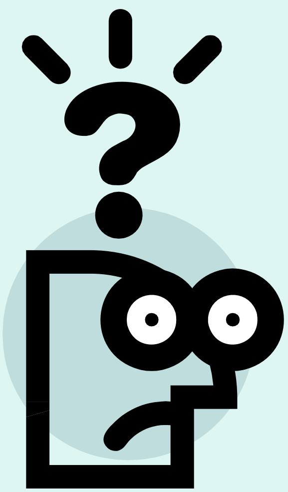
Spin Torque for Dummies



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Outline

1) Spin dynamics

2) Magnetotransport

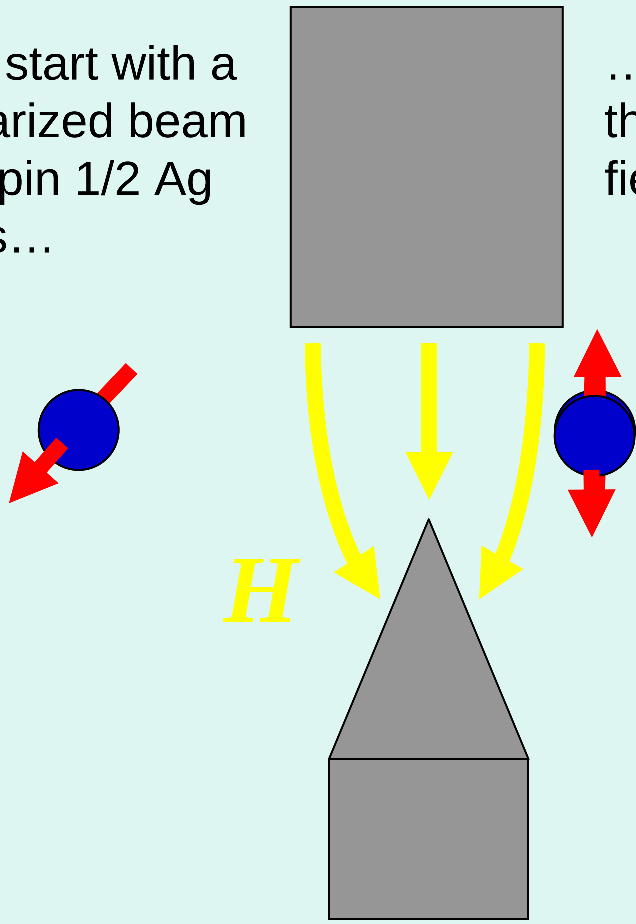
3) Spin momentum transfer

4) Spin torque nano-oscillators

But first… a puzzle!

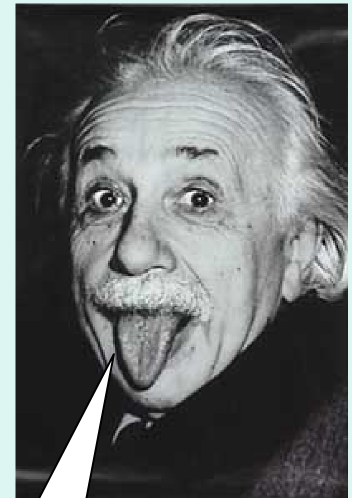
The “Stern-Gerlach” experiment

We start with a polarized beam of spin 1/2 Ag ions…



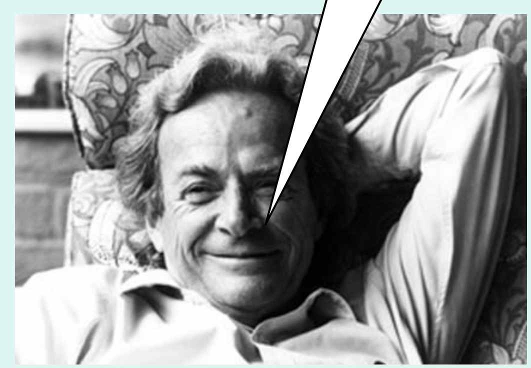
… we pass the beam through a magnetic field gradient…

… and the beam “diffracts” into two beams, ***polarized along the axis of the magnetic field***.



Very strange…

… but true!!!



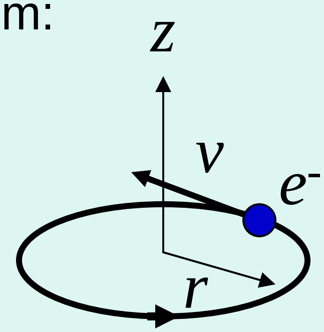
Q: What happened to the angular momentum ***in the original polarization direction???***

(For more details, see Feynman’s Lectures on Physics, Vol. III, page 5-1)

Part 1: Spin dynamics

Magnets are Gyroscopes!

Classical model for an atom:



magnetic moment for atomic orbit:

$$\vec{\mu}_L = I\vec{A}$$

$$= -\left(\frac{ev}{2\pi r}\right)\left(\pi r^2\right)\hat{z}$$

$$= -\frac{evr}{2}\hat{z}$$

angular momentum for atomic orbit:

$$\vec{L} = \vec{r} \times \vec{p}$$

$$= rmv\hat{z}$$

$$\gamma_L \doteq \frac{\mu_z}{L_z}$$

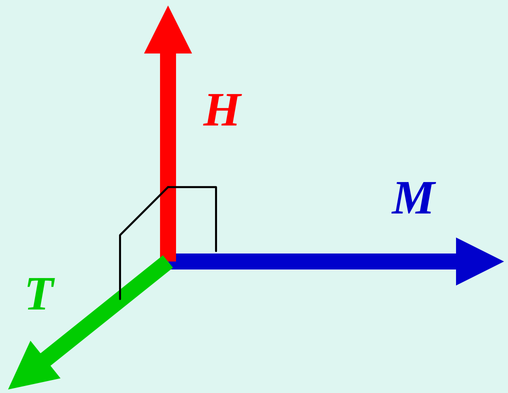
$$= -\frac{evr/2}{rm_e v}$$

$$\boxed{\gamma_L = -\frac{e}{2m_e} = -\frac{\mu_B}{\hbar}} \longrightarrow \gamma_s = -\frac{2\mu_B}{\hbar}$$

For spin angular momentum, extra factor of 2 required.

“The gyromagnetic ratio”

Larmor Equation



$$\vec{T} = \mu_0 \vec{M} \times \vec{H}$$

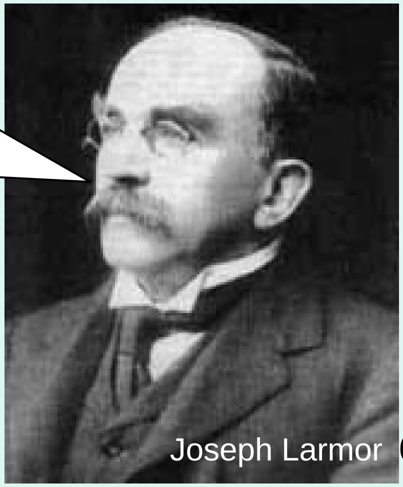
Magnetic field exerts torque on magnetization.

(definition of torque) $$\frac{d\vec{L}}{dt} = \vec{T}$$

$$\gamma \equiv \frac{\mu}{L}$$ (gyromagnetic ratio)

$$\frac{d\vec{M}}{dt} = \gamma \vec{T} = \gamma \mu_0 \left(\vec{M} \times \vec{H} \right)$$

Magnets make me dizzy!



