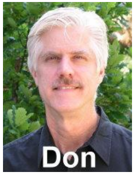
Electronics - PHYS 2371/2



Calendar of Topics Covered

Physics PHYS 2371/2372, Electronics for Scientists

Don Heiman and Hari Kumarakuru
Northeastern University, Fall 2020

Also see **Course Description** and **Syllabus**

This is a schedule of the topics covered, but it may be modified occasionally (12/02/2020).

Week #	Lectures	Weekly Topics (Chs.)	Homework (Ch-Problem)	Lab Experiments (always look for latest version)
IX Nov 2, 4-6 **MON/WED**	MON Digital-1 Digital-1 video WED Digital-2 Digital-2 Lecture	**Mon/Wed Lectures** Digital Logic (Ch-19,22), Binary Numbers (Ch-54) Logical Networks (Ch-20)	19-all, 20-all	**Lab-8a, *Digital Circuits*** (truth table, 4-bit decoder) Lab-8a Digital video
X Nov 11-13	**Monday Lecture** Pulsed ICs Pulsed Lecture	Lecture: Pulsed ICs Digital Summary	21-1/2	**Lab-8b, *Pulsed Digital*** (Flip-flops, counter, displays) Lab-8b Pulsed video
XI Nov 18-20 **WED EXAM**	**EXAM-II - Wed** Final Project	**EXAM-II: Magnetoelectronics, Optoelectronics, Digital/Pulsed**		***Final Project*** Simulink Tutorial video ***Poster Instructions***
XII Nov 25-27	No Lecture	**Thanksgiving**		No Lab
XIII Dec 2	**Wed Lecture** Future Electronics	Present and Future Technology		***Project PowerPoint*** **due Sunday Dec 6**
XIV Dec 7-9	**No Classes**			

Project PowerPoint

Background Memories and Logic

Some Future Electronics

Magnetic Electronics or *"Spintronics"*

Quantum Computers

Neuromorphic Computing

Introduction

The Internet requires huge amounts of

Nonvolatile Memory

Internet/Computers Require Memory and Logic Devices

Internet – world wide web (1989)

- **Size of WWW**
  5.3 Billion indexed pages (2020)

- **Data Storage**
  55 billion data pages – trillions of gigabytes, 10^{23}B
  10^{13} movies

- **Energy Usage**
  10% of world's electricity (1/2 cooling)

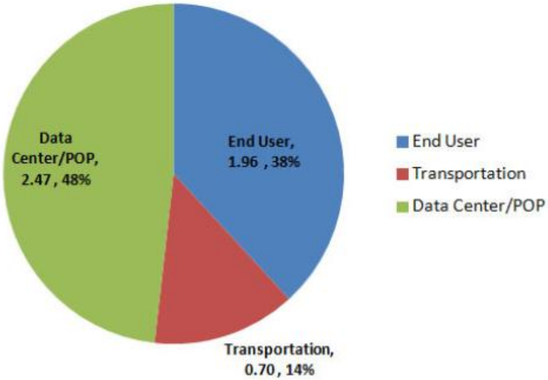
- **Transfer Energy** 0.2 kWh/GB data transfer (2009)
  $0.02 /GB electricity ($0.10/movie)

Computer/Server Energy

- Energy efficiency doubled every 1.5 years for 6 decades
- 20% in the manufacturing stage
- 80% of energy in the use stage

Google Server Farm

Figure 1. Internet Energy Breakdown (kWh per GB)



Smaller and Smaller Nonvolatile Memories

Magnetic Tape Cassette
Sony Walkman
1979

Guardians of the Galaxy

12 songs
stores **one** music album
0.3-0.4 MB

CD Player
Sony Diskman
1984

stores 200 songs
with compression
700 MB

Hard Disk Drive
Apple iPod
2001

stores 10^3 songs
2-32 GB
Spintronic read head

The Science behind Memory Devices

Nonvolatile

HDD – *Hard Disk* – Rotating magnetic disk

SSD – *Solid State Drive* – NAND gates – No moving parts

HDD

SSD

HDD - Hard Disk Drive Memory

Now – 2020

2 Terabyte (10^{12} characters) \$50

7,200- 10,000 RPM (~100 R/s)

