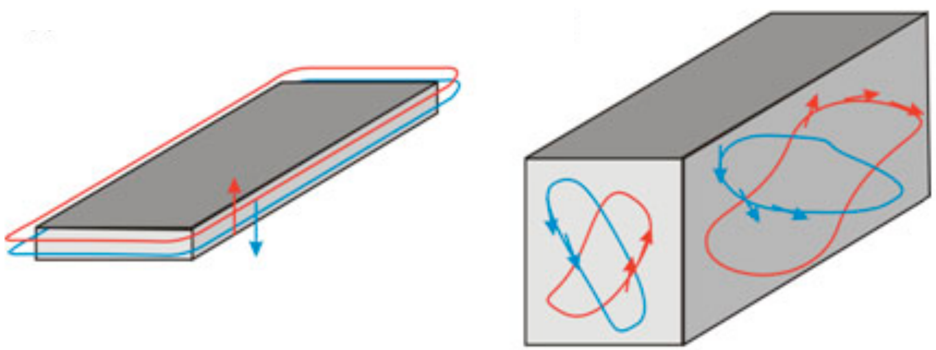
News from NBIA

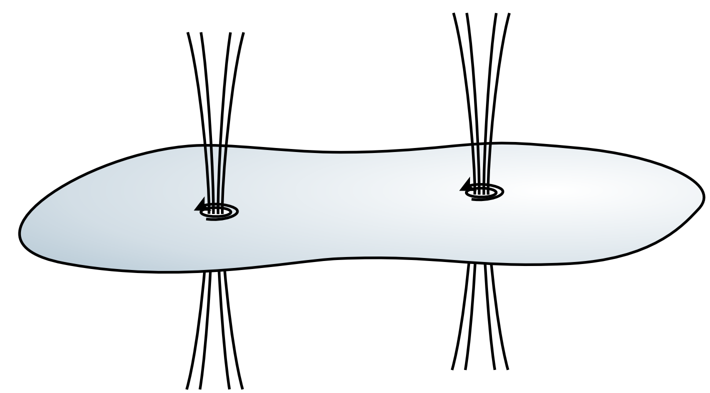
Condensed Matter Physics: from new materials to quantum technology

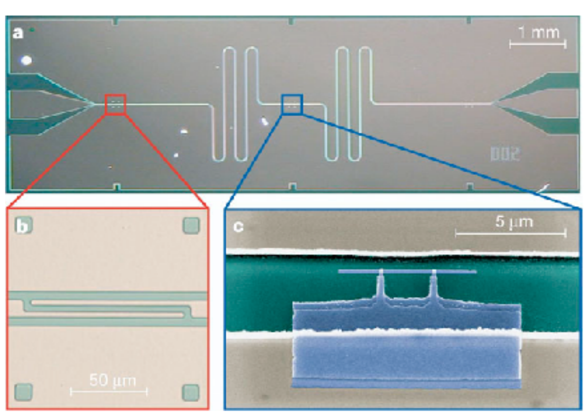
Mark Rudner

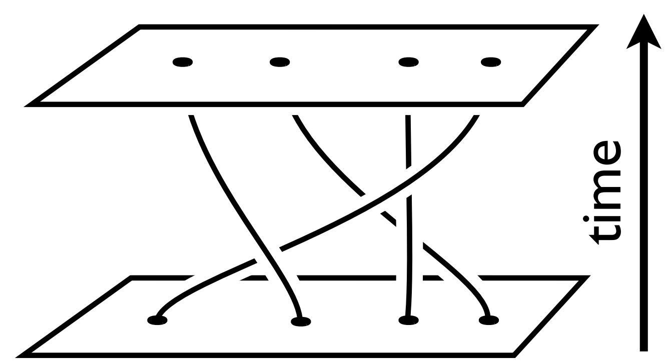


2D topological insulator

3D topological insulator







~100 years after Bohr, the basic laws and players are established

1913

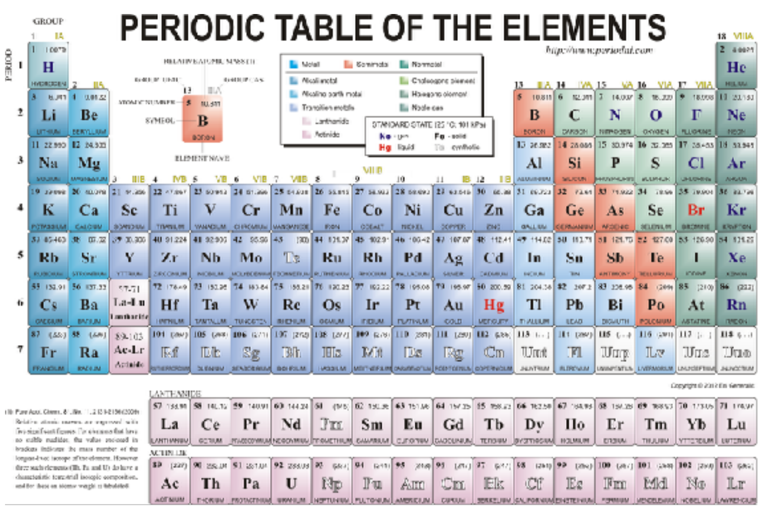
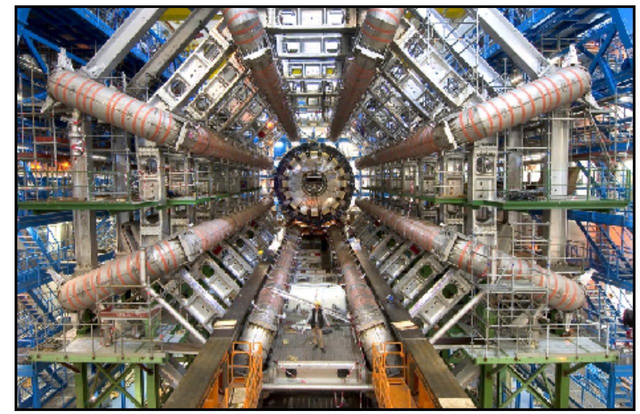
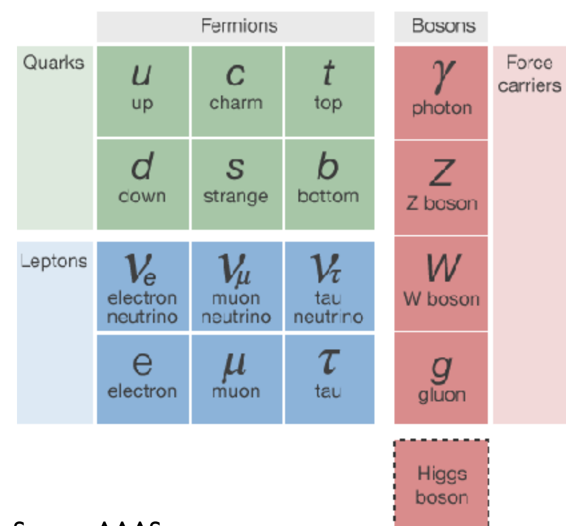


Image from www.periodni.com

2013

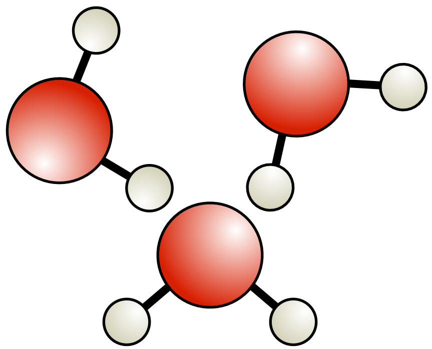




Source: AAAS

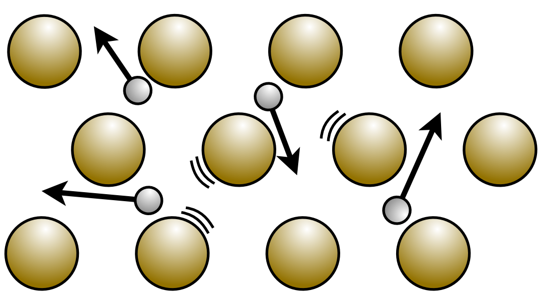
Collective behavior unlike that of individual constituents

Water molecules

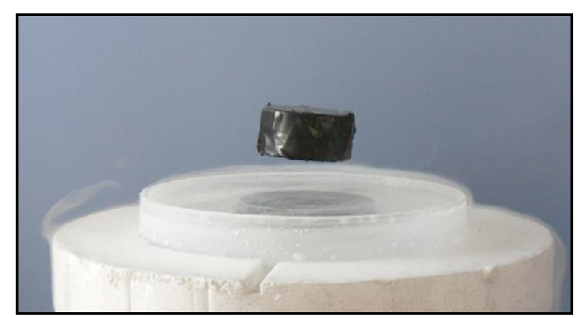


Ocean waves

Electrons in a crystal



Superconductivity



“For theoretical discoveries of topological phase transitions and topological phases of matter”

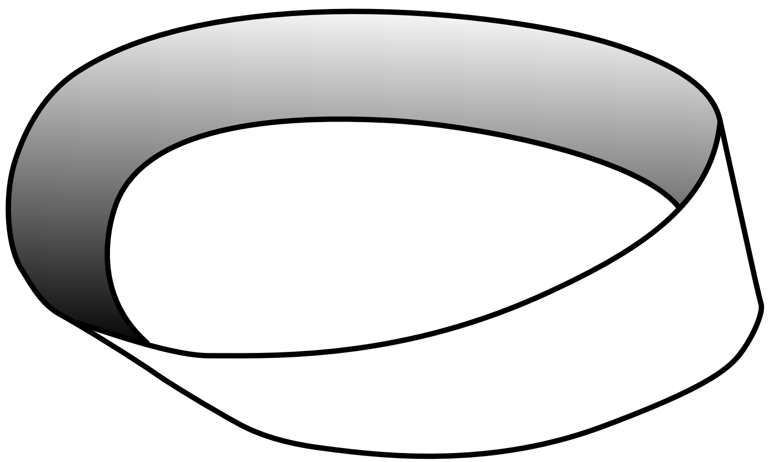
David Thouless
(U. Washington)

Duncan Haldane
(Princeton)

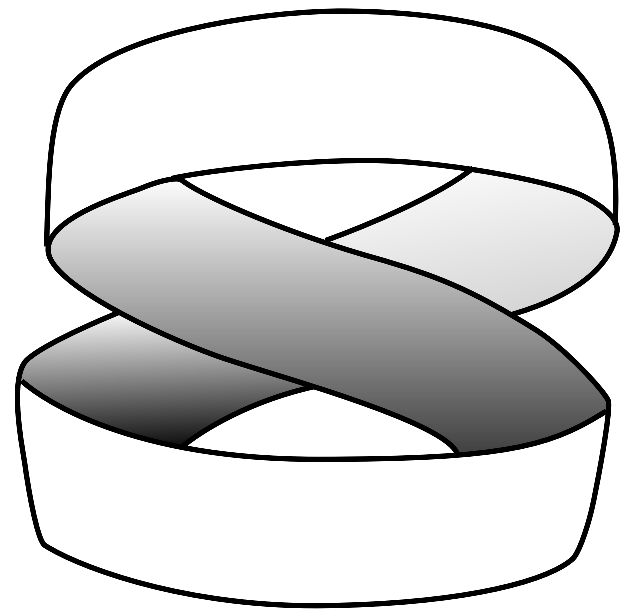
Michael Kosterlitz
(Brown)

Nobel prize, 2016

Topologically distinct objects cannot be smoothly interconverted

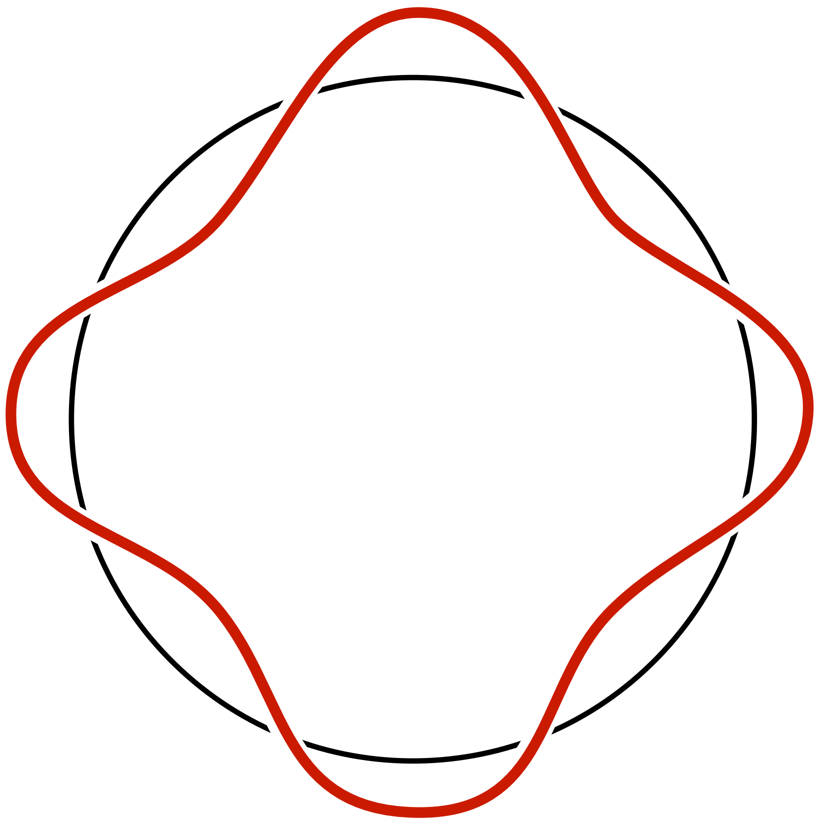


Simple Loop

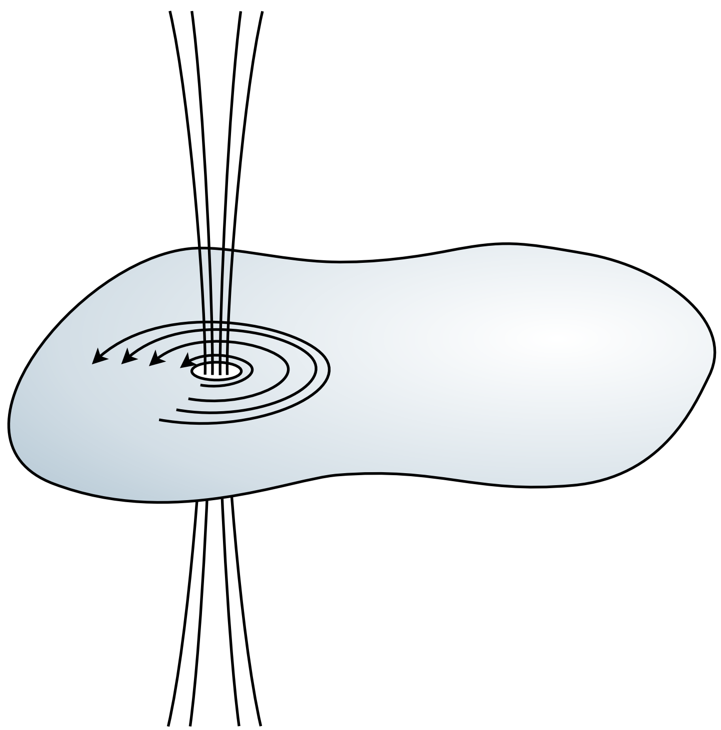


Twisted Strip

Bohr model: wave must "catch its tail" going around a ring, number of wavelengths is quantized and ***topological***

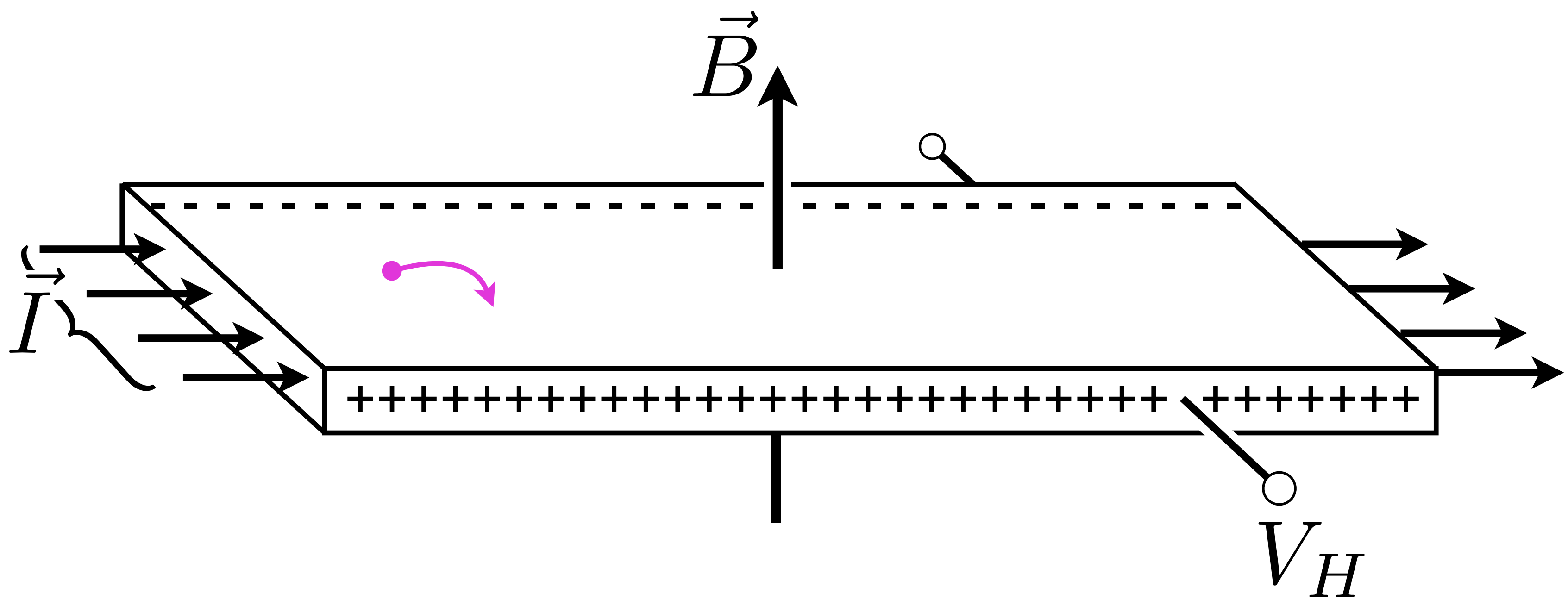


Vortices in superconductors: "quantum whirlpools"



