The Weird World of the Very Very Small

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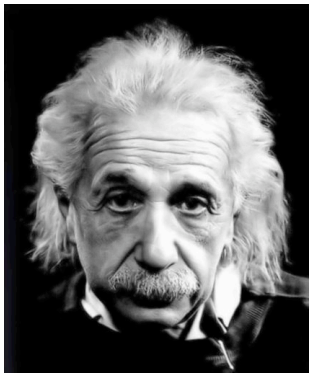
IOP Lanc and Cumb
1 May 2013

Introduction



"Everything should be made as simple as possible, but not simpler"

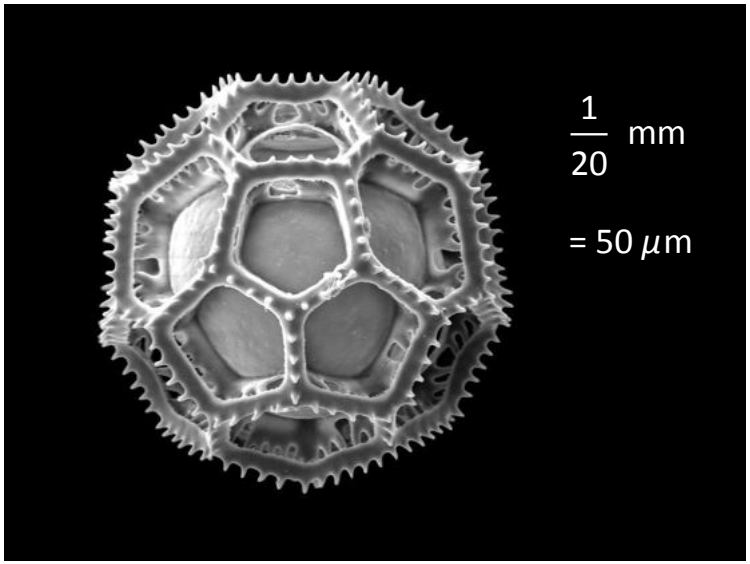
Introduction

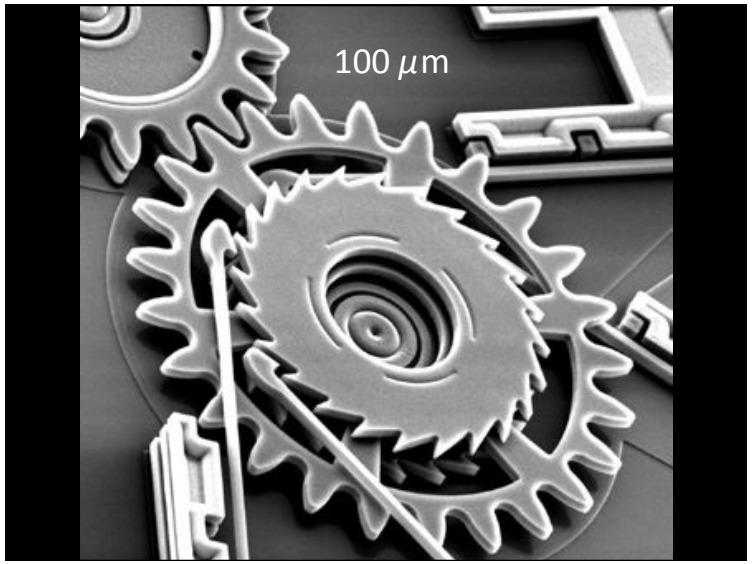
A Sense of Scale
Metres → Nanometres

A Sense of Symmetry
Underlying Structure

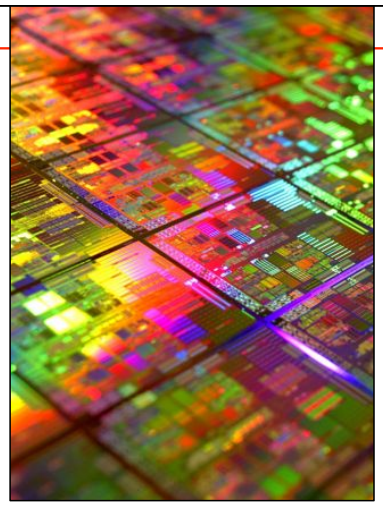
The Quantum World
Seeing Atoms

A Sense of Scale





A Sense of Scale



Microprocessor chip area ~ mm^2 …

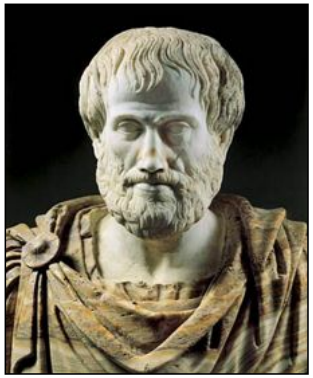
10 million transistors…

so size of components ~ 10–100 nm

Structure Within

- What is the world made of?
- How can we tell?
- What clues do we have?

