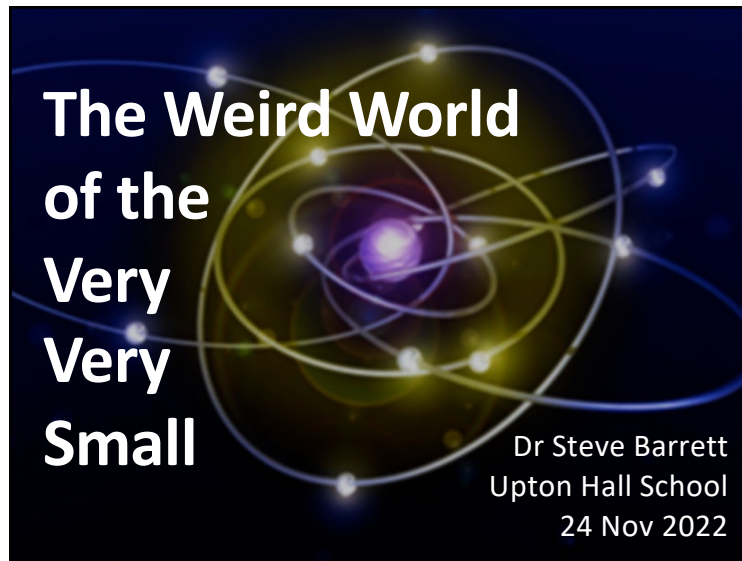


# Weird World of the Very Very Small



## Introduction

### A Sense of Scale

Metres >> Nanometres

### A Sense of Symmetry

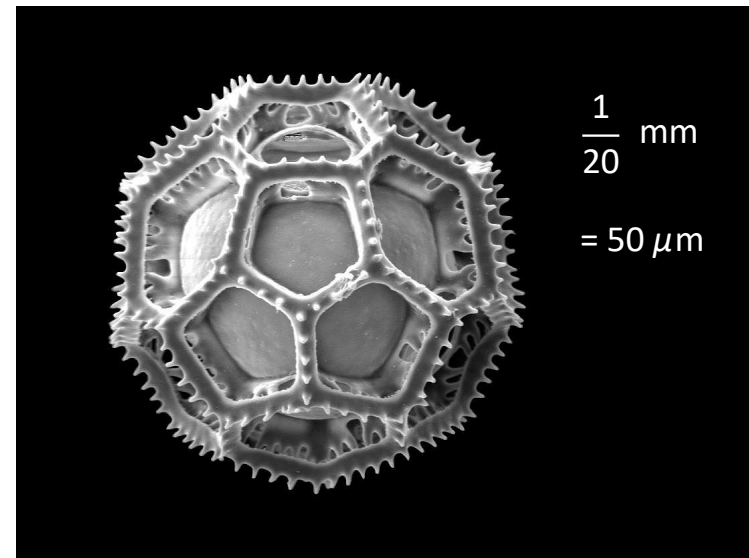
Underlying Structure

### The Quantum World

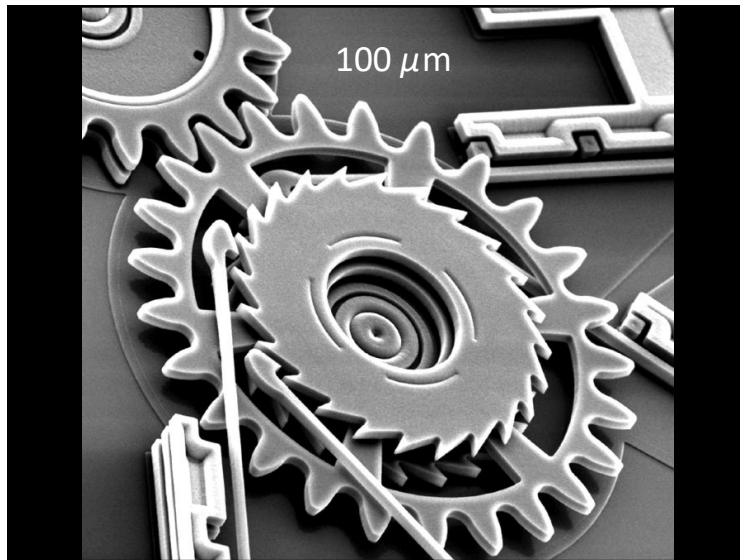
Seeing Atoms



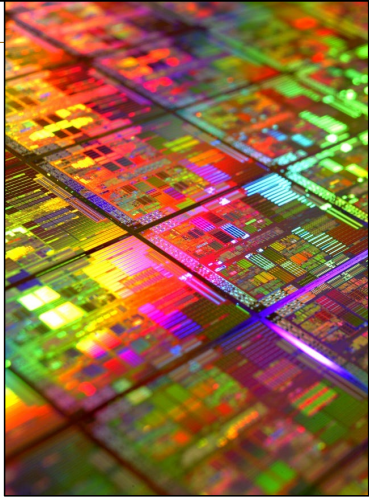
2



# Weird World of the Very Very Small



### A Sense of Scale



Microprocessor chip area  $\sim \text{mm}^2$  ...

