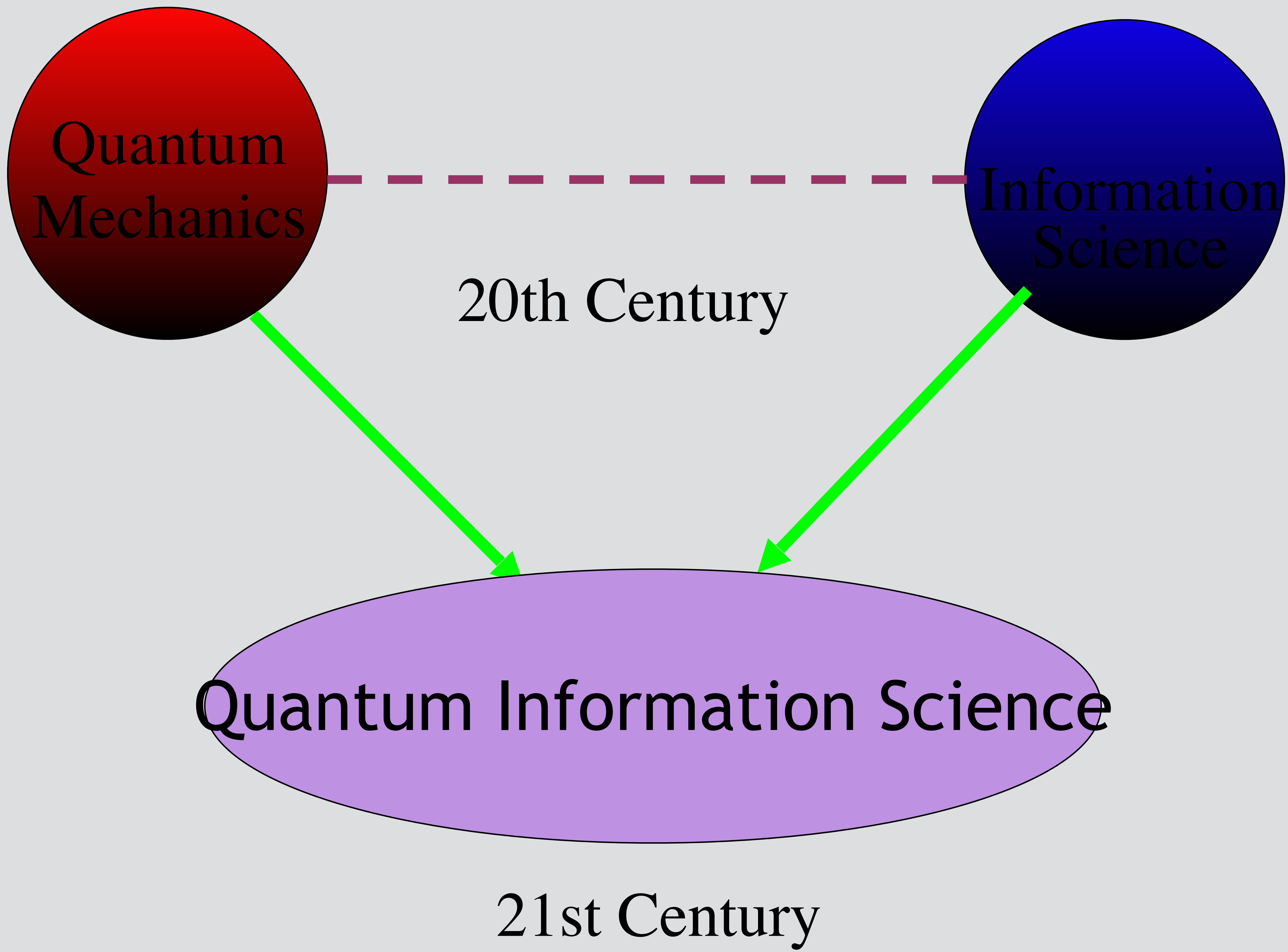
From QIS to QML

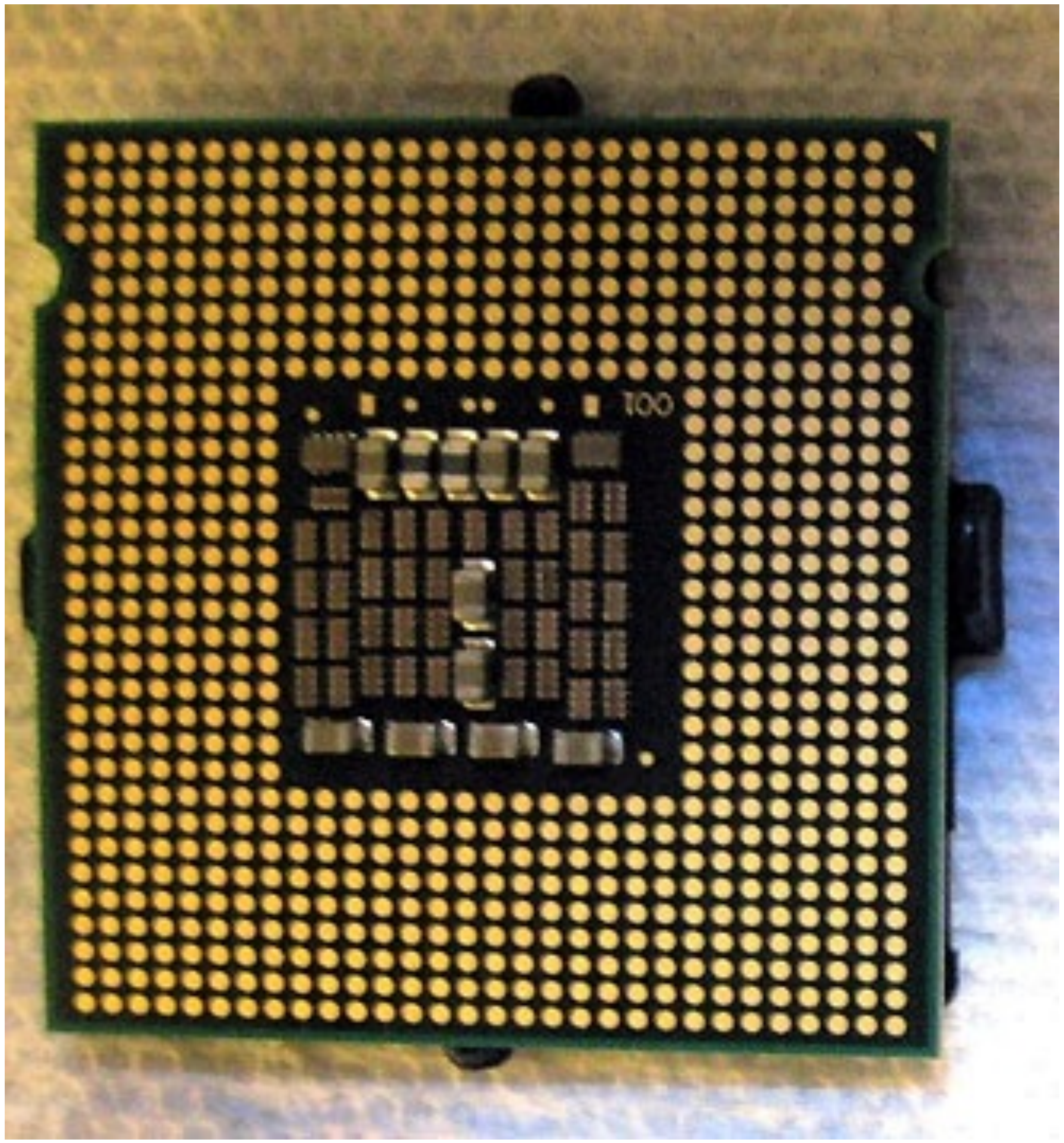
NS

12/2018

A New Science!



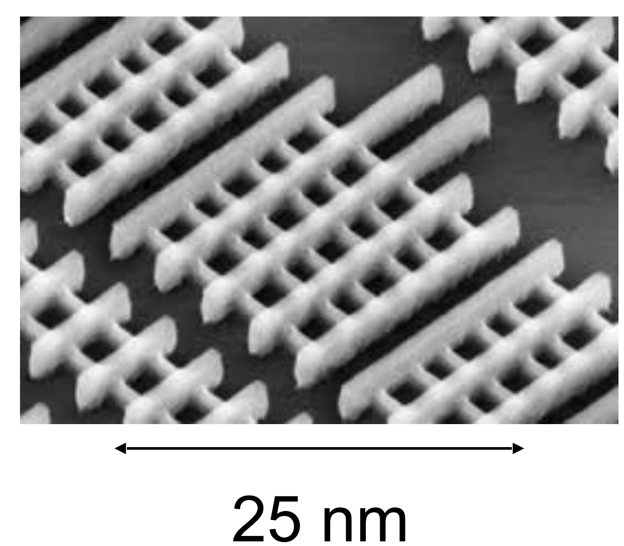
How do we compute?

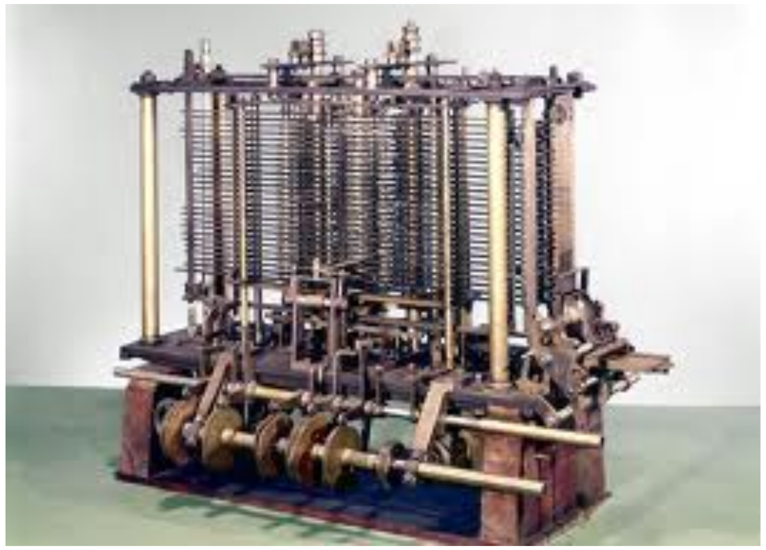


Shown is an Intel processor capable of performing 3,000,000,000 (3 billion) processes per second!

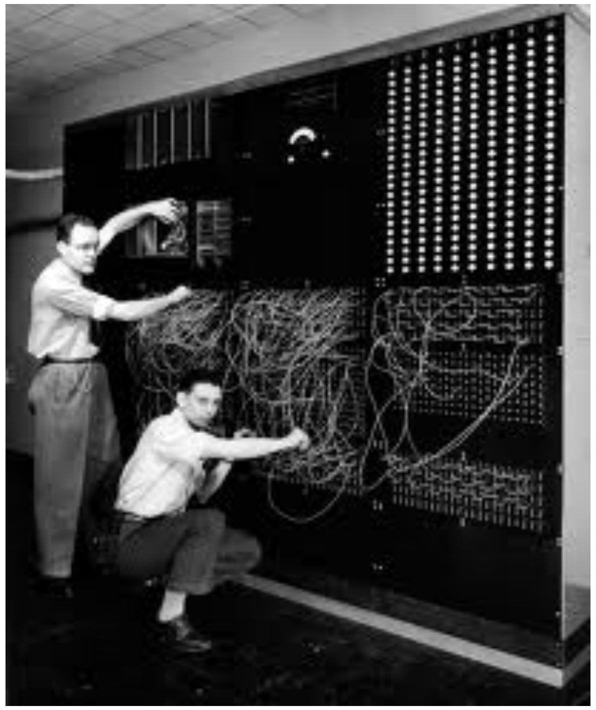
It is composed of ~400,000,000 individual Transistors!

Current generation technology uses 14nm scale technology, with 10nm semiconductors anticipated for release in 2017 or 2018

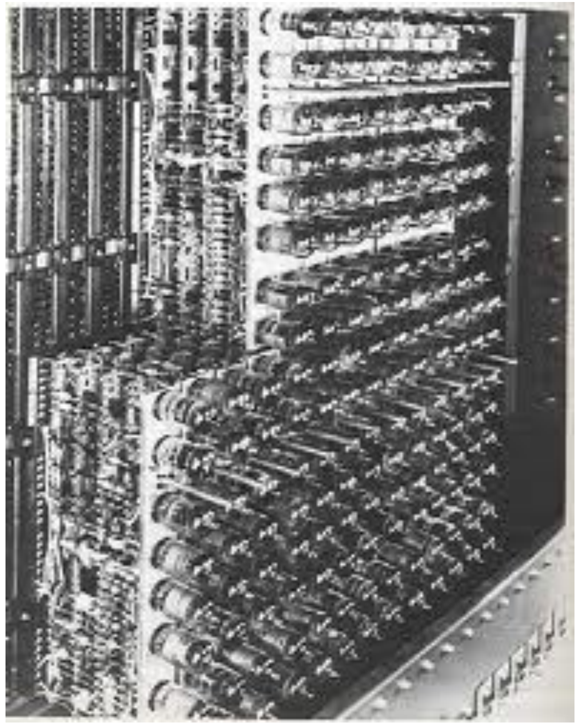




pre-1940s
Mechanical



1940s
Electromagnetic
Relays



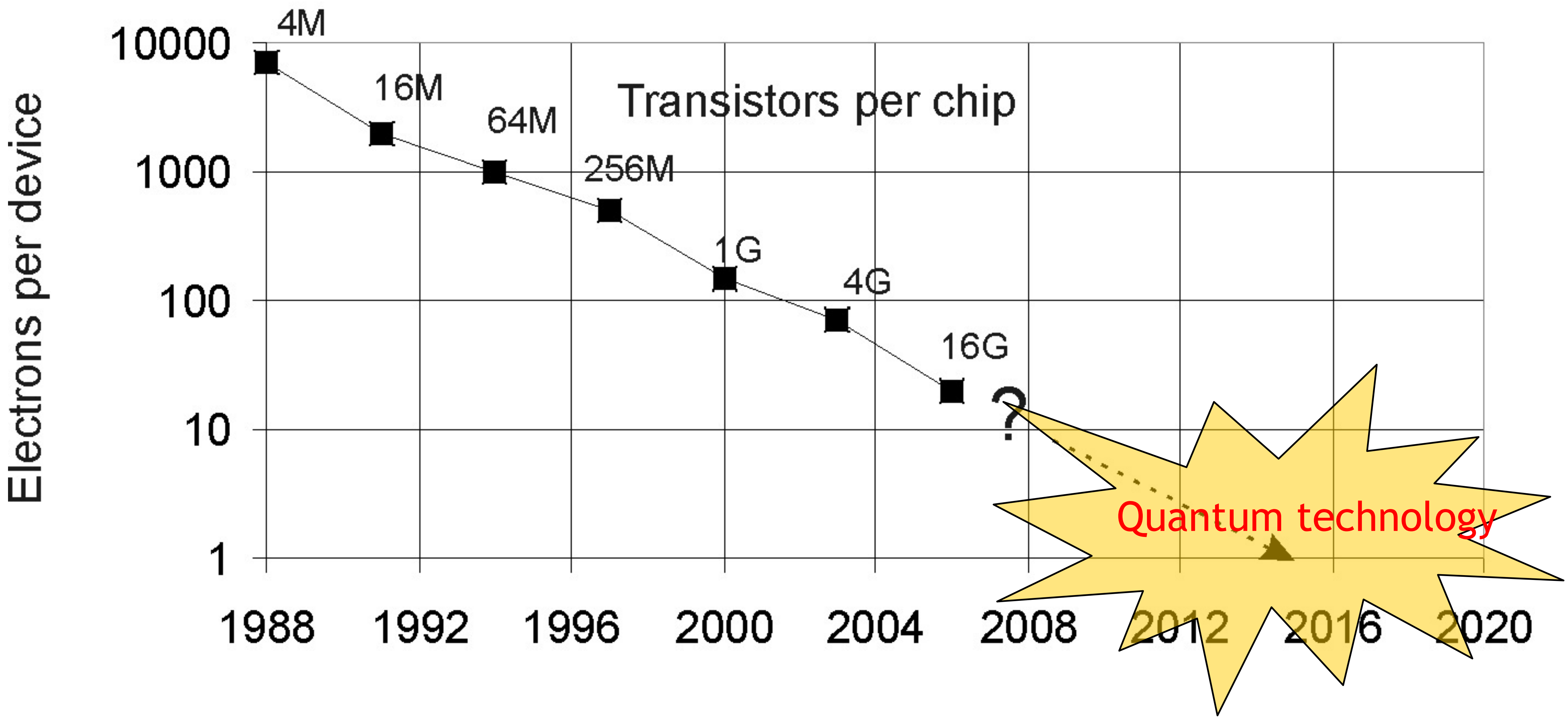
1950s
Vacuum
Tubes

since 1970s
Integrated
Circuits

The Future ???

