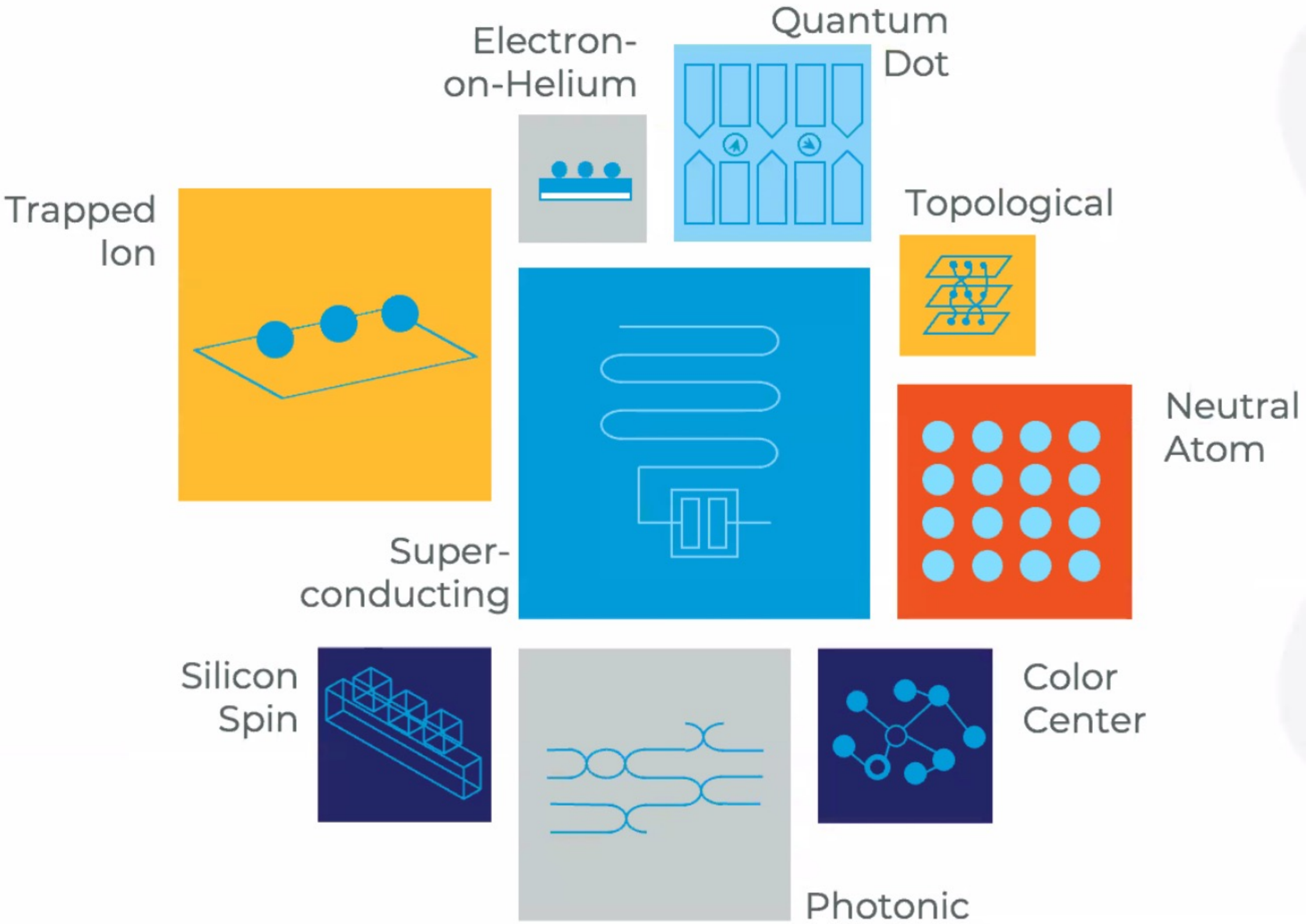
CSCI C290 6W2 SUMMER 2022

PROGRAMMING QUANTUM COMPUTERS


Heterogeneous Computing
Hardware and Software Perspectives
Mohamed Zahran
THE NATURE of COMPUTATION
Cristopher Moore & Stephan Mertens
The National Academies of SCIENCES · ENGINEERING · MEDICINE
CONSENSUS STUDY REPORT
QUANTUM COMPUTING
Progress and Prospects
Quantum Computing for High School Students
Yuly Billig
Ciaran Hughes · Joshua Isaacson Anastasia Perry · Ranbel F. Sun Jessica Turner
Quantum Computing for the Quantum Curious
Springer
Building a Quantum Engineering Undergraduate Program
arXiv:2108.01311v1 [physics.ed-ph] 3 Aug 2021
Development of an Undergraduate Quantum Engineering Degree
arXiv:2110.12598v1 [physics.ed-ph] 25 Oct 2021
Defining the quantum workforce landscape: a review of global quantum education initiatives
Maninder Kaur, Araceli Venegas-Gomez
arXiv:2202.08940v3 [physics.ed-ph] 21 Apr 2022
QUANTUM COMPUTING FOR PROGRAMMERS
Robert Hundt
Ray LaPierre
Introduction to Quantum Computing
Springer

