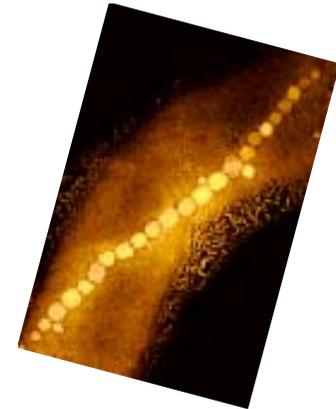
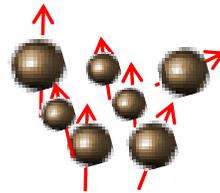
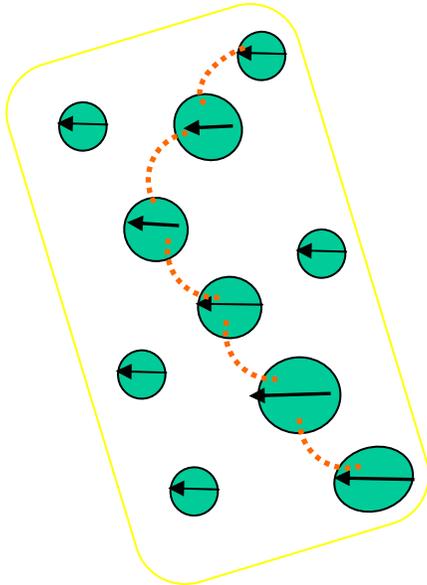
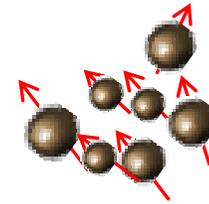
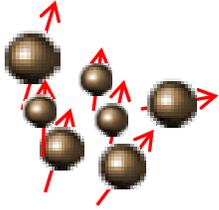


# Magnetismo y Materiales Magnéticos



# Bibliografía



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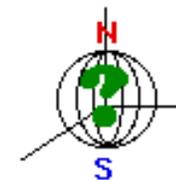
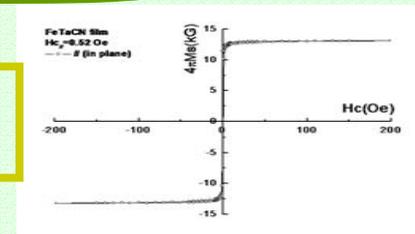
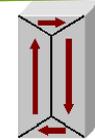
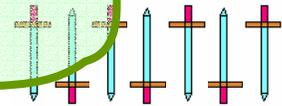
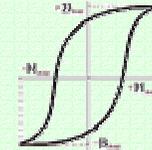
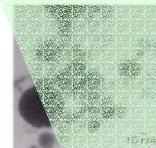
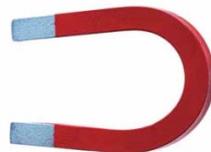
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*Magnetic Domains* (The analysis of Magnetic Microstructures), Alex Hubert y Rudolf Schäfer, Springer 1998

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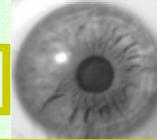
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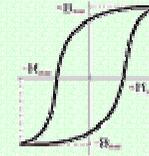


Imanes modernos

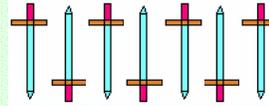
¿Cómo es un material magnético?



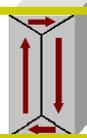
Cantidades Magnéticas de interés práctico



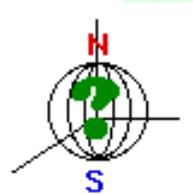
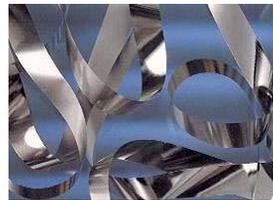
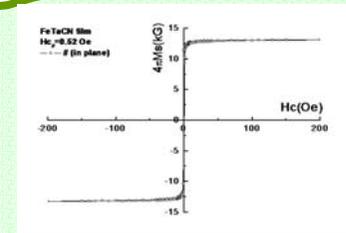
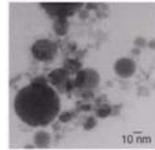
Interacciones Magnéticas



Dominios

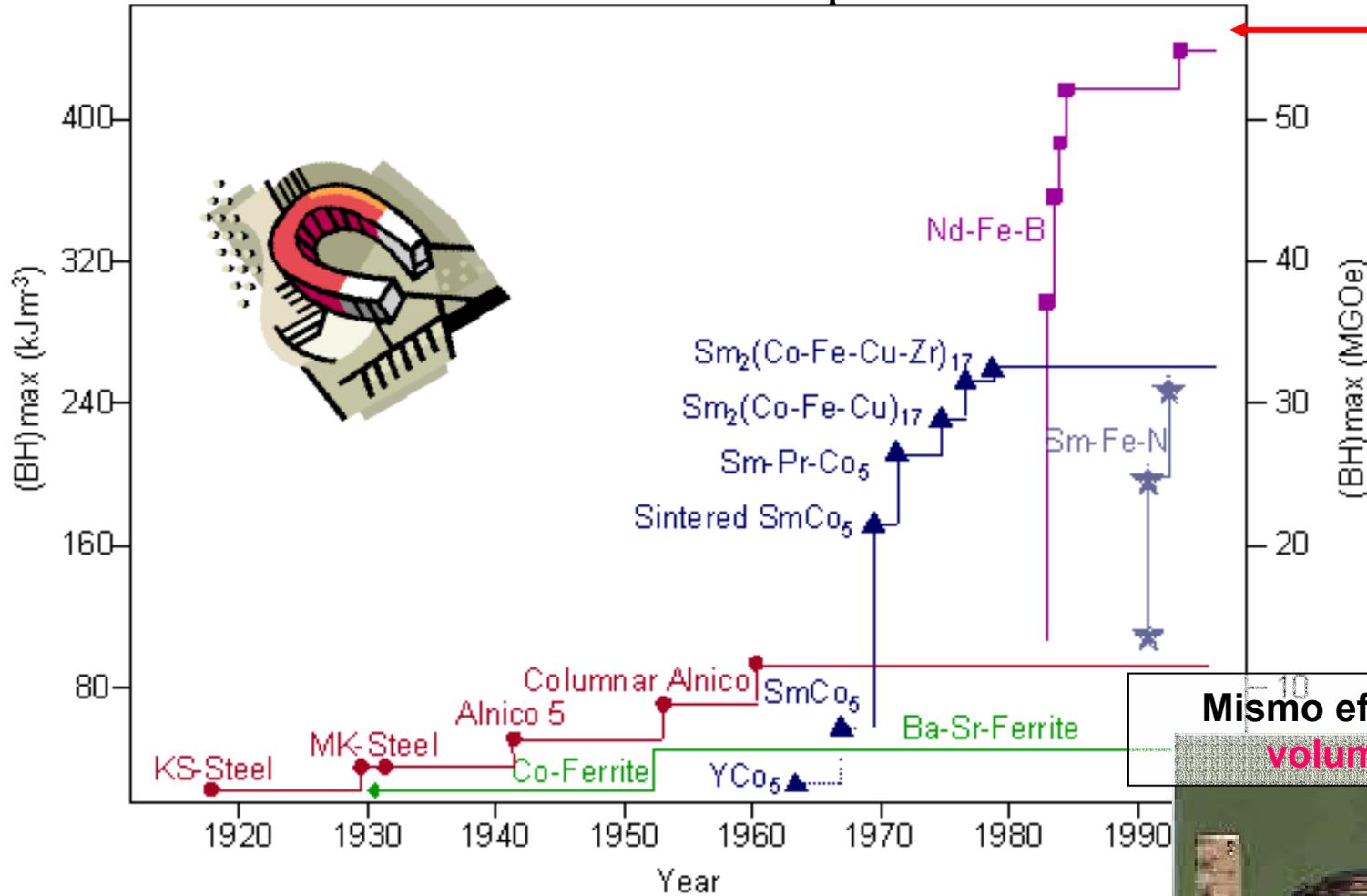


Pequeñas partículas

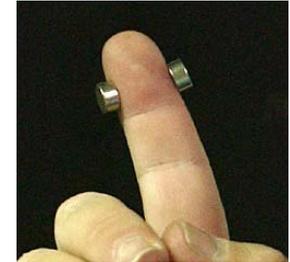


Finale... e raccomandazione...

# Desarrollo de imanes permanentes



Imanes nanocompuestos de tierras raras



Mismo efecto magnético, volumen diferente



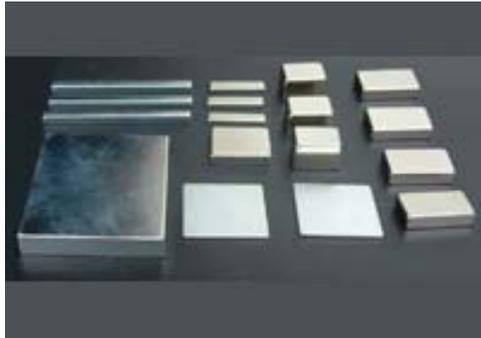
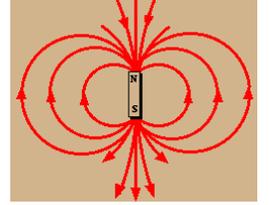
Motores, generadores, dispositivos de sujeción, aceleradores, magnetómetros, etc. etc. etc.

magnetita alnico

Nd-Fe-B

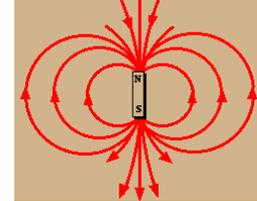


## Imanes modernos



*Formas  
arbitrarias*





Alnico

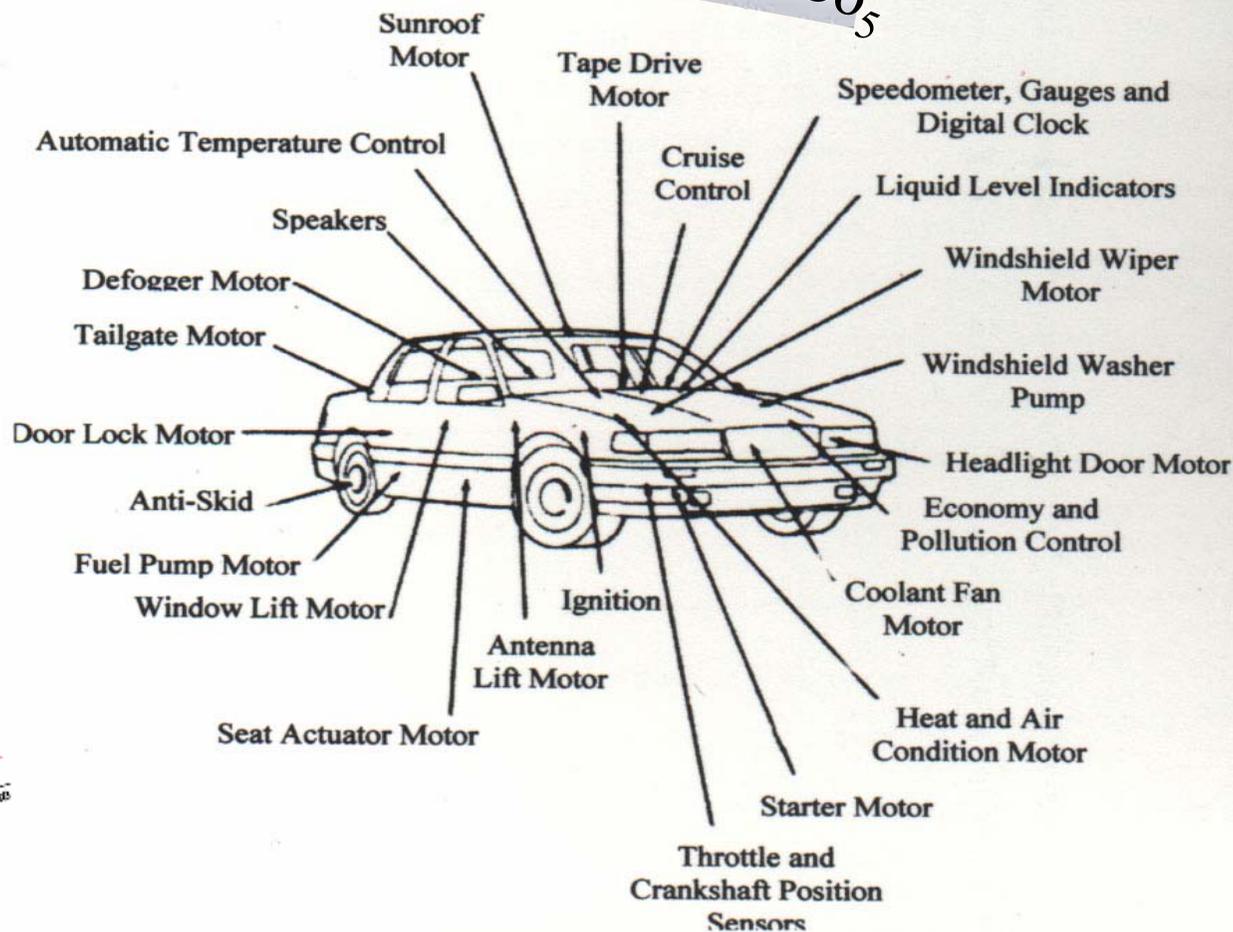
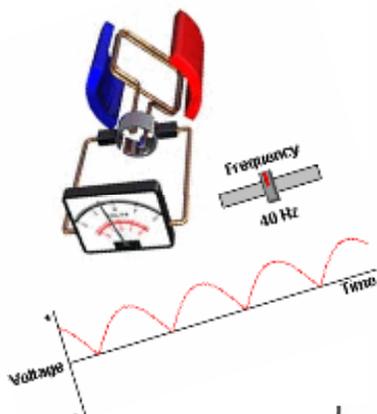


