Quantum Stuff – Why, Where and When?

Robert, Bobby, Bob and/or Bo Ewald
LASL, LANL, Cray Research, SGI, Linux Networx, . . . D-Wave, ColdQuanta
Topics

- Quantum?
- Technology Waves and Building Blocks
- Quantum Product Families
  - Timing and Positioning
  - Communications
  - Computing
- Early Proto-apps
- A Quantum of Summary
In the Beginning, Mother Nature did the easy things first:

- Electrons: $BB + 10^{-6}$ seconds
- Photon epoch: $BB + 10$ seconds
- H & He atoms: $BB + 380,000$ years
- Heavier atoms: $BB + 1B$ years
- Quantum Revolution: $BB + 13.8B$ years
Physics, circa 1900

...it was generally accepted that all the important laws of physics had been discovered...

Quantum is... a three-headed hydra

Three independent formulations of quantum mechanics have been proposed.

The three formulations have been shown to be mathematically identical.

Werner Heisenberg  
Matrix mechanics 1932

Erwin Schrödinger  
Wave mechanics 1933

Richard Feynman  
Path integrals 1965
Quantum Essentials

• Events are probabilistic
• States are described by superposition (wavefunction)
• A state changes in time according to a precise equation
• Entangled states that are not separable arise naturally
• Measuring a state causes its wavefunction to collapse
A little trouble understanding or accepting quantum mechanics?

Entanglement – “I don’t believe in spooky action at a distance.”

Probability – “God does not play dice with the Universe.”

Measurement - “I like to think the moon is there even if I’m not looking at it.”

Quantum Theory – “If this is correct, it signifies the end of physics as a science.”
Why Quantum?

Quantum technology is the closest thing to the way Mother Nature operates the Universe.
Quantum systems will be faster, more accurate, more sensitive, more powerful by factors of 10-1000.

- Drug discovery: Quantum computers can do chemistry calculations that are intractable with supercomputers.
- Unhackable, time & location information: With no satellite vulnerability, time and location are secure and always available.
- RF Communications & Radar: Quantum devices provide secure communication and early detection of impending threats.
- AI and Machine Learning: Quantum signal processors can address “needle in a haystack” problems in real time.
McKinsey & Co. estimates that combined worldwide spending on nonclassified quantum-technology research amounted to around some €1.5 billion in 2015. Here’s how those numbers were distributed globally—and some highlights of government quantum initiatives since then.

In May 2016, the European Commission announced that it would launch a ten-year, €1 billion "quantum flagship" R&D program in 2018.

In 2013, the U.K. government initiated a National Quantum Technology Program with a pledged investment of £770 million over five years.

In the U.S., the National Photonics Initiative has advocated for a "National Quantum Initiative" involving US$500 million in new public-private funding (see p. 18).

China is said to be making a major investment in quantum technology, including a quantum research "supercenter" in Hefei at a cost believed to be in the billions of US$.

United States: €360 m

U.K.: €105 m

E.U. total: €550 m

Canada: €100 m

U.K.: €220 m

China: €13 m

Singapore: €44 m

Brazil: €11 m

Australia: €75 m

Germany: €120 m

France: €52 m

Italy: €36 m

Austria: €35 m

Netherlands: €27 m

Spain: €25 m

Denmark: €22 m

Sweden: €15 m

Finland: €12 m

Poland: €12 m

Source: Optical Society of America, Optics & Photonics, Feb. 2018

Global Quantum R&D Spending - 2020

Quantum effort worldwide

Global effort 2020

$22b (estimate)

Source: Qureca
September 2020
Dr. Araceli Venegas-Gomez and Ramya Mani, QURECA Ltd.

https://www.qureca.com/overview-on-quantum-initiatives-worldwide/
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The Digital Wave

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Flashlamp from the first ruby laser

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CD’s and DVD’s
Medical Instruments
Scanners
Machining

The Quantum Wave

1995: Exquisite control over the atom.

False color image of the first quantum gas

Instruments
Secure Communications
New Sensing Systems
Radar, Airport Scanners, . . .
Quantum Positioning System (QPS)
Computing
Quantum Aided Design . . .

ELECTRONICS
PHOTONICS
QUANTUM ATOMICs
“Quest for Qubits”

Gabriel Popkin

A bit of the action
In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

Superconducting loops
A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition states.