Variety of Quantum Hardware Technologies



Superconducting
- IBM
- Google
- Rigetti

Trapped Ion
- IonQ
- Quantinuum
- AQT

Neutral Atom
- Atom Computing
- ColdQuanta
- Pasqal

Photonic
- Xanadu
- PsiQuantum

Quantum Dot
- Intel

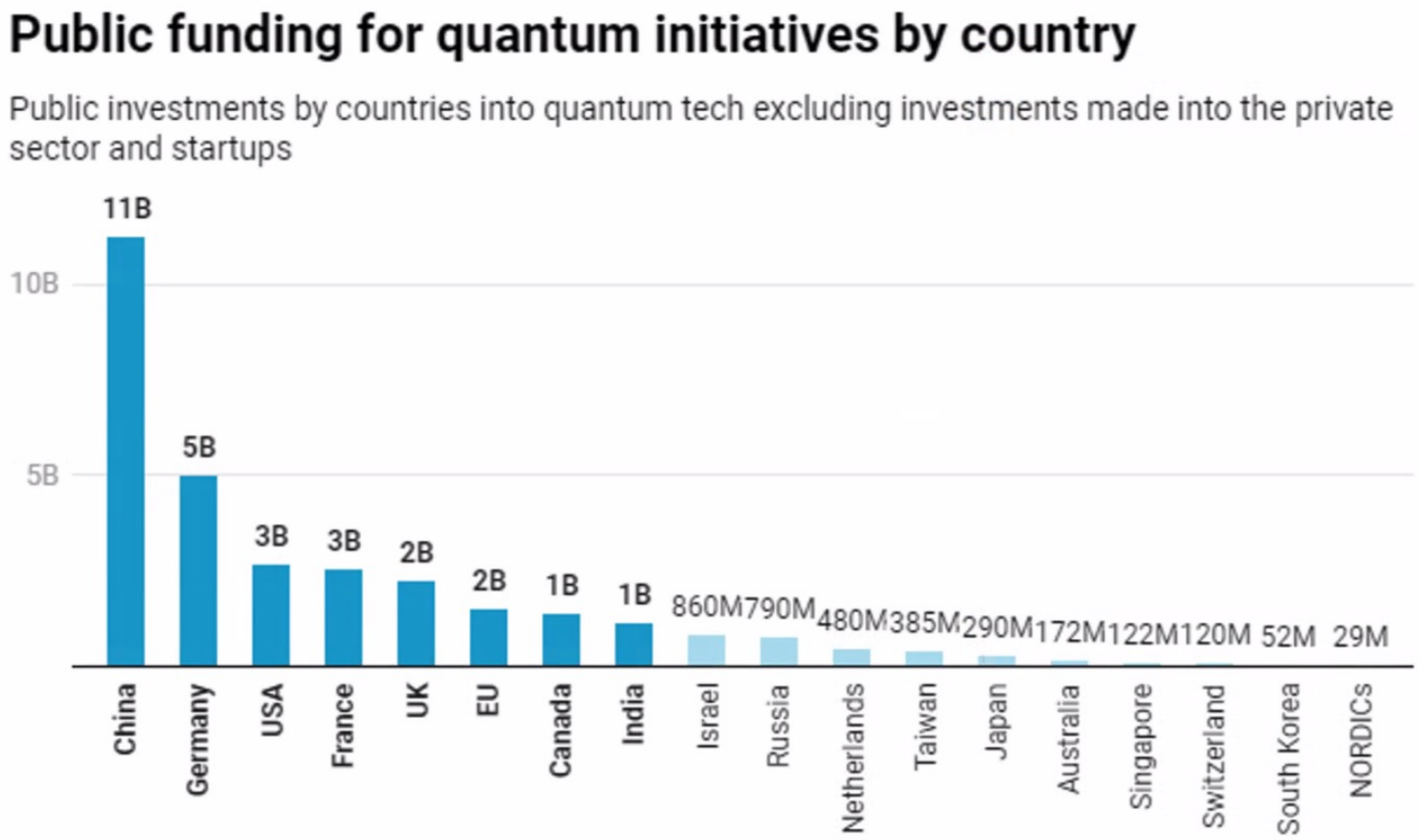
Color Center
- Quantum Brilliance

Electron-on-Helium
- EeroQ

Silicon Spin
- Silicon Quantum Computing

Topological
- Microsoft

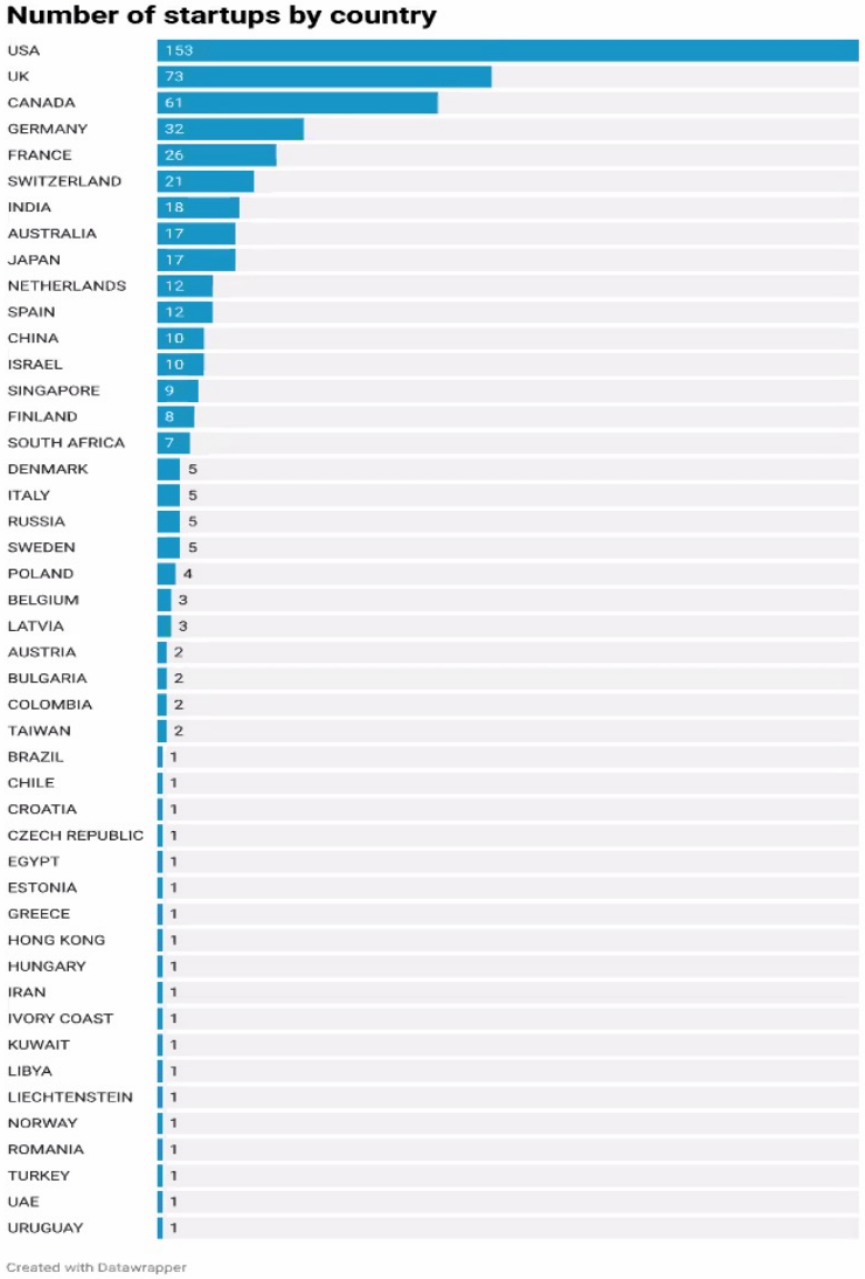
Government Programs for Quantum Computing



atom computing

Startups by Country

- Concentration in North America, parts of Europe and Australia
- Israel is emerging strongly



