Quantum Computing

Recent Developments

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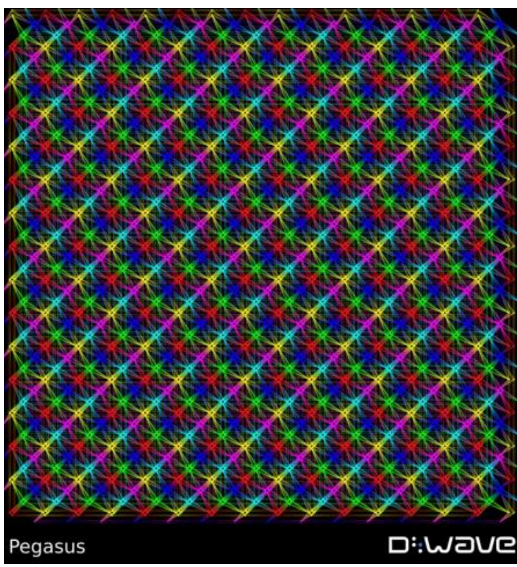
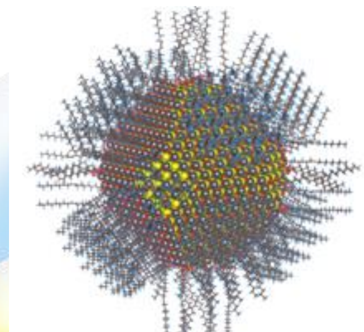
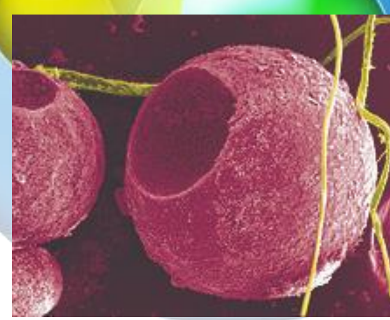
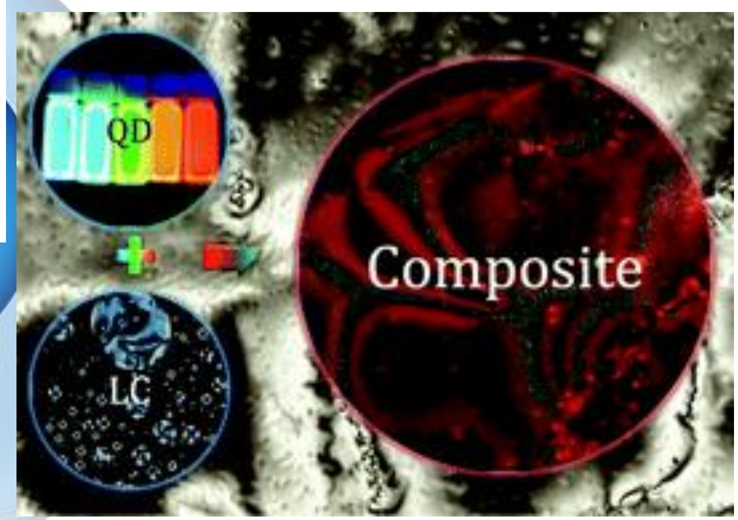
Institute for Advanced Physical Studies









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

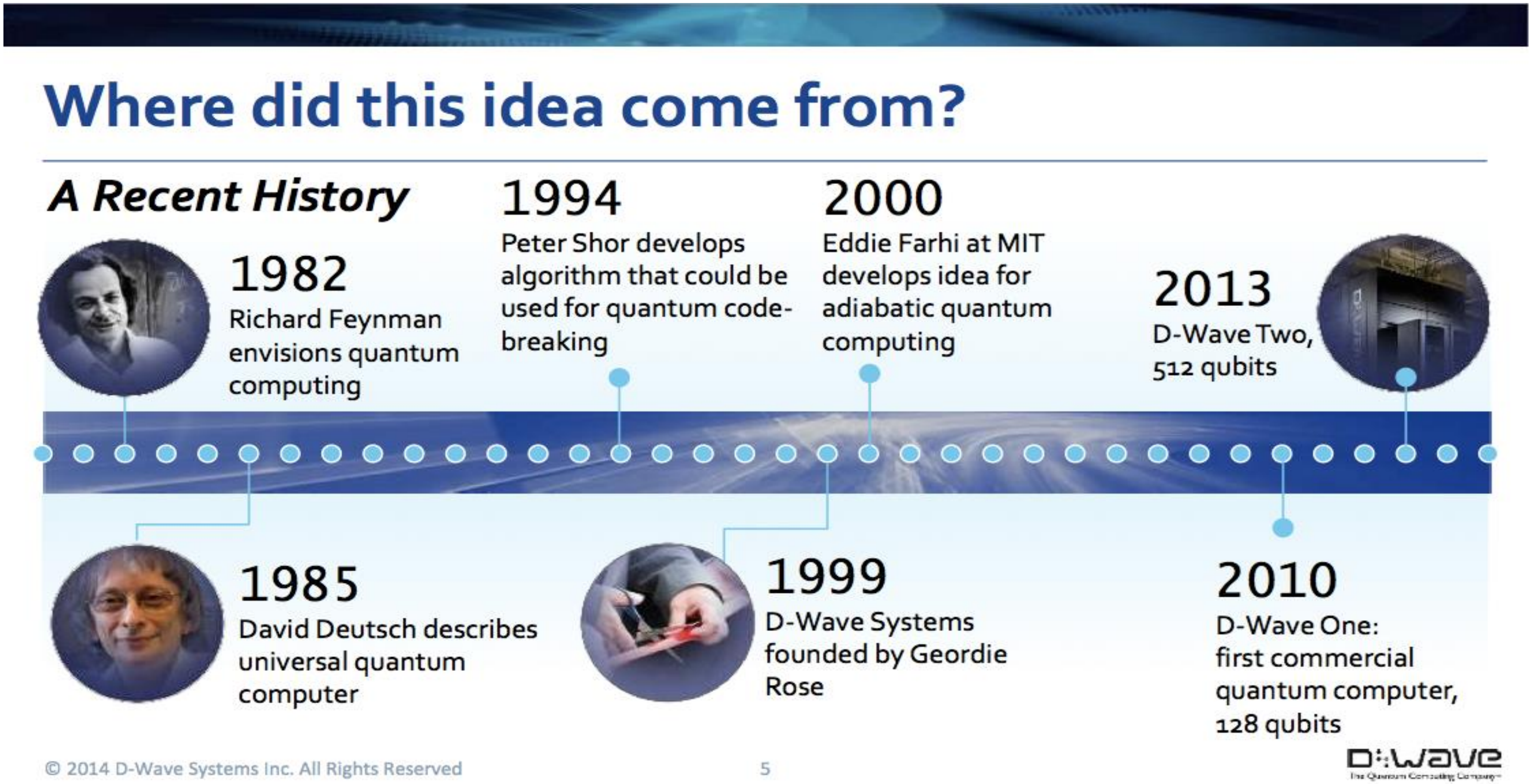
Go to **www.menti.com** and use the code **7427 2778**

Homework

What QC resources do you know about?

