A Physicist Peeks into Quantum Architecture

Fractured Fairy Tales about Quantum Computer Engineering

04 October 2019

A Bit of a Story: Evolving a New Computing Technology

- single-bit memory

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- single-bit memory
- extend storage lifetime

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A Bit of a Story: Evolving a New Computing Technology

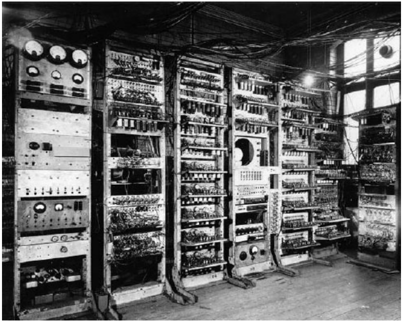
- single-bit memory
- extend storage lifetime
- improve storage methods
- enhance manipulation capabilities
- perform computation

A Bit of a Story: Evolving a New Computing Technology

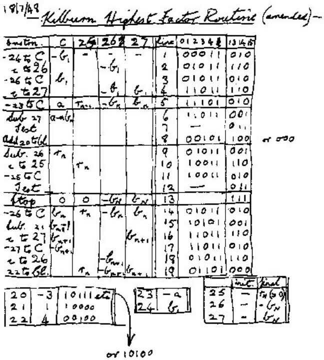
- single-bit memory (1946)
  - 1 s base lifetime of phosphor on cathode ray tube (CRT)
- extend storage lifetime (1946)
  - read charge and rewrite value (regeneration)
- improve storage methods (1947)
  - dot-dash and focus-defocus allows 2048 bits stored on 6-inch CRT
- enhance manipulation capabilities (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: 131 072)

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



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

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- devise a better way to compute
- secure funding

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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 m × 2.4 m × 0.9 m, 27 ton, 150 kW to operate
  - clock speed of 200 μs
- incorporate fault tolerance (1945)
  - manual replacement (15 min) of vacuum tubes ≈ 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

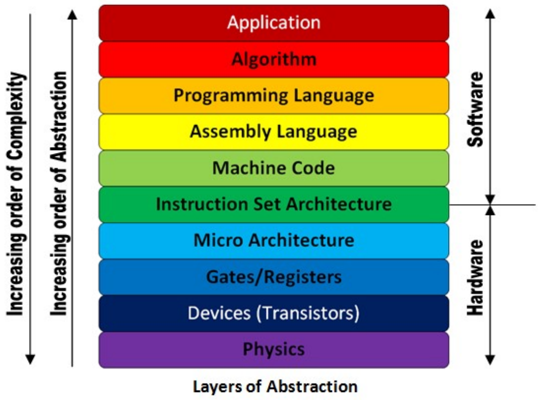


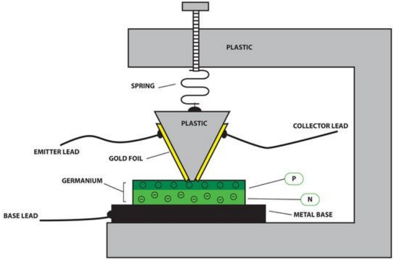
Image from StackExchange `https://electronics.stackexchange.com/q/353915`

Outside-in

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

Bits are Mother Nature's Children

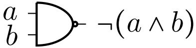
Devices, like the transistor, behave based on physical principles. Engineers and scientists use their understanding of Mother Nature to craft useful things.

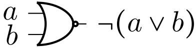


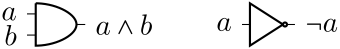
images from Computer History Museum [12]

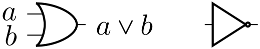
Gates and Universal Computing

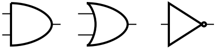
Gates are one way to represent actions within a circuit, modifying inputs to output. Some logic gate sets are known to be Turing complete — capable of universal computing [6, 7].

