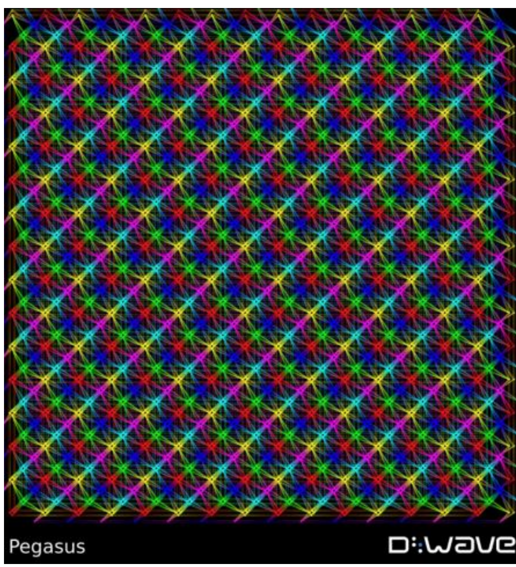
Quantum Computing

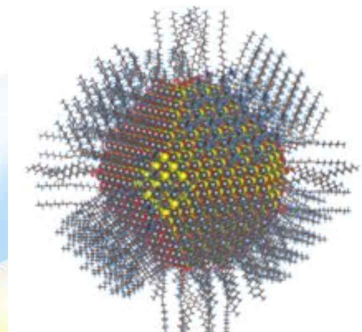
Recent Developments

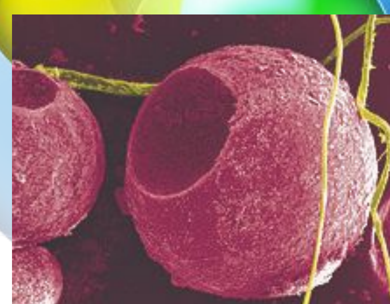
Vesselin G. Gueorguiev

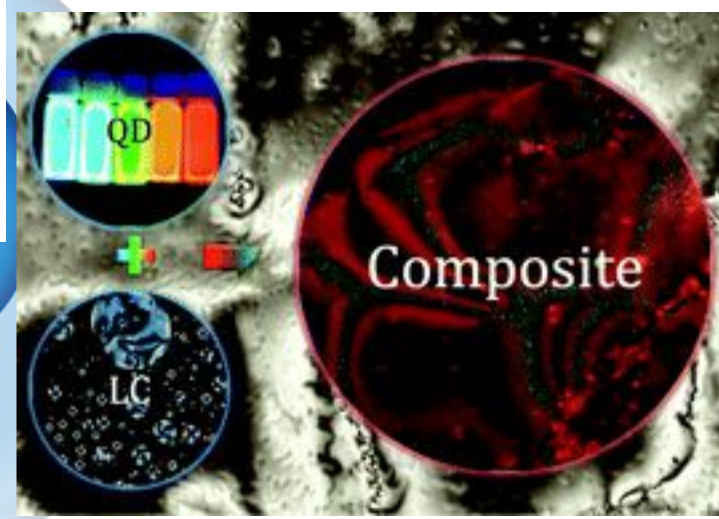
Ronin Institute &

Institute for Advanced Physical Studies









Outline

- Key Concepts in Quantum Computing
- Possible Applications of QC
- Present Status on QC Resources
- Recent Developments and Future Directions
- Conclusion
- Q&A and Discussion

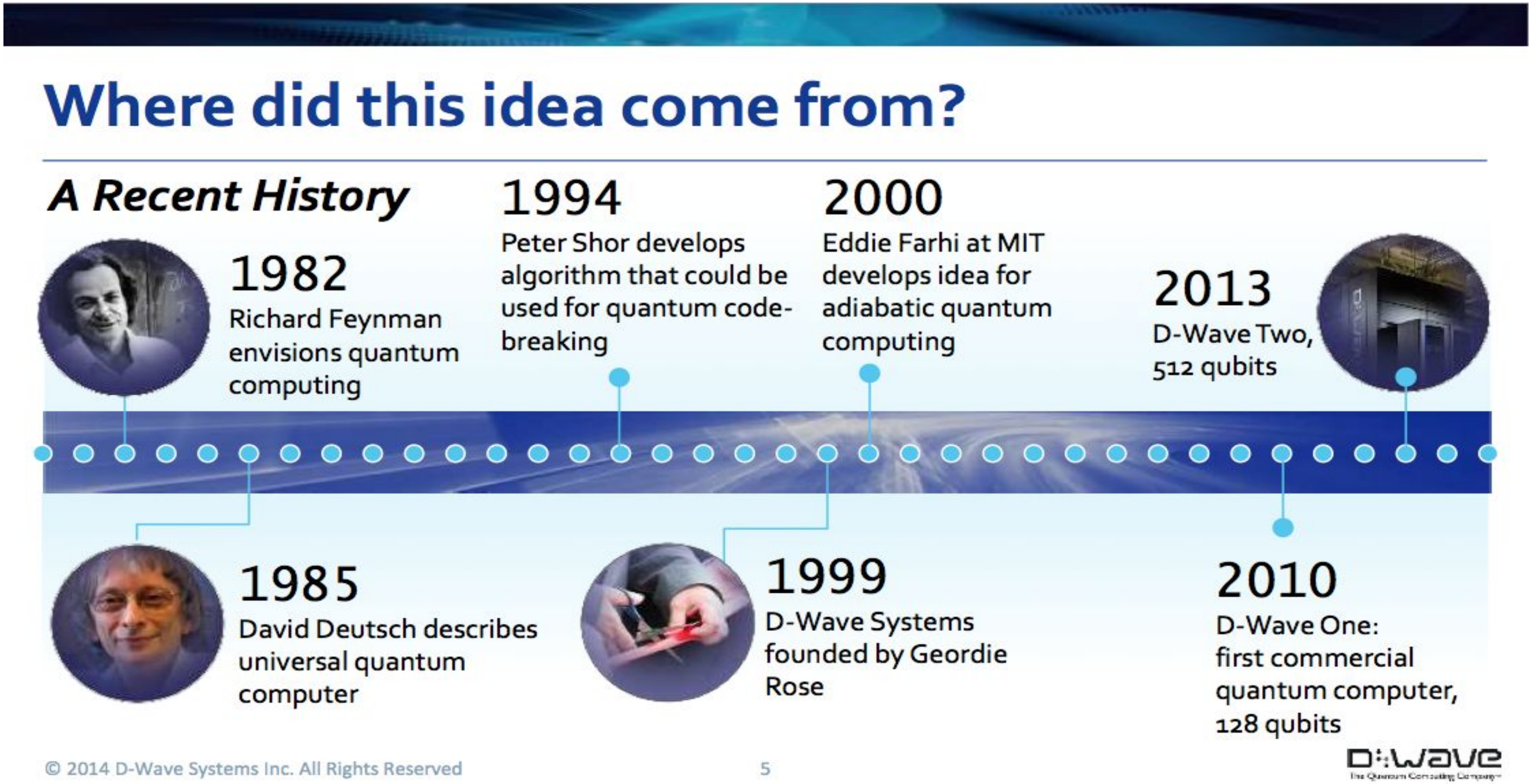
Go to **www.menti.com** and use the code **7427 2778**

Homework

What QC resources do you know about?