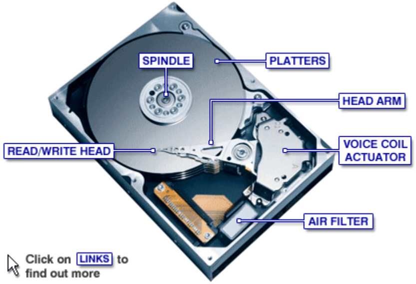
0.5 MB

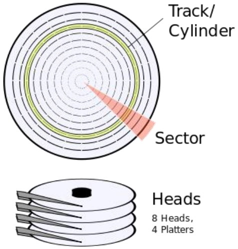
← 1975

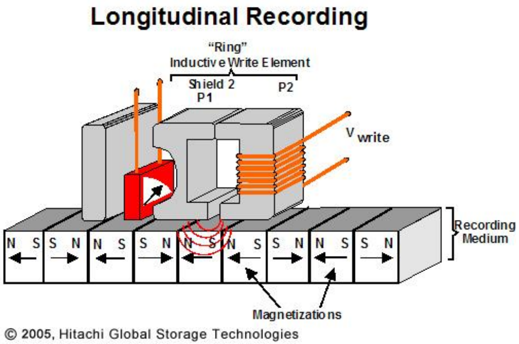
↓

500 GB

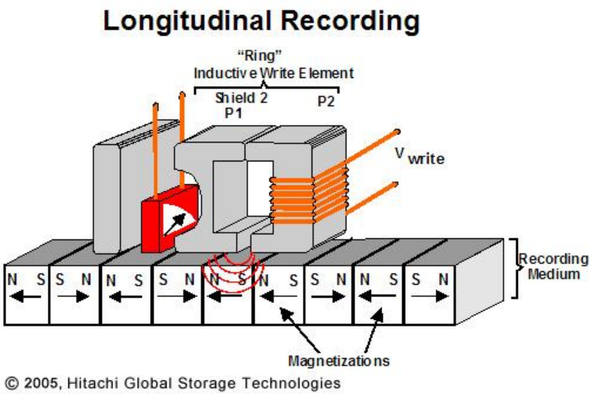
2005

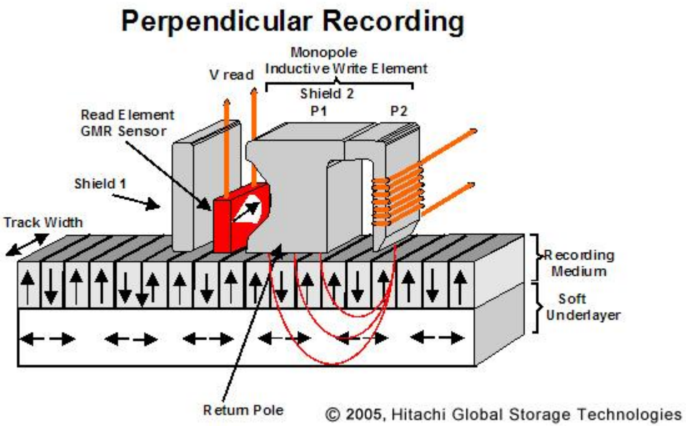






Parallel (longitudinal) vs Perpendicular Recording





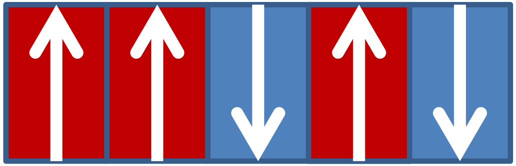
Perpendicular Recording takes up less space per bit… increases areal density

Perpendicular Recording – Increased Bit Density

The HDD bits need to have a high magnetic stability.

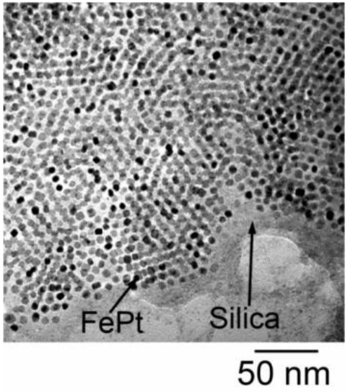
If not, the bit can spontaneously flip by thermal fluctuations.

Bits are too small and can spontaneously flip.



Make bit **long** in vertical direction,
but keep the areal density the same.
Bits are now thermally stable.

