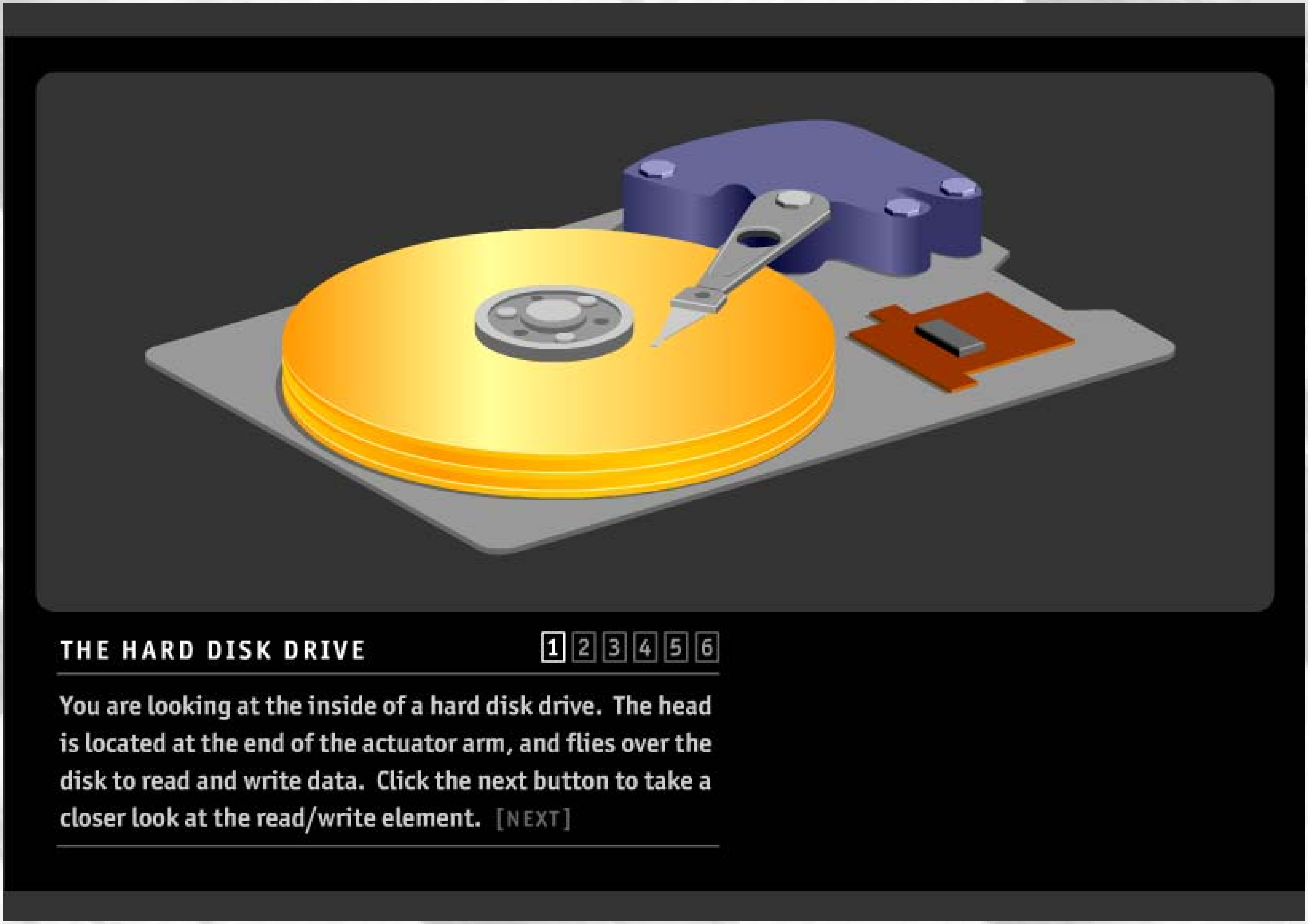
With an applied field the moments became aligned.

Resistance dropped!!!!

