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PHYSICAL PRINCIPLES FOR QUANTUM HARDWARE MODELS

Quantum Information: Short Overview

Emergence of quantum physics II

- Wave function interpretation
- Quantum ``paradoxes``
- Quantum mechanics as a universal theory
- Quantum information
- Quantum computation

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Emergence of quantum physics II

1. Wave function interpretation

- Schrodinger had found the right wave equation (1926)

$$-\frac{\hbar^2}{2m}\frac{\partial^2\Psi(x,t)}{\partial x^2}+V(x,t)\Psi(x,t)=i\hbar\frac{\partial\Psi(x,t)}{\partial t}$$

- Solving this equation we are able to find the energy of the electron orbits without *ad hoc* supositions, like in Bohr model (1913)

- For a time-independent potential $V(x, t) = V(x)$

Emergence of quantum physics II

1. Wave function interpretation

- We are able to find the energies (eigenvalues)

$$E_1, E_2, E_3, \ldots, E_n, \ldots$$

- Each eigenvalue is related with an eigenfunction

$$\psi_1(x), \psi_2(x), \psi_3(x), \ldots, \psi_n(x), \ldots$$

- Each eigenvalue has a correspondent wave function

$$\Psi_1(x,t), \Psi_2(x,t), \Psi_3(x,t), \ldots, \Psi_n(x,t), \ldots$$

- Each wave function is a particular solution for the potential V(x)

$$\Psi(x,t) = c_1\Psi_1(x,t) + c_2\Psi_2(x,t) + \cdots + c_n\Psi_n(x,t) + \cdots$$

Emergence of quantum physics II

1. Wave function interpretation

- All enforts to give a material meaning to ψ(x,t) were incosistents
- In 1926, Born gave the wave function an interpretation that survives until today

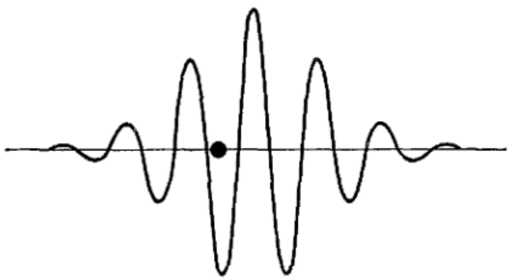


Figure 5-2 A very schematic picture of a wave function and its associated particle. The particle must be at some location where the wave function has an appreciable amplitude.

Quantum physics, Eisberg & Resnick

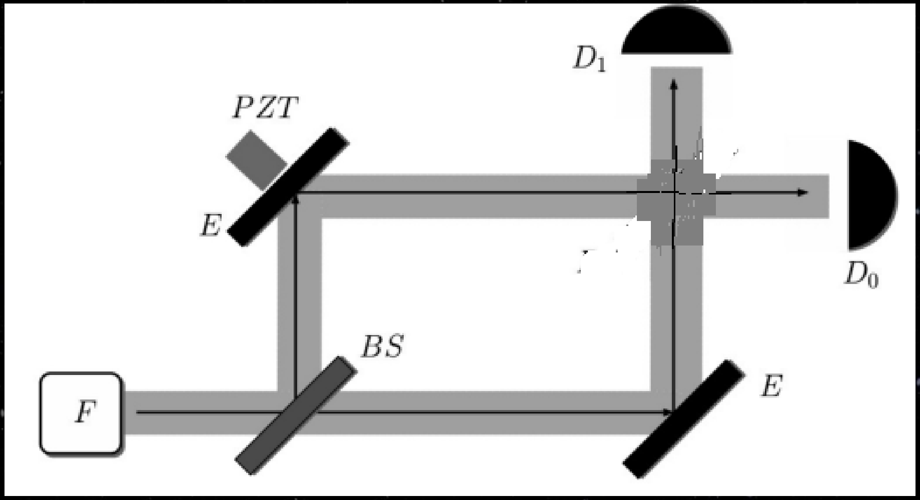
ψ(x,t) → Express the probability to the electron is placed in one orbit or another