Joseph Larmor

Gyromagnetic precession with energy loss: The Landau-Lifshitz equation

<u>Landau & Lifshitz (1935):</u>

$\vec{T}_p$ = precession torque

$$= \mu_0 \vec{M} \times \vec{H}$$

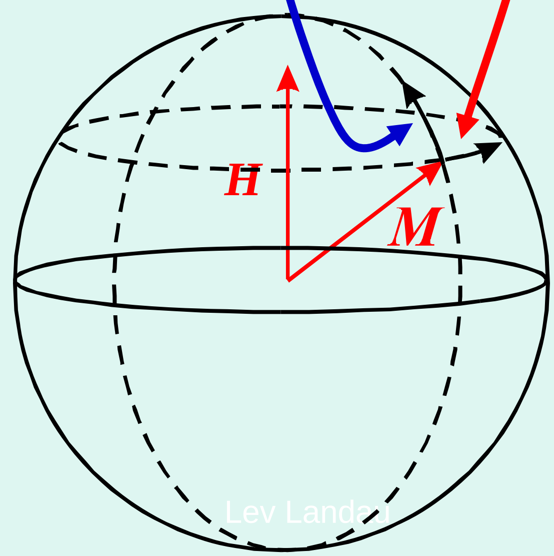
$\vec{T}_d$ = damping torque

$$= \frac{\alpha \mu_0}{M_s} \vec{M} \times \left(\vec{M} \times \vec{H} \right)$$

α = dimensionless Landau-Lifshitz damping parameter

$$\frac{d\vec{M}}{dt} = -|\gamma|\vec{T} = -|\gamma|\left(\vec{T}_p + \vec{T}_d\right)$$
$$= -|\gamma|\mu_0 \vec{M} \times \vec{H}$$
$$- \frac{\alpha|\gamma|\mu_0}{M_s} \vec{M} \times \left(\vec{M} \times \vec{H}\right)$$

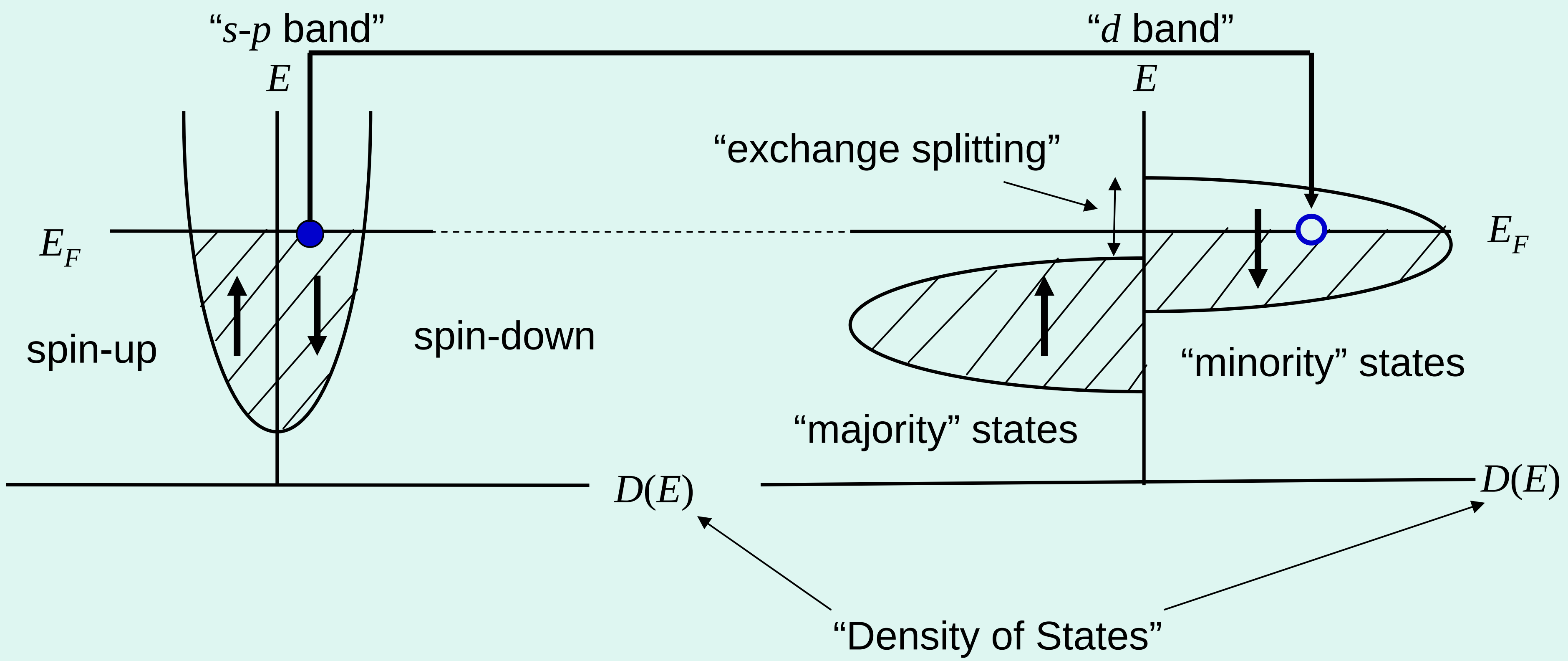
Damping happens!!



L. Landau and E. Lifshitz, Physik. Z. Sowjetunion **8**, 153-169 (1935).

Part 2: Charge transport in magnetic heterostructures (Magneto-transport)

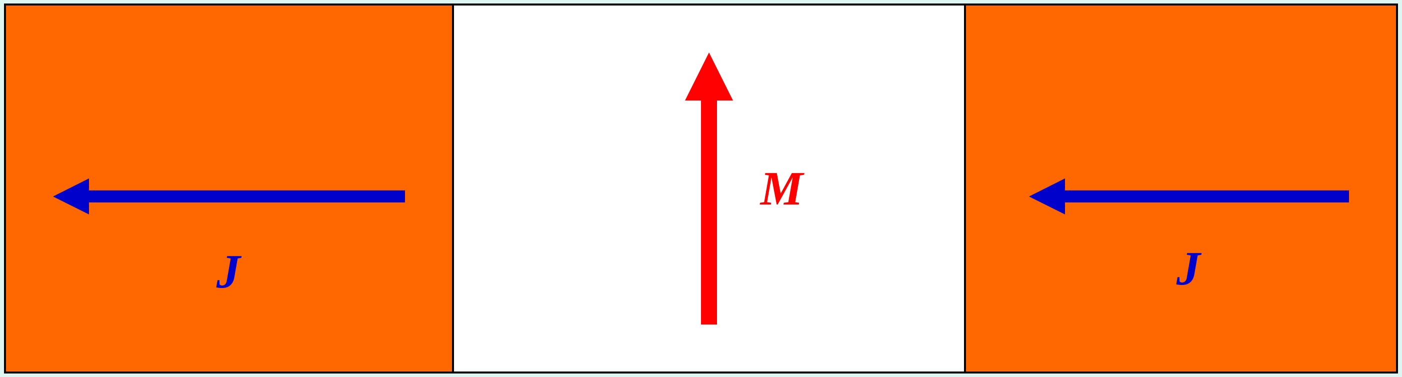
Ferromagnetism in Conductors: Band Structure



