Information processing in nanoscale systems

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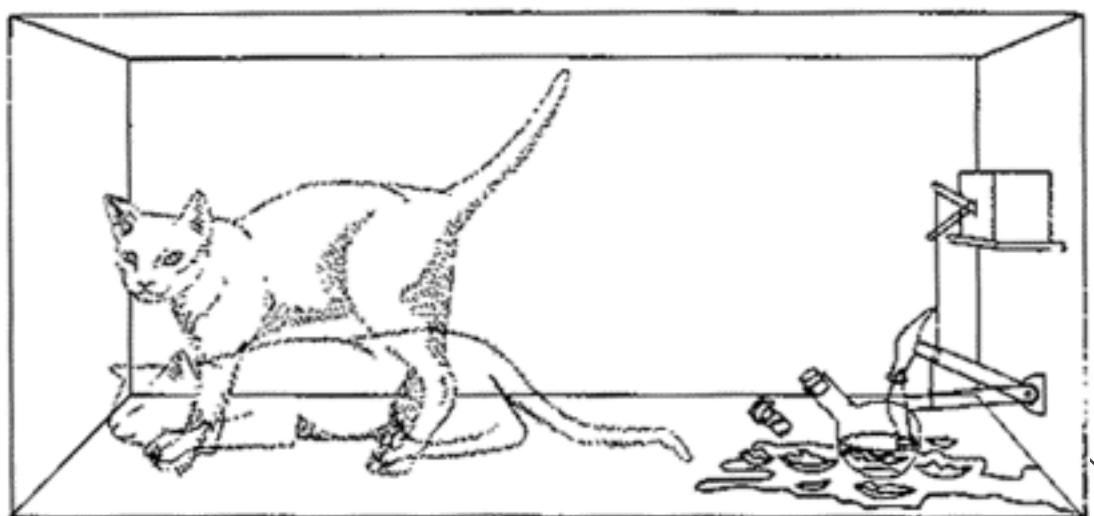
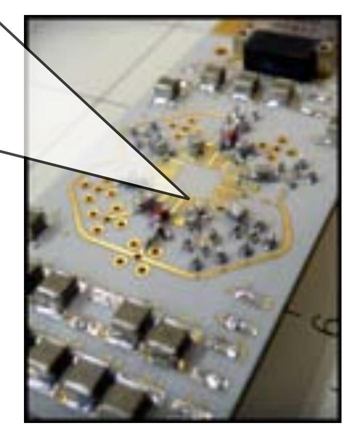


Image from: www.upscale.utoronto.ca



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

1913

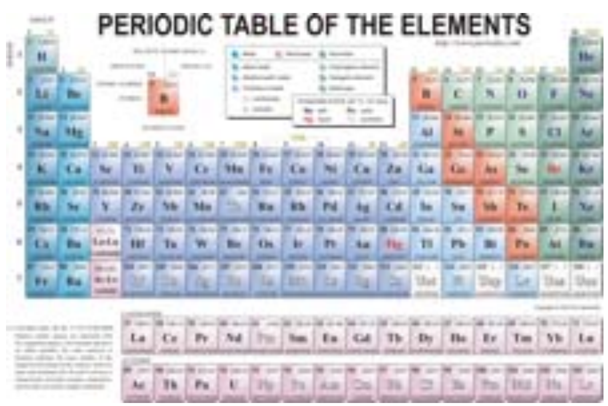
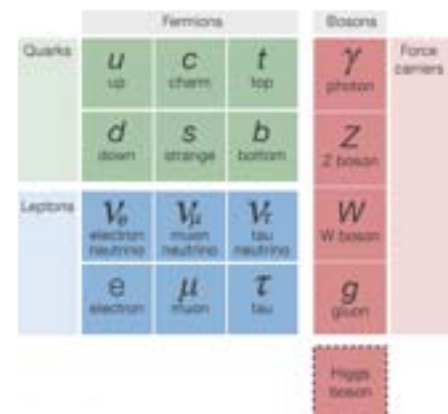


Image from www.periodni.com

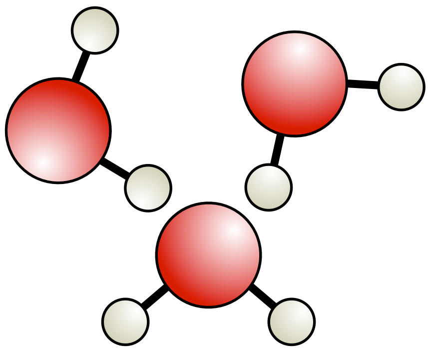
2013



Source: AAAS

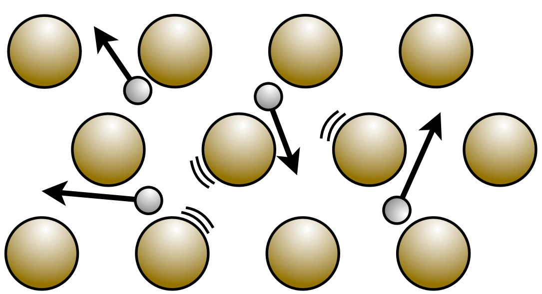
Collective behavior unlike that of individual constituents

Water molecules

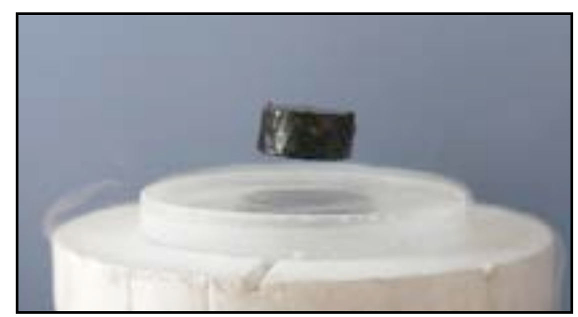


Ocean waves

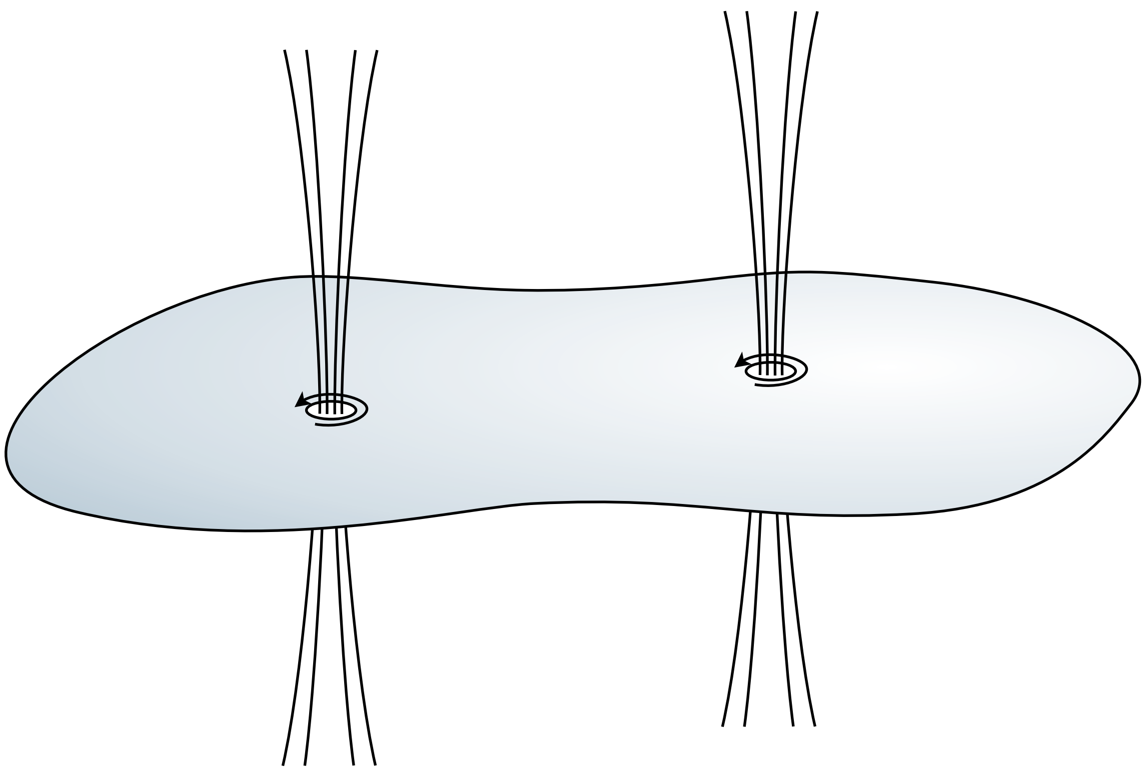
Electrons in a crystal



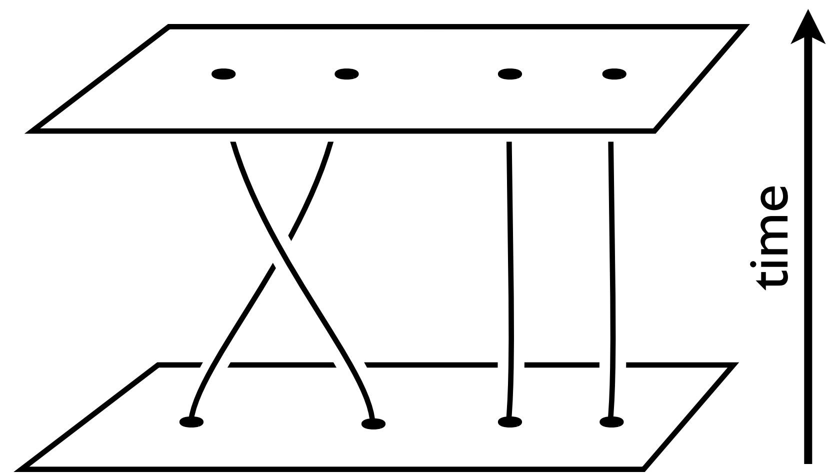
Superconductivity



Each phase is a new "vacuum," with new elementary particles



Ex: vortices in exotic 2D superconductor



State retains "braiding" history

New class of "topological" materials recently discovered

Image from: images-of-elements.com

vs.

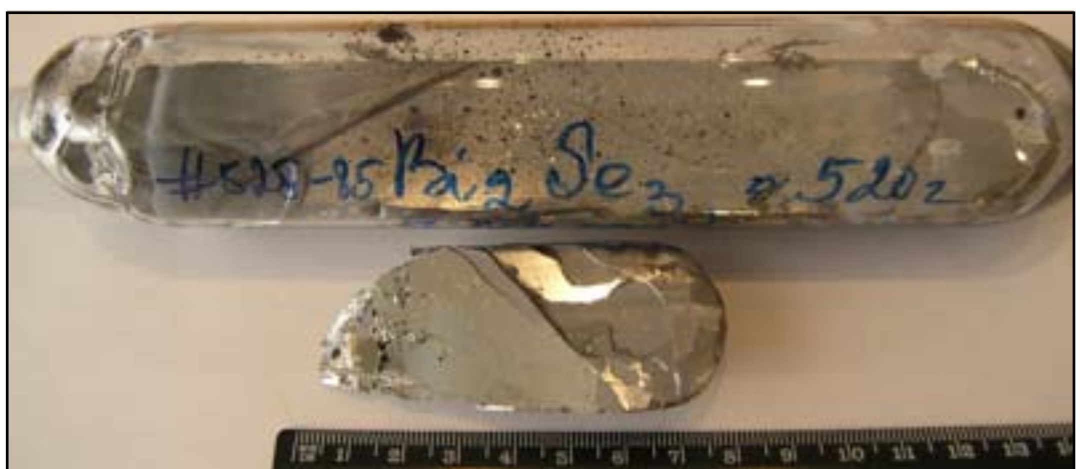


Image from: www.sttic.com.ru

Smaller, faster, lighter; underlying idea remains the same

several inches

1947

2.31 inches
58.6 mm

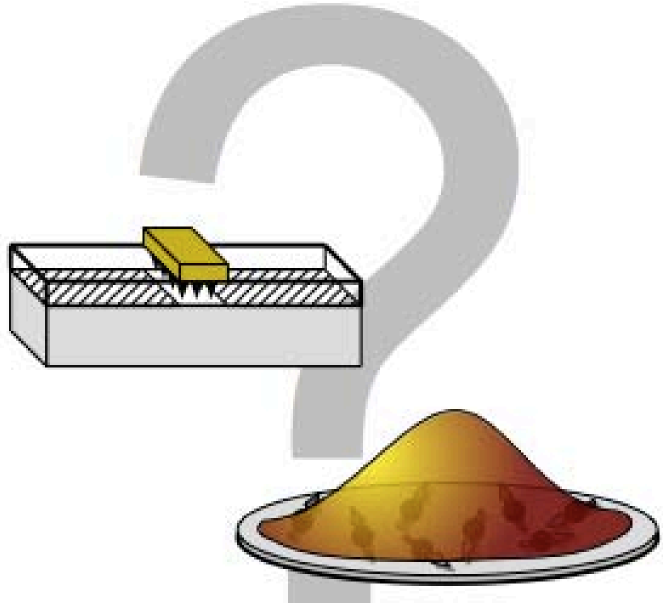
4.87 inches
123.8 mm

Today

Here's how far we've come:

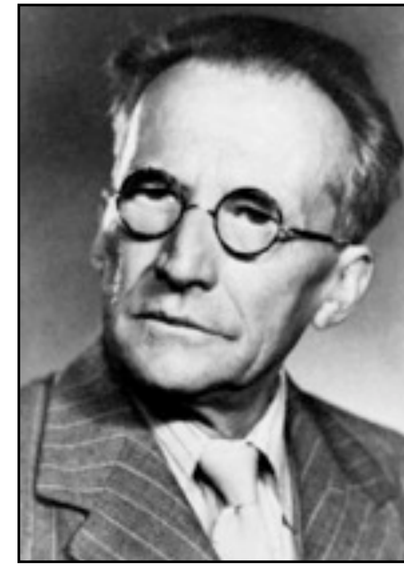
Nanoscale regime: where quantum meets classical

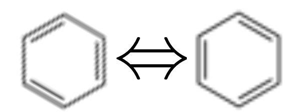
$$N \sim 10^{23}$$



"nanoscale"

$$N \sim 10^{6}$$





$$N \sim 1 - 10$$

The Plan

I. Miniaturization of solid state electronics

II. Brief introduction to quantum mechanics

III. Nanoelectronic devices

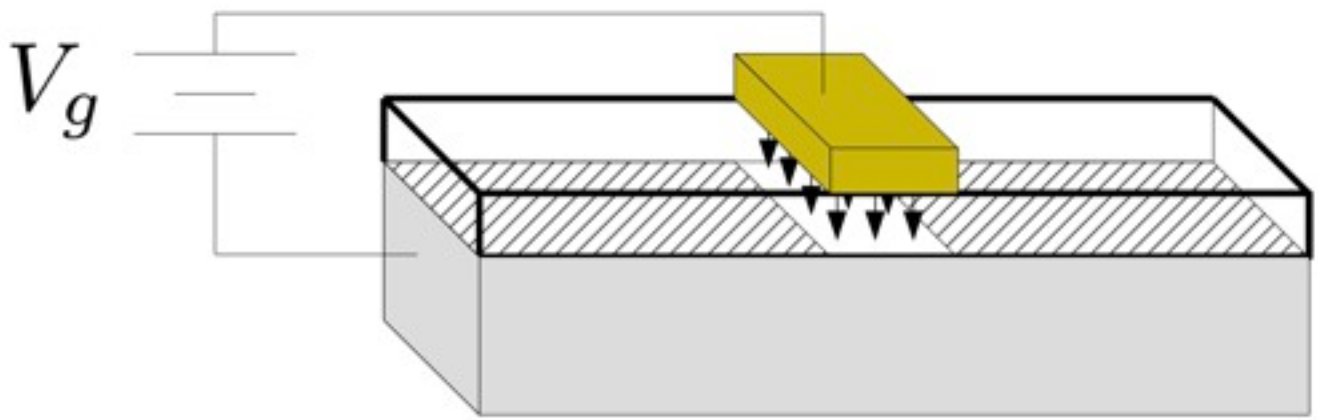
IV. Quantum nanoelectronic devices

Part 1: Miniaturization of solid state electronics

Goals: understand Field Effect Transistor's

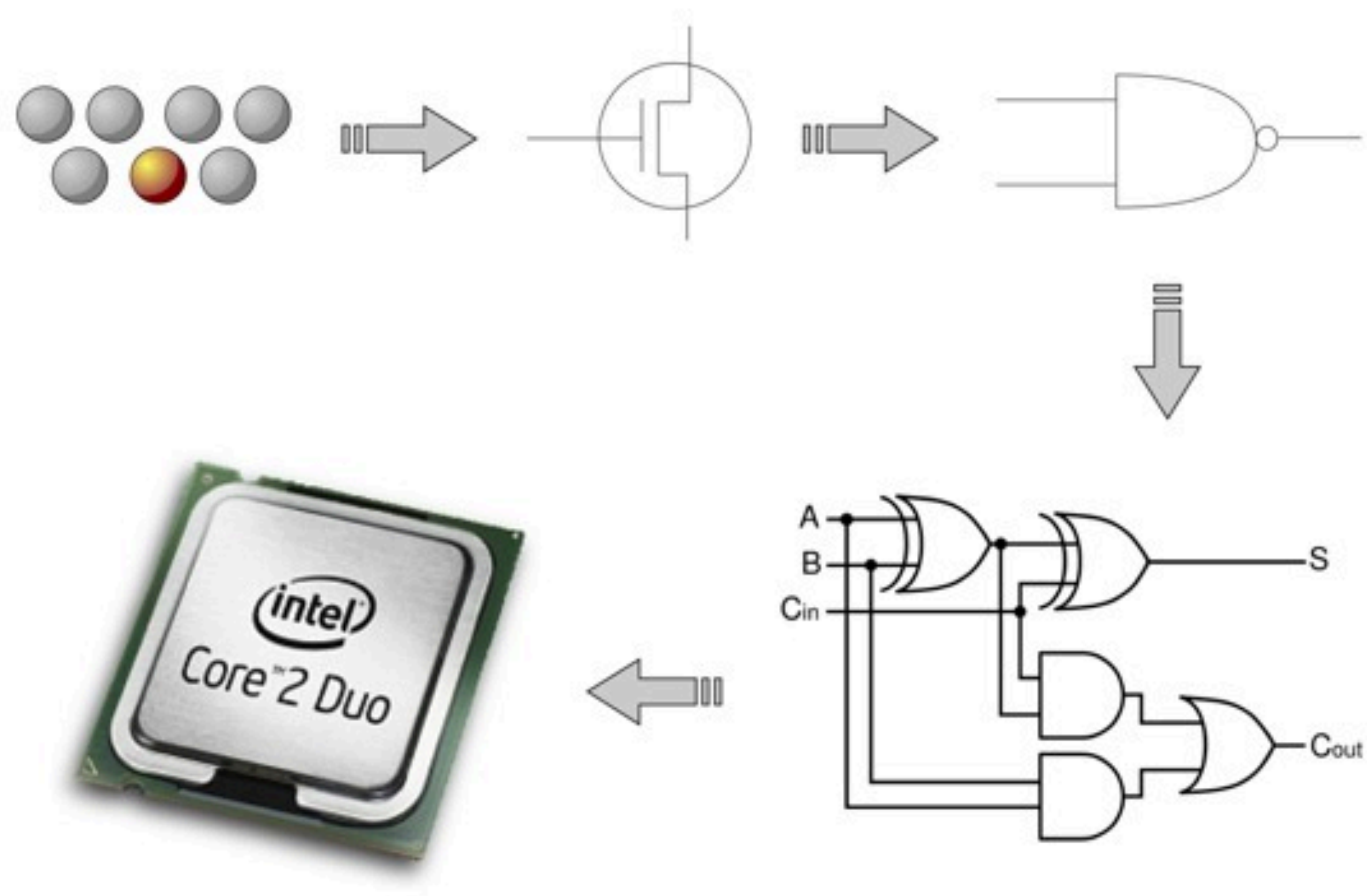
1) basic operating principle*

2) role in information processing



*Will set up discussion for quantum devices

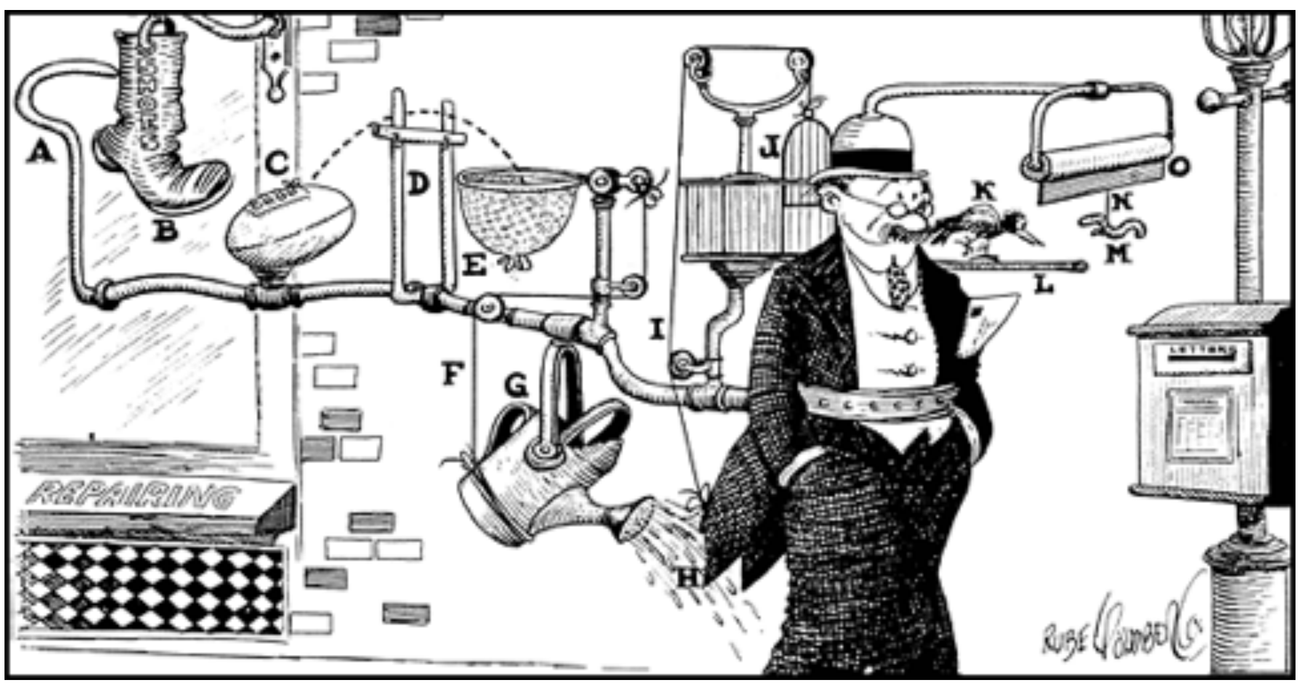
Transistor is the basic functional element in a digital processor



