

A Physicist Peeks into Quantum Architecture

Fractured Fairy Tales about Quantum Computer Engineering

04 October 2019

1 Computing

- Tall Tales of Truth
- Stacking Layers

2 Quantum Computing

- Surveying the Strata
- Physical Basis
- Quantum Computer Engineering

3 References

A Bit of a Story: Evolving a New Computing Technology

- single-bit memory

A Bit of a Story: Evolving a New Computing Technology

- single-bit memory
- extend storage lifetime

A Bit of a Story: Evolving a New Computing Technology

- single-bit memory
- extend storage lifetime
- improve storage methods

A Bit of a Story: Evolving a New Computing Technology

- single-bit memory
- extend storage lifetime
- improve storage methods
- enhance manipulation capabilities

A Bit of a Story: Evolving a New Computing Technology

- single-bit memory
- extend storage lifetime
- improve storage methods
- enhance manipulation capabilities

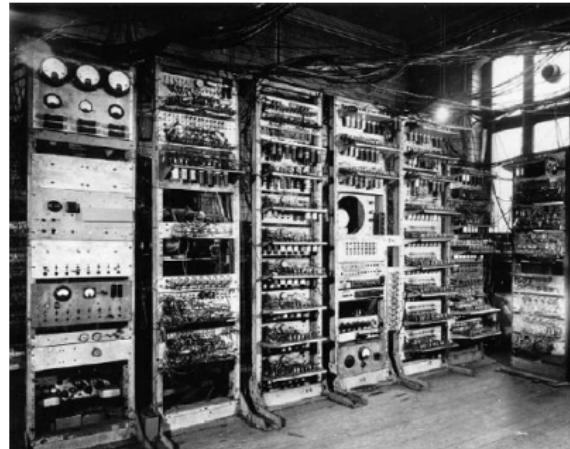
- perform computation

A Bit of a Story: Evolving a New Computing Technology

- single-bit memory (1946)
 - 1 s base lifetime of phosphor on cathode ray tube (CRT)
- extend storage lifetime (1946)
 - read charge and rewrite value (regeneration)
- improve storage methods (1947)
 - dot-dash and focus-defocus allows 2048 bits stored on 6-inch CRT
- enhance manipulation capabilities (1948)
 - *design computer around CRT storage device*
 - automate bit reset at electronic speeds
 - permit random access memory
 - store 32 32-bit words (1024 bits total), values and instructions
- perform computation (1948)
 - only one arithmetic function in hardware, subtraction
 - application was to find *highest proper divisor* of a number x
 - $x = 2^{18}$ took 52 minutes to compute (answer: 131072)

from history-computer.com [1]

Baby (the SSEM) and its Program



The Small-Scale Experimental Machine (SSEM) computing system nicknamed *Baby* started with a glowing bit on a screen controlled by an electron beam and grew to a vacuum tube-filled system to control 1024 bits for a simple calculation

1947 A8
Kilburn Highest Factor Routine (united)

function	C	26	26	27	time	012345	1345
-26 C	-G ₁	-	-	-	1	000111	010
< 0 26		-G ₁			2	010111	110
-26 G C	G ₁				3	010111	010
< 0 27		-G ₁	G ₁	4	110111	110	
-23 5 C	a	T ₂₆	-G ₁	G ₁	5	111011	010
dub 27 a=15					6	110111	001
dub 26					7	-	011
add 26 25					8	001101	100
dub 26	T _n				9	010111	001
c 5 25	T _n				10	100111	110
-26 GC					11	100111	010
14C					12	-	011
stop	0	0	-G ₁	G ₁	13	-	111
-26 5 C	T _n	T _n	-G ₁	G ₁	14	010111	010
dub 21	T _n	T _n	-G ₁	G ₁	15	010111	001
< 0 27	G ₁	T _n	G ₁	T _n	16	110111	110
-27 5 C	T _n	T _n	G ₁	T _n	17	110111	010
< 0 26		-G ₁	T _n	T _n	18	010111	110
-22 5 G	T _n	-G ₁	T _n	T _n	19	010111	001

func	func
20 -3	1011110
21 1	10000
22 4	000100

or 10100

Baby's first program — 7 instructions to find highest proper divisor of a number

Story of a Killer App

- devise a better way to compute

Story of a Killer App

- devise a better way to compute
- secure funding

Story of a Killer App

- devise a better way to compute
- secure funding
- build a complex system

Story of a Killer App

- devise a better way to compute
- secure funding
- build a complex system
- incorporate fault tolerance

Story of a Killer App

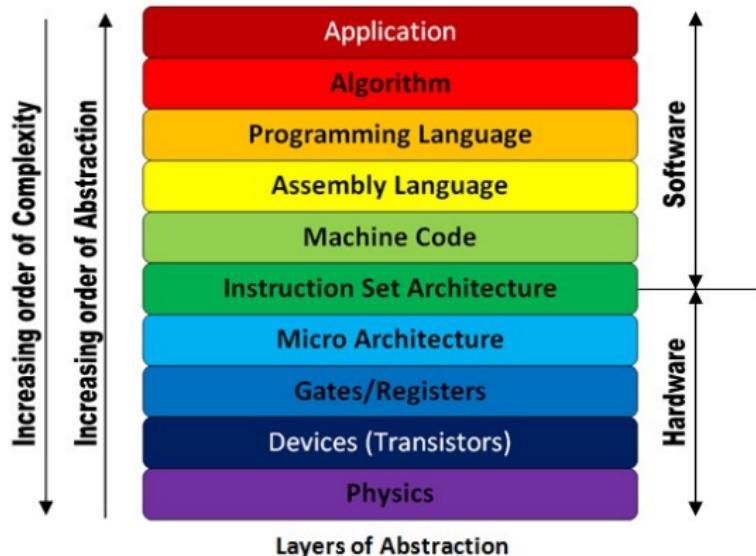
- devise a better way to compute
- secure funding
- build a complex system
- incorporate fault tolerance
- execute application

