

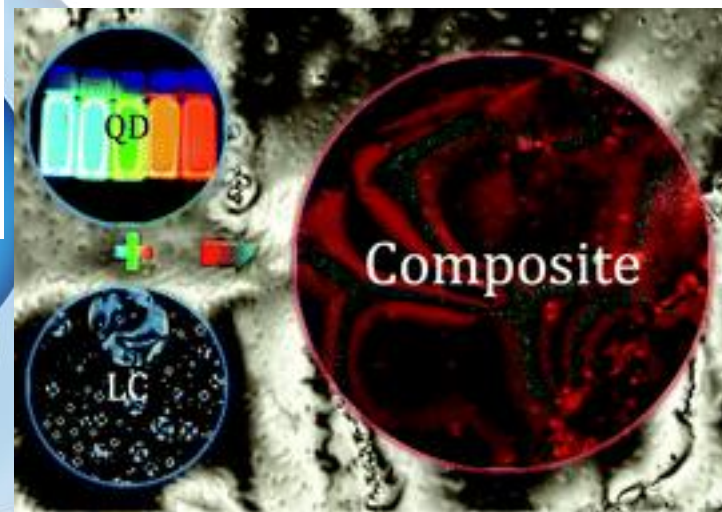
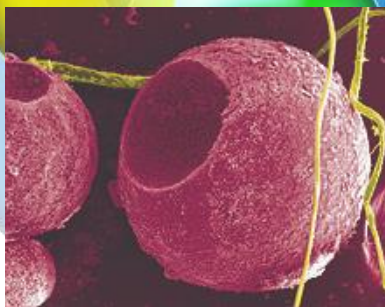
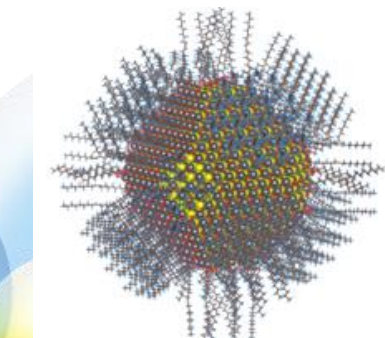
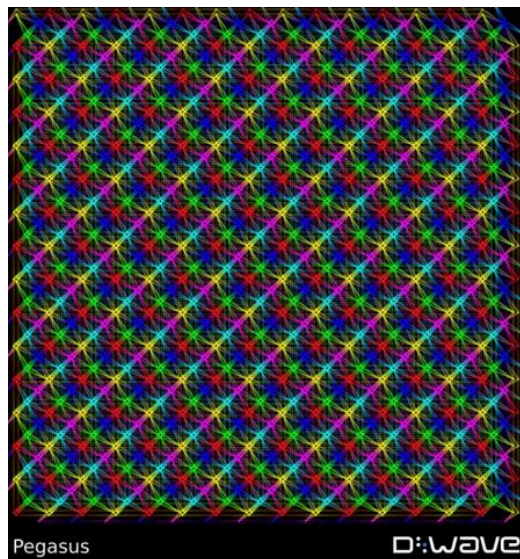
Quantum Computing

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

Where did this idea come from?

A Recent History



1982

Richard Feynman envisions quantum computing

1994

Peter Shor develops algorithm that could be used for quantum code-breaking

2000

Eddie Farhi at MIT develops idea for adiabatic quantum computing

2013

D-Wave Two, 512 qubits



1985

David Deutsch describes universal quantum computer



1999

D-Wave Systems founded by Geordie Rose

2010

D-Wave One: first commercial quantum computer, 128 qubits

© 2014 D-Wave Systems Inc. All Rights Reserved

5

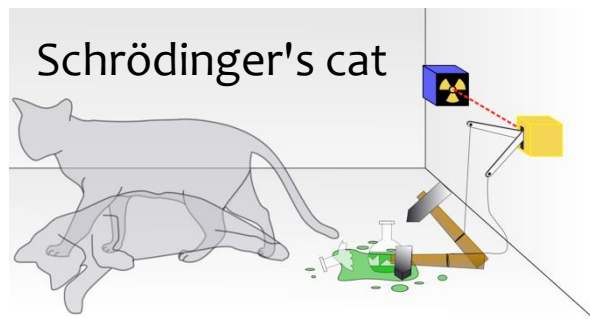
D-WAVE
The Quantum Computing Company

For more details see Wikipedia: [Timeline of quantum computing and communication](#)^{ing}