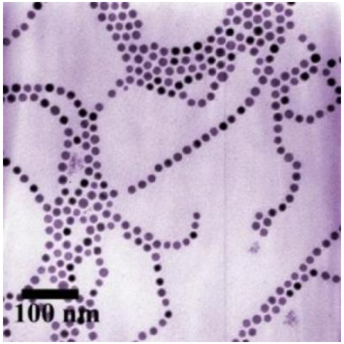
Granular Nanoparticles



On a HDD the magnetic nanoparticles (MNP ~ 5 nm) are surrounded by silica (SiO_2) to keep them apart.

Note the expensive platinum in the FePt MNPs!

Platinum - $1,000 per ounce (gold $1,800)



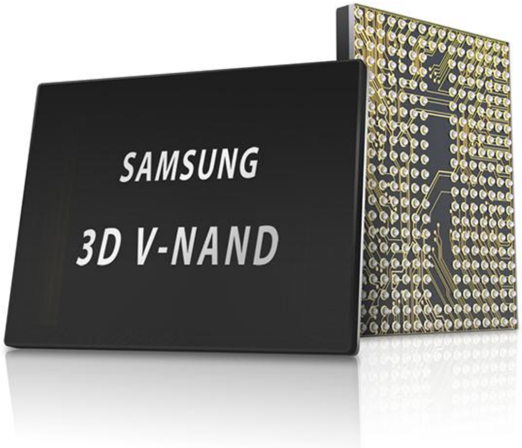
Small magnetic nanoparticles (MNP) must be kept apart, otherwise they will interact and become useless, as shown by these chains.

In the chain, the MNPs are aligned N-S, N-S, N-S, making it difficult to switch one.

SSD - Solid State Drive Memory

Nonvolatile SSD vs HDD Memory

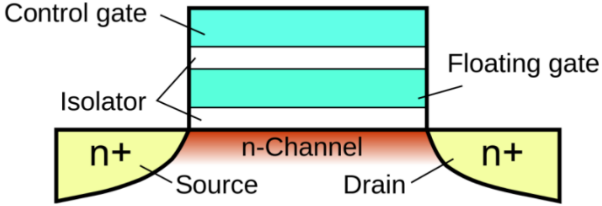
+ **No moving parts**
+ **4x faster than HDD**
  200-500MB/s read/write speed
+ **Lower power than HDD**
– **4x more expensive $200/2TB**
  HDD $ 50/2TB



SSD uses
NAND-based flash memory
10-19 nm size bits
Floating-gate MOSFET transistors

Flash Memory (NAND, NOR gates)

Floating Gate MOSFET NAND/NOR



The NAND flash memory had FET two gates, a control gate (CG) and a floating gate (FG). **The FG is extremely well insulated so that it can store an electrical charge for many years**. When the FG is charged, it applies an electrical field to the n-channel below it to cut off the conduction between the source and the drain.

The CG can apply voltage high enough to set or clear the charges on the FG.

Applying a lower voltage to the CG is used to determine if the FG has a large charge and the source-drain has high resistance (a "0"). On the other hand, if the FG is uncharged the source-drain has a low resistance (a "1"). wiki

The Science behind Spintronics

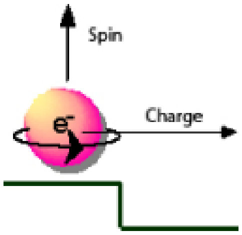
Relies on the Quantum Nature of Electrons

Magnetoelectronics – "Spintronics"

The electron has:

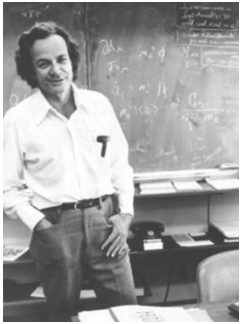
- **Mass** (9.11 x 10^{-31} kg)
- **Charge** (1.602 x 10^{-19} C)
- **Spin-1/2 – angular momentum**

magnetic moment = μ_B (Bohr Magneton)



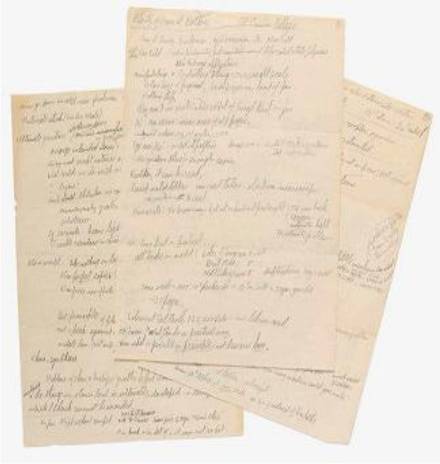
Spintronics

Utilizes the
Electron Spin (magnet)
in electronic devices



Birth of Nanoscience – Richard Feynman

Richard Feynman's 1959 address
to the American Physical Society
"There's Plenty of Room at the Bottom"



