Κβαντικοί Προσομοιωτές Φωτονίων

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Ερευνητική ομάδα: Κβαντικής Οπτικής και Κβαντικής Πληροφορίας,

επιβλέπων: Επ. Καθηγητής Δημήτρης Γ. Αγγελάκης
A New Science!

Quantum Mechanics

Information Science

20th Century

Quantum Information Science

21st Century
How do we compute?

Shown is an Intel processor capable of performing 3,000,000,000 (3 billion) processes per second!

It is composed of ~400,000,000 individual Transistors!

The typical size of a transistor in the picture is about 65nm.
pre-1940s Mechanical
1940s Electromagnetic Relays
1950s Vacuum Tubes
since 1970s Integrated Circuits
The Future Quantum Computers?
Towards the quantum limit

Every 18 months microprocessors double in speed
FASTER = SMALLER

- Recent research predicts an end to Moore’s Law in 2018. Smaller than this quantum effects begin to take over, electronics becomes unpredictable.

- Physical limitation at a 16 nm process. In that scale the behaviour of nature follows the laws of Quantum Mechanics!
What is a quantum computer?

- 1982 - Feynman proposed the idea of creating machines based on the laws of quantum mechanics instead of the laws of classical physics.

- A quantum computer is a machine that performs calculations based on the laws of quantum mechanics, which is the behaviour of particles at the sub-atomic level.

- These laws are weird and counter-intuitive. “I think I can safely say that nobody understands quantum mechanics” - Feynman

- **wave-particle duality**

- **quantum entanglement**

- **quantum super-position**
Images of Quantum World

Electrons (yellow-orange) on the surface of a piece of copper are (cyan-purple) bound by 48 iron atoms (the spikes at the perimeter)

Glowing and vibrating beryllium ions in a linear ion trap.
Atom as Bits - Qubits

A bit of data is represented by a single atom that is in one of two states denoted by $|0\rangle$ and $|1\rangle$. A single bit of this form is known as a *qubit*.

A physical implementation of a qubit could use the two energy levels of an atom. An excited state representing $|1\rangle$ and a ground state representing $|0\rangle$. 

![Diagram showing qubit states](image)
Two things in one?

What do you see?

- An old woman smiling
- A young lady with her head turned
Electrons have a wave property which allows a single electron to be in two orbits simultaneously. In other words, the electron can be in a superposition of both orbits.

For every extra qubit you get, you can store twice as many numbers.
Classical vs. quantum computation

In quantum systems possibilities count, **even if they never happen!**

<table>
<thead>
<tr>
<th>0 0 0</th>
<th>compute $F(000)$</th>
<th>0</th>
</tr>
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<tbody>
<tr>
<td>0 0 1</td>
<td>compute $F(001)$</td>
<td>0</td>
</tr>
<tr>
<td>0 1 0</td>
<td>compute $F(010)$</td>
<td>1</td>
</tr>
<tr>
<td>0 1 1</td>
<td>compute $F(011)$</td>
<td>0</td>
</tr>
<tr>
<td>1 0 0</td>
<td>compute $F(100)$</td>
<td>0</td>
</tr>
<tr>
<td>1 0 1</td>
<td>compute $F(101)$</td>
<td>1</td>
</tr>
<tr>
<td>1 1 0</td>
<td>compute $F(110)$</td>
<td>0</td>
</tr>
<tr>
<td>1 1 1</td>
<td>compute $F(111)$</td>
<td>1</td>
</tr>
</tbody>
</table>

quantum compute $F(\text{000})$ → 0
Interesting Algorithm
Factoring Prime Numbers

- Prime numbers used in current day cryptography
- Peter Shor discovered quantum factoring algorithm
- Quantum “time” to factor \( O\left(\log(N)^3\right) \)
- Classical “time” to factor \( O\left(2^{\log(N)^{1.5}}\right) \)

**Polynomial vs. Exponential time to calculate.**

*Exponential Speedup using quantum computer!*

Quantum simulations

use one controllable quantum system to investigate the behaviour and properties of another, less accessible one

Optimized for specific problems:
- High energy physics
- Material science
- Metamaterials (graphene)
- Nanotechnology

Analog QS
- Continuous evolution
- Hamiltonian engineering
- No error correction

Digital QS
- Discrete evolution
- Error correction


Nature insight: Goals and opportunities in quantum simulation by Zoller and Cirac, Nat. Phys, April 2012

Fully fledged quantum computers are still a long way off. But devices that can simulate quantum systems are proving uniquely useful.
Possible implementation platforms - Quantum hardware

I) Cold ions in ions traps

II) Cold atoms in optical lattices

III) Photons in QED resonators

IV) Circuit QED resonators
Quantum simulators with trapped photons by Angelakis group

Quantum physics although relatively simple for single atoms and electrons when applied to real materials becomes extremely complex

**HOW TO MAKE MATERIALS OUT OF LIGHT**

If photons can be made to interact, the resulting “material” could form the basis of a quantum computer or simulator. One idea is to place atoms inside cavities in a photonic crystal. Each atom-cavity can be tuned to absorb exactly one photon and reject others, a condition known as “photon blockade.” Disturbing this causes a phase transition—one of the hallmarks of a material.

1. **Material is a “photon insulator”**
   - When photon blockade is in effect, each atom-cavity can hold only one photon. This makes it hard for photons to move around. If enough are present, they become locked in place.

2. **Phase transition**
   - Shining a laser on each atom-cavity makes the photon blockade vanish, so the photon material changes state...

3. **Photons become “superfluid”**
   - Photons flow freely throughout the array, like particles in a superfluid.

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See also New Scientist, 2007; Innovation 2010; BHMA Science 2011
Θέμα διδακτορικής διατριβής:
Υλοποίηση Κβαντικών Υπολογισμών σε Κβαντικά Φωτονικά Συστήματα

I. Μοντελοποίηση φωτονικών κβαντικών συστημάτων χρησιμοποιώντας αρχές κβαντικής μηχανικής-οπτικής, ατομικής φυσικής και φυσικής στερεάς κατάστασης για πραγματοποίηση κβαντικών υπολογισμών και προσομοιώσεων

II. Υπολογιστικά εργαλεία: αναλυτικές και υπολογιστικές μέθοδοι
Χρησιμοποιούμε προηγμένες υπολογιστικές μεθόδους διαγωνοποίησης μεγαλών πινακών όπως η μέθοδος DMRG.

Εστιάζουμε στην Θεωρητική μοντελοποίηση της αλληλεπίδρασης ατόμων - φωτονίων μεσα σε υπεραγώγιες φωτονικές κοιλότητες φωτονικών και υπεραγώγιμων κυκλωμάτων.

Συνεργασίες με μεγάλα ερευνητικά κέντρα του εξωτερικού για την υλοποίηση των θεωρητικών προτάσεων μας. UK (Oxford, Cambridge), Singapore (CQT), Finland (Aalto), USA (NIST), Germany (Friedrich Schiller University Jena)
• Quantum physics allows an exciting alternative to computation
• One of the most promising platforms is quantum photonics materials
Thank you for listening

More at www.dimitrisangelakis.org