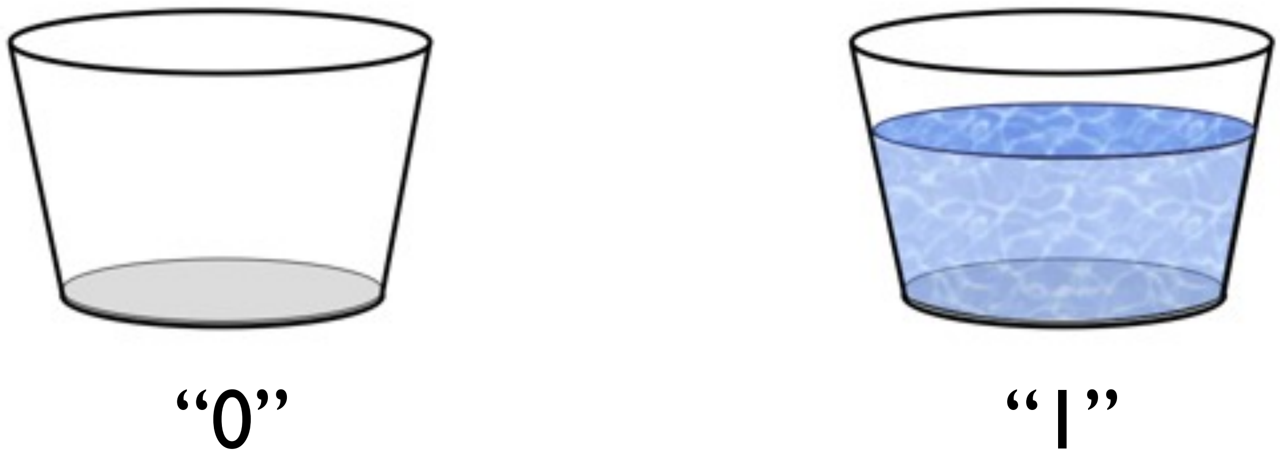
Minimalist view of a (digital) computer

Store information (discretely) in state of physical system

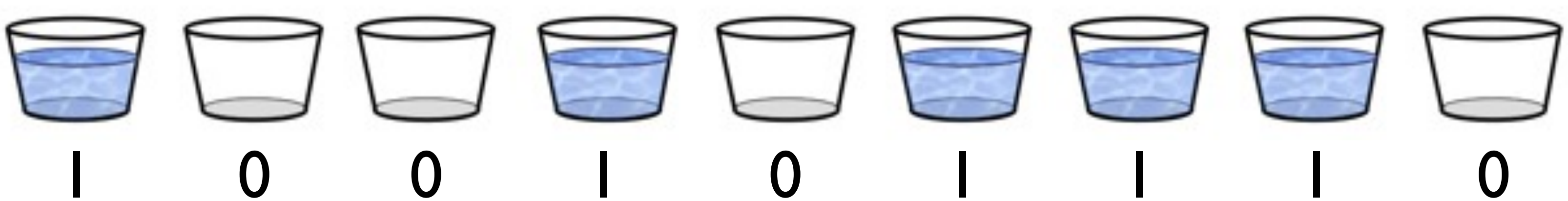
Control behavior of system based on this information



Mechanical analogy: how to store information with water



Example: store a number in binary



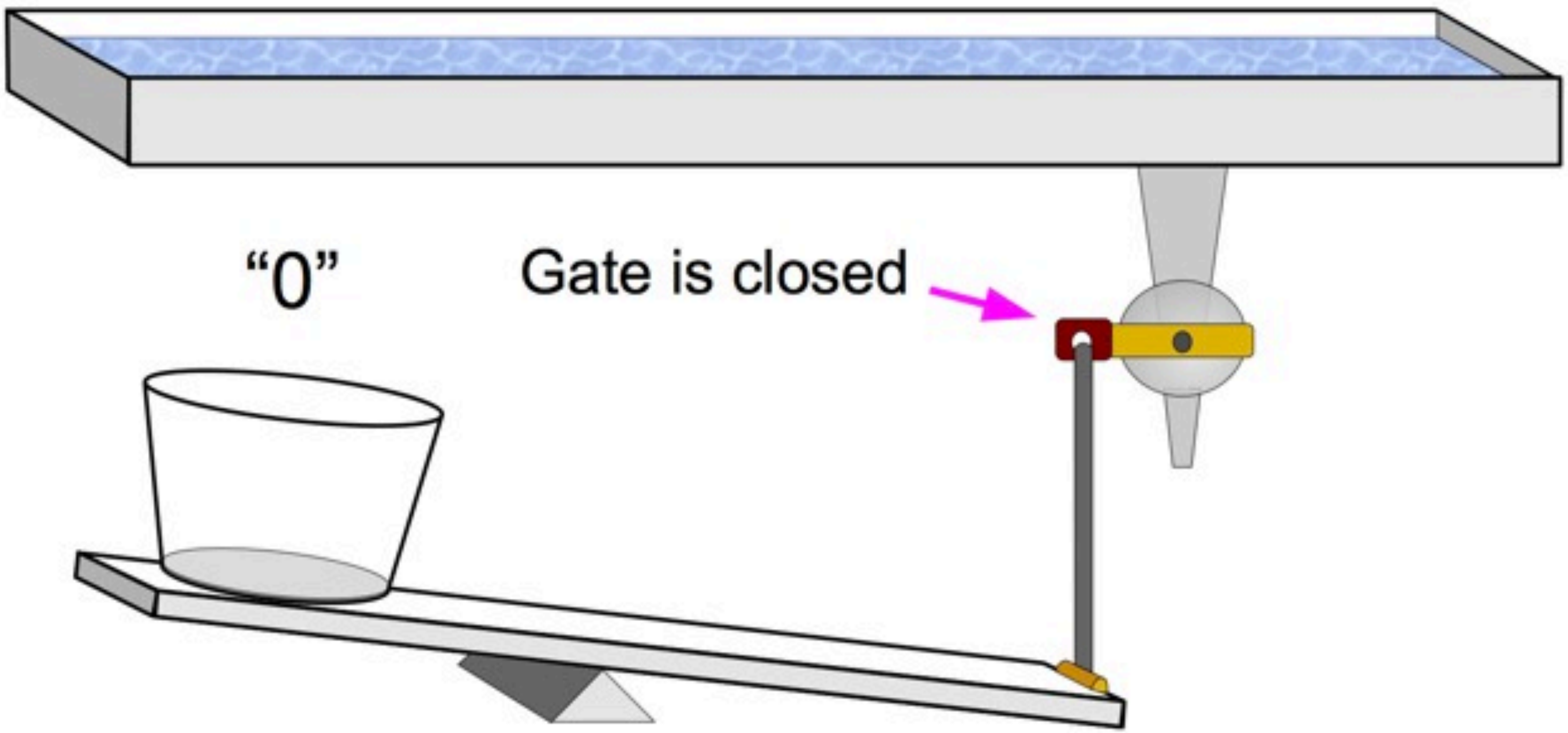
Mechanical analogy: how to store information with water

"0" "1"

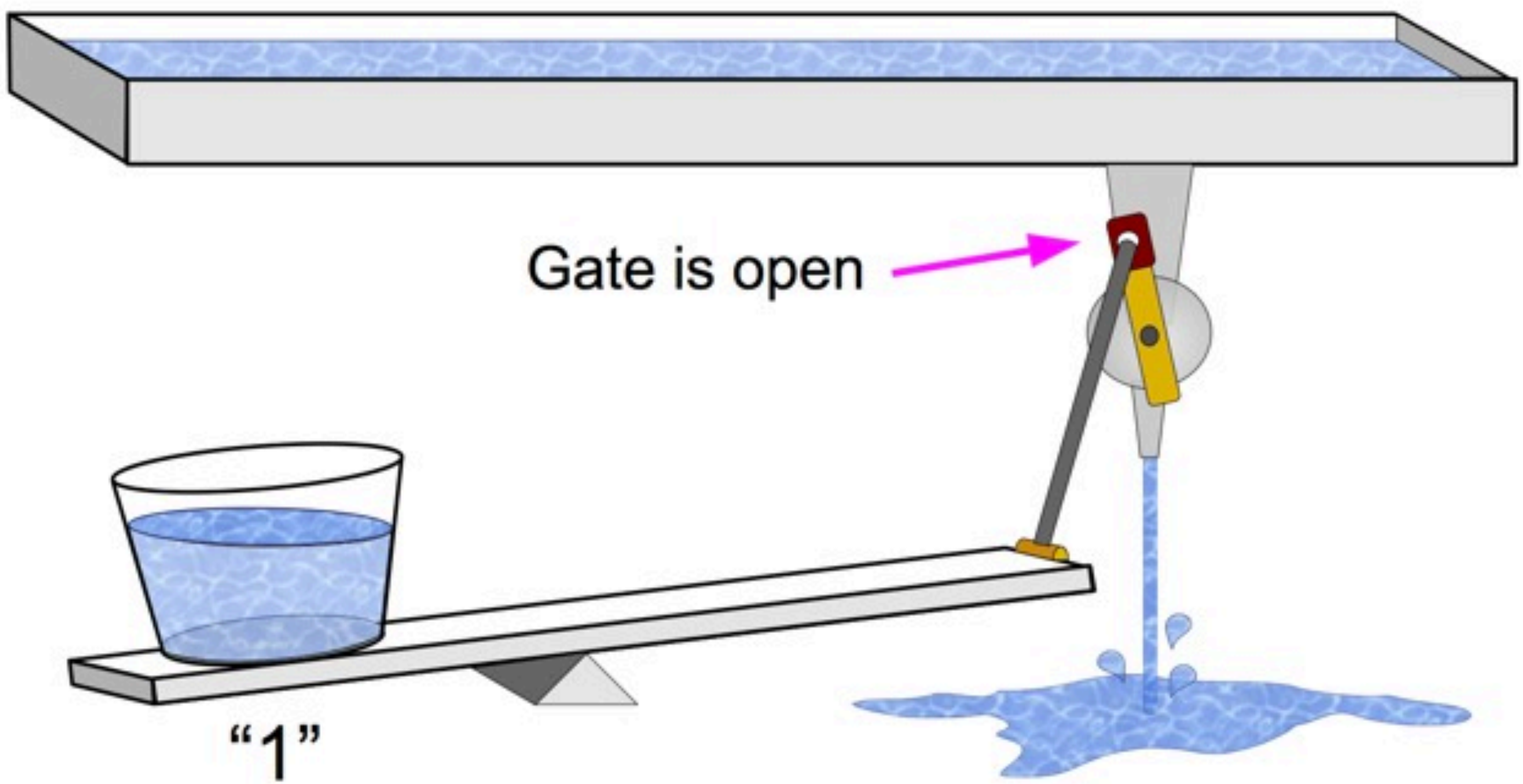
Example: store a number in binary

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

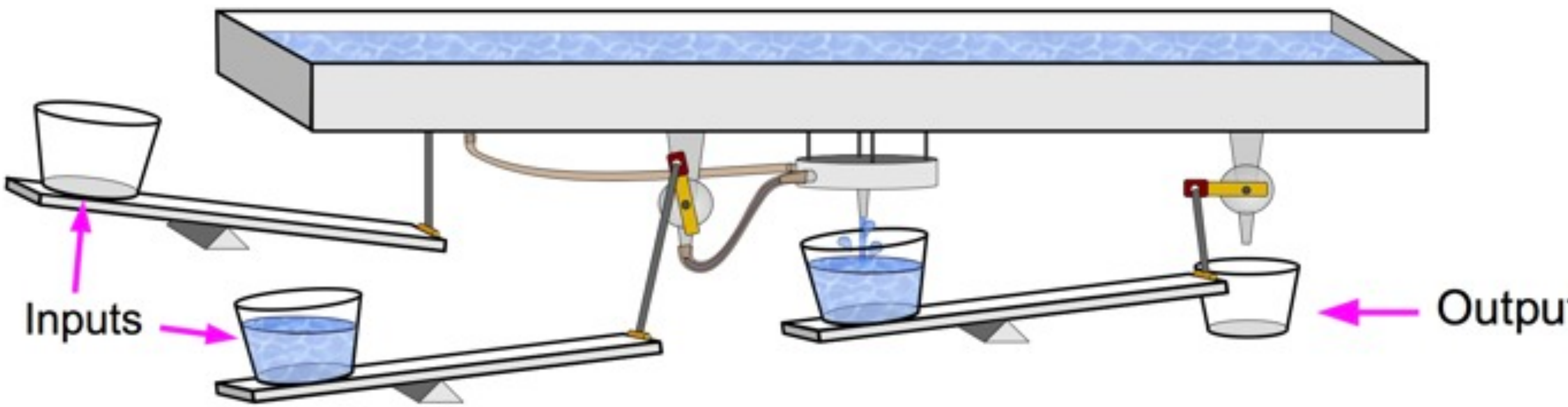


A “water transistor:” use buckets to control flow



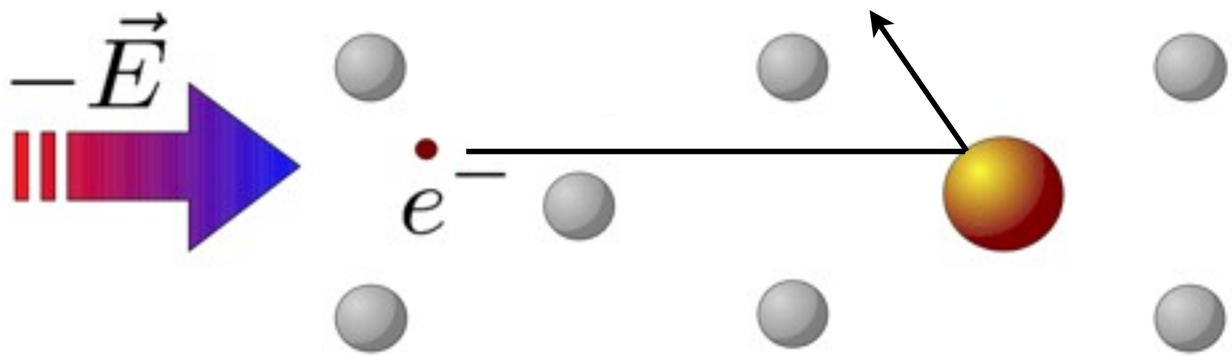
Water-based digital logic (approximate NOR gate)

Filling of inputs determines output:



Electrical transistor: use charge to control electrical channel

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



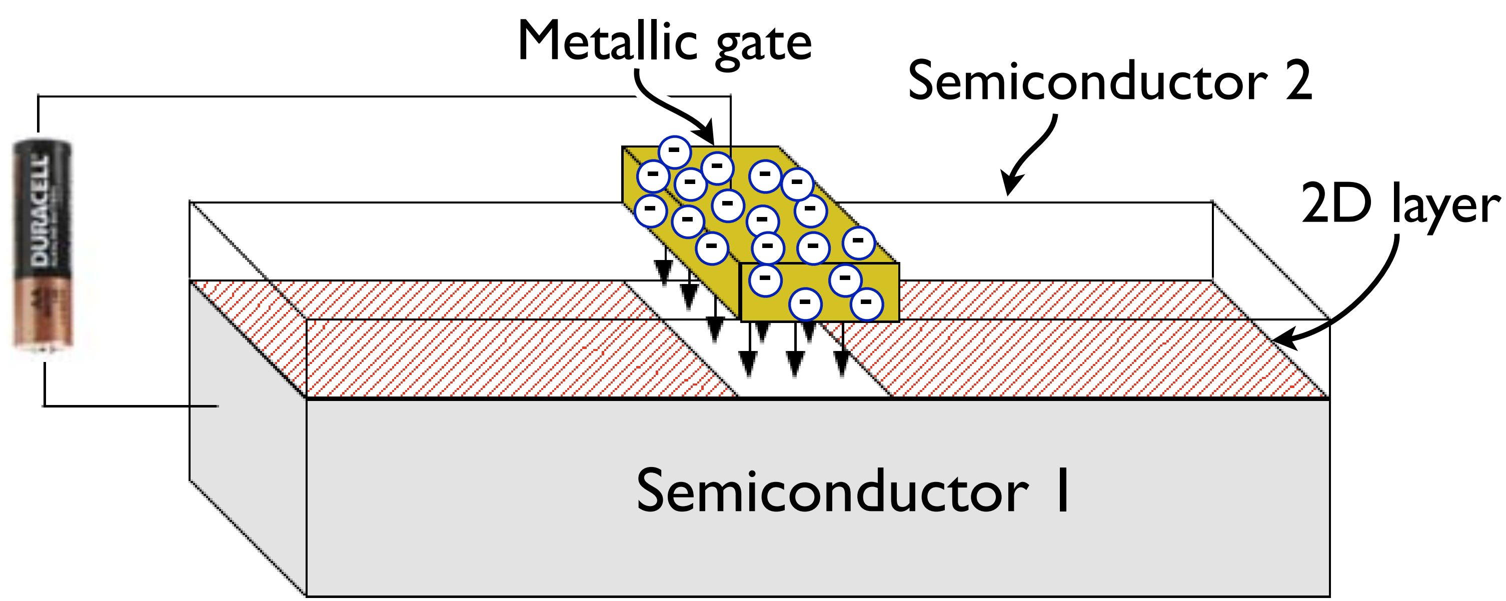
$$(\text{Conductivity}) = (\text{Carrier Density}) \cdot (\text{Mobility})$$

Idea: control conduction through channel by changing carrier density

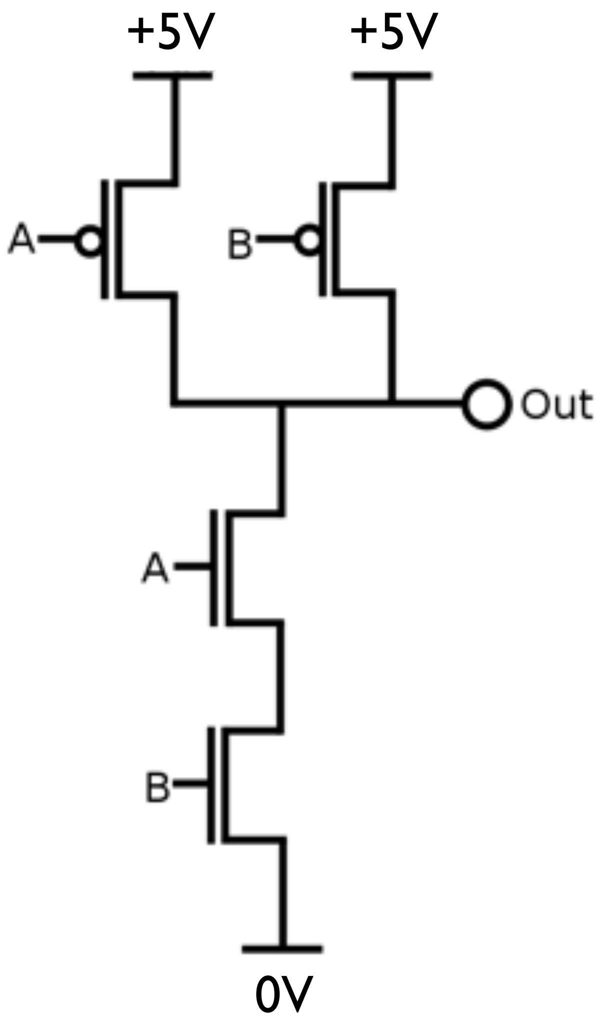
Electrical transistor: use charge to control electrical channel

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)

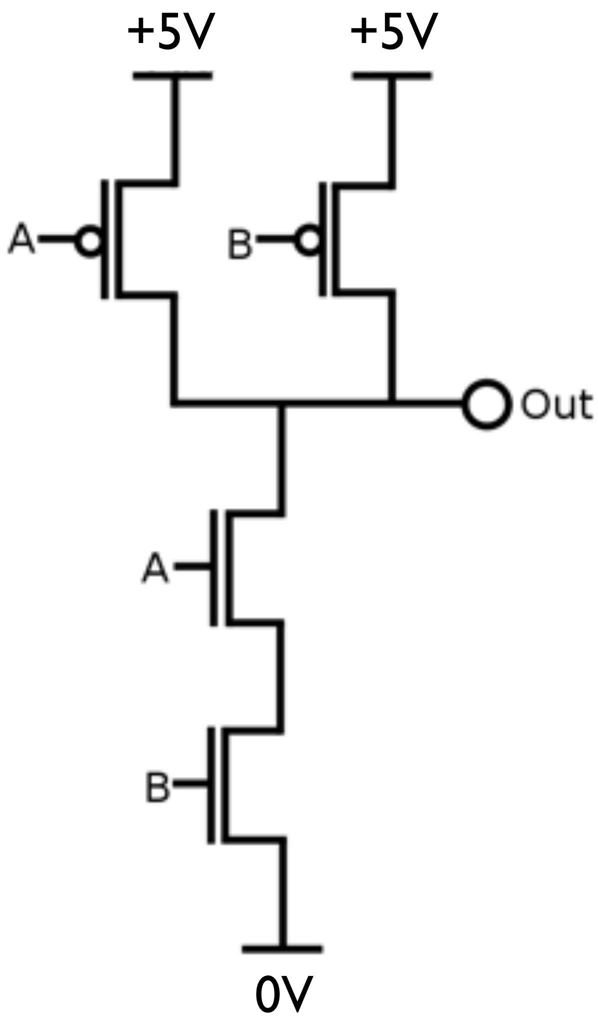
low voltage (0): channel opened

high voltage (1): channel blocked

low voltage (0): channel blocked

high voltage (1): channel opened

Logic gate produced by connecting several transistors



CMOS NAND gate
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low voltage (0): channel opened

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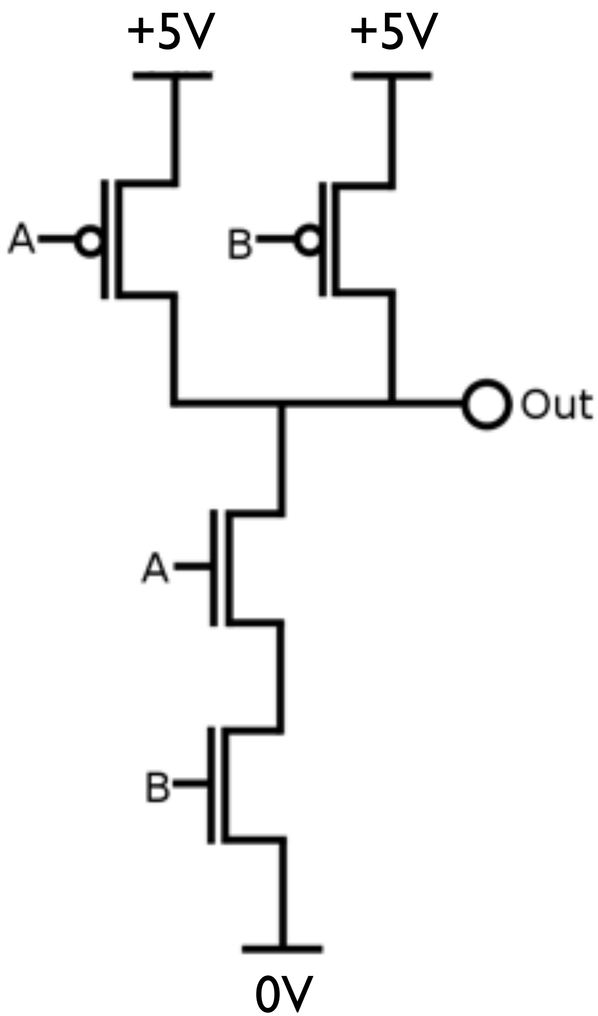
low voltage (0): channel blocked

high voltage (1): channel opened

A	B	Out
0	**0**	

Logic gate produced by connecting several transistors



CMOS NAND gate
(Wikipedia)

low voltage (0): channel opened

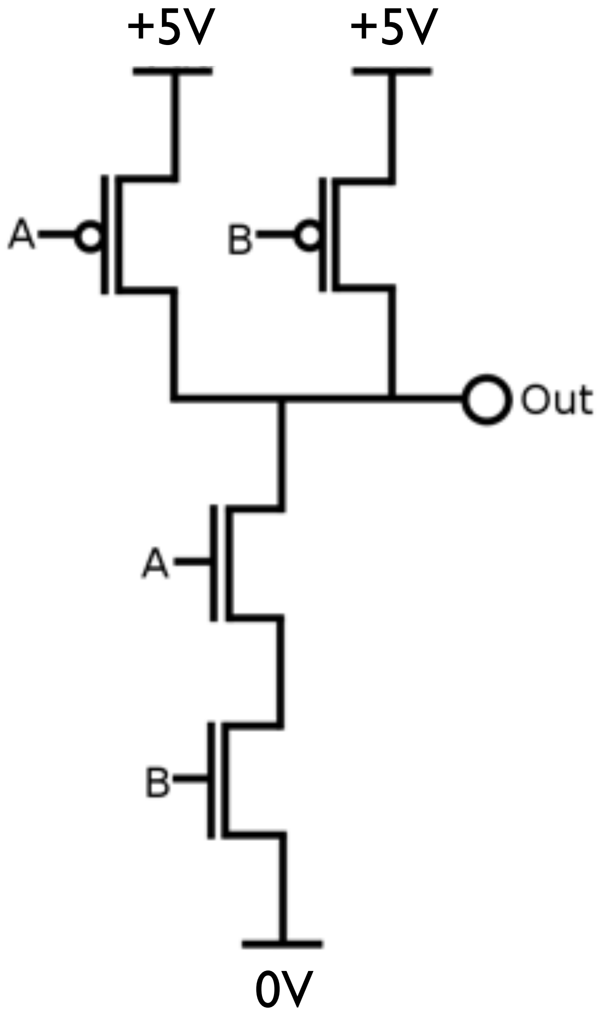
high voltage (1): channel blocked

low voltage (0): channel blocked

high voltage (1): channel opened

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

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	+5V (1)
0	1	+5V (1)
1	0	+5V (1)
1	1	0V (0)

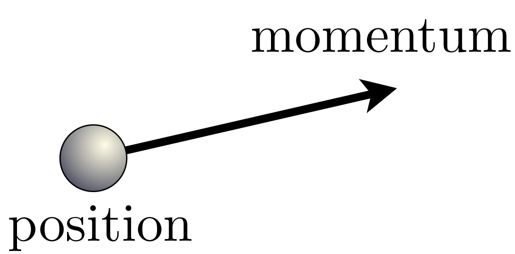
Now, make it smaller. What could go wrong?