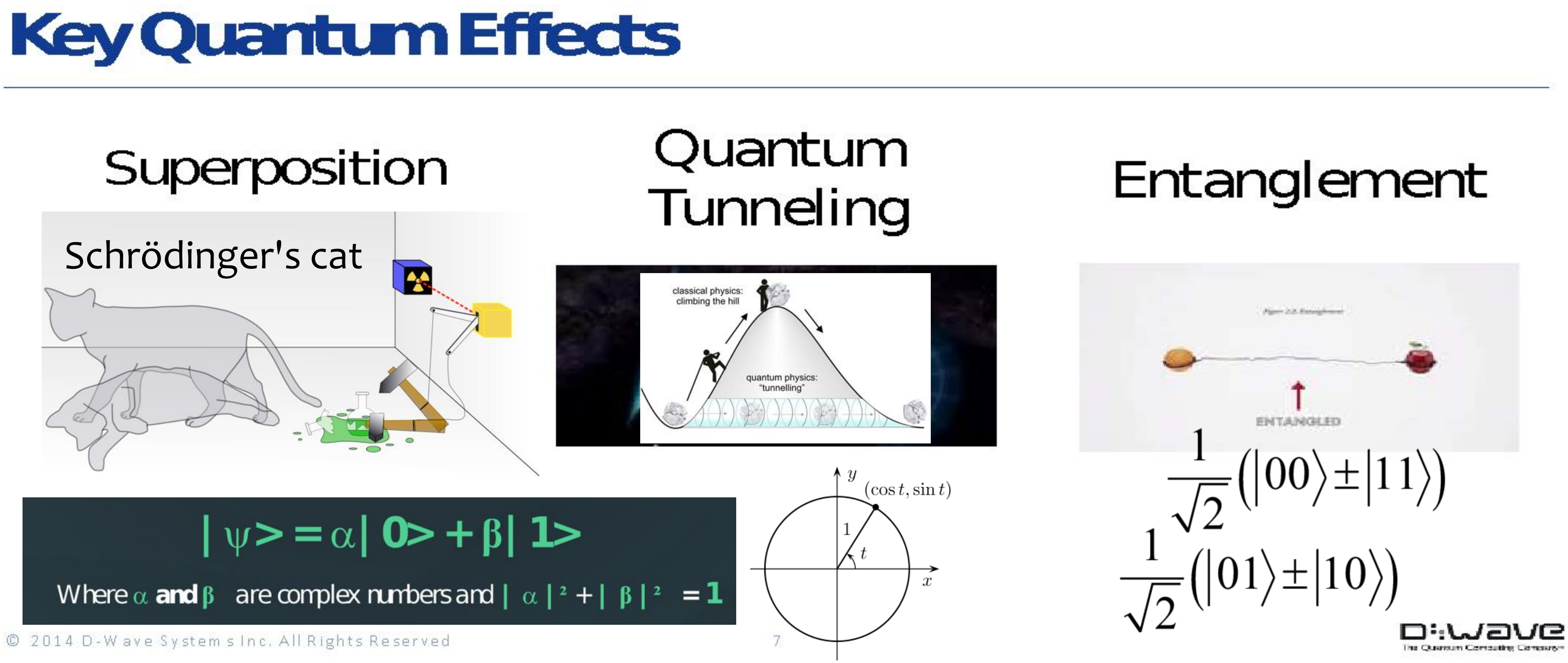
Key Concepts in Quantum Computing

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 Computing



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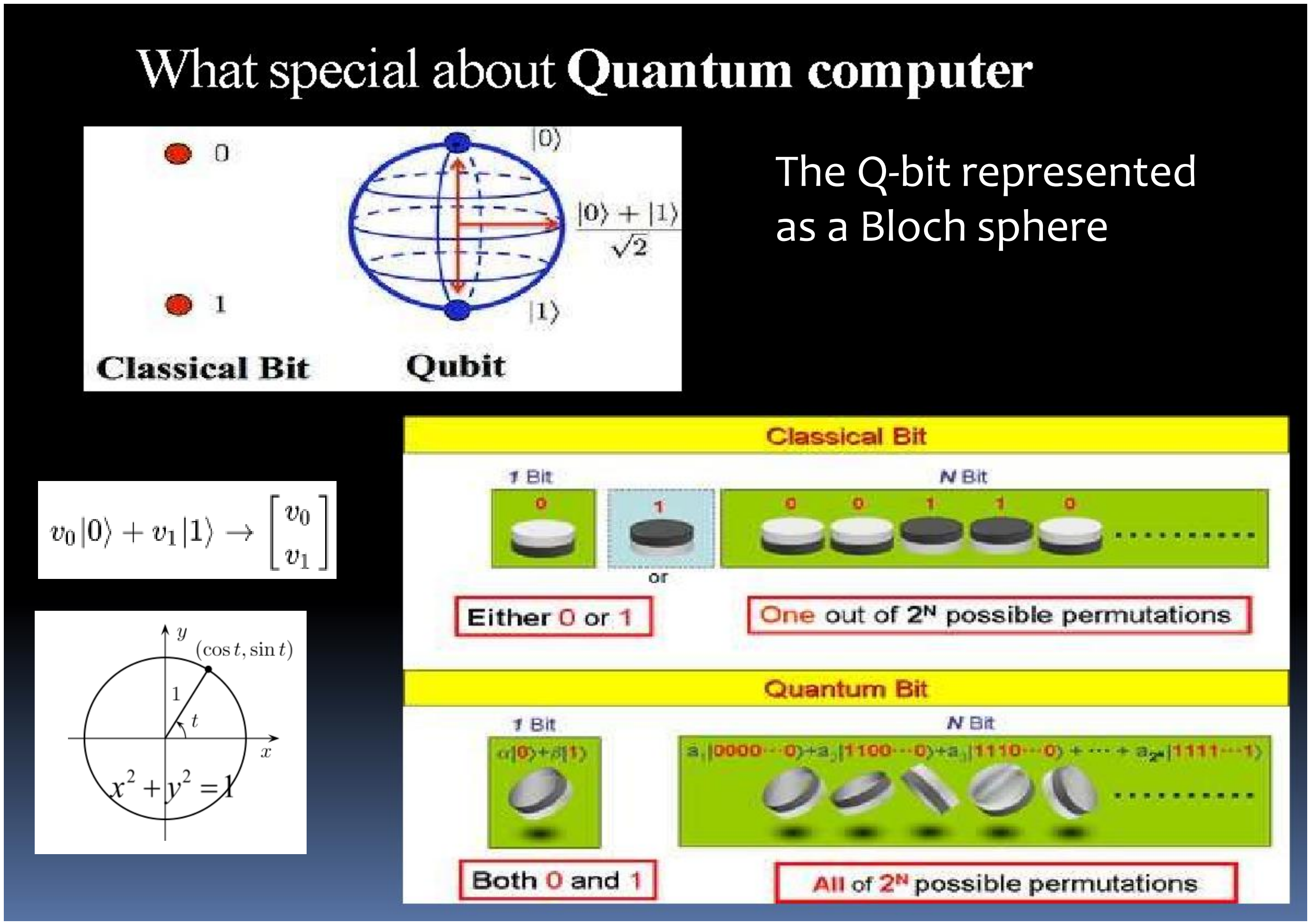
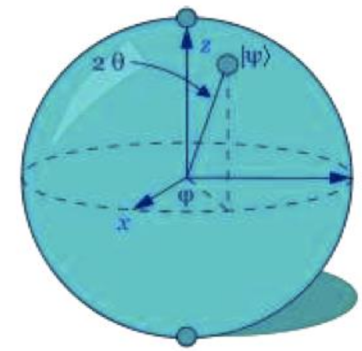
