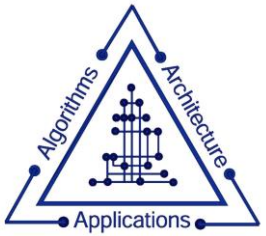
Quantum Stuff – Why, Where and When?

Robert, Bobby, Bob and/or Bo Ewald

LASL, LANL, Cray Research, SGI, Linux Networx, . . . D-Wave, ColdQuanta



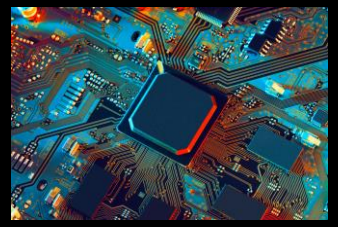
40TH ANNIVERSARY LECTURE SERIES

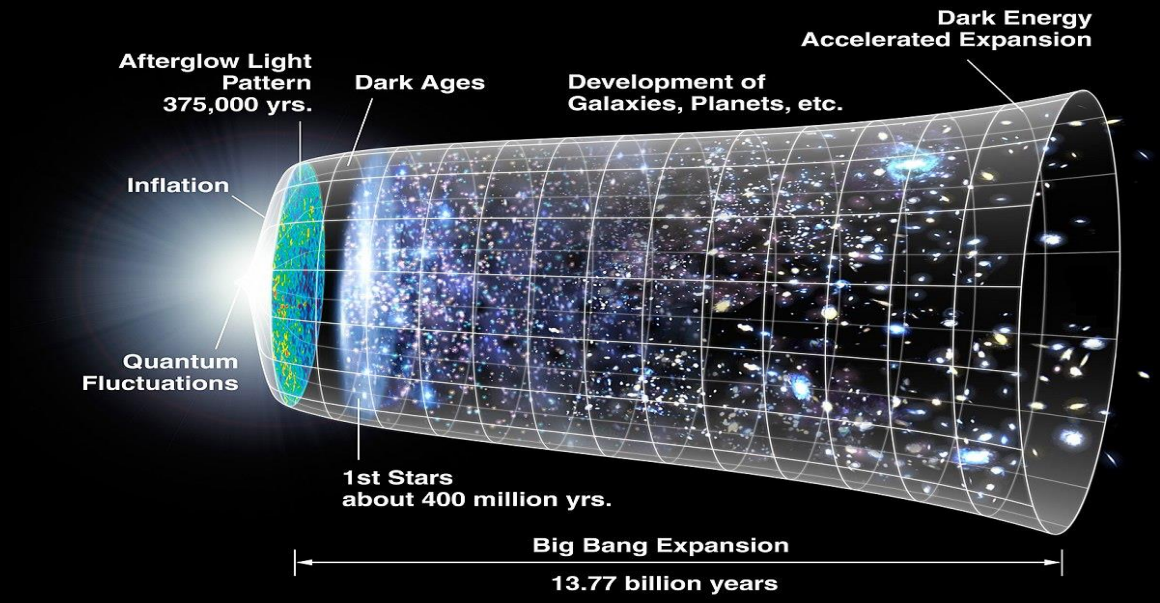
Topics

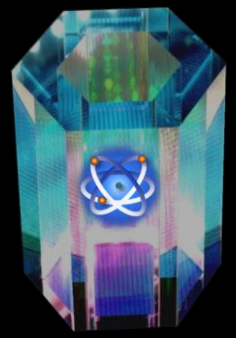
- Quantum?
- Technology Waves and Building Blocks
- Quantum Product Families
  - Timing and Positioning
  - Communications
  - Computing
- Early Proto-apps
- A Quantum of Summary

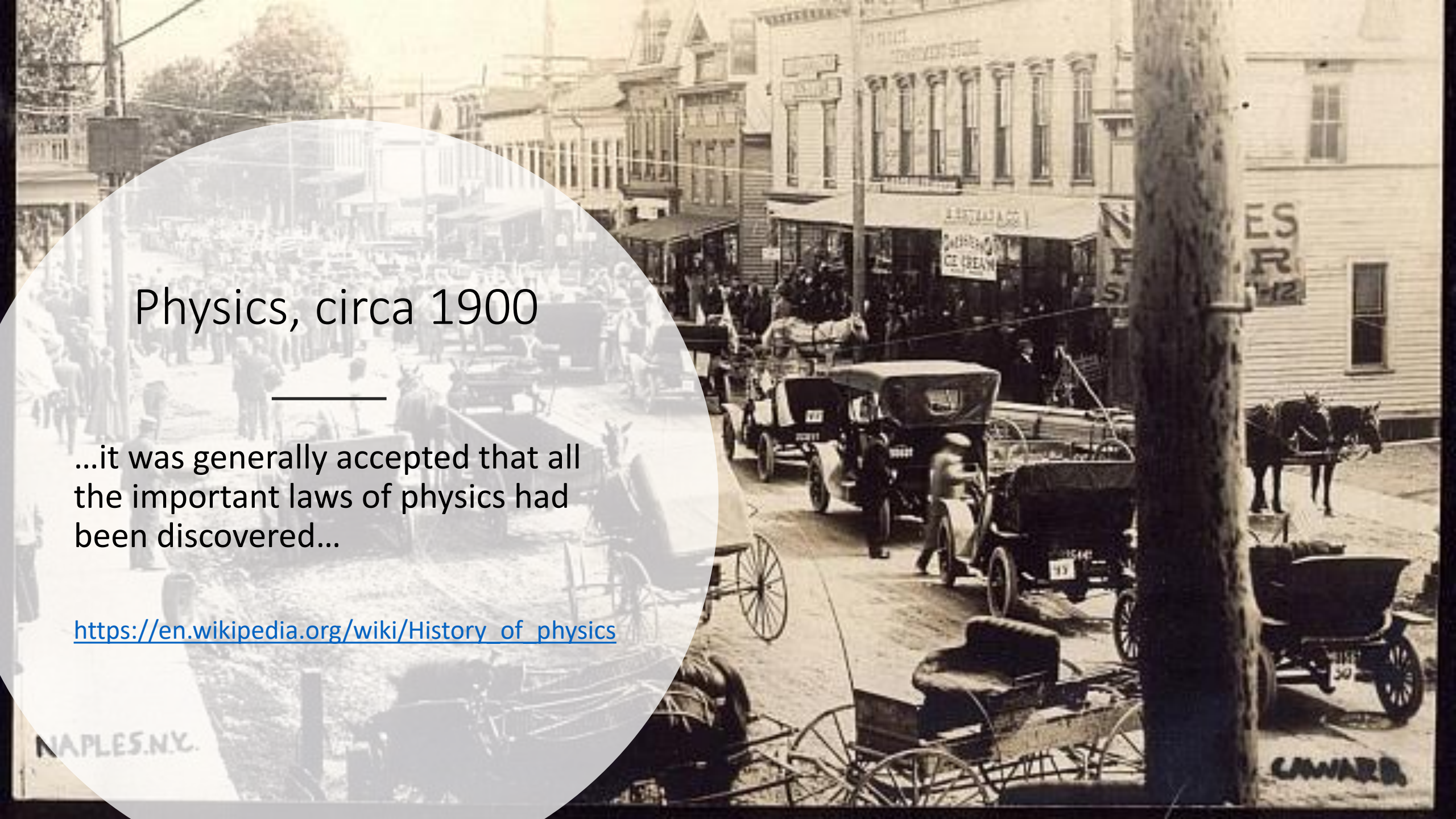
In the Beginning, Mother Nature did the easy things first:

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…

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

Quantum is…
a three-headed hydra

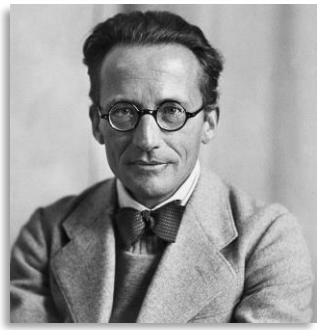
Three independent formulations of quantum mechanics have been proposed.

The three formulations have been shown to be mathematically identical.