Part II: Brief introduction to quantum mechanics

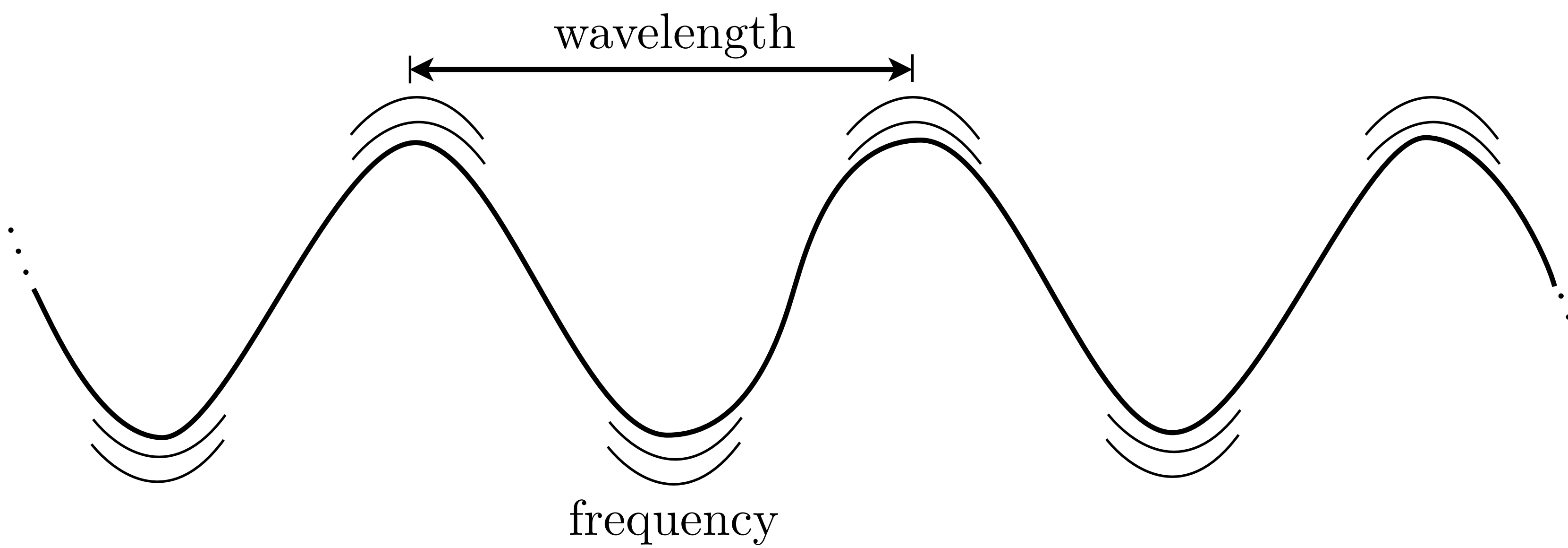
Goals: introduce basic principles

1) wave particle duality
2) quantum tunneling

A classical particle has a position and momentum



A wave has wavelength and a frequency

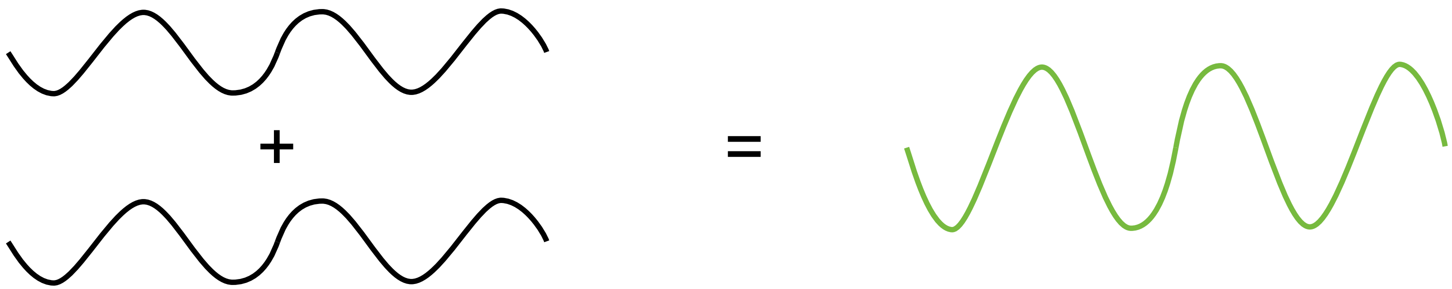


wave repeats over and over and over...

When two waves come together, they interfere

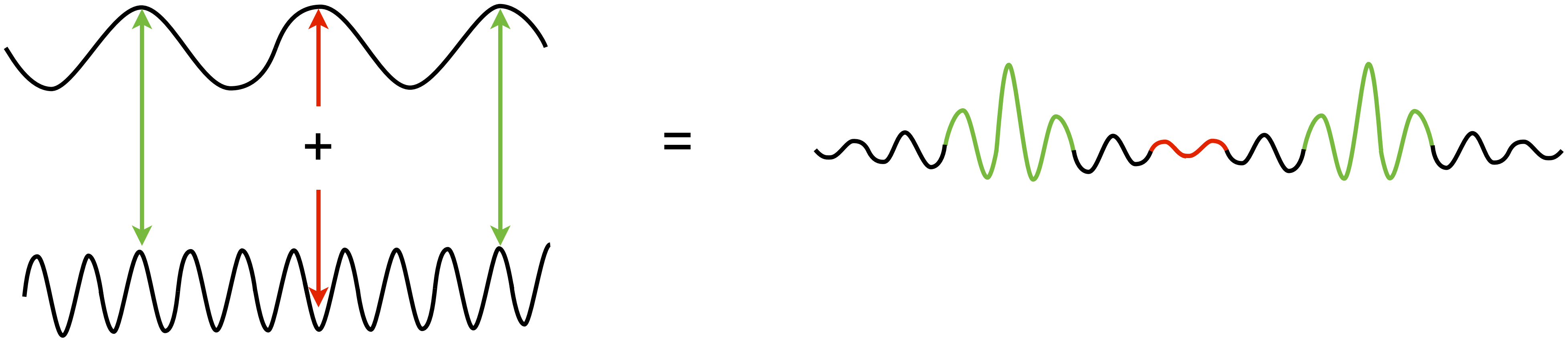
When two waves come together, they <u>interfere</u>

Constructive interference

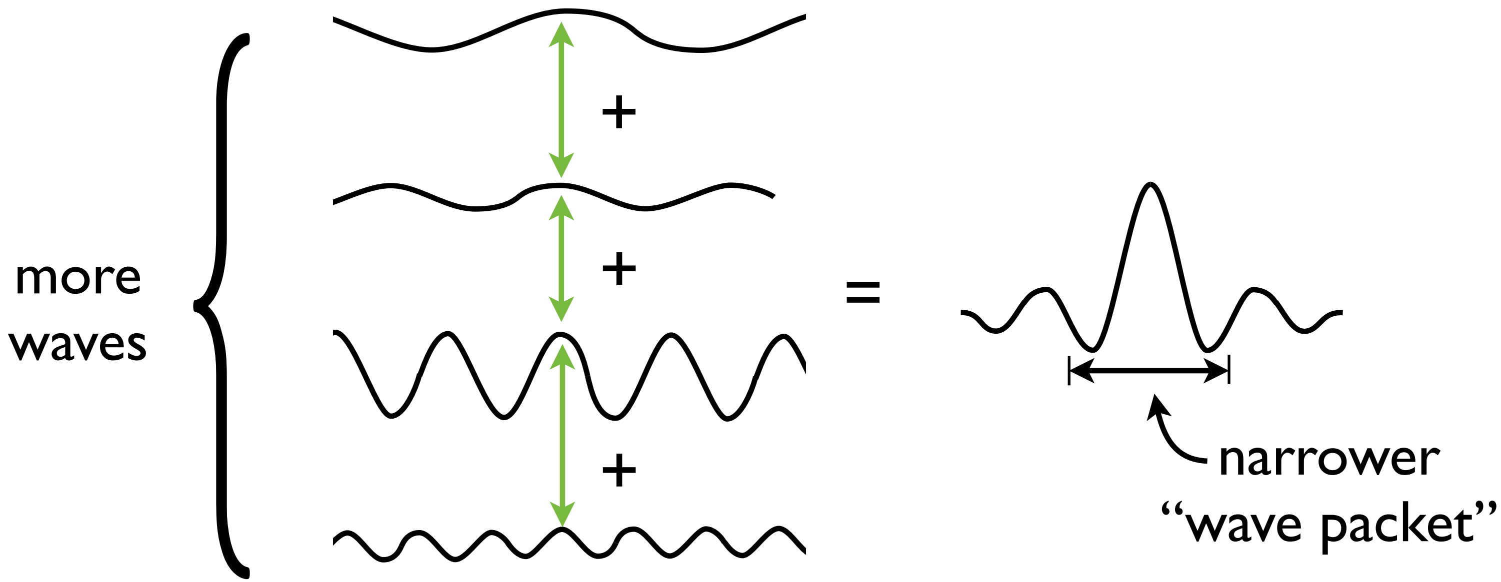


Destructive interference

If waves have different wavelengths, *beats* appear



With many different wavelengths, can make a localized spike



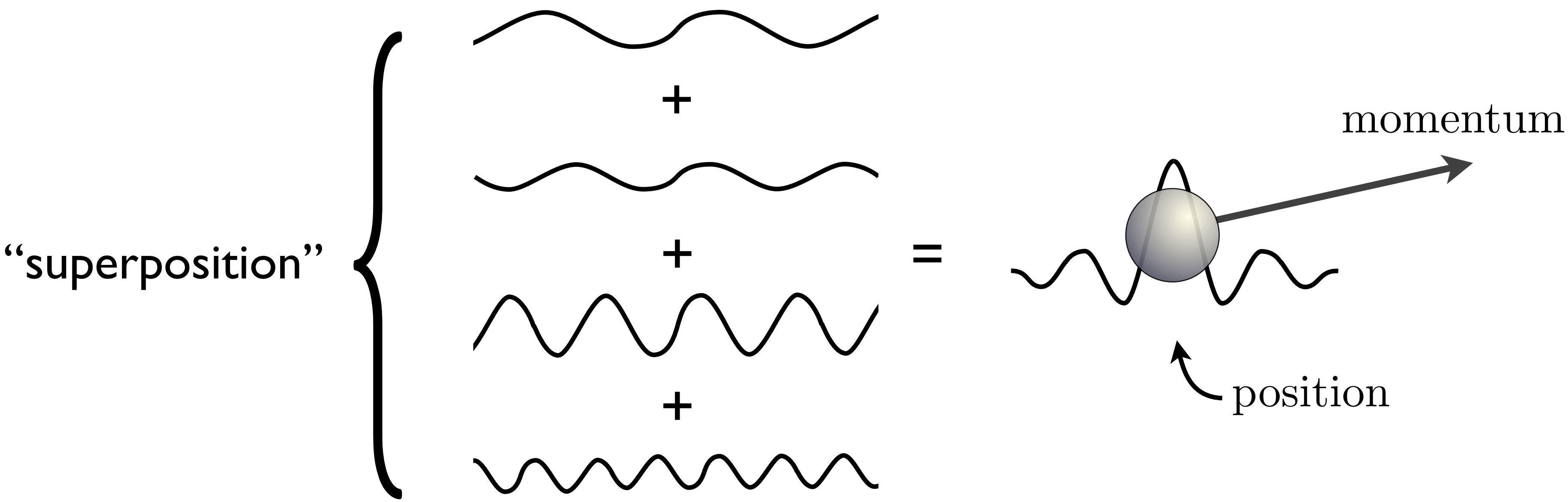
In QM, particle motion is described by equation for a wave (!)

De Broglie's relation between momentum and wavelength:

$$(\text{wavelength}) = \frac{(\text{Planck's Constant})}{(\text{momentum})}$$

PhD thesis, 1924

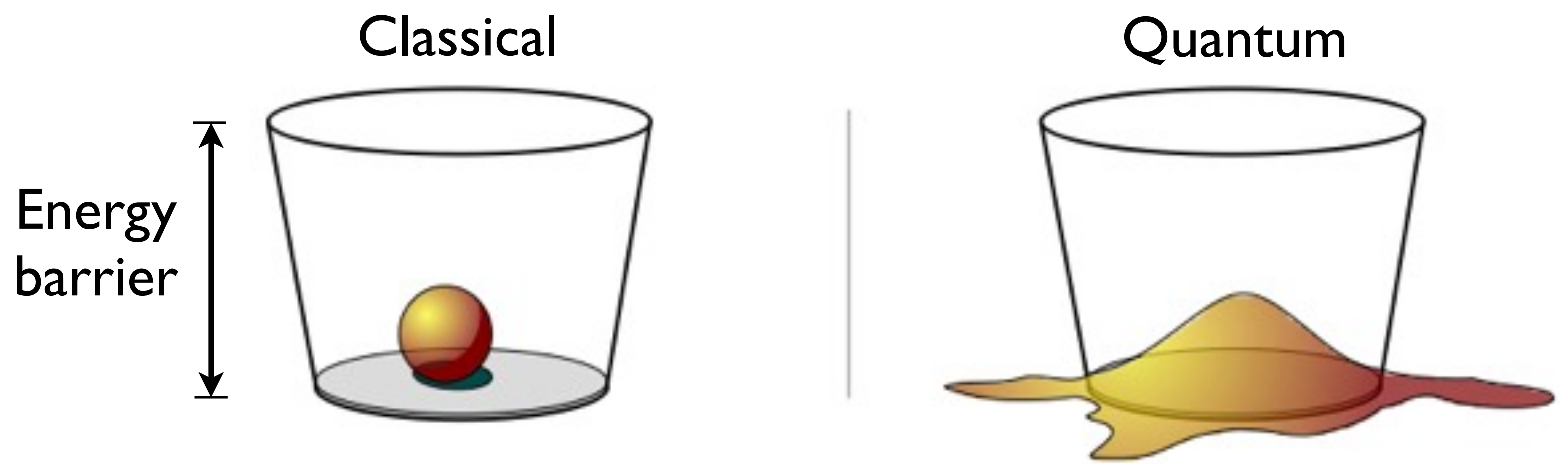
A localized particle requires many different wavelengths



<u>Heisenberg Uncertainty Principle</u>

Tradeoff between certainty of position and momentum

Quantum tunneling: "matter wave" cannot be fully trapped

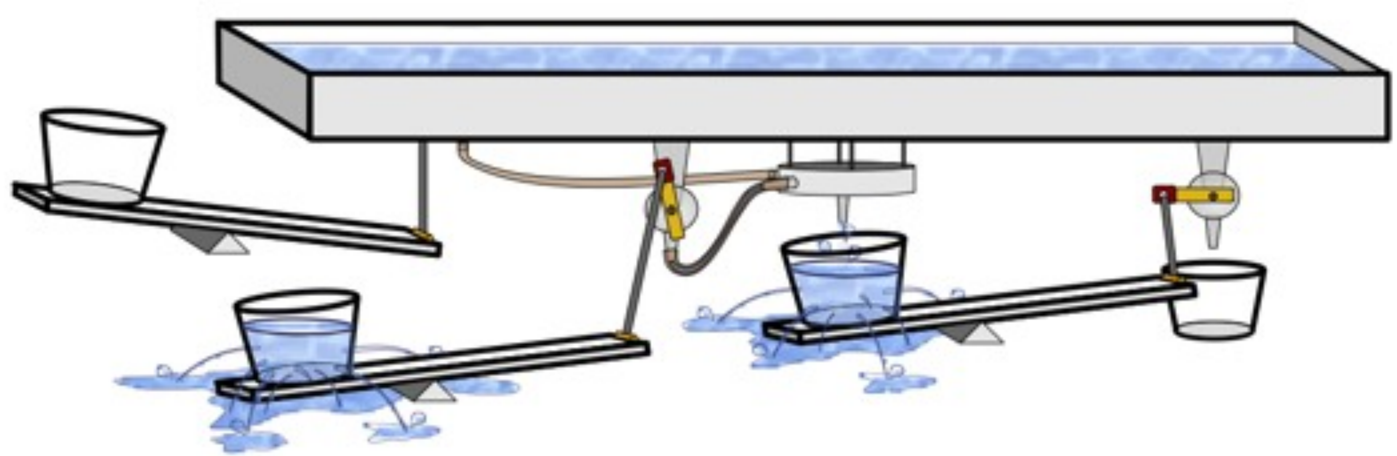


Tunneling speeds up *exponentially* as barrier thickness shrinks

Smaller transistors leads to greater leakage, power consumption

a) Bad for the **environment**

b) Excessive heating hinders further downsizing

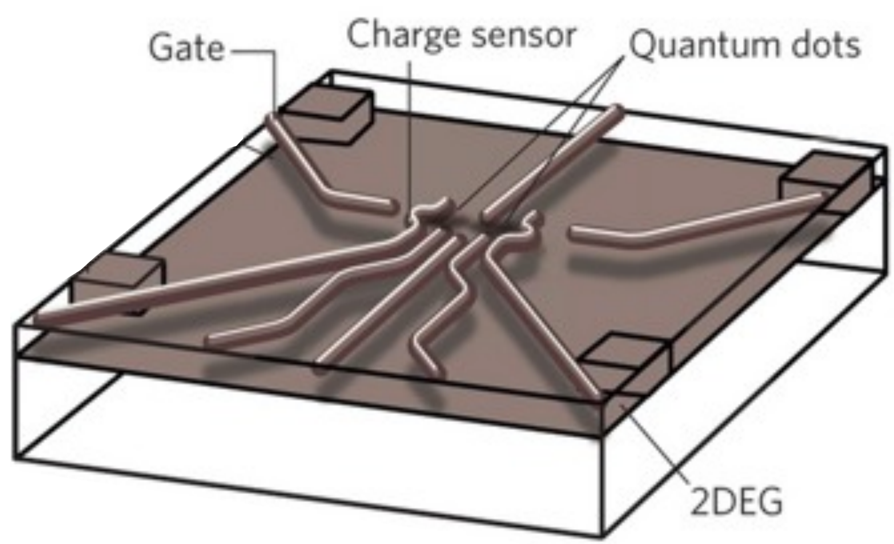


Part III: Nanoelectronic devices

Goals: introduce common elements

1) quantum dot

2) single electron transistor



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

A quantum dot is an "artificial atom"

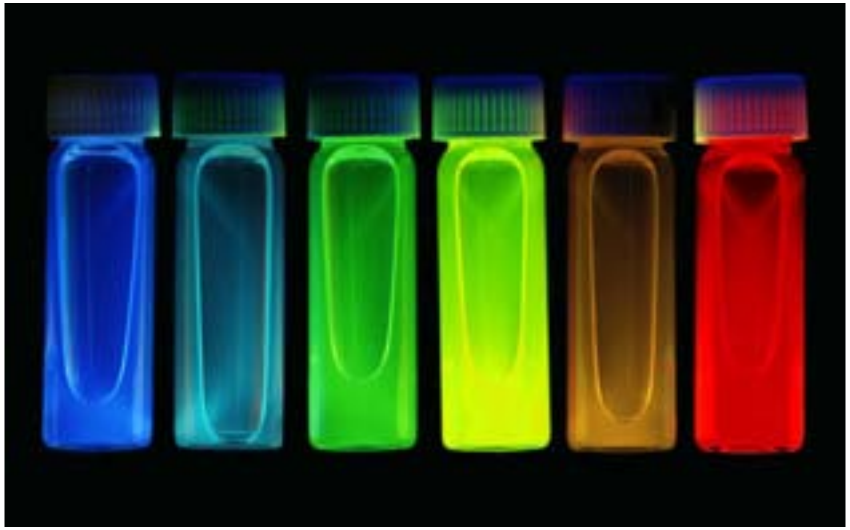
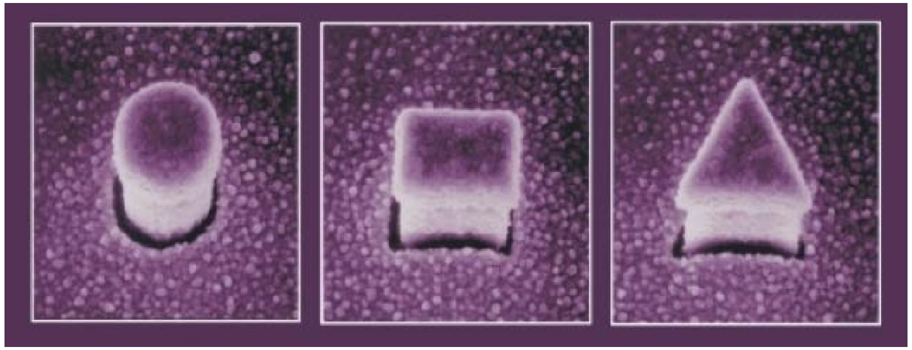
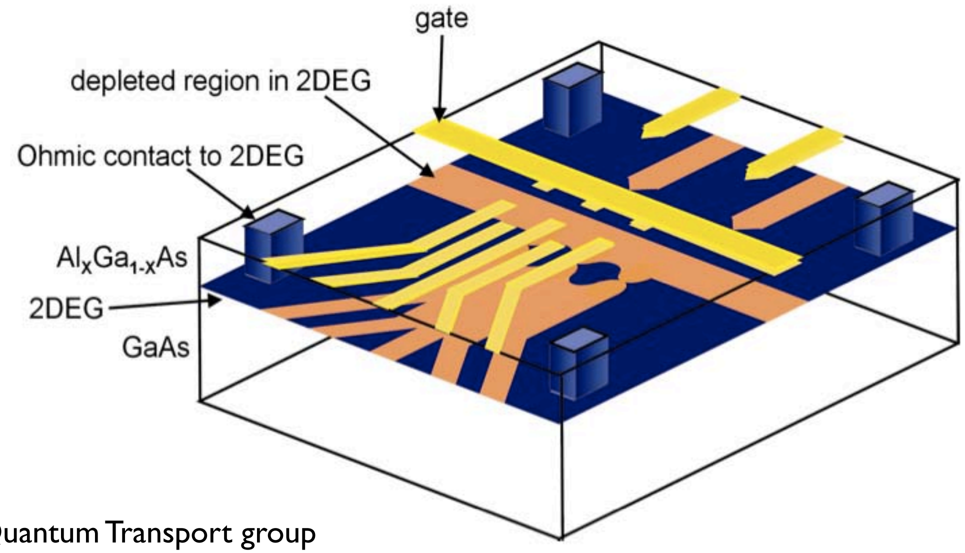