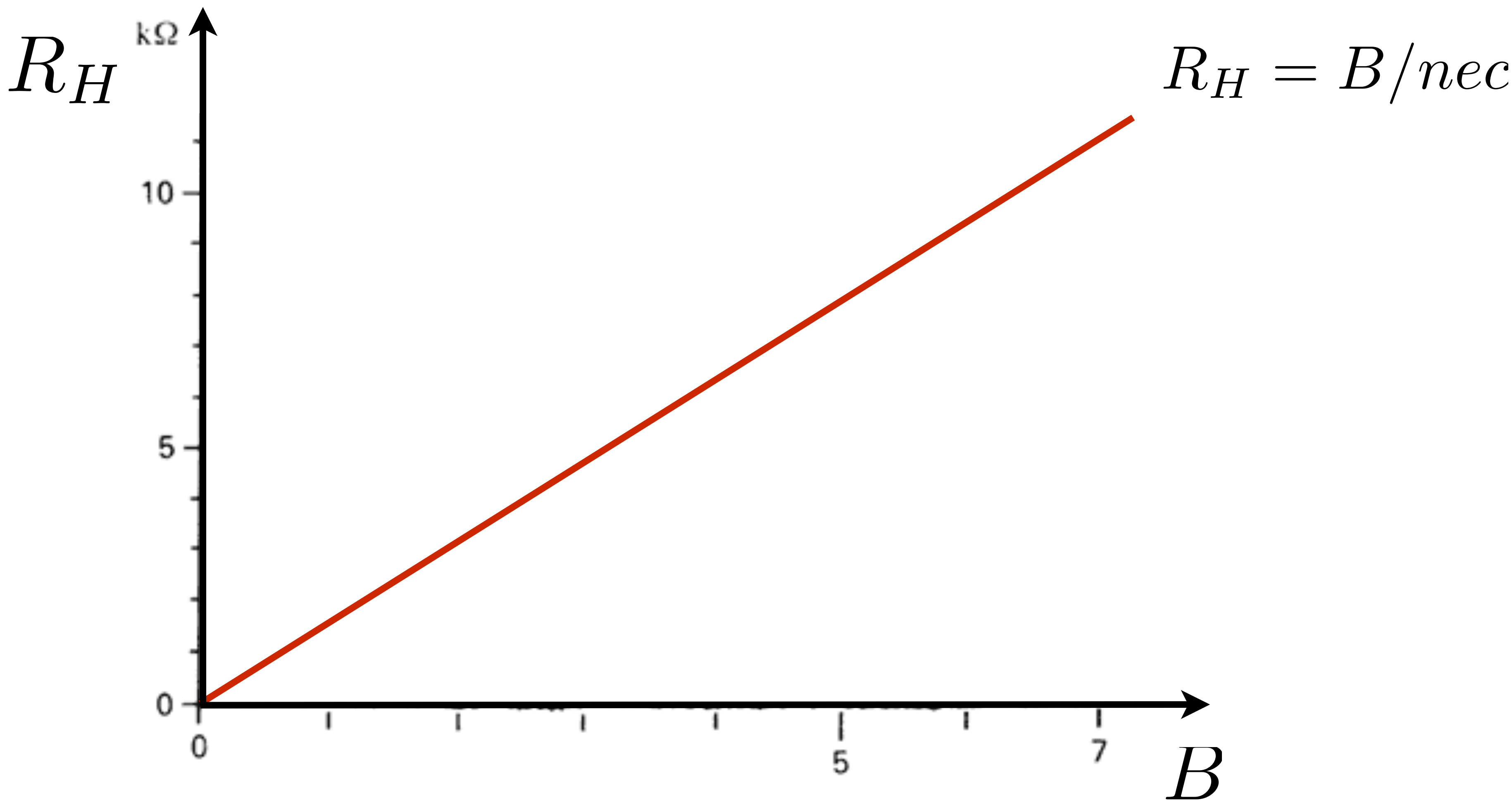
* Kosterlitz + Thouless: vortices crucial for phase transition in 2D

Hall effect: out-of-plane magnetic field generates voltage transverse to applied current



$$R_H \equiv V_H / I$$

Classically, Hall resistance is proportional to B



Hall resistance features extremely flat steps at low T, high B

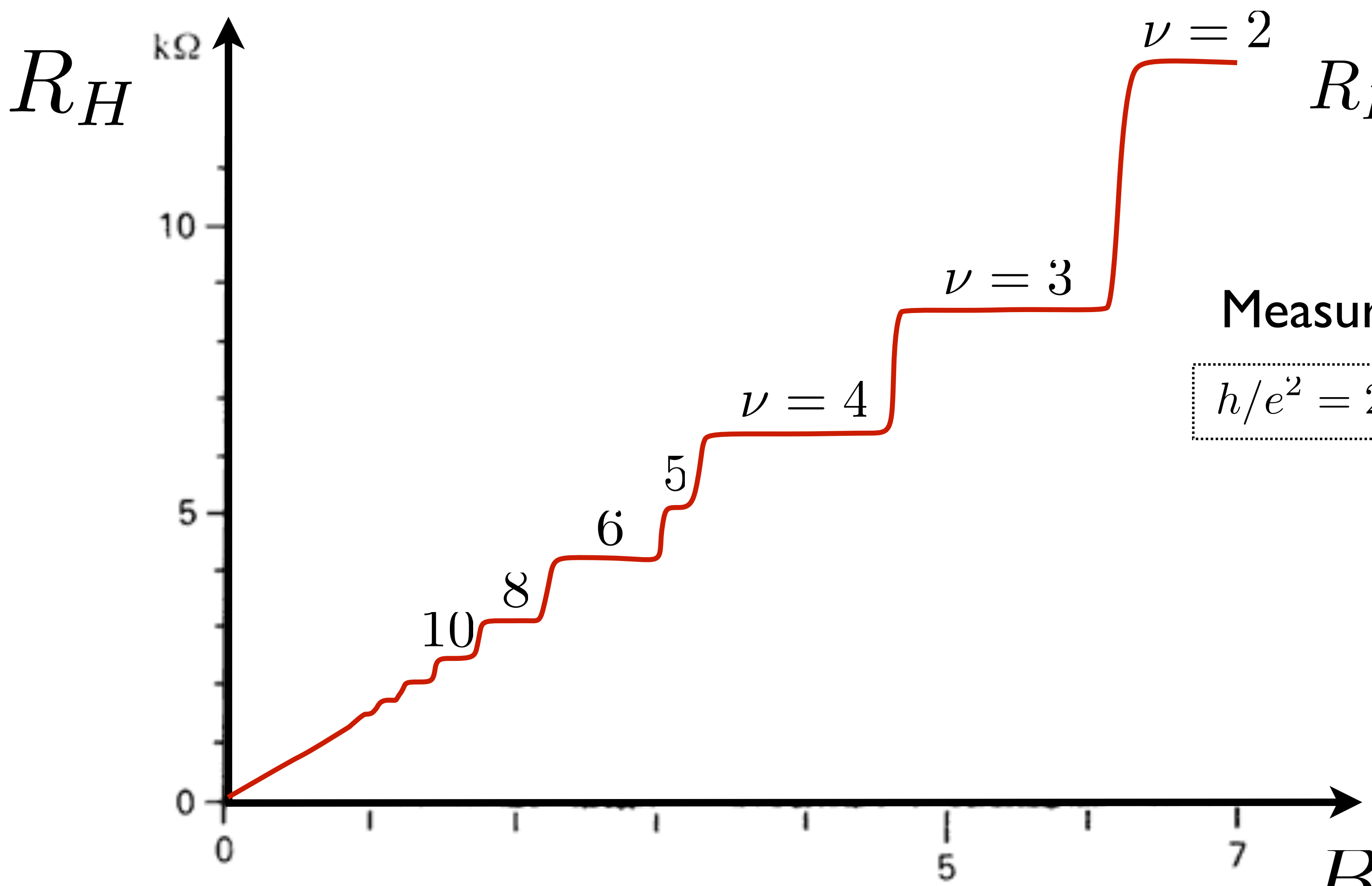


Figure adapted from nobelprize.org

$$R_H = h/\nu e^2$$

Measurement Standard

$$h/e^2 = 25812.807557(18)\,\Omega$$

Hall resistance features extremely flat steps at low T, high B

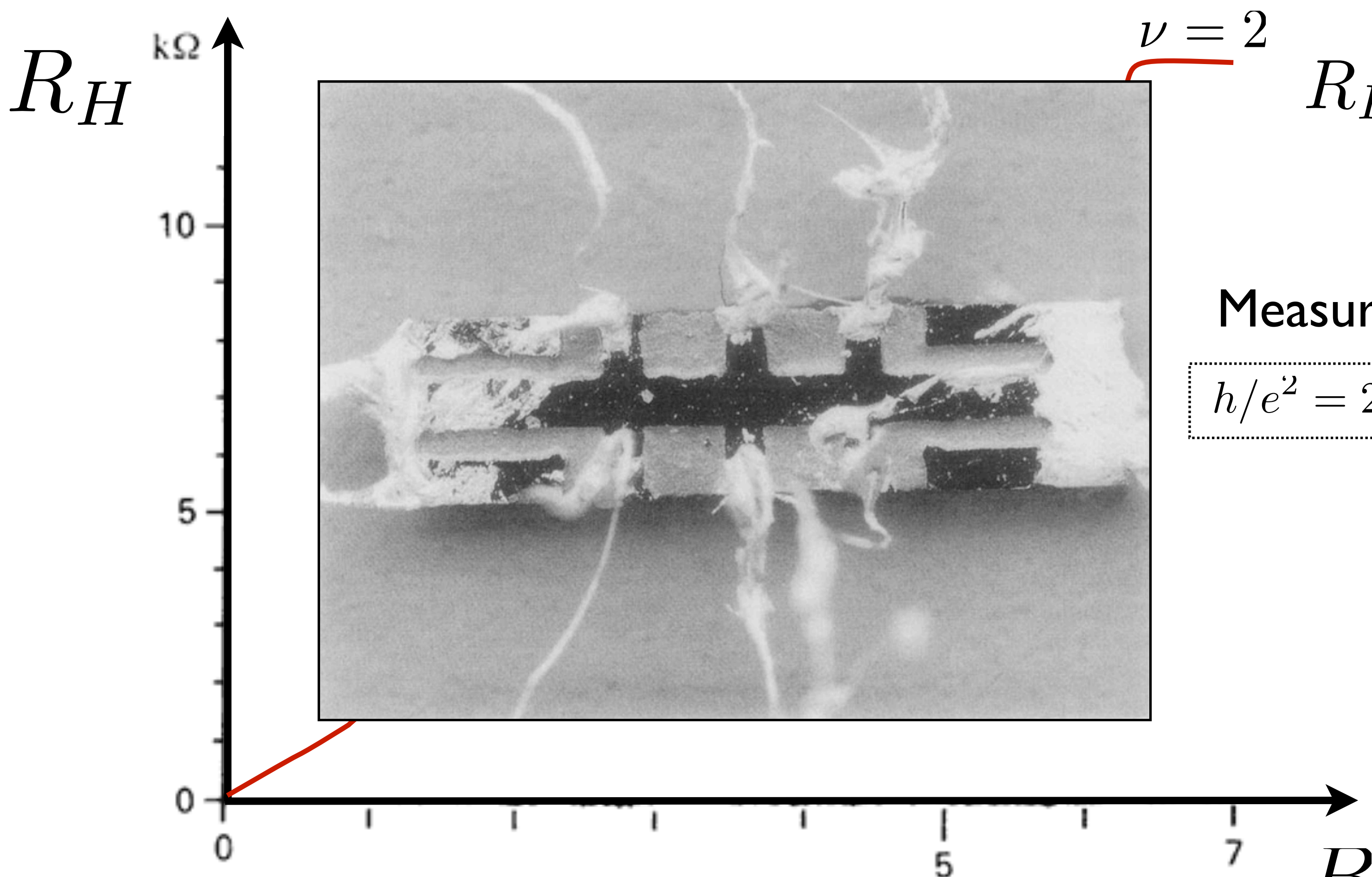


Figure adapted from nobelprize.org

$$R_H = h/\nu e^2$$

Measurement Standard

$$h/e^2 = 25812.807557(18)\,\Omega$$

Key theoretical insight, linking robustness to topology:

D. J. Thouless, M. Kohmoto, M. P. Nightingale, and M. den Nijs, Phys. Rev. Lett. **49**, 405 (1982).

Let’s play a game: conductor or insulator?

Image from: images-of-elements.com

Let's play a game: conductor or insulator?

Let's play a game: conductor or insulator?

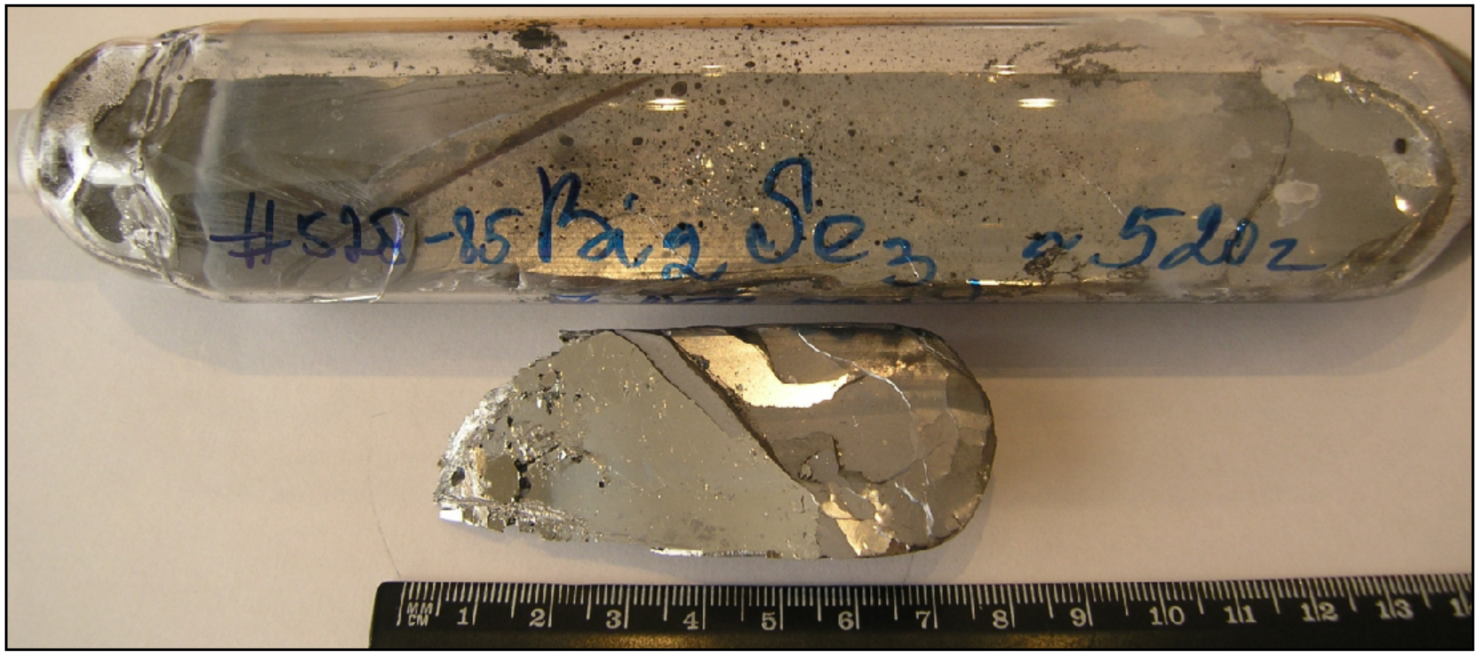
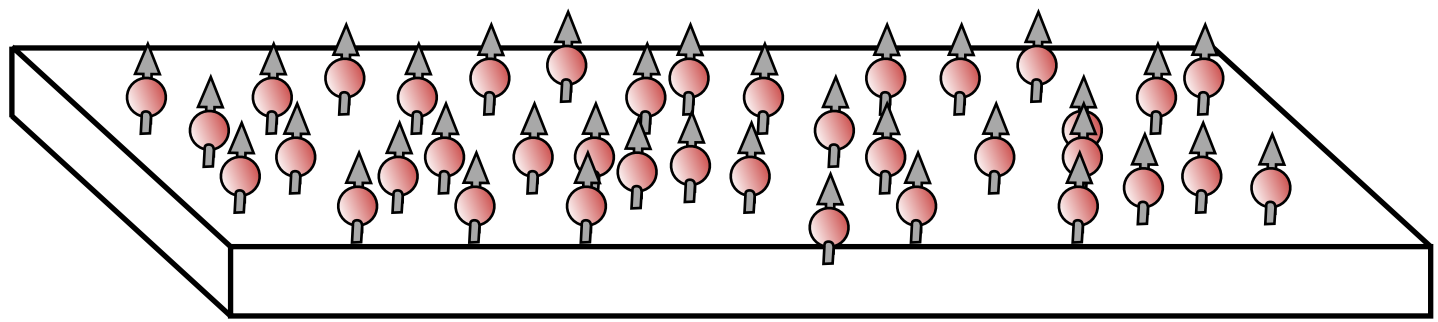
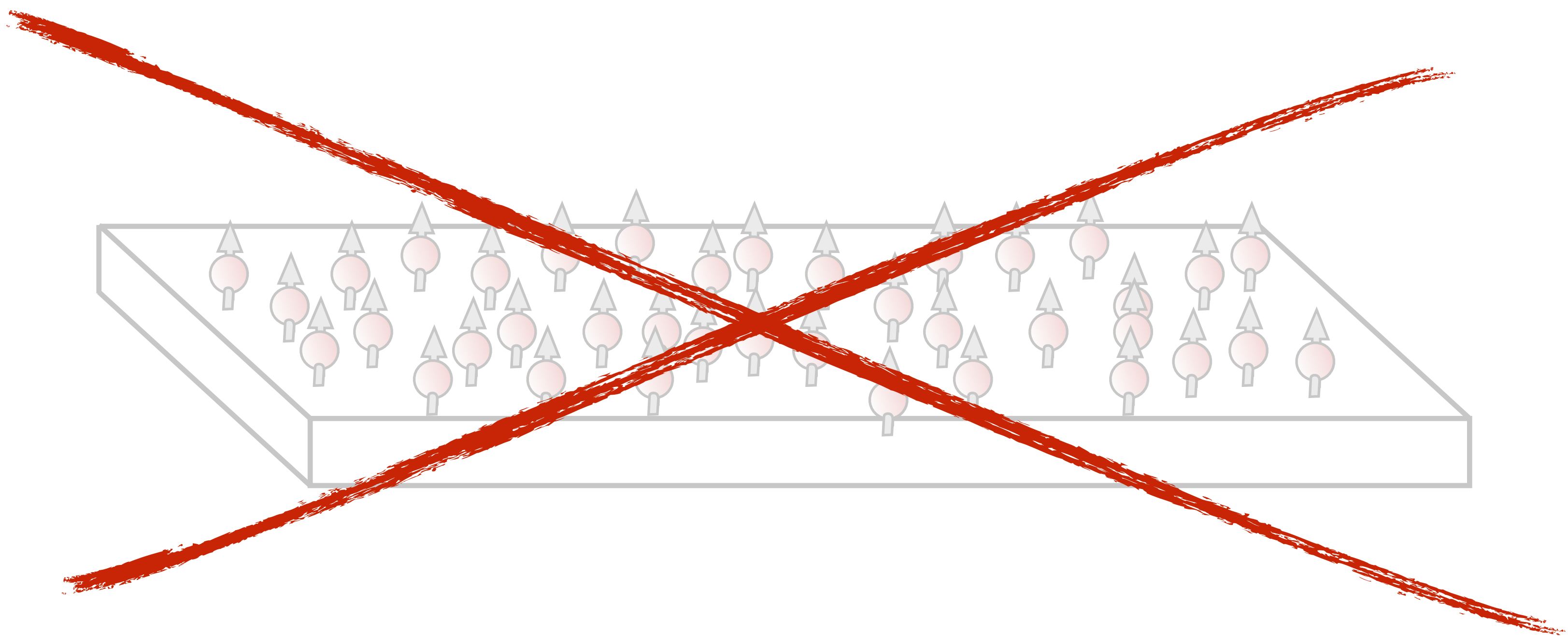


