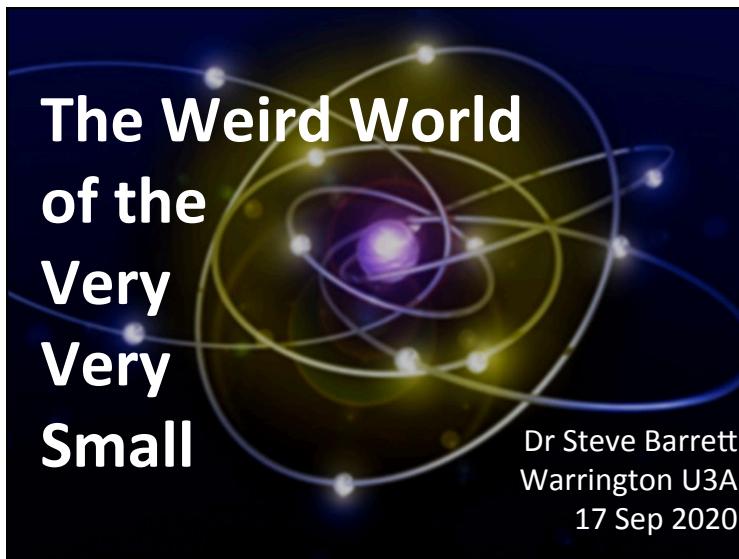
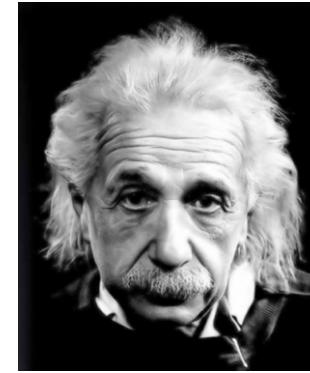


The Weird World of the Very Very Small



Introduction



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



2

Introduction

A Sense of Scale

Metres → Nanometres

A Sense of Symmetry

Underlying Structure

The Quantum World

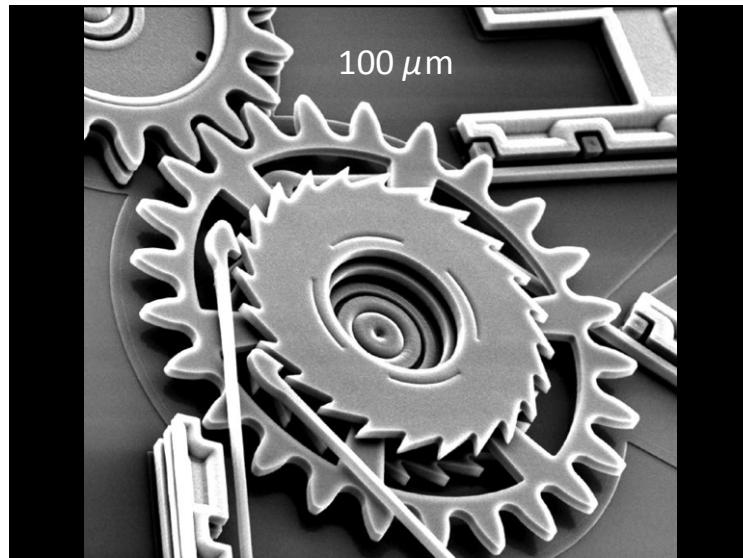
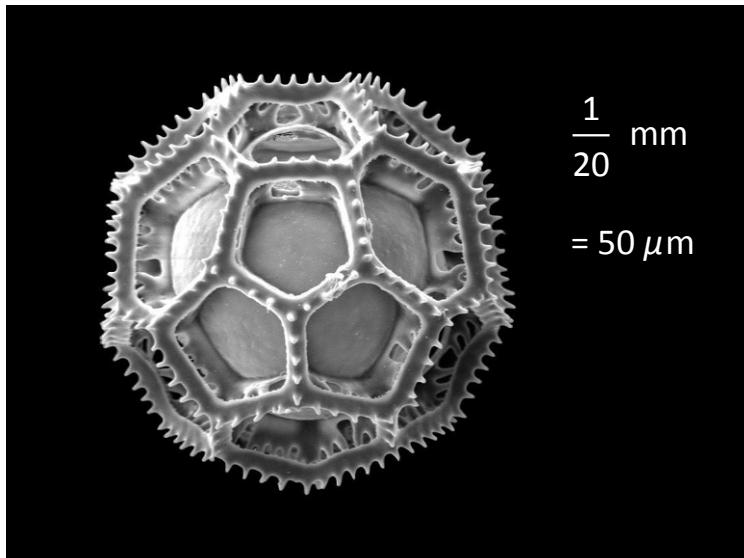
Seeing Atoms