$$P(x, t) = \psi*(x, t)\psi(x, t)$$

Emergence of quantum physics II

1. Wave function interpretation

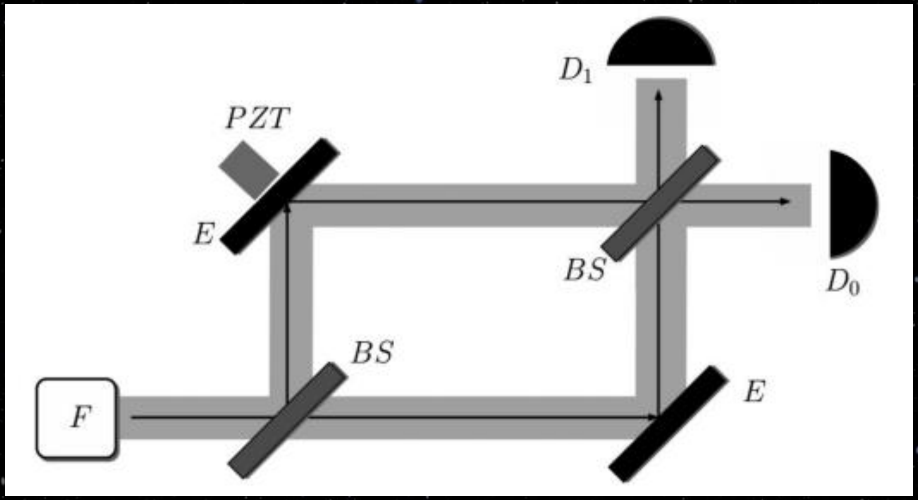
- Experiments
- Photons are send from F
- Half of them are detected in D_0 and half in D_1



Emergence of quantum physics II

1. Wave function interpretation

- Let us placed a second BS as indicated (Grangier, G. Roger and A. Aspect - 1986)
- Now, only D_0 clicks. What happened?



Schematic picture of Mach – Zender Interferometer
https://www.scielo.br/j/rbef/a/vsbkGBMwDqK9LHPMbnHzfsF/?format=pdf&lang=p

Emergence of quantum physics II

1. Wave function interpretation

- Let us placed a second BS as indicated (Grangier, Roger, and Aspect - 1986)
- Now, only D_0 clicks. What happened?
- The photons behaves like waves

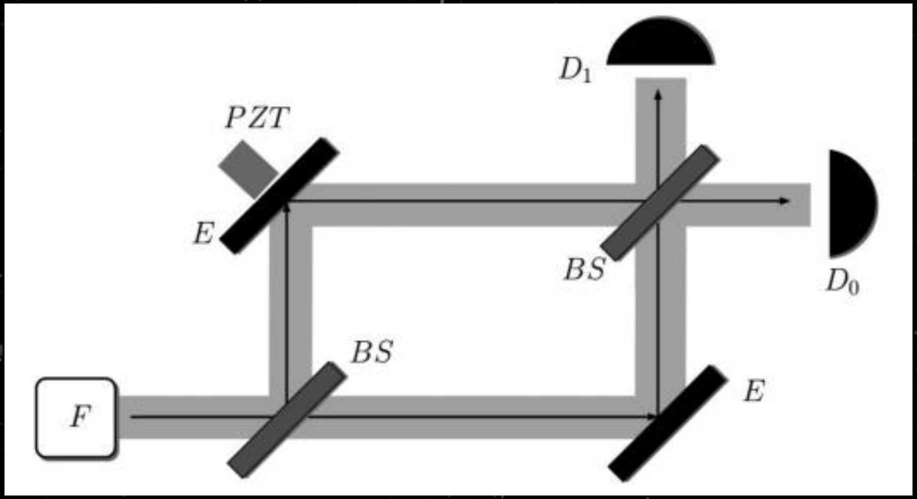
→ the waves that arrived in D_1 are phase opposed and cancel out each other