Key Concepts in QC





Generators of Rotations as quantum gates:

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

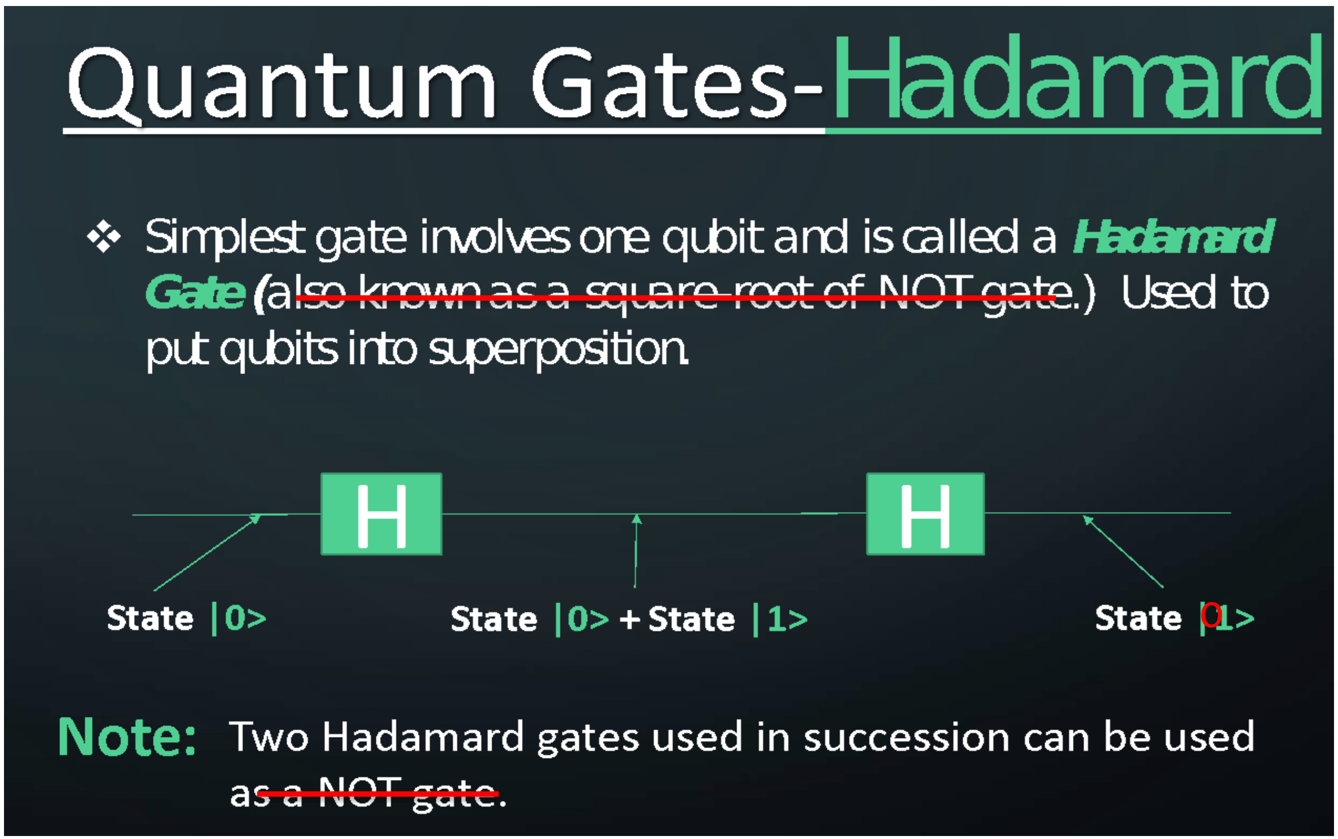
Pauli-Y gate $Y = \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$