3



The Weird World of the Very Very Small



A Sense of Scale

Microprocessor chip area $\sim \text{mm}^2$...
10 million transistors...
so size of components $\sim 10\text{--}100 \text{ nm}$

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7

Structure Within

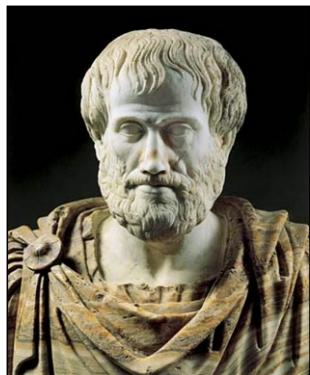
- What is the world made of?
- How can we tell?
- What clues do we have?

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Aristotle



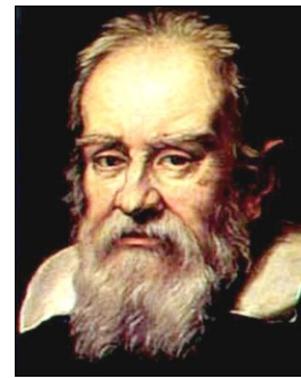
Elements

Fire
Air
Water
Earth



9

Galileo

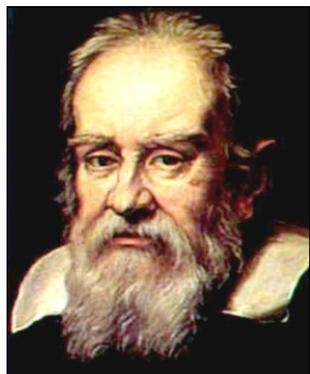


The nature of the world around us should be determined by quantitative experiments, not by qualitative intellectual arguments



10

Galileo



Ask not
"What **should**
happen if... ?"

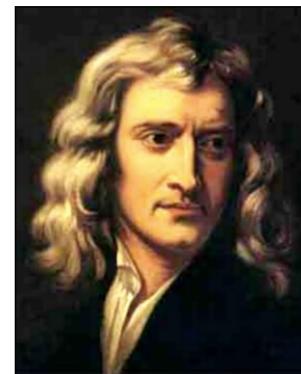
but

"What **actually**
happens if... ?"



