Σχολή Ηλεκτρονικών Μηχανικών & Μηχανικών Υπολογιστών

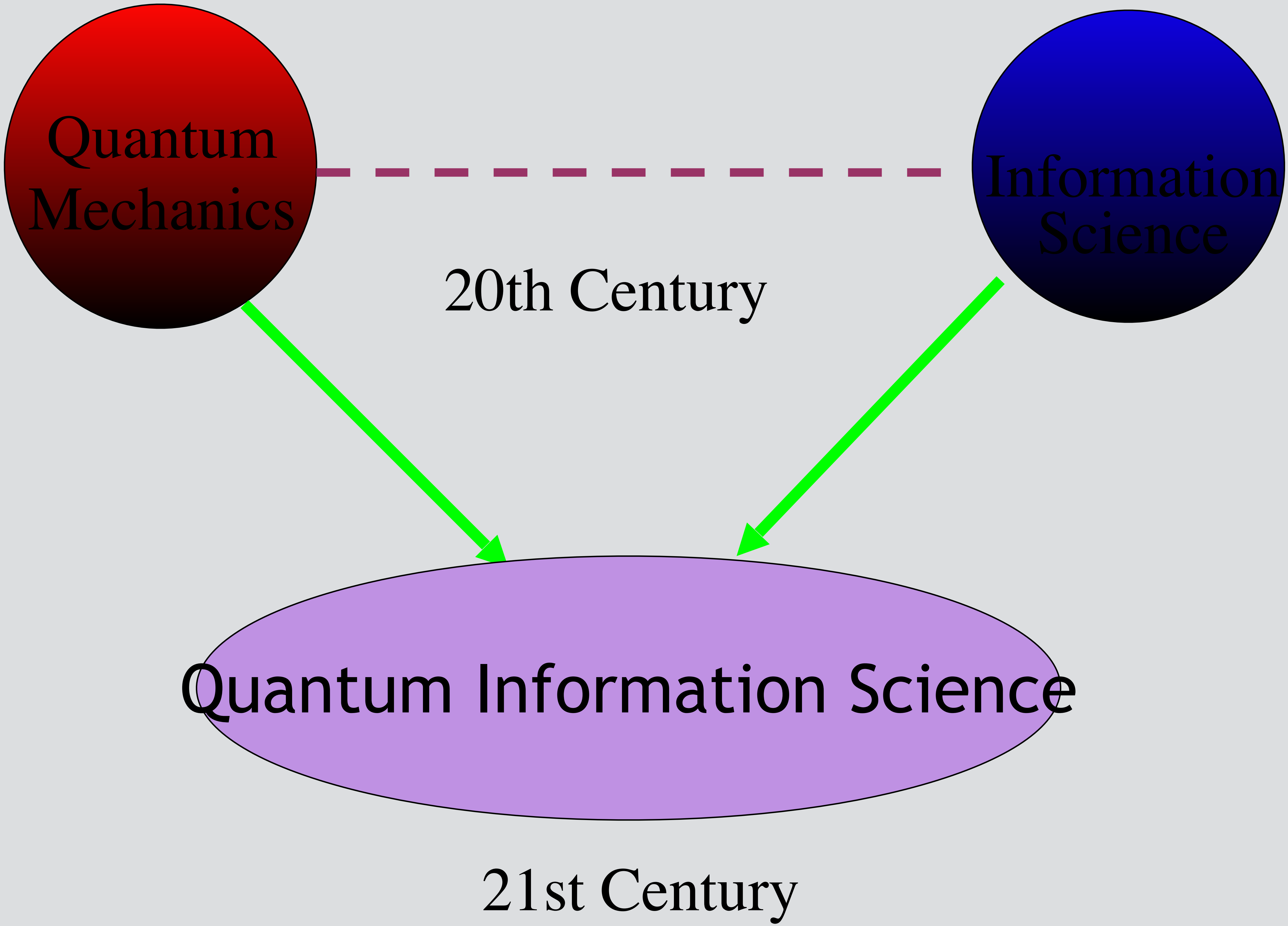
Κβαντικοί Προσομοιωτές Φωτονίων

Νικόλαος Σχετάκης

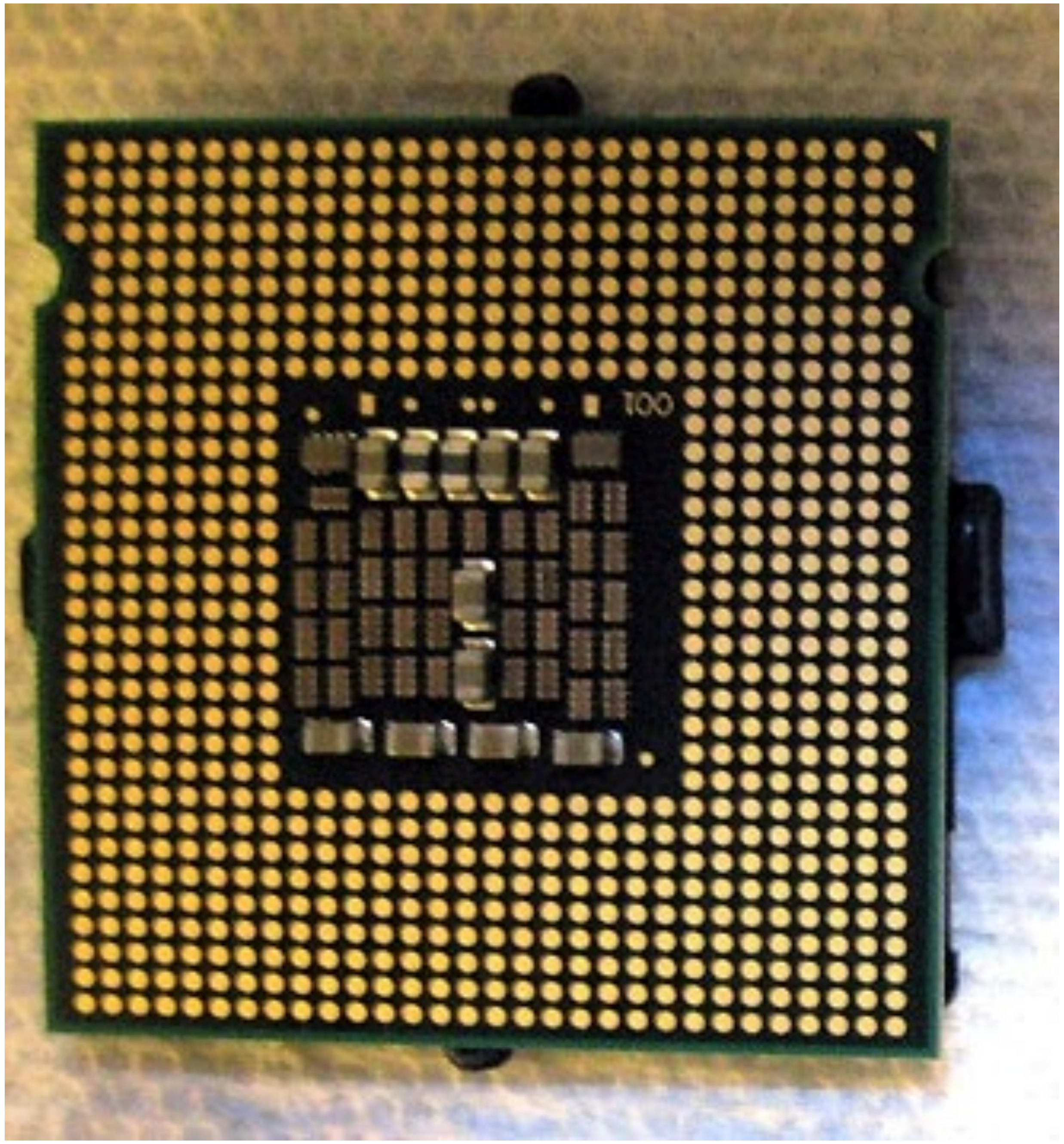
Ερευνητική ομάδα: **Κβαντικής Οπτικής και Κβαντικής Πληροφορίας,**