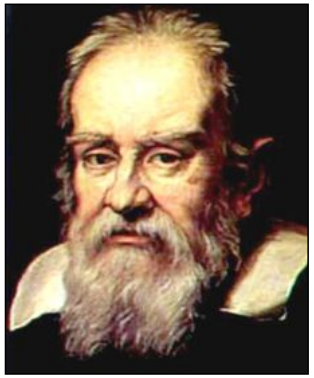
Aristotle



Elements

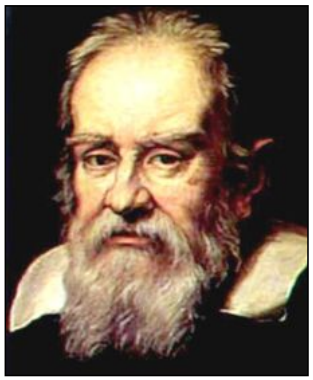
Fire
Air
Water
Earth

Galileo



The nature of the world around us should be determined by quantitative experiments, not by qualitative intellectual arguments

Galileo



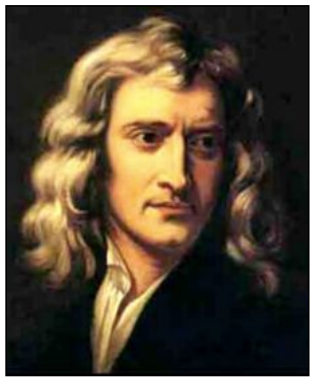
Ask not

"What should happen if… ?"

but

"What actually happens if… ?"