11

Newton



Laws of Motion

Law of Gravity

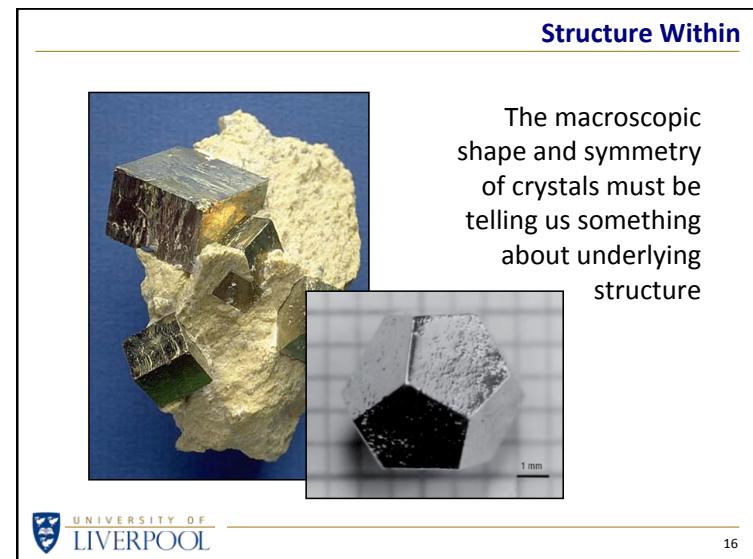
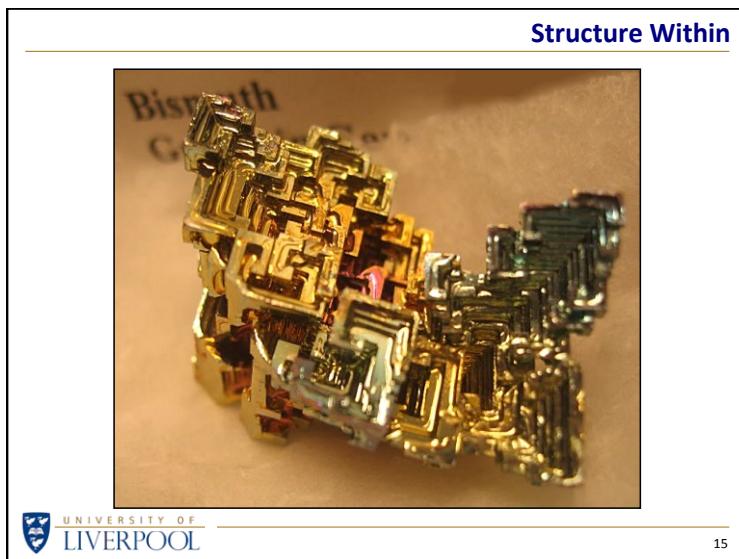
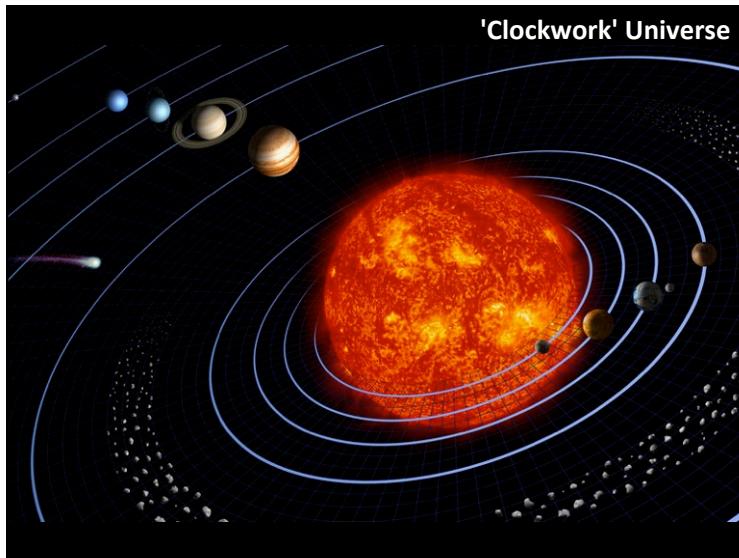
Nature of Light

"Classical Mechanics"

