L2: Introduction to Memory I

Recap: Assessments

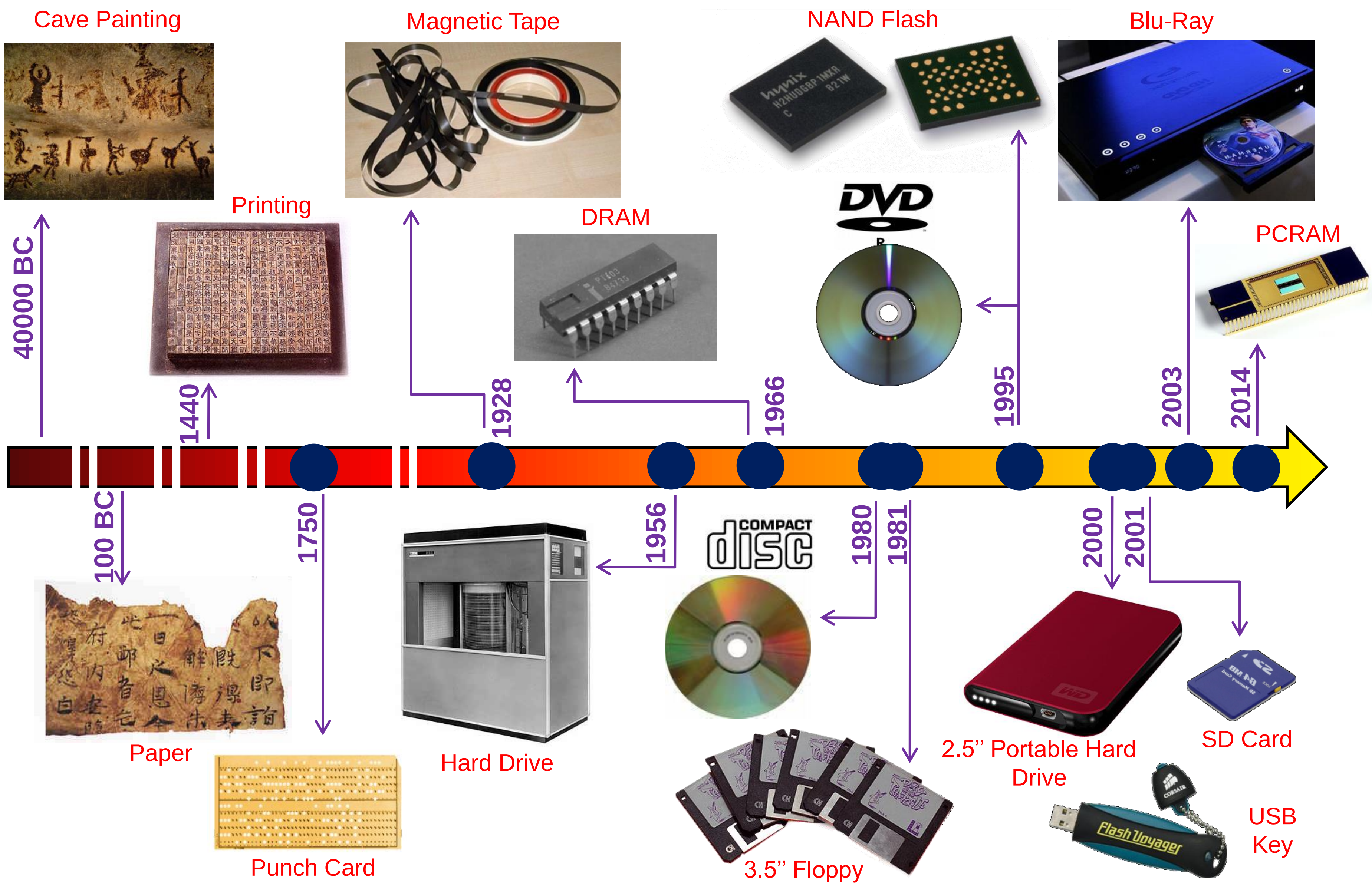
- **Literature review** on a relevant emerging memory technology topic (from a minimal of 3 papers)
- Oral presentations (15 mins)
- 4-page report due on **Feb 26th**

- Team project: ~5 people per team
- Proposing a 3-year memory research effort
  - Discuss your topic with the instructor
  - Finalize your team and topic by **Mar 4th**
- Oral presentations on **Apr 15th**
  - 30 minutes per team
  - everyone needs to present
- 15-page NSF style report due on **Apr 15th**

Recap: Course Schedule

Course Schedule for Spring 2020 ECE 2263 Emerging Memory			
Week	**Date**	**Topic**	**Notes**
1	W 1/8	Syllabus and Requirement	
2	W 1/15	Introduction to Memory I	
3	W 1/22	**Instructor traveling NO class**	
4	W 1/29	Introduction to Memory II	
5	W 2/5	PCM: Scaling and Opportunities	Term topic due
6	W 2/12	RRAM I: Scaling and Opportunities	
7	W 2/19	Term Paper Presentations	
8	W 2/26	Term Paper Presentations	Term paper due
9	W 3/4	**Instructor traveling NO class**	Team topic due
10	W 3/11	**Spring break NO class**	
11	W 3/18	RRAM II: Scaling and Opportunities	
12	W 3/25	Intro to Neuromorphic Computing	
13	W 4/1	Synaptic Device: PCM	
14	W 4/8	Synaptic Device: RRAM	
15	W 4/15	Final Project Presentation	Final report due