100 million transistors ...

so the sizes of the components are  $\sim 10 \text{ nm}$

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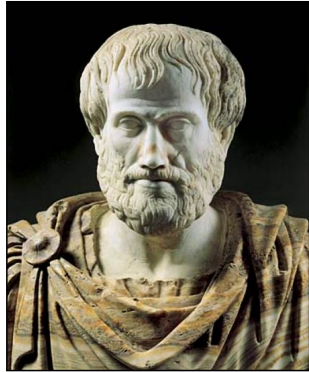
### Structure Within

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

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7

### Aristotle



#### Elements

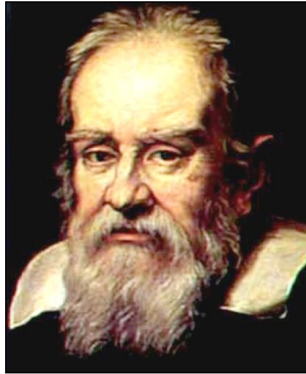
Fire  
Air  
Water  
Earth

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8

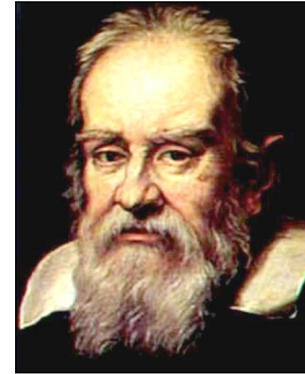
# Weird World of the Very Very Small

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



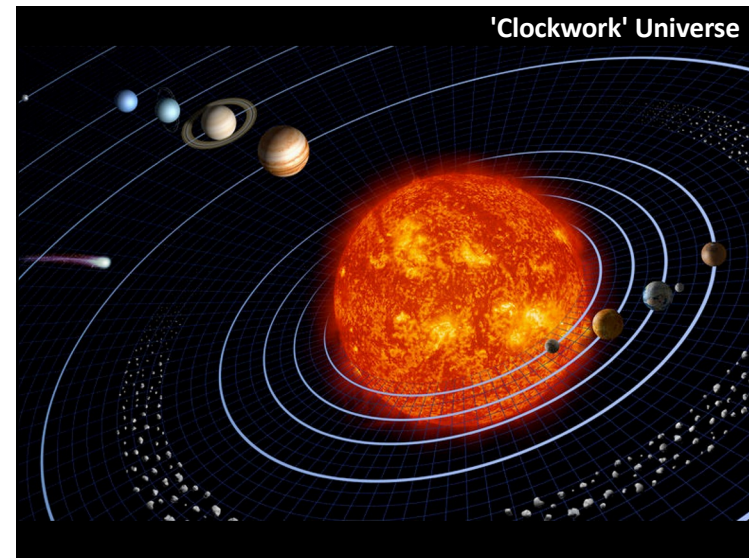
Laws of Motion

Law of Gravity

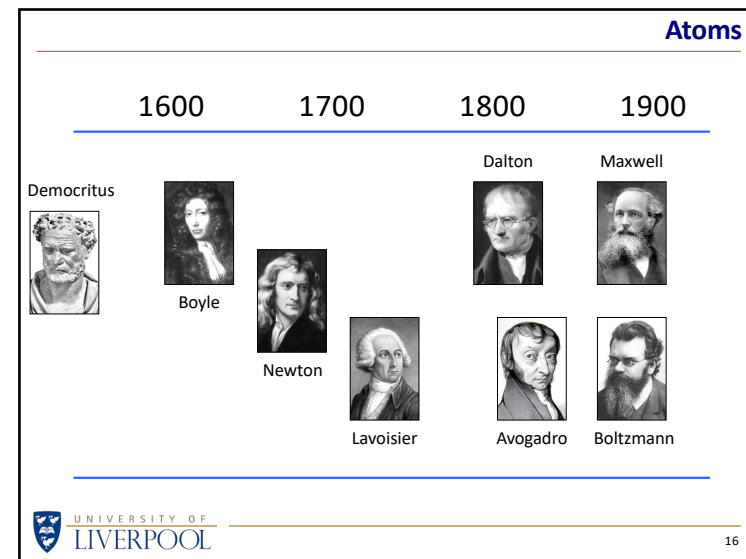
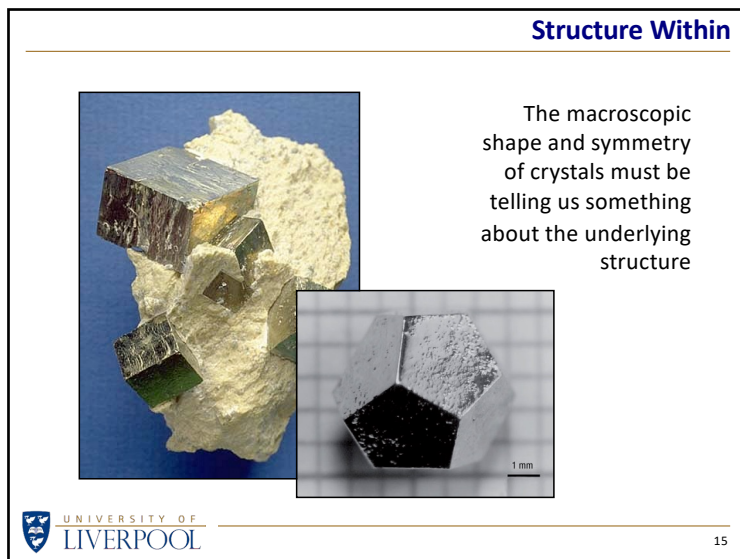
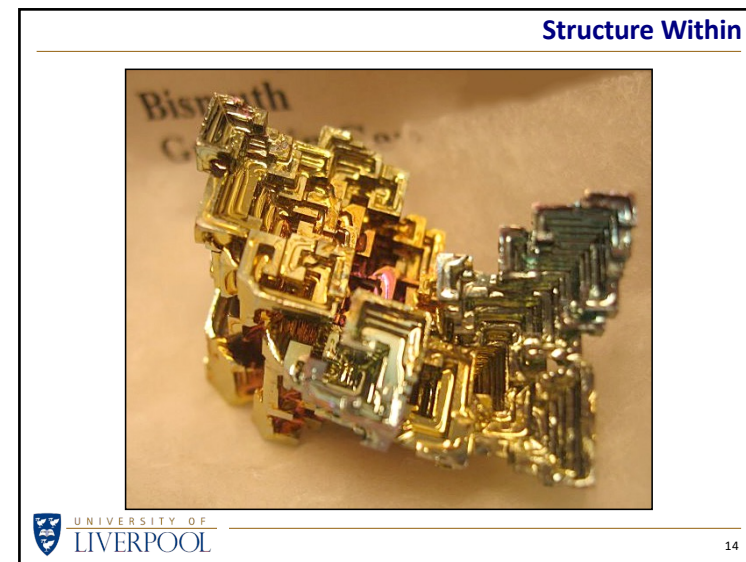
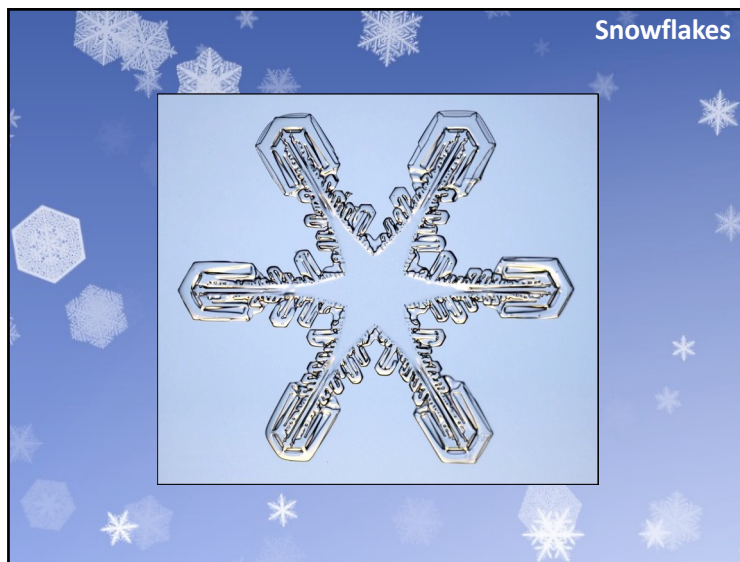
Nature of Light

"Classical Mechanics"