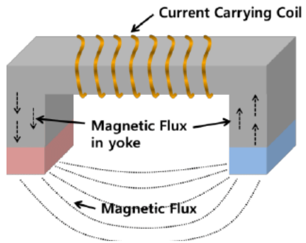
He envisioned and challenged listeners:

- "*sequence the bases in the DNA*"
  (1869 isolated; 1953 Watson-Crick-Franklin; 2001 Genome)
- miniaturizing computers with wires *"10 to 100 atoms in diameter"*
- a microscope that could *"see the individual atoms"*
  (1967 TEM; 1981 STM)
- machines *"maneuvering things atom by atom"*
- *"systems involving the quantized energy levels or the* ***interactions of quantized spins****"*

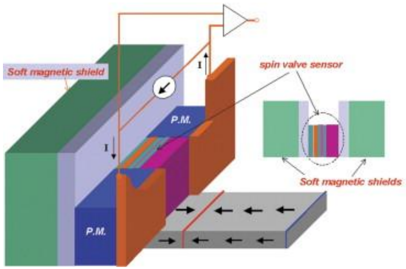
Problem in Reading Small Magnetic Bits on a HDD

How do you read the magnetic bits on a HDD as they travel by at high speeds?

Instead of using a very small micromagnet to detect the changing magnetic field of a magnetic bit on the disk



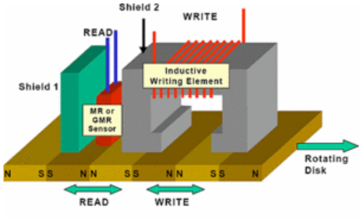
Spintronics utilizes a **magnetoresistive** device where the resistance changes then the magnetic field from the magnetic bit travels by



MagnetoResistance Devices

Want to read the magnet bits in a HDD

Use a **magnetoresistance** material,
where the fringing magnetic field
of a bit on the HDD disk
changes the resistance in the read head.



MERGED READ-WRITE HEAD
Figure 4

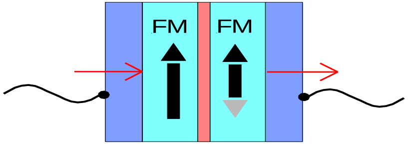
First Spintronic Device

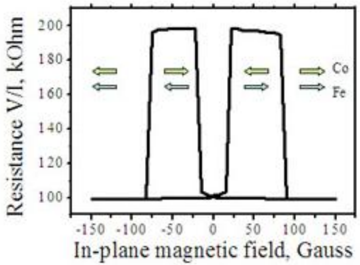
Read head for the HDD in the Sony Walkman

One layer is fixed.
The other layer can switch.
A magnetic bit on the HDD
switches one layer.

Magnetic Tunnel Junction - MTJ

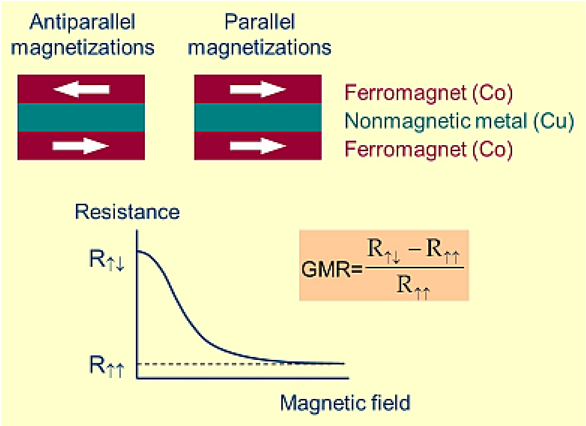
FM - insulator – FM
1 nm thick **insulator**