History of Memory and Storage

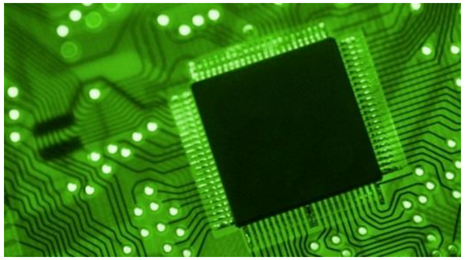


Memory in Our Lives

64 GB

Memory Industry
~ 1000 Giga GB
~ $100 Billions

512 GB

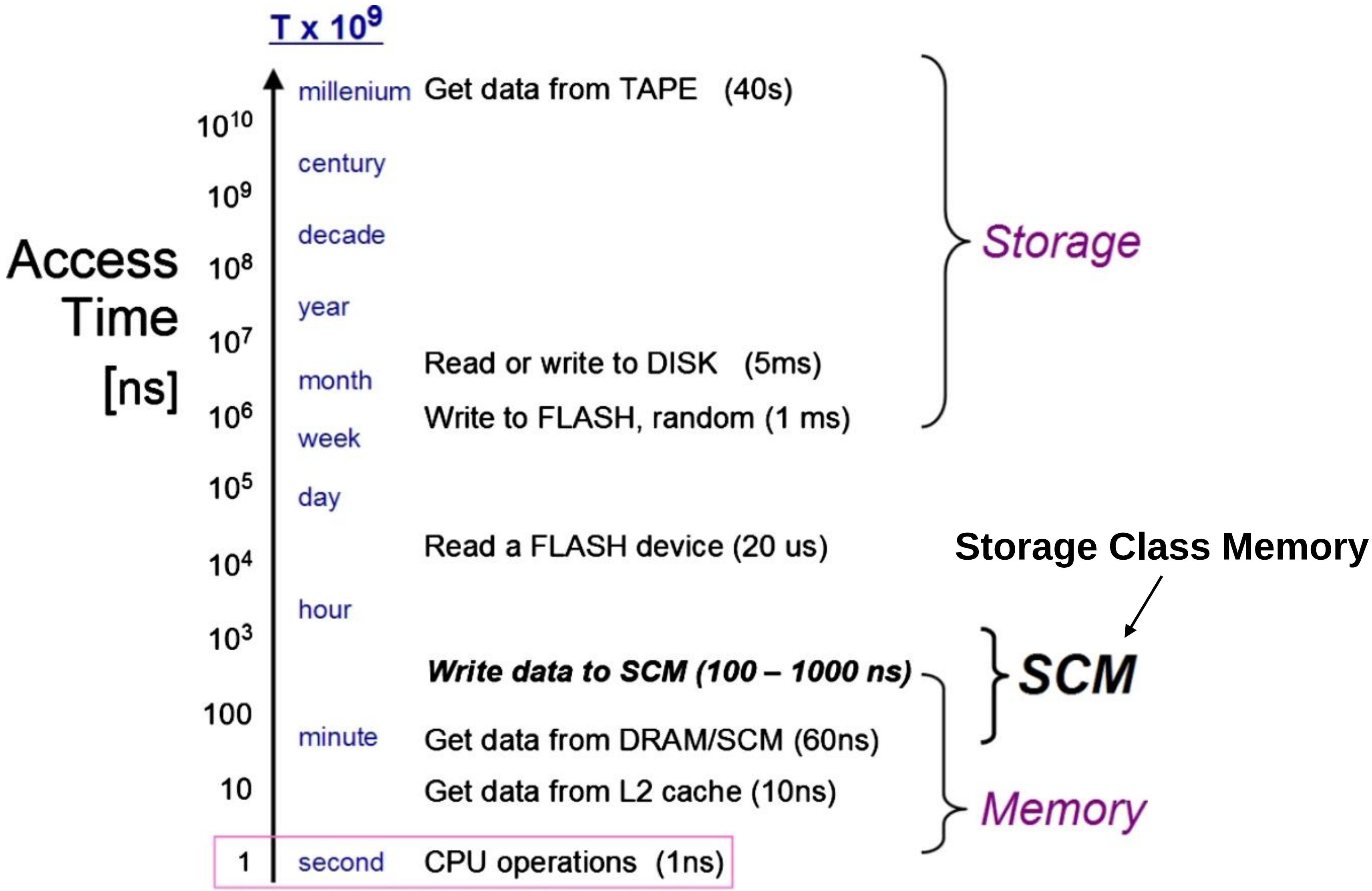


128 GB

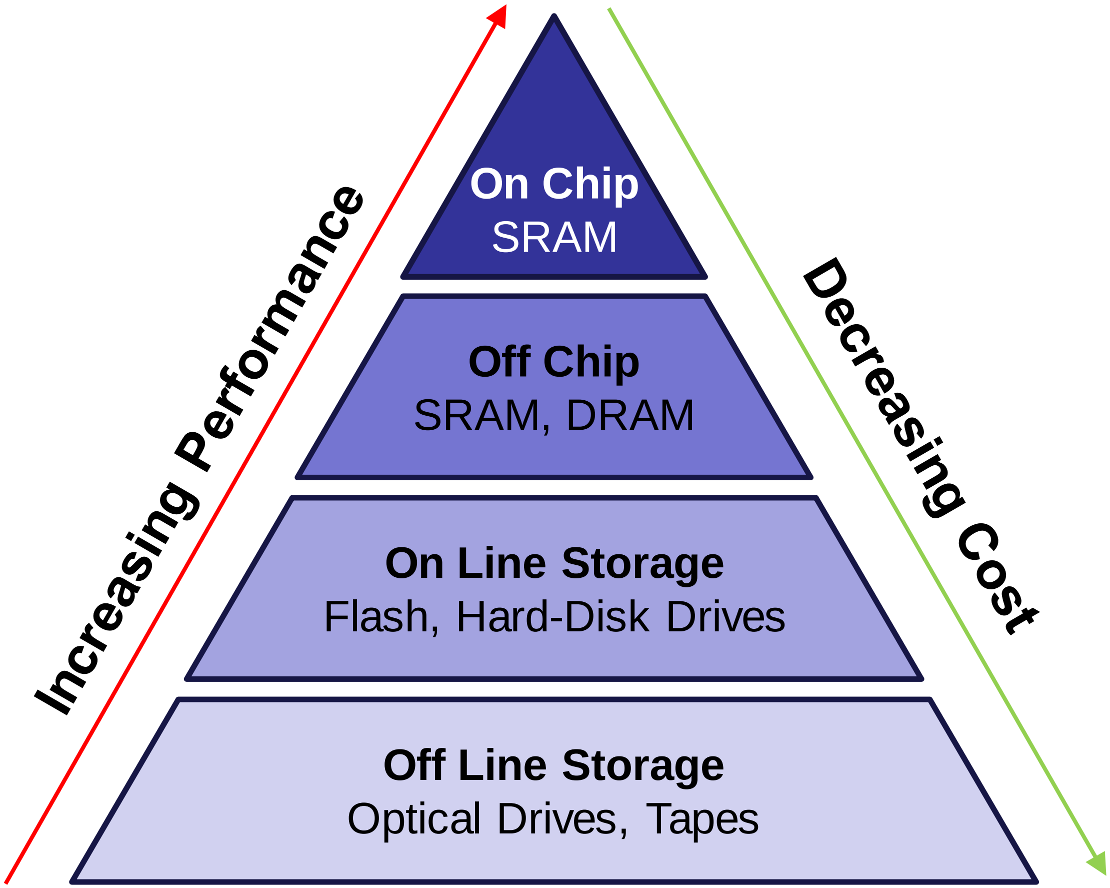
32 GB

64 GB

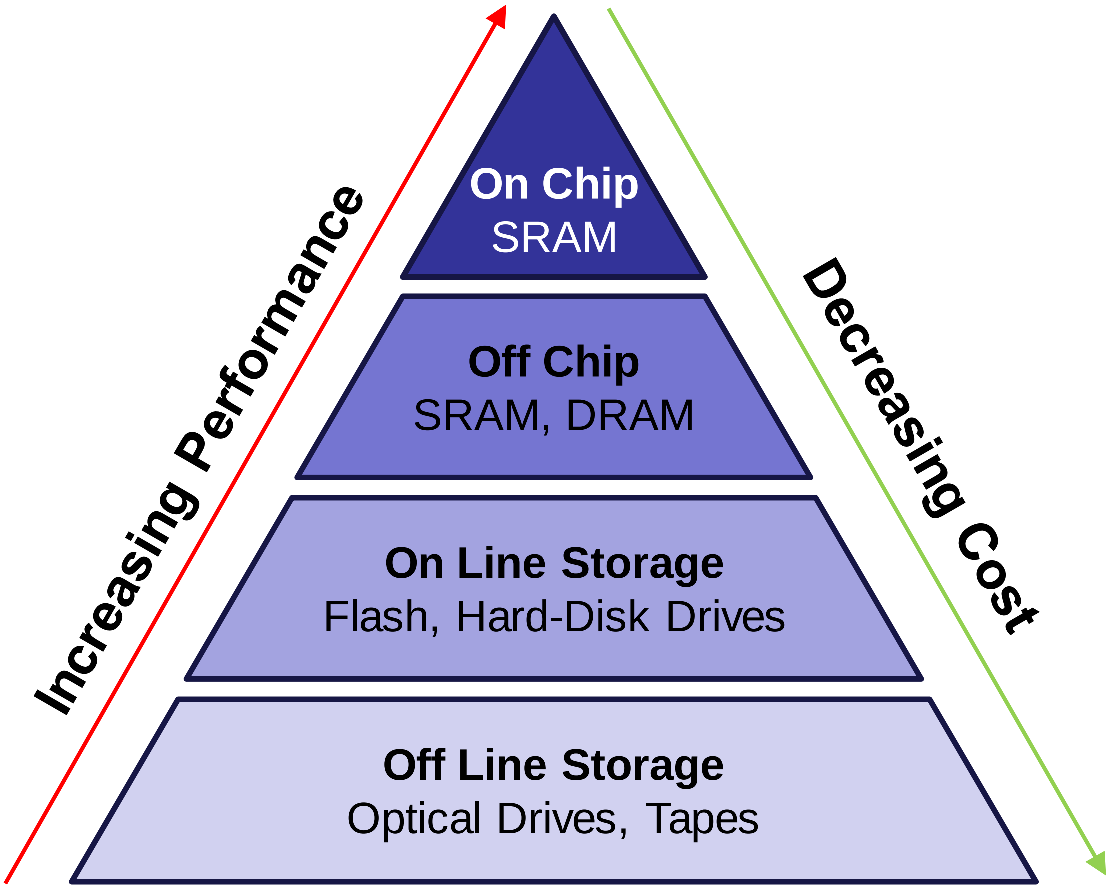
Memory vs Storage



Memory Hierarchy



Memory Hierarchy



- **Cost**
- **Speed**
- **Density/Capacity**
- Energy
- Scalability
- Endurance
- Volatility
- Radiation

Magnetic Storage

- Most affordable and widely used memory technology
- Magnetic polarities to represent ‘0’ and ‘1’

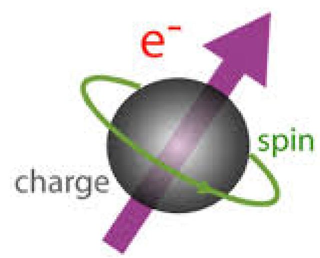
Magnetic Tape

Cassette

Hard Disk Drive (HDD)

Floppy Disk

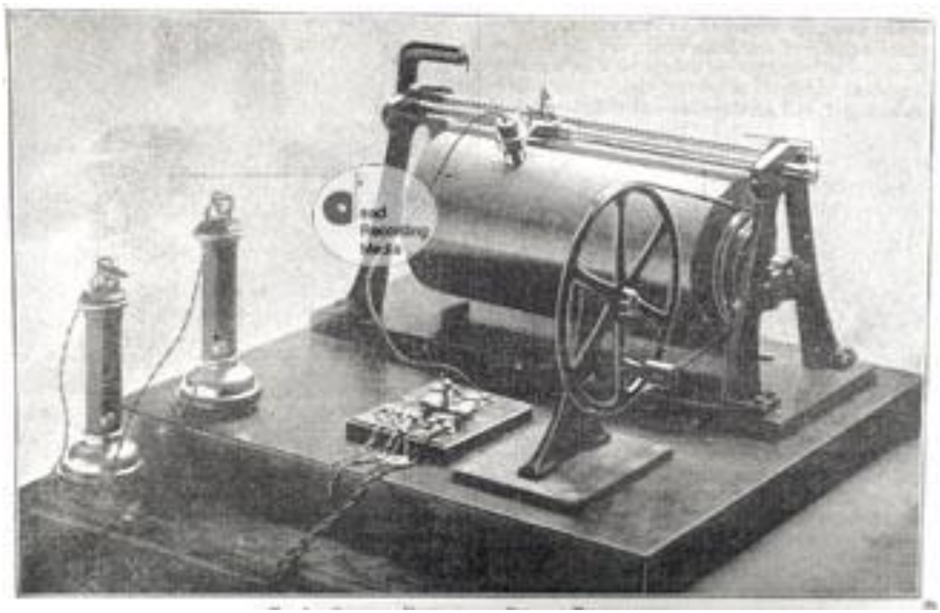
Magnetic Random Access Memory (MRAM)



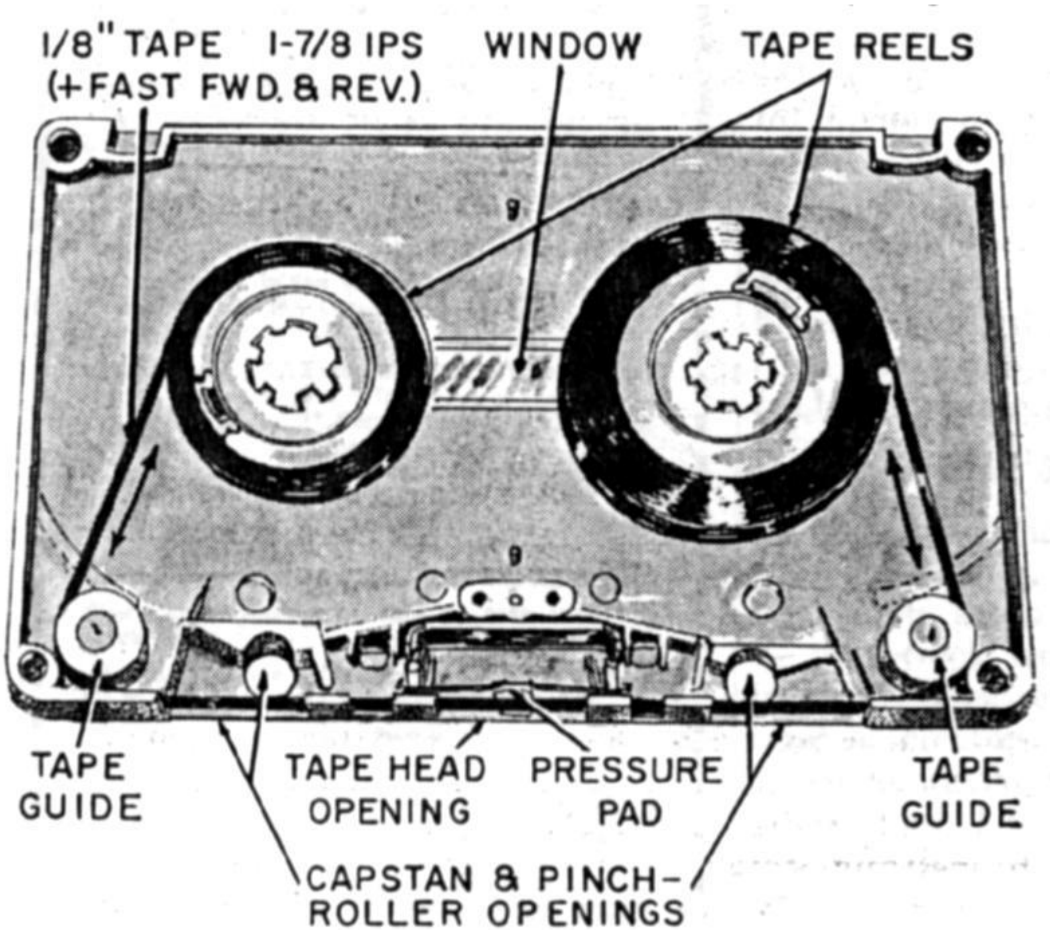
Spin Transfer Torque RAM (STT RAM)

Magnetic Tape

- History
- 1898 – wire recorder by V. Poulsen (Denmark)
- 1900 – Poulsen patented Telegraphone, a device to record sound on a tape
- 1934 BASF manufacture reels of plastic-based magnetic tape



