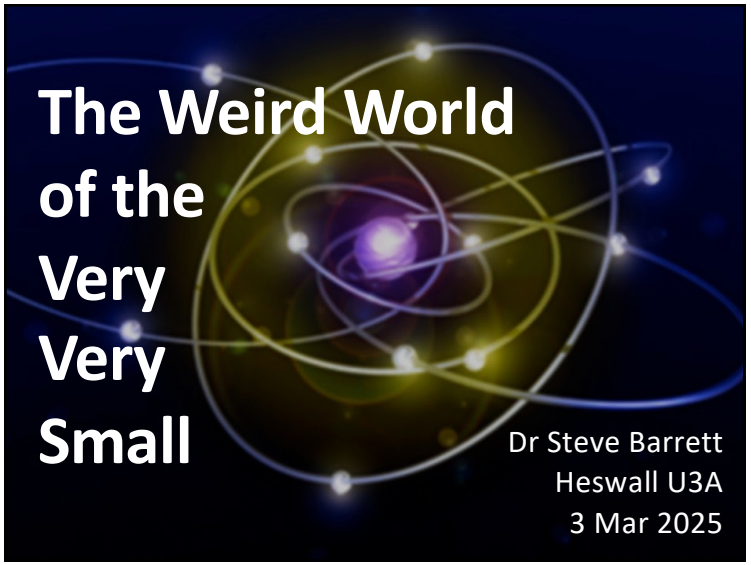
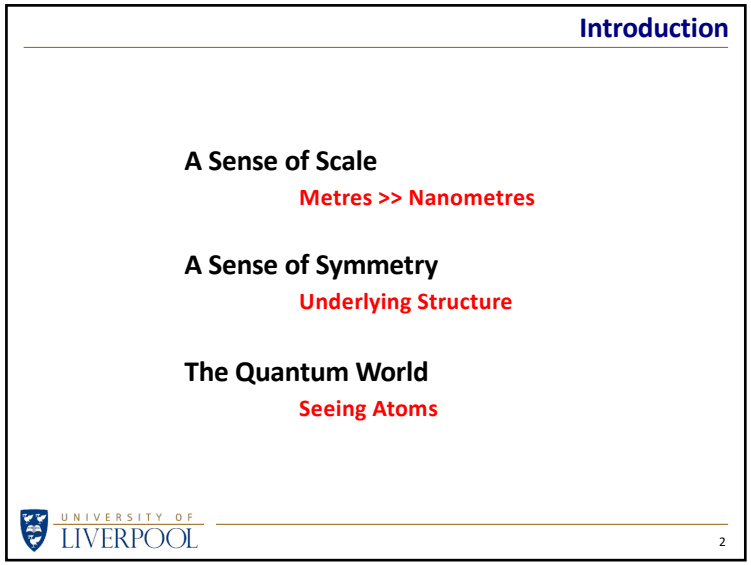
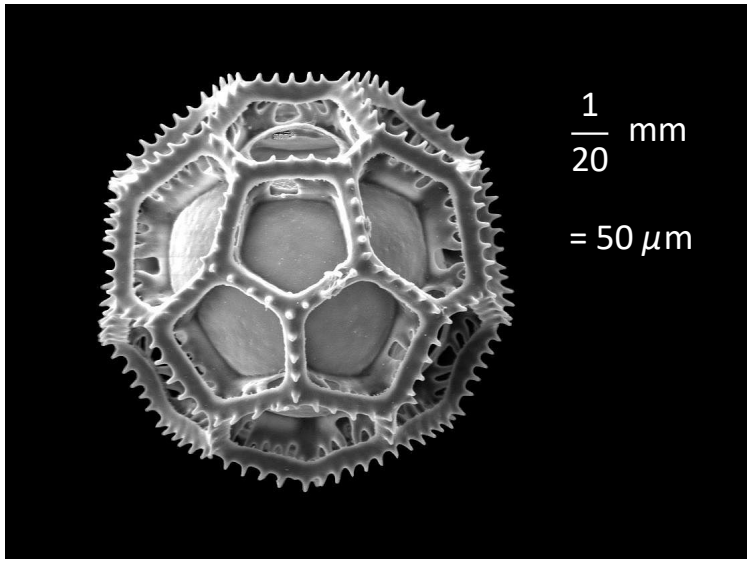
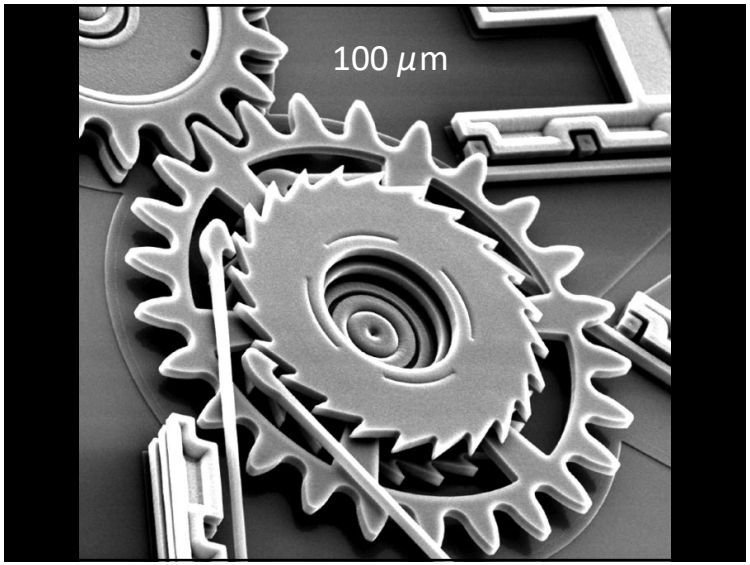
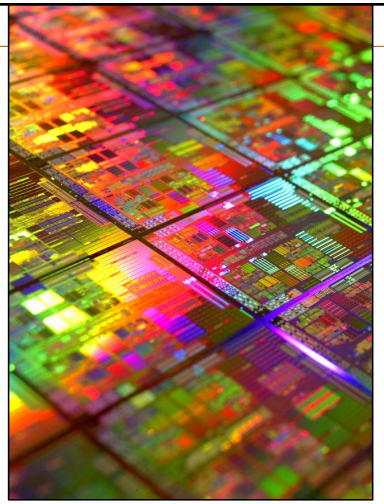

