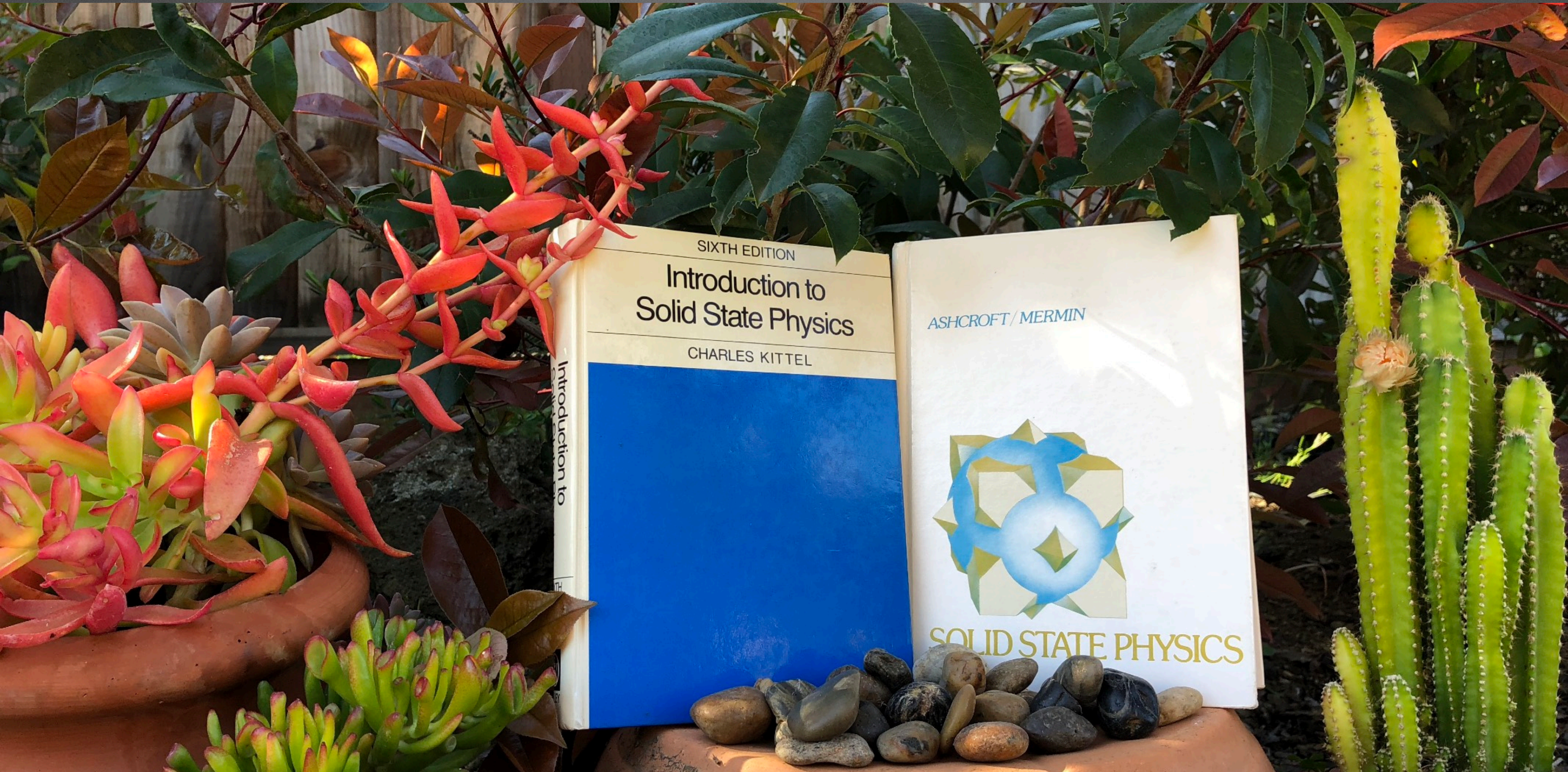
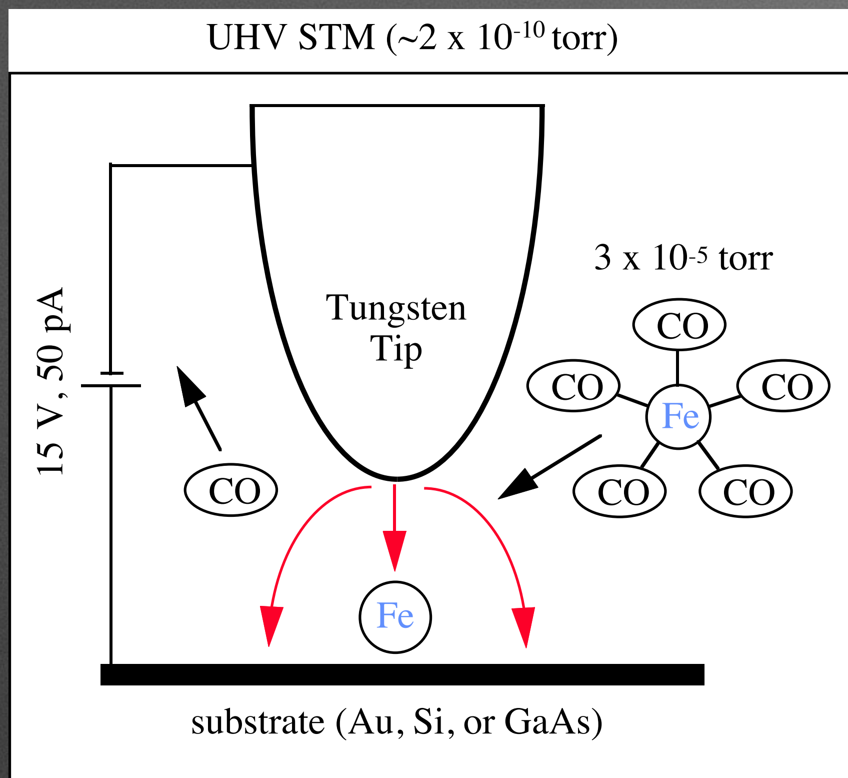
Solid State Physics in the Wild

Savas Gider

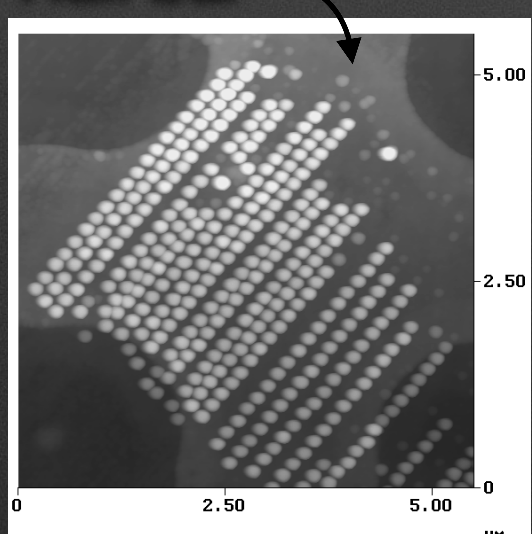


PhD Research

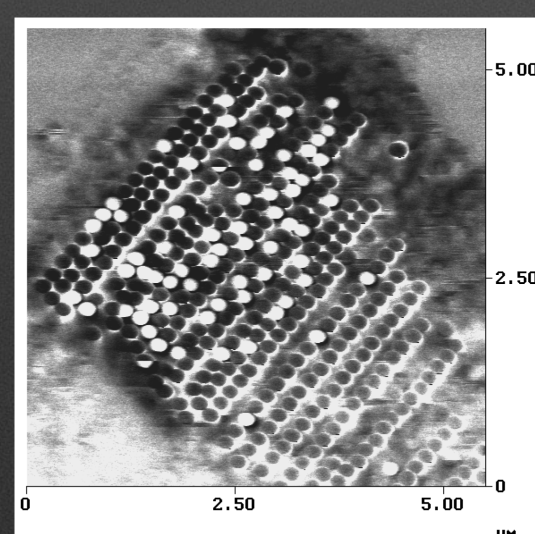
Artificial Magnets



Hall bar

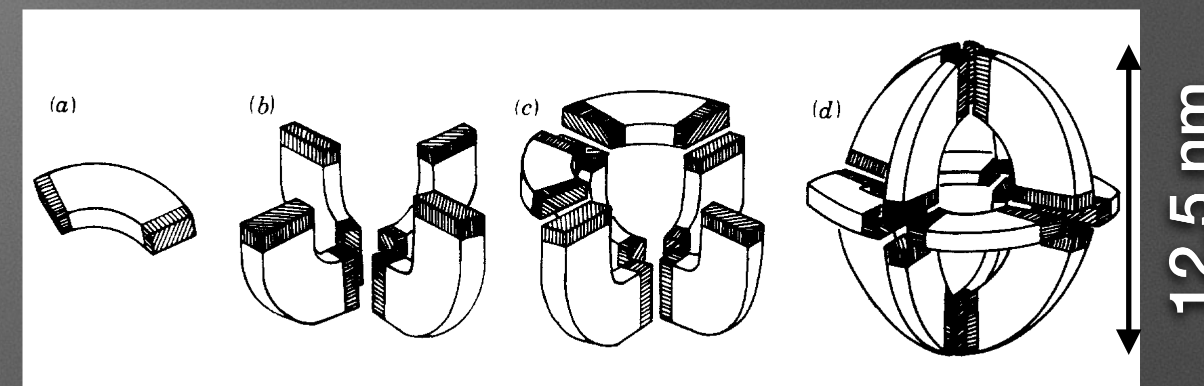


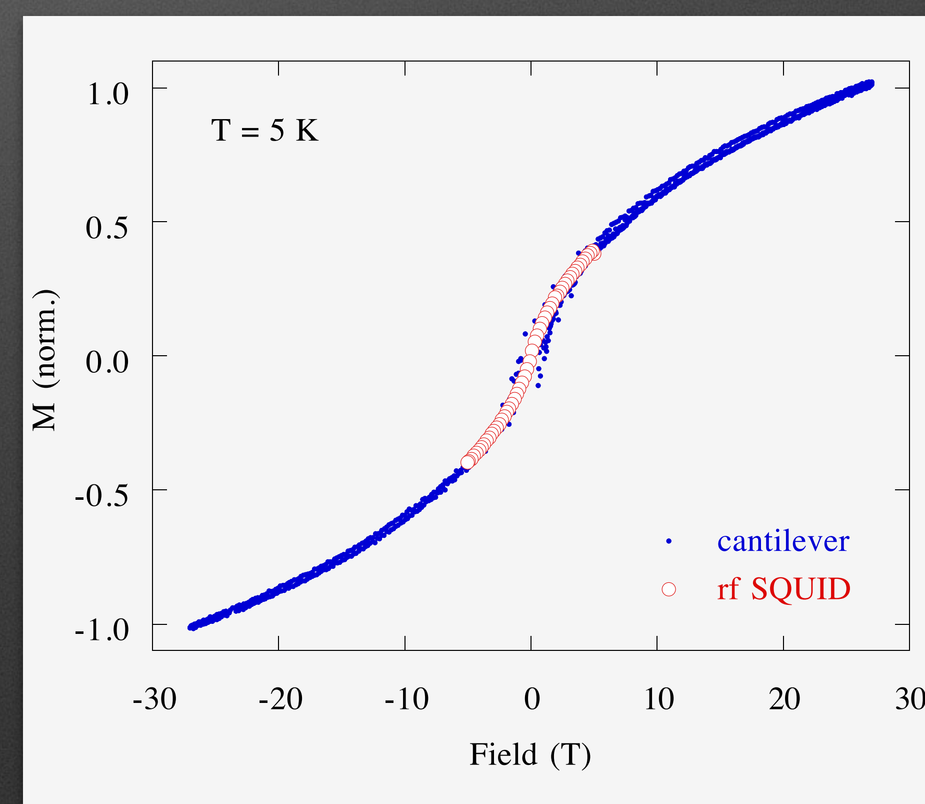
AFM



MFM

Biological Magnets (Ferritin)

