Quantum computing and Nanotechnology

Quantum computing

- Is currently done on your laptop today
- Numbers as we commonly use them are in decimal (base 10) format. Computers represent them in binary (base 2).
- Each computational operation is done one step at a time.

Decimal vs. Binary

Decimal Representation			
10^3	10^2	10^1	10^0
1000	100	10	1

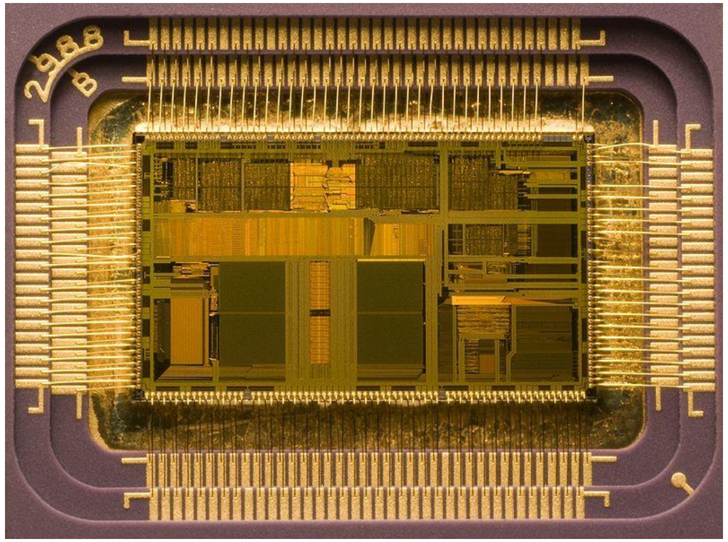
The number 14: 1 in the 10’s and 4 in the 1’s

How do we represent this in another base?
Add up all the digits to get the same value.

Binary Representation			
2^3	2^2	2^1	2^0
8	4	2	1

$14 = 8+4+2 \rightarrow 1110$ **BITS!**

How do we do this?



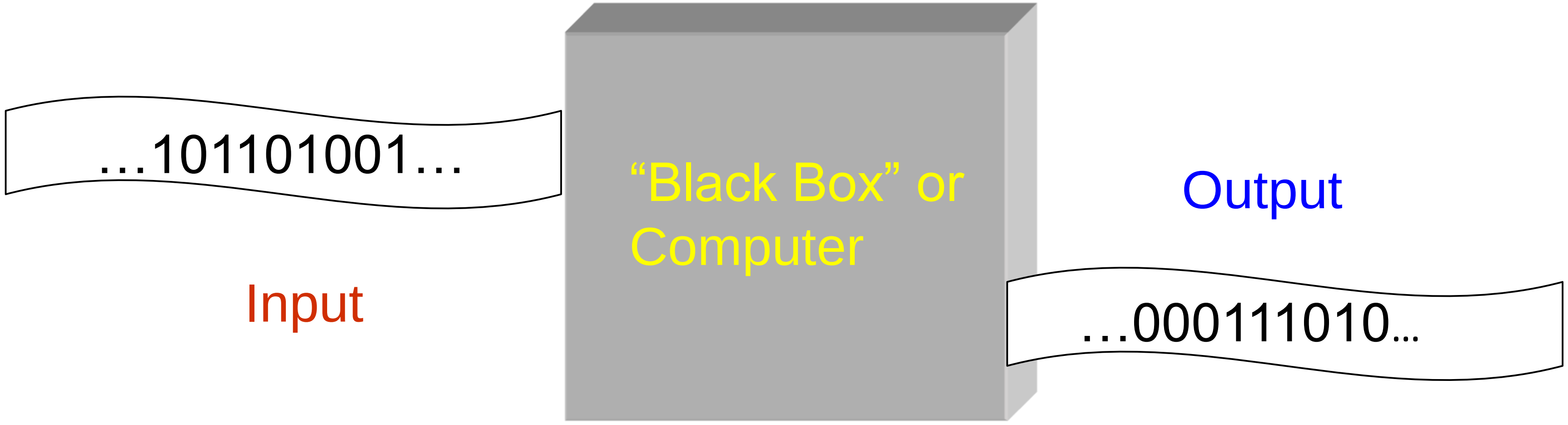
Shown is an Intel processor capable of performing 1,000,000,000 (1 billion) mathematical operations per second!

It is composed of ~500,000,000 individual Transistors! (Transisitors have no moving parts and are turned on and off by electrical signals)

The typical size of a transistor in the picture is about 0.04mm

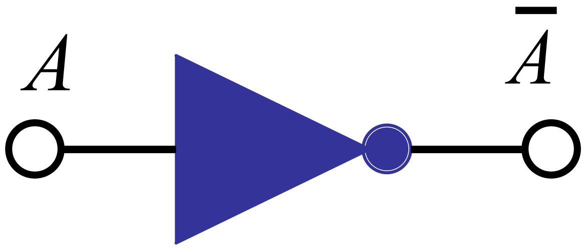
What is a computation? (Let’s revise)

Generation of an output number (string of bits) based on an input number.



How does the computer achieve this?

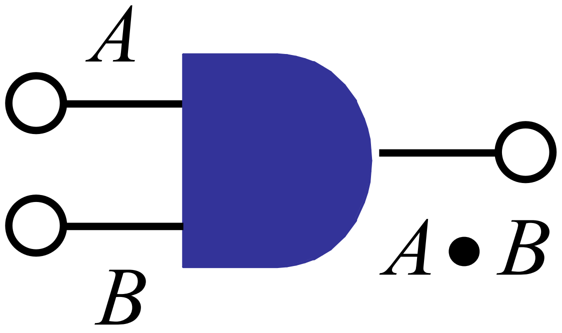
Single bit operation



A	$\bar{A}$
0	1
1	0

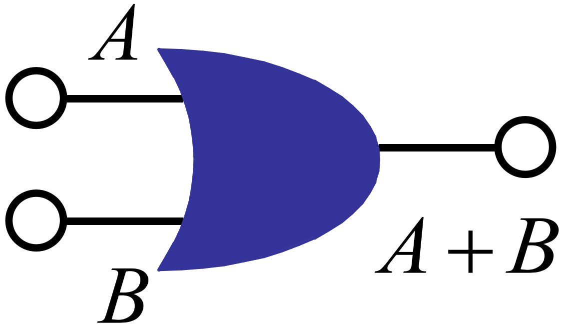
NOT gate

Two bit operations



A	B	$A \bullet B$
0	0	0
0	1	0
1	0	0
1	1	1

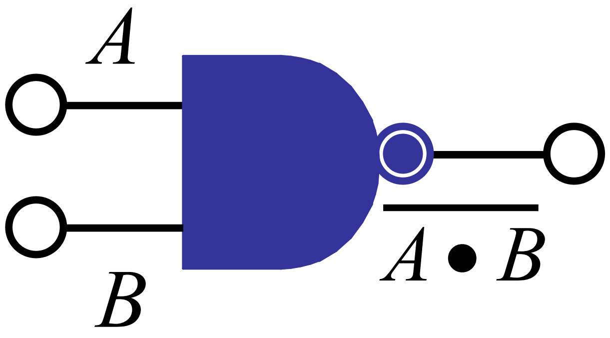
AND gate



A	B	$A + B$
0	0	0
0	1	1
1	0	1
1	1	1

OR gate

Two bit operations



A	B	$\overline{A \bullet B}$
0	0	1
0	1	1
1	0	1
1	1	0

NAND gate

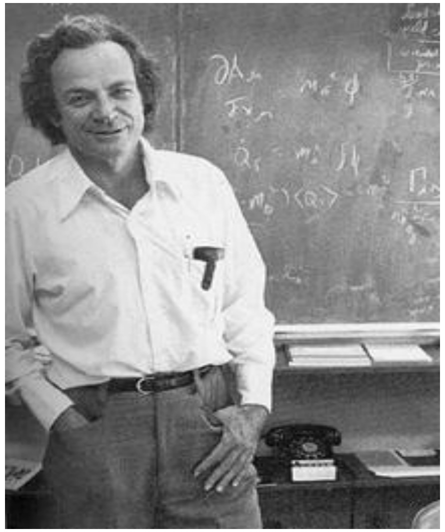
Not all the gates are needed

A small set of gates (e.g. NAND, NOT) is universal in that any logical operation can be made from them.

Nanotechnology: Plenty of space

- "Simulating Physics with Computers"

  Richard Feynman – Keynote Talk, 1st Conference on Physics and Computation, MIT, 1981



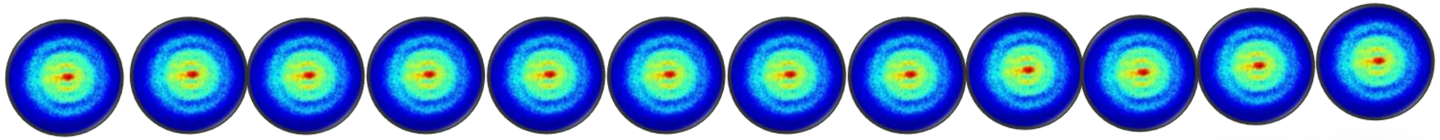
"There is plenty of room at the bottom"

Nanotechnology in computer: Nano-computing

Computers in the 20th century showed a miniaturization of microprocessors and are in a process of being nano-metre scale.