Towards the quantum limit

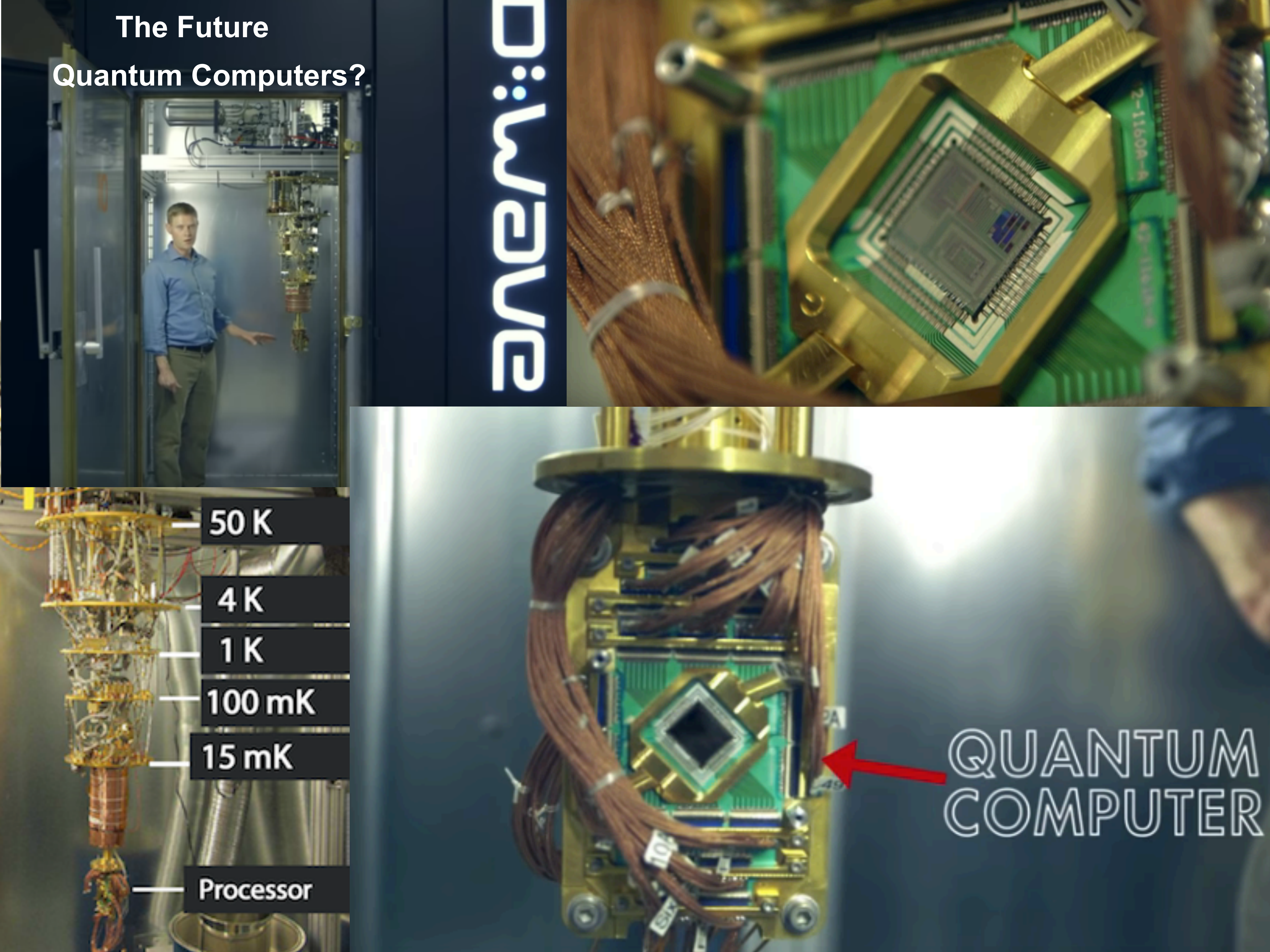
Every 18 months microprocessors double in speed
FASTER = SMALLER



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

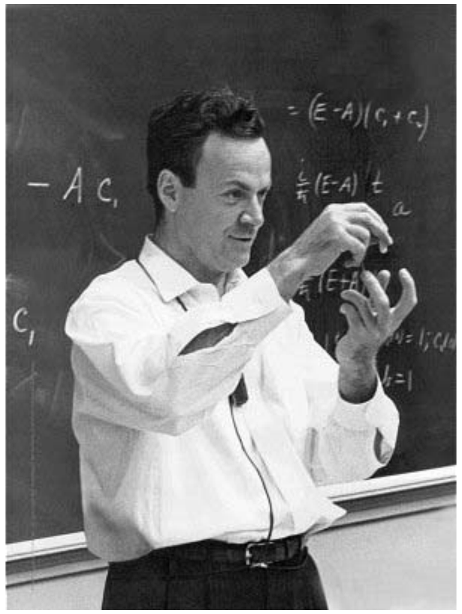
- Physical limitation at a 16 nm process. In that scale the behaviour of nature follows the **laws of Quantum Mechanics**!

The Future
Quantum Computers?



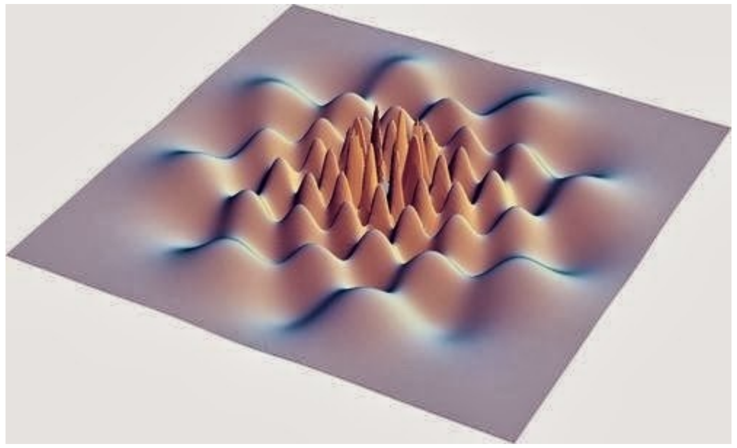
What is a quantum computer?

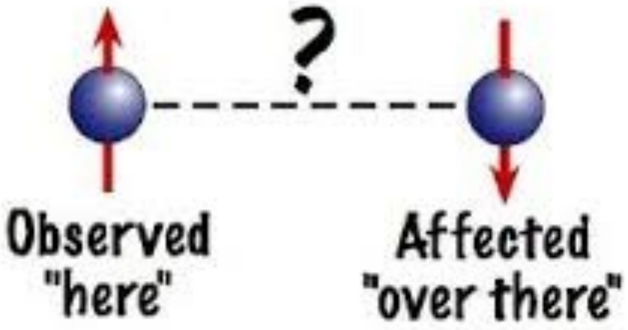
- 1982 - Feynman proposed the idea of creating machines based on the laws of quantum mechanics instead of the laws of classical physics.

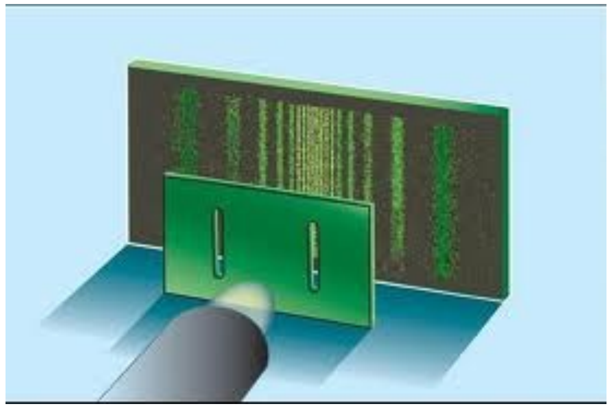


- A quantum computer is a machine that performs calculations based on the laws of quantum mechanics, which is the behavior of particles at the sub-atomic level.
- These laws are weird and counter-intuitive. “I think I can safely say that nobody understands quantum mechanics” - Feynman

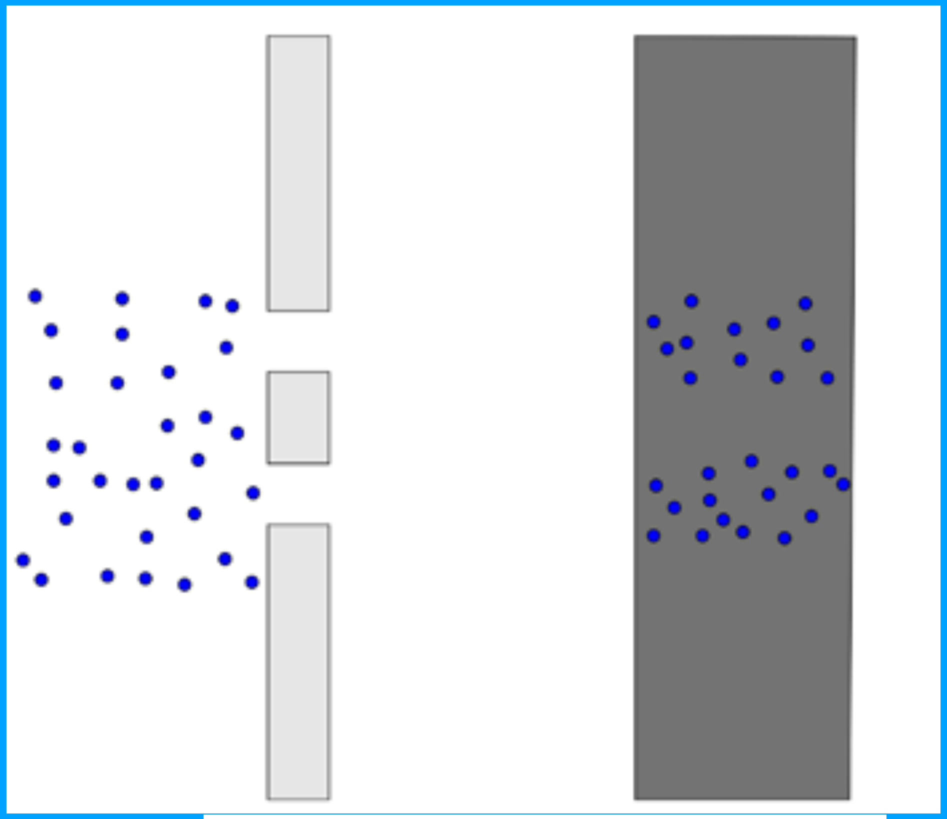
- *wave-particle duality*
- *quantum entanglement*
- *quantum super-position*



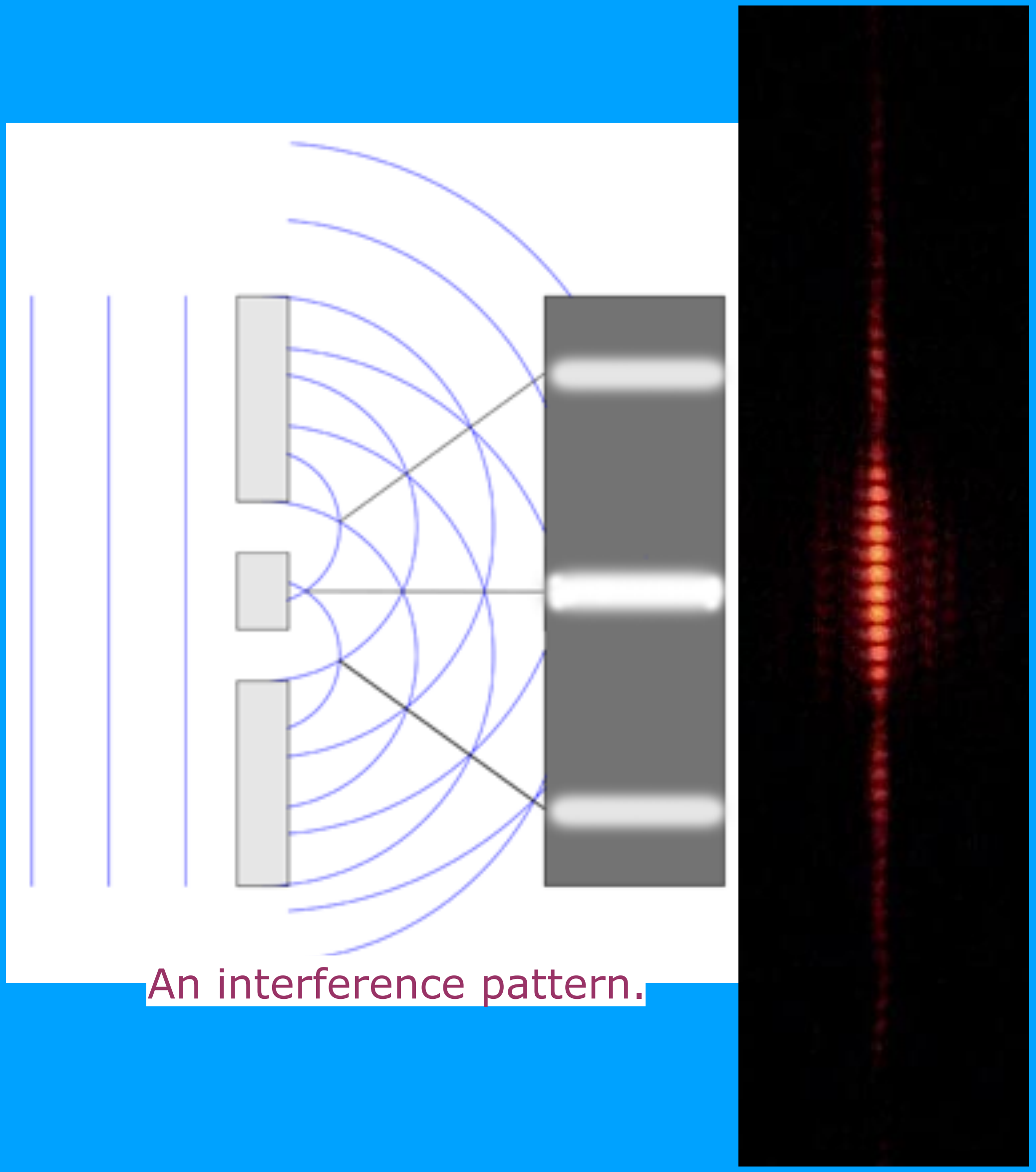




One of the most famous experiments in physics is the **double slit** experiment. It demonstrates, with unparalleled strangeness, that little particles of matter have something of a wave about them, and suggests that the very act of observing a particle has a dramatic effect on its behavior.



The pattern you get from particles.