Werner Heisenberg

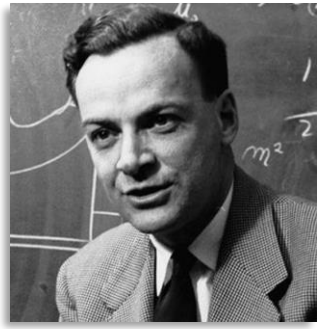
Matrix mechanics
1932

Erwin Schrödinger

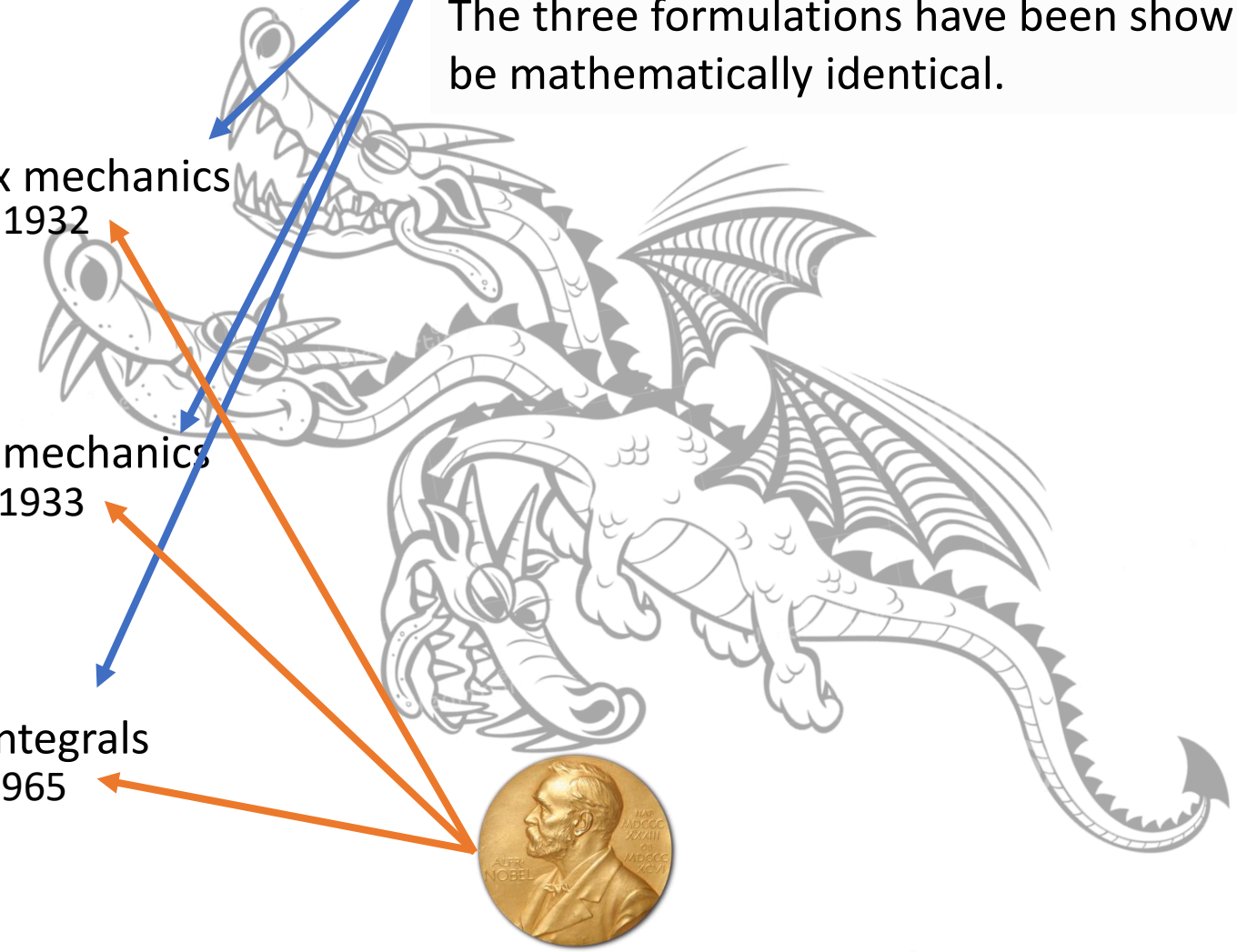


Wave mechanics
1933

Richard Feynman

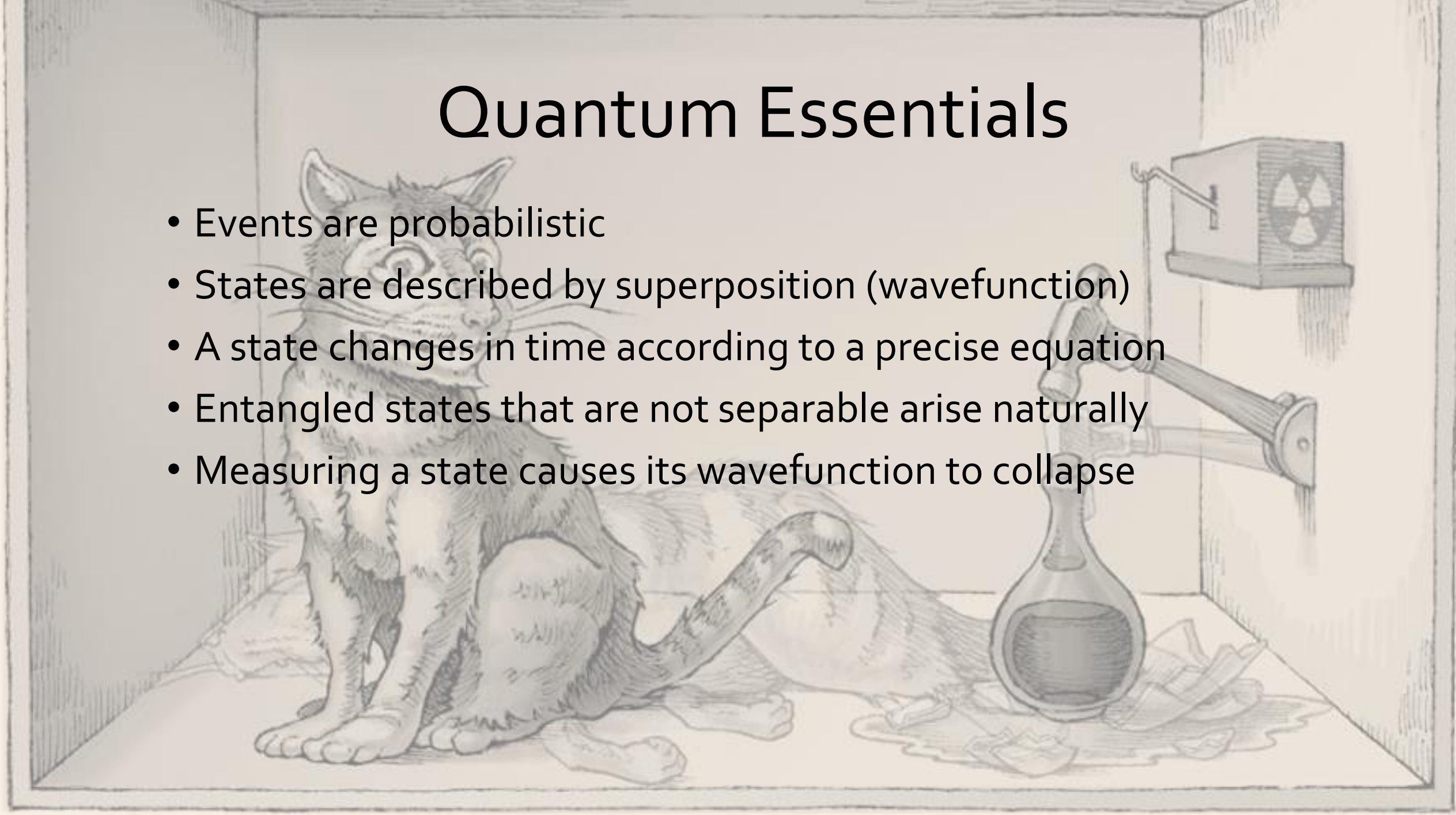


Path integrals
1965



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



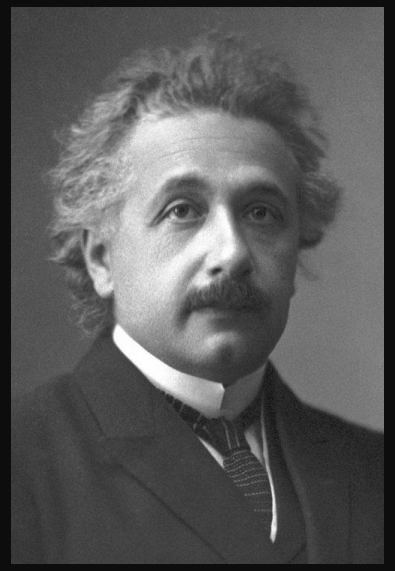
A little trouble understanding or accepting quantum mechanics?

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

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

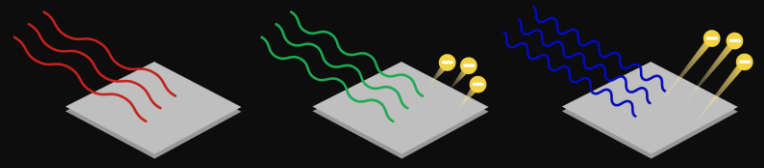
Measurement - “I like to think the moon is there even if I’m not looking at it.”

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



Einstein

1905

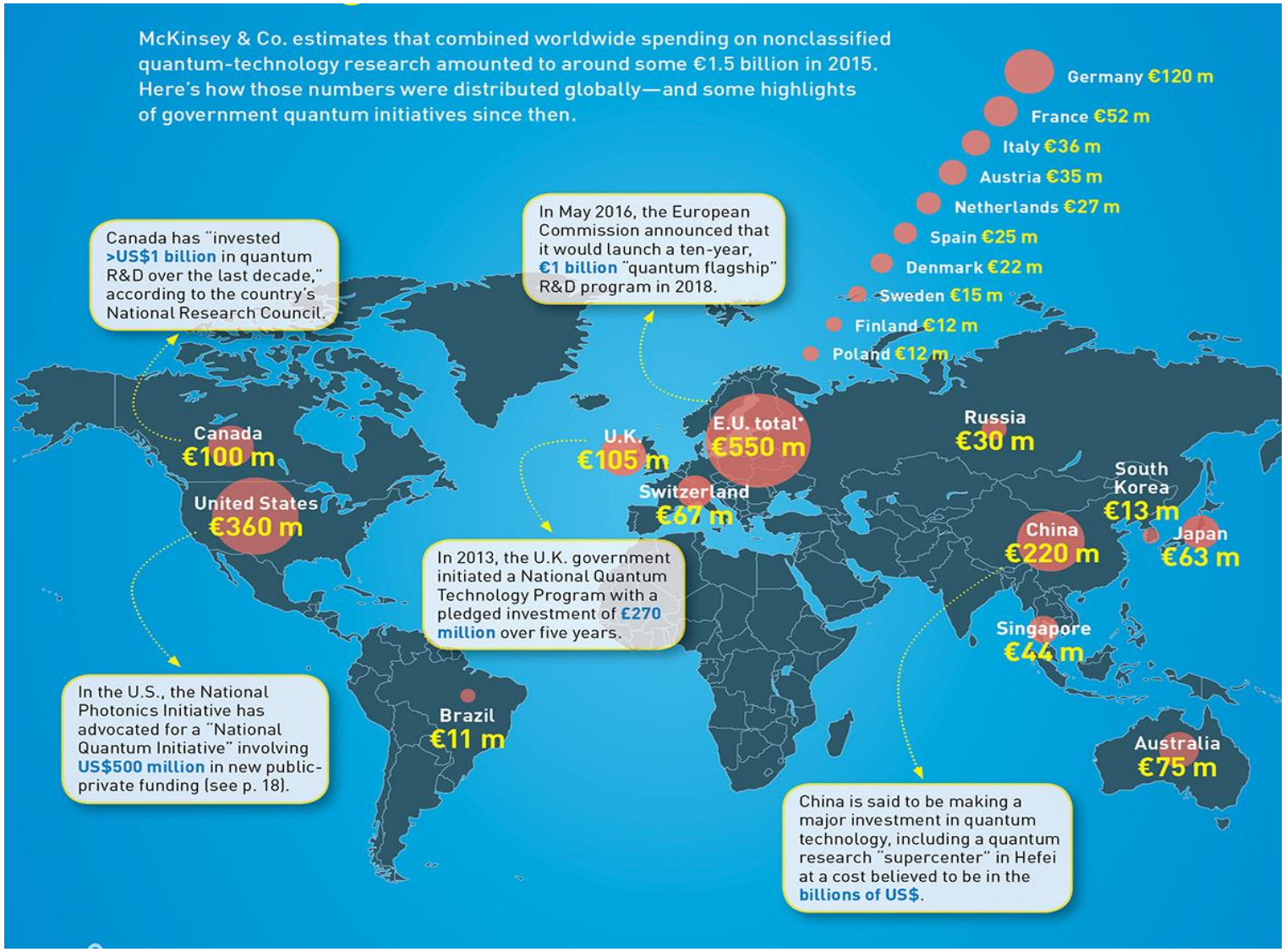


Why Quantum?