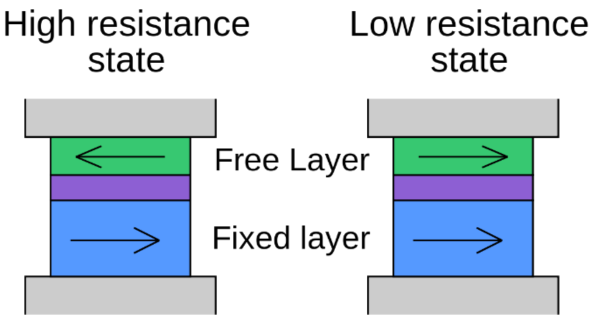
Types of Magnetoresistance HDD Read Heads

GMR - Giant MagnetoResistance



2007 Nobel Prize
Albert Fert and Peter Grünberg

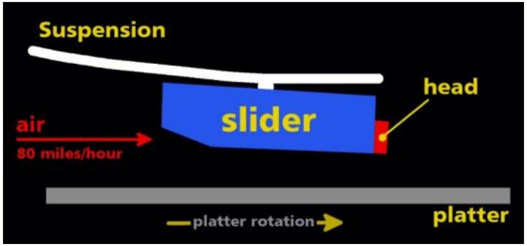
MTJ – Magnetic Tunnel Junction

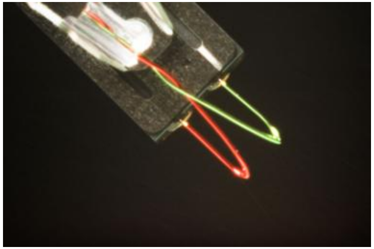


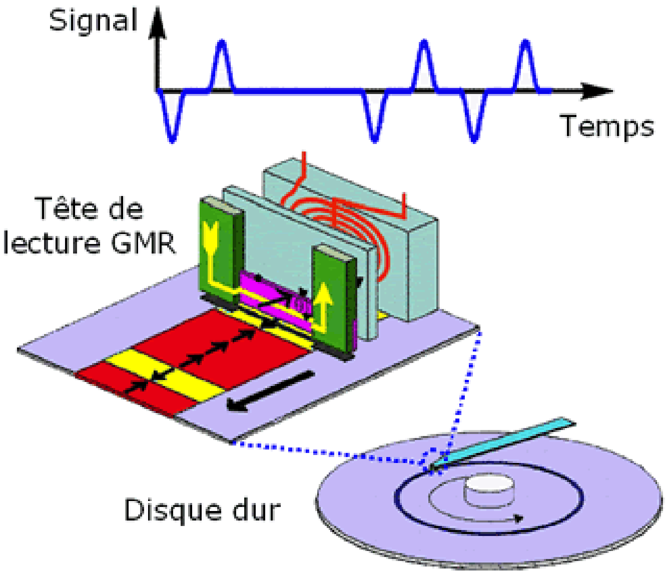
2009 Buckley Condensed Matter Prize
Jagadeesh Moodera, MIT

MTJ HDD Read Head

Disk track - 80 miles/hour







Comparison of Solid State Memories

	MRAM	SRAM	DRAM	Flash	FeRam
Read Speed	Fast	Fastest	Medium	Fast	Fast
Write Speed	Fast	Fastest	Medium	Low	Medium
Array Efficiency	Med/High	High	High	Med/Low	Medium
Future Scalability	Good	Good	Limited	Limited	Limited
Cell Density	Med/High	Low	High	Medium	Medium
Non-Volatility	Yes	No	No	Yes	Yes
Endurance	Infinite	Infinite	Infinite	Limited	Limited
Cell Leakage	Low	Low/High	High	Low	Low
Low Voltage	Yes	Yes	Limited	Limited	Limited
Complexity	Medium	Low	Medium	Medium	Medium