The Weird World of the Very Very Small
Dr Steve Barrett
Heswall U3A
3 Mar 2025


Introduction
A Sense of Scale
Metres >> Nanometres
A Sense of Symmetry
Underlying Structure
The Quantum World
Seeing Atoms
UNIVERSITY OF LIVERPOOL
2


A Sense of Scale
mm


1/20 mm
= 50 μm





A Sense of Scale

Microprocessor chip area ~mm^2 …

100 million transistors …

so the sizes of the components are ~10nm

UNIVERSITY OF LIVERPOOL

6

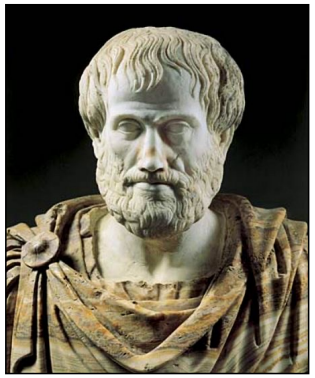
Structure Within

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

UNIVERSITY OF LIVERPOOL

7

Aristotle



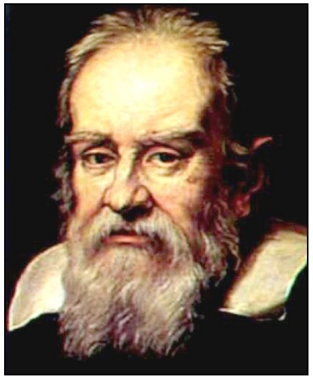
Elements

Fire
Air
Water
Earth

UNIVERSITY OF LIVERPOOL

8

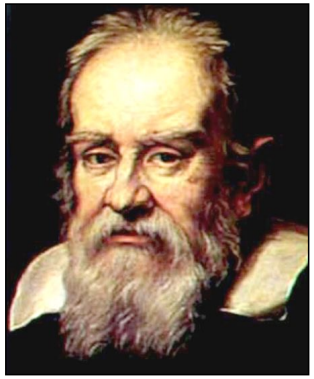
Galileo



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

UNIVERSITY OF LIVERPOOL 9

Galileo



Ask not

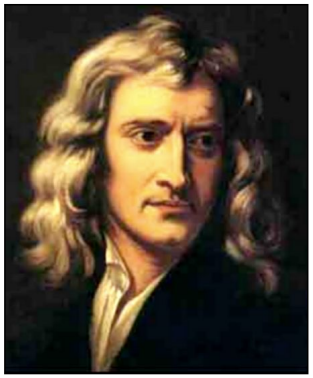
"What should happen if… ?"

but

"What actually happens if… ?"