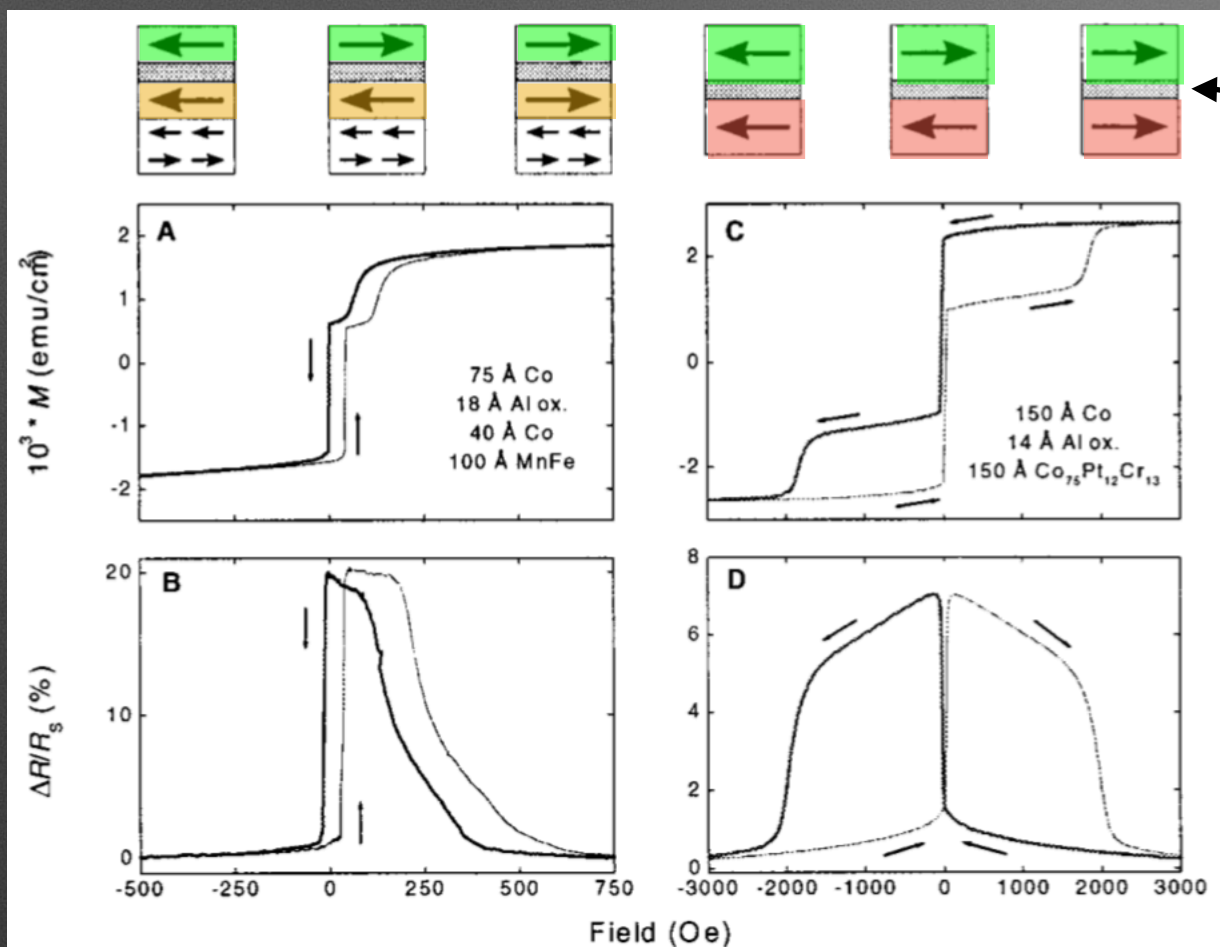




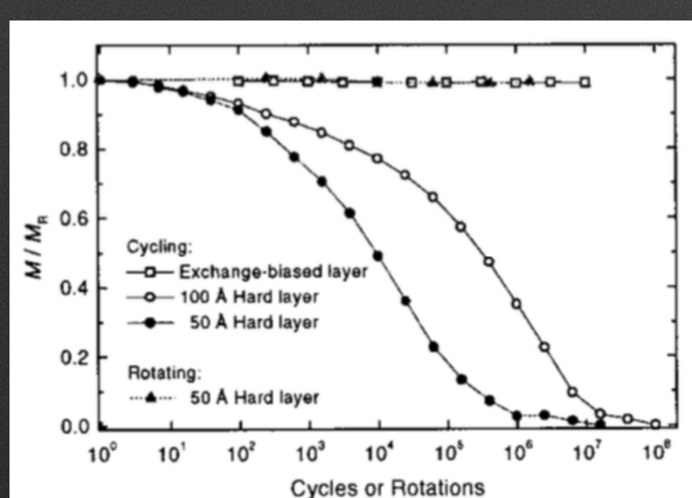
Post-Doc Research

Tunneling MagnetoResistance

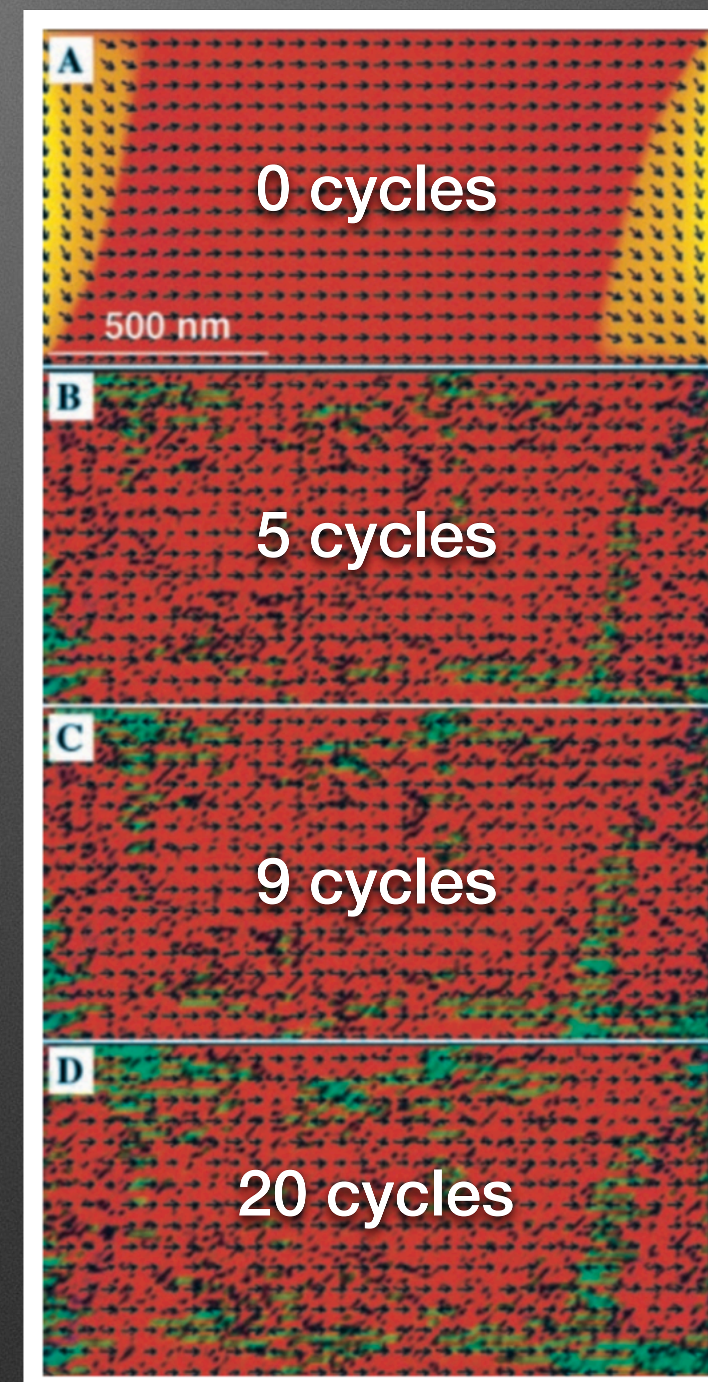
Antiferro. Ref. Hard Ref.



tunnel barrier



Hard Ref. Simulation

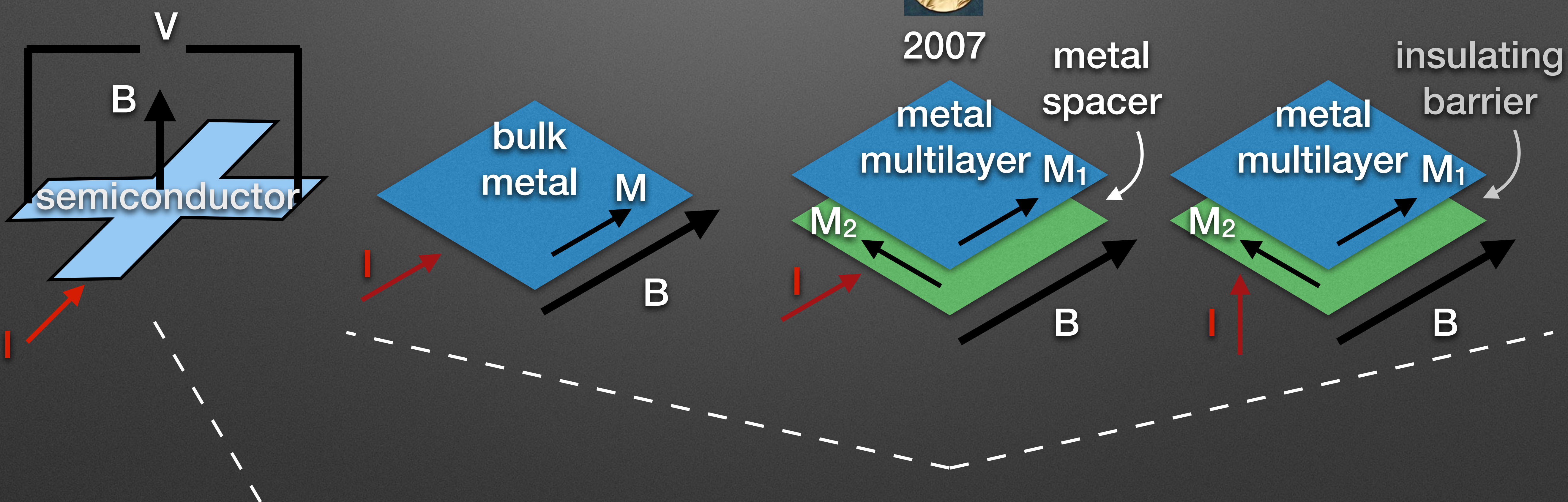


Professional Career

Magnetic Sensors (& Memories)

Magnetoresistance (MR)

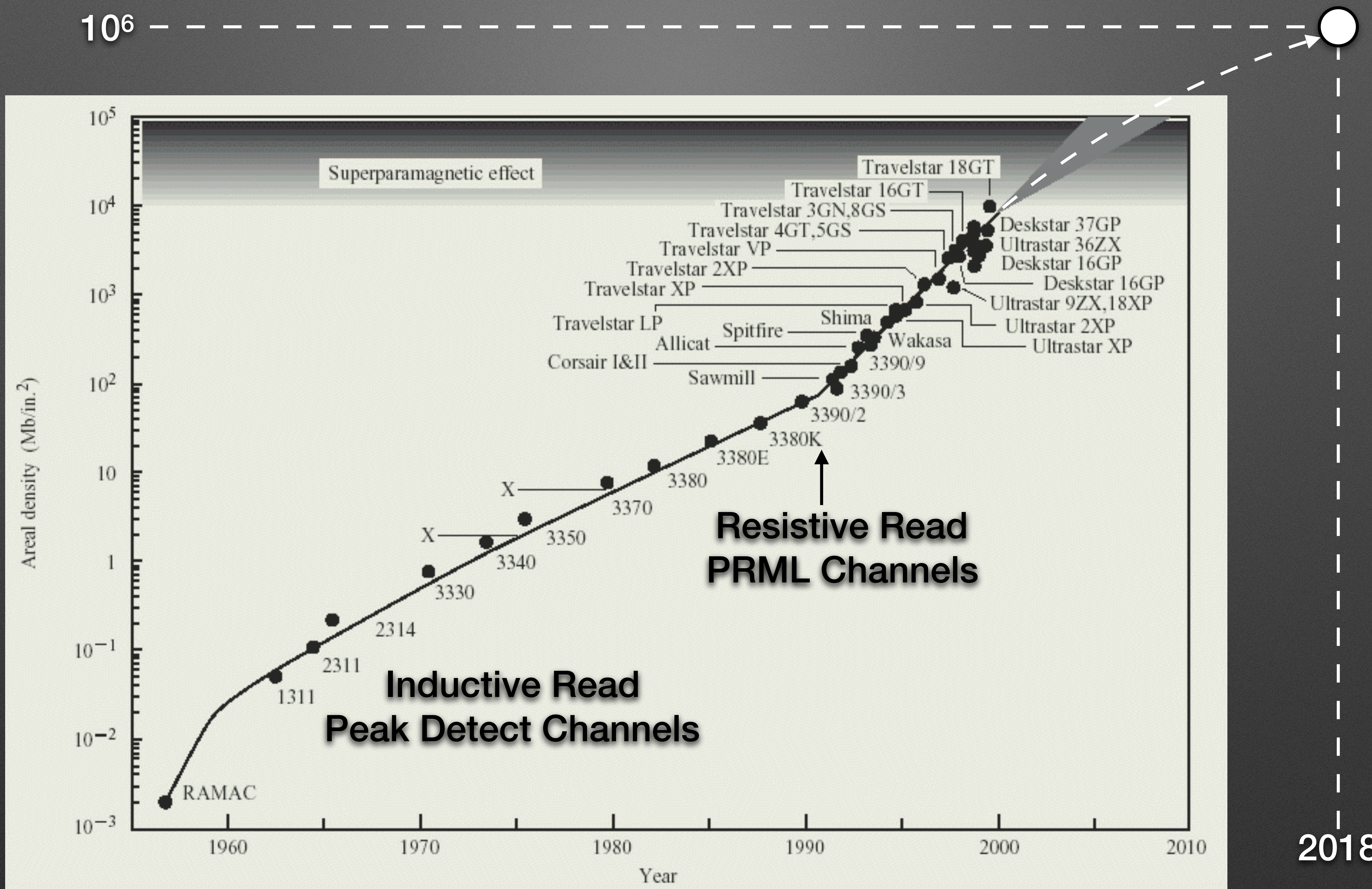
Hall Effect	AMR	GMR	TMR
	(Anisotropic MR)	(Giant MR)	(Tunneling MR)
~0.1 %	~1 %	~10 %	~100 %
1879	1856	1988	1975/1995
			4.2 K 300 K