***επιβλέπων*: Επ. Καθηγητής Δημήτρης Γ. Αγγελάκης**

A New Science!



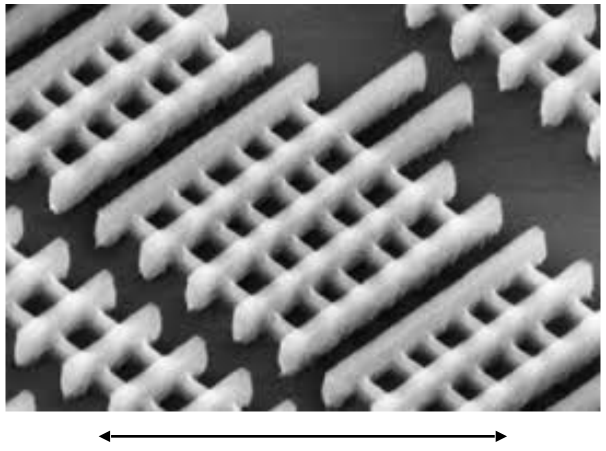
How do we compute?



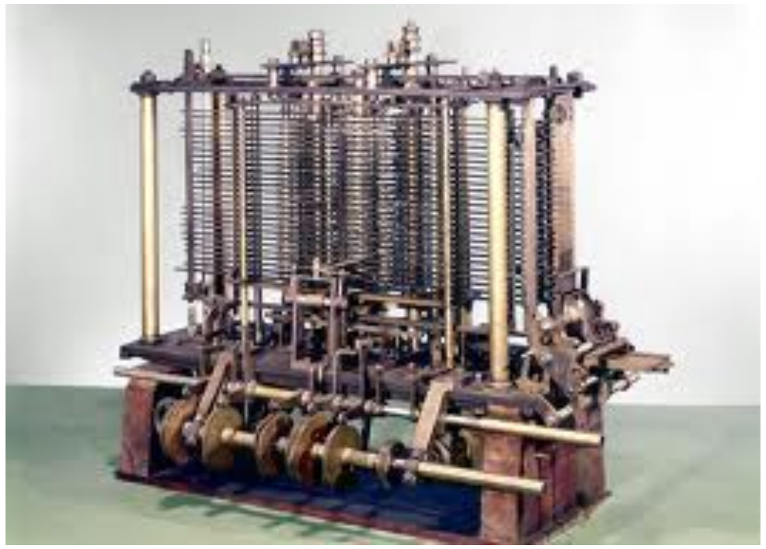
Shown is an Intel processor capable of performing 3,000,000,000 (3 billion) processes per second!

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

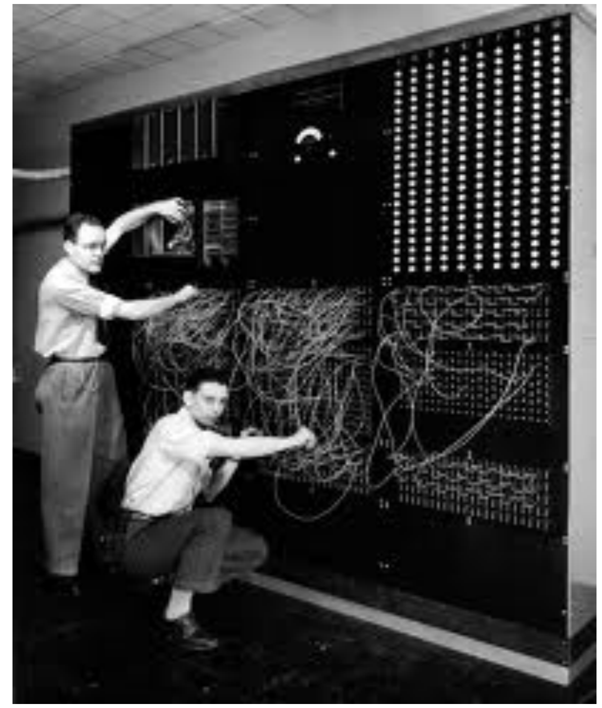
The typical size of a transistor in the picture is about 65nm