1 nm= 2 times the size of hydrogen atom

5 nm= 10 times the dimension of one hydrogen atom



Quantum effects!!

Introduction

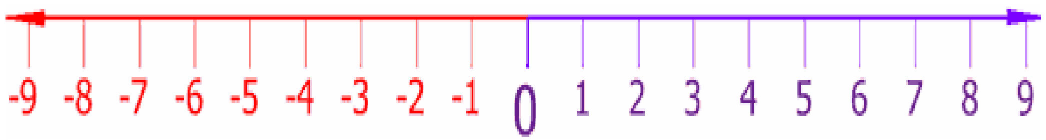
What is a quantum computer?

A quantum computer is a machine that performs calculations based on the laws of quantum mechanics, which is the behavior of particles at the sub-atomic level.

- 1982 - Feynman proposed the idea of creating machines based on the laws of quantum mechanics instead of the laws of classical physics.
- 1985 - David Deutsch developed the quantum turing machine, showing that quantum circuits are universal.
- 1994 - Peter Shor came up with a quantum algorithm to factor very large numbers in polynomial time.
- 1997 - Lov Grover develops a quantum search algorithm with $O(\sqrt{N})$ complexity

Classical Physics vs Quantum Physics

- Predictable outcomes!
- Variables are continuous



- Take on finite known values
- Always has a known state
- Binary numbers in the form of switches that are on or off!

- Violate classical laws at a small scale (~h, Plank's Constant)
- Variables are discrete |0> or |1>
- Can be in a superposition of values (representing all states simultaneously)

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

- State is indeterminate until measured.

Conventional memory:
Tossed coin

Result is either 0 or 1

sequence of 11 bits:

11111011011

stores only one number:
2011

quantum memory:
Spinning coin

Result is 0 and 1 (both)

sequence of 11 quantum bits:

(0+1)(0+1)(0+1)(0+1)(0+1)(1+0)
(0+1)(0+1)(1+0)(0+1)(0+1)

stores all numbers from 1 to 2048 (**All possibilities !!**)

Classical bits (Cbits)

- The two states of a Classical bit by a pair of **ortho-normal vectors** denoted by the symbols **|0>** and **|1>**.

- It is convenient to represent the four states of two Cbits

  |0>|0>, |0>|1>, |1>|0> and |1>|1> or more readably **|00> |01> |10> |11>**

- Most compactly of all, using the decimal representation of 2-bit number represented by the pair of C-bits

  $|0\rangle_2, |1\rangle_2, |2\rangle_2, |3\rangle_2$

- One represents the states of 'n' as the 2^n orthonormal vectors in 2^n dimensions.

  Thus for example $|19\rangle_6 = |010011\rangle = |0\rangle|1\rangle|0\rangle|0\rangle|1\rangle|1\rangle$

Quantum bits

- A major part of quantum mechanics consists of an analogous expansion of the notion of the state of a Cbit, called in this extended setting a quantum bit or Q bit.
- In general state of a single **Qubit is a superposition** of the two classical basis states

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Where the amplitudes **α and β are complex numbers** constrained only by the normalization condition

$$|\alpha|^2 + |\beta|^2 = 1$$

The **general state of n Qubits** has the form

$$|\psi\rangle = \Sigma\alpha_x|x\rangle_n$$

With complex amplitudes constrained only by the normalization condition

$$\Sigma\left|\alpha_x\right|^2 = 1$$

- Most general possible state of two Qubit has the form

$$
\begin{aligned}
|\psi\rangle &= \alpha_3|3\rangle_2 + \alpha_2|2\rangle_2 + \alpha_1|1\rangle_2 + \alpha_0|0\rangle_2 \\
&= \alpha_3|11\rangle_2 + \alpha_2|01\rangle_2 + \alpha_1|10\rangle_2 + \alpha_0|00\rangle_2
\end{aligned}
$$

- **Classical Information:**

– A bit is in state 0 or state 1

state1=|1>

state2=|0>

- **Classical Information with Uncertainty**

– State (p_0, p_1)

state1=|1>
with prob p_0

state1=|0>
with prob p_1

- **Quantum Information**

– State is simultaneously both 0(tail) and 1 (head)

– State is (α_0, α_1) where α_0, α_1 are complex.

α_0 |  ⟩ $+\, \alpha_1$ |  ⟩

Information: n(=3) Bit example

- **Classical Information:**
  - State of n bits specified by a string x in $\{0,1\}^n$

- **Classical Information with Uncertainty**
  - State described by probability distribution over 2^n possibilities
  - $(p_0, p_1, \ldots, p_{2^n-1})$

- **Quantum Information**
  - State is a superposition over 2^n possibilities
  - $(\alpha_0, \alpha_1, .. \alpha_{2^n-1})$, where a is complex

state1=|000>, p_{000}

state1=|001>, p_{001}

state1=|010>, p_{010}

state1=|011>, p_{011}

state1=|100>, p_{100}

state1=|100>, p_{101}

state1=|100>, p_{110}

state1=|100>, p_{111}

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  – State of n bits specified by a string x in $\{0,1\}^n$

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- **Quantum Information**
  – State is a superposition over 2^n possibilities
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state1=|000>, p_{000}

state1=|001>, p_{001}

state1=|010>, p_{010}

state1=|011>, p_{011}

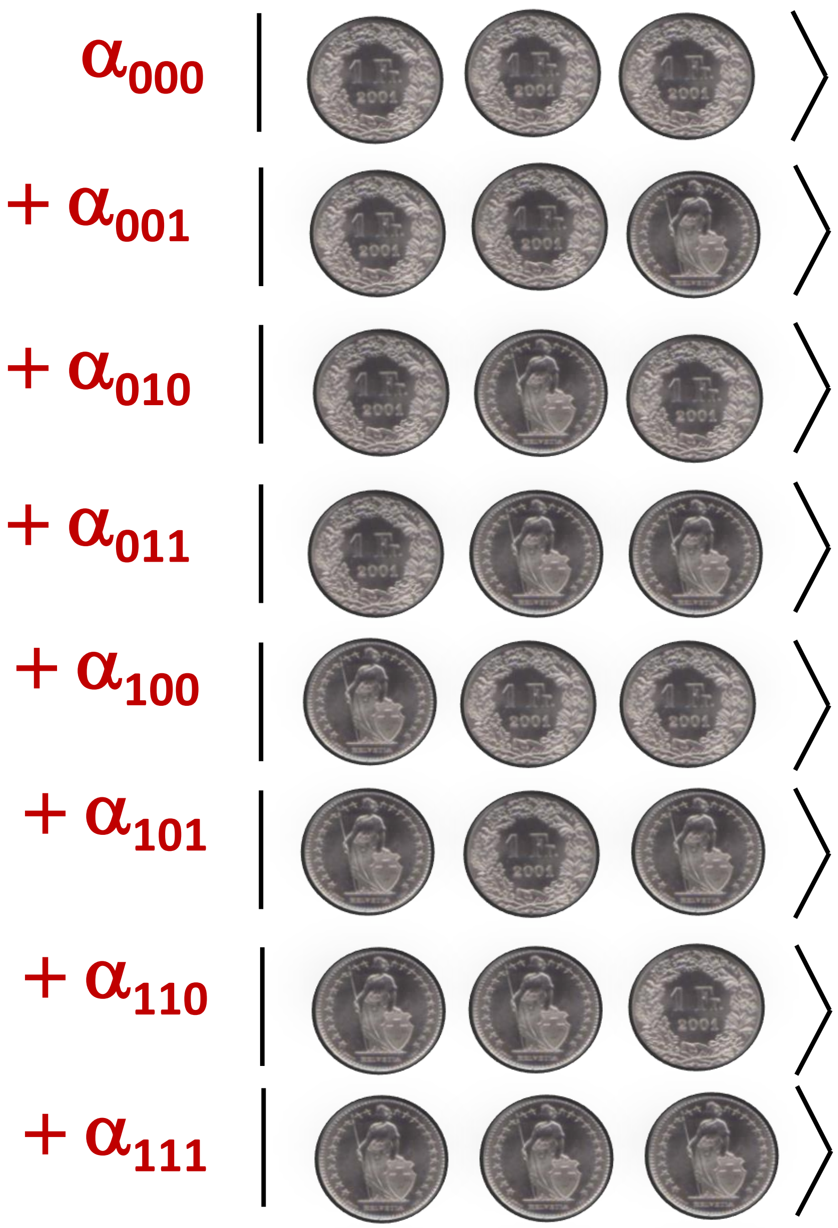
state1=|100>, p_{100}

state1=|100>, p_{101}

state1=|100>, p_{110}

state1=|100>, p_{111}

- **Quantum Information**
  - State is a superposition over 2^n possibilities
  - $(\alpha_0, \alpha_1, \ldots\ldots \alpha_{2^n-1})$, where α is complex



A **‘bit’** is the basic unit of classical information, but the term is also used to refer to an elementary classical system that can be in one of two states.

For example, a fair coin, is a bit, if the coin lands heads or tails when tossed and not any other feature of the coin, such as its weight or its size.