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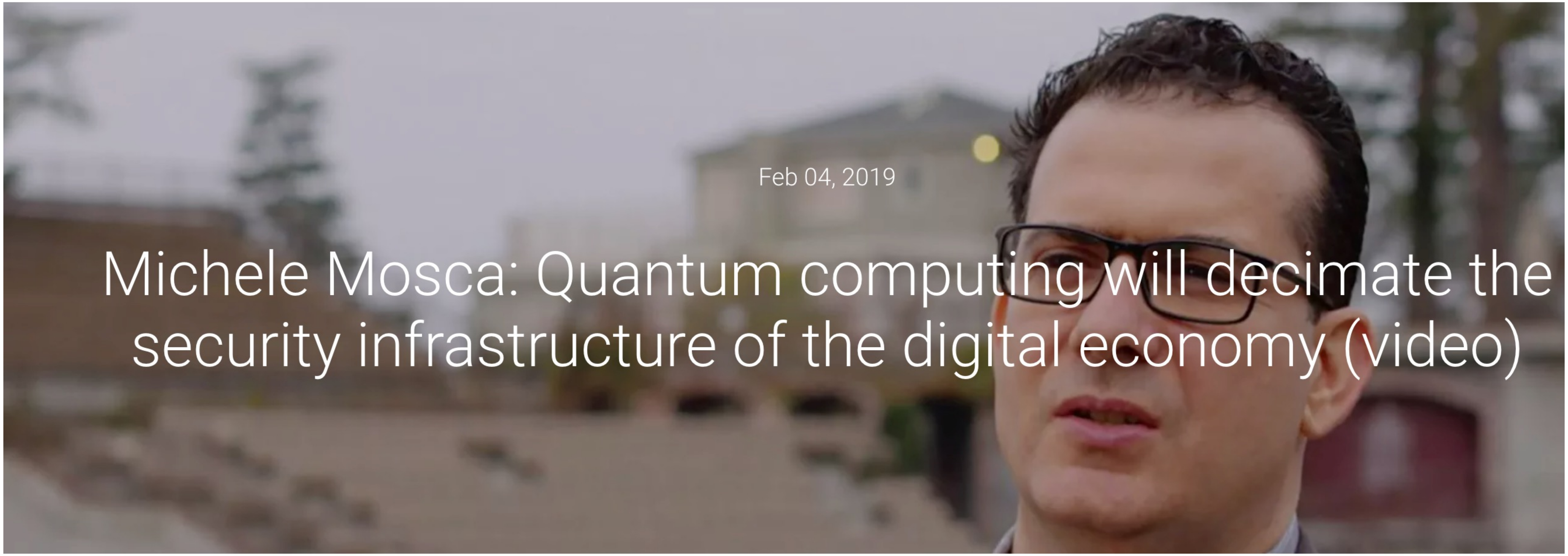

Feb 04, 2019

Michele Mosca: Quantum computing will decimate the security infrastructure of the digital economy (video)

Quantum computing will decimate the security infrastructure of the digital economy. Quantum computing in general is certainly a blessing to humanity in many respects and it promises to disrupt evolution of technology in more than one dimensions. But it is also a curse to security, as cryptographic algorithms that proved to be secure for decade may be breached by quantum computers within minutes.

Public Hardware Companies

Company	Description	Market Cap
ARCHER	Former mining company, now focused on quantum and healthcare, developing silicon quantum chip (Australia: ARRXF)	$294M AUD
IONQ	October 2021: SPAC to develop trapped ion quantum hardware and applications software; on NYSE: IONQ	$1.2B
rigetti	Announced plans to become publicly traded via merger with Supernova Partners Acquisition Company II SPAC in 2022	$0.84B

Quantum Computers available on the Cloud

Major Cloud Providers	Quantum Devices Available
Amazon Braket (aws)	rigetti, IONQ, QuEra Computing Inc., OQC
Microsoft Azure Quantum	rigetti, IONQ, QUANTINUUM
Google Cloud	IONQ
IBM Q	IBM Q (20+ devices)

Note that many other systems can be accessed directly through the manufacturer.

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The Number of Qubits Does *Not* Determine the Quality of a Quantum Computer

Many factors determine the strength of a computer, including:

Error Rates

Fidelity

Connectivity

Depth of circuits

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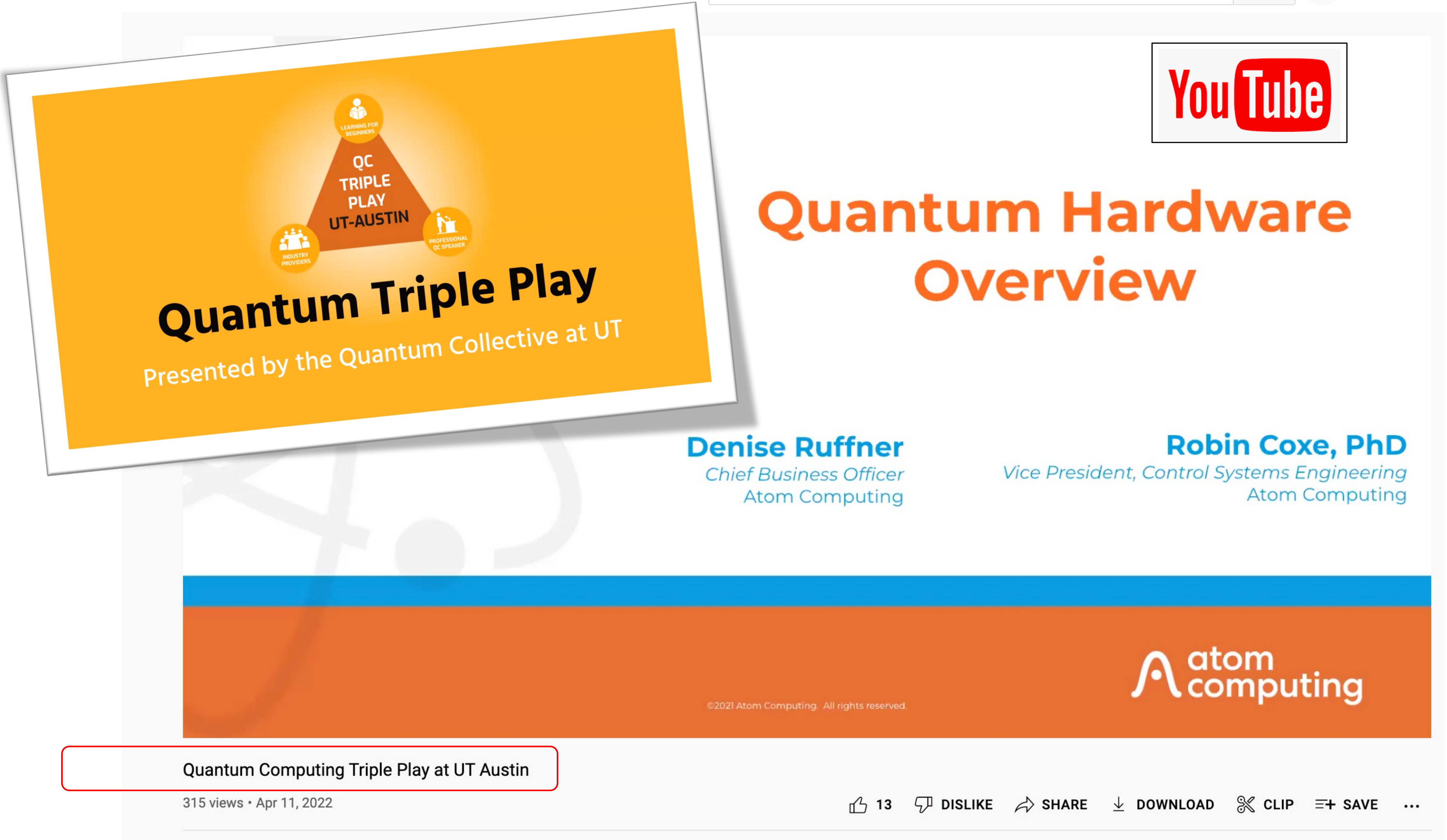
LEARNING FOR BEGINNERS
QC TRIPLE PLAY UT-AUSTIN
INDUSTRY PROVIDERS
PROFESSIONAL QC SPEAKER
Quantum Triple Play
Presented by the Quantum Collective at UT
YouTube
Quantum Hardware Overview
Denise Ruffner
Chief Business Officer
Atom Computing
Robin Coxe, PhD
Vice President, Control Systems Engineering
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atom computing
Quantum Computing Triple Play at UT Austin
315 views • Apr 11, 2022
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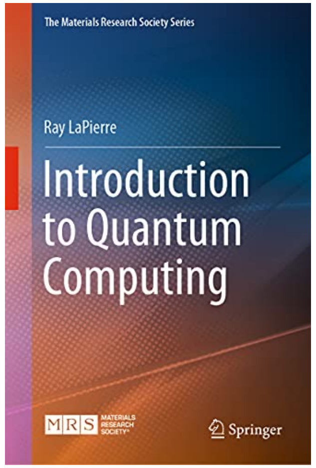
How to Use This Book