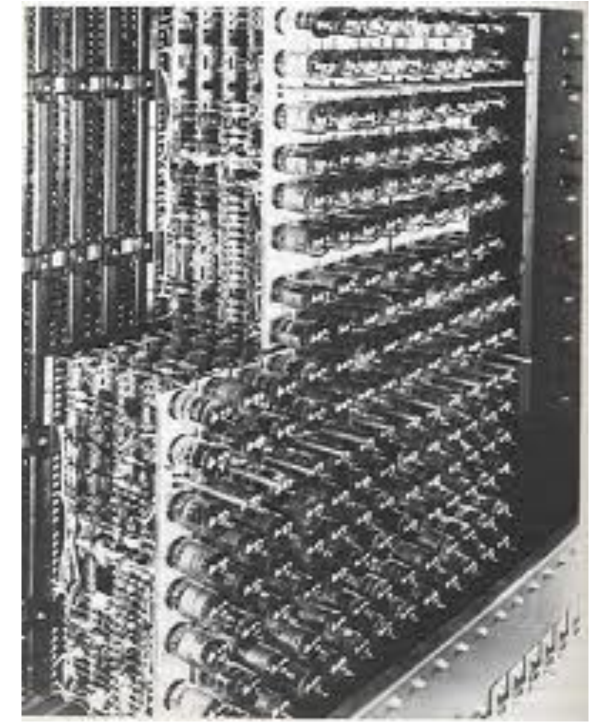
25 nm



pre-1940s
Mechanical

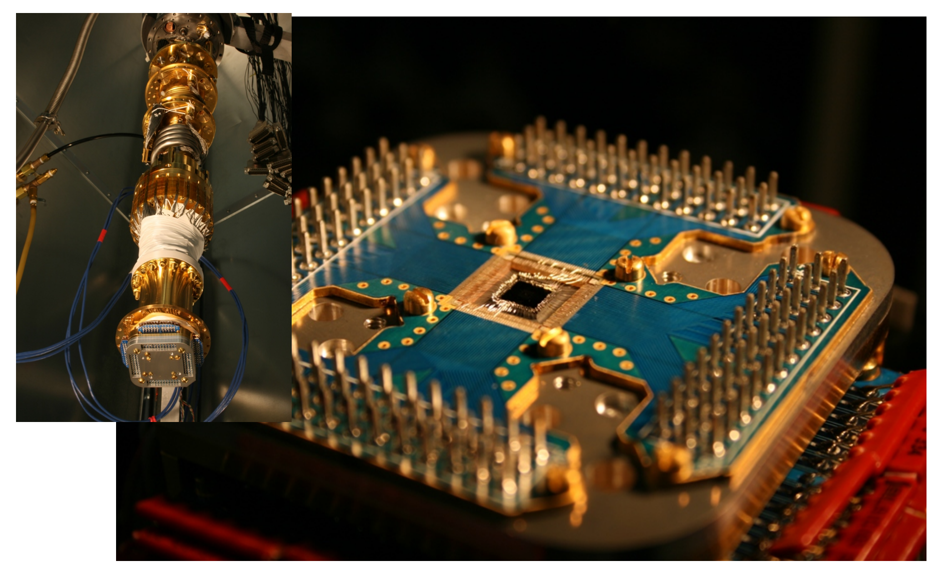


1940s
Electromagnetic
Relays



1950s
Vacuum
Tubes

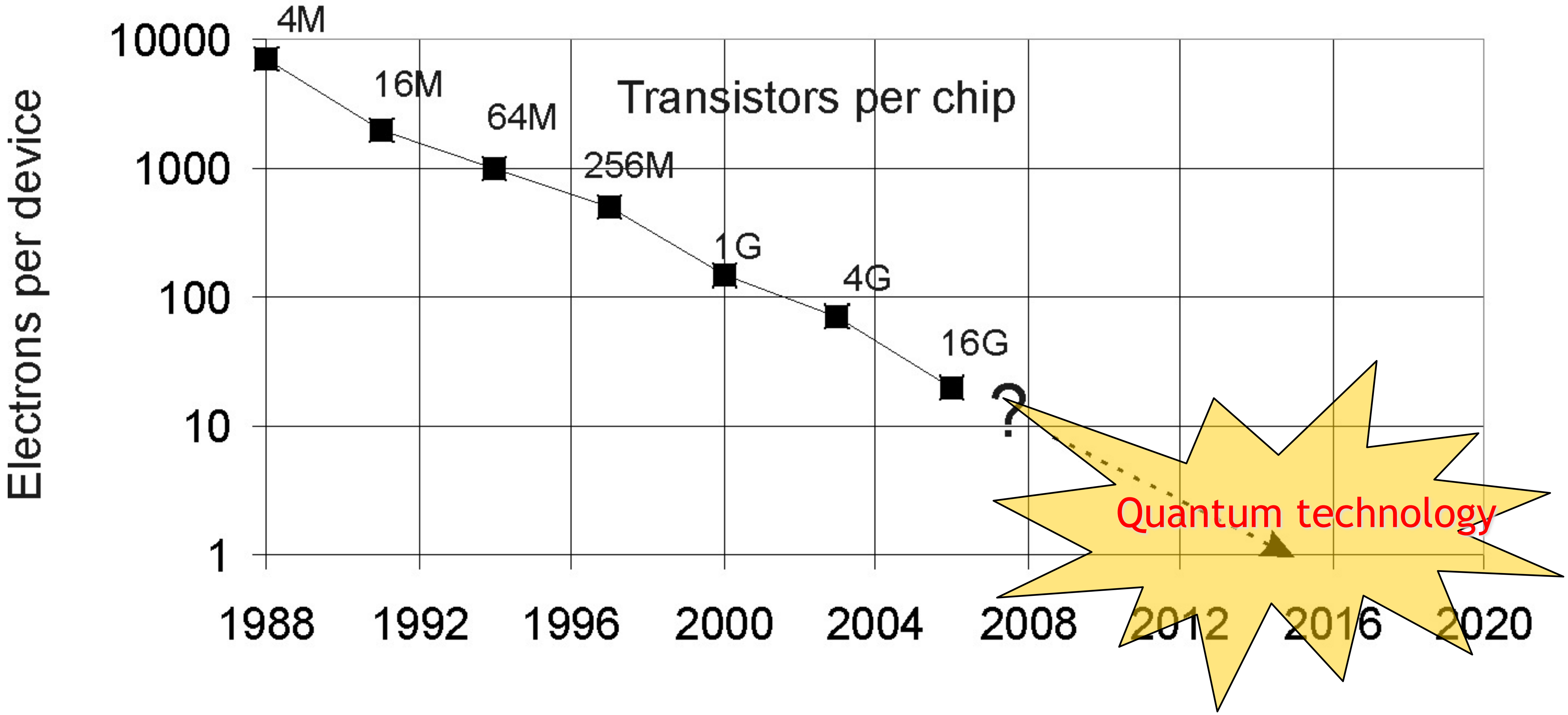
since 1970s
Integrated
Circuits



The Future
Quantum
Computers?

Towards the quantum limit

Every 18 months microprocessors double in speed
FASTER = SMALLER

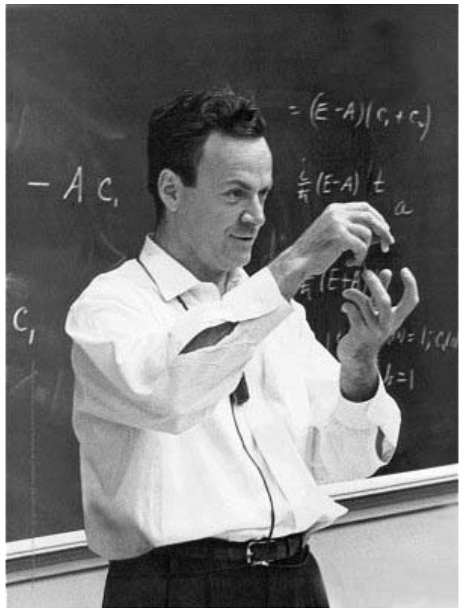


- Recent research predicts an end to Moore's Law in 2018. Smaller than this quantum effects begin to take over, **electronics becomes unpredictable**.

- Physical limitation at a 16 nm process. In that scale the behaviour of nature follows the **laws of Quantum Mechanics**!