A qubit can ‘somehow’ be both at the same time are simply confused.

But, unlike a classical bit, a qubit is associated with an infinite set of non-commuting two-valued observables that can’t all have definite values simultaneously.

- **State of n qubits** $(\alpha_0,\ldots,\alpha_{2^n-1})$

- **If all n Qubits are examined:**
  - ✓ Outcome is **010** with probability $|\alpha_{010}|^2$.
  - ✓ The measurement causes the state of the system to change:
  - ✓ The state "collapses" to **010**

Single Qubit measurement

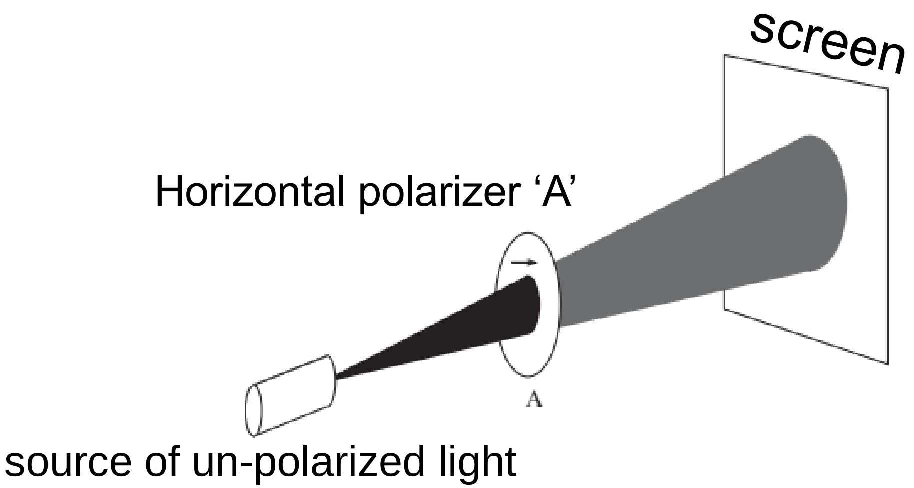
- Measurement of a quantum state changes the state.
- If a state $|v\rangle = a|u_{\|}\rangle + b|u_{\perp}\rangle$ is measured as $|u_{\|}\rangle$, then the state $|v\rangle$, changes to $|u_{\|}\rangle$.
- A second measurement with respect to the same basis will return $|u_{\|}\rangle$, with probability *1*.
- Thus, unless the original state happens to be one of the basis states, a single measurement will change that state, making it impossible to determine the original state from any sequence of measurements.

Implementations of a "Qubit"

- *Polarization of a photon.*
- *Spin orientation of an electron*
- *Energy level of an atom*
- *NMR, Ion traps,…*

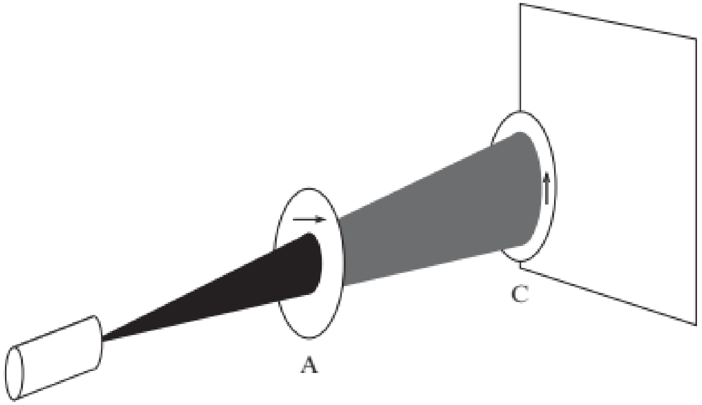
Photon polarization experiment (using un-polarized light)

case1

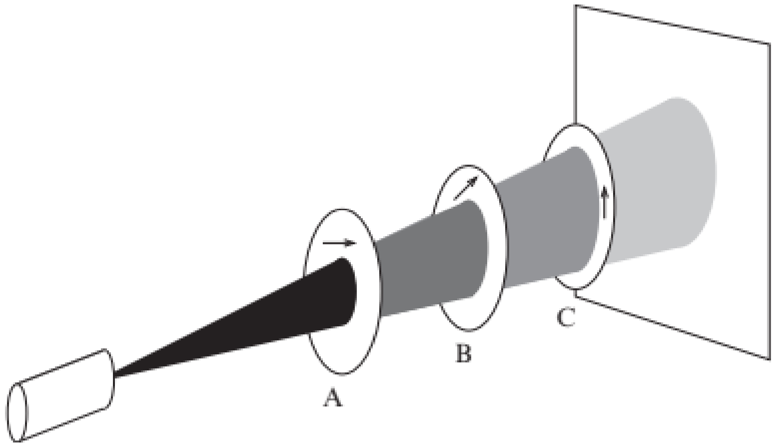


Single polaroid attenuates un-polarized by 50 percent

case2



Two orthogonal polaroid block all photons case3



Inserting a third polaroid allows some photons to pass

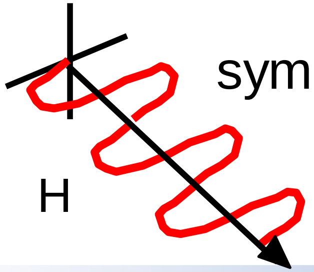
How do we understand these results?
Malu's law !

What about, if source is very **dim !! (**with very few photons!!)
Rules of Quantum Physics!!!

Quantum Mechanics

- Represent the light polarization by a unit vector: a vector of length '1', pointing appropriate direction.

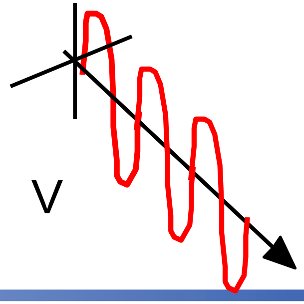
Example: horizontally polarized light



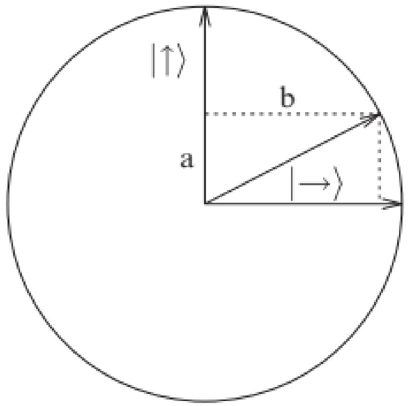
symbol: $|0\rangle$

vertically polarized light

symbol: $|1\rangle$



Any arbitrary polarization can be written as a linear combination two basis vectors, $|0\rangle$ and $|1\rangle$ by