- Longevity (seconds)
  - A: 0.00005
  - B: >1000

- Logic success rate
  - A: 99.4%
  - B: 99.9%

- Number entangled
  - A: 9
  - B: 14

Company support
- Google, IBM, Quantum Circuits
- IonQ

Pros
- Fault tolerant, build on existing semiconductor industry.
- Very stable, highest achieved gate fidelities.

Cons
- Collapse easily and must be kept cold.
- Slow operation, many lasers are needed.

Trapped ions
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.

- Longevity (seconds)
  - A: 0.03

- Logic success rate
  - A: ~99%

- Number entangled
  - A: 2

Silicon quantum dots
These “artificial atoms” are made by adding an electron to a small piece of pure silicon. Microwaves control the electron’s quantum state.

- Logic success rate
  - A: N/A

- Number entangled
  - A: N/A

Topological qubits
Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.

- Logic success rate
  - A: N/A

- Number entangled
  - A: 10

Diamond vacancies
A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.

- Logic success rate
  - A: 99.2%

- Number entangled
  - A: 6

Pros
- Greatly reduce errors.
- Can operate at room temperature.

Cons
- Existence not yet confirmed.
- Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state. Logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Credits: (Graphic) C. Bickel/Science; (Data) Gabriel Popkin
Technology approaches to Quantum Computing

Superconducting qubits
- IBM
- Google
- Rigetti
- D-Wave

Neutral atom qubits
- QuEra
- Pasqal
- ColdQuanta
- Atom Computing

Photonic qubits
- Xanadu
- PsiQuantum

Trapped Ion qubits
- IonQ
- AQT
- Honeywell

Topological qubits
- Microsoft
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GPS is a Vulnerable $10B+ System

“...We’ll push the performance envelope in timing and navigation technology by harnessing Nobel Prize-winning physics research that uses lasers to cool atoms.”

-Ash Carter, 25th US Secretary of Defense
Quantum Sensing – Quantum Positioning System (QPS)

(INS) Inertial Navigation System

(Calendar) + 

(IMU) Inertial Measurement Unit

+ 

Clock

Accelerometer

Gyroscope
ColdQuanta’s Inertial Sensing and Clock Prototype Programs

**Accelerometers**

![Accelerometer Chart]

**Gyroscope**

![Gyroscope Chart]

**Clocks**

![Clocks Chart]

Down and to the left is goodness
Each tic mark down is a 10X performance improvement
Left is less “Size, Weight and Power”
Quantum allows trading performance for SWaP depending on application
UK Research & Innovation: High-BIAS2 Program

“Navigation using space-based satellite signals underlies many critical technologies across the UK. Most advanced navigation technologies rely on the signals from networks known as the Global Navigation Satellite System (GNSS) to remain accurate over long distances. Loss of these signals result in an unstable navigation systems and increasingly less accurate location and direction estimation during operation.

GNSS signals may be lost accidentally from criminal activity or due to military action. For example, in 2018 several passenger flights off the Norwegian coast lost GNSS signals due to signal ‘jamming’ from military exercises. In addition, ‘Spoofing’ or deliberately transmitting false guidance signals has been demonstrated as an insidious cyberweapon that can deliberately mislead and fool cargo or passenger vessels. As systems are increasingly automated, the consequences of the loss of GNSS signals dramatically increase and may include loss of property, or in the extreme case, loss of life. Local on-board instruments can provide measurements to stabilise current navigation system technology without GNSS signals. Quantum technology-based sensors have the potential to provide stability to navigation systems over long periods of time due to the unique combination of high sensitivity to motion with superb isolation from changes in the surrounding environment. High-BIAS2 will demonstrate the ability of a quantum rotation sensor’s ability to stabilise the orientation of aircraft guidance system in the absence of GNSS signals. Local stabilisation using quantum technology will decrease the reliance of navigation systems on GNSS and provides a measure of protection against signal loss, jamming, and spoofing to increase safety and security.”
QRF – Quantum Signal Detection

• Detect very faint signals
• Precisely locate their source
• Across a wide frequency spectrum
• Without huge antenna farms
DARPA Quantum Apertures Program

“The Microsystems Technology Office at DARPA seeks innovative proposals in the area of quantum-based RF receivers. The program will demonstrate the potential to receive modulated RF signals over a very large spectral range using a single receiving element with state of the art sensitivity.”
9:00 A.M. Richard Feynman
“Tiny Computers Obeying Quantum-Mechanical Laws”
Two Quantum Computer Architectures