SmCo5

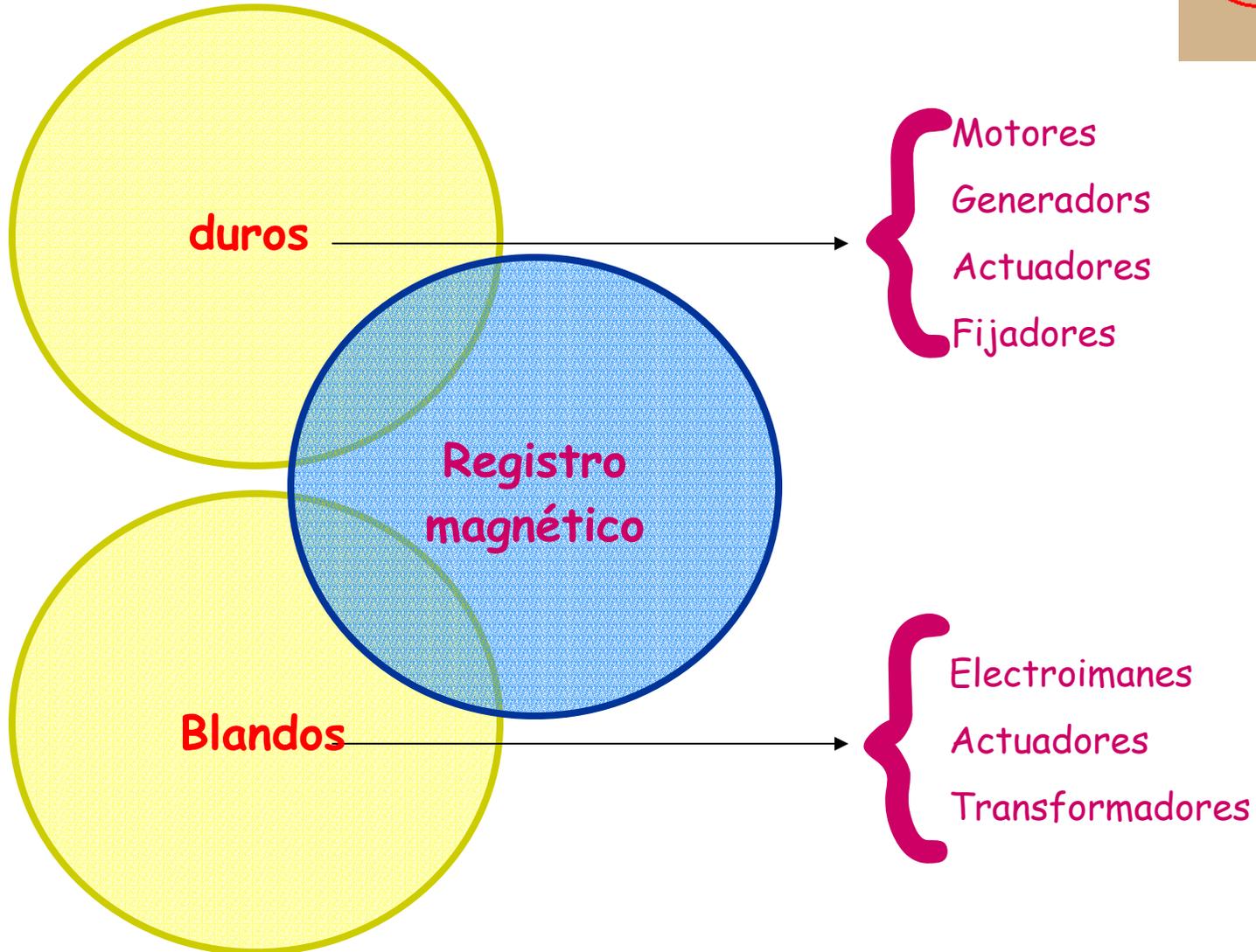
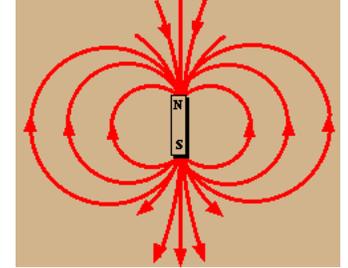
Más energía  
amacenada

Dispositivos  
más eficientes

Motores más  
pequeños

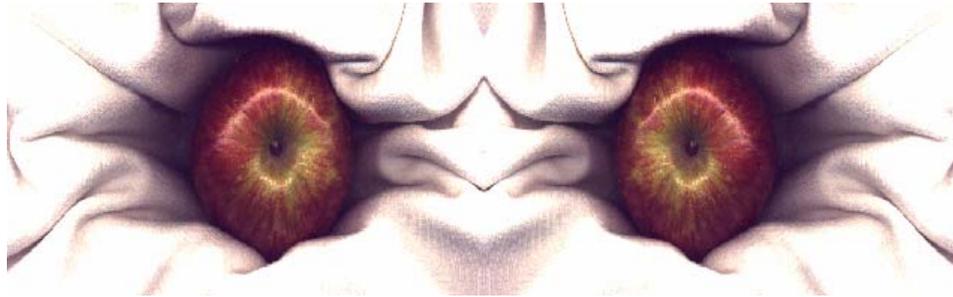


# Materials magnéticos de uso masivo y global





¿Cómo es un material magnético?



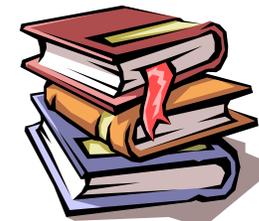
Veamos....



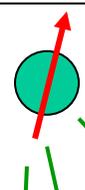
Momento Angular atómico  $\mathbf{J}$



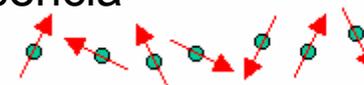
## ¿Cómo es un material magnético?



( $\mathbf{J} \neq 0$ ) momento magnético permanente



Paramagnetos (ausencia de interacciones)



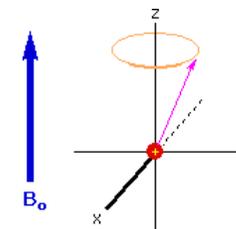
Ferromagnetos (Fe, Co, Ni)



Antiferromagnetos (Cr)

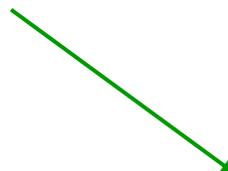


Ordenamientos diferentes (ejemplo: tierras raras)



Ausencia de momento magnético permanente

( $\mathbf{J} = 0$ )



Diamagnetos (ej: gases nobles, Ca, Ba)

## Momento magnético

Al spin atómico  $\mathbf{s}$  le corresponde un momento magnético  $\mathbf{m}$  o  $\mu$ :

$$\vec{\mu} = -g \vec{s} \mu_B$$

## ferromagneto

Existe una interacción de corto alcance, de origen cuántico, llamada interacción de **intercambio**, que induce el ordenamiento paralelo de spines y momentos magnéticos.

$$E_{ex}^{ij} = -2J \vec{s}_i \cdot \vec{s}_j$$

En presencia de un campo magnético externo  $\mathbf{H}$  cada momento interactúa con los vecinos vía intercambio y con el campo externo vía la interacción Zeeman.

$$E_i = -\vec{\mu}_i \cdot (\mu_0 \vec{H}) - 2 \sum_j J \vec{s}_i \cdot \vec{s}_j$$

## paramagneto

No hay interacción entre los momentos magnéticos. En presencia de un campo magnético externo  $\mathbf{H}$  cada momento sólo experimenta la interacción Zeeman.

$$E_i = -\vec{\mu}_i \cdot (\mu_0 \vec{H})$$

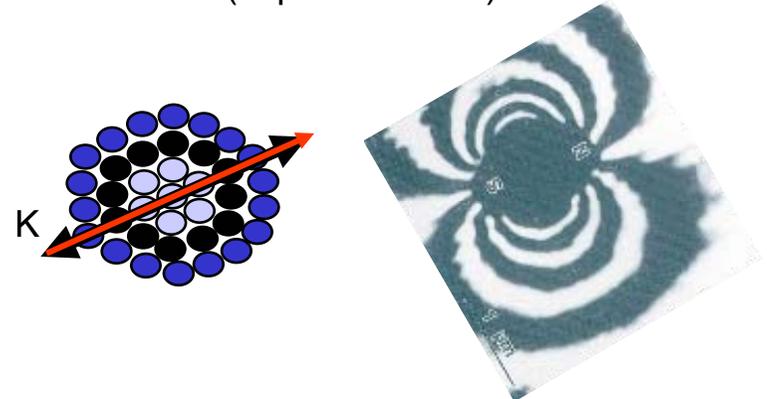
## superparamagneto

Partículas magnéticas monodominio que no interactúan entre sí. La partícula tiene un momento total igual a la suma vectorial de sus momentos atómicos (supermomento). Poseen anisotropía (eje fácil).

$$\vec{\mu}_p = \sum_i \vec{\mu}_i^{at}$$

En el caso más simple:

$$\vec{\mu}_p = N\vec{\mu}_i^{at}$$



A temperaturas altas, en presencia de un campo magnético externo  $\mathbf{H}$  sólo se observa la interacción Zeeman de la partícula con el campo.

$$E_p = -\vec{\mu}_p \cdot (\mu_0 \vec{H})$$

# The periodic table of the elements

	1A	2A	3A	4A	5A	6A	7A	8	1B	2B	3B	4B	5B	6B	7B	8		
1	H															He		
2	Li	Be									B	C	N	O	F	Ne		
3	Na	Mg									Al	Si	P	S	Cl	Ar		
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
5	Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
6	Cs	Ba	L	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	Ra	A															
	L	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu		
	A	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr		

Para

Dia

Anti

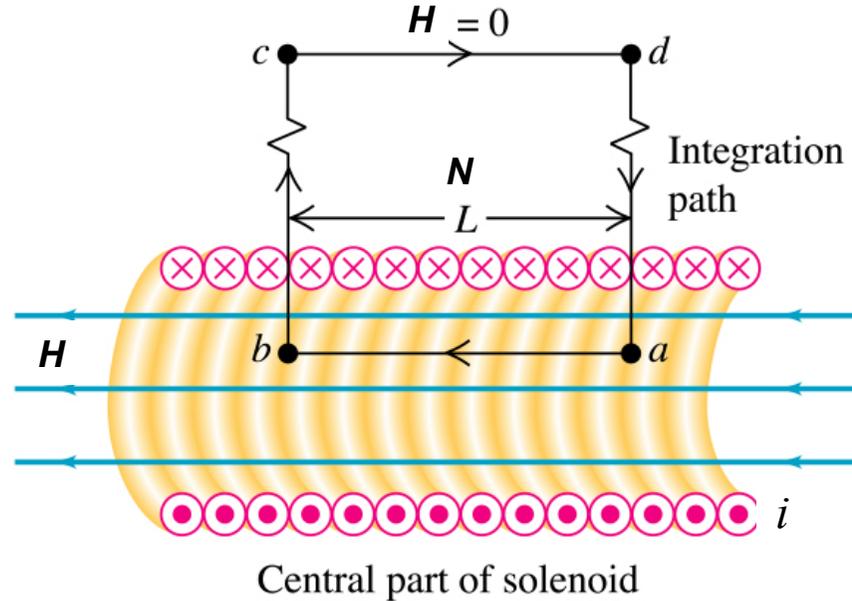
Ferro

- Metals
- Metalloids
- Non-metals
- Transition Metals
- Gases

# Campo Magnético $H$

Ley de Ampere  $\oint \vec{H} \cdot d\vec{l} = I_{tot} \Rightarrow H = Ni / L \Rightarrow [H] = A / m$