UNIVERSITY OF LIVERPOOL 10

Newton



Laws of Motion

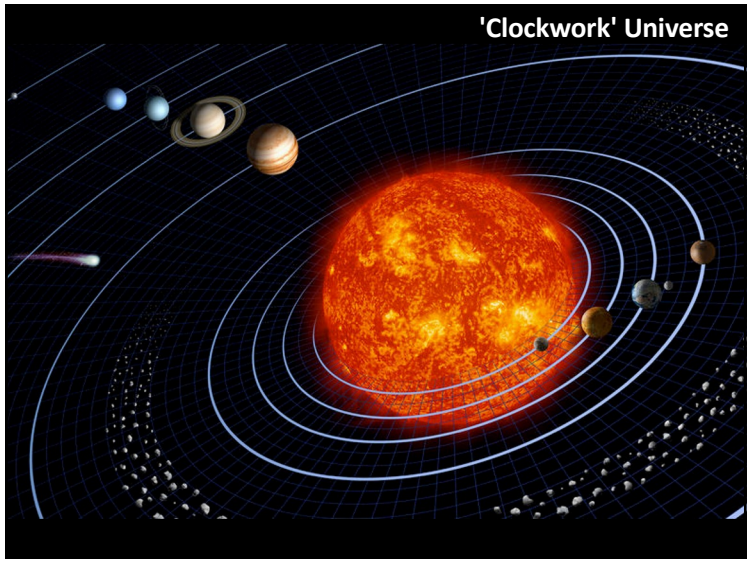
Law of Gravity

Nature of Light

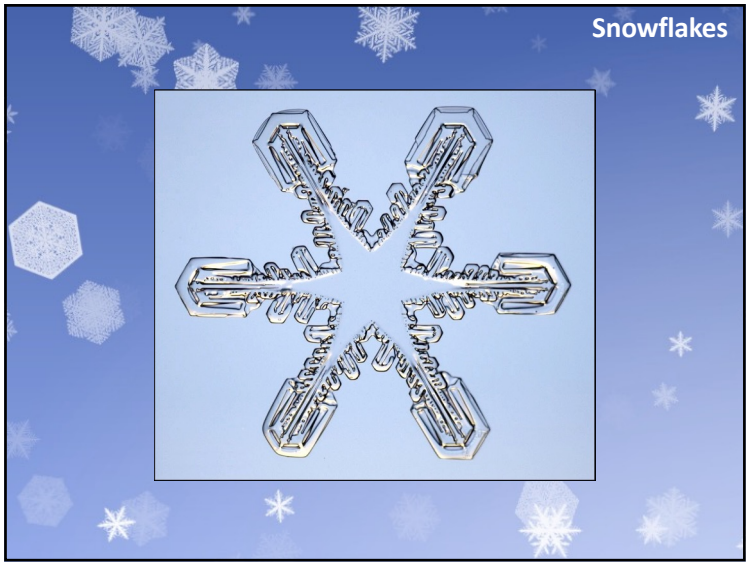
"Classical Mechanics"