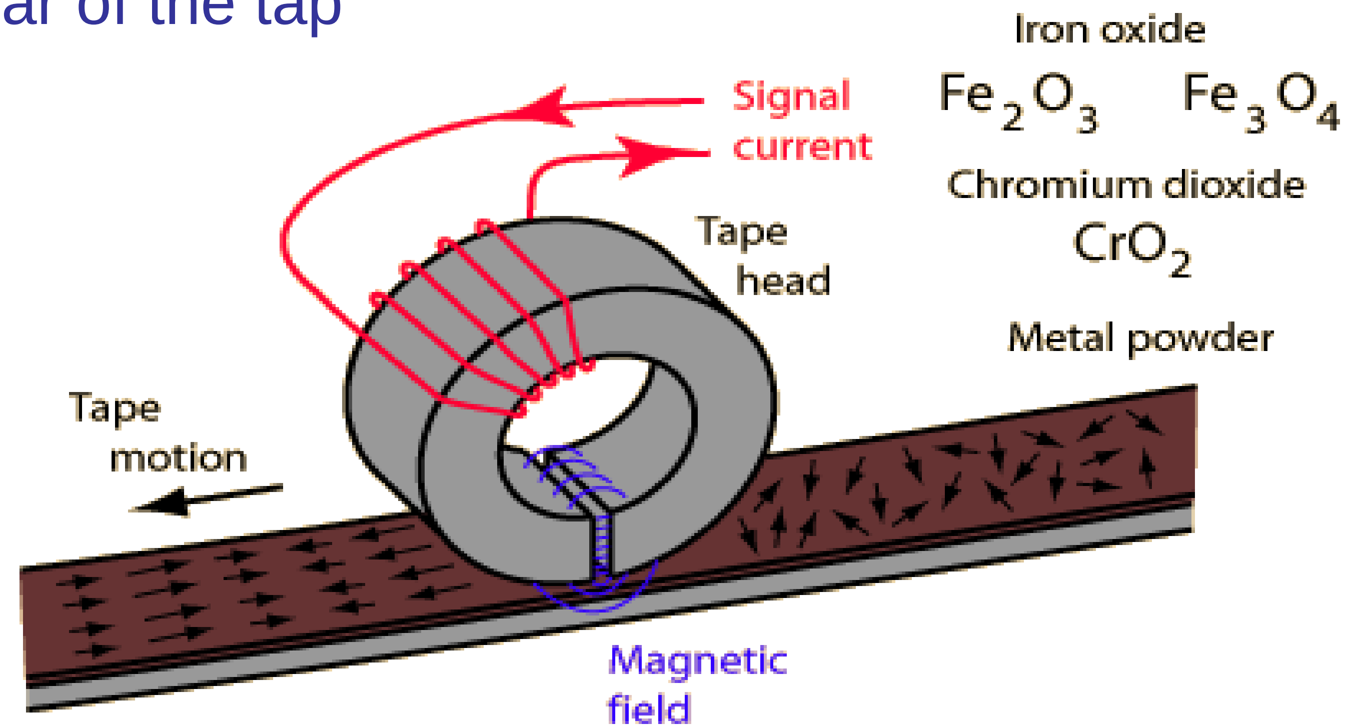
Magnetic Tape



- Key components:
  - recording head, tape, movement components

Magnetic Tape

- Paramagnetic recording medium: e.g. iron oxide
- Electromagnetically program the polarities as “0” and “1”
- Read: convert stored magnetic pattern into electrical signal
- Tape movement at constant speed to avoid straining and wear of the tap



Magnetic Tape

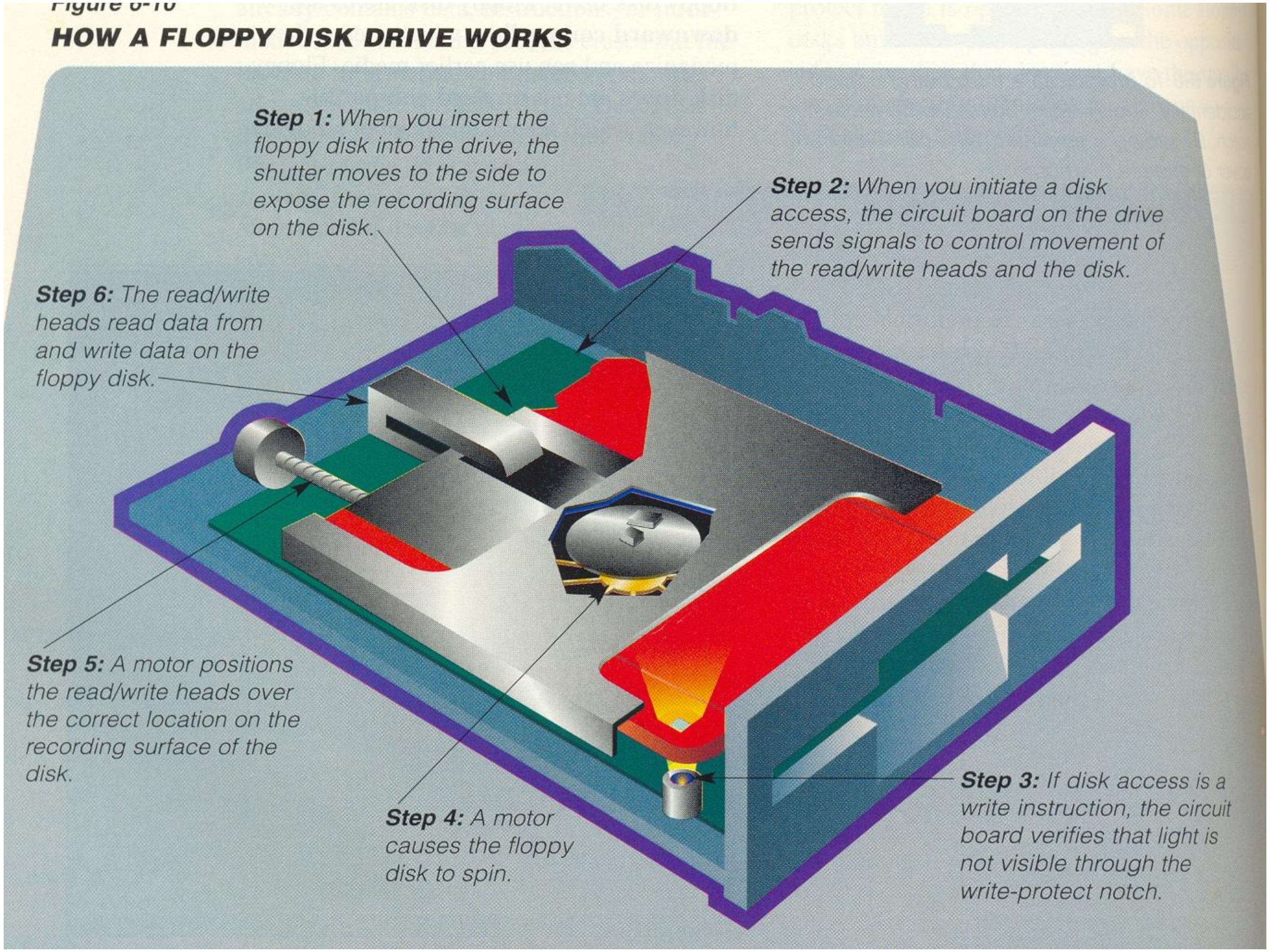
- Price: very cheap $/MB
- Access time:
  - serial access
  - needs to rewind the tape to the right place
  - very slow, 10-100 ms
- Capacity: large, just miles of tapes
- Retention: 30 years
- Dominant in 1950 – 1980s; now secondary storage
- Still popular in: surveillance, medical research, spying

Floppy Disk

- Removable storage media
- 8”, 80 KB, 1971
- 5.25”, 360 KB, 1976
- 3.5”, 1.44 MB, 1987
- 3.5” superdisk, 240 MB, 1996

- Ubiquitous in 1980s and 1990s
  – ~50 billion floppy disks in 1996
- Store operating system and software
  – often required >a dozen disks
- Replaced by USB, portable hard disk, rewritable CD/DVD
- Legacy device

Floppy Disk



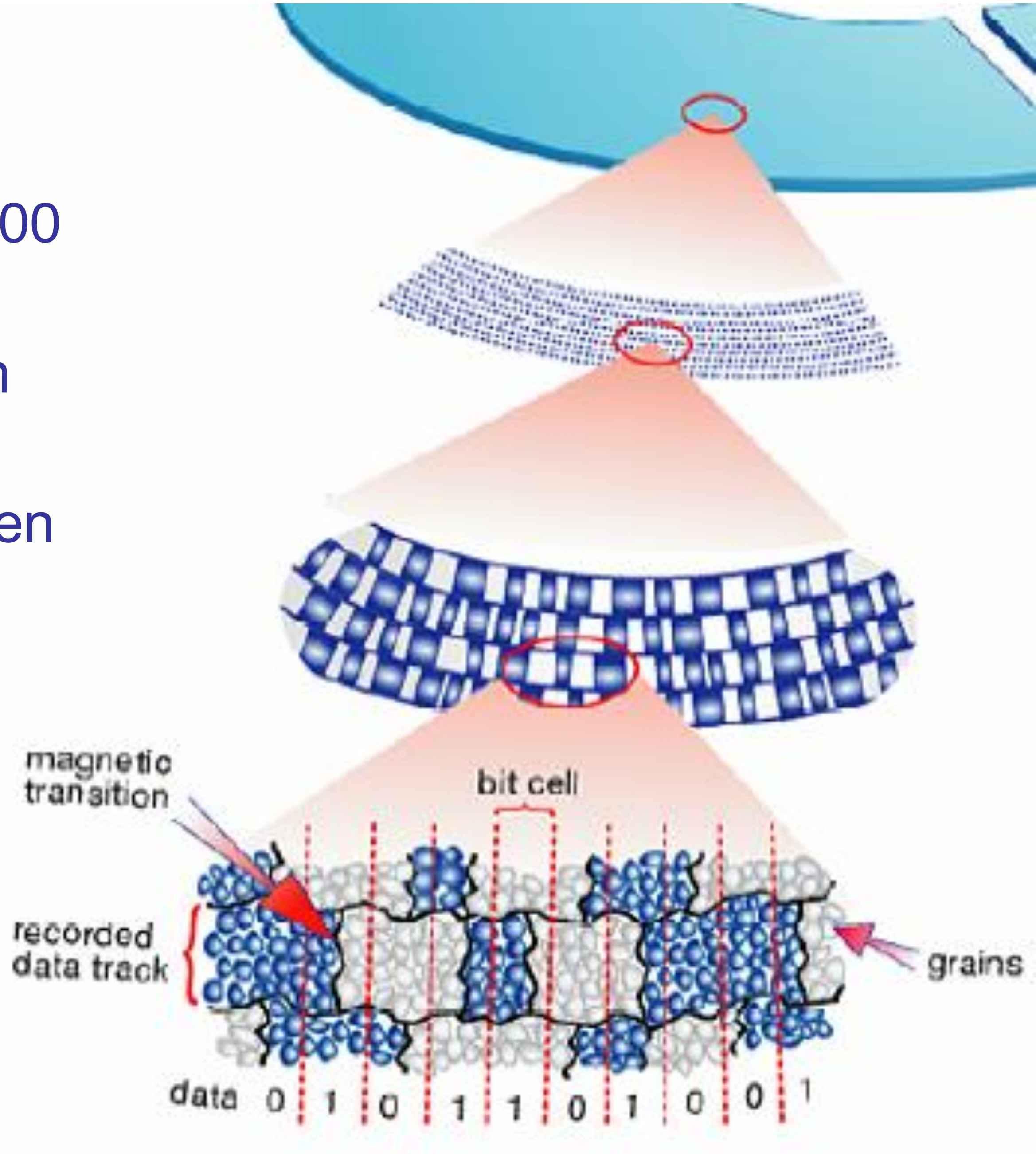
- slow and low capacity

Hard Disk Drive (HDD)