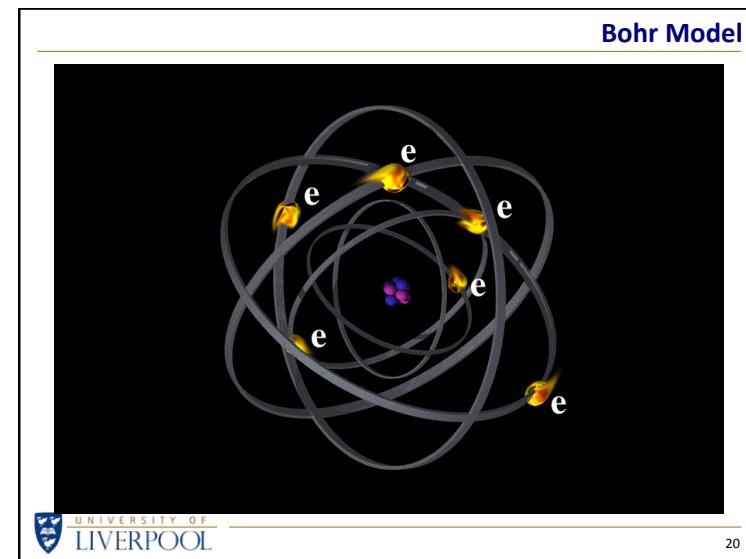
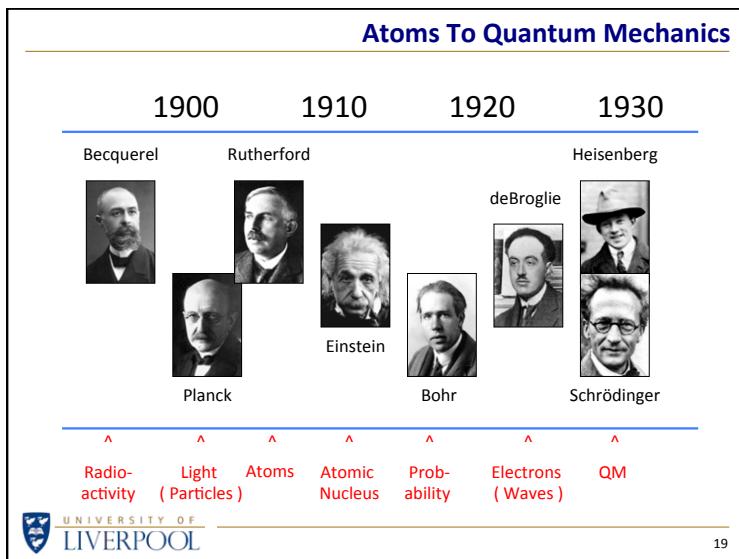
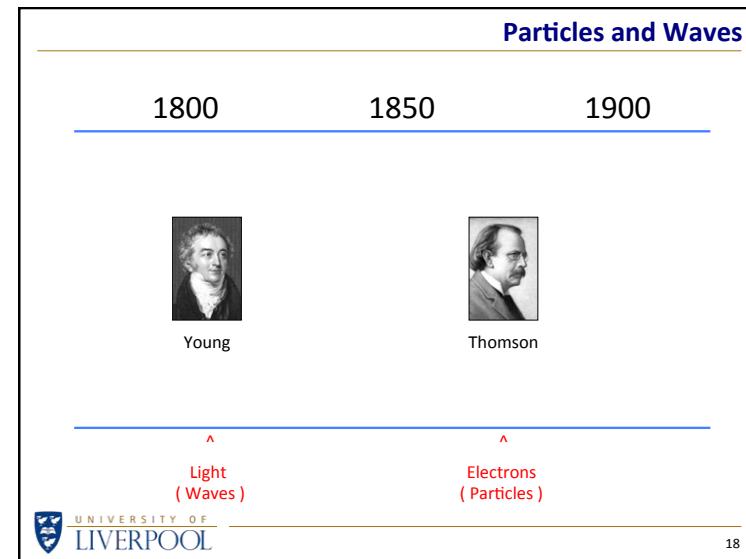
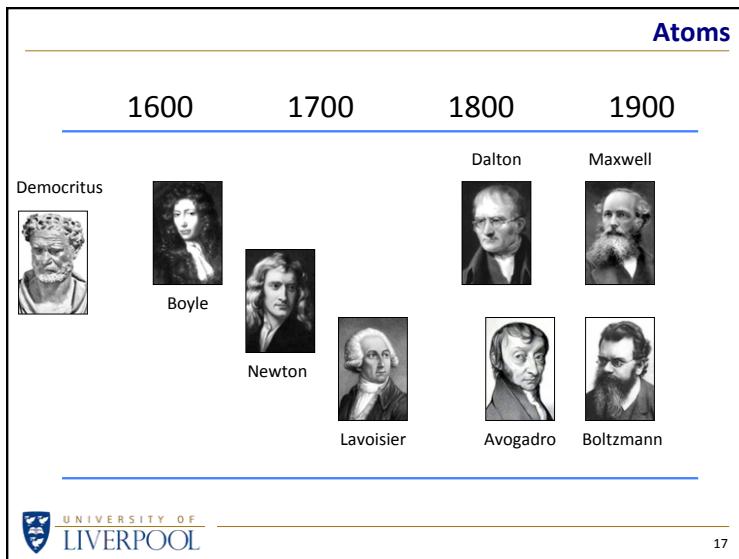