Key Concepts in Quantum Computing

LinkedIn SlideShare: 17 Nov 2014 – "Quantum Computing: Welcome to the Future" by Vern Brownell CEO

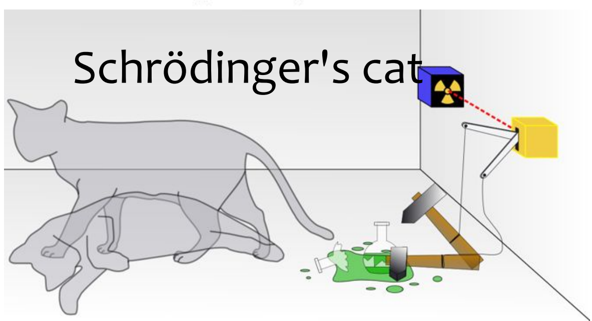


For more details see Wikipedia: [Timeline of quantum computing and communication]

Key Concepts in Quantum Physics

Key Quantum Effects

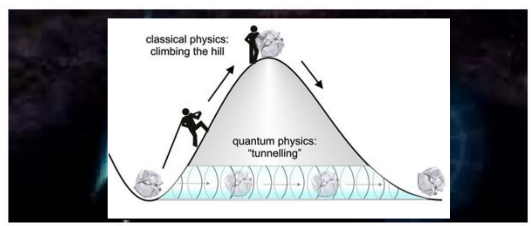
Superposition

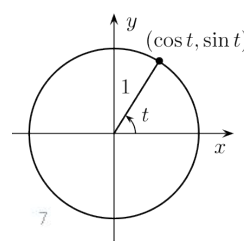


$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

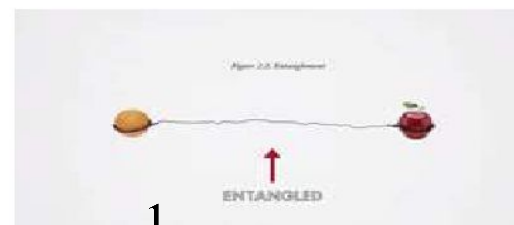
Where α **and** β are complex numbers and $|\alpha|^2 + |\beta|^2 = 1$

Quantum Tunneling





Entanglement



$$\frac{1}{\sqrt{2}}\left(|00\rangle \pm |11\rangle\right)$$

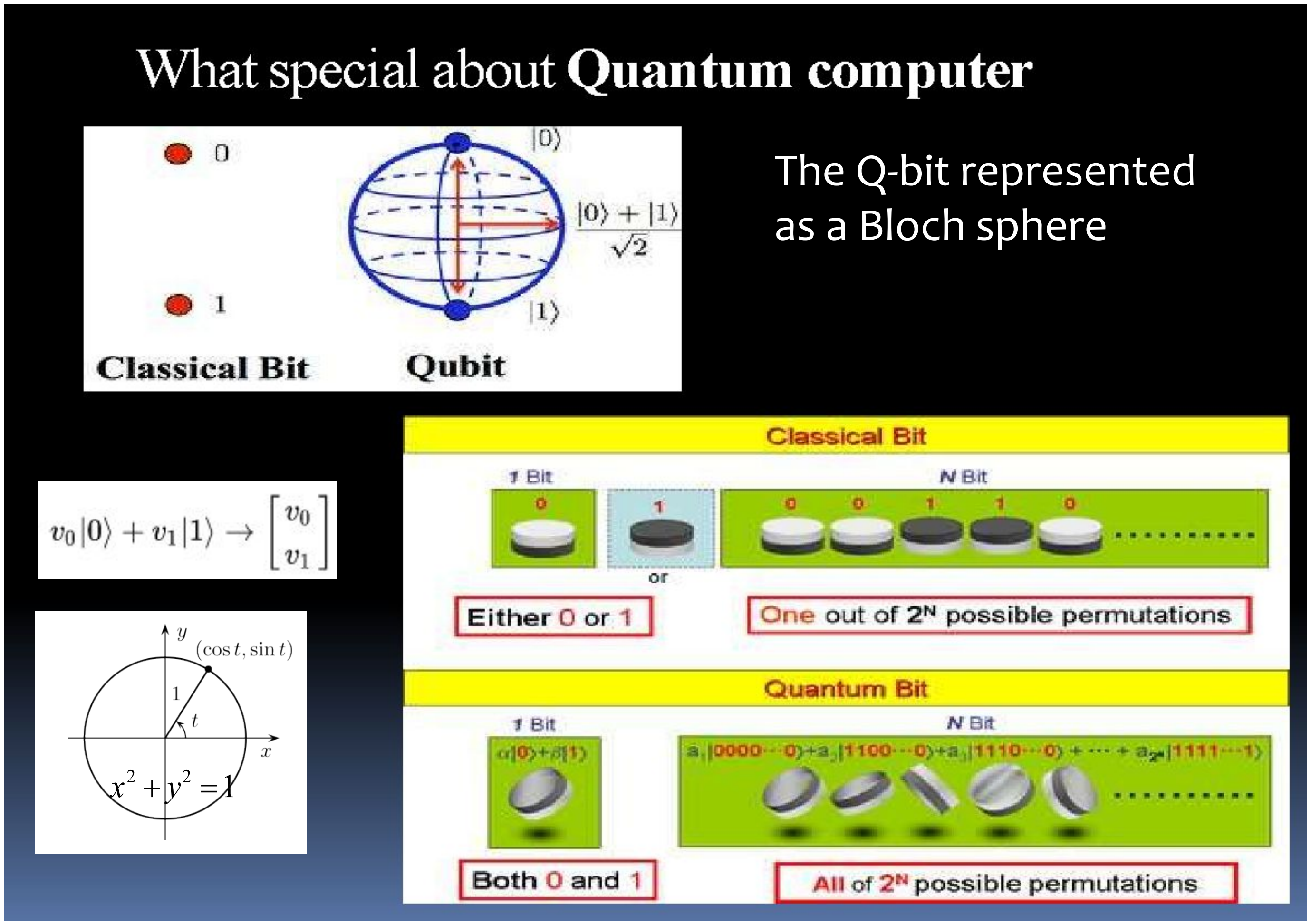
$$\frac{1}{\sqrt{2}}\left(|01\rangle \pm |10\rangle\right)$$

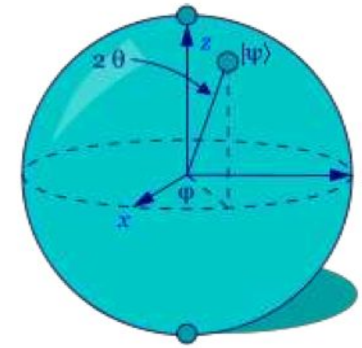
7

D-Wave The Quantum Computing Company

LinkedIn SlideShare: 17 Nov 2014 – "Quantum Computing: Welcome to the Future" by Vern Brownell CEO

Key Concepts in QC





Generators of Rotations as quantum gates:

Pauli-X gate $X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$

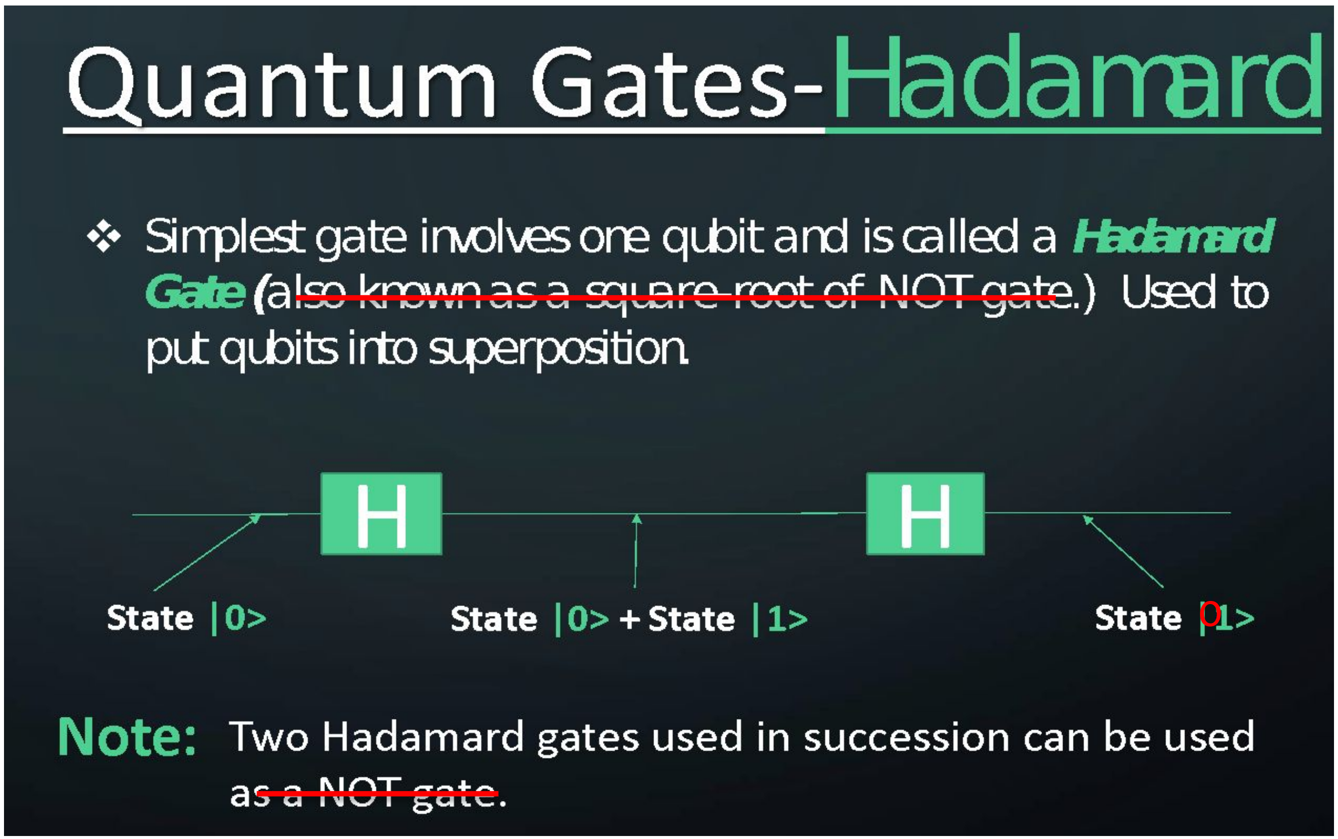
Pauli-Y gate $Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}.$