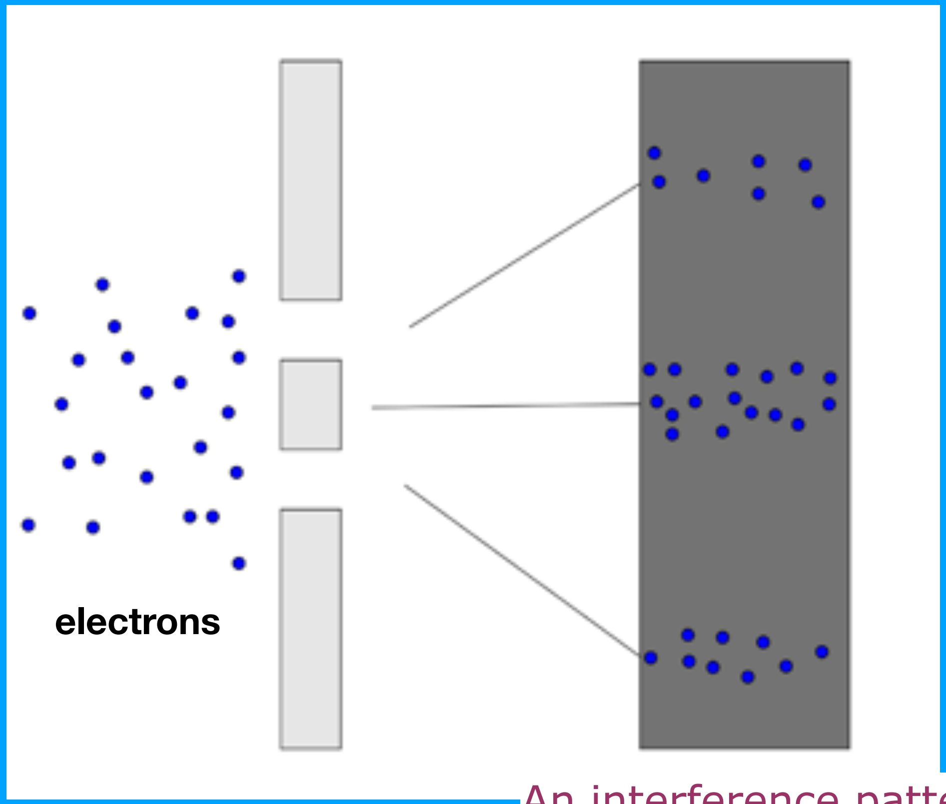


An interference pattern.

Let’s go Quantum

Imagine firing electrons at our wall with the two slits, but **block** one of those slits off for the moment. You'll find that some of the electrons will pass through the open slit and strike the second wall **just as tennis balls would**: the spots they arrive at form a strip roughly the same shape as the slit.

Now **open the second slit**. You'd expect two rectangular strips on the second wall, as with the tennis balls, but what you actually see is very different: the spots where electrons hit build up to **replicate the interference pattern from a wave.**



An interference pattern.

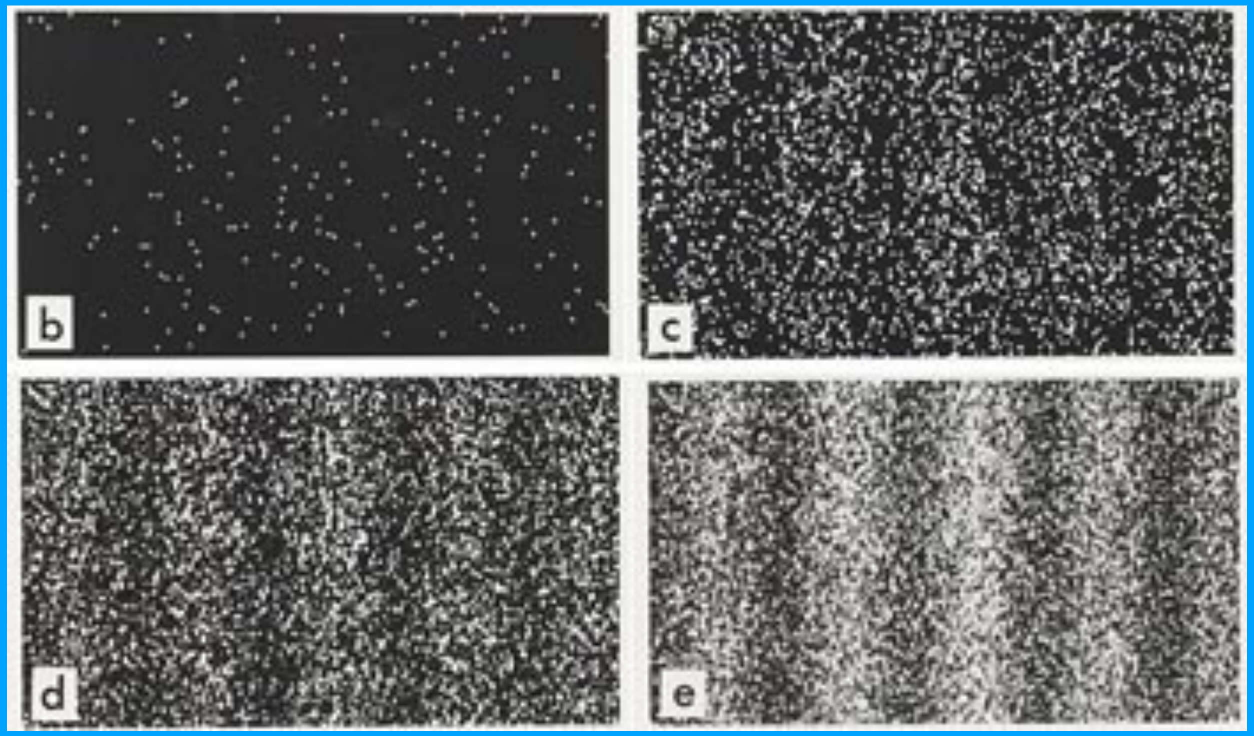


image of a real double slit experiment with electrons. The individual pictures show the pattern you get on the second wall as more and more electrons are fired.

How can this be?

One possibility might be that the electrons **somehow interfere with each other**, so they don't arrive in the same places they would if they were alone.

However, the interference pattern remains even when you fire the electrons one by one, so that they have no chance of interfering. Strangely, each individual electron contributes one dot to an overall pattern that looks like the interference pattern of a wave.

Could it be that each electrons somehow splits, passes through both slits at once, interferes with itself, and then recombines to meet the second screen as a single, localised particle?

To find out, you might place a detector by the slits, to see which slit an electron passes through. And that's the really weird bit. If you do that, then the pattern on the detector screen turns into the particle pattern of two strips

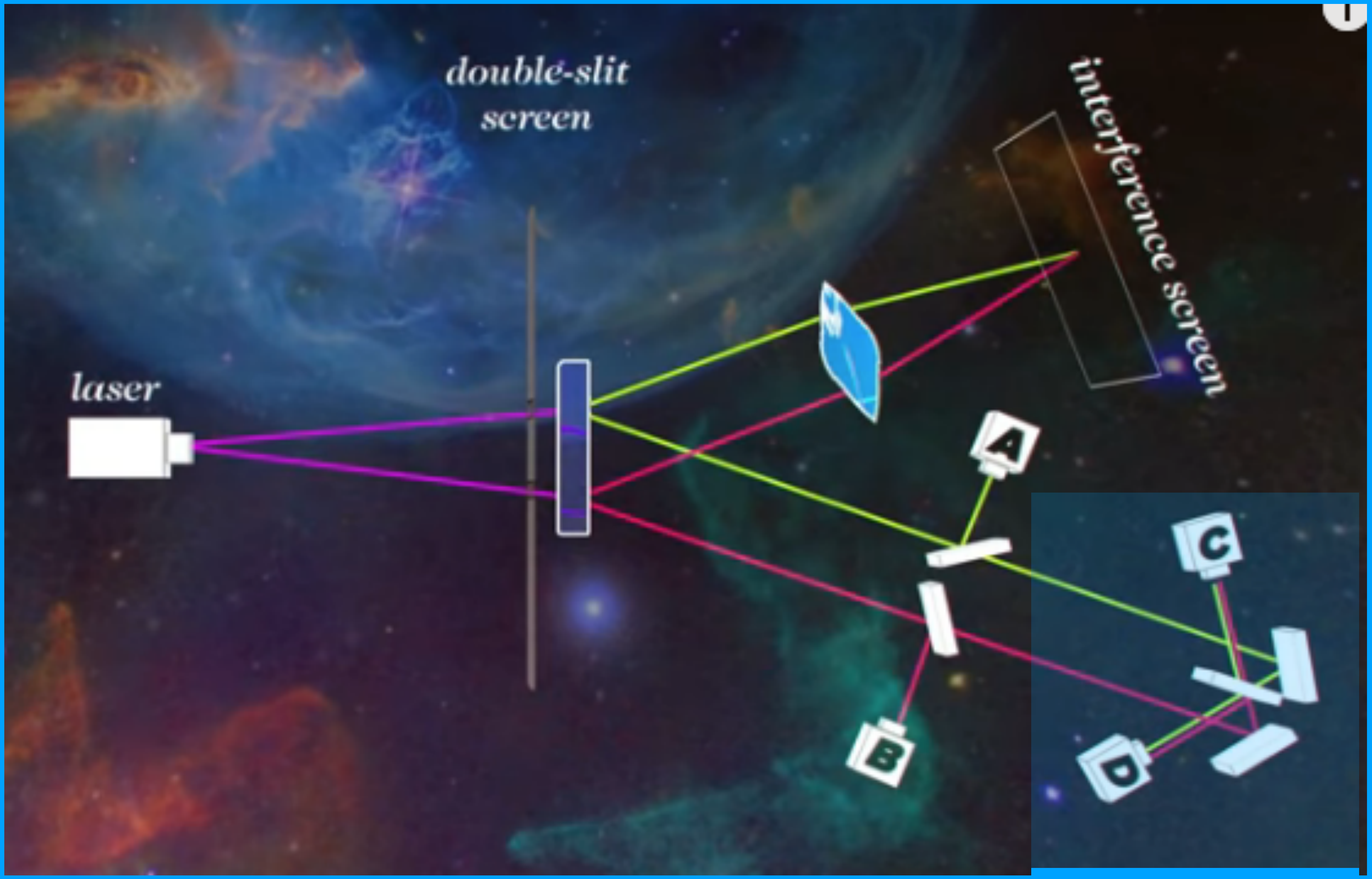
Somehow, the very act of looking makes sure that the electrons travel like well-behaved little tennis balls. It's as if they knew they were being spied on and decided not to be caught in the act of performing weird quantum shenanigans.

That's the famous *wave particle duality* of quantum mechanics

Can things get more creepy???

Can reality be adjusted AFTER events have occur? What is causality?

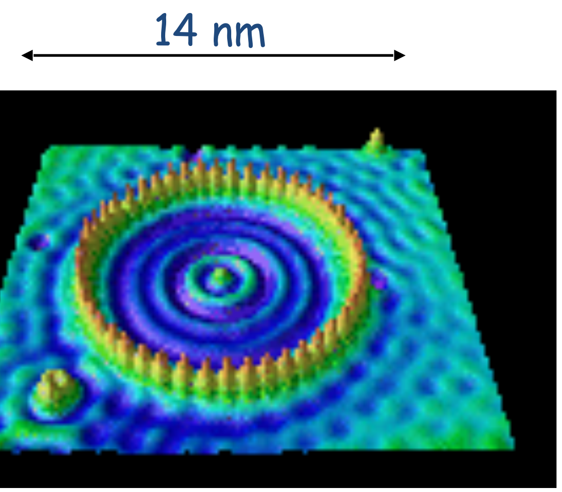
Delayed Choice Quantum Eraser Experiment



Quantum eraser

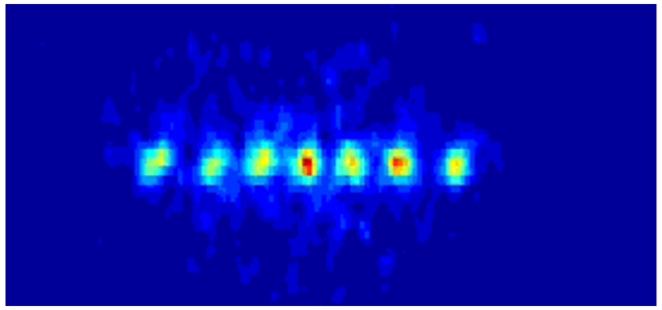
Images of Quantum World

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.