12

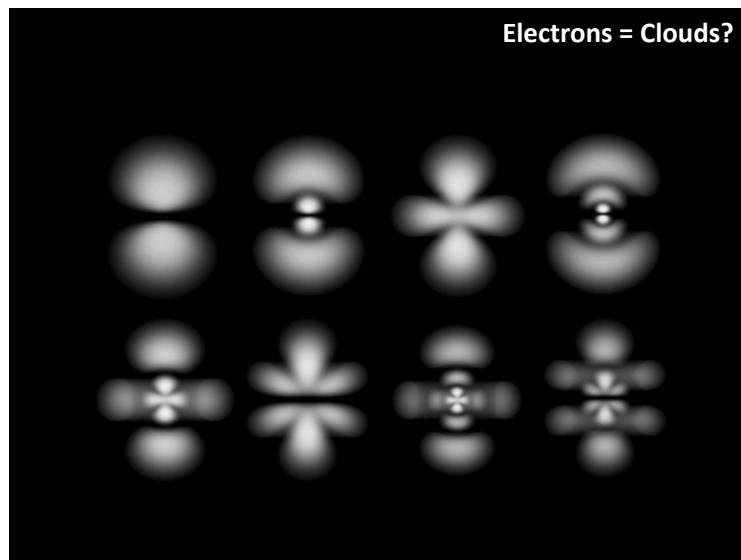
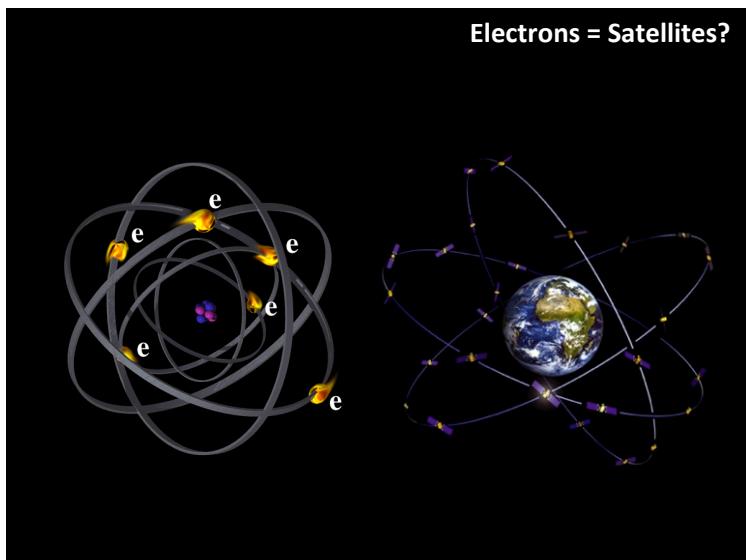
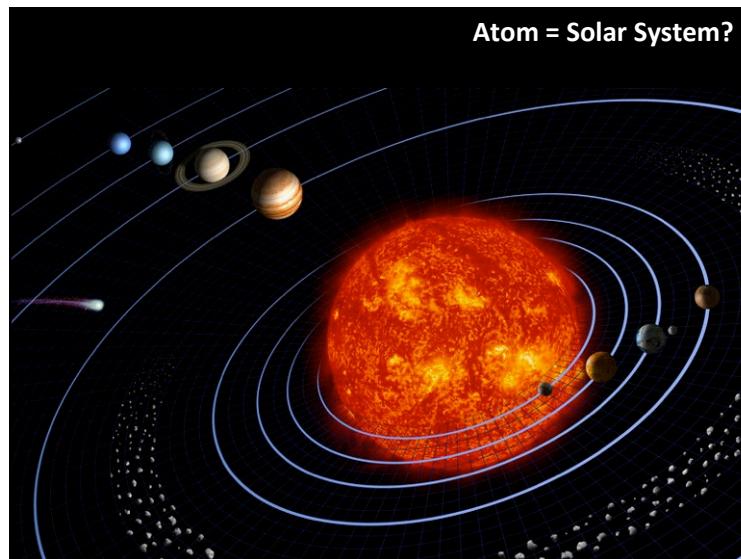
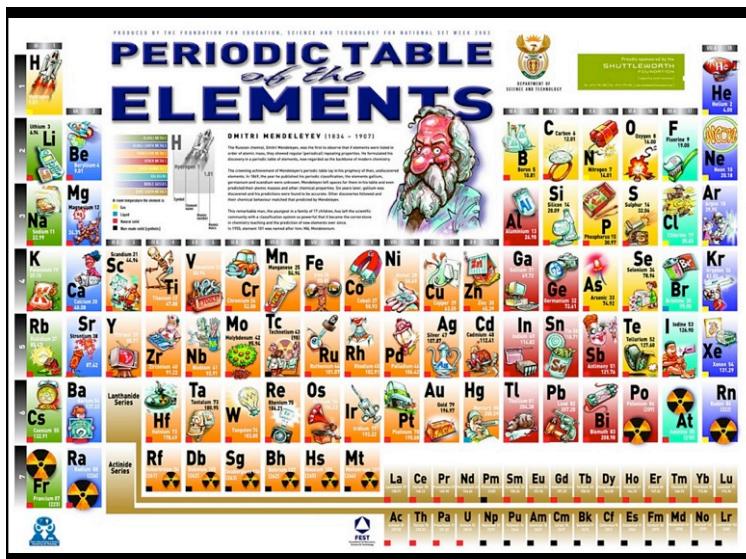
The Weird World of the Very Very Small