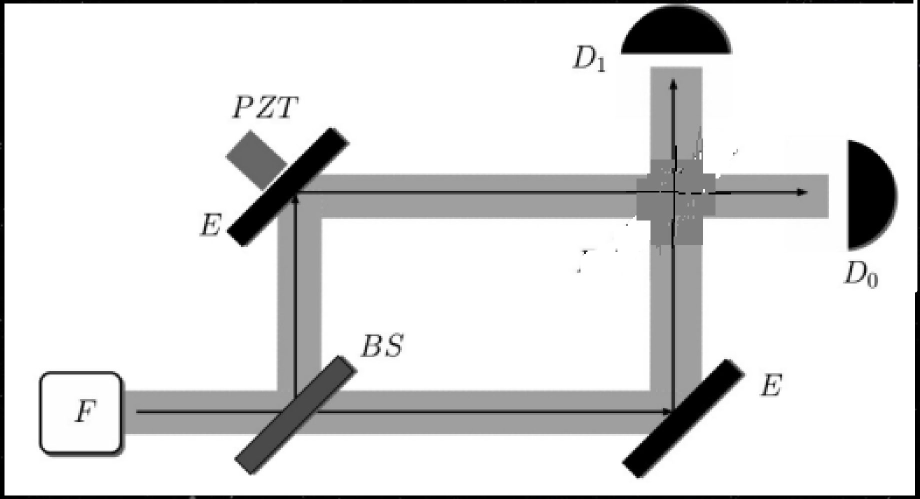
→From the other hand, the waves in D_0 are in phase and increases

Emergence of quantum physics II

1. Wave function interpretation

We saw that with the second BS the photons follow both paths, and without the second BS they follow one or the other





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Emergence of quantum physics II

1. Wave function interpretation

- Now, let us take this experiment to the last consequences
- Wheeler (1978) → What happens if we decide to place (or not) the second BS after the photons had passed the first BS? The photons behaves like waves or particles? When they decided they are wave or particles?
- The decision to place the second BS is made randomly after the photons went through the first BS
- The photons behaved exactly as before

Jacques, Wu, Crosshans, Treussart, Grangier, Asprct, Roch – ''Experimental realization of Wheeler's Delayed-Choice Gedanken Experiemnt''. Science, 315, 966 (2007)

Emergence of quantum physics II

1. Wave function interpretation

The ‘’oficial’’ QM’s interpretation is the Copenhaghen interpretation

It establishes a separation between observers (macroscopic devices) and observables (microscopic objects)

And says that we can only know the microscopic world through our devices or through their manifestations in the macroscopic world

These manifestations are governed by the COMPLEMENTARITY PRINCIPLE

The photon manifests its corpuscular nature in experiments in which it is required to specify its route and its wave nature when the experiment allows it

The measurement is so special in QM that there is a postulate to it

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Emergence of quantum physics II

2. Quantum ''paradoxes''

- Suppose now that we have two particles (photons) in a Mach-Zehnder interferometer
- One is polarized vertically (0) and the other horizontally (1)

$$\frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

- This is a superposition state
- It could be 0 the left photon and 1 the right photon or 1 the left photon and 0 the right photon
- Simmetry → no photon has more reason than the other to have one polarization or another.→ However, there aren't external agents that force the system to choose

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2. Quantum ‘’paradoxes’’

- This state is named entangled state

$$\frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

- Why so special ?
- When the state in superposition collapses we have one of two possibilities

$$|01\rangle \Leftrightarrow |10\rangle$$

- Meaning → Although we are measuring the polarization of one of the photons, the other acquires a determined value; even they are kilometers away

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2. Quantum ''paradoxes''

- This is the idea behind the Einstein, Podolsky, and Rosen -- EPR ''paradox'' (1935)
- Einstein believed that QM was incomplete because it should exists hidden variables that was not present in theory that solved this ''puzzle''
- Bohr → two entangled particles should not be considered two separated systems, but one single system that maintains the unity, no matter how far away they are
- Einstein → ''Spooky action at a distance''

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2. Quantum ''paradoxes''

- von Neumann settled the mathematical basis of QM in 1932
- First of all, EPR, Schrodinger cat, etc are not true paradoxes
- QM is a theory mathematically rigorous based in a series of postulates
- There cannot be any logical contradiction in your statements
- The ''Paradoxes'' cited above seems to be in the light of common sense, which is not necessarily logical
- This does not mean that QM is totally correct!
- Its validation depends on the experiments which validates the postulates