Pauli-Z gate $Z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}.$

LinkedIn SlideShare: 29 Sep 2012 – “Topic: Quantum computer” By Nisarg Y Bhagavantanavar

Key Concepts in QC

$$H = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$



|0> =[1, 0]^T

|1> =[0,1]^T

|0> ↔ |1>

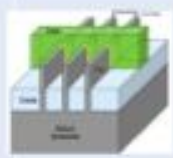
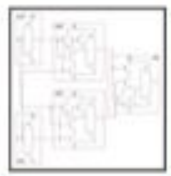
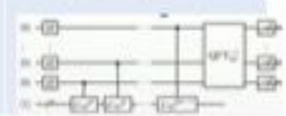
$$X = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

$$X = (\sqrt{NOT})^2$$

$$\sqrt{X} = \sqrt{NOT}$$

$$= \frac{1}{2}\begin{bmatrix} 1+i & 1-i \\ 1-i & 1+i \end{bmatrix}$$

LinkedIn SlideShare: 21 Apr 2014 – "Quantum Computing" by Rohit Mishra & Ankit Agarwal

Classical Computers		Quantum Computers	
Calculates with transistors which can represent *either* 0 or 1		Calculates with Qubits, which can represent 0 and 1 *simultaneously*	
Uses transistors to create these logical switches		Uses either trapped ions, superconducting loops, quantum dots, diamond vacancies to create Qubits	
Multiple transistors (~2-14) make up basic logic gates		Multiple Qubits make up a logical Qubit (9-100's?)	
Compute power scales in a 1-to-1 relationship with the number of transistors and clock speed		Compute power increases exponentially in proportion to the number of logical Qubits	
Low error rates and operate at room temperature		High error rates and need to be ultracold	
Used for general purpose computing		Used for optimization and factoring. A sufficient number of Qubits = *Cryptographically Relevant Quantum Computer*	 

Source: Steve Blank/CBInsights

Possible Applications of QC

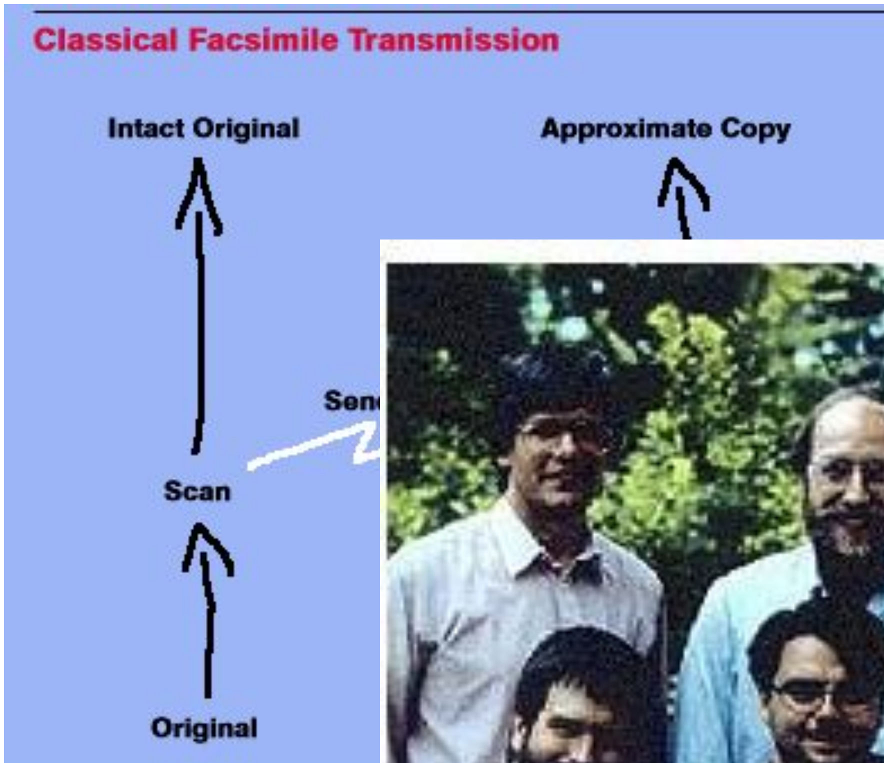
- Quantum Communications and Quantum Sensing
  - Quantum Key Distribution (BB84 Bennett & Brassard 1984)
  - Cryptography – Prime Number Factorization (Peter Shor 1994)
  - State Teleportation (Charles Bennett et al 1993)

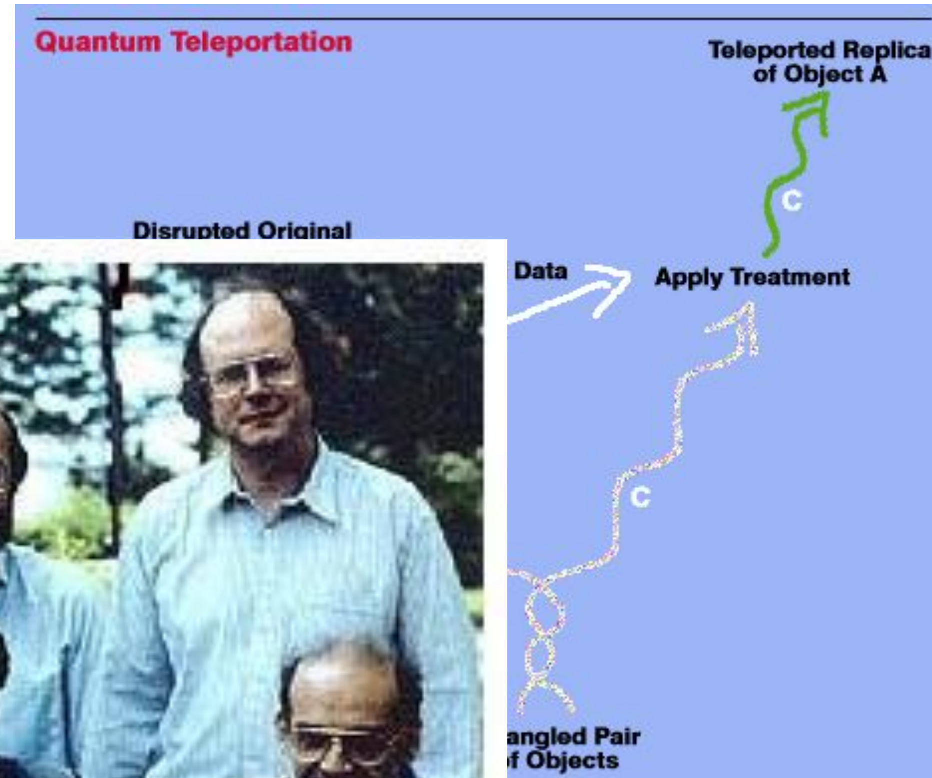
- Artificial Intelligence
  - Large Data processing (Lov Grover search 1997)
  - Optimization problems …
  - Pattern Recognition …

- Variety of Art form expressions …
  - Quantum Music Composer
  - Wearable Gadgets

- ???

