Future of Quantum Computing

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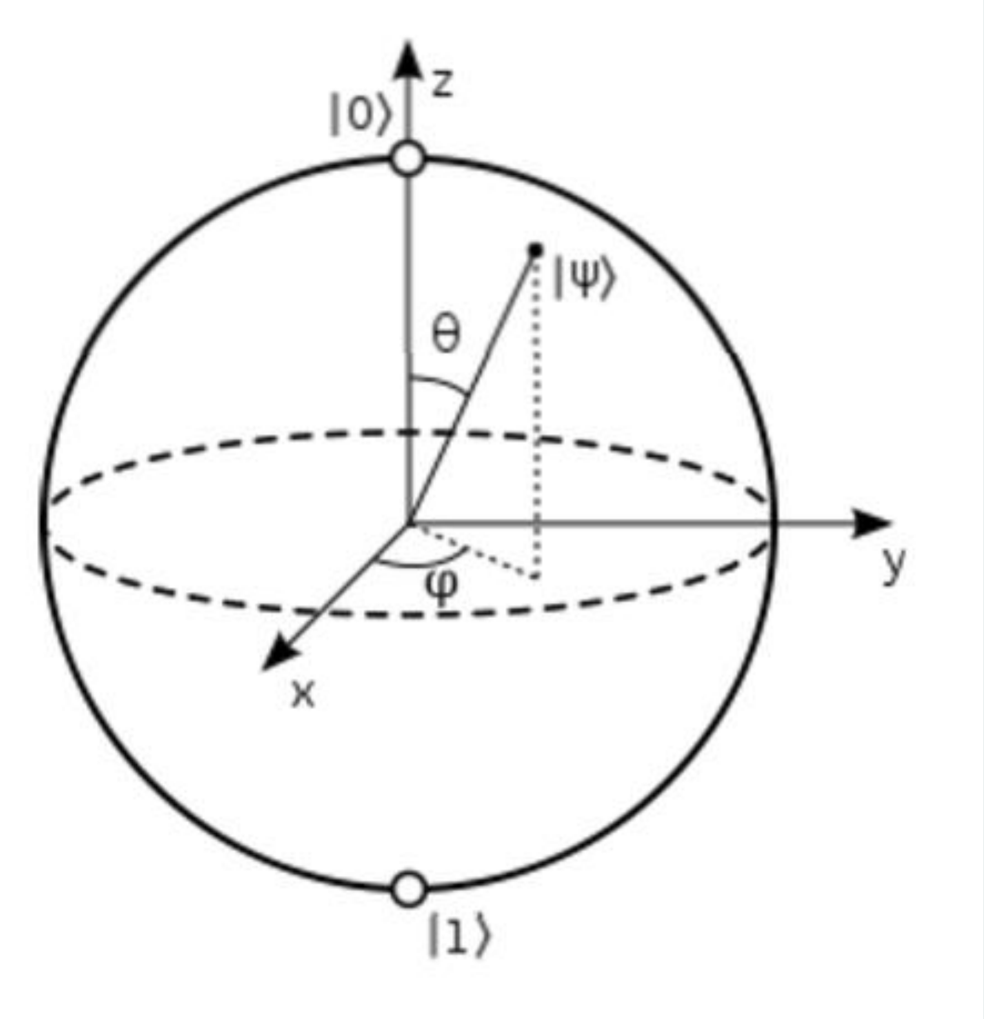
What is a quantum computer?

- a computer that relies on special memory, "quantum bit", to perform massively parallel computing.

What is a quantum bit?

- a basic unit of memory that uses superposition of "quantum" effect (entanglement) to store information.
- a "qubit" stores the probability of information. It represents both "1" and "0" at the same time.


z
|0⟩
|ψ⟩
θ
y
φ
x
|1⟩

What is the advantage?

- It is very very fast compared to conventional computers
- It has very large memory, example 10-qubit is ….

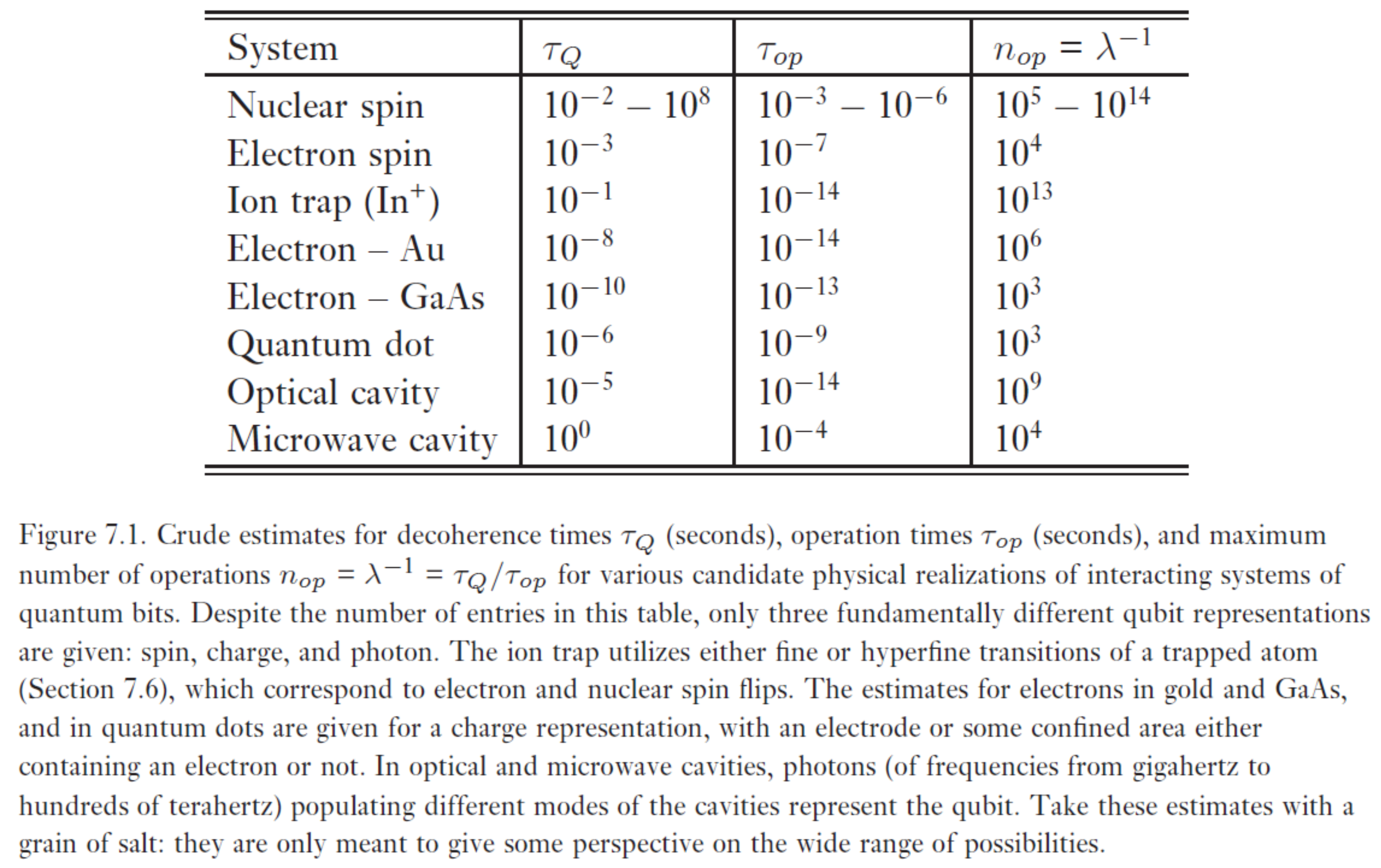
10 Qubits

```
>>> print(2**(2**10))
179769313486231590772930519078902473361797697894230657273
430081157732675805500963132708477322407536021120113879871
393357658789768814416622492847430639474124377767893424865
485276302219601246094119453082952085005768838150682342462
881473913110540827237163350510684586298239947245938479716
304835356329624224137216
>>>
```

How to make a quantum bit?