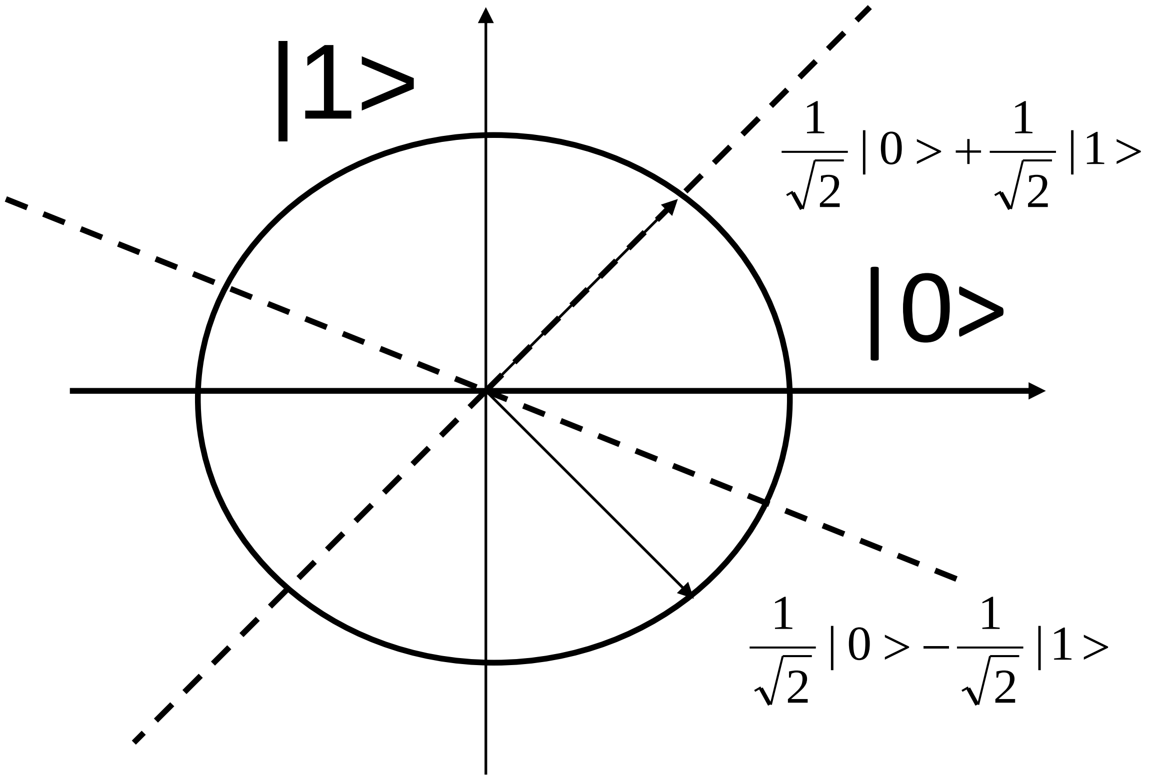
$$|v\rangle = a|0\rangle + b|1\rangle$$

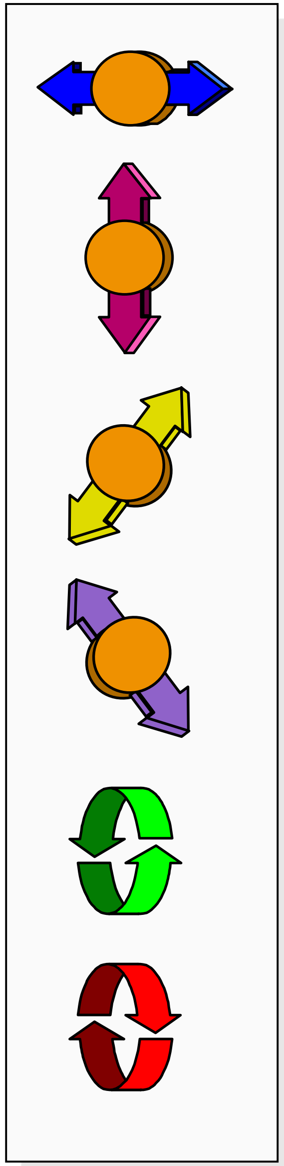
State $|v\rangle$ superposition of horizontal and vertical polarization constitute a Qubit

Probability that a photon passes through the polaroid is the square of the magnitude of the amplitude of its polarization in the direction of the polaroid's preferred axis.

When a photon with polarization, $|v\rangle = a|0\rangle + b|1\rangle$ meets a polaroid with preferred axis $|\uparrow\rangle = |0\rangle$,the photon will get through with probability $|a|^2$ and will be absorbed with probability $|b|^2$

$|v\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$ is a unit vector representing polarization of 45 degrees.

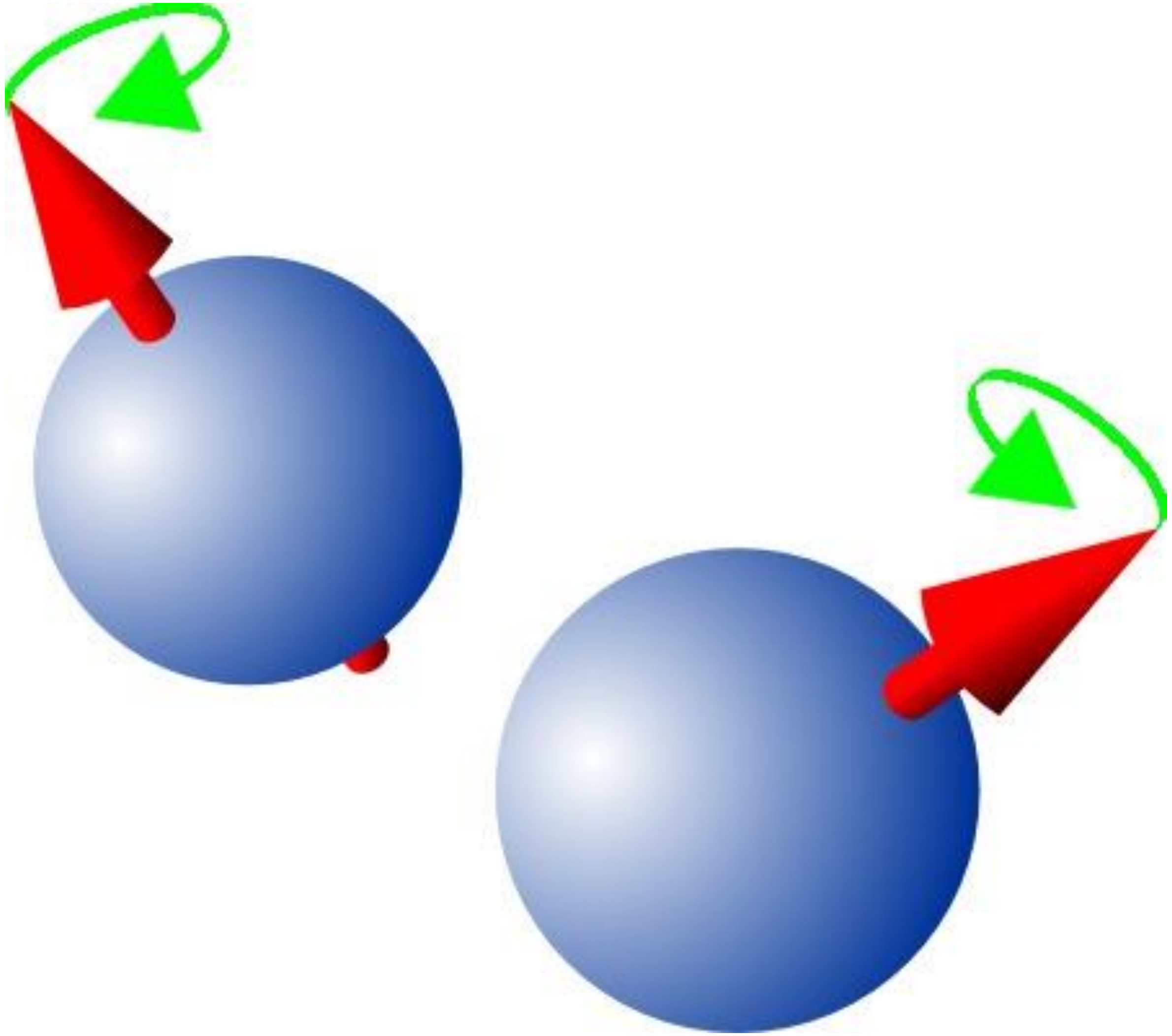

|1>
$\frac{1}{\sqrt{2}}|0> + \frac{1}{\sqrt{2}}|1>$
|0>
$\frac{1}{\sqrt{2}}|0> - \frac{1}{\sqrt{2}}|1>$



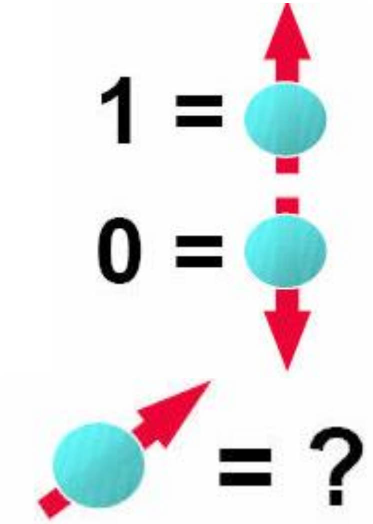
Horizontal	$\lvert 0\rangle$
Vertical	$\lvert 1\rangle$
Diagonal up	$\frac{1}{\sqrt{2}}\left(\lvert 0\rangle + \lvert 1\rangle\right)$
Diagonal down	$\frac{1}{\sqrt{2}}\left(\lvert 0\rangle - \lvert 1\rangle\right)$
Left circular	$\frac{1}{\sqrt{2}}\left(\lvert 0\rangle + i\lvert 1\rangle\right)$
Right circular	$\frac{1}{\sqrt{2}}\left(\lvert 0\rangle - i\lvert 1\rangle\right)$

Thus for light polarization, Diagonal up, diagonal down, Left circular and right circular constitute an example of Qubit.

Qubits from Electron spin



Classical Bits

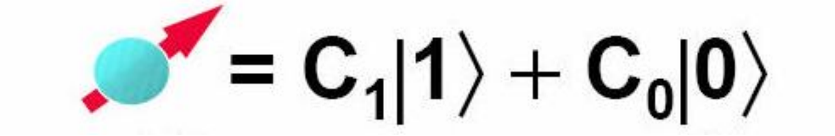


It's an error!