Quantum Teleportation





(top, left) Richard Jozsa, William K. Wootters, Charles H. Bennett. (bottom, left) Gilles Brassard, Claude Crépeau, Asher Peres. Photo: André Berthiaume.

Advantage of the Shor's Algorithm

Quantum Algorithm: Shor's Algorithm

In 2001, Shor's algorithm was demonstrated by a group at IBM, who factored 15 into 3 × 5, using an NMR implementation of a quantum computer with 7 qubits

with a classical computer

# bits	1024	2048	4096
factoring in 2006	10^5 years	$5\text{x}10^{15}$ years	$3\text{x}10^{29}$ years
factoring in 2024	38 years	10^{12} years	$7\text{x}10^{25}$ years
factoring in 2042	3 days	$3\text{x}10^8$ years	$2\text{x}10^{22}$ years

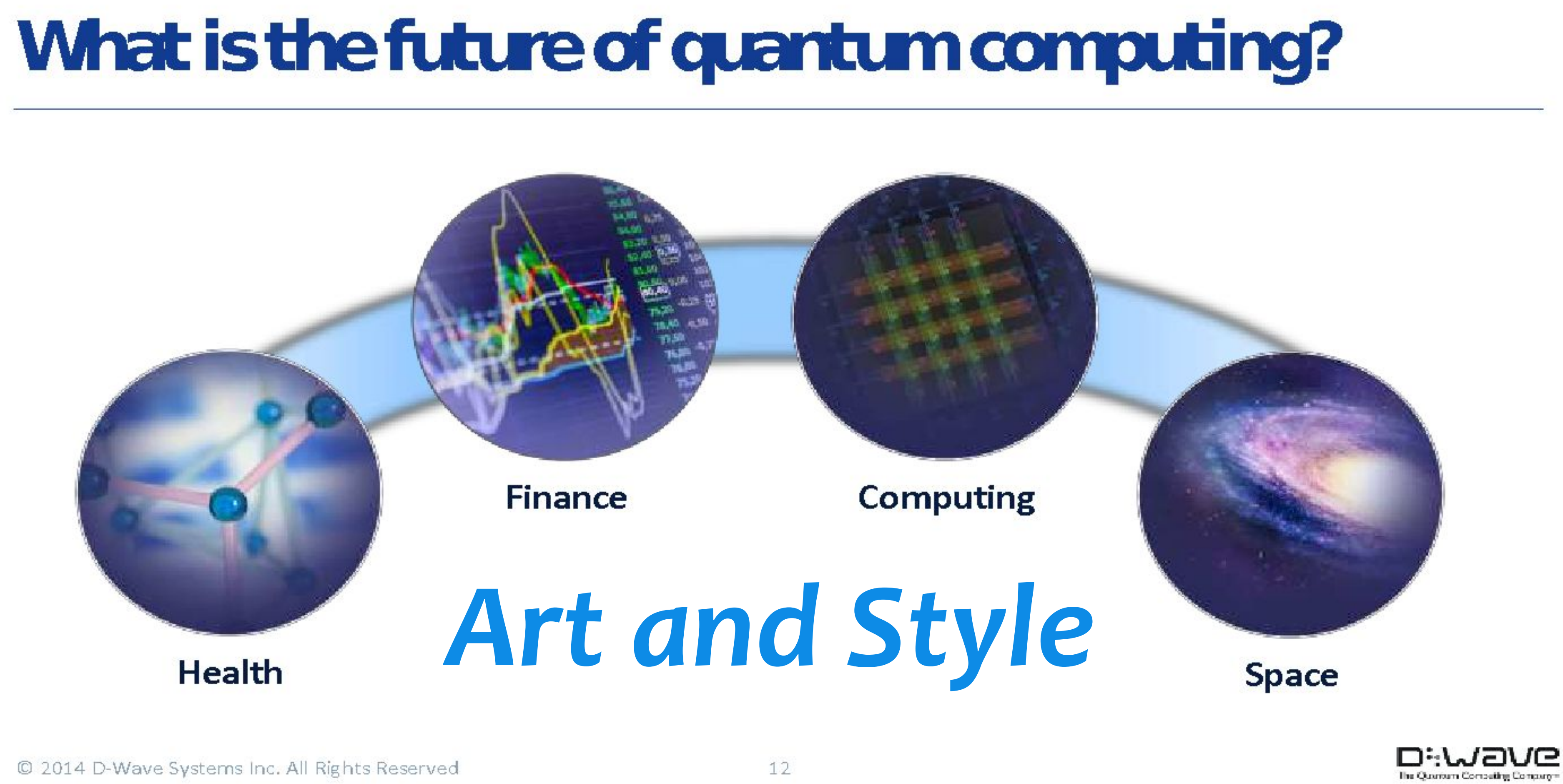
with potential quantum computer

# bits	1024	2048	4096
# qubits	5124	10244	20484
# gates	$3\text{x}10^9$	$2\text{X}10^{11}$	$\text{X}10^{12}$
factoring time	4.5 min	36 min	4.8 hours

Slide by Meghaditya Roy Chaudhury on "Quantum Computing" at Jadavpur University

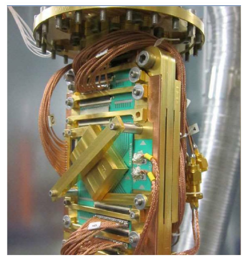
See also R. J. Hughes, LA-UR-97-4986

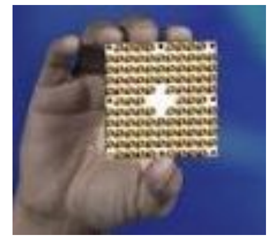
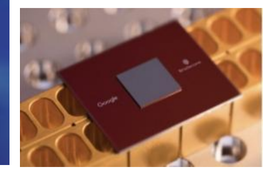
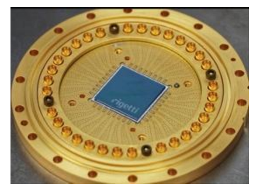
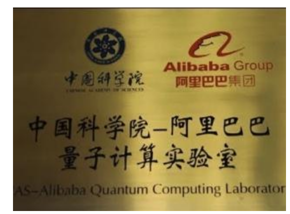
Possible Applications of QC



Present Status on QC Resources

- Quantum Computing Hardware
  - D-Wave (128/512)[Q5000]
  - IBM (50)[127]
  - Intel (49)
  - Google (72)
  - Rigetti (19)[32]
  - AliBaba (11)

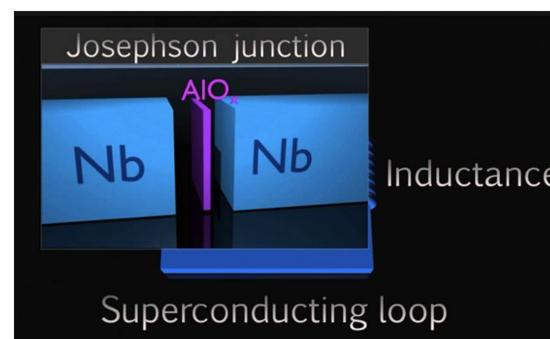


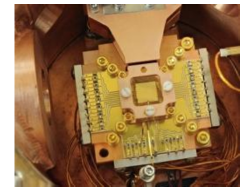
- Quantum Computing Software
  - D-Wave
  - IBM Q-Experience and QISKit
  - Rigetti Forest
  - Microsoft #Q, Google CirQ, QC Ware
  - Amazon Braket

D:WAVE Leap
rigetti
Microsoft
Qiskit
<qlp>
QC WARE
The Quipper System
Amazon Braket