Solenoid largo

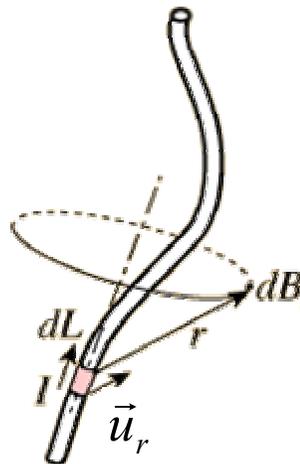


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# Campo de Inducción $B$

## Ley de Biot Savart

Corriente lineal

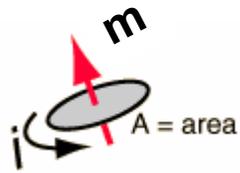


$$d\vec{B} = \frac{\mu_0 I d\vec{L} \times \vec{u}_r}{4\pi r^2}$$

$$[B] = \text{Tesla}$$

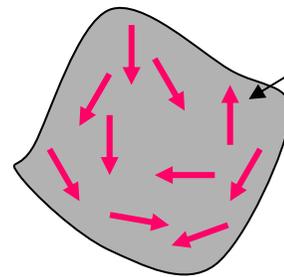
$$\mu_0 = 4\pi \times 10^{-7} Tm / A$$

## Momento magnético $\mathbf{m}$ y Magnetización $\mathbf{M}$



$$\vec{m} = iA\vec{n}$$

$$[m] = Am^2$$



Volumen  $V$

Momento  
magnético  $\mathbf{m}_i$

$$\vec{M} = \sum_i \vec{m}_i / V$$

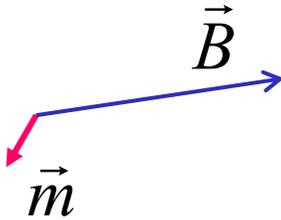
$$[M] = A / m$$

## Relación entre $\mathbf{M}$ , $\mathbf{H}$ y $\mathbf{B}$

$$\vec{B} = \mu_0 (\vec{H} + \vec{M})$$

$$[H] = A / m; \quad [B] = \text{Tesla}$$

Energía de un Dipolo  $\vec{m}$  en un Campo  $\vec{B}$



$$E = -\vec{m} \cdot \vec{B}$$

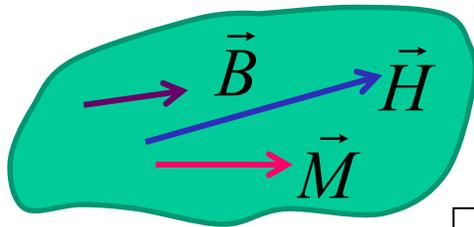
Interacción Zeeman

Torque sobre un Dipolo  $\vec{m}$  en un Campo  $\vec{B}$

$$\vec{\tau} = \vec{m} \times \vec{B}$$

## Susceptibilidad $\chi$ y Permeabilidad $\mu$

En un medio material



susceptibilidad

$$\vec{M} = \chi \vec{H}$$

permeabilidad

$$\vec{B} = \mu \vec{H}$$

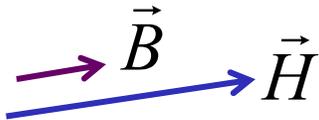
Validez  
Restringida

$$\vec{B} = \mu_0 (\vec{H} + \vec{M})$$

Validez  
General

$\vec{B}, \vec{H}, \vec{M}$  no paralelos

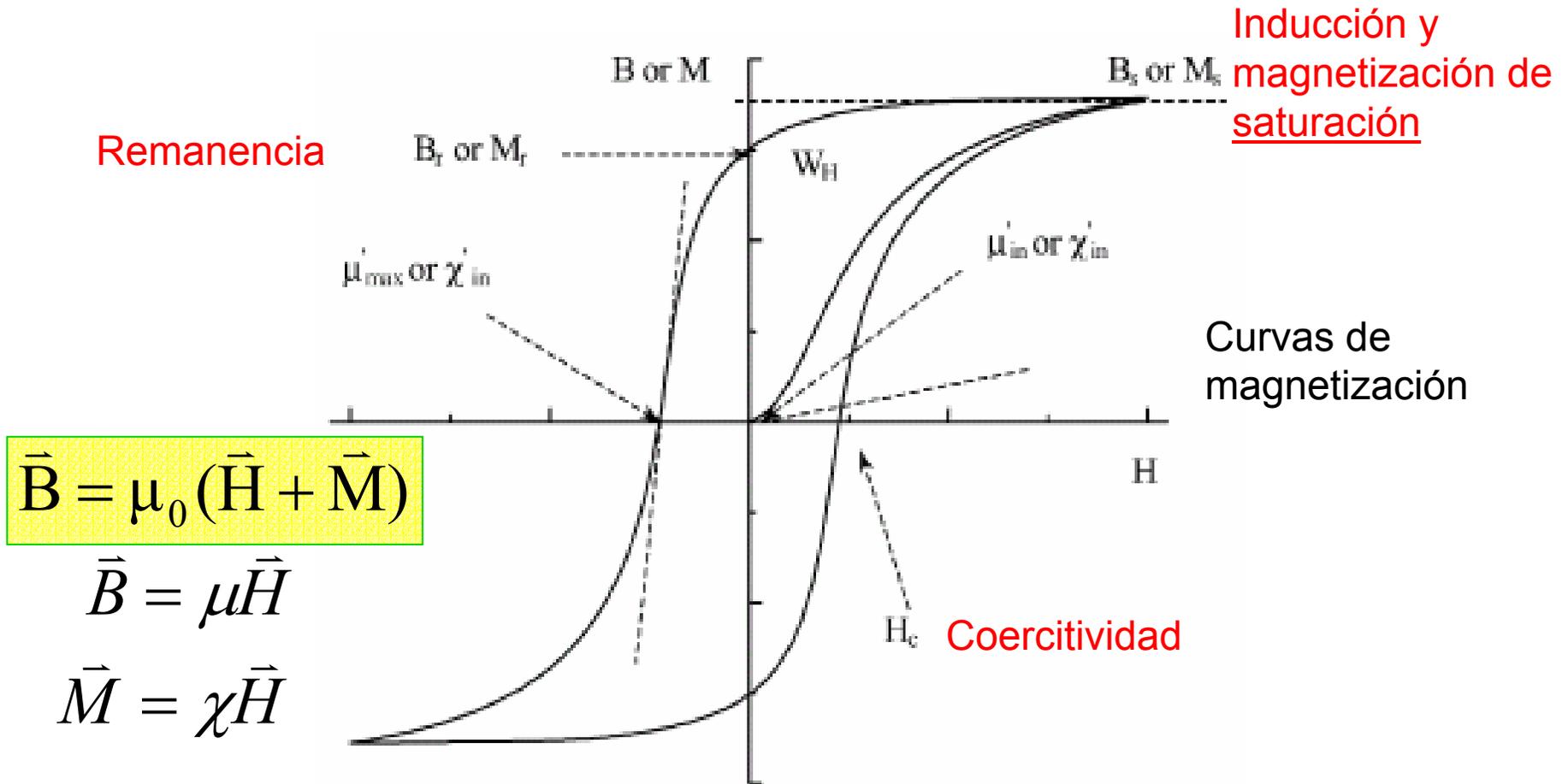
En el vacío



$$\vec{B} = \mu_0 \vec{H}$$

$\vec{B}, \vec{H}$  paralelos

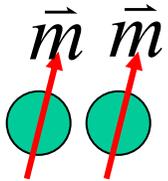
# Cantidades magnéticas de interés práctico



# Saturación y momento medio por átomo

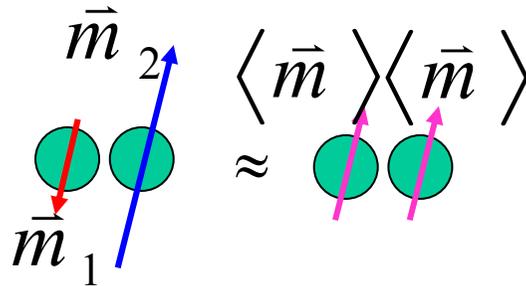
$$\vec{M}_S = n \langle \vec{m} \rangle$$

ferro

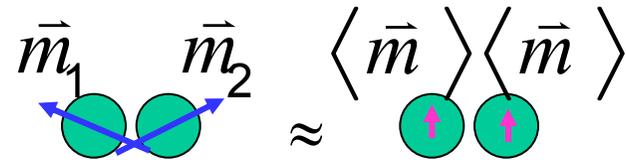


$$\vec{M}_S = n \vec{m}$$

ferri



Weak ferro



# Cantidades magnéticas de interés práctico

$$\mu = \mu_0(1 + \chi)$$

$\mu_0 = 4\pi \times 10^{-7}$  [SI] - permeabilidad del vacío

$$\mu_R = \frac{\mu}{\mu_0} = 1 + \chi$$

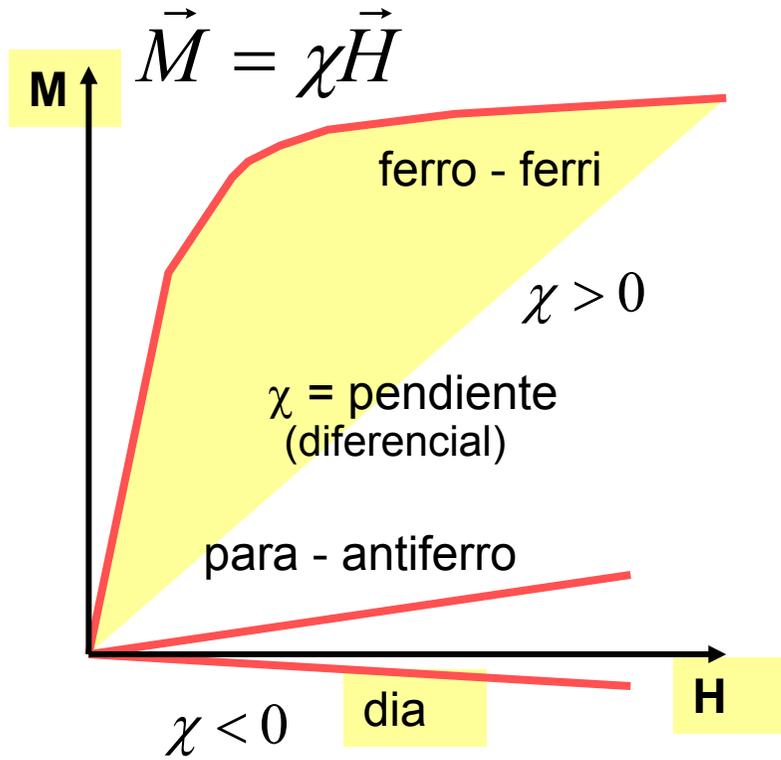
permeabilidad relativa al vacío

Diamagnetos  $\rightarrow \mu_R < 1 \rightarrow \chi = \mu_R - 1 < 0;$   $\chi \approx -10^{-6}$

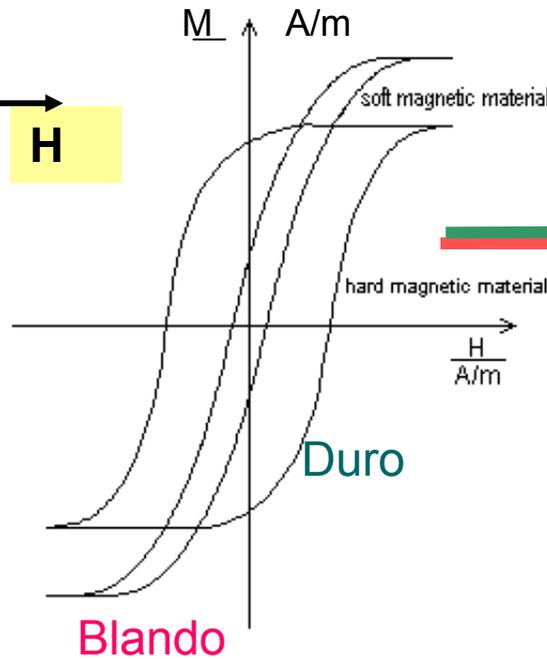
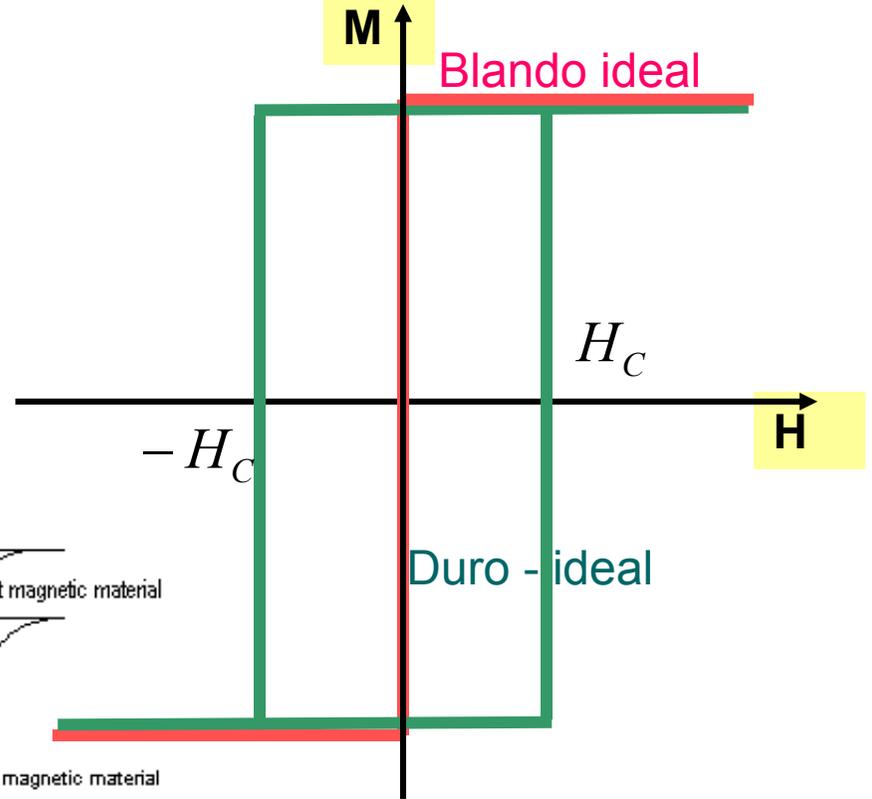
Paramagnetos  $\rightarrow \mu_R > 1 \rightarrow \chi = \mu_R - 1 > 0;$   $\chi \approx 10^{-5}$

Ferromagnetos  $\rightarrow \mu_R \gg 1 \rightarrow \chi \approx \mu_R \gg 1,$   $\chi \approx 10 - 10^5$

# Tipos de materiales magnéticos



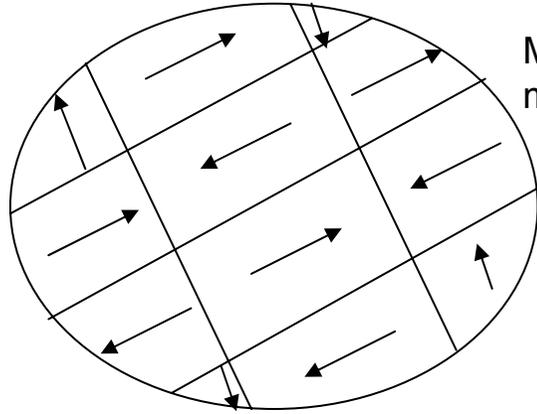
ferromagnetos



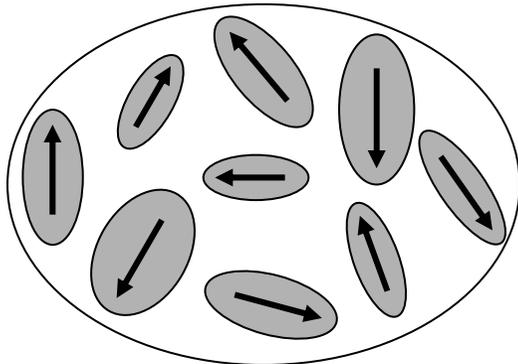
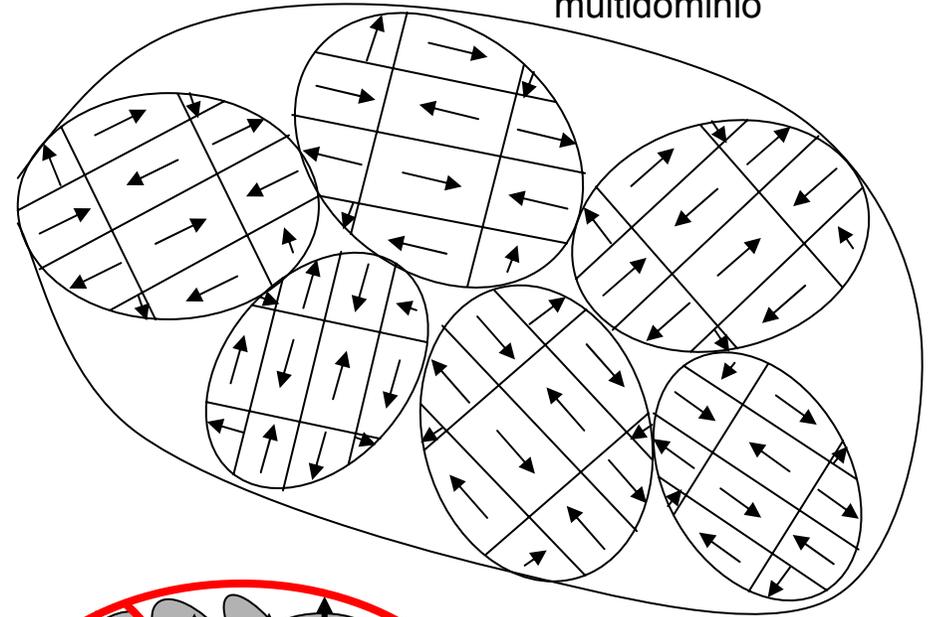
# Ejemplos de materiales ferromagnéticos