Senses out-of-plane fields

Senses in-plane fields

Magnetic Recording History



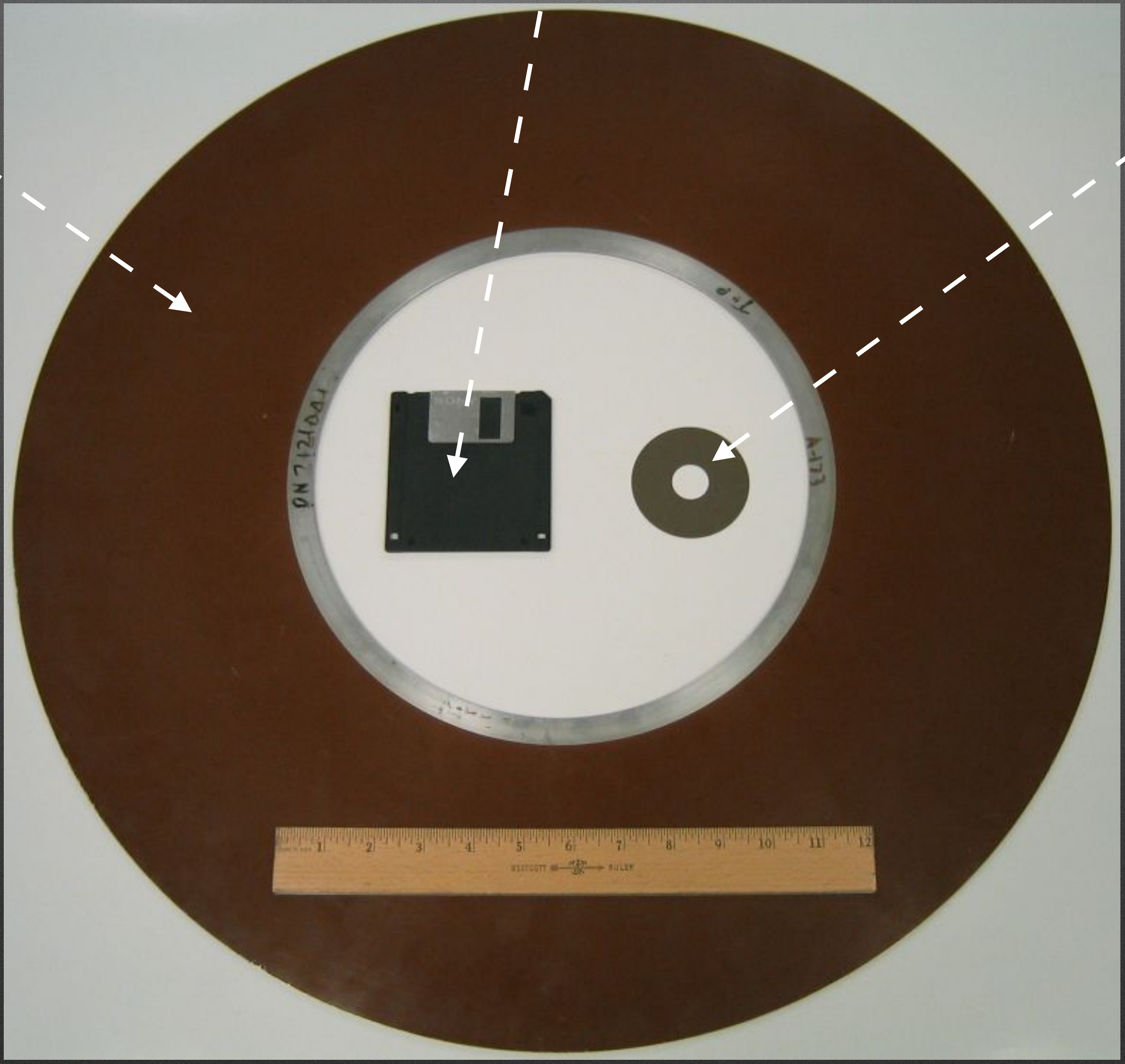
Source: D. A. Thompson & J. S. Best, *IBM J. Res. Dev.* **44**, 3 (2000)

Magnetic Recording Artifacts

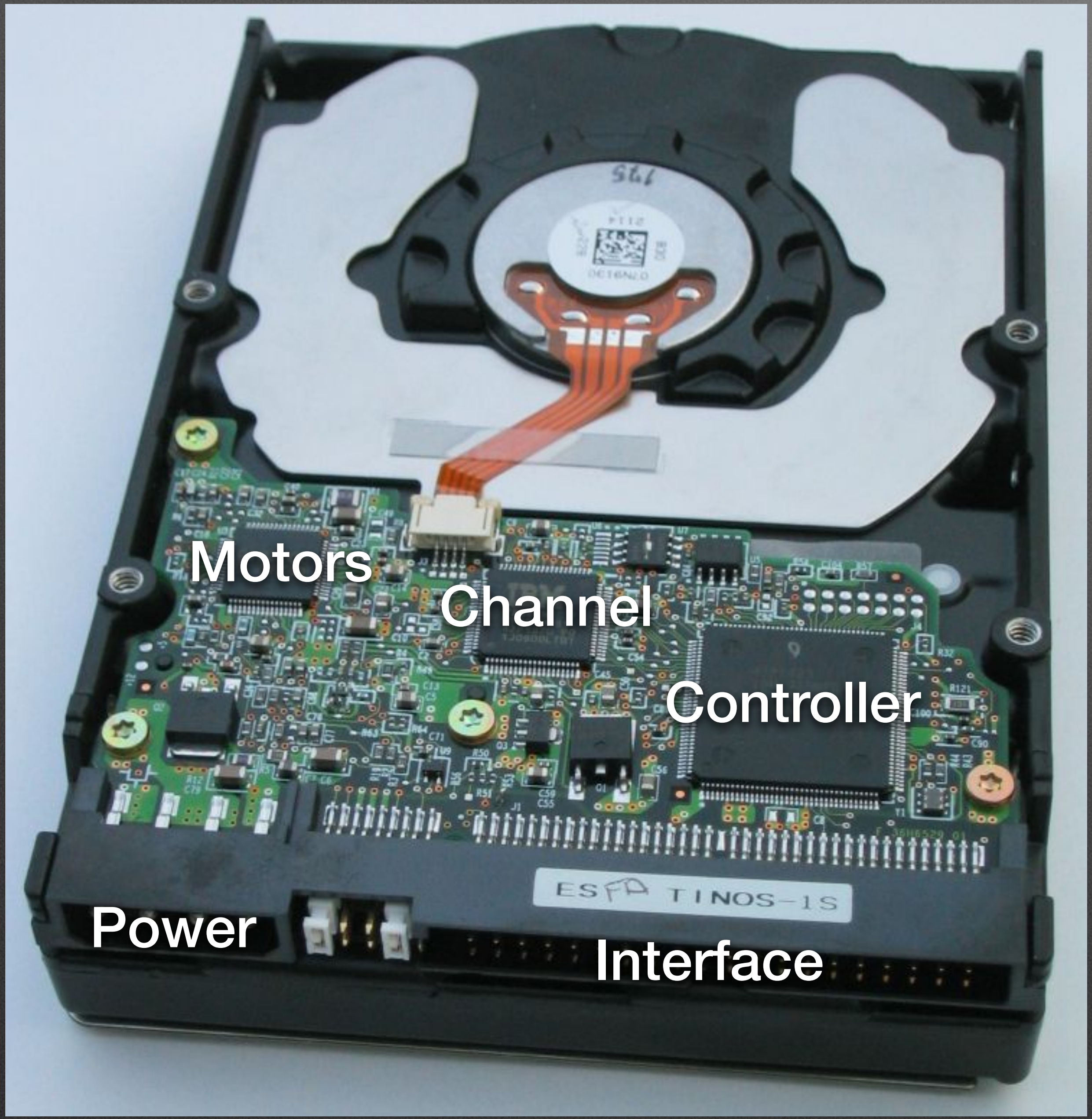
<u>305 RAMAC (1956)</u>
24 in., 1200 RPM
87.5 KB/disk
20 μm fly height

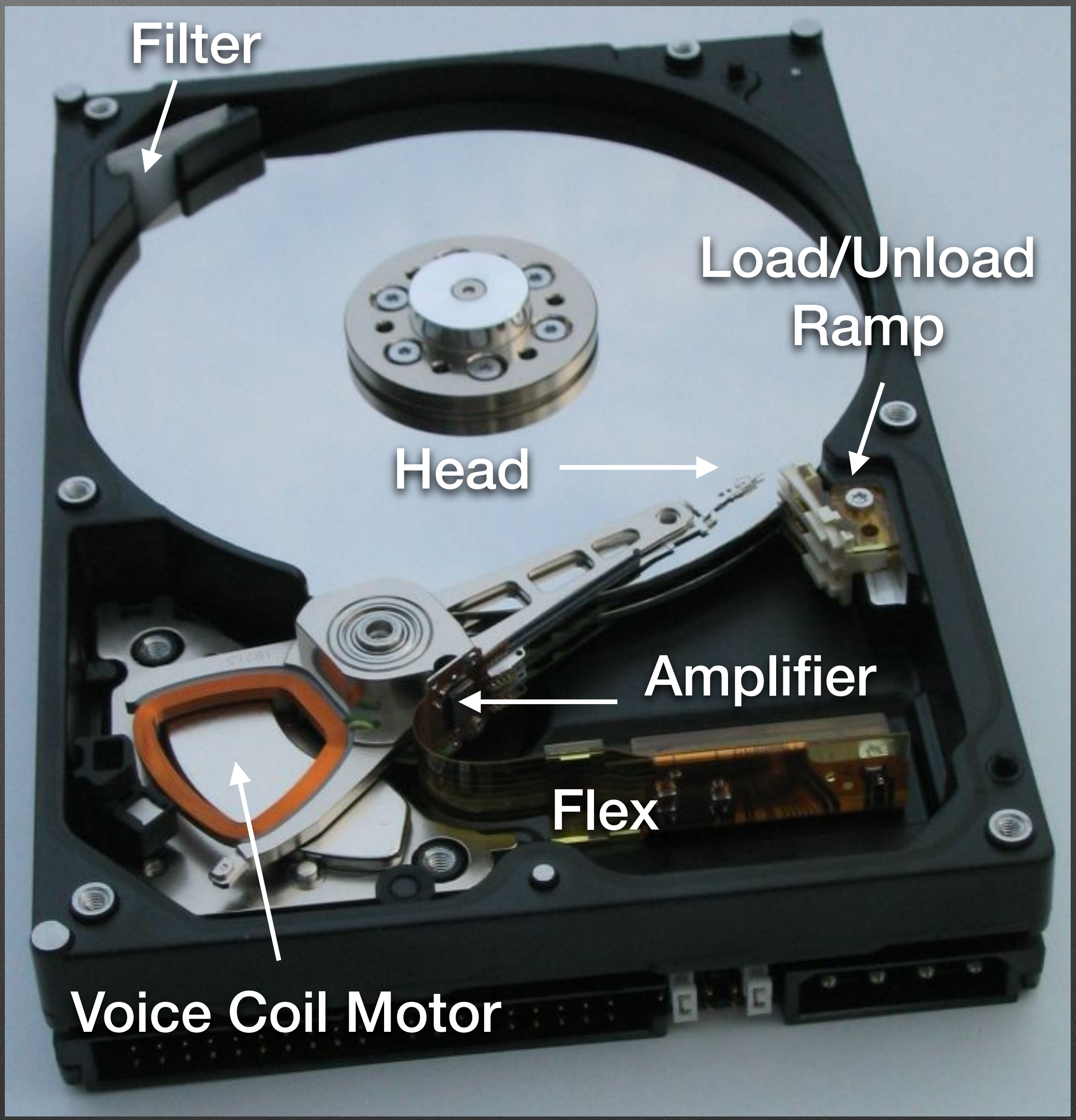
<u>Floppy Disk (1987)</u>
3.5 in., 300 RPM
~1 MB/disk
contact

