

“Quantum is surreal but is
classical real?”

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What I want to say

Quantum world has some unusual features, but does not warrant so much philosophy.

A whole century of evidence has gathered. It is time we assimilate the knowledge rather than mystify it.

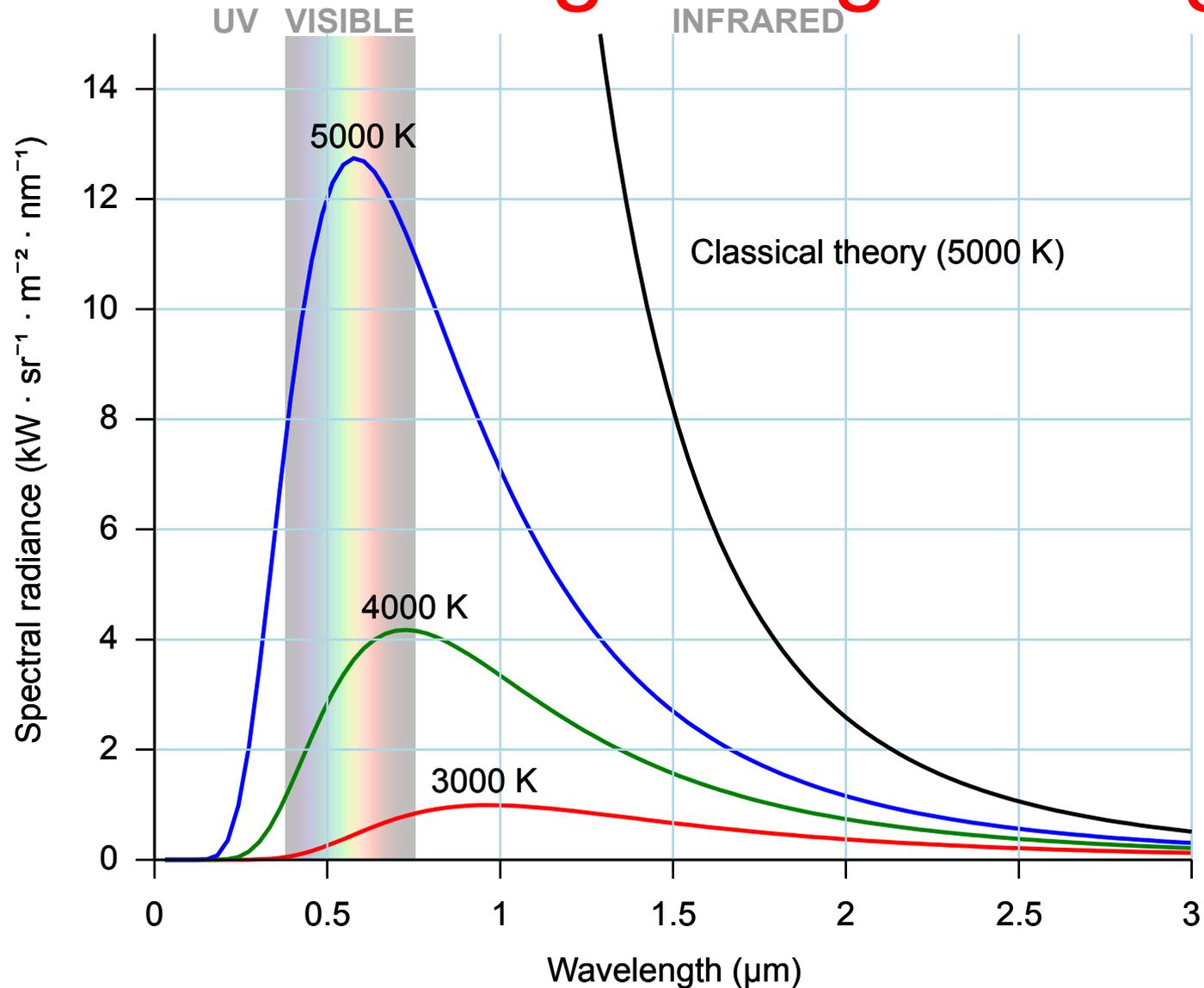
Next generation should simply learn the basics in school and need not go through “un-learning”.

Outline of this presentation

- Recap of the Quantum world
- Some (non-)puzzles
- Things not usually emphasised
- **Why we need not remain mystified**
 - Or be just as mystified as with the classical

Where it all began

Where it all began – gas of light



Where it all began



Ludwig Boltzmann's atomistic theory of heat –

Was gas of light also made of atoms?