Dominio: región donde todos los momentos están alineados

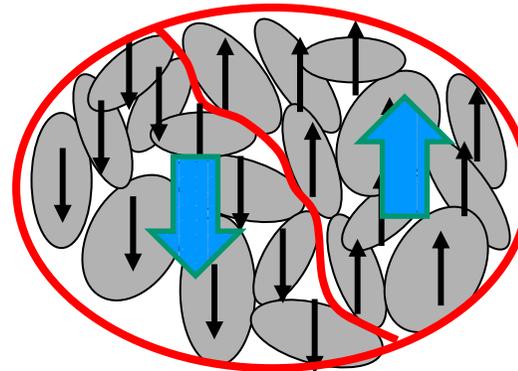
Conjunto de monocristales multidominio



Monocristal multidominio

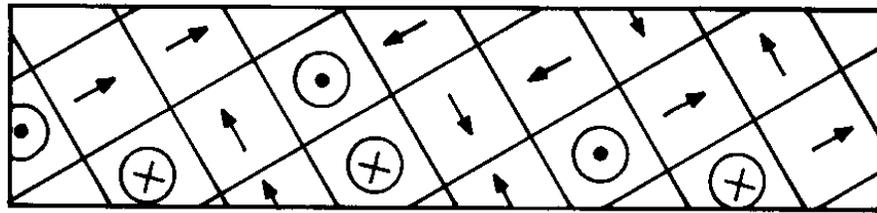


Conjunto de partículas cristalinas monodominio



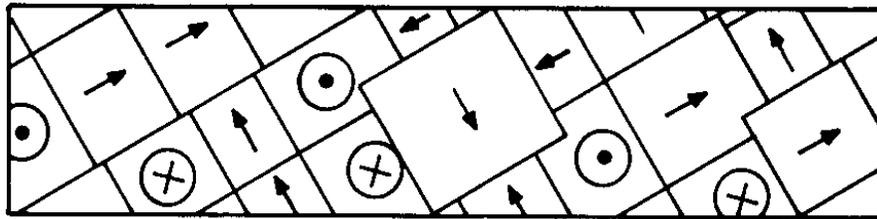
Material multidominio compuesto de monocristales monodominio

# Procesos de magnetización en un monocristal multidominio



(a)

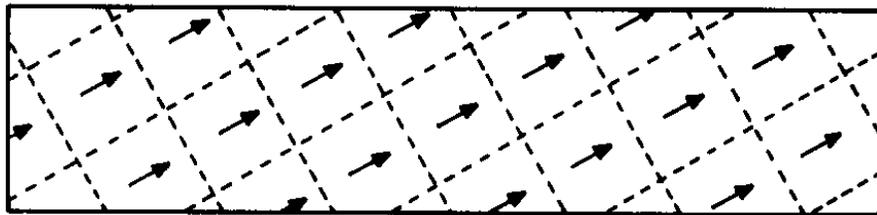
$H = 0$



(b)

$H$

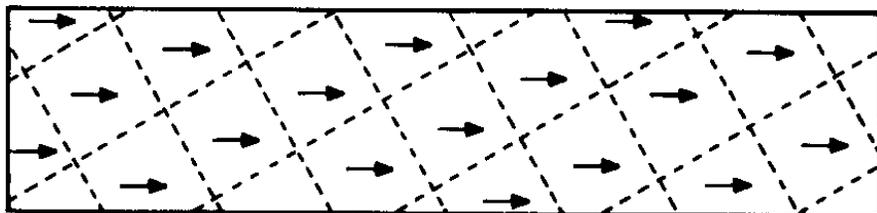
Movimiento de paredes reversible e irreversible



(c)

$H$

Orientación con el campo (reversible)

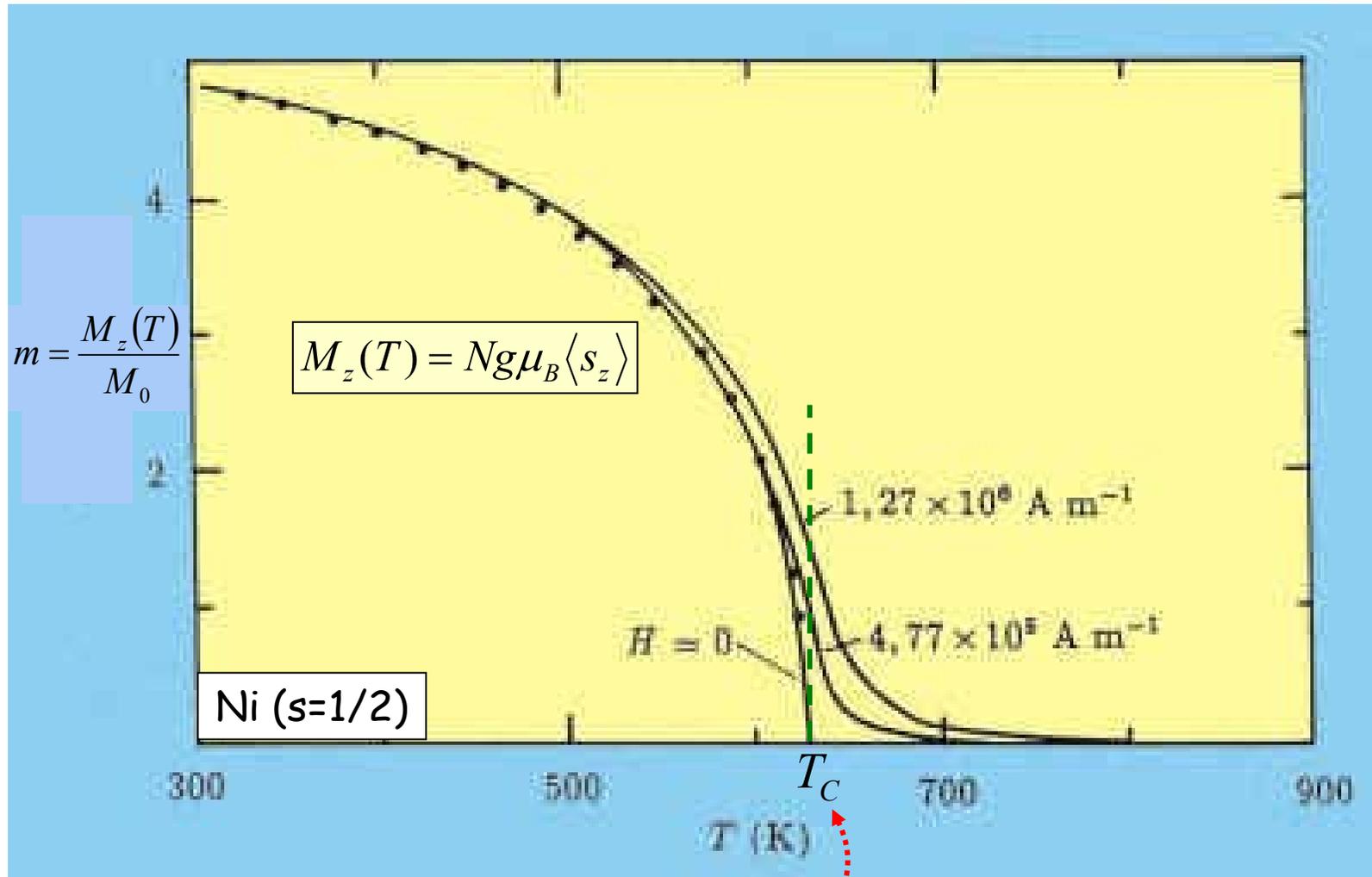


(d)

$H$

saturación

# Magnetización vs temperatura



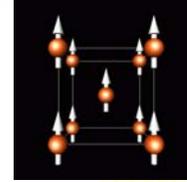
$$T_C = \frac{2pJs(s+1)}{3k}$$

# Interacciones Magnéticas

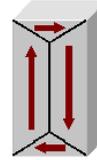
Interacción de Intercambio



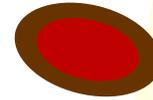
Anisotropía Magnetocristalina



Energía Magnetostática



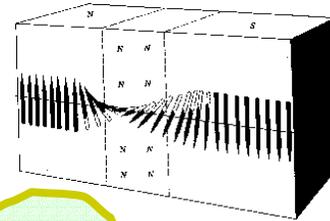
Anisotropía interfacial



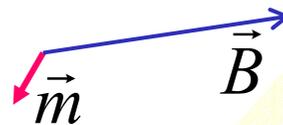
Energía Magnetoelástica



Energía de pared de Dominio



Interacción Zeeman



$\vec{B}$  externo

# Interacciones Magnéticas

Intercambio: interacción de corto alcance que involucra solamente interacción entre vecinos.

Un fenómeno **Mecánico-Cuántico** conducente al ordenamiento magnético: ferro, antiferro, ferri, etc.

$$E_J = - \sum_i^N \sum_j^z J_{i,j} \vec{S}_i \cdot \vec{S}_j$$

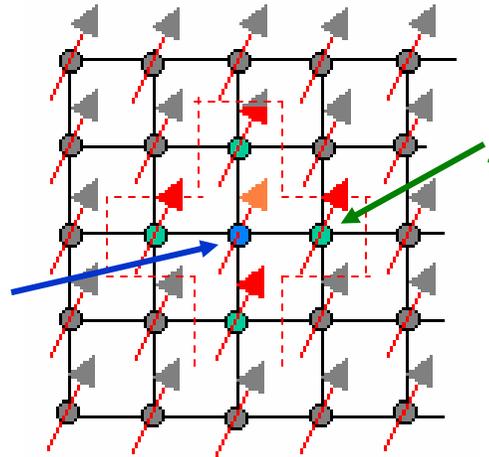
Número total de átomos interactuantes

$N$

Número de vecinos

$z$

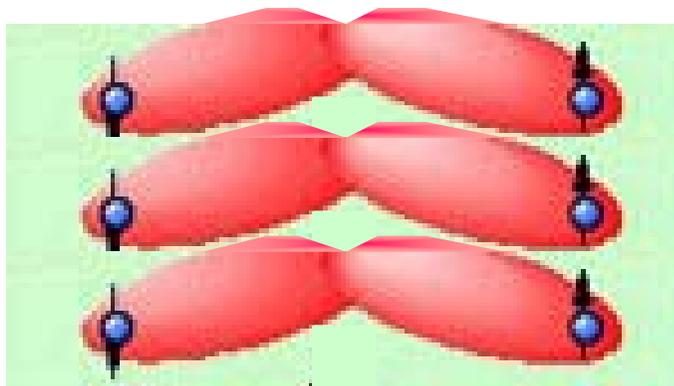
$i$



Integral de intercambio

$$J(r) \approx e^{-r/r_0}$$

# Interacción de Intercambio



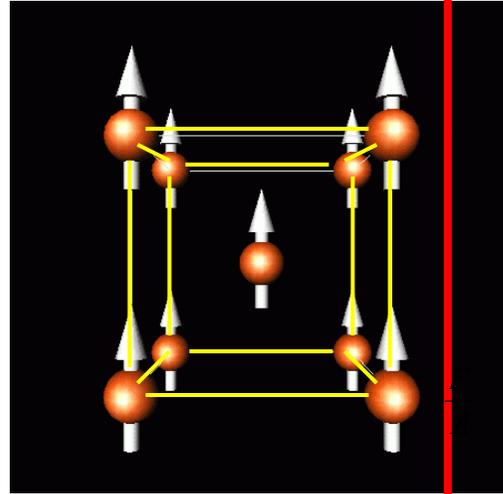
overlap of electrons  
causes spin-spin coupling

$$\mathcal{H} = \underbrace{-\frac{1}{2} \sum_{\substack{i,j \\ i \neq j}} J(\vec{r}_{ij}) \hat{S}_i \cdot \hat{S}_j}_{\text{Intercambio}} - \underbrace{g\mu_B \sum_i \vec{B} \cdot \hat{S}_i}_{\text{Zeeman}}$$
$$\mathcal{H} = \underbrace{-\frac{1}{2} \sum_{\substack{i,j \\ i \neq j}} J(\vec{r}_{ij}) \hat{S}_i \cdot \hat{S}_j}_{\text{Intercambio}} - \underbrace{g\mu_B B \sum_i S_i^z}_{\text{Zeeman}}$$