<u>Travelstar 7K1000 (2018)</u>
2.5 in., 7200 RPM
500 GB/disk
7 nm fly height



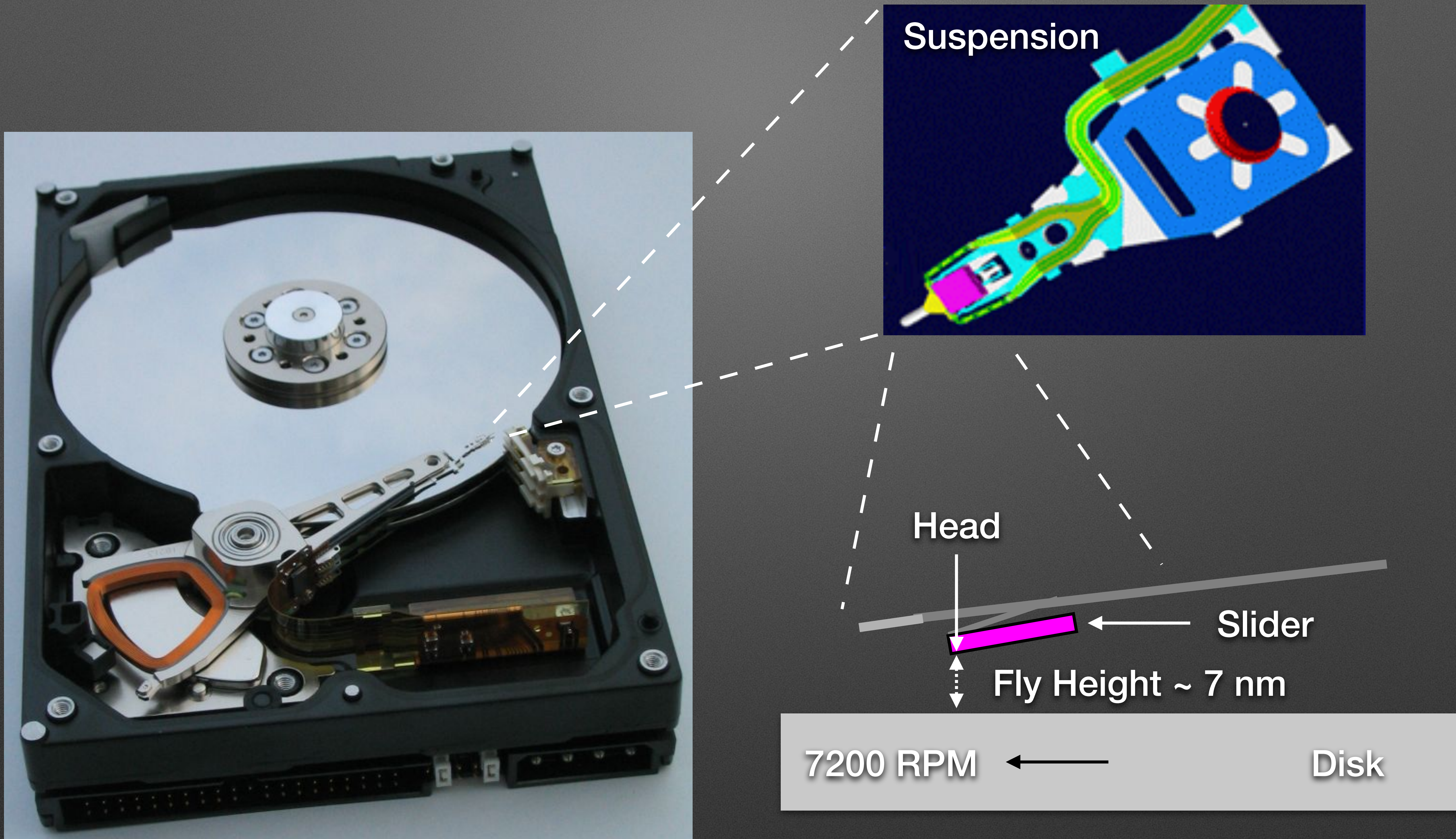
Hard Disk Drive





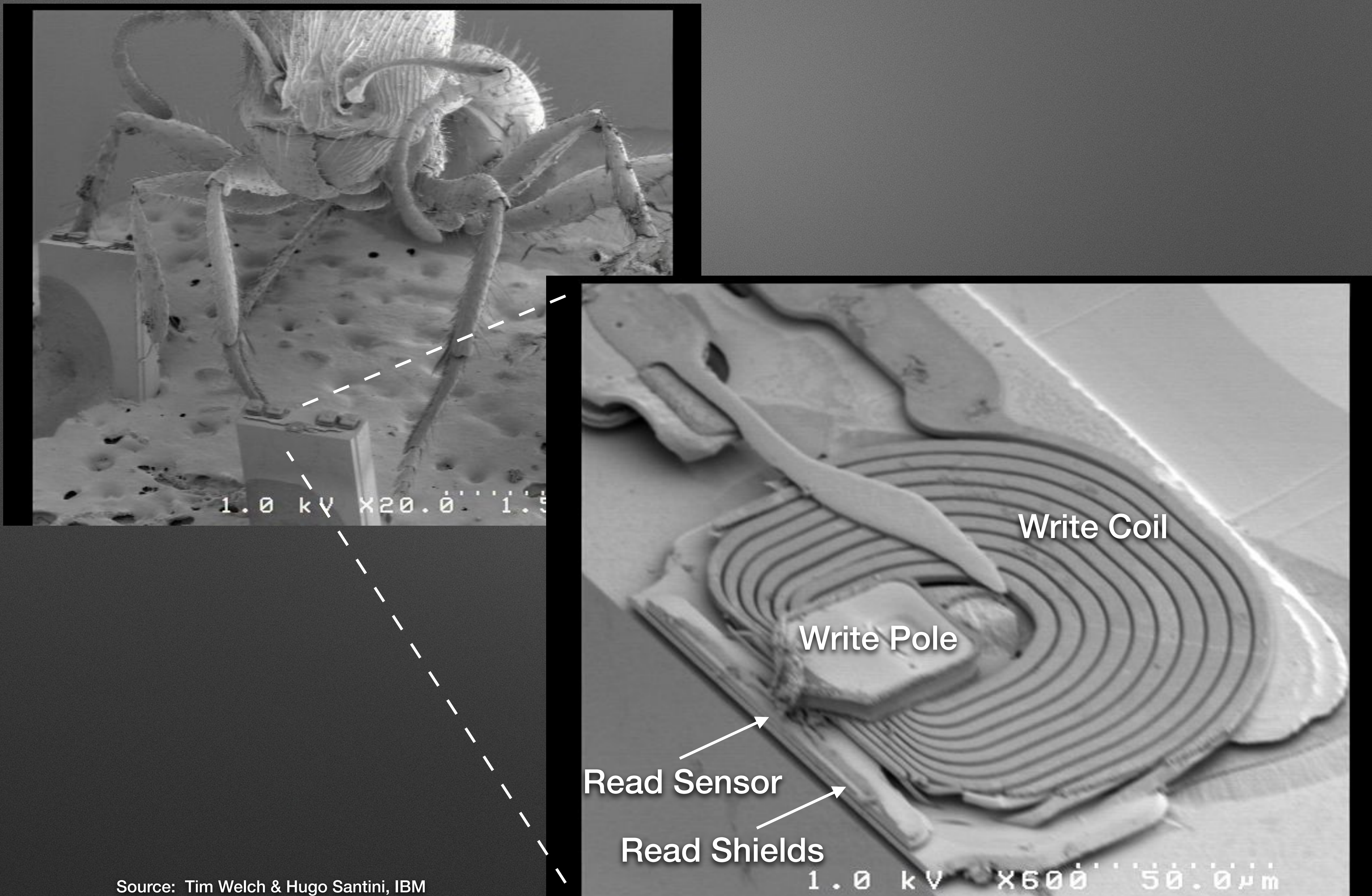
Deskstar 180GXP, 3.5 in., 7200 RPM, 60 GB/disk (2006)

Head-Disk Interface



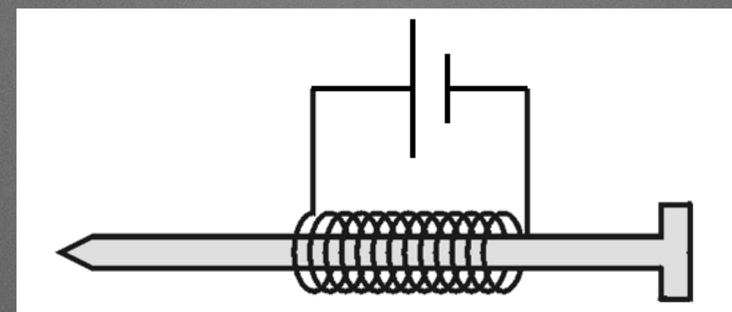
velocity = 7200 RPM * π * 3.5 in. = 75 mph!