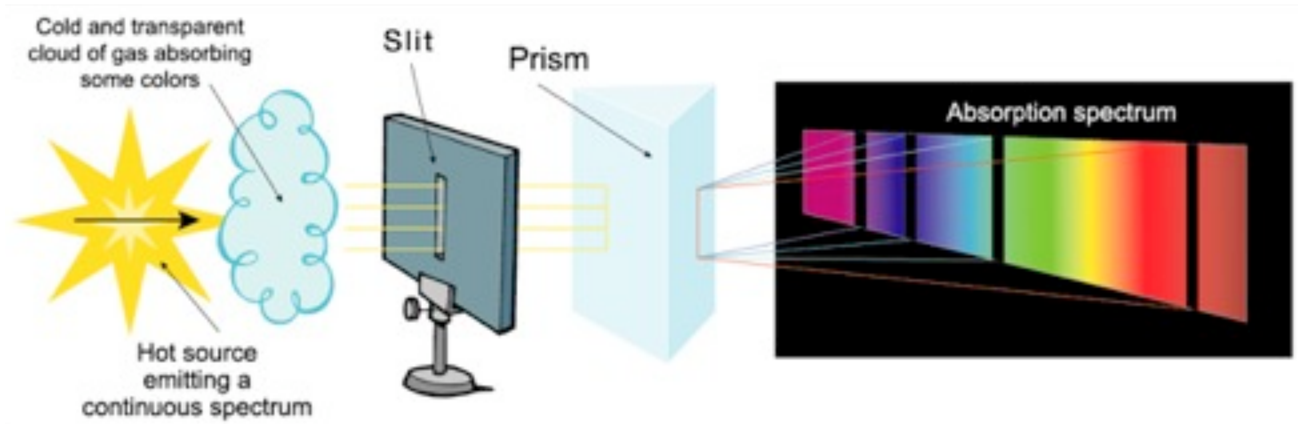
Photo by Felice Frankel, MIT (web.mit.edu)

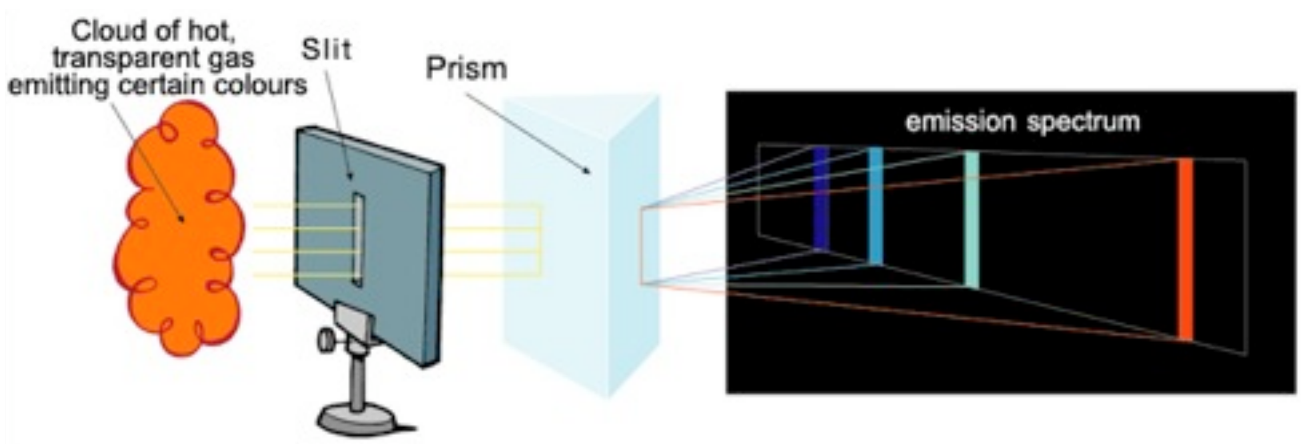




Images from TU Delft Quantum Transport group

Early 1900s: energy absorbed/emitted in discrete amounts

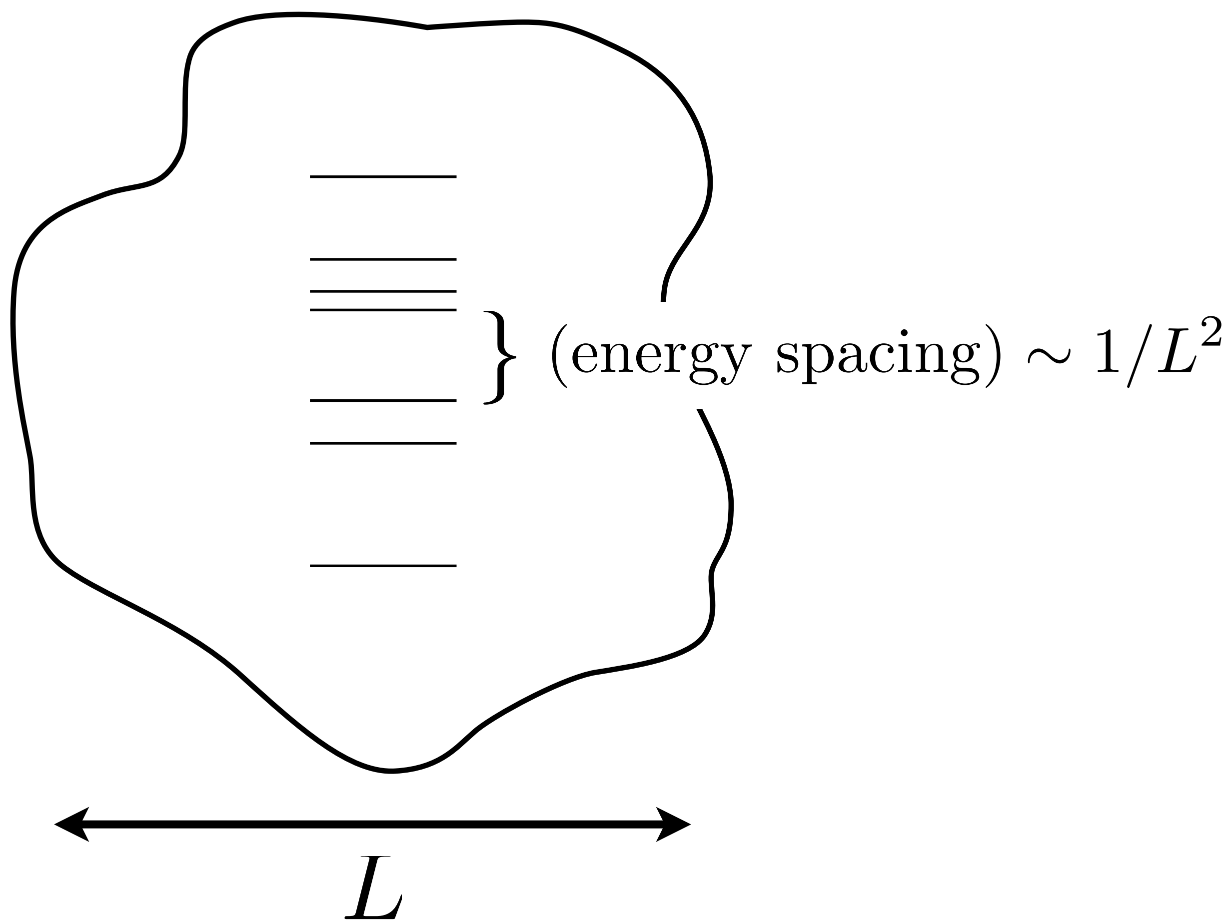




Figures from astro-canada.ca

Wavelength (momentum) set by size of confinement region

Electron confined in nanoscale "box"



(also sets wavelength)

Confinement reduces wavelength, increases energy scale

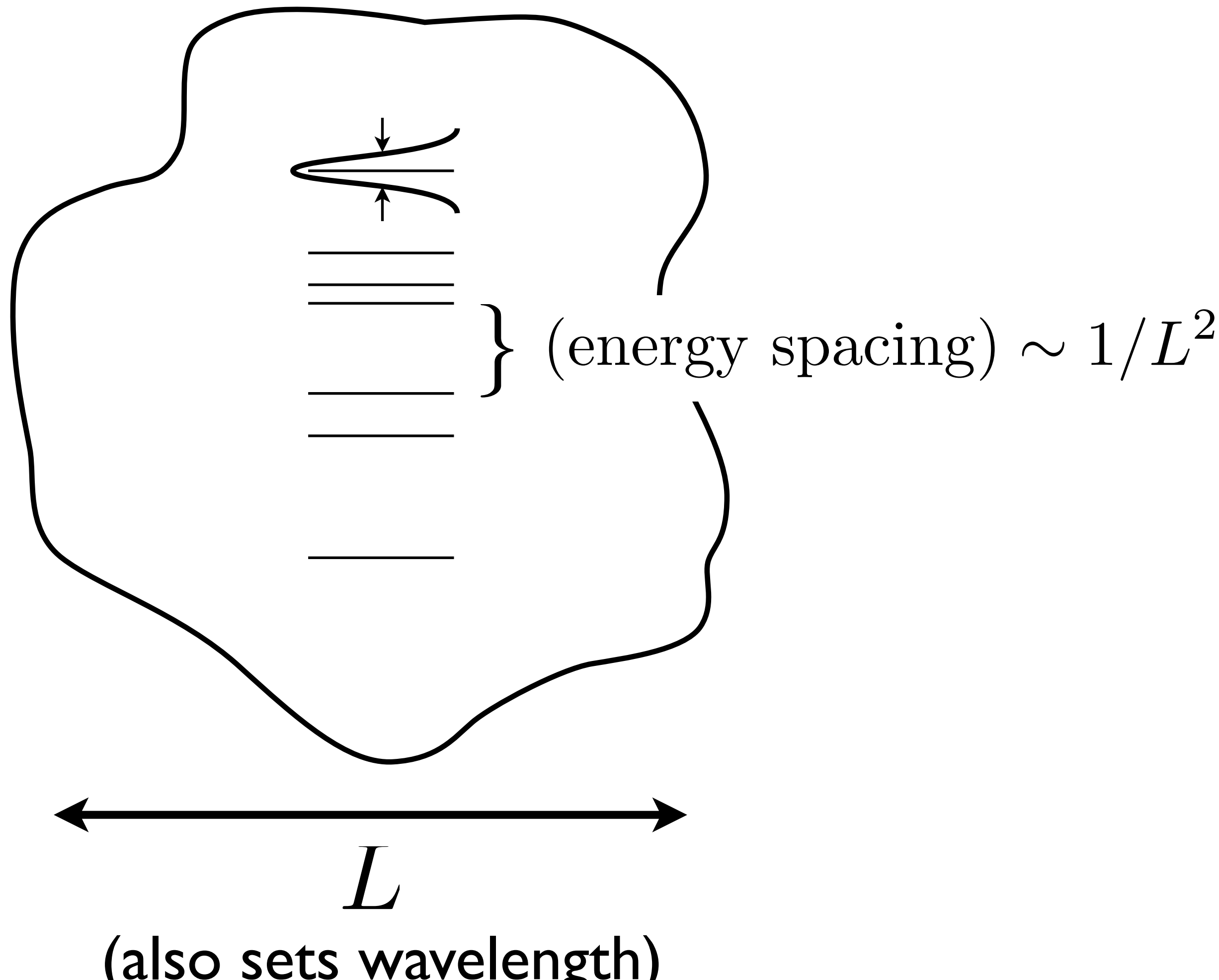
Analogy:

Smaller drum, higher frequency

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

Discrete energies visible when splitting exceeds resolution

Electron confined in nanoscale "box"



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

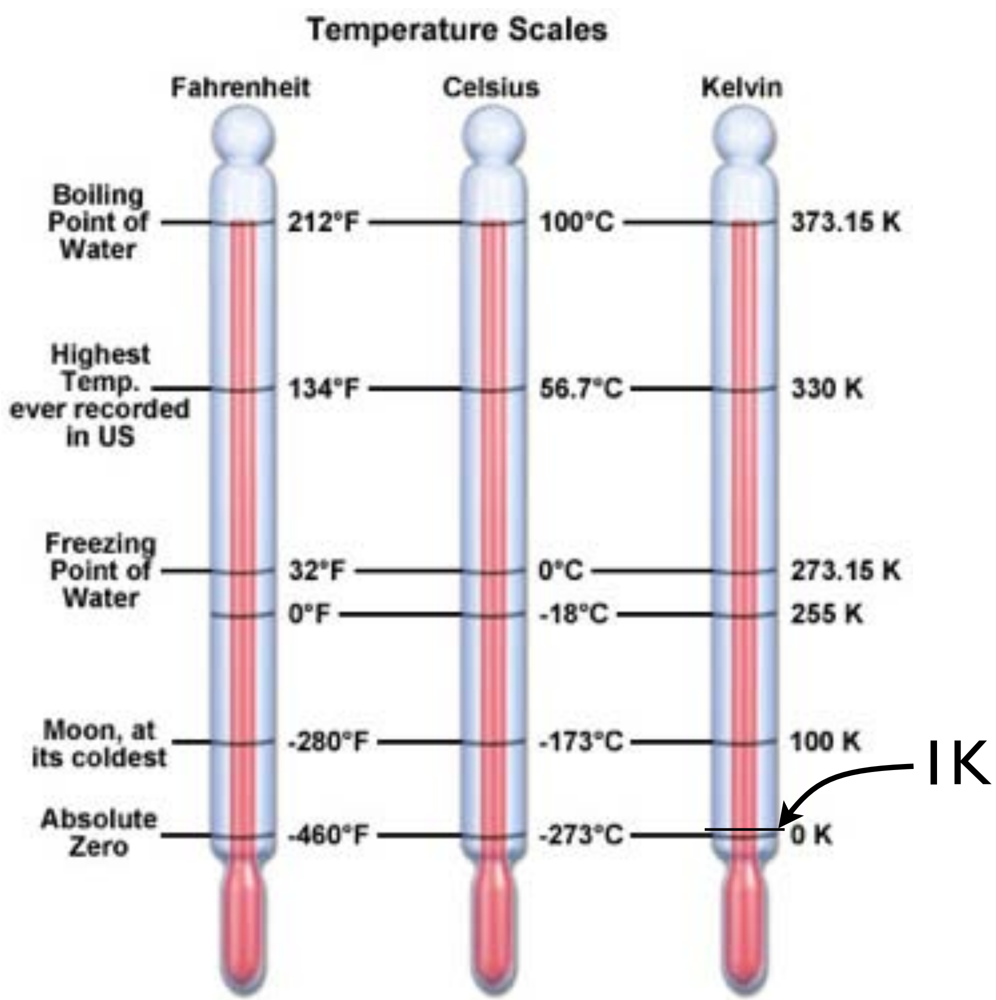


Image from www.magnet.fsu.edu

How big is 100 nm?

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

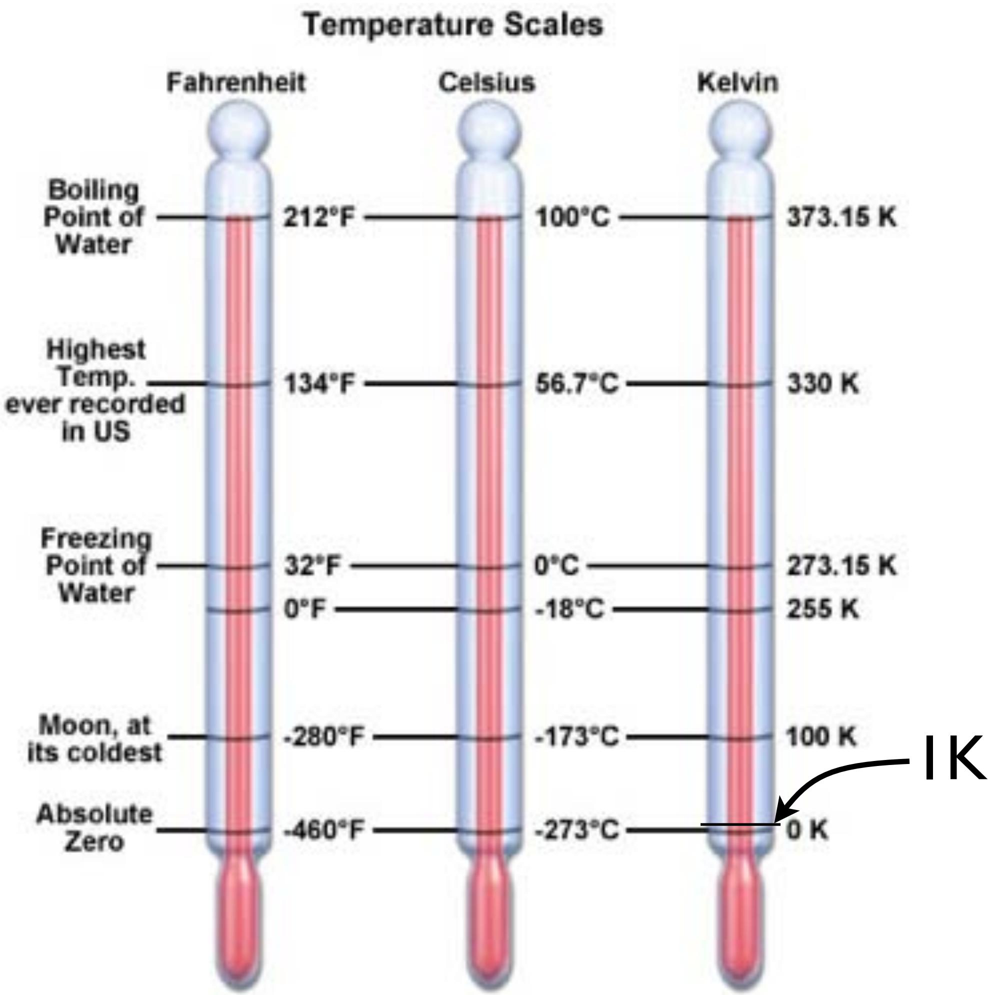


Image from www.magnet.fsu.edu

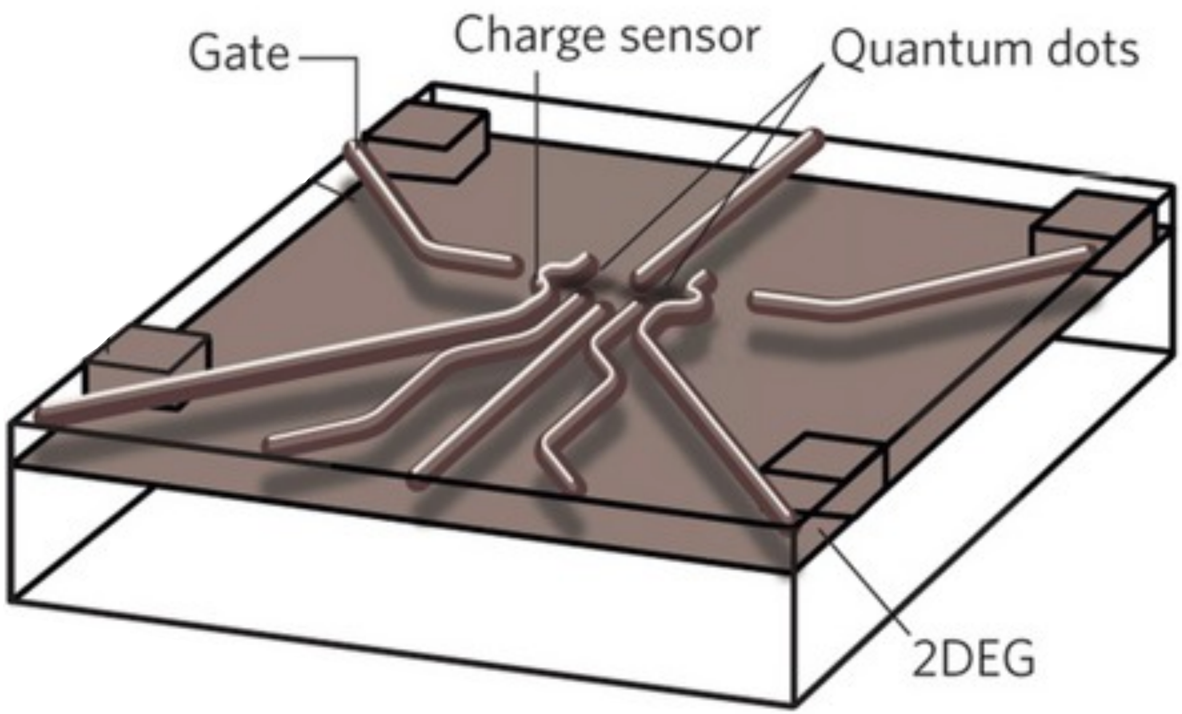
How big is 100 nm?