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.

Global Quantum R&D Spending - 2015



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

McKinsey & Co., 2015

Global Quantum R&D Spending - 2020

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

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

Topics

- Quantum?
- **Technology Waves and Building Blocks**
- Quantum Product Families
  - Timing and Positioning
  - Communication
  - Computing
- Early Proto-apps
- A Quantum of Summary

The Digital Wave

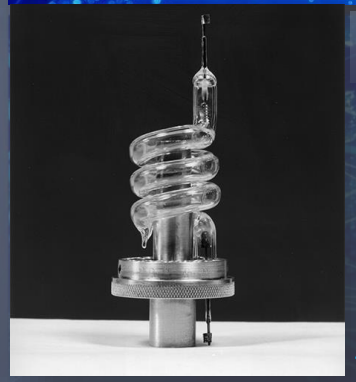
ELECTRONICS

1946: Exquisite control over the electron.

Replica of the 1946 Bell Labs Transistor.

Instruments
Calculators
Computers
Communications
Signal Processing
Video Games
. . .

The Communications Wave



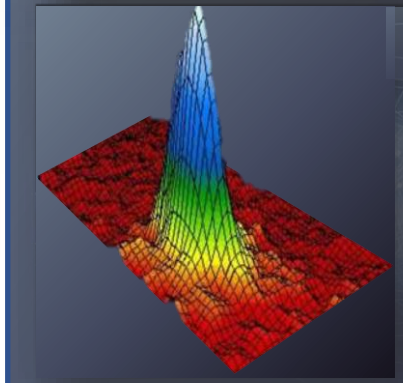
PHOTONICS

1957: Exquisite control over the photon.

Flashlamp from the first ruby laser

Communications
CD's and DVD's
Medical Instruments
Scanners
Machining
. . .

The Quantum Wave



QUANTUM ATOMICS

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 . . .
. . .

“Quest for Qubits”

Gabriel Popkin*

Science 02 Dec 2016:
Vol. 354, Issue 6316, pp. 1090-1093
DOI: 10.1126/science.354.6316.1090

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	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 vacancy 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%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	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.

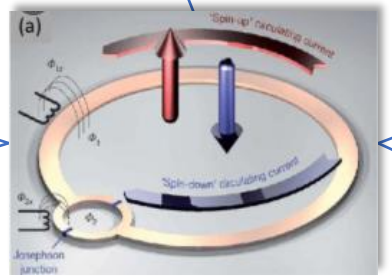
CREDITS: (GRAPHIC) C. BICKEL/*SCIENCE*; (DATA) GABRIEL POPKIN

Technology approaches to Quantum Computing

Quantum Circuits

IBM

Google



Rigetti

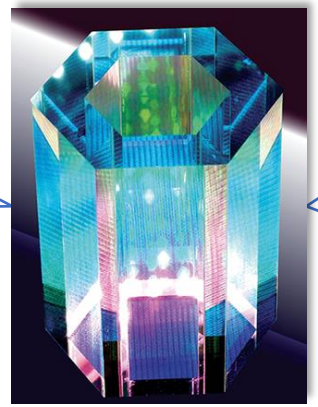
D-Wave

Superconducting qubits

Neutral atom qubits

QuEra

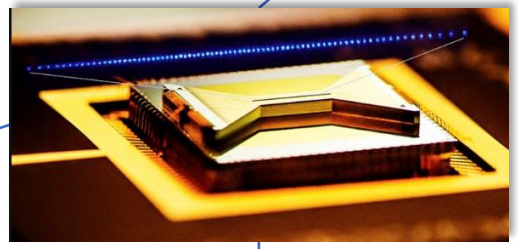
Pasqal



Atom Computing

ColdQuanta

IonQ

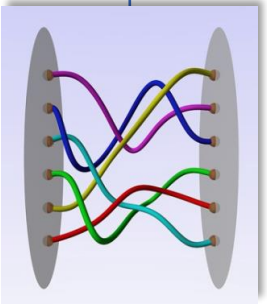


AQT

Honeywell

Trapped Ion qubits

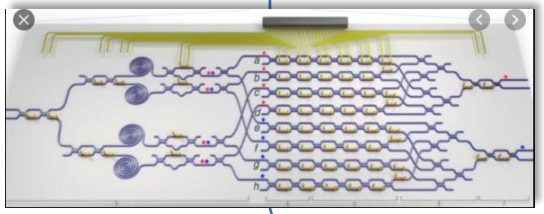
Microsoft



Topological qubits

Photonic qubits

Xanadu



PsiQuantum

Topics

- Quantum?
- Technology Waves and Building Blocks
- **Quantum Product Families**
  - Timing and Positioning
  - Communication
  - Computing
- Early Proto-apps
- A Quantum of Summary

GPS is a Vulnerable $10B+ System

Ships fooled in GPS spoofing attack suggest Russian cyberweapon

New Report Details GNSS Spoofing Including Denial-of-Service Attacks

Students hijack luxury yacht with GPS spoofing

RQ-170 drone's ambush facts spilled by Iranian engineer

by Nancy Owens , Phys.org

RQ-170 Sentinel. © TruthDowser / Wikimedia Commons / CC-BY-SA-3.0

(PhysOrg.com) -- In the aftermath of the Iran capture of a US military drone earlier this month now come arguments over how Iran managed to pull it off. An Iranian engineer's exclusive interview with *The Christian Science Monitor* has been published, which details how the Iranians captured the drone through jamming. An opposing camp says the story is just that, a story, while others schooled in GPS systems say that the Iranians' technique is technically possible but they would not bet on it.

"I hate GPS....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

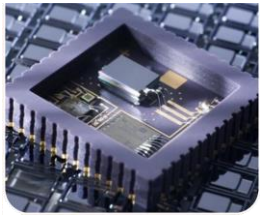
Quantum Sensing – Quantum Positioning System (QPS)