- "quantum effect"
- photon entanglement
- cold atom
- electron spin

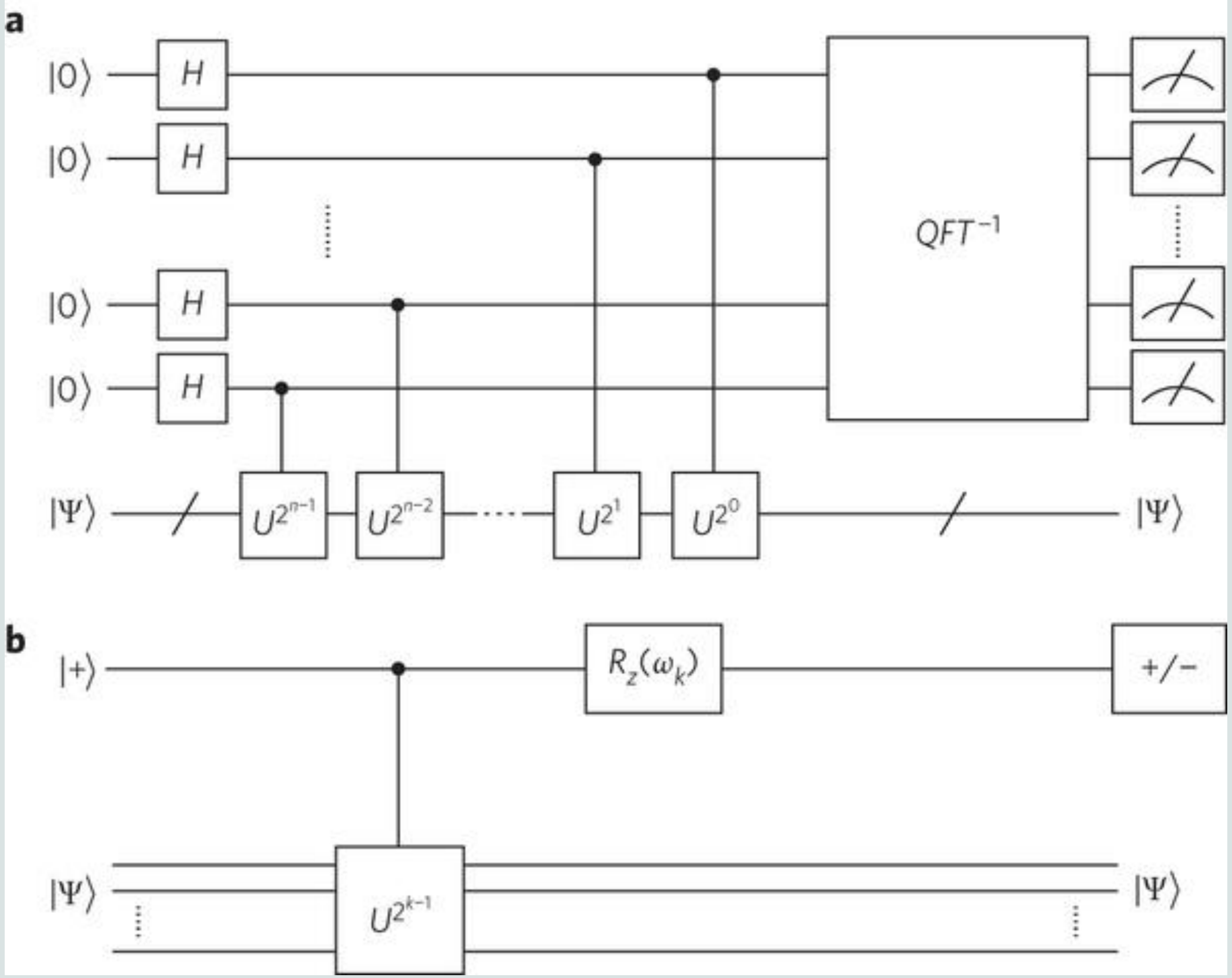
Technology to implement Quantum bits



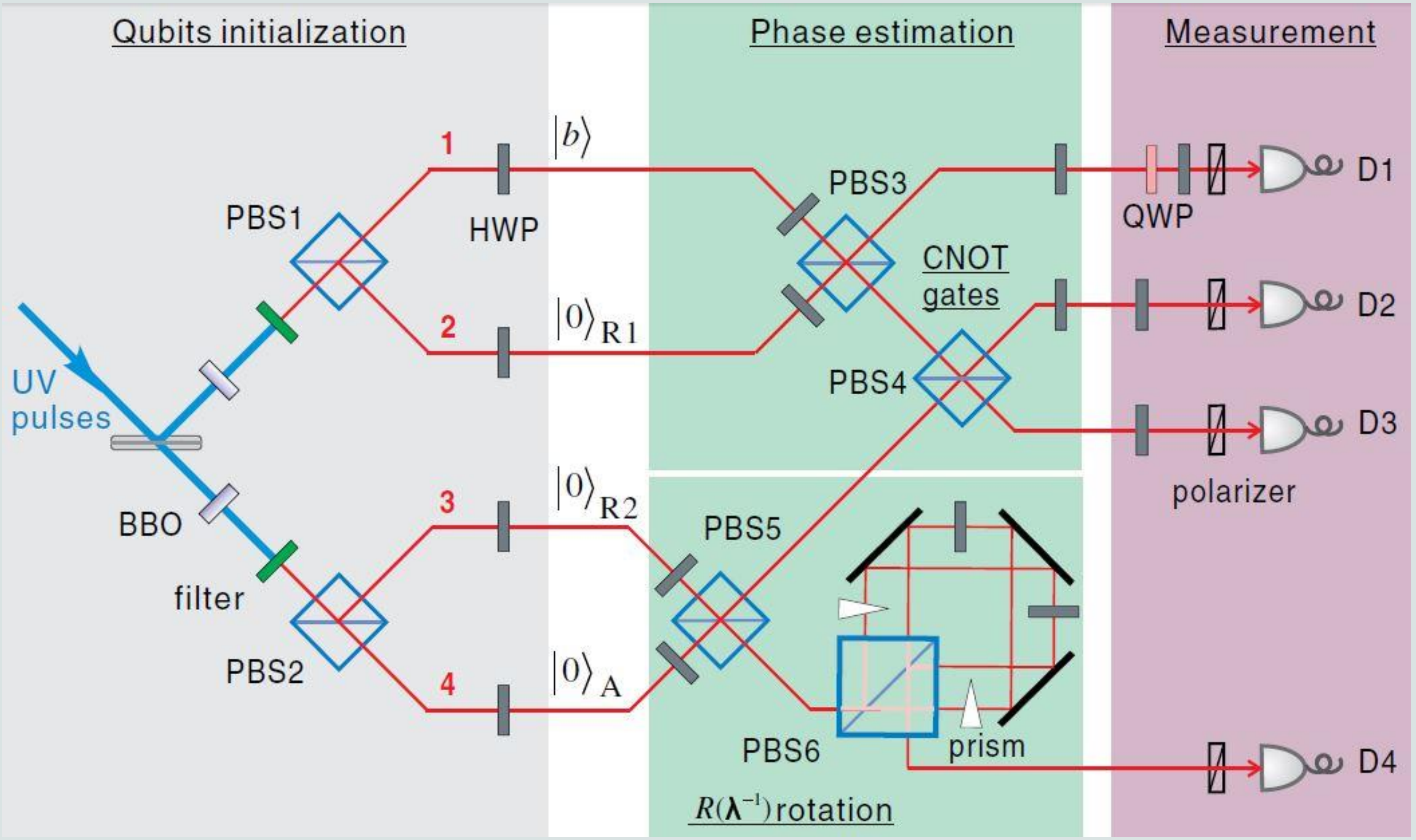
System	τ_Q	τ_{op}	$n_{op} = \lambda^{-1}$
Nuclear spin	$10^{-2} - 10^{8}$	$10^{-3} - 10^{-6}$	$10^{5} - 10^{14}$
Electron spin	10^{-3}	10^{-7}	10^{4}
Ion trap (In$^+$)	10^{-1}	10^{-14}	10^{13}
Electron – Au	10^{-8}	10^{-14}	10^{6}
Electron – GaAs	10^{-10}	10^{-13}	10^{3}
Quantum dot	10^{-6}	10^{-9}	10^{3}
Optical cavity	10^{-5}	10^{-14}	10^{9}
Microwave cavity	10^{0}	10^{-4}	10^{4}

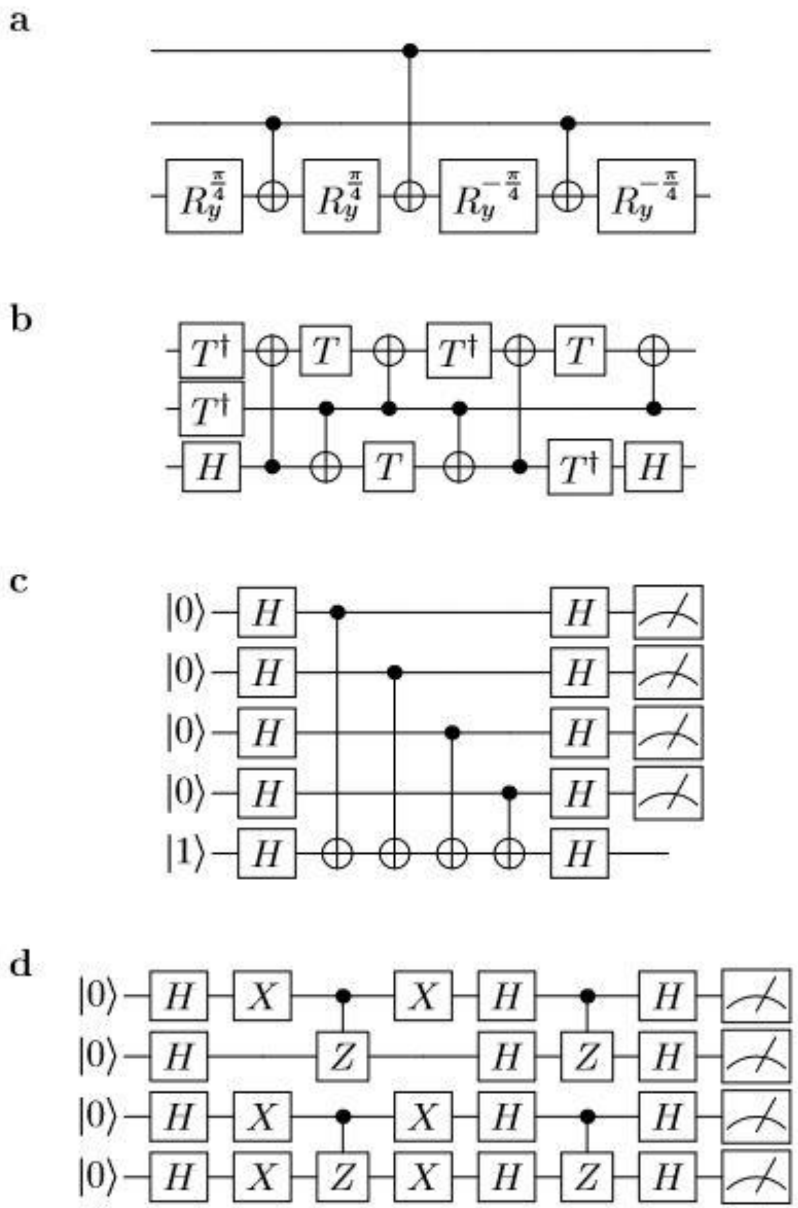
Figure 7.1. Crude estimates for decoherence times τ_Q (seconds), operation times τ_{op} (seconds), and maximum number of operations $n_{op} = \lambda^{-1} = \tau_Q/\tau_{op}$ for various candidate physical realizations of interacting systems of quantum bits. Despite the number of entries in this table, only three fundamentally different qubit representations are given: spin, charge, and photon. The ion trap utilizes either fine or hyperfine transitions of a trapped atom (Section 7.6), which correspond to electron and nuclear spin flips. The estimates for electrons in gold and GaAs, and in quantum dots are given for a charge representation, with an electrode or some confined area either containing an electron or not. In optical and microwave cavities, photons (of frequencies from gigahertz to hundreds of terahertz) populating different modes of the cavities represent the qubit. Take these estimates with a grain of salt: they are only meant to give some perspective on the wide range of possibilities.

Quantum circuits



Quantum circuits




a
$R_y^{\frac{\pi}{4}}$
$R_y^{\frac{\pi}{4}}$
$R_y^{-\frac{\pi}{4}}$
$R_y^{-\frac{\pi}{4}}$
b
$T^\dagger$
$T^\dagger$
H
T
T
$T^\dagger$
T
$T^\dagger$
H
c
$|0\rangle$
$|0\rangle$
$|0\rangle$
$|0\rangle$
$|1\rangle$
H
d
$|0\rangle$
$|0\rangle$
$|0\rangle$
$|0\rangle$
H
X
Z

Quantum algorithms

- computer programs that work on quantum computers

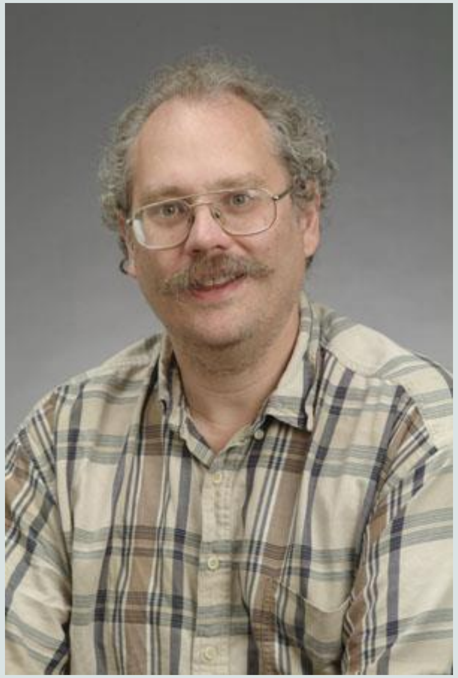
Famous algorithms

- Shor's integer factorization
- Given an integer N, find its prime factors

Quantum Algorithms

1994   Peter Shor

a quantum algorithm for integer factorization formulated .



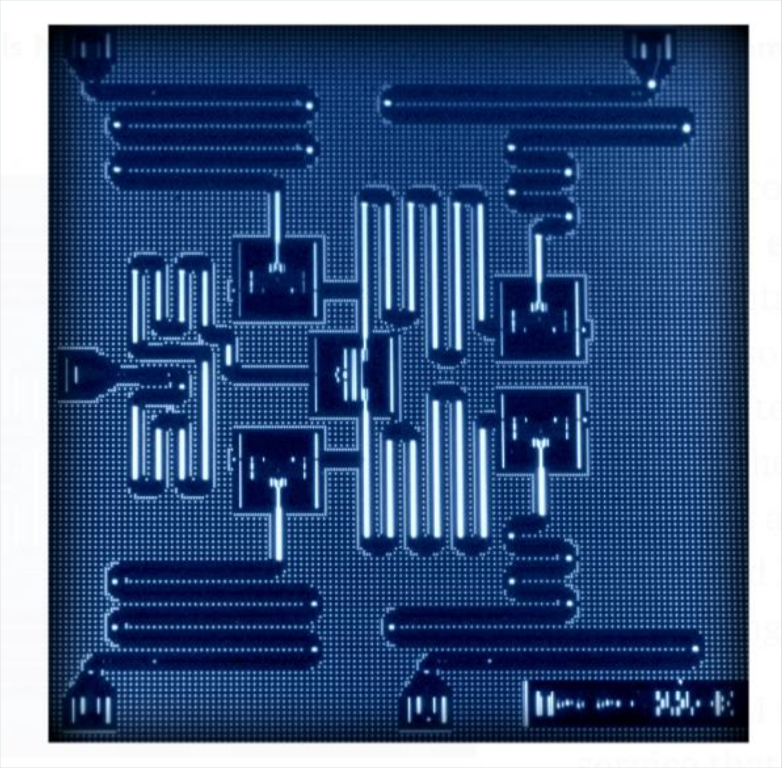
Shor's algorithm

The factorization also needs huge amount of quantum gates. It increases with N as $(\log N)^3$. Thus factoring of a 4096-bit number requires 4,947,802,324,992 quantum gates.