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



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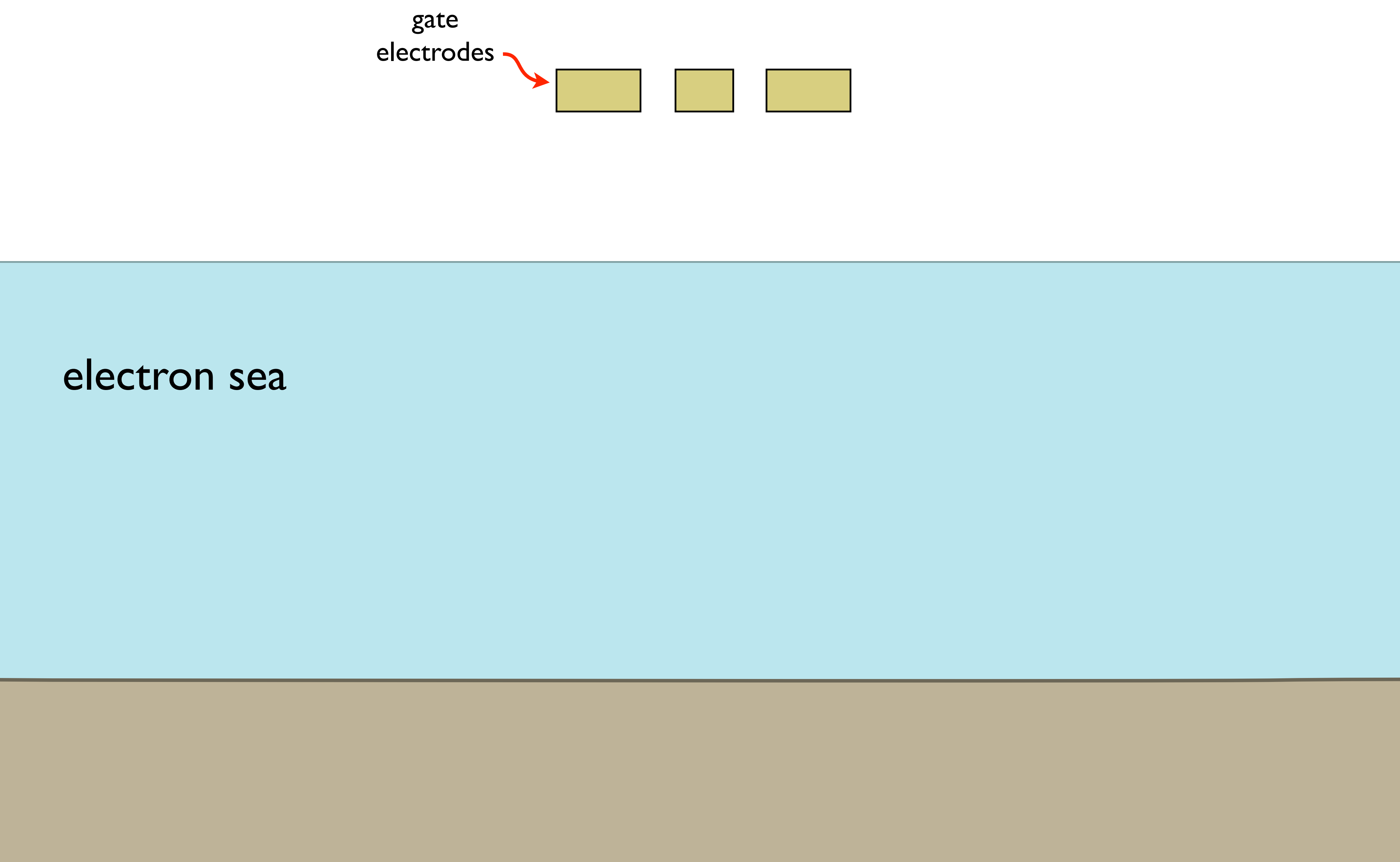
Analogy: raising mountains from the sea



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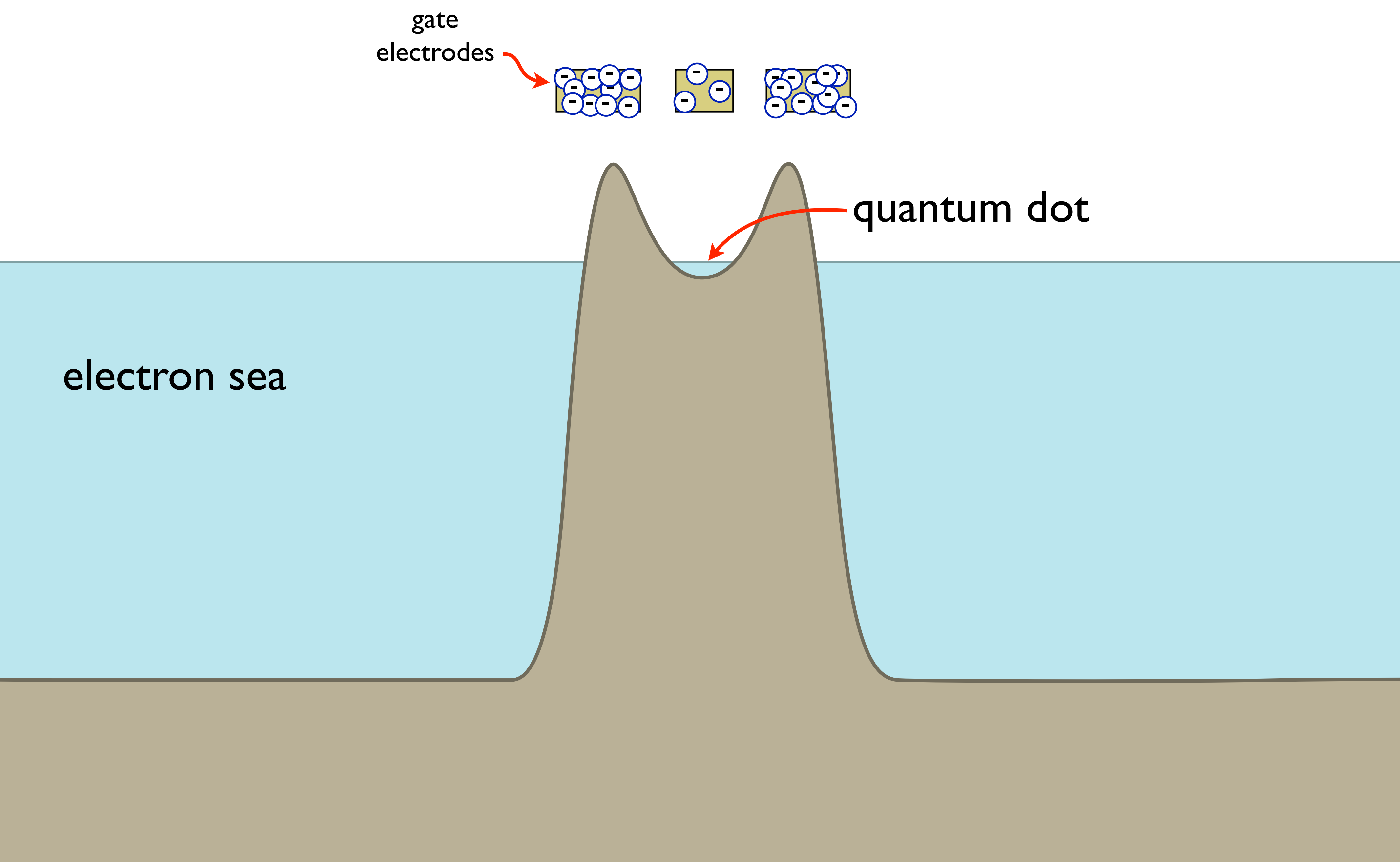

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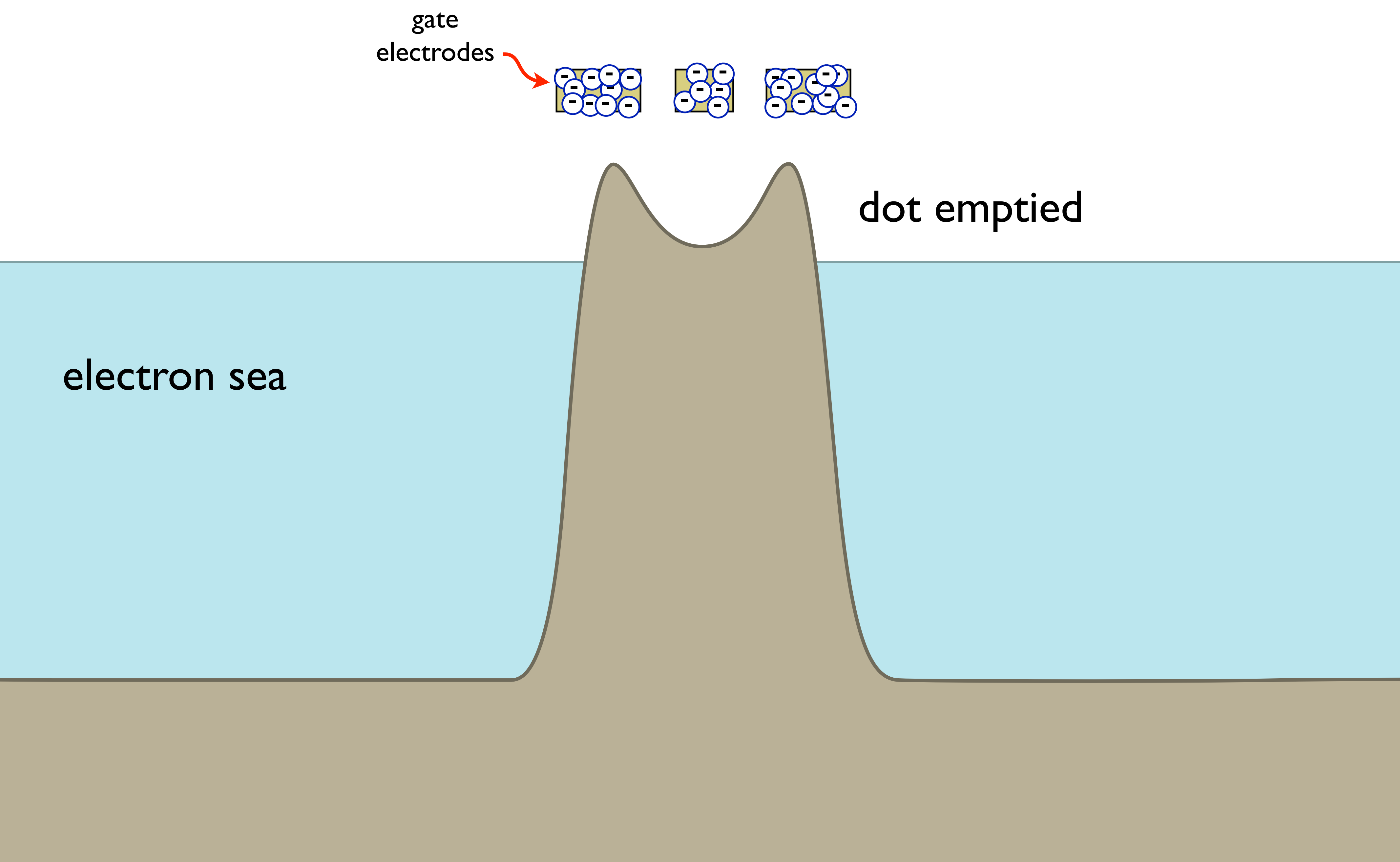
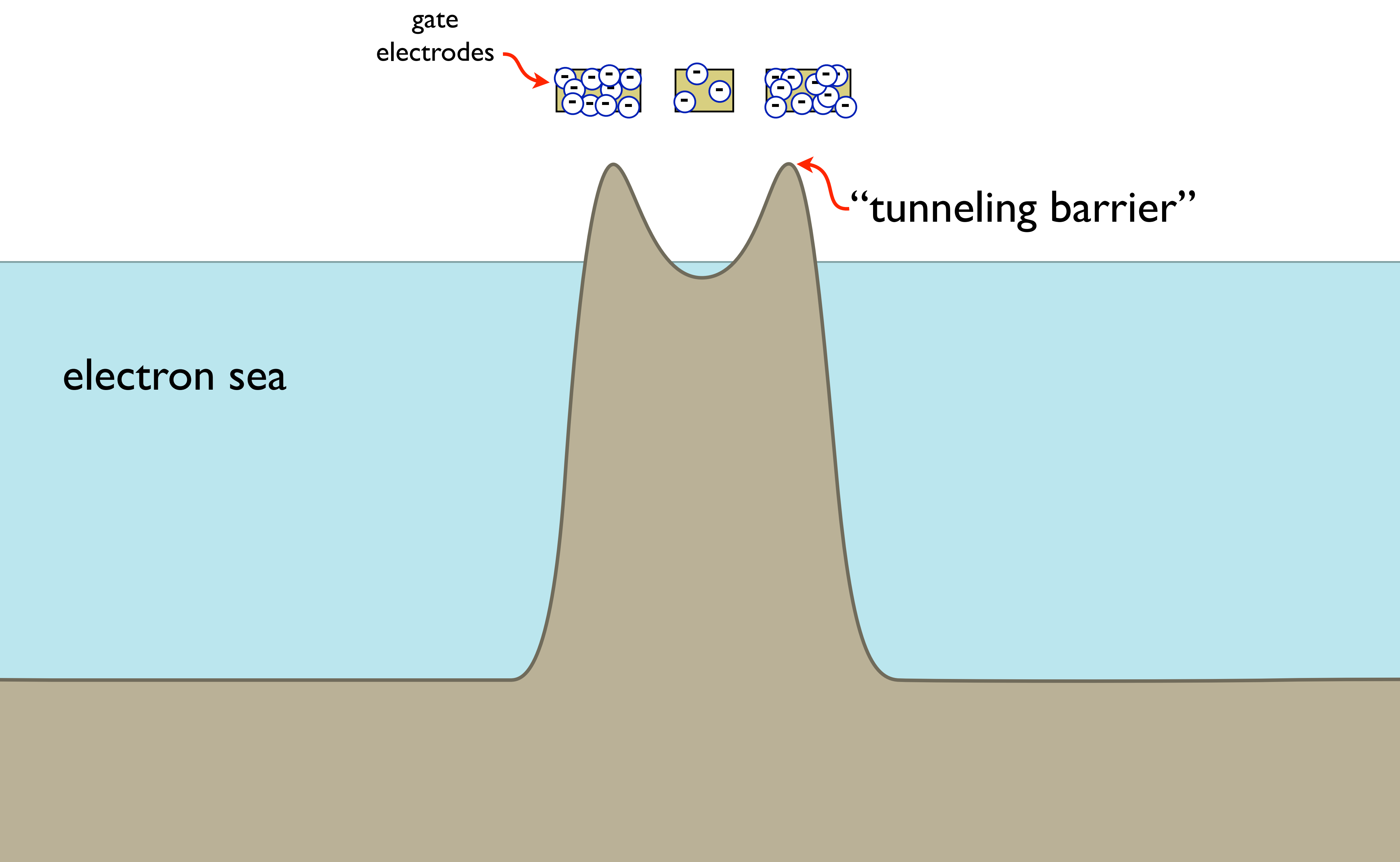
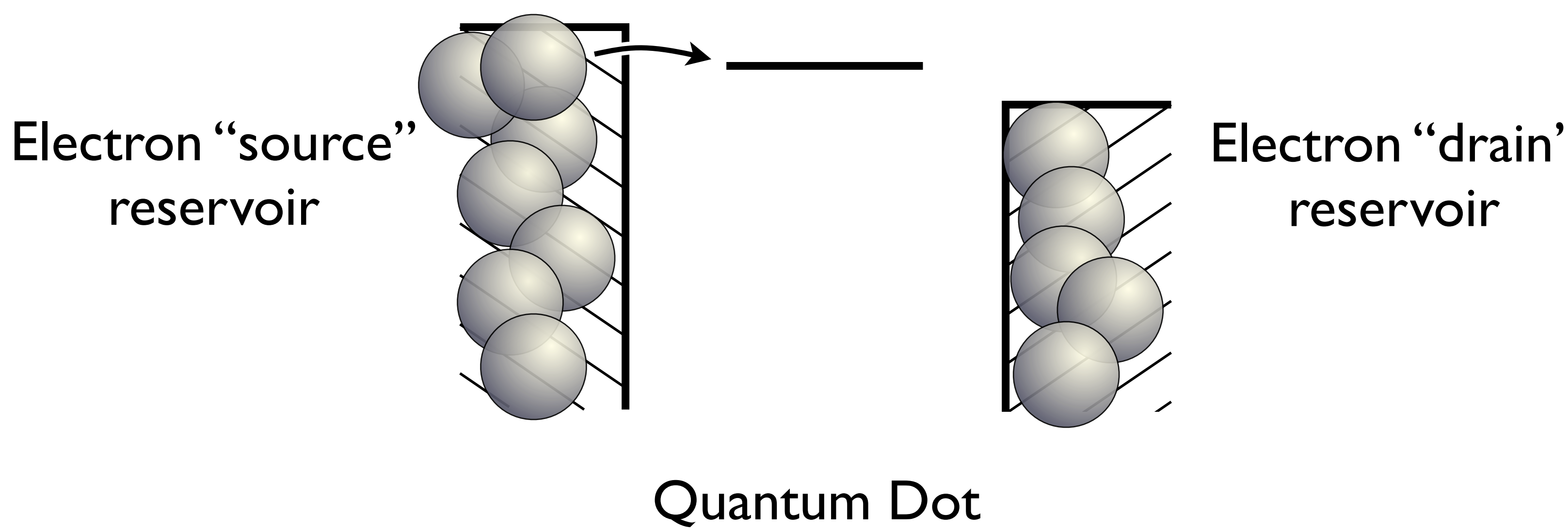


Analogy: raising mountains from the sea



Electrons flow one by one through the dot



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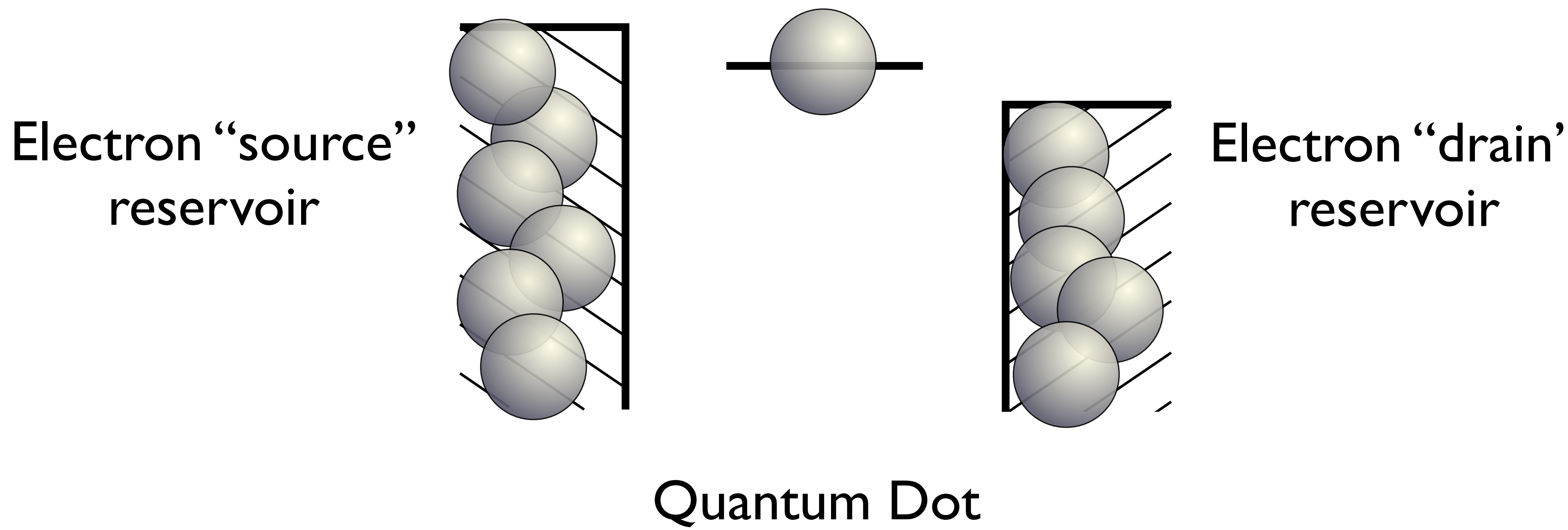
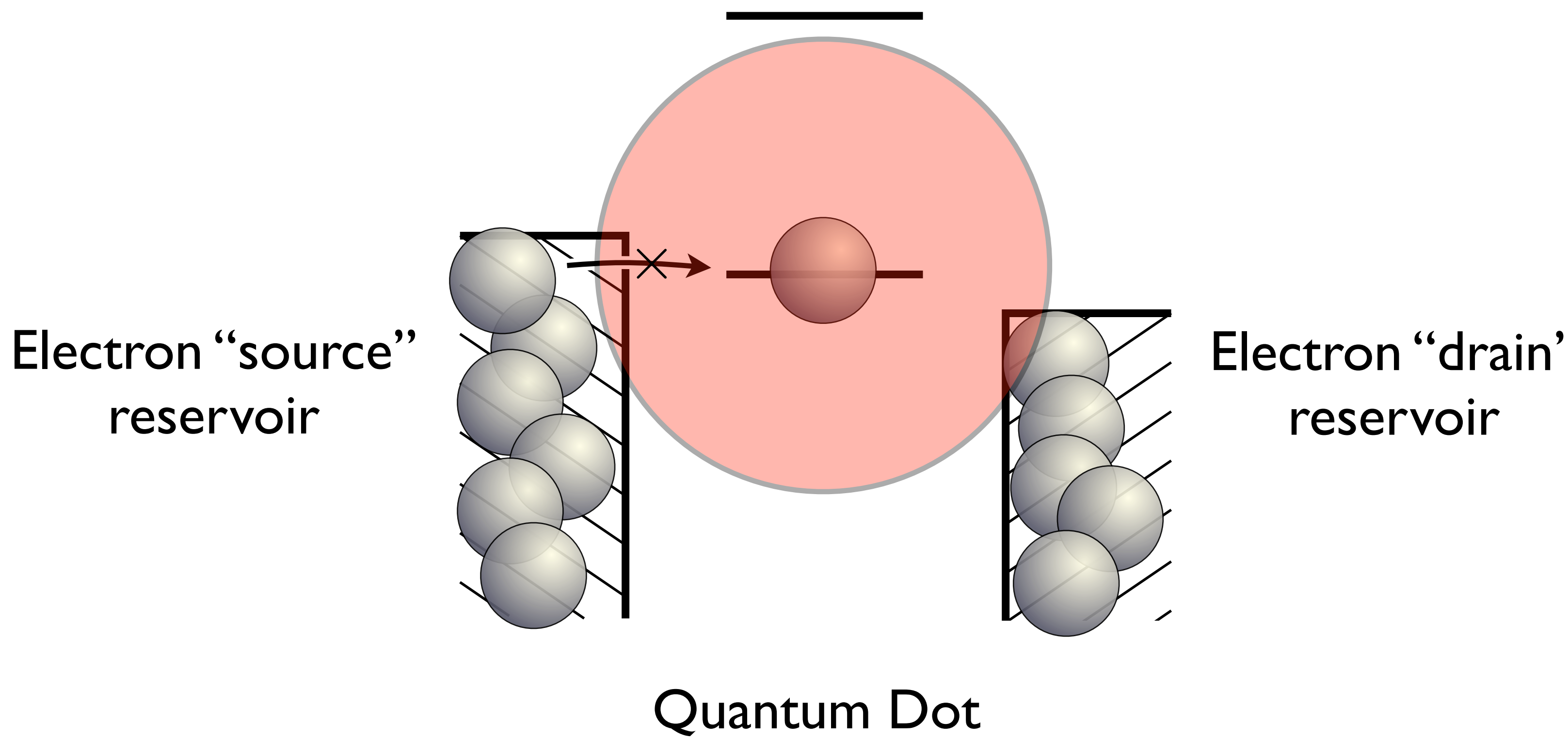
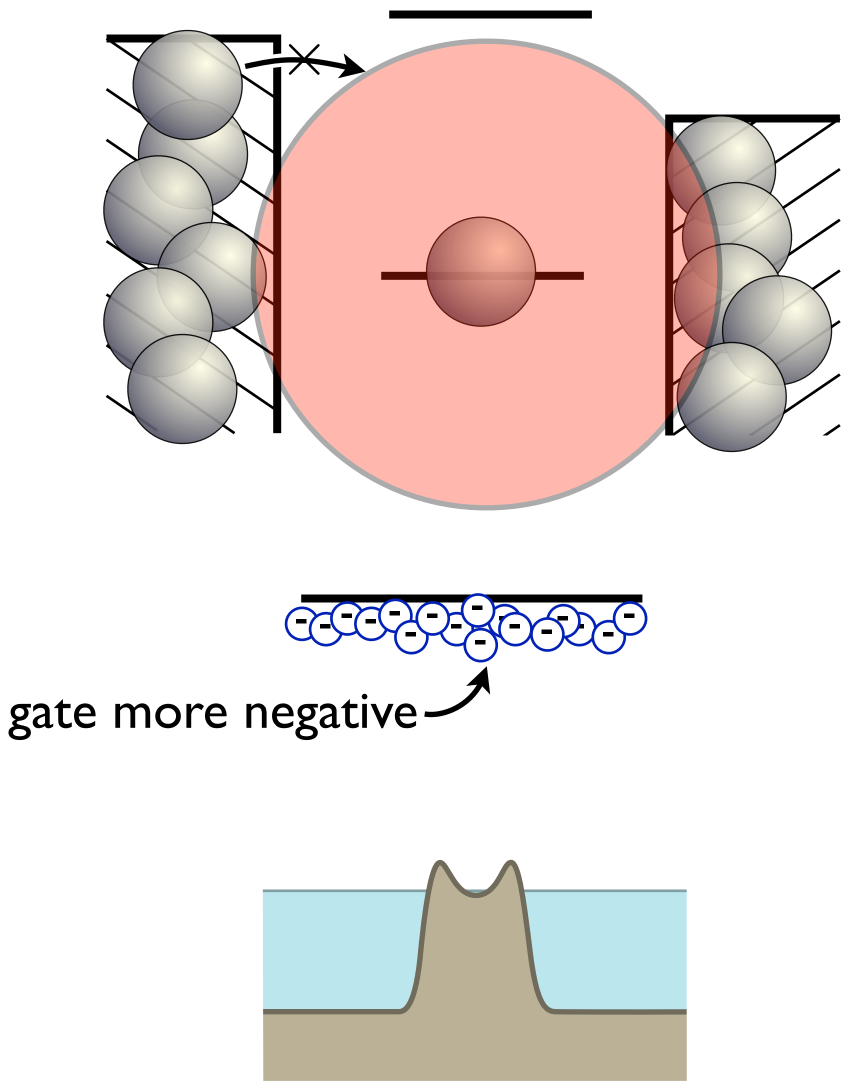


