Magnetism the Big picture

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I. Science rules the Earth - OK?

II. The end of an aether

III. What the ancients knew

IV. Billions of magnets for billions of people

www.tcd.ie/Physics/Magnetism

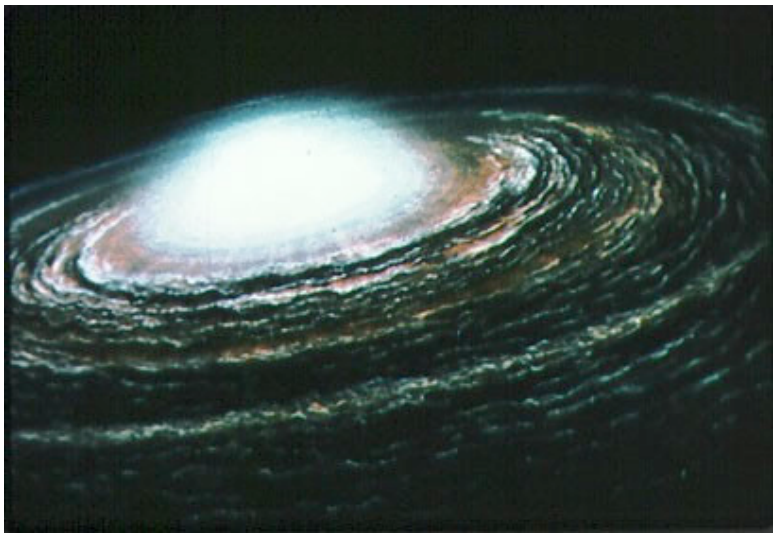
The first 3.5 Ga.

1	1	one	x
10	10	ten	
10^2	100	hundred	
10^3	1000	thousand	kx kilo
10^4	10000	ten thousand	
10^5	100000	hundred thousand	
10^6	1000000	million	Mx mega
10^7	10000000	ten million	
10^8	100000000	hundred million	
10^9	1000000000	billion	Gx giga
10^{10}	10000000000	ten billion	

1	1	one	x
10^{-1}	0.1	tenth	
10^{-2}	0.01	hundredth	
10^{-3}	0.001	thousandth	mx milli
10^{-4}	0.0001	ten thousand	
10^{-5}	0.00001	hundred thousand	
10^{-6}	0.000001	millionth	μx micro
10^{-7}	0.0000001	ten millionth	
10^{-8}	0.00000001	hundred millionth	
10^{-9}	0.000000001	billionth	nx nano
10^{-10}	0.0000000001	ten billionth	

Formation of the Earth 4.5 Ga

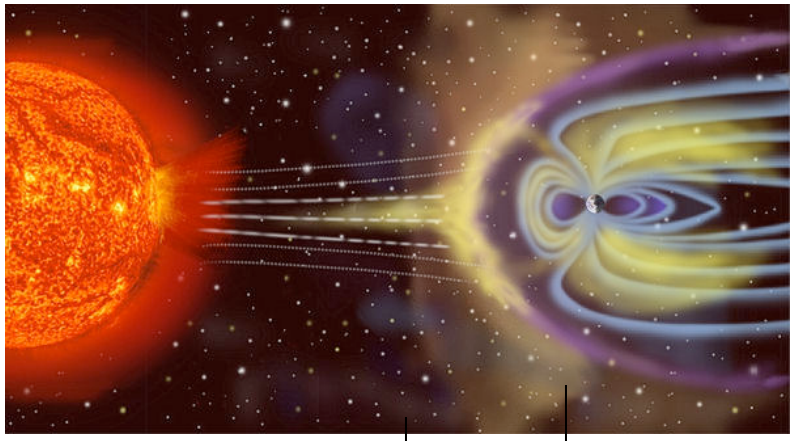
Big bang 14 Ga



Pangaea 240 Ma

Magnetotactic bacteria 150 Ma

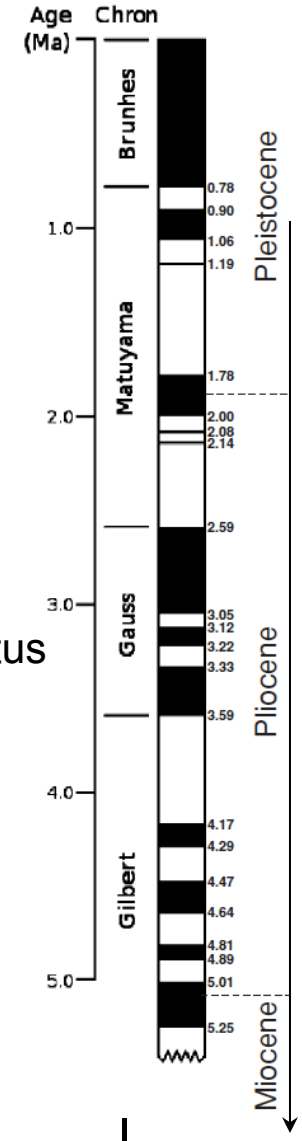
Earth's magnetic field 3.5 Ga



10 9 8 7

log *t*(a)

Homo erectus
1.8 Ma



Last reversal
700 ka

Homo sapiens
200 ka

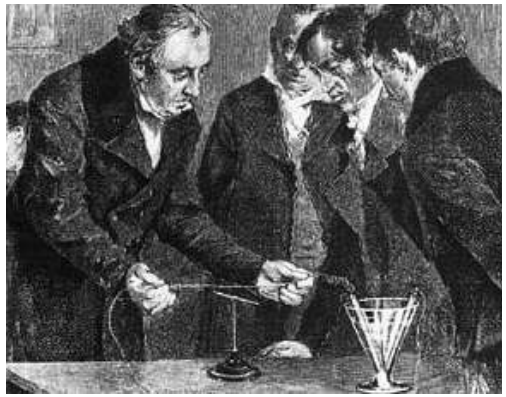
Agriculture 11 ka

7 6 5 4

log *t*(a)

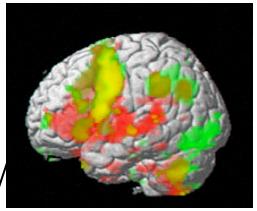
Discovery ~3 ka

Columbus
520 a



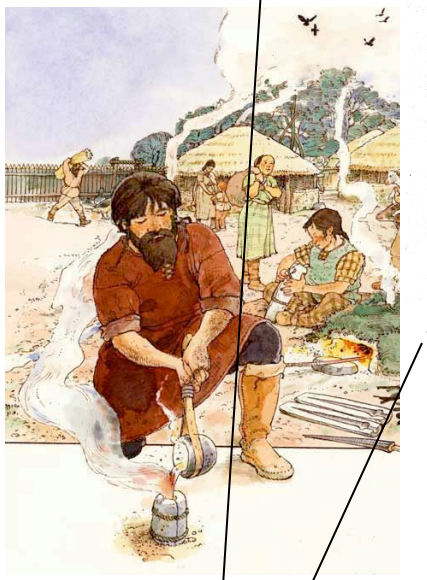
Oersted 190 a

AHM 45 a

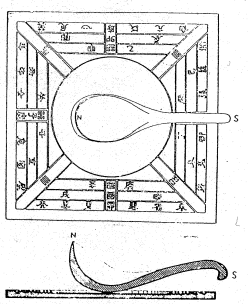


fMRI 20 a

Writing 7 ka

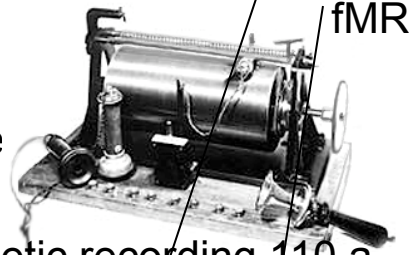


Iron metallurgy
3.8 ka

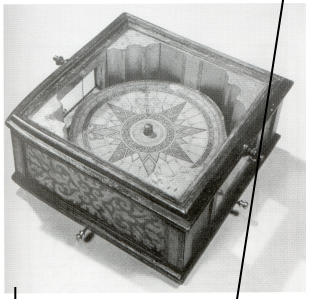


South pointer 2.2 ka

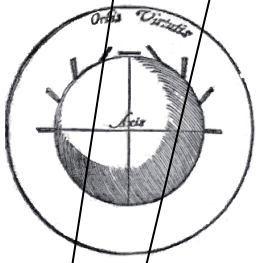
Horseshoe
250 a



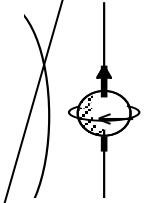
Magnetic recording 110 a



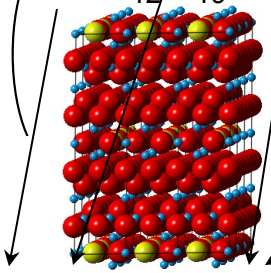
Compass 1.0 ka



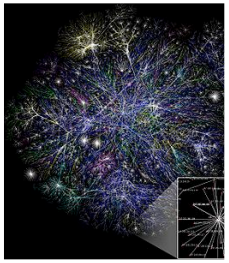
De Magnete
410 a



Spin
80 a



$BaFe_{12}O_{19}$ 55 a



www 20 a

4 3 2 1

log *t*(a)

4. Billions of magnets for billions of people

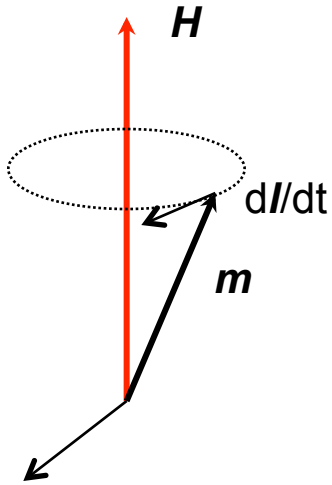
- *De Magnete* The first scientific text
- The Earth's magnetic field
- Gauss's *Magnetverein*
- Chaos - It reverses !
- The Earth moves.