This book is intended for a single semester (~12 weeks) elective course on quantum computing, comprised of approximately 36 one-hour lectures (3 hours per week). A suggested lecture schedule is as follows:

Lecture 1–2: Chapter 1—Superposition
Lecture 3–4: Chapter 2—Quantization
Lecture 5–6: Chapter 3—Spin
Lecture 7–8: Chapter 4—Qubits
Lecture 9–10: Chapter 5—Entanglement
Lecture 11: Chapter 6—Quantum Key Distribution
Lecture 12–13: Chapter 7—Quantum Gates
Lecture 14: Chapter 8—Teleportation
Lecture 15: Chapter 9—Tensor Products
Lecture 16: Chapter 10—Quantum Parallelism and Computational Complexity
Lecture 17: Chapter 11—Deutsch Algorithm
Lecture 18: Chapter 12—Grover Algorithm
Lecture 19: Chapter 13—Shor Algorithm
Lecture 20–21: Chapter 14—Precession
Lecture 22: Chapter 15—Electron Spin Resonance
Lecture 23: Chapter 16—Two-State Dynamics
Lecture 24: Chapter 17—Implementing Two-Qubit Gates
Lecture 25: Chapter 18—DiVincenzo Criteria
Lecture 26: Chapter 19—Nuclear Magnetic Resonance
Lecture 27–28: Chapter 20—Solid-State Spin Qubits
Lecture 29: Chapter 21—Trapped Ion Quantum Computing
Lecture 30–31: Chapter 22—Superconducting Qubits
Lecture 32: Chapter 23—Adiabatic Quantum Computing
Lecture 33: Chapter 24—Optical Quantum Computing
Lecture 34–35: Chapter 25—Quantum Error Correction



Lecture 36: Chapter 26—Topological Quantum Computing

The book assumes that students have successfully completed an introductory course in quantum mechanics, which is typically in the second year of a four-year undergraduate program in science, engineering, or related disciplines. Thus, this book is intended for the third or fourth year of an undergraduate program or the entry level of a graduate program.

The book is divided into three main parts. Chapters 1–13 focus on the basic principles underlying quantum computing and an understanding of quantum algorithms. Chapters 14–18 introduce the principles underlying the physical implementation of single-qubit and two-qubit gates. Finally, Chaps. 19–26 present specific physical platforms for quantum computers, as well as quantum error correction.

Each chapter is intended to be taught consecutively. Chapter 6 on quantum key distribution and Chap. 8 on teleportation, are given as sample applications of entanglement and may be considered optional (although students typically enjoy this material). Chapter 25 on quantum error correction, although of importance to quantum computing, may also be considered optional or quickly skimmed. Instructors who wish to emphasize quantum algorithms may choose to focus on Chaps. 1–13, while those more interested in hardware can focus on Chaps. 14–26.

Each chapter includes exercises which can be completed by the student as homework assignments or used for tutorial instruction. A solutions manual is available for qualified instructors. Each chapter also includes references for more advanced study, and further reading is listed at the end of the book.

Hamilton, Canada — Ray LaPierre

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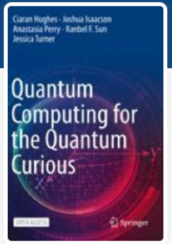

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Quantum Computing for the Quantum Curious

Authors: (view affiliations) Ciaran Hughes, Joshua Isaacson, Anastasia Perry, Ranbel F. Sun, Jessica Turner

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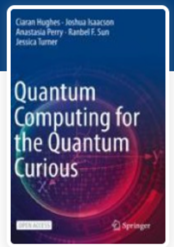

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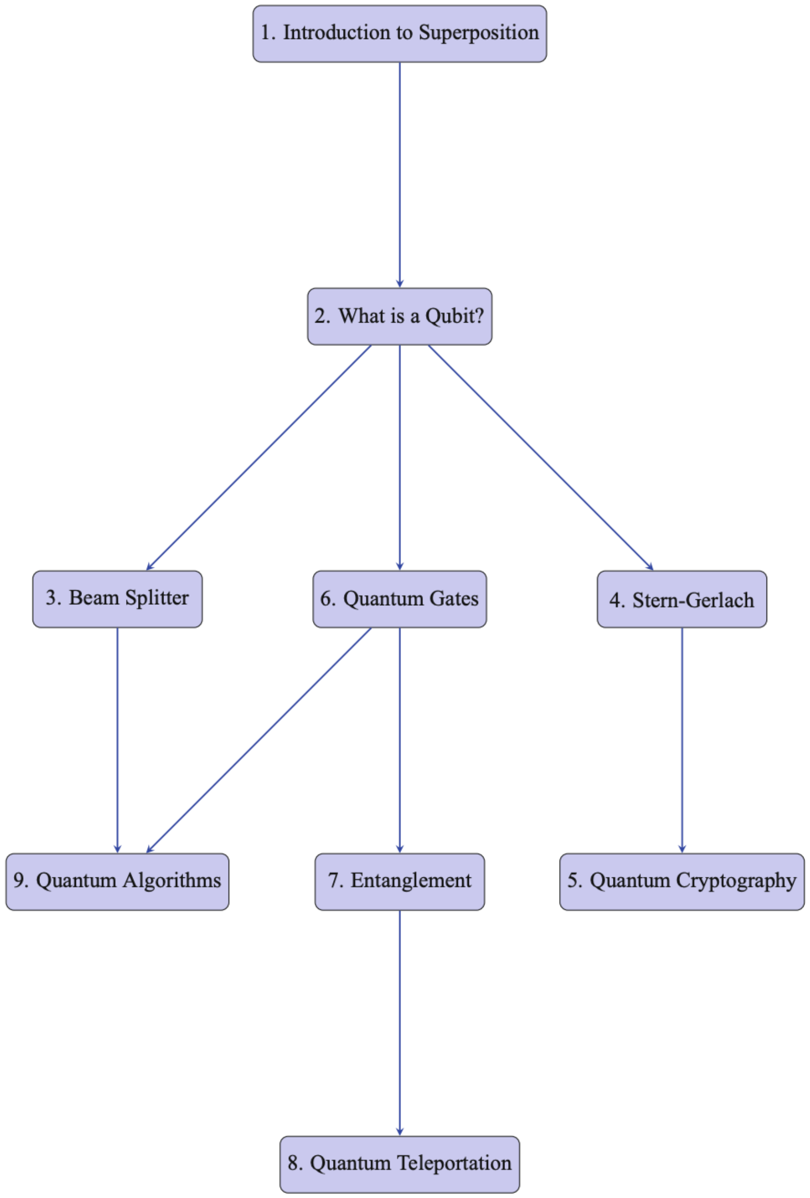

Fig. 1 Flowchart of learning outcomes.