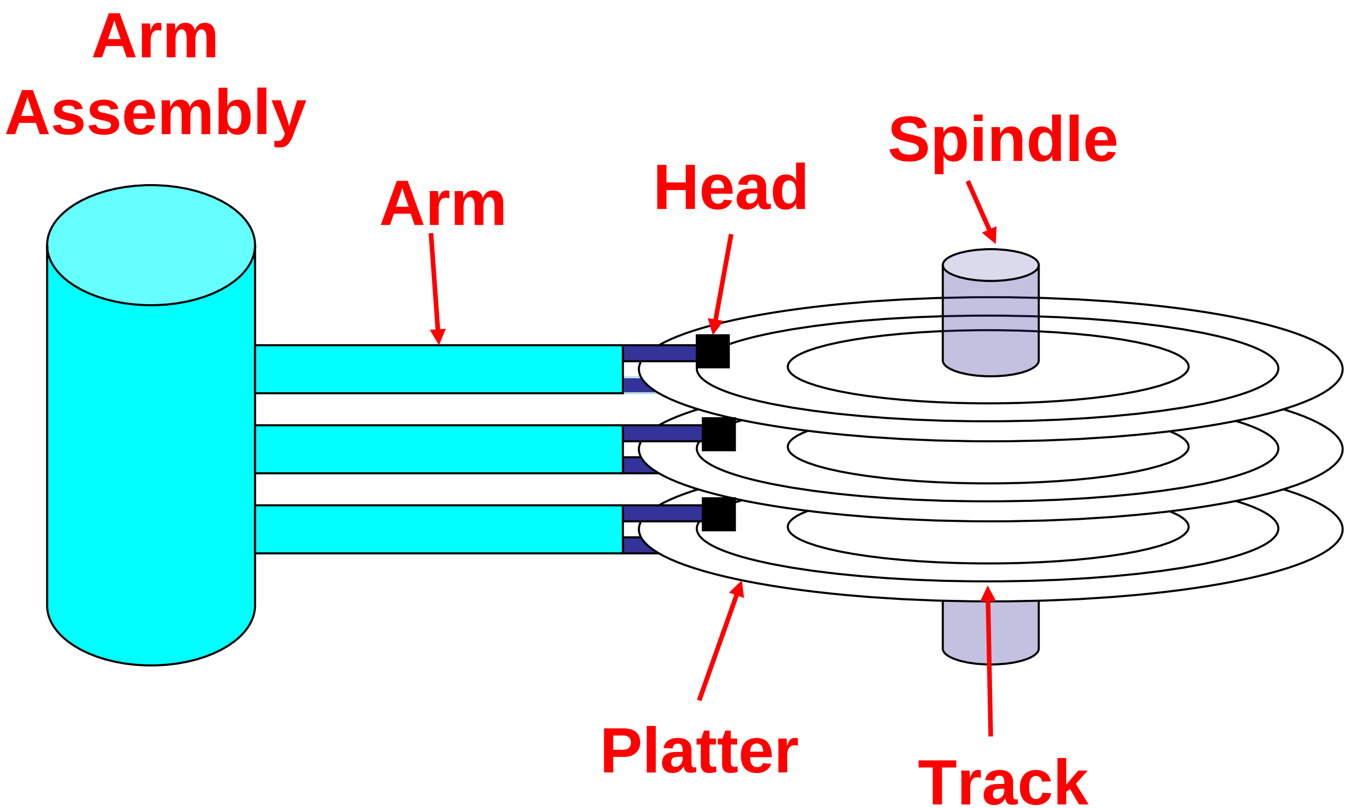
- Price: $/GB, very low
- Capacity: ~TB, large
- Access time: ~10 ms, slow, random access
- Endurance
  - Mean time between failures (MTBF) = 1, 200, 000 hours = 137 years
  - Reliability decreases with increasing temperature
- Reliability
  - electromechanical

Magnetic Bit

- a magnetic bit = 50-100 grains
- ‘0’ = grains of uniform magnetic polarity
- ‘1’ = boundary between regions of opposite magnetization



HDD Organization



HDD Parameters

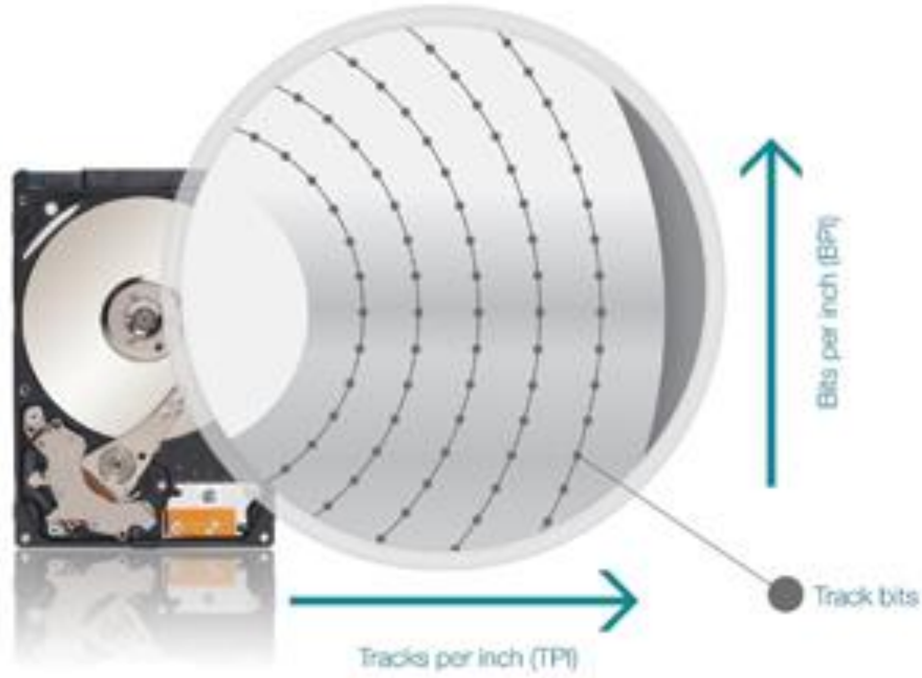
- Typical parameters
  - platter diameter: 3,7'', 3.3'', 2.6''
  - RPMs: 5400, 7200, 10000, 15000
  - number of platters: 1-5

- Power = (**# of platters**) × (**RPM**)$^{2.8}$ × (**Diameter**)$^{4.6}$

- Read/write operations
  - read → Faraday's Law
  - write → magnetic induction

Storage Density

- Density Metrics
- Bits per inch (BPI) – linear density
- #Track per inch (TPI)
  - bits are grouped into 512 B of data in sectors
- Areal Density = BPI × TPI



HDD Speed

- Access time: serial access, 5-10 ms
- Queuing delay: disk gets to do this operation
- Seek time: head moves to correct track
  - Speed up: arm accelerates
  - Coast: arm moving at max. speed
  - Slow down: arm brought to rest near destination
  - Settle: head is adjusted to reach the access
    - Head switch
    - track switch, longer with high TPI
- Very short seek – settle dominates
- Short seek – speed up/slow down dominates
- Long seek – coast-time dominates
- Data transfer time

Reliability

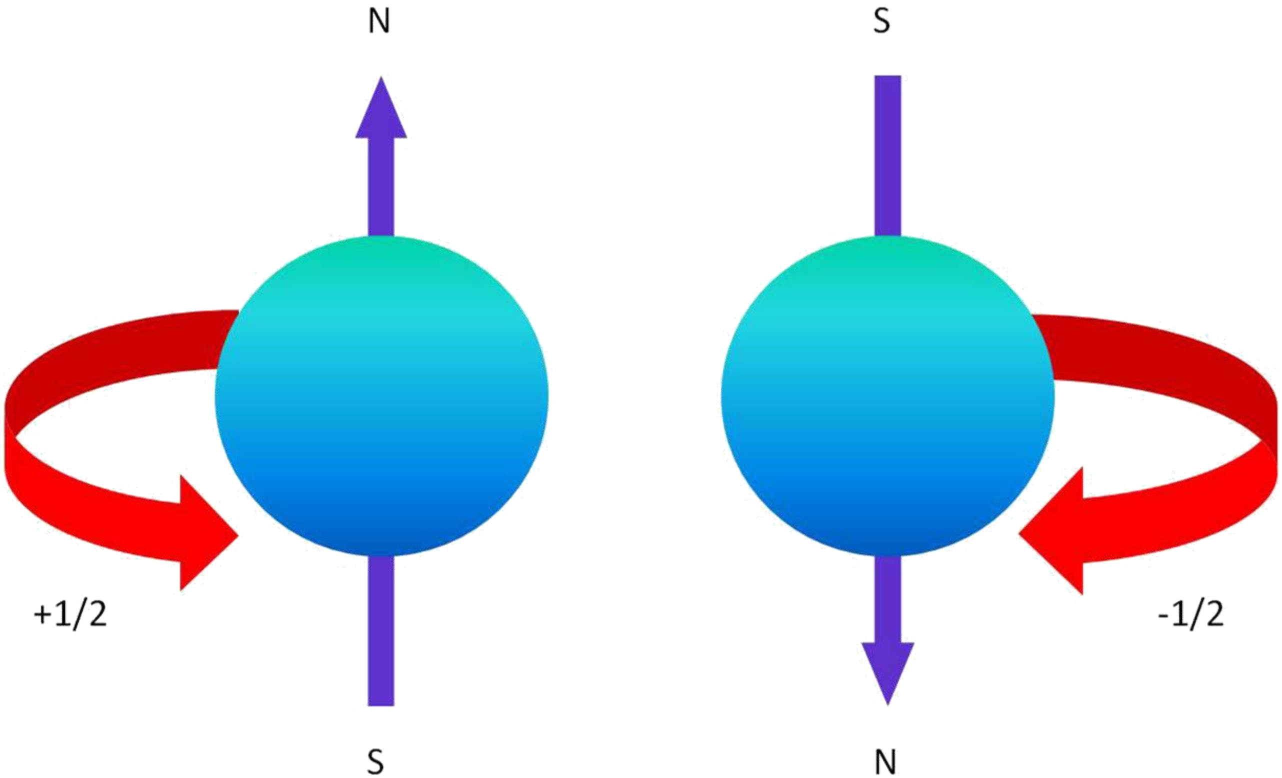
- HDD is sensitive to vibration
- Cause off-track errors
- Worse at high TPI due to smaller tolerance
- Design measures for higher amount of vibration tolerance

- Temperature
- more failure at higher temperature
- 15 C rise from room temperature can double the failure rate

- Duty cycle
- the amount of mechanical work required, i.e. during seeking

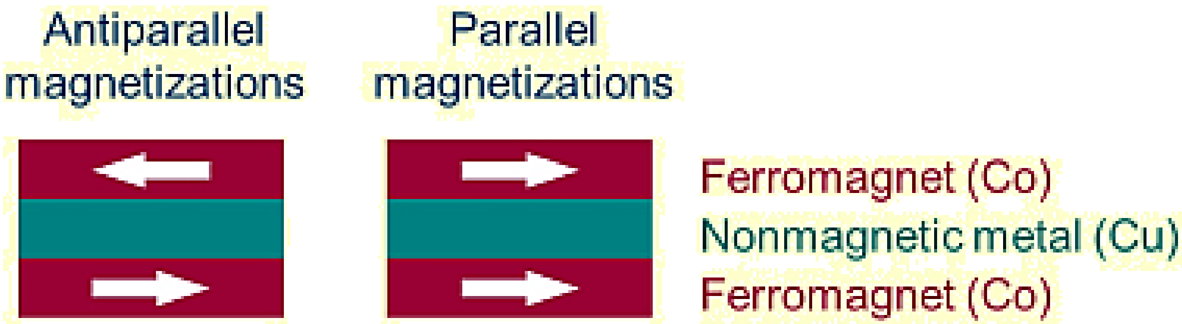
Spintronics

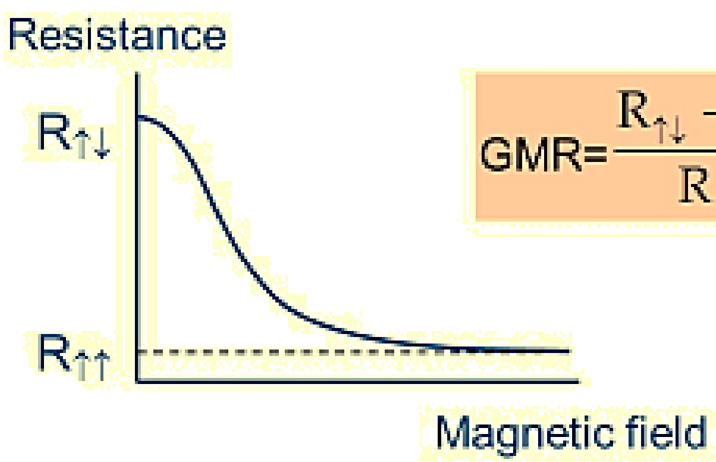
- Spintronics: Spin-based electronics
- Electron spin has two possible orientations
- Information stored as spin orientations