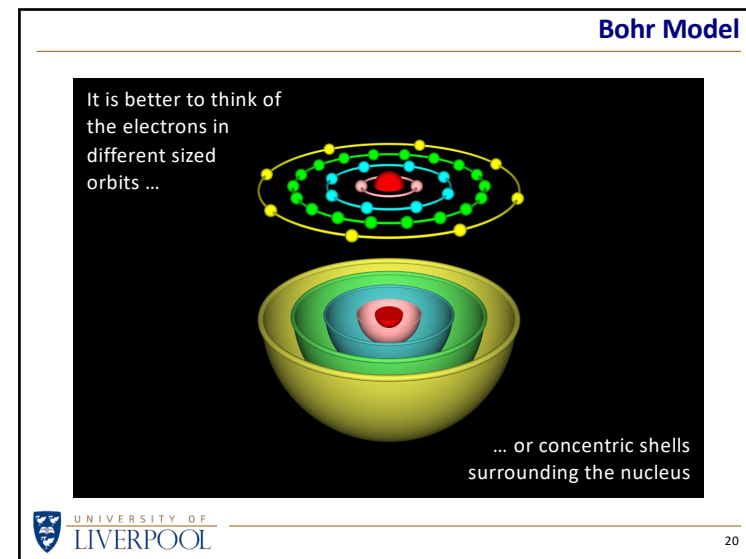
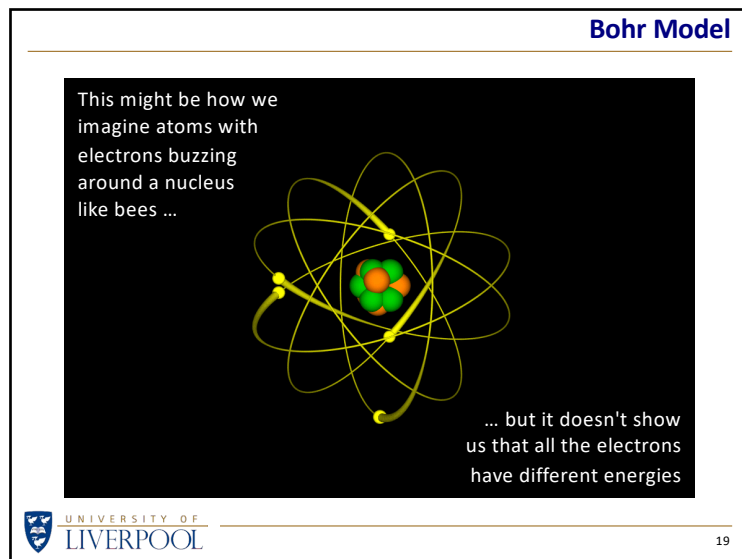
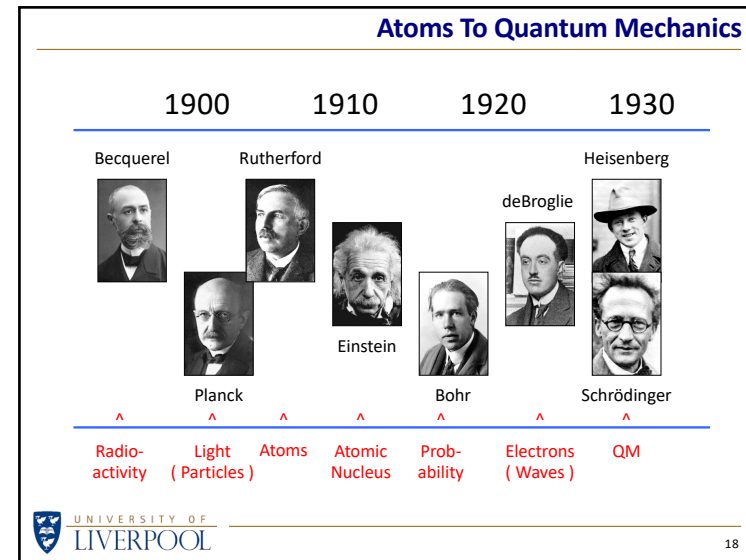
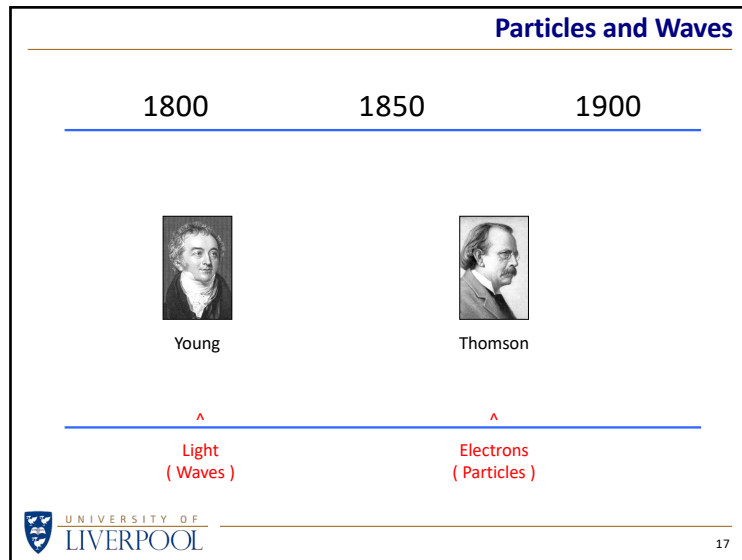
'Clockwork' Universe