(INS) Inertial Navigation System

Clock

+

(IMU) Inertial Measurement Unit



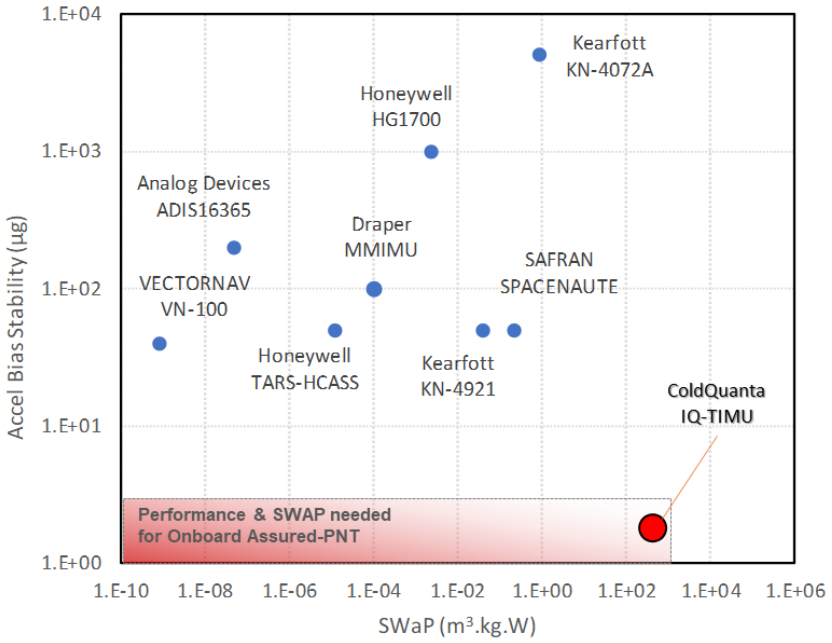
Accelerometer

+

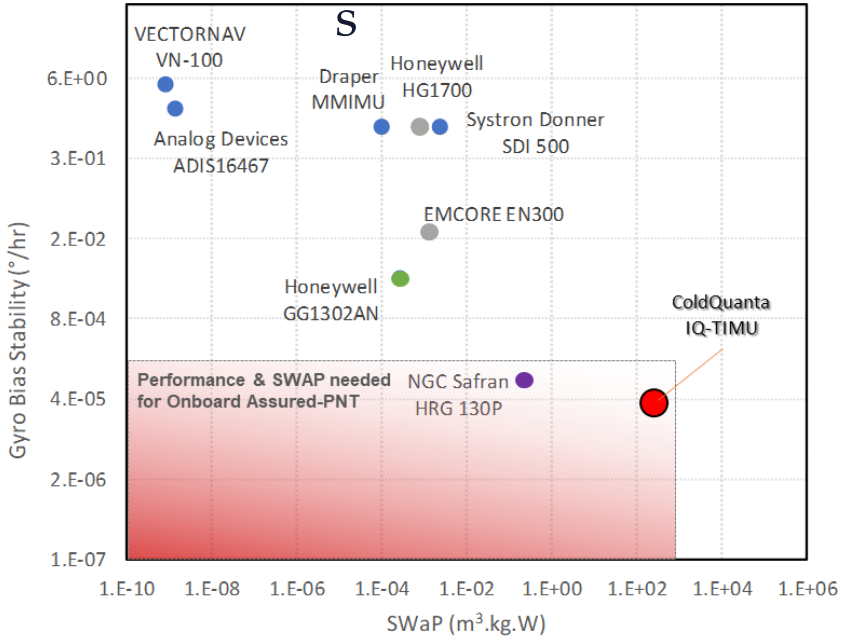
Gyroscope

ColdQuanta's Inertial Sensing and Clock Prototype Programs

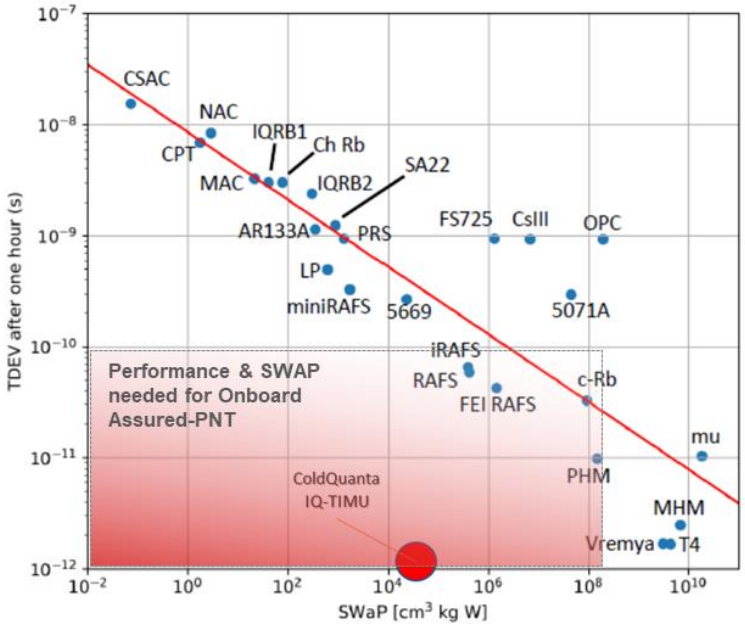
Accelerometers



Gyroscopes

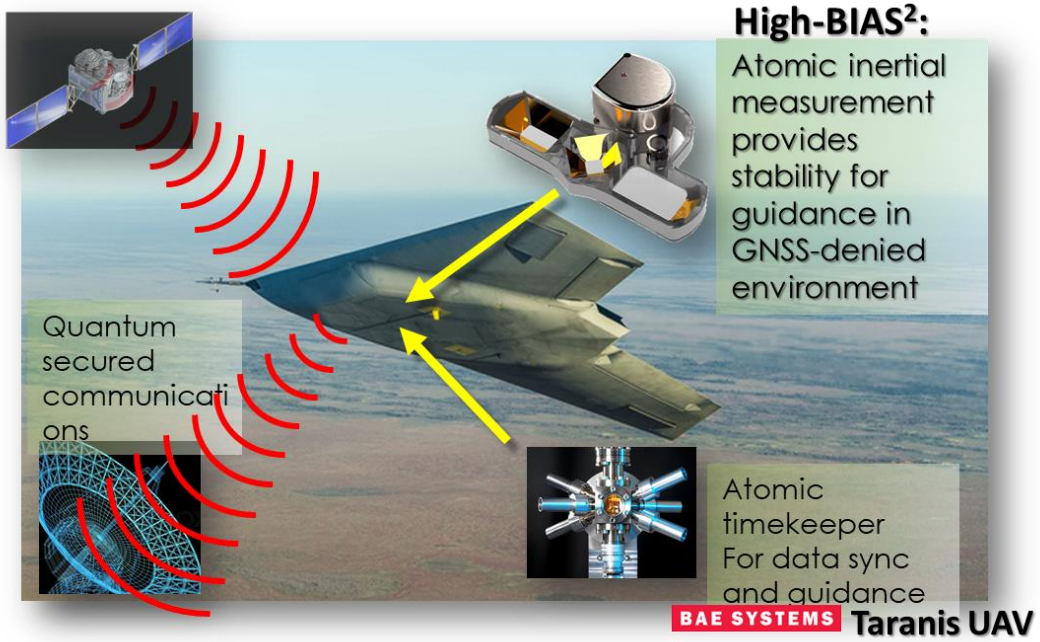


Clocks



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

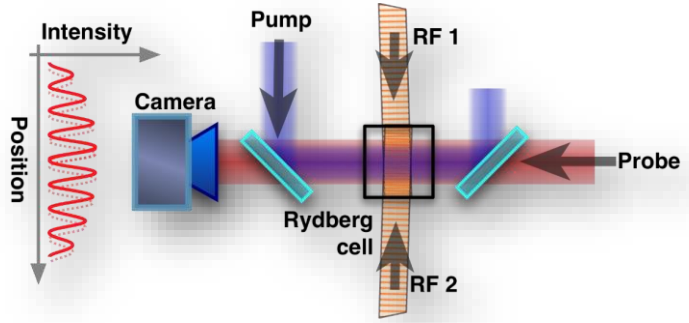


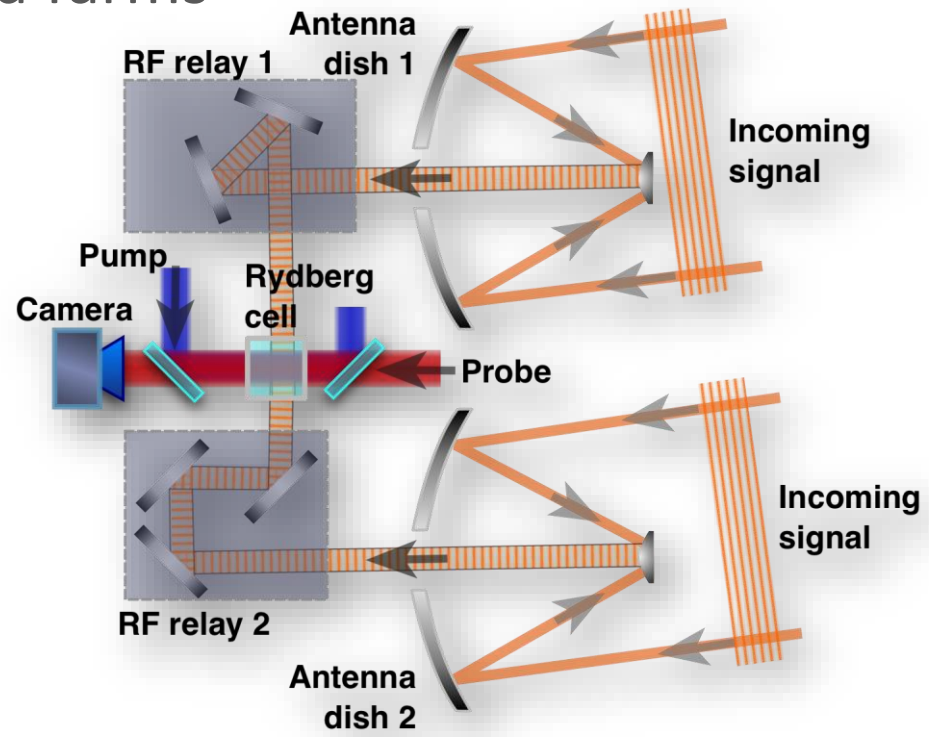
“Navigation using space-based satellite signals underlies many critical technologies across the UK. Most advanced navigation technologies rely on the signals from networks known as the Global Navigation Satellite System (GNSS) to remain accurate over long distances. Loss of these signals result in an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

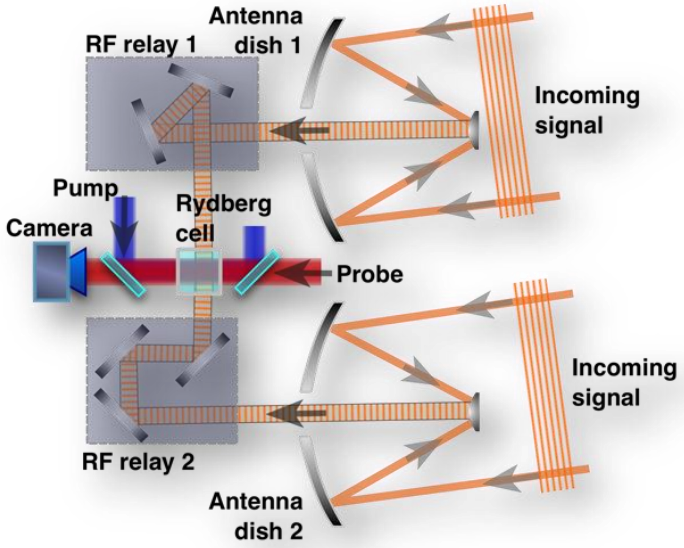
- Detect very faint signals
- Precisely locate their source
- Across a wide frequency spectrum
- Without huge antenna farms





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."



April 1983 – Richard Feynman's Talk at Los Alamos

LOS ALAMOS NATIONAL LABORATORY
40th ANNIVERSARY CONFERENCE
NEW DIRECTIONS IN PHYSICS AND CHEMISTRY
April 13–15, 1983

Wednesday, April 13
6:00–8:00 P.M.—Informal Reception at Fuller Lodge
Thursday, April 14
Main Auditorium, Administration Building
8:45 A.M. Welcome—Donald M. Kerr, Director
Los Alamos National Laboratory
Session I—Robert Serber, Chairman
9:00 A.M. Richard Feynman
"Tiny Computers Obeying Quantum-Mechanical Laws"
10:00 A.M. I. I. Rabi
"How Well We Meant"
11:00–11:15 A.M.—Intermission
Session II—Donald W. Kerst, Chairman
11:15 A.M. Owen Chamberlain
"Tuning Up the Time Projection Chamber"
12:15–1:15 P.M.—Lunch
1:15 P.M. Felix Bloch
"Past, Present and Future of Nuclear Magnetic Resonance"
2:15–2.30 P.M.—Intermission
Session III—Edwin McMillan, Chairman
2:30 P.M. Robert R. Wilson
"Early Los Alamos Accelerators and New Accelerators"
3:30 P.M. Norman Ramsey
"Experiments on Time-Reversal Symmetry and Parity"
4:30 P.M. Ernest Titterton
"Physics with Heavy Ion Accelerators"