Newton

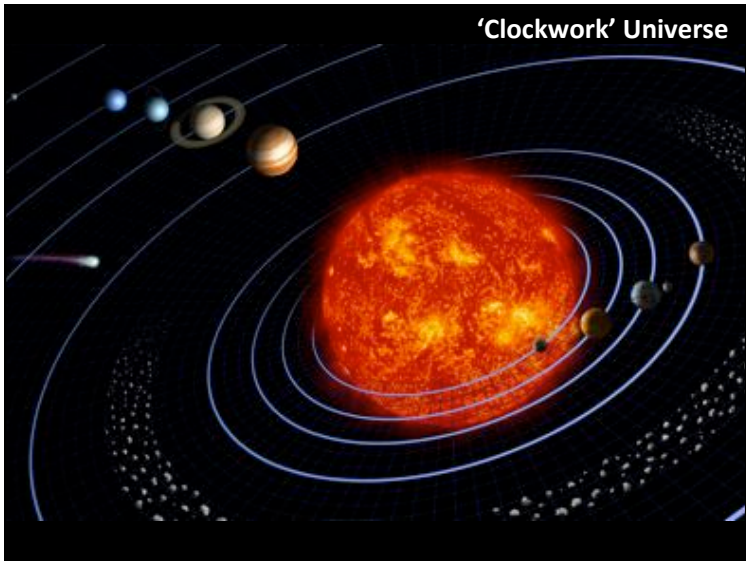


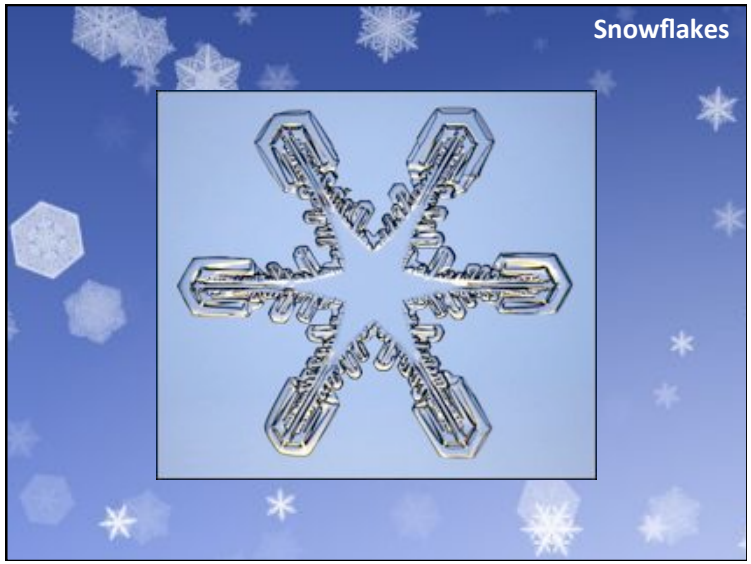
Laws of Motion

Law of Gravity

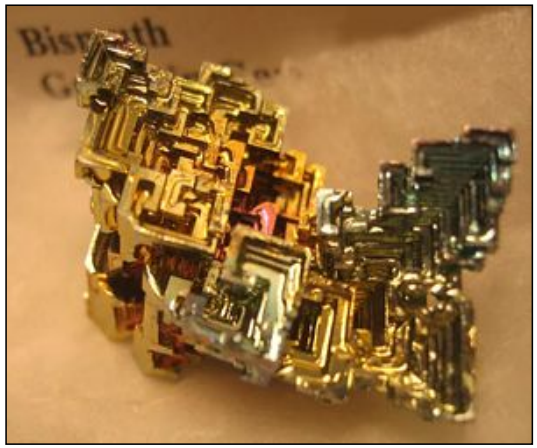
Nature of Light

"Classical Mechanics"

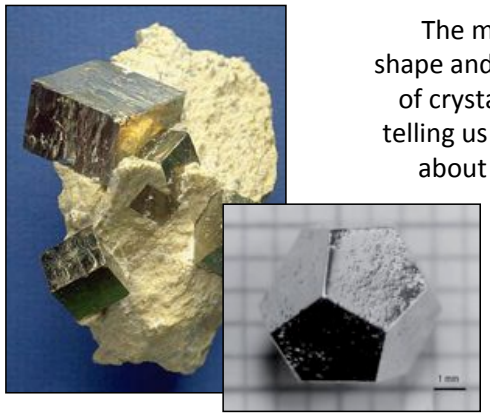




Structure Within



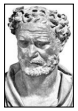
Structure Within



The macroscopic shape and symmetry of crystals must be telling us something about underlying structure

Atoms

1600 1700 1800 1900

Democritus 


Boyle


Newton


Lavoisier

Dalton 


Avogadro

Maxwell 


Boltzmann

Particles and Waves

1800 1850 1900


Young


Thomson

^ Light (Waves)

^ Electrons (Particles)

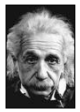
Atoms To Quantum Mechanics

1900 1910 1920 1930

Becquerel 

Rutherford 


Planck


Einstein


Bohr

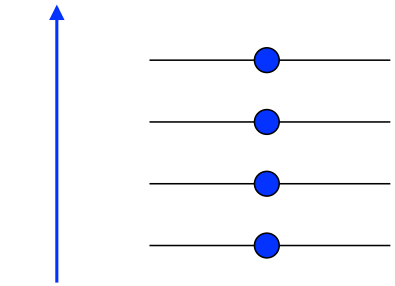
deBroglie 

Heisenberg 

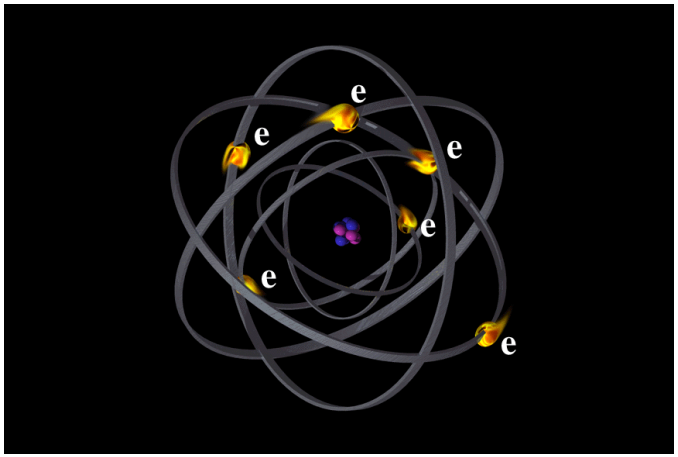

Schrödinger

^ Radio-activity ^ Light (Particles) ^ Atoms ^ Atomic Nucleus ^ Prob-ability ^ Electrons (Waves) ^ QM