4. Billions of magnets for billions of people

The mystery of magnetism was solved in 1930, but it was only when the shape barrier was shattered in 1950 that the technology that serves our modern lives could emerge. Set free from the straightjacket of bars and horseshoes, the quality of magnets began to double every ten years. Small, powerful rare-earth magnets power countless gadgets from screwdrivers to carrot slicers. But the greatest miracle is magnetic recording — our magnets have multiplied a billion-fold so we now make more of them than we grow grains of rice. Every bit of information on the internet needs one.

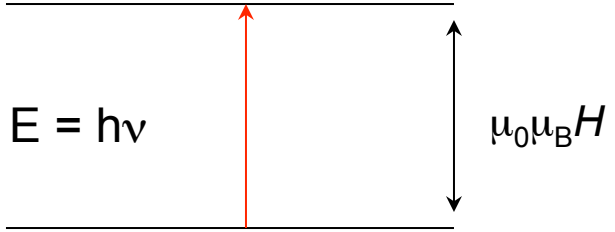
5. Magnetic resonance

The high-frequency age; 1935 to 1955



$\Gamma = \mu_0 \boldsymbol{m} \times \boldsymbol{H}$

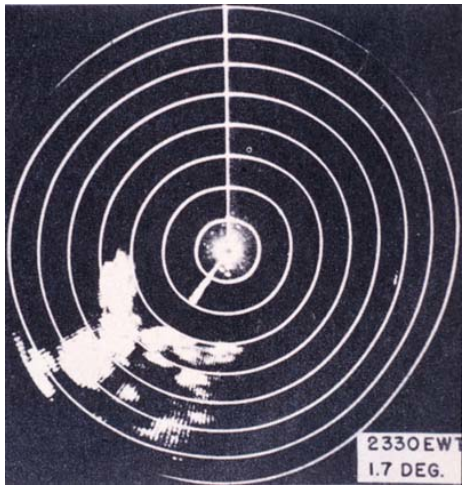
classical



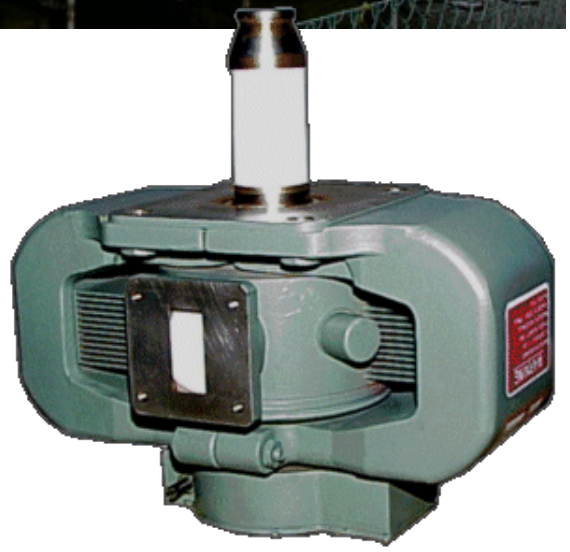
quantum

$\nu_L = \mu_0 e H / 2 m_e \pi$

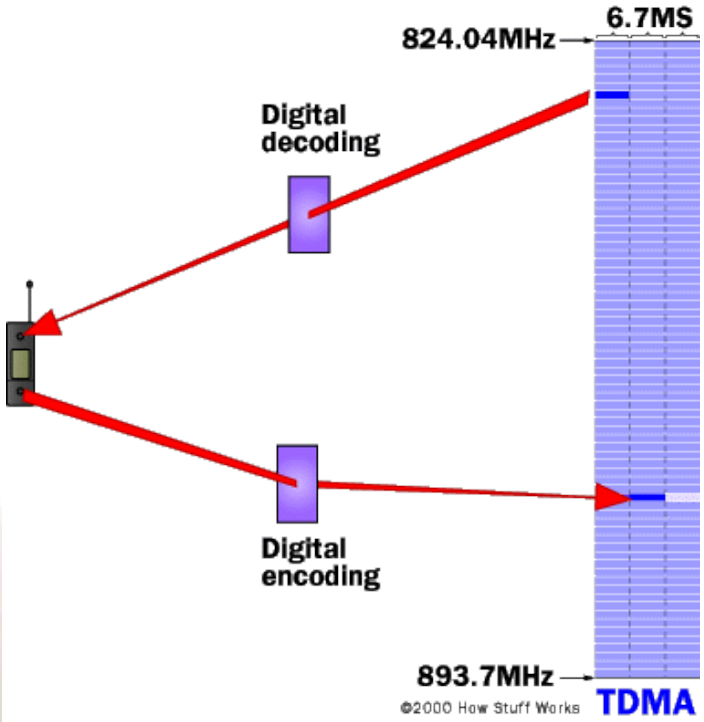
$\nu_L = 35\ \text{Hz}/(\text{A m}^{-1})$



Radar was developed during WWII



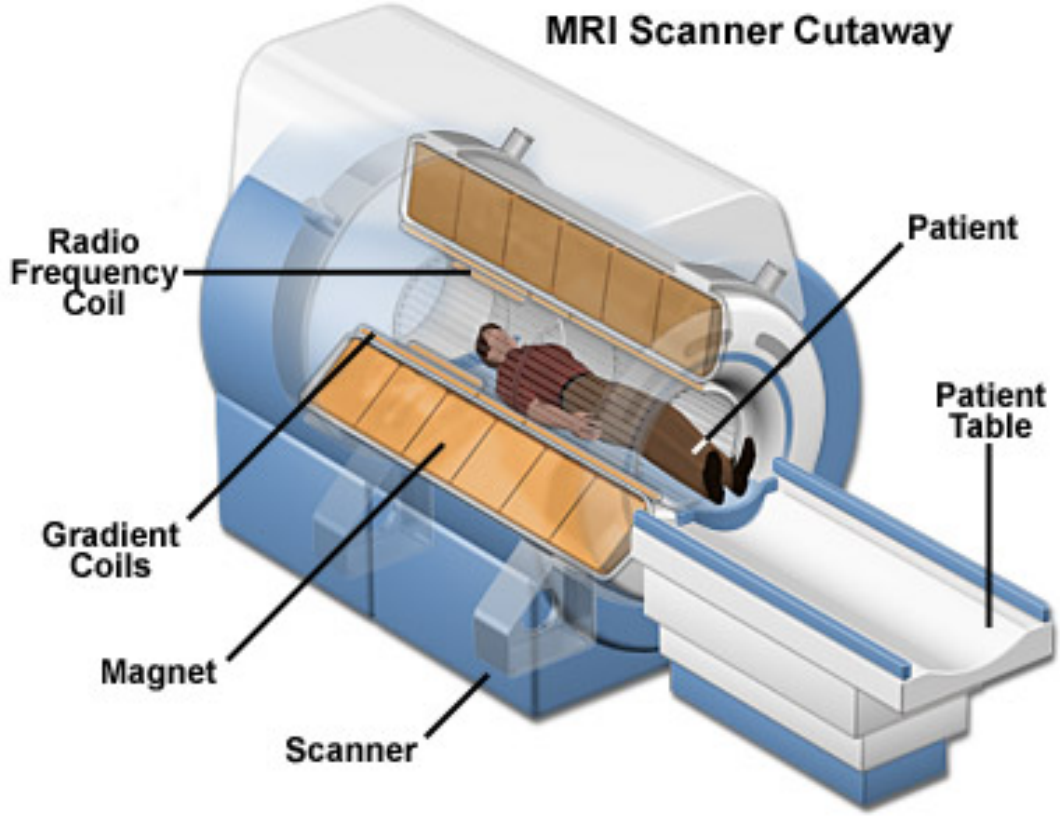

NOKIA
PACIFIC BELL

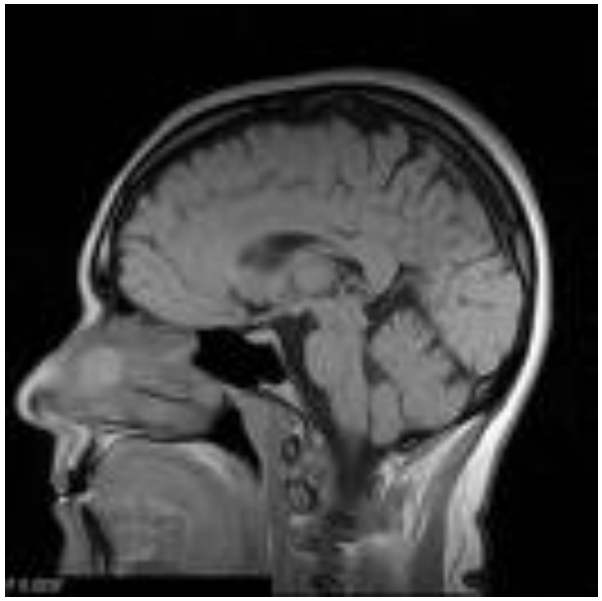

824.04MHz
6.7MS
Digital
decoding
Digital
encoding
893.7MHz
©2000 How Stuff Works
TDMA