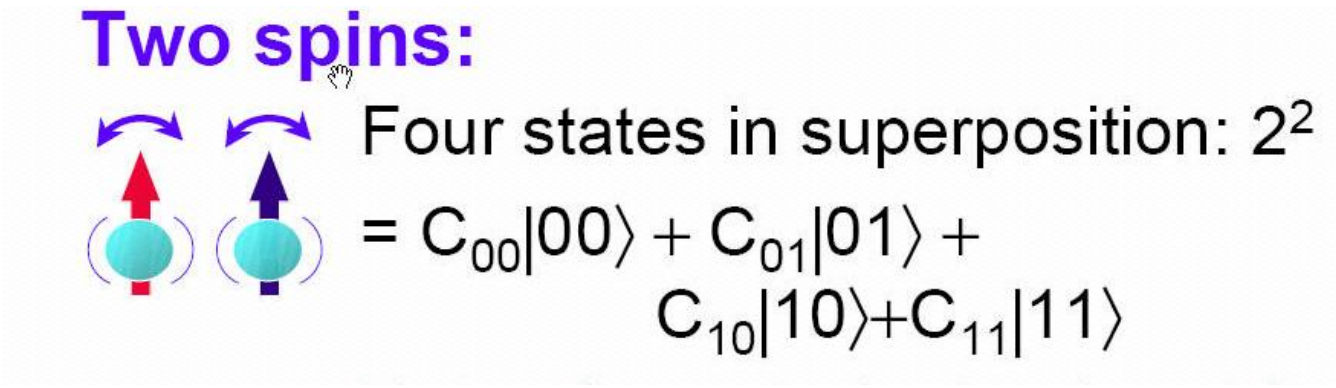
Quantum bits: Superposition state

spin up

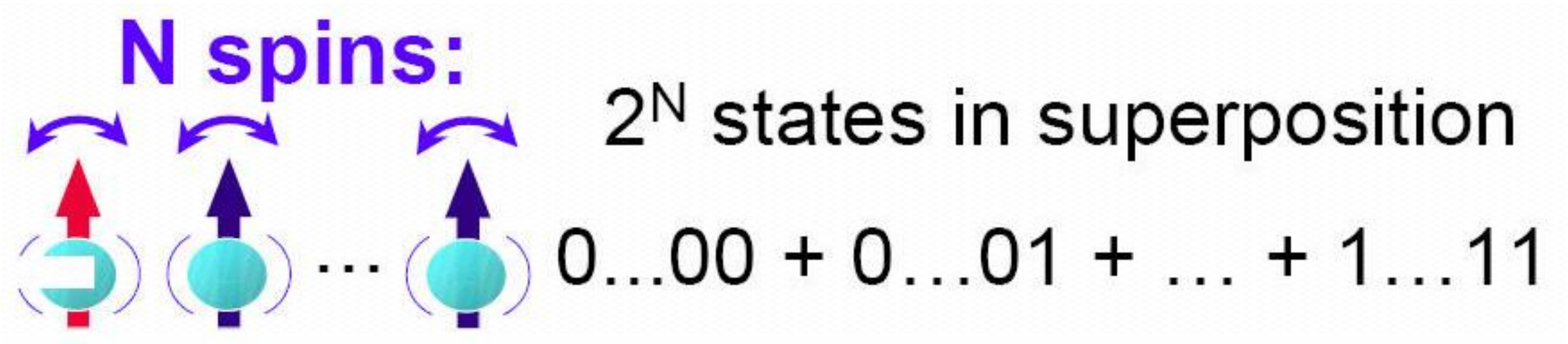
spin down



It's a superposition!



When you measure the spin, it can be in ***spin up*** or ***spin down*** state. But before you measure It, it can be in a quantum super position state; where these coefficients C_1&C_2 indicate the relative probability of finding the electron in one state or other.



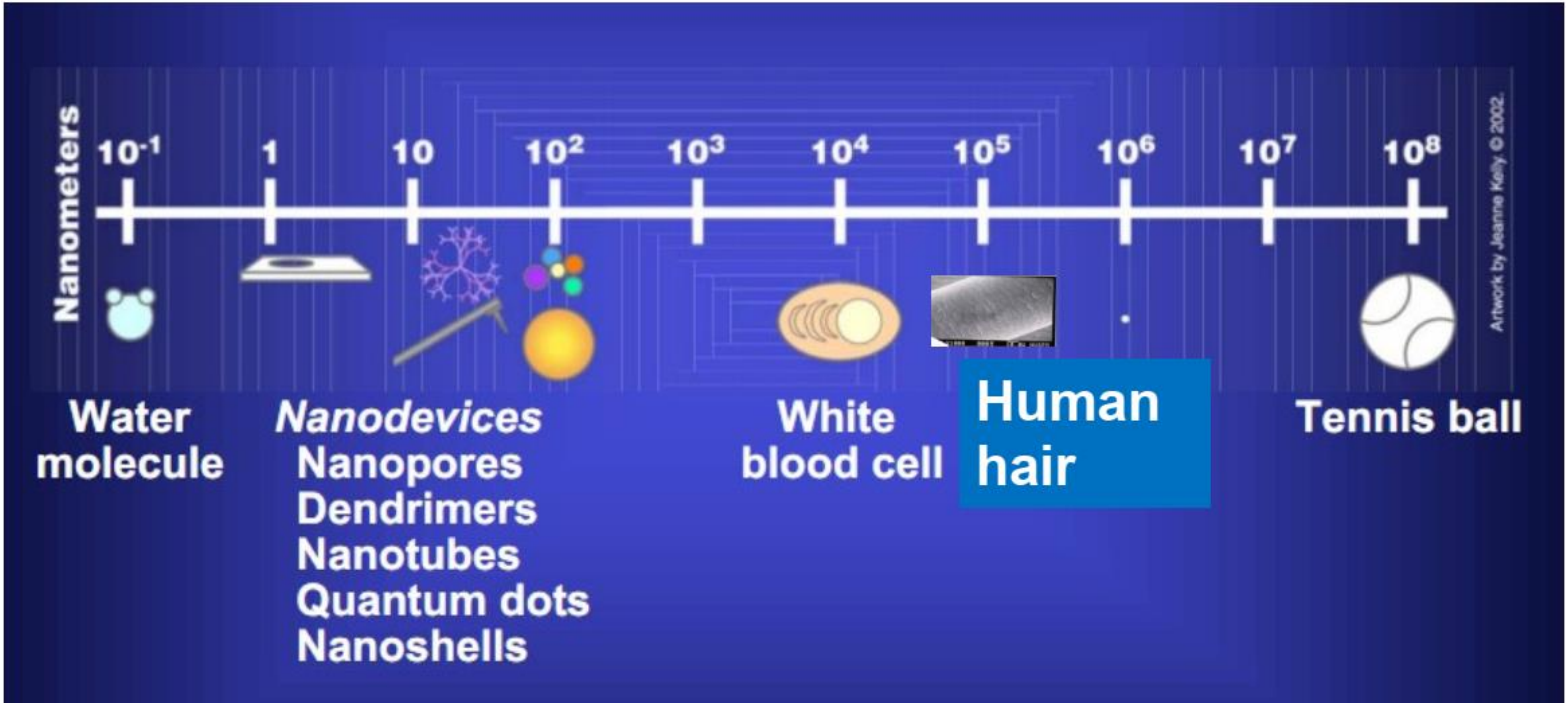
Introduction to Nanomaterial and Nanotechnology

What is nanomaterial?

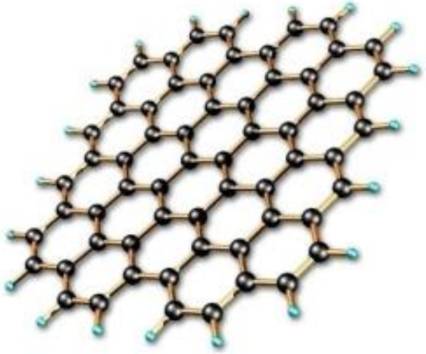
- Nanoscale : generally refers to the size scale of 1 – 100 nm in at least one dimension.

1 nanometer (nm) = 10^{-9} m

How small is 1 nanometer?



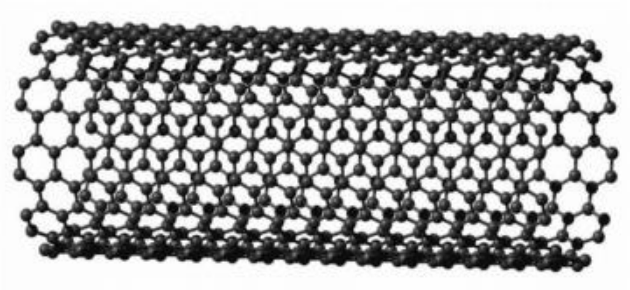
Nanomaterial: refers to the matter whose length scale, in any dimension, is approximately 1 to 100 nanometers.