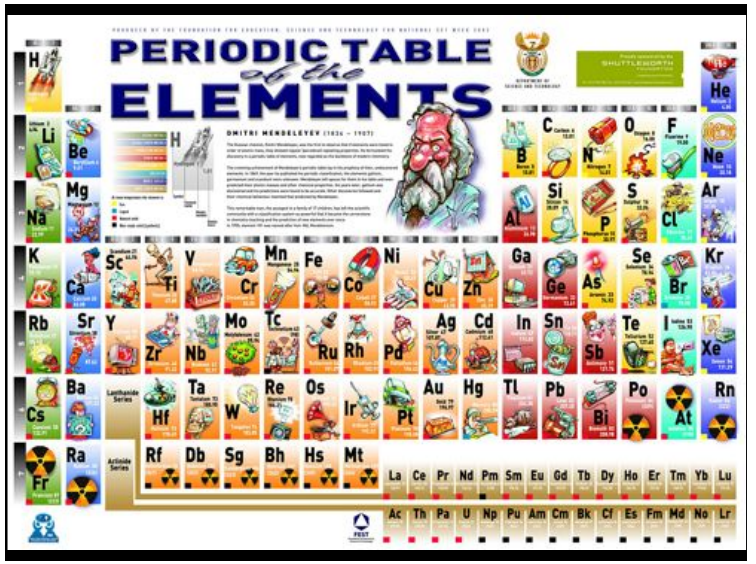
Quantised States



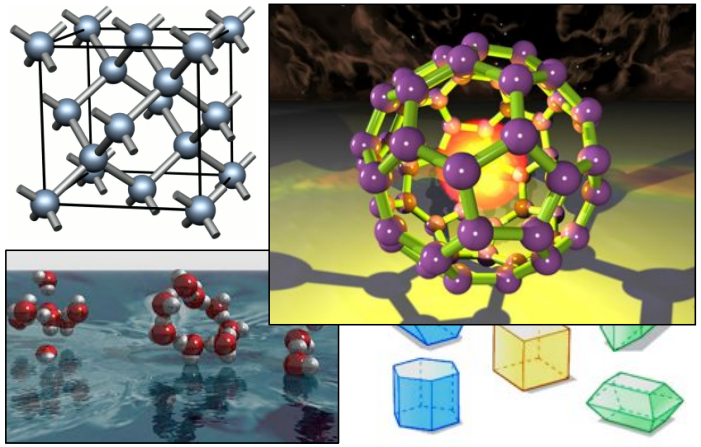
Bohr Model



The Weird World of the Very Very Small 21



Atom + Atom



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