The Weird World of the Very Very Small



The Weird World of the Very Very Small



The Weird World of the Very Very Small

Dealing With Atoms

A diagram illustrating the concepts of quantum mechanics. On the left, a vertical list of terms: Particles, Waves, Orbitals, Spin, and Energy. To the right, three red-outlined ovals: 'Words' (containing the term 'Orbitals'), 'Pictures' (containing a Bohr-style atomic model with orbits and a central nucleus), and 'Maths' (containing the equation $H\psi = E\psi$). Lines connect 'Words' and 'Pictures' to the central concept of 'Orbitals'. Below the diagram is the University of Liverpool logo and the number 25.

Heisenberg

A black and white portrait of Werner Heisenberg, a German theoretical physicist. He is wearing a dark suit, a white shirt, and a patterned tie, and is smiling. Below the portrait is the University of Liverpool logo and the number 26.

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

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"

Below the text is the University of Liverpool logo and the number 27.

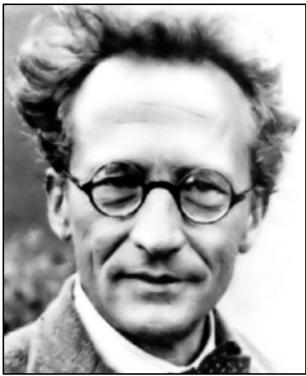
Bohr

A black and white portrait of Niels Bohr, a Danish theoretical physicist. He is wearing a dark suit, a white shirt, and a patterned tie. Below the portrait is the University of Liverpool logo and the number 28.