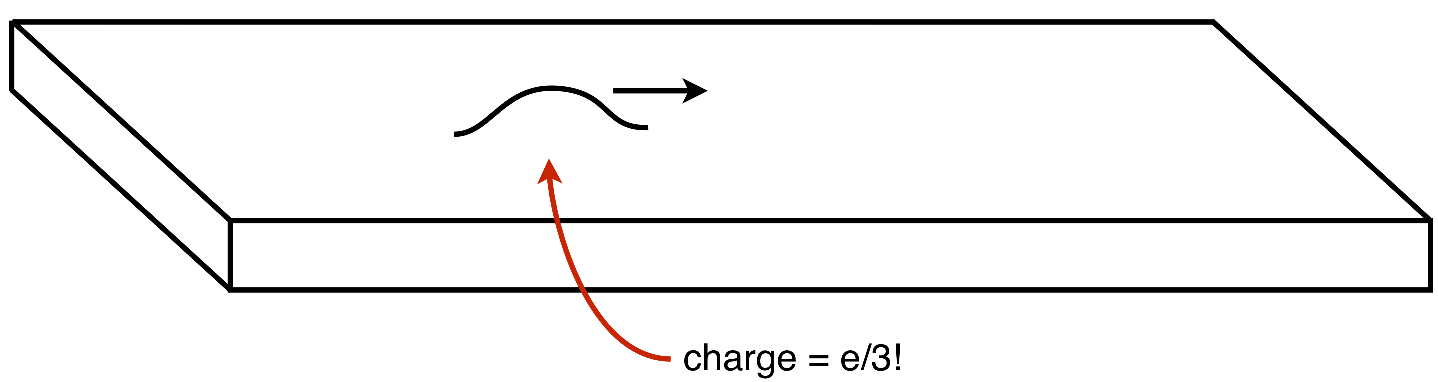
Image from: www.sttic.com.ru

New states with *fractional* values of ν: "split" the electron!



New states with *fractional* values of ν: "split" the electron!





Opportunities to discover new fundamental particles, in tabletop experiments!

We aim to understand the “dance” of the electrons

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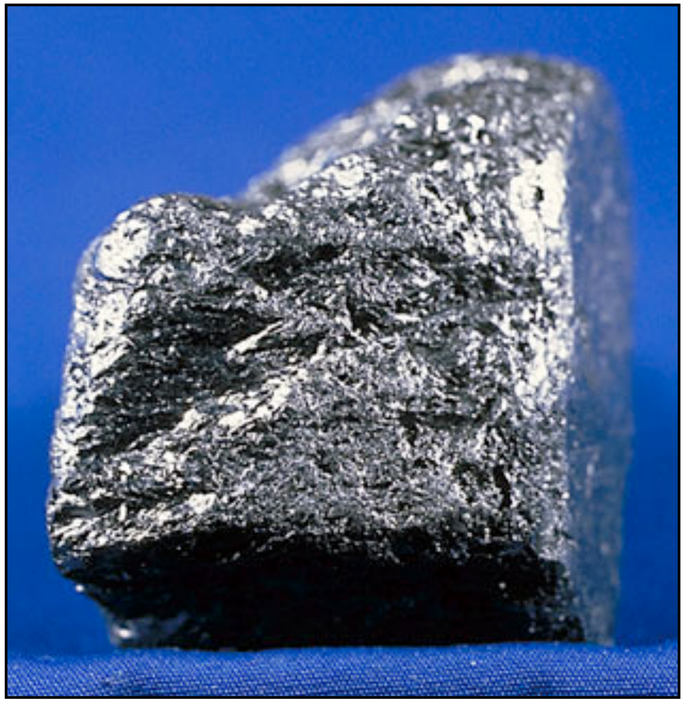
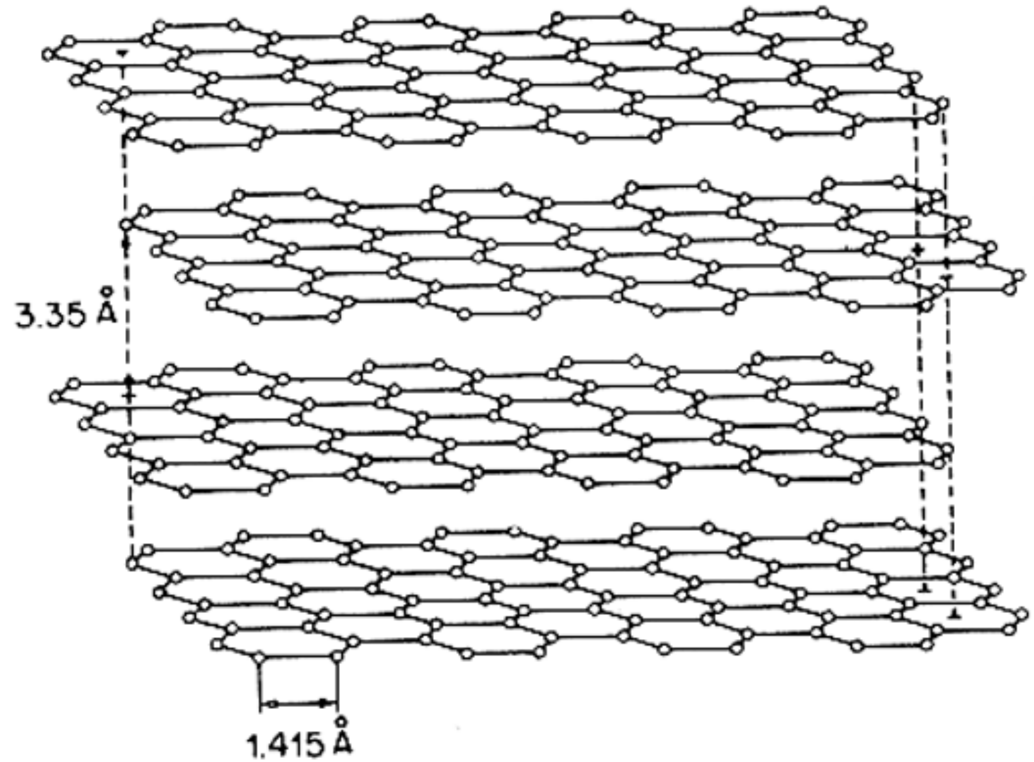
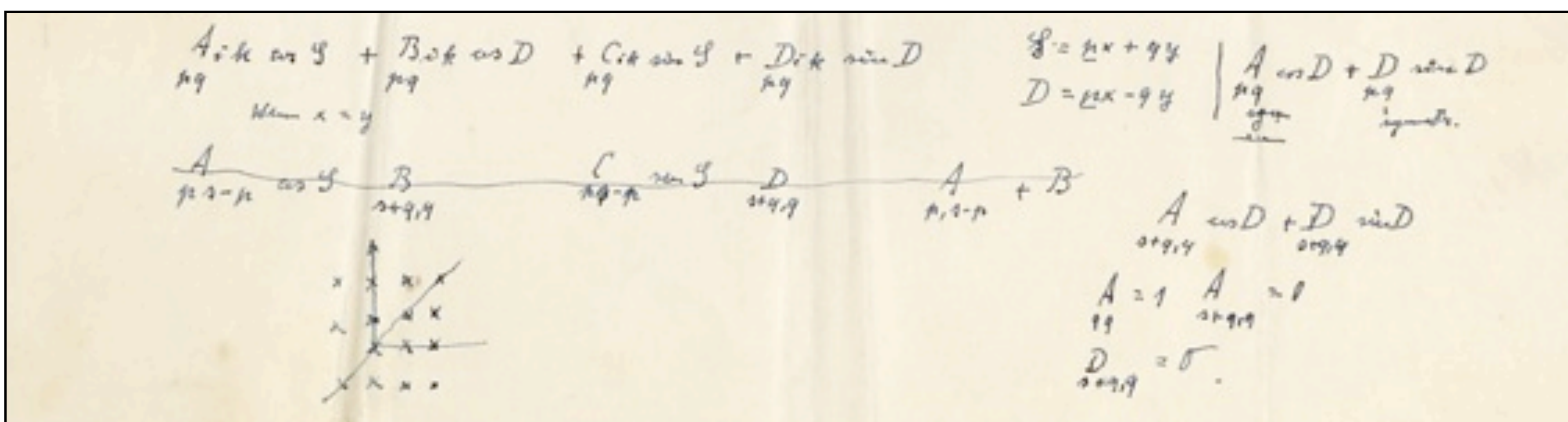
Graphite: stacked 2D sheets of carbon