Story of a Killer App

- devise a better way to compute (1942)
 - “physicist [...] proposed an all-electronic calculating machine”
- secure funding (1943)
 - \$7M (2018 dollars) from Army Ordnance Corps R&D Command
- build a complex system (1945)
 - Electronic Numerical Integrator and Computer (ENIAC)
 - 18 000 vacuum tubes, $30\text{ m} \times 2.4\text{ m} \times 0.9\text{ m}$, 27 ton, 150 kW to operate
 - clock speed of $200\text{ }\mu\text{s}$
- incorporate fault tolerance (1945)
 - manual replacement (15 min) of vacuum tubes \approx every 2 day
 - operate below maximum thresholds
- execute application (1945–1955)
 - artillery ballistic tables
 - single-trajectory calculation time reduction from 20 hr to 30 s

from various sources [3, 4]

A Classical Computing Stack



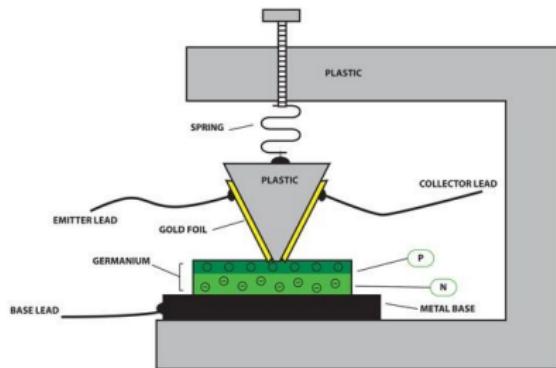
Outside-in

- ① Applications
- ② Physical foundations
- ③ Building between the extremes

Image from StackExchange <https://electronics.stackexchange.com/q/353915>

Bits are Mother Nature's Children

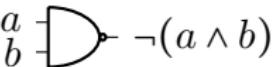
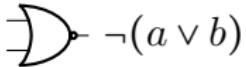
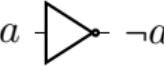
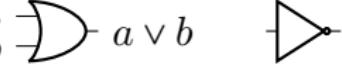
Devices, like the transistor, behave based on physical principles. Engineers and scientists use their understanding of Mother Nature to craft useful things.



images from Computer History Museum [12]

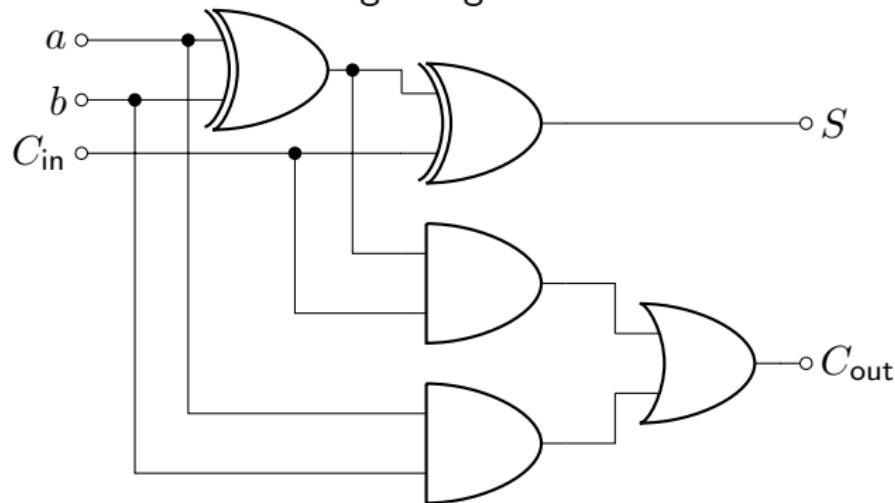
Gates and Universal Computing

Gates are one way to represent actions within a circuit, modifying inputs to output. Some logic gate sets are known to be Turing complete — capable of universal computing [6, 7].