Write/Read Head

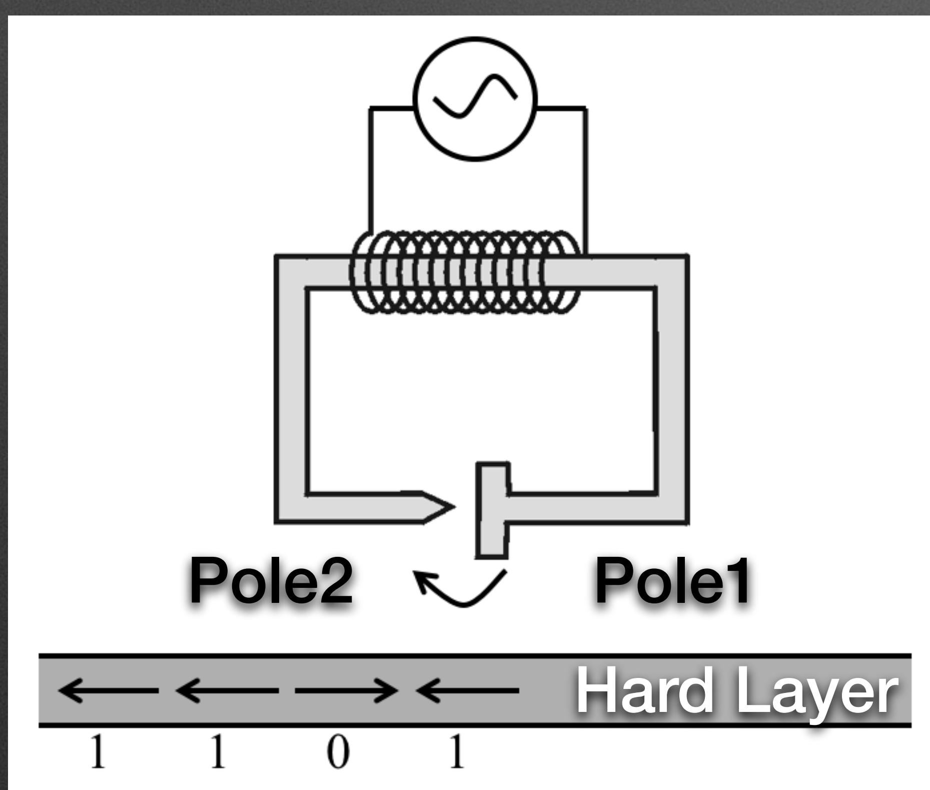


Source: Tim Welch & Hugo Santini, IBM

Writing the Data

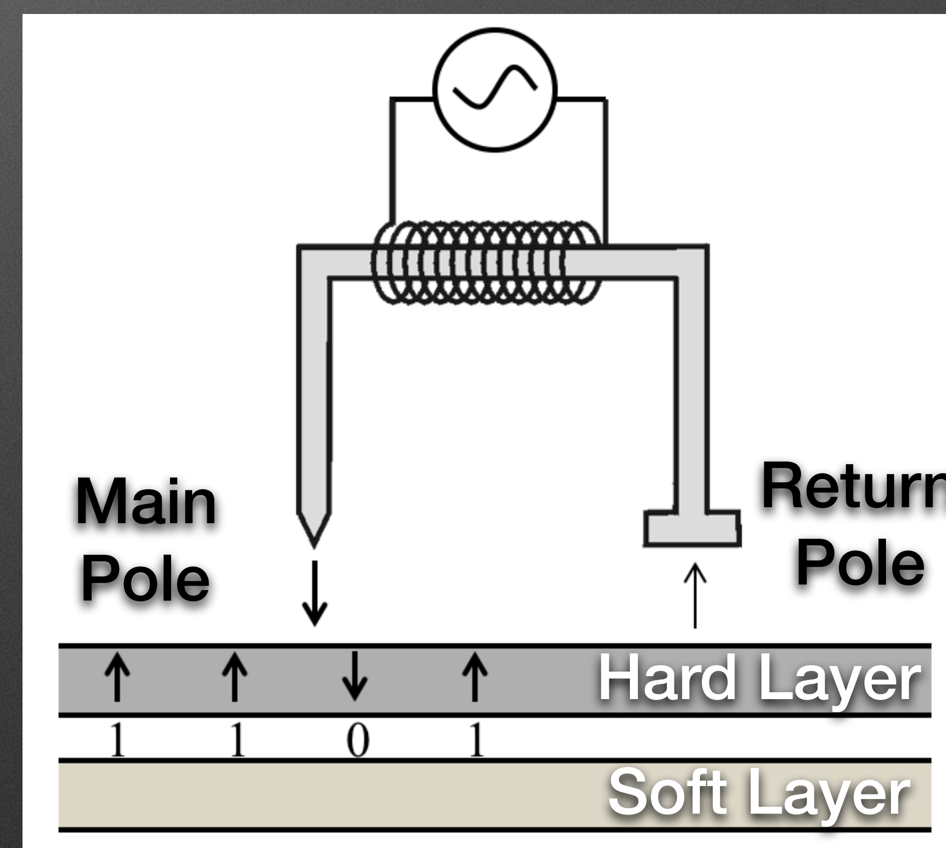


Longitudinal Recording



1956-2006

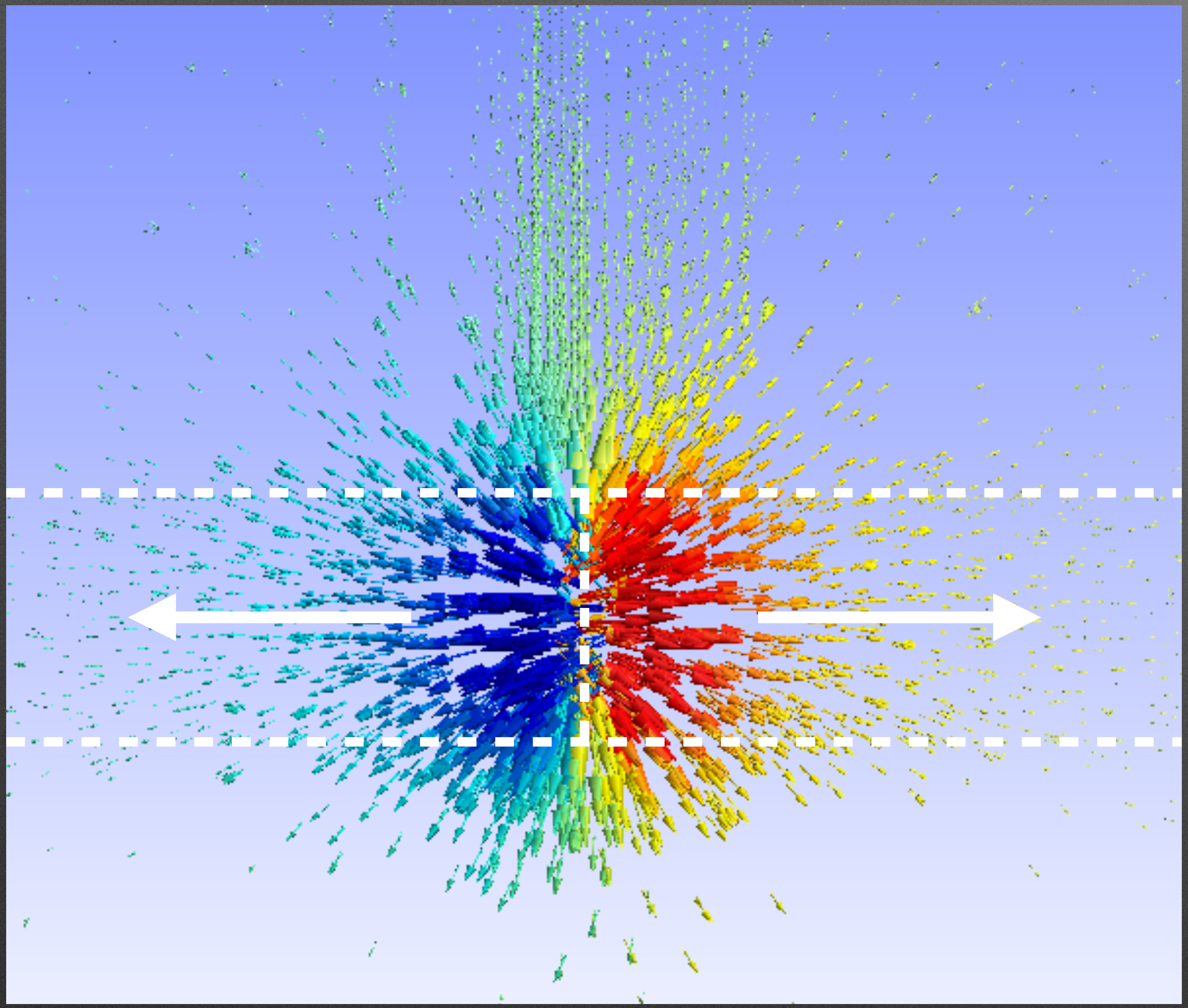
Perpendicular Recording



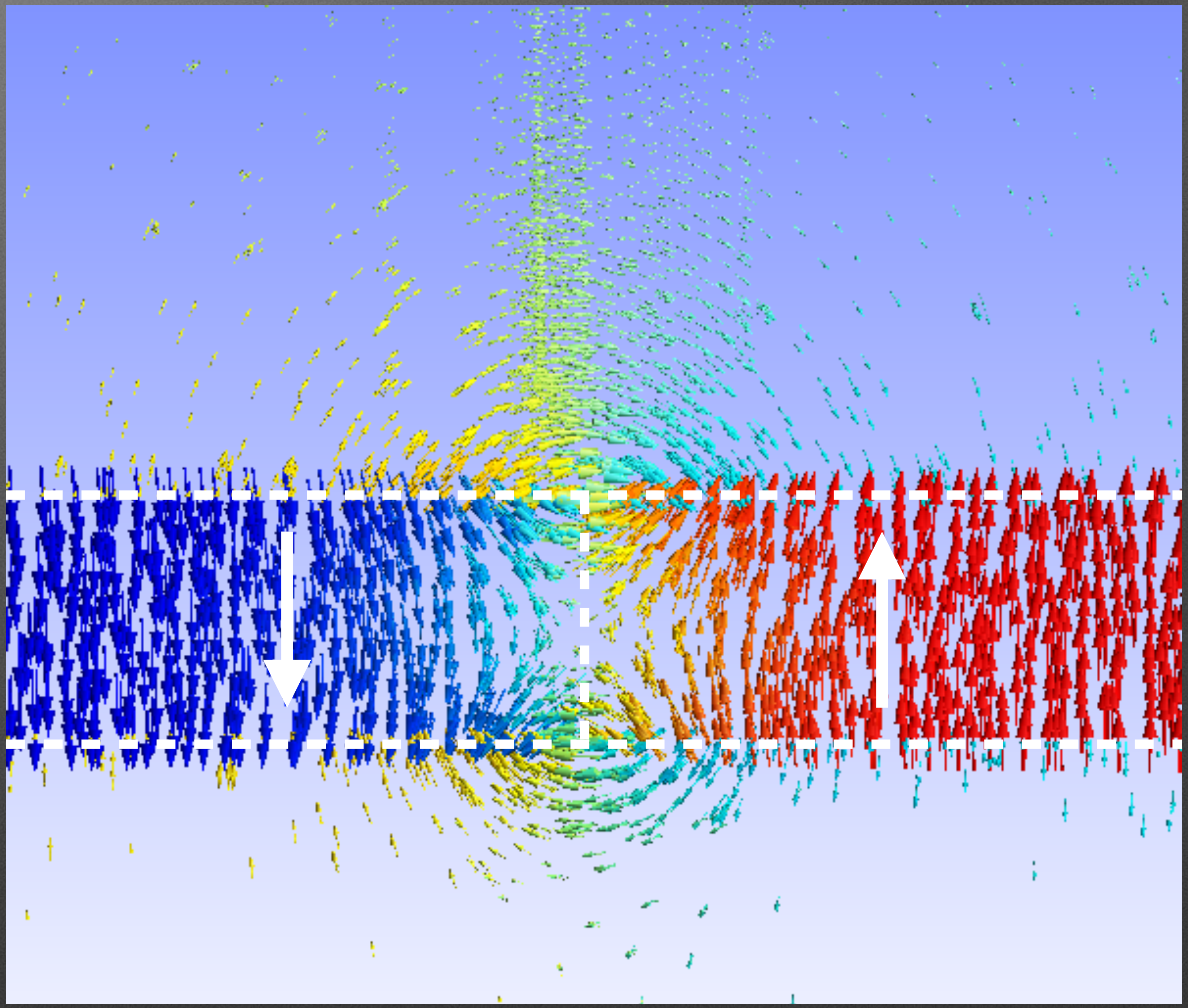
2007-

Writing the Data

Longitudinal Recording



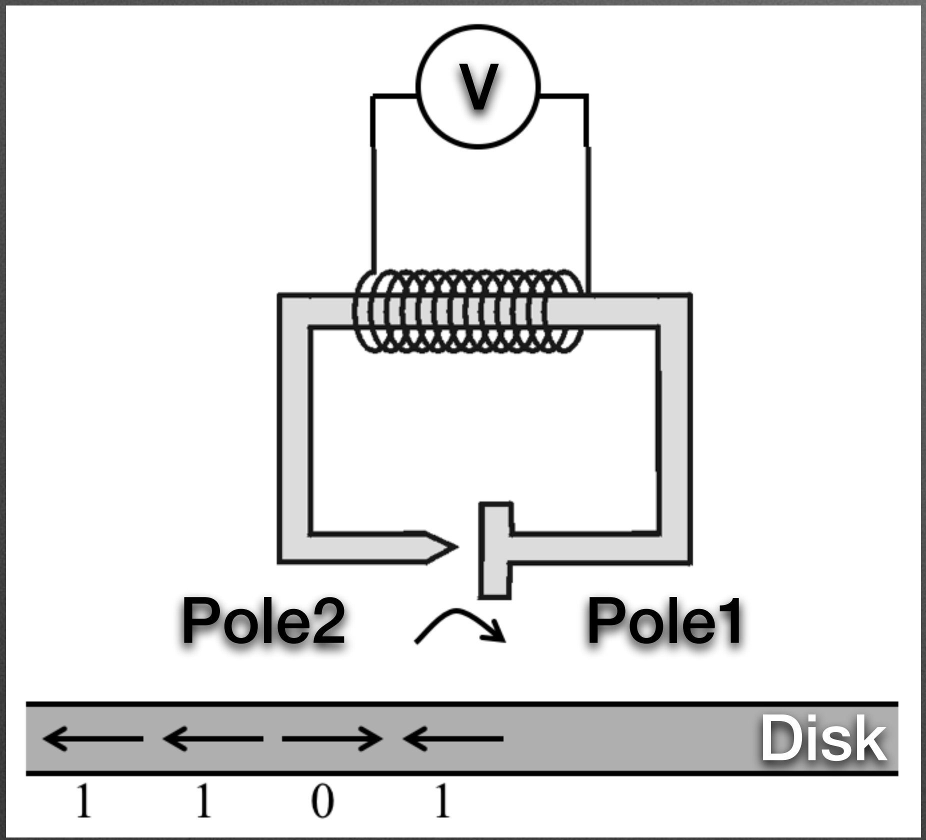
Perpendicular Recording



Reader measures perpendicular component of field in both cases.