- NAND 

- NOR 

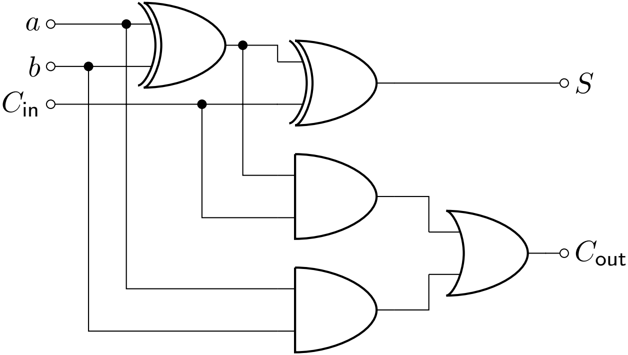
- AND with NOT 

- OR with NOT 

- 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.

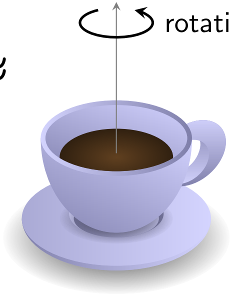
```
def simpleFunction(inValOne, inValTwo):
    # set x and y to the inputs
    x = copy(inValOne)
    y = copy(inValTwo)
    # perform operation on the inputs (e.g. add)
    operate(x, y, out=z)
    # obtain the output of the operation
    s = measure(z)
    return s

# 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, $i\hbar$).

$\hbar \approx$



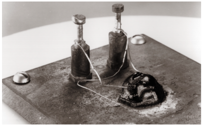
rotating a cup a billionth of a turn ...

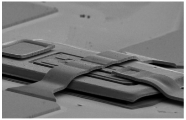
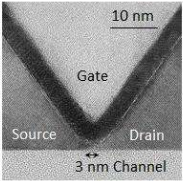
... over the lifetime of the universe!

$\hbar \equiv 6.626\,070\,15 \times 10^{-34}\ \mathrm{J\,s}$

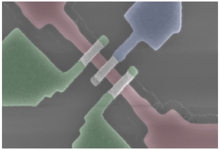
Finding the Electron in Electronics

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

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- envision computation with quantum resources
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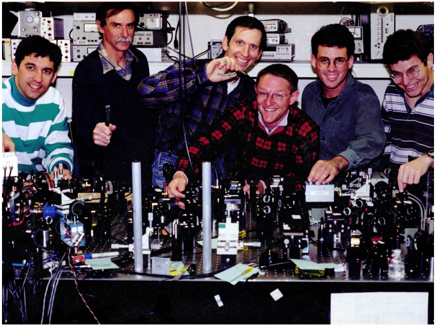
A Qubit of a Story

- generalize Shannon information theory for quantum systems (1976)
  - n quantum bits (qubits) *access* more information that 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

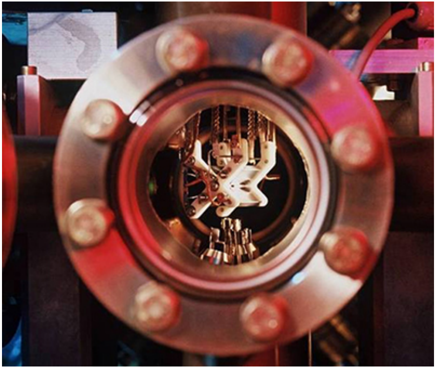
various sources [15, 16]

Sisyphus at the Gate of Five Ions