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

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



$|0\rangle = [1, 0]^T$

$|1\rangle = [0,1]^T$

$|0\rangle \leftrightarrow |1\rangle$

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

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

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

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

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

Possible Applications of QC

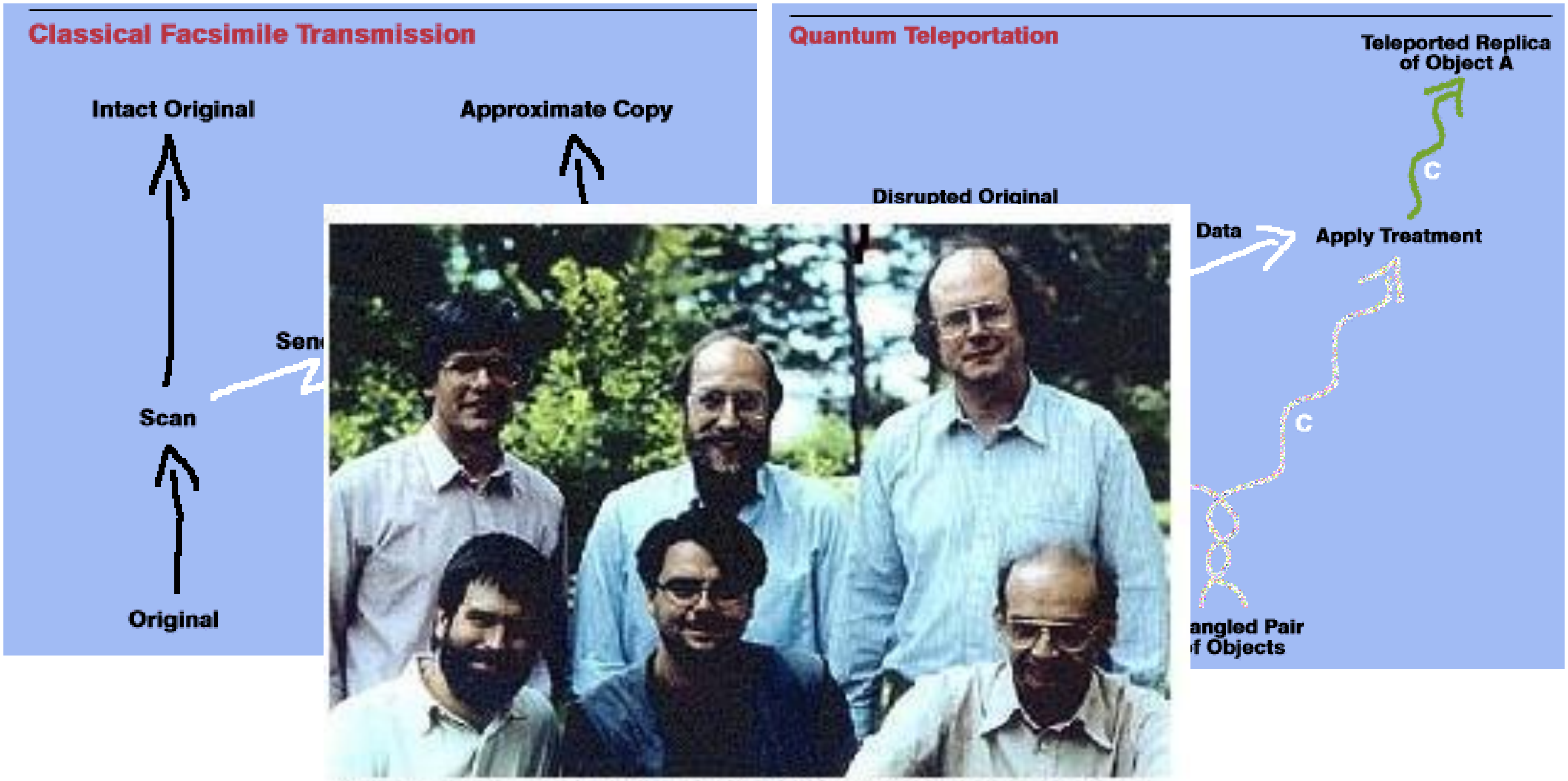
- **Quantum Communications**
  - **Quantum Key Distribution (BB84 Bennett & Brassard 1984)**
  - **Cryptography – Prime Number Factorization (Peter Shor 1994)**
  - **State Teleportation (Charles Bennett et al 1993)**

- **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	$5x10^{15}$ years	$3x10^{29}$ years
factoring in 2024	38 years	10^{12} years	$7x10^{25}$ years
factoring in 2042	3 days	$3x10^8$ years	$2x10^{22}$ years