Better,
but still expensive

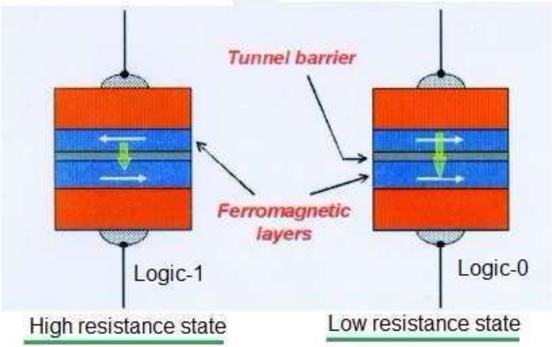
Now in SSD
and thumb drives

Spintronic SSD

Magnetic Random Access Memory - MRAM

MRAM is based on the Magnetic Tunnel Junction

FM – insulator – FM

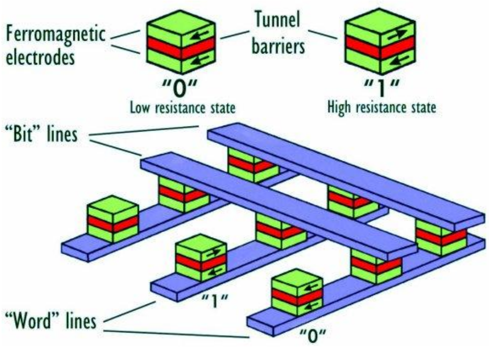


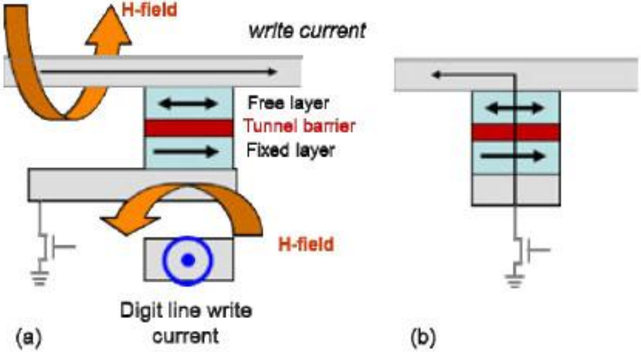
To make a memory bit,
need to be able to flip the
moment direction of one FM layer.

MRAM - Magnetic Random Access Memory

MRAM

- Nonvolatile memory
- Stores a bit of data in a MTJ
  (magnetic tunnel junction)
- **Switches by current in wires - NG**

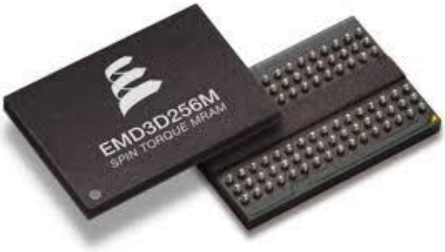


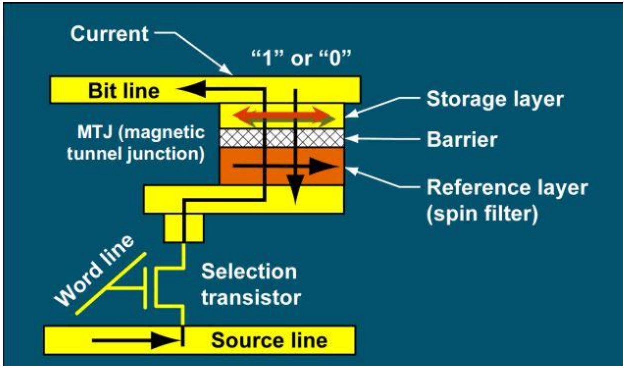


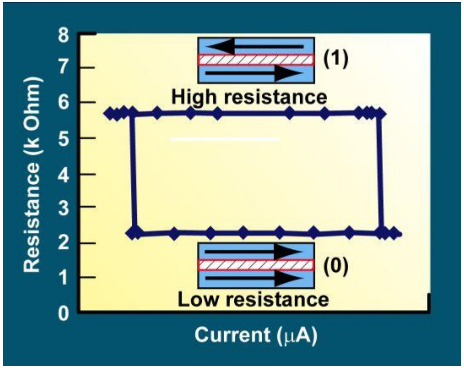
STT – Spin Transfer Torque Memory

STT RAM

- Nonvolatile memory
- Simpler than MRAM
  only need 2 wires
- **Switches by current in STT**







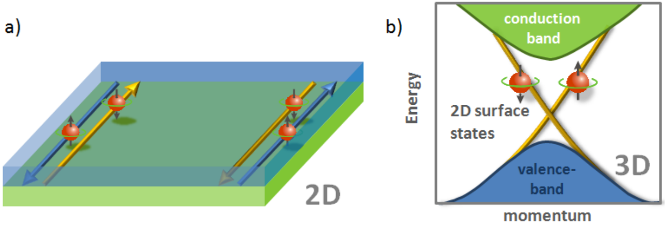
Topological Quantum Electronics

Topological Insulators – Bi_2Se_3

TIs have separate highway lanes for spin-up and spin-down electrons.

In other words, the spin direction is locked to the momentum direction.

Note different spin states for different directions.