Giant Magneto-Resistance (GMR)

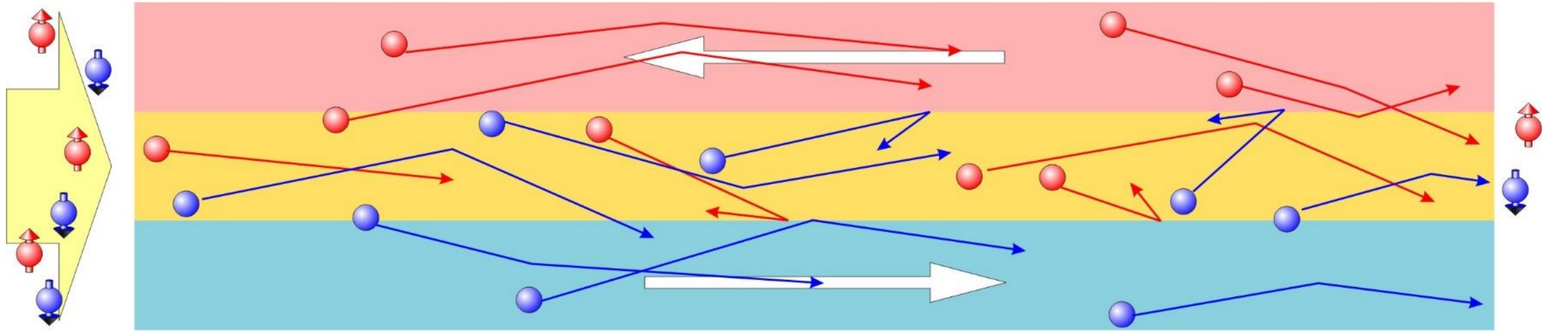
- Giant magneto-resistance
  - discovered in 1988 by Albert Fert (French) and Peter Grunberg (German), independently
  - Winning 2007 Nobel Prize in Physics



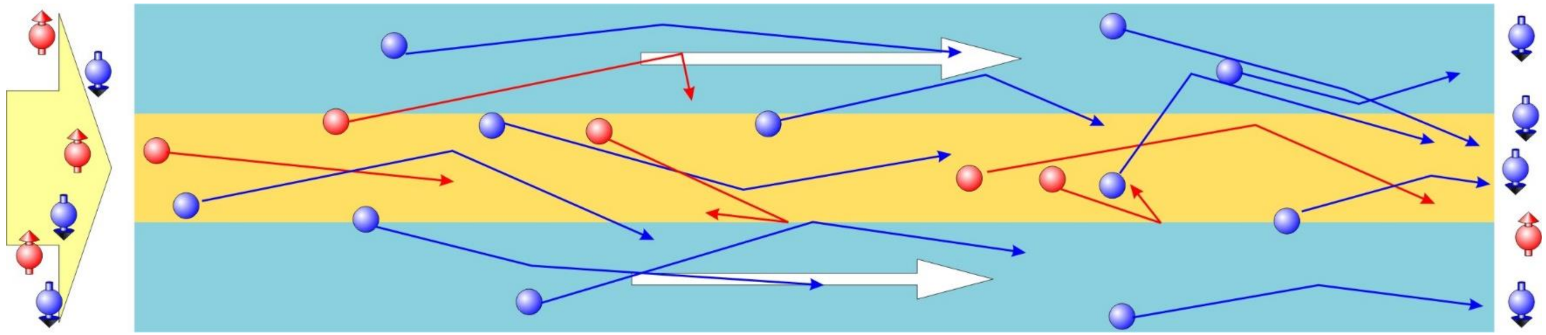


$$\text{GMR} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}$$

Spin-Dependent Scattering



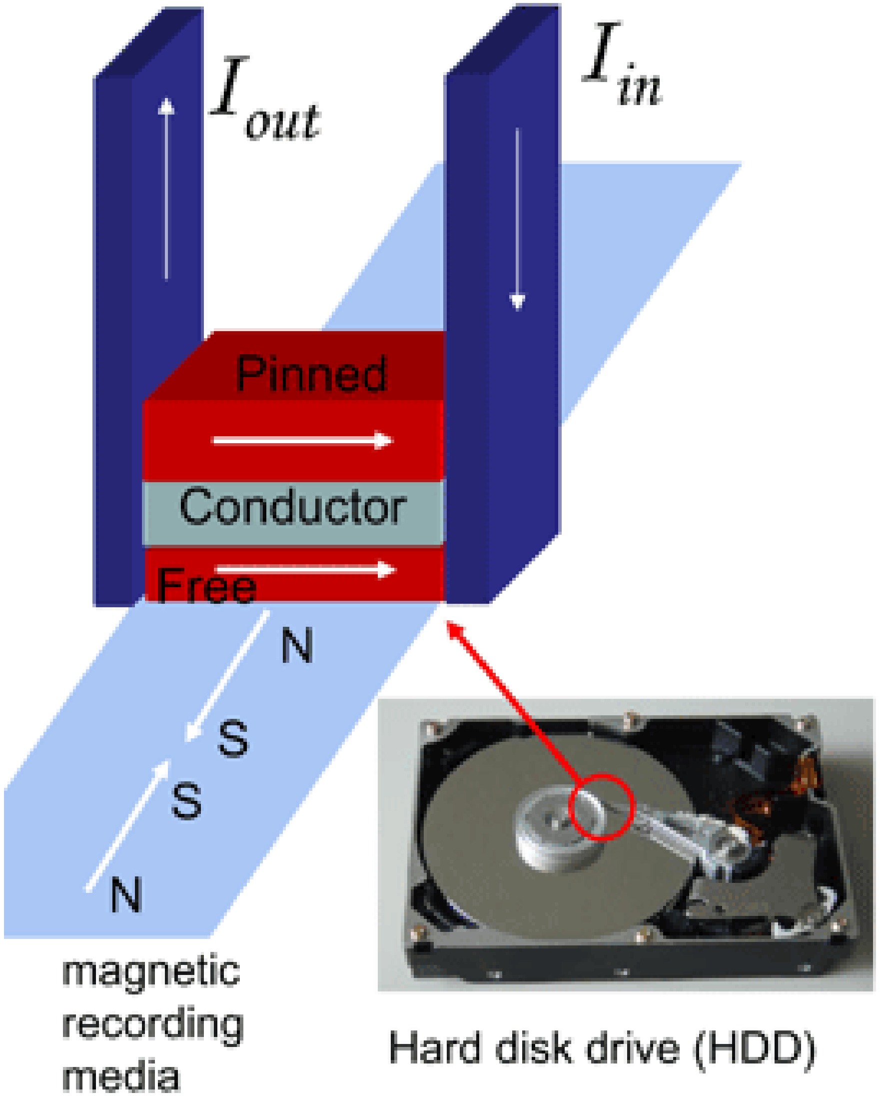
- Anti-parallel magnetization → Electrons will scatter strongly across the boundary → High resistance



- Parallel magnetization → Very few scattering across the boundary → Low resistance

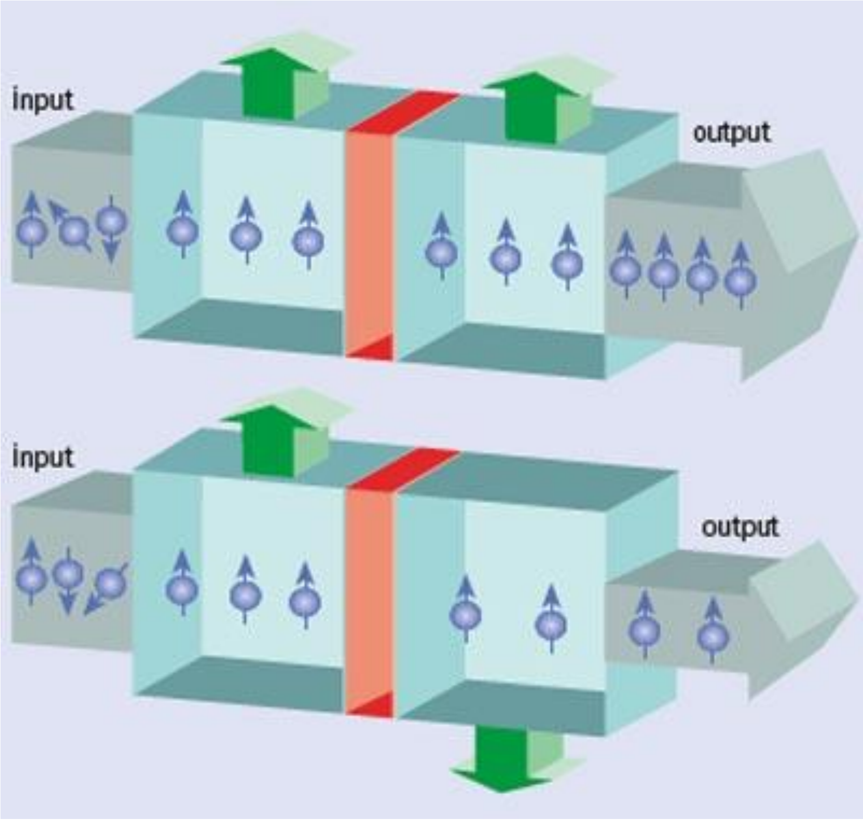
Parallel Current in GMR

- Current runs parallel between the ferromagnetic layers
- ~200% resistance difference
- Commonly used in magnetic read heads in HDD
- R changes depending on the magnetization of the domain



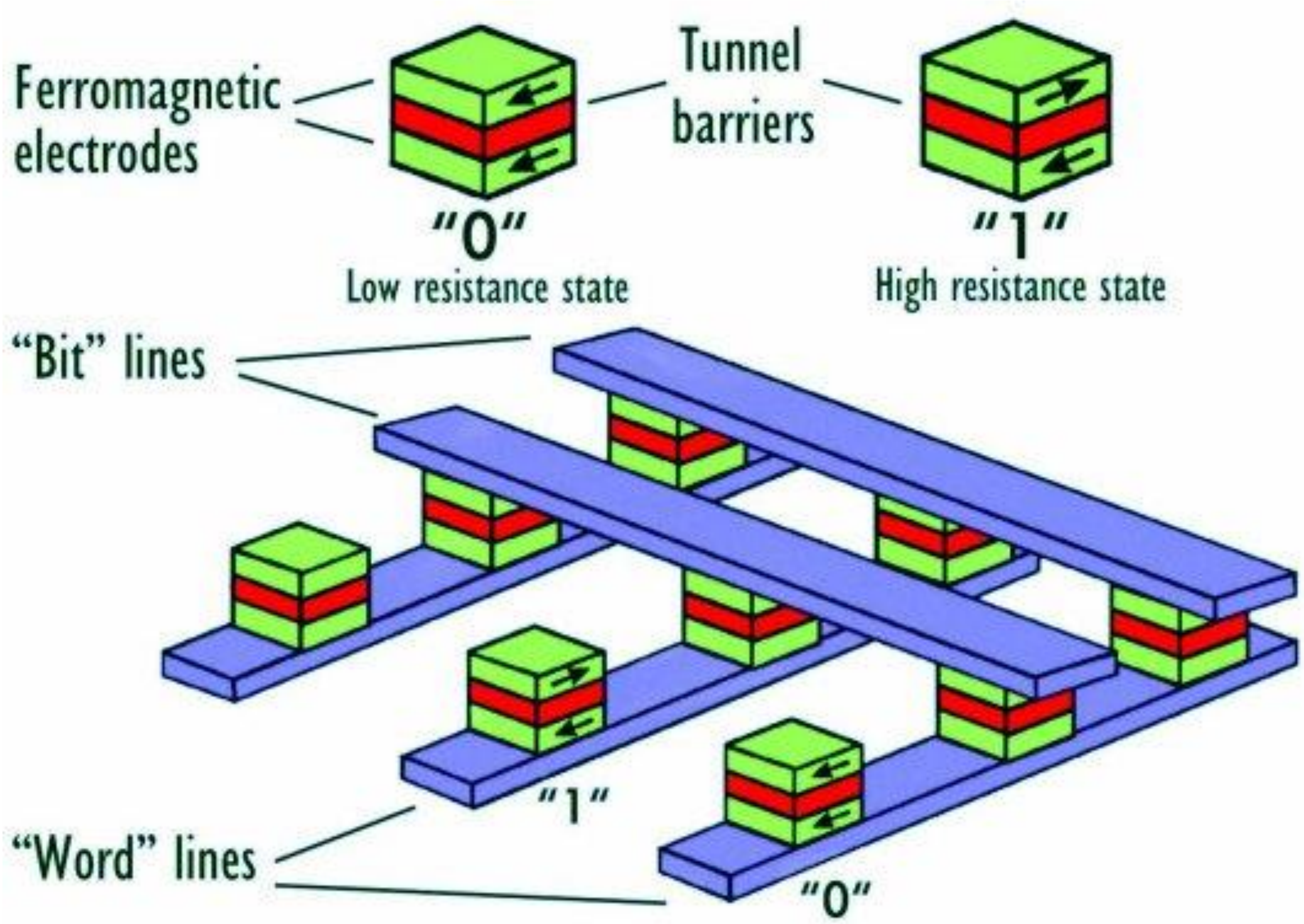
Tunnel Magneto-Resistance (TMR)