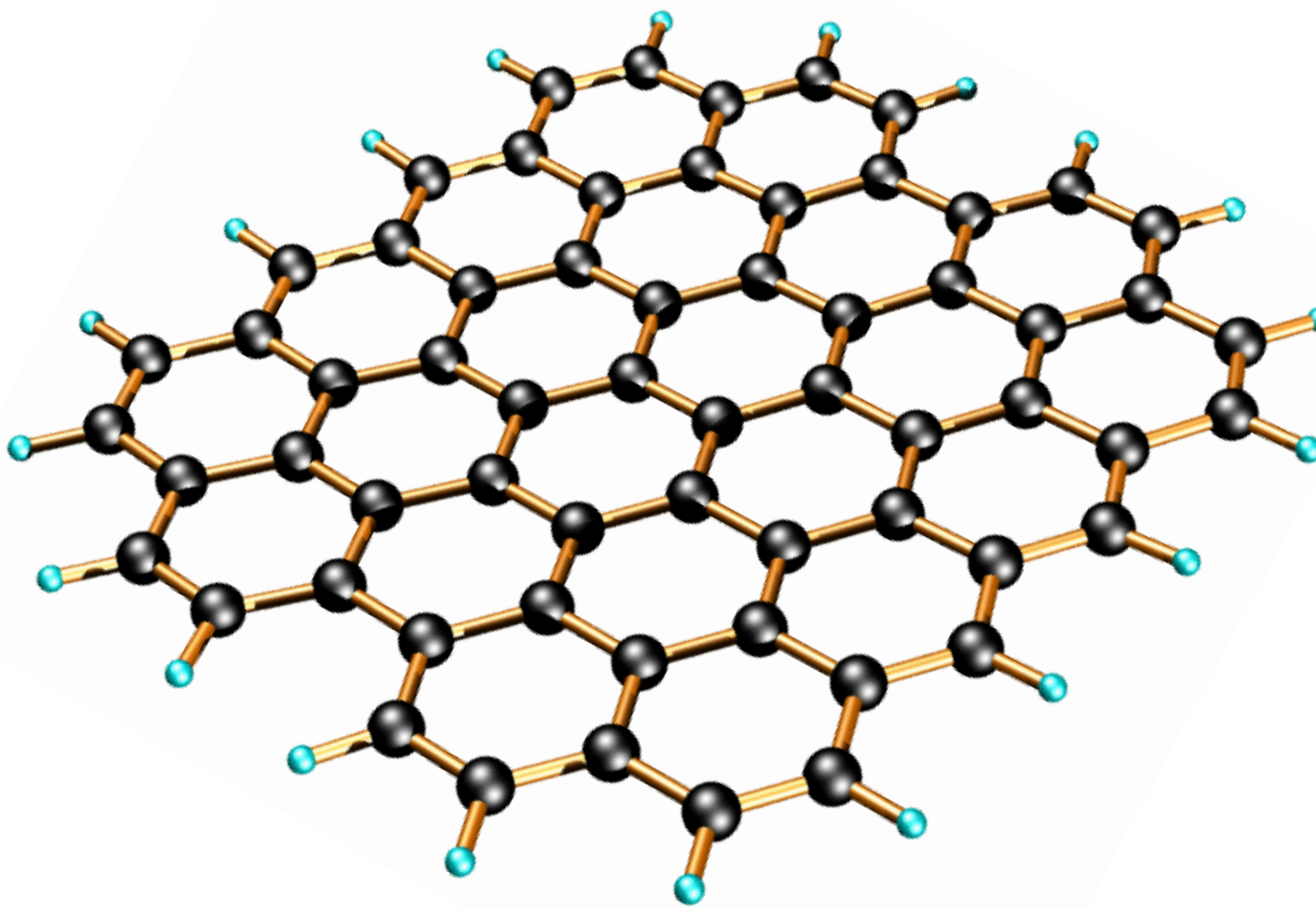


* Strong in-plane bonds, weak interaction between planes

Graphite: stacked 2D sheets of carbon



Graphene: a single atomic plane of carbon

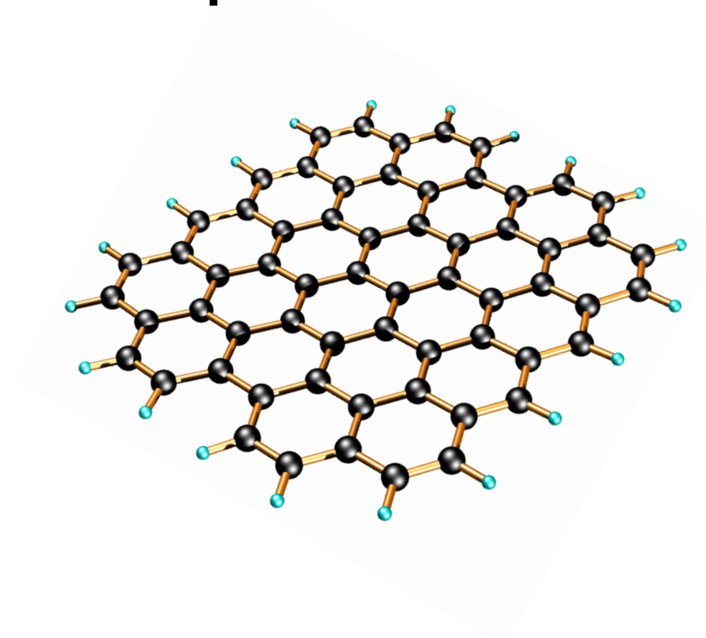


Exfoliation (Scotch tape) preparation protocol

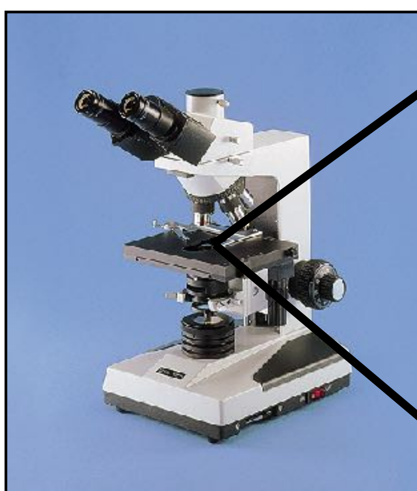
Step 1

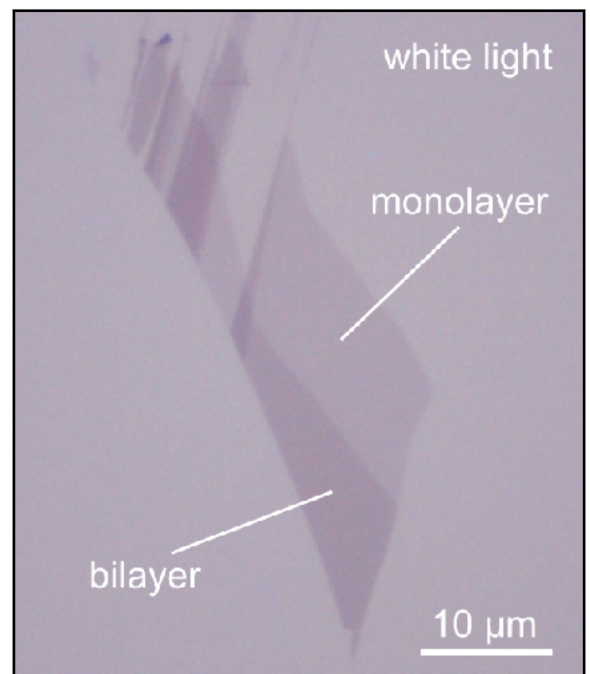
+

=



Step 2





Applications: sensitive, high-speed photodetectors

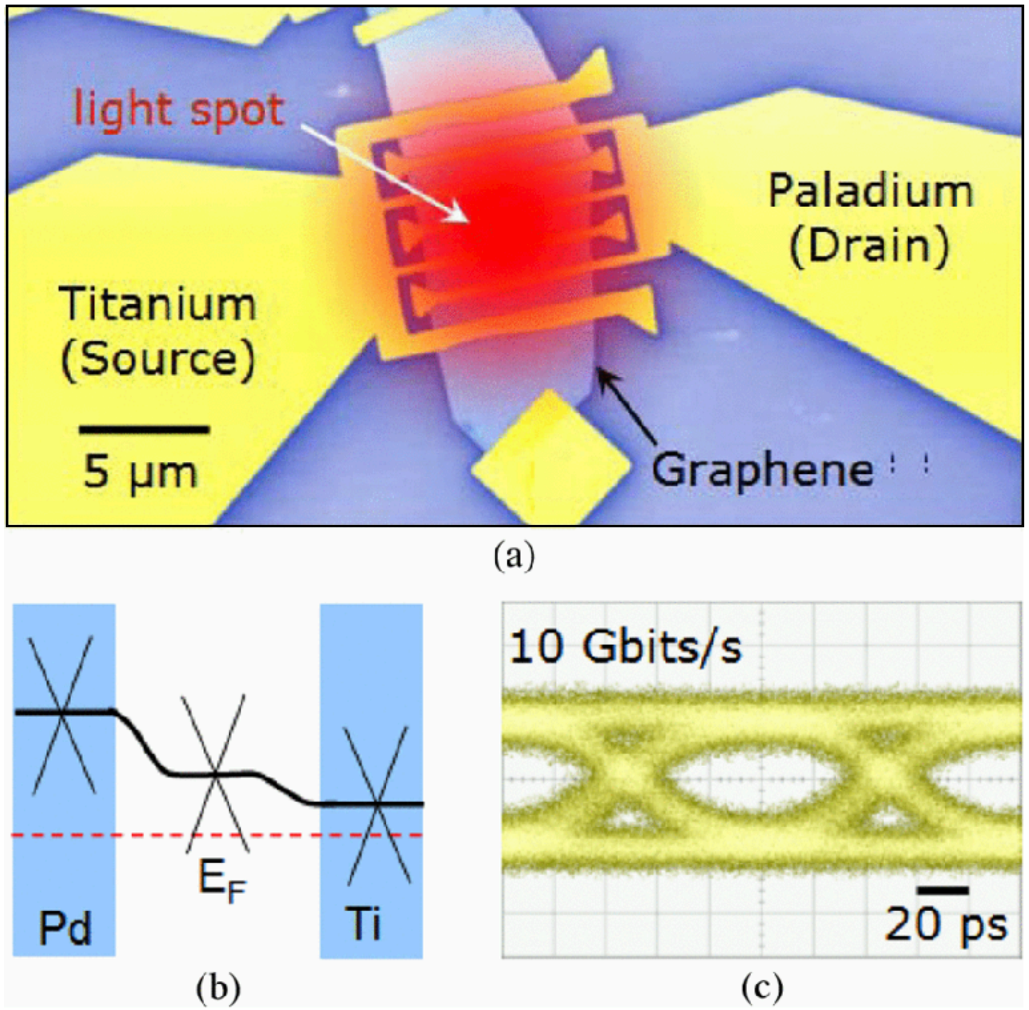
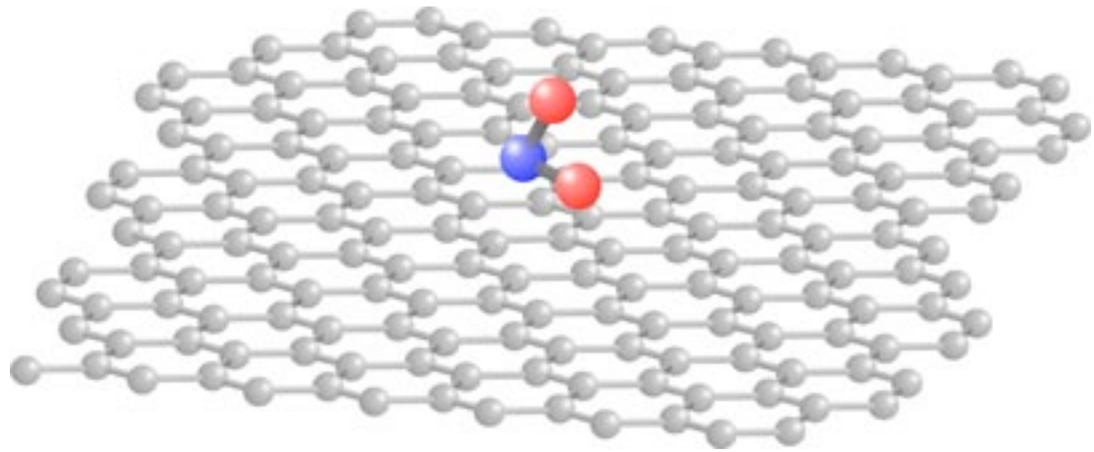


Figure adapted from T. Mueller, F. Xia, and P. Avouris, Nature Photonics 4, 297 (2010).

Applications: adsorbed gas detection



Directly exposed surface

Conductivity highly sensitive to doping

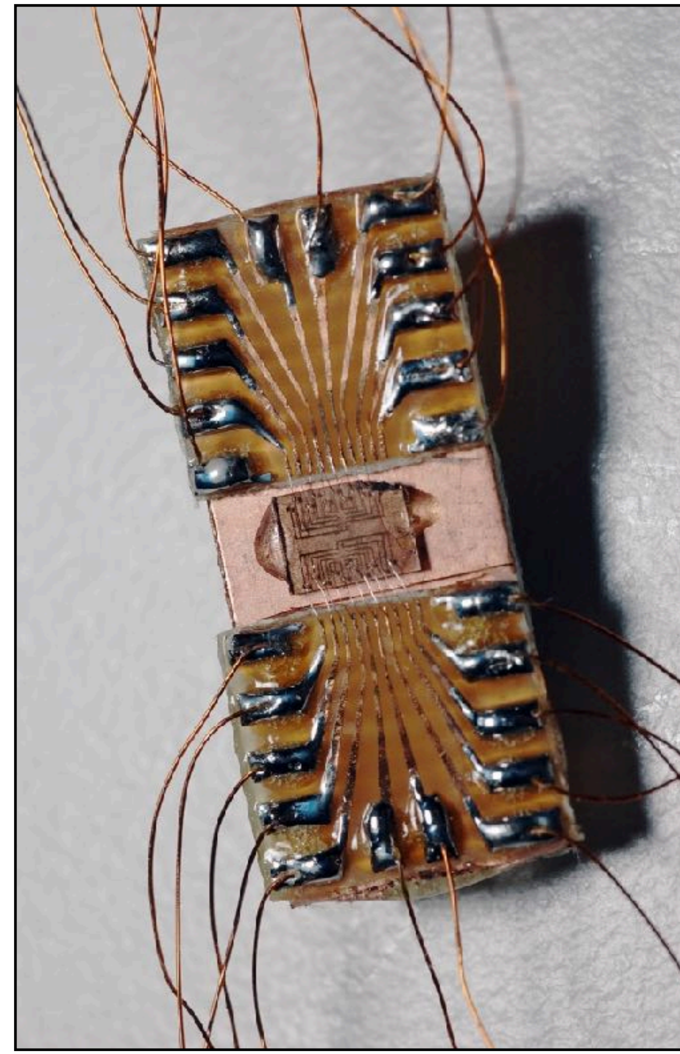
Applications: is carbon the new silicon?

High mobility (fast ops.)

Tunable carrier density

Small samples

No band gap



The future: hybrid materials built layer-by-layer

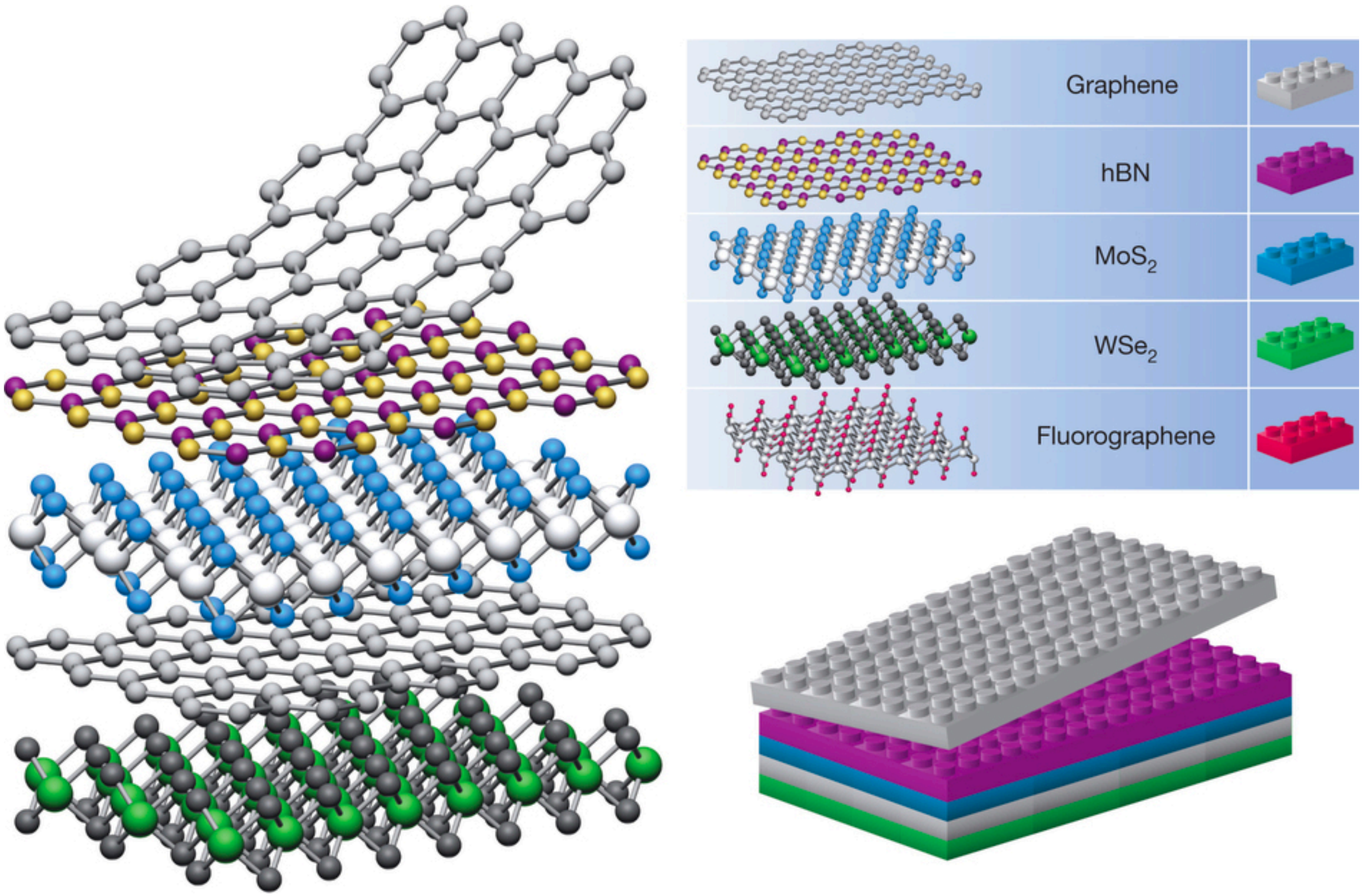


Figure from A. K. Geim et al., Nature 499, 419 (2013).

How can we use lasers, microwaves to *dynamically* control the behavior, properties of quantum systems?

~~Past~~

~~$Pb \rightarrow Au$~~

Present

$GaAs \rightarrow HgTe?$

$\rightarrow \quad \ldots \quad ?$

$100M Question: Can a system governed by *quantum mechanical* laws compute better?

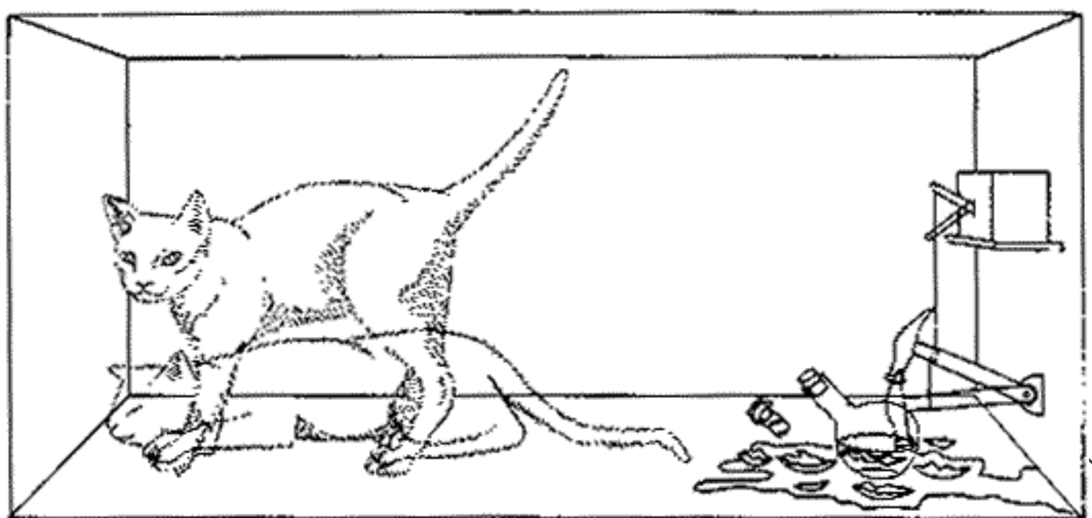
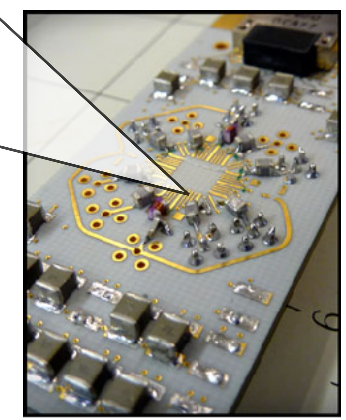


Image from: www.upscale.utoronto.ca



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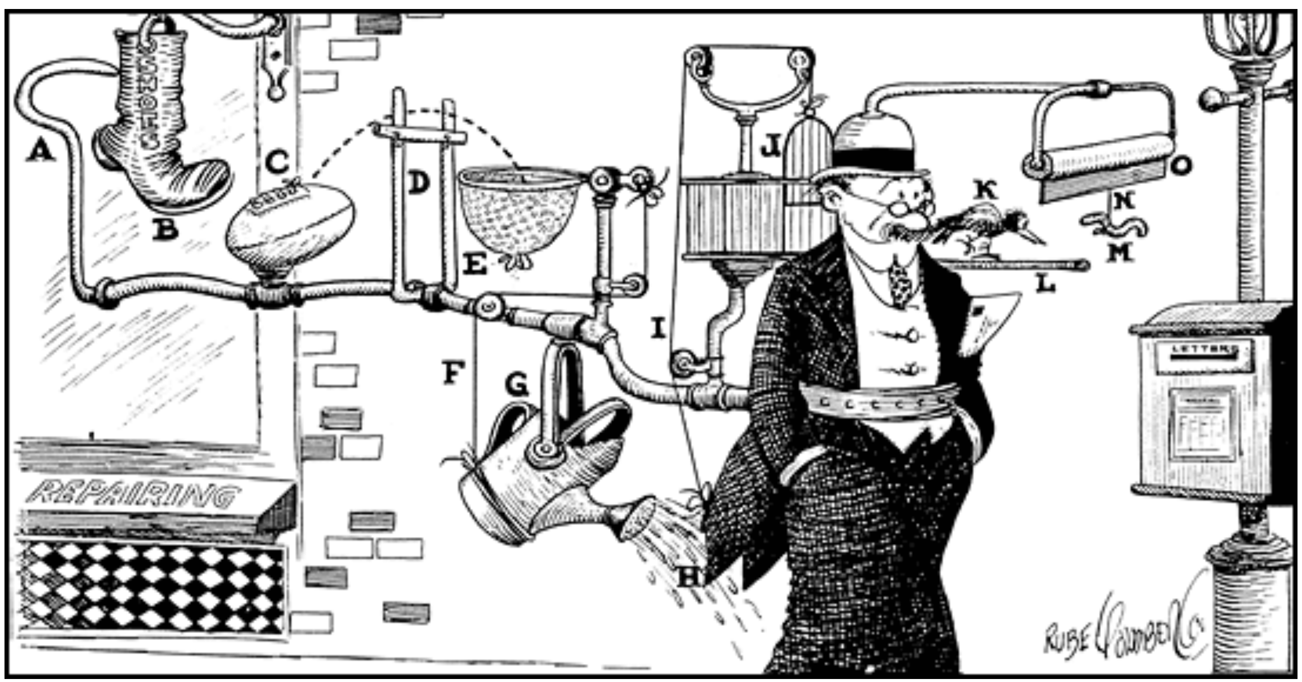
Part II: Information is physical