Once filled, charge of electron prevents another from entering

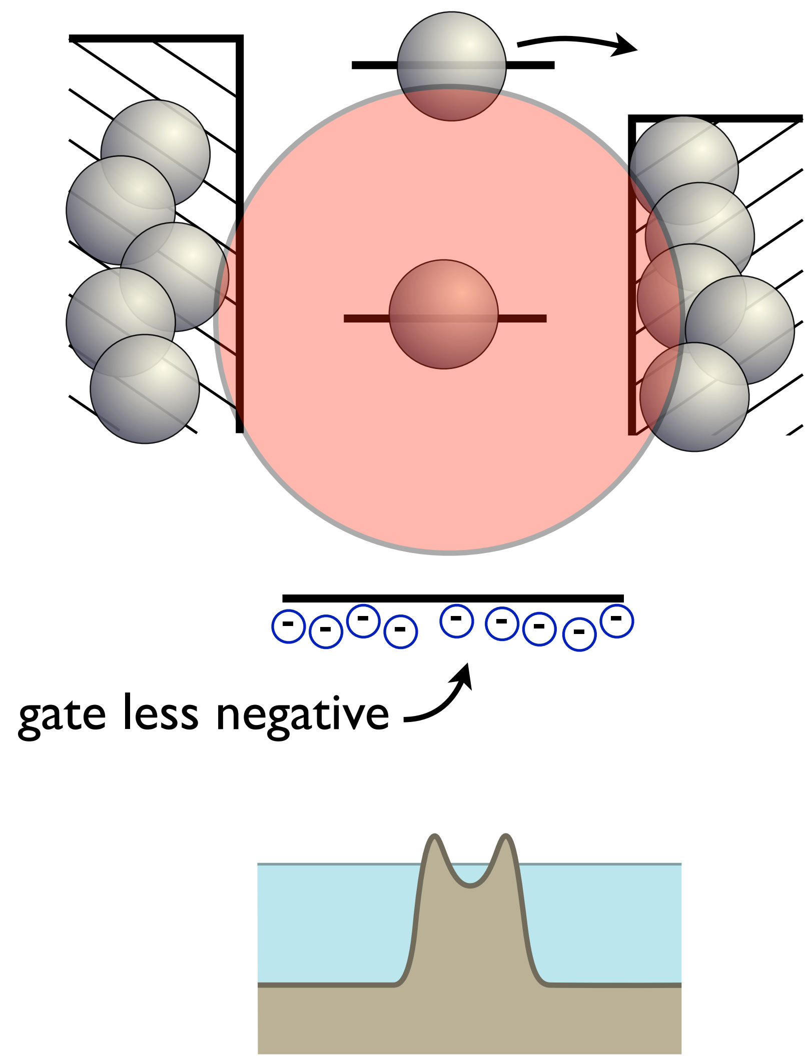


Single electron transistor: operating on the edge

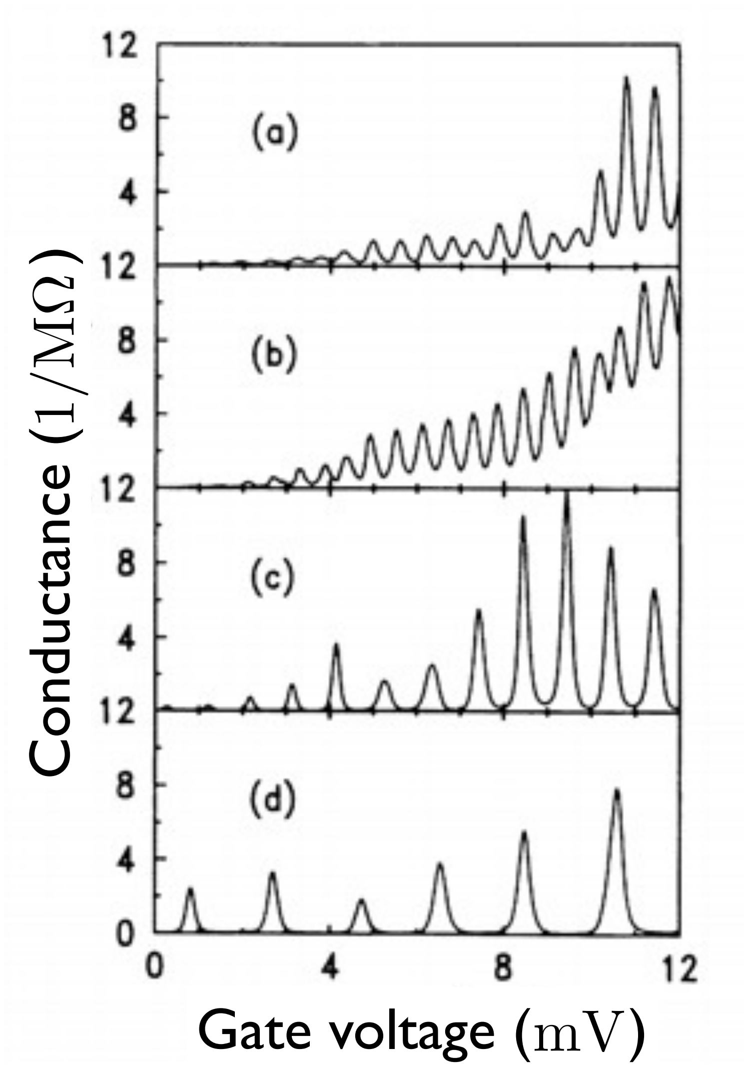
No current flows



Current flows

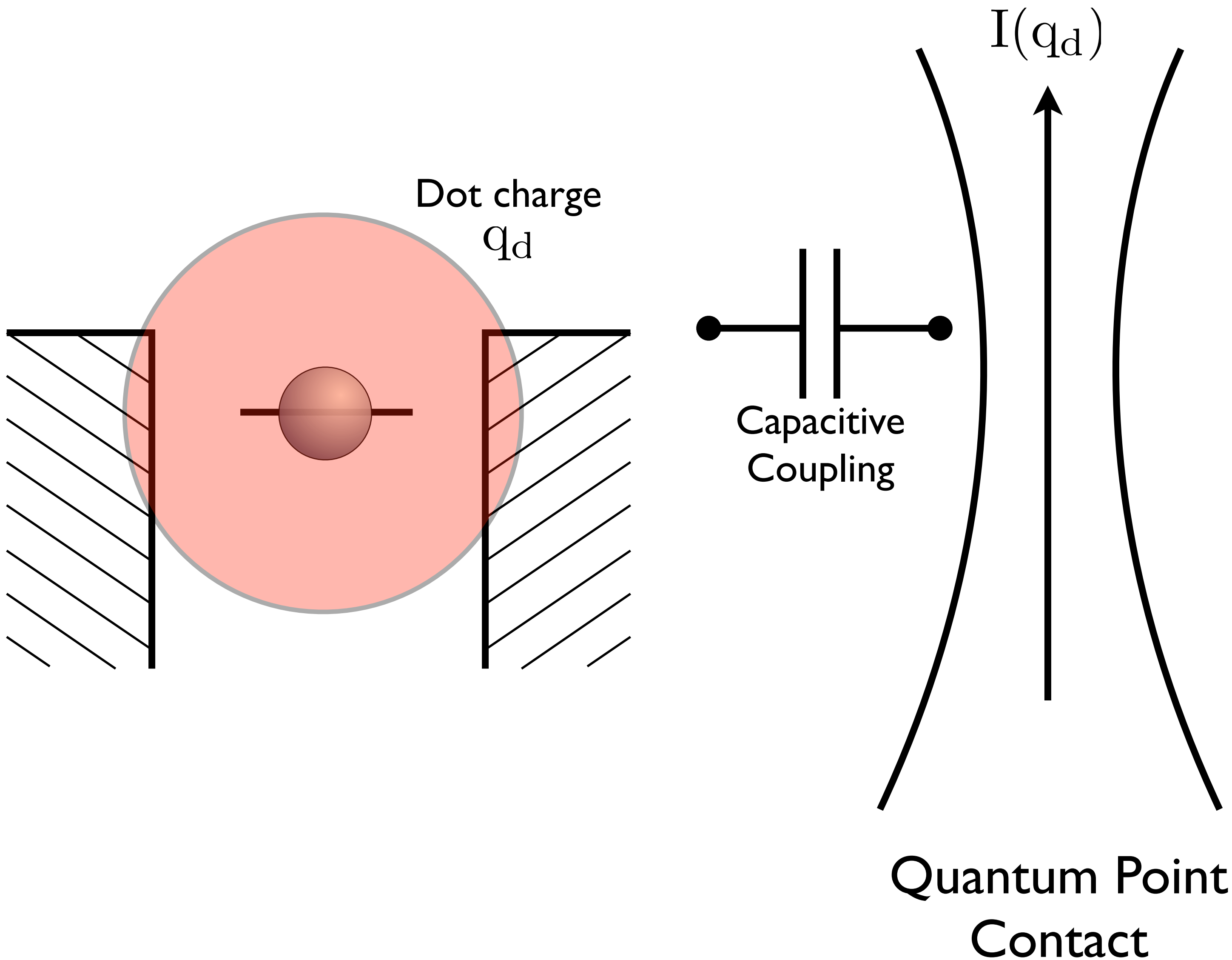


Single electron transistor: conductance very sensitive to voltage



U. Meirav, M. A. Kastner, and S. J. Wind, Phys. Rev. Lett. **65**, 771 (1990).

Similar principle allows *sensing* of single electron tunneling



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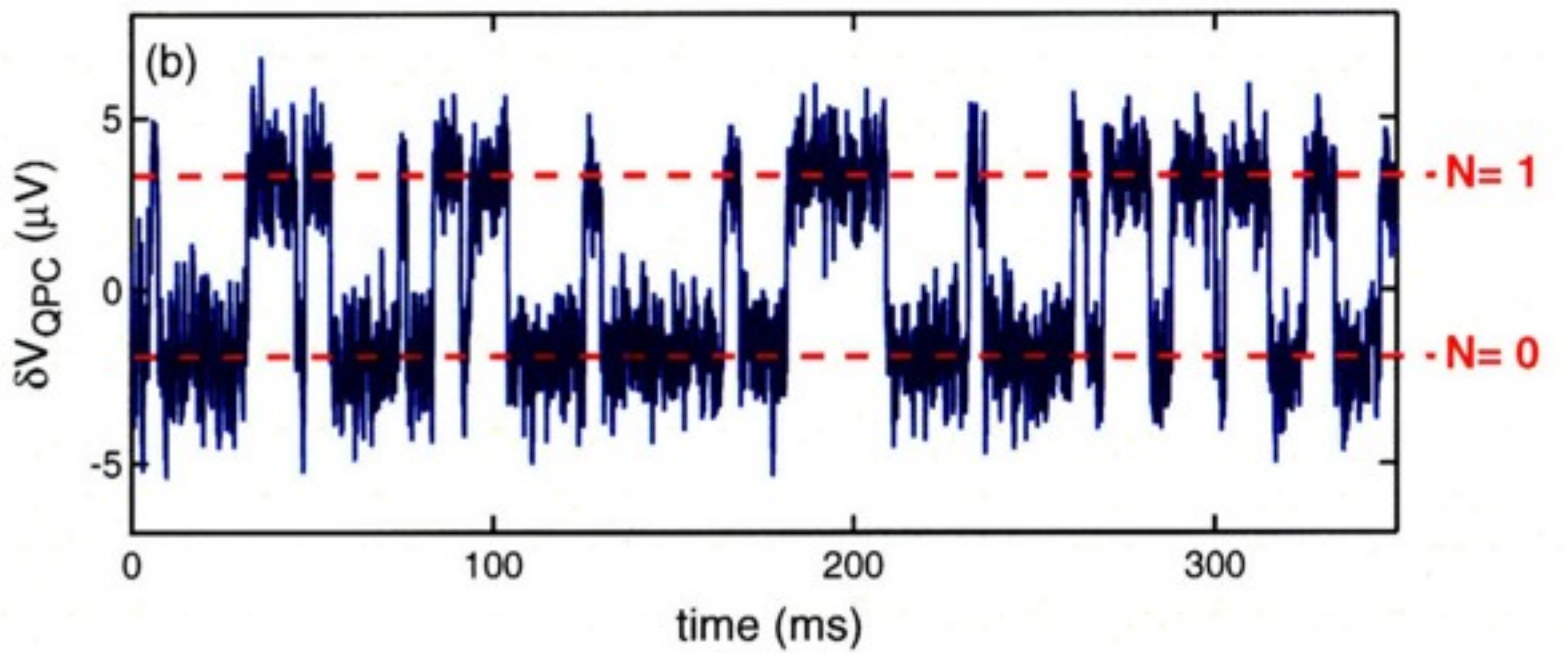
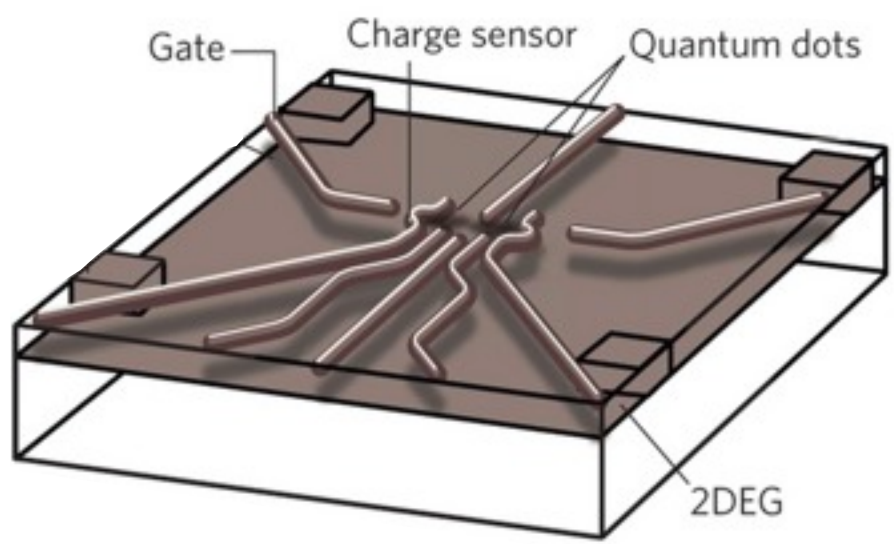


From PhD thesis of Sami Amasha, MIT (2008)

Part IV: *Quantum* nanoelectronic devices

Goals: introduce concepts of

1) electron spin
2) "quantum bit"



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Information is physical, subject to the laws of physics

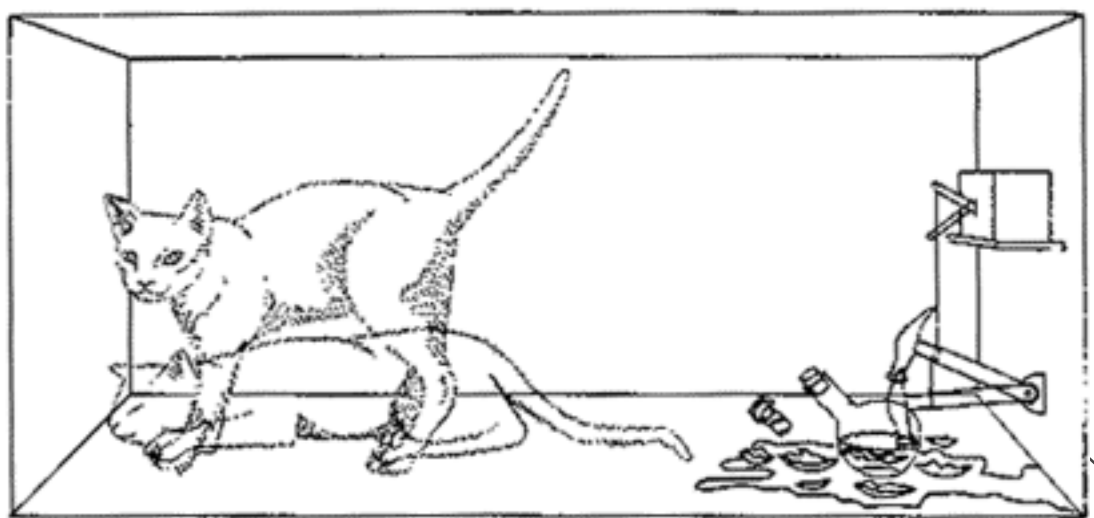
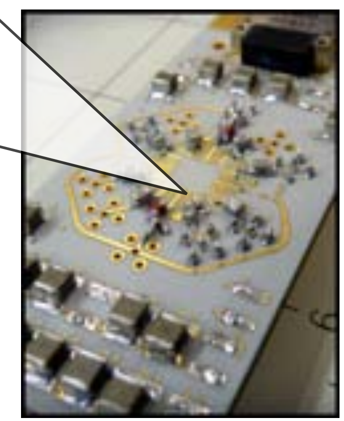
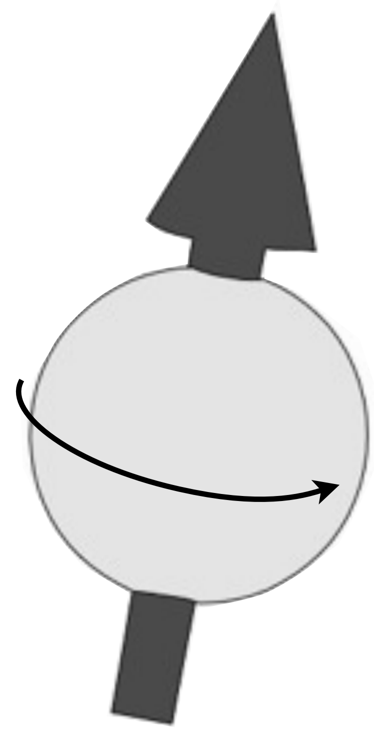


Image from: www.upscale.utoronto.ca

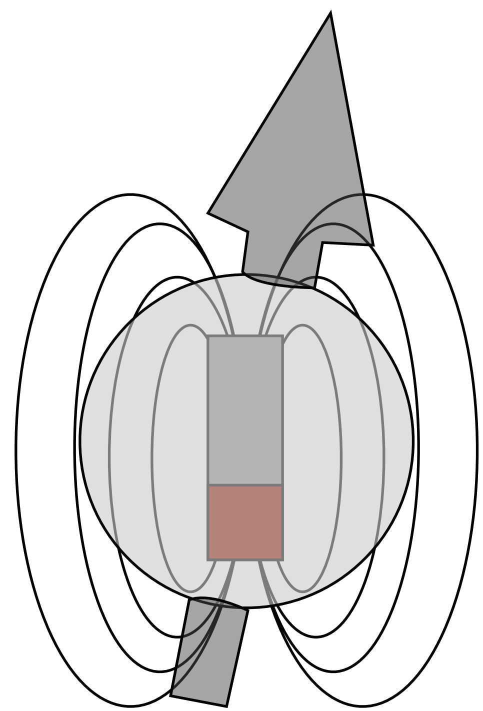


Can a system governed by quantum mechanical laws compute better?

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

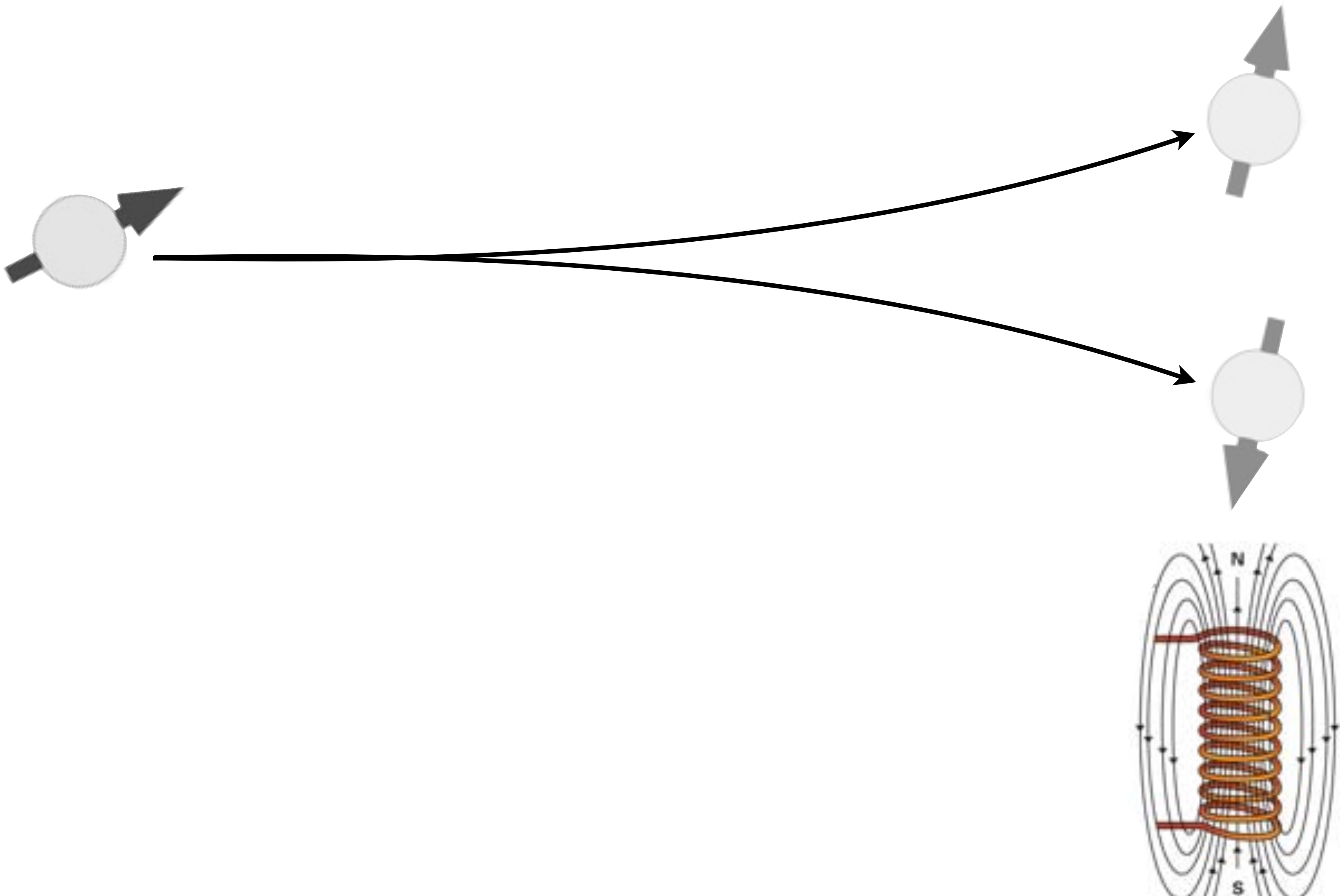


Image from ece.neu.edu

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"