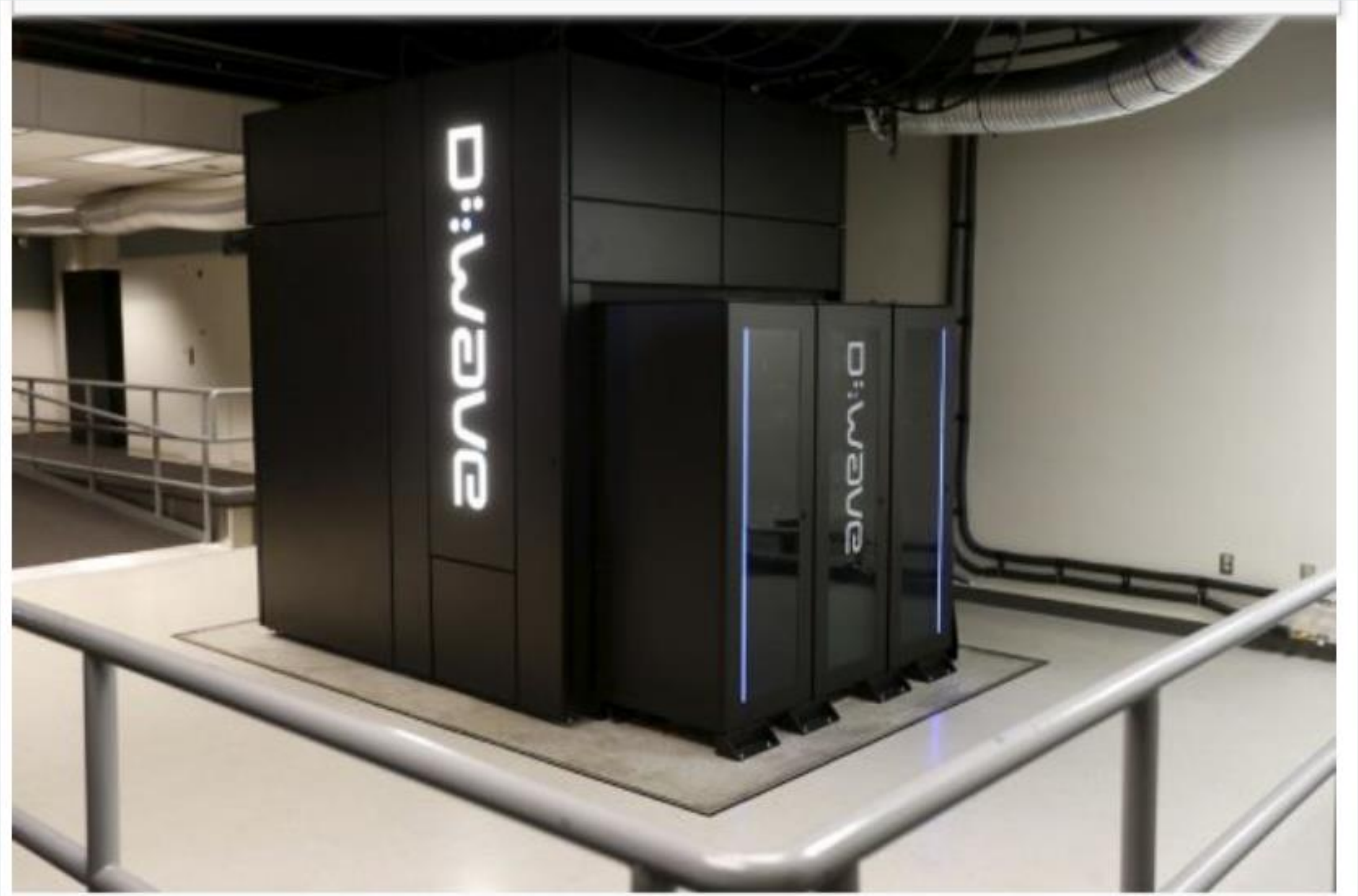
Example of quantum computers

- ibm 5 qubits
- D-wave two, quantum annealing

IBM 5 qubits processor



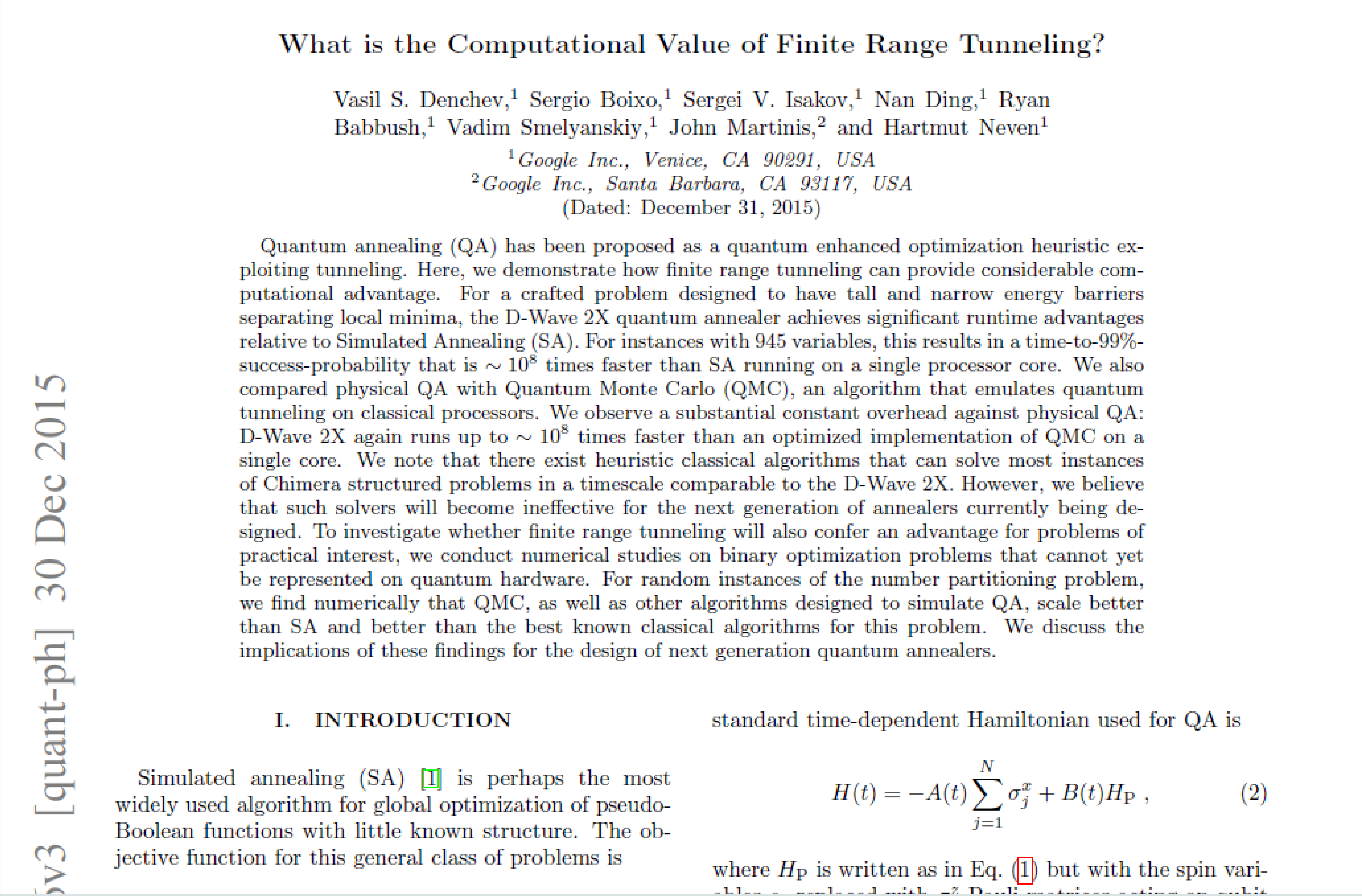
Google Nasa, D-Wave 2x machine



STEPHEN LAM / REUTERS

Claim Quantum Computer is fast

- google quantum lab's paper
- claim of 100,000,000x speed up



What is the Computational Value of Finite Range Tunneling?

Vasil S. Denchev,[1] Sergio Boixo,[1] Sergei V. Isakov,[1] Nan Ding,[1] Ryan Babbush,[1] Vadim Smelyanskiy,[1] John Martinis,[2] and Hartmut Neven[1]

[1] *Google Inc., Venice, CA 90291, USA*
[2] *Google Inc., Santa Barbara, CA 93117, USA*
(Dated: December 31, 2015)

Quantum annealing (QA) has been proposed as a quantum enhanced optimization heuristic exploiting tunneling. Here, we demonstrate how finite range tunneling can provide considerable computational advantage. For a crafted problem designed to have tall and narrow energy barriers separating local minima, the D-Wave 2X quantum annealer achieves significant runtime advantages relative to Simulated Annealing (SA). For instances with 945 variables, this results in a time-to-99%-success-probability that is $\sim 10^8$ times faster than SA running on a single processor core. We also compared physical QA with Quantum Monte Carlo (QMC), an algorithm that emulates quantum tunneling on classical processors. We observe a substantial constant overhead against physical QA: D-Wave 2X again runs up to $\sim 10^8$ times faster than an optimized implementation of QMC on a single core. We note that there exist heuristic classical algorithms that can solve most instances of Chimera structured problems in a timescale comparable to the D-Wave 2X. However, we believe that such solvers will become ineffective for the next generation of annealers currently being designed. To investigate whether finite range tunneling will also confer an advantage for problems of practical interest, we conduct numerical studies on binary optimization problems that cannot yet be represented on quantum hardware. For random instances of the number partitioning problem, we find numerically that QMC, as well as other algorithms designed to simulate QA, scale better than SA and better than the best known classical algorithms for this problem. We discuss the implications of these findings for the design of next generation quantum annealers.

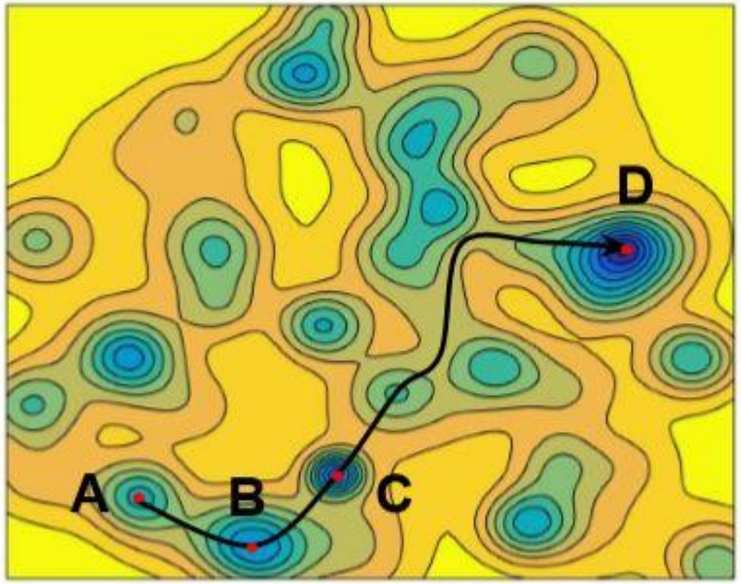
I. INTRODUCTION

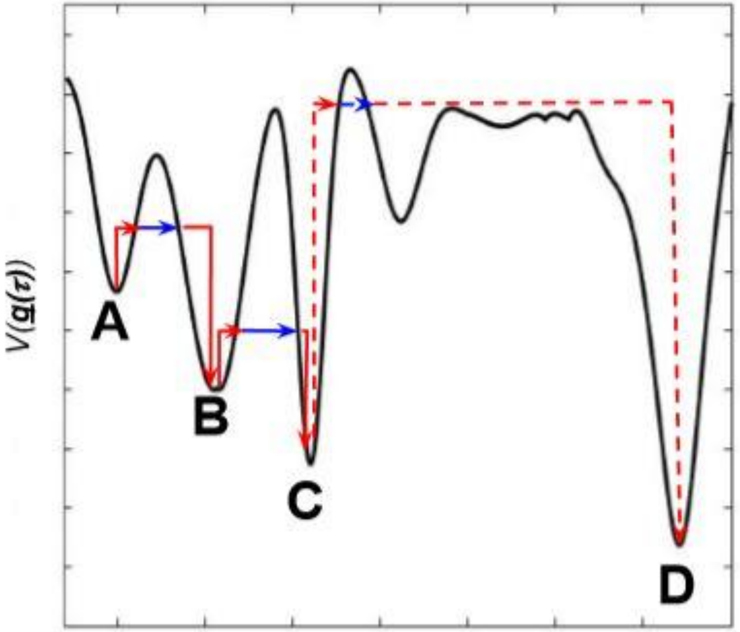
Simulated annealing (SA) [1] is perhaps the most widely used algorithm for global optimization of pseudo-Boolean functions with little known structure. The objective function for this general class of problems is