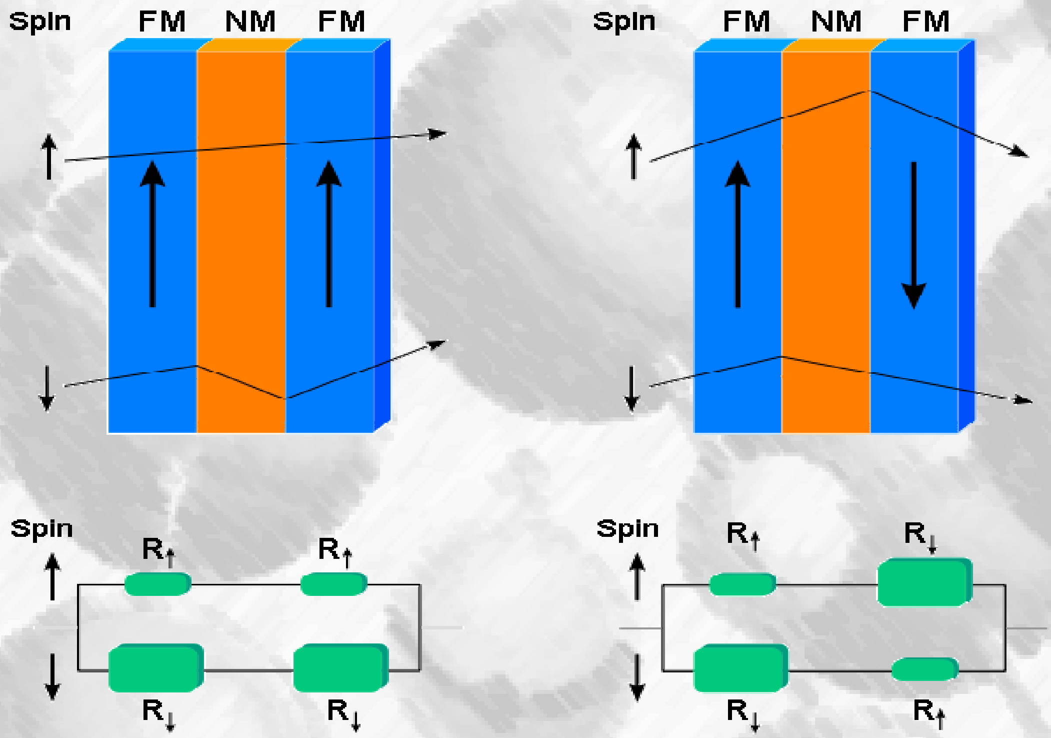
Change in resistance @4.2K ~ 50%

Now that is “Giant”

Hard Disk/Read Head Animation from IBM Web Site.



Simple two current series resistor model for GMR

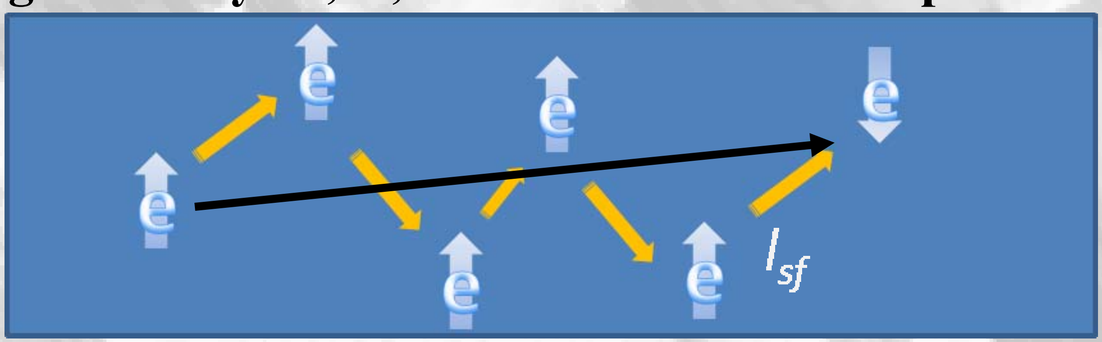


e^- with *up* and *down* moments are divided into two channels

Resistance of each channel is merely the sum of bulk and interfaces of the channel.

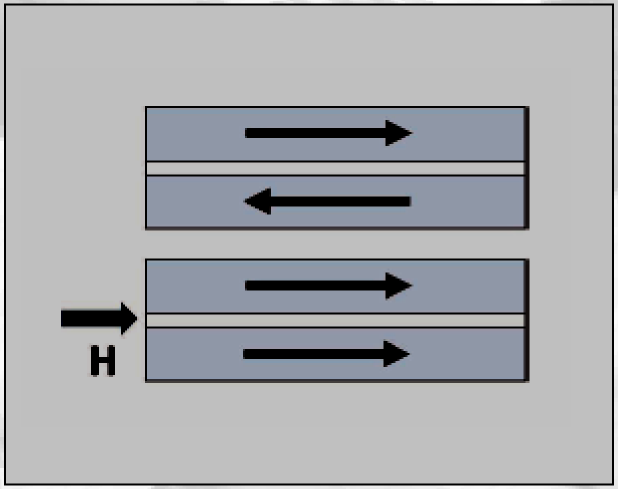
Assumptions!