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

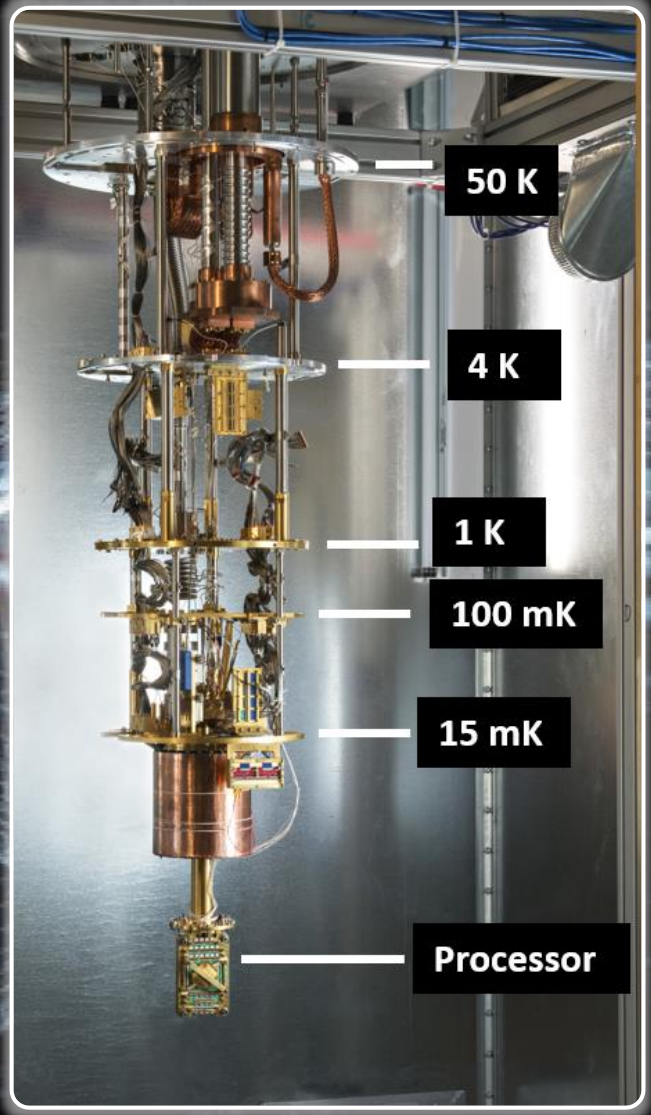
- D-Wave

"Gate Model"

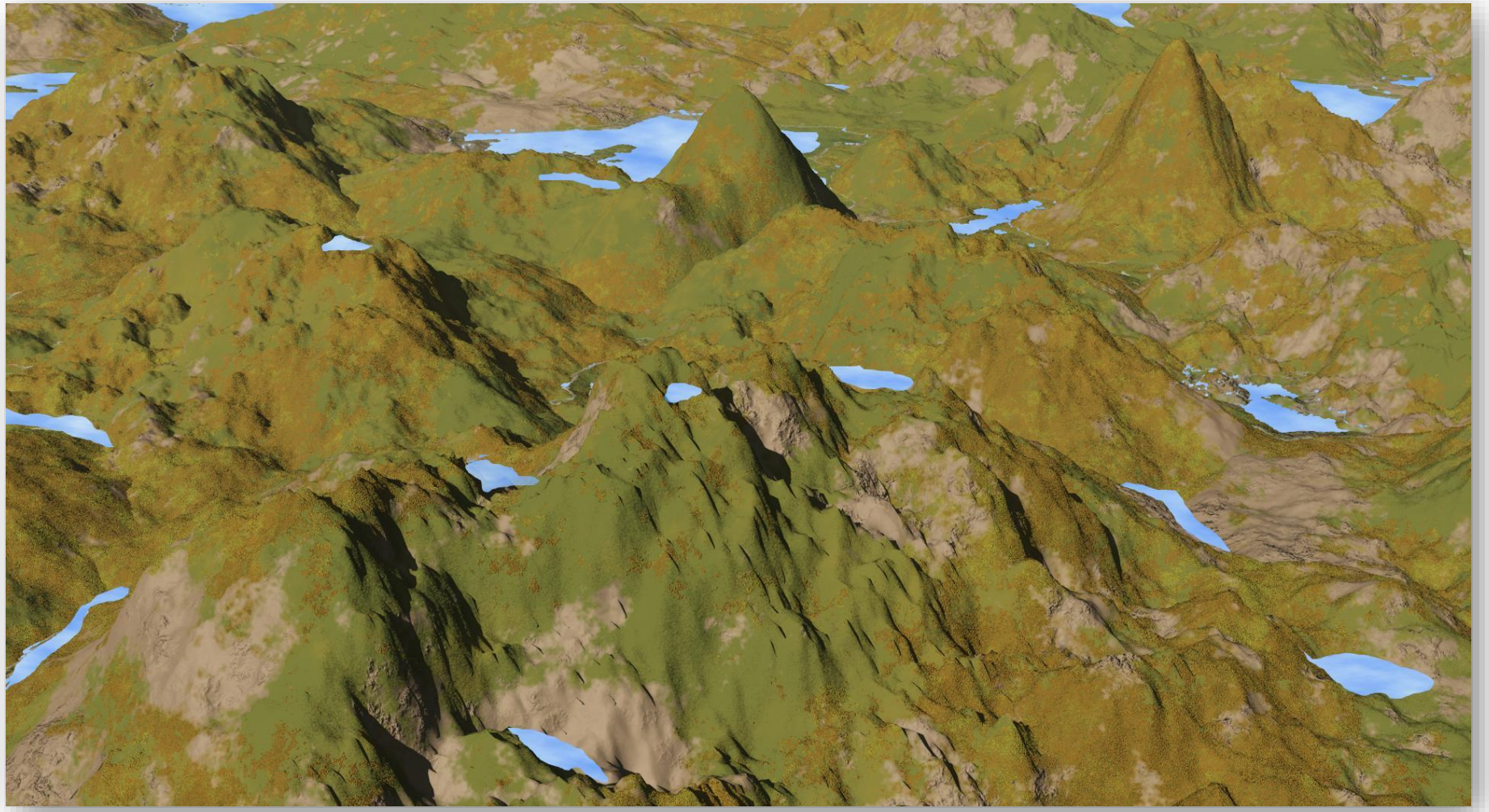
- More like digital computer
- Program it by connecting gates to represent your algorithm
- With error correction, should be a universal computer that delivers "the answer"
- But, no error correction yet (NISQ)
- IBM, Google, Rigetti, IonQ, . . .

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

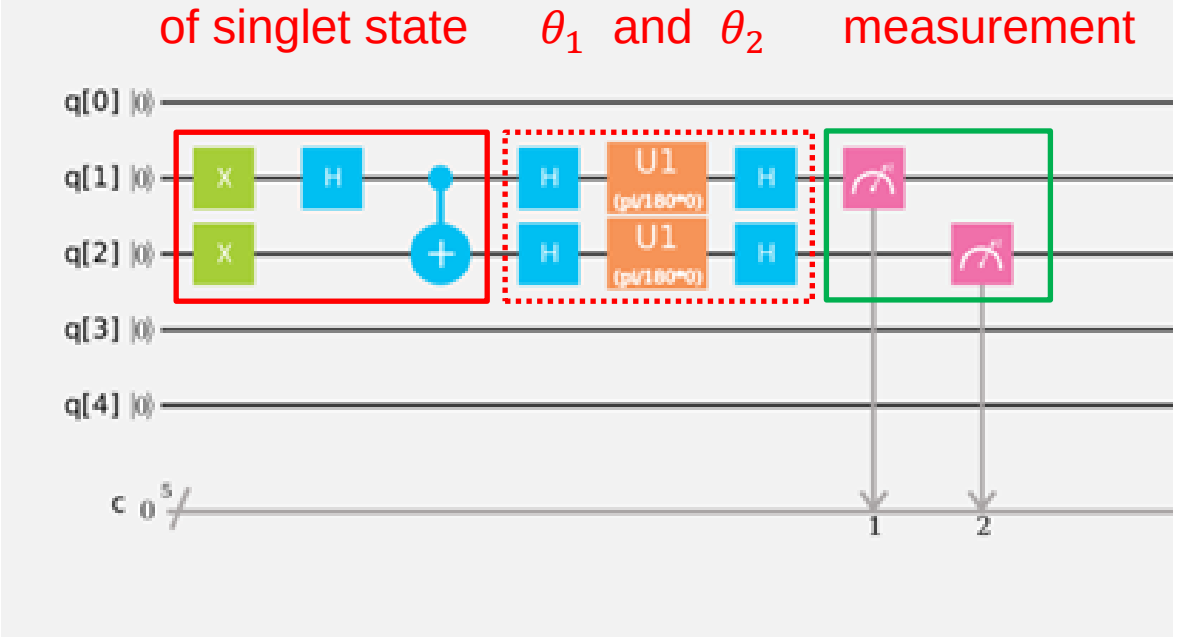
Simulation on IBM Quantum Experience (IBM QX)

IBM QX, Yorktown Heights, USA

Preparation of singlet state

Rotation by θ_1 and θ_2

Readout measurement



X

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

H

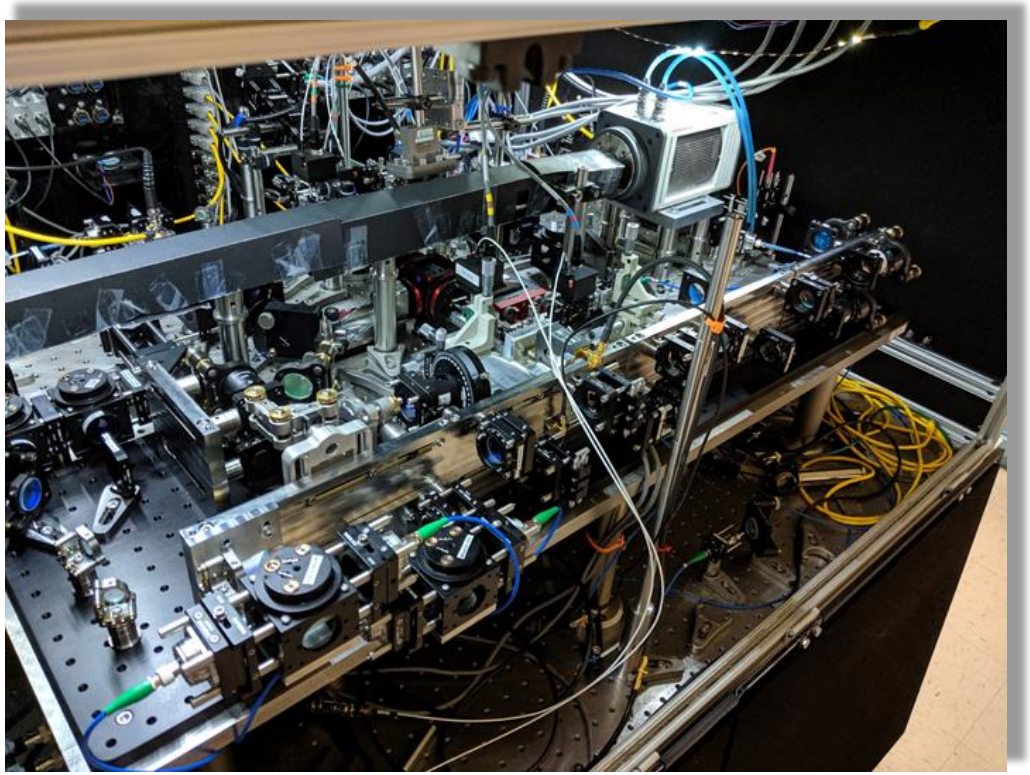
Hadamard gate:
$H|0\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$
$H|1\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$