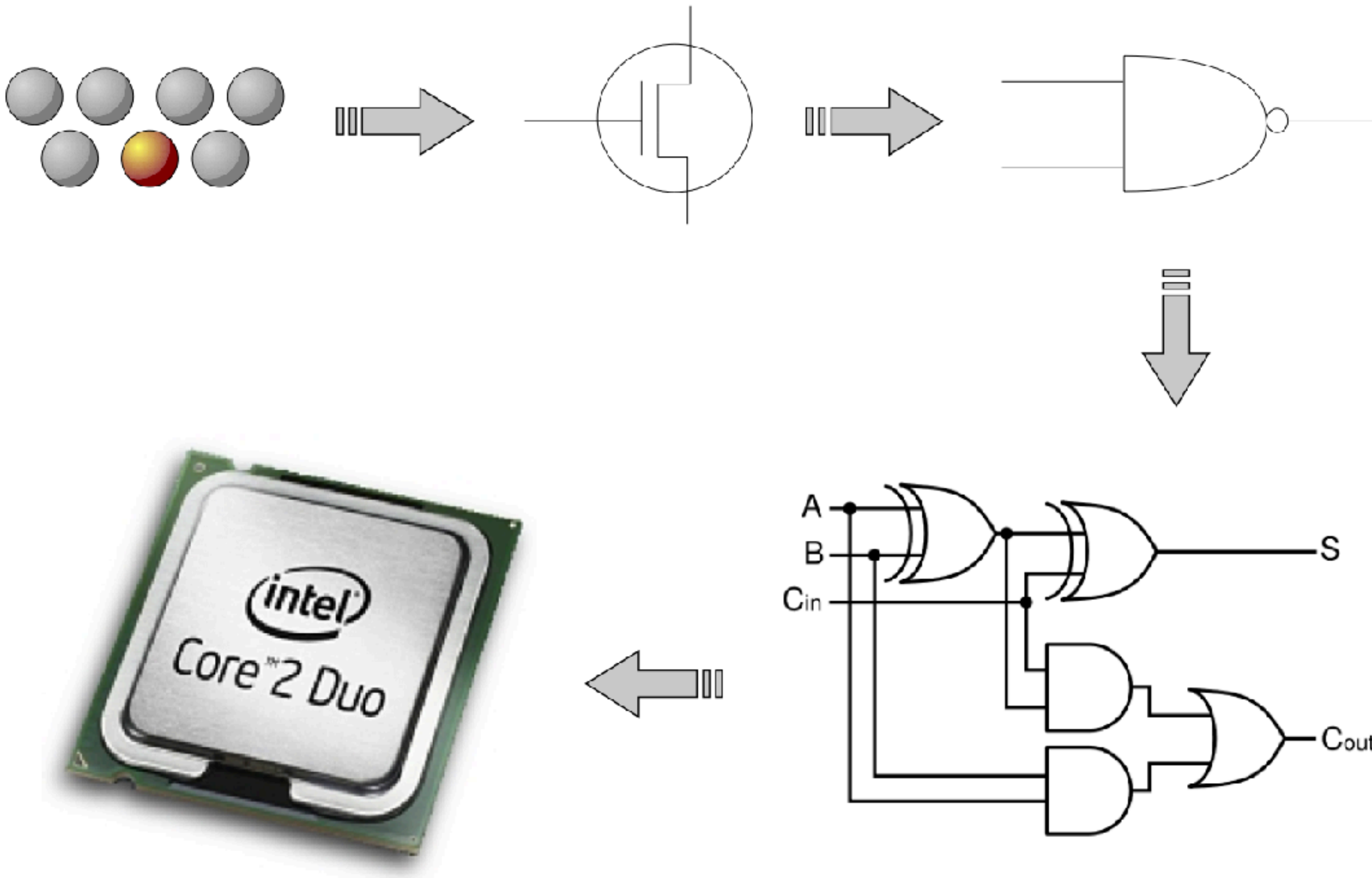
Minimalist view of a (digital) computer

Store information (discretely) in state of physical system

Control behavior of system based on this information

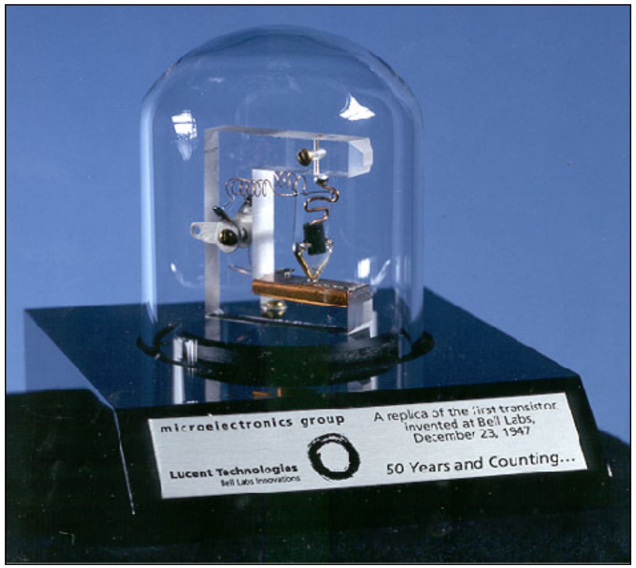


Transistor is the basic functional element in a digital processor



Smaller, faster, lighter; underlying idea remains the same

several inches



1947

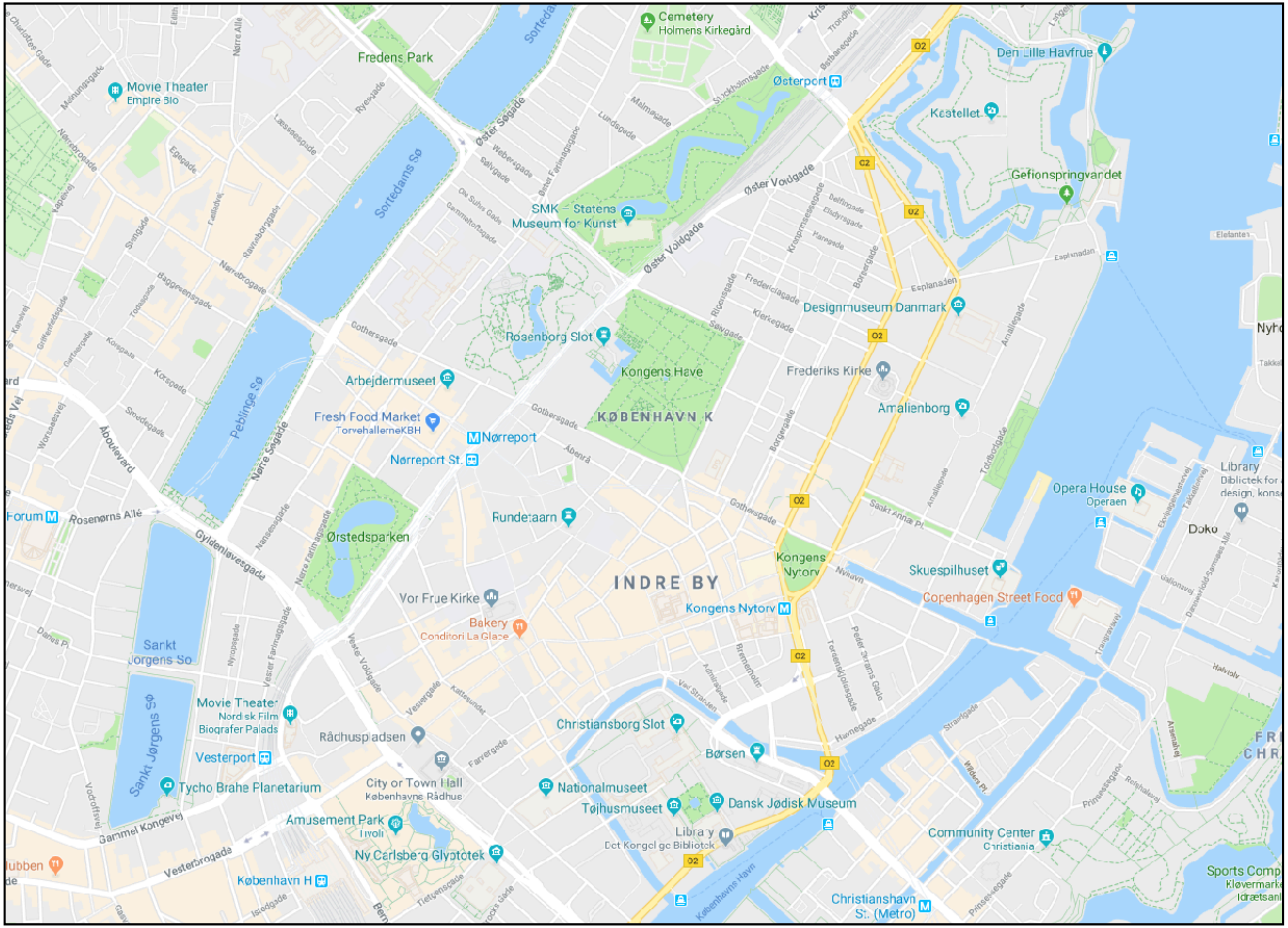
2.31 inches
58.6 mm

4.87 inches
123.8 mm

Today

Question: how big would an iPhone be with original transistors?

Here’s how far we’ve come:



Here's how far we've come:

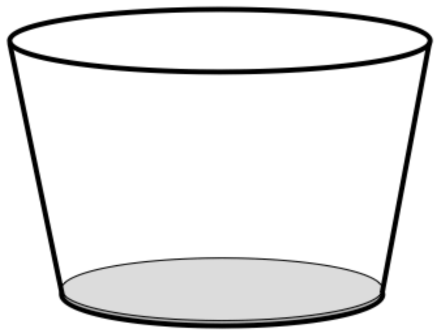
Mechanical analogy: how to store information with water

“0” “1”

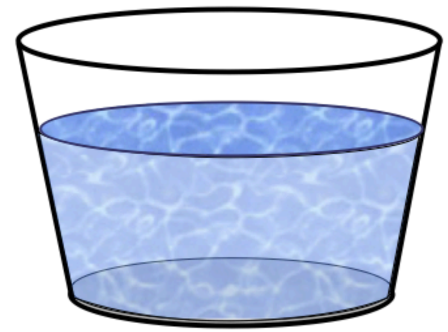
Example: store a number in binary

1 0 0 1 0 1 1 1 0

Mechanical analogy: how to store information with water



“0”

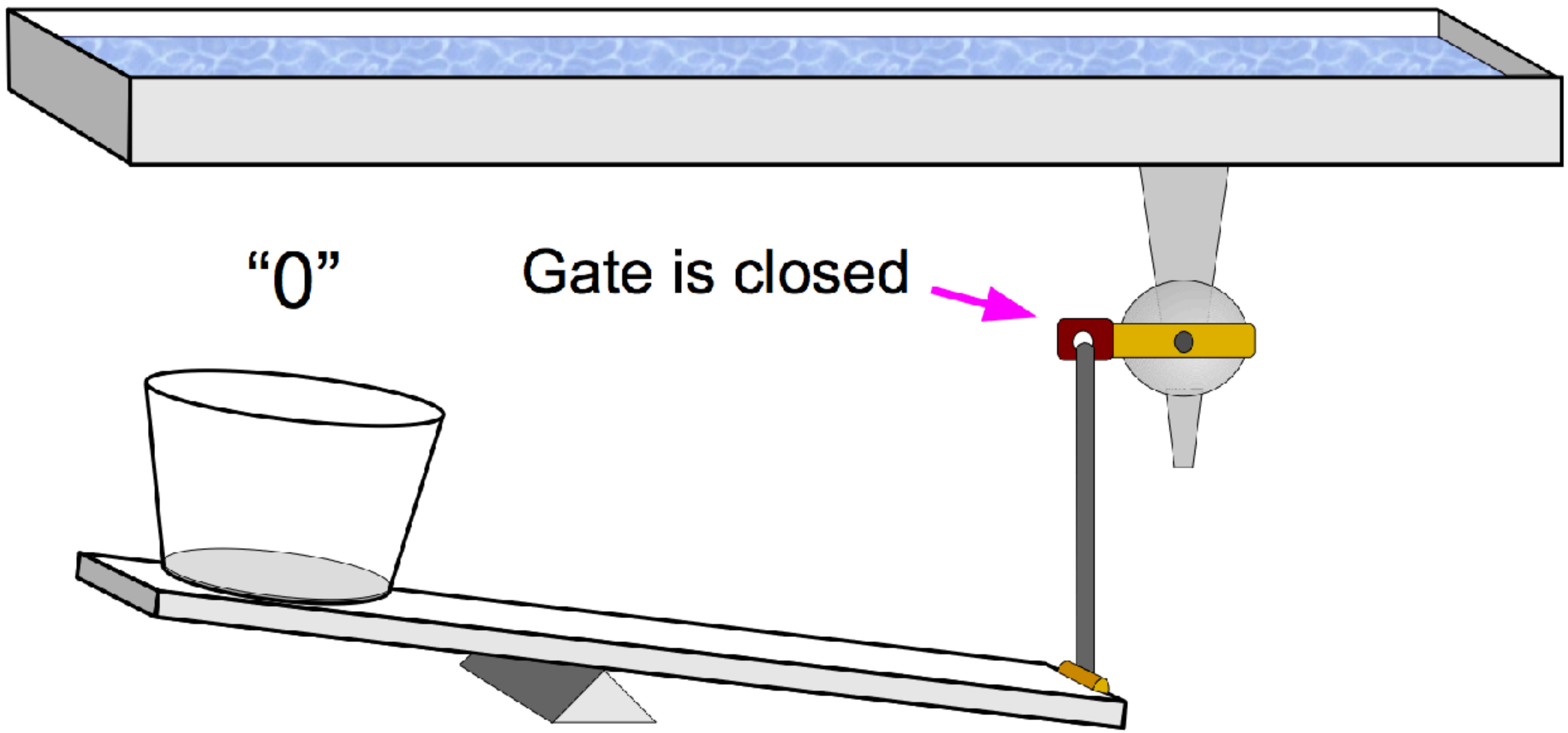


“1”

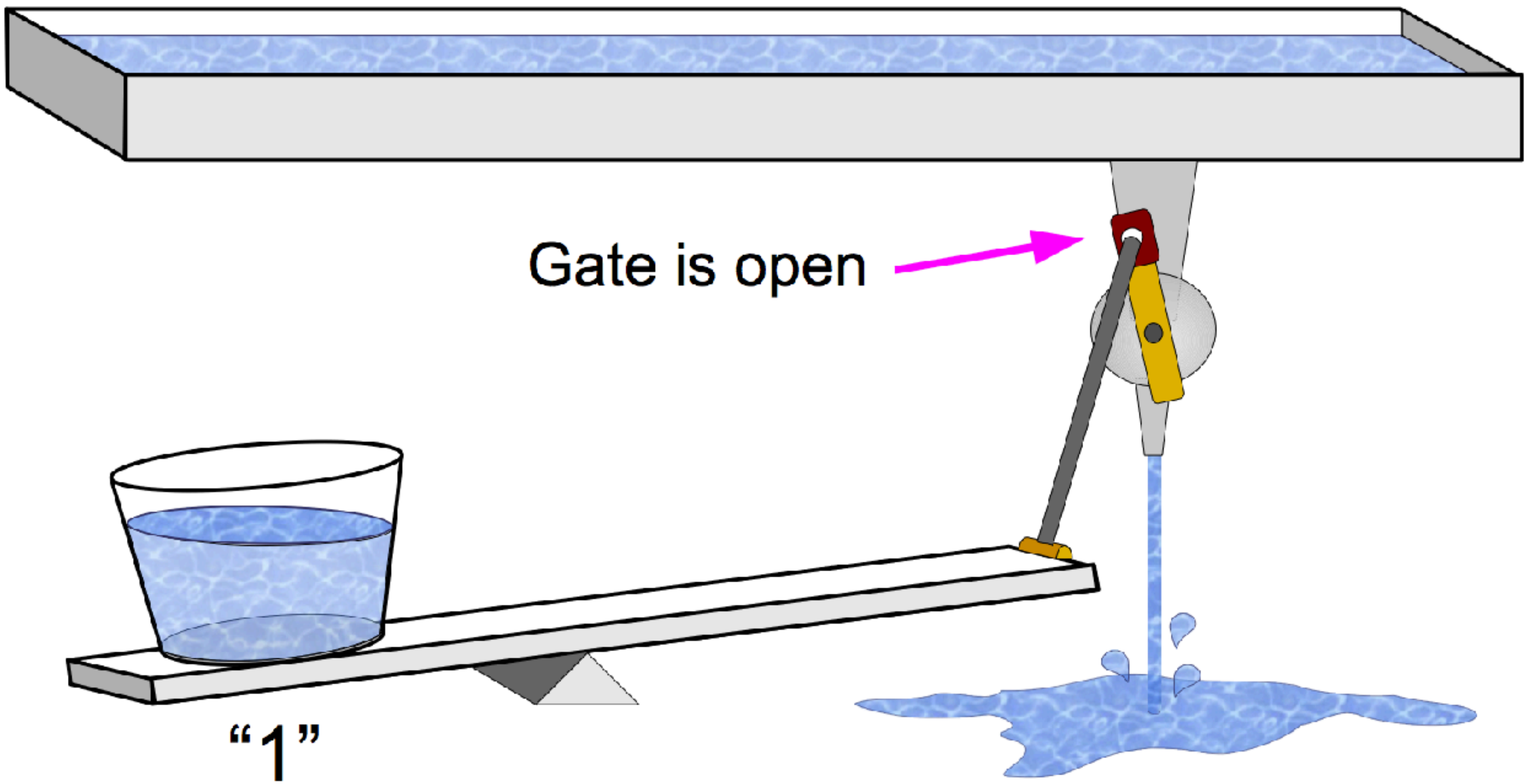
Example: store a number in binary

1	0	0	1	0	1	1	1	0		
256	128	64	32	16	8	4	2	1	=	302

A "water transistor:" use buckets to control flow

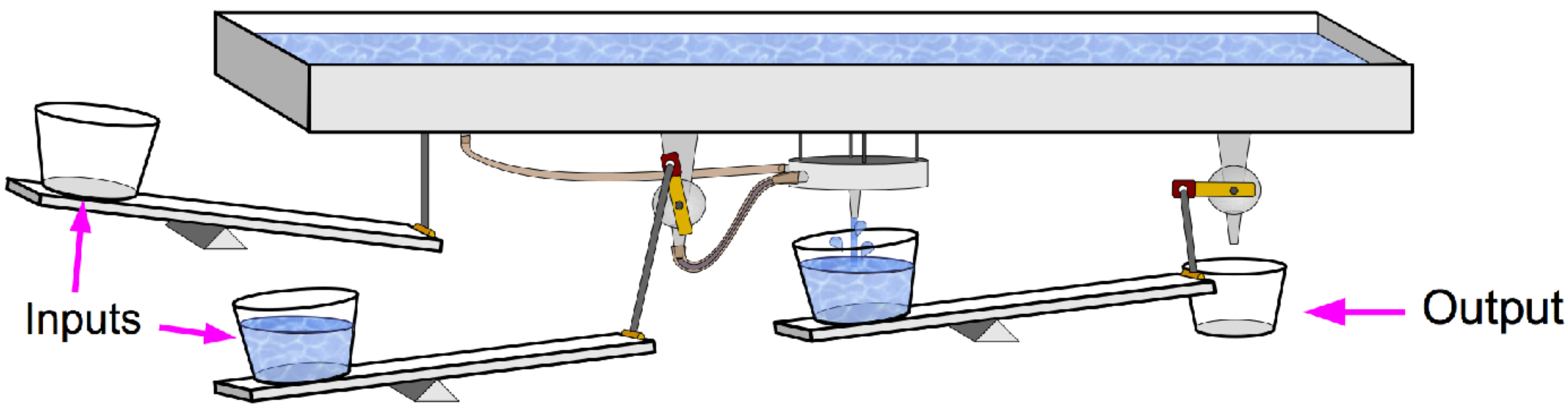


A “water transistor:” use buckets to control flow



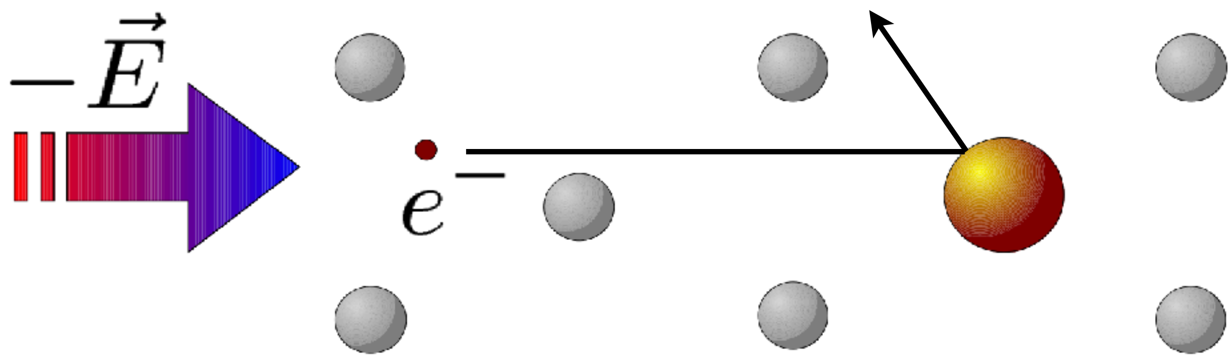
Water-based digital logic (approximate NOR gate)