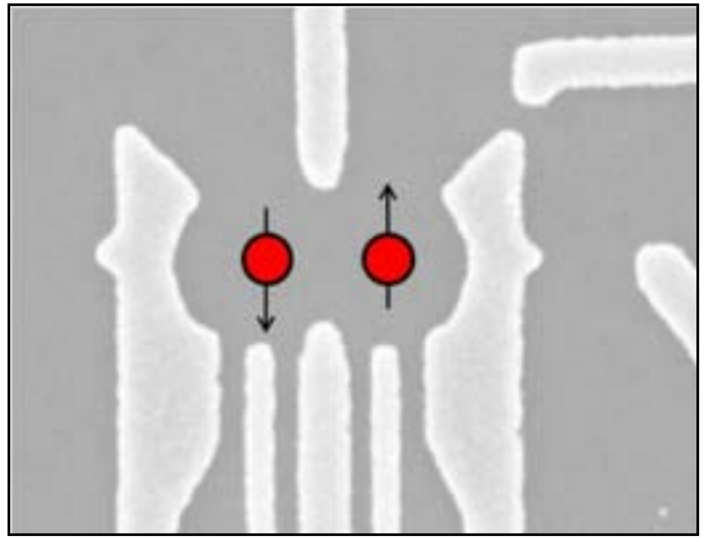


Image from Yacoby group, Harvard

$$\begin{array}{ccc} \downarrow & = & 0 \\ \uparrow & = & 1 \end{array}$$

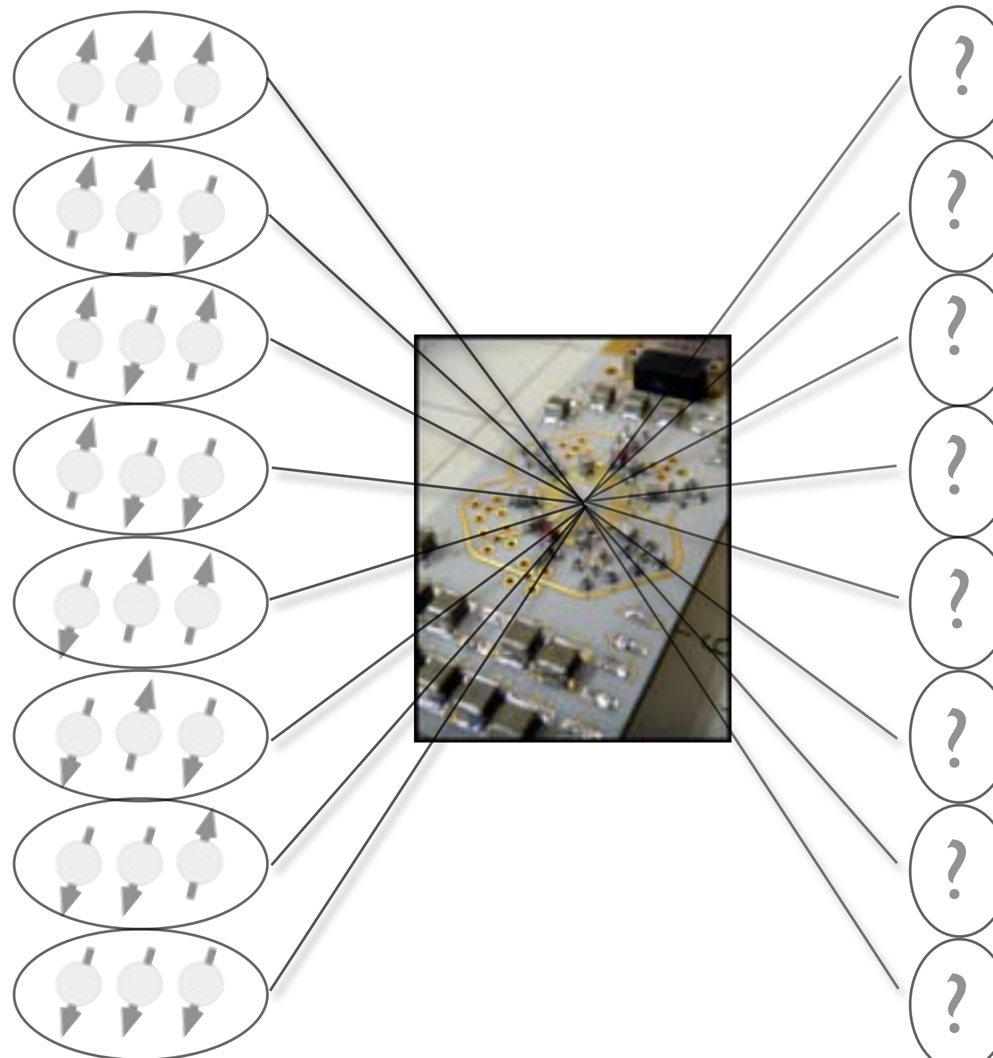
Original proposal:

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

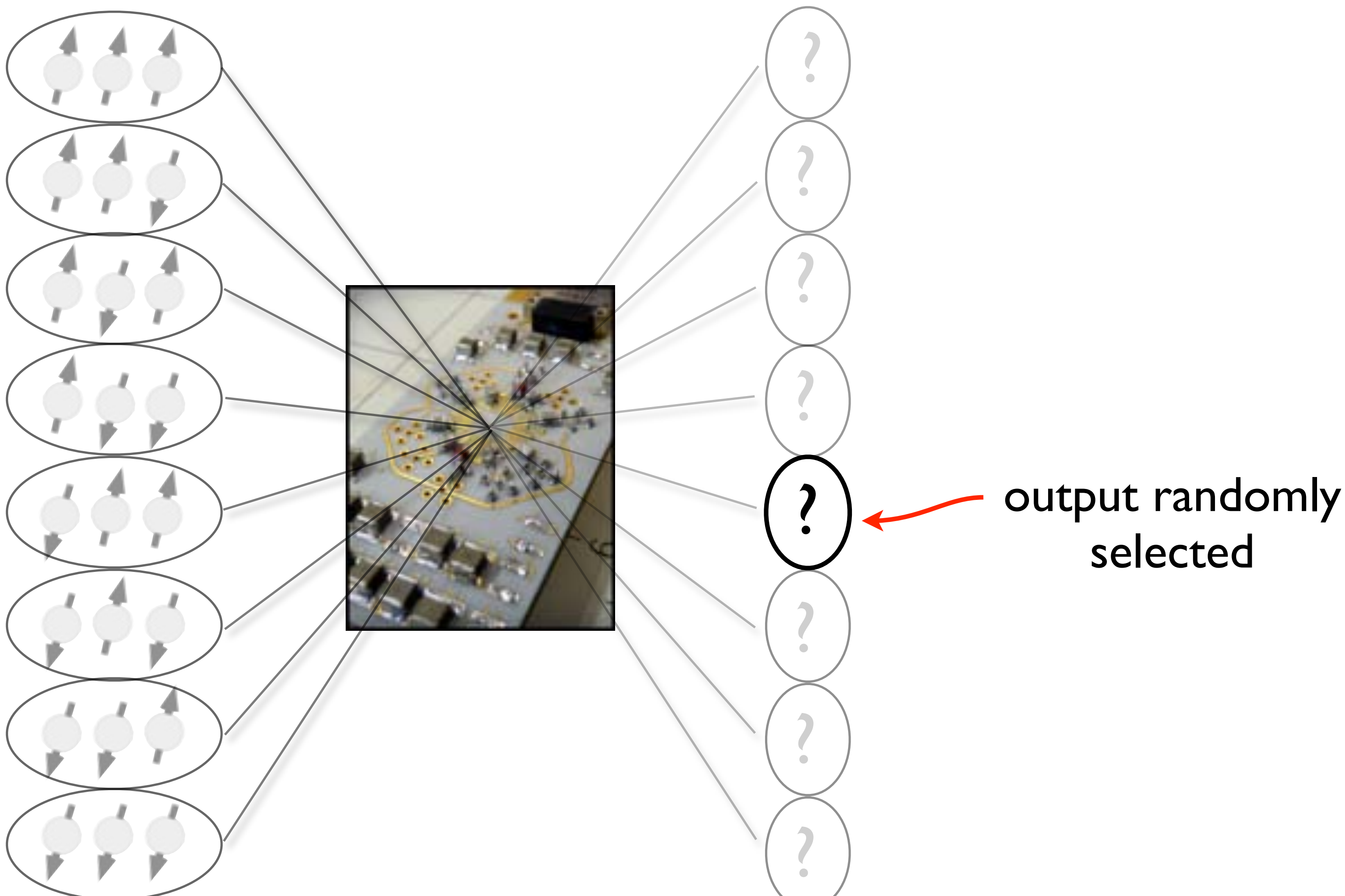
Quantum parallelism: use superposition run all inputs at once

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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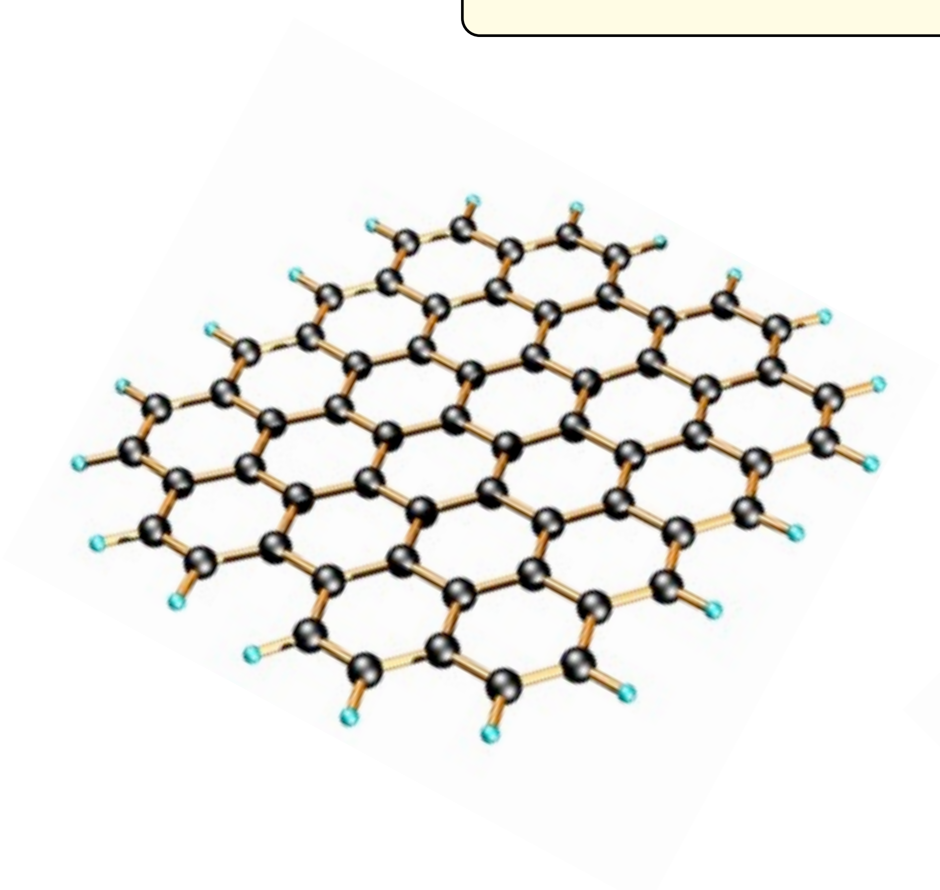
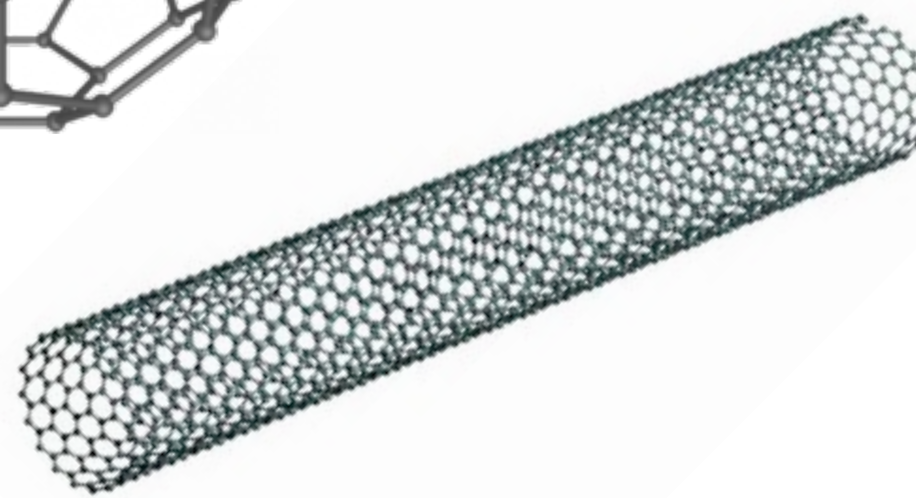
Bonus section: Carbon based nanomaterials

Goals: become familiar with

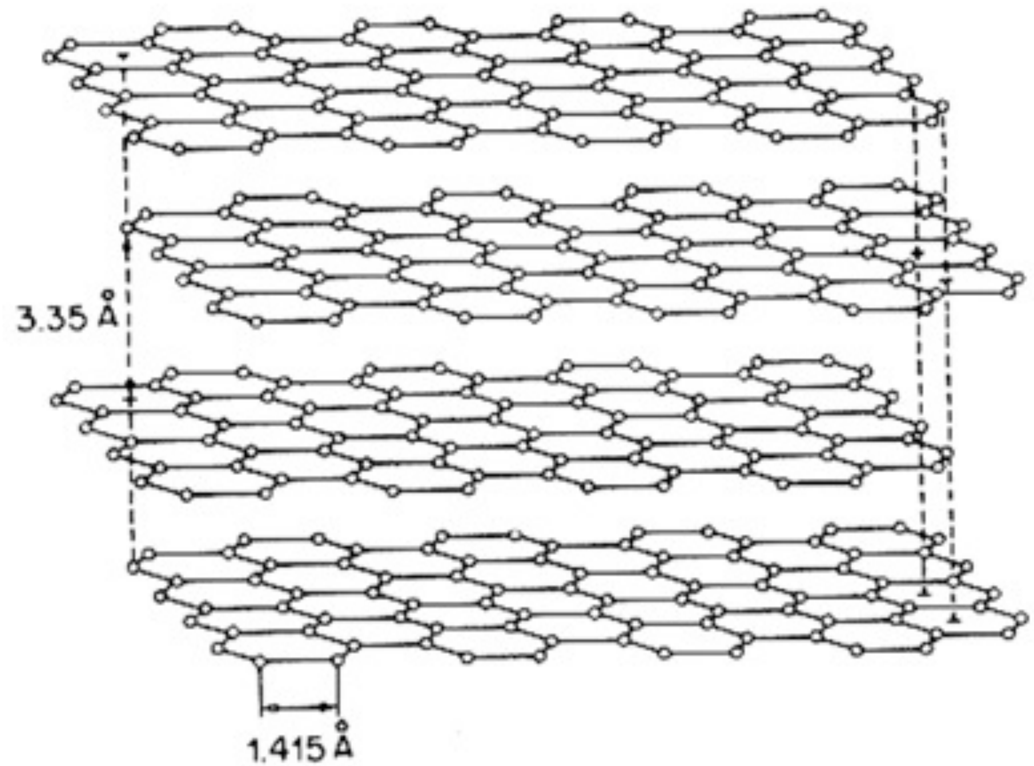
1) graphene
2) carbon nanotubes



In nature, carbon comes in many forms

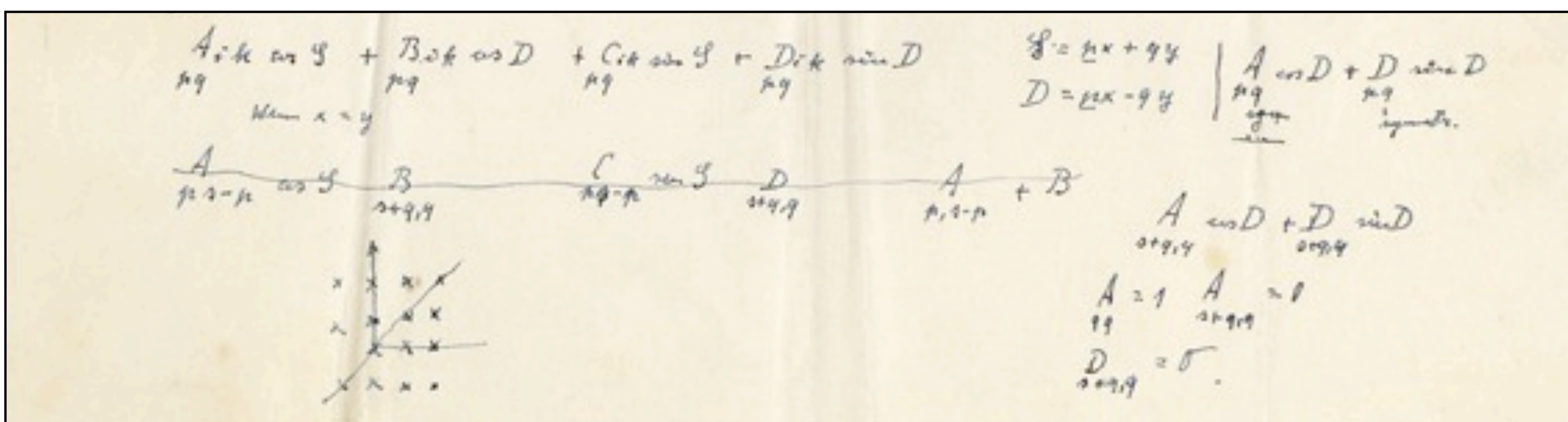


Graphite: stacked 2D sheets of carbon

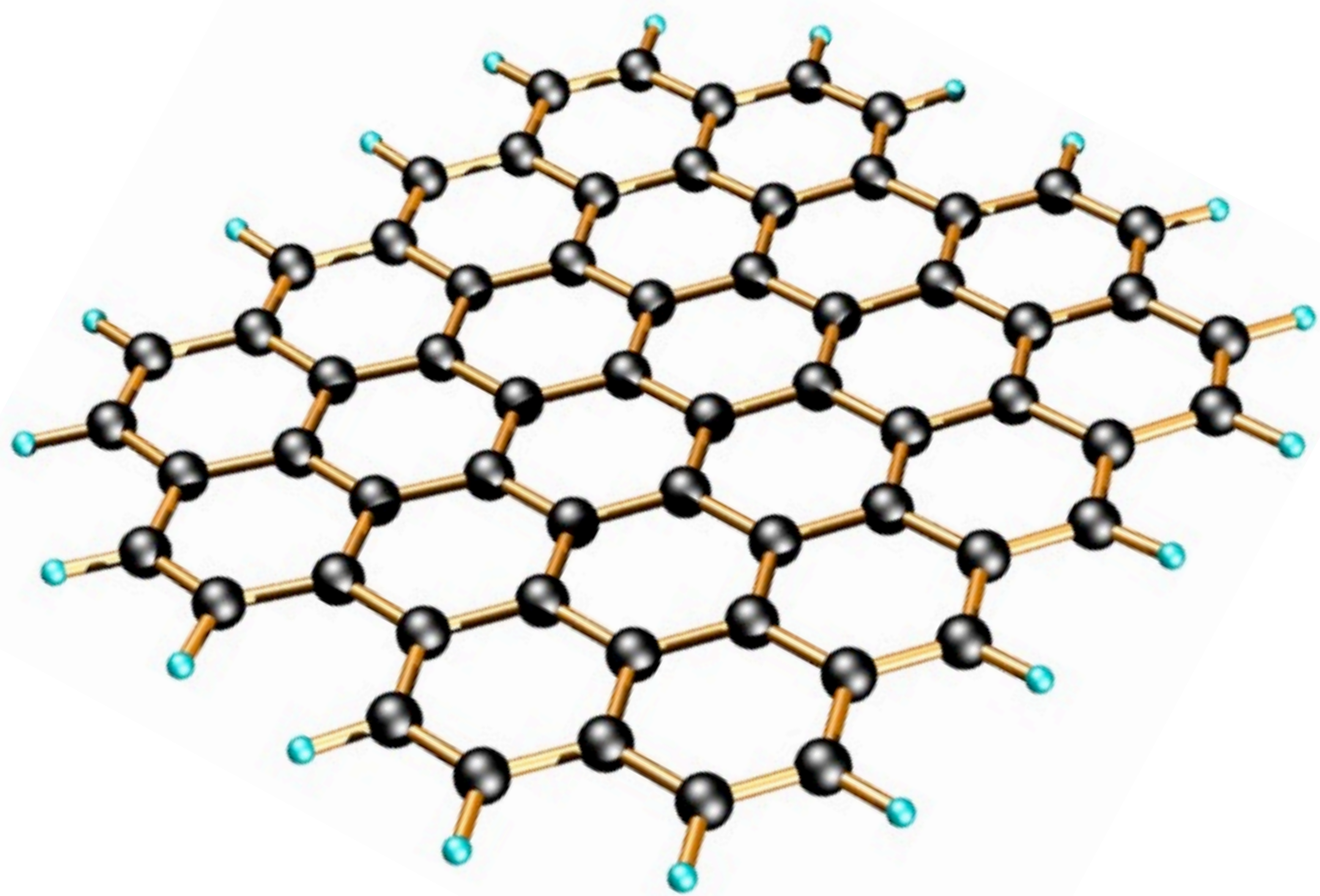


* Strong in-plane bonds, weak interaction between planes

Graphite: stacked 2D sheets of carbon



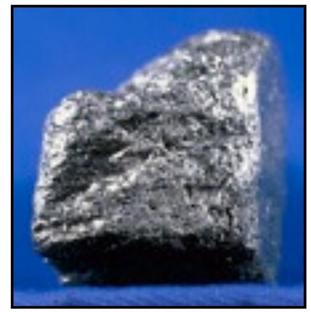
Graphene: a single atomic plane of carbon



Exfoliation (Scotch tape) preparation protocol

Step 1

+



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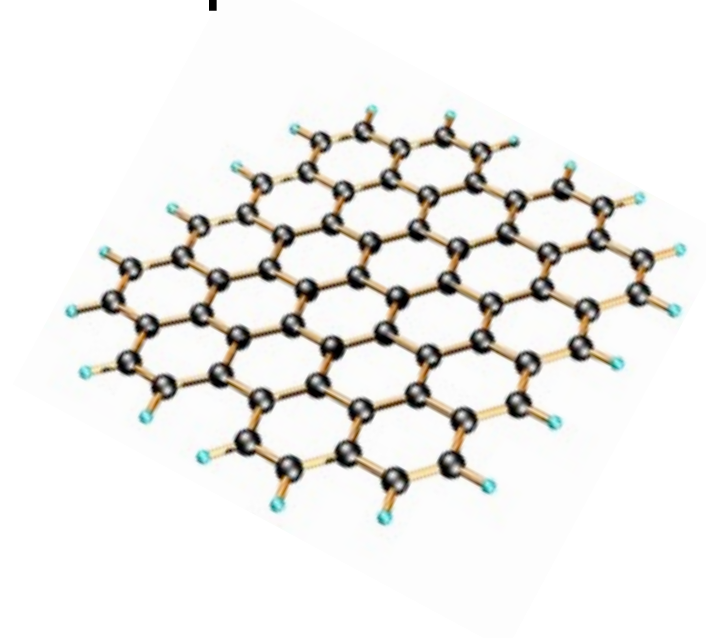
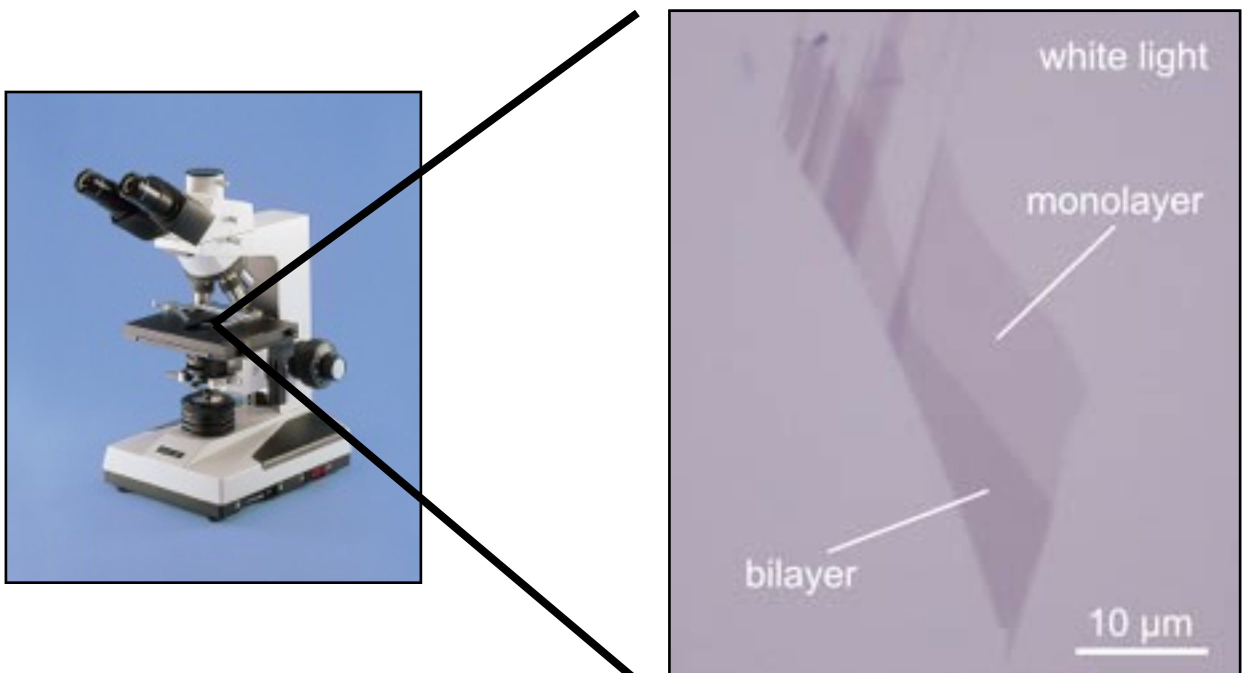