- NAND  $\neg(a \wedge b)$
- NOR  $\neg(a \vee b)$
- AND with NOT  $a \wedge b$  $\neg a$
- OR with NOT  $a \vee b$ 
- AND with OR with NOT 

Simple Arithmetic Circuit: Add with Carry

Too much to add two bits? No — marvelous electronic devices are borne from such humble beginnings



Speaking its Language for Computational Conversations

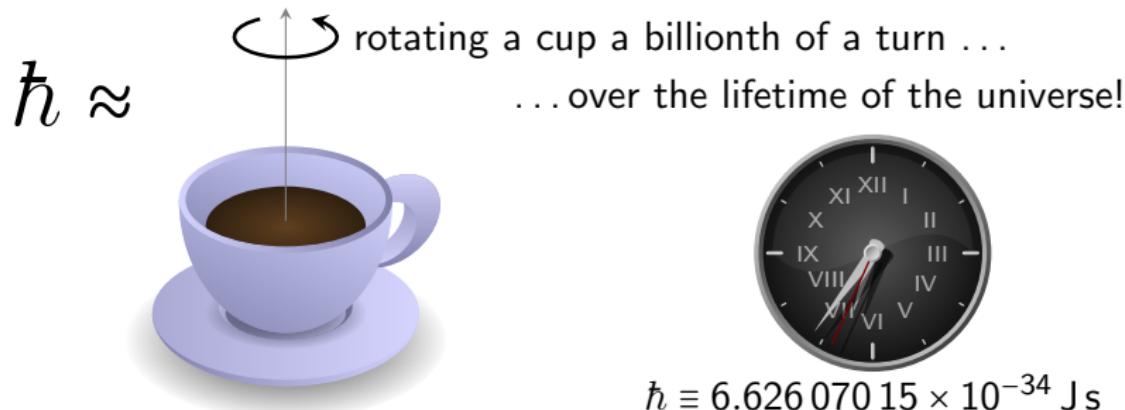
High-level, expressive language is translated to more primitive operations and to *supported* instructions for a given system to carry out and return results.

```
def simpleFunction(inValOne, inValTwo):
    # set x and y to the inputs
    x = copy(inValOne)
    y = copy(inValTwo)
    # perform operation on the inputs (e.g. add)
    operate(x, y, out=z)
    # obtain the output of the operation
    s = measure(z)
    return s

# Example script
out = simpleFunction(2,2)
print('result = {}'.format(out)) # Result = a reproducible value
```

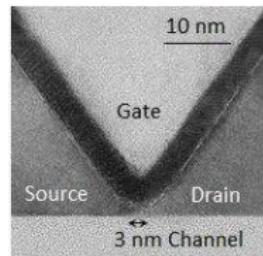
Planck's Call to Action

The difference between classical physics and quantum physics is Planck's constant \hbar (technically, $i\hbar$).

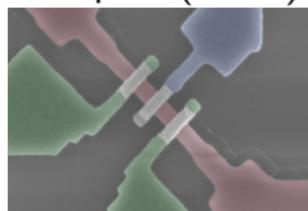


Finding the Electron in Electronics

Transistor sizes from centimeters to nanometers



Single electron transport (NIST)



Hello Planck

orbit angular momentum of electron in lowest energy state of hydrogen is $\sqrt{2}\hbar$

images from various sources [12, 21, 22, 23, 24]

Peering Into the Future of Quantum Information

History does not repeat itself, but it often rhymes.

— *Anonymous (often misattributed to Mark Twain [5])*

A Qubit of a Story

- generalize Shannon information theory for quantum systems

A Qubit of a Story

- generalize Shannon information theory for quantum systems
- envision computation with quantum resources

A Qubit of a Story

- generalize Shannon information theory for quantum systems
- envision computation with quantum resources
- develop algorithms with quantum-advantage over classical

A Qubit of a Story

- generalize Shannon information theory for quantum systems
- envision computation with quantum resources
- develop algorithms with quantum-advantage over classical
- demonstrate quantum component

A Qubit of a Story

- generalize Shannon information theory for quantum systems
- envision computation with quantum resources
- develop algorithms with quantum-advantage over classical
- demonstrate quantum component
- perform computation

A Qubit of a Story

- generalize Shannon information theory for quantum systems (1976)
 - n quantum bits (qubits) access more information than n bits
 - at most n classical bits can be *output* from n qubits
- envision computation with quantum resources (1980–1985)
 - universal quantum computer justified (Deutsch)
- develop algorithms with quantum-advantage over classical (1990s)
 - prime factorization (Shor's algorithm)
 - database search (Grover's algorithm)
- demonstrate quantum component (1995)
 - controlled not gate with trapped ions
- perform computation (2016)
 - *probabilistic* factorization of 15 *without foreknowledge* of factors

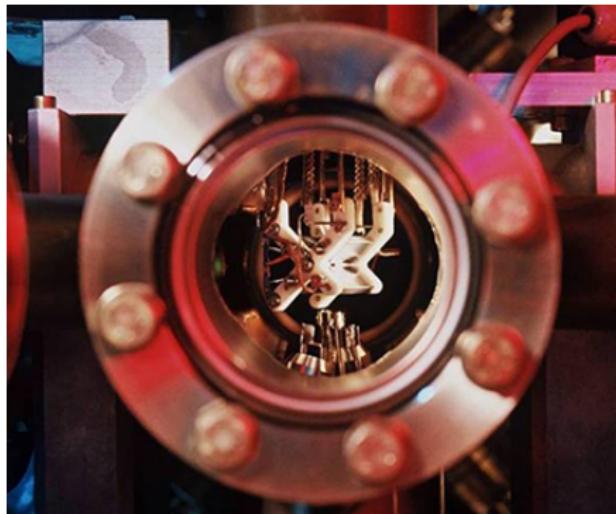
various sources [15, 16]