Key Concepts in Quantum Computing

Key Quantum Effects

Superposition

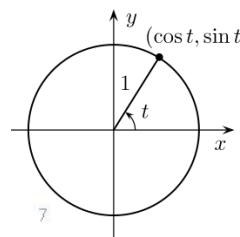
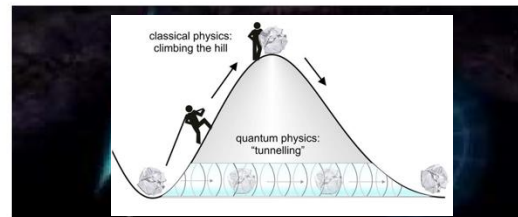


$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

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

© 2014 D-Wave Systems Inc. All Rights Reserved

Quantum Tunneling



Entanglement



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

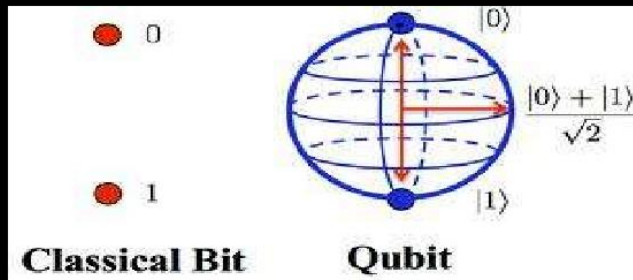
$$\frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$$

D-WAVE
The Quantum Computing Company

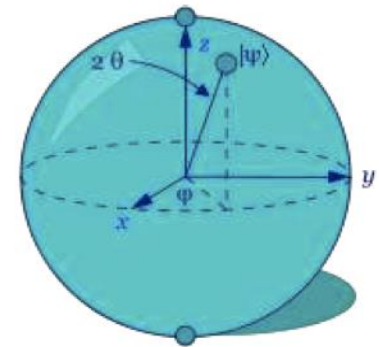
LinkedIn SlideShare: 17 Nov 2014 – “Quantum Computing: Welcome to the Future” by Vern Brownell CEO

Key Concepts in QC

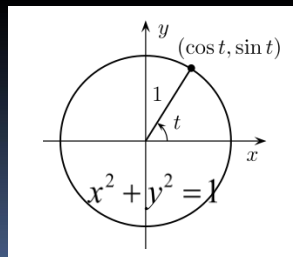
What special about Quantum computer



The Q-bit represented as a Bloch sphere



$$v_0|0\rangle + v_1|1\rangle \rightarrow \begin{bmatrix} v_0 \\ v_1 \end{bmatrix}$$



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

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

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

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

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

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

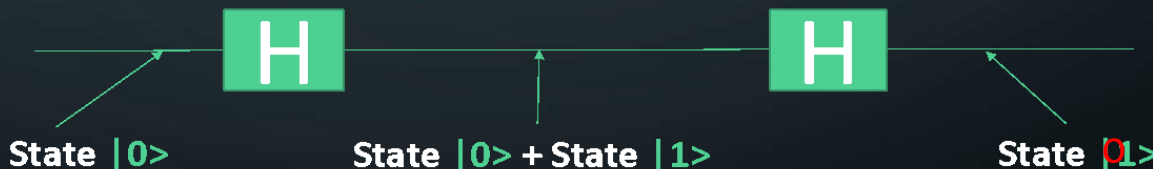
$$X = (\sqrt{NOT})^2$$

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

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

Quantum Gates-~~Hadamard~~

- ❖ Simplest gate involves one qubit and is called a ~~Hadamard Gate~~ (also known as a square root of NOT gate.) Used to put qubits into superposition.



Note: Two Hadamard gates used in succession can be used as a ~~NOT gate~~.

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

Classical Facsimile Transmission

Intact Original

Approximate Copy

Scan

Original

Send

Quantum Teleportation

Disrupted Original

Teleported Replica
of Object A

Apply Treatment

Data

Entangled Pair
of Objects



(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	5×10^{15} years	3×10^{29} years
factoring in 2024	38 years	10^{12} years	7×10^{25} years
factoring in 2042	3 days	3×10^8 years	2×10^{22} years