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

The Weird World of the Very Very Small

Schrödinger

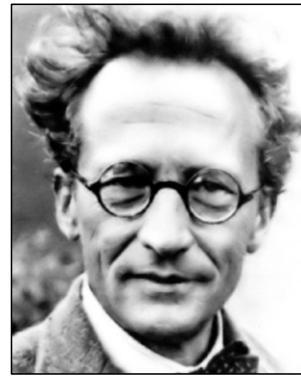


"Atomic physics has shown that atoms have no meaning, but can only be understood in experimental measurement "



29

Schrödinger



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



30

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, ...

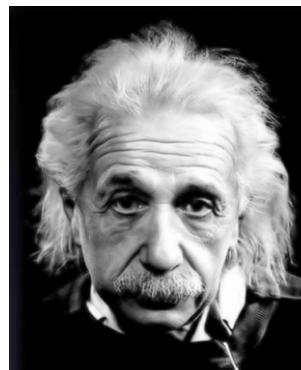
Atoms do not have a finite size
An electron 'in' an atom could be **anywhere**

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



31

Einstein



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



32

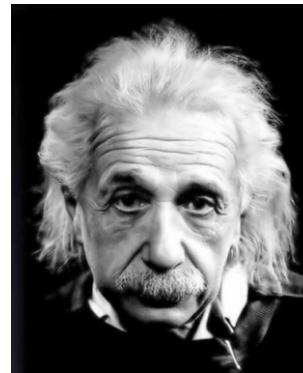
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Heads or Tails?



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Einstein



"God does not play dice"

"God is subtle but he is not malicious"

34

Bohr



"Stop telling God what to do!"



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Three Aspects of QM

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



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Order Matters

In algebra

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

In Quantum Mechanics

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

So what?



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If Order Matters



Top pair : carnivores

Bottom pair : veggies

Left pair : 4 legs

Right pair : wings



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!



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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!



40

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Schrödinger's Cat



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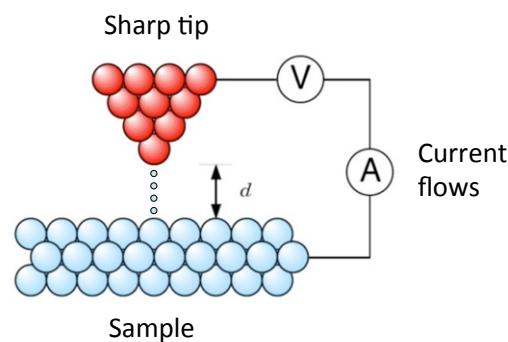
How Do We Know QM Is Right?