Sisyphus at the Gate of Five Ions

Laboratory-sized quantum gate using bulk optics

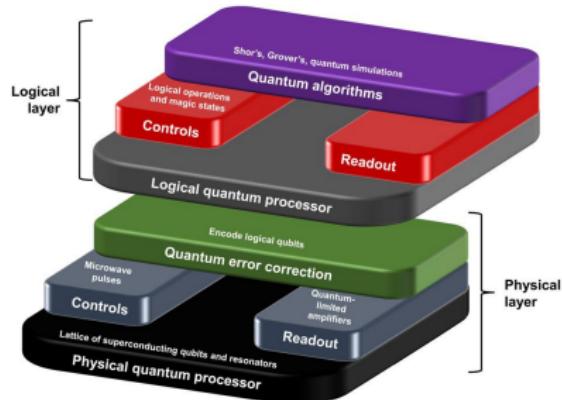


Demonstrating a controlled not gate using trapped ions (NIST) [18]

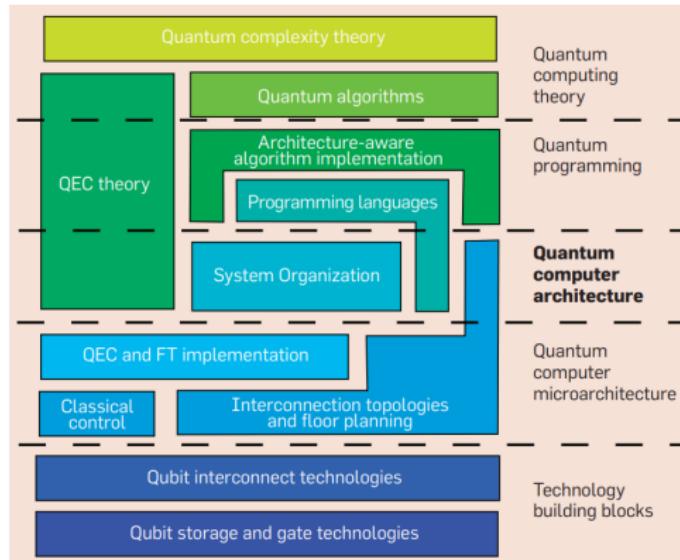


Five ion qubits used Shor's algorithm to factor the number 15 [13]

Quantum Computing Stacks



A notional stack for quantum computers from IBM [19]

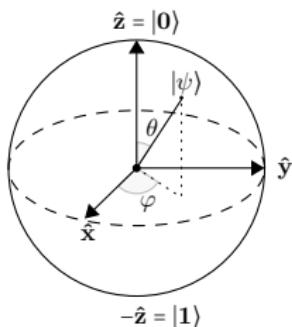


A more detailed view of quantum computer architecture from the Association for Computing Machinery [2]

A Superposition of What?

In the abstract, a qubit is a complex, linear superposition of two (exclusive and complete) states of a system in a two-dimensional Hilbert space — **not a vector in three dimensions**

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \alpha\begin{pmatrix} 1 \\ 0 \end{pmatrix} + \beta\begin{pmatrix} 0 \\ 1 \end{pmatrix}$$



Atomic (spin)

$$|\psi\rangle_{\text{electron-spin}} = \alpha|\uparrow\rangle_{\text{el}} + \beta|\downarrow\rangle_{\text{el}}$$

$$|\psi\rangle_{\text{nuclear-spin}} = \alpha|\uparrow\rangle_{\text{nuc}} + \beta|\downarrow\rangle_{\text{nuc}}$$

Photonic (polarization and number)

$$|\psi\rangle_{\text{photon-pol}} = \alpha|\rightarrow\rangle_{\text{ph}} + \beta|\leftarrow\rangle_{\text{ph}}$$

$$|\psi\rangle_{\text{photon-num}} = \alpha|0\rangle_{\text{ph}} + \beta|1\rangle_{\text{ph}}$$

Electronic (charge, current)

$$|\psi\rangle_{\text{chg}} = \alpha|0\rangle_{\text{chg}} + \beta|2e\rangle_{\text{chg}}$$

$$|\psi\rangle_{\text{curr}} = \alpha|\circlearrowleft\rangle_{\text{curr}} + \beta|\circlearrowright\rangle_{\text{curr}}$$

The Delicate, Competitive Dance of Quantum Information

- Isolation

- Generated quantum states are fragile
- Noise destroys, or at least complicates, their coherent nature
- Segregation from environment and other systems is paramount . . .

- Interaction

- . . . except splendid isolation leaves no means for control
- Manipulation and detection of quantum states is necessary for utility
- Quantum systems need to influence one another and another and . . .

- Interconnection

- . . . a completely other
- Collections of heterogeneous quantum systems must inter-communicate quantum information

Pardigms Lost

- Measurement is not deterministic
 - Probabilistic results
 - *Logic structure of quantum physics is different*
 - $X \wedge P \wedge X \neq X \wedge X \wedge P$
- Short lifetimes of stability
 - transistor: $\sim 10^9$ yr $\approx 10^{16}$ s
 - qubit: $\sim 10^{-3}$ s
 - *Ultra-fast operation of quantum devices is necessary*
- No-cloning theorem
 - *An arbitrary quantum state cannot be copied*

Paradigms Gained

Teleportation, increased correlations, computational speedup, etc.