standard time-dependent Hamiltonian used for QA is

$$H(t) = -A(t)\sum_{j=1}^{N} \sigma_j^x + B(t)H_{\mathrm{P}} \,, \qquad (2)$$

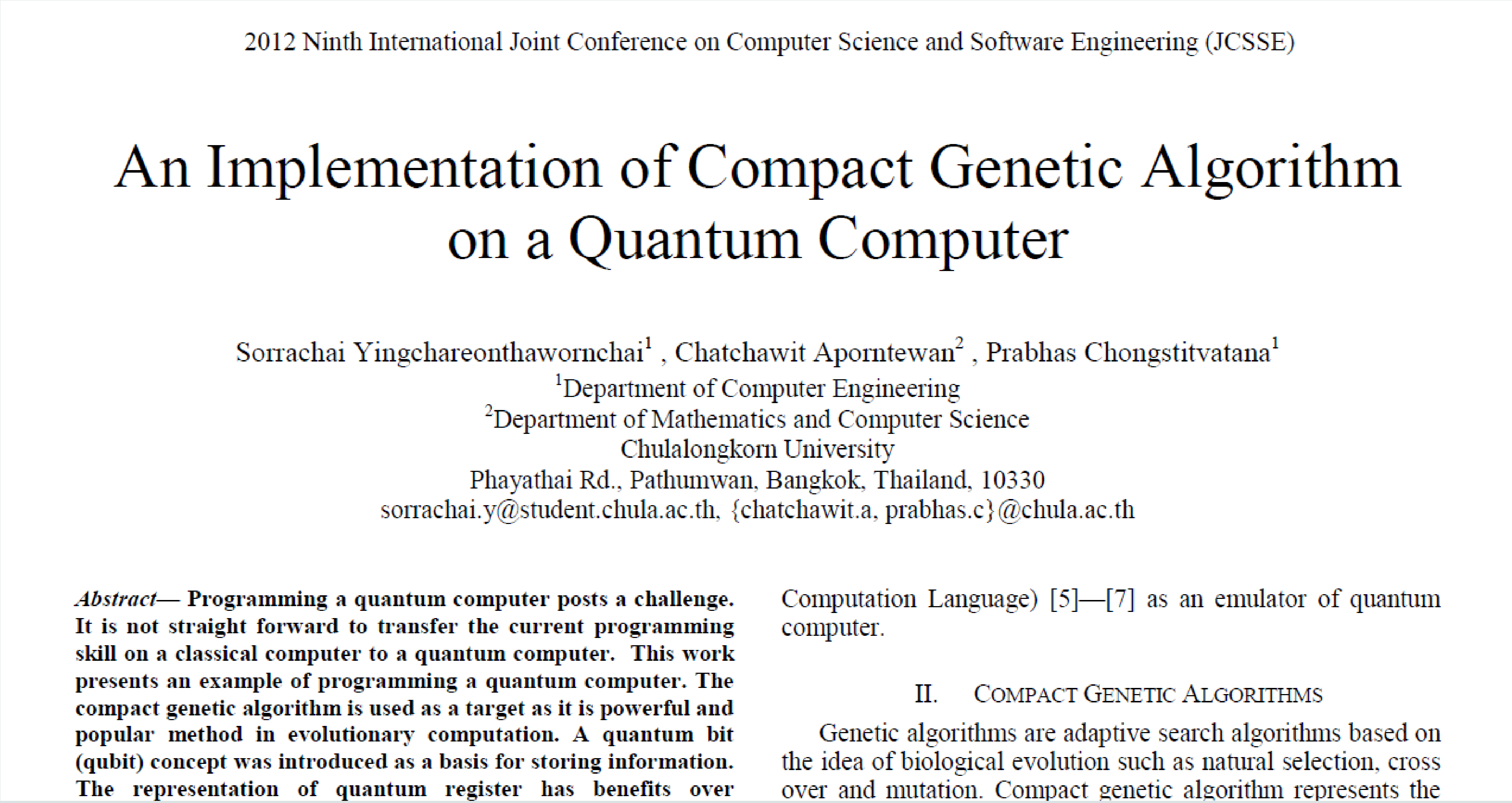
where H_{P} is written as in Eq. (1) but with the spin vari-


A
B
C
D


V(q(τ))
A
B
C
D

My own example of quantum computation

- compact genetic algorithm by quantum computers
- exponential speedup



2012 Ninth International Joint Conference on Computer Science and Software Engineering (JCSSE)

An Implementation of Compact Genetic Algorithm on a Quantum Computer

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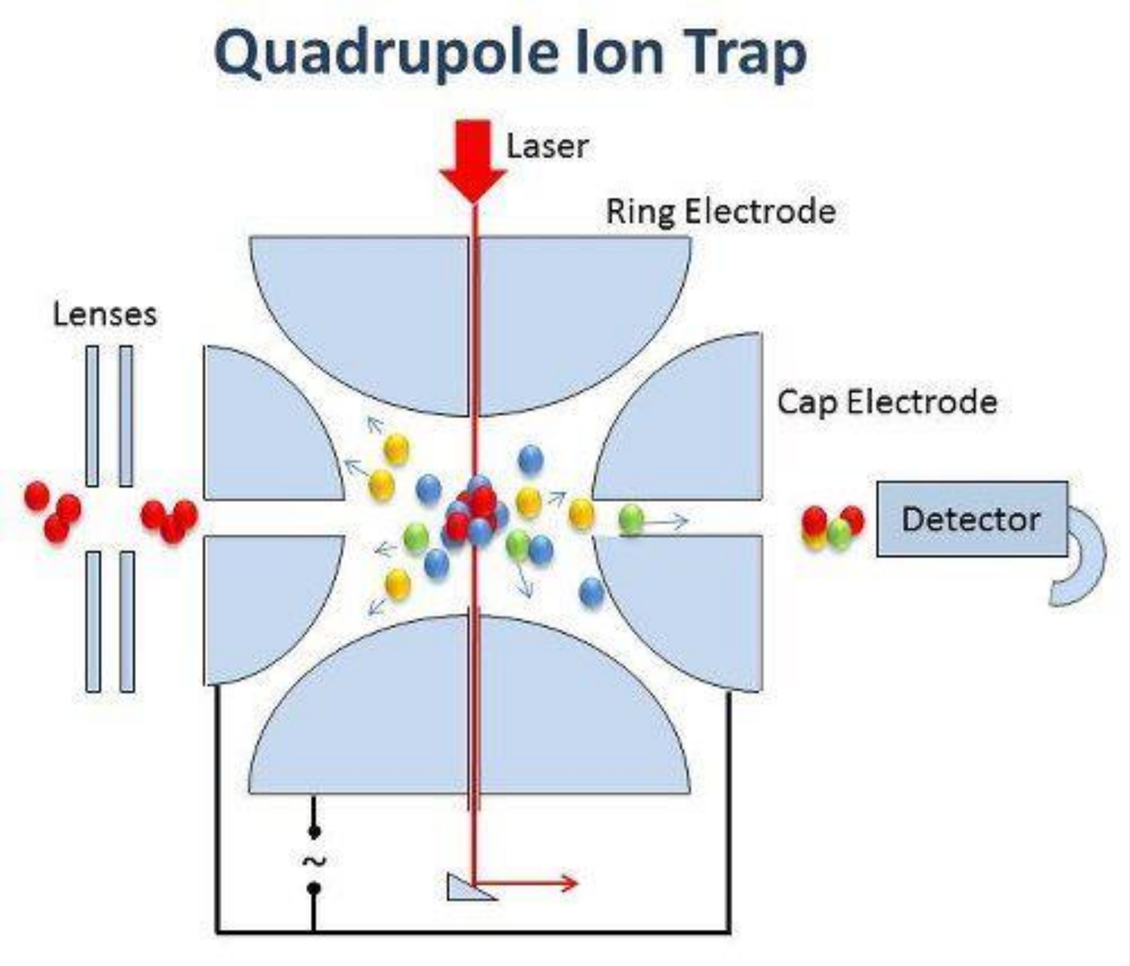
Abstract— **Programming a quantum computer posts a challenge. It is not straight forward to transfer the current programming skill on a classical computer to a quantum computer. This work presents an example of programming a quantum computer. The compact genetic algorithm is used as a target as it is powerful and popular method in evolutionary computation. A quantum bit (qubit) concept was introduced as a basis for storing information. The representation of quantum register has benefits over**

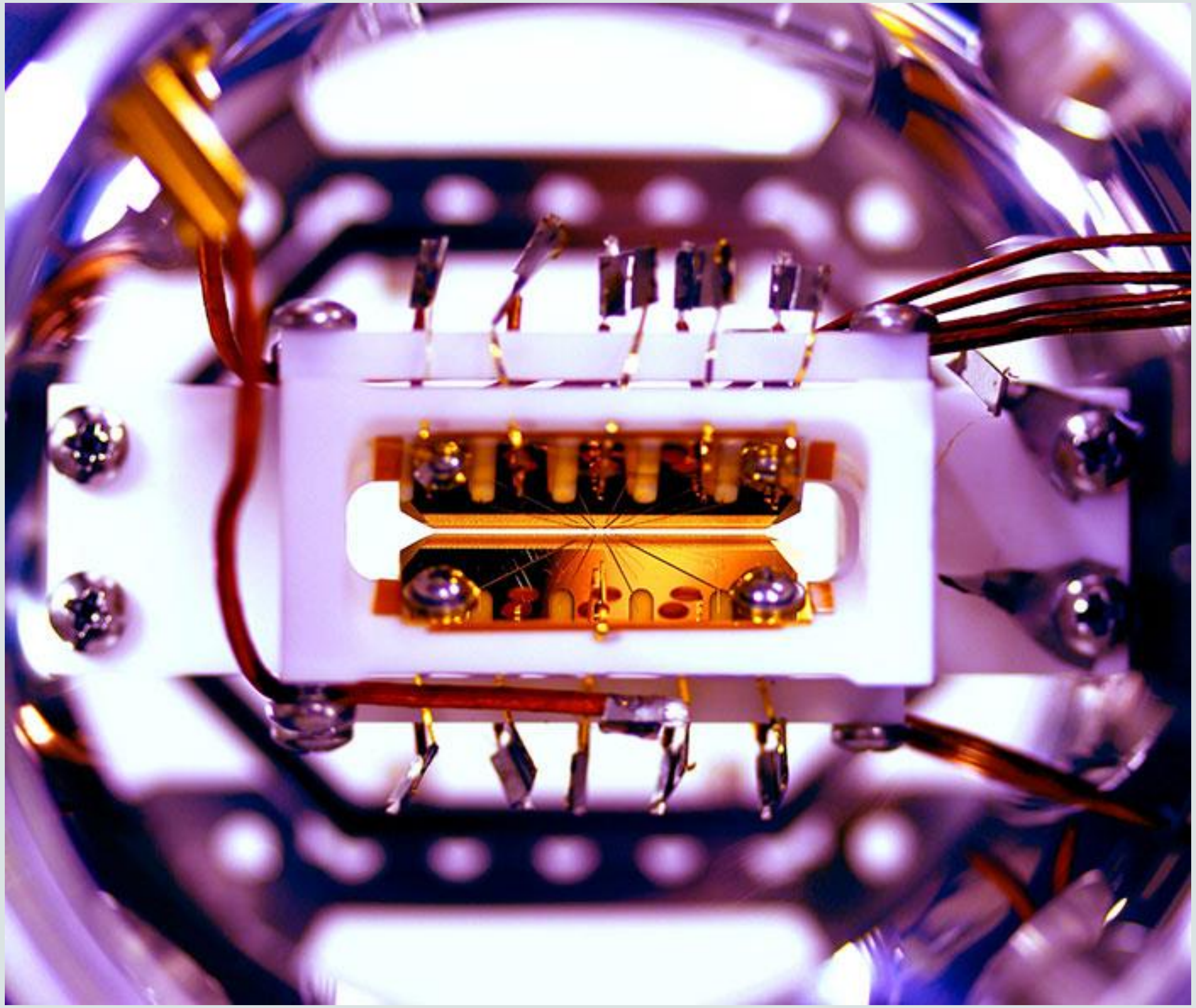
Computation Language) [5]—[7] as an emulator of quantum computer.

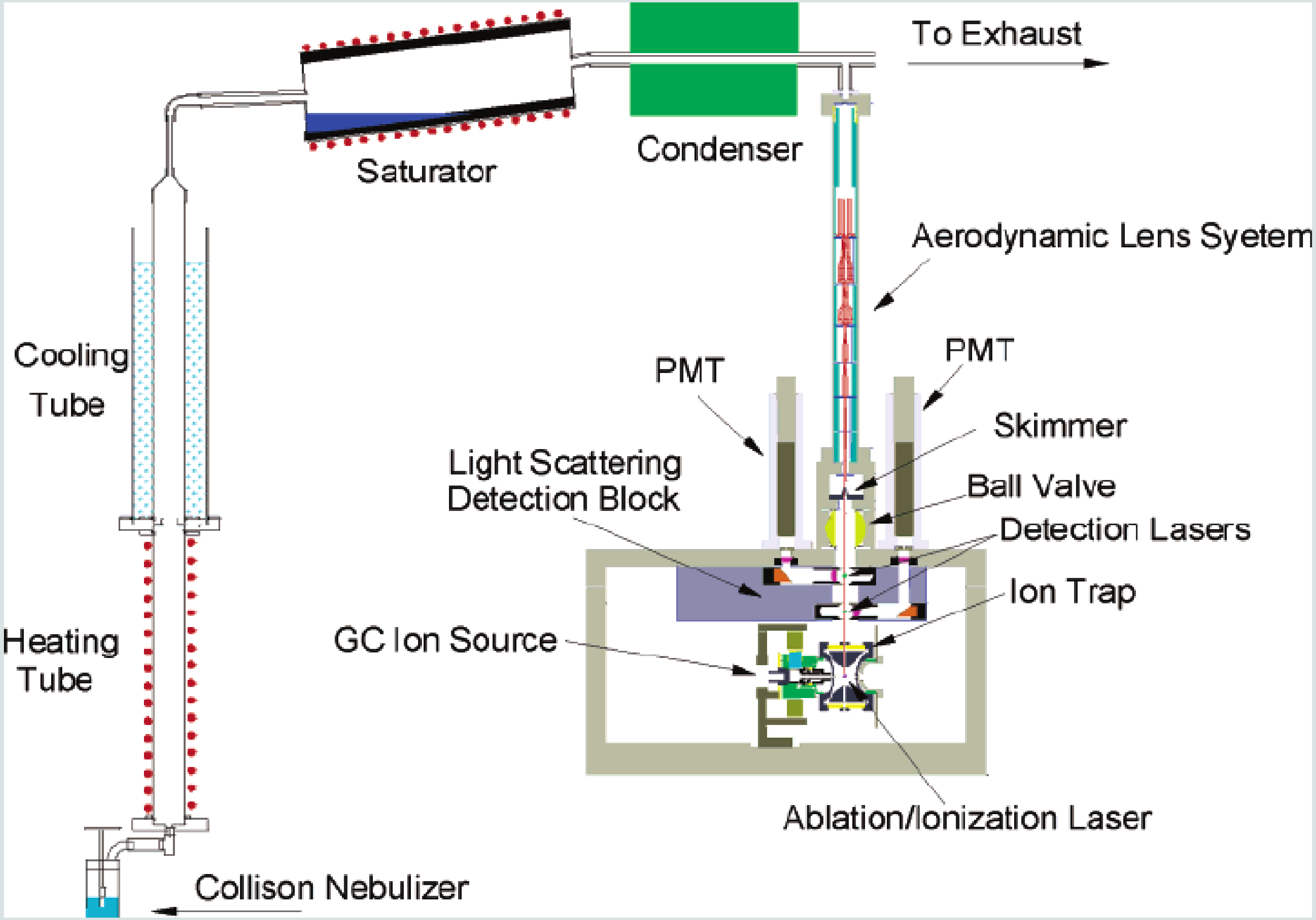
II. COMPACT GENETIC ALGORITHMS

Genetic algorithms are adaptive search algorithms based on the idea of biological evolution such as natural selection, cross over and mutation. Compact genetic algorithm represents the