# Weird World of the Very Very Small



# Weird World of the Very Very Small



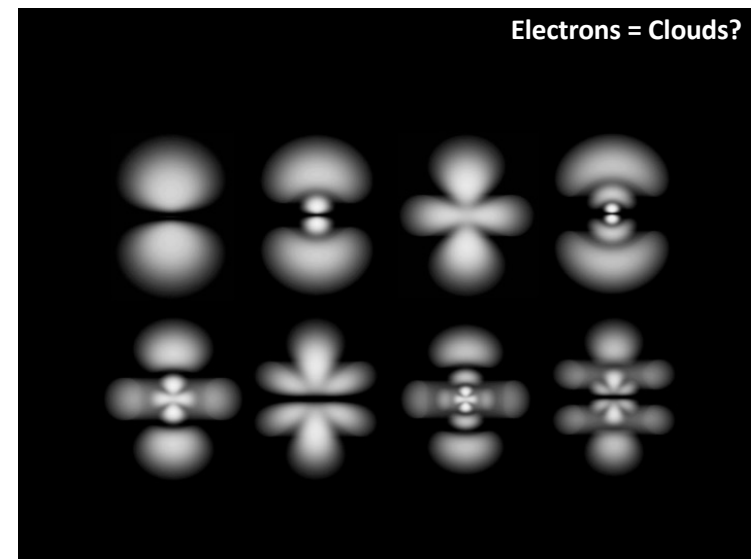
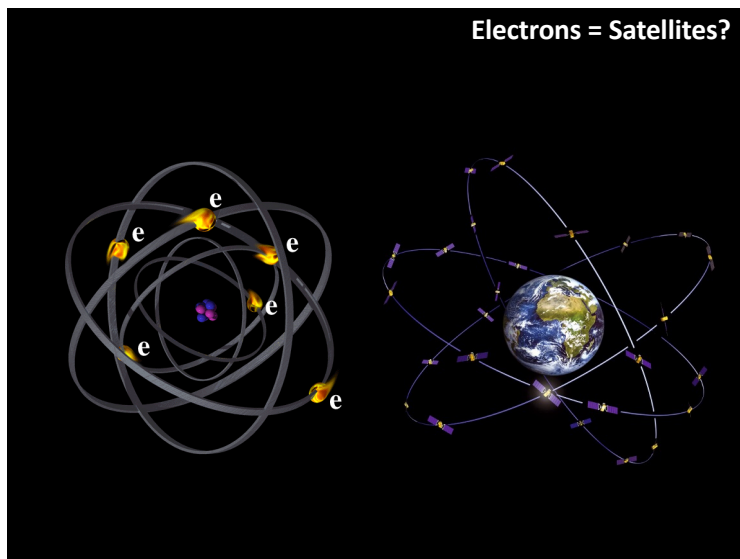
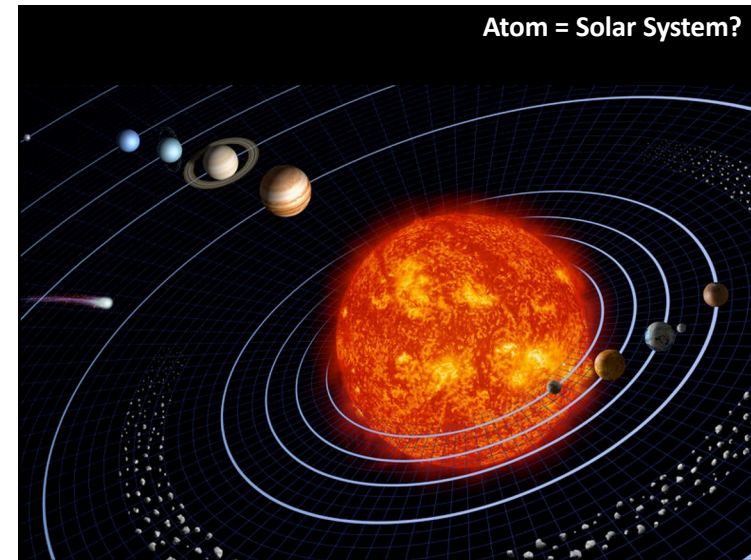
# Weird World of the Very Very Small

PRODUCED BY THE FOUNDATION FOR EDUCATION, SCIENCE AND TECHNOLOGY FOR NATIONAL SET WEEK 2012

## PERIODIC TABLE of the ELEMENTS

DMITRI MENDELEEV (1834 - 1907)

The Russian chemist, Dmitri Mendeleev, was the first to arrange the elements into a table of periodicity. He arranged the elements in order of increasing atomic weight, and noticed that certain groups of elements had similar properties. He predicted the existence of elements that had not yet been discovered, and his predictions were found to be accurate. His discovery of periodicity and his prediction of the existence of new elements were the basis of the periodic table.