# Interacciones Magnéticas

Anisotropía

Fe



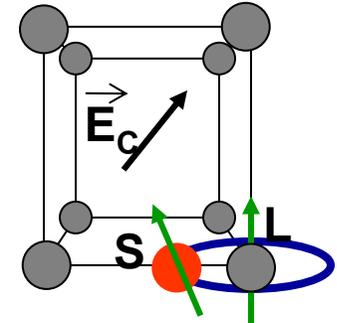
Estructura cristalina :  
anisotropía  
magnetocristalina

$$e_K = K(\cos^2 \theta_1 + \cos^2 \theta_2 + \cos^2 \theta_3)$$

Energía de anisotropía  
por unidad de volumen

Cosenos directores de **M**  
con los ejes principales

interacción Spin –  
órbita + campo  
cristalino



# Interacciones Magnéticas

Anisotropía  
magnetoelástica



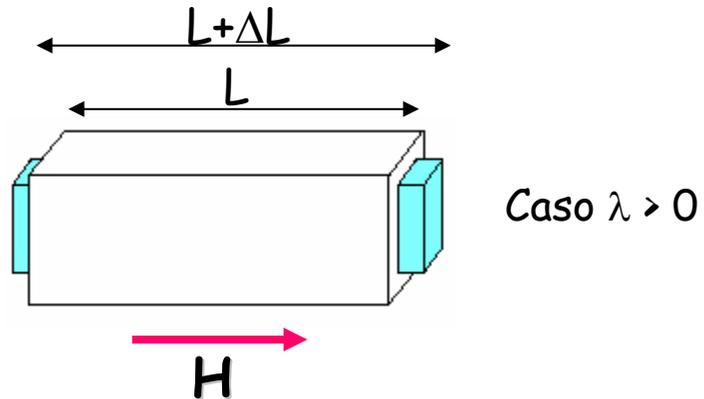
Esfuerzos

$$E_{\sigma} = (3/2)\lambda_{SI} \sigma \text{ sen}^2\theta$$

$$\lambda = \left( \frac{\Delta l}{l} \right)_{Mag}$$

$$\sigma = \frac{F}{A}$$

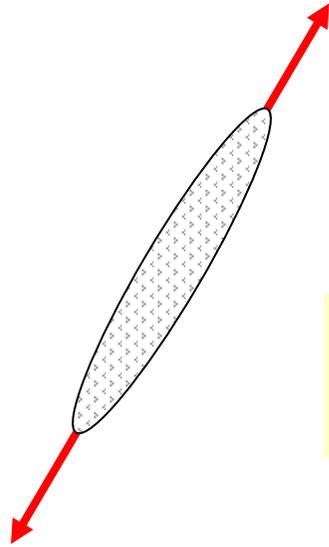
# anisotropía magnetoelástica



$$\lambda_s = \Delta L / L \text{ (magnetostricción)}$$

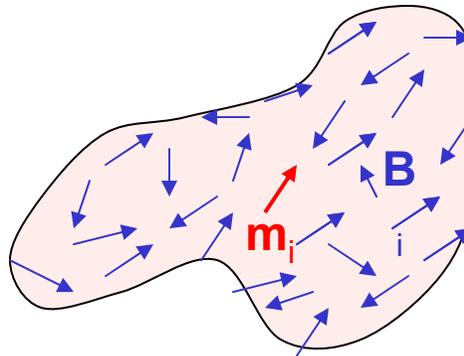
# Interacciones Magnéticas

Anisotropía de Forma



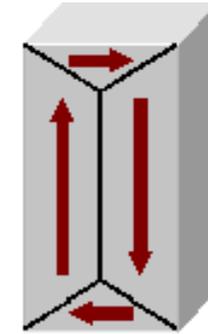
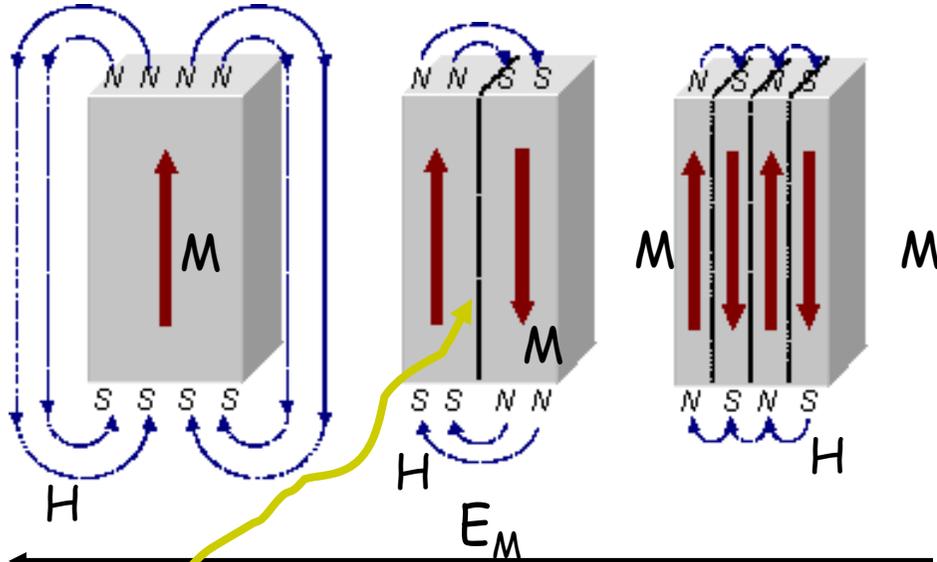
$$E_M = -\frac{1}{2} \sum_i \vec{m}_i \cdot \vec{B}_i \approx -\frac{\mu_0}{2} \int \vec{M} \cdot \vec{H} dV$$

$$\vec{B}_i = \sum_{j \neq i} \vec{B}_j(\vec{r}_i)$$



Energía  
magnetostática

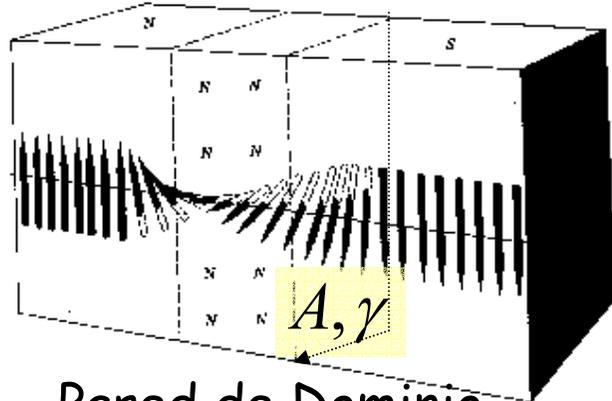
# energías magnetostática + pared de dominio



dominio de cierre

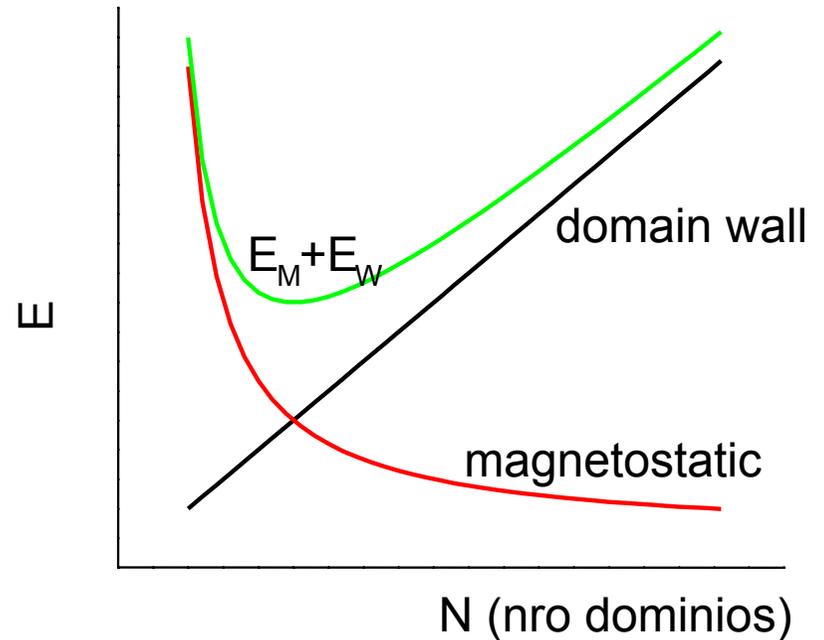
$$E_M \approx \frac{\alpha E_1}{n}$$

número de dominios ( $n$ )



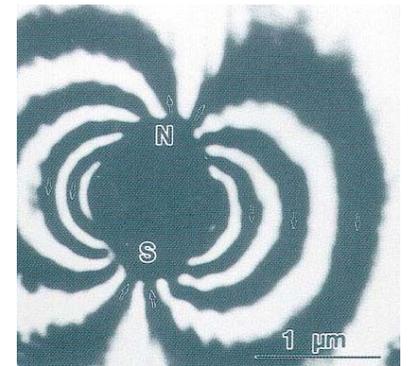
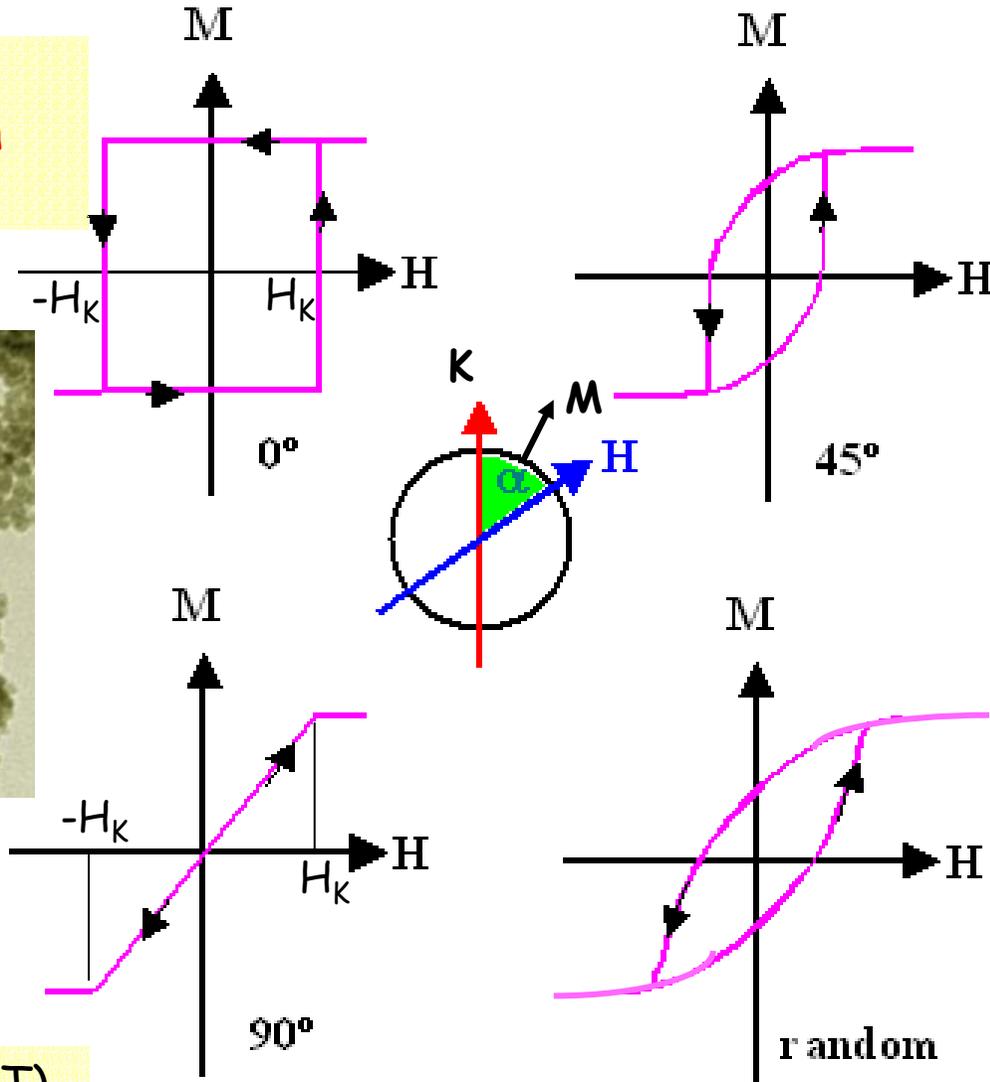
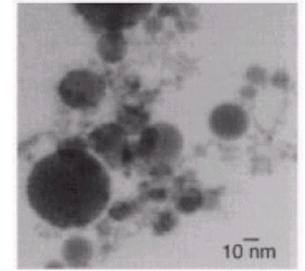
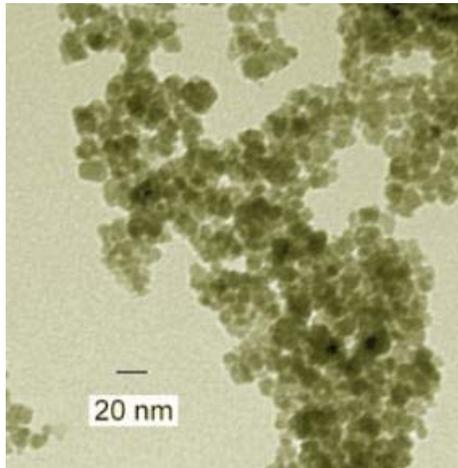
Pared de Dominio (Bloch)