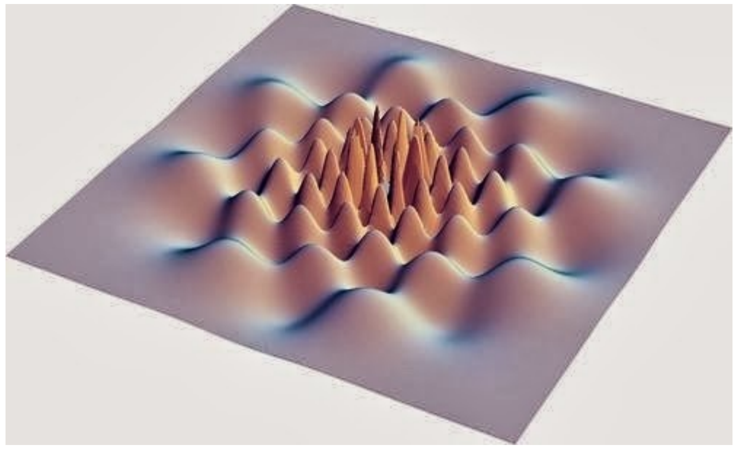
What is a quantum computer?

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

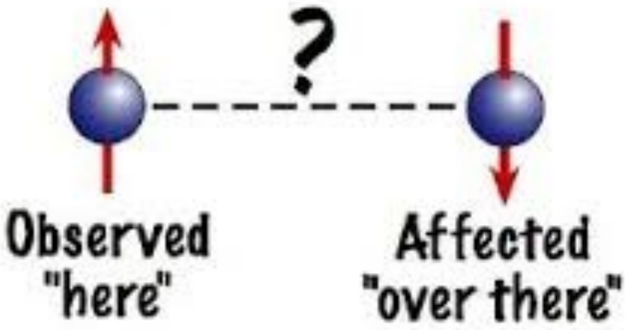


- A quantum computer is a machine that performs calculations based on the laws of quantum mechanics, which is the behaviour of particles at the sub-atomic level.
- These laws are weird and counter-intuitive. “I think I can safely say that nobody understands quantum mechanics” - Feynman

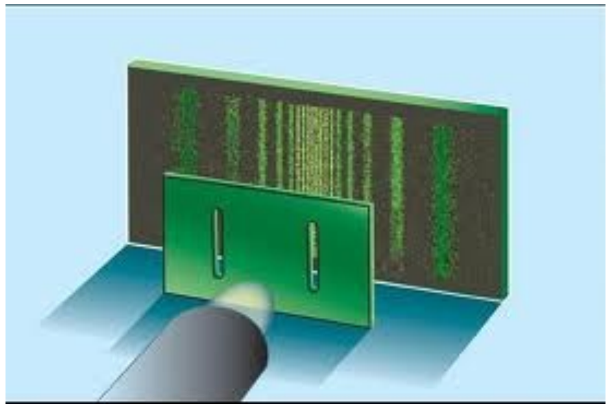
- *wave-particle duality*



- *quantum entanglement*

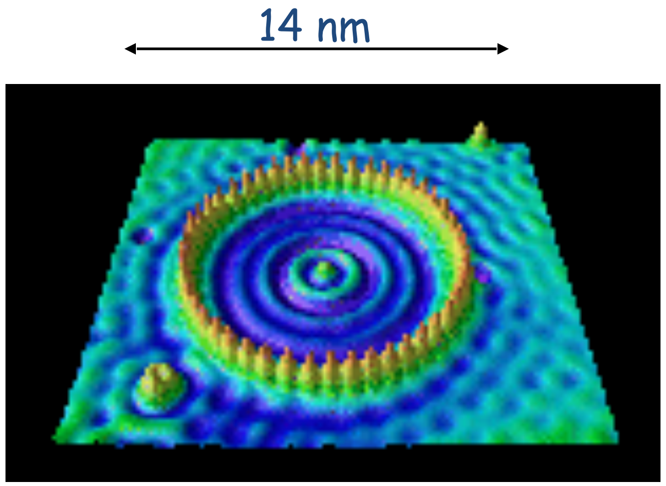


- *quantum super-position*



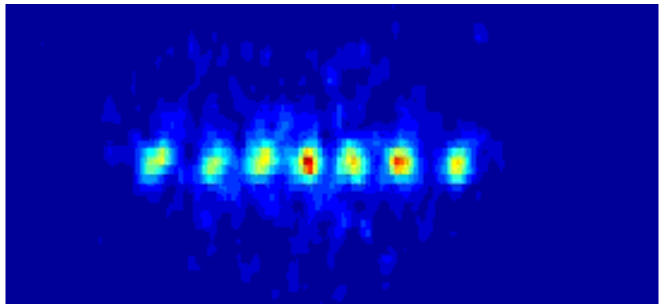
Images of Quantum World

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



STM picture © IBM

Glowing and vibrating beryllium ions in a linear ion trap.



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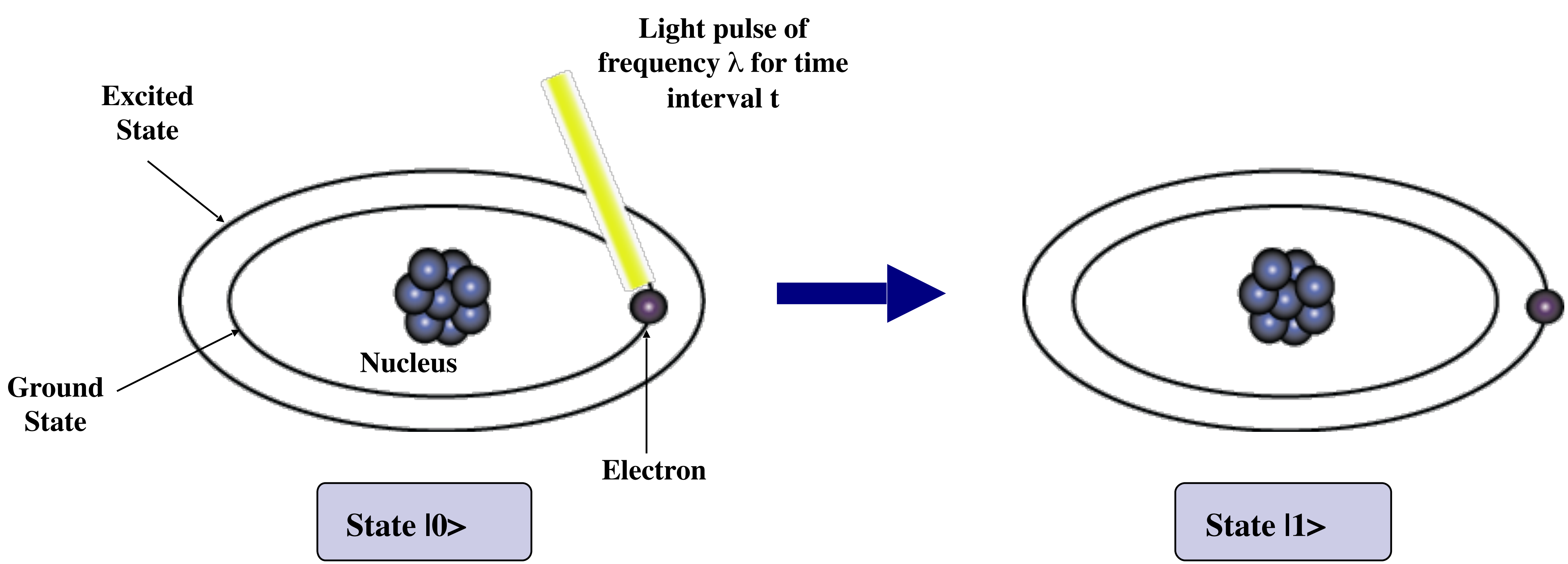
Atom as Bits - Qubits