U1

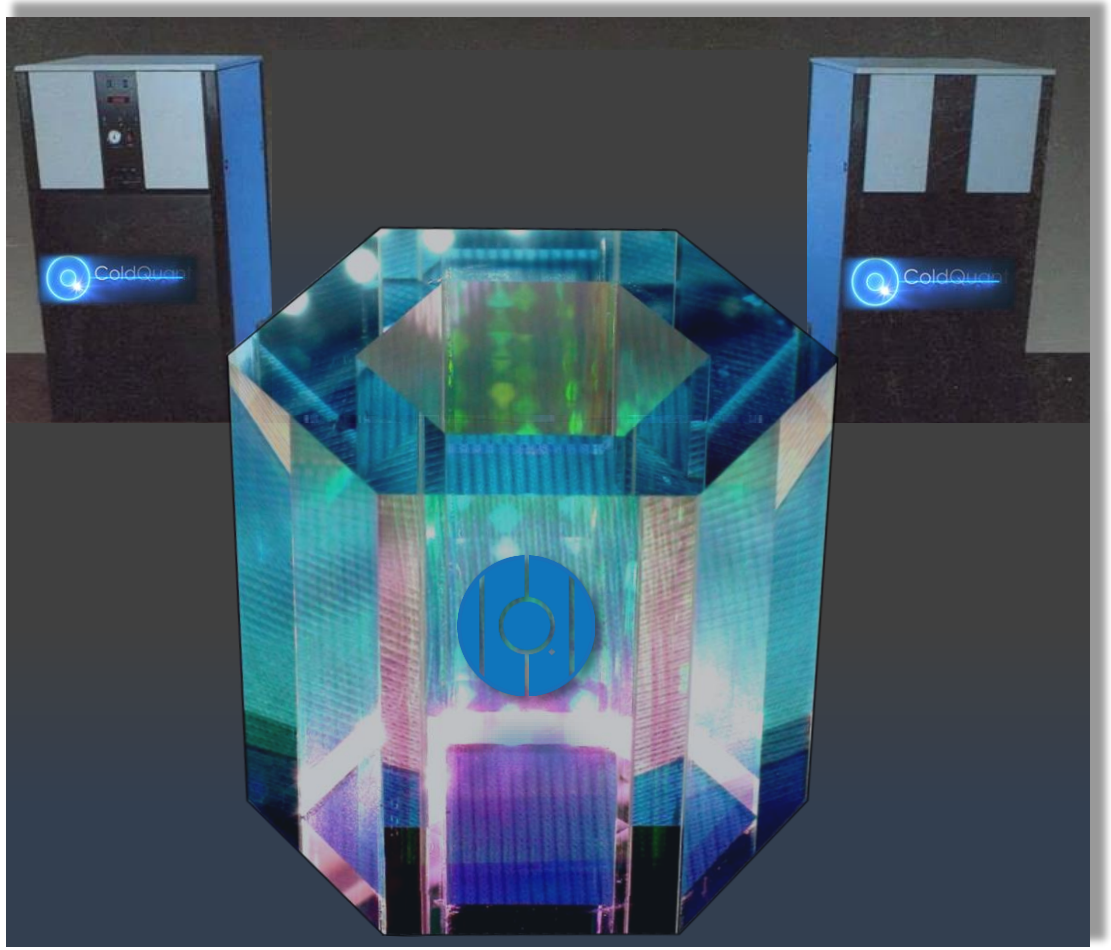
phase-gate:
$U1|0\rangle = |0\rangle,\ U1|1\rangle = e^{i\theta}|1\rangle$

CNOT gate: $C_{01}|0_1 0_0\rangle = |0_1 0_0\rangle$
$C_{01}|0_1 1_0\rangle = |1_1 1_0\rangle$
$C_{01}|1_1 0_0\rangle = |1_1 0_0\rangle$
$C_{01}|1_1 1_0\rangle = |0_1 1_0\rangle$

Prototype Cold Atom QC



If I were an Industrial Designer!

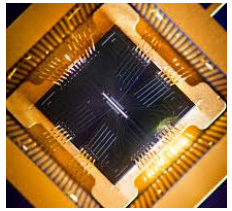


QC Hardware Landscape – Q1 2021

Annealing (SC)

D-Wave Advantage (5000 qubits)

Trapped Ions

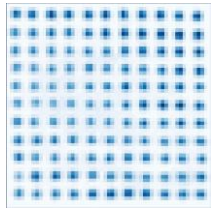


IonQ (11q, 32q? cloud)
Honeywell (10q cloud)
AQT, Oxford Ionics, Universal Quantum

Super -conducting

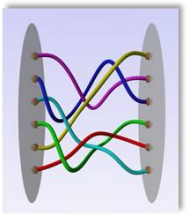
IBM (20q, 65q? cloud)
Rigetti (32q cloud)
Google (54q?)
QCI, IQM, Oxford Quantum Circuits

Cold atoms



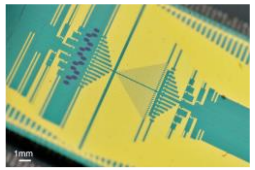
ColdQuanta
QuEra
AtomComputing
Pasqal

Topological



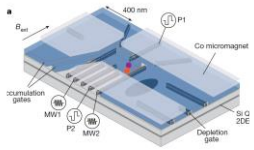
Microsoft

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
- . . .

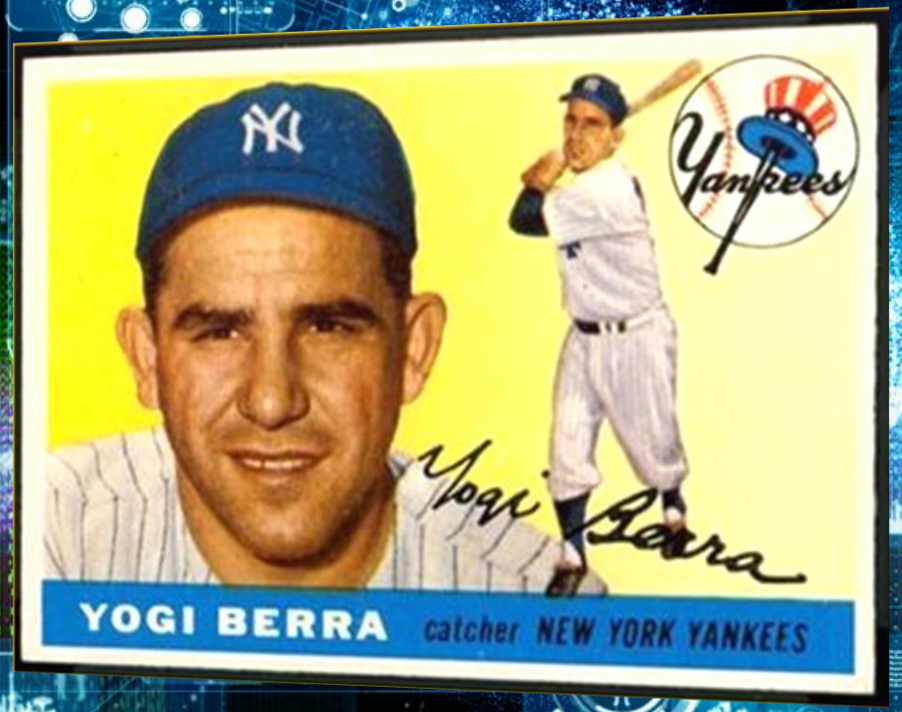
*See https://quantumcomputingreport.com/tools/ for a list of ~50 quantum software tools

Topics

- Quantum?
- Technology Waves and Building Blocks
- Quantum Product Families
  - Timing and Positioning
  - Communication
  - Computing
- **Early Proto-apps**
- A Quantum of Summary

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?



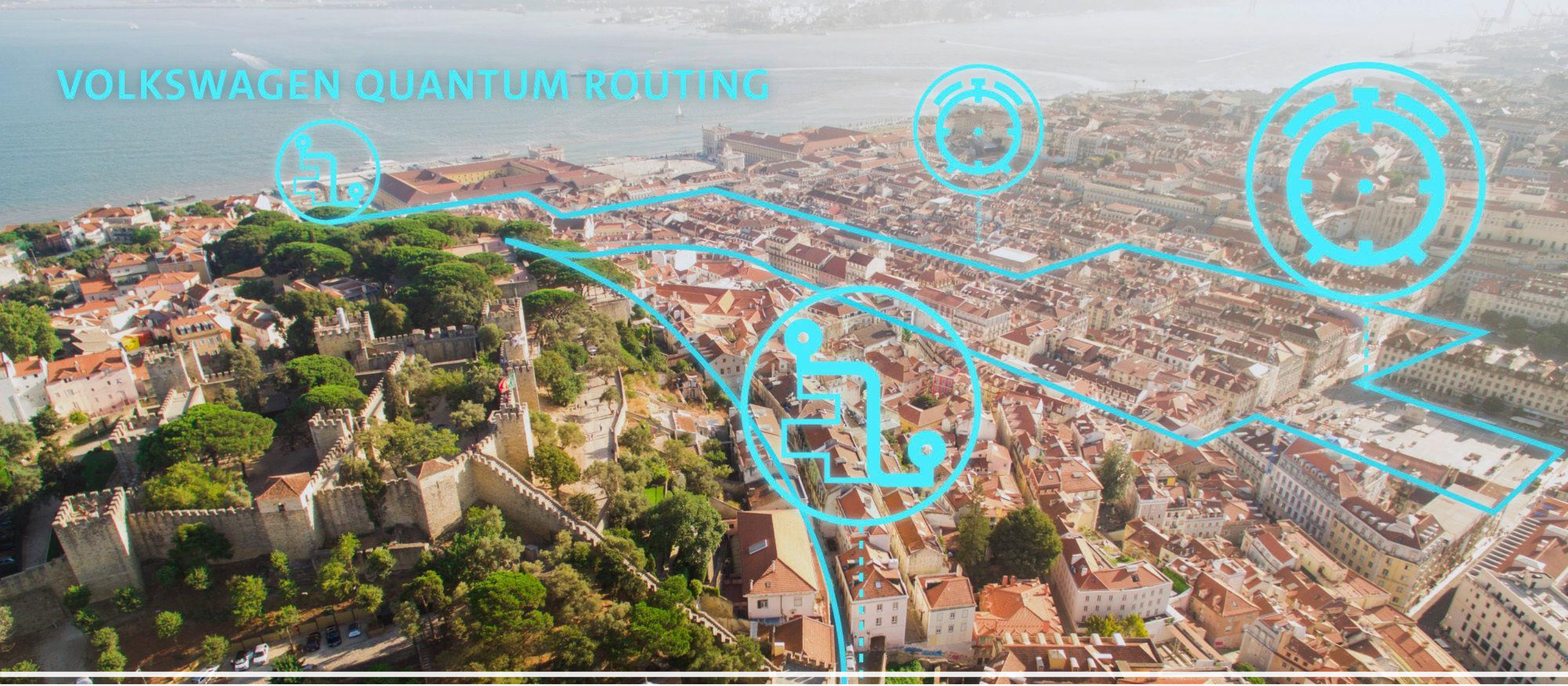
"It's tough to make predictions, especially about the future."