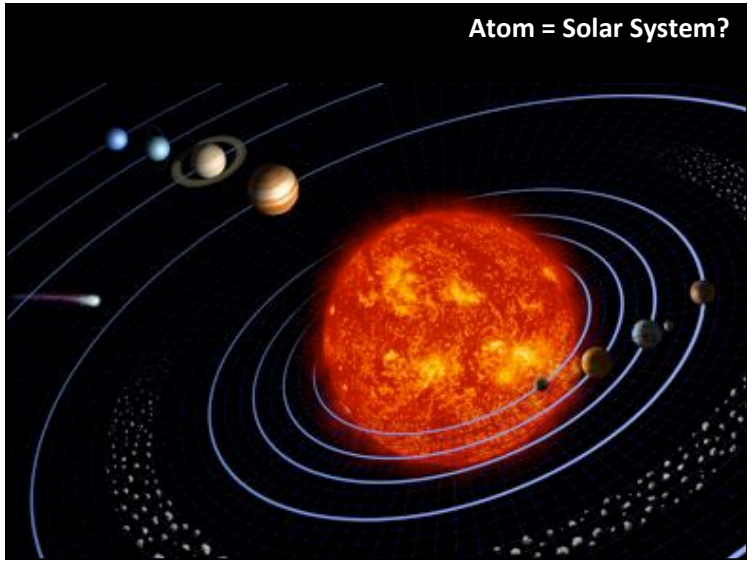
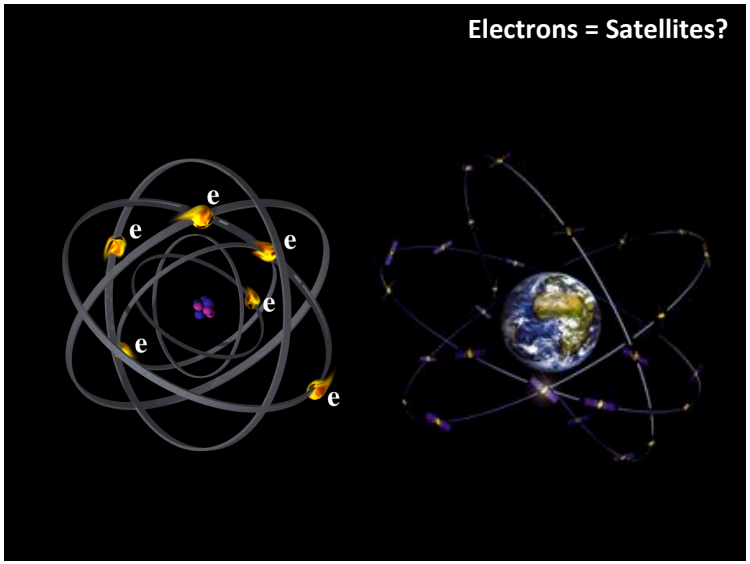
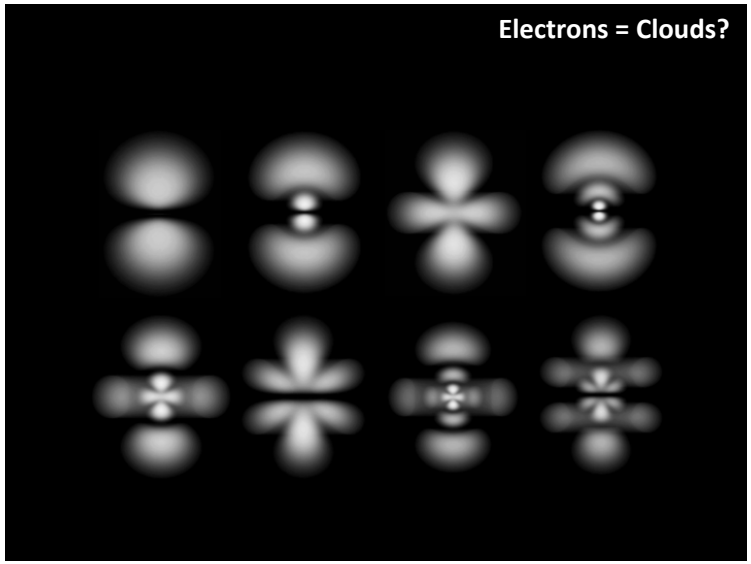
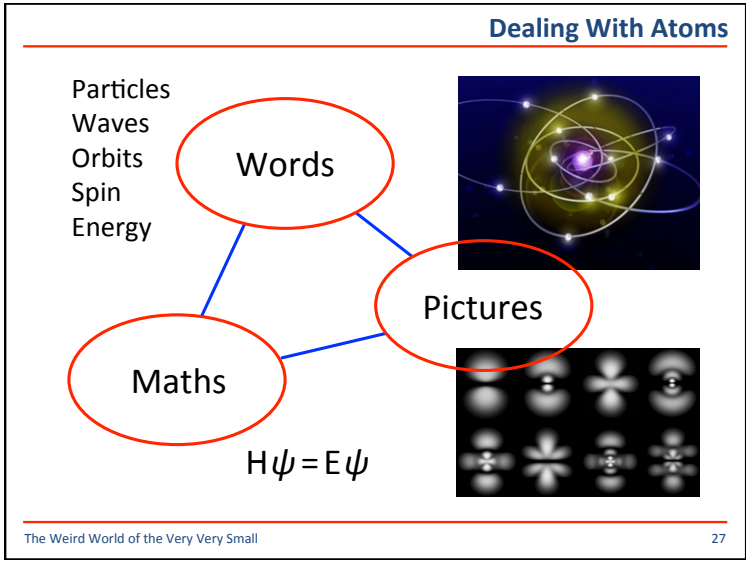
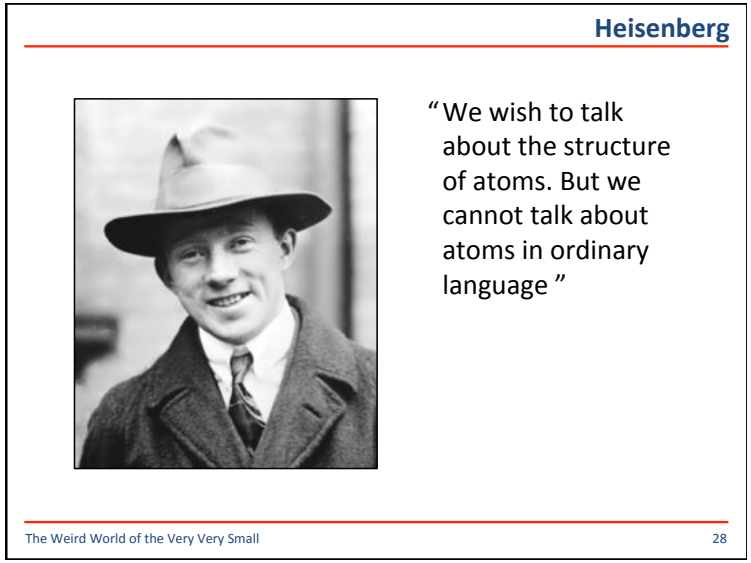
Atom = Solar System?