A bit of data is represented by a single atom that is in one of two states denoted by **|0>** and **|1>**. 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> and a ground state representing |0>.



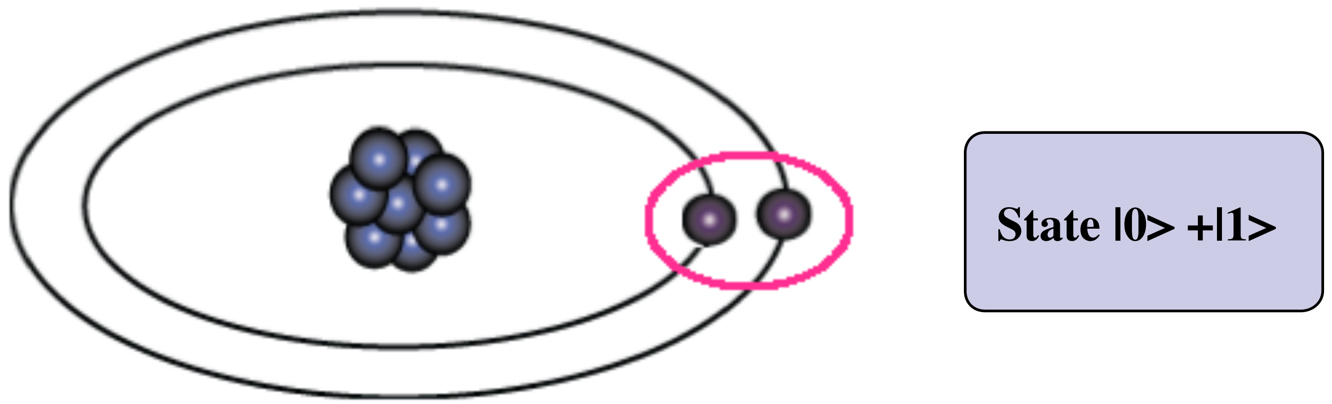
Two things in one?

What do you see?

- An old woman smiling
- A young lady with her head turned

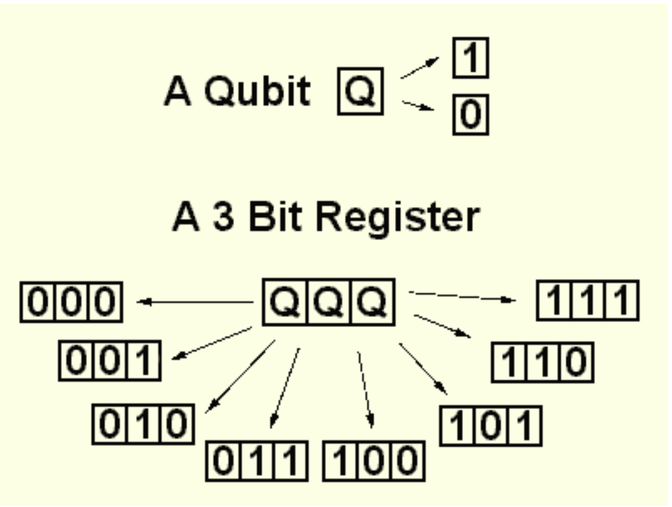
?

Quantum Superposition



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

qubits	*stores simultaneously*	*total number*
1	(0 and 1)	$2^1 = 2$
2	(0 and 1)(0 and 1)	$2x2 = 2^2 = 4$
3	(0 and 1)(0 and 1)(0 and 1)	$2x2x2 = 2^3 = 8$
:	:	:
300	(0 and 1)(0 and 1)........(0 and 1)	$2x2......x2 = 2^{300}$