D-Wave 2000-qubit processor

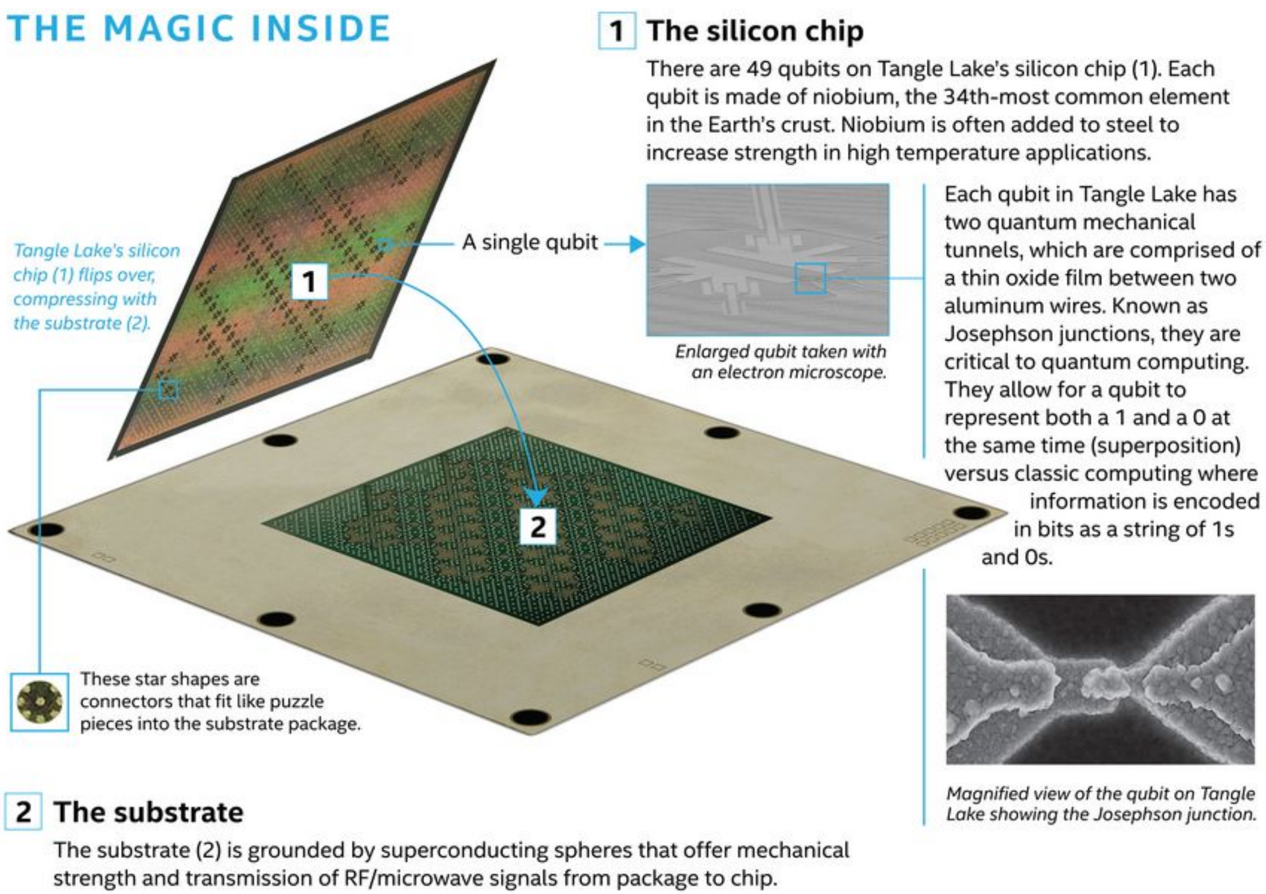


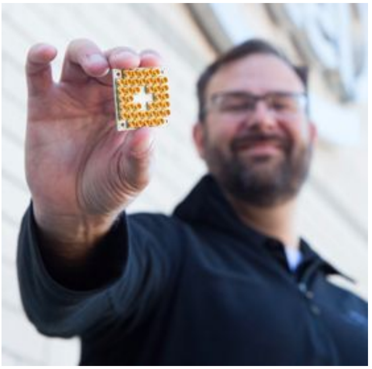
IBM 50-Qubit Processor



Qiskit

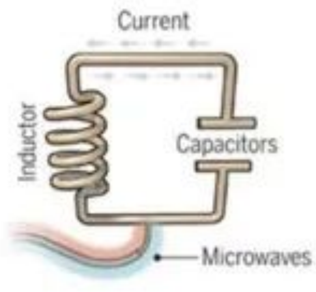
‘Tangle Lake,’ Intel’s 49-Qubit Processor

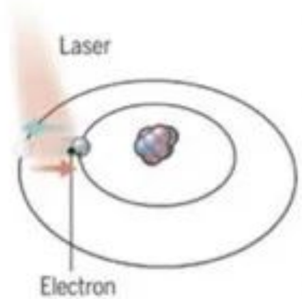


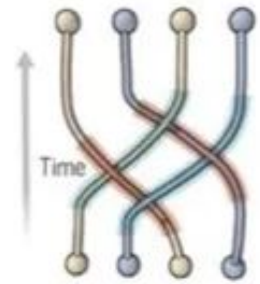


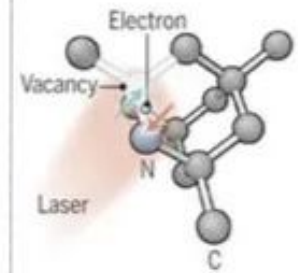
26 spin q-bits

https://newsroom.intel.com/news/future-quantum-computing-counted-qubits/









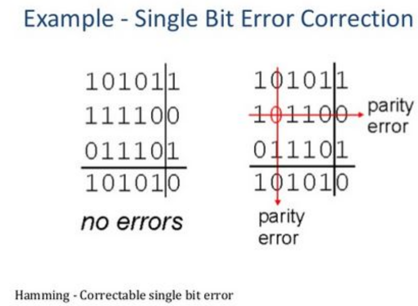
	Superconducting loops	**Trapped ions**	**Silicon quantum dots**	**Topological qubits**	**Diamond vacancies**
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacanc add an electron to a diamond lattice. Its quantum spin state along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%

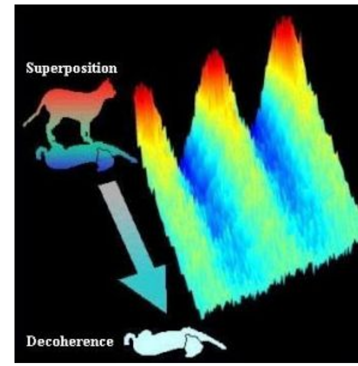
Source IBM

Problems and Future Directions

$$|\psi\rangle = \sum_n c_n |n\rangle \longrightarrow |n_i\rangle$$

- De-coherence
- Error Correction
- Output Measurement





- Finding "the right problems" for a quantum computer


NEWS

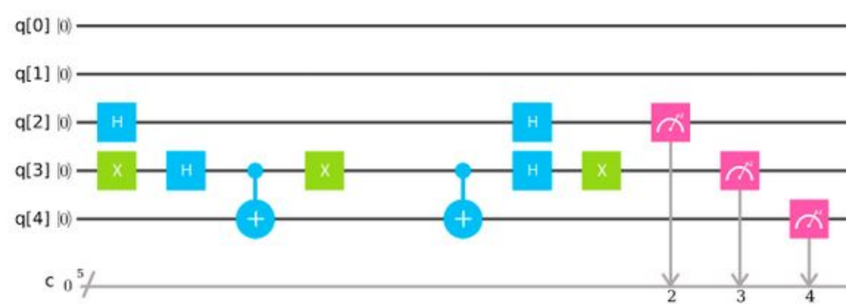
D-Wave's $15 million quantum computer runs a staggering 2,000 qubits

D-Wave's 2000Q quantum computer will ship to select customers but could ultimately be available to others via the cloud