- Tunnel Magneto-Resistance
- Combining GMR and quantum tunnel effect
- Magnetic Tunnel Junction MgO and Al_2O_3

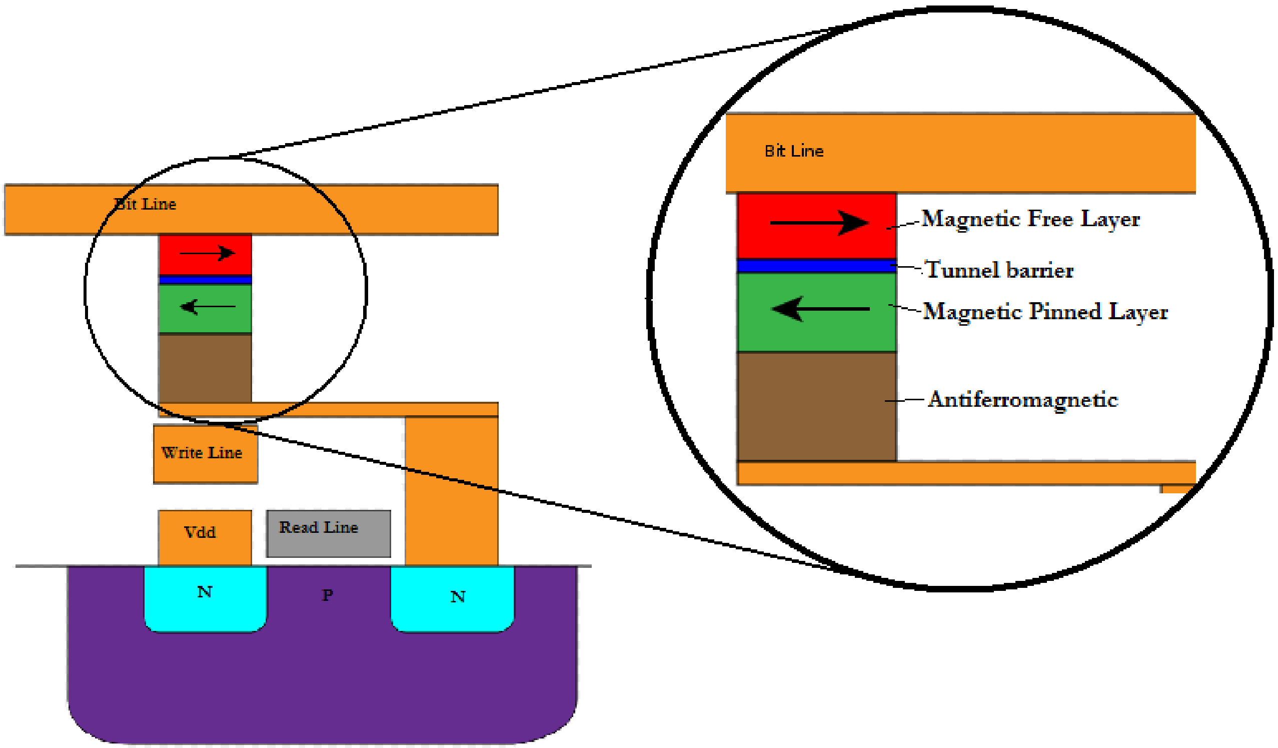


Magneto-resistive RAM (MRAM)

- MRAM – magnetic storage element in memory array
- ‘0’ for parallel, low R; ‘1’ for anti-parallel, high R

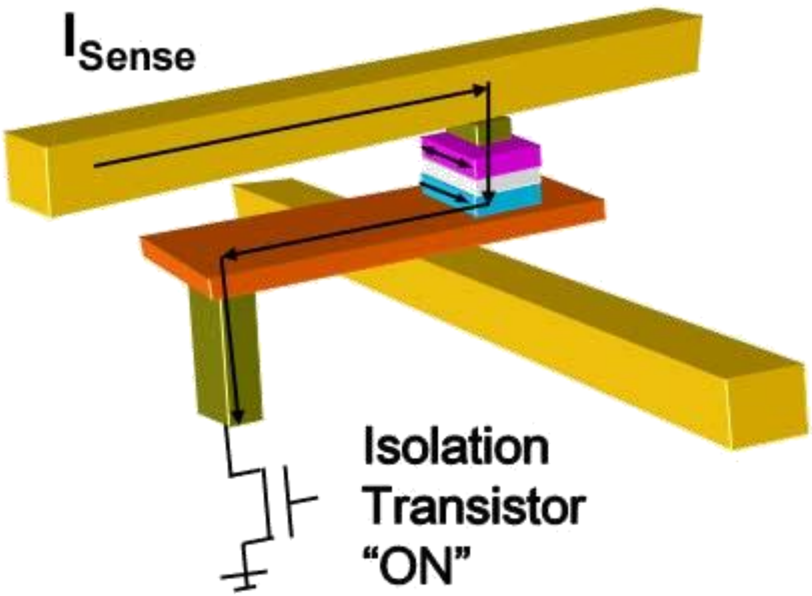


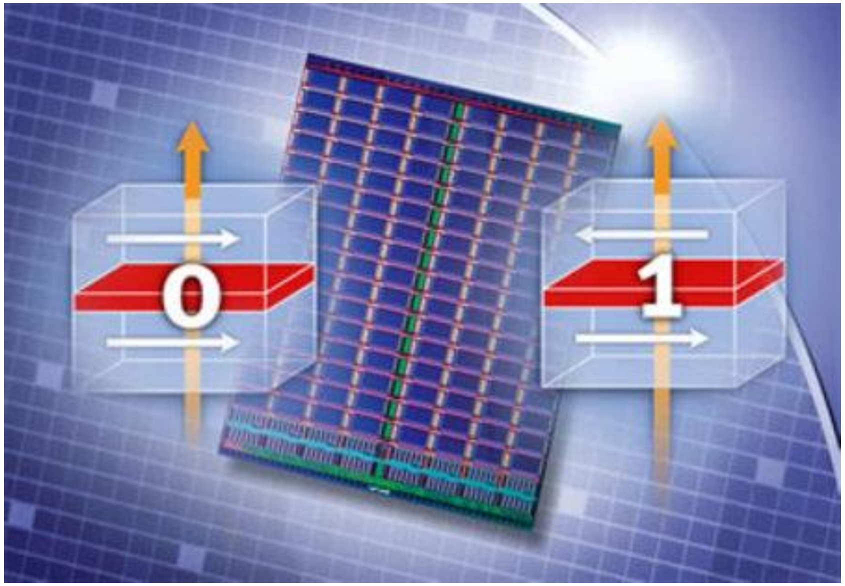
MRAM Structure



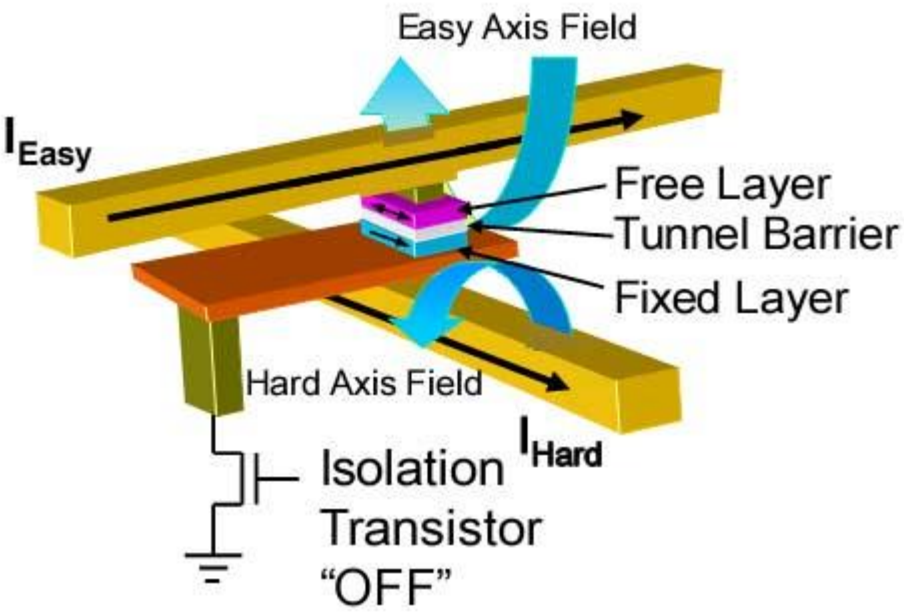
- Hard layer: magnetic polarity is fixed/pinned
- Soft layer: magnetic polarity can be changed