Quantum Gates and Universal Quantum Computing

H, S, T , and CNOT are a universal set of quantum gates

Phase

$$|1\rangle \xrightarrow{S} e^{i\pi/2} |1\rangle$$

$$\begin{pmatrix} 1 & 0 \\ 0 & i \end{pmatrix}$$

Hadamard

$$|0\rangle \xrightarrow{H} (|0\rangle + |1\rangle)/\sqrt{2}$$

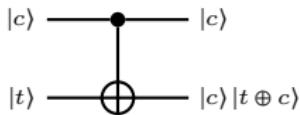
$$\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

T (also known as $\pi/8$)

$$|1\rangle \xrightarrow{T} e^{i\pi/4} |1\rangle$$

$$\begin{pmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{pmatrix} = e^{i\pi/8} \begin{pmatrix} e^{-i\pi/8} & 0 \\ 0 & e^{i\pi/8} \end{pmatrix}$$

CNOT (two-qubit gate)



$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Get Sum Mod Quantum

Build-up of quantum circuit to compute $(a + b) \bmod N$

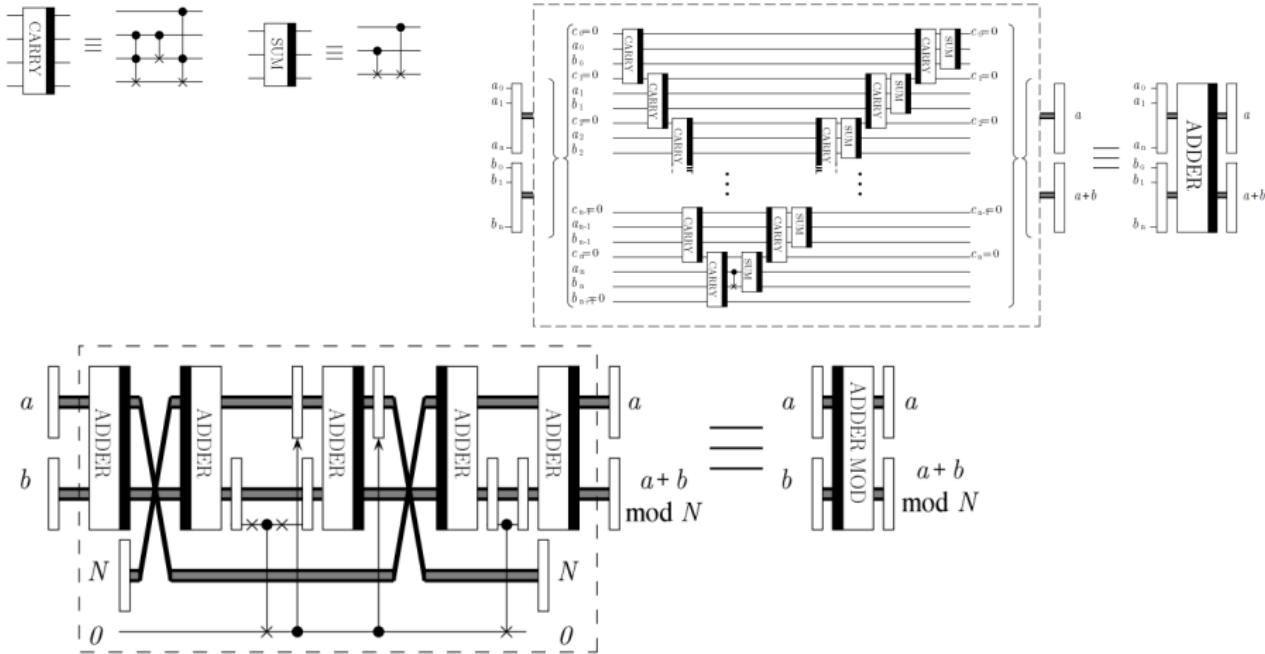
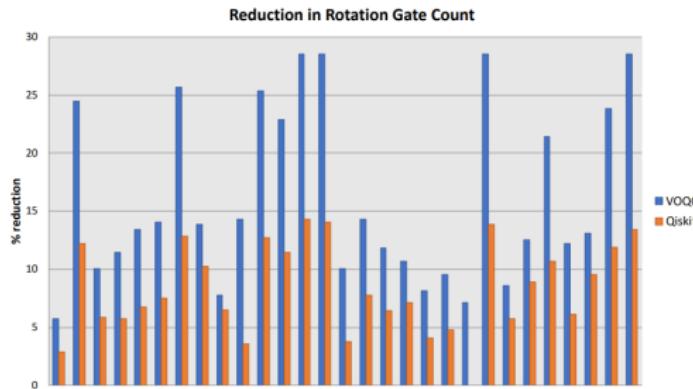
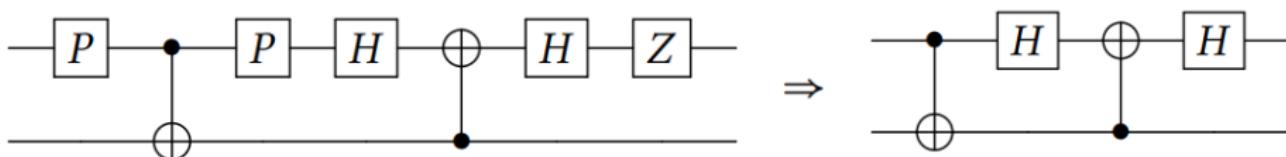