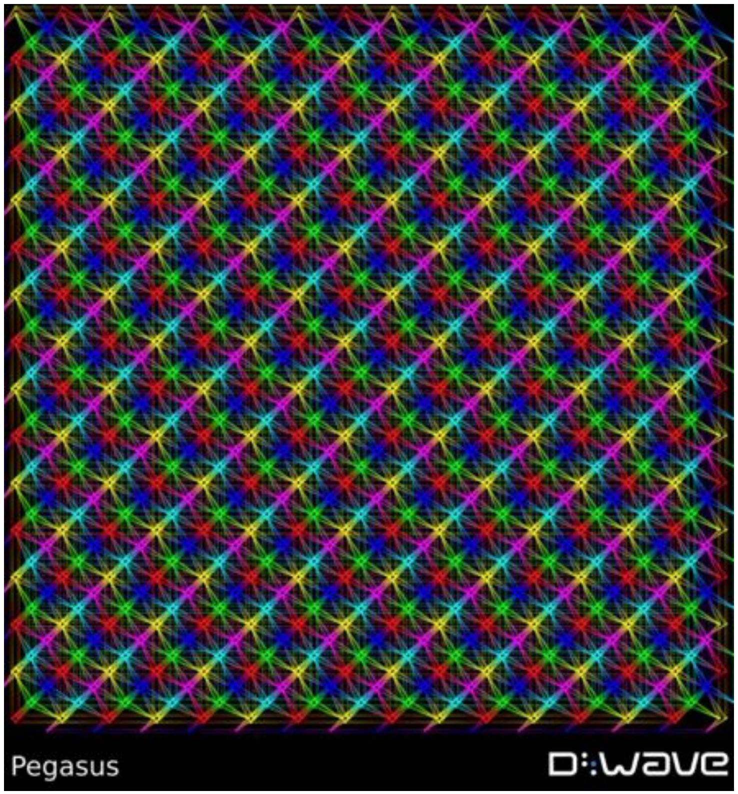
By Agam Shah

U.S. Correspondent, IDG News Service

JAN 24, 2017 6:14 AM PT



Recent Developments and Future Directions

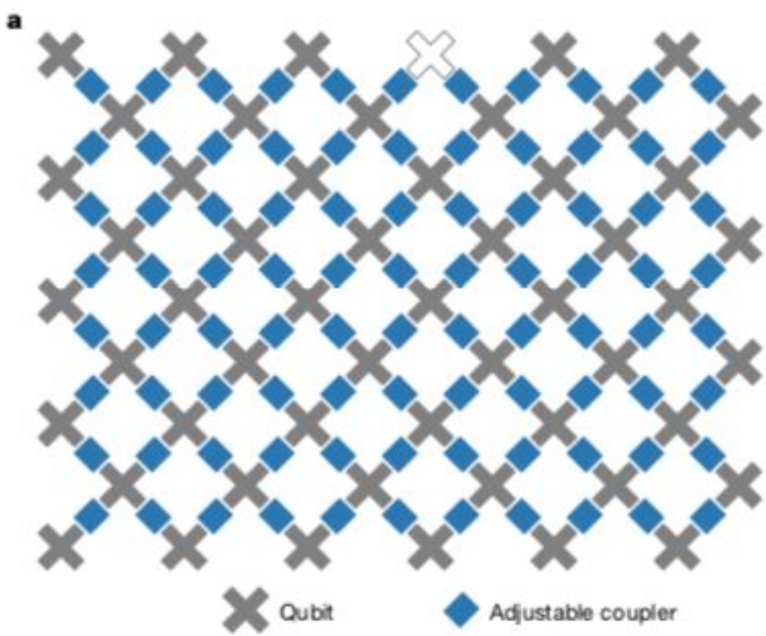


D-Wave Previews Next-Generation Quantum Computing Platform (5000 qubits)

Current Chimera™ topology:
each qubit is connected to **six other** qubits.

Pegasus topology:
each qubit is connected to **15 other** qubits!

Google's Sycamore Qubits Geometry!



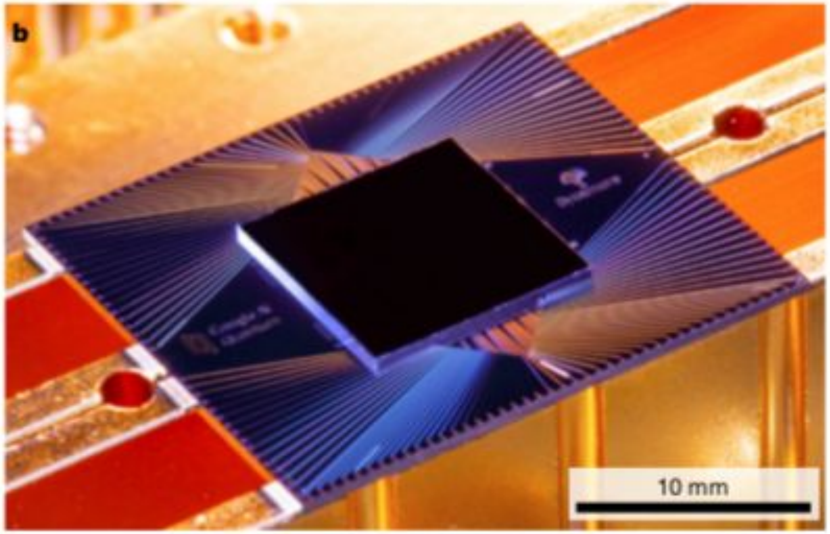
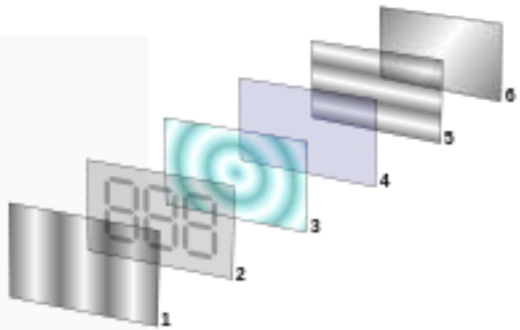
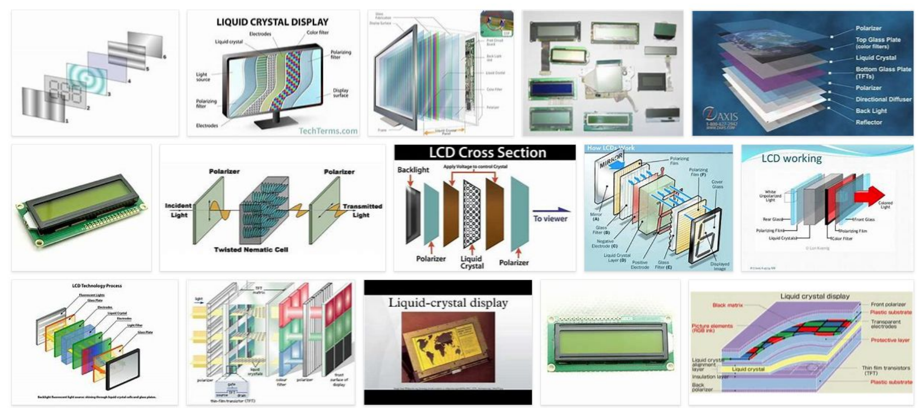


Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

Future Directions

Are liquid-crystals part of the future QCs?



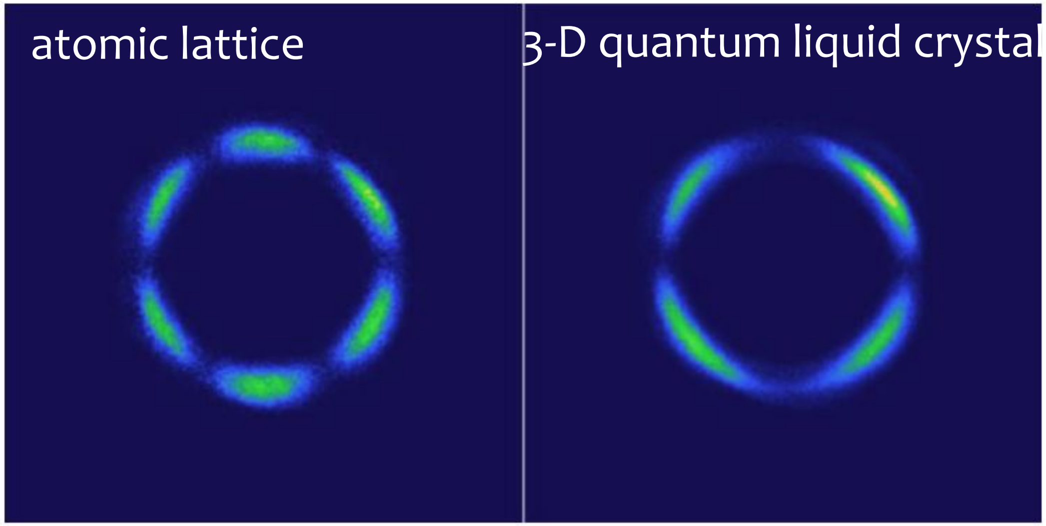


Future Directions

First 3D quantum liquid crystal!