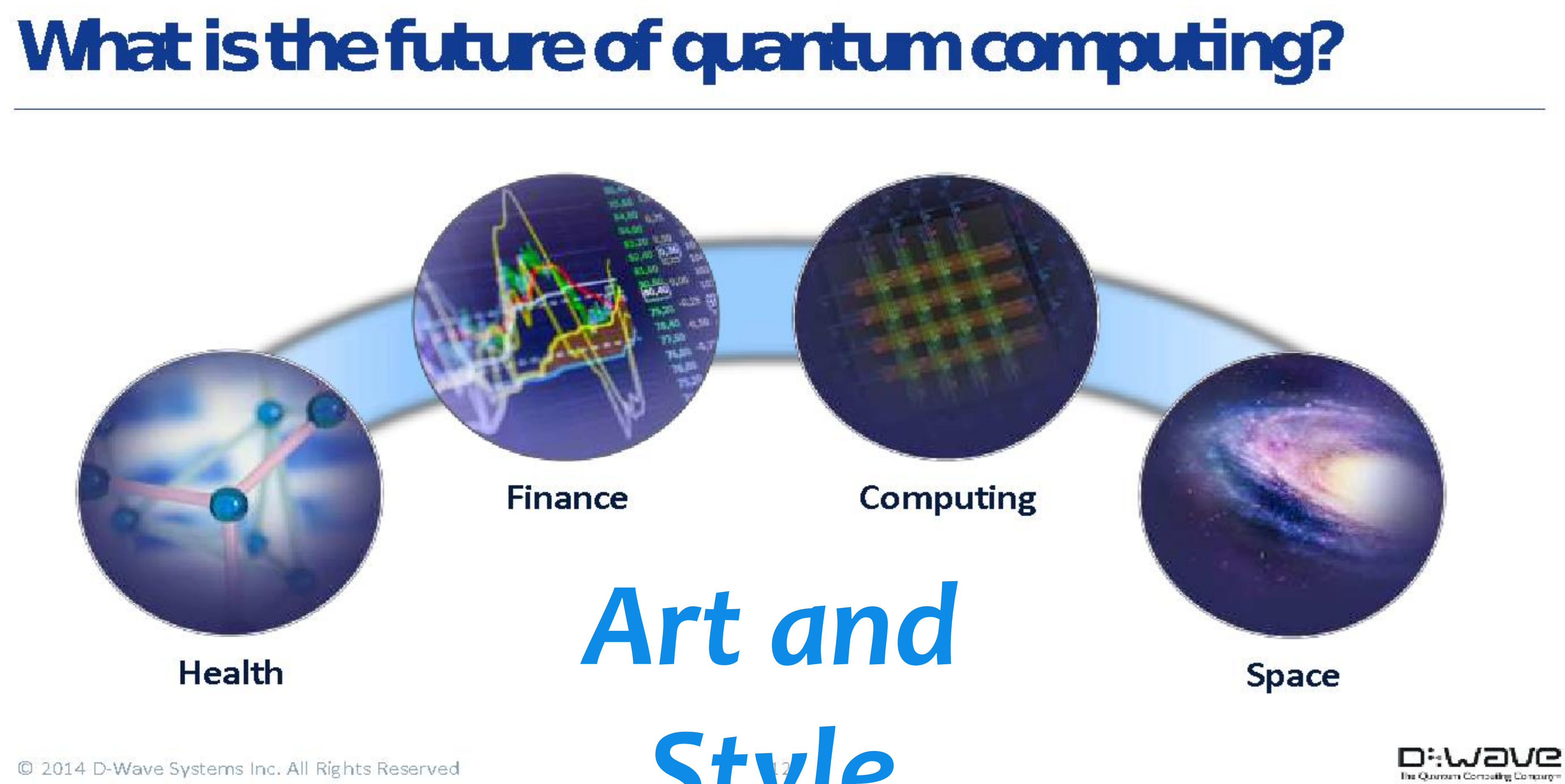
with potential quantum computer

# bits	1024	2048	4096
# qubits	5124	10244	20484
# gates	$3x10^9$	$2X10^{11}$	$X10^{12}$
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

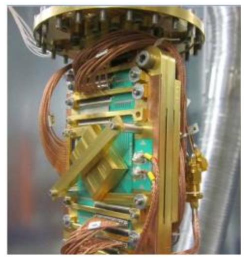
Possible Applications of QC

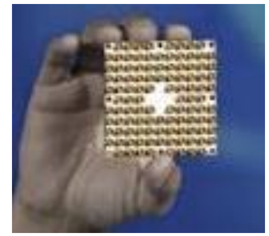
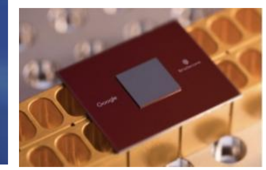
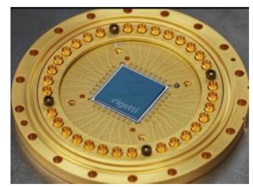
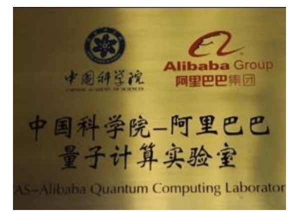


Art and Style

Present Status on QC Resources

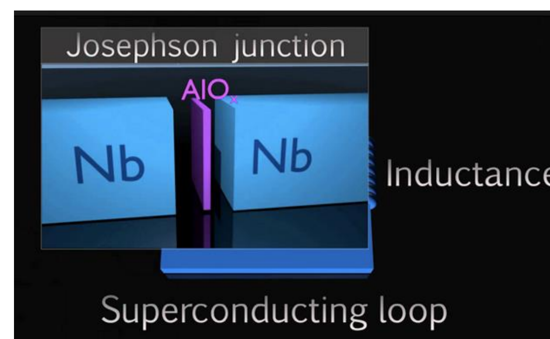
- **Quantum Computing Hardware**
  - **D-Wave (128/512)[Q5000]**
  - **IBM (50)[127]**
  - **Intel (49)**
  - **Google (72)**
  - **Rigetti (19)[32]**
  - **AliBaba (11)**



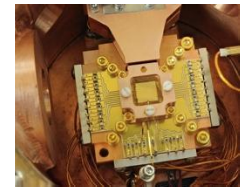





- **Quantum Computing Software**
  - **D-Wave**
  - **IBM Q-Experience and QISKit**
  - **Rigetti Forest**
  - **Microsoft #Q, Google CirQ, QC Ware**
  - **Amazon Braket**