with potential quantum computer

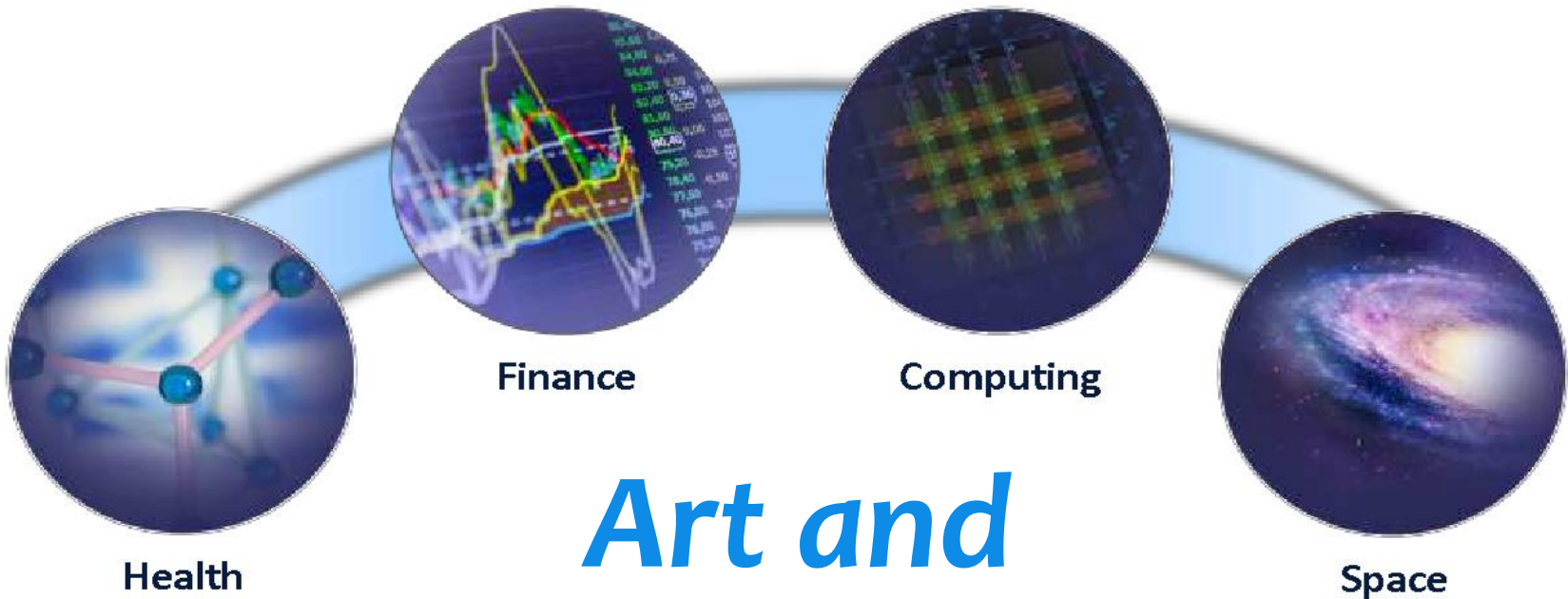
# bits	1024	2048	4096
# qubits	5124	10244	20484
# gates	3×10^9	2×10^{11}	1×10^{12}
factoring time	4.5 min	36 min	4.8 hours

Slide by Meghaditya Roy Chaudhury on “Quantum Computing” at Jadavpur University

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

Possible Applications of QC

What is the future of quantum computing?



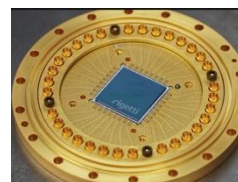
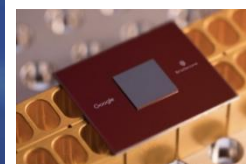
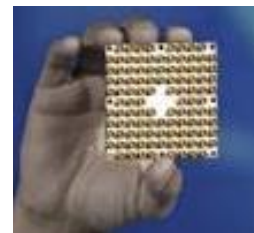
© 2014 D-Wave Systems Inc. All Rights Reserved