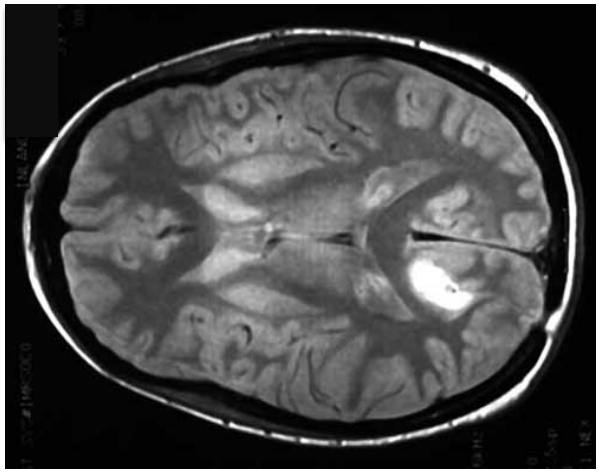
Paramagnetic resonance

Ferromagnetic resonance

Nuclear magnetic resonance



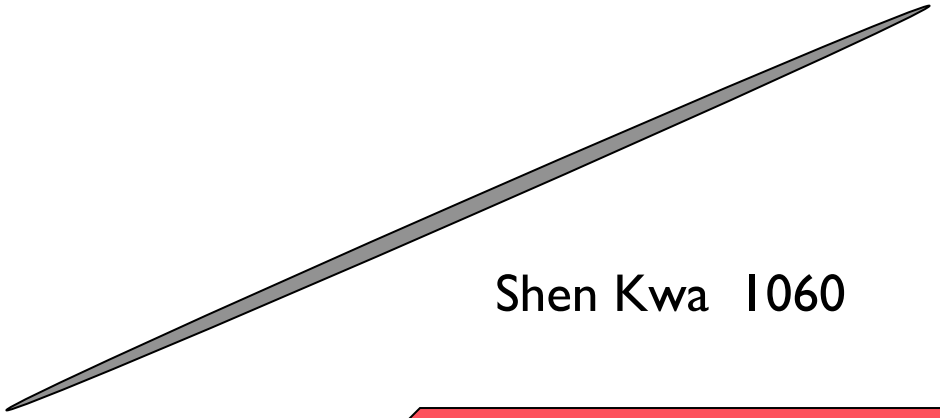




6. The shape barrier broken

Magnets for all; 1955 to 1985

Daniel Bernouilli
1743



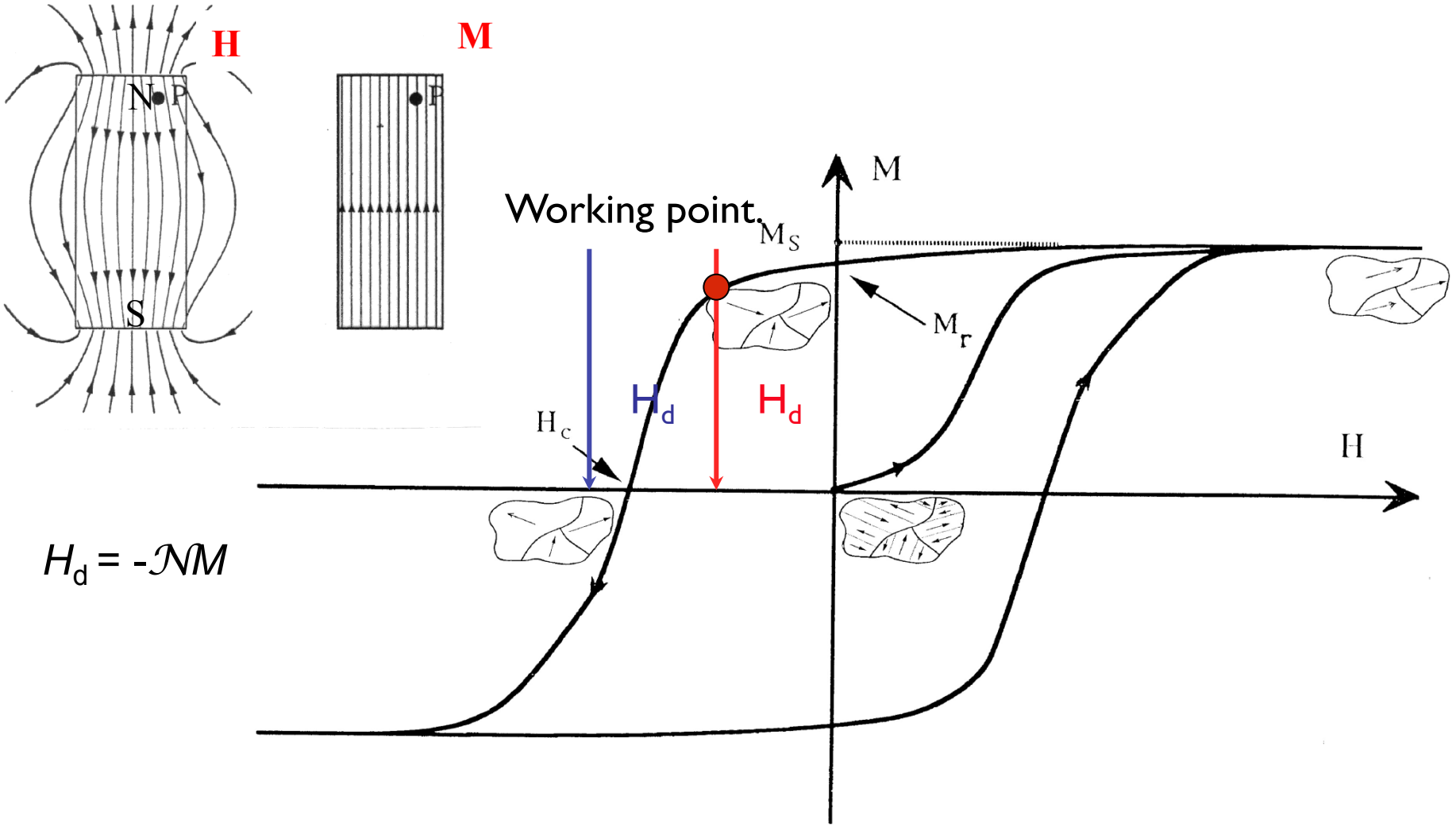
Shen Kwa 1060

Gowind Knight
1760

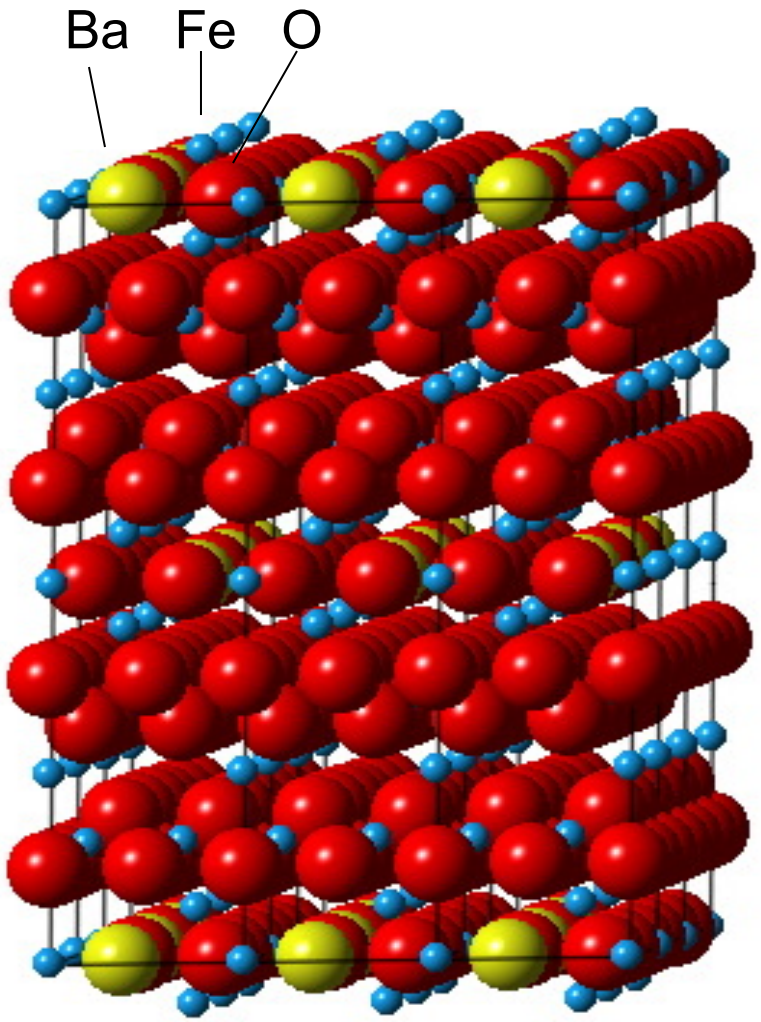
Mishima 1930

For centuries, magnets had to be made in awkward shapes, to avoid demagnetization.

The hysteresis loop - the icon of magnetism



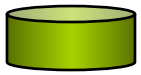
$H_d = -\mathcal{N}M$



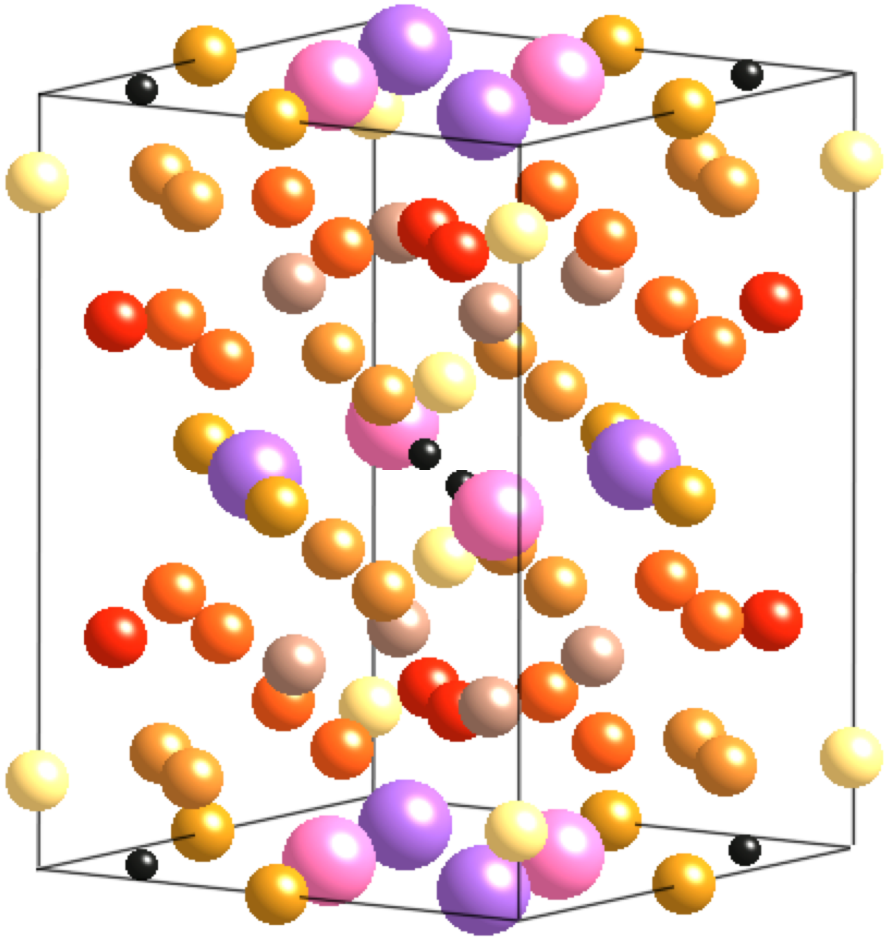
$BaFe_{12}O_{19}$

A new magnet material $BaFe_{12}O_{19}$ was developed at Philips 1954, Since then it has been possible to make them any shape. 90 % of all magnets are now made of hexagonal ferrite. Annual production is ≈ 800,000 tonnes (>100 g for everyone on Earth!)