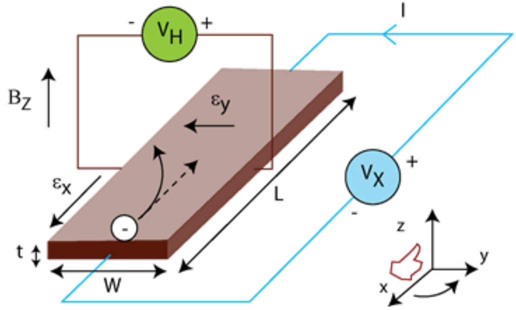


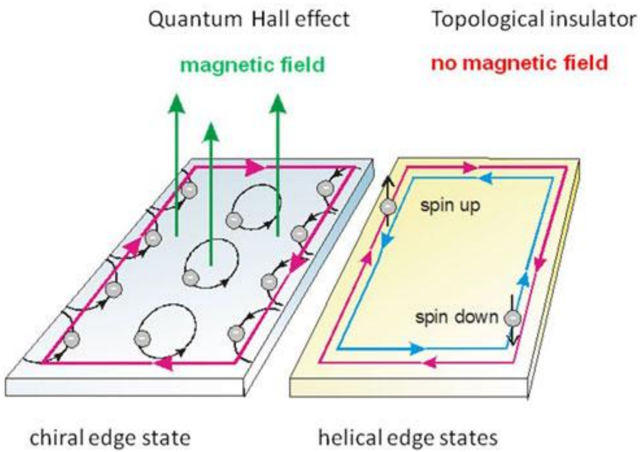
Note states in the forbidden gap

Hall Effect in Topological Insulators

[Video of TI]

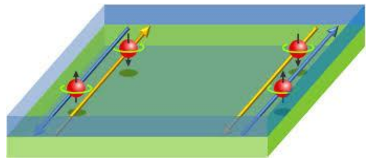
Hall Effect - **magnetic field**
forces electrons to edges.
$\underline{\mathbf{F}} = q\, \underline{\mathbf{v}} \times \underline{\mathbf{B}}$





Superconductor-like Topological Insulator

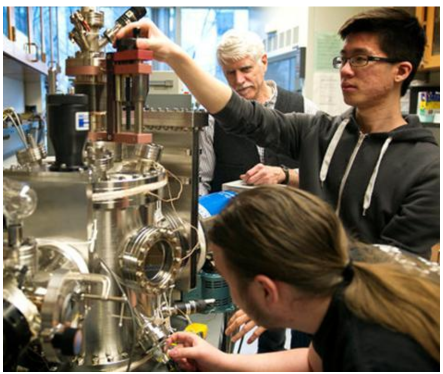
Donuts, Superconductors and Green Electronics – A Physics Professor Explains Their Connection



Quantum Anomalous Hall Effect
- **Nearly zero resistance $\rho_{xx} \sim 0$**
C.-Z. Chang, D. Heiman, et al.
Nature Materials *14, 473 (2015).*

When electrons of one spin (say up) **encounter a defect**, they cannot backscatter, as the backward-going direction has the opposite spin (down).

Nonmagnetic defects cannot flip the spin, thus, the electrons do not have resistance as they **cannot change direction by scattering**.

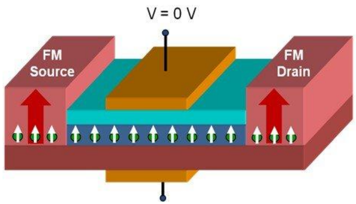


Heiman and collaborators took a new approach to magnetizing topological insulators, a goal that's been pursued for some time now. They put thin layers of the insulator together with thin layers of a ferromagnet. This produces a conducting material that produces much less scattering of electrons when used, producing a phenomenon known as the Quantum Anomalous Hall Effect. The reduction in electron scatter results in what's called a dissipationless current, essentially producing a **superconductor-like** material — a highly efficient conducing material that experiences very little resistance and can therefore function with much less power and on far less energy.