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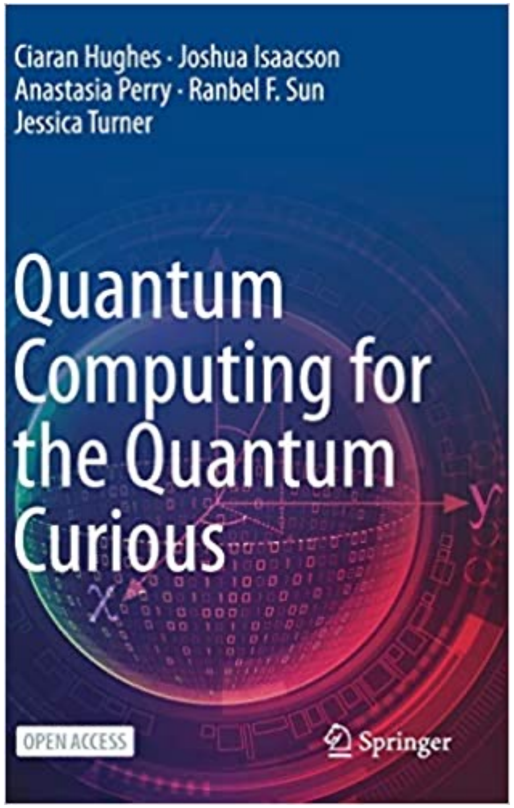

Ciaran Hughes · Joshua Isaacson
Anastasia Perry · Ranbel F. Sun
Jessica Turner
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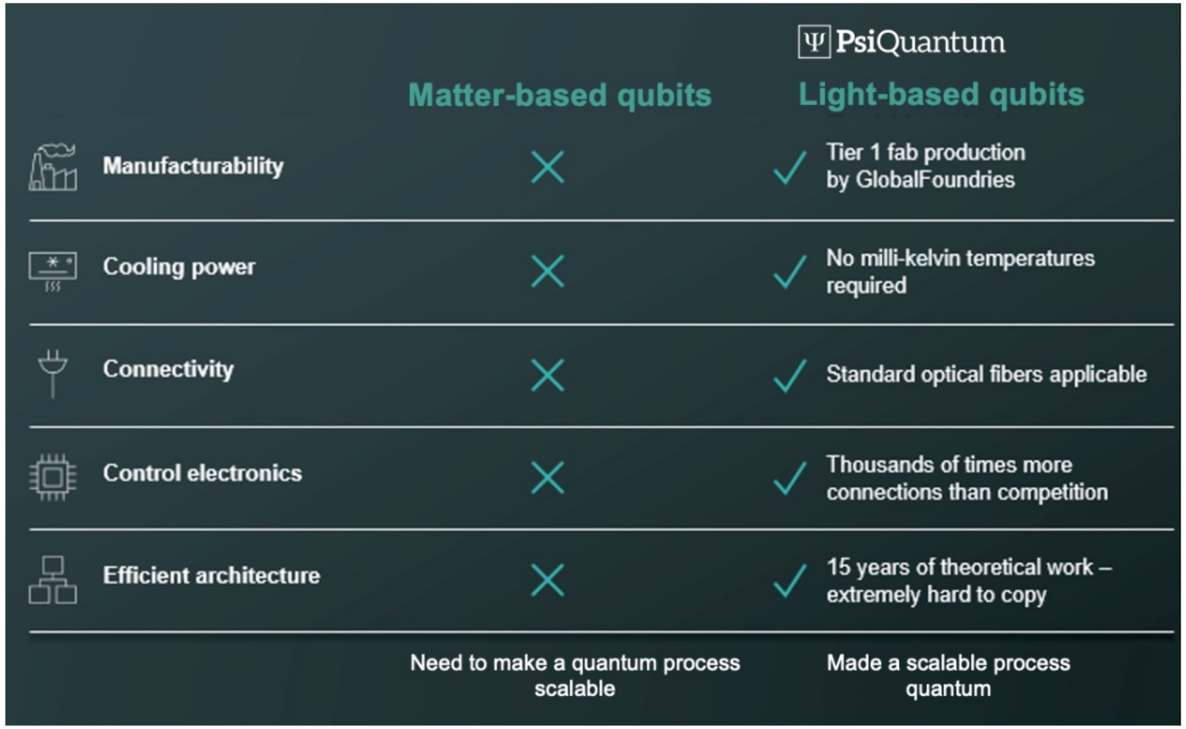
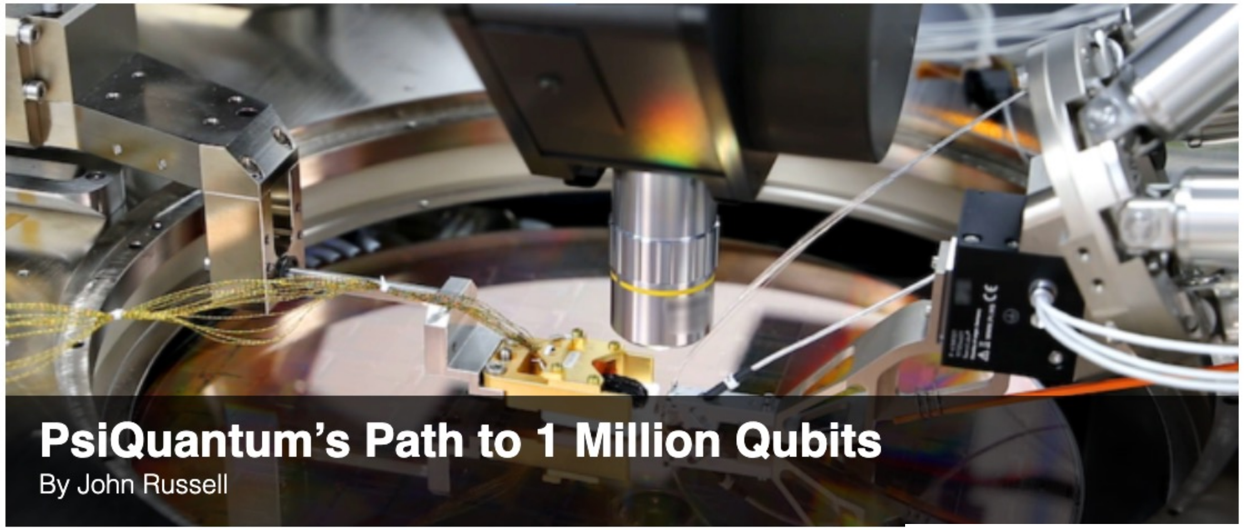
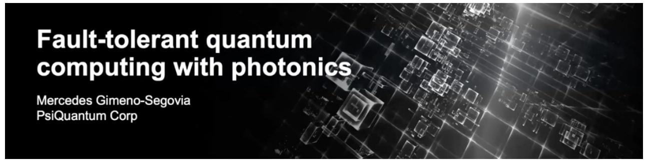