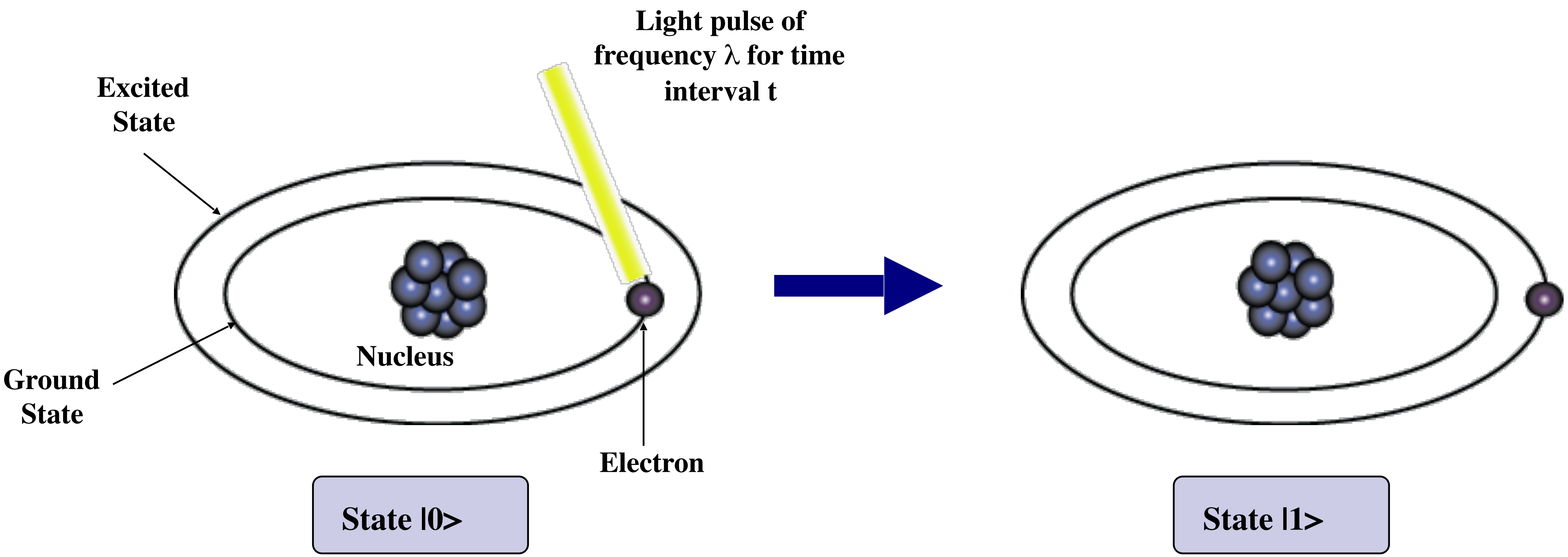


© Innsbruck University

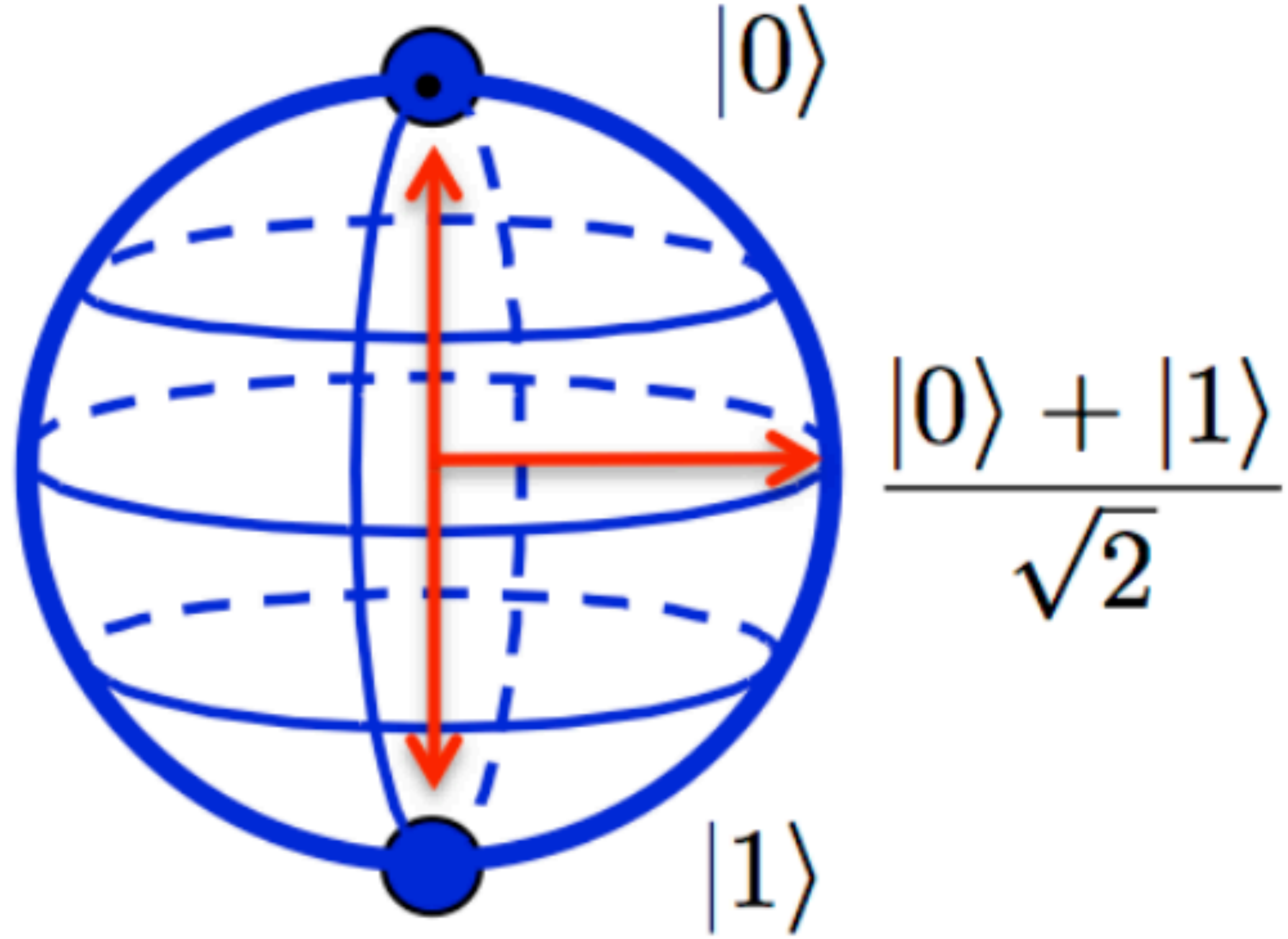
Atom as Bits - Qubits

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>.



Classical Bit



Qubit

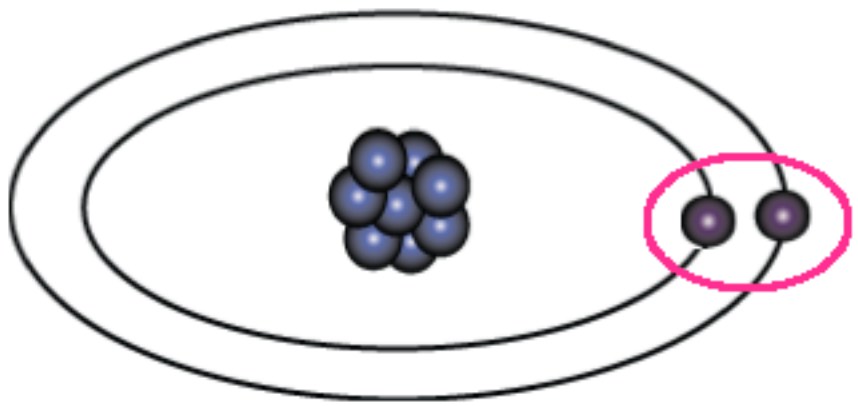
Two things in one?

What do you see?

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

?

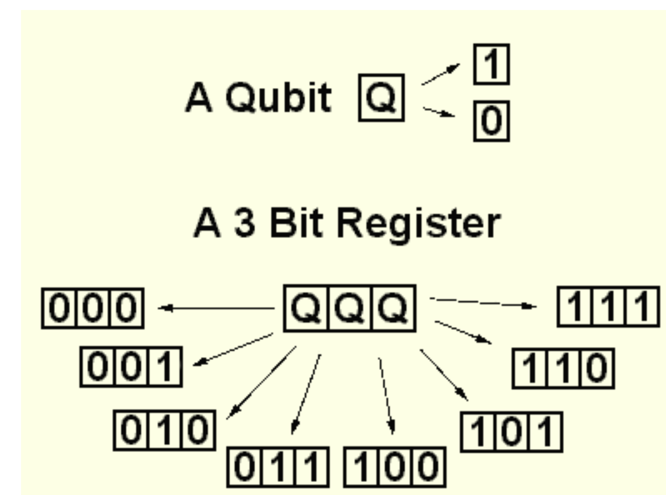
Quantum Superposition



State |0> +|1>

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)	$2x2......x2 = 2^{300}$

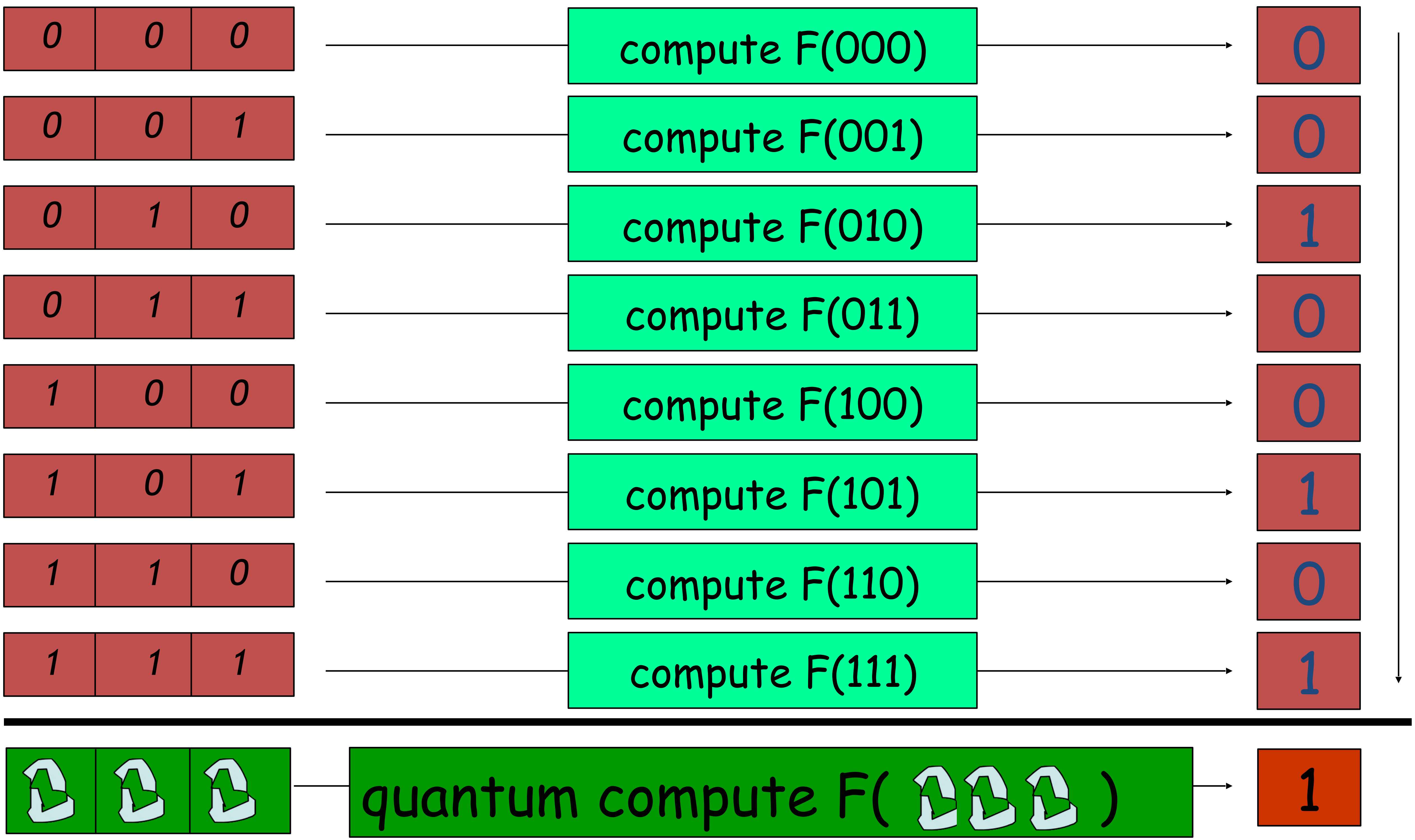


Bigger number than the number of atoms in the universe, and calculations can be performed simultaneously on each of these numbers

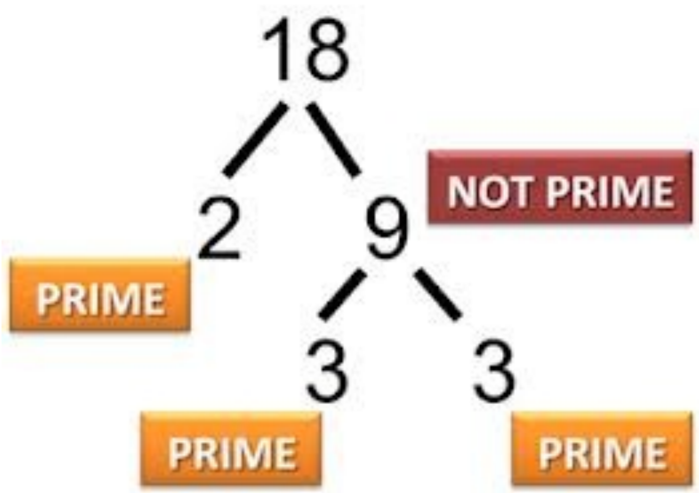
<u>For every extra qubit you get, you can store twice as many numbers</u>

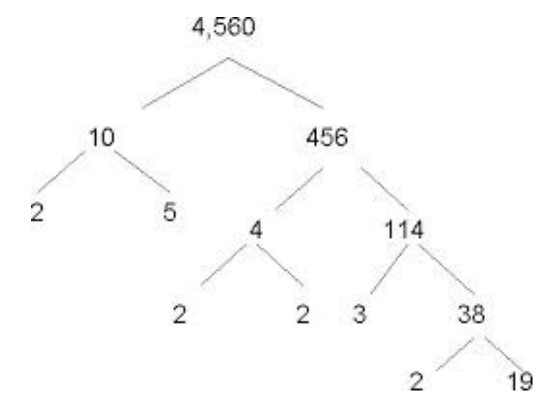
Classical vs. quantum computation

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

Quantum information has shown promising algorithmic developments leading to quantum speedups of computational problems such as **prime number factoring** and **searching an unstructured database.**

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.

Μια... κβαντική πεταλούδα με την υπογραφή Έλληνα φυσικού

Ερευνητές της Google, του Πανεπιστημίου της Καλιφόρνια και του Πολυτεχνείου Κρήτης, με επικεφαλής έναν Έλληνα φυσικό, χρησιμοποίησαν έναν **κβαντικό προσομοιωτή** σε ένα κβαντικό επεξεργαστή της Google, για να δημιουργήσουν μια κβαντική... πεταλούδα.

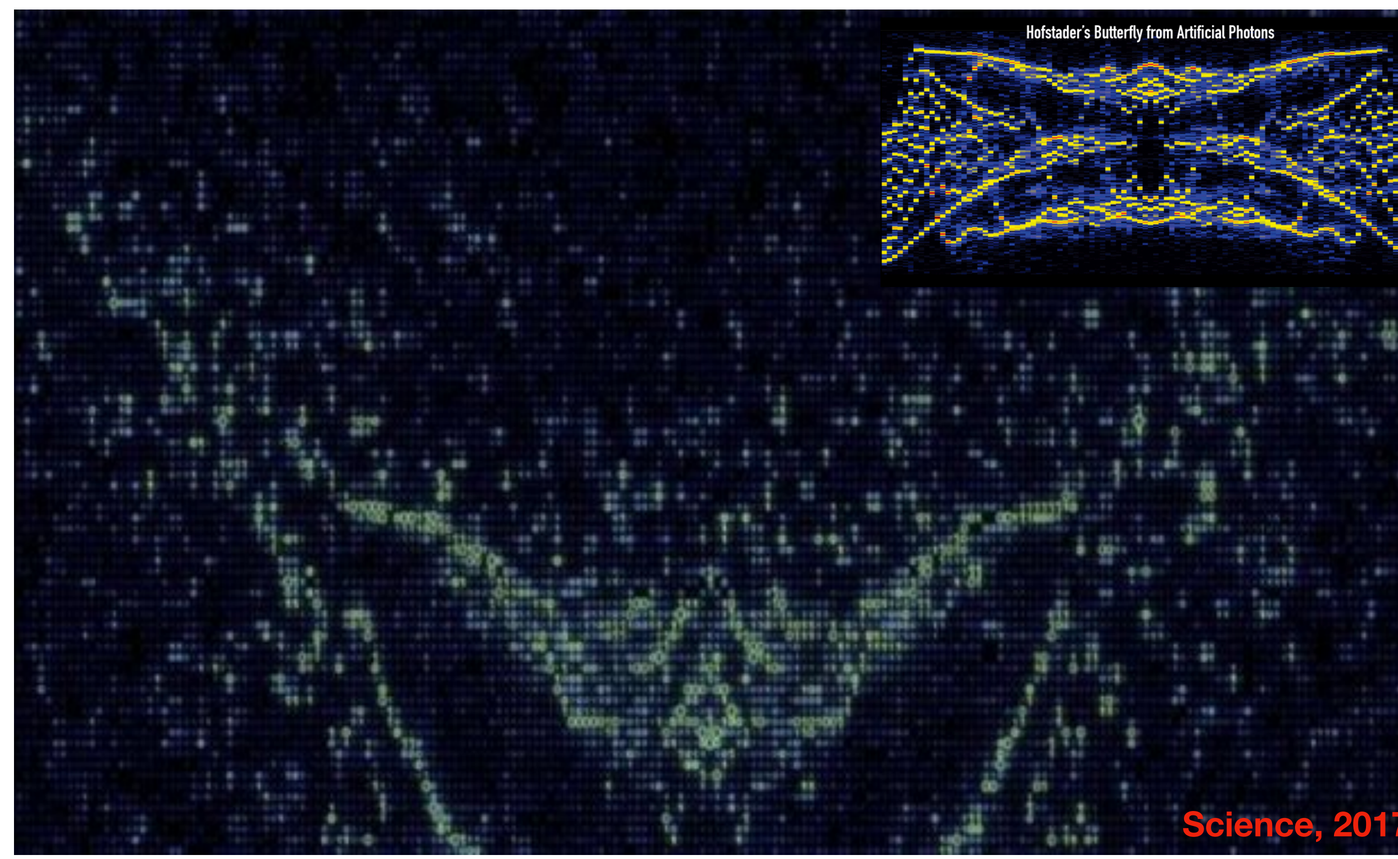
Οι κβαντικοί προσομοιωτές είναι κβαντικοί υπολογιστές συγκεκριμένου σκοπού που βασίζονται σε κβαντικά «τσιπάκια» και θα βοηθήσουν μελλοντικά τους επιστήμονες, μεταξύ άλλων πρακτικών εφαρμογών, να ανακαλύψουν υλικά με εξωτικές και χρήσιμες ιδιότητες. Το νέο επίτευγμα αποτελεί ένα σημαντικό βήμα προόδου προς αυτή την κατεύθυνση, καθώς δείχνει ότι οι κβαντικοί προσομοιωτές αρχίζουν πλέον να λειτουργούν ως ισχυρά εργαλεία.