Optimum magnet shape



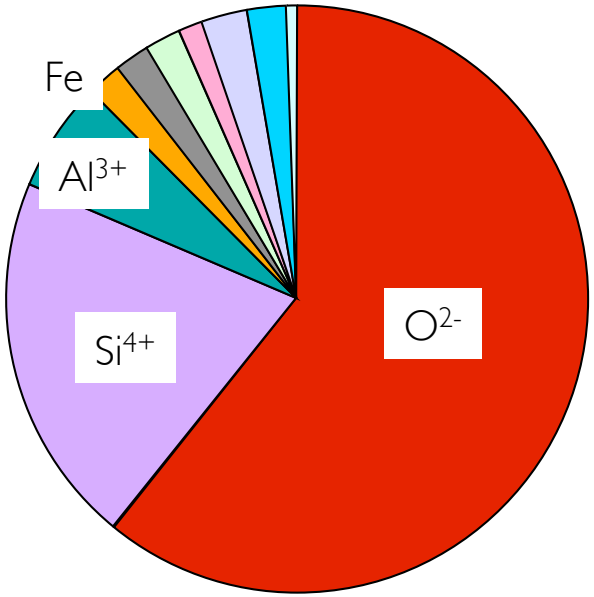
$\mathcal{N} = 1/2$

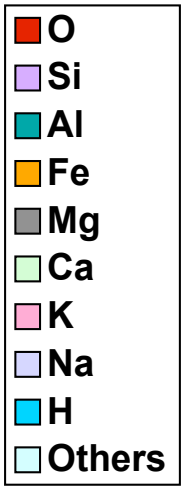


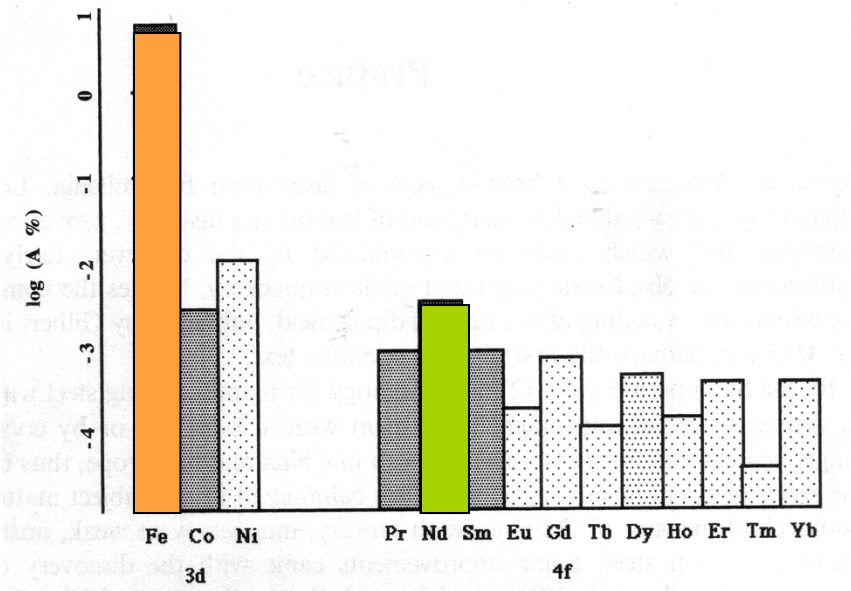
$Nd_2Fe_{14}B$

Rare-earth magnets based on Sm-Co or Nd-Fe-B are the best we can make. Used for high-end applications, billions of permanent magnet motors are manufactured every year. Annual production is ≈ 50,000 tonnes (≈7 g for everyone on Earth!)

Abundances of magnetic elements







Crustal abundances (top 9)

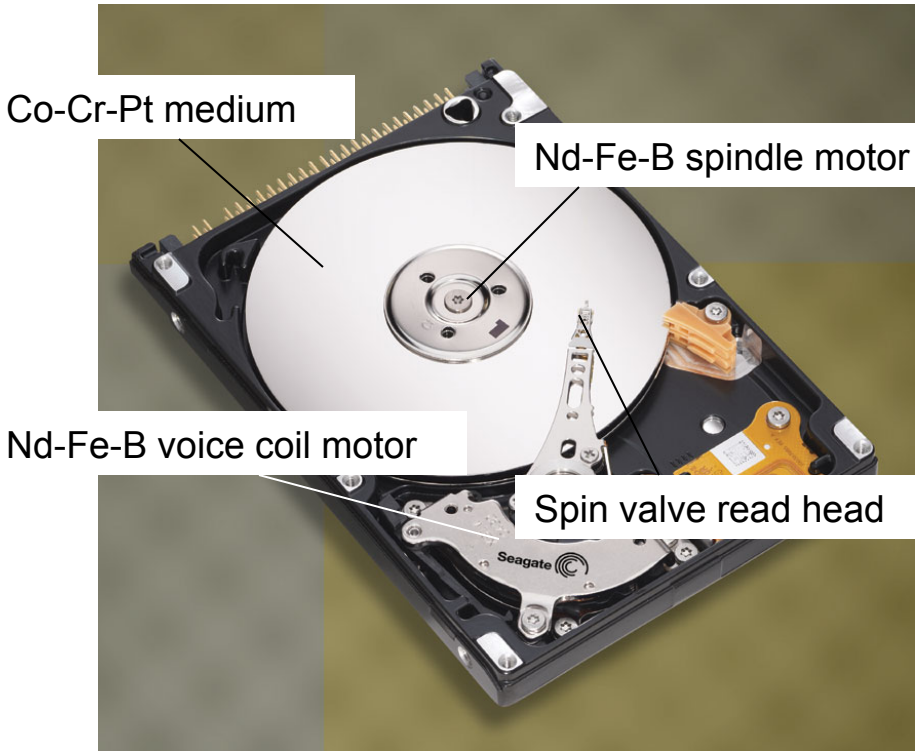
All magnetic elements (log scale}

The consumer revolution

How many magnets do you own?

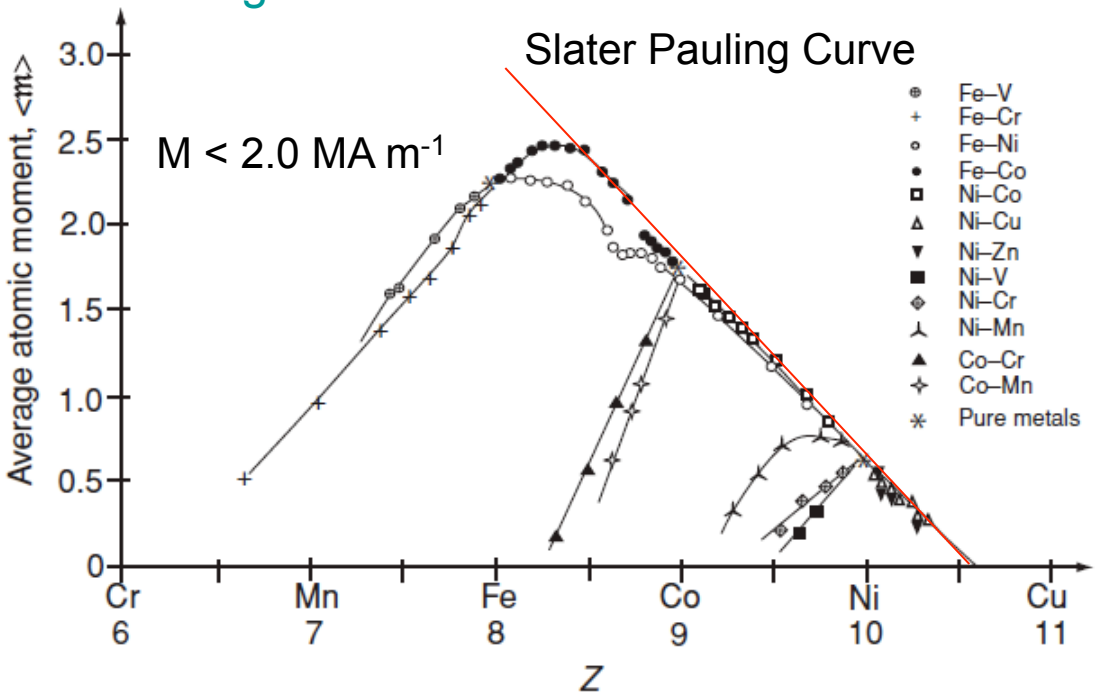
100 - 200

~100 billion



Where are the limits for magnetic materials?