Quantum Liquid Crystals Could Speed Up Computers

Fri, 04/21/2017 - 9:57am by Kenny Walter , Science Reporter - @RandDMagazine



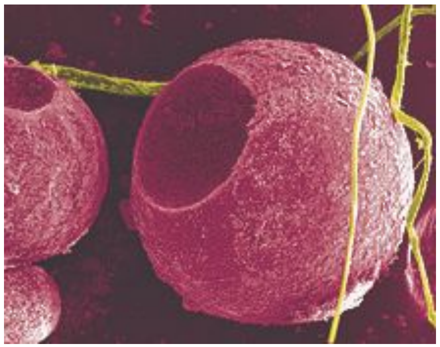
These images show light patterns generated by a rhenium-based crystal using a laser method called optical second-harmonic rotational anisotropy. At left, the pattern comes from the atomic lattice of the crystal. At right, the crystal has become a 3-D quantum liquid crystal, showing a drastic departure from the pattern due to the atomic lattice alone. Credit: Hsieh Lab/ Caltech

The electrons have different magnetic properties, depending on whether they flow forward or backward on a given axis!

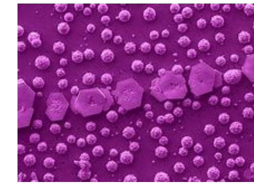
Future Directions

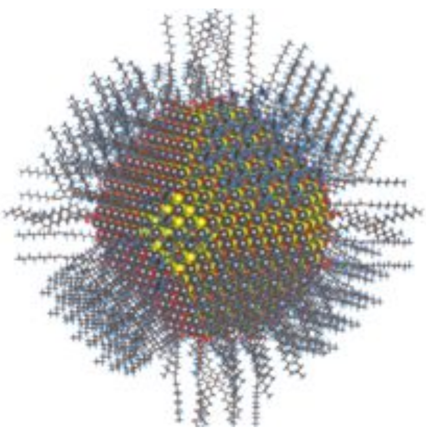
What about the Quantum Dots?

Cadmium sulfide quantum dots

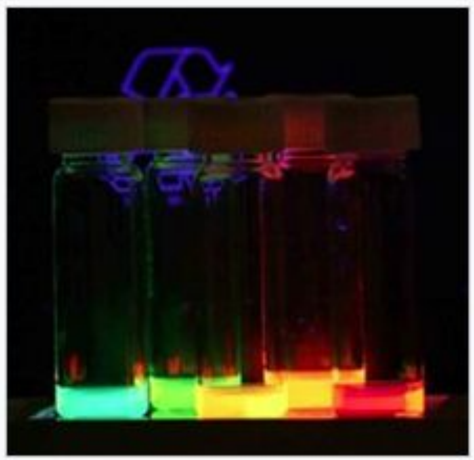


QDs can contain as few as 100 to 100,000 atoms
diameter of ≈10 to 50 atoms (2 to 10 nanometers)
nearly 3 million quantum dots could be lined up
end to end and fit within the width of a human thumb.





lead sulfide (selenide)

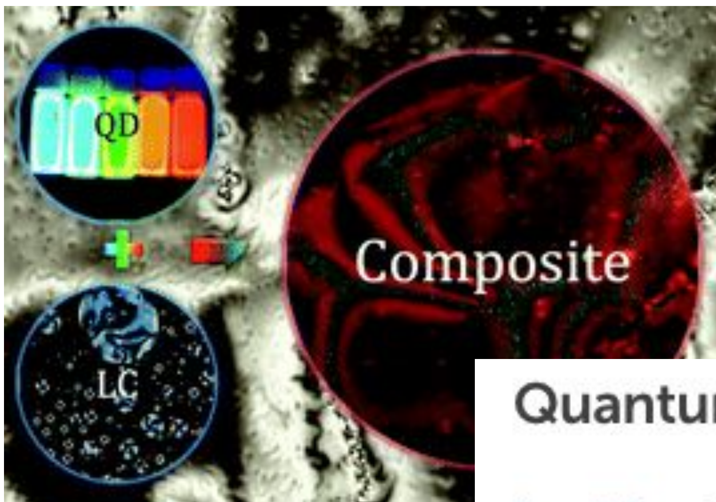


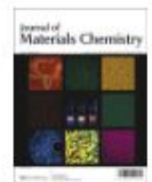
Colloidal quantum dots irradiated with a UV light. Different sized quantum dots emit different color light due to quantum confinement.

https://en.wikipedia.org/wiki/Quantum_dot

Future Directions

Quantum dots as liquid crystal dopants !





From the journal:
Journal of Materials Chemistry

Quantum dots as liquid crystal dopants

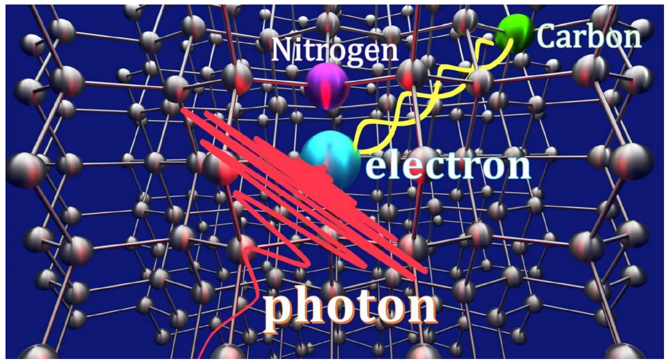
Javad Mirzaei,[a] Mitya Reznikov[b] and Torsten Hegmann*[abcd]

J. Mater. Chem., 2012,22, 22350-22365 ;
https://pubs.rsc.org/en/content/articlelanding/2012/jm/c2jm33274d#!divAbstract

Future Directions

Are diamonds only for jewelry ?