Electrons = Satellites?
e
e
e
e
e
e


Electrons = Clouds?


Dealing With Atoms
Particles
Waves
Orbits
Spin
Energy
Words
Pictures
Maths
$H\psi = E\psi$
The Weird World of the Very Very Small
27


Heisenberg
"We wish to talk about the structure of atoms. But we cannot talk about atoms in ordinary language"
The Weird World of the Very Very Small
28

Dealing With Atoms

Would it be better to use words that don't carry any 'baggage', or preconceptions?

Rather than say…

" The electrons orbit and spin in the atom "

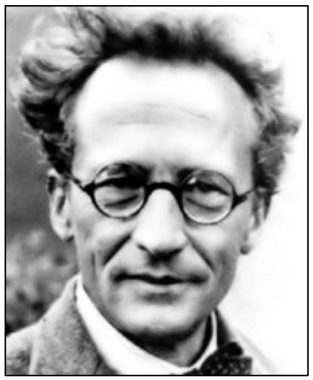
Would it be better to say…

" The slithy toves did gyre and gimbal in the wabe "

Bohr

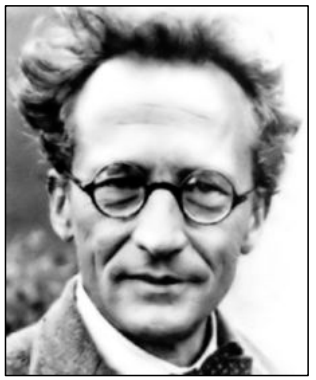
" Everything we call real is made of things that cannot be regarded as real "

Schrödinger



" Atomic physics has shown that atoms have no meaning, but can only be understood in experimental measurement "

Schrödinger



" I don't like it, and I'm sorry I ever had anything to do with it "

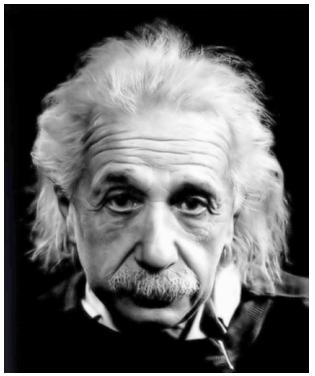
QM vs Common Sense

Atoms (indeed, all particles) are unpredictable
We can know only the ***probability*** of an atom having a particular position, speed, energy, …

Atoms do not have a finite size
An electron 'in' an atom could be ***anywhere***

Atoms can be in two states at the same time
Electron 'spin' can be simultaneously clockwise ***and*** anticlockwise

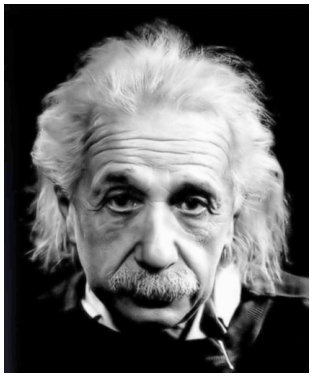
Einstein



"Common sense is the collection of prejudices acquired by age eighteen"

Heads or Tails?