UNIVERSITY OF LIVERPOOL 11

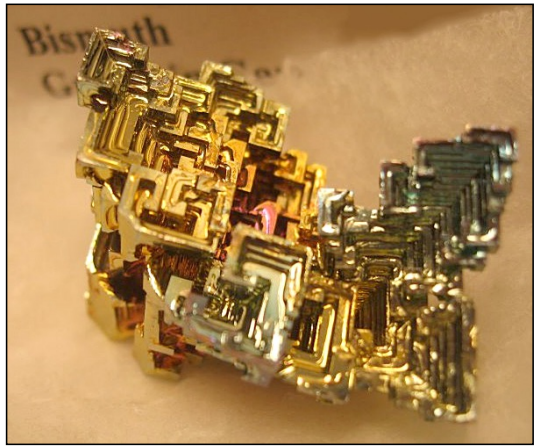
'Clockwork' Universe



Snowflakes



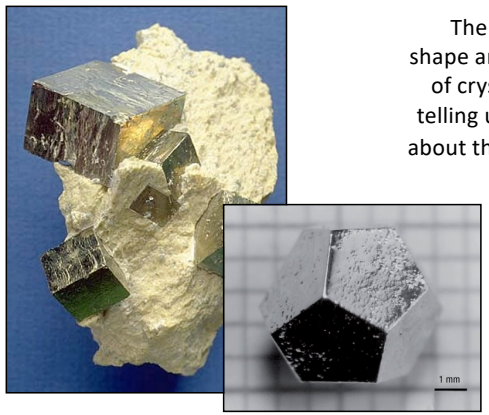
Structure Within



UNIVERSITY OF LIVERPOOL

14

Structure Within



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

UNIVERSITY OF LIVERPOOL

15

Atoms

1600 1700 1800 1900

Democritus

Boyle

Newton

Lavoisier

Dalton

Maxwell

Avogadro

Boltzmann

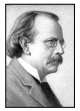
UNIVERSITY OF LIVERPOOL

16

Particles and Waves

1800 1850 1900

Young



Thomson

Light (Waves)

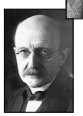
Electrons (Particles)

Atoms To Quantum Mechanics

1900 1910 1920 1930

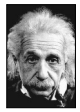
Becquerel

Rutherford



Planck

Einstein



Bohr

deBroglie

Heisenberg

Schrödinger

Radio-activity

Light (Particles)

Atoms

Atomic Nucleus

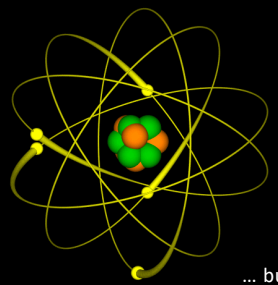
Prob-ability

Electrons (Waves)

QM

Bohr Model

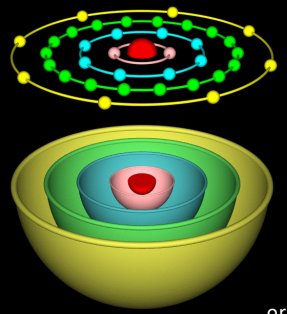
This might be how we imagine atoms with electrons buzzing around a nucleus like bees …