“Quantum Annealing”
- Like analog computing
- Map a problem on the system
- Collapses to a low energy state
- May/may not be “the answer”
- Run problems 100’s of times

- D-Wave

“Gate Model”
- More like digital computer
- Program it by connecting gates to represent your algorithm
- With error correction, should be a universal computer that delivers “the answer”
- But, no error correction yet (NISQ)
- IBM, Google, Rigetti, IonQ, . . .
Processor Environment

- Cooled to 0.015 Kelvin, 175x colder than interstellar space
- Shielded to 50,000× less than Earth’s magnetic field
- In a high vacuum: pressure is 10 billion times lower than atmospheric pressure
- On low vibration floor
- <25 kW total power consumption – for the next few generations
Quantum Annealing “Circuit Diagram”
IBM Q System One
Simulation on IBM Quantum Experience (IBM QX)

Preparation of singlet state

Rotation by $\theta_1$ and $\theta_2$

Readout measurement

X-gate:
- $X|0\rangle = |1\rangle$
- $X|1\rangle = |0\rangle$

Hadamard gate:
- $H|0\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$
- $H|1\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$

$U_1$ phase gate:
- $U_1|0\rangle = |0\rangle$, $U_1|1\rangle = e^{i\theta}|1\rangle$

CNOT gate:
- $C_{01}|0_10_0\rangle = |0_10_0\rangle$
- $C_{01}|0_11_0\rangle = |1_11_0\rangle$
- $C_{01}|1_10_0\rangle = |1_10_0\rangle$
- $C_{01}|1_11_0\rangle = |0_11_0\rangle$
Prototype Cold Atom QC

If I were an Industrial Designer!
QC Hardware Landscape – Q1 2021

**Annealing (SC)**
- D-Wave Advantage (5000 qubits)

**Superconducting**
- IBM (20q, 65q? cloud)
- Rigetti (32q cloud)
- Google (54q?)
- QCI, IQM, Oxford Quantum Circuits

**Trapped Ions**
- IonQ (11q, 32q? cloud)
- Honeywell (10q cloud)
- AQT, Oxford Ionics, Universal Quantum

**Cold atoms**
- ColdQuanta
- QuEra
- AtomComputing
- Pasqal

**Topological**
- Microsoft

**Optical**
- Xanadu (12q cloud)
- PsiQuantum, Orca Computing

**Quantum dots**
- Intel, SQC, Quantum Motion
QC Usage Model & Software Landscape Examples*

Usage Model
- Loosely coupled attached processors
- No OS on QPU
- “Remote Batch” with some time sharing
- Software environment on front-end
- Simulators for most systems

Full(ish) Stack
- IBM Qiskit
- Google CIRQ
- Rigetti Forest
- Strangeworks
- ...

Optimizers & Tools
- Parity QC
- QCI
- ...

Applications
- 1QBit
- Zapata
- ...

*See [https://quantumcomputingreport.com/tools/](https://quantumcomputingreport.com/tools/) for a list of ~50 quantum software tools
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Toward Quantum Applications

- 1982 – Richard Feynman proposed the idea of creating machines based on the laws of quantum mechanics
- 1985 – David Deutsch developed the quantum Turing machine, which became a model for quantum computation
- 1994 – Peter Shor created an algorithm for factoring large numbers quickly on a quantum computer
- 1997 – Lov Grover develops a fast quantum search algorithm
- Now and the future?
“It’s tough to make predictions, especially about the future.”
LANL Rapid Response Projects

The LANL Rapid Response Project results for 2016 and 2017 are available as PDF's via the link:

VW Quantum Bus Routing Optimization
Ocado Technology

Ocado is the world’s largest online-only supermarket

Ocado Technology builds the software for Ocado, Morrisons, and other customers

Recently signed with Kroger (USA) to build 20 CFCs
Study Name: “Waste Collection Route Optimization”
Verification Bodies: Groovenauts, Inc. and Mitsubishi Estate Co., Ltd.
Scope of Study: 26 buildings owned, or operated and managed, by Mitsubishi Estate in the Marunouchi area of Tokyo

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<th>Item</th>
<th>Current</th>
<th>Optimized</th>
<th>Difference</th>
</tr>
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<tbody>
<tr>
<td>Total Route Distance</td>
<td>2,296.2 km</td>
<td>1004.2 km</td>
<td>▲1,292.0 km</td>
</tr>
<tr>
<td>Number of Trucks</td>
<td>75</td>
<td>31</td>
<td>▲44</td>
</tr>
<tr>
<td>Total Work Time</td>
<td>8,650.9 mins.</td>
<td>5,372.2 mins.</td>
<td>▲3,278.7 mins.</td>
</tr>
</tbody>
</table>