D-Wave 2000-qubit processor

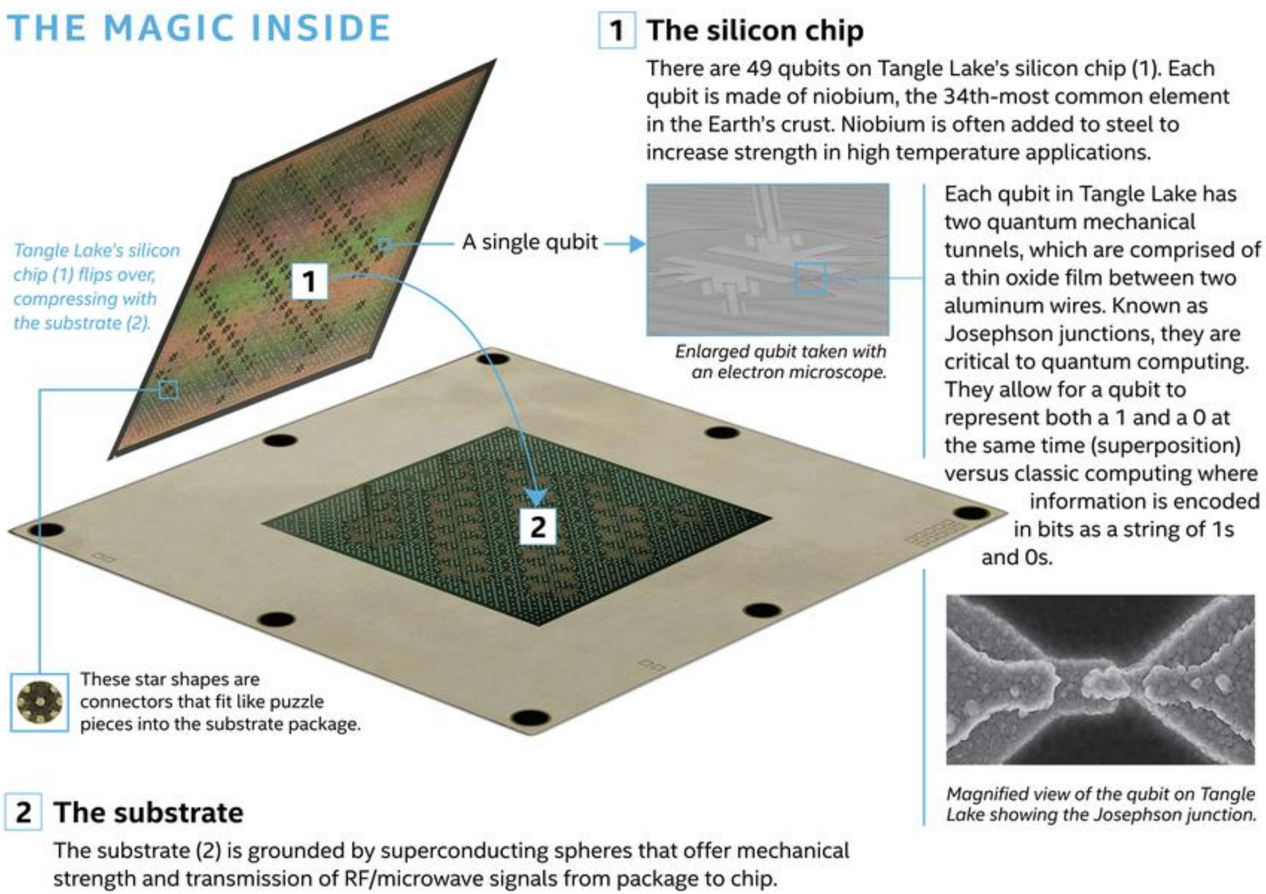


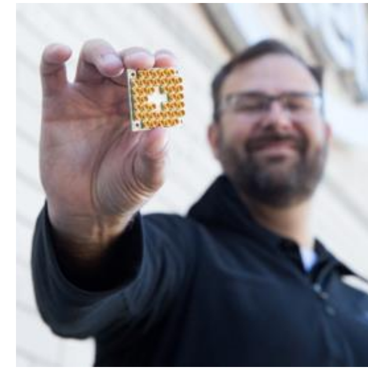
IBM 50-Qubit Processor



Qiskit

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





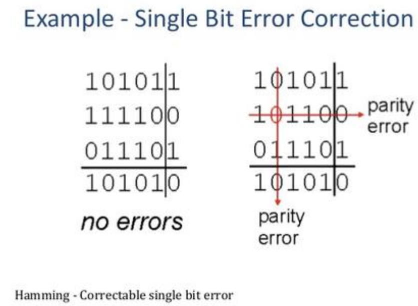
26 spin q-bits

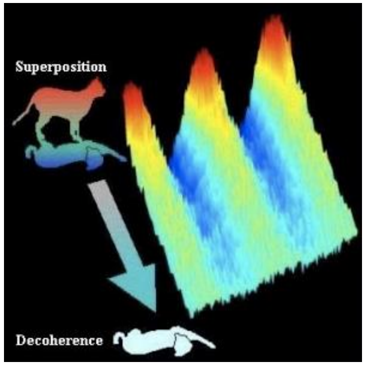
https://newsroom.intel.com/news/future-quantum-computing-counted-qubits/

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

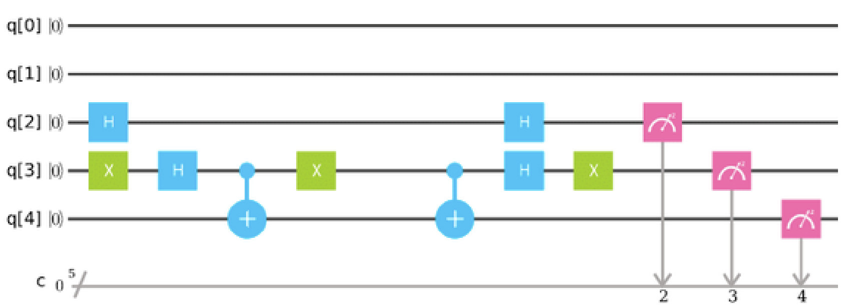
D-Wave's $15 million quantum computer runs a staggering 2,000 qubits

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

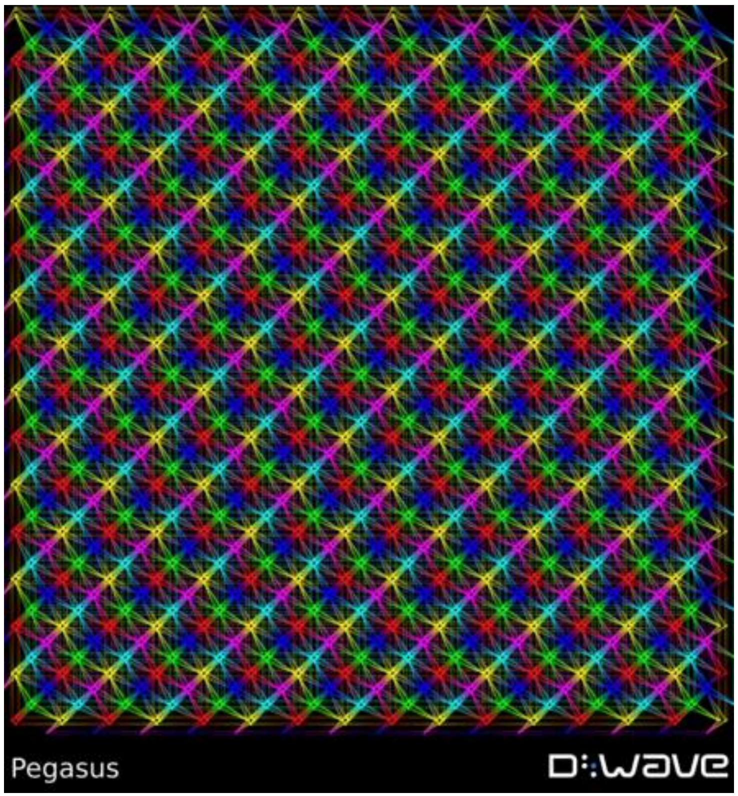
By Agam Shah

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!