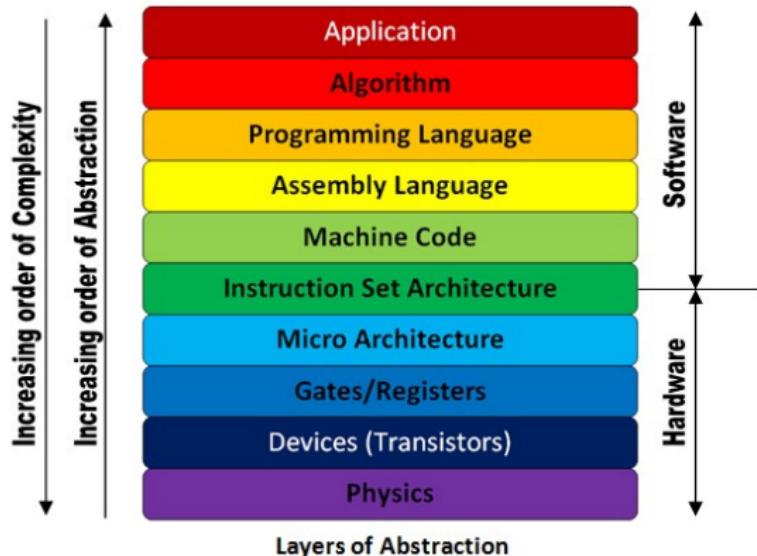
image credit [29]

Circuit Optimization for Application

Optimization takes advantage of allowed transformations (e.g. commutation and cancellation) to reduce gate count, decrease circuit depth, accommodate gate set, etc.



A Classical Computing Stack



Outside-in

- ① Applications
- ② Physical foundations
- ③ Building between the extremes

Image from StackExchange <https://electronics.stackexchange.com/q/353915>

Applications of Quantum Information

Sensing

- spatial measurements (e.g. translation, rotation)
- metrology of physical quantities (e.g. electric field, gravity)
- imaging (e.g. ghost imaging, computational imaging)

Computing

- factor prime numbers (e.g. crack encryption)
- database search
- optimization (e.g. traveling salesman problem)
- machine learning

Communication

- provably-secure key generation and distribution (e.g. cryptography)
- network security using untrusted nodes
- transaction protection (e.g. financial, voting)
- collective exposure (e.g. secret sharing)
- non-repudiation (e.g. contracts)

Simulation

- chemical reactions
- genetics
- pharmaceuticals

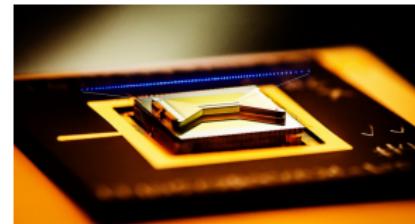
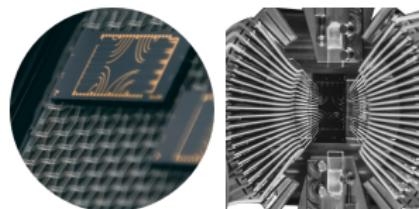
Quantum Hardware

Quantum-specific aspects constitute a small portion of a system



IBM Q dilution refrigerator
(15 mK) and interface
wiring to 50
superconducting charge
qubits (transmons) [9]

Xanadu cluster state
photonic computer on chip
(electronics and controls
not shown) [10]

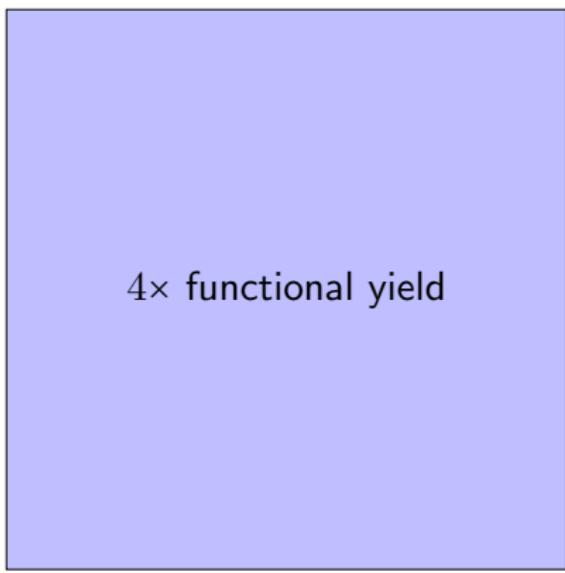
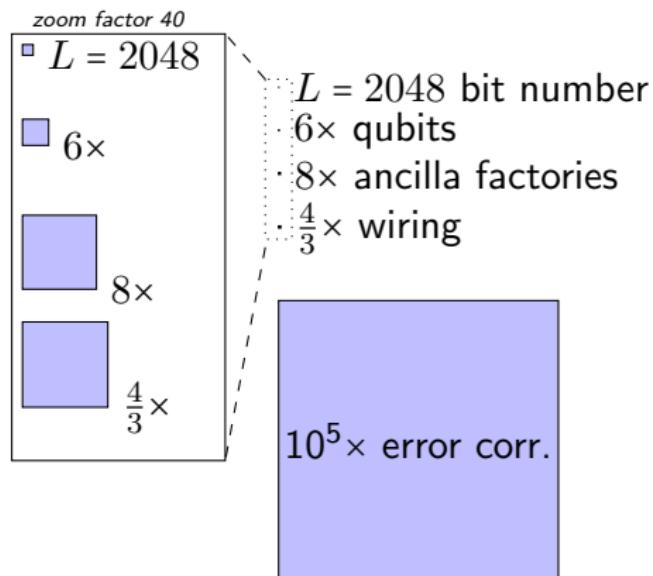