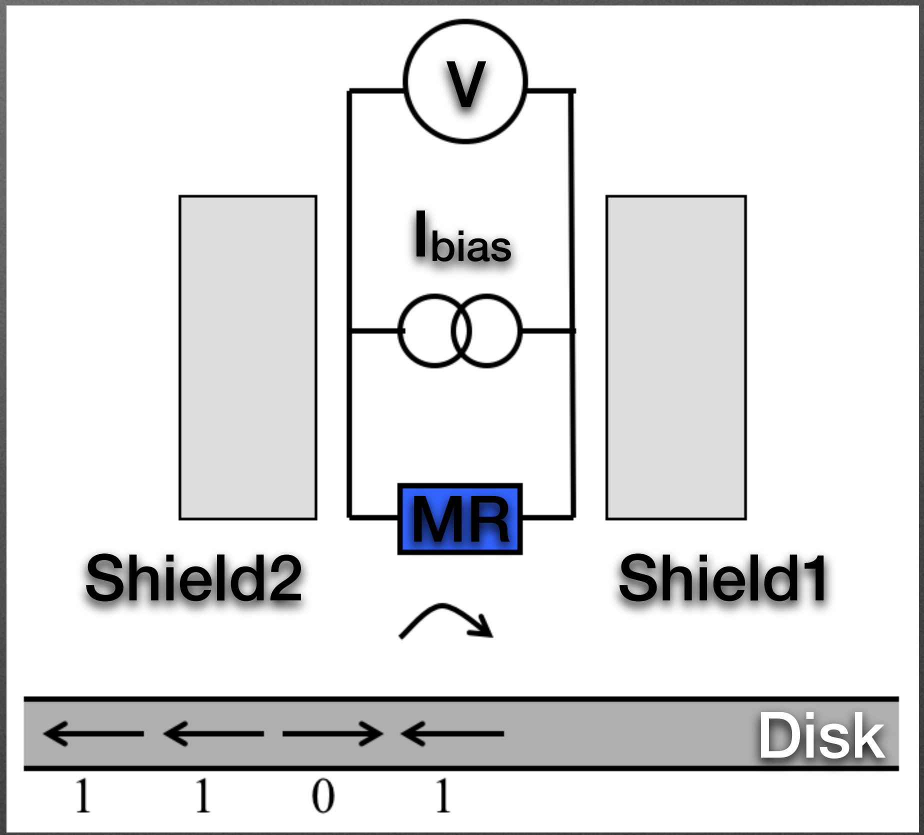
Reading the Data

Inductive Reader



1956-1990

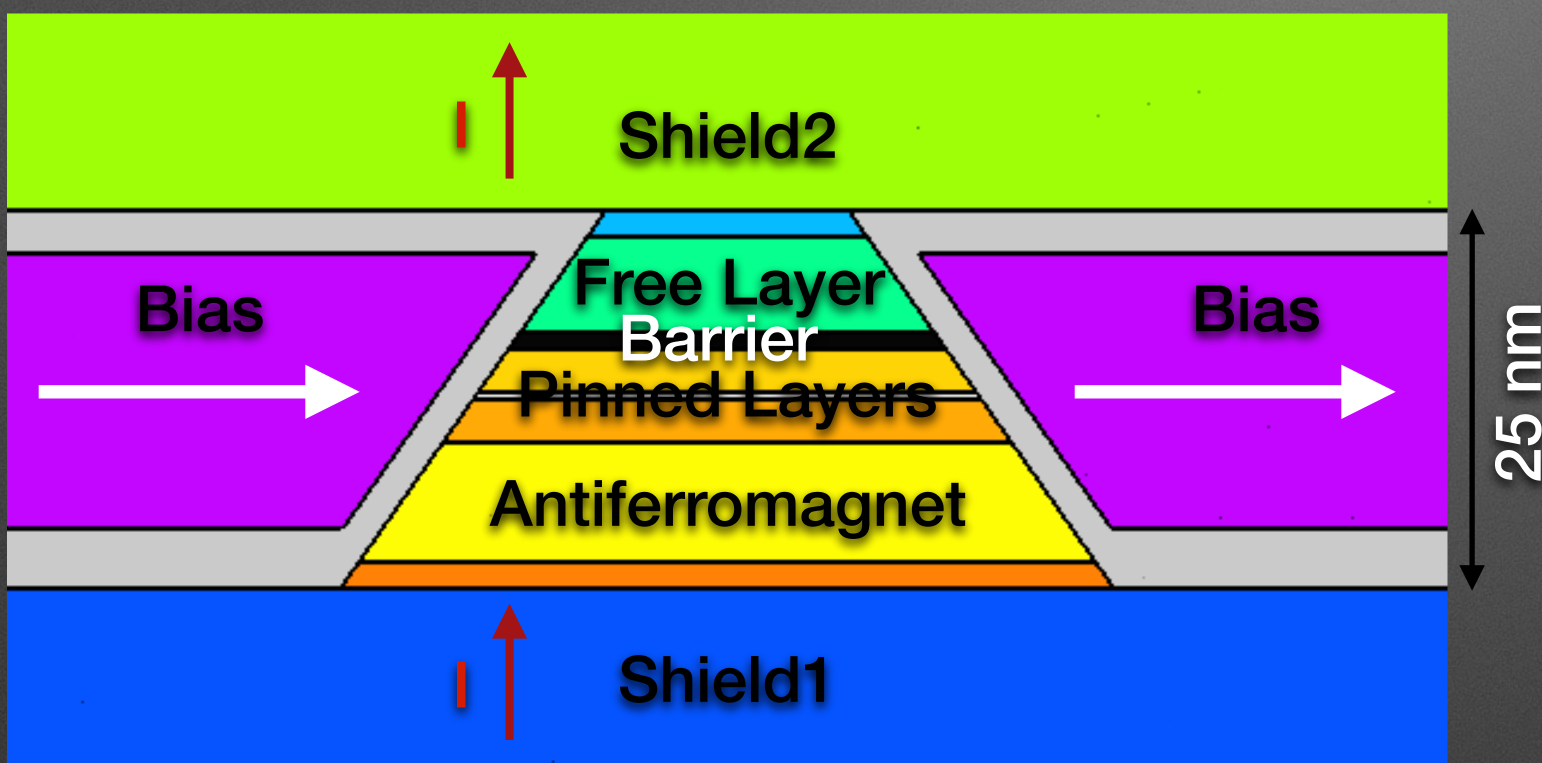
MagnetoResistive (MR) Reader



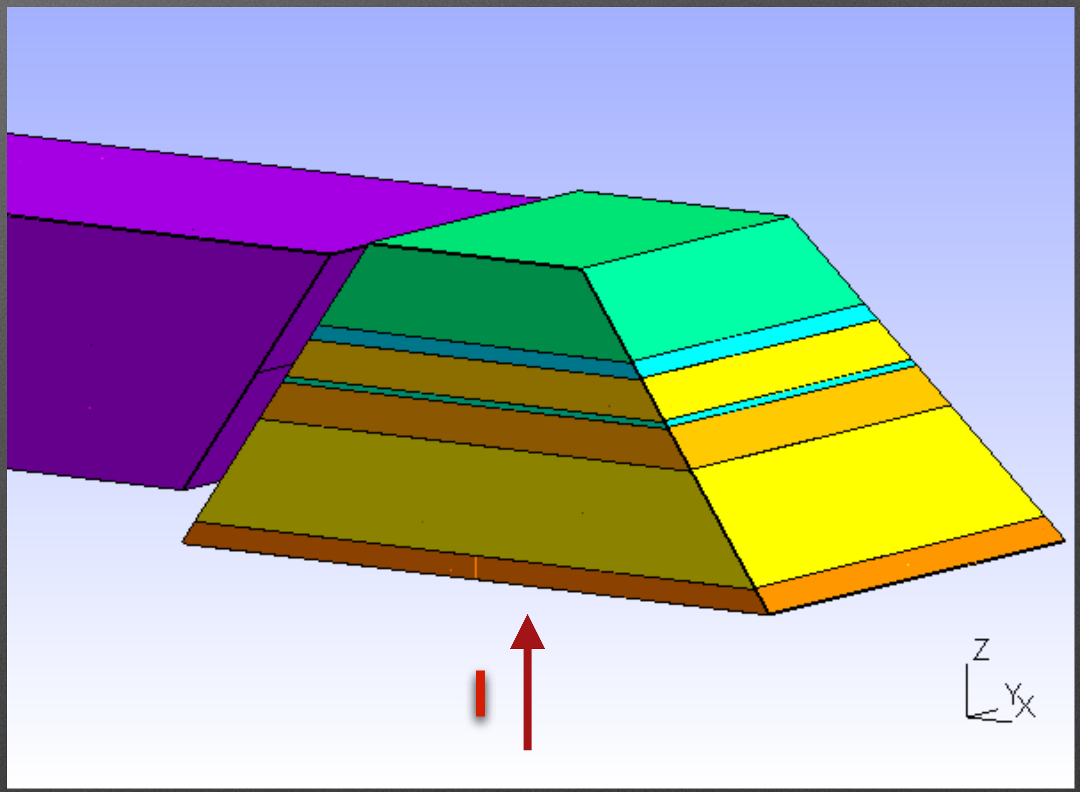
AMR = Anisotropic MR (1991-)
GMR = Giant MR (1997-)
TMR = Tunneling MR (2007-)

Reading the Data

Tunneling MagnetoResistance (TMR)



Shields also serve as current leads.



Shields & right bias not shown.

Barrier is typically single crystal MgO (~1 nm) for coherent tunneling and maximum MR effect.

Information Theory

radio telephone	transmitter point A	→	receiver point B
		channel	
hard disk drive memory	writer time 1	→	reader time 2

What is the maximum information rate or storage density?

$$C = B \log_2(1 + SNR)$$

The Channel Coding Theorem (C. E. Shannon, Bell Labs, 1948)

C = channel capacity (bit/s), B = bandwidth (Hz), SNR = Signal/Noise

The Viterbi Algorithm is used for decoding
in Voyager probes, cell phones, and hard disk drives.
(A. J. Viterbi, UCLA, 1967)

Intermission

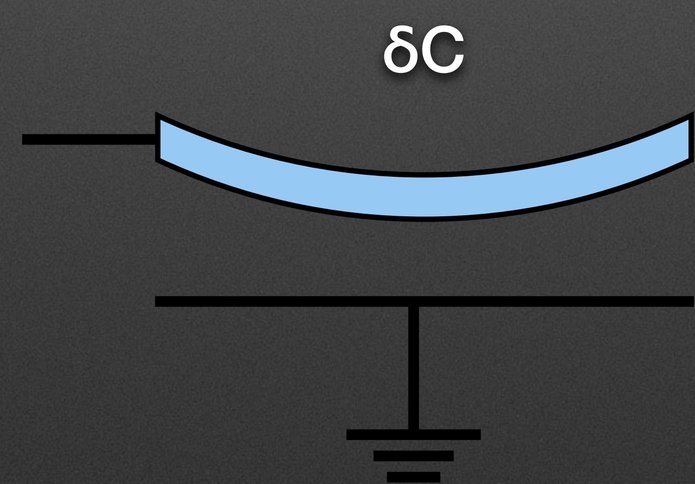
MEMS

Micro-Electro-Mechanical System

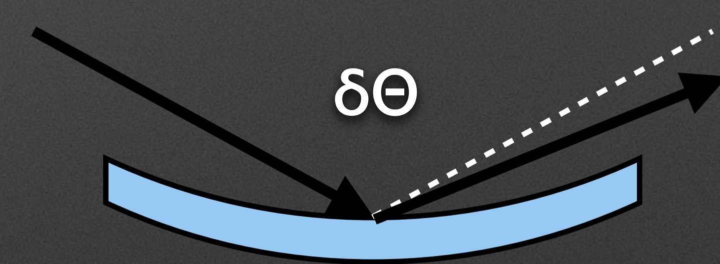
	Young's Modulus (GPa)
Steel	200
Amorphous Silicon	130
Single Crystal Silicon	170
Diamond	1000

(Piezo)Resistive

Capacitive

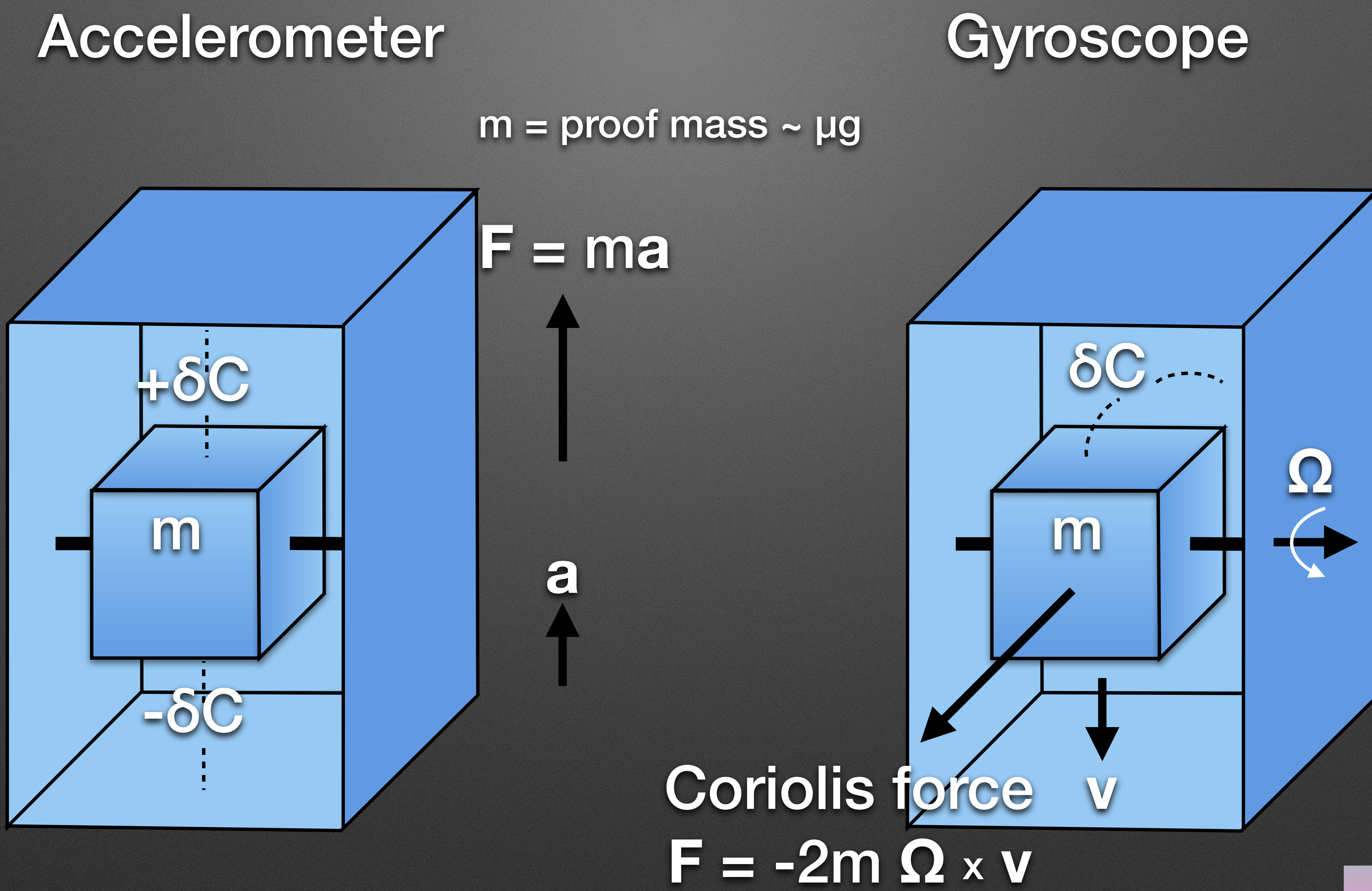


Optical



MEMS are packaged usually with ASIC
for analog drive/sense and digital interface to larger system.

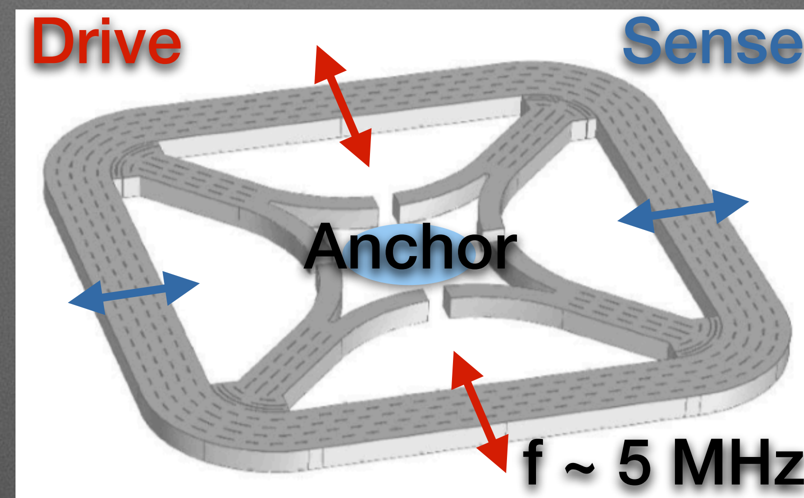
MEMS Motion Sensors

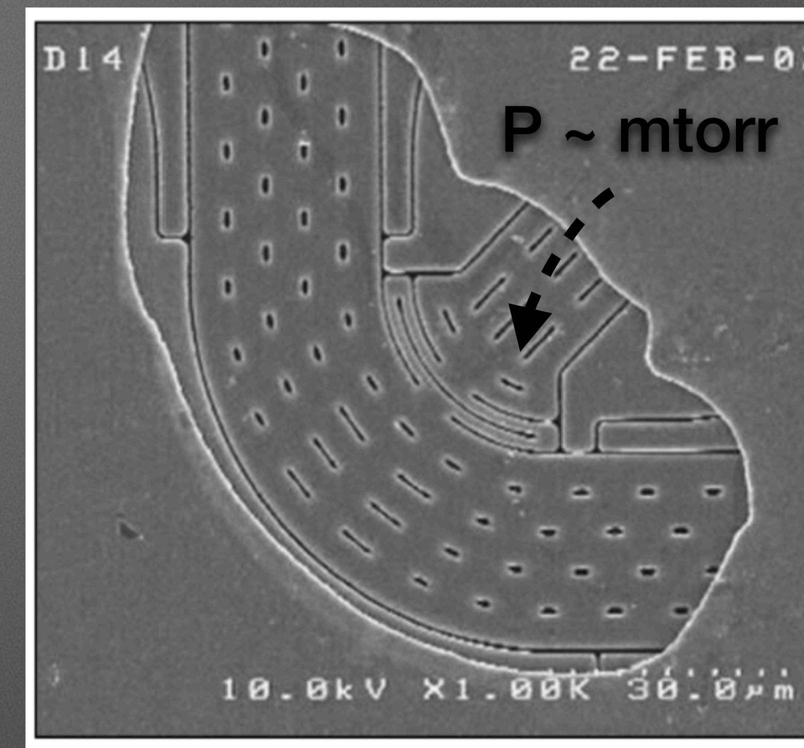


Most accel and gyro applications need all 3 axes.