(Einstein receiving first Planck Medal from Planck 1930)



Interpretations

Copenhagen

de Broglie–Bohm pilot waves

Hidden-variable

Many-worlds

.... and a whole menagerie from Wikipedia :

Consistent histories; Ensemble; Objective collapse; Bayesian;
Quantum logic; Relational; Stochastic; Scale relativity; Transactional

Essential concepts

1. Linear superposition of states
2. Dynamical variables as operators
3. Outcomes of experiments – eigenvalues
4. Transition amplitudes and expectation values
5. States with many quanta – “statistics”
 $[x, p] = i\hbar$ $i\hbar\dot{O} = [O, H]$
6. Kinematics ; Dynamics

All is quantum

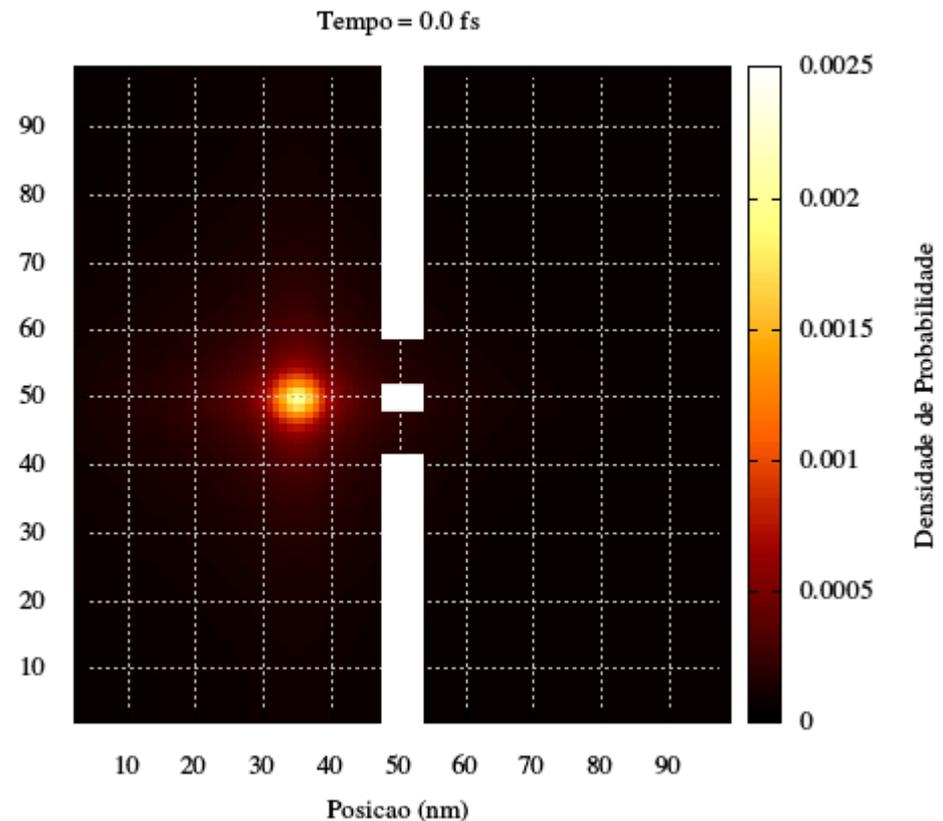
- **Valence** : chemistry; biochemistry
- **Color** ... (shielding in atoms and approximate equality of light frequencies; evolution of vision)
- **Solids** : no solidity without Exclusion Principle
- **Magnetism** : spin
- **White Dwarfs** : super-atoms strung in the sky
- **Stars** : Thermonuclear cycle of fusion

Two classic manifestations – I

The double slit (Davisson and Germer)