IonQ and Joint Quantum
Institute atomic ion trap
(laser cooling, atomic
manipulation controls, and
electronics not shown) [11]

Problem-Specific Qubit Scaling

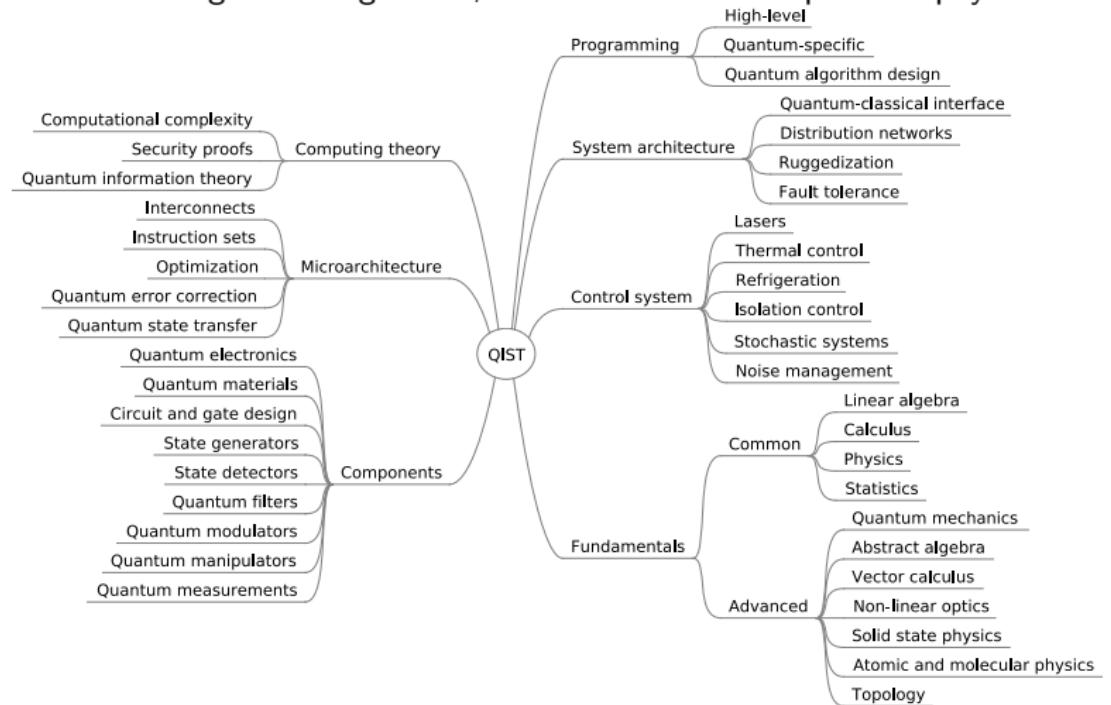
Problem: Factor 2048-bit number

Solution: Design device for Shor's algorithm with logical qubits, ancilla generation, connections, surface code error correction, and imperfect device yield [2]



Ready to be QIST

Contributors to Quantum Information Science and Technology (QIST) will come together from a range of backgrounds, few of which will be quantum physics.



Omne rerum principia parva sunt¹

Quantum theory provides us with a striking illustration of the fact that we can fully understand a connection though we can only speak of it in images and parables.

— Werner Heisenberg in *Physics and Beyond: Encounters and Conversations*

¹All beginnings are small

Further Reading

- Quantum Computing Reports, Tools [25]
- Quantum Programming (Wikipedia) [26]
- Quantum Computing: An Overview Across the System Stack [27]
- Full-Stack, Real-System Quantum Computer Studies [28]
 - “the purpose of our work is to build insights in how architecture and compiler design choices can best support the different technologies”
- Quantum Networks for Elementary Arithmetic Operations [29]
- Automated optimization of large quantum circuits with continuous parameters [30]

Abstract

In analogy with a classical computing stack, aspects of quantum information processing are explored from physical underpinnings of devices to application programming. Particular emphasis is given to the subsystems between these extremes regarding challenges to realize them such as scaling and error correction. Potential applications that could benefit from quantum processing and the skills of computer engineering are discussed, especially those that might be considerably more near-term than a universal quantum computer. As Tank said in ‘Matrix’ [31], “It’s a very exciting time. We got a lot to do. We gotta get to it.”