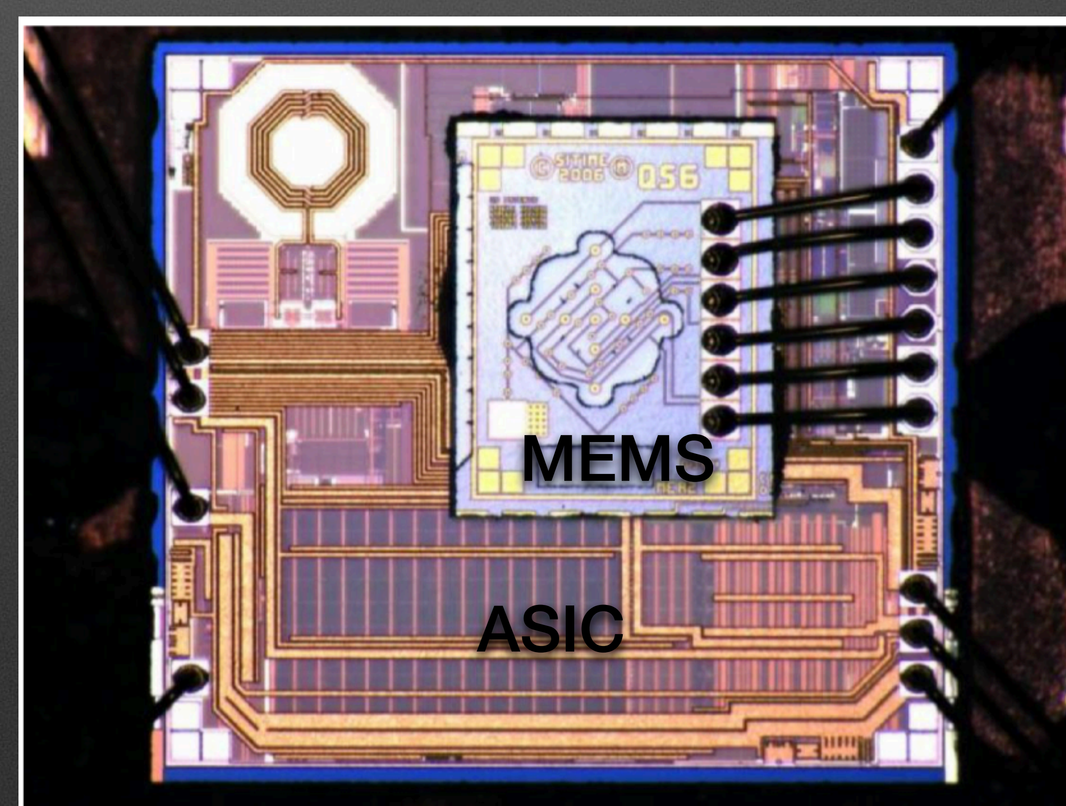
MEMS Resonators

SiTime





Accuracy:	Δf/f
Harrison H-1	10^{-5}
XO (Quartz) Crystal Oscillator	10^{-5}
TCXO Temp. Compensated XO	10^{-6}
OCXO Oven Controlled XO	10^{-8}
Rb clock	10^{-9}
Cs clock	10^{-12}

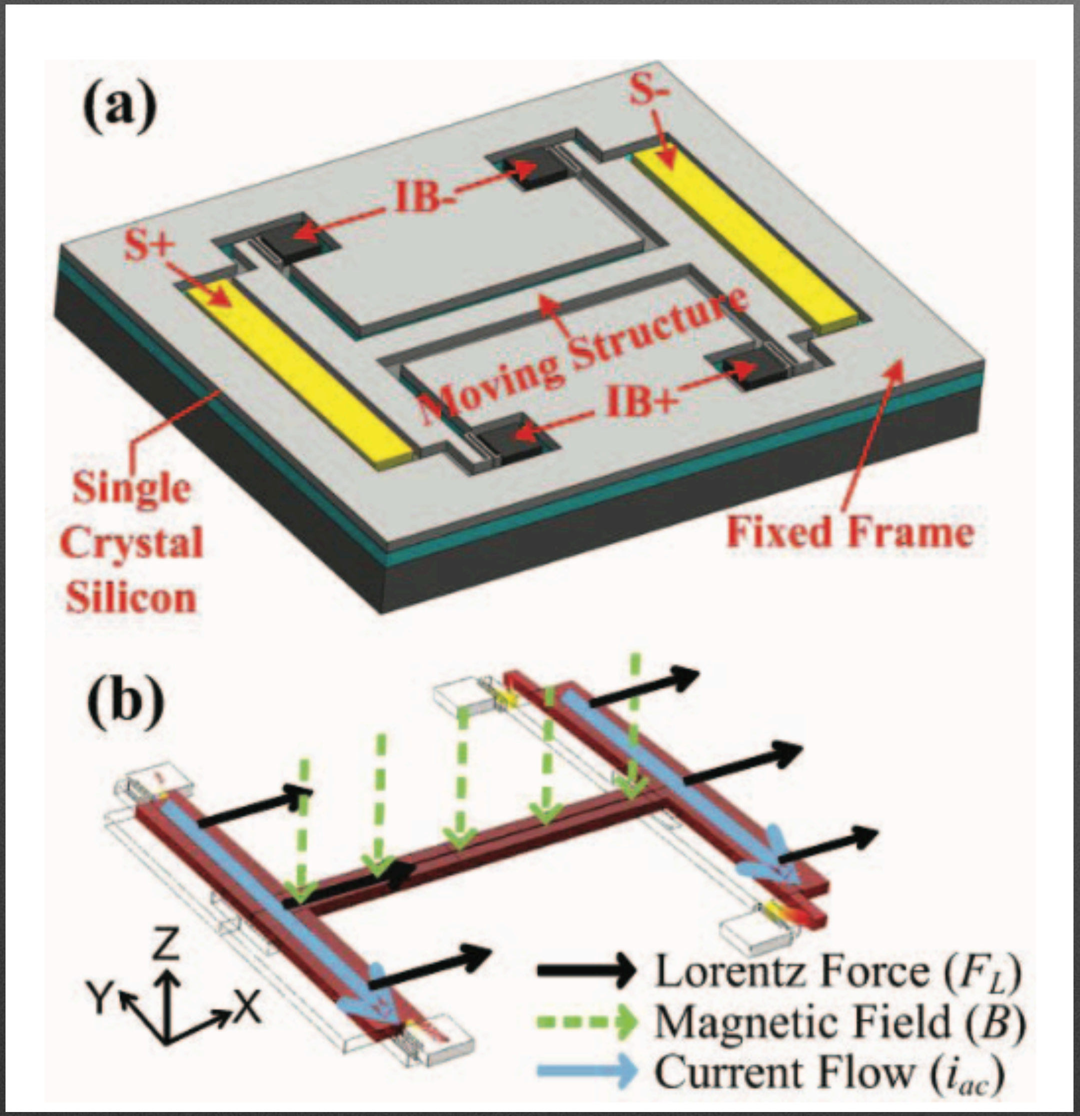


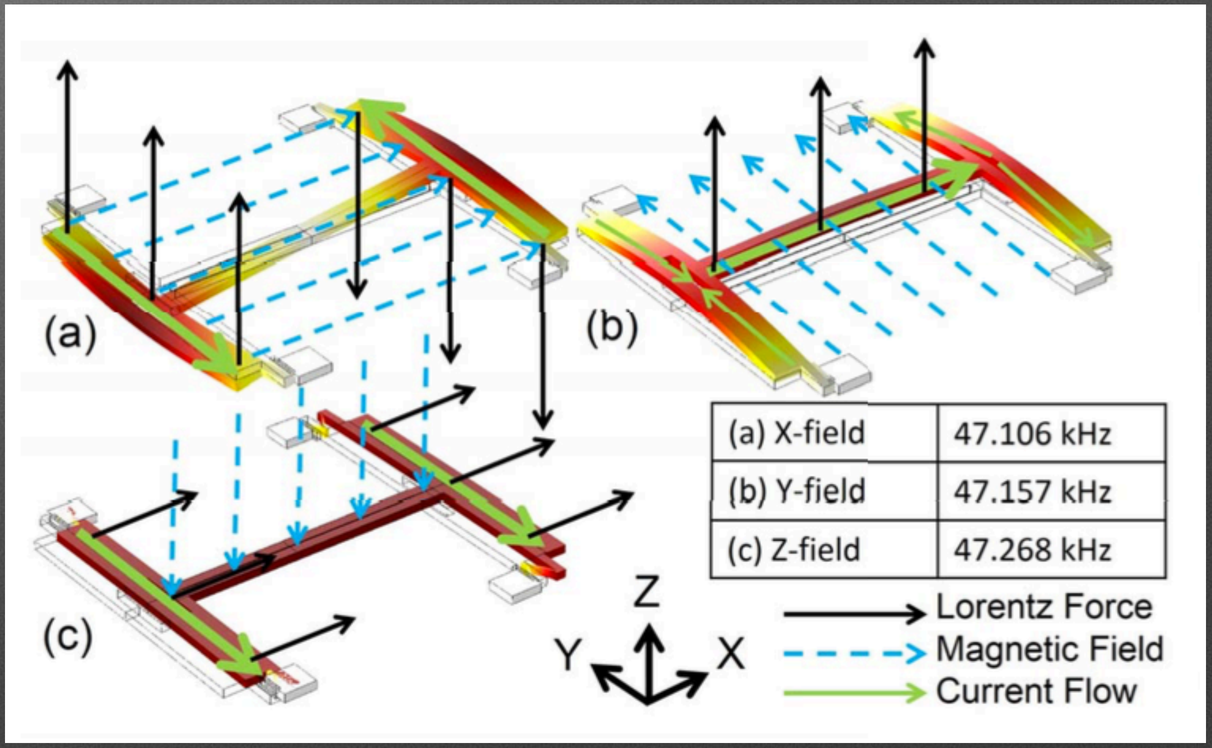
Source: A. Partridge, ISSCC 2012

MEMS Magnetometers

Lorentz force

F = ILB





All 3 axes can be measured
by changing the current direction.

Source: M. Li *et al.*, MEMS 2014

Analog *vs.* Digital Compass

Analog compass only works horizontally.

Digital compass works at any orientation.
Sensor fusion enables smarter detection.

Navigation

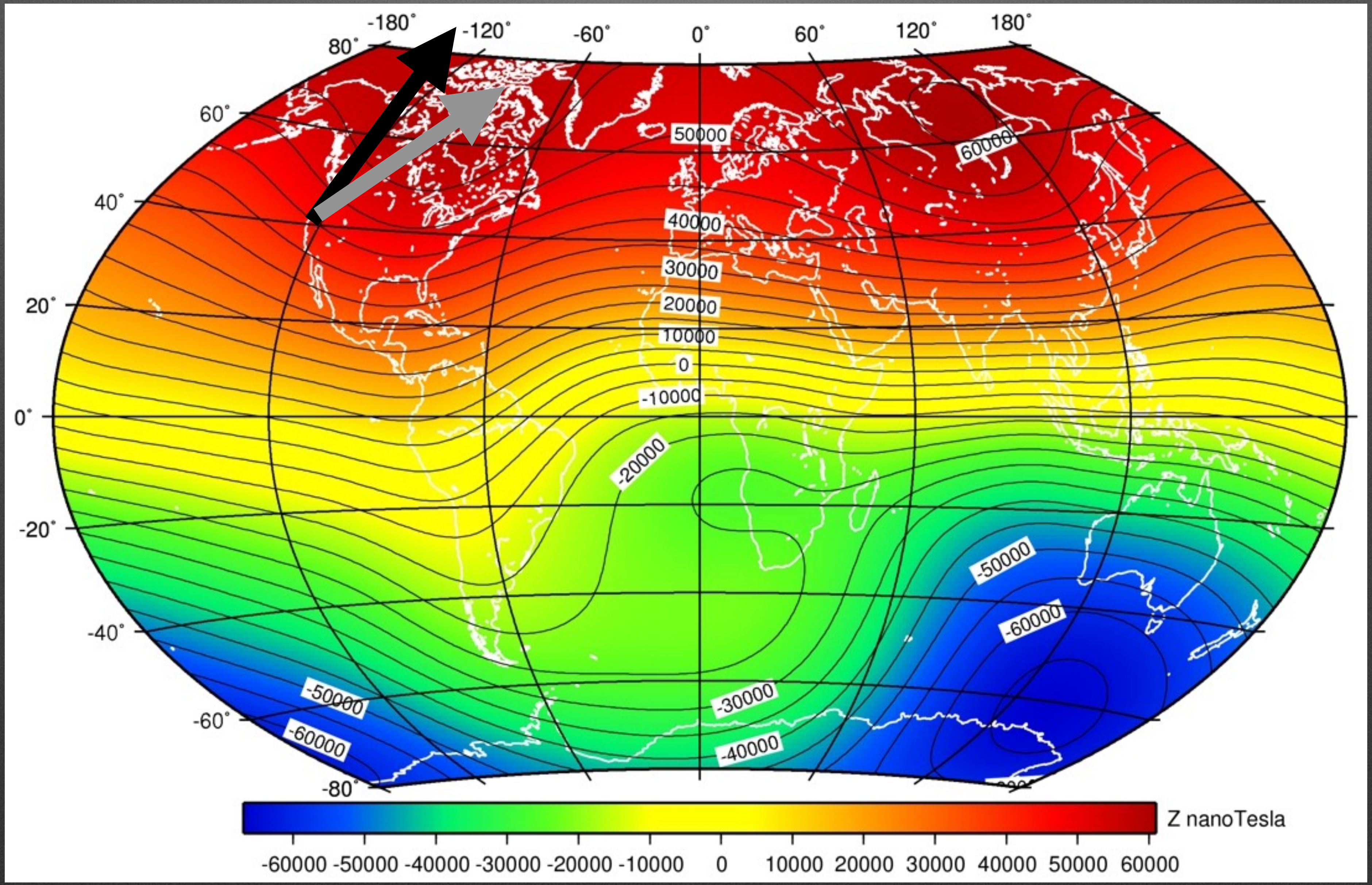
Maps

AR/VR

Indoor Positioning

Earth's Magnetic Field

On the West Coast, declination is ~10°
between *geographic* and *magnetic* north.



Source: British Geological Survey

Magnetic field, device orientation, and global position
are necessary to find geographic north.