LANL Rapid Response Projects

Use Case	2016	2017	Total	%
Combinatorial Optimization	5	5	10	45%
Machine Learning, Sampling	2	2	4	18%
Understanding Device Physics	2	1	3	14%
Software Stack/Embeddings	1	1	2	9%
Simulating Quantum Systems		2	2	9%
Other (good) Ideas	1		1	5%
Total	11	11	22	100%

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

http://www.lanl.gov/projects/national-security-education-center/information-science-technology/dwave/index.php



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

Hartree Centre
Science & Technology Facilities Council

Groovenauts

MITSUBISHI ESTATE

- 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

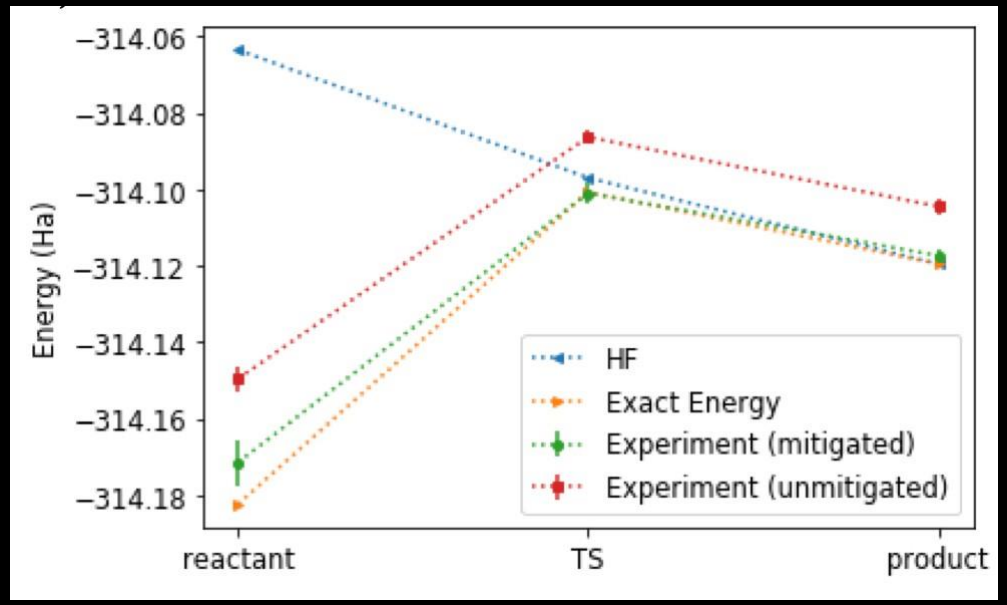
Item	Current	**Optimized**	Difference
Total Route Distance	2,296.2 km	1004.2 km	▲1,292.0 km
Number of Trucks	75	31	▲44
Total Work Time	8,650.9 mins.	5,372.2 mins.	▲3,278.7 mins.

*Approximately 57% reduction (≒ CO2 emissions)

Improving Lithium Ion Batteries: IBM & Mitsubishi Chemical

Determining the barrier for Li_2O_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

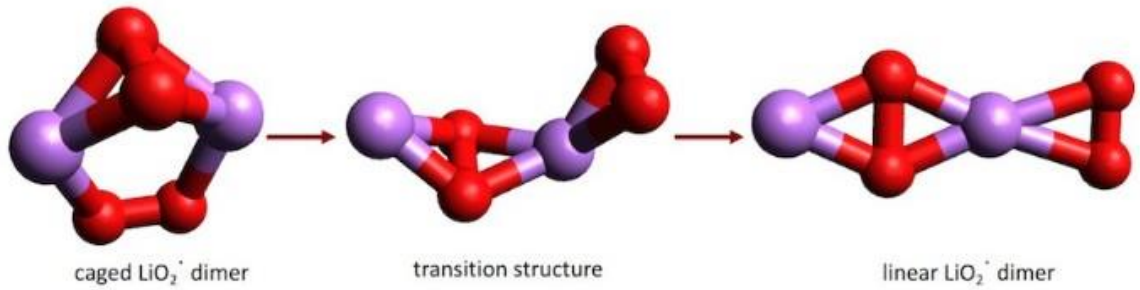


Computational Investigations of the Lithium Superoxide Dimer Rearrangement on Noisy Quantum Devices

Qi Gao,[1,2] Hajime Nakamura,[2,3] Tanvi P. Gujarati,[4] Gavin O. Jones,[4] Julia E. Rice,[4] Stephen P. Wood,[5] Marco Pistoia,[5] Jeannette M. Garcia[4] and Naoki Yamamoto[2]

[1]Mitsubishi Chemical Corp.
[2]Quantum Computing Center, Keio University
[3]IBM Research – Tokyo
[4]IBM Research – Almaden
[5]IBM Thomas J. Watson Research Center

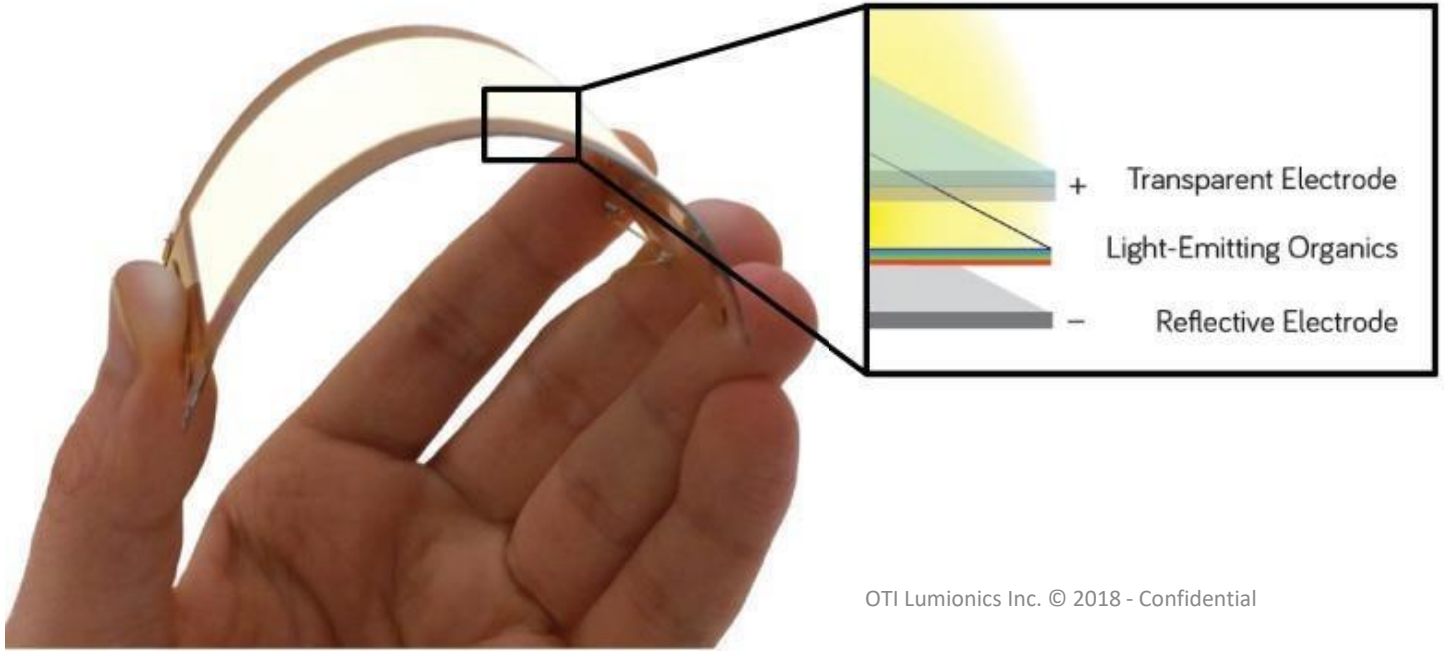
MITSUBISHI CHEMICAL



https://arxiv.org/abs/1906.10675

Organic Light Emitting Diode (OLED)