https://www.eurekalert.org/pub_releases/2019-06/ynu-rti062519.php



EurekAlert! AAAS

HOME NEWS RELEASES MULTIMEDIA MEETINGS PORTALS ABOUT

NEWS RELEASE 28-JUN-2019

Researchers teleport information within a diamond

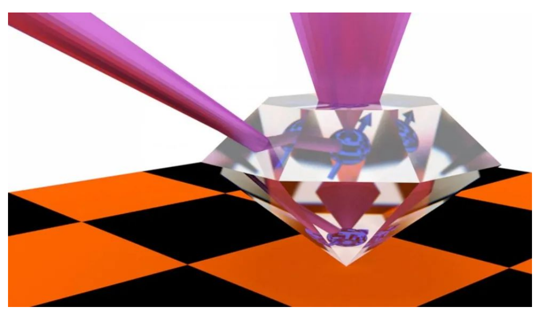
YOKOHAMA NATIONAL UNIVERSITY

https://bigthink.com/robby-berman/the-future-internet-could-be-built-of-diamonds

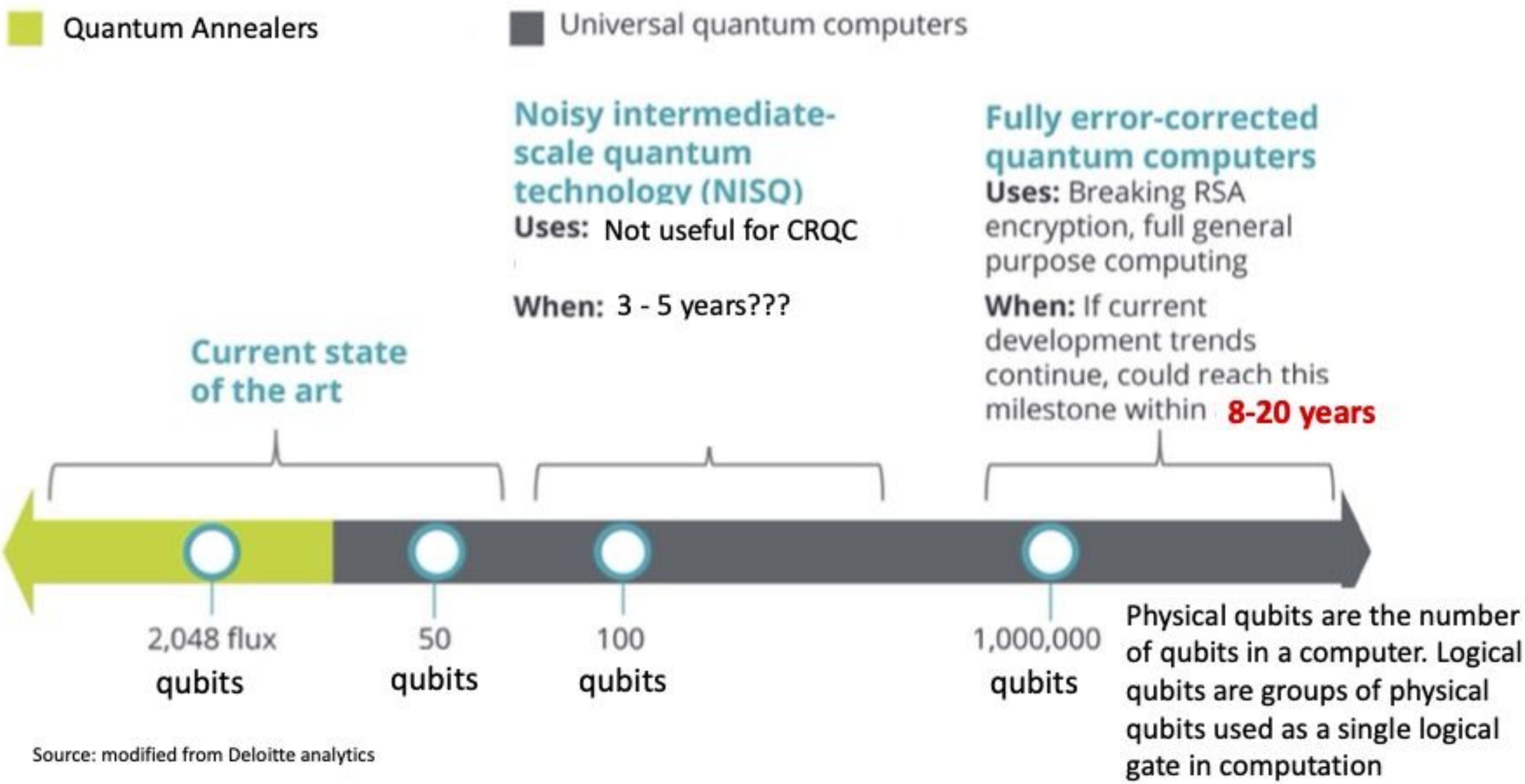
The future internet could be built of diamonds

Researchers at Princeton engineer a new type of diamond with silicon and boron that solves past issues with quantum data storage and retrieval.

ROBBY BERMAN 10 July, 2018

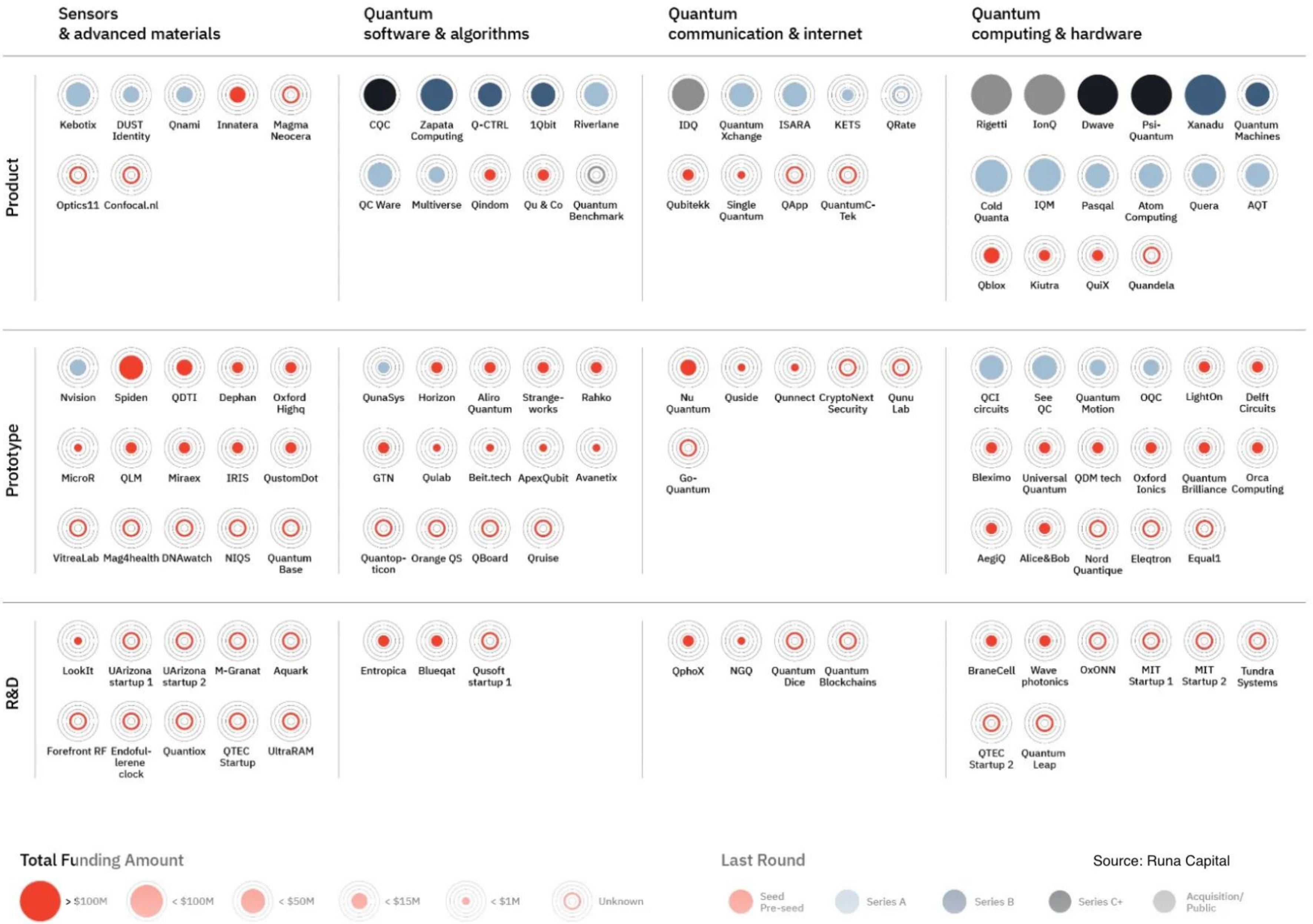


BIG THINK



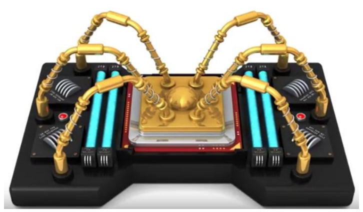
Source: modified from Deloitte analytics

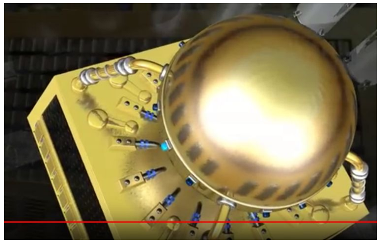
Current Investment Efforts



Conclusion

- **QC will be complementary to classical computing!**
- **It will be few more years until becoming of age!**
- **The QC territory is a wide-open field of opportunities:**
  - **Hardware development**
  - **Software development**
  - **Future QC based services and applications**
- **???**





Homework Assignments and Open Discussion

Review and start reading 1804.10068:

- Self-assessment using self-tests/quizzes from QWorld on the IAPS qc-page https://qc.iaps.institute/
- Linear Algebra Review and References by Zico Kolter (updated by Chuong Do) https://cs229.stanford.edu/section/cs229-linalg.pdf

➔ Quantum machine learning for data scientists by Dawid Kopczyk https://arxiv.org/abs/1804.10068

Some more questions and topics from Vlado for his lectures next week!