$$E_W \approx nA\gamma$$



# Propiedades magnéticas de partículas pequeñas, monodominio

Temperaturas bajas: **régimen bloqueado**

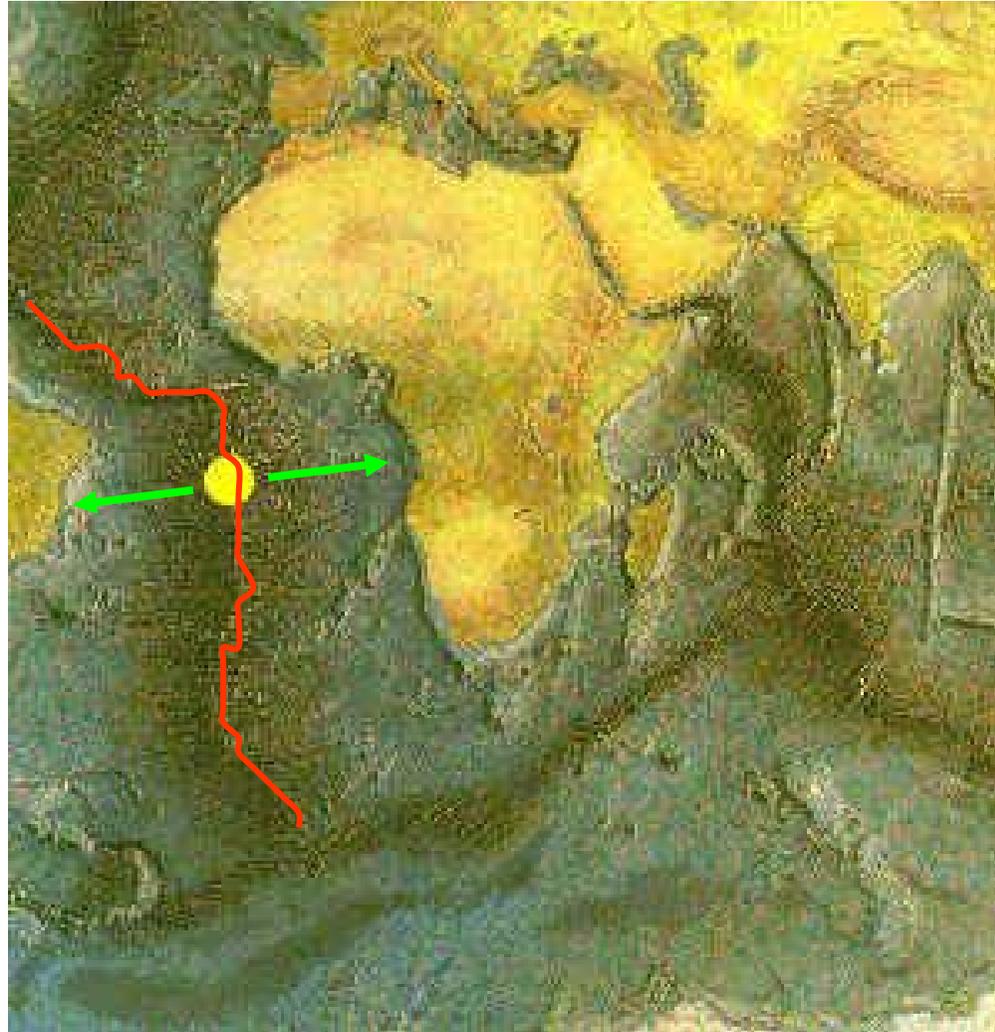


$$\tau = \tau_0 \exp(KV/kT)$$

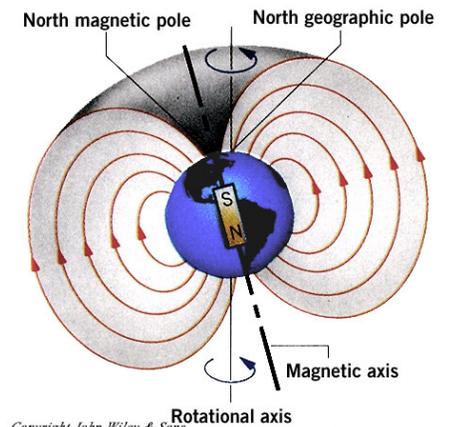
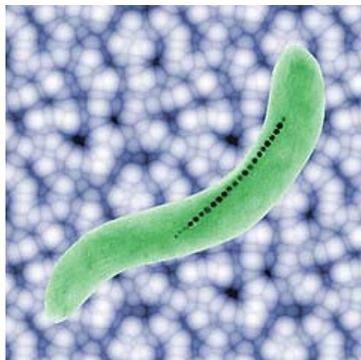
$T < T_B$   $kT < KV \rightarrow \tau \gg \tau_{exp} \rightarrow$  regime bloqueado

# Registro Magnético en el Fondo Oceánico

## Deriva continental



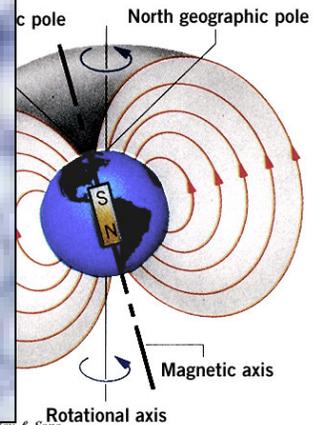
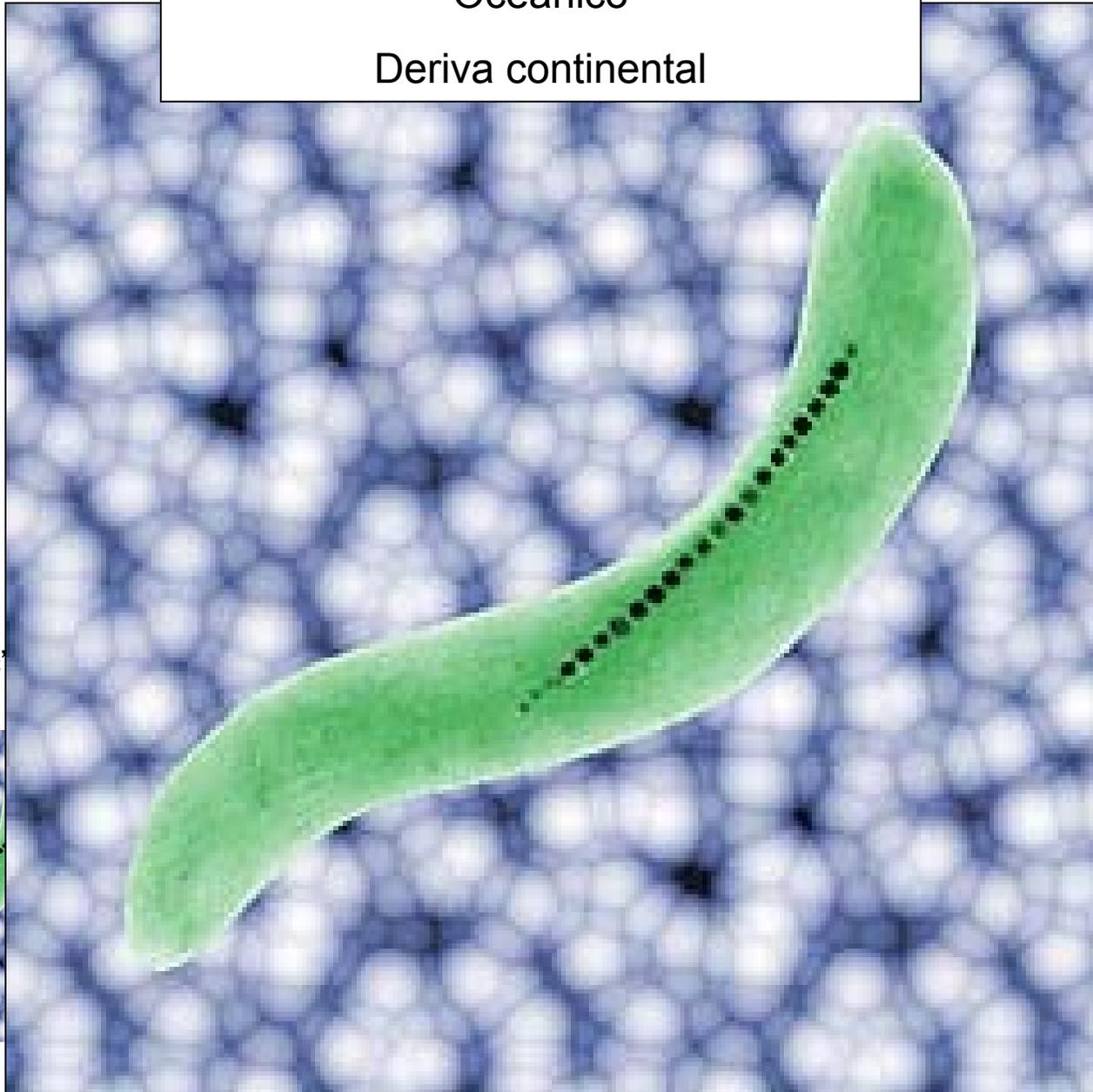
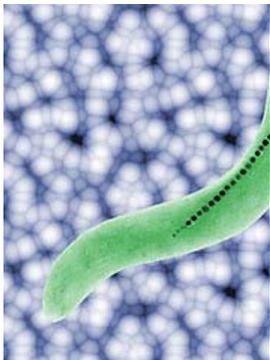
Magnetic or  
"magnetotactic"  
bacteria



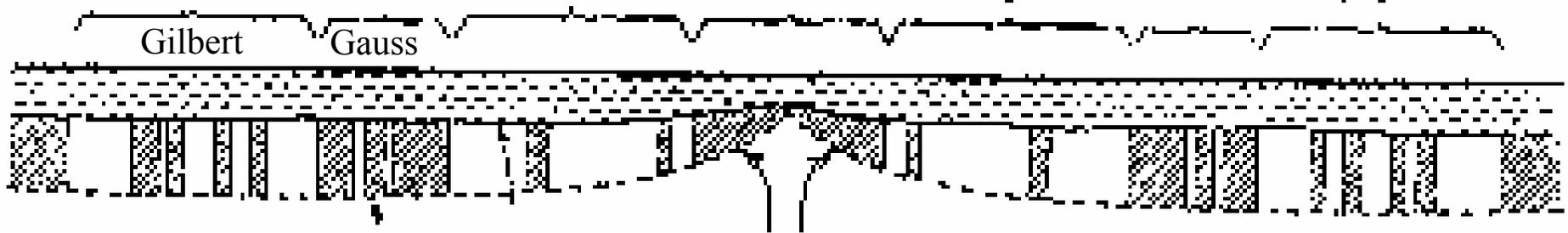
# Registro Magnético en el Fondo Oceánico

## Deriva continental

Magnetic or  
"magnetotactic"  
bacteria

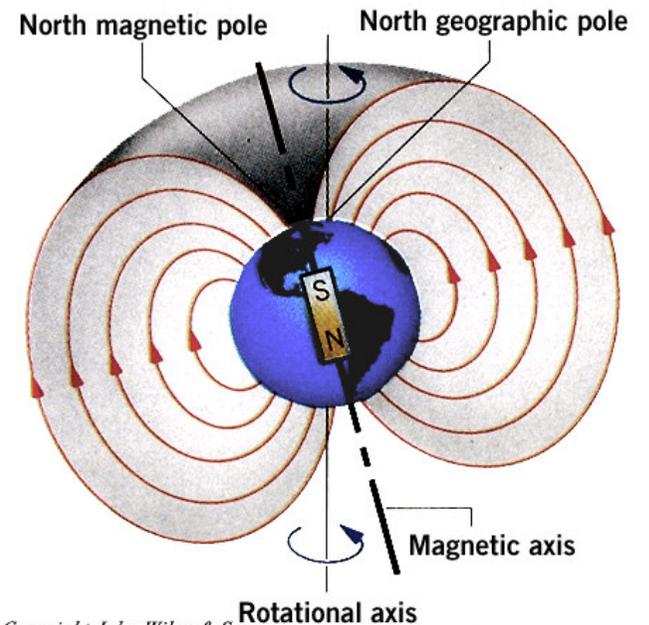
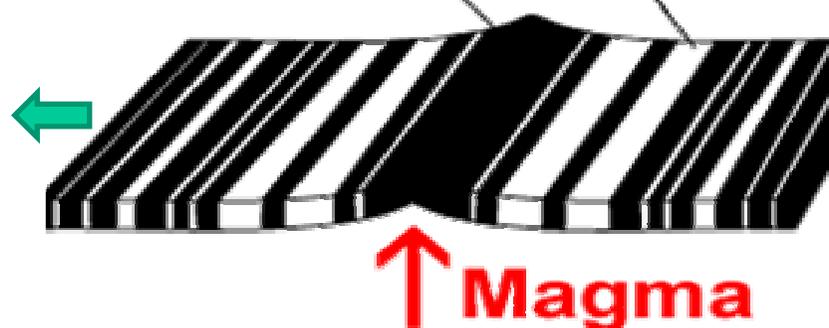


# Fondo Oceánico



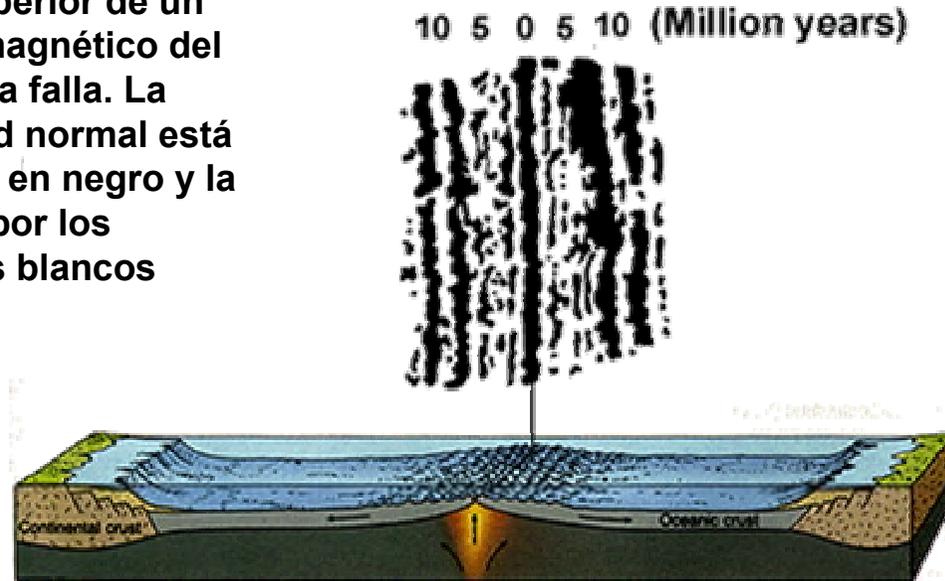
Positive Negative

El fondo marino se separa, la roca muestra franjas magnéticas simétricas alejándose de la falla



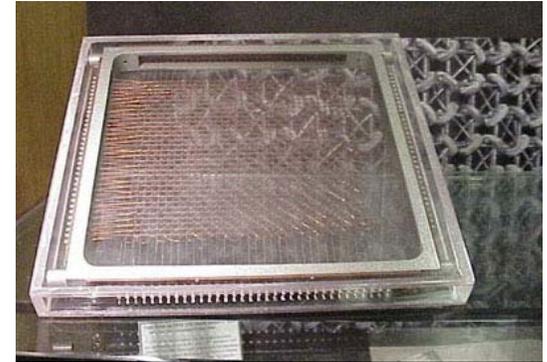
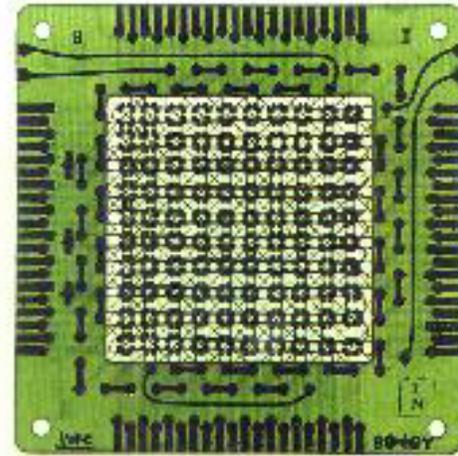
## Fondo Oceánico

Vista superior de un patrón magnético del área de la falla. La polaridad normal está indicada en negro y la inversa por los espacios blancos



El campo magnético terrestre, aparentemente generado por el movimiento convectivo del núcleo líquido del planeta, cambia de polaridad caóticamente con un período medio de unos 100000 años.