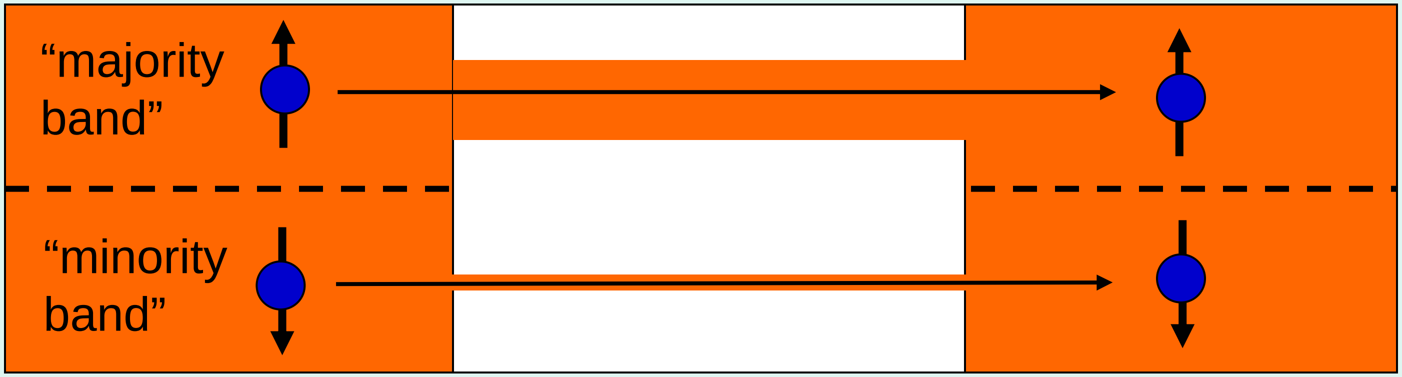
➔s-band states (l = 0) have higher mobility than d-band states (l = 2) in conductors due to the much lower effective mass of the s-band.

➔Minority band electrons scatter more readily from the s-p band to the d-band due to the availability of hole states in the minority d-band.

Spin-dependent conductivity in ferromagnetic metals



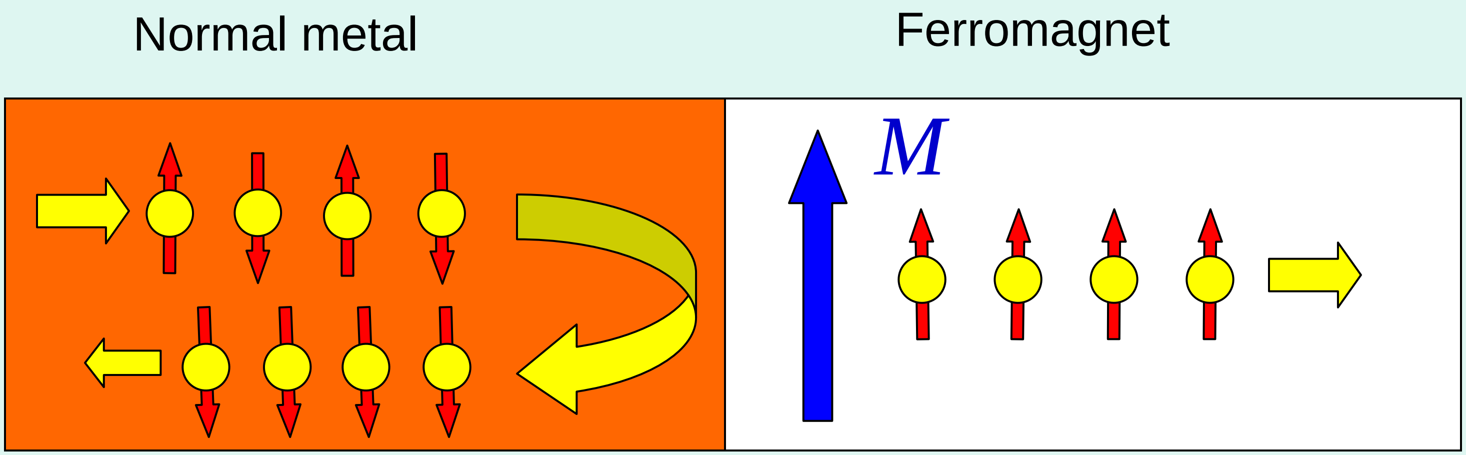
Analogy: Like water flowing through pipes. Large conductivity = big pipe, etc…



➔Conductivities in ferromagnetic conductors are different for majority and minority spins.

➔In an “ideal” ferromagnetic conductor, the conductivity for minority spins is zero.

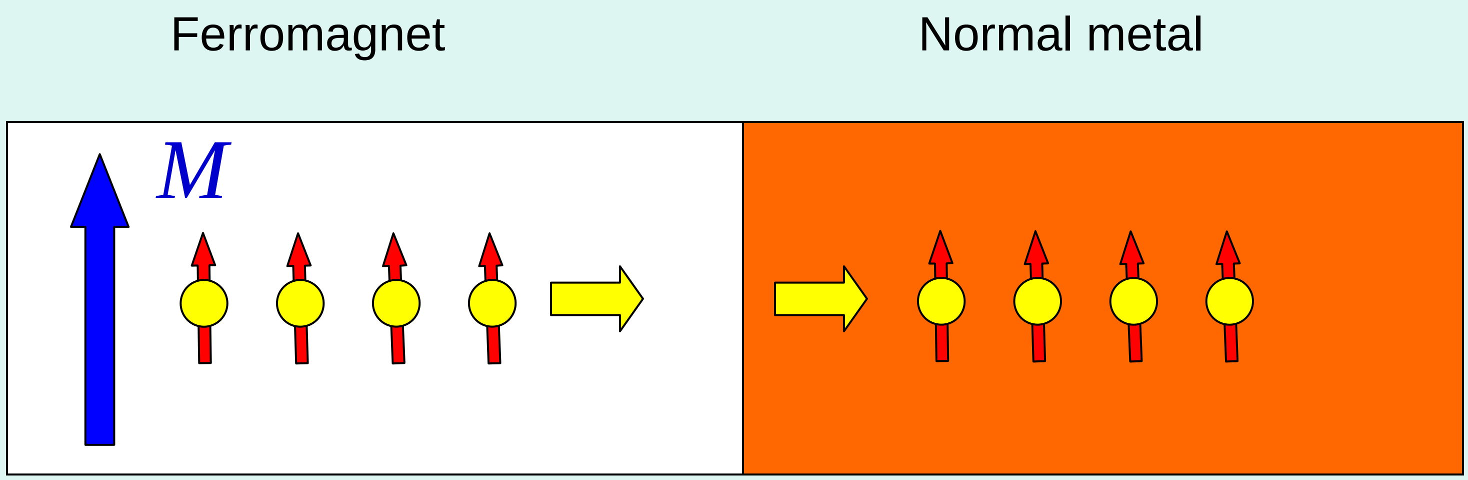
Concept: interfacial spin-dependent scattering



➔“Majority” spins are preferentially transmitted.

➔”Minority” spins are preferentially reflected.

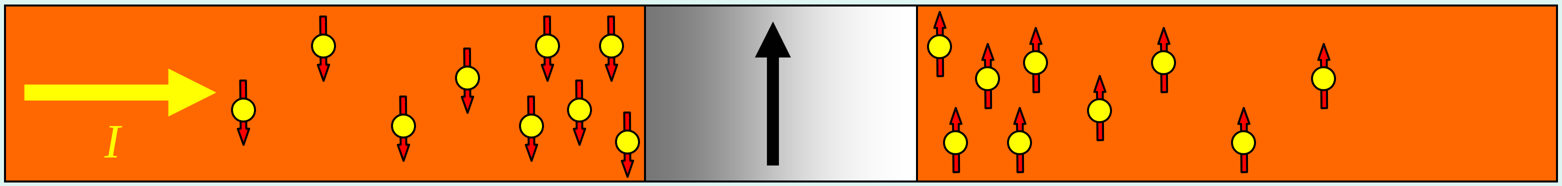
Concept: ferromagnets as spin polarizers