Filling of inputs determines output:



Electrical transistor: use charge to control electrical channel

Conductivity expresses how easy/hard it is to make current flow



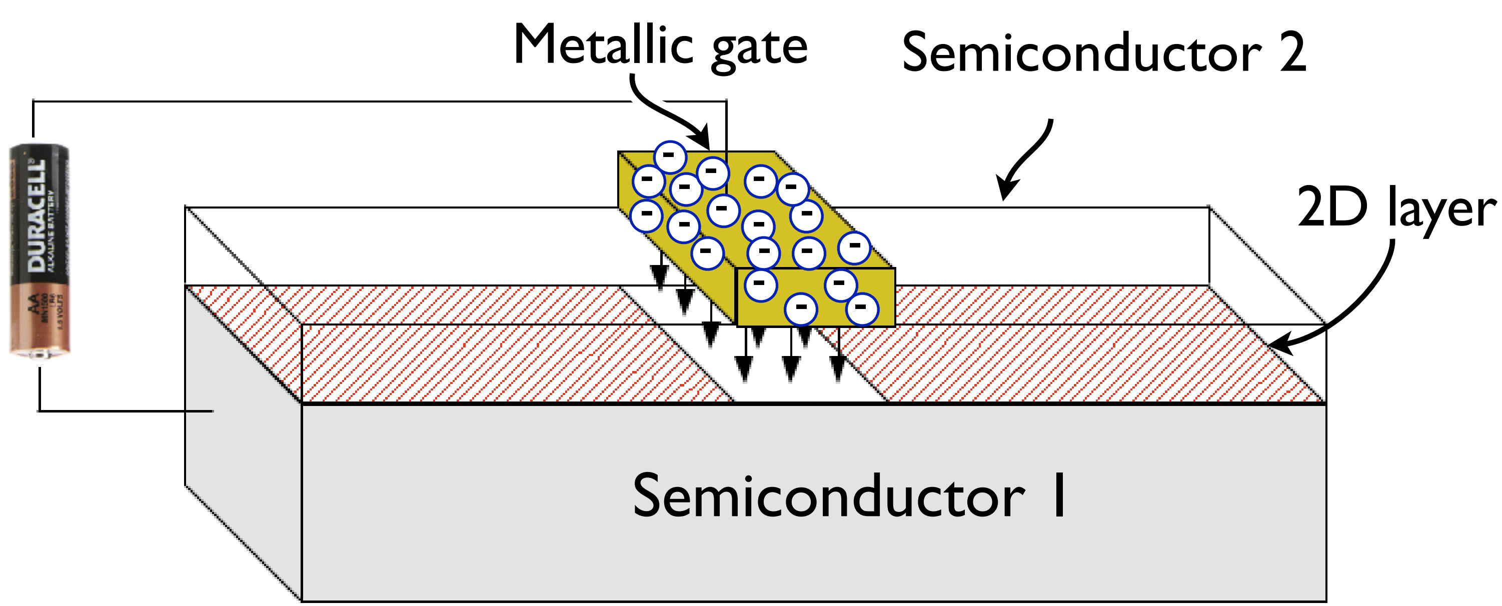
$$(\text{Conductivity}) = (\text{Carrier Density}) \cdot (\text{Mobility})$$

Idea: control conduction through channel by changing carrier density

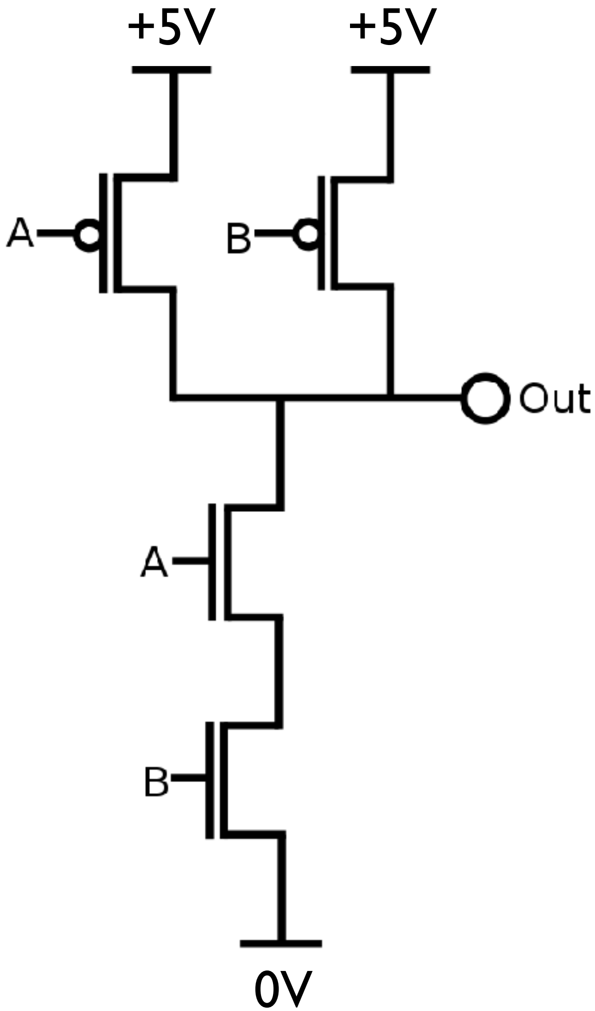
Electrical transistor: use charge to control electrical channel

Electrons trapped at interface, move in 2D layer

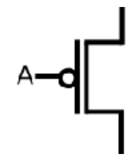
Charge on gate controls electron density below



Logic gate produced by connecting several transistors



CMOS NAND gate
(Wikipedia)



low voltage (0): channel opened

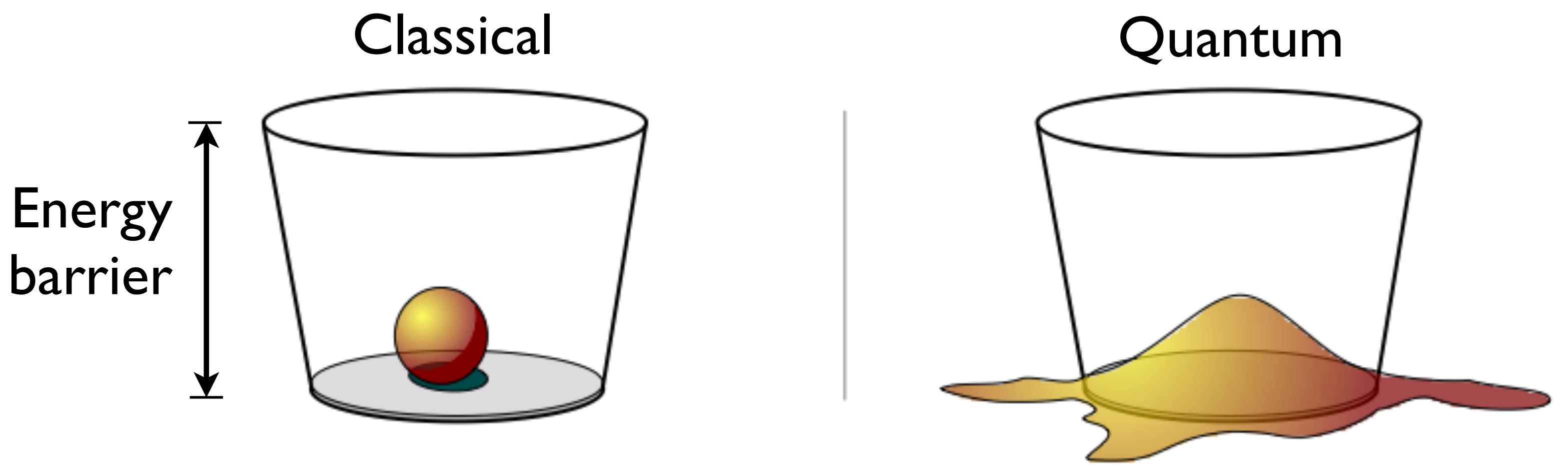
high voltage (1): channel blocked

low voltage (0): channel blocked

high voltage (1): channel opened

Now, make it smaller. What could go wrong?

Quantum tunneling: “matter wave” cannot be fully trapped

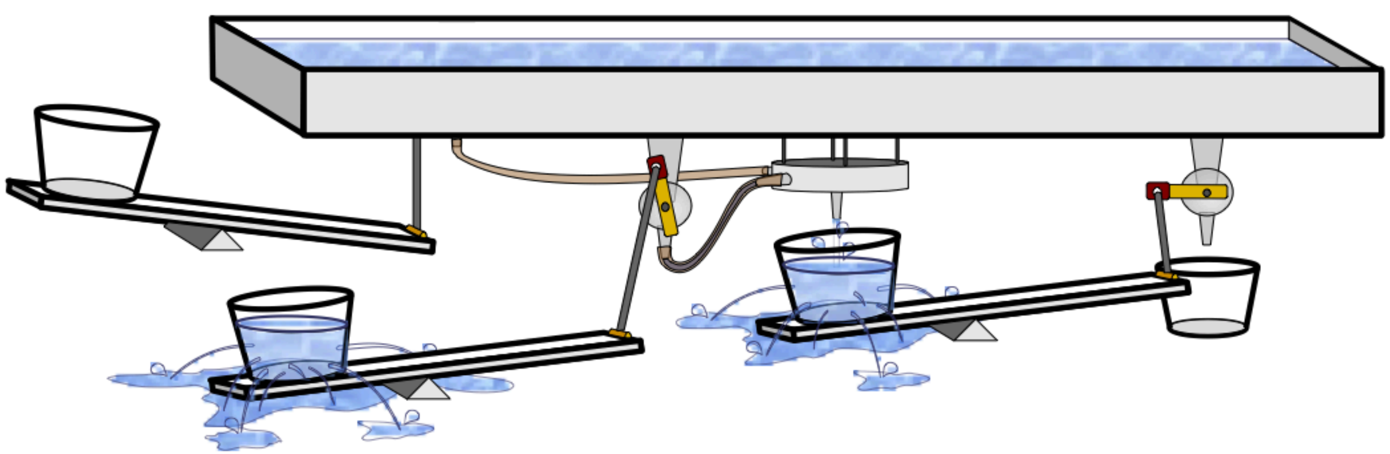


Tunneling speeds up *exponentially* as barrier thickness shrinks

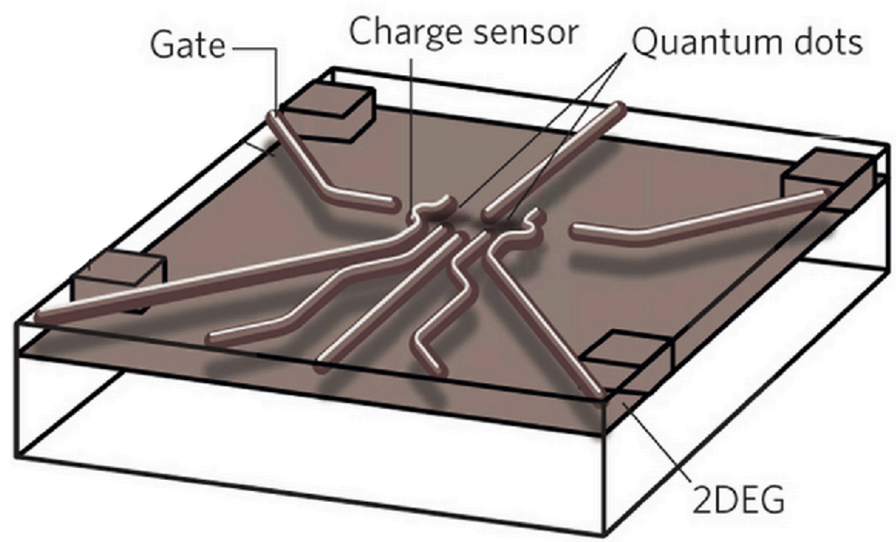
Smaller transistors leads to greater leakage, power consumption

a) Bad for the **environment**

b) Excessive heating hinders further downsizing

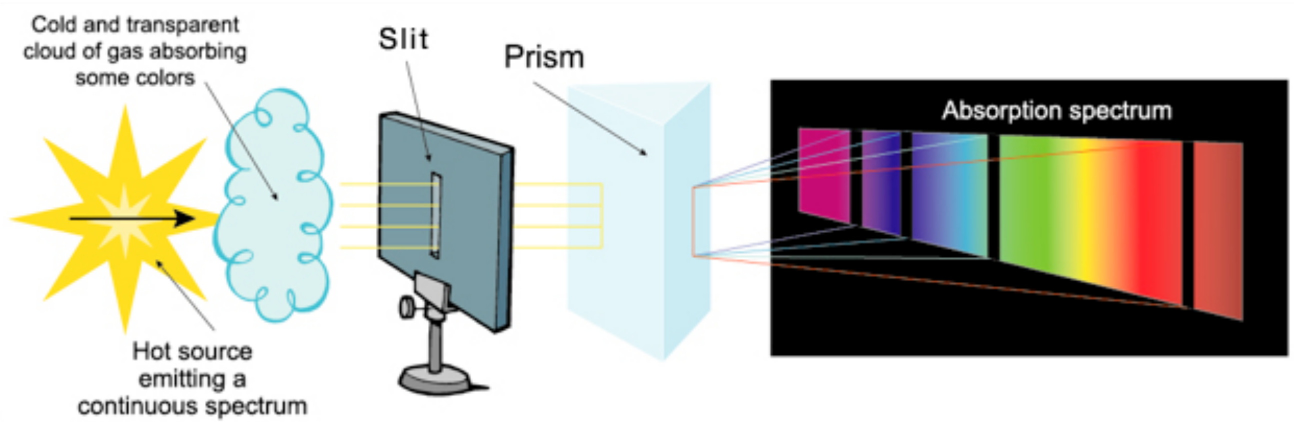


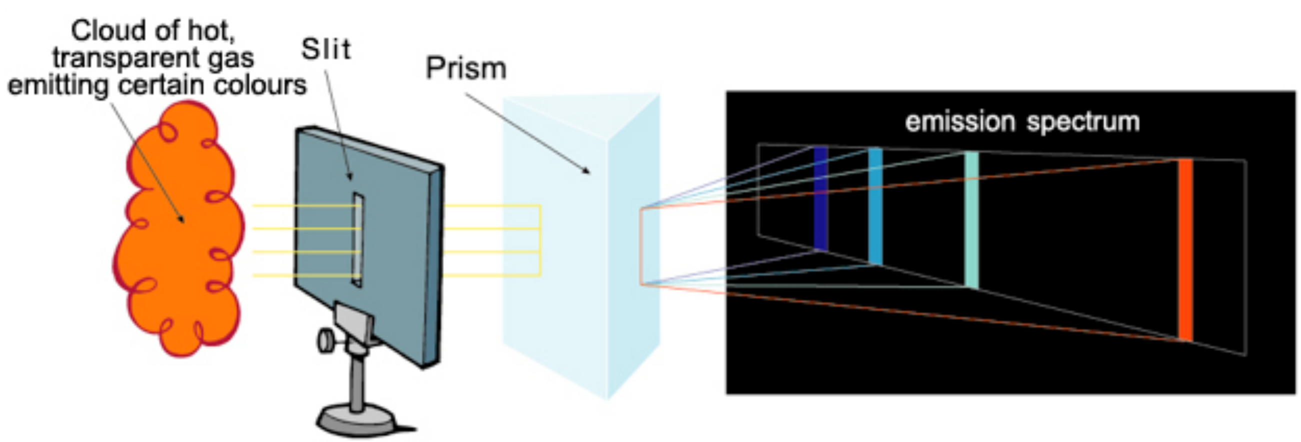
Part III: *Quantum* nanoelectronic devices



Nature Materials **12**, 494 (2013)

Early 1900s: energy absorbed/emitted in discrete amounts





Figures from astro-canada.ca

A quantum dot is an "artificial atom"