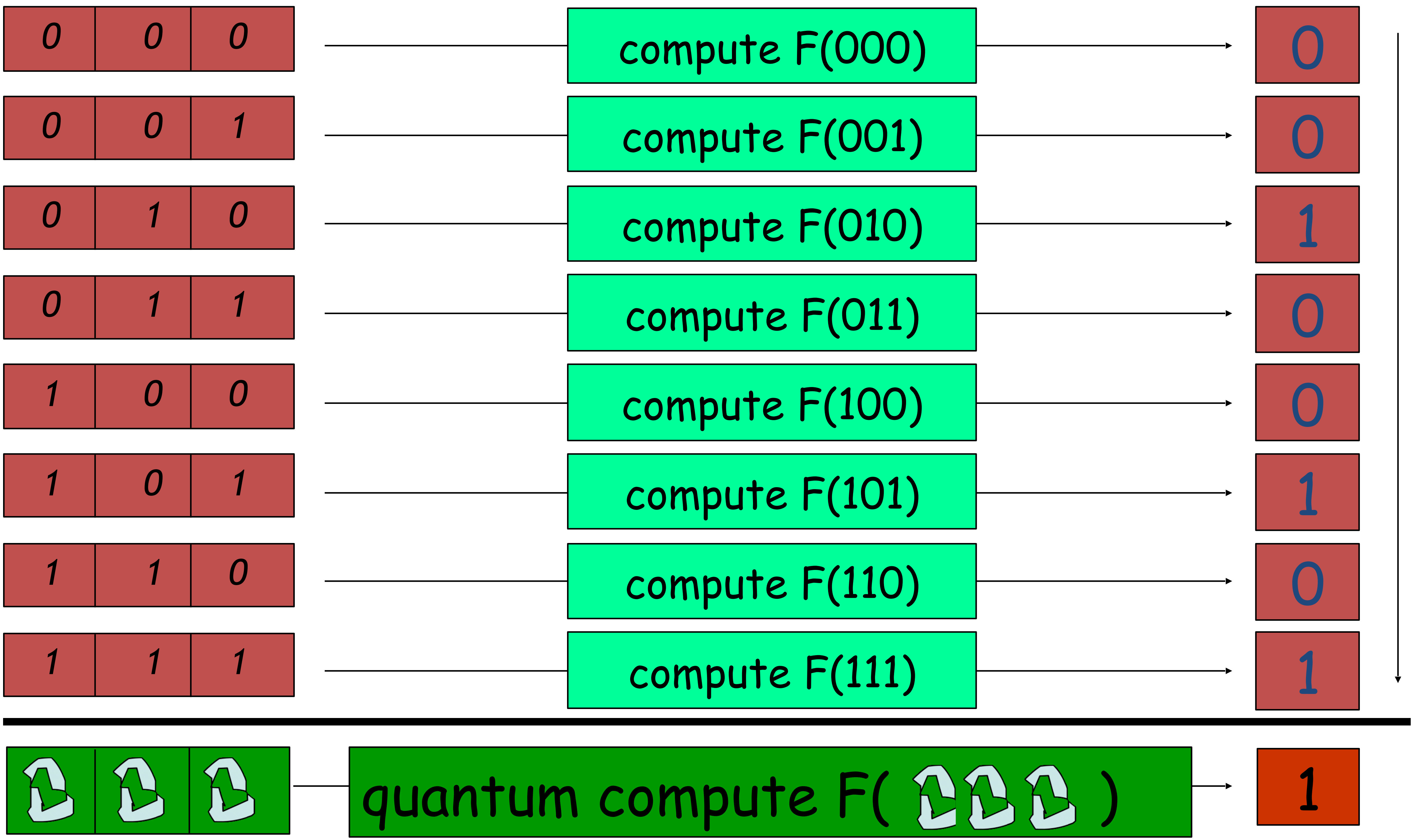


Bigger number than the number of atoms in the universe, and calculations can be performed simultaneously on each of these numbers

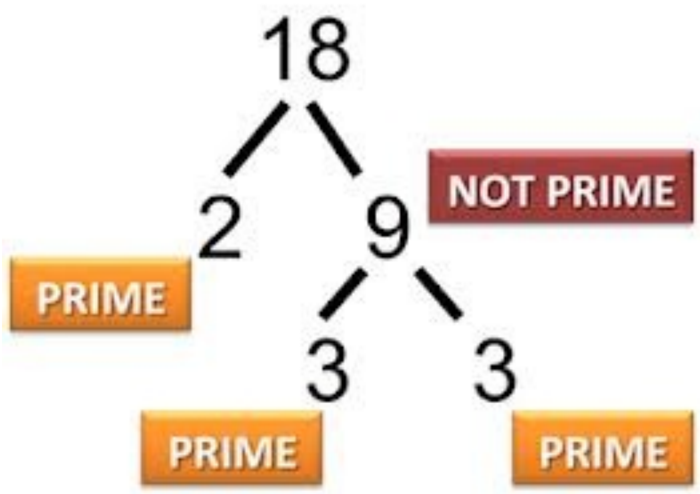
<u>**For every extra qubit you get, you can store twice as many numbers**</u>

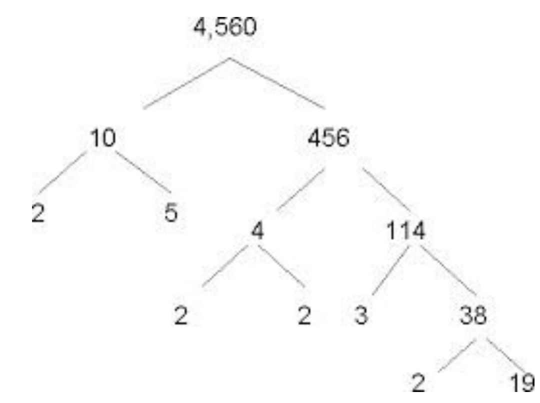
Classical vs. quantum computation

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



Interesting Algorithm
Factoring Prime Numbers





Peter Shor

- 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 $O\left(2^{\log(N)^{\frac{1}{3}}}\right)$

Polynomial vs. Exponential time to calculate.

Exponential Speedup using quantum computer!

Shor, Peter W. (1997), "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer", SIAM J. Comput. 26 (5): 1484–1509, arXiv:quant-ph/9508027v2,

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

Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

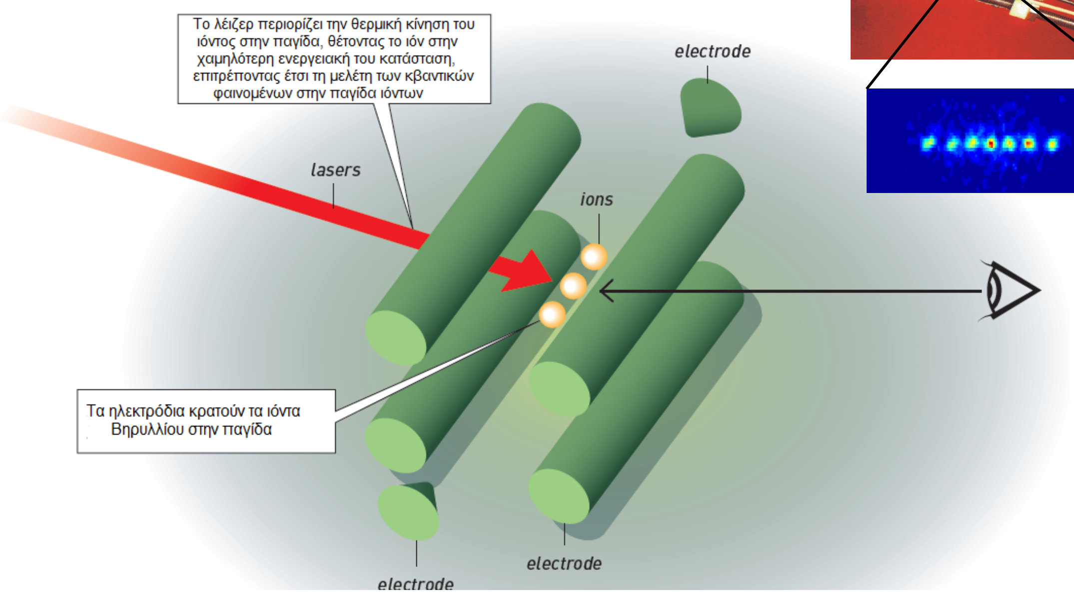
Analog QS	Digital QS
Continuous evolution	Discrete evolution
Hamiltonian engineering	Error correction
No error correction	
Feynman, Int. J. Theoret. Phys. 21, 467 (1982)	Lloyd, Science 273, 1073 (1996)

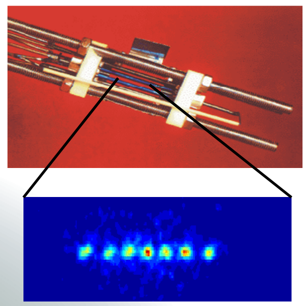
Nature insight: Goals and opportunities in quantum simulation by Zoller and Cirac, Nat, Phys, April 2012

Fully fledged quantum computers are still a long way off. But devices that can simulate quantum systems are proving uniquely useful.