Planetary Fields

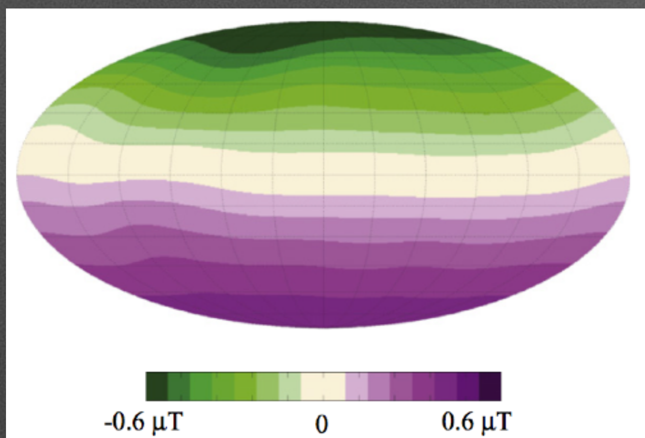
Mercury
0.3 μT

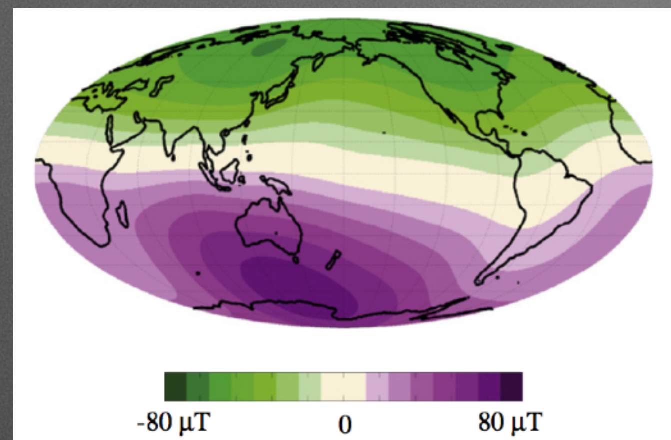
Earth
38 μT

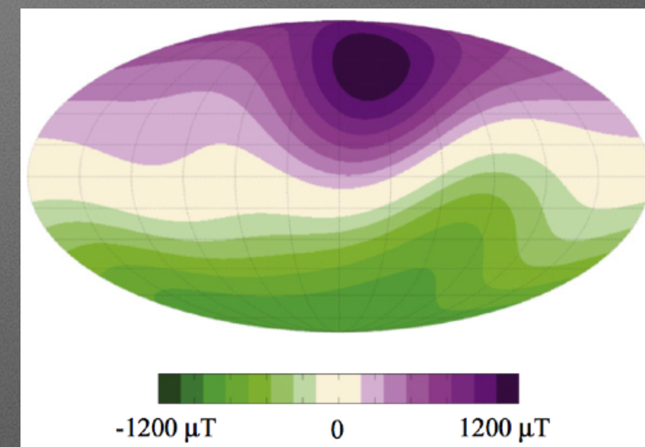
$\langle B_z \rangle$

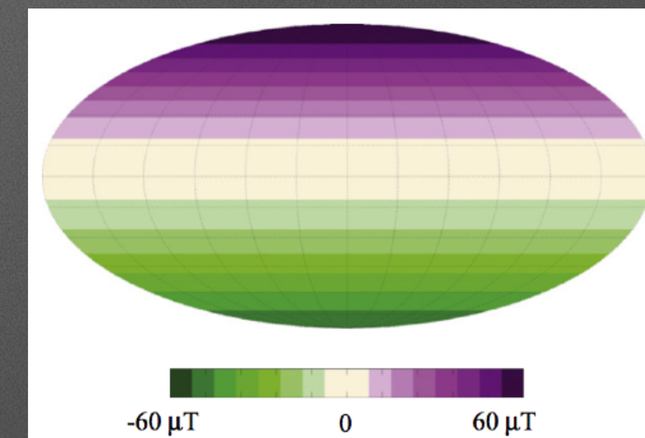
Jupiter
550 μT

Saturn
28 μT







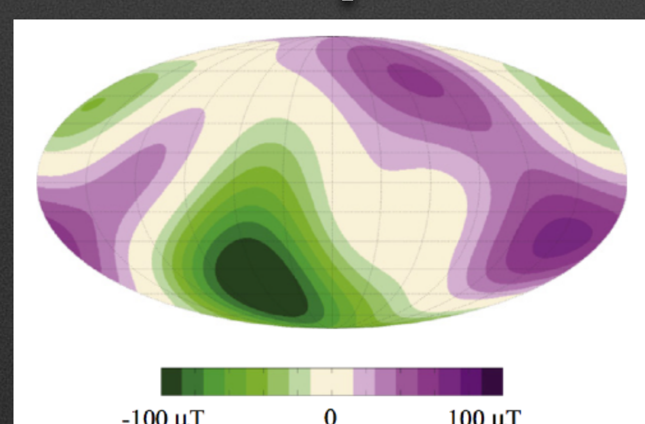


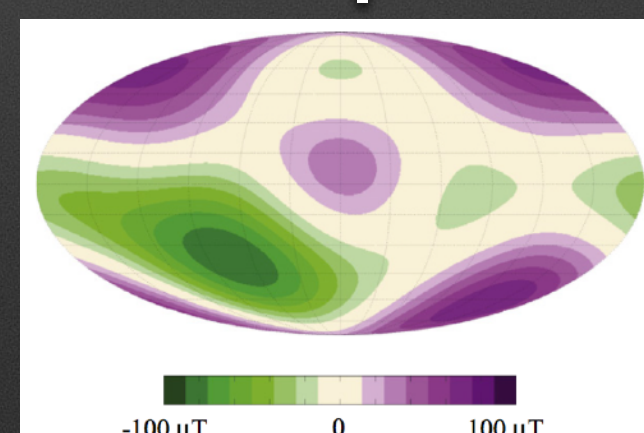
Venus and Mars have no magnetic field.

The “ice giants” have multipolar fields rather than a dipole field.

Uranus
32 μT

Neptune
27 μT

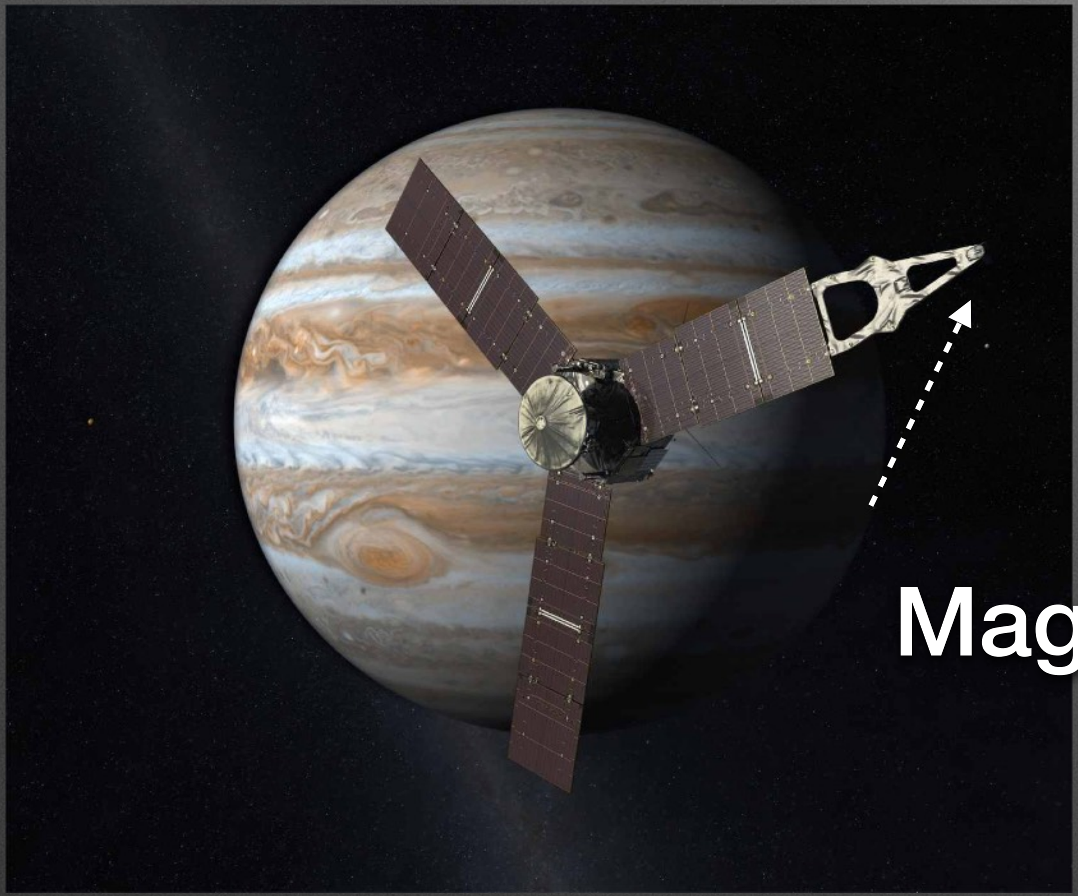




Source: G. Schubert & K. M. Soderlund, *Phys. Earth Planet Int.* **187**, 92 (2011)

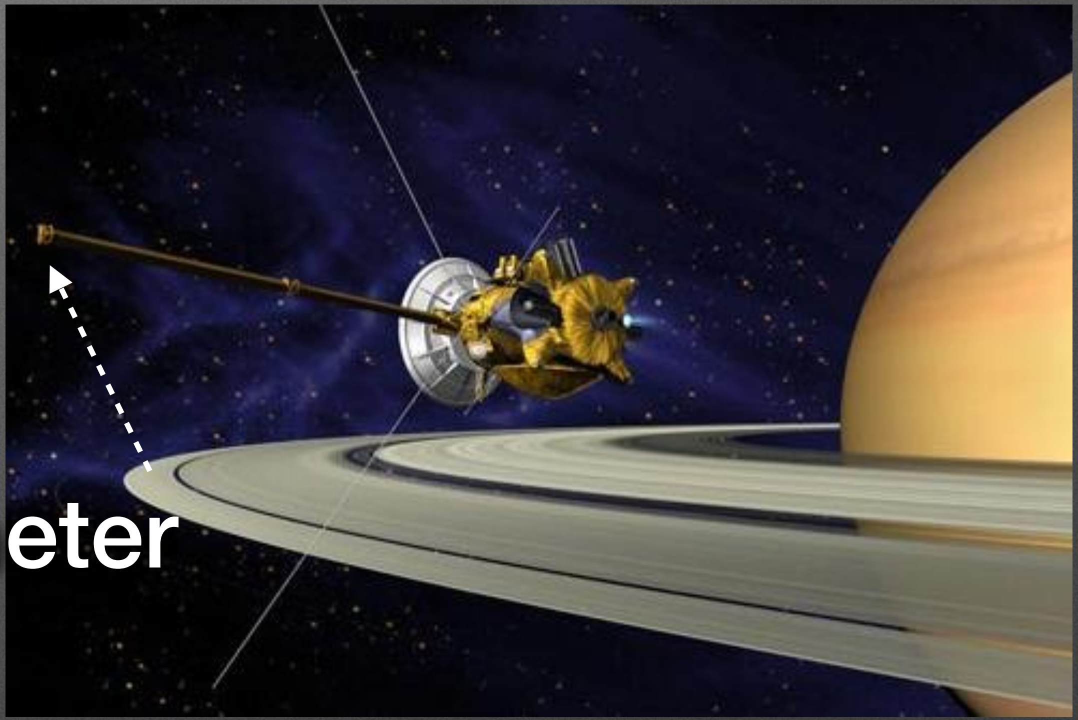
Planetary Probes

Juno



Source: NASA / JPL

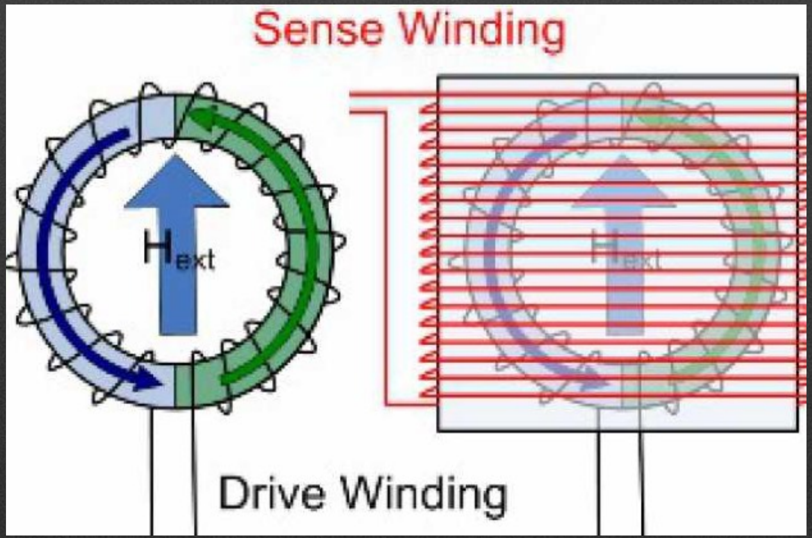
Cassini



Source: NASA / JPL

Magnetometer Boom

Fluxgate



Source: M. Dougherty, Imperial College London

"Inductive Reader"

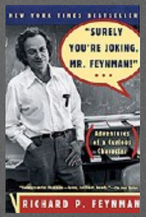
Academia *vs.* Industry

Research	Development & Mass Production
Generalization Design, Fabricate, Measure, Analyze	Specialization Focus on only one task
Success = 1 or 2 good devices	Success = 10^6 - 10^9 good devices
Ignore failures	Focus on failures
Too little data	Too much data

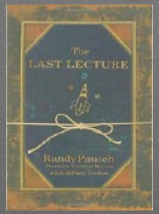
Communication makes your reputation.

References

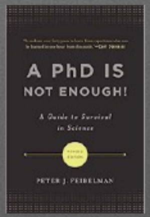
R. P. Feynman, *Surely You're Joking, Mr. Feynman!*



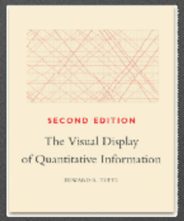
R. Pausch, *The Last Lecture*



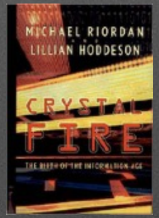
P. Feibelman, *A PhD Is Not Enough!*



E. Tufte, *The Visual Display of Quantitative Information*



M. Riordan & L. Hoddeson, *Crystal Fire*



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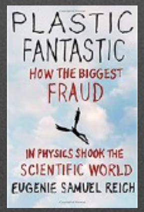

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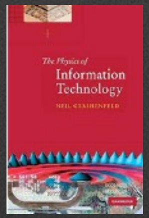
N. Gershenfeld, *The Physics of Information Technology*



D. Kahneman, *Thinking, Fast and Slow*