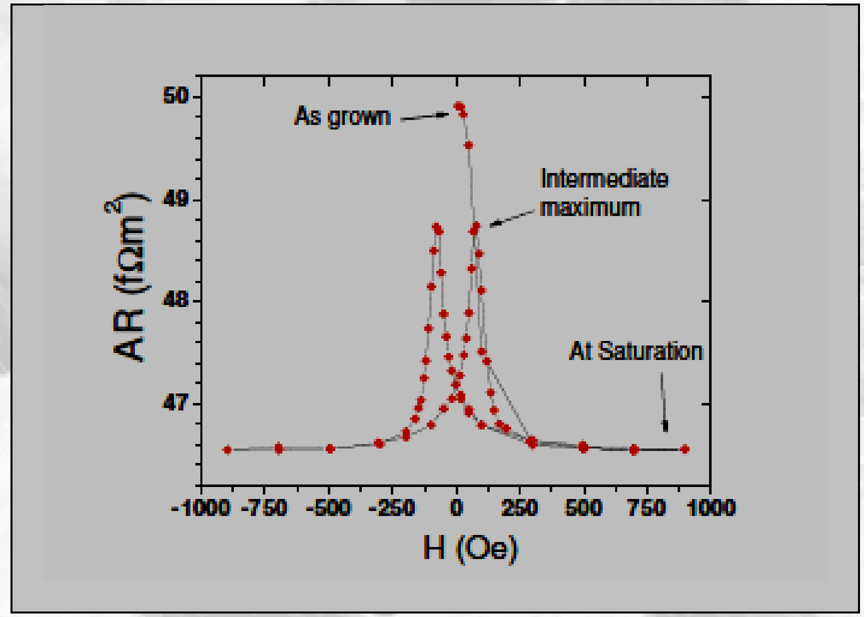
No spin flipping in the layers, ie, the thicknesses are < spin diffusion lengths



How to get control over magnetic ordering of the F layers?

Antiferromagnetically coupled F/N multilayers

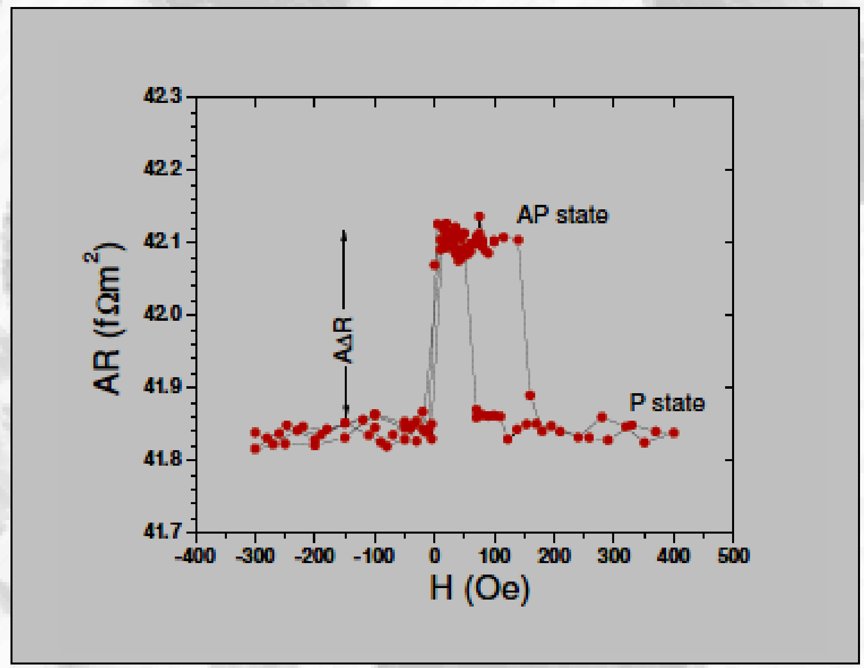




Spin Valves

Hybrid

Exchange Biased



Next significant step in Spintronics - Spin Transfer Torque

Let's first look at Magnetization Dynamics without killing ourselves!