MRAM: Read Process



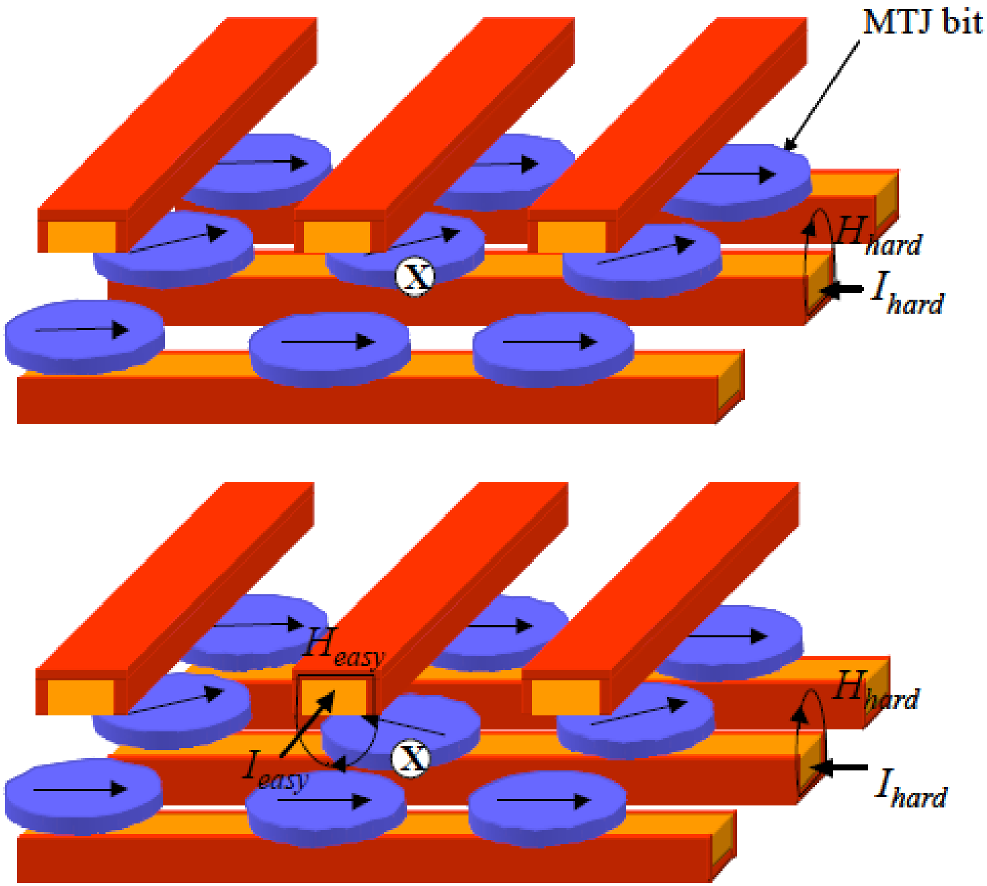


MRAM: Write Process



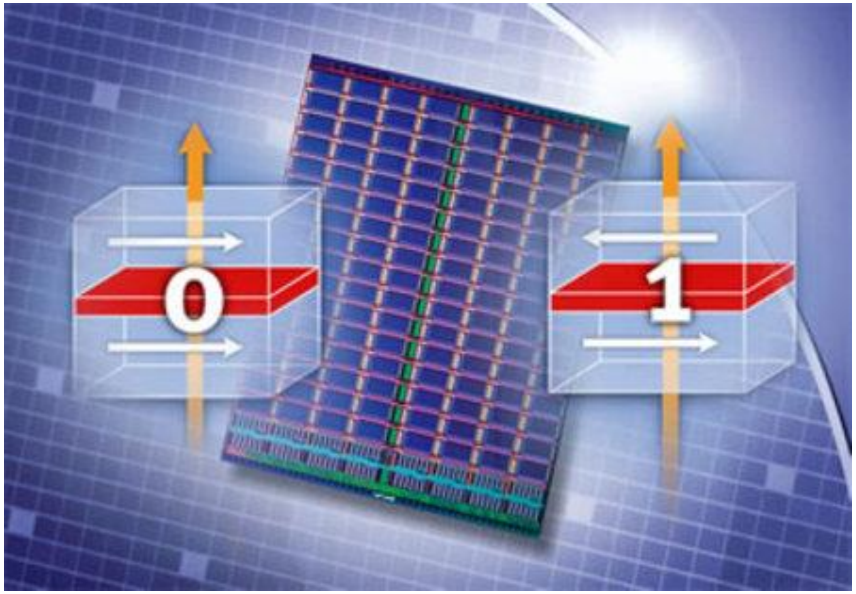
- Isolation transistor is OFF
- Current passed through write lines
- Induced magnetic field
- Alters the polarity of the free layer

MRAM: Write Process



- Both magnetic field is necessary for programming
- Thus only the bit that are selected by both bit line and word line will be written

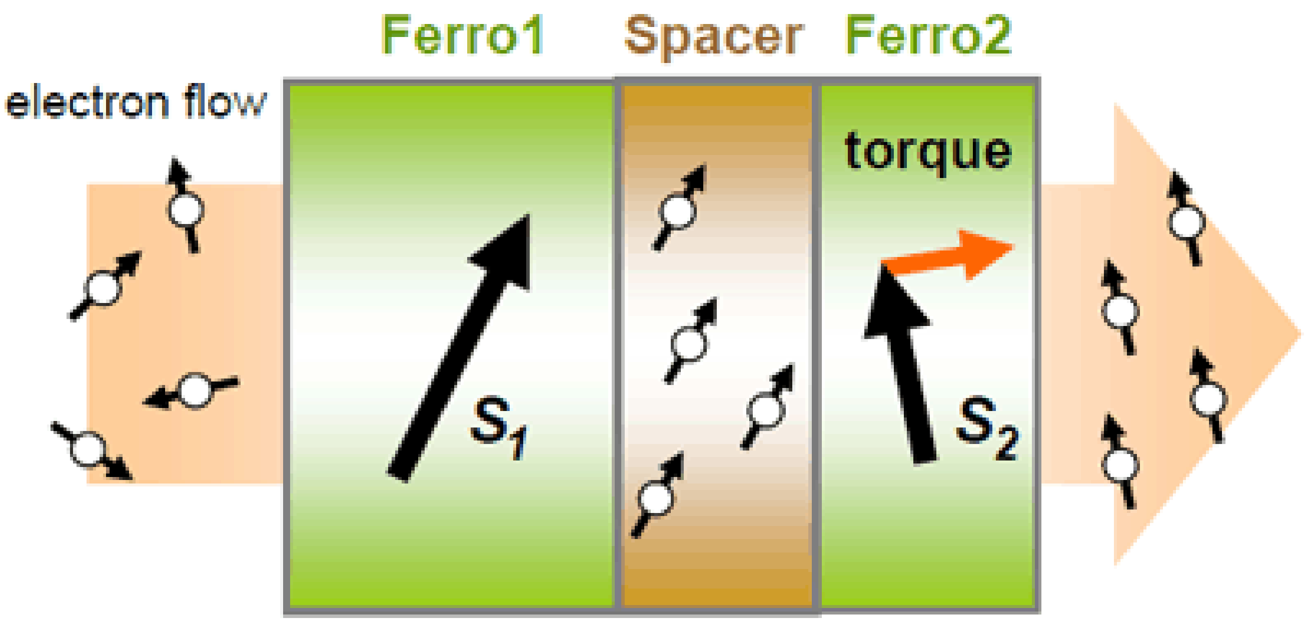
MRAM Properties



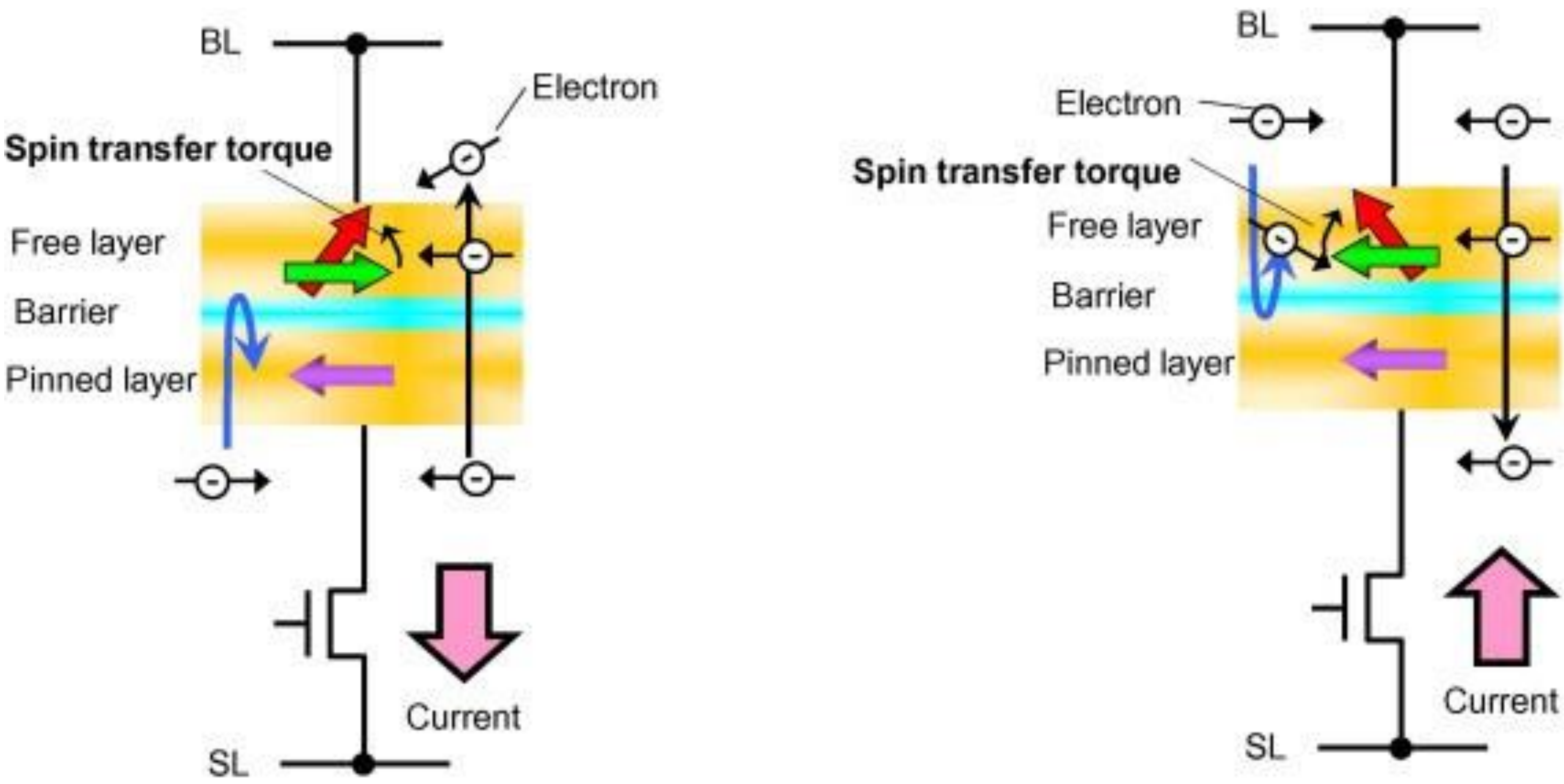
- Non-volatile
- Infinite endurance
- Moderately high speed
- Low cost
- High power

Spin Torque Transfer RAM (STT RAM)

- Discovered by Slonczewski and Berger in 1996
- Magnetization of a magnetic layer can be reversed by injection of a spin polarized current, i.e. spin transfer to the layer
- No applied magnetic field to switch magnetic devices

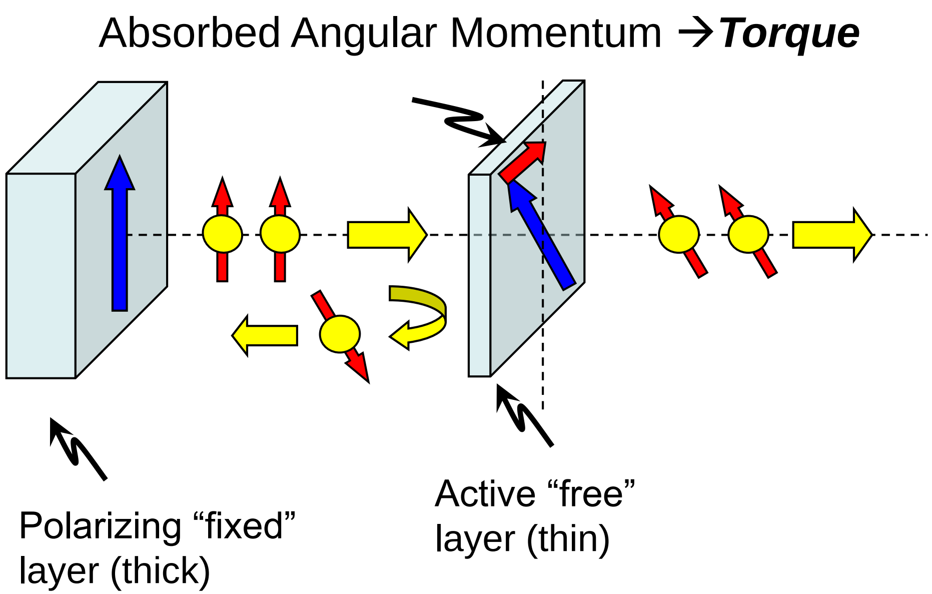


STT RAM Switching



(a) Anti-Parallel (AP) to Parallel (P) switching (b) Parallel (P) to Anti-Parallel (AP) switching