Quantum computers






To Exhaust
Condenser
Saturator
Aerodynamic Lens Syetem
Cooling Tube
PMT
PMT
Skimmer
Light Scattering Detection Block
Ball Valve
Detection Lasers
Ion Trap
Heating Tube
GC Ion Source
Ablation/Ionization Laser
Collison Nebulizer

Large array of ion-trap system

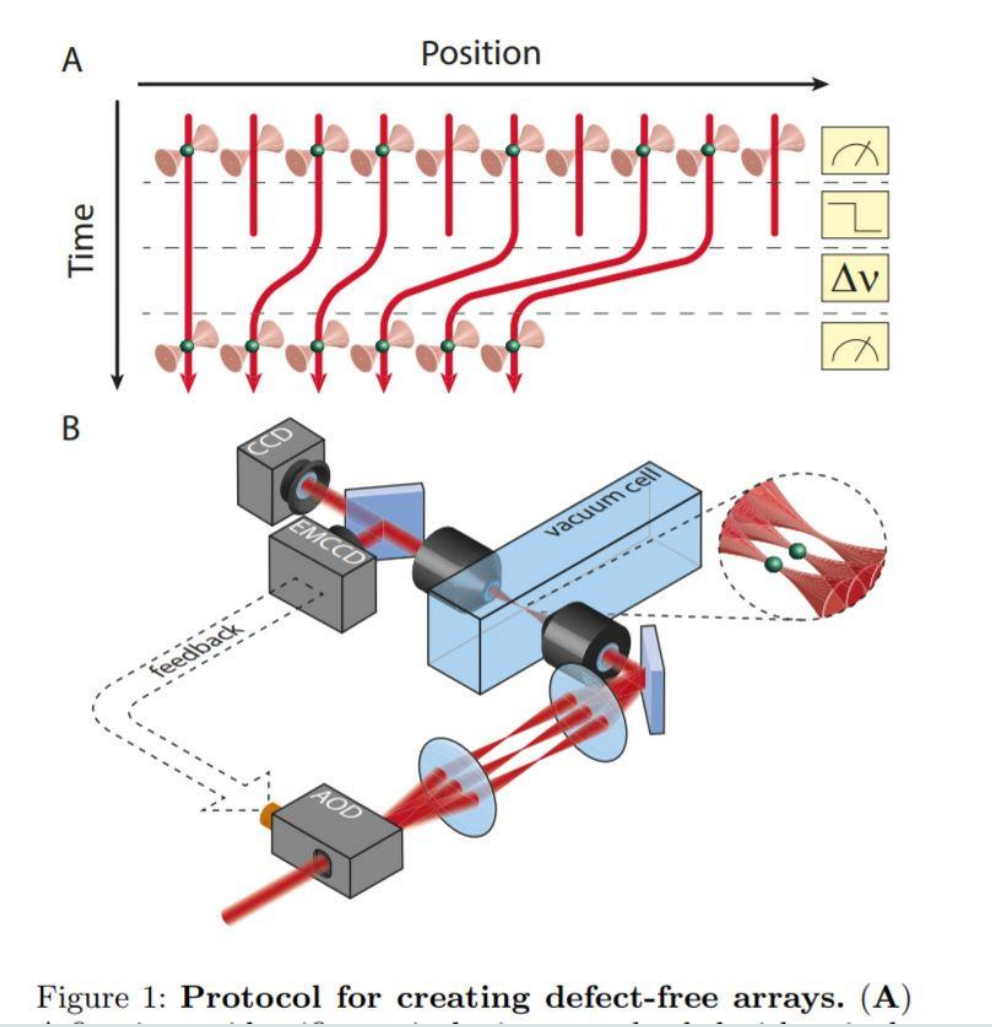
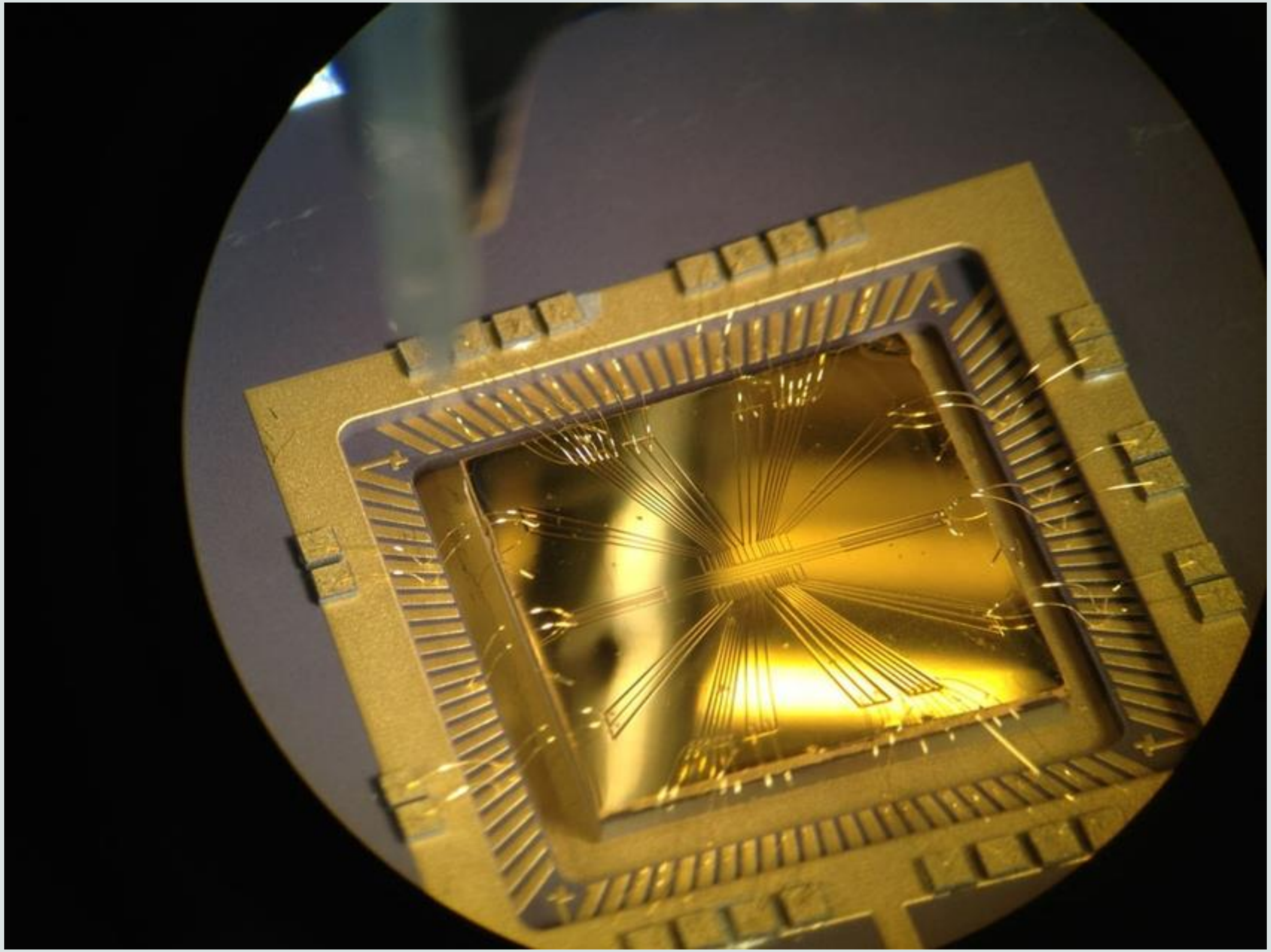
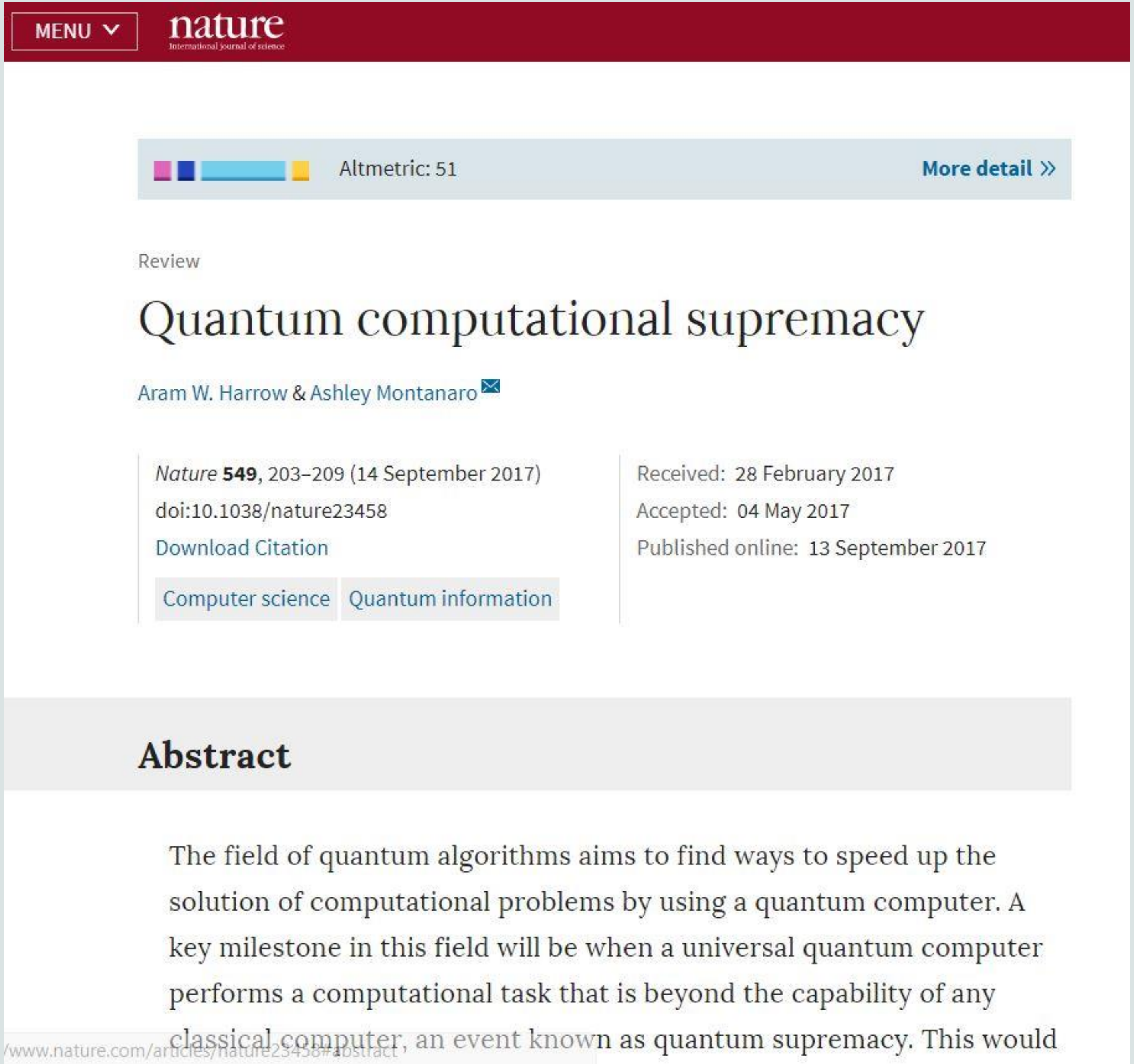