Ψ PsiQuantum

	Matter-based qubits	Light-based qubits
Manufacturability	✗	✓ Tier 1 fab production by GlobalFoundries
Cooling power	✗	✓ No milli-kelvin temperatures required
Connectivity	✗	✓ Standard optical fibers applicable
Control electronics	✗	✓ Thousands of times more connections than competition
Efficient architecture	✗	✓ 15 years of theoretical work – extremely hard to copy
	Need to make a quantum process scalable	Made a scalable process quantum

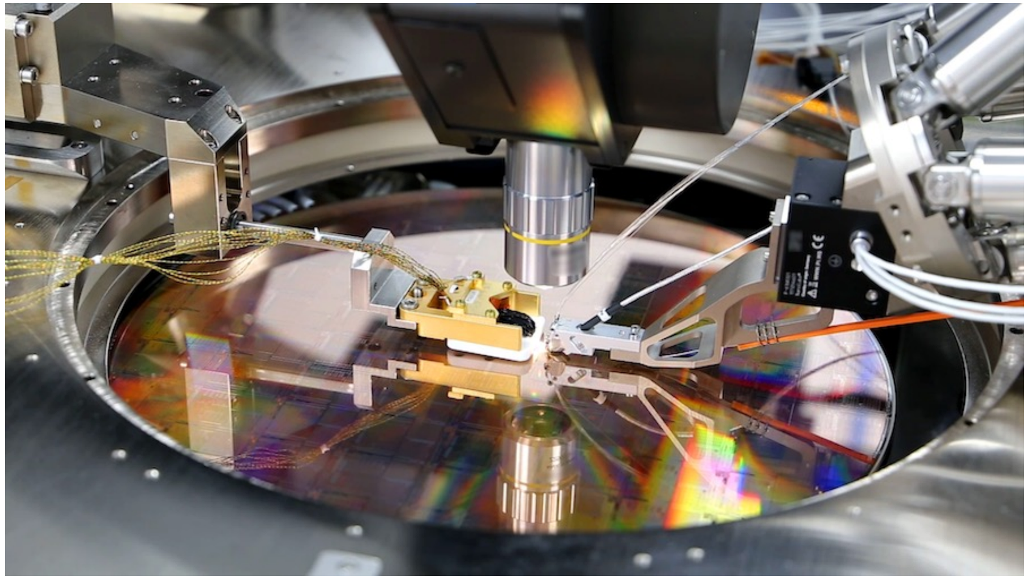


April 21, 2022



HPCwire

Since 1987 - Covering the Fastest Computers in the World and the People Who Run Them



PsiQuantum wafer

The biggest challenges for PsiQuantum, he suggests, are developing manufacturing techniques and system architecture around well-known optical technology. The company argues having a Tier-1 fab partner such as GlobalFoundries is decisive.

and especially you can't increment with five qubits, 10 qubits, 20 qubits, 50 qubits to a million. That is not a good strategy. But it's also not true to say that we're planning to leap from zero to a million," said Shadbolt. "We have a whole chain of incrementally larger and larger systems that we're building along the way. Those

John Preskill
@preskill

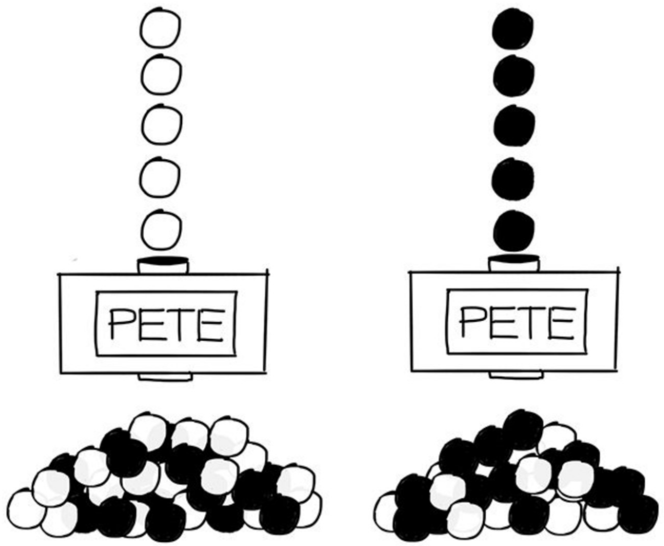
Tez-isms from Terry Rudolph of PsiQuantum:
"I have a lot of respect for Google, in spite of their hiring Dave Bacon."
"There are a million ways to make one qubit, but only one way to make a million qubits."
#quantumopportunities2018

3:35 PM · Oct 3, 2018 · Twitter Web Client

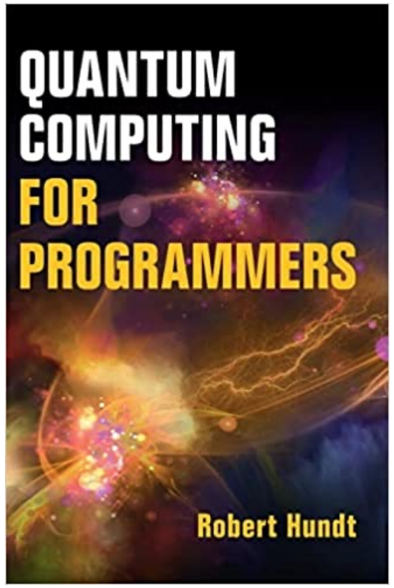
FACT BASED *INSIGHT*

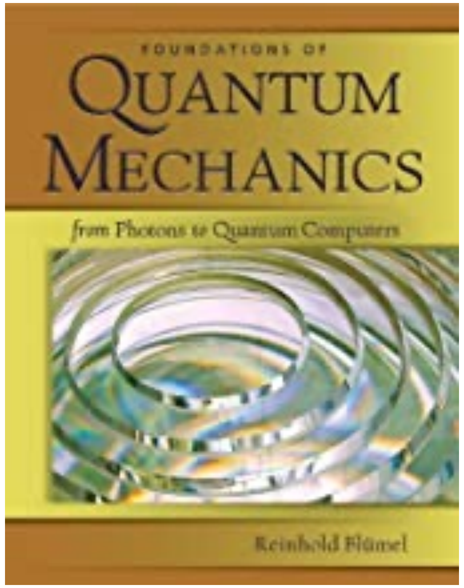
Quantum Value Chain
Quantum Software
Quantum Hardware
factbasedinsight.com