Einstein



"God does not play dice"

"God is subtle but he is not malicious"

Bohr

"Stop telling God what to do!"

Three Aspects of QM

- Order matters
- Schrödinger's Cat
- Using QM to see atoms

Order Matters

In algebra

$$A \times B = B \times A$$

In Quantum Mechanics

$$A \times B \neq B \times A$$

So what?

If Order Matters

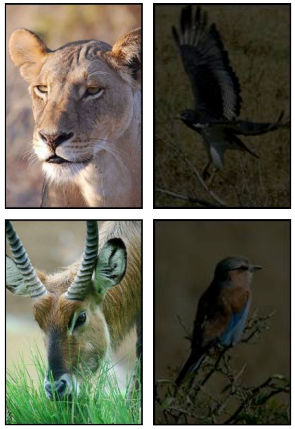
Top pair : carnivores

Bottom pair : veggies

Left pair : 4 legs

Right pair : wings

If Order Matters



Pick 2 out of the 4

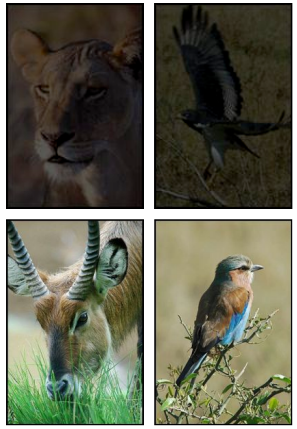
For instance, pick the **veggie** animals

From these, pick again

For instance, pick the **4-legged** animals

You're left with waterbuck **and** lion!

If Order Matters



If we had picked in a different order…

First pick the **4-legged** animals

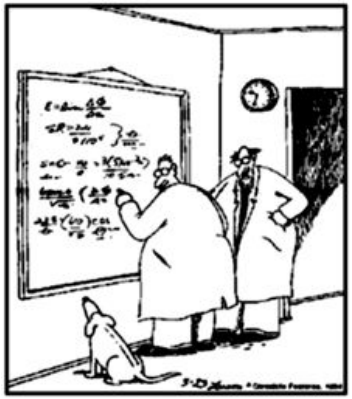
Then pick the **veggie** animals

You're left with waterbuck **and** roller!

Schrödinger's Cat

Schrödinger's Cat

QM and Dogs

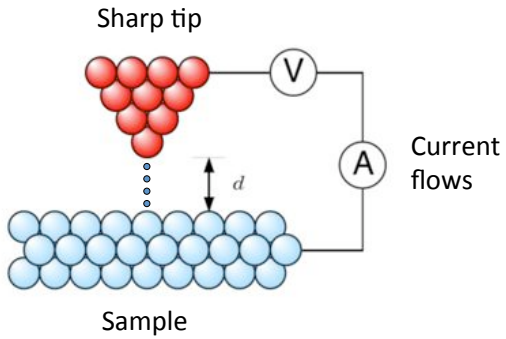


"Ohhh, look at that…
dogs are so cute when they try to comprehend quantum mechanics"

How Do We Know QM Is Right?

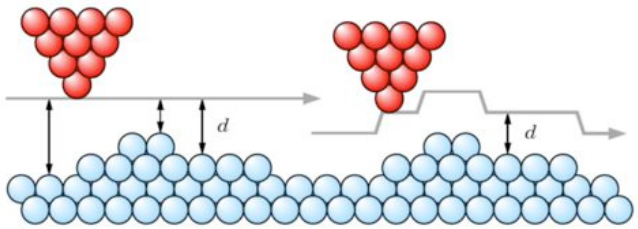
- So far, nothing has proved it wrong
- Quantum Mechanics predicts results that are impossible by 'Classical Mechanics'
- Using QM theory, we can build a microscope that can 'see' atoms