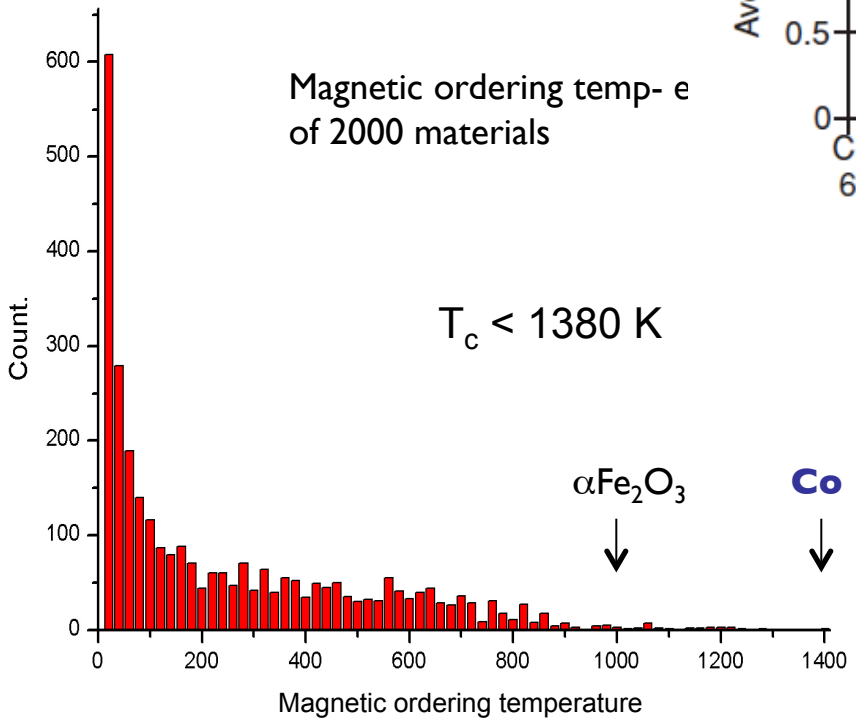
Magnetization



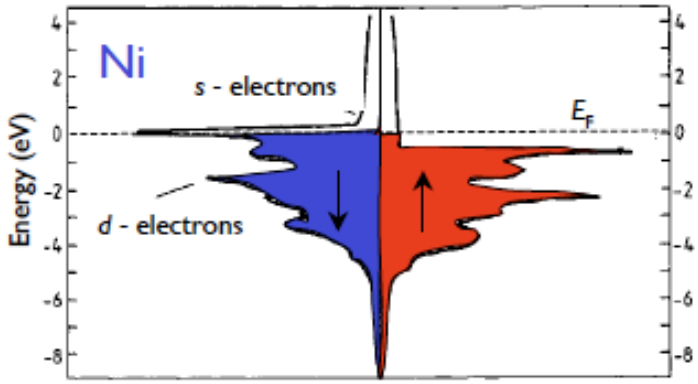
Curie Temoerature

Magnetic ordering temp- e
of 2000 materials

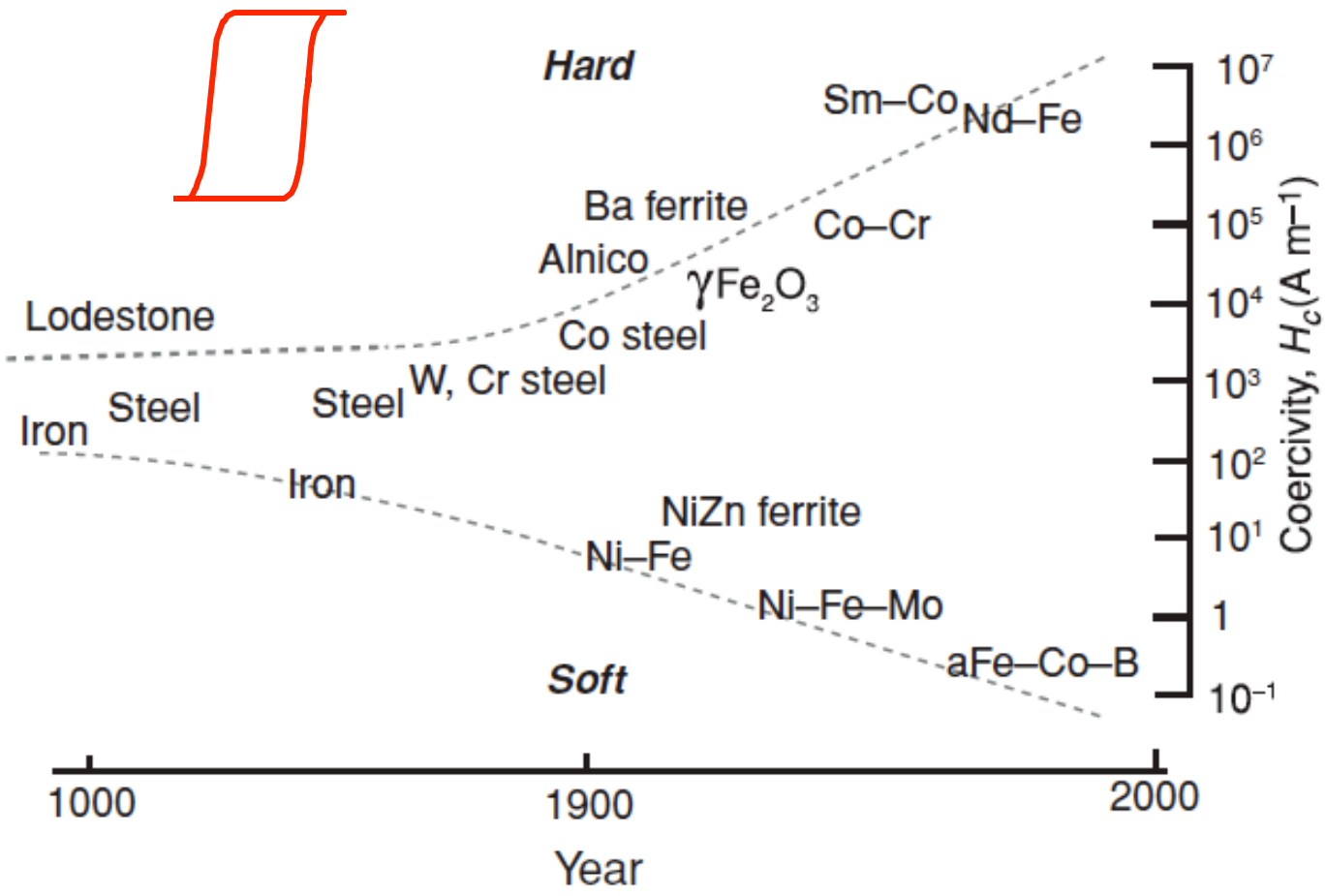
T_c < 1380 K



Rigid-band model



Coercivity



The story of magnetic materials in the 20th century has been the story of mastery of *coercivity*

1900: $10^3 < H_c < 10^5$ A m^{-1} *2000:* $1 < H_c < 2\ 10^7$ A m^{-1}

7. Spin electronics

The new frontier; 1995 to ?

Conventional electronics has ignored the spin on the electron.

Can we build a new electronics using the spin of the electron as well as (or instead of) its charge?

- Pure charge currents; charge flow

- Spin-polarized charge currents charge and angular momentum flow

- Pure spin currents angular momentum flow

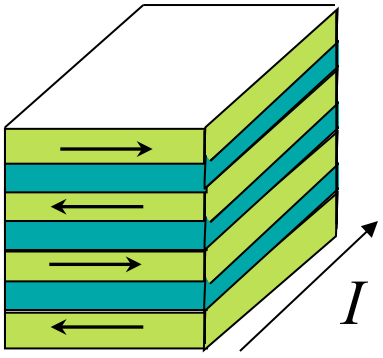
Giant magnetoresistance. The first step in spin electronics.

Peter Grunberg and Albert Fert;