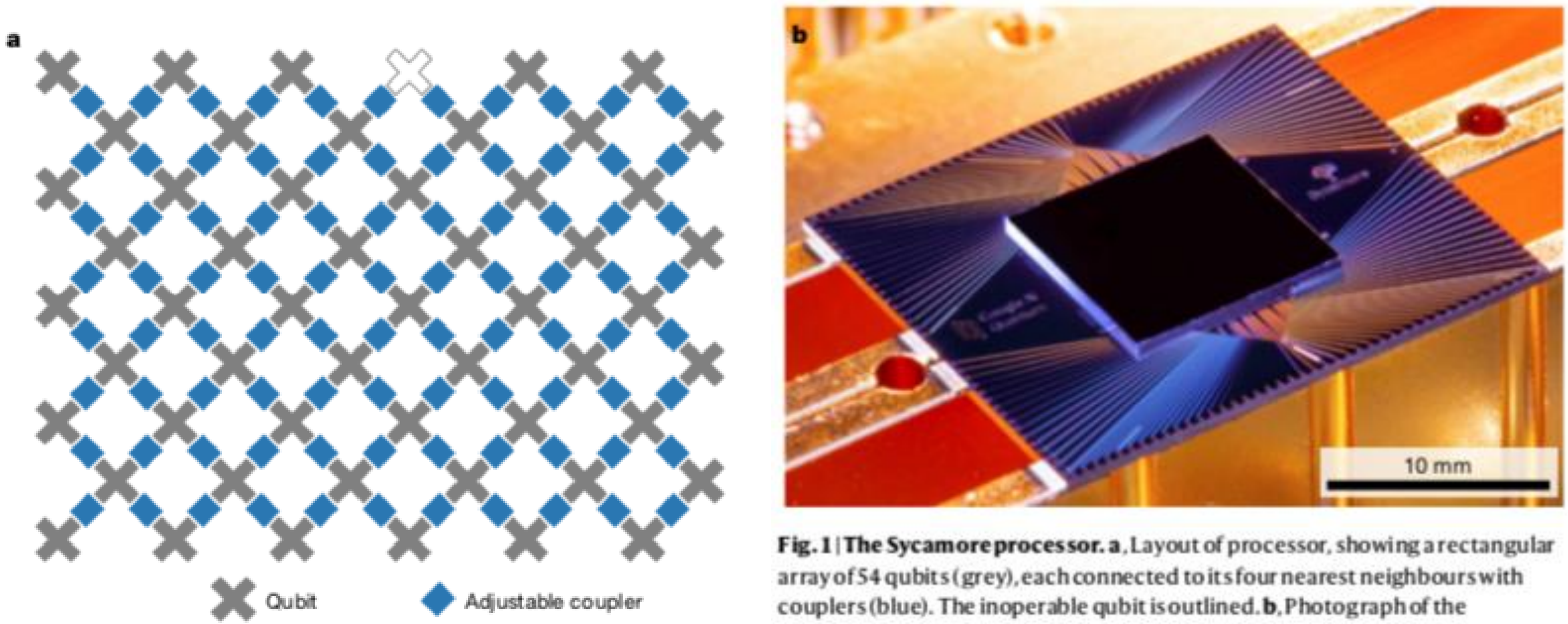
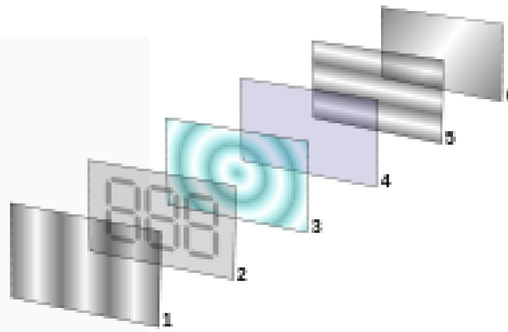
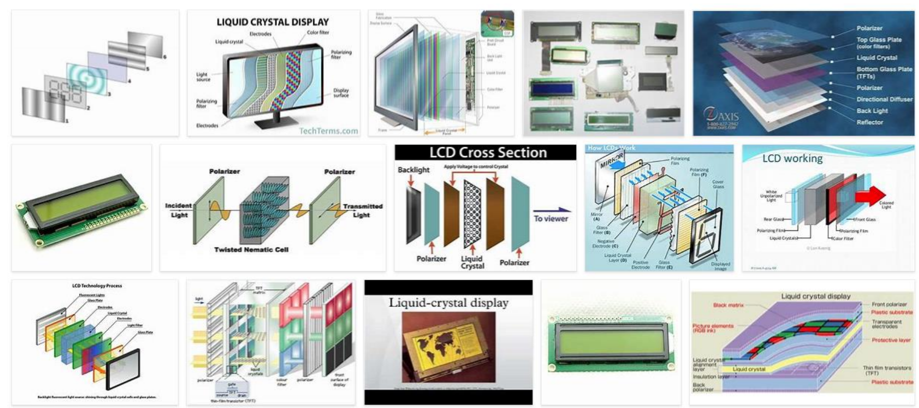


Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

Future Directions

Are liquid-crystals part of the future QCs?