Figure 1: **Protocol for creating defect-free arrays.** (**A**)





Review

Quantum computational supremacy

Aram W. Harrow & Ashley Montanaro

Nature **549**, 203–209 (14 September 2017)
doi:10.1038/nature23458
Download Citation
Computer science Quantum information

Received: 28 February 2017
Accepted: 04 May 2017
Published online: 13 September 2017

Abstract

The field of quantum algorithms aims to find ways to speed up the solution of computational problems by using a quantum computer. A key milestone in this field will be when a universal quantum computer performs a computational task that is beyond the capability of any classical computer, an event known as quantum supremacy. This would

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Quantum Physics

A blueprint for demonstrating quantum supremacy with superconducting qubits

C. Neill, P. Roushan, K. Kechedzhi, S. Boixo, S. V. Isakov, V. Smelyanskiy, R. Barends, B. Burkett, Y. Chen, Z. Chen, B. Chiaro, A. Dunsworth, A. Fowler, B. Foxen, R. Graff, E. Jeffrey, J. Kelly, E. Lucero, A. Megrant, J. Mutus, M. Neeley, C. Quintana, D. Sank, A. Vainsencher, J. Wenner, T. C. White, H. Neven, J. M. Martinis

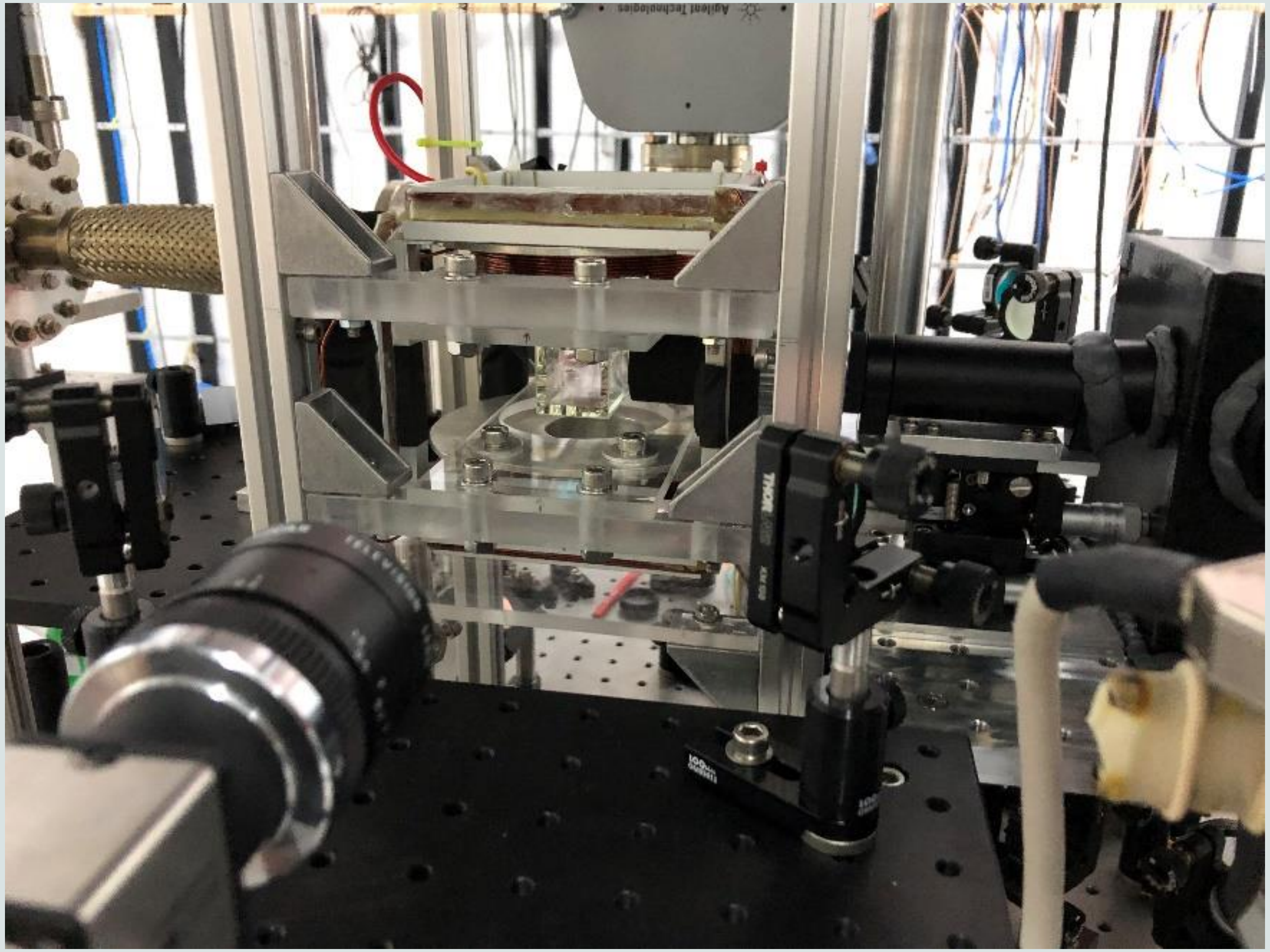
(Submitted on 19 Sep 2017)

Fundamental questions in chemistry and physics may never be answered due to the exponential complexity of the underlying quantum phenomena. A desire to overcome this challenge has sparked a new industry of quantum technologies with the promise that engineered quantum systems can address these hard problems. A key step towards demonstrating such a system will be performing a computation beyond the capabilities of any classical computer, achieving so-called quantum supremacy. Here, using 9 superconducting qubits, we demonstrate an immediate path towards quantum supremacy. By individually tuning the qubit parameters, we are able to generate thousands of unique Hamiltonian evolutions and probe the output probabilities. The measured probabilities obey a universal distribution, consistent with uniformly sampling the full Hilbert-space. As the number of qubits in the algorithm is varied, the system continues to explore the exponentially growing number of states. Combining these large datasets with techniques from machine learning allows us to construct a model which accurately predicts the measured probabilities. We demonstrate an application of these algorithms by systematically increasing the disorder and observing a transition from delocalized states to localized states. By extending these results to a system of 50 qubits, we hope to address scientific questions that are beyond the capabilities of any classical computer.

Subjects: **Quantum Physics (quant-ph)**
Cite as: **arXiv:1709.06678 [quant-ph]**
(or **arXiv:1709.06678v1 [quant-ph]** for this version)

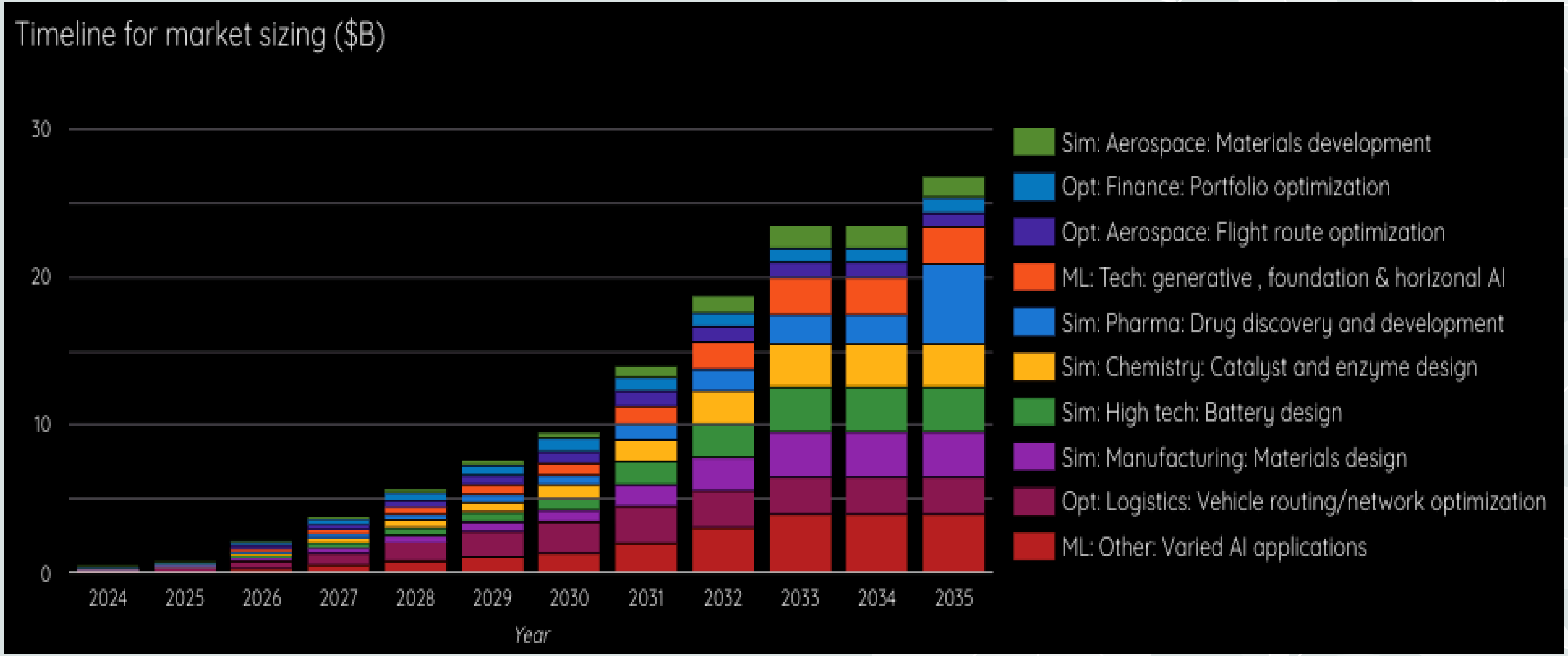
IBM 50 qubits quantum computer

Cold Atom Trap experiment at Physics, Chiengmai University, 2020 (5 Rubidium atoms)



Experiment setup

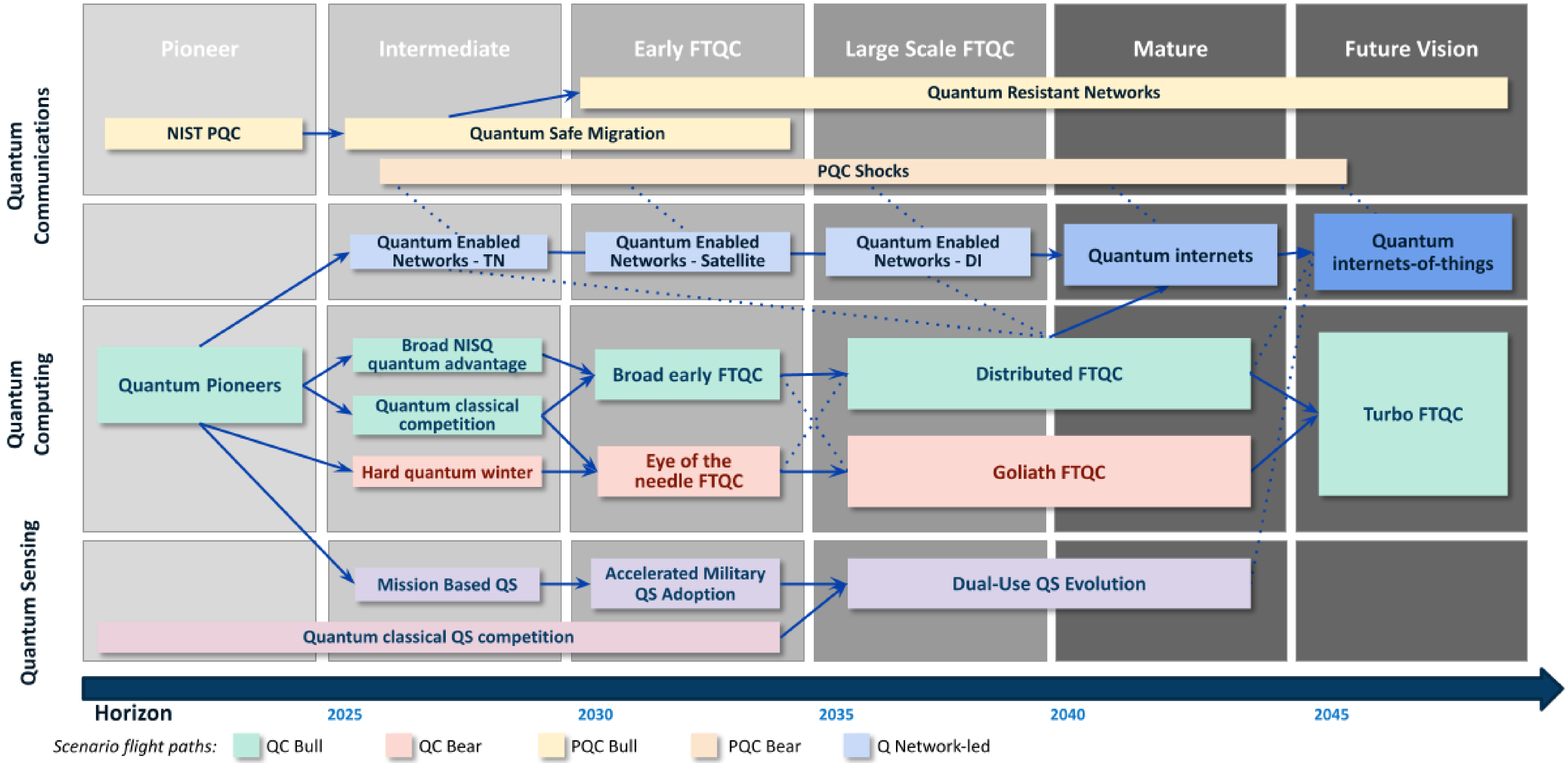
Global View



Quantum computing addressable market 2024-2035
Source: Quantum computing report 2024