… but it doesn't show us that all the electrons have different energies

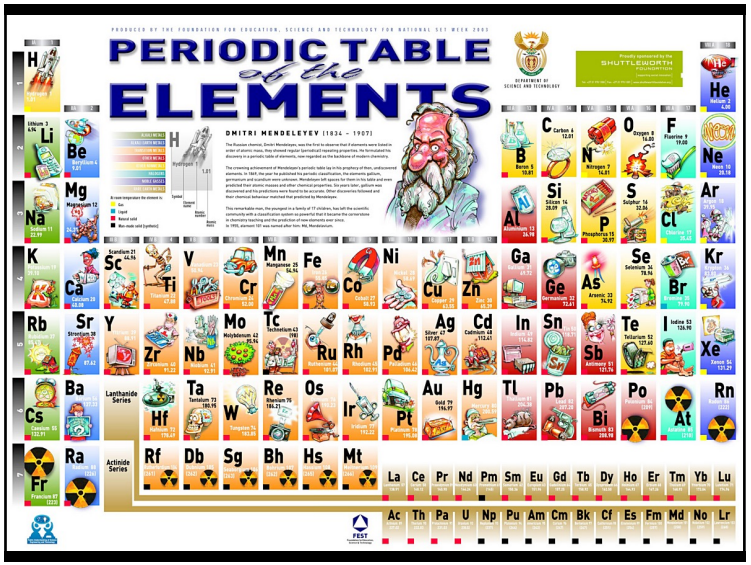
Bohr Model

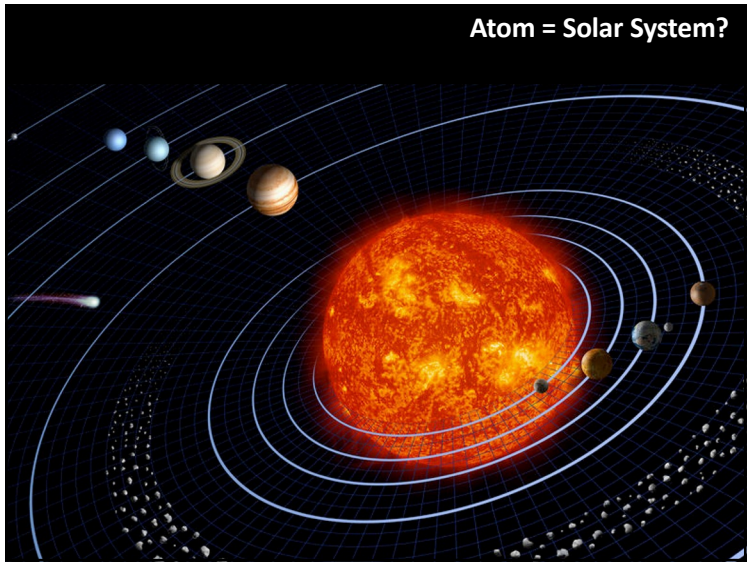
It is better to think of the electrons in different sized orbits …

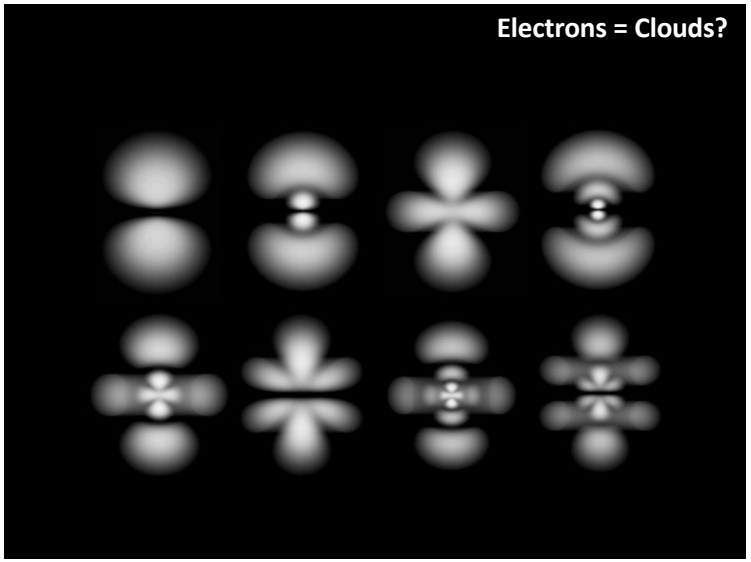


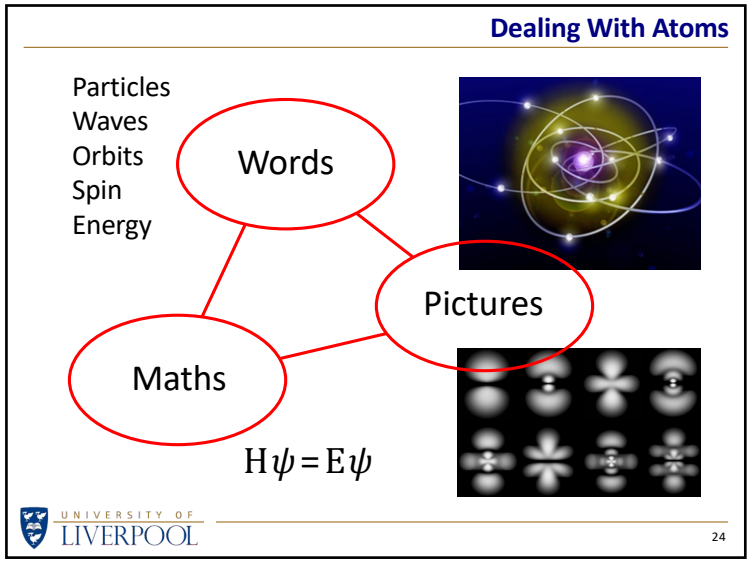
… or concentric shells surrounding the nucleus