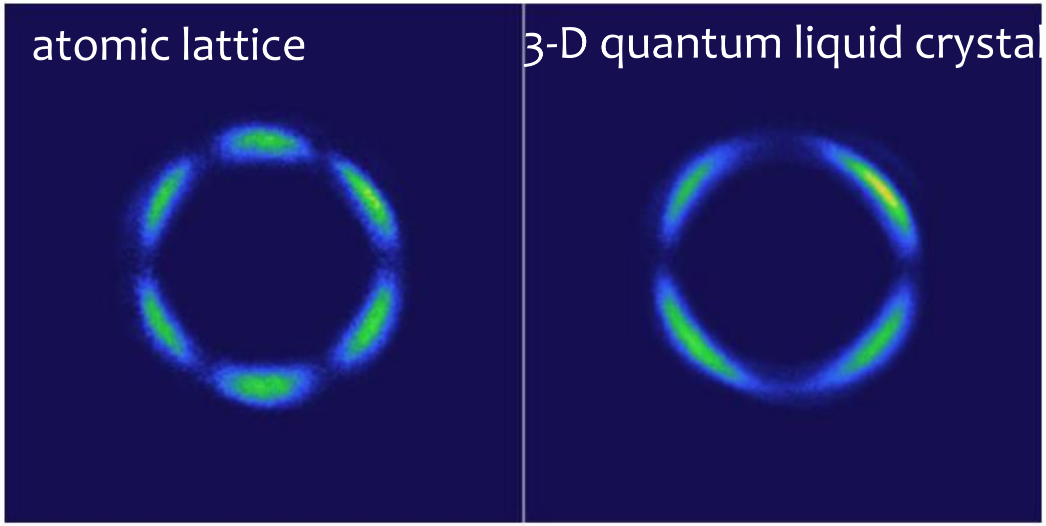


Future Directions

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

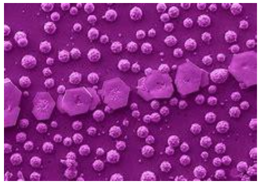
The electrons have different magnetic properties, depending on whether they flow forward or backward on a given axis!

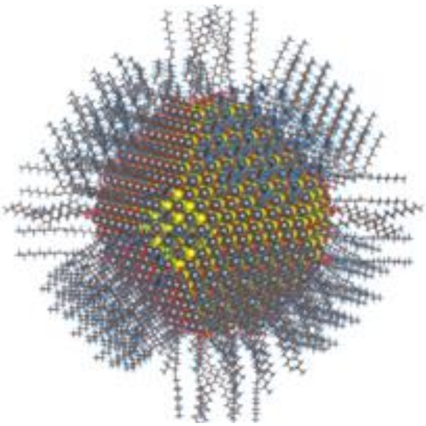
Future Directions

What about the Quantum Dots?

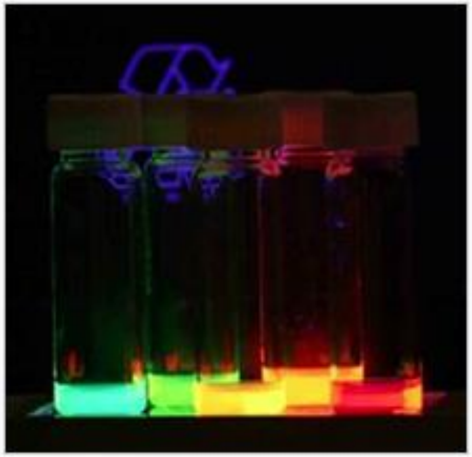
Cadmium sulfide quantum dots

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)

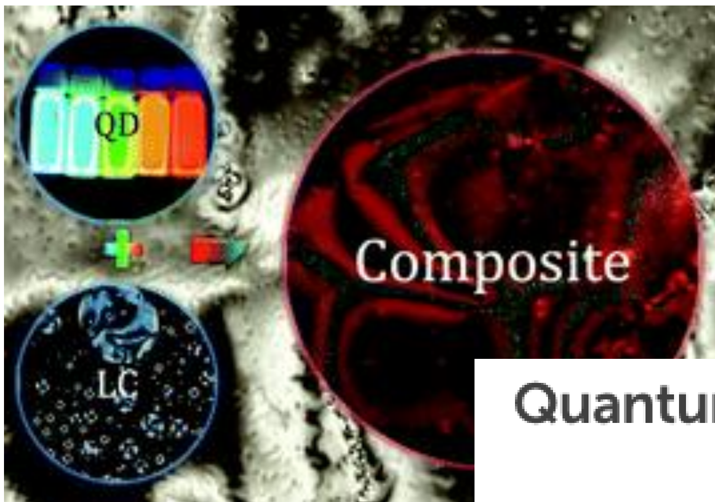


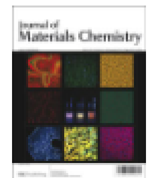
Colloidal quantum dots irradiated with a UV light. Different sized quantum dots emit different color light due to quantum confinement.

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

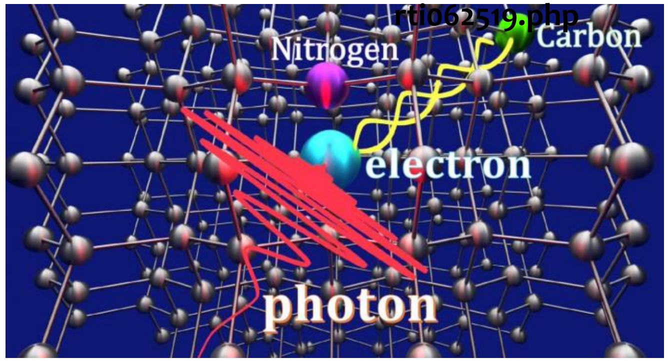
Javad Mirzaei,[a] Mitya Reznikov[b] and Torsten Hegmann*[abcd]

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

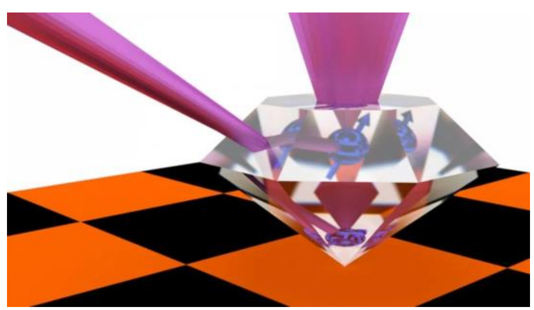


https://bigthink.com/robby-berman/the-future-internet-could-be-built-of-diamonds

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.

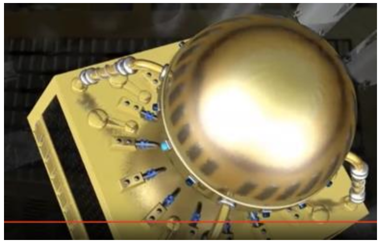
ROBBY BERMAN 10 July, 2018



BIG THINK

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!