What should we expect from quantum computers?

Nahum Sá
Qiskit Advocate
PhD Student

CBPF

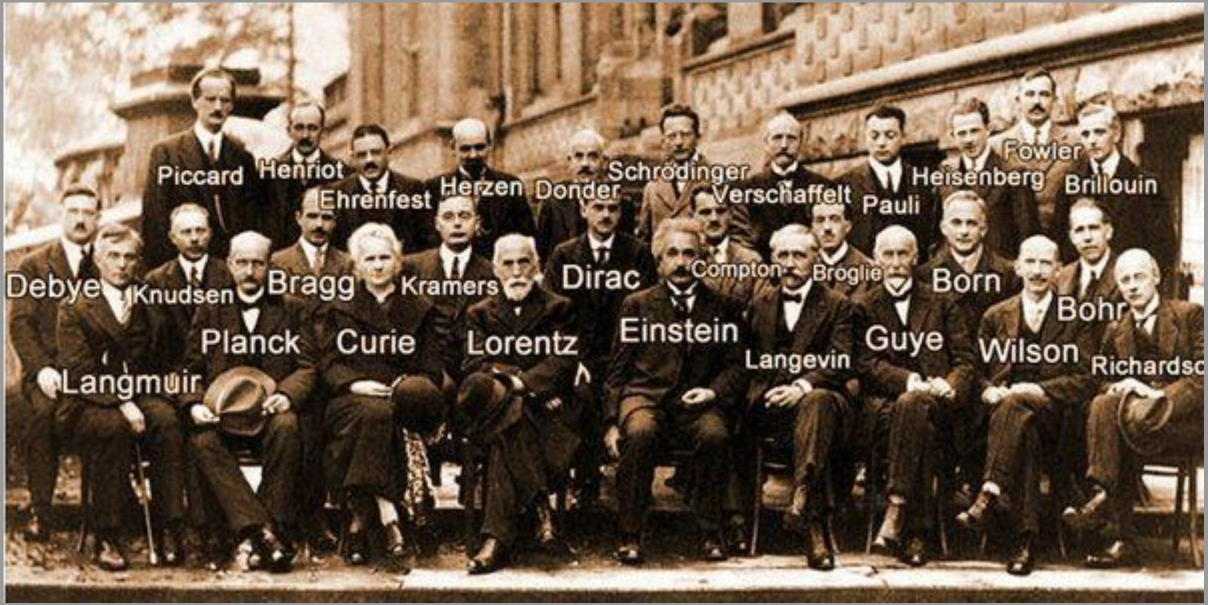
Outline

- History
- Quantum Circuits
- Variational Quantum Algorithms
- How can you contribute?

Introduction

1927

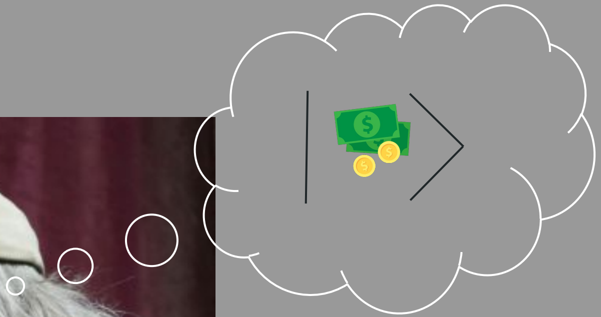
1936

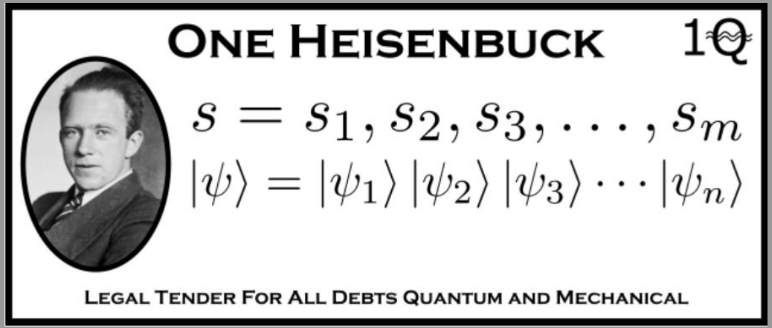


Introduction

1927 1970

Quantum Money