Weird World of the Very Very Small

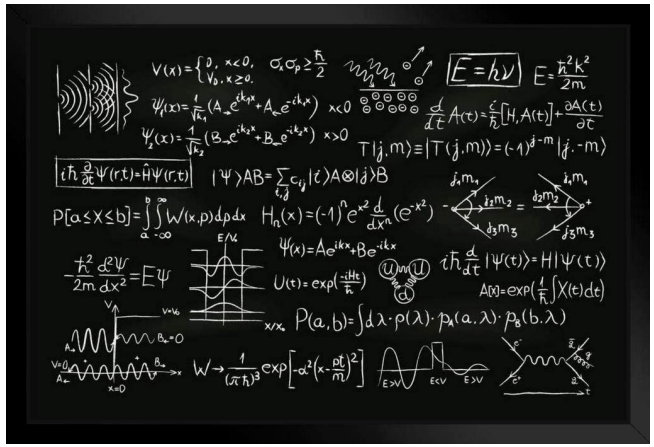








Dealing With Atoms



UNIVERSITY OF LIVERPOOL

25

Heisenberg

" We wish to talk about the structure of atoms. But we cannot talk about atoms in ordinary language "

UNIVERSITY OF LIVERPOOL

26

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 "

UNIVERSITY OF LIVERPOOL

27

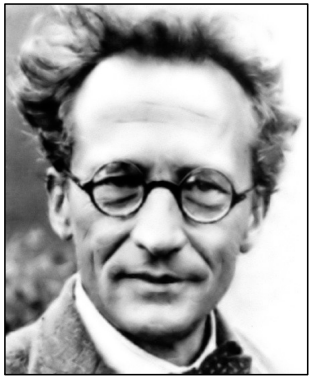
Bohr

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

UNIVERSITY OF LIVERPOOL

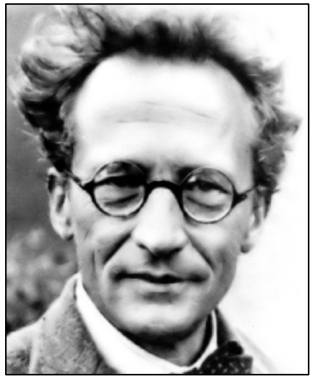
28

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 "

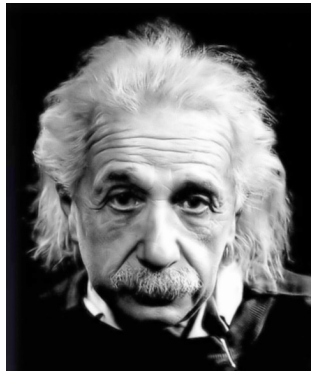
QM vs Common Sense

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



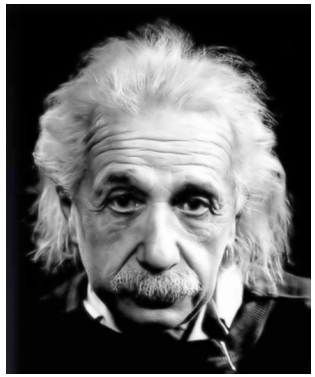
" Common sense is the collection of prejudices acquired by age eighteen "

Heads or Tails?

UNIVERSITY OF LIVERPOOL

33

Einstein



" God does not play dice "

" God is subtle but he is not malicious "

UNIVERSITY OF LIVERPOOL

34

Bohr

" Stop telling God what to do! "

UNIVERSITY OF LIVERPOOL

35

Three Aspects of QM

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

UNIVERSITY OF LIVERPOOL

36

Order Matters

In algebra

$A \times B = B \times A$

In Quantum Mechanics

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

So what?

UNIVERSITY OF LIVERPOOL

37

If Order Matters




Top pair : carnivores

Bottom pair : veggies

Left pair : four legs

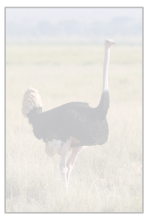
Right pair : wings

UNIVERSITY OF LIVERPOOL

38

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!