Οι ερευνητές, με επικεφαλής τον **Δημήτρη Αγγελάκη**, αναπληρωτή καθηγητή του Πολυτεχνείου Κρήτης και συνεργαζόμενο ερευνητή του Κέντρου Κβαντικών Τεχνολογιών της Σιγκαπούρης, που έκαναν τη σχετική δημοσίευση στο περιοδικό "**Science**", χρησιμοποίησαν φωτόνια στον κβαντικό επεξεργαστή της Google για να προσομοιώσουν το σχήμα της λεγόμενης «πεταλούδας Χοφστάντερ», μιας όμορφης γεωμετρικής μορφοκλασματικής δομής (φράκταλ), που χαρακτηρίζει τη συμπεριφορά των ηλεκτρονίων σε ισχυρά μαγνητικά πεδία.

«**Πάντα είχαμε την ιδέα ότι μπορούμε να χρησιμοποιήσουμε τα φωτόνια για να προσομοιώσουμε και να κατανοήσουμε καλύτερα τη φύση**. Η ερευνητική συνεργασία μας πετυχαίνει πλέον κάτι τέτοιο στην πράξη», δήλωσε ο Αγγελάκης, ο οποίος συνεργάσθηκε με ομάδα ερευνητών της Google και του Πανεπιστημίου της Καλιφόρνια-Σάντα Μπάρμπαρα με επικεφαλής τον πρωτοπόρο της κβαντικής υπολογιστικής τεχνολογίας καθηγητή Τζον Μαρτίνις.

Ο επεξεργαστής της Google διέθετε μια αλυσίδα **εννέα υπεραγώγιμων κβαντικών δυφίων** (quantum bits ή qubits). Η «πεταλούδα Hofstadter» είχε εμφανισθεί για πρώτη φορά το 1976, σε υπολογισμούς ηλεκτρονίων σε ένα δισδιάστατο υλικό με ισχυρό μαγνητικό πεδίο. Η πεταλούδα απεικονίζει τις μεταβολές στα ενεργειακά επίπεδα των ηλεκτρονίων, καθώς μεταβάλλεται η ισχύς του μαγνητικού πεδίου.

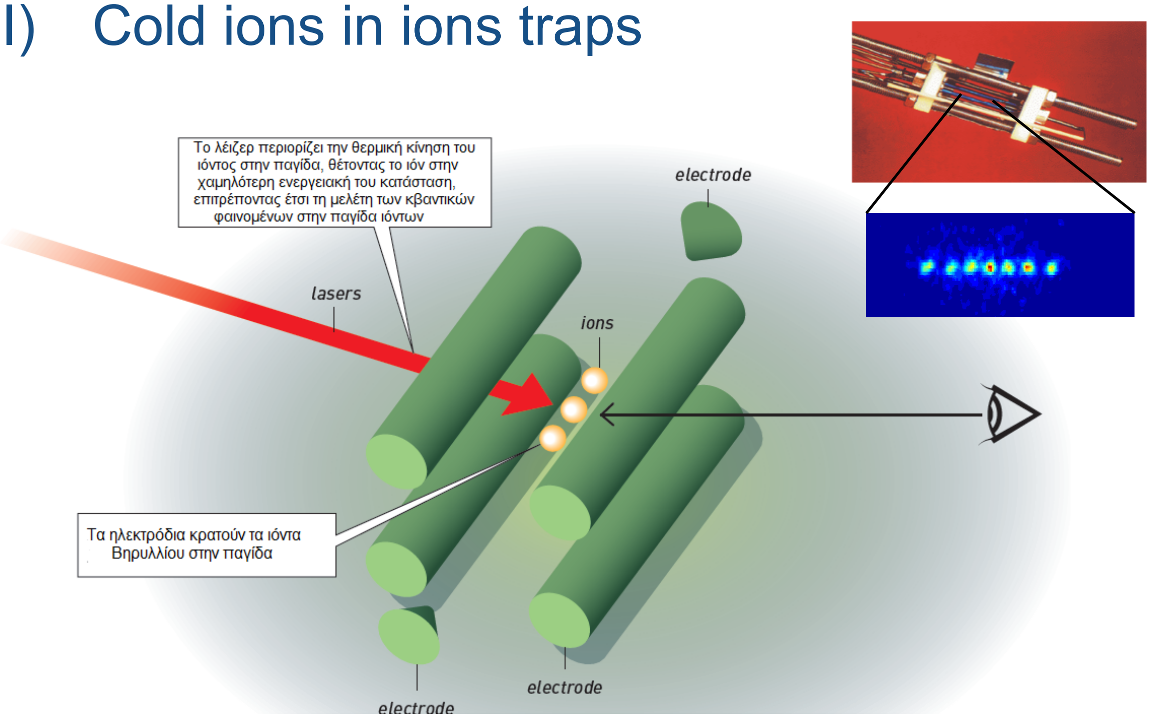
Στην κβαντική προσομοίωση τα φωτόνια έπαιξαν το ρόλο των ηλεκτρονίων, ενώ οι «πύλες» των qubits ήσαν το ανάλογο ενός μαγνητικού πεδίου. Το φράκταλ της κβαντικής πεταλούδας προέκυψε, καθώς οι ερευνητές έκαναν τις σχετικές μετρήσεις με τη βοήθεια μιας νέας φασματοσκοπικής τεχνικής, που βαφτίσθηκε «χτύπα και άκου» και η οποία «χαρτογραφεί» τα ενεργειακά επίπεδα των σωματιδίων του φωτός στα qubits.



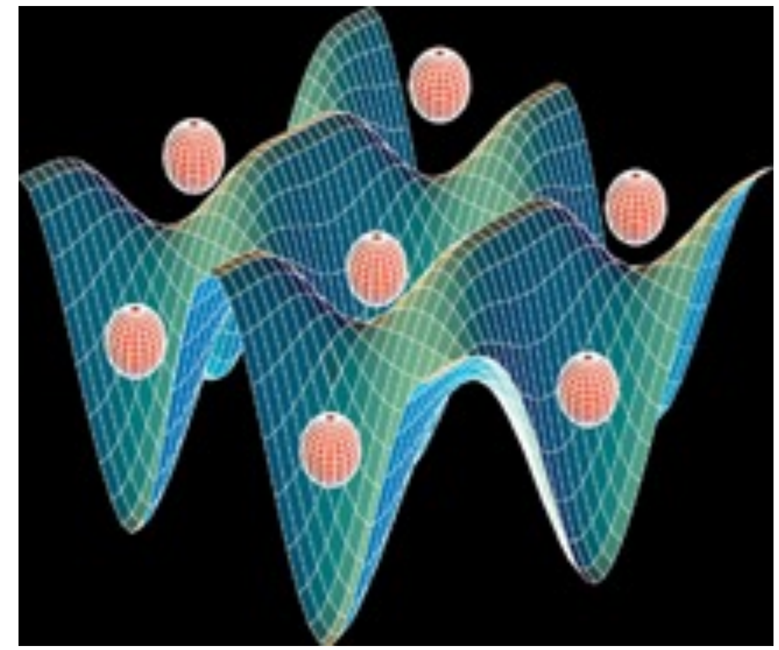
Ο **Δημήτρης Αγγελάκης** είναι αναπληρωτής καθηγητής στη Σχολή Ηλεκτρολόγων Μηχανικών και Μηχανικών Υπολογιστών του Πολυτεχνείου Κρήτης και διευθυντής της ερευνητικής ομάδας Κβαντικής Οπτικής και Κβαντικής Πληροφορίας (QOQI). Εργάζεται παράλληλα σαν επισκέπτης κύριος ερευνητής στο Κέντρο Κβαντικών Τεχνολογιών του Εθνικού Πανεπιστημίου της Σιγκαπούρης. Σπούδασε Φυσική στο Πανεπιστήμιο Κρήτης και πήρε το διδακτορικό δίπλωμά του σ στη Θεωρητική Φυσική από το Imperial College του Λονδίνου το 2002.

Possible implementation platforms - Quantum hardware

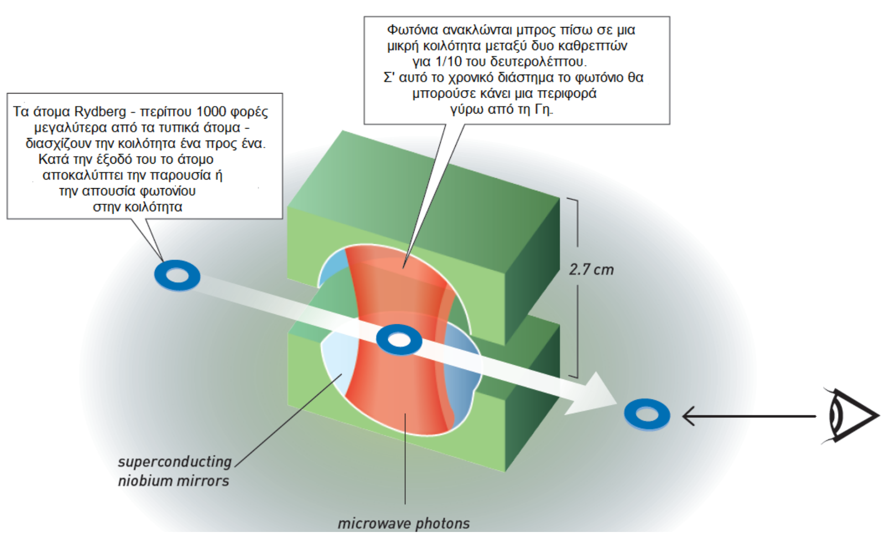
I) Cold ions in ions traps



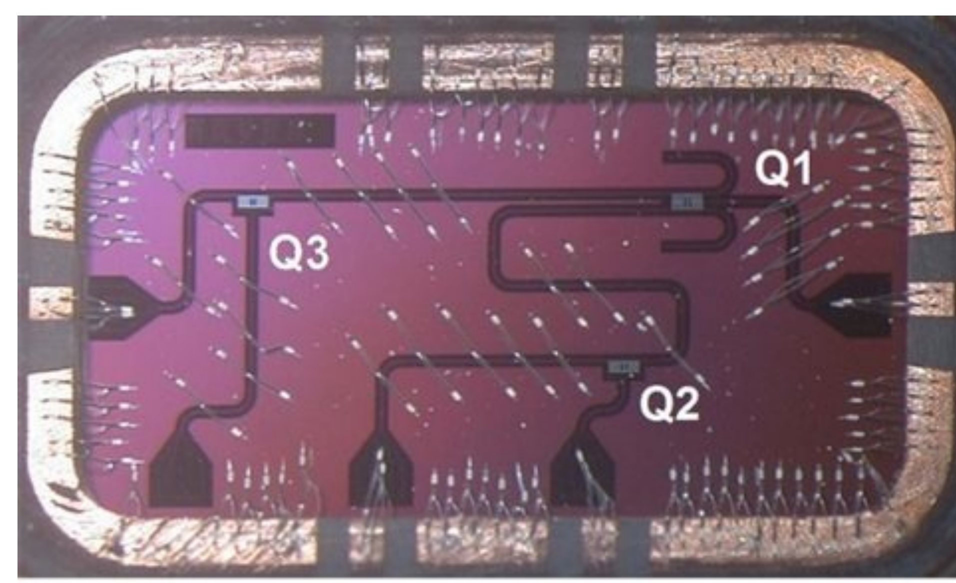
II) Cold atoms in optical lattices



III) Photons in QED resonators



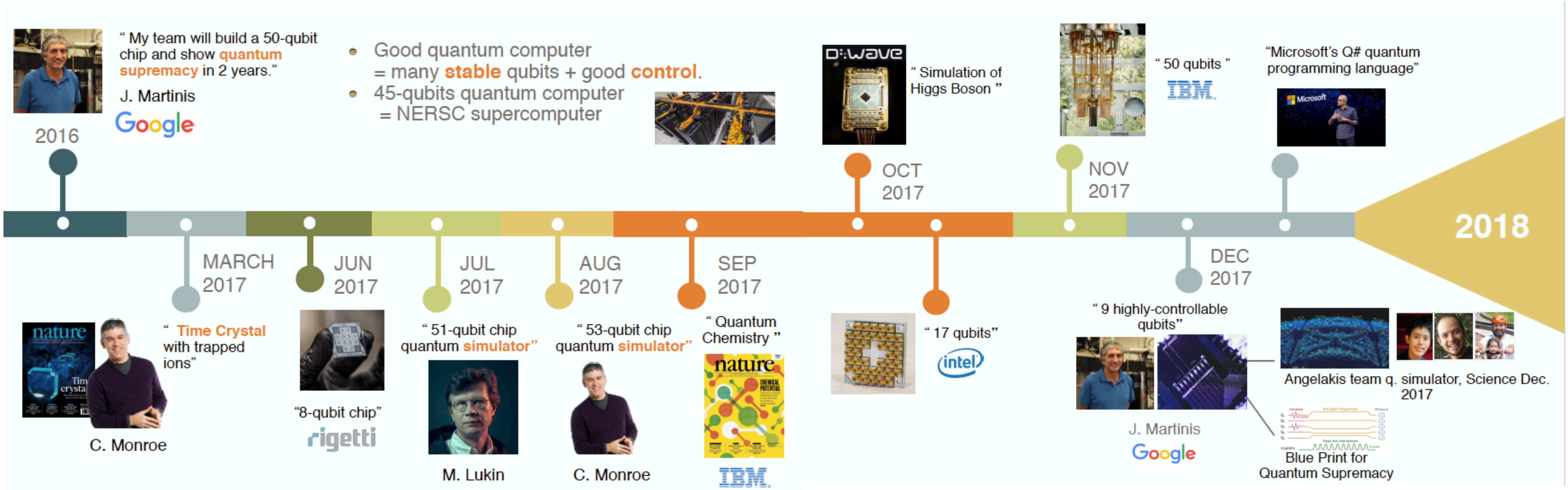
IV) Circuit QED resonators



Prototype Quantum Processors from Companies (2018)

and many more…

Quantum Race



10 Breakthrough Technologies 2017

Practical Quantum Computers

Advances at Google, Intel, and several research groups indicate that computers with previously unimaginable power are finally within reach.