Spin-FET – Spin Field Effect Transistor

skip

Gate V = 0
current flows
Source → Drain
Low resistance

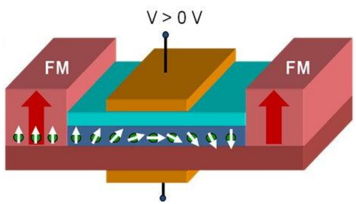


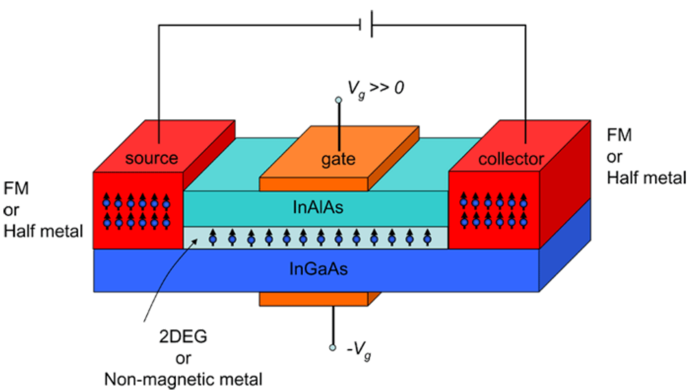
Electrons moving in an electric field feel an **effective magnetic field**

The magnetic field then rotates the spin directions

Antialigned spins are then **blocked**

Gate V > 0
no current flows
High resistance





Quantum Computers

What is a Quantum Computer?

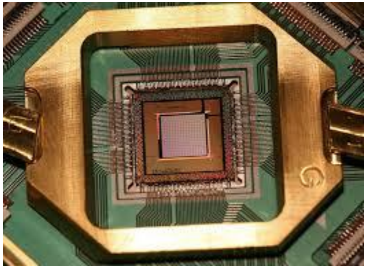
What is a Qbit?

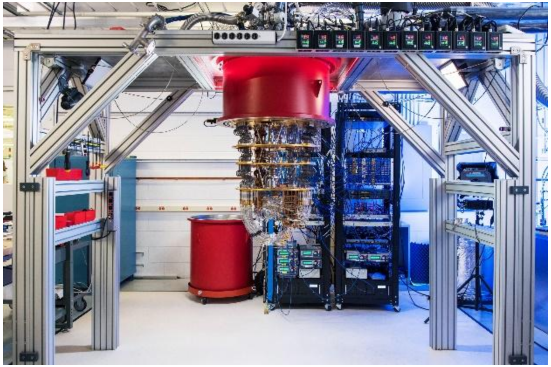
What are QCs good for?

What is a Quantum Computer?

Physical QC

- Contains an array of N quantum mechanically coupled **Qbits** (N ~ 53+)
- Held at sub-Kelvin temperatures in a cryostat the size of a refrigerator
- Connected to hundreds of wires and a number of common computers





Qbits

- QC rely on the quantum states of Q-bits (Qb).
  A Qbit is a two-state quantum mechanical system,
  e.g. **electron spin**
- A Qb can simultaneously be in two states a once.
  Both 0 and 1. This is called coherent **superposition**
- Any measurement changes the quantum state.
- Several Qbs interacting results in **entanglement**.
  The Qbs are connected without wires.
- Cannot describe one Qb without also describing the others,
  even if they are far apart.
  Einstein referring to it as "*spooky action at a distance.*"
- Number of states is 2^N, N is the number of Q-bits.
  N=10 Qbs -> 10^3 states; N=20 -> 10^6 states.
  72 Qb have been demonstrated by Google.

What are QCs Good For?

QCs are useful for **encrypting** information

Algorithms for QCs will be so-called fault tolerant. There are basically only two well known examples:

- Shor's **factorization** algorithm
  56153=233×241 factored with only 4 Qb
- Grover's algorithm for unstructured **search**

Nearly all classical calculations
cannot be accelerated on a QC.

Google
IBM
Microsoft
Intel

> 18 possible physical systems for QC (wiki-QC)
semiconductors (Si:P), optics, NMR,
diamond, spintronics, **superconductors**

https://www.nytimes.com/2019/10/30/opinion/google-quantum-computer-sycamore.html

Neuromorphic Computing

- Third generation AI (artificial Intelligence)
- Seeks to emulate the **neural structure** of the **human brain**
- Uses conventional ICs for integrated circuits analog
- Probabilistic computing addresses the fundamental uncertainty and noise of natural data
- Deals with the uncertainty, ambiguity, and contradiction in the natural world
- Incorporates learning and development, adapts to local change (plasticity), and facilitates **evolutionary** change.

https://www.intel.com/content/www/us/en/research/neuromorphic-computing.html

https://en.wikipedia.org/wiki/Neuromorphic_engineering

The END
종료