# Weird World of the Very Very Small

Dealing With Atoms

Particles  
Waves  
Orbits  
Spin  
Energy

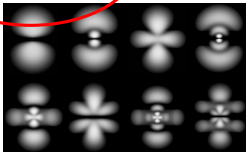
**Words**



**Maths**

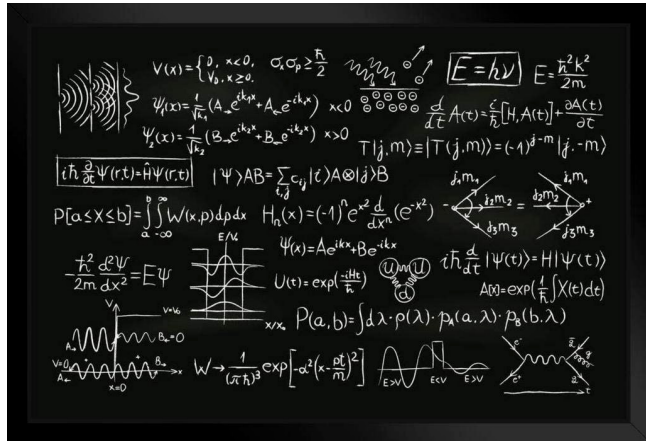
$H\psi = E\psi$

**Pictures**




25

Dealing With Atoms



26

Heisenberg



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

27

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 "

28

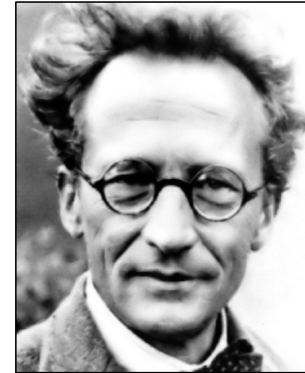
# Weird World of the Very Very Small

Bohr



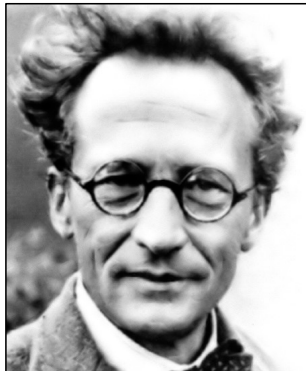
" Everything we call real is made of things that cannot be regarded as real "

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

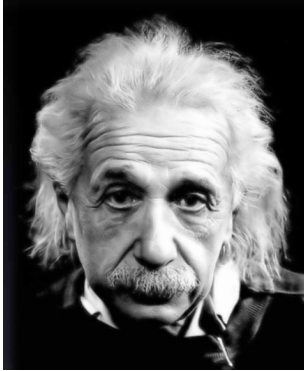
An electron 'in' an atom could be **anywhere**

Atoms can be in two states at the same time

Electron 'spin' can be simultaneously clockwise **and** anticlockwise

# Weird World of the Very Very Small

Einstein

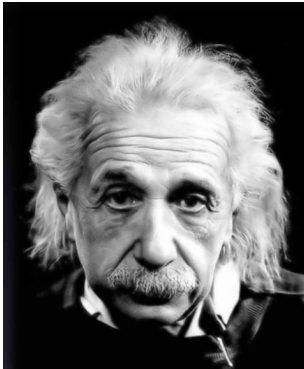


" Common sense is the collection of prejudices acquired by age eighteen "

Heads or Tails?



Einstein



" God does not play dice "

" God is subtle but he is not malicious "

Bohr



" Stop telling God what to do! "

# Weird World of the Very Very Small

## Three Aspects of QM

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

## Order Matters

In algebra

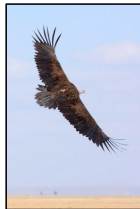
$$A \times B = B \times A$$

In Quantum Mechanics

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

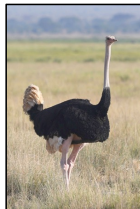
So what?

## If Order Matters



Top pair : carnivores

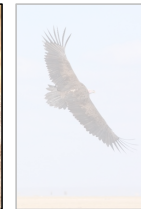
Bottom pair : veggies



Left pair : four 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!

# Weird World of the Very Very Small

## If Order Matters



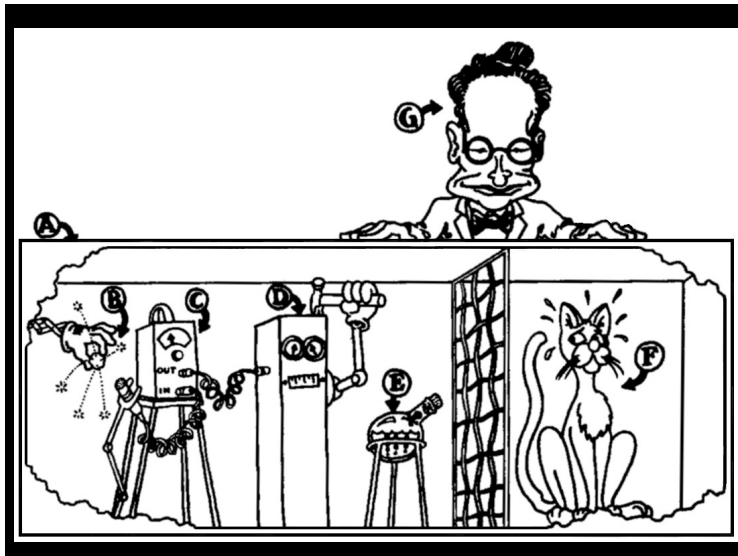
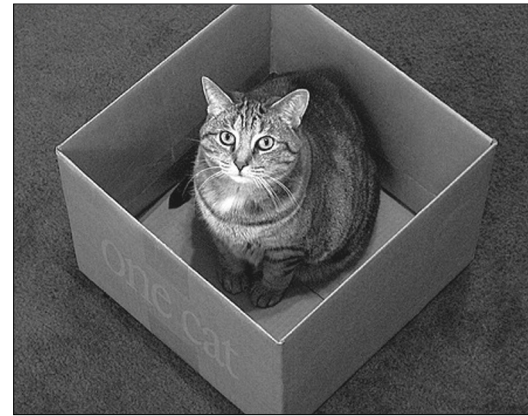
If we had picked in a different order ...