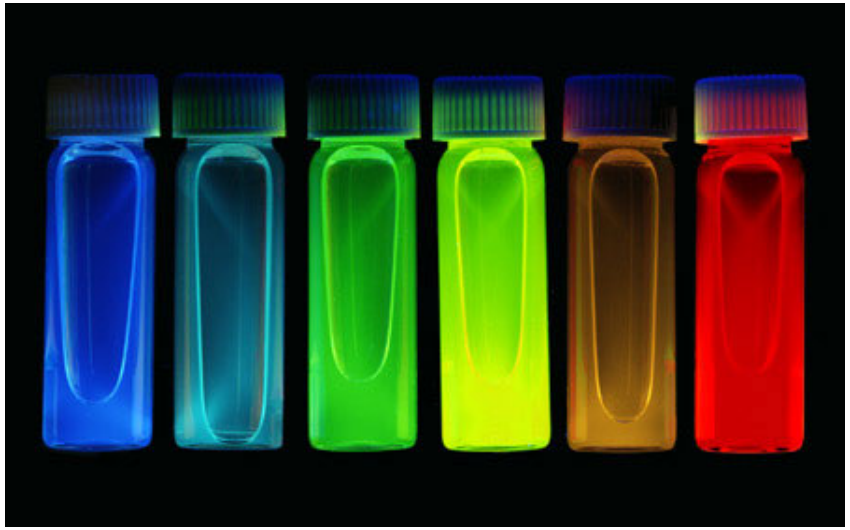
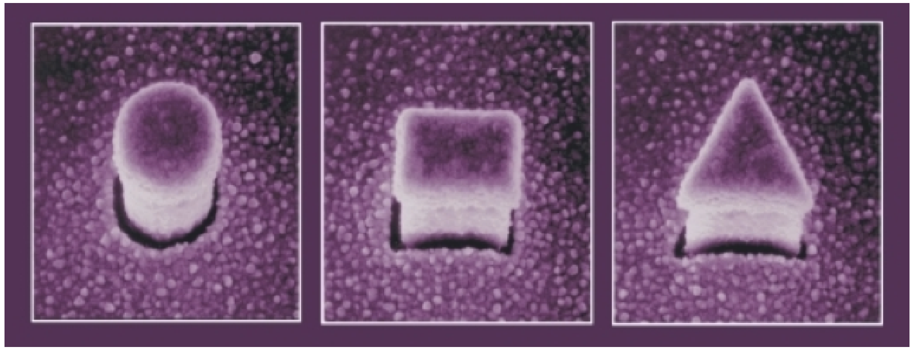
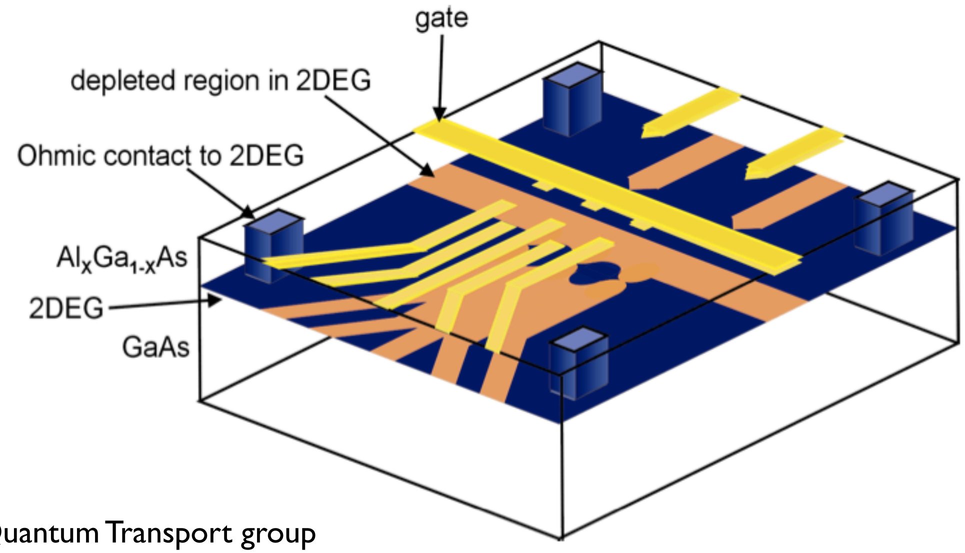


Photo by Felice Frankel, MIT (web.mit.edu)





Images from TU Delft Quantum Transport group

Confinement reduces wavelength, increases energy scale

Analogy:

Smaller drum, higher frequency

$$(\text{energy}) = (\text{Planck's Constant}) \cdot (\text{frequency})$$

For 100 nm dot, temperature must be close to 1 Kelvin

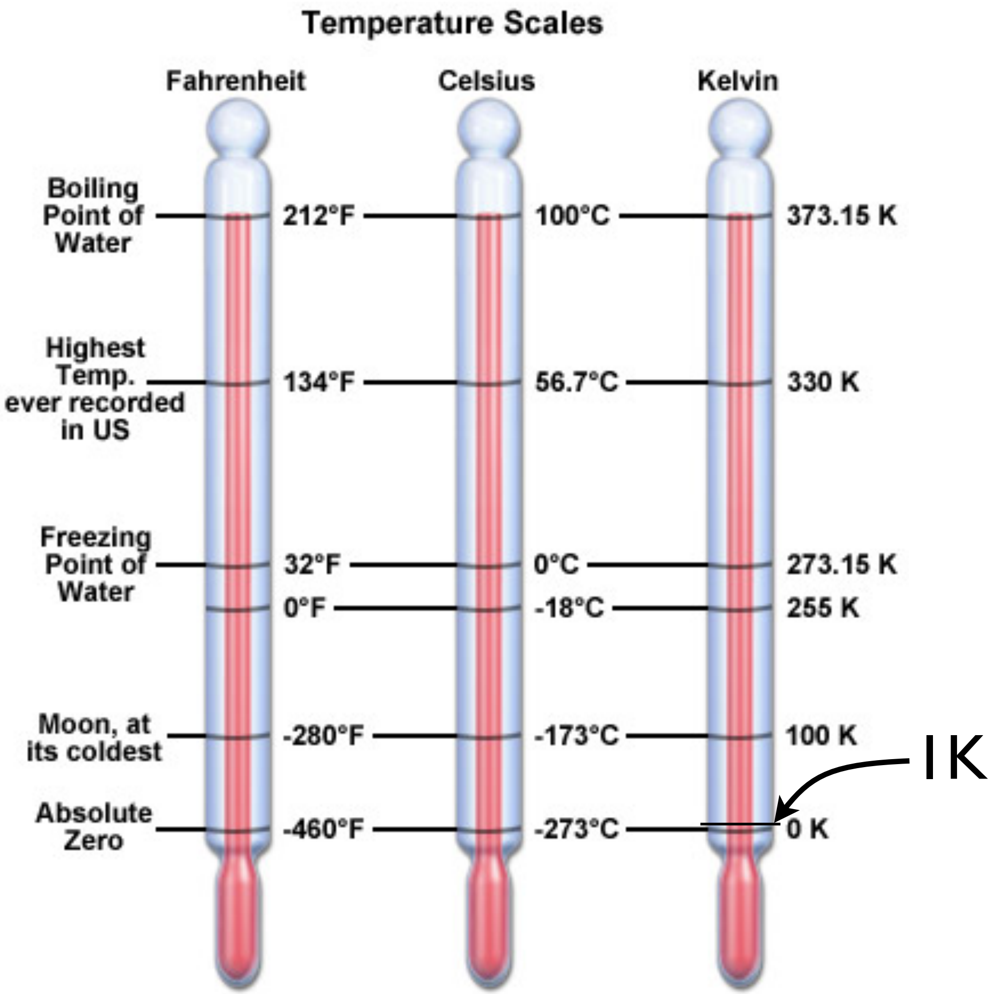


Image from www.magnet.fsu.edu

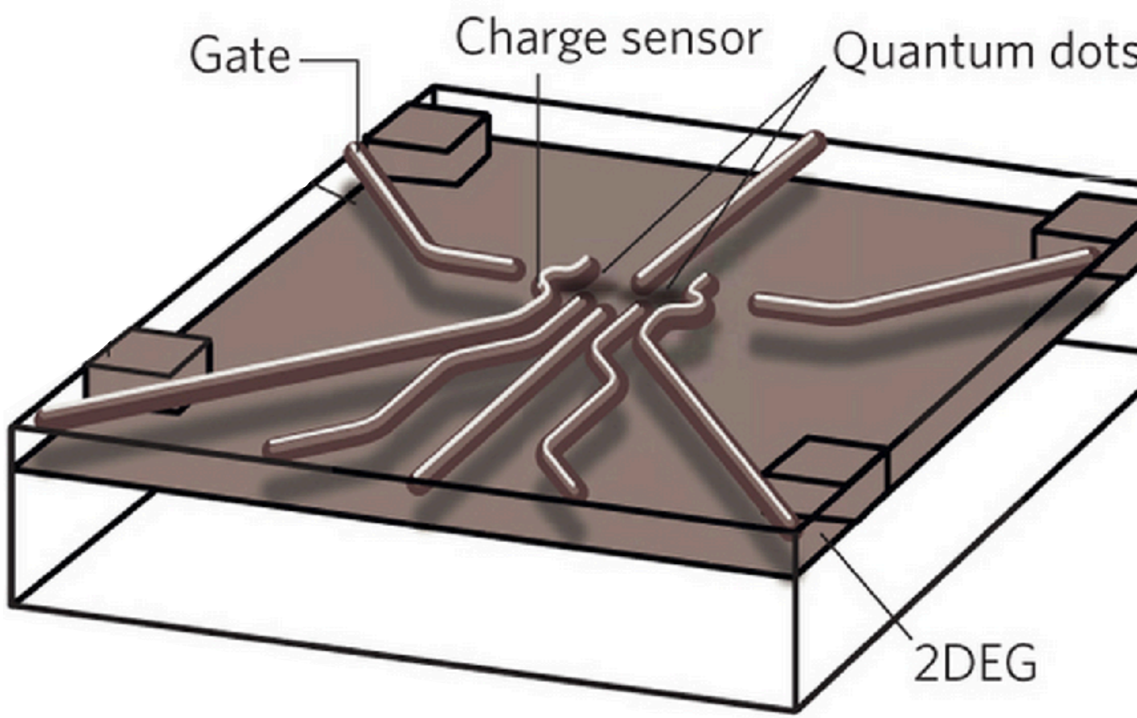
How big is 100 nm?

200 atoms side-by-side

1/100 size of red blood cell

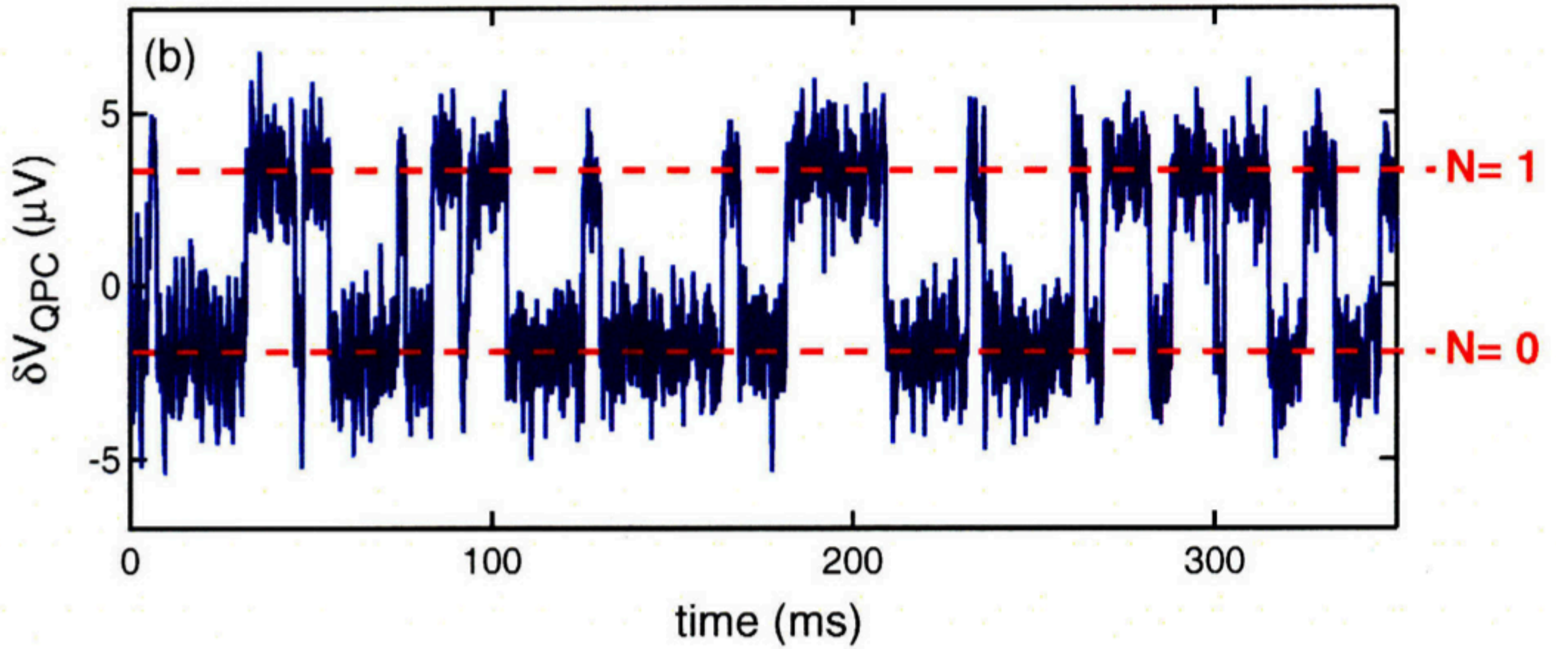
1/1000 width of a human hair

Use gates to deplete 2D layer, trap electrons in small puddles



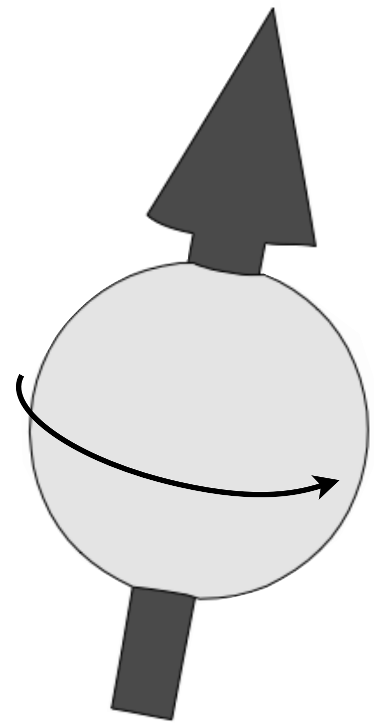
Nature Materials **12**, 494 (2013)

Single electron tunneling in and out of device is sensed directly

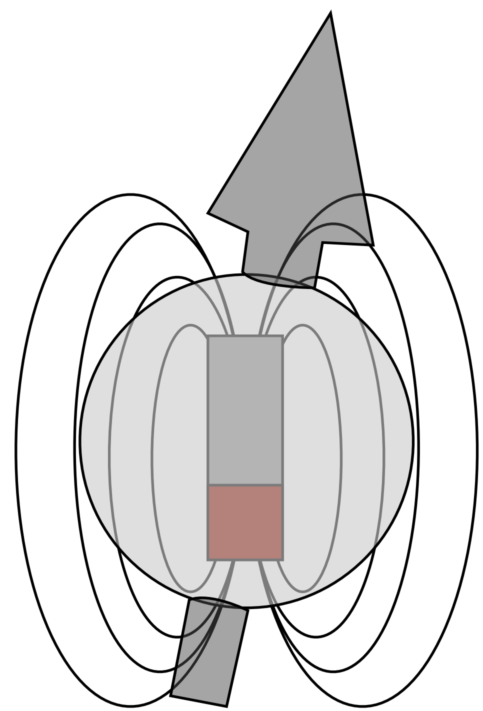


From PhD thesis of Sami Amasha, MIT (2008)

Besides mass and charge, electron also has "spin"



A spin is like a tiny magnet,



which prefers to align with a magnetic field

State of spin is a *superposition* of only two choices: up or down

"Down" spin moves to stronger field

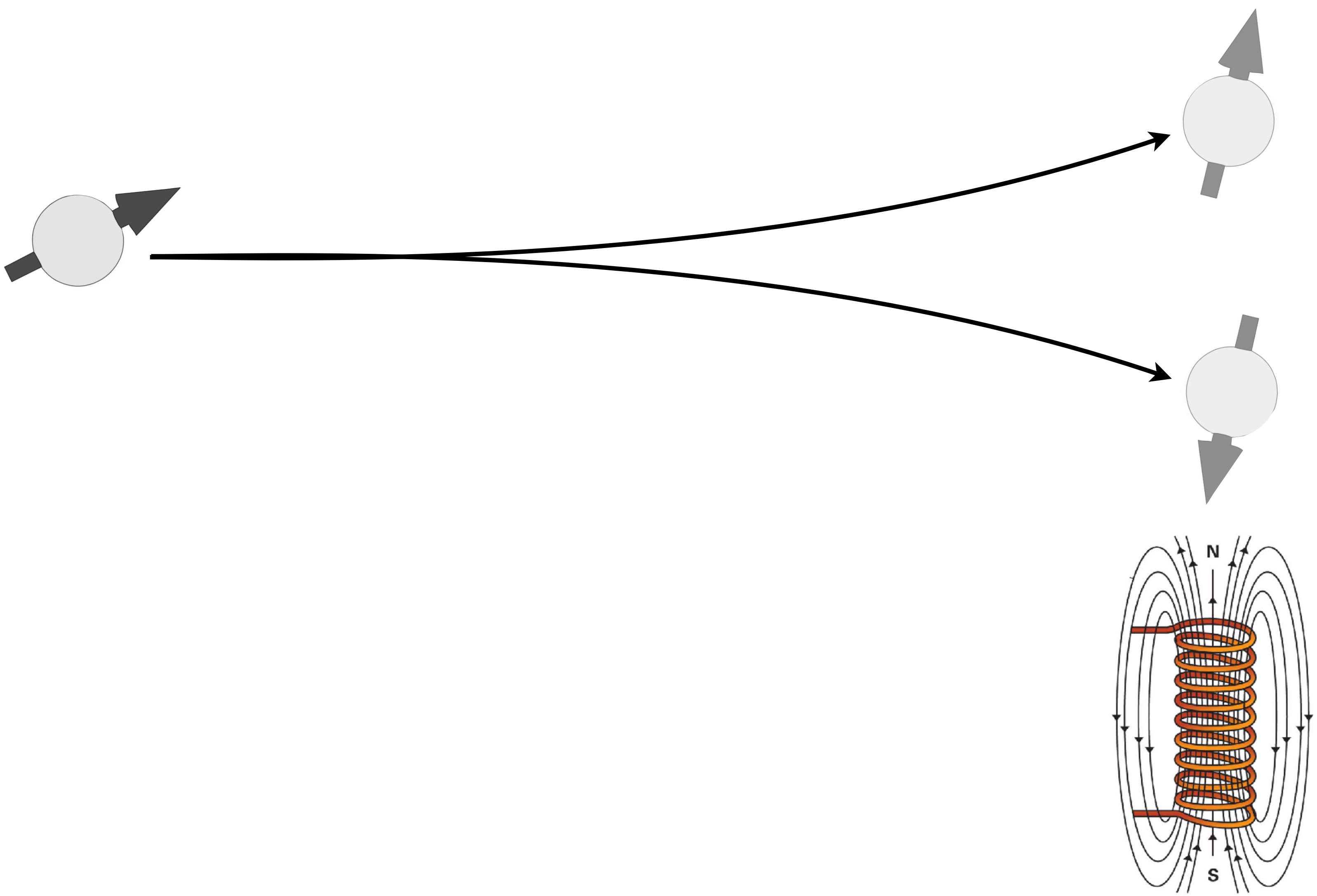


Image from ece.neu.edu

A bit also has two choices (0 or 1); this is a *quantum* bit

Classical bit

Bit is on (1) **or** off (0)