*Approximately 57% reduction (≈ CO2 emissions)
Improving Lithium Ion Batteries: IBM & Mitsubishi Chemical

Determining the barrier for $\text{Li}_2\text{O}_2$ formation and reversibility is key to understanding the chemistry of a Li-air battery

Energy barrier calculated on IBM Q quantum computer with SW-based error mitigation

https://arxiv.org/abs/1906.10675
Organic Light Emitting Diode (OLED)
Light from organic pigments sandwiched between electrodes
Statistical Classification of High-throughput Multi-omics Cancer Data on Quantum Computing Architectures

Tom Chittenden, PhD, DPhil, PStat
Chief AI Scientist
Founding Director, Advanced AI Research Laboratory
Lecturer on Pediatrics, Harvard Medical School
A.I. and Precision Medicine

The computational power of modern A.I. technology is well-positioned to uncover new and actionable insights from the exponentially growing pool of biological data.

- **FEATURE LEARNING**
  The intelligent simplification of high-dimensional multi-omic data without loss of information

- **MACHINE & DEEP LEARNING**
  Intelligent algorithms capable of self-optimization to achieve incredible accuracy with complex, layered data

- **CAUSAL INFERENCE**
  Specialized statistical learning models capable of elucidating causal dependencies within biological data

- **NATURAL LANGUAGE PROCESSING**
  Intelligent scanning of sentence syntax to understand and validate findings in context, at scale

The combination of several A.I. methods create a proprietary ensemble A.I. strategy capable of revealing novel patterns and causal dependencies in disparate and varied biological data.
1. Oncology
2. Cardiovascular Disease
3. Alzheimer’s Disease
4. Liver Disease
5. Inverse Molecular Design
6. Quantum Machine Learning
Quantum Machine Learning

- Quantum computing promises enhanced performance for many classes of problems associated with large datasets.

- We are in the process of replacing algorithmic components of our Ensemble Computational Intelligence Strategy with their respective quantum counterparts.

- Our first algorithm was a quantum hierarchical clustering (qHCl), based on a modified Grover’s algorithm, a quantum search algorithm that runs quadratically faster than any equivalent classical algorithm.

- We have now built statistical quantum machine learning classifiers on both IBM’s universal quantum circuit architecture and the D-Wave Two X (DW2X) processor and DW2000Q Adiabatic quantum computer. Our D-Wave qML algorithms achieve comparable, and in some cases slightly better, classification performance than their classical counterparts on high-dimensional, multi-omic cancer data from the Cancer Genome Atlas (TCGA).
ABSTRACT Many challenging scheduling, planning, and resource allocation problems come with real-world input data and hard problem constraints, and reduce to optimizing a cost function over a combinatorially defined feasible set, such as colorings of a graph. Toward tackling such problems with quantum computers using quantum approximate optimization algorithms, we present novel efficient quantum alternating operator ansatz (QAOA) constructions for optimization problems over proper colorings of chordal graphs. As our primary application, we consider the flight-gate assignment problem, where flights are assigned to airport gates to minimize the total transit time of all passengers, and feasible assignments correspond to proper graph colorings of a conflict graph derived instancewise from the input data. We leverage ideas from classical algorithms and graph theory to show our constructions have the desirable properties of restricting quantum state evolution to the feasible subspace, and satisfying a particular reachability condition for most problem parameter regimes. Using classical preprocessing we show that we can always find and construct a suitable initial quantum (superposition) state efficiently. We show our constructions in detail, including explicit decompositions to a universal set of basic quantum gates, which we use to bound the required resource scaling as low-degree polynomials of the input parameters. In particular, we derive novel QAOA mixing operators and show that their implementation cost is commensurate with that of the QAOA phase operator for flight-gate assignment. A number of quantum circuit diagrams are included such that our constructions may be used as a template toward development and implementation of quantum gate-model approaches for a wider variety of potentially impactful real-world applications.
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Quantum Positioning System (QPS)
Computing
Quantum Aided Design . . .
Quantum humor

How's your quantum computer prototype coming along?

Great!

The project exists in a simultaneous state of being both totally successful and not even started.

Can I observe it?

That's a tricky question.
40TH ANNIVERSARY LECTURE SERIES