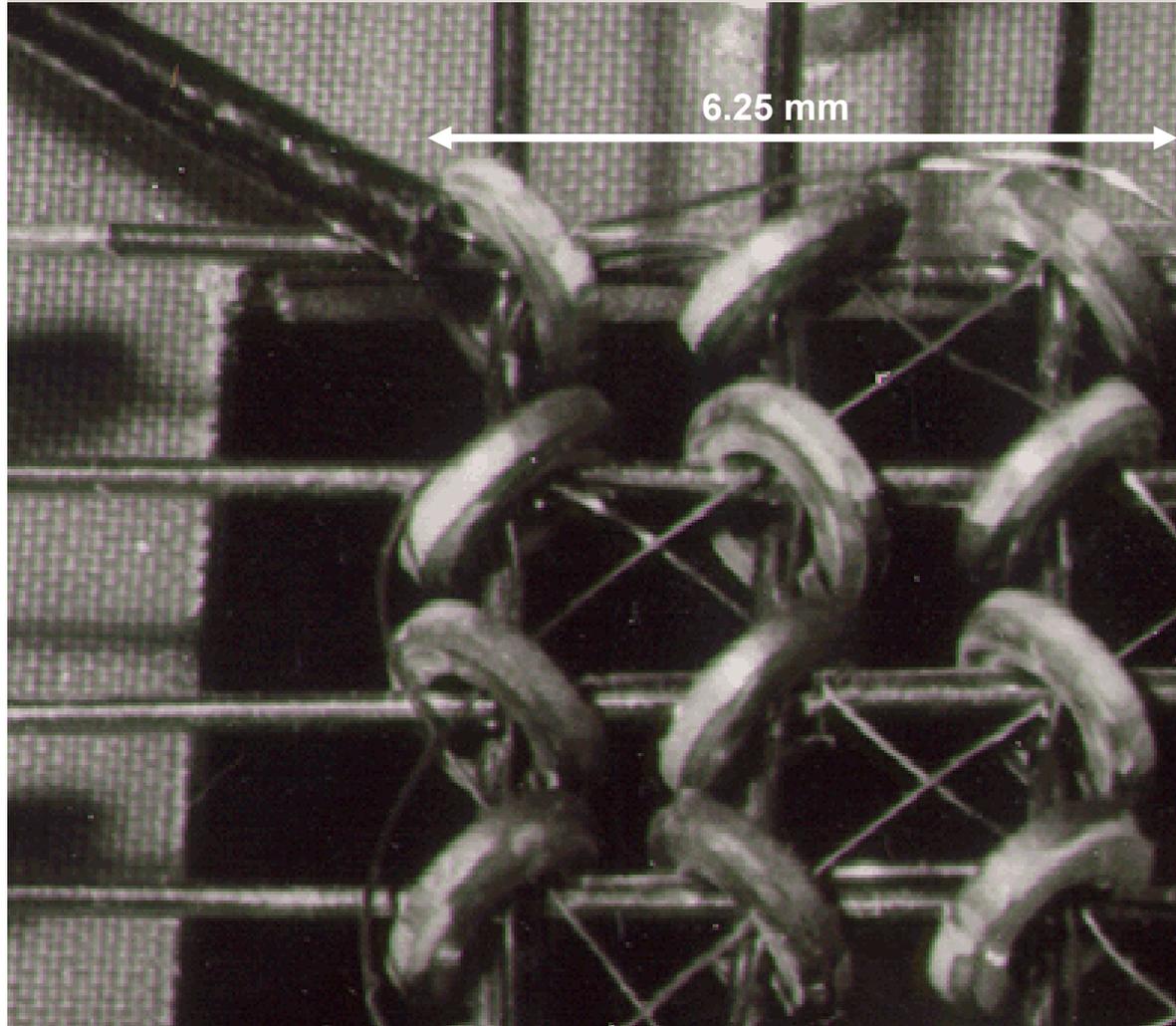
# Datos



En 1953, un equipo del MIT llamado Whirlwind introdujo la memoria de núcleo magnético (izquierda), como un arreglo de millares de pequeños imanes de forma toroidal (anillos) enhebrados con conductores capaces de cambiar el estado magnético de los imanes mediante pulsos eléctricos y de ese modo manipular datos en forma binaria.

# Datos

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**Núcleos de memoria de Whirlwind**

# Datos



**Proyecto Whirlwind  
1953-1970**

CESPI: IBM 1620 16 kB, IBM 360 256 kB

Datos

# ¿Cómo trabaja un disco duro?

**FILES** are stored as magnetically encoded areas on platters. A single file may be scattered among several areas on different platters.

**MAGNETICALLY COATED PLATTERS** made of metal or glass spin at several thousand revolutions per minute, driven by an electric motor. The capacity of the drive depends on the number of platters (which may be as many as eight) and the type of magnetic coating.

**HEAD ACTUATOR** pushes and pulls the read-write head arms across the platters. It precisely aligns the heads with the concentric circles of tracks on the surface of the platters.

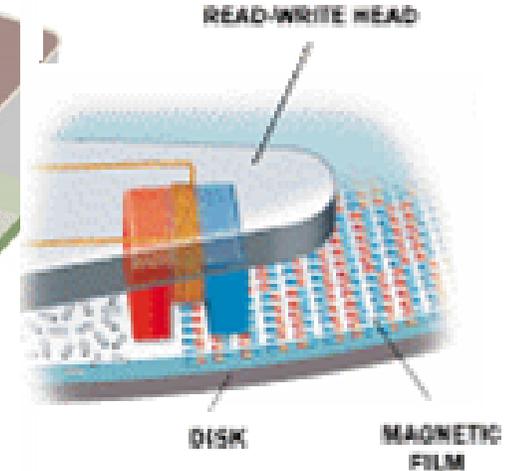
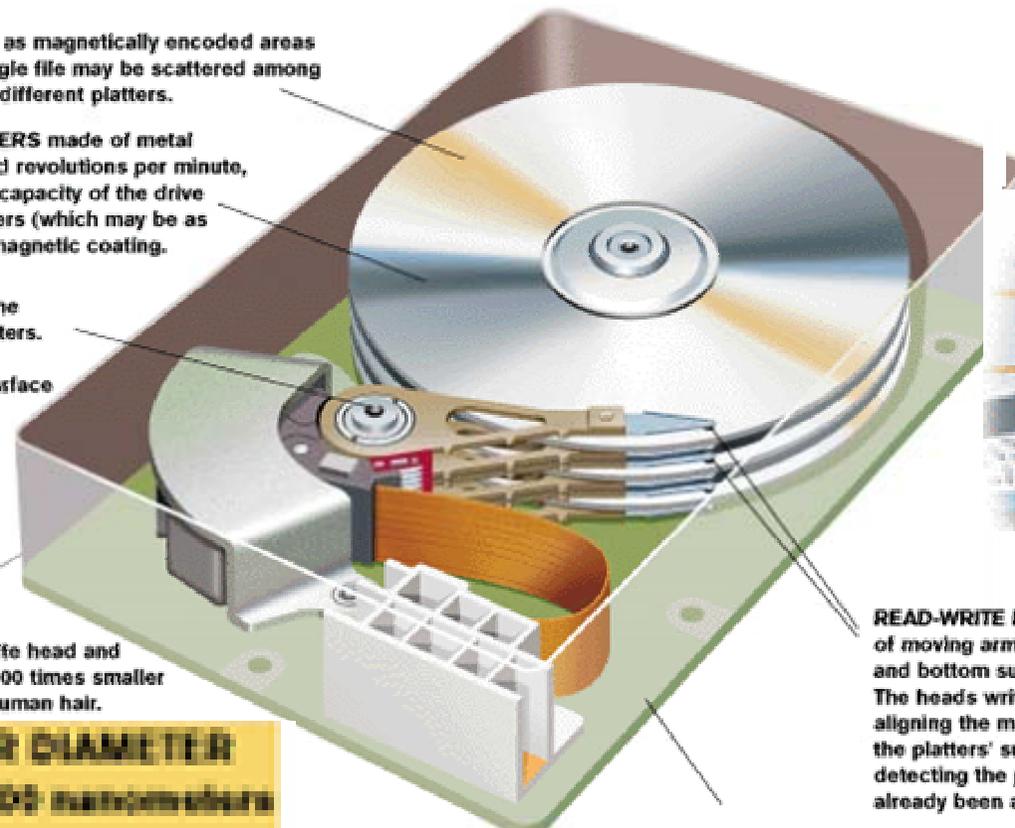
PROTECTIVE HOUSING

**GAP** between a read-write head and the platter surface is 5,000 times smaller than the diameter of a human hair.

**HAIR DIAMETER**  
75,000 nanometers

HEAD

**GAP**  
15 nanometers

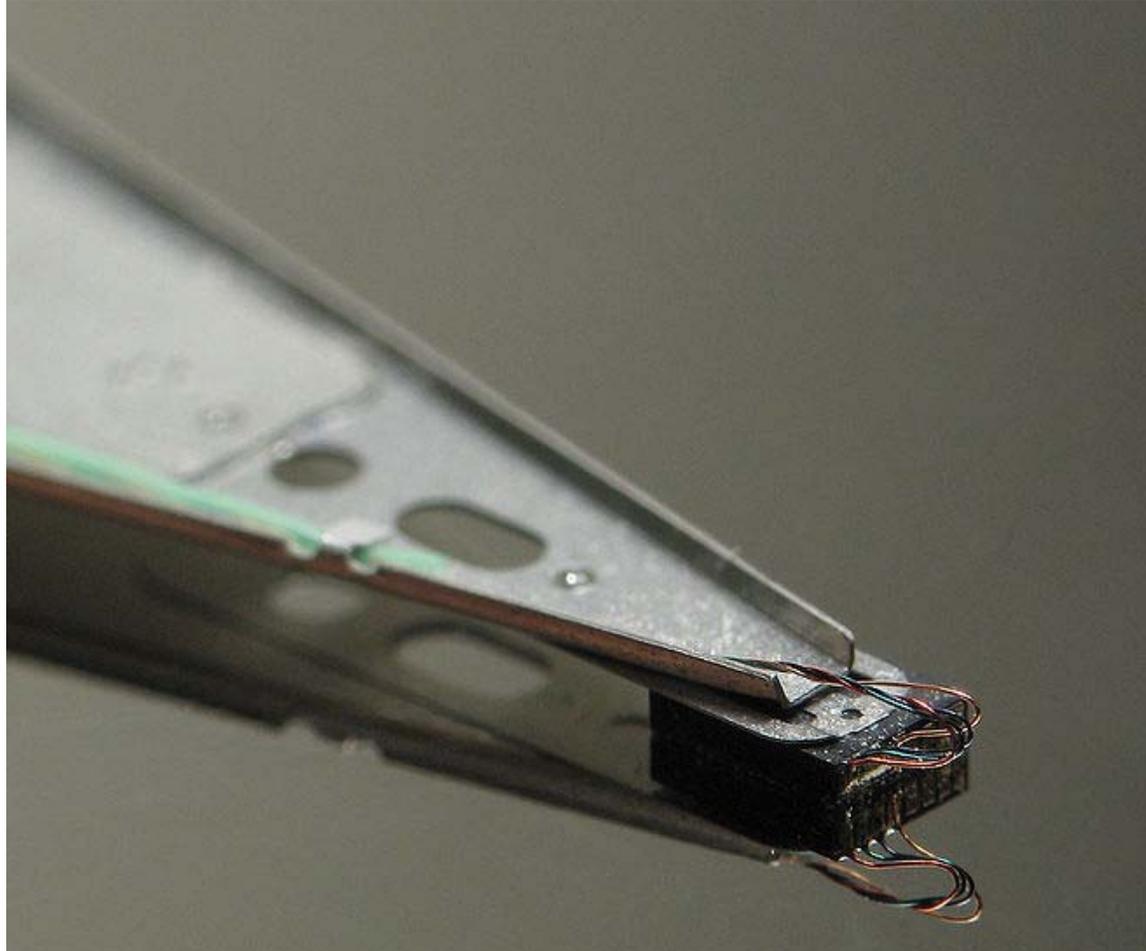


**READ-WRITE HEADS**, attached to the ends of moving arms, slide across both the top and bottom surfaces of the spinning platters. The heads write the data to the platters by aligning the magnetic fields of particles on the platters' surfaces; they read data by detecting the polarities of particles that have already been aligned.