It's really not yet clear which of the qubit technologies – semiconductor-based superconducting, trapped ions, neutral atoms, photonics, or something else – will prevail and for which applications. What's not ambiguous is PsiQuantum's Go Big or Go Home strategy. Its photonics approach, argues the company,



Qiskit





From Photons to Quantum Computers

Examples in Java

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25	Tue	July 26	Lecture 16: Supremacy (Advantage)
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edX BerkeleyX CS-191x
Quantum Mechanics and Quantum Computation

Quantum Mechanics and Quantum Computation

BerkeleyX - CS-191x   10 weeks long, 5-12 hours a week

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Dirac taught us there is a minimum disturbance that accompanies a measurement (inherent in the nature of things, and that cannot be overcome by improved experimental technique). If minimum disturbance accompanying a measurement is non-negligible, the object is absolutely small, and its properties fall in the realm of quantum mechanics. The quantum properties of absolutely small particles are not strange; they are just unfamiliar and not subject to our classical intuition. The double-slit experiment performed w/ electrons introduces both the phenomenon of interference and the wave-particle duality principle. According to this principle: A quantum object (a) is produced as a particle, (b) propagates like a wave, and (c) is detected as a particle with a probability distribution that corresponds to a wave. The double-slit experiment also introduces the Heisenberg uncertainty principle at the level of paths (trajectories). A qubit is a superposition of bit states and is represented as a vector via complex numbers w/ brief review of trigonometry. Two-dimensional vector spaces with complex (or real) amplitudes are introduced. We define measurement as the probability of a state projecting itself on any of the two vectors of an orthogonal basis. Define the standard (computational) basis, and the sign basis. Heisenberg's uncertainty principle imposes a fundamental limit on the accuracy w/ which the values of two incompatible observables can be measured simultaneously. It is not possible to know with perfect accuracy both the bit value and the sign value of a qubit, yet another manifestation of the uncertainty principle. Photons as qubits. Polarization.

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Systems of two qubits exhibit a remarkable property called entanglement, that plays a critical role in quantum computation. Start with k-level systems, introduce bra-ket notation, use the measurement axiom in an orthonormal basis, inner products, complex conjugates and the superposition principle. Describe partial measurement in a system of two qubits with renormalization and then define entanglement. Three quantum phenomena are used in quantum algorithms: superposition, interference and entanglement. State of a composite system. Taking the tensor product. Factoring a product into individual components. Bell states. Measuring the Bell state. Spin of two electrons in a covalent bond. The paradoxical features of Bell states. The EPR paradox. Local realism.
A test for quantum mechanics: Bell inequalities. Classer, Horne, Shimony, and Holt (1969). Alain Aspect (1982). No Signaling Theorem. Entanglement can be used to create non-classical correlations. Rotational invariance of a Bell state. State of the spin of electrons in a covalent bond: singlet state. Designing a test for quantum-ness: creating instant remote non-classical correlations. CHSH and local realism. John Stewart Bell was 7 years old in 1935 the year of the EPR paradox paper. Nature is consistent with QM and inconsistent with any local hidden variable theory. It took a brilliant insight by John Bell and further simplification by CHSH plus the language of qubits to explain in a lecture what Einstein spent decades of his life without any luck or success. This shows there can be remarkable power in very simple concepts. Quantum Mechanics has three axioms we discuss next.

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So far we've talked about what the allowable states of a quantum system are and what happens when we measure the state of a quantum system. These are encapsulated in the first two axioms of Quantum Mechanics: the superposition principle and the measurement axiom. Quantum gates address the issue of how the state of a quantum system evolves in time (unitary evolution, the third axiom of QM). Simple axioms with very complex consequences. Third axiom says that the state evolution of a quantum system in time is via a rotation in a Hilbert space. Example: evolution of a qubit (rotate the space). Rotation of the space is a linear transformation. Represent by a matrix. Unitary transform(ation)s and their properties. Single qubit gates: X (bit flip), Z (phase flip), H (the Hadamard gate). Two qubit gates and tensor products. The CNOT gate. Tensor products and the dimension of two qubit gates. If we try construct a quantum circuit that copies an unknown quantum state we find there is no unitary transformation that achieves this, i.e., the No-Cloning Theorem. The Bell state circuit: building a maximally entangle state. Bell basis states. It's impossible to clone quantum information but it is possible to teleport a quantum state to another location. We build the complete teleportation protocol: Alice has this unknown quantum state, she wants to transport it to Bob. In the course of teleportation she destroys her qubit. She then has to call up Bob and tell him two classical bits of information. In the process, she allows Bob to reconstruct her qubit (by creating an entangled state without quantum communication between the two of them). We end with an interpretation of what measurement of a qubit really is.

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We are ready to go to the next topic, which is quantum algorithms. We focus on how to specify a quantum algorithm in terms of a quantum circuit. Such a quantum circuit act on a system of n qubits. The state of an n qubit system is an exponential superposition. But we cannot reach in and update all the exponentially many amplitudes one at a time, so instead we want to perform some kind of quantum gate on some of the qubits and we show that behind the scenes nature updates all those complex amplitudes. At the end we measure the answer and then the exponential superposition disappears. And so, quantum algorithms is the art of making use of these resources that quantum mechanics gives us: (a) extravagant resources, w/ (b) some degree of control, but (c)very limited access, and to use those to solve a difficult computational problem. We then talk about the universal gate set. In classical circuits, e.g. NAND is universal, a certain set of gates enables universal computation. The quantum analogue is { CNOT, H, X, Z, and something like a $\frac{\pi}{8}$ rotation}. Other sets exist important aspect here is that you can restrict yourself to two qubit gates. Equipped with a model of a quantum computer we start exploring what we can do with it. Since evolution in quantum mechanics is unitary it's actually reversible. We can simulate any classical circuit reversibly using NOT, CSWAP and CNOT. One of the basic questions in quantum algorithms is how to create interesting superpositions to exploit the exponential power of quantum systems. And the key is quantum Fourier sampling. Bernstein-Vazirani and through Simon's algorithm QC violates extended Church-Turing thesis.

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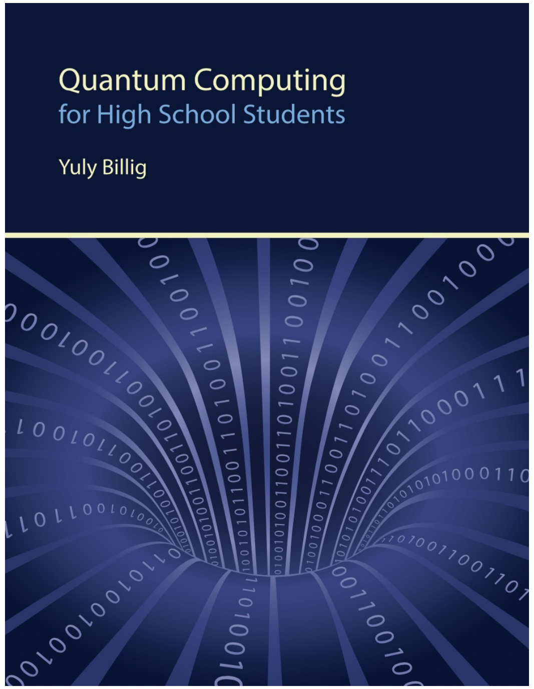
25 Tue July 26 Lecture 16: Supremacy (Advantage)
26 Wed July 27 Assignment 8.1
27 Thu July 28 Assignment 8.2
28 Fri July 29 Final Exam

We now get right to the heart of our discussion about quantum algorithms and we talk about the quantum factoring algorithm and the Quantum Fourier Transform (QFT, the workhorse of quantum algorithms).