Laboratory-sized quantum gate using bulk optics

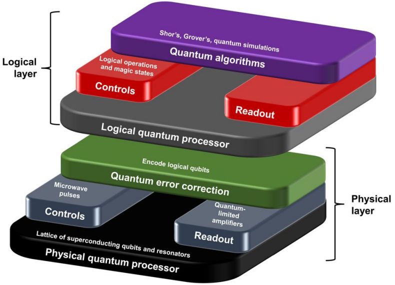


Demonstrating a controlled not gate using trapped ions (NIST) [18]

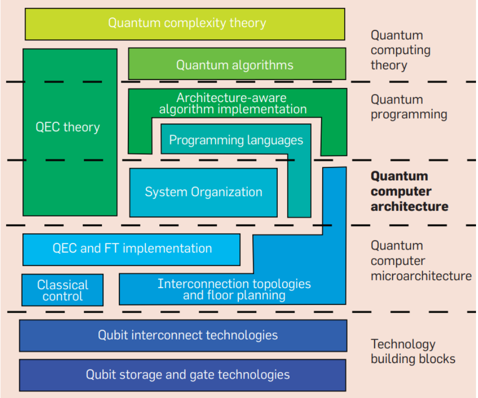


Five ion qubits used Shor's algorithm to factor the number 15 [13]

Quantum Computing Stacks



A notional stack for quantum computers from IBM [19]

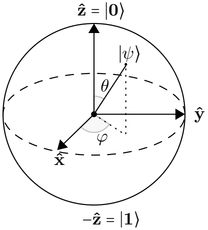


A more detailed view of quantum computer architecture from the Association for Computing Machinery [2]

A Superposition of What?

In the abstract, a qu**b**it 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)

$$|\psi\rangle_{\text{photon-pol}} = \alpha\,|{\nwarrow\!\searrow}\rangle_{\text{ph}} + \beta\,|{\swarrow\!\nearrow}\rangle_{\text{ph}}$$
$$|\psi\rangle_{\text{photon-num}} = \alpha\,|0\rangle_{\text{ph}} + \beta\,|1\rangle_{\text{ph}}$$

Electronic (charge, current)

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

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

$$|1\rangle \; -\!\boxed{S}\!- \; e^{i\pi/2}|1\rangle$$

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

Hadamard

$$|0\rangle \; -\!\boxed{H}\!- \; (|0\rangle + |1\rangle)/\sqrt{2}$$

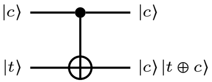
$$\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

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

$$|1\rangle \; -\!\boxed{T}\!- \; e^{i\pi/4}|1\rangle$$

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