D-WAVE
The Quantum Computing Company

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



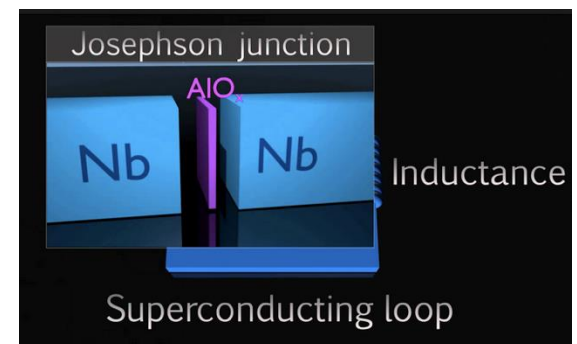
Qiskit



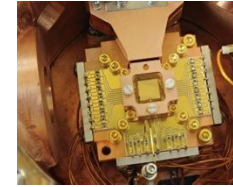
Amazon Braket

The Quipper System

D-Wave 2000-qubit processor

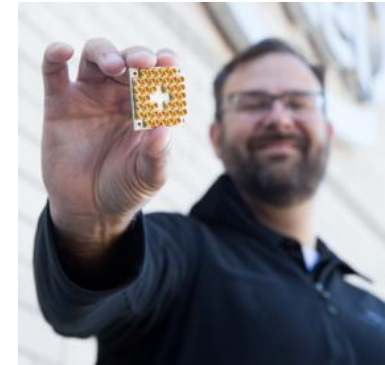
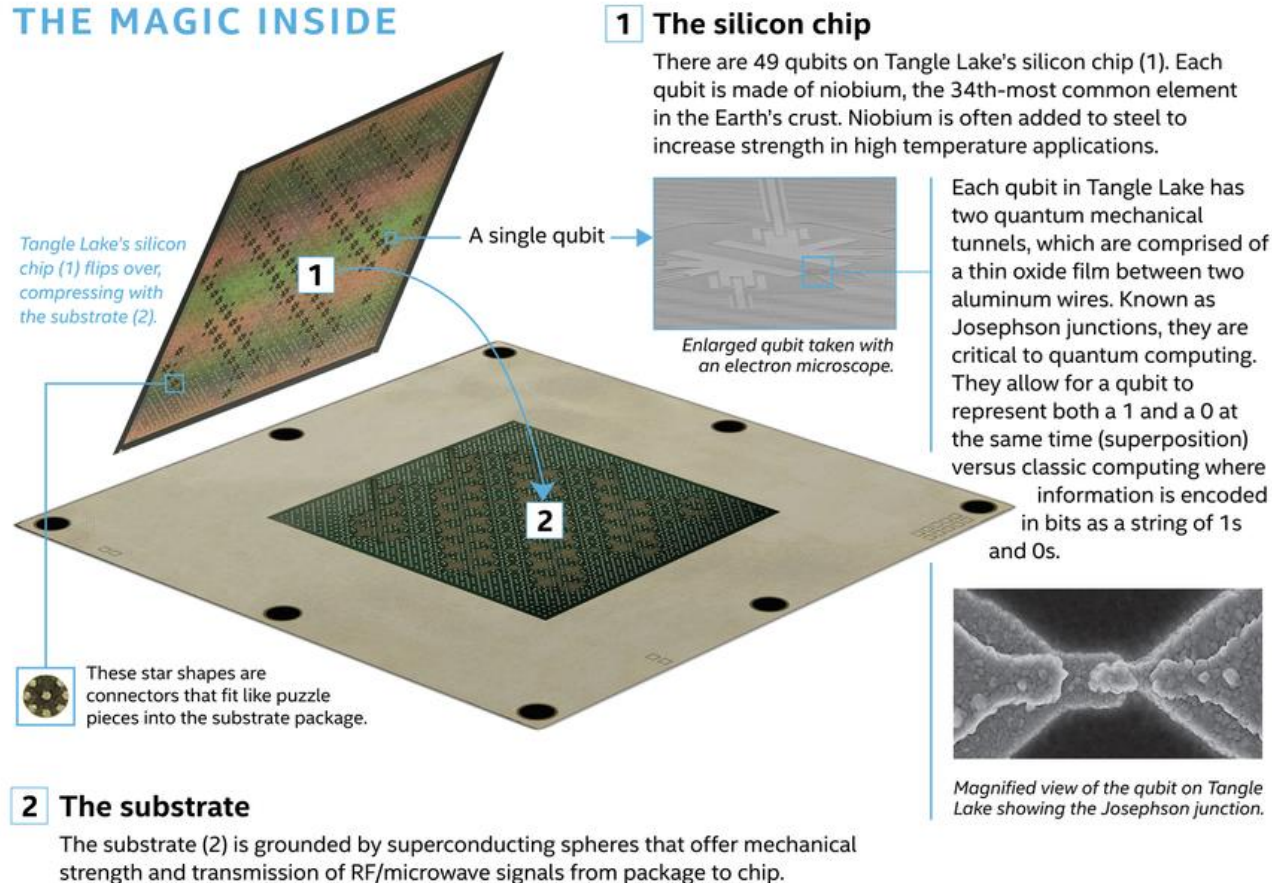