Quantum market scenarios across quantum eras

GQI QAM Interactive Model



Pioneer

Intermediate

Early FTQC

Large Scale FTQC

Mature

Future Vision

Quantum Communications

Quantum Resistant Networks

NIST PQC

Quantum Safe Migration

PQC Shocks

Quantum Enabled Networks - TN

Quantum Enabled Networks - Satellite

Quantum Enabled Networks - DI

Quantum internets

Quantum internets-of-things

Quantum Computing

Quantum Pioneers

Broad NISQ quantum advantage

Quantum classical competition

Hard quantum winter

Broad early FTQC

Eye of the needle FTQC

Distributed FTQC

Goliath FTQC

Turbo FTQC

Quantum Sensing

Mission Based QS

Accelerated Military QS Adoption

Dual-Use QS Evolution

Quantum classical QS competition

Horizon

2025

2030

2035

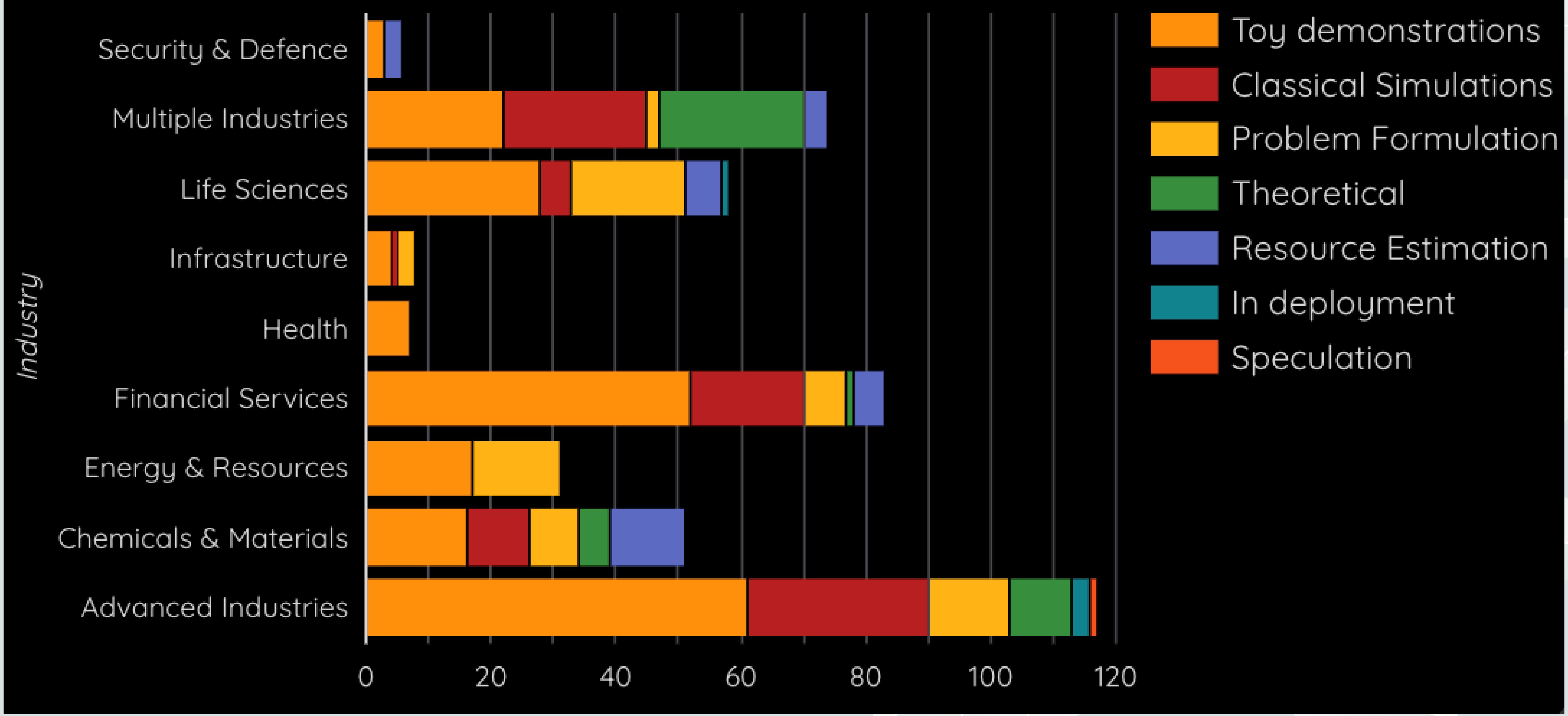
2040

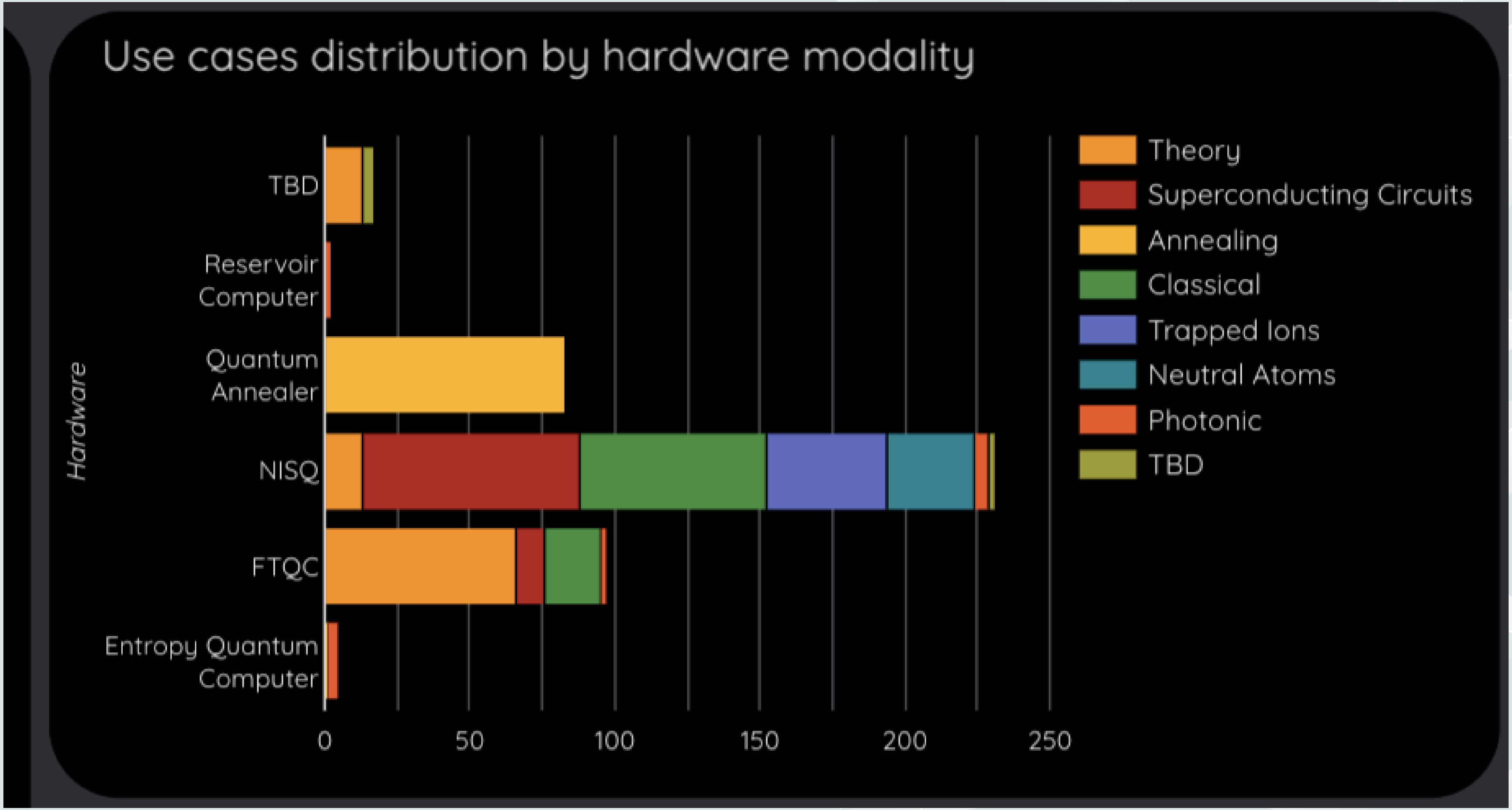
2045

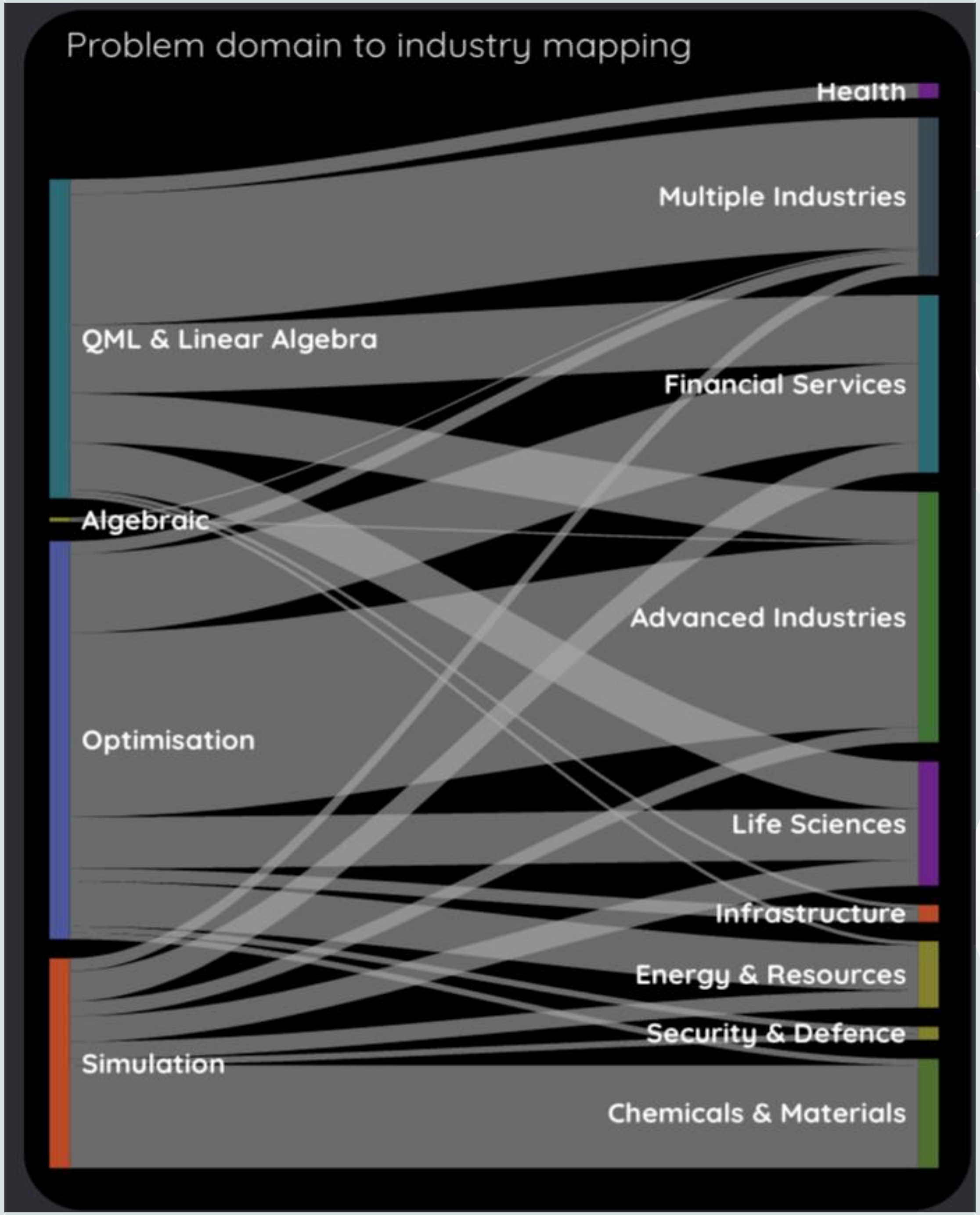
Scenario flight paths: 🟩 QC Bull 🟥 QC Bear 🟨 PQC Bull 🟧 PQC Bear 🟦 Q Network-led