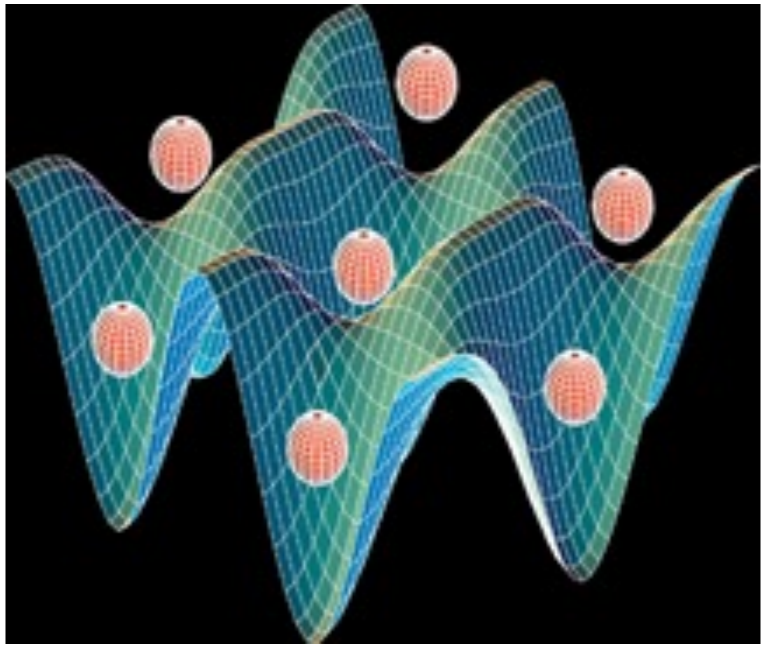
Possible implementation platforms - Quantum hardware