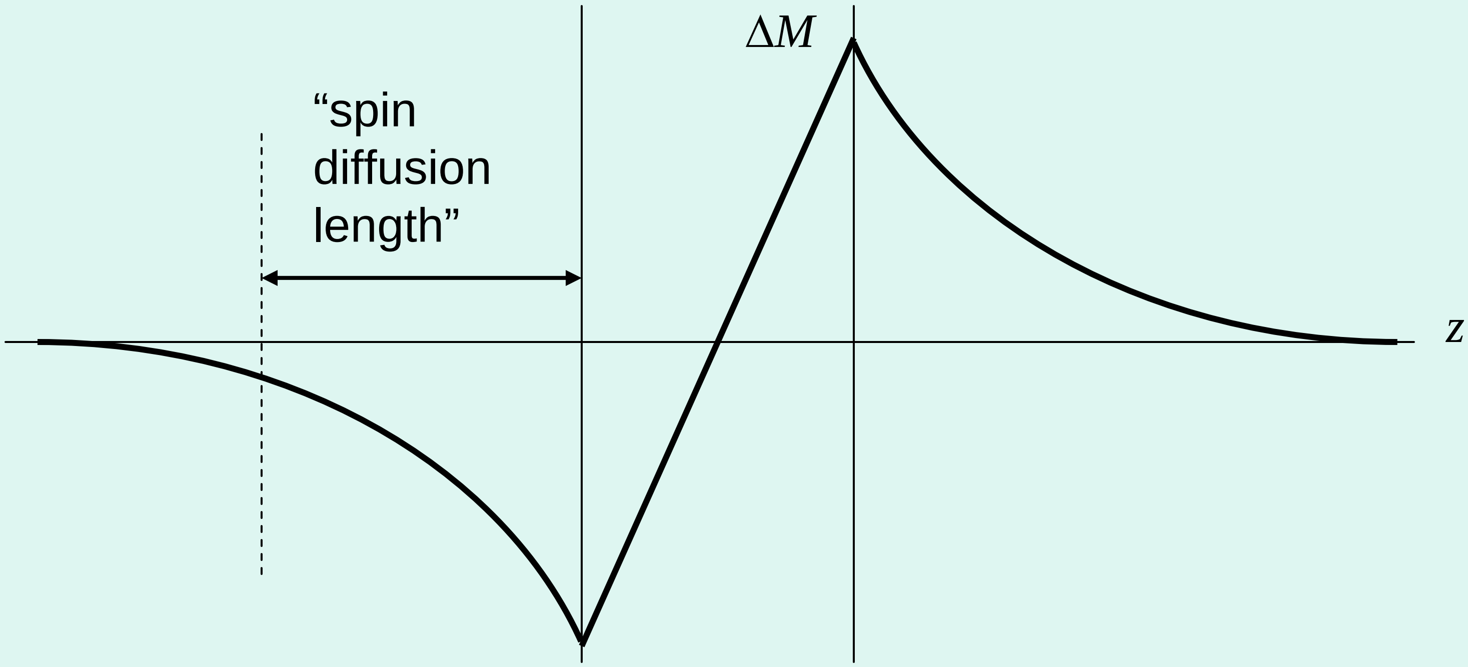
➔“Majority” spins are preferentially transmitted.

Ferromagnetic conductors are relatively permeable for majority spins.
Conversely, they are impermeable for minority spins.

Concept: spin accumulation



$$M(z) = M_s + \Delta M$$

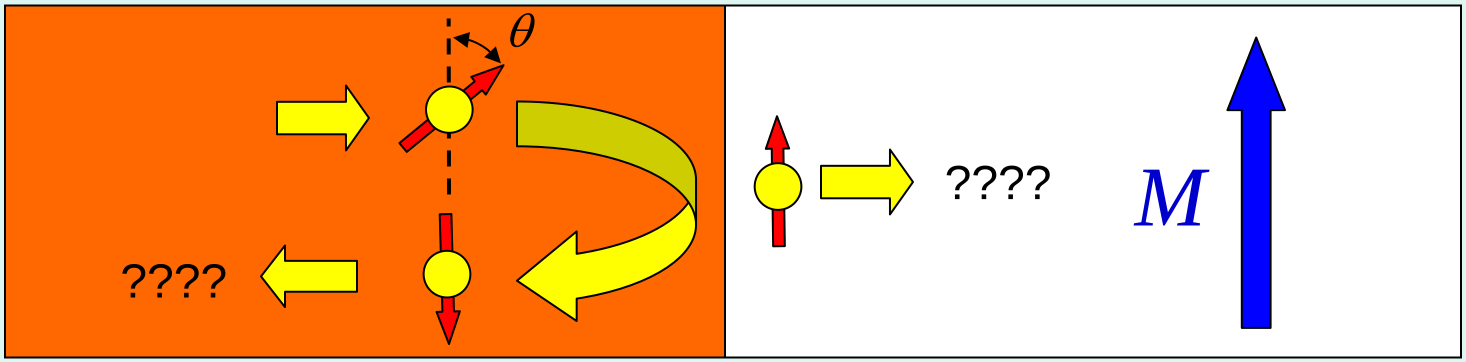


Non-equilibrium spin polarization “accumulates” near interfaces of ferromagnetic and non-magnetic conductors.

Part 3: Spin momentum transfer

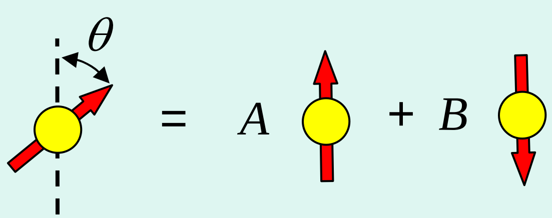
Non-collinear spin transmission

What if the spin is neither in the majority band nor the minority band???



Is the spin reflected or is it transmitted?

Quantum mechanics of spin:



$$\begin{cases} A = \cos\left(\frac{\theta}{2}\right) \\ B = \sin\left(\frac{\theta}{2}\right) \end{cases}$$

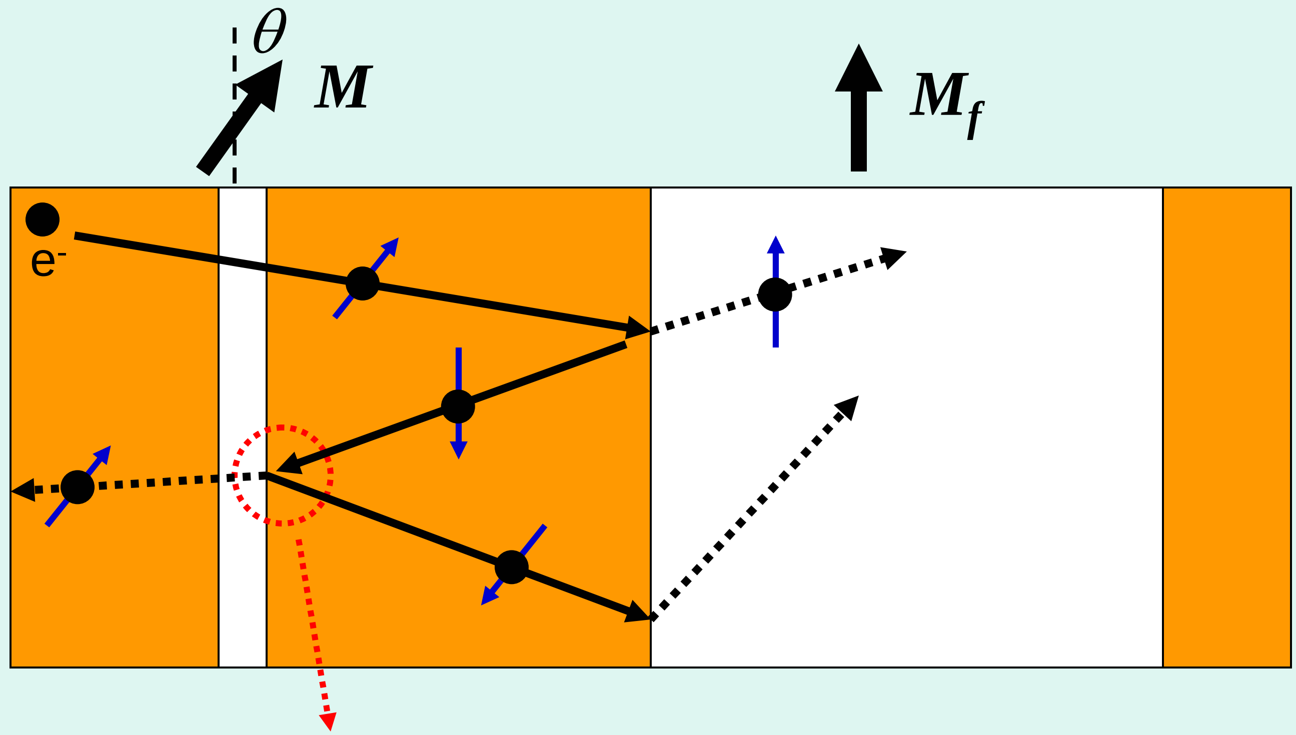
An arbitrary spin state is a coherent superposition of “up” and “down” spins.