IBM 50-Qubit Processor



'Tangle Lake,' Intel's 49-Qubit Processor

THE MAGIC INSIDE



26 spin q-bits



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

Problems and Future Directions

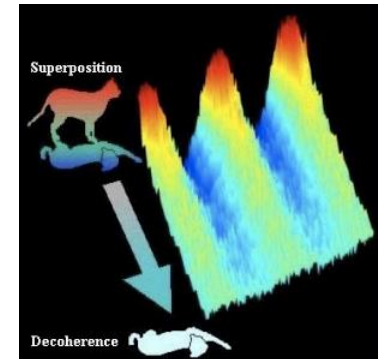
$$|\psi\rangle = \sum_n c_n |n\rangle \longrightarrow |n_i\rangle$$

- De-coherence
- Error Correction
- Output Measurement
- Finding “the right problems” for a quantum computer

Example - Single Bit Error Correction

101011	101011
111100	1 01100
011101	011101
101010	101010
no errors	parity error

Hamming - Correctable single bit error



NEWS

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

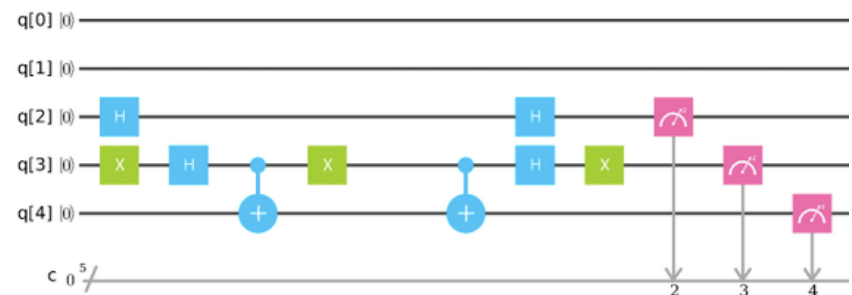
D-Wave's 2000Q quantum computer will ship to select customers but could ultimately be available to others via the cloud



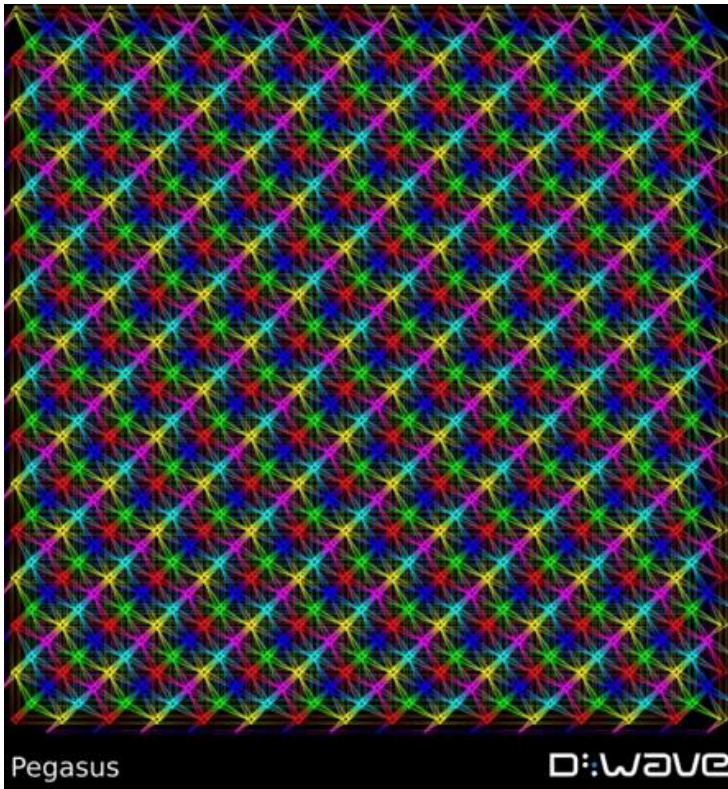
By Agam Shah

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!