Source: Global Quantum Intelligence (GQI) | All rights reserved | © 2024

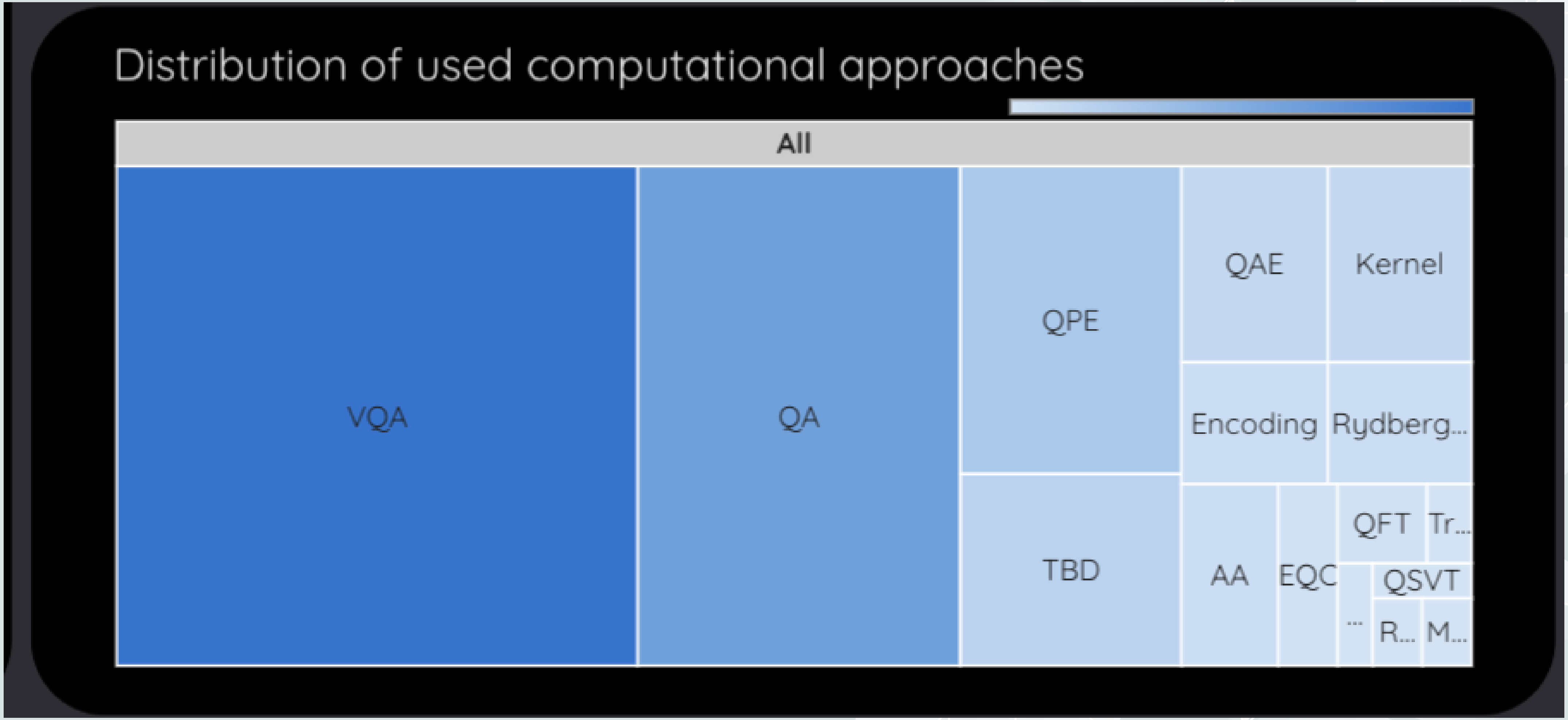
Use cases distribution by industry and implementation status




Use cases distribution by hardware modality
Hardware
TBD
Reservoir Computer
Quantum Annealer
NISQ
FTQC
Entropy Quantum Computer
0
50
100
150
200
250
Theory
Superconducting Circuits
Annealing
Classical
Trapped Ions
Neutral Atoms
Photonic
TBD



Problem domain to industry mapping



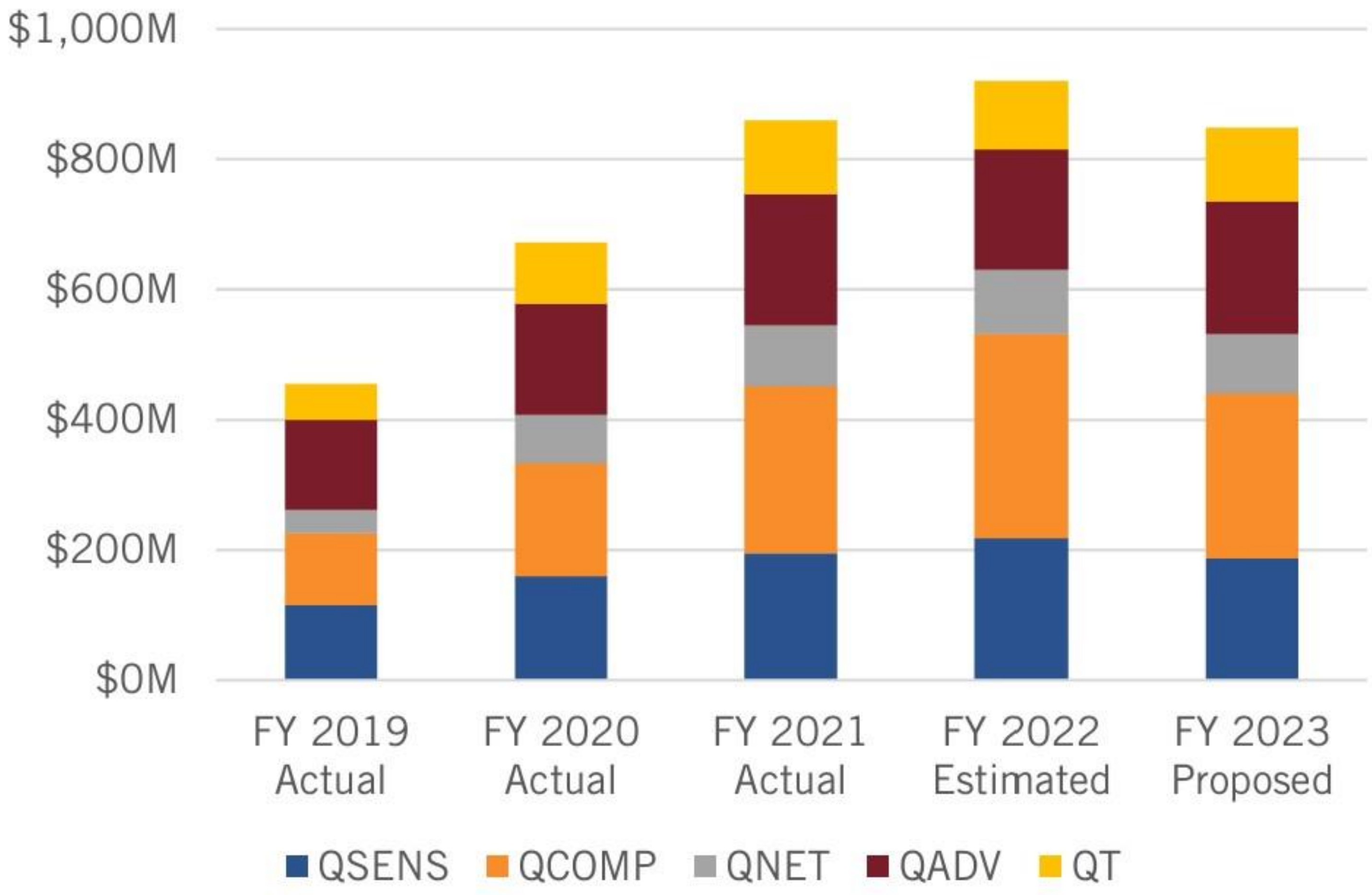
Distribution of used computational approaches

US Quantum Policy

Quantum Information Science (QIS) encompass:

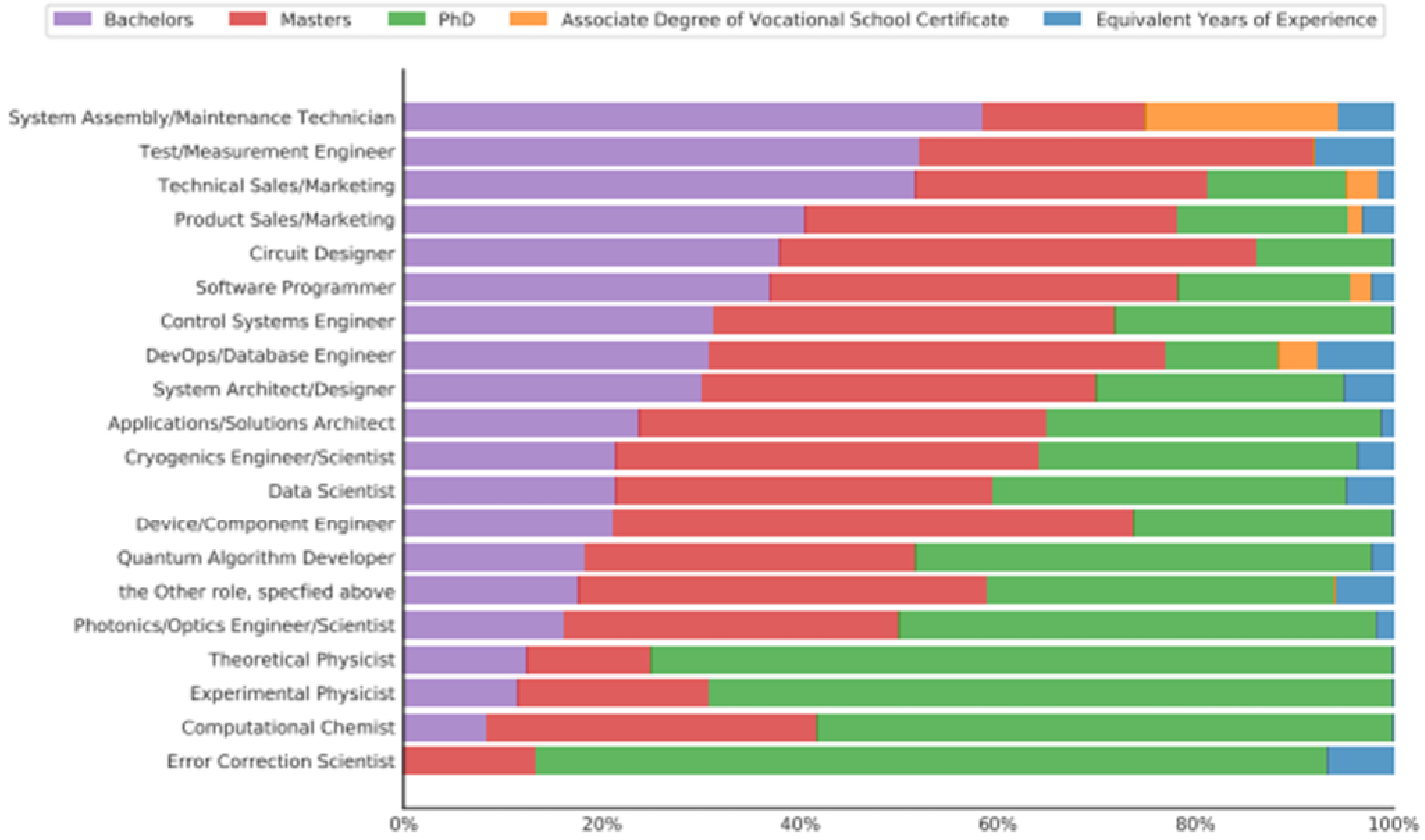
Quantum sensing and metrology
Quantum computing
Quantum networking
QIS for advancing fundamental science
Quantum technology

Figure 2: U.S. Quantum Information Science R&D by program component area[12]



Source: The U.S. Approach to Quantum Policy By Hodan Omaar, October 10, 2023

Figure 5: The distribution of degrees needed for different job roles in the quantum industry[50]



Source: The U.S. Approach to Quantum Policy By Hodan Omaar, October 10, 2023

Looking into the future

- Studying quantum computer give rise to new ideas
- Quantum “thinking” promises a new kind of method to solve really difficult problems
- Quantum Computers will change the face of computing forever

Contributors (student team 2019)

Thank you