UNIVERSITY OF LIVERPOOL

39

If Order Matters




If we had picked in a different order …

First pick the **4-legged** animals

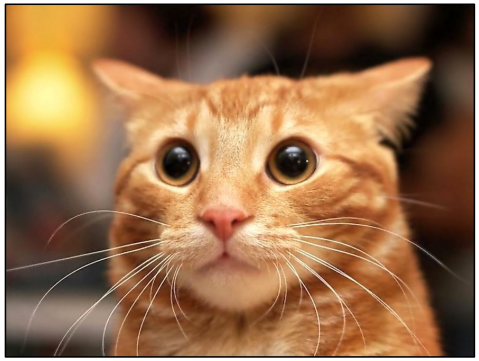
Then pick the **veggie** animals

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

UNIVERSITY OF LIVERPOOL

40

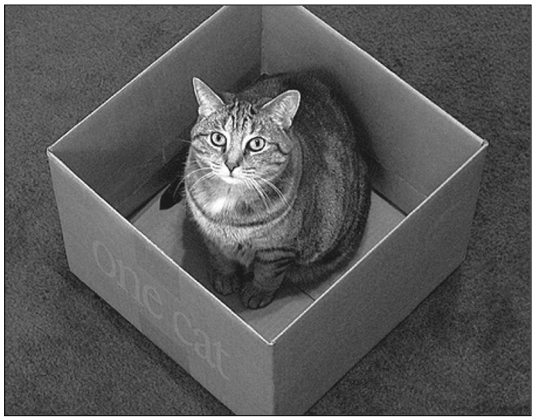
Schrödinger's Cat



UNIVERSITY OF LIVERPOOL

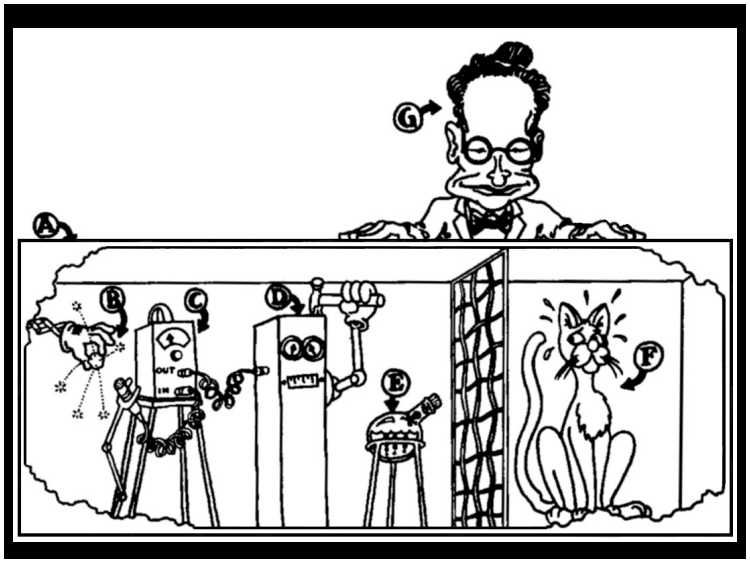
41

Schrödinger's Cat



UNIVERSITY OF LIVERPOOL

42



Schrödinger's Cat

UNIVERSITY OF LIVERPOOL

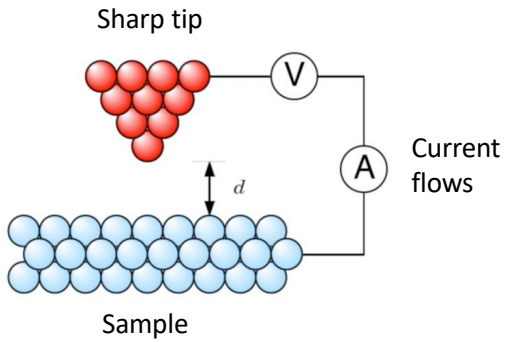
44

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

UNIVERSITY OF LIVERPOOL 45

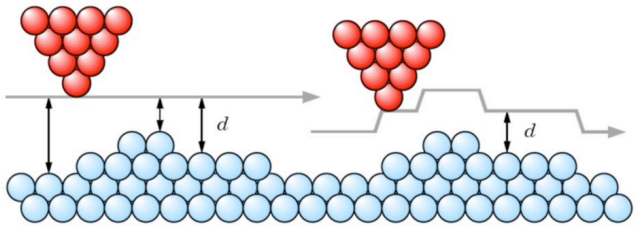
Scanning Tunnelling Microscope



UNIVERSITY OF LIVERPOOL 46

STM

Move the tip across the sample …



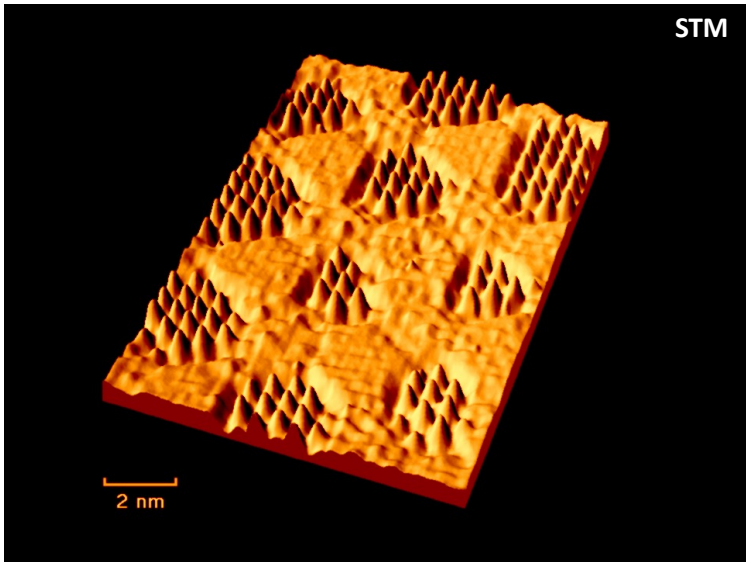
… measuring the current at each point

UNIVERSITY OF LIVERPOOL 47