Bibliography I

- [1] *SSEM (Small Scale Experimental Machine)*,
<https://history-computer.com/ModernComputer/Electronic/SSEM.html>
- [2] *A Blueprint For Building a Quantum Computer*, Rodney Van Meter and Clare Horsman, Communications of the ACM, Vol. 56 No. 10, Pages 84-93, (2013) <https://m-cacm.acm.org/magazines/2013/10/168172-a-blueprint-for-building-a-quantum-computer/fulltext>
- [3] *ENIAC (Birth of the Computer)*, Computer History Museum,
<https://www.computerhistory.org/revolution/birth-of-the-computer/4/78>

Bibliography II

- [4] *Crystal Fire: The Invention of the Transistor and the Birth of the Information Age*, Mitchael Rioradan and Lillian Hoddeson, W.W. Norton and Company, (1997)
- [5] *History Does Not Repeat Itself, But It Rhymes*, Quote Investigator, <https://quoteinvestigator.com/2014/01/12/history-rhymes>
- [6] *A set of five independent postulates for Boolean algebras, with application to logical constants*, Henry Maurice Sheffer, Trans. Amer. Math. Soc. 14 481-488, (1913)
- [7] *Universal Logic Gates*, <https://www.electronics-tutorials.ws/logic/universal-gates.html>
- [8] *Quantum Computation and Quantum Information*, Michael A. Nielsen and Isaac L. Chuang, Cambridge University Press, 2000

Bibliography III

- [9] *The future is quantum*, IBM Research Editorial Staff, IBM Research Blog, (2017), <https://www.ibm.com/blogs/research/2017/11/the-future-is-quantum>
- [10] Xanadu Hardware, date retrieved 2019-09-29,
<https://www.xanadu.ai/hardware/>
- [11] *JQI scientists Monroe and Gorshkov are part of a new, \$15 million NSF quantum computing project*, Joint Quantum Institute, University of Maryland, (2018), <https://jqi.umd.edu/news/jqi-scientists-monroe-and-gorshkov-are-part-new-15-million-nsf-quantum-computing-project>
- [12] *Inventing the Transistor*, Computer History Museum, <https://www.computerhistory.org/revolution/digital-logic/12/273>

Bibliography IV

- [13] *Shor's algorithm is implemented using five trapped ions*, Hamish Johnston, Physics World, (2016), <https://physicsworld.com/a/shors-algorithm-is-implemented-using-five-trapped-ions/>
- [14] *Quantum Information Theory*, Roman Ingarden, Reports on Mathematical Physics, Volume 10, Issue 1, Pages 43-72, (1976)
- [15] *The History and Future of Quantum Information*, Ben P. Stein, National Institute of Standards and Technology, <https://www.nist.gov/history-and-future-quantum-information>
- [16] *Timeline of Quantum Computing*, Wikipedia, date accessed 2019-10-01, https://en.wikipedia.org/wiki/Timeline_of_quantum_computing
- [17] *Quantum Algorithm Zoo*, <https://quantumalgorithmzoo.org>

Bibliography V

- [18] *Quantum Logic Gates*, NIST,
<https://www.nist.gov/topics/physics/introduction-new-quantum-revolution/quantum-logic-gates>
- [19] *Building logical qubits in a superconducting quantum computing system*, Jay M. Gambetta, Jerry M. Chow, and Matthias Steffen, npj Quantum Information volume 3, Article number: 2 (2017),
<https://www.nature.com/articles/s41534-016-0004-0>
- [20] *A Verified Optimizer for Quantum Circuits (draft)*, Kesha Hietala, Robert Rand, Shih-Han Hung, Xiaodi Wu, and Michael Hicks,
http://www.cs.umd.edu/~rrand/voqc_draft.pdf
- [21] *The Lost History of the Transistor*, Michael Riordan, IEEE Spectrum, (2004), <https://spectrum.ieee.org/tech-history/silicon-revolution/the-lost-history-of-the-transistor>

Bibliography VI

- [22] , *Nanoelectronics*, U.S. Naval Research Laboratory Electronics Science and Technology Division, <https://www.nrl.navy.mil/estd/research-highlights/nanoelectronics>
- [23] , *Success in operation of transistor with channel length of 3 nm*, Advanced Industrial Science and Technology, (2013), <https://phys.org/news/2013-02-success-transistor-channel-length-nm.html>
- [24] , *NIST-on-a-Chip: Quantum-Based Electrical Standards - Current*, NIST Physical Measurement Laboratory, <https://www.nist.gov/pml/nist-chip-quantum-based-electrical-standards-current>
- [25] *Tools (for working with quantum computation)*, <https://quantumcomputingreport.com/resources/tools/>

Bibliography VII

- [26] *Quantum computing*, Wikipedia, date retrieved 28 Sep 2019
https://en.wikipedia.org/w/index.php?title=Quantum_computing&oldid=918292451
- [27] *Quantum Computing: An Overview Across the System Stack*, Saloni Resch and Ulya R. Karpuzcu, (2019)
<https://arxiv.org/abs/1905.07240>
- [28] *Full-Stack, Real-System Quantum Computer Studies: Architectural Comparisons and Design Insights*, Prakash Murali, Norbert Matthias Linke, Margaret Martonosi, Ali Javadi Abhari, Nhung Hong Nguyen, and Cinthia Huerta Alderete, (2019)
<https://arxiv.org/abs/1905.11349>

Bibliography VIII

- [29] *Quantum Networks for Elementary Arithmetic Operations*, V. Vedral, A. Barenco and A. Ekert, (1995)
<https://arxiv.org/abs/quant-ph/9511018>
- [30] *Automated optimization of large quantum circuits with continuous parameters*, Yunseong Nam, Neil J. Ross, Yuan Su, Andrew M. Childs and Dmitri Maslov, npj Quantum Information volume 4, Article number: 23 (2018)
<https://www.nature.com/articles/s41534-018-0072-4>
- [31] *Matrix* movie written and directed by The Wachowskis, (1999)