**PRINTED CIRCUIT BOARD** receives commands from the drive's controller. The controller is managed by the operating system and the basic input-output system, low-level software that links the operating system to the hardware. The circuit board translates the commands into voltage fluctuations, which force the head actuator to move the read-write heads across the surfaces of the platters. The board also controls the spindle that turns the platters at a constant speed and tells the drive heads when to read from and when to write to the disk.

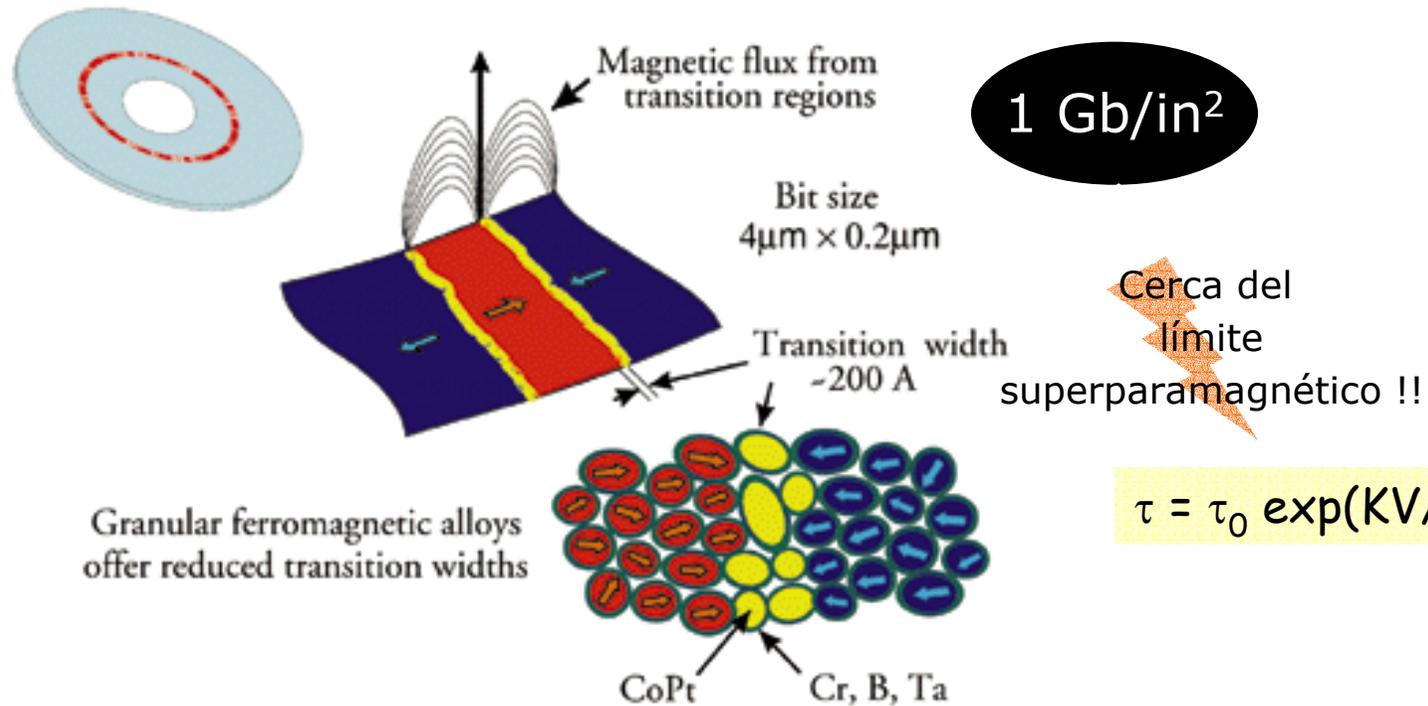
Datos

# ¿Cómo trabaja un disco duro?



Close-up of a hard disk head resting on a platter, and its suspension. A reflection of the disk head and suspension are visible beneath on the mirror-like disk.

# Registro magnético en disco



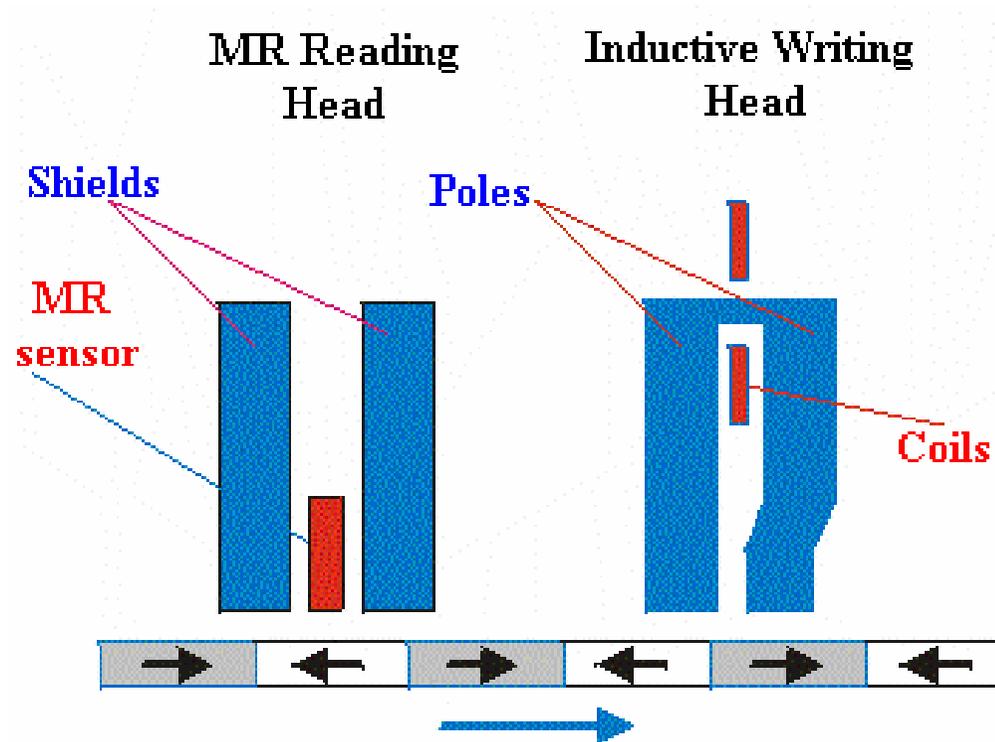
Material magnético granular (Co-Pt-Cr).

B, Ta, etc. para minimizar la transición entre “dominios” a fin de alcanzar alta densidad de flujo magnético perpendicular a la superficie.

El flujo magnético en la superficie del disco rotante es sentido por la cabeza lectora.

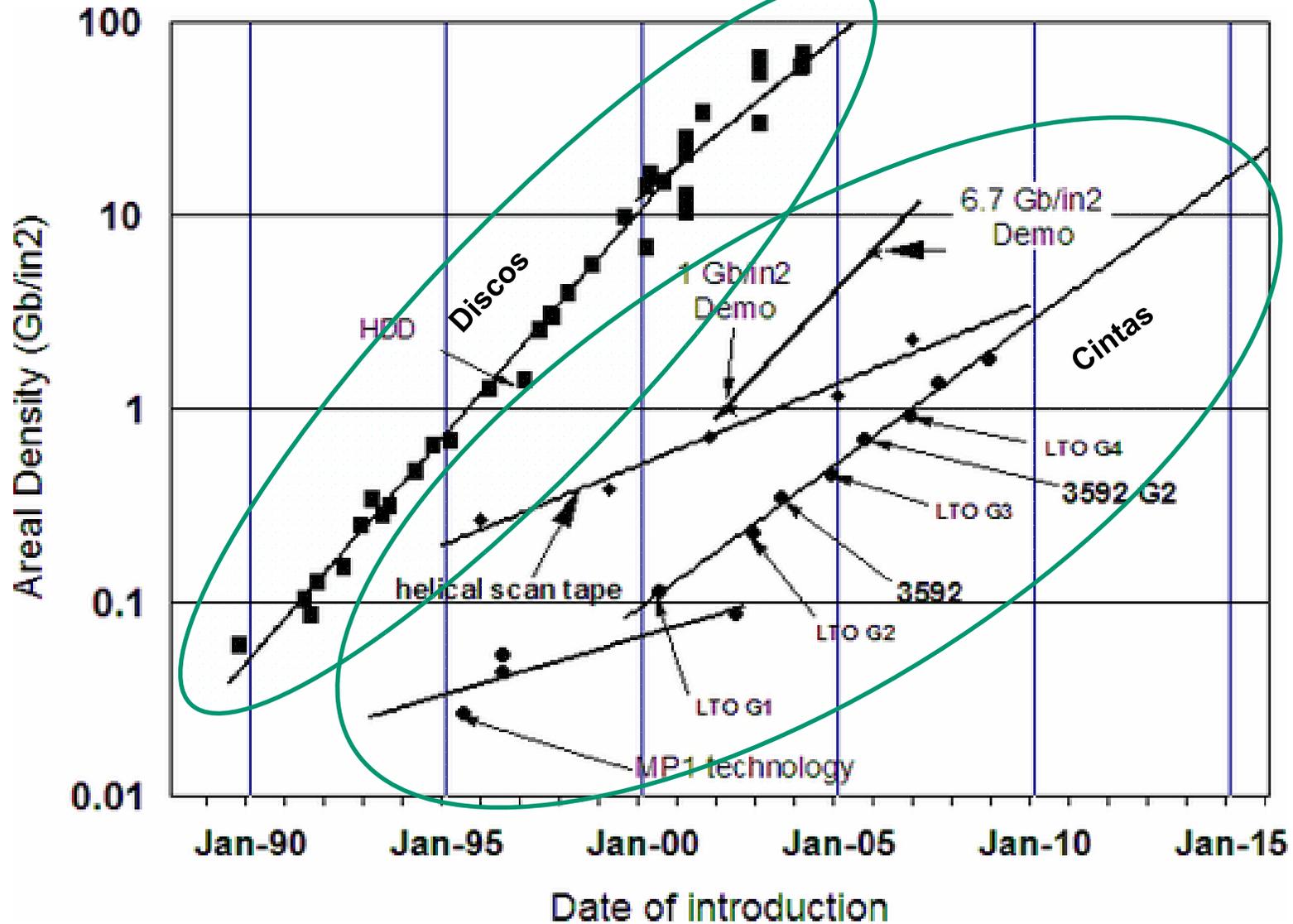
[Figura: J. Stöhr, IBM Research Center.]

# Registro magnético en disco

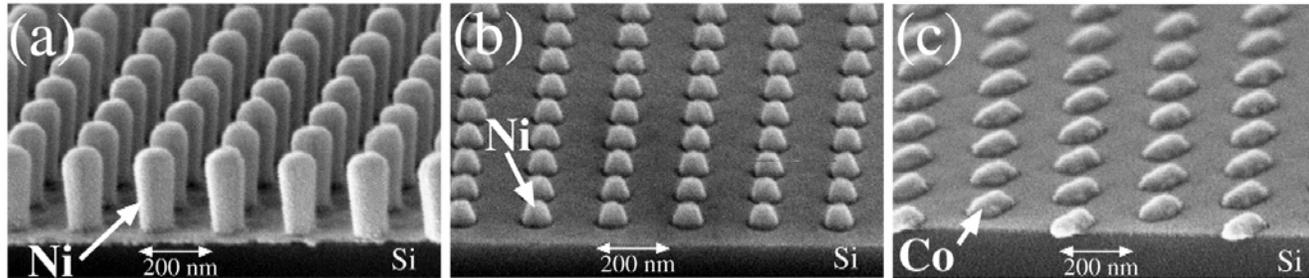


Los bits de información se graban con la cabeza inductiva.  
El flujo magnético en la superficie del disco rotante es sentido por la cabeza lectora magneto-resistiva.

# Discos duros - evolución



## Diseño nanoscópico de nuevos materiales para almacenamiento de datos



Nanomagnetos fabricados por (a) electroplateado, (b) evaporación, (c) lift-off. Los objetos de la Fig 1a son nanomagnetos de Ni de 220 nm de alto y 90 nm de diámetro. Los nanomagnetos de Ni de la Fig. 1b, fueron formados por evaporación y despegue lift-off. La Fig. 1c muestra nanomagnetos elongados de Co con eje magnético fácil en el plano. <http://nanoweb.mit.edu/annual-report00/10.html>

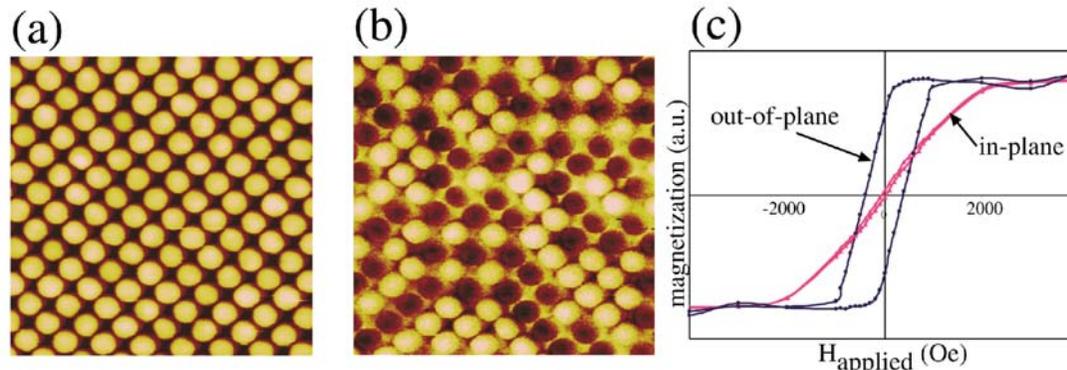


Imagen topográfica (a) y magnética (b) de los objetos de Ni de la Fig 1a. Círculos oscuros: magnetization apuntando hacia arriba, círculos claros: magnetization hacia abajo. Magnetization “up” puede interpretarse como el binario ‘1’ y Magnetization “down” como el binario ‘0’



Finale... e  
recomendazione...





Los superimanes no son para las  
heladeras...



Tell me, Randy,  
has someone eaten all the  
fridge magnets again?