Light from organic pigments sandwiched between electrodes



Organic Pigments

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

WuXiNextCODE

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

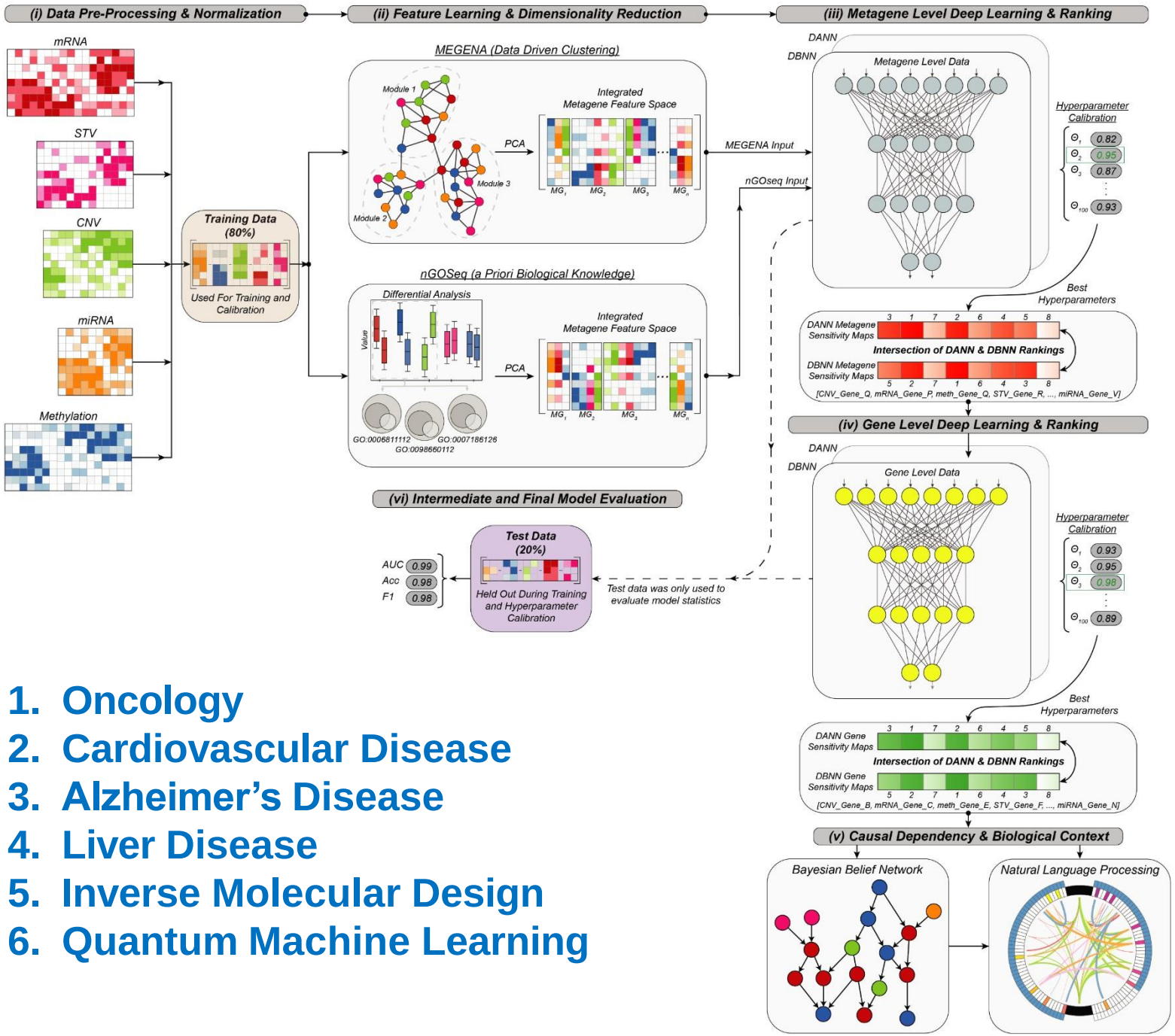
Specialized statistical learning models capable of elucidating casual dependencies within biological data

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.

Ensemble Computational Intelligence



1. Oncology
2. Cardiovascular Disease
3. Alzheimer's Disease
4. Liver Disease
5. Inverse Molecular Design
6. Quantum Machine Learning

WuXiNextCODE

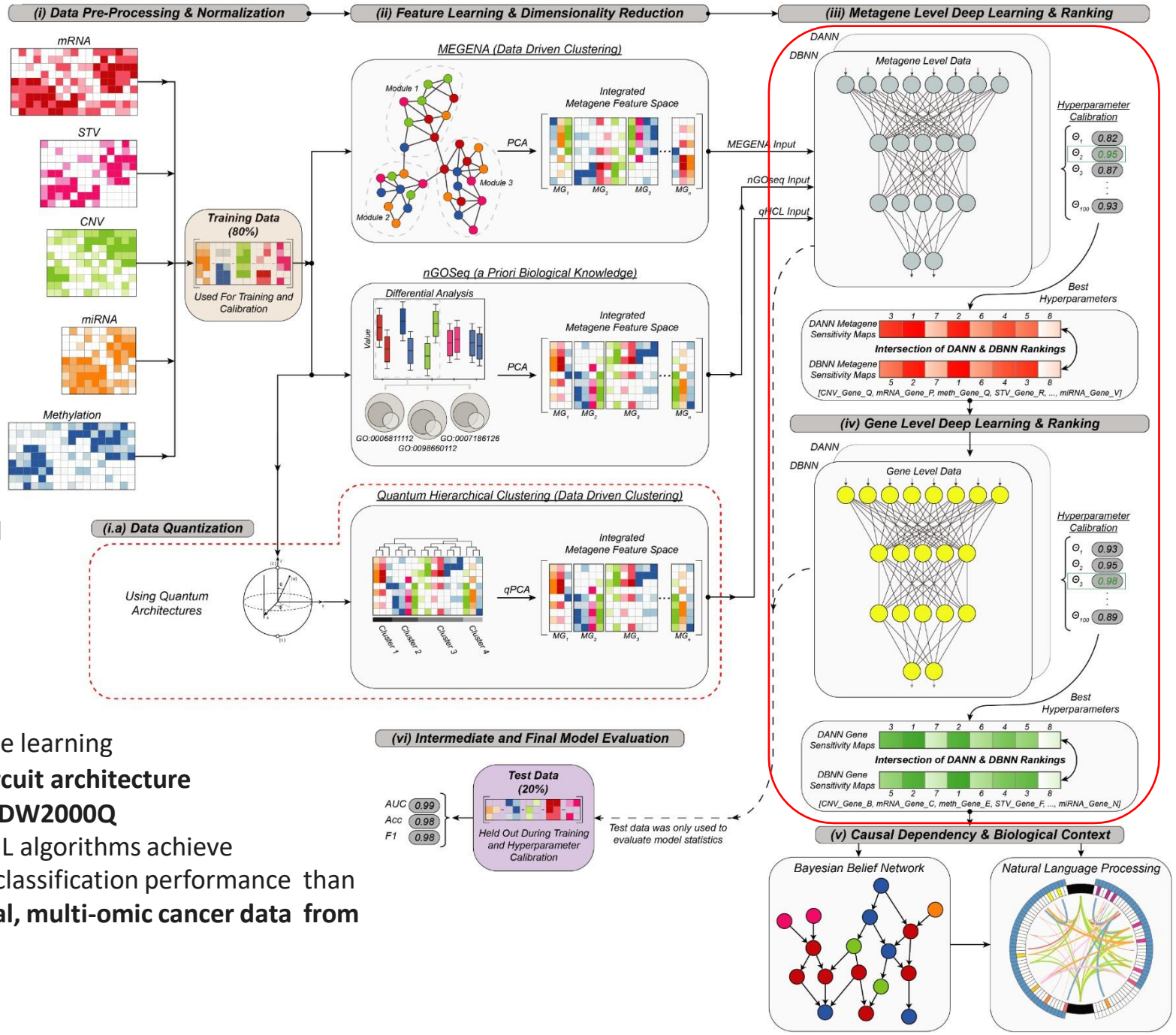
Quantum Machine Learning

- 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)**.



Toward Quantum Gate-Model Heuristics for Real-World Planning Problems

TOBIAS STOLLENWERK[1] , STUART HADFIELD[2,3], AND ZHIHUIWANG[2,3]

1 German Aerospace Center (DLR), 51147 Cologne, Germany

2 Quantum Artificial Intelligence Lab, NASA Ames Research Center, Moffett Field, CA 94035 USA

3 USRA Research Institute for Advanced Computer Science, Mountain View, CA 94043 USA

ABSTRACT Many challenging scheduling, planning, and resource allocation problems come with realworld 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 as 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.

Topics

- Quantum?
- Technology Waves and Building Blocks
- Quantum Product Families
  - Timing and Positioning
  - Communication
  - Computing
- Early Proto-apps
- **A Quantum of Summary**

The Digital Wave

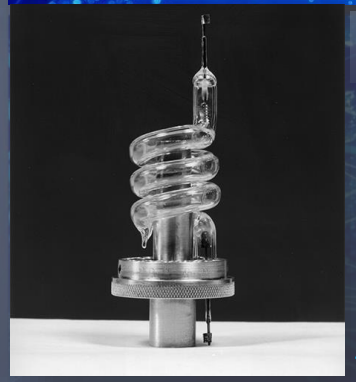
ELECTRONICS

1946: Exquisite control over the electron.

Replica of the 1946 Bell Labs Transistor.

Instruments
Calculators
Computers
Communications
Signal Processing
Video Games
. . .

The Communications Wave



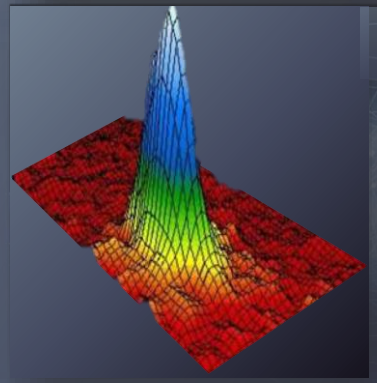
PHOTONICS

1957: Exquisite control over the photon.

Flashlamp from the first ruby laser

Communications
CD's and DVD's
Medical Instruments
Scanners
Machining
. . .

The Quantum Wave



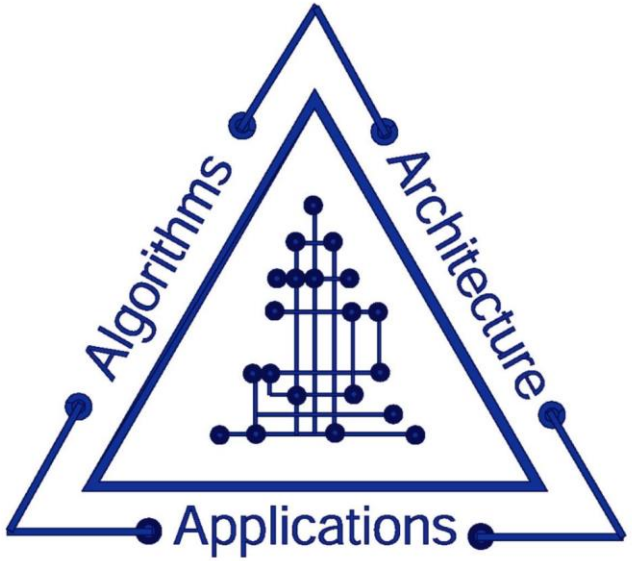
QUANTUM ATOMICS

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 . . .
. . .

Quantum humor



40TH ANNIVERSARY LECTURE SERIES