Quantum mechanical probabilities:

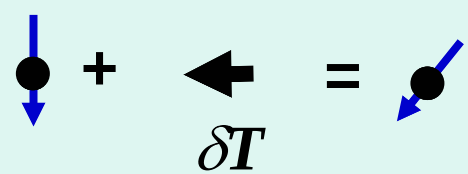
$$\Pr[\uparrow] = |A|^2 = \frac{1}{2}\left(1+\cos(\theta)\right)$$

$$\Pr[\downarrow] = |B|^2 = \frac{1}{2}\left(1-\cos(\theta)\right)$$

Spin Momentum Transfer: Small Current Limit

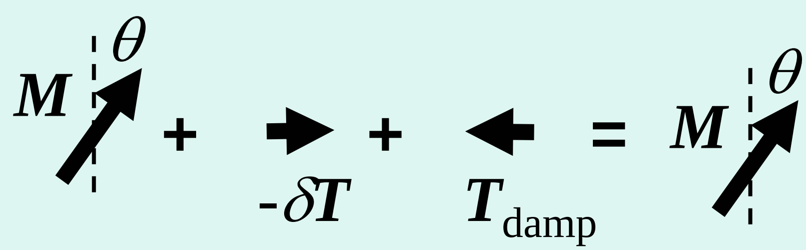


Electrons:



$$\delta\vec{T} \propto \theta; \theta \ll 1$$

Polarizer:

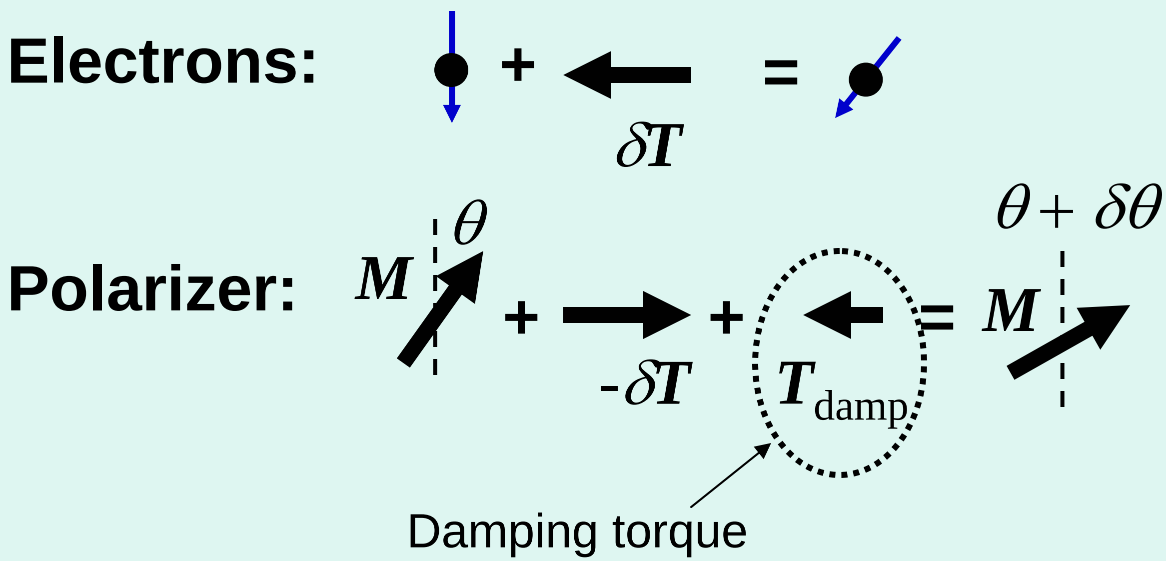


At low electron flux,
damping torque compensates spin torque: Magnetization is stable.

Spin Momentum Transfer: Large Current Limit

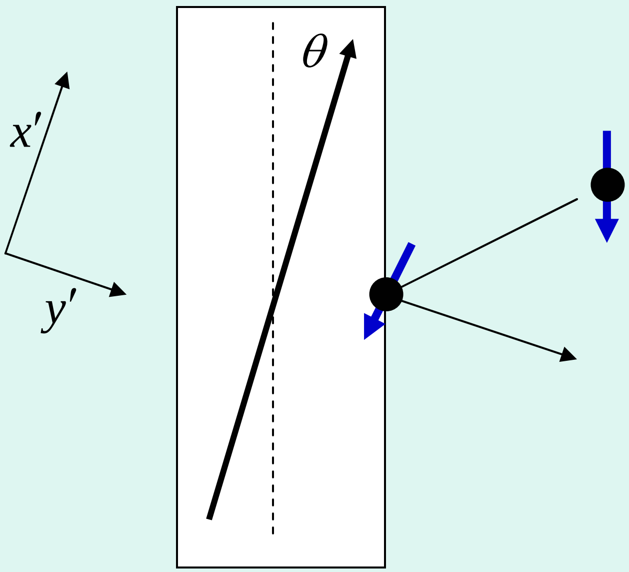
δT is driven by spin accumulation in the Cu spacer.

Spin accumulation is proportional to current flowing through the structure.



Spin torque exceeds damping torque: Polarizer reacts with changing *M*. Torque proportional to angle *θ*: Unstable!

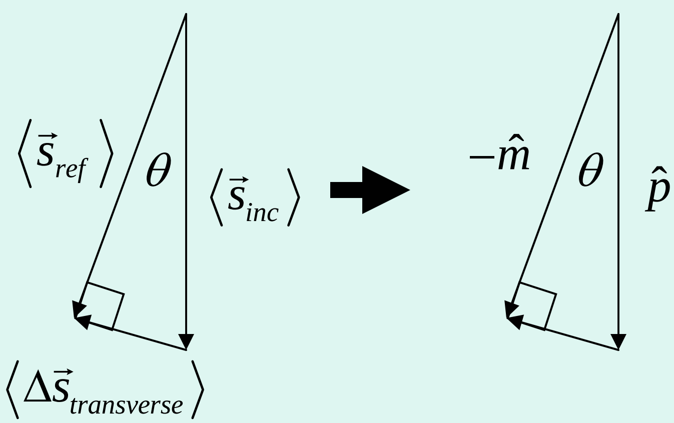
Transverse torque via spin reorientation/reflection



Consider only reflection events...

AND

Consider only change in angular momentum **transverse** to magnetization axis. (Equivalent to assuming magnitude of $\boldsymbol{M}$ does not change.)