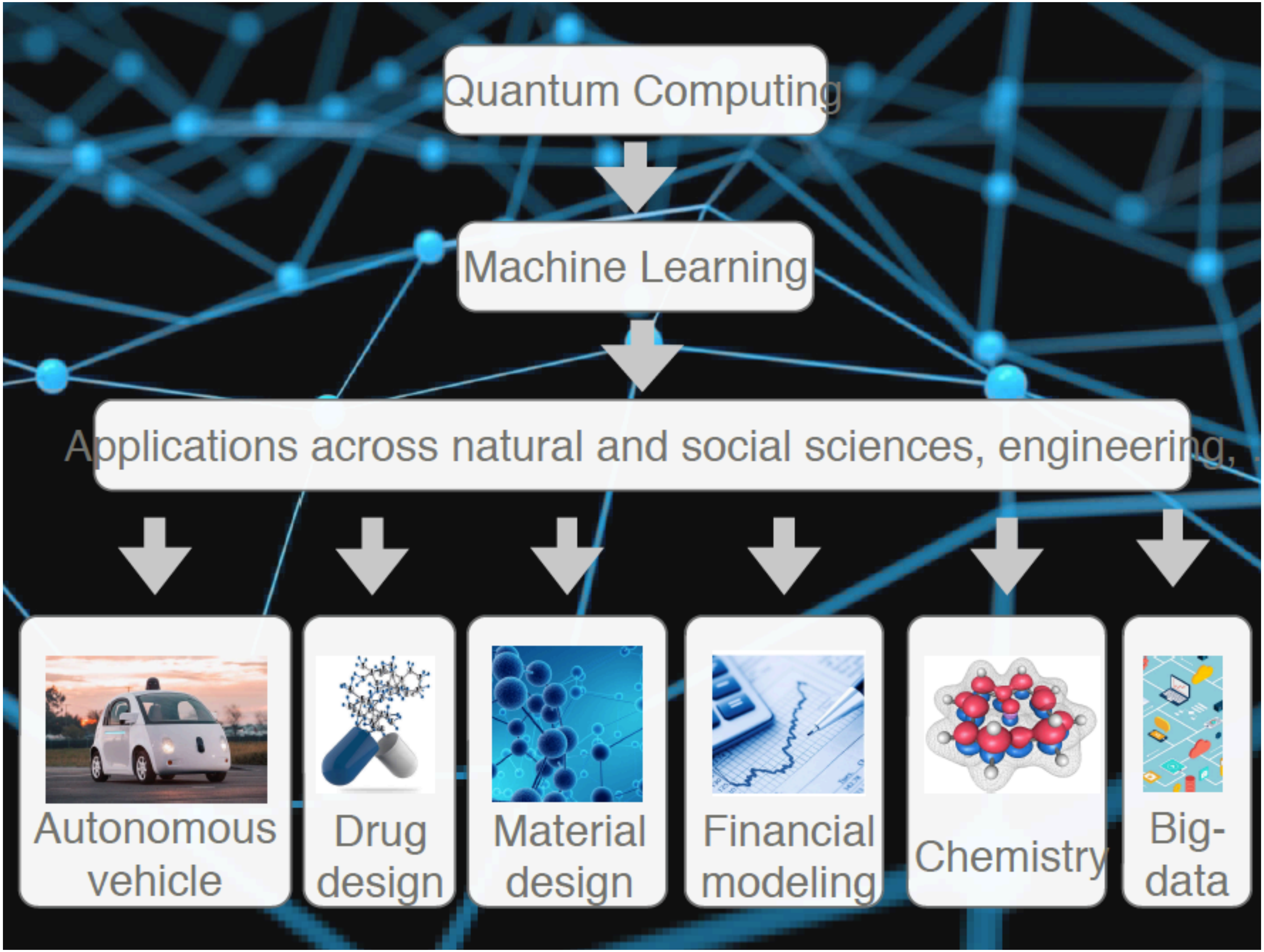
MIT Technology Review https://goo.gl/1zGprq

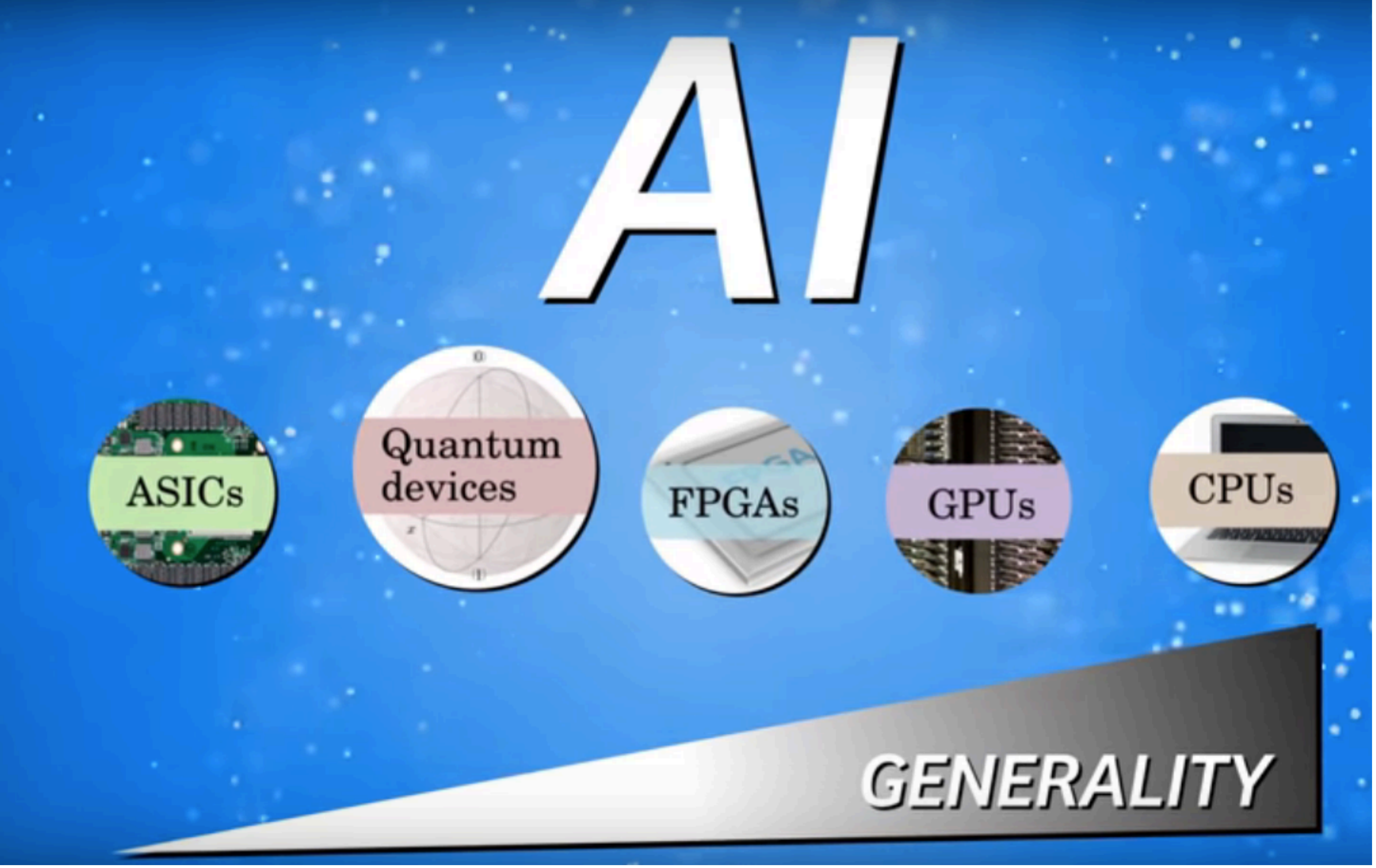
Forbes

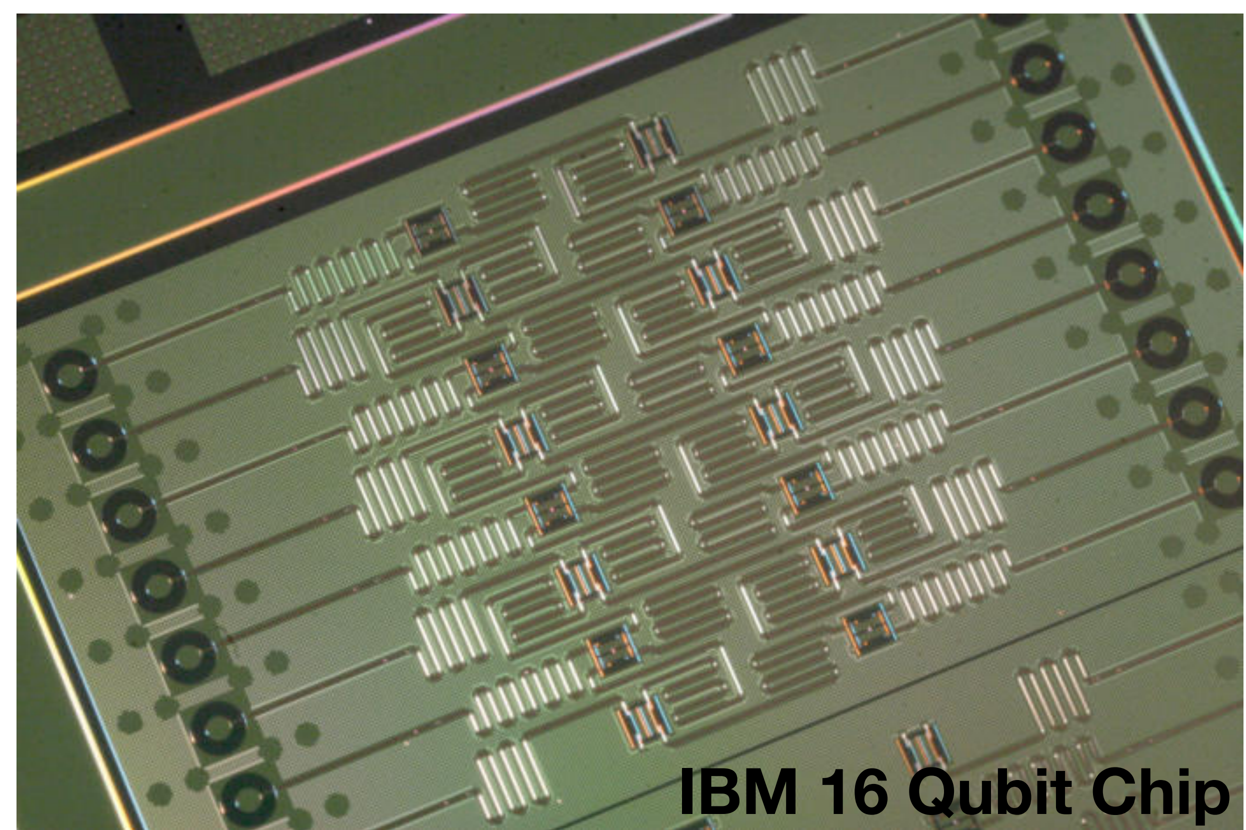
How Quantum Computers Will Revolutionize Artificial Intelligence, Machine Learning And Big Data

- Solve Complex Problems
- Optimize Solutions

https://goo.gl/xtrZBk


Quantum Computing
Machine Learning
Applications across natural and social sciences, engineering,
Autonomous vehicle
Drug design
Material design
Financial modeling
Chemistry
Big-data


AI
ASICs
Quantum devices
FPGAs
GPUs
CPUs
GENERALITY


IBM 16 Qubit Chip

> We are not trying to replace existing computers. We are talking about speed up for certain computational tasks. These are realistic goals.

- Pedram Roushan,
Google

http://www.ebooks.in.th/OQC-LED/

Quantum Computing **on the Cloud** (IBM)

https://www.research.ibm.com/ibm-q/

“They don’t provide capabilities to solve problems from undecidable or NP Hard problem classes.”

The problem set that quantum computers are good at solving involves:

1. Number or data crunching with a huge amount of inputs, such as “**complex optimisation problems** and **communication systems analysis problems**” — calculations that would typically take supercomputers days, years, even billions of years to brute force.

2. Cracking **RSA encryption**. A recent study by the Microsoft Quantum Team suggests this could well be the case, calculating that it’d be doable with around a 2330 qubit quantum computer.

The most cutting edge quantum computers built by heavyweights like Intel, Microsoft, IBM all are currently hovering at around the **50 qubit mark**, however Google have recently announced **Bristlecone, their 72-qubit project**. Given Moore’s law and the current speed of development of these systems, strong RSA may indeed be cracked within 10 years.

Classical machine learning was employed in a variety of related fields:

1. The discovery of the Higgs Boson,
2. Molecular energy prediction trained using databases of known energy spectra
3. Gravitational wave detection

1. Pierre Chiappetta, Pietro Colangelo, P. De Felice, Giuseppe Nardulli, and Guido Pasquariello. Higgs search by neural networks at LHC.vPhys. Lett. B,v322(3):219–223, 1994.

2. Matthias Rupp. Machine learning for quantum mechanics in a nutshell. Int. J. Quantum Chem., 115(16):1058–1073, 2015.

3. Rahul Biswas, Lindy Blackburn, Junwei Cao, Reed Es-sick, Kari Alison Hodge, Erotokritos Katsavounidis, Kyungmin Kim, Young-Min Kim, Eric-Olivier Le Bigot, Chang-Hwan Lee, John J. Oh, Sang Hoon Oh, Edwin J.
Son, Ye Tao, Ruslan Vaulin, and Xiaoge Wang. Application of Machine learning algorithms to the study of noise artifacts in gravitational-wave data. Phys Rev D, September 2013

Google's PageRank machine learning algorithm for search engines that was patented by Larry Page in 19971 and led to the rise of what is today one of the biggest IT companies in the world.

Other important applications of machine learning are:
1. Spam mail filters.
2. Iris recognition for security systems.
3. The evaluation of consumer behaviour.
4. Assessing risks in the financial sector
5. Developing strategies for computer games.
6. etc..

In short, machine learning comes into play wherever we need **computers to interpret data based on experience.** This usually involves huge amounts of previously collected input-output data pairs, and machine learning algorithms have to be very efficient in order to deal with so called **big data**.

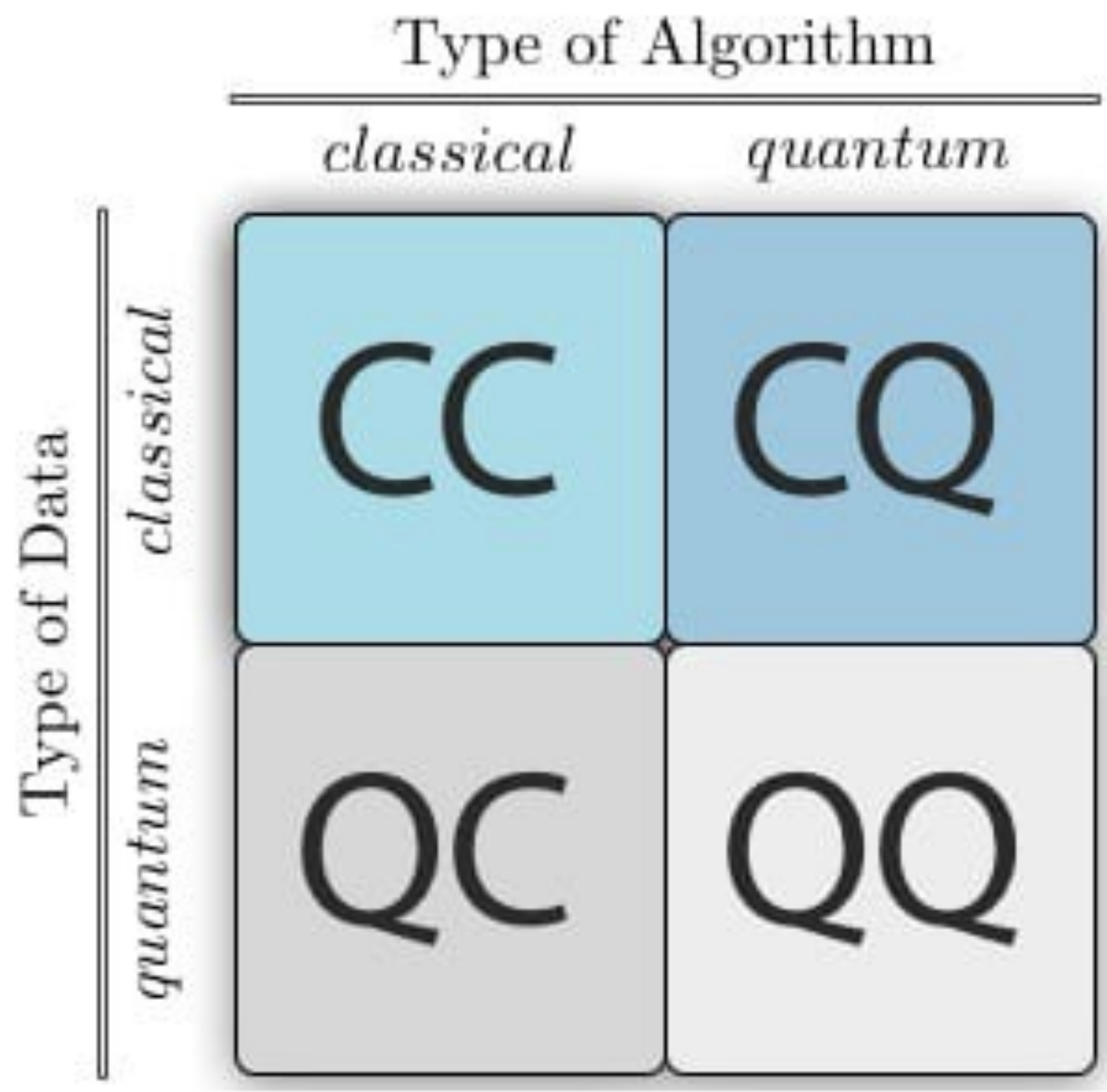
In 1959, Arthur Samuel gave his famous definition of machine learning as the ‘**field of study that gives computers the ability to learn without being explicitly programmed”.**

Since the volume of globally stored data is growing by around 20% every year (currently ranging in the order of several hundred exabytes), the pressure to find innovative approaches to machine learning is rising.