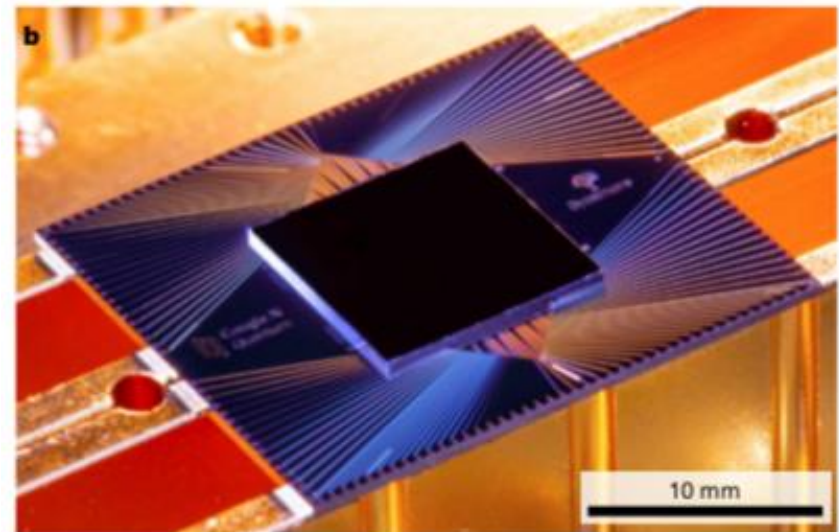
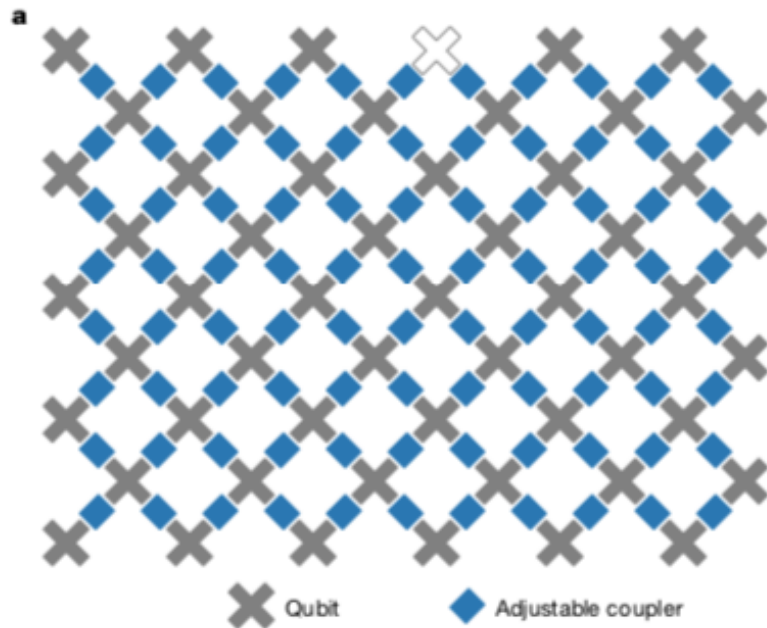


Fig. 1 | The Sycamore processor. **a**, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b**, Photograph of the Sycamore chip.

Future Directions

Are liquid-crystals part of the future QCs?

1 General characteristics

2 History

2.1 1880s–1960s

2.2 1970s

2.3 1980s

2.4 1990s

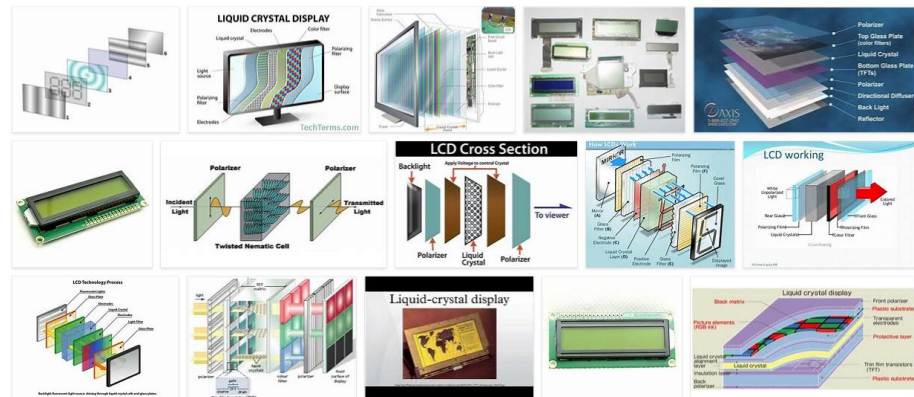
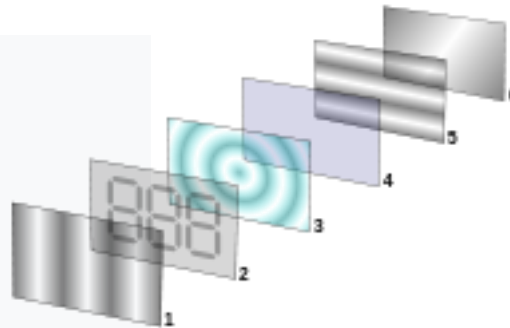
2.5 2000s–2010s