Emergence of quantum physics II

3. Quantum mechanics as a universal theory

Quantum Mechanics

QED (EM - interactions)
QCD (W-S interactions)

Quantum Information,
Condensed matter

Standard Model

??QG, ?? TOE, ?? DM,
?? SUSY, Primordial
universe, etc

Quantum
Computation

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Emergence of quantum physics II

4. Quantum Information

- Bell Inequalities (1964)

The Idea

Values of normal (classical) quantities fulfill a trivial inequality, and the result is that the quantum quantities are linked in such a way that they don’t fulfill this inequality

The point is that it is possible to contrast the inequality experimentally and the discussion between Einstein and Bohr will no longer be a matter of opinions

Here I will present a simplified version found by Clauser, Horne, Shimony, and Holt (CHSH), *Proposed experiment to test local hidden-variable theories*, Phys Rev. Let, 23, 880 (1969)

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4. Quantum Information

- Bell Inequalities (1964)
- Consider four quantities, each one associated with a photon polarization (A, B, C, D) → Pol = cosθ |V> + sin θ |H>

1. If the photon is horizontally polarized A or B, etc assumes the value +1
2. If the photon is vertically polarized A or B, etc assumes the value -1

Following Einstein, the polarization has always defined values. Thus, A, B, C or D will have defined values +1 or -1

Emergence of quantum physics II

4. Quantum Information

- Choosing the following expression → $(A+C)xB + (A-C)xD$

1. Because A, B, C, D are +1 or -1

$$(A+C)xB + (A-C)xD = 2 \quad \text{or } (A+C)xB + (A-C)xD = -2$$

2. The absolute value is

$$|(A+C)xB + (A-C)xD| = |AB + CB + AD - CD| = 2$$

3. As in general $|F + G| \leq |F| + |G|$ it is possible to show that after several measurements we will have the following inequlity for the average values of A, B, C, D

$$|\langle AB\rangle + \langle CB\rangle + \langle AD\rangle - \langle CD\rangle| \leq 2$$

Emergence of quantum physics II

4. Quantum Information

- Quantum Mechanic view

Now if we take into account the QM tools for this experiment, the CHSH inequality is not true

QF
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Emergence of quantum physics II

4. Quantum Information

- Quantum Mechanic view

Now if we take into account the QM tools for this experiment, the CHSH inequality is not true

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Entanglement-based quantum communication over 144 km

R. Ursin, F. Tiefenbacher, T. Schmitt-Manderbach, H. Weier, T. Scheidl, M. Lindenthal, B. Blauensteiner, T. Jennewein, J. Perdigues, P. Trojek, B. Ömer, M. Fürst, M. Meyenburg, J. Rarity, Z. Sodnik, C. Barbieri, H. Weinfurter & A. Zeilinger