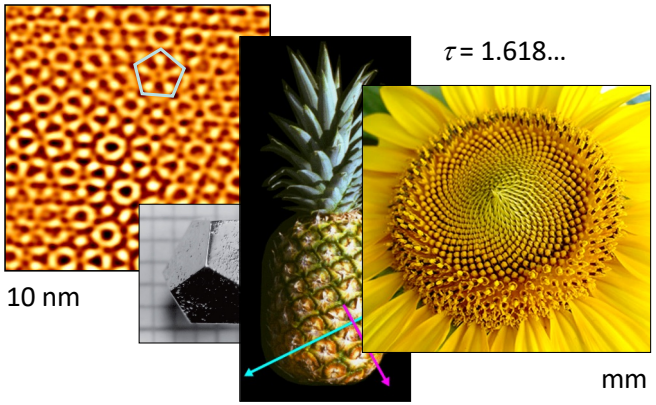
Surface Science

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

48



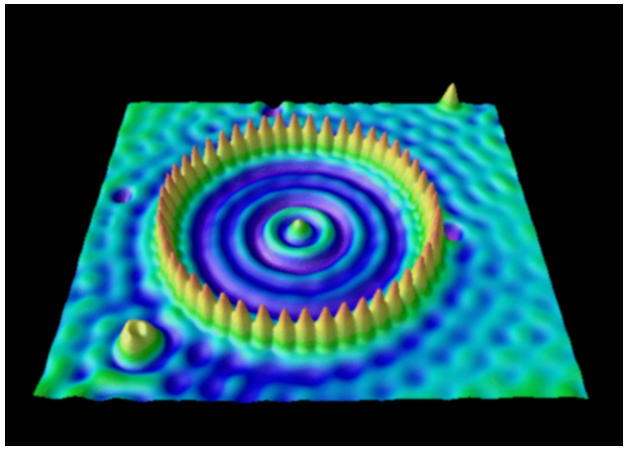
Patterns — Large and Small



UNIVERSITY OF LIVERPOOL

50

STM of Atomic Corral



UNIVERSITY OF LIVERPOOL

51

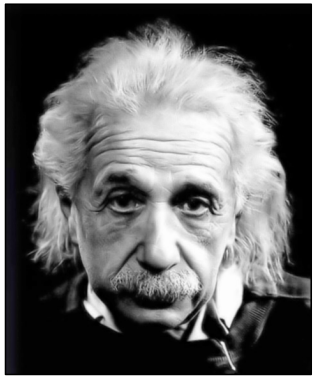
Bohr

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

UNIVERSITY OF LIVERPOOL

52

Einstein



" The most incomprehensible thing about the world …

… is that it is comprehensible "

UNIVERSITY OF LIVERPOOL

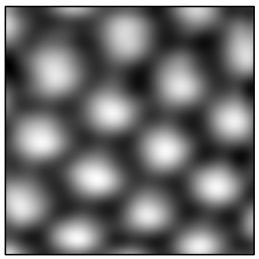
53

Hmmm…

UNIVERSITY OF LIVERPOOL

54

A World of Atoms



850 pm

On this scale, a grain of sand would be about the size of the Moon.

" To see a world in a grain of sand … "

William Blake

UNIVERSITY OF LIVERPOOL

55

The Weird World of the Very Very Small

Dr Steve Barrett
Heswall U3A
3 Mar 2025

www.liverpool.ac.uk/~sdb/Talks