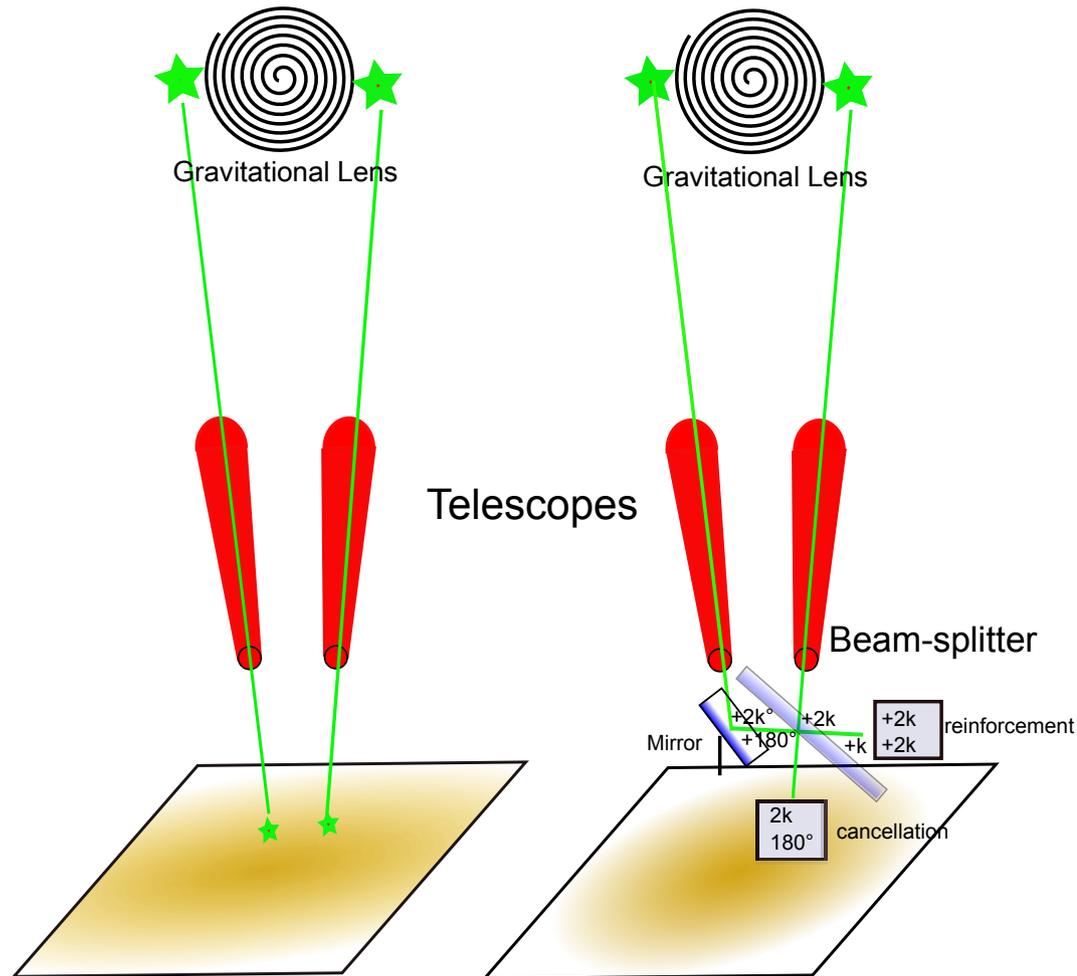
Linear superposition

(source : [duas_fendas.gif](#)
Wikimedia commons)



Two classic manifestations – I

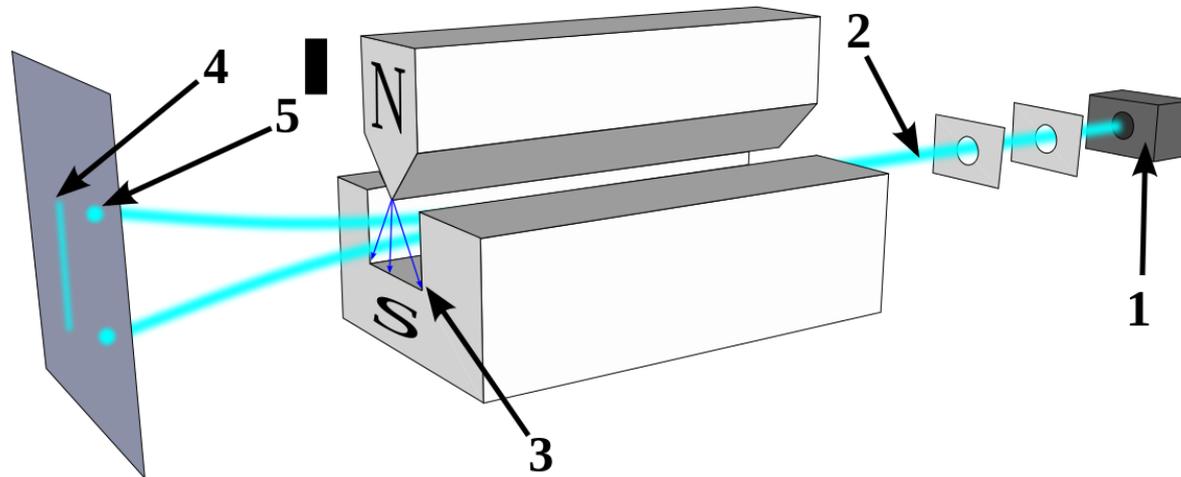
... Delayed choice (J. A. Wheeler)