Nature Physics **3**, 481–486 (2007) | Cite this article

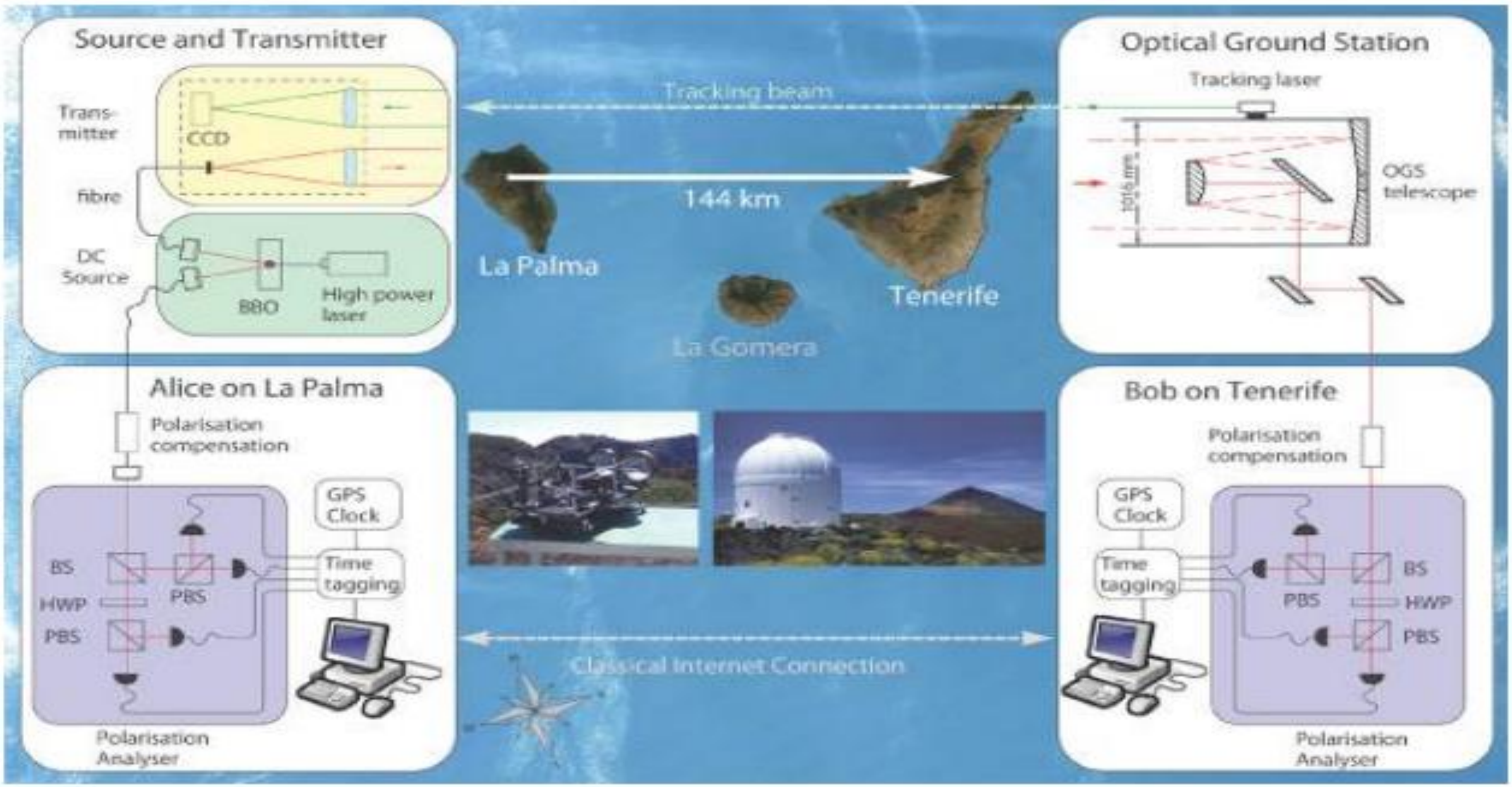


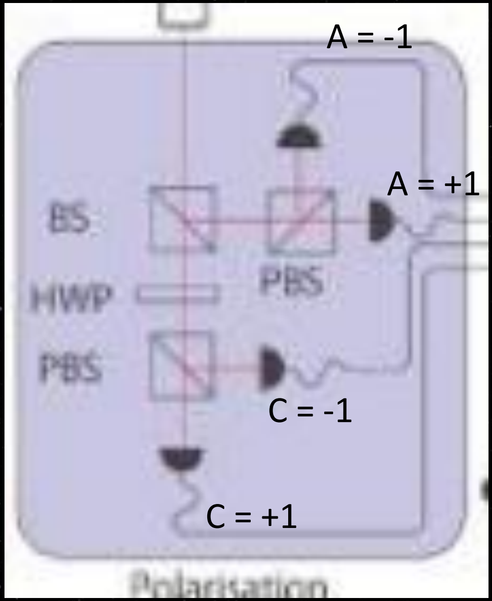
Figure 1: The setup for free-space entanglement distribution between La Palma and Tenerife. Polarisation entangled photon pairs are produced in a type-II parametric down conversion (DC) source by pumping a β-barium-borate crystal (BBO) with a high power UV laser. One photon is measured locally on La Palma, the other one is sent through a 15 cm transceiver lens over the 144 km free-space optical link to the 1 m mirror telescope of the Optical Ground Station (OGS) on the island of Tenerife. The link is actively stabilised by analyzing the direction of a tracking beam (532 nm) sent from OGS to La Palma, which is received in a second lens focusing it on a CCD (s. Fig 2). Because the tracking laser was sent in the opposite direction, no cross-talking occured to the quantum channel. Both parties are using four-channel polarisation analysers, consisting of a 50/50 beam-splitter (BS), a half-wave plate (HWP), and two polarising beam-splitters (PBS), which analyse the polarisation of an incident photon either in the H/V or in the +/-45° basis, randomly split by the BS. Time-tagging units are used to record the individual times at which each detection event occurs relative to a timescale disciplined by the Global Positioning System (GPS). Already during data taking, Bob transmits his time tags via a public internet channel to Alice. She finds the coincident photon pairs in real time by maximising the cross-correlation of these time-tags using fast time-correlation software.