M can align along a H_{Eff} which varies as a function of position

Main contributions:

- **Externally applied magnetic field**
- **Magnetocrystalline anisotropy**
- **Micromagnetic exchange**
- **Magnetostatic field**

$$\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{ext}} + \frac{2K_u}{\mu_0 M_s^2}\hat{\mathbf{n}}(\hat{\mathbf{n}}\cdot\mathbf{M}(\mathbf{r})) + \frac{2A_{\text{ex}}}{\mu_0 M_s^2}\nabla^2\mathbf{M} + \frac{1}{4\pi}\int d^3r'\,\frac{3(\mathbf{M}(\mathbf{r}')\cdot\mathbf{x})\mathbf{x} - \mathbf{M}(\mathbf{r}')|\mathbf{x}|^2}{|\mathbf{x}|^5}.$$

Easy Axis along n

Away from equilibrium, magnetization precesses around instantaneous *effective* field

$$\dot{\mathbf{M}} = -\gamma_0'\mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\lambda}{M_s}\mathbf{M} \times (\mathbf{M} \times \mathbf{H}_{\text{eff}}) \quad \text{(Landau−Lifshitz)}$$

$$\dot{\mathbf{M}} = -\gamma_0\mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M_s}\mathbf{M} \times \dot{\mathbf{M}} \quad \text{(Gilbert)}$$

λ is the Landau-Lifshitz damping term
α is the Gilbert damping term

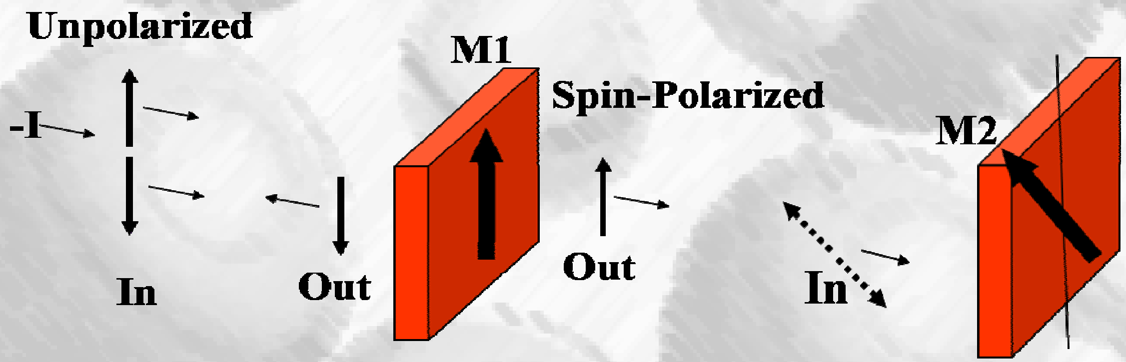
So far no spin transfer torque considered….

Spin Transfer Torque, STT- Slonczewski & Berger (1989)

Arises when the flow of spin angular momentum through a sample is not constant.

- **When spin filtering created by one magnetic layer is non collinear with the second magnetic layer.**
  - **In the process of filtering, the second magnetic layer absorbs a portion of the angular momentum carried by the e^- spins.**

To Simplify, Assume only up-moment ↑ (Maj. e^-) pass through M1.



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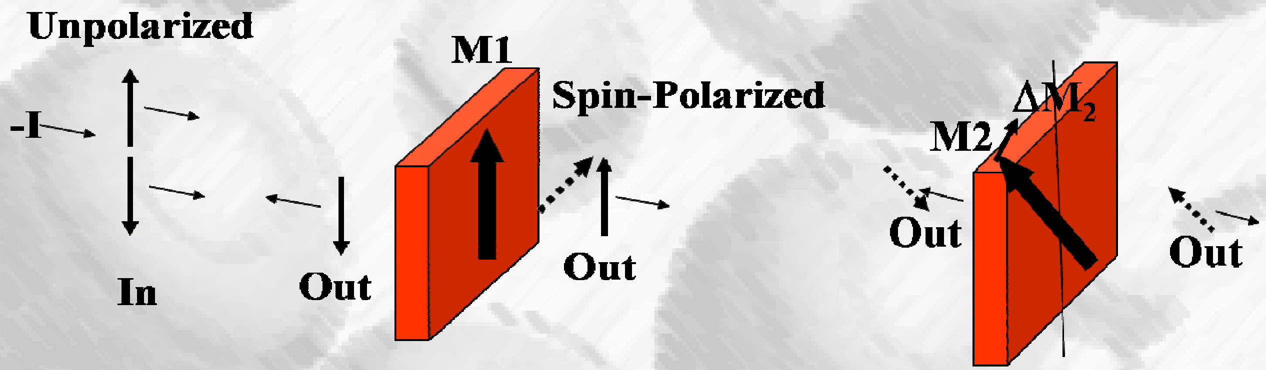


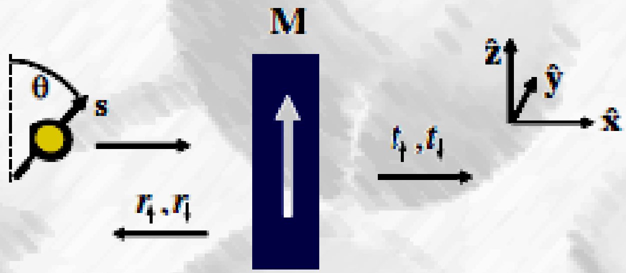
The magnetization of the F changes the flow of spin-angular momentum by exerting a torque on the flowing spins to reorient them