For the electron:

$$\langle \Delta\vec{s}_{transverse} \rangle = -\left|\langle \vec{s}_{inc} \rangle\right| \frac{\left|\langle \Delta\vec{s}_{transverse} \rangle\right|}{\left|\langle \vec{s}_{inc} \rangle\right|} \hat{y}'$$

$$= -\frac{\hbar}{2}\sin(\theta)\,\hat{y}'$$

$$= -\frac{\hbar}{2}\hat{m}\times(\hat{m}\times\hat{p}) \quad \text{where} \quad \hat{p} = \frac{2}{\hbar}\langle \vec{s}_{inc} \rangle$$

$$= \frac{\hbar}{2}\hat{m}\times(\hat{m}\times\hat{m}_f)$$

Newton's Second Law

If…

$$\left\langle \Delta \vec{s}_{trans} \right\rangle = \frac{\hbar}{2} \hat{m} \times \left(\hat{m} \times \hat{m}_f \right)$$

Total moment of "free" magnetic layer

…then…

$$\left(\Delta \vec{M} \right) V = \left| \gamma \right| \frac{\hbar}{2} \hat{m} \times \left(\hat{m} \times \hat{m}_f \right)$$

…per electron.

For a flowing stream of electrons:

Rate of electron impingement on "free" layer

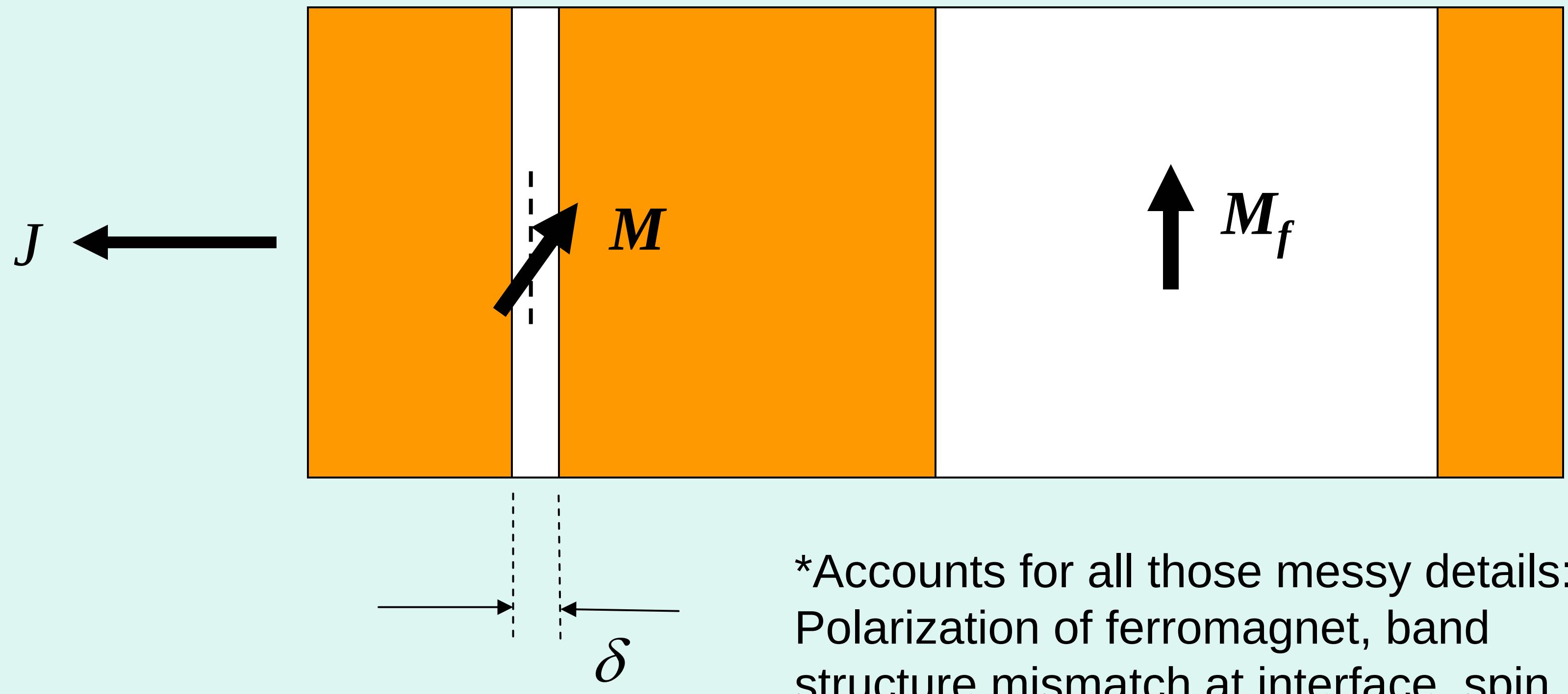
$$\left(\frac{d\vec{M}}{dt} \right) = \frac{\left| \gamma \right| \frac{\hbar}{2} \hat{m} \times \left(\hat{m} \times \hat{m}_f \right)}{V} \left(\frac{I}{e} \right)$$

$$= \left(\frac{I \left| \gamma \right| \hbar}{2eM_s^2 V} \right) \left(\vec{M} \times \left(\vec{M} \times \hat{m}_f \right) \right)$$

The Slonczewski Torque Term

efficiency* ~ 0.2 - 0.3

$$\vec{T}_{Slonczewski} = \frac{J\hbar\varepsilon}{2e\delta M_s^2}\vec{M}\times(\vec{M}\times\hat{m}_f)$$



*Accounts for all those messy details: Polarization of ferromagnet, band structure mismatch at interface, spin decoherence, etc…

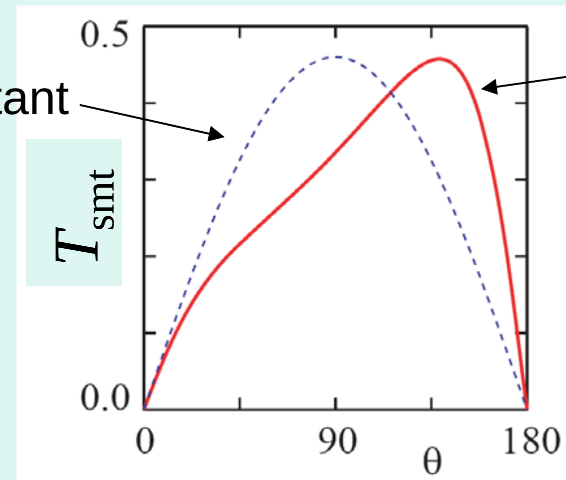
J. Slonczewski, Journal of Magnetism and Magnetic Materials, vol. 159, page L1 (1996)

The "FAQ Page"

Q: Don't the reflected spins affect the spin accumulation in the spacer layer?