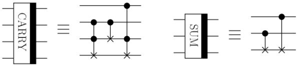
CNOT (two-qubit gate)

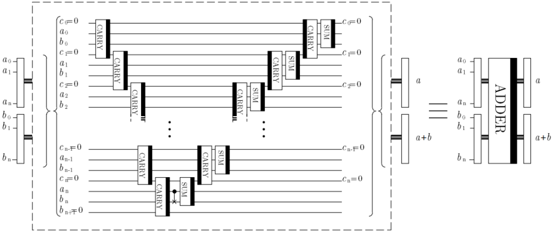


$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Get Sum Mod Quantum

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





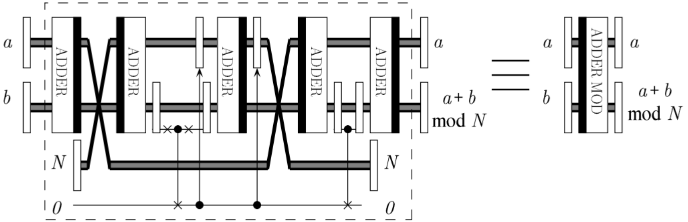
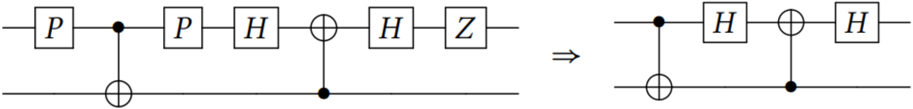
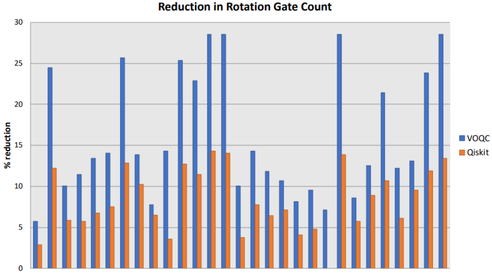


image credit [29]

Circuit Optimation for Application

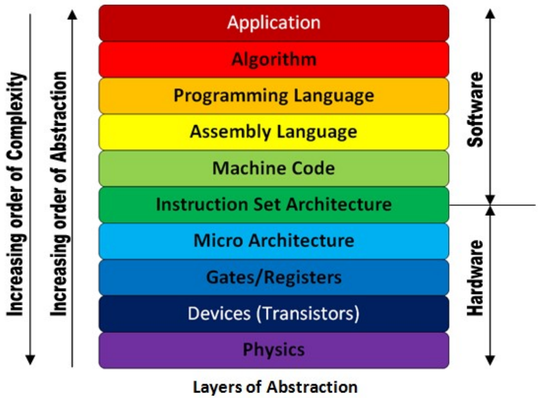
Optimization takes advantage of allowed transformations (e.g. commutation and cancellation) to reduce gate count, decrease circuit depth, accommodate gate set, etc.





Verified Optimizer for Quantum Computing (VOQC) [20]

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

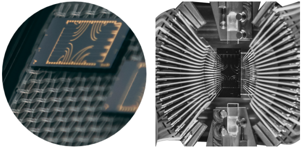
- chemical reactions
- genetics
- pharmaceuticals

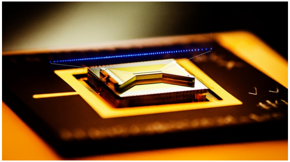
Quantum Hardware

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]

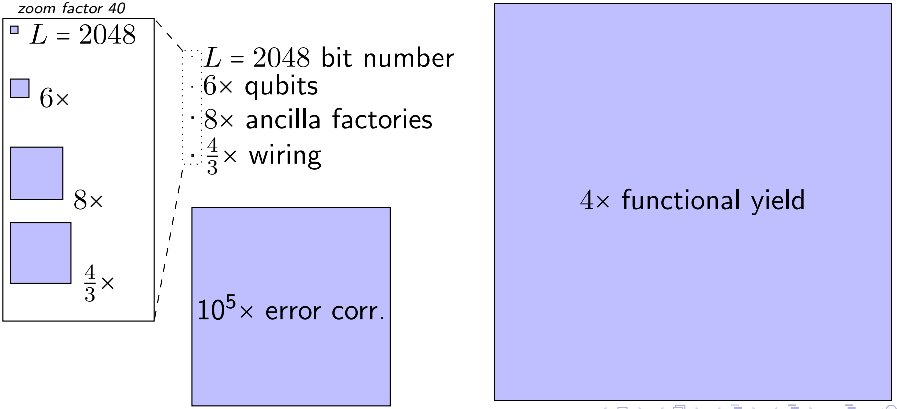




IonQ and Joint Quantum Institute atomic ion trap (laser cooling, atomic manipulation controls, and electronics not shown) [11]

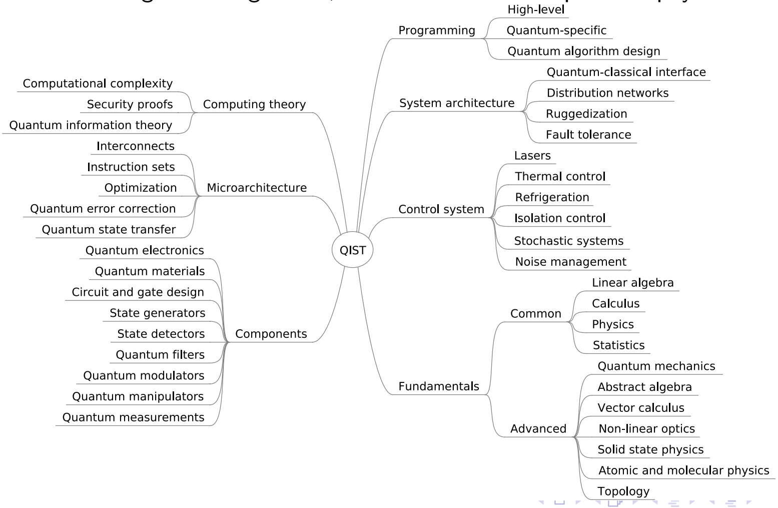
Problem-Specific Qubit Scaling

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 sunt[1]

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 Conversation

[1] All 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."

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