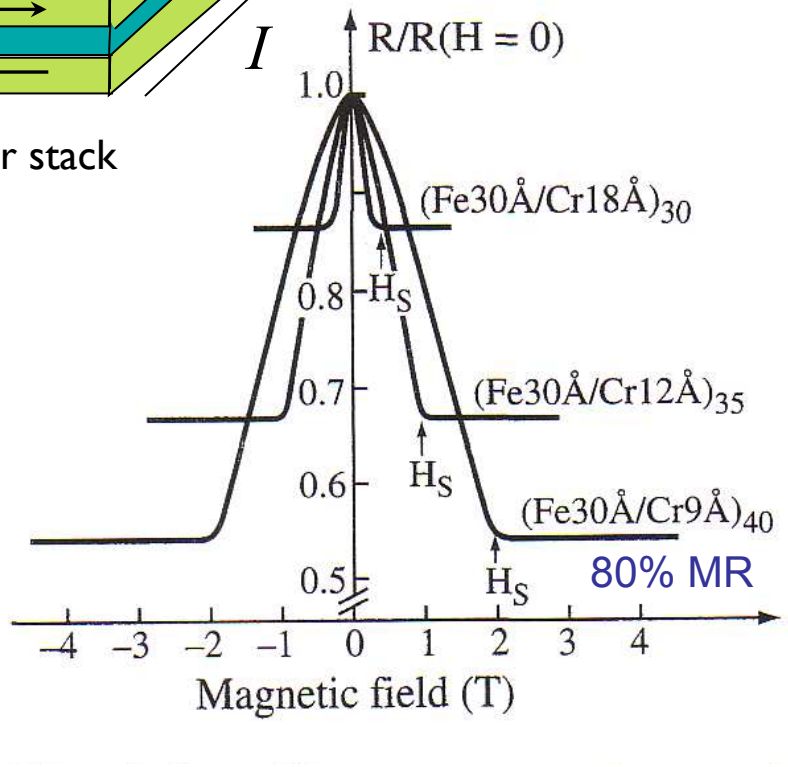
Discovery of GMR 1988

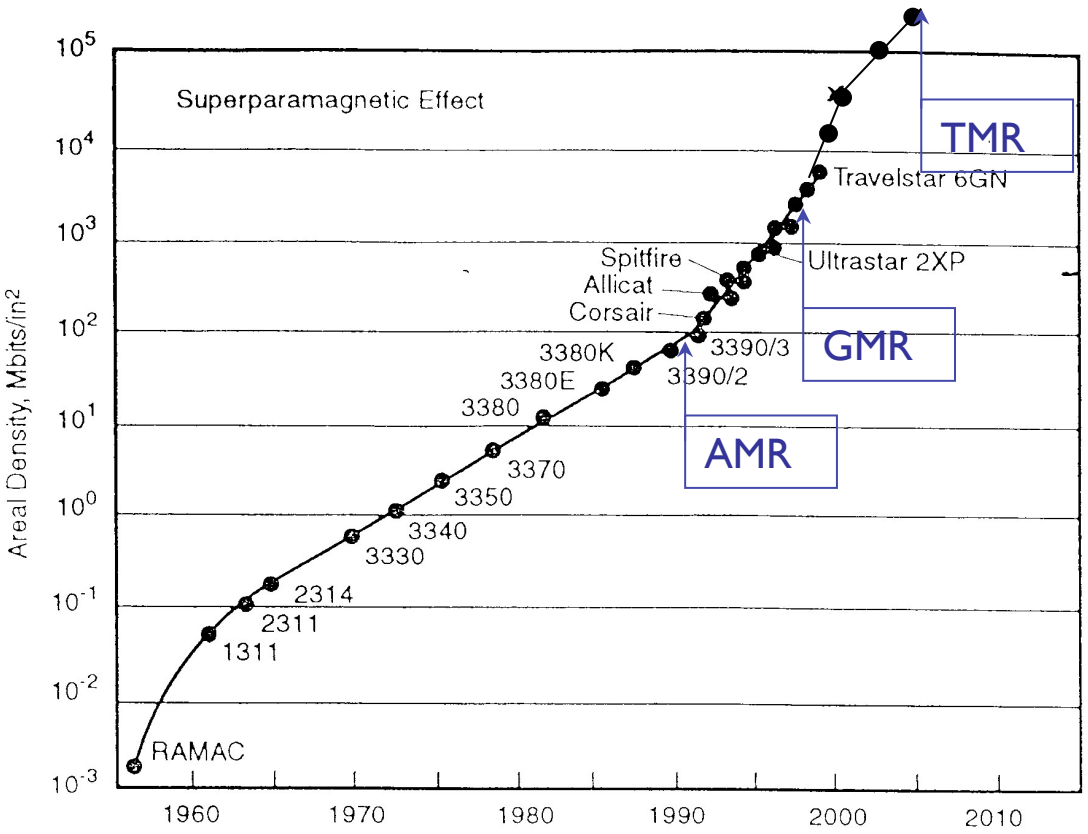
Implementation in hard disk drives 1998

Nobel Prize 2007

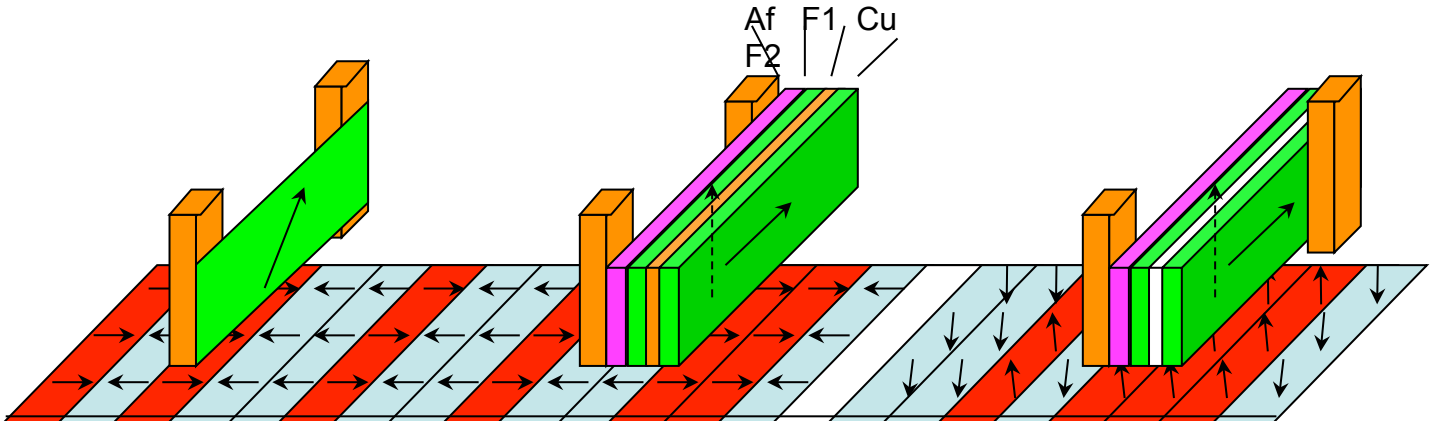


Fe/Cr stack

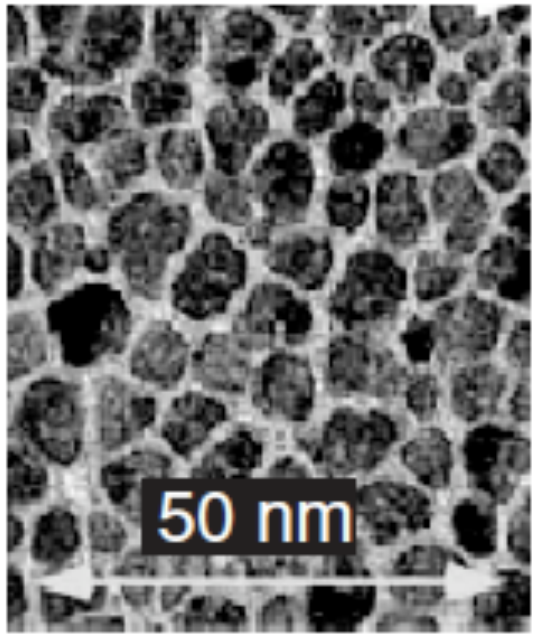


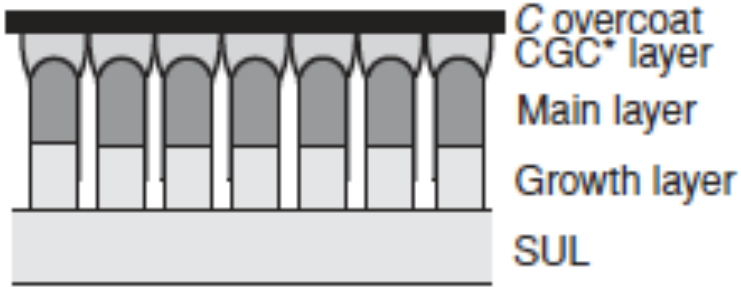


1 μm²

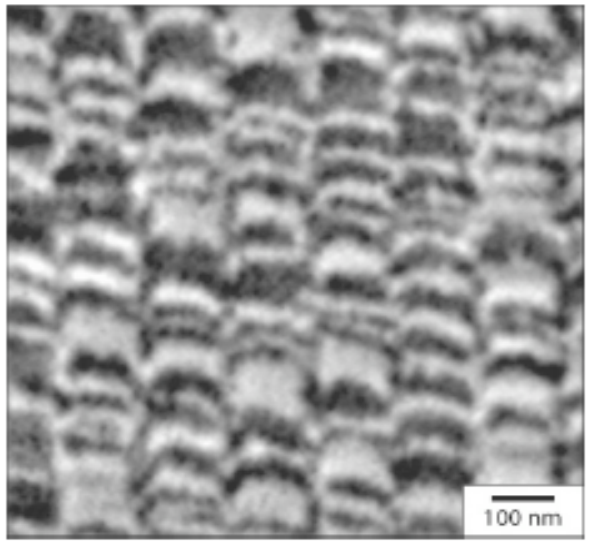


AMR GMR TMR



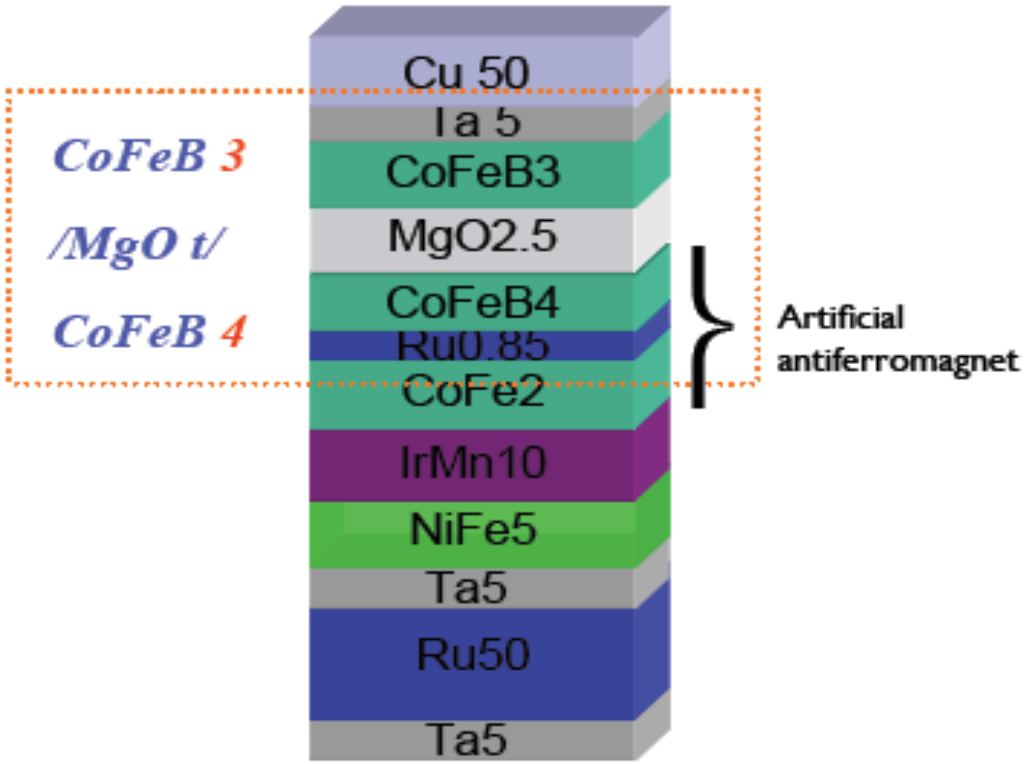


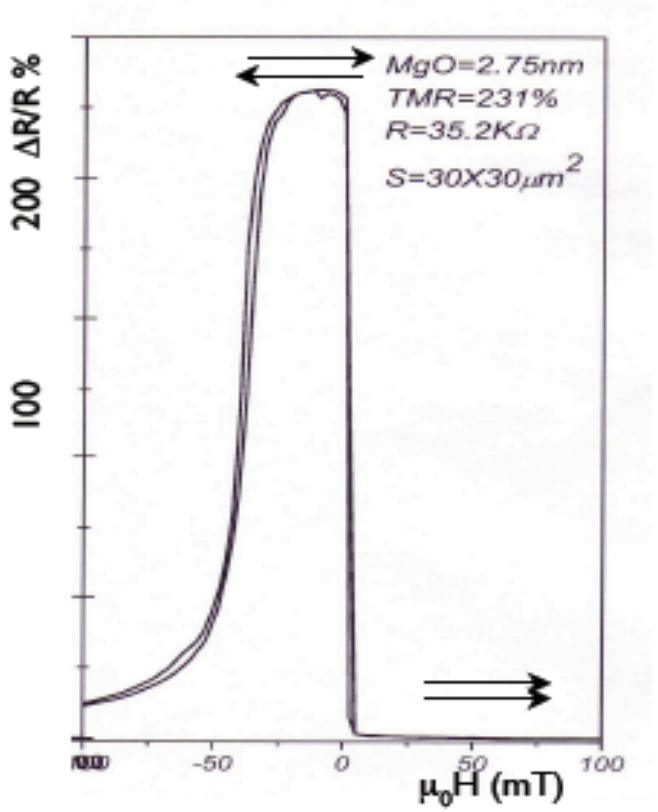
(* continuous granular composite)