- 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



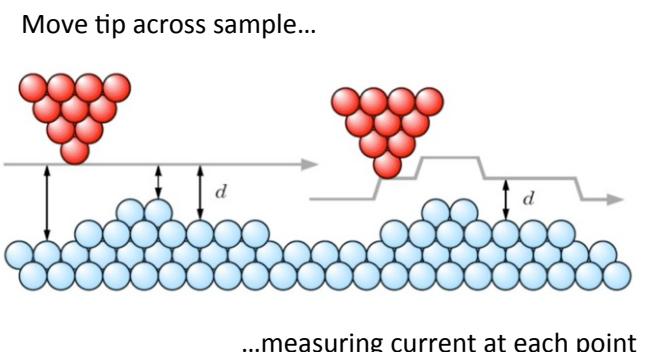
42

Scanning Tunnelling Microscope



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STM



44

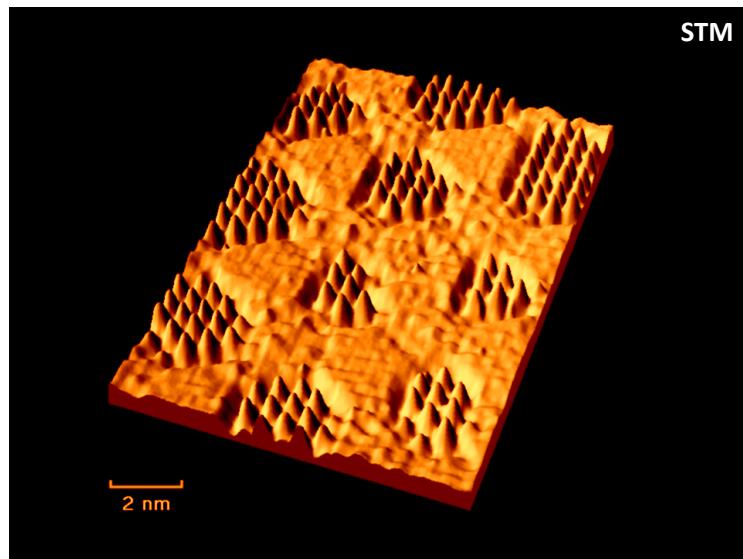
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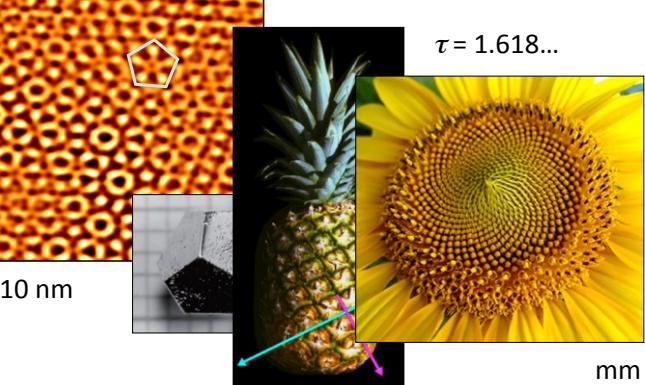
Surface Science

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

45



Patterns — Large and Small



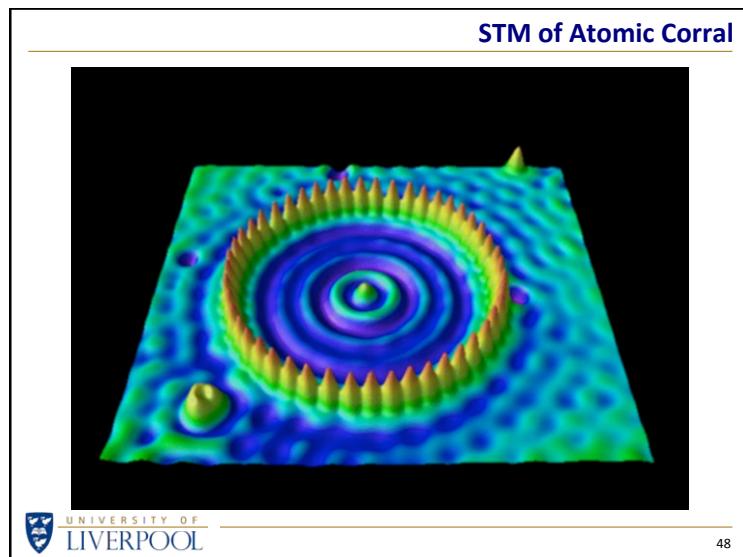
10 nm

$\tau = 1.618\dots$

mm

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Bohr

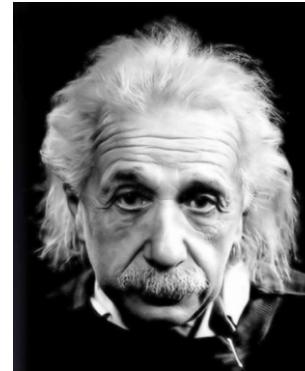


"If quantum mechanics hasn't profoundly shocked you, you haven't understood it"



49

Einstein



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



50

William Blake

*To see a world in a grain of sand
And a heaven in a wild flower,
Hold infinity in the palm of your hand
And eternity in an hour.*



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**The Weird World
of the
Very
Very
Small**

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

Dr Steve Barrett
Warrington U3A
17 Sep 2020