I) Cold ions in ions traps

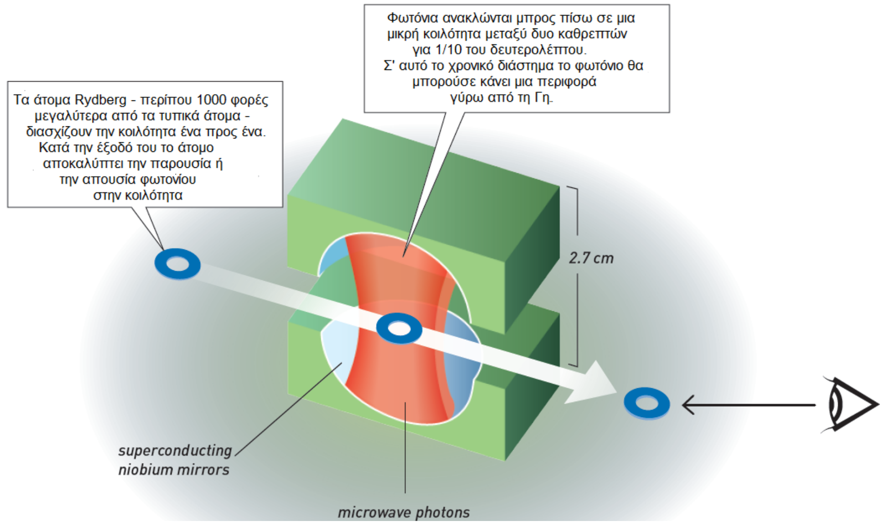




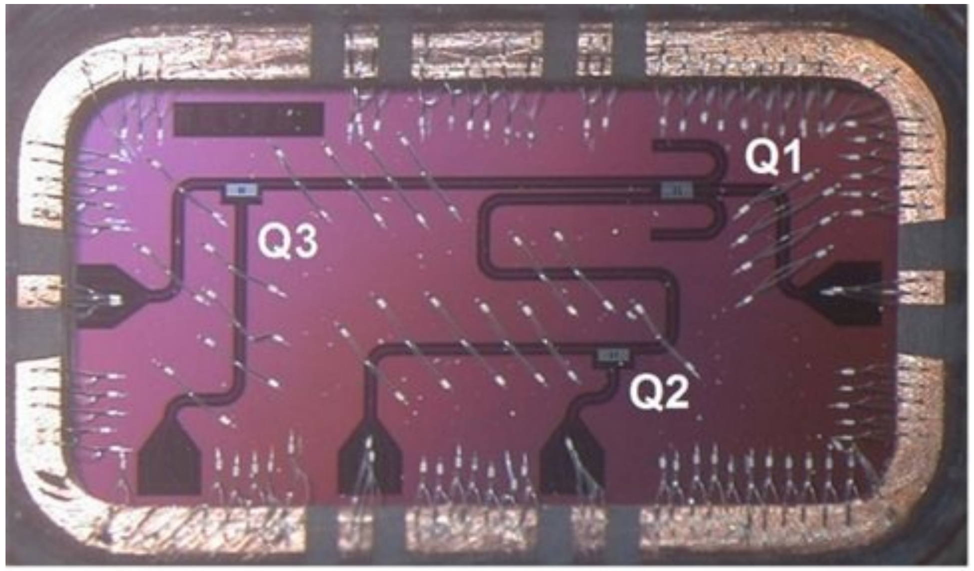
II) Cold atoms in optical lattices



III) Photons in QED resonators

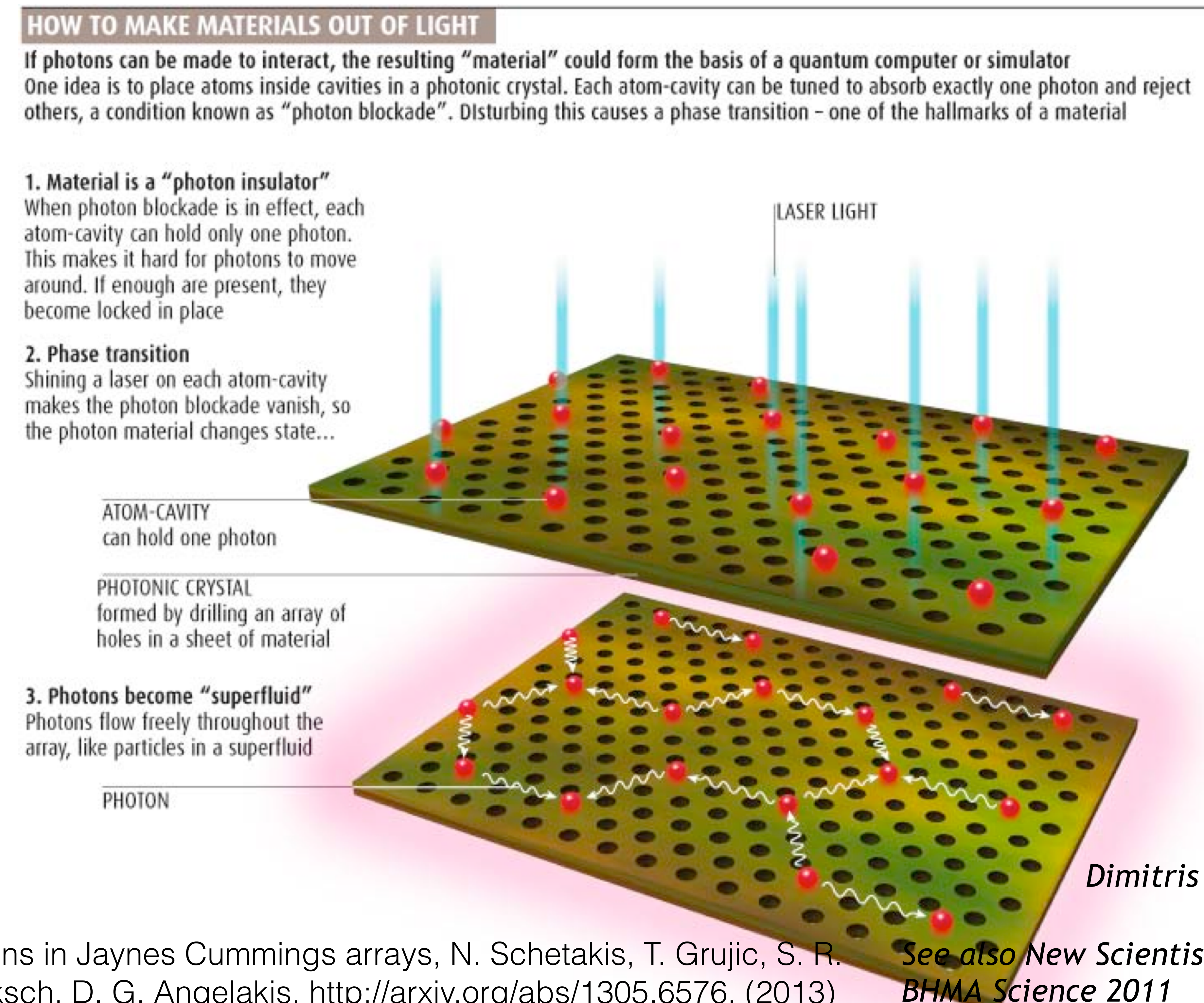


IV) Circuit QED resonators



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



Dimitris G. Angelakis et al, 2007

Frozen photons in Jaynes Cummings arrays, N. Schetakis, T. Grujic, S. R. Clark, D. Jaksch, D. G. Angelakis, http://arxiv.org/abs/1305.6576, (2013)

See also New Scientist, 2007; Innovation 2010 BHMA Science 2011

Θέμα διδακτορικής διατριβής:

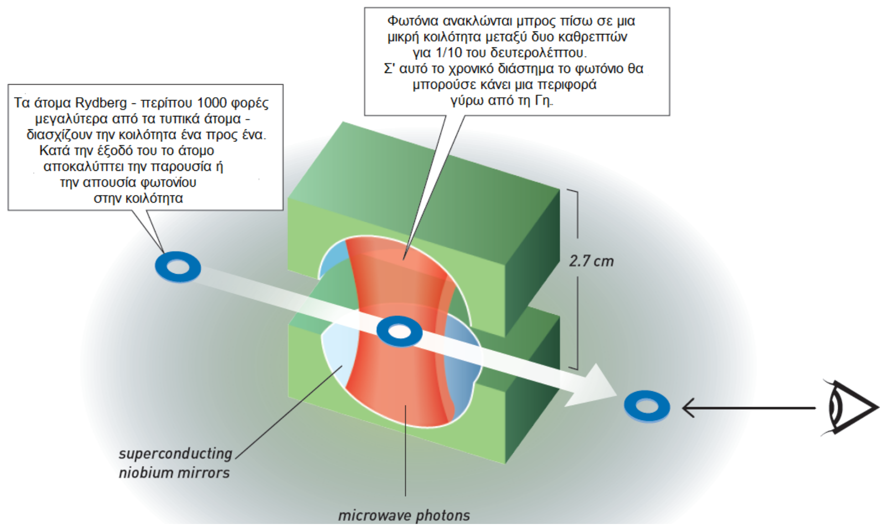
Υλοποίηση Κβαντικών Υπολογισμών σε Κβαντικά Φωτονικά Συστήματα

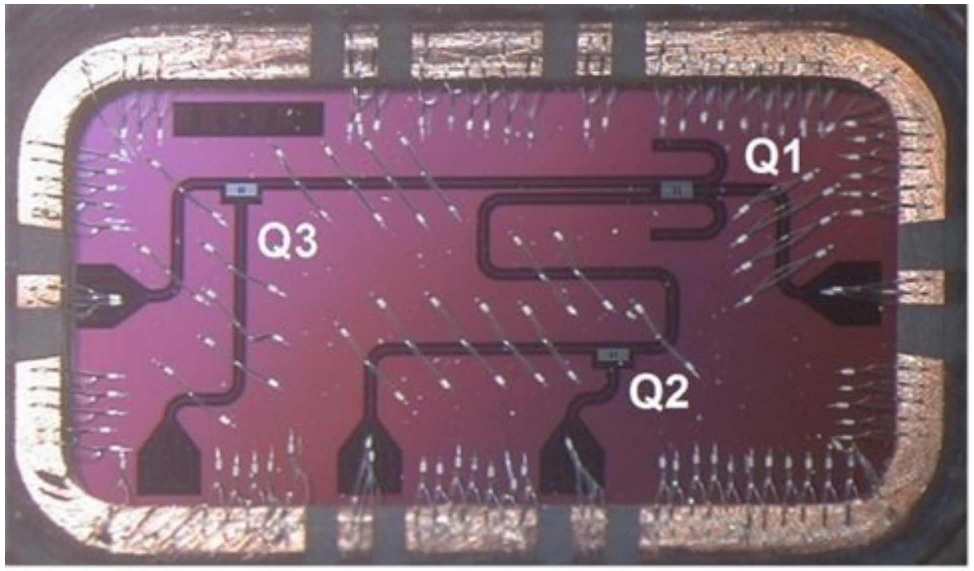
I. Μοντελοποίηση φωτονικών κβαντικών συστημάτων χρησιμοποιώντας αρχές κβαντικής μηχανικής-οπτικής, ατομικής φυσικής και φυσικής στερεάς κατάστασης για πραγματοποίηση κβαντικών υπολογισμών και προσομειώσεων

II. Υπολογιστικά εργαλεία: αναλυτικές και υπολογιστικές μέθοδοι

Χρησιμοποιούμε προηγμένες υπολογιστικές μεθόδους διαγωνοποίησης μεγαλων πινακων οπως η μέθοδος DMRG.

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





Συνεργασίες με μεγαλα 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)

Summary

- 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