3 Illumination

4 Connection to other circuits

5 Passive and active-matrix

6 Active-matrix technologies

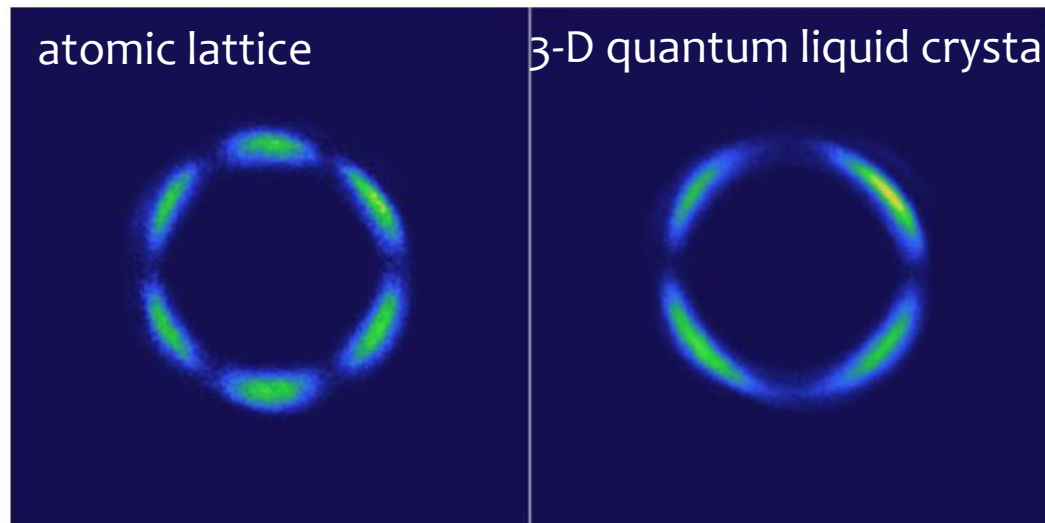


Future Directions

First 3D quantum liquid crystal!

Quantum Liquid Crystals Could Speed Up Computers

Fri, 04/21/2017 - 9:57am by Kenny Walter, Science Reporter - [@RandDMagazine](#)



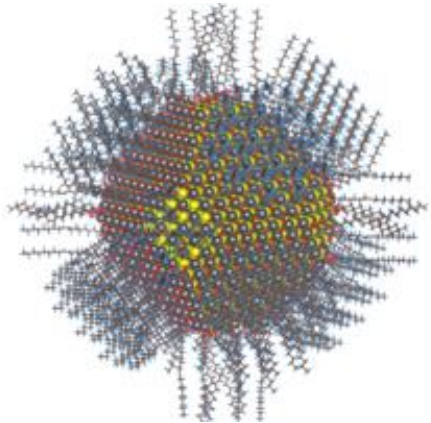
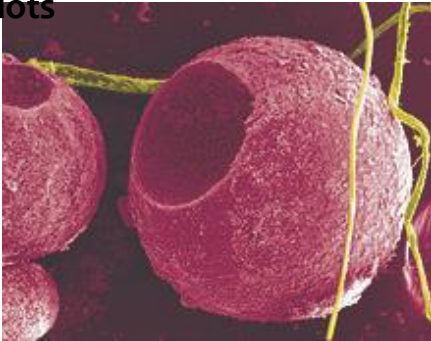
These images show light patterns generated by a rhenium-based crystal using a laser method called optical second-harmonic rotational anisotropy. At left, the pattern comes from the atomic lattice of the crystal. At right, the crystal has become a 3-D quantum liquid crystal, showing a drastic departure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

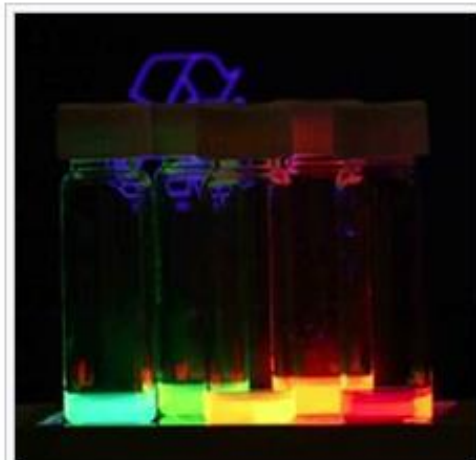
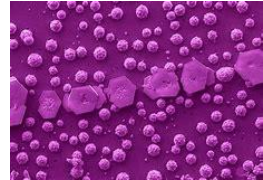
What about the Quantum Dots?