Two classic manifestations – II

The Stern – Gerlach experiment

Only the eigenvalues as outcome



Stern-Gerlach experiment animation from <http://www.toutestquantique.fr>

Some (non)-puzzles

- Wave particle “duality”
 - Superposition of momentum eigenstates
- “Uncertainty” principle
 - Superposition principle and complementarity of x and p (recall kinematics)



A new plus sign

- Dirac emphasises that
 1. Revelation of Planck's constant for the first time tells you where the large ends and the small begins – sets the scale
 2. QM reveals a new fundamental principle absent in the classical world

The Principle of Linear Superposition

A new plus sign

- The fact is there are no “waves” of probability amplitude
- An amazing fact of QM is that states of different momenta can be superposed to obtain a new permissible state
 - Existence of \hbar associates a length scale with a momentum (de Broglie)
 - Use of Fourier series as for classical waves gives a strong analogy to wave phenomenon
- Convenience yes, paradox, no

Some (non)-puzzles

- “Entanglement”
 - Quanta are not particles

	CL	Q_{BE}	Q_{FD}
H H	$\frac{1}{4}$	$\frac{1}{3}$	0
H T	$\frac{1}{2}$	$\frac{1}{3}$	1
T H			
T T	$\frac{1}{4}$	$\frac{1}{3}$	0

Quanta are not particles

Bosons



Quanta are not particles

Only **completely symmetric** states for bosons

Only **completely anti-symmetric** states for fermions

God does not play billiards or golf, she juggles quanta

Only the independent states can be enumerated not the quanta. The term “statistics” gives the impression of random sampling. It is really **enumeration** not statistics.

Quanta are not particles

- Degrees of freedom can be many but only one independent Hilbert space vector.
- Number operator is an observable but it cannot be interpreted as number of billiard balls.
- Several quanta together make up one state. What was not distinct need not be considered *entangled*. (The terminology assumes putative emergence as incoherent particles post observation, but that is not how the quantum state is organised prior to observation).

Some (non)-puzzles

- Einstein-Podolski-Rosen and “non-locality”

State vector in quantum mechanics is intrinsically non-local due to superposition of eigenstates of distinct locations as an acceptable new state. And it is the state that matters not number of quanta ... a key lesson of Bose's enumeration.

Schrödinger's cat

- Yes, we do not have a clear demarkation where the quantum domain ends ... work in progress. We should eventually have enough controlled examples.

Is classical physics all well?

What is motion?

- Location (position)
- Locomotion (movement)

Motion is the simplest form of “change”.

Unlike complicated transformations of entities, here something merely changes location.

An intellectual struggle

Motion from ancient times and variety of secular and religious philosophical systems posed a problem.

- Zeno's paradox – conflict of observation and logic
- Aristotalian conception proposed that sustained motion required a “motive force”

An intellectual struggle

Nagarjuna (circa 200 CE) in *Madhyamika Karika* :

- *Does “motion” have reality independent of that which moves?*
- *Does the space through which motion occurs exist before that motion occurs?*
- *Can the notion of “state of rest” (no motion) be valid if its modification (motion) has not occurred?*

Galileo cuts the Gordian Knot

- Perform empirical observation
 - “Tower of Pisa experiment”
- Proposes thought experiments in lieu of actual empirical experiment
 - The chess players inside a moving ship
 - The ball rolling onto a plane offering *progressively* less friction

Newton formalises ...

- The limit process (progressive improvement of Galileo's thought experiment)
- At home with Zeno's paradox – infinite series can have finite answers

- **Newton formalises ...**

A key concept we accept and also make our students accept is



*Instantaneous
velocity*

Newton formalises ...

- Nagarjuna could well have questioned :

*Can something **be at a place** ...*

*.... and also **be moving**?*

In fact all orders of time derivatives exist at an instant !!!

Newton formalises

Can we be sure that the limit process is valid?

A “koti kasharpan” question of observation, not of logic!!!!

Are we not overdoing Galileo's gedanken experiment?

Has anybody actually used a stop watch and let its time intervals go to zero??? Or a measuring rod whose least count actually became zero???

Well ... when they did, Newtonian idealisation collapsed and we discovered the quantum world.

“Uncertainty” sets in

- We use Euclidean conception of idealised point as location
- We use Newtonian concept of instantaneous velocity
- Now we expect both to be workable simultaneously

Similarly Electromagnetism uses continuum fields and interaction with point charges ... also results in contradictions; resolved only by Quantum Electrodynamics (QED).

Conclusion :

The need to reshape our intuition

- From superconductivity to high temperature superconductivity
- SQUID, Graphene, Quantum dots ...
- Quantum information storage and transmission
- Majorana-like quasi-particles in “topological” insulators

Quantum on our table top

Thank You !