A: Yes, they do. There are several theories that take this "back-action" on the spin accumulation into account. See J. C. Slonczewski, J. Magn. Magn. Mater. **247**, 324 (2002); A. A. Kovalev, *et al.*, Phys. Rev. B **66**, 224424 (2002); J. Xiao, *et al.*, Phys. Rev. B **70**, 172405 (2004); A. Fert, *et al.*, J Magn. Magn. Mater. **69**, 184406 (2004).

$$\varepsilon(\theta) = \frac{q_+}{B_0 + B_1 \cos\theta} + \frac{q_-}{B_0 - B_1 \cos\theta}$$

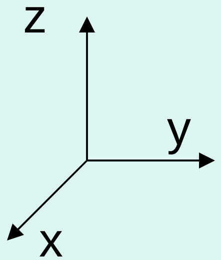


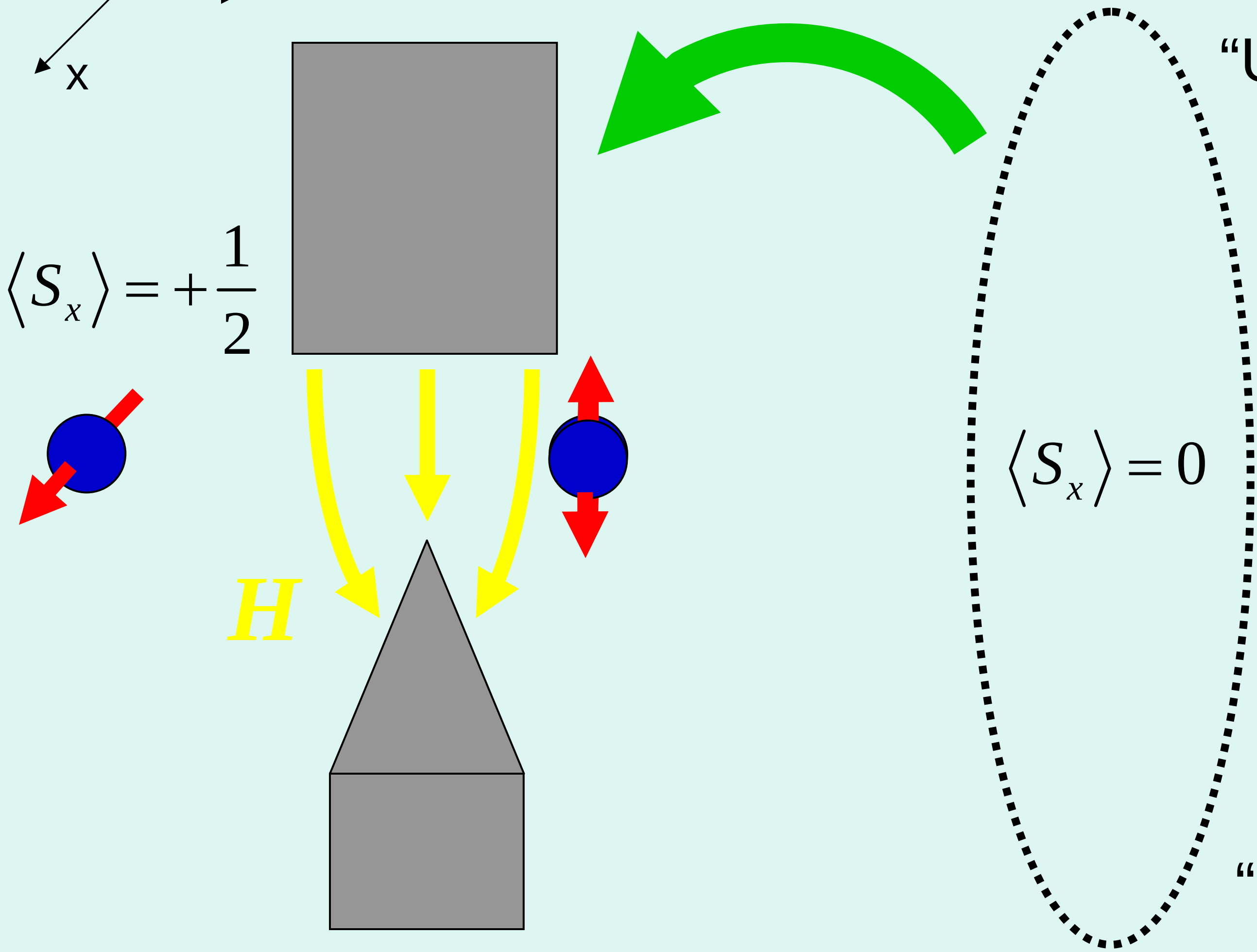
Q: What if the spin is transmitted through the "free" layer rather than reflected?

A: Doesn't matter. Quantum mechanically, there is an amplitude for both transmission and reflection, but only for spin along the axis of magnetization. The transverse component of spin for the incident electrons is "lost" once the electron wavefunction is split into the transmitted and reflected components. Conservation of angular momentum dictates that the transverse component is transferred to the magnetic layer. This is a purely quantum mechanical phenomenon: There is no classical analog!

Back to the puzzle…

The "Stern-Gerlach" experiment, revisited.





"Up" spin current

Once the linear momentum for the two spin components is split, the transverse angular momentum is "released" to do work on the magnet system.

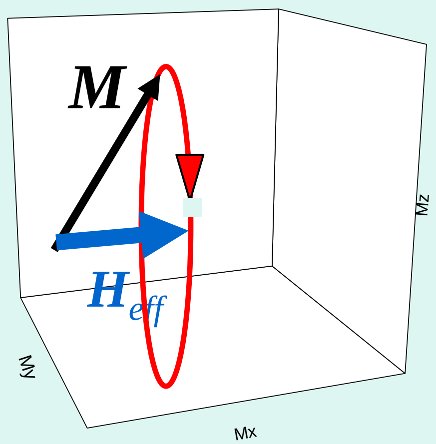
"Down" spin current

A: The quantum equivalent of a card trick. If a card "vanishes" magically from one deck, it must reappear somewhere else. *No mechanism for the transfer of angular momentum need be invoked!*

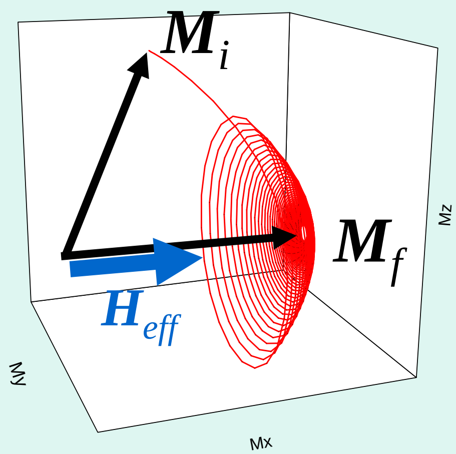
Magnetodynamics: Three Torques

$$\frac{d\vec{M}}{dt} = |\gamma|\left(\vec{T}_{Larmor} + \vec{T}_{damp} + \vec{T}_{smt}\right)$$

$$\frac{d\vec{M}}{dt} = \gamma\mu_0 \vec{M} \times \vec{H}_{eff} \quad - \frac{\alpha\gamma\mu_0}{M_s^2}\vec{M} \times (\vec{M} \times \vec{H}_{eff}) \quad + \frac{Jg\,\mu_B\varepsilon}{2e\delta M_s^2}\vec{M} \times (\vec{M} \times \hat{m}_f)$$