Therefore the flowing e^- must exert an equal and opposite torque on F.
This torque by non-equilibrium conduction of e^- onto F is *Spin Transfer Torque*

Primary quantity to focus on is spin current density

$$\mathrm{Q} = \frac{\hbar^2}{2m}\mathrm{Im}(\psi^* \boldsymbol{\sigma} \otimes \boldsymbol{\nabla}\psi)$$

$$\psi = \frac{\mathrm{e}^{ikx}}{\sqrt{\Omega}}(a|\uparrow\rangle + b|\downarrow\rangle)$$

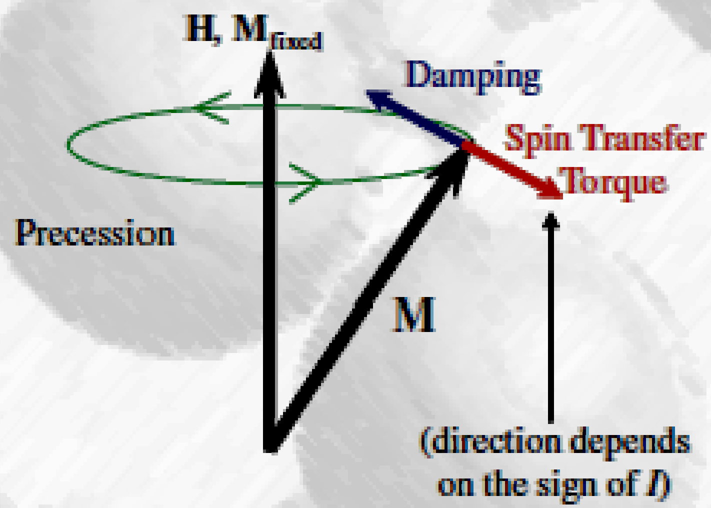


$$\mathrm{N}_{\mathrm{st}} = A\hat{\mathrm{x}} \cdot (\mathrm{Q}_{\mathrm{in}} + \mathrm{Q}_{\mathrm{refl}} - \mathrm{Q}_{\mathrm{trans}}) \approx A\hat{\mathrm{x}} \cdot \mathrm{Q}_{\mathrm{in}\perp}$$

Spin transfer torque can be computed by determining the net flux of non-equilibrium spin current through a volume

Introduce this term in the LLG equation to account for STT

$$\dot{\mathrm{M}}_{\mathrm{st}} = -\mathrm{N}_{\mathrm{st}}|g|\mu_{\mathrm{B}}/(\hbar\mathscr{V})$$



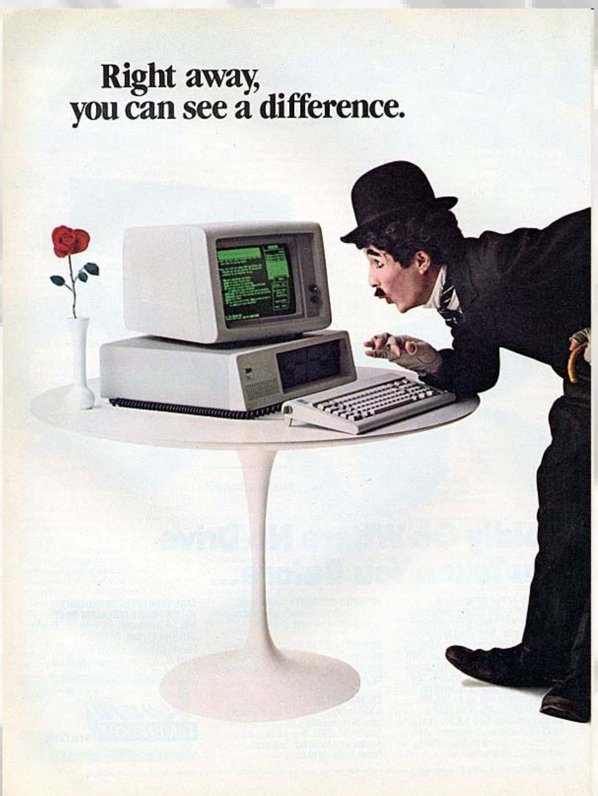
Applications

Used for writing without the presence of magnetic field

STT does not disturb neighboring MRAM cells

Lower writing currents compared to magnetic field switching

Nanoscale device dimensions!!!!



Thank You

References and further enlightenment

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