A promising idea that is currently investigated by academia as well as in the research labs of leading IT companies exploits the potential of **quantum computing** in order to optimize classical machine learning algorithms.

Martin Hilbert and Priscila L´opez. The world’s technological capacity to store, communicate, and compute information. Science, 332(6025):60–65, 2011.

How can Quantum Computing advance Machine Learning ?



The 4 approaches to machine learning, categorised by whether the system under study is classic or quantum, and whether the information processing device is classical or quantum.

A number of recent academic contributions explore the idea of using the advantages of quantum computing in order to improve machine learning algorithms.

A. **Quantum versions of artificial neural networks** (based on a more biological perspective) [1, 2, 3].

B. **Quantum algorithms that solve problems of pattern recognition** [5, 6, 7].

C. **Run subroutines of classical machine learning algorithms on a quantum computer**, hoping to gain a speed up.

1. Gerasimos G Rigatos and Spyros G Tzafestas. Neurodynamics and attractors in quantum associative memories. Integrated Computer-Aided Engineering, 14(3):225–242, 2007.
2. Elizabeth C Behrman and James E Steck. A quantum neural network computes its own relative phase. arXiv preprint arXiv: 1301.2808, 2013.
3..Sanjay Gupta and RKP Zia. Quantum neural networks. Journal of Computer and System Sciences, 63(3):355–383, 2001.
4. Maria Schuld, Ilya Sinayskiy, and Francesco Petruccione. The quest for a quantum neural network. Quantum Information Processing, DOI 10.1007/s11128-014-0809-8, 2014.
5. Dan Ventura and Tony Martinez. Quantum associative memory. Information Sciences, 124(1):273–296, 2000.
6. Carlo A Trugenberger. Quantum pattern recognition. Quantum Information Processing, 1(6):471–493, 2002.
7. Ralf Sch¨utzhold. Pattern recognition on a quantum computer. Physical Review A, 67:062311, 2003.

Other types of speedups are related to **prime number factoring** and **finding eigenvalues and eigenvectors of large matrices**.

This speedup is enabled by:

1. **Quantum phase estimation.**
2. **Quantum Fourier transform.**
3. **Quantum simulation methods.**
4. **Matrix multiplication. A Quantum gate is a linear layer of a giant neural net !**

The number of quantum gates is proportional to **O(logN)** for preparing a quantum state encoding eigenvalues of an N×N matrix and the associated eigenstates, while classically **O(N)** operations are required to find eigenvalues and eigenvectors.

How will classic computing and quantum computing work together?

Quantum computers will never “replace” classic computers, simply because there are some problems that classic computers are better and/or more efficient at solving.

“Likely future scenario is that quantum computing will augment subroutines of classical algorithms that can be efficiently run on quantum computers, such as sampling, to tackle specific business problems.“

For instance:

1. a company seeking to find the ideal route for retail deliveries could split the problem into two parts and leverage each computer for its strengths.”
2. Numburi likes the use case for **blockchain**, suggesting that it be used to “speed permissions on the extremely laggy Proof of Work system which is necessary for the blockchain to hold true right now. **Quantum computers can handle the level of processing computers** in this day and age can’t.”

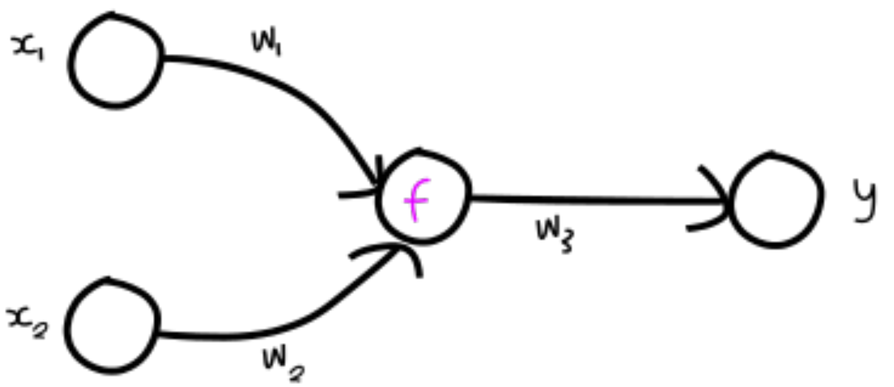
Deep learning = parallel "for" loops

All classical algorithms based on serial processing ,It depends on the feedback of the first loop ,On applying a serial classical algorithm in multiple clusters wont give a good result ,but some light weight parallel classical algorithms(Deep learning) doing the job in multiple clusters but are not suitable for complex problems, What is the solution for then?

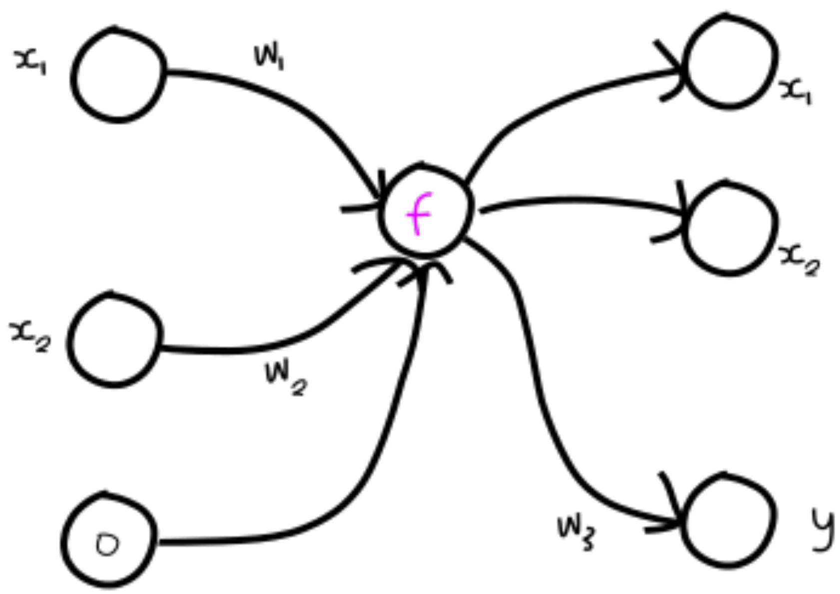
The advantage behind deep learning is doing the batch processing simply on the data ,but quantum machine learning designed to do batch processing as per the algorithm

The product companies realised this one and they started migrating to quantum machine learning and executing the classical algorithms on quantum concept gives better result than deep learning algorithms on classical computer and the target to merge both to give very wonderful result

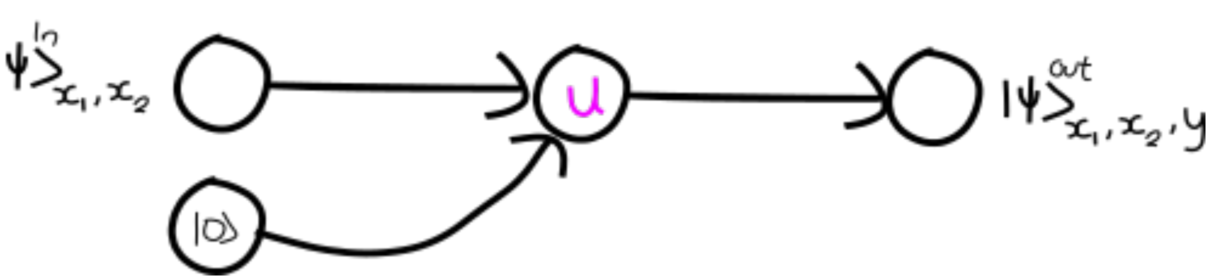
Classical - Not Reversible



Classical - Reversible



Quantum



QUANTUM NEURAL NETWORK

Its really one of the hardest topic , To understand easily ,Normal Neural Network is doing parallel processes ,**QNN is doing parallel of parallel processess** ,In theory <u>combination of various activation functions is possible in QNN.</u> In Normal NN more than one activation function reduce the performance and increases the complexity.

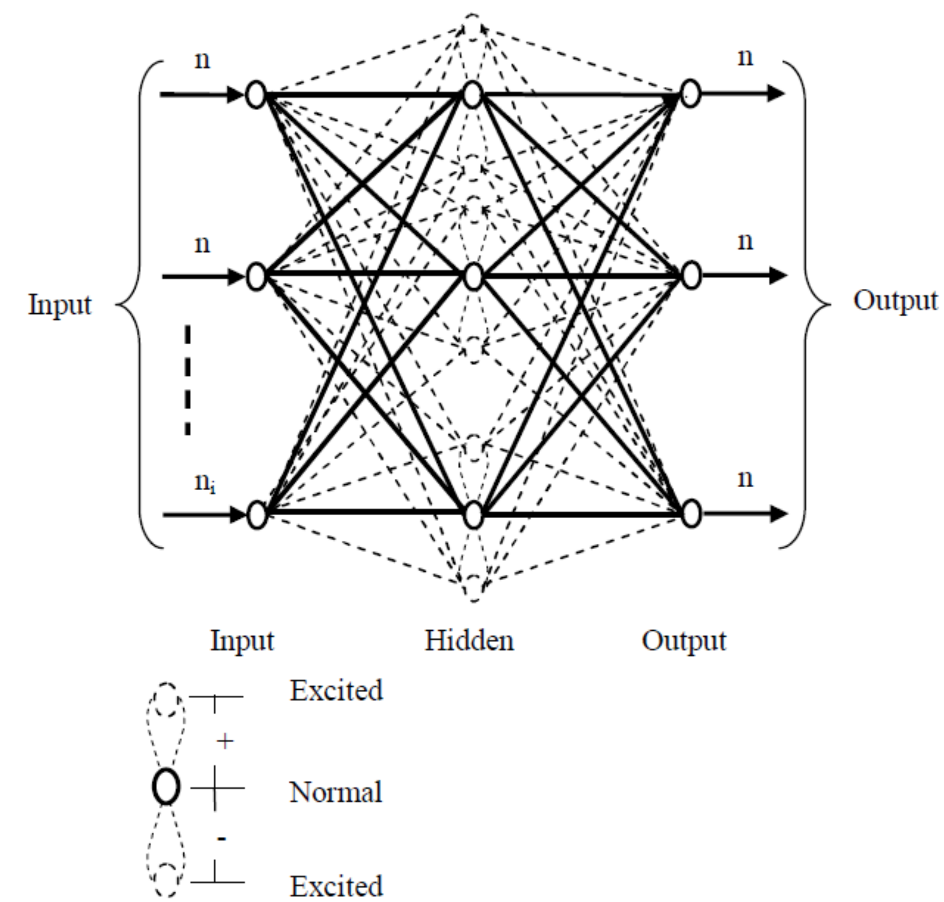


Fig.1 Architecture of Quantum Neural Network

Quantum versions of machine learning algorithms

Ideas range from running computationally costly algorithms or their subroutines efficiently on a quantum computer to the translation of stochastic methods into the language of quantum theory.

The most notable examples include quantum enhanced algorithms for:

A. **Least-square fitting.**
B. **Principal component analysis.**
C. S**upport vector machines.**
D. **Deep-learning**
E. Q**uantum Boltzmann machines (QBM)** (Overcome the vanishing gradient problem).

vanishing gradient problem is a difficulty found in training artificial neural networks with gradient-based learning methods and backpropagation. In such methods, each of the neural network's weights **receives an update proportional to the partial derivative of the error function** with respect to the current weight in each iteration of training. The problem is that in some cases, the gradient will be vanishingly small, effectively preventing the weight from changing its value. In the worst case, this may completely stop the neural network from further training.

QBM: https://arxiv.org/pdf/1601.02036.p

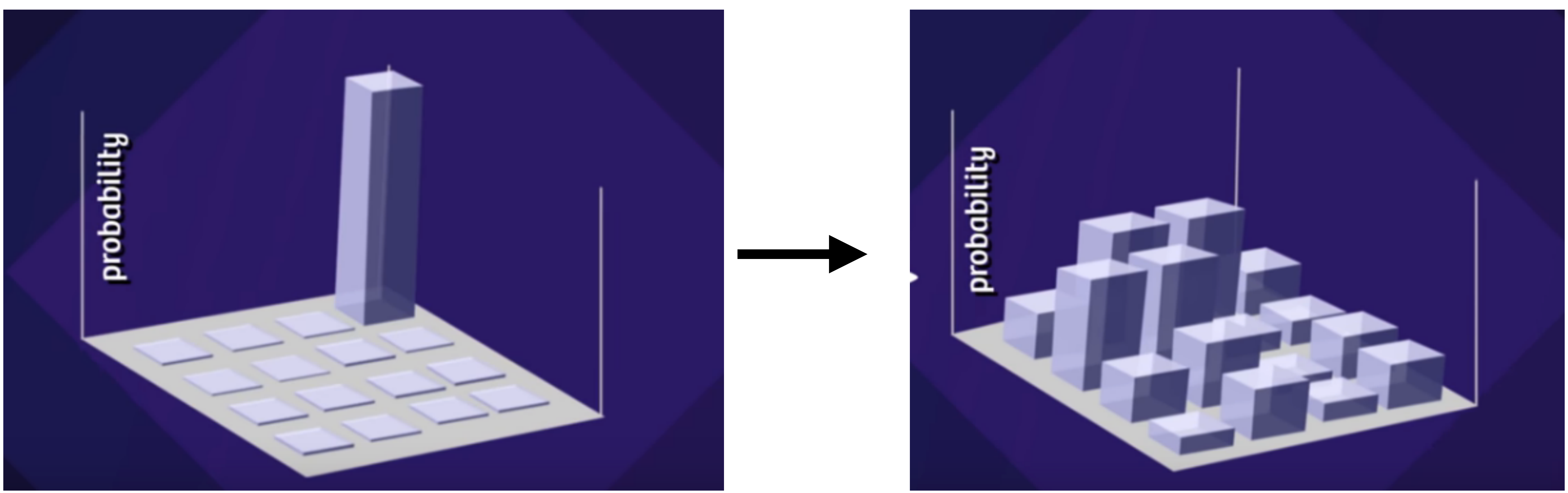
Quantum Sampling

Amplitude amplification is commonly used to quadratically reduce the number of samples needed in sampling algorithms.

Specifically, if N samples would be required on average in a sampling algorithm then amplitude amplification can be used to reduce this to O(√N) samples on average. **Quantum Grover search problem** is a well known example of amplitude amplification, and so such quadratic speedups are often called “Grover-like”.