1 D

film

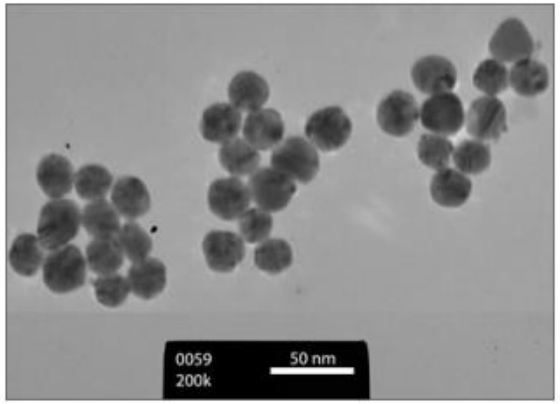
Graphene



2 D

nanowire,

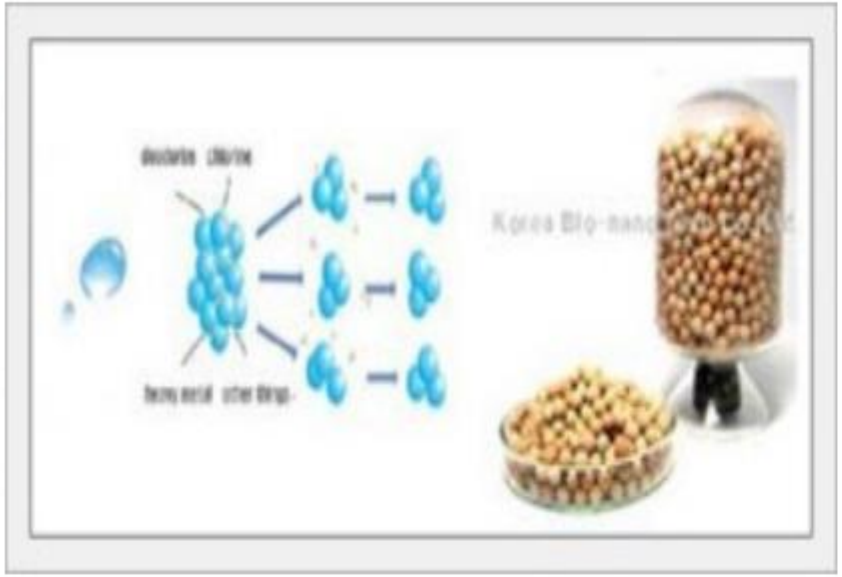
nanotube

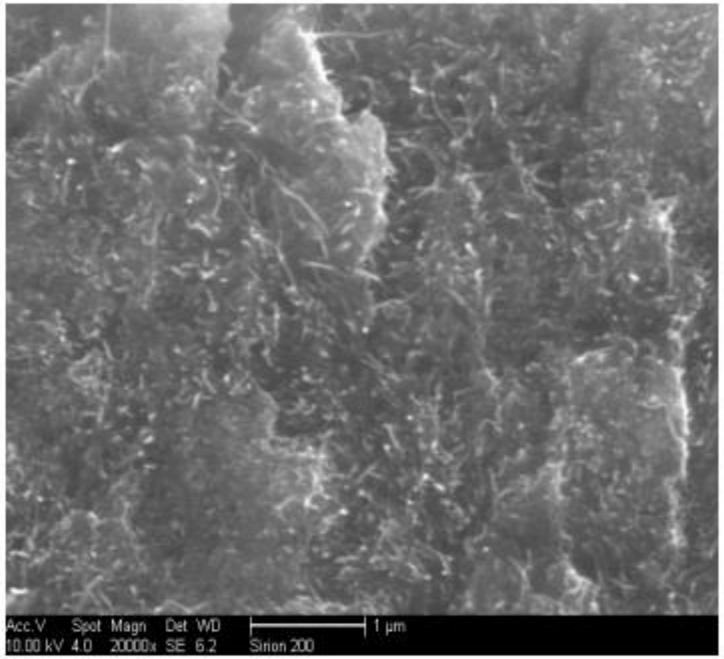


3 D

nanoparticle

Nanomaterials can be metals, ceramics, polymeric materials, or composite materials.





What has happened when reduced to the nanoscale?

- Small size effect (Quantum size effect)

  Quantum Mechanics

  --Contain very small number of atoms(molecules)

  --Electromagnetic forces are dominant.

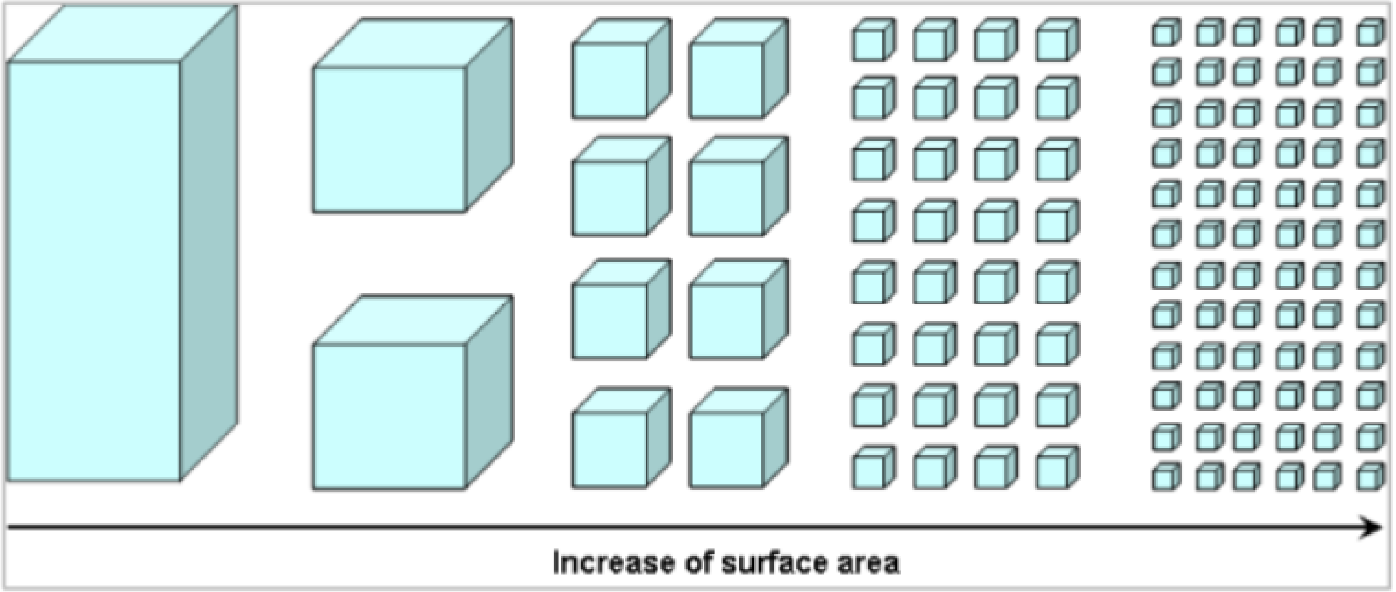
  --Wave particle duality. The electrons exhibit wave behavior.

  --Quantum confinement.

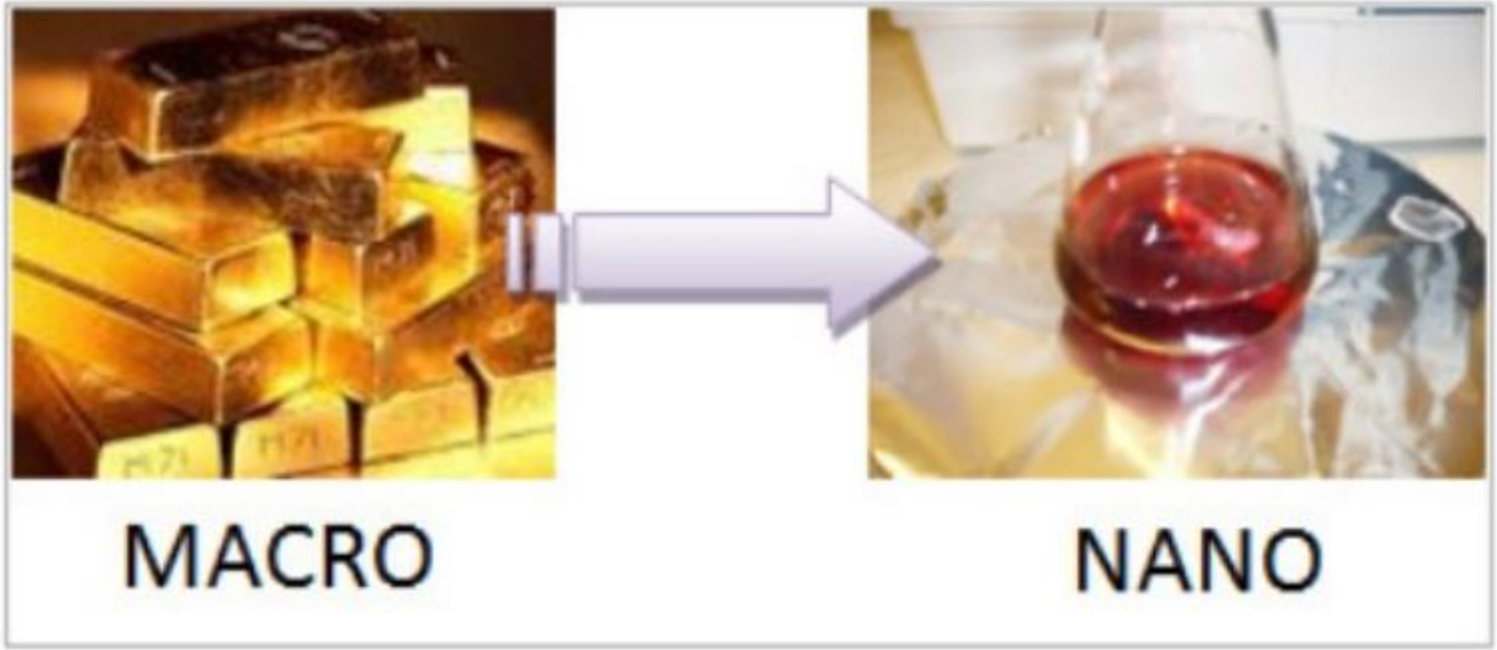
  --Discrete energy levels

Large surface effect:

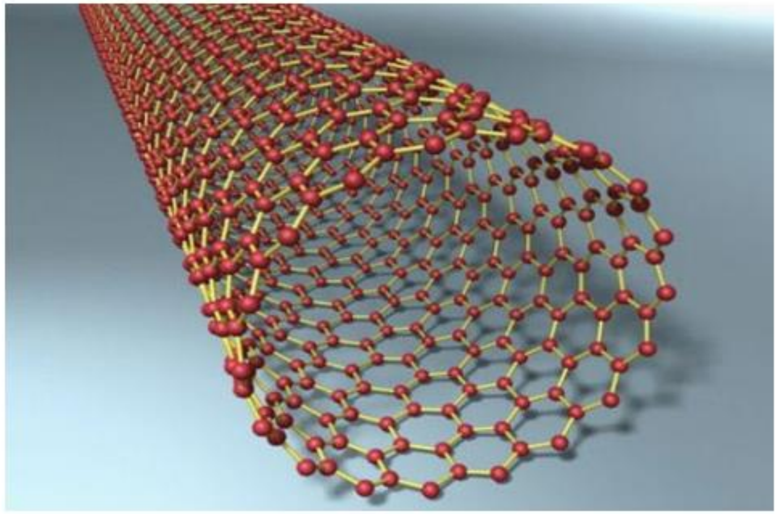
--The vastly increased ratio of surface area to volume.