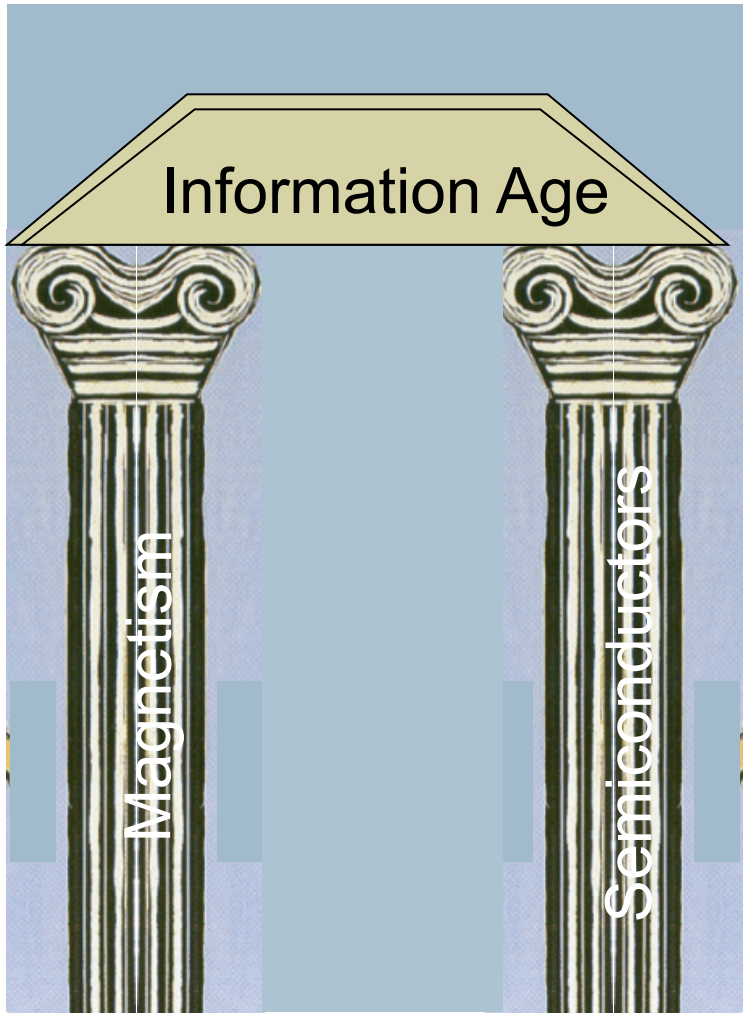


Perpendicular tracks on a hard disc imaged by high-resolution magnetic force microscopy. The width of the tracts is determined by the width of the write head. The recording density here is 300 bits μm^{-2} or 250 Gbit/square inch. (Courtesy of Nanoscan AG.)

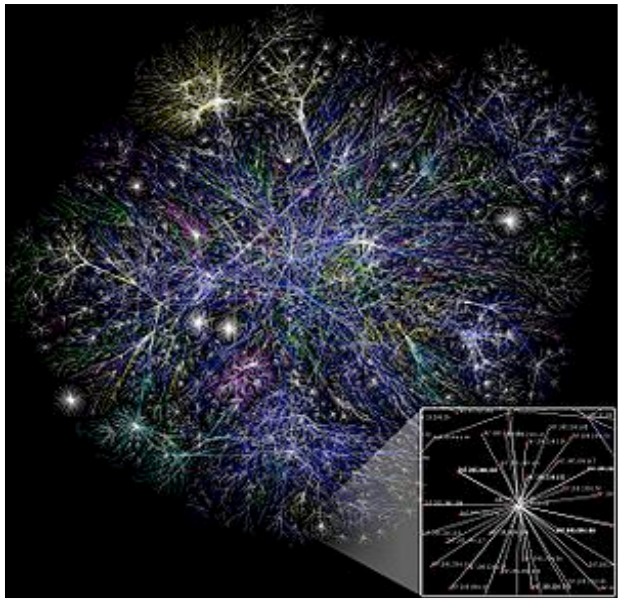
MgO barrier magnetic tunnel junctions





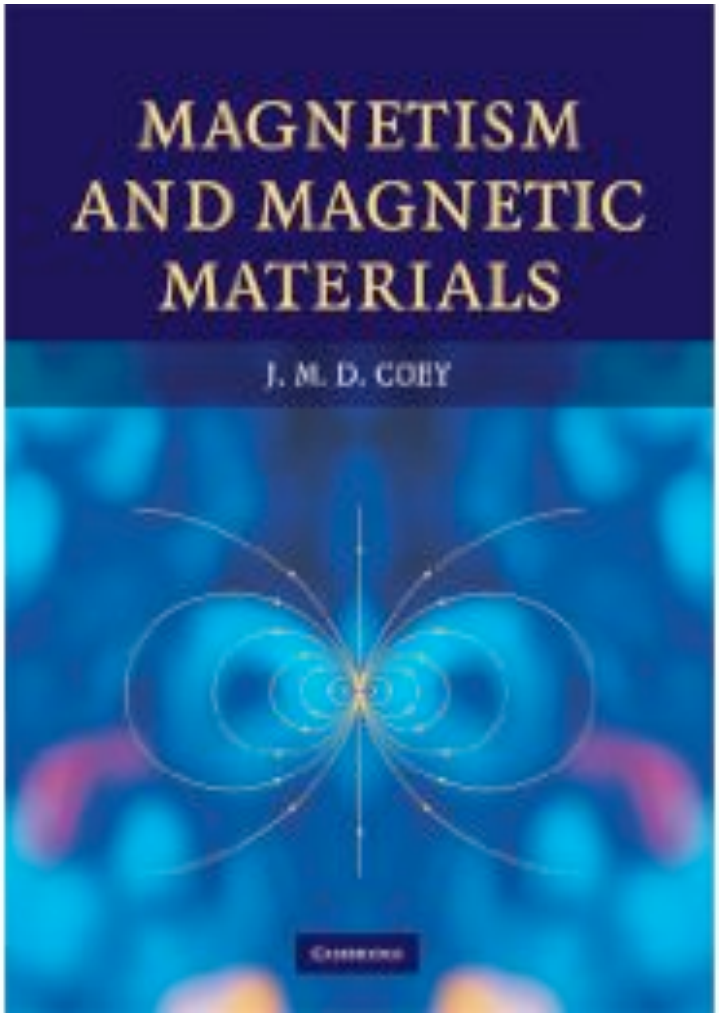


10^{21} bytes of information are stored every year.



We now make more transistors and magnets every year in our fabs than we grow grains of wheat and rice in our fields.