Step 2

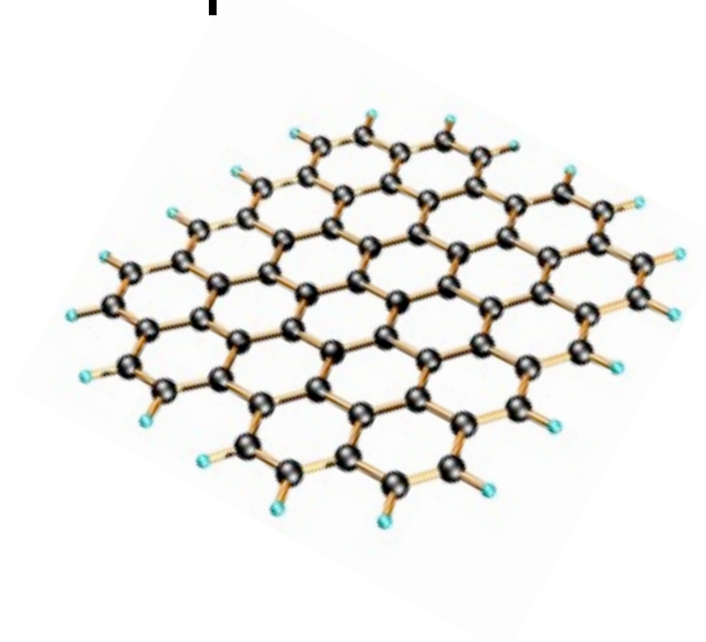


Exfoliation (Scotch tape) preparation protocol

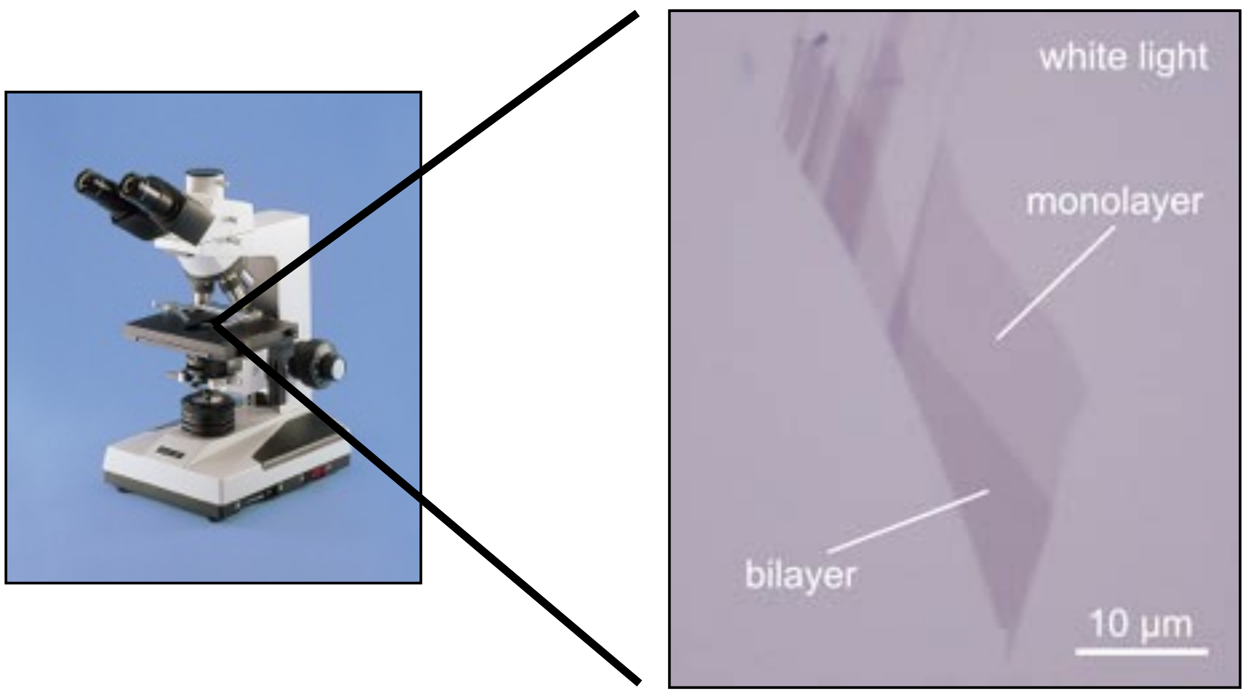
Step 1

+

=



Step 2



Step 3

2010 Nobel Prize

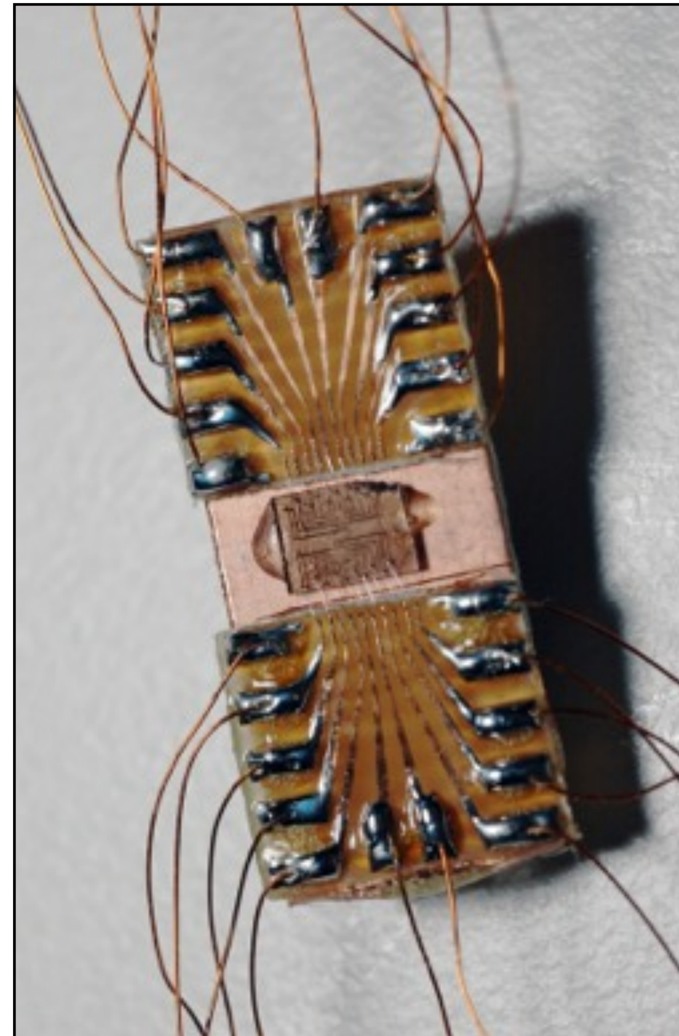
Applications: is carbon the new silicon?

High mobility (fast ops.) 🙂

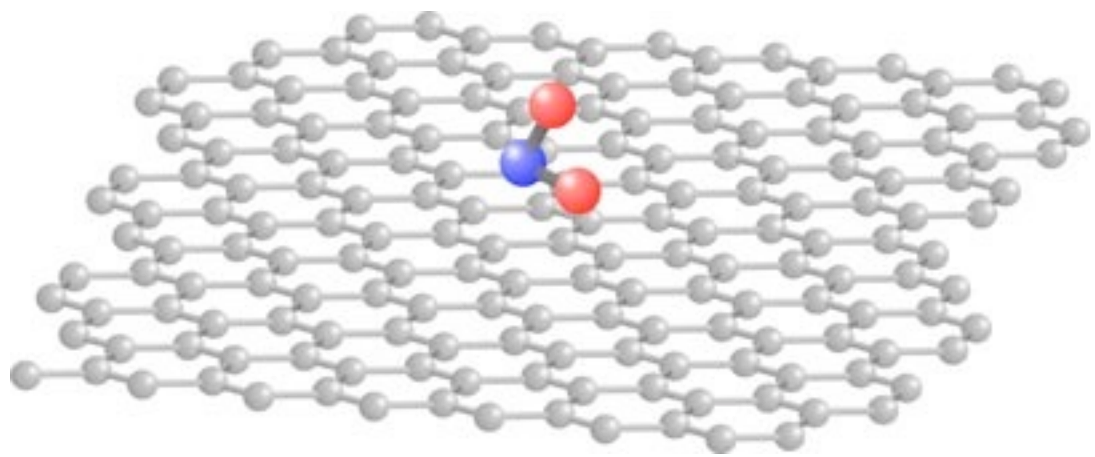
Tunable carrier density 🙂

Small samples 🙁

No band gap 🙁



Applications: adsorbed gas detection

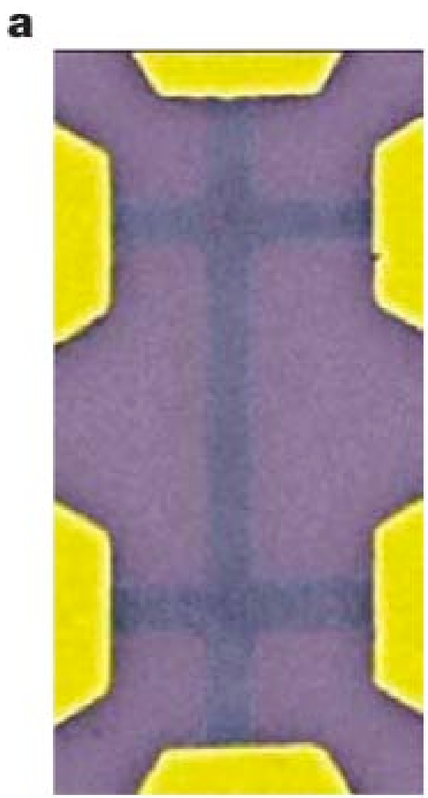


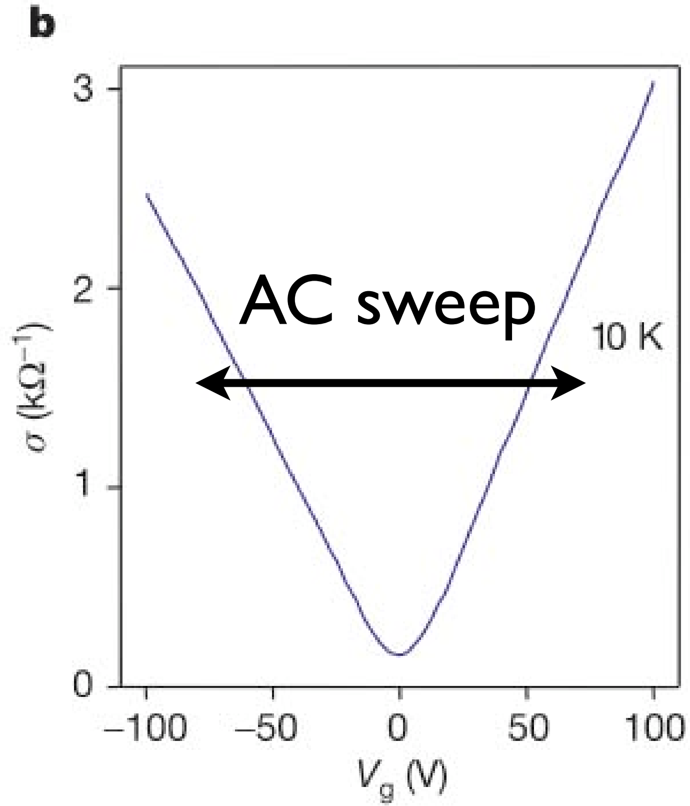
Directly exposed surface

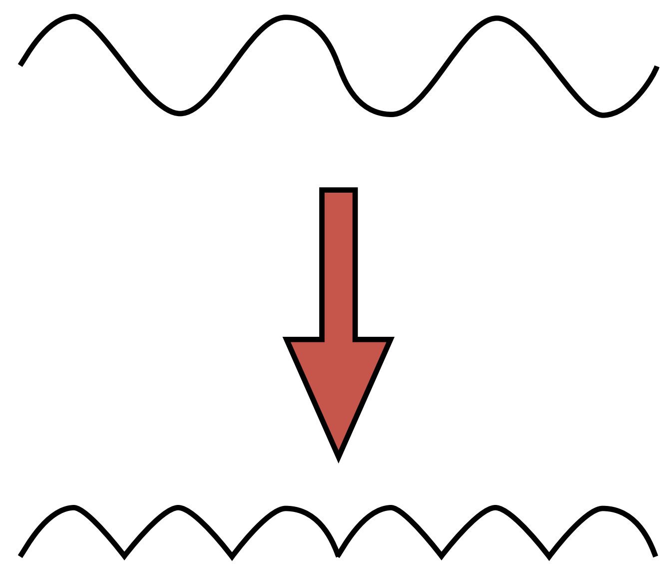
Conductivity highly sensitive to doping

Applications: frequency multiplier (MIT, data unavailable)

Conductivity minimum at zero field, symmetric for +/-

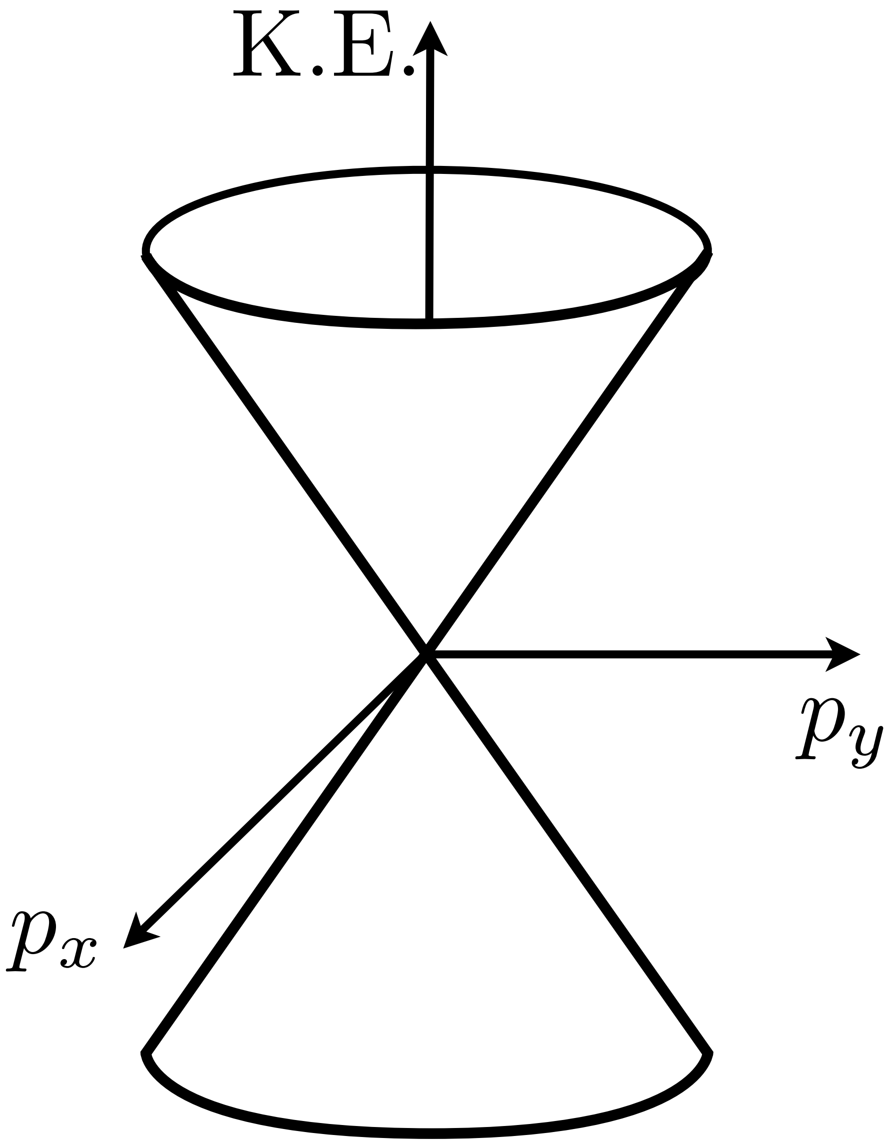






Data from Geim/Novoselov group, Manchester, UK

Kinetic energy of low energy electrons very strange



$\text{K.E.} = v_F|\vec{p}|$ doesn't look like usual kinetic energy of a particle

... OR DOES IT?

Linear momentum-energy relation for relativistic massless particle

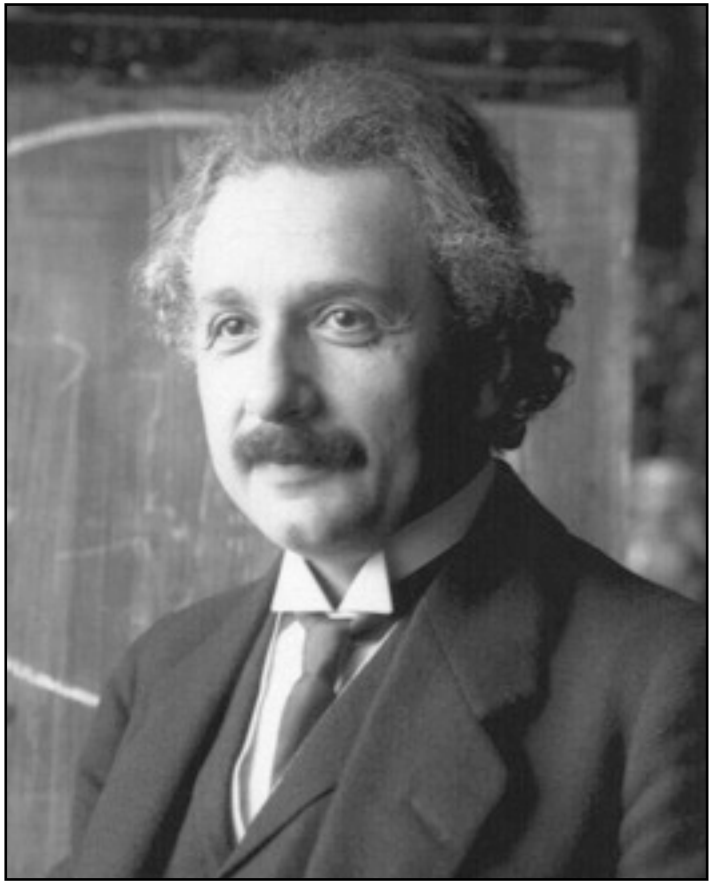
Invariant relationship:

$$E^2 - p^2c^2 = (mc^2)^2$$

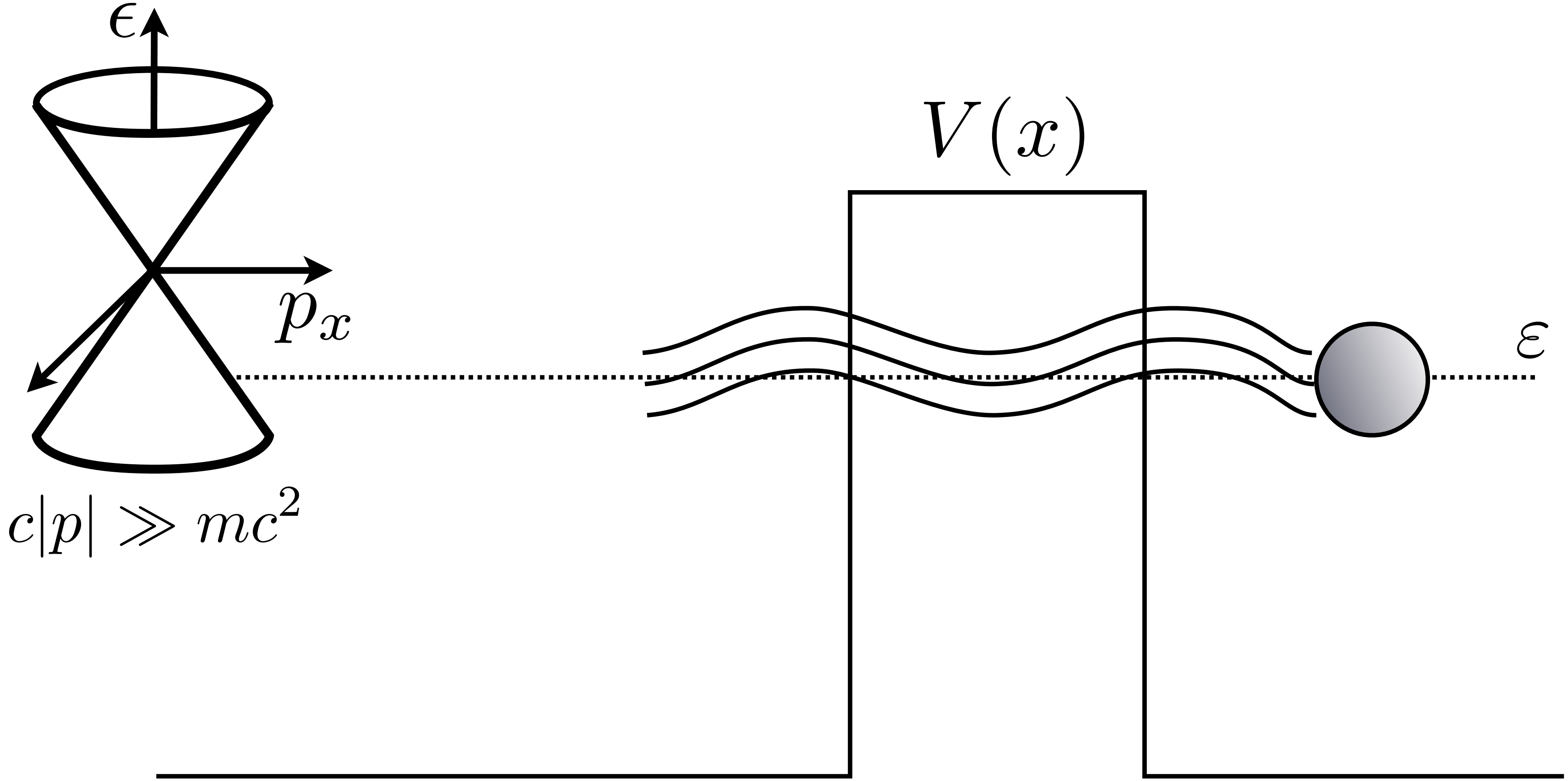
$$E = \sqrt{(mc^2)^2 + p^2c^2}$$

if $m = 0\,, \;\; E = c|p|$ 

neutrinos, photons, ...



Klein Paradox: perfect transmission through any barrier



Originally noted for ultra-relativistic electrons, but hard to observe

Perfect transmission at normal incidence, any barrier