Scanning Tunnelling Microscope



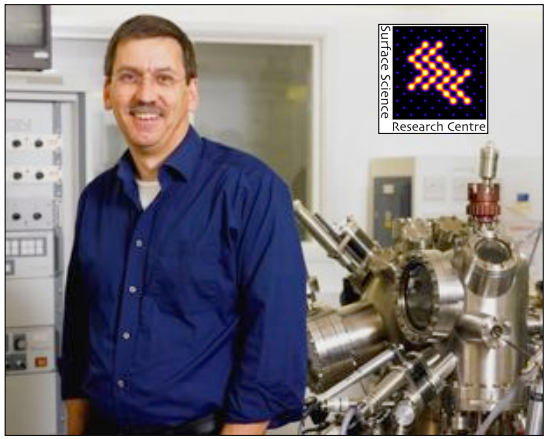
STM

Move tip across sample…



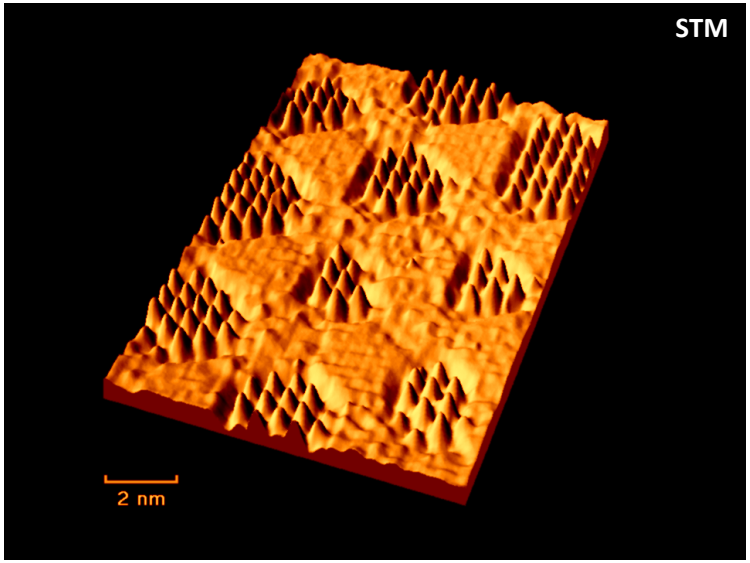
…measuring current at each point

Surface Science

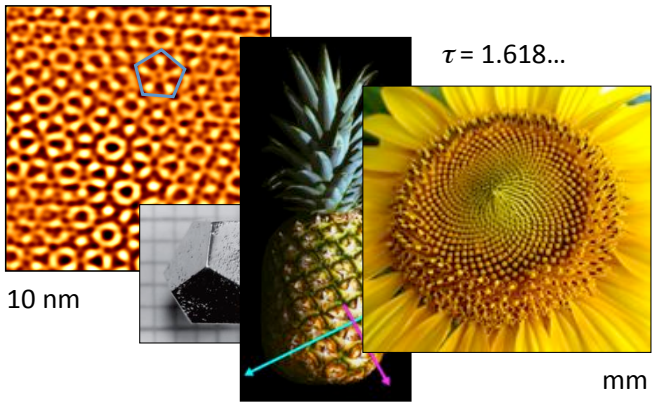


Surface Science

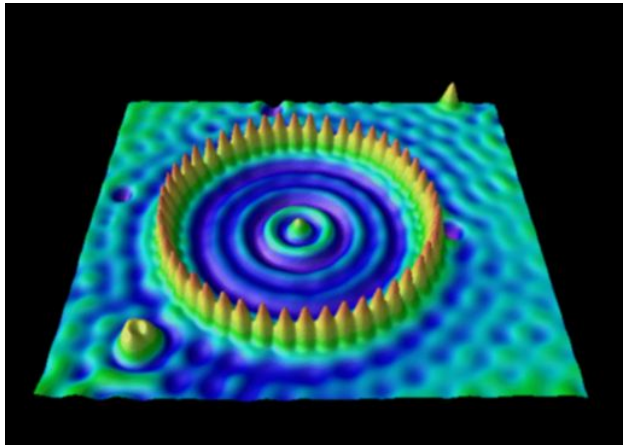
The STM is sealed inside an ultra-high vacuum vessel (10^{-13} atms) to keep it and the sample surface clean.



Patterns — Large and Small



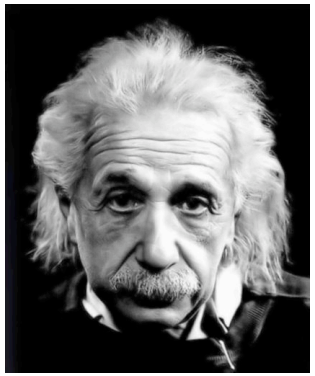
STM of Atomic Corral



Bohr

"If quantum mechanics hasn't profoundly shocked you, you haven't understood it "

Einstein



"The most incomprehensible thing about the world is that it is comprehensible "