Cadmium sulfide quantum dots



lead sulfide (selenide)

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.



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

1 Production

- 1.1 Colloidal synthesis
- 1.2 Plasma synthesis
- 1.3 Fabrication
- 1.4 Viral assembly
- 1.5 Electrochemical assembly
- 1.6 Bulk-manufacture
- 1.7 Heavy-metal-free quantum dots

2 Health and safety

3 Optical properties

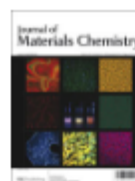
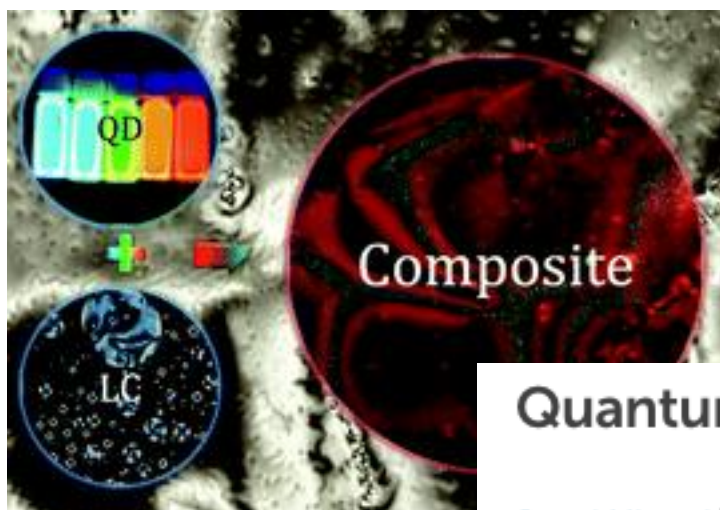
4 Potential applications

- 4.1 Biology
- 4.2 Photovoltaic devices

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}

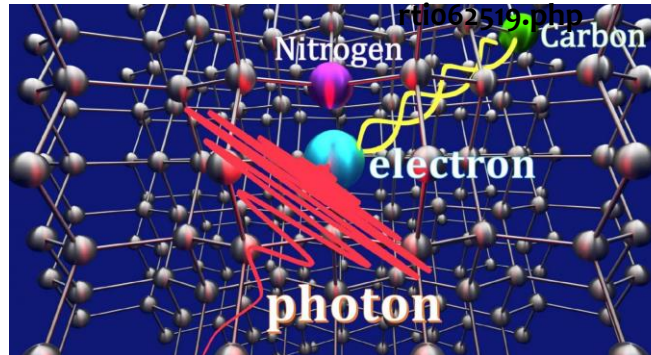
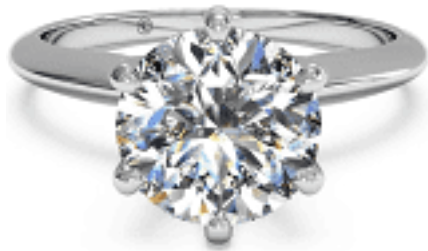
J. Mater. Chem., 2012,22, 22350-22365 ;

<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-r1062519.php



NEWS RELEASE 28-JUN-2019

Researchers teleport information within a diamond

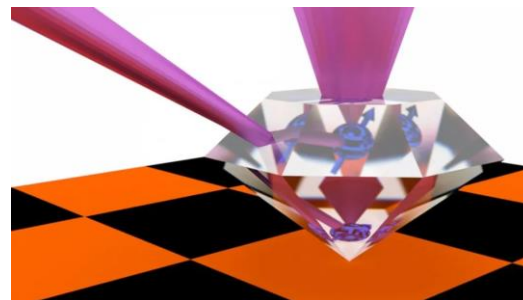
YOKOHAMA NATIONAL UNIVERSITY

<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

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/](https://qc.iaps.institute/)
- [Linear Algebra Review](https://cs229.stanford.edu/section/cs229-linalg.pdf) 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 Kopiczyk <https://arxiv.org/abs/1804.10068>

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