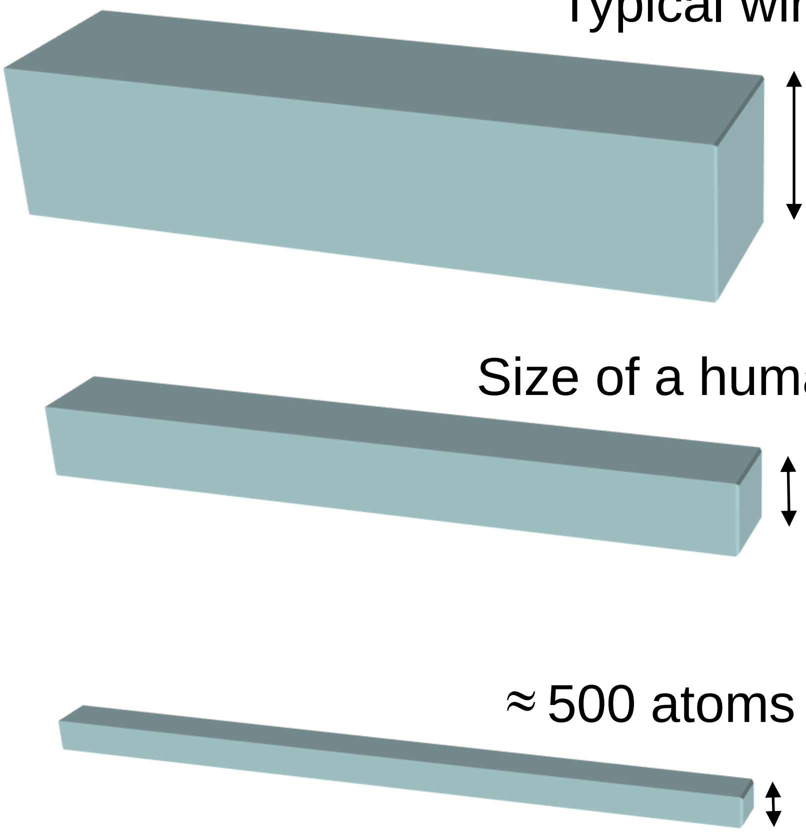
Spin Torque Transfer



- 1st spin filtering: electrons align themselves with fixed layer
- 2nd spin filtering: electrons align themselves with free layer
- Spin angular momentum conservation: spin-polarized current generates torque on the magnetization of the free layer
- Reflected current too weak to change the fixed layer

STT RAM Current Scaling

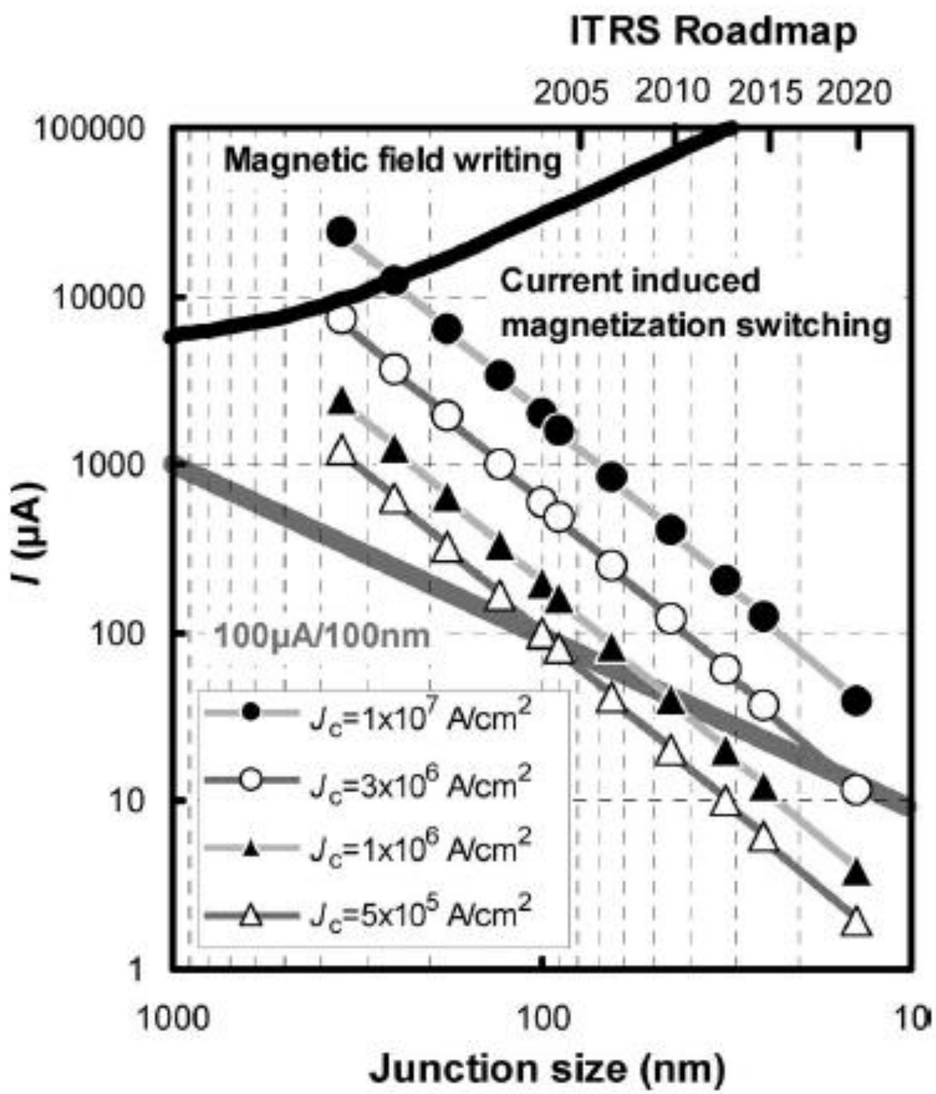
Torque ∝ to current **density**: must have high current *densities* to produce large torques



		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
≈ 500 atoms across	100 nm	$I \approx 1$ mA	✓

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

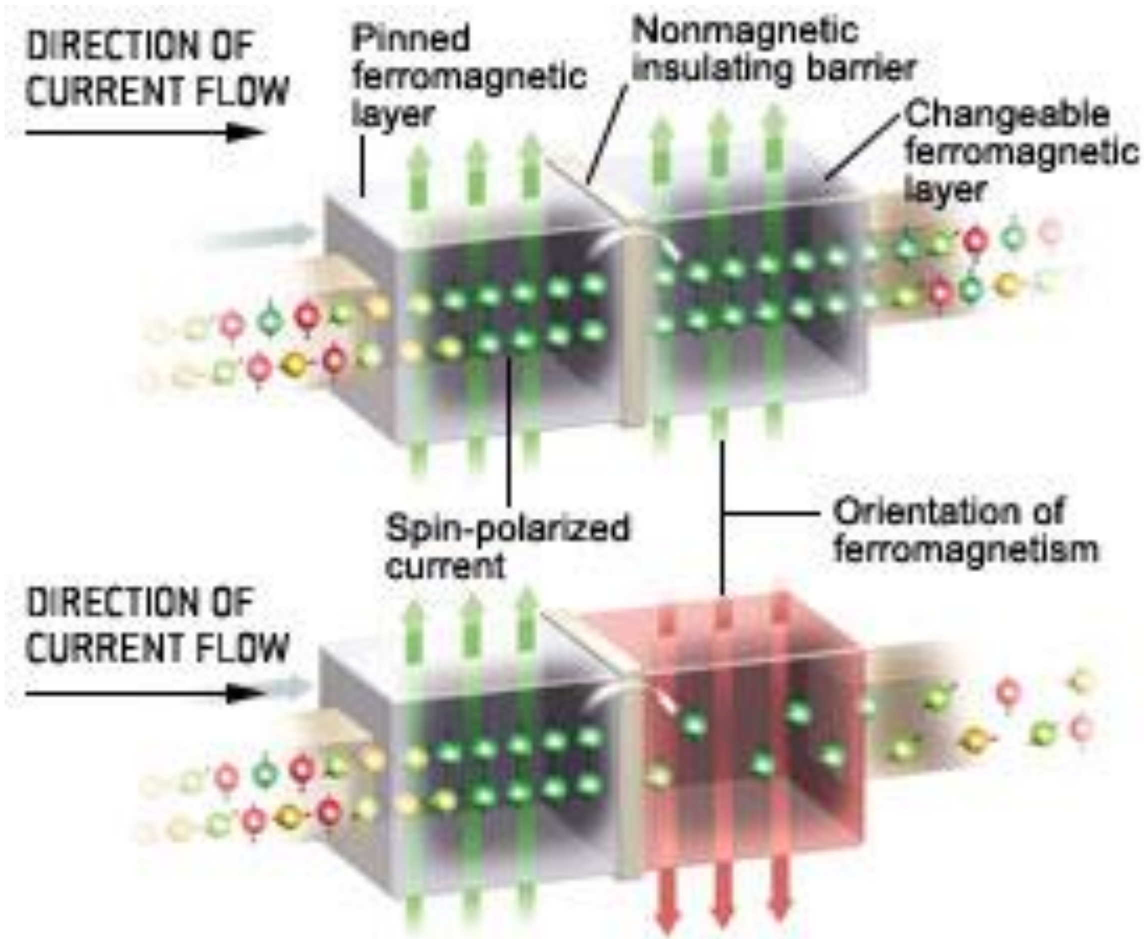
High Switching Current in STT RAM



- Switching current density → Too high!
- Current scales with decreasing size of the junction cell
- J_c needs to be lowered to ~10^5 A/cm^2

STT RAM Potentials

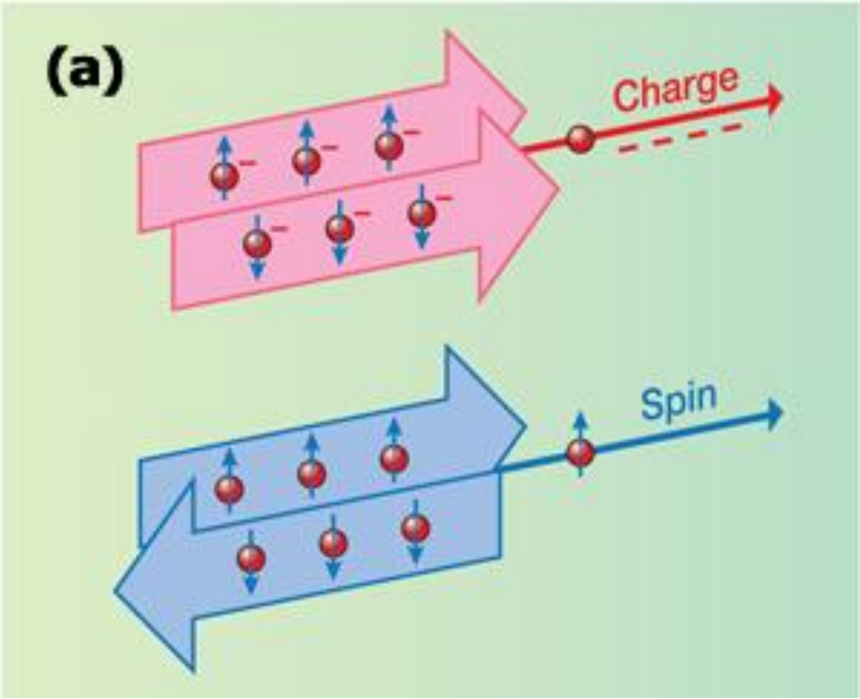
- High speed: ~ ns
- Non-volatile
- Infinite endurance
- Simple architecture
- Highly scalable
- But high power



Pure Spin Current?

Ordinary current:
transport of charge

"Pure spin current":
transport of spin



- Spin current → transport of spin
- No charge transfer → zero power dissipation