The total volume remains the same, the collective surface area is greatly increased.
Catalysis properties



A piece of gold is golden in color.
A colloid of gold nanoparticles is ruby red in color.

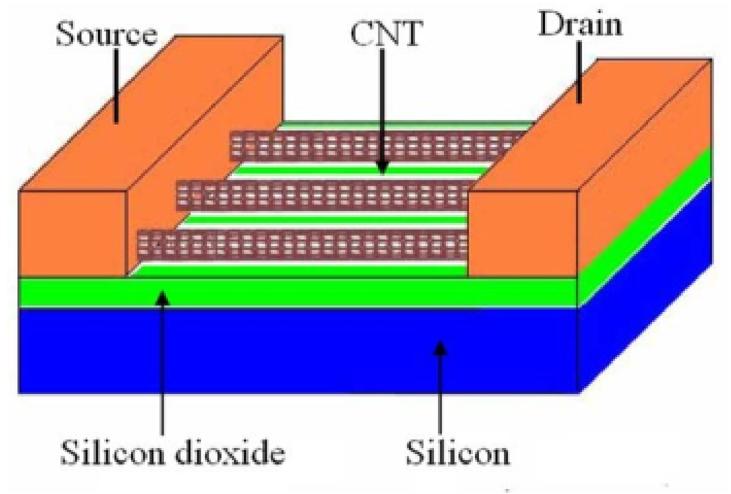


200 times stronger than steel of the same diameter.

Space elevator its principle is through a 100,000km long super-human strength of the cable into space, one end of the cable located on the earth, one end located on satellite.

- Moore's law

  If the number of chips keeps on increasing, more heat, excessive leakage current.



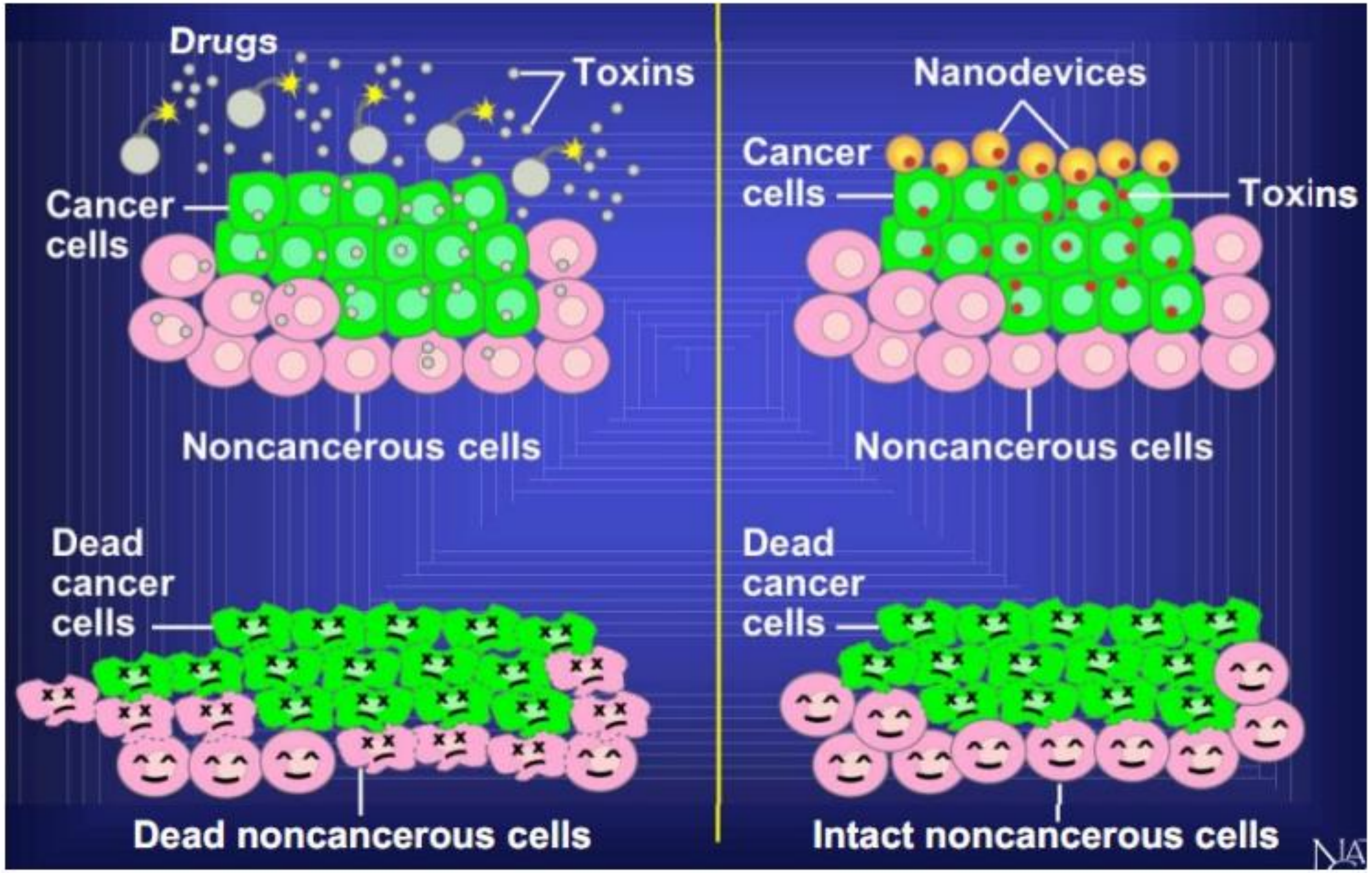
nanomaterial electronics,

molecular electronics.

- Excellent conductors of electricity and heat

  much smaller, lower power consumption, faster calculation.

Nanomedicine

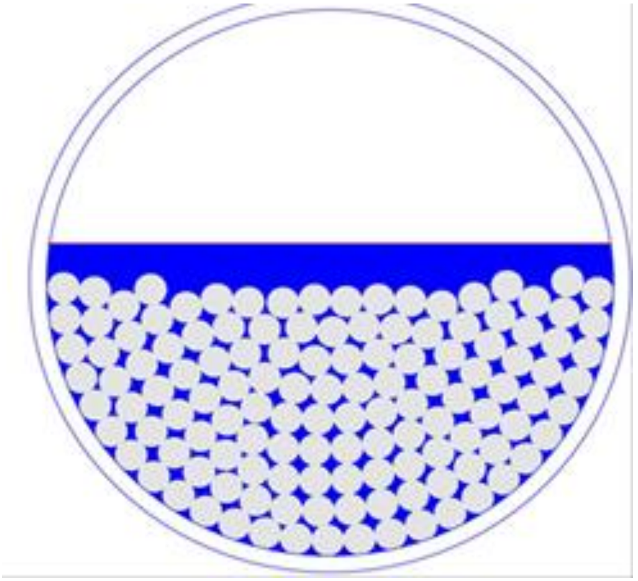


Nanomedicine can detect the cancer cells and deliver the toxin in a controlled, time-released manner.