First pick the **4-legged** animals

Then pick the **veggie** animals

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

## Schrödinger's Cat



## Schrödinger's Cat

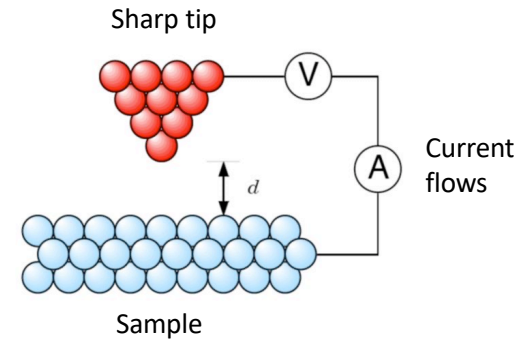


# Weird World of the Very Very Small

## How Do We Know QM Is Right?

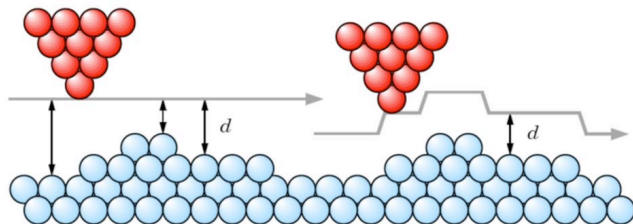
- So far, nothing has proved it wrong
- Quantum Mechanics predicts results that are impossible by 'Classical Mechanics'
- Using QM theory, we can build a microscope that can 'see' atoms

## Scanning Tunnelling Microscope



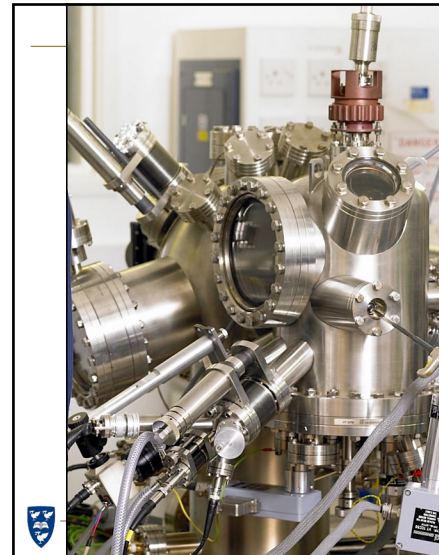
## STM

Move the tip across the sample ...