Quantum bit

Qubit can be on (1) **AND** off (0)

The spin of a single electron in a quantum dot is a "qubit"

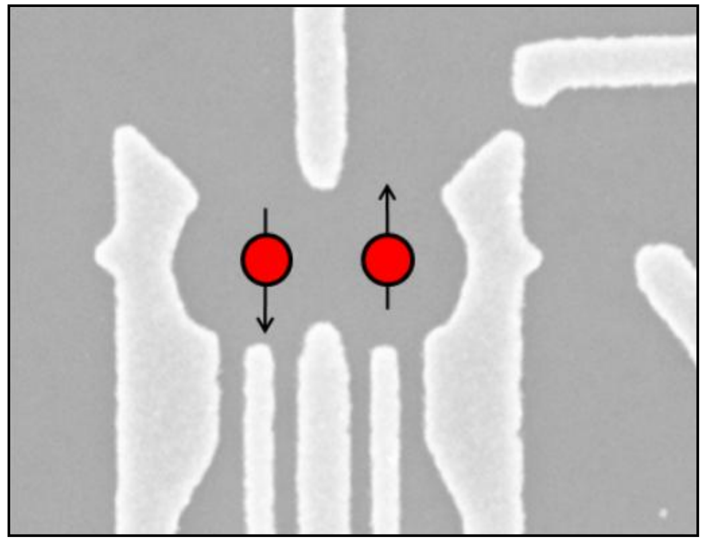


Image from Yacoby group, Harvard

$$\downarrow \;=\; 0$$
$$\uparrow \;=\; 1$$

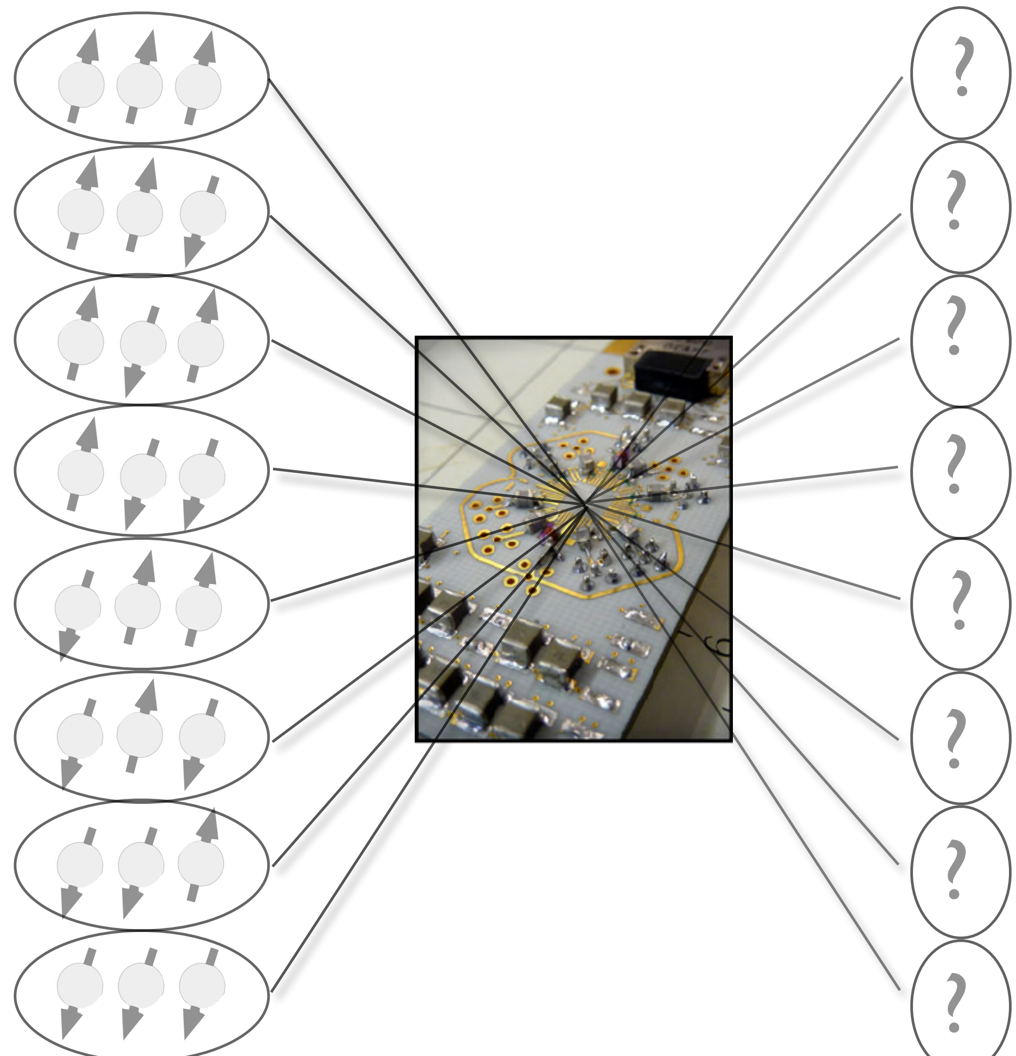
Original proposal:

D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).

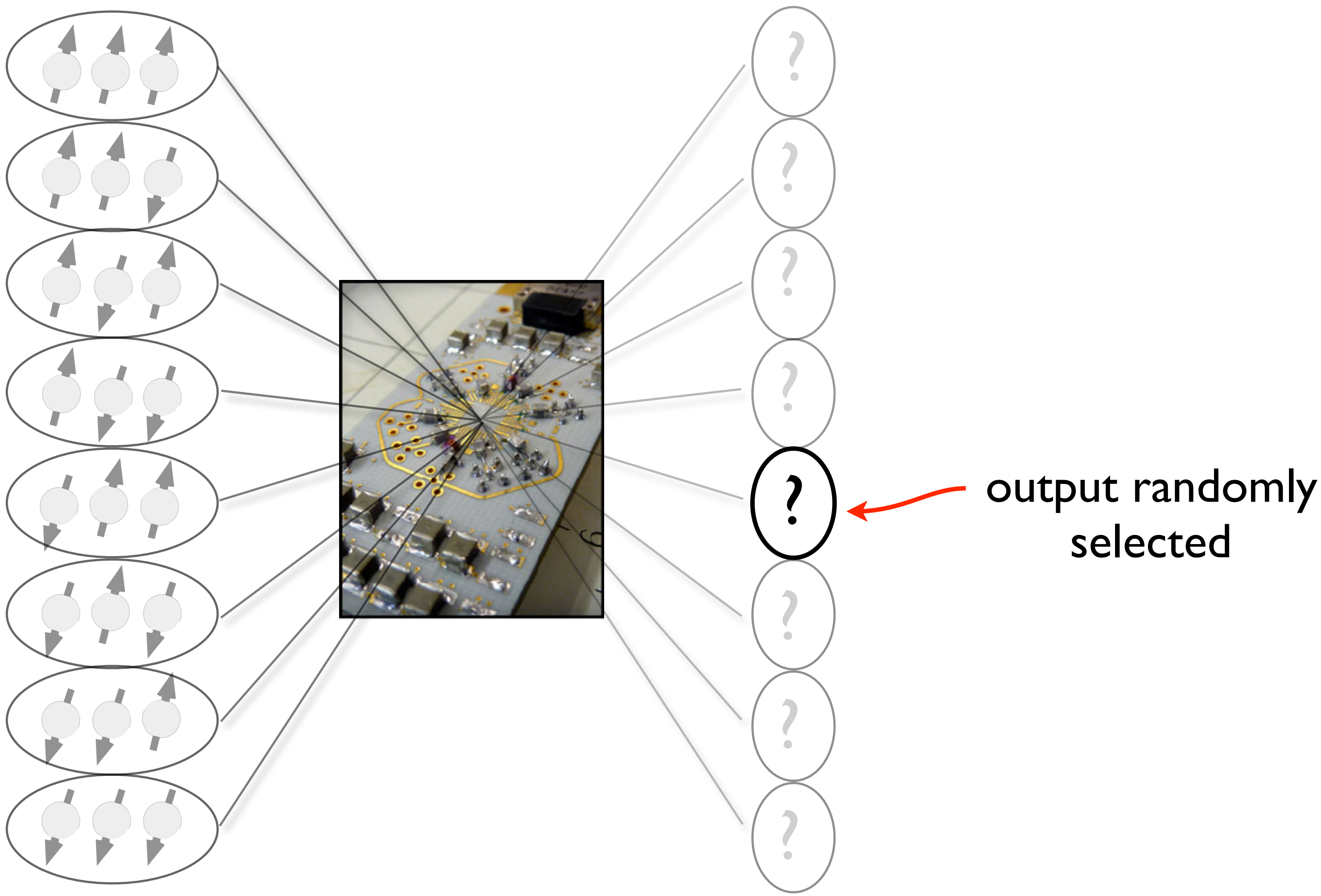
Quantum parallelism: use superposition to run all inputs at once

Each case run one by one

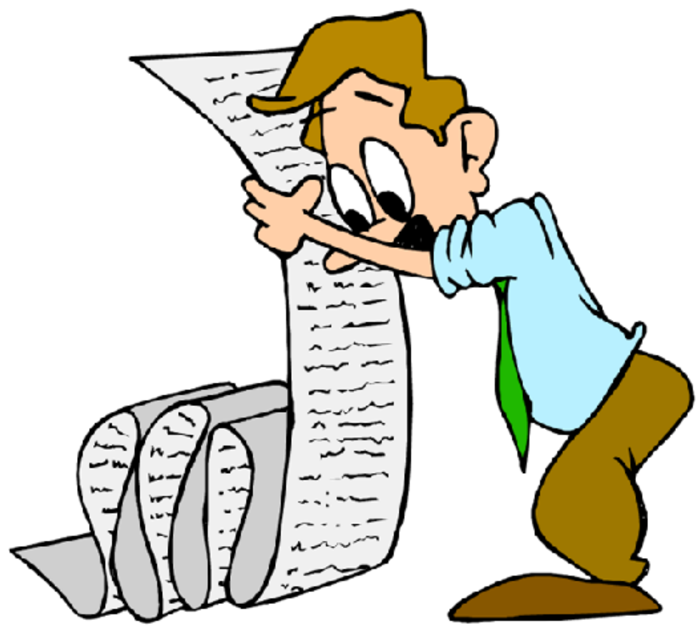
Quantum computer runs all at once



On any run, only get to see one of the possible answers



Clever tricks use interference to amplify desired output



Example: Highly efficient searching possible

"Big Data" applications
Sociology
Genomics
Economics
...

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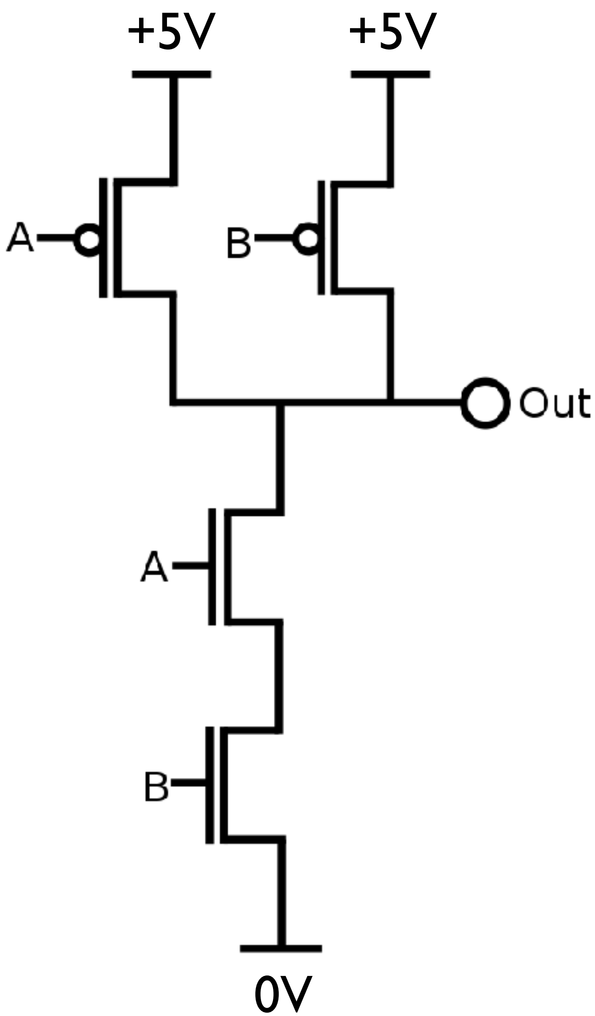
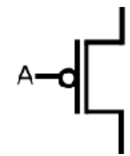
Logic gate produced by connecting several transistors



CMOS NAND gate
(Wikipedia)



low voltage (0): channel opened

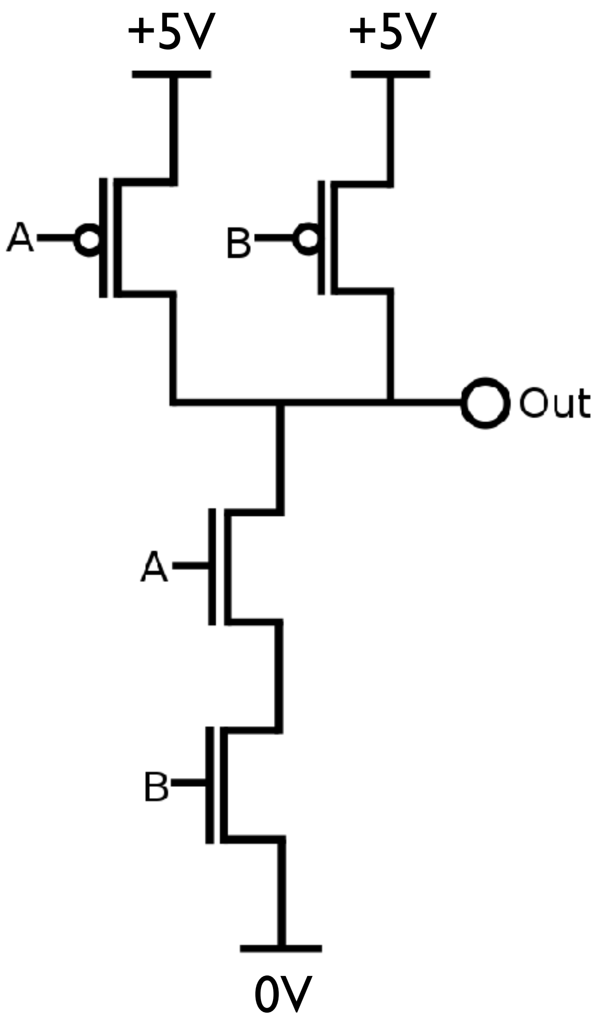
high voltage (1): channel blocked

low voltage (0): channel blocked

high voltage (1): channel opened

A	B	Out
0	**0**	

Logic gate produced by connecting several transistors



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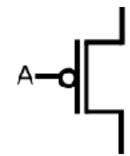


low voltage (0): channel opened

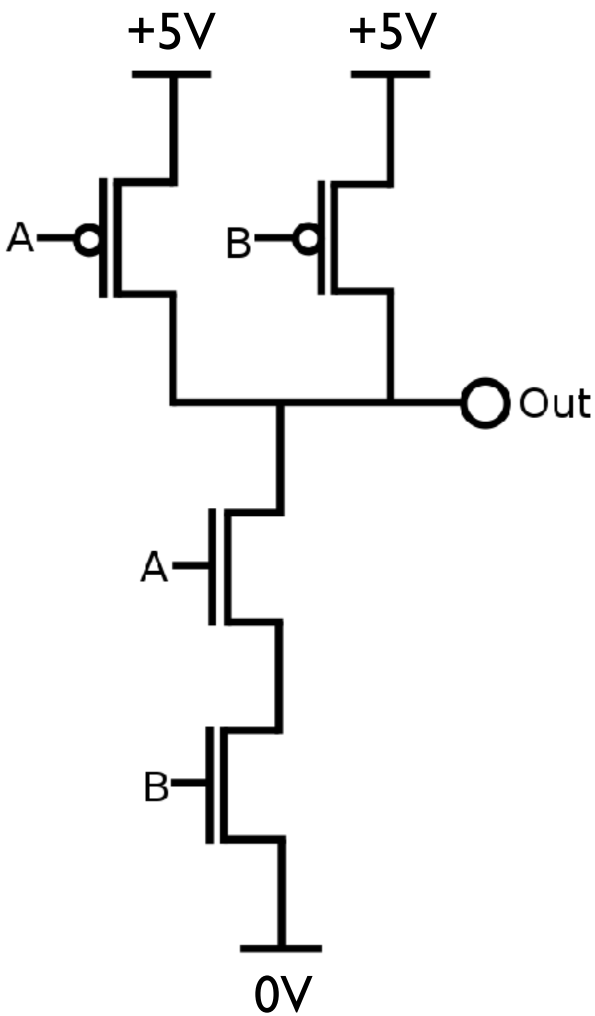
high voltage (1): channel blocked

low voltage (0): channel blocked

high voltage (1): channel opened

A	B	Out
0	**0**	+5V (1)

Logic gate produced by connecting several transistors



CMOS NAND gate
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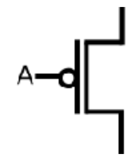

low voltage (0): channel opened

high voltage (1): channel blocked

low voltage (0): channel blocked

high voltage (1): channel opened

A	B	Out
0	0	+5V (1)
0	1	+5V (1)
1	0	+5V (1)
1	1	0V (0)