- Preparation
- Characterization

(Physical method)

Mechanical attrition: Break the particles into nanostructures



High energy mill,

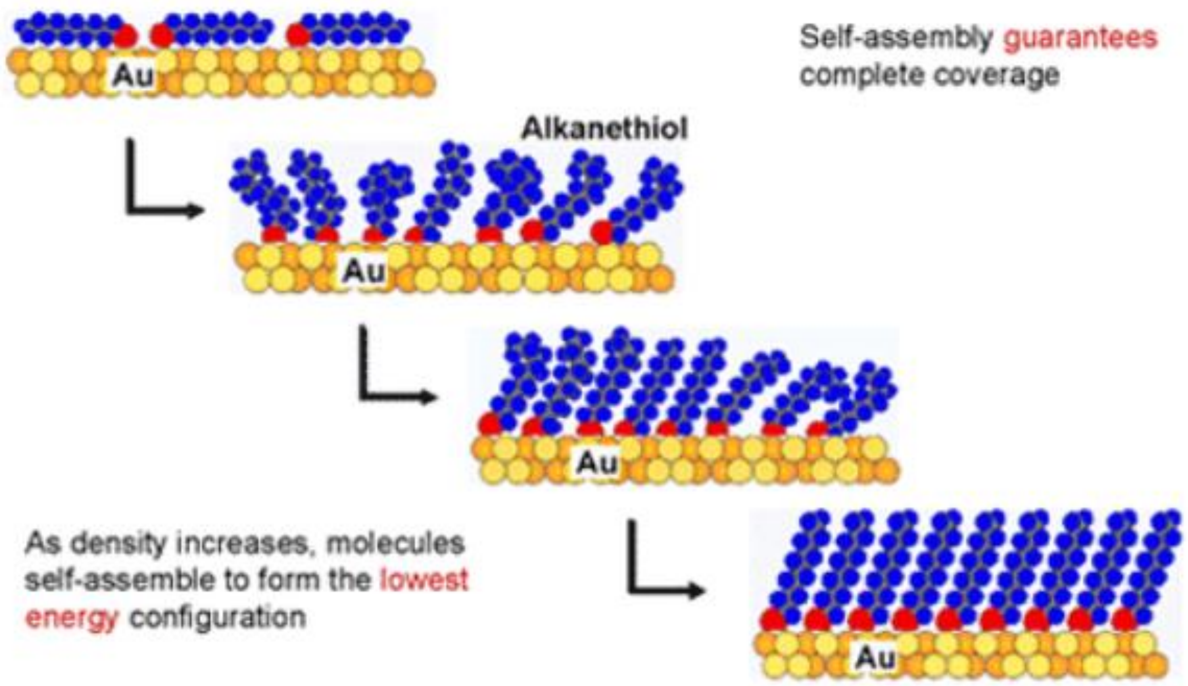
(chemical method)

(1) Chemical Vapor Deposition (CVD)

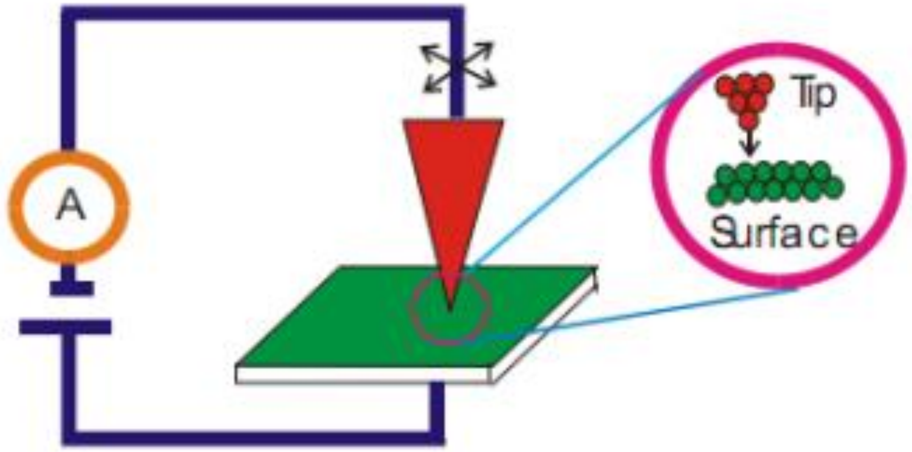
(2) Self Assembly

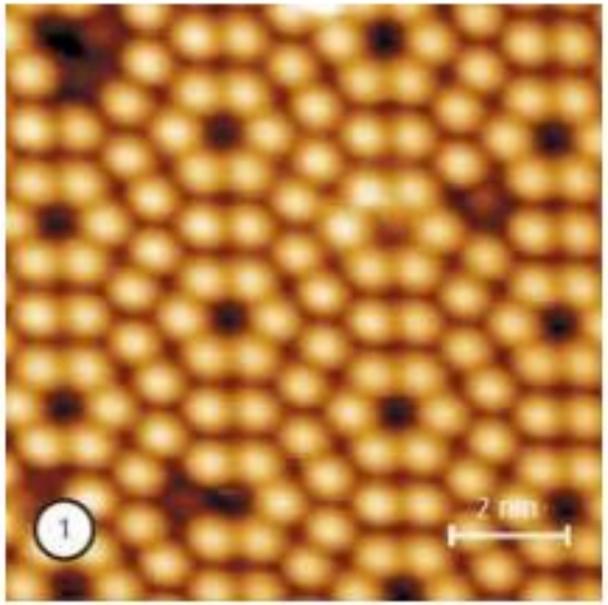
Directed by Van der Waals force

Hydrogen bonding….



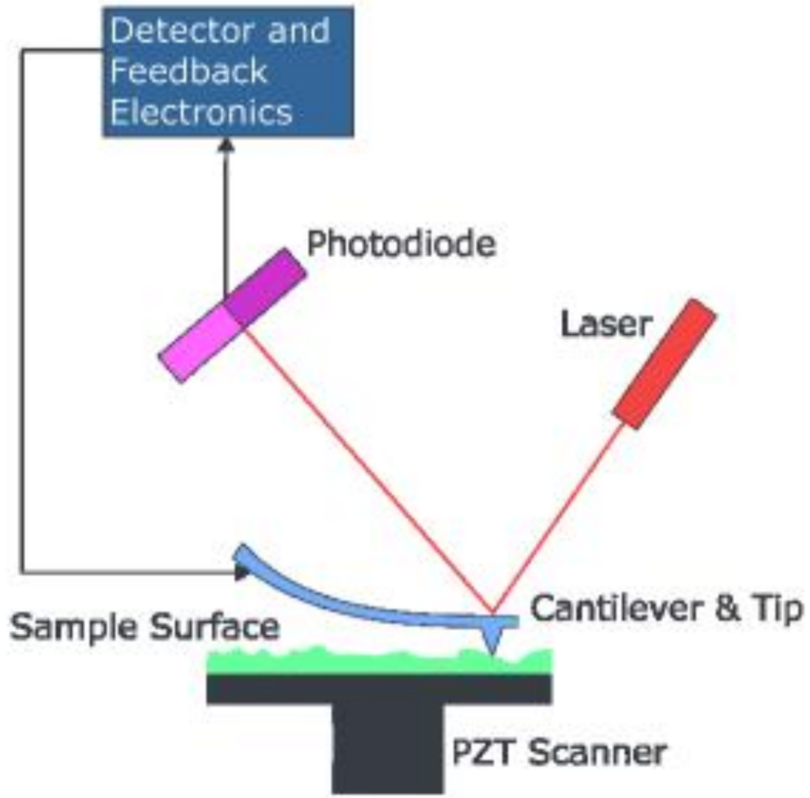
Works by sensing the tunneling current between the sharp tip and the conducting surface when the tip is brought close to the surface.

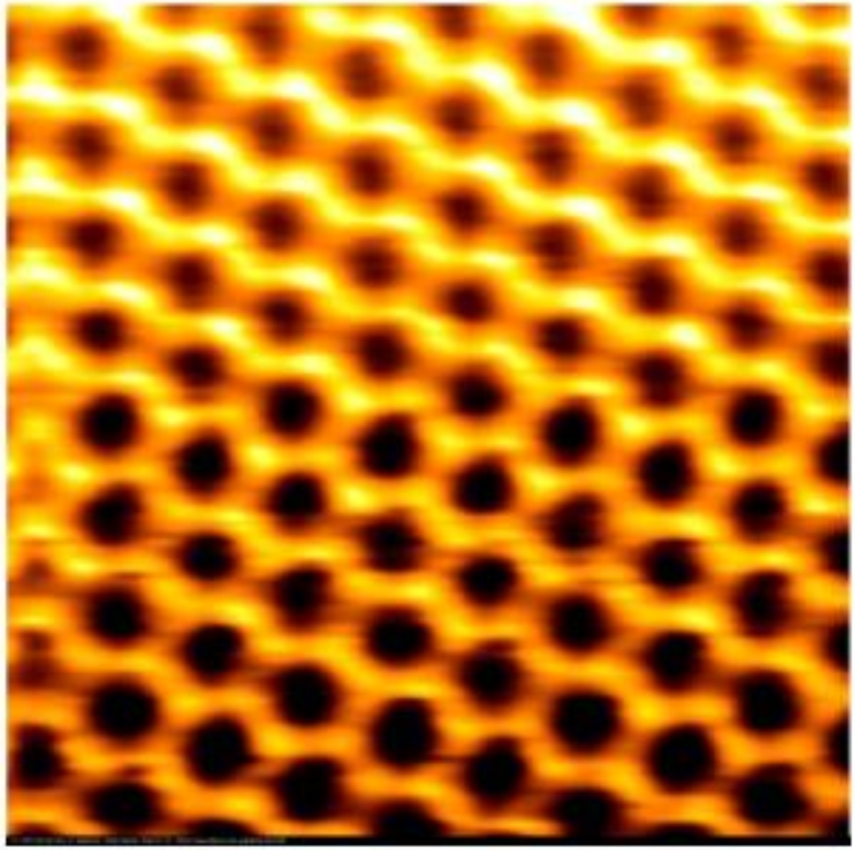




silicon

Measure the Van der Waals Force





tungsten