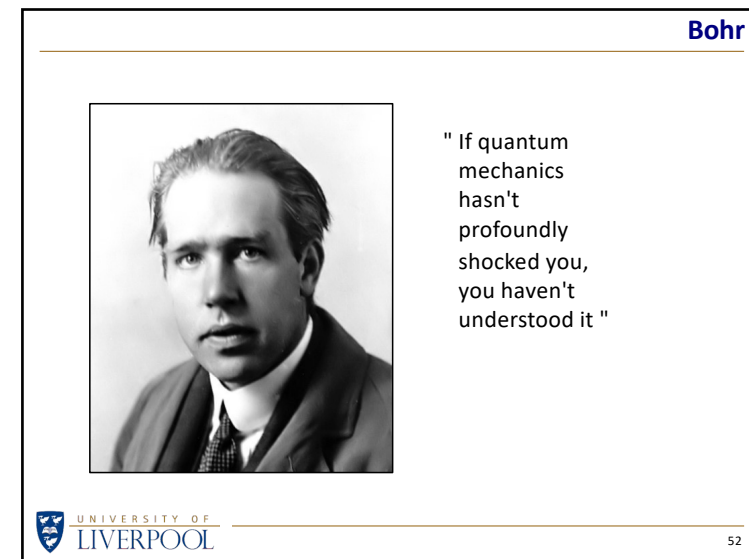
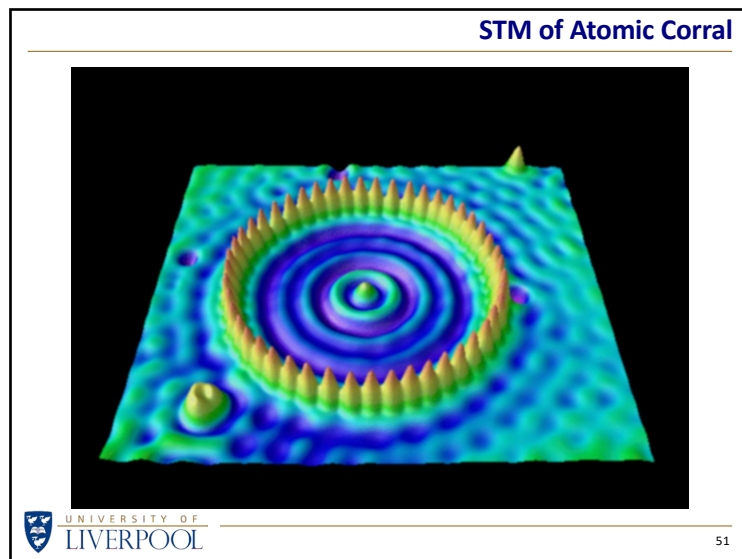
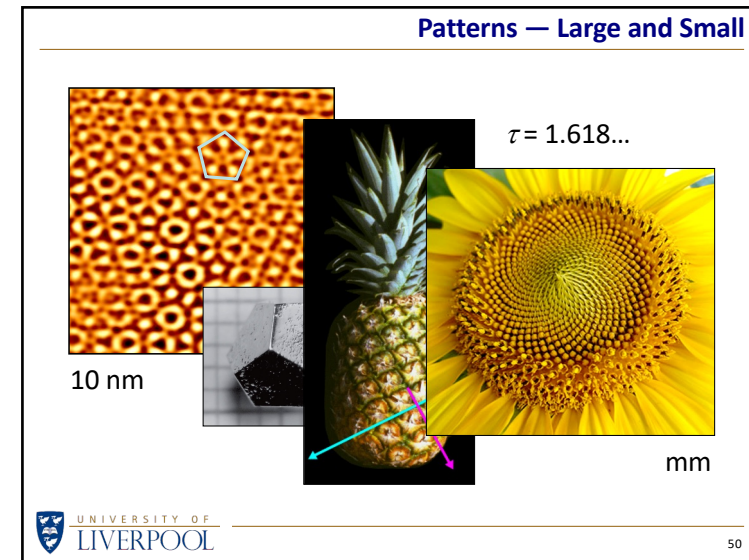
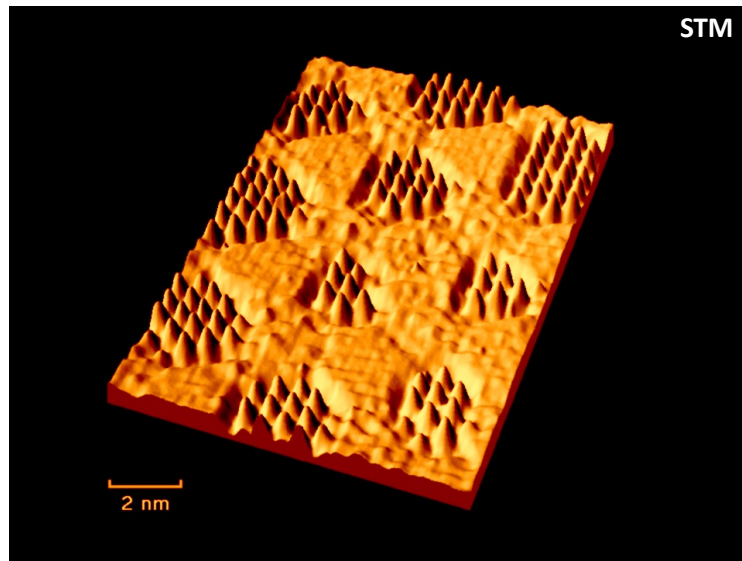
... measuring the current at each point

## Surface Science



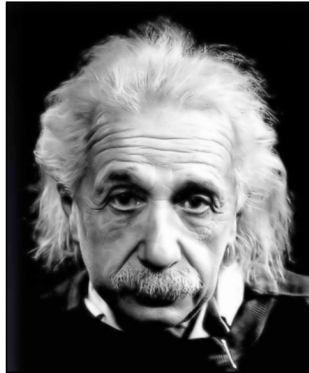
The STM is sealed inside an ultra-high vacuum vessel ( $10^{-13}$  atms) to keep it and the sample surface clean.

# Weird World of the Very Very Small



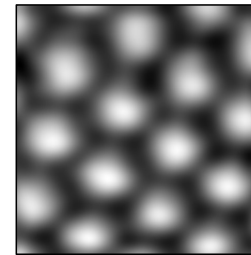
# Weird World of the Very Very Small

## Einstein



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

## 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*

## 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.*

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

Dr Steve Barrett  
Upton Hall School

[www.liverpool.ac.uk/~sdb/Talks](http://www.liverpool.ac.uk/~sdb/Talks)

24 Nov 2022