Quantum computers as samplers that prepare a class of distributions and sample from them with measurements

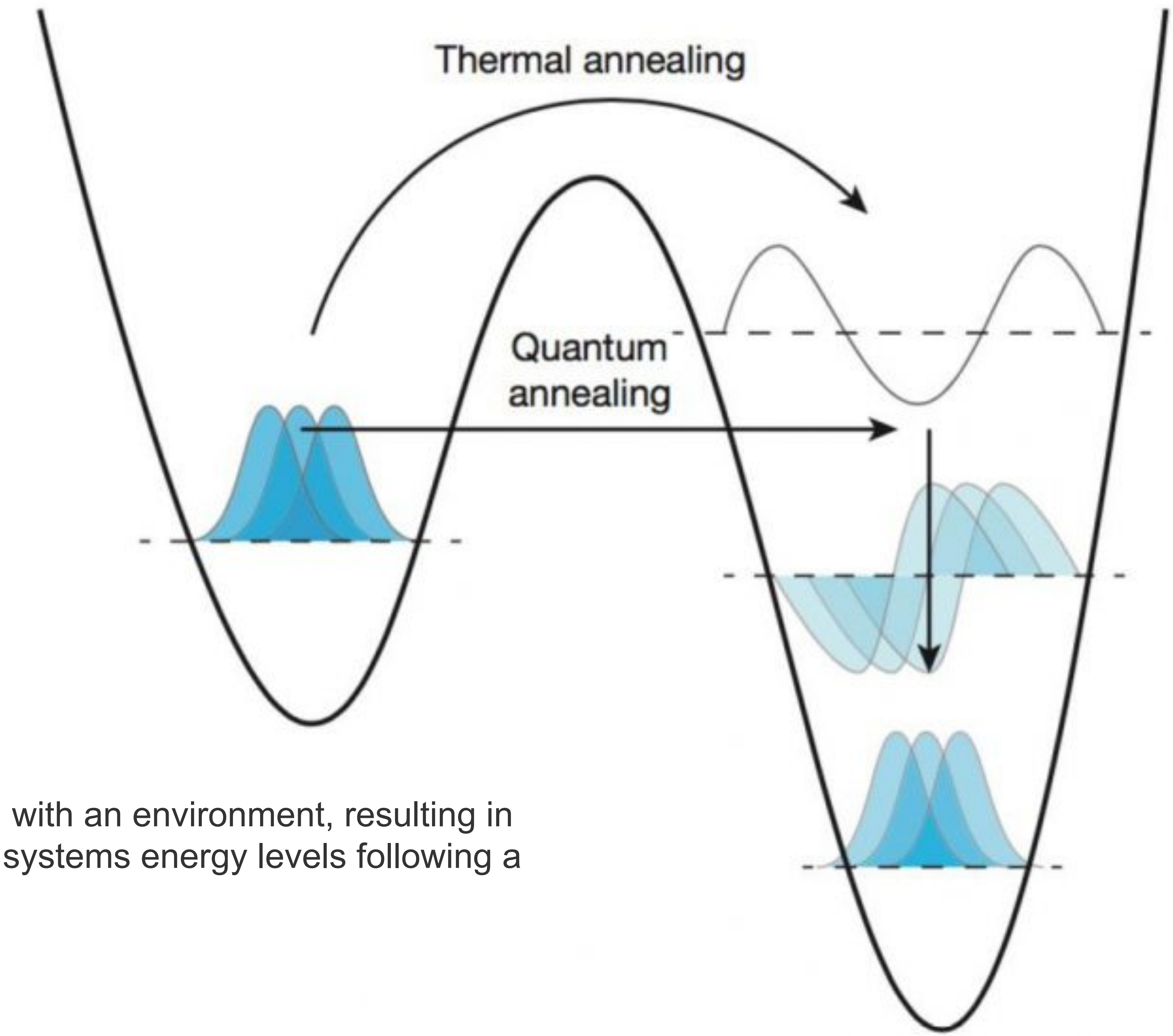
Initial State **Sample**



Sample based training for Boltzman machines **https://arxiv.org/abs/1702.03061**

Quantum Annealing

Potential Barrier

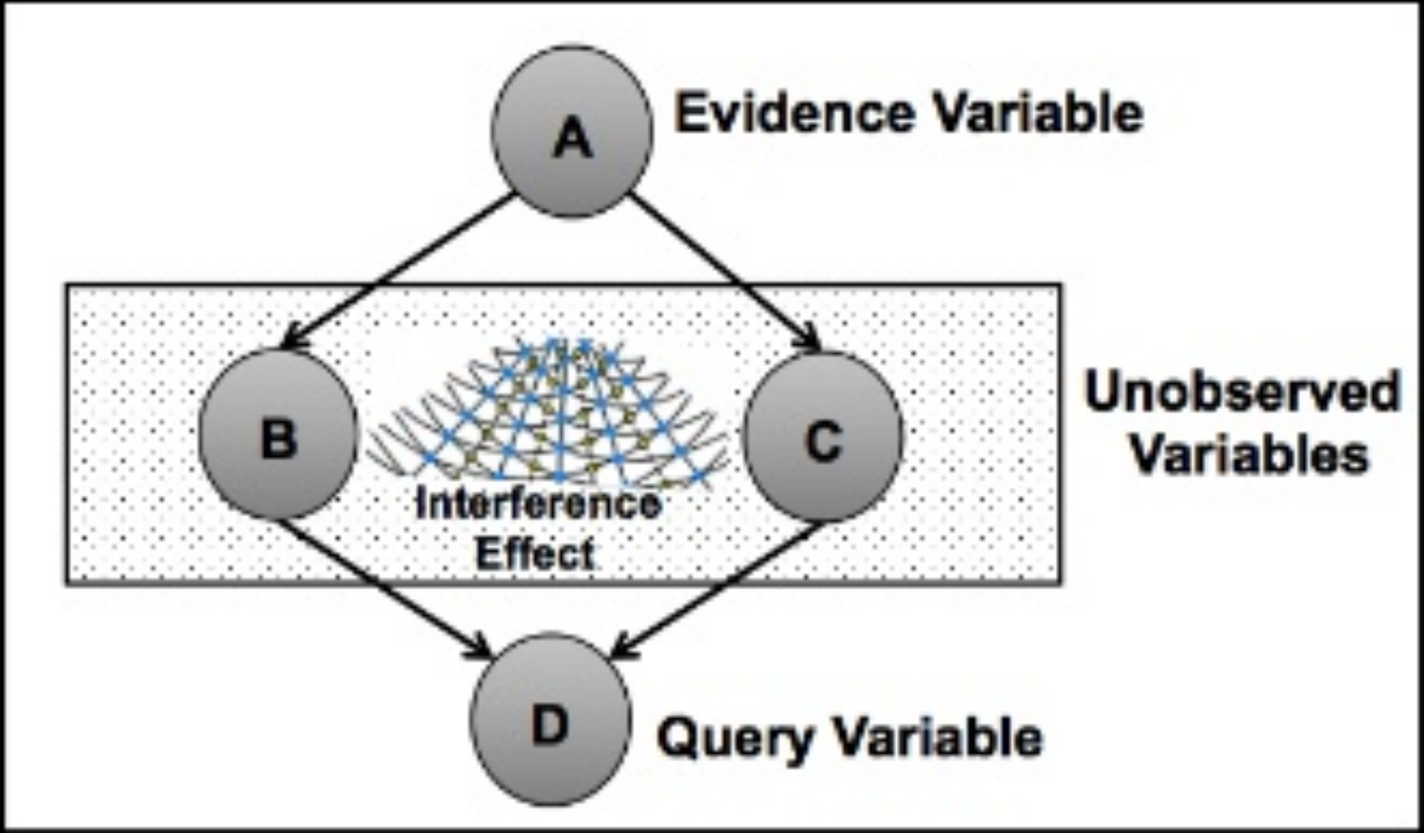


Coherent effects decay through interaction with an environment, resulting in a probability distribution in occupancy of a systems energy levels following a Gibbs distribution

A quantum state tunnels when approaching a resonance point before decoherence induces thermalization.

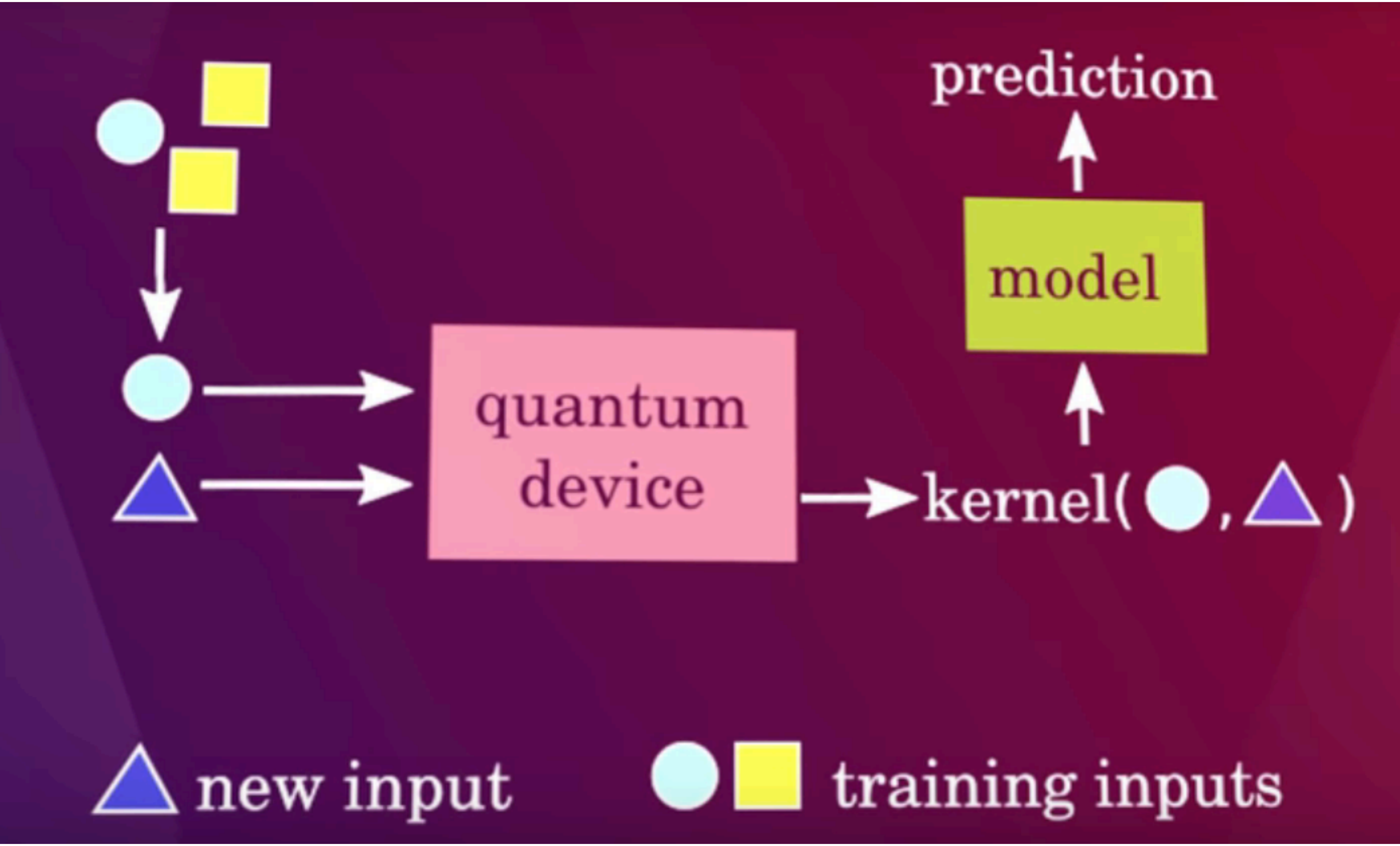
Quantum-Like Bayesian Networks

* Under unknown events, the quantum-like Bayesian Networks can use interference effects.
* Under known events, no interference is used, since there is no uncertainty.

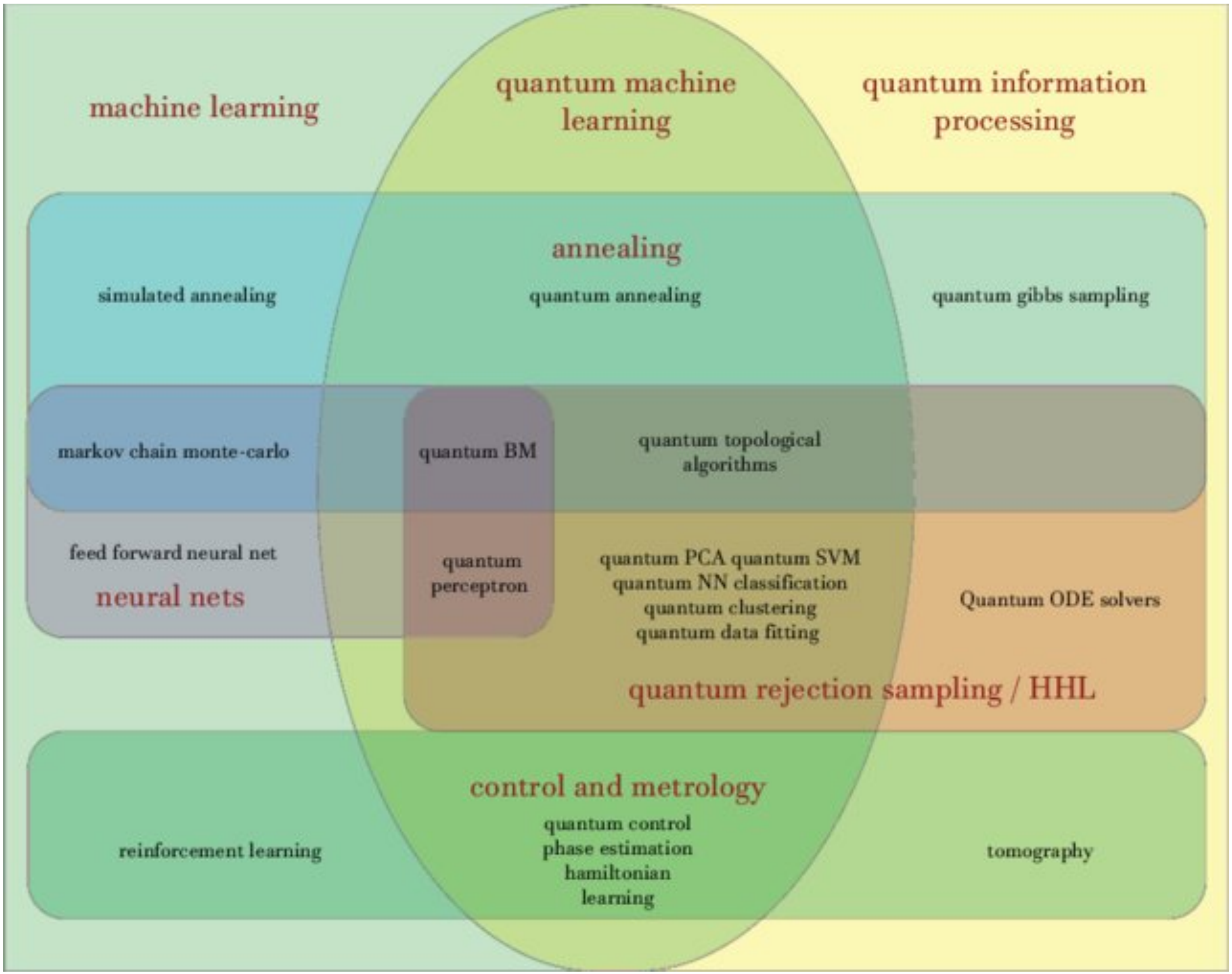


Moreira & Wichert (2014), Interference Effects in Quantum Belief Networks, Applied Soft Computing, 25, 64-85

Kernel evaluation



Conceptual depiction of mutual crossovers between quantum and traditional machine learning




MERGING
CONDENSED MATTER
with QUANTUM optics
DIMITRIS ANGELAKIS
CQT, NUS
QUANTUM simulation with PHOTONS
QUANTUM THERMALIZATION
PHOTON BLOCKADE
AS A RESULT, A PHOTON LATTICE model IS BORN!

Ευχαριστώ !!!