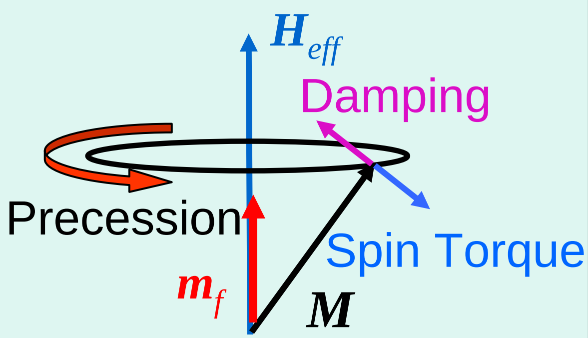


Larmor term:
precession



Damping term:
aligns M with H

Spin Torque Term



Spin torque can
counteract damping

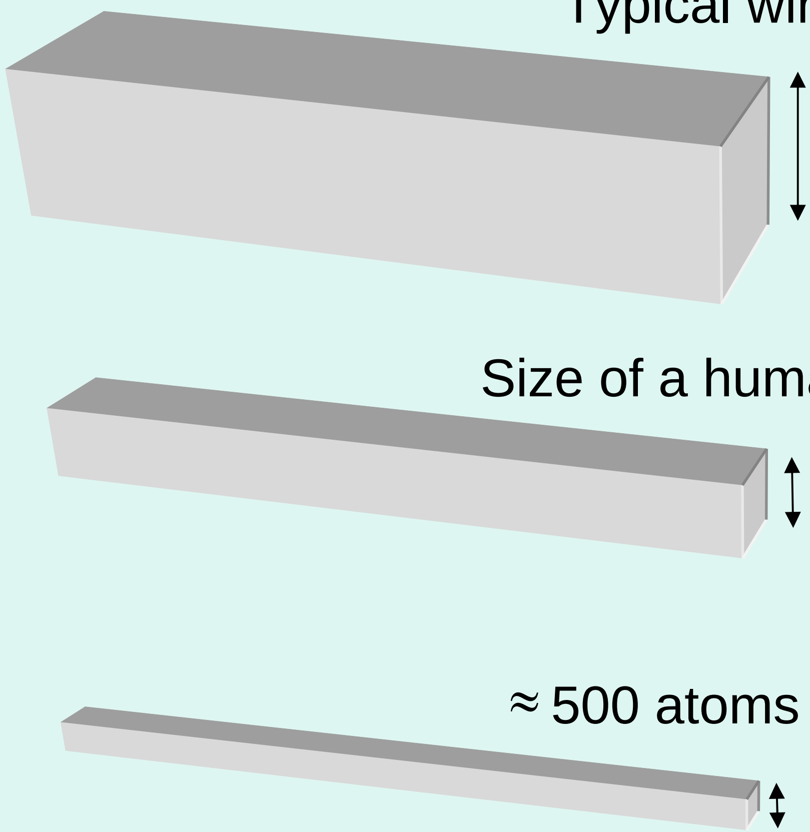
$T_{smt} \cong -T_{damp}$

$J \sim 10^7 A/cm^2$

Slonczewski 1996

How Can We See This?

Torque $\propto$ to current **density**: must have high current *densities* to produce large torques



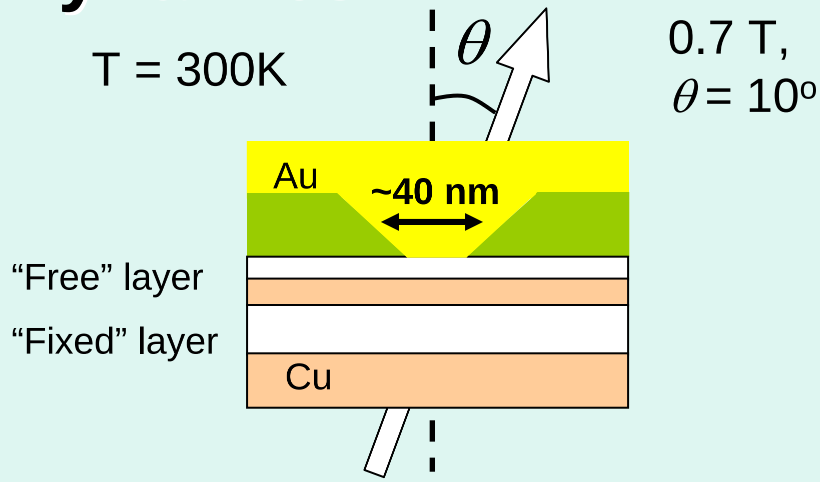
	Required I_{dc}	Possible
Typical wire, 1 mm	$I \approx 0.1$ MA	X
Size of a human hair, 10 μm	$I \approx 10$ A	X
$\approx$ 500 atoms across, 100 nm	$I \approx 1$ mA	✓

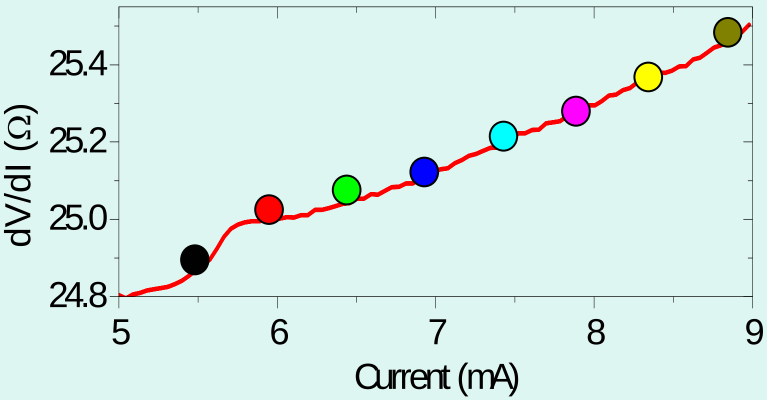
We will use ***nanopillar*** and ***nanocontact*** structures

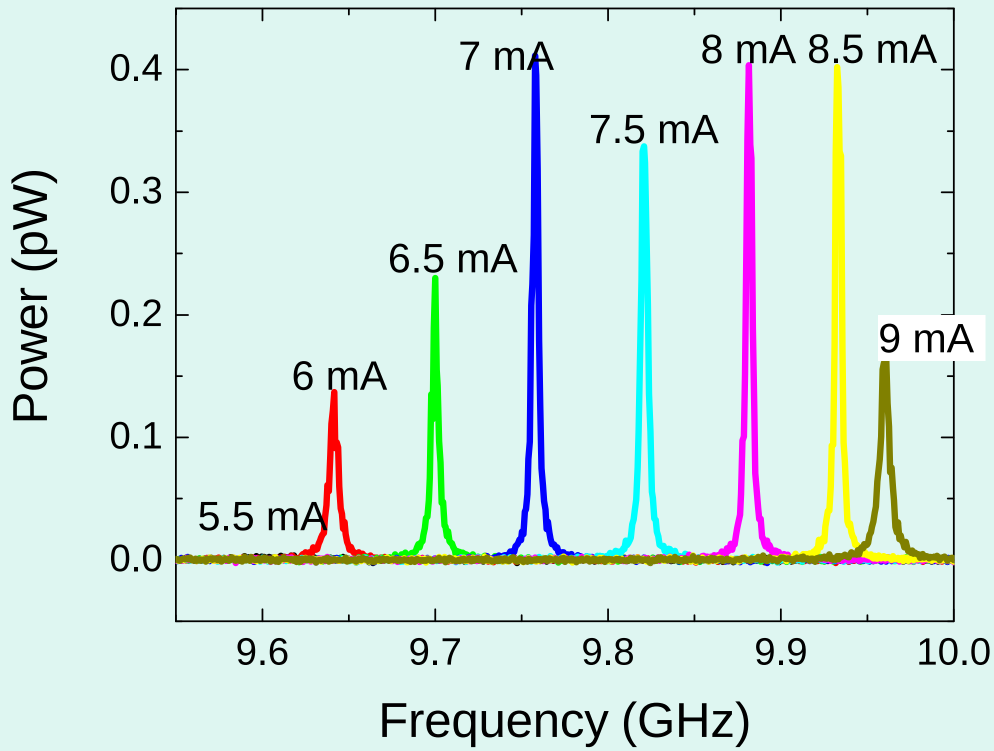
Part 4: Spin torque nano-oscillators

Nanocontact Dynamics

- Step DC current
- Measure DC *R*, microwave power output







Devices are nanoscale current-controlled microwave oscillators

Summary

➔Magnetization dynamics tutorial: *Magnets are gyroscopes.*

➔Magnetotransport tutorial: *Magnets are spin filters.*

➔Spin momentum transfer: *Back action of spin polarized carriers on magnet.*

➔Spin torque nano-oscillator: *Spin torque compensates damping.*

An excellent review article!!

M. D. Stiles and J. Miltat, "Spin Transfer Torque and Dynamics," Topics in Applied Physics **101**, 225-308 (2006).