Emergence of quantum physics II

4. Quantum Information

- If the photon is reflected by BS, Alice will measure the polarization for the quantity A
- If the photon is transmitted by BS, Alice will measure the polarization for the quantity C
- The decision to measure in one or another direction is given by chance

La Palma (Alice)

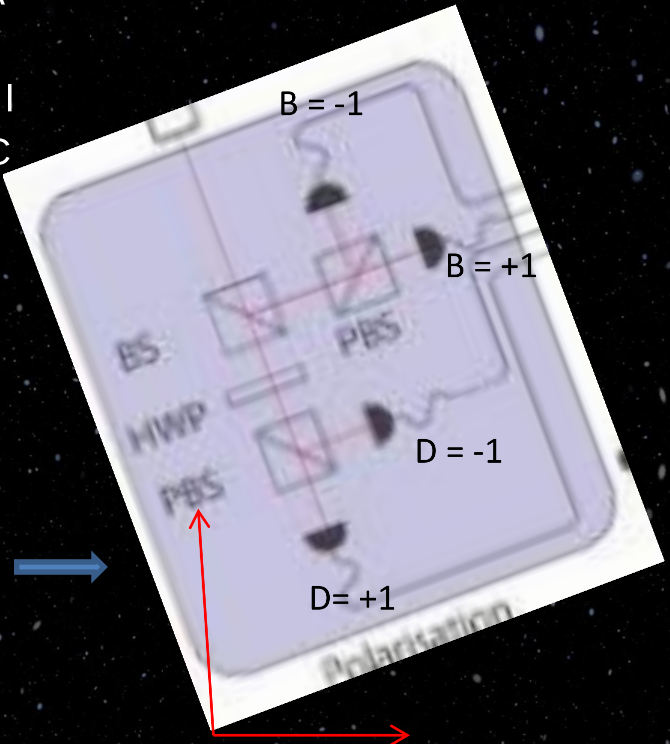


Emergence of quantum physics II

4. Quantum Information

- If the photon is reflected by BS, Bob will measure the polarization for the quantity A
- If the photon is transmitted by BS, Bob will measure the polarization for the quantity C
- The decision to measure in one or another direction is given by chance

Tenerife (Bob)



The polarization is rotated by 22.5°

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4. Quantum Information

With this data is possible to find

$|\langle AB\rangle + \langle CB\rangle + \langle AD\rangle - \langle CD\rangle| = 2.5$

The inequality is broken!

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Emergence of quantum physics II

4. Quantum Information

Quantum Information

Quantum Criptography (Ekert et al)

Teleportation (Bennet et al)

Quantum Computers

Emergence of quantum physics II

5. Quantum Computation

Quantum Computation

- Quantum Algorithms
  - Deutsch-Jozsa, Bernstein-Vazirani, Teleportation, QKD, QFT, Shor, Grover, Parity, QML, etc
- Quantum Error Corrections
  - Bit Flip code, Phase Flip code, Shor code, etc
- Quantum Hardwares
  - Optocal photonic, Optical cavity QED, Ion traps, NMR, Superconducting, topological, etc

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COMING NEXT …

- Mathematical tools of Quantum Mechanics
- Postulates of Quantum Mechanics
- Quantum Computers – Physical Realization

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COMING NEXT …

- Mathematical tools of Quantum Mechanics
- Postulates of Quantum Mechanics
- Quantum Computers – Physical Realization
- Extras → ''round table'', quantum mechanics interpretations