III. Where now?



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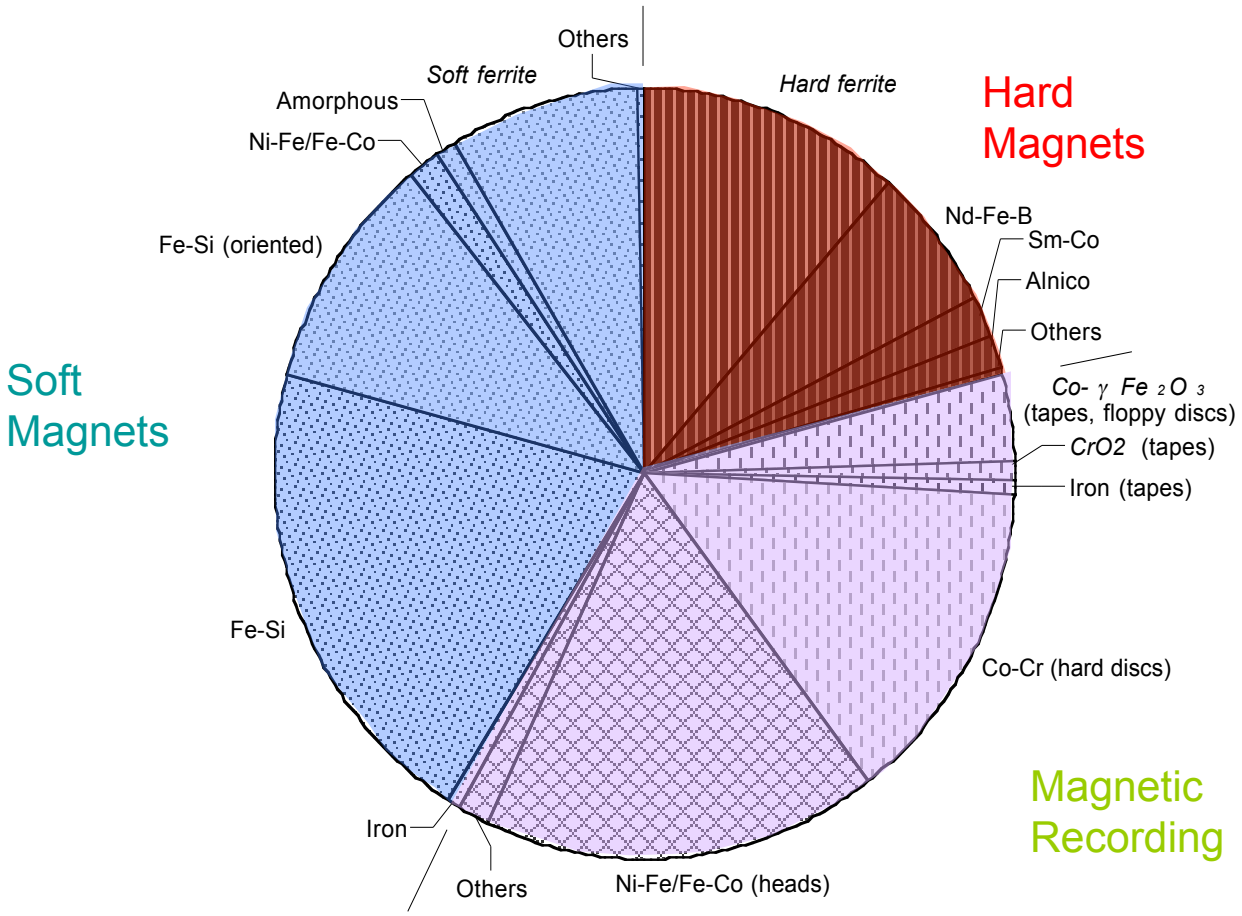
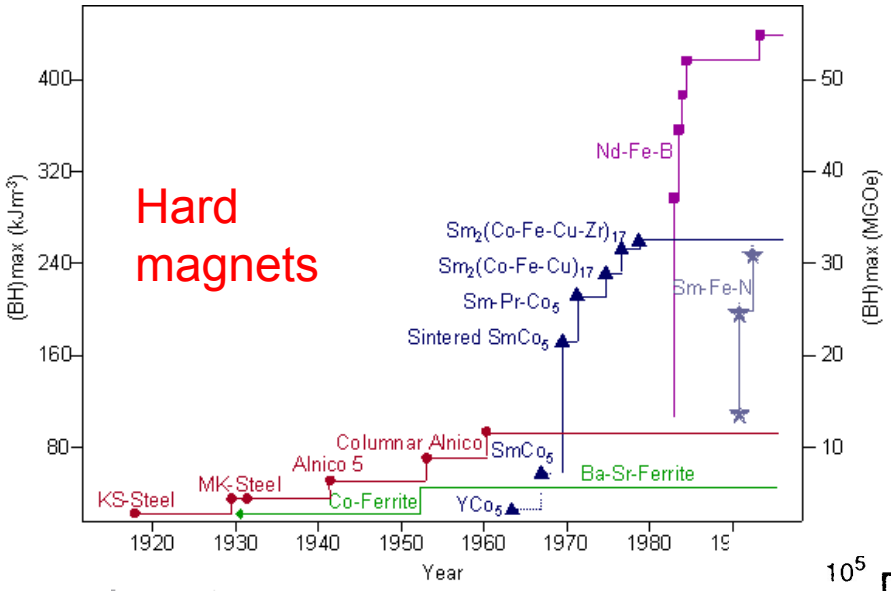
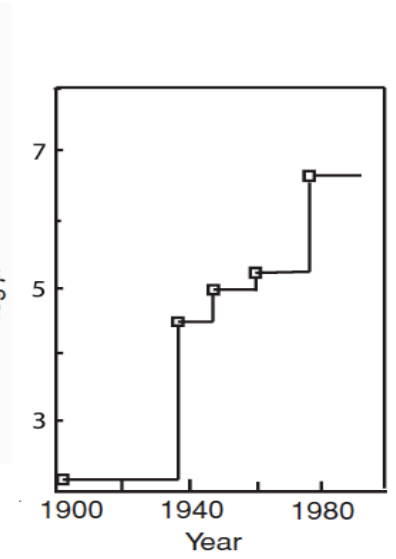
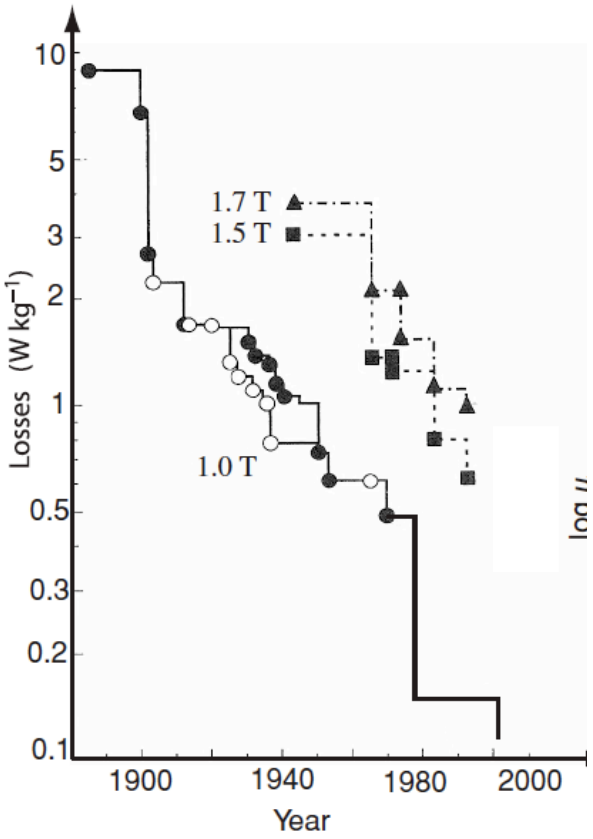
Magnet Materials; A 30 B€ market

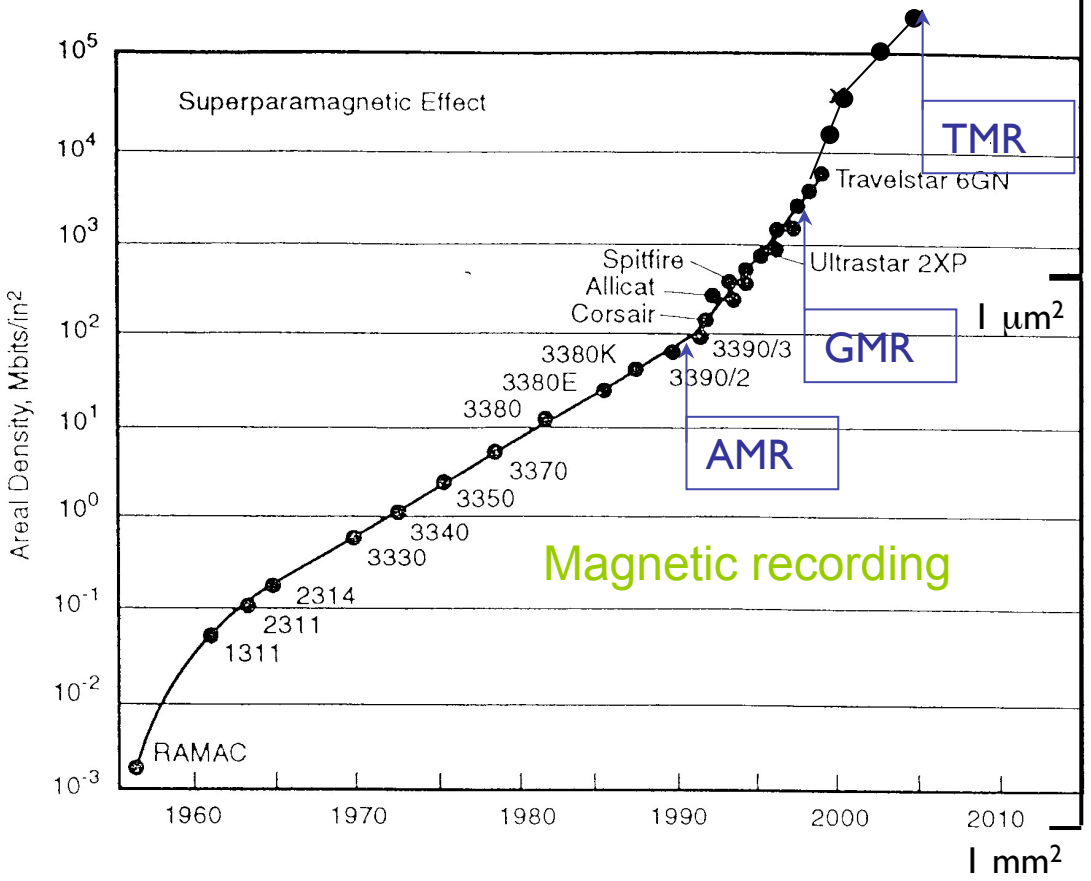


Average production per person (approximate):
30 g hard ferrite, 2 g rare earth magnet, 1 m^2 flexible medium, 1/10 hard disc, 1/10 read/write head, 0.25 m^2 electrical sheet steel, 30 g soft ferrite, 0.1 g metallic glass.


Hard magnets
(BH)max (kJm^{-3})
(BH)max (MGOe)
Nd-Fe-B
$Sm_2(Co\text{-}Fe\text{-}Cu\text{-}Zr)_{17}$
$Sm_2(Co\text{-}Fe\text{-}Cu)_{17}$
Sm-Pr-Co_5
Sintered $SmCo_5$
Sm-Fe-N
Columnar Alnico
$SmCo_5$
Alnico 5
Ba-Sr-Ferrite
MK-Steel
KS-Steel
Co-Ferrite
YCo_5
Year


Soft magnets
log μ
Year


Losses (W kg^{-1})
1.7 T
1.5 T
1.0 T
Year


Superparamagnetic Effect
Areal Density, Mbits/in^2
TMR
Travelstar 6GN
Spitfire
Allicat
Corsair
Ultrastar 2XP
GMR
3380K
3380E
3380
3390/3
3390/2
AMR
3370
3350
3340
3330
2314
2311
1311
RAMAC
Magnetic recording
l nm^2
l μm^2
l mm^2

Property combinations