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In 1994, Peter Shor discovered a quantum algorithm which will allow one to break cryptography used today in Internet communications, once large scale quantum computers become a reality. Rigorous exposition of Shor's algorithm is the central goal of this book.

Proper description of quantum mechanics requires complex numbers and complex vector spaces. In order to make presentation of the theory more accessible, we avoid using complex numbers in this book. This simplification still allows us to convey all significant ideas of quantum computing, while making it much easier to visualize quantum states and quantum gates. In the last chapter, we briefly touch upon the aspects of the theory left outside the scope of this book.

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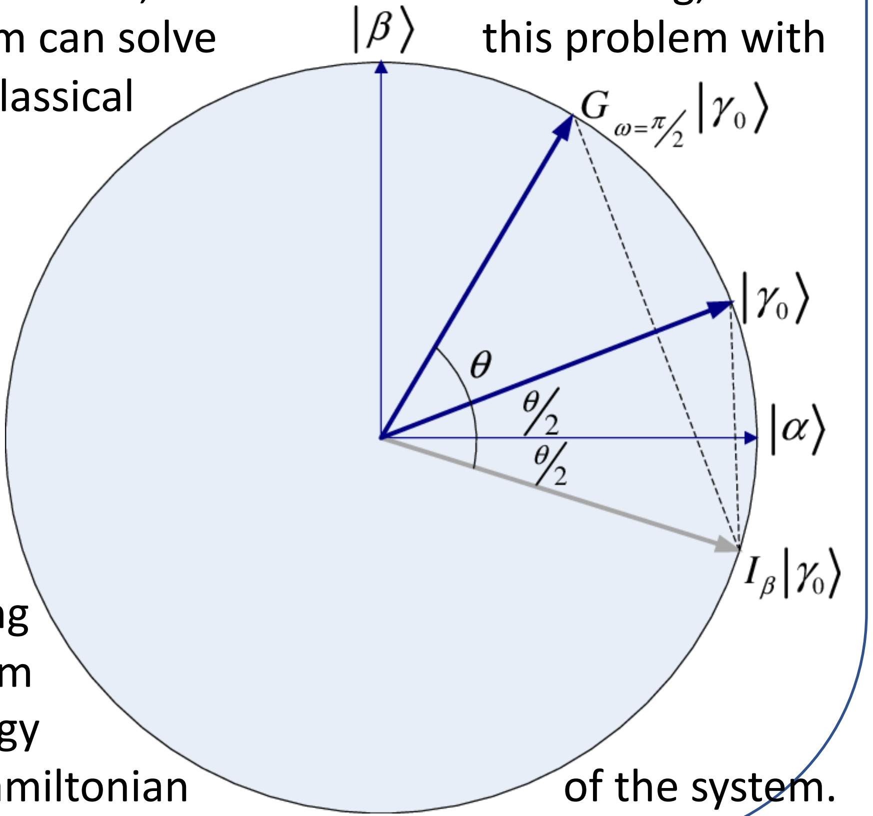
Searching for a needle in a haystack. Reverse phone book problem. Why is it an important problem? There's a whole class of problems called NP-complete problems, which are extremely important problems from a computational viewpoint not only in computer science but also in every discipline of science, physics, chemistry, etc. A quintessential such problem is satisfiability. There are thousands, tens of thousands of problems which are computationally equivalent to satisfiability. If you solve one of these problems quickly, you can solve all of them quickly. These are problems that are classically believed to be hard; at least as hard as factoring, or much harder. Grover's algorithm can solve this problem with a quadratic speedup over the classical algorithm. Phase inversion and inversion around the mean. Implementation of Grover's algorithm. On the right we see geometric visualization of a single Grover iteration. An observable for a k-level system is a k by k Hermitian matrix (a fancy way of specifying an orthonormal basis). Quantum equation of motion has energy observable H called the Hamiltonian of the system.



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Now we are ready to understand how qubits are implemented. So far, our model for a qubit is that it's implemented using the ground and excited states of an electron in a hydrogen atom. So what we did was we assumed that the states of an electron in a hydrogen atom are quantized. So what we're going to do is we'll actually show how this quantization emerges naturally. And we'll use a very simple toy model for a hydrogen atom. We abstract this problem as a one-dimensional problem, we have an electron free to move around on the line, except that it's confined to the segment of length 1. And now we want to study (a) how to describe the state of the electron. But this electron is allowed to be anywhere on this line (continuous quantum states). So how do we describe that state? The second question we'll ask is, what is that the Hamiltonian? We said it's a free particle. Once we have the Hamiltonian, we want to understand what are the energy eigenstates, i.e., the eigenstates of the Hamiltonian? And this is where we'll see the quantization emerge naturally. Finally, we'll see how to implement qubits. We use some of the mechanisms developed in the previous section, Schrödinger's equation for 1D free particle. Next we discuss spin. Elementary particles, like electrons and protons, carry an intrinsic angular momentum, which is called spin. And when the particle charged, like an electron, there's also an associated intrinsic magnetic moment. So an electron acts like a little magnet. This magnetic moment, angular momentum, these are quantized. So the spin can point either up or down. Stern-Gerlach. Bloch sphere. Pauli spin matrices.

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Larmor precession. In the first lecture we we'll talk about how to manipulate spin, that is, how to actually implement quantum gates on a spin qubit. First we understand what a quantum gate looks like on the Bloch sphere because in order to understand how the spin qubit interacts with the external world, we have to locate the spin qubit on a Bloch sphere. So the answer says that a quantum gate, or a unitary transformation, on a qubit state is performed by a rotation of a Bloch sphere about some axis. So, we pick some axis and we just rotate this Bloch sphere through some angle about this axis. We first see how we can use Larmor precession to implement an arbitrary single cubit gate on a spin. It turns out this is not a really practical way of implementing a quantum gate, because the B-field required for this is very large. And it's difficult in the lab to actually move this field, to change its direction, rapidly as we want for quantum gates. So as it turns out there's a different way of implementing single cubit quantum gates due to an effect called spin resonance, which gives much finer control Now, what we basically have as a model for a quantum computer is a set of qubits which are being controlled through an external classical computer. We are trying to control our qubits externally, by some external means, so we are interacting with the qubits from that side. And this gives us a lot of flexibility, this classical computer then represents the programming of the quantum computer. This is what makes it all really feasible. But then, this seems to contradict goal number two, which is to isolate our qubits. This kind of inadvertent measurement of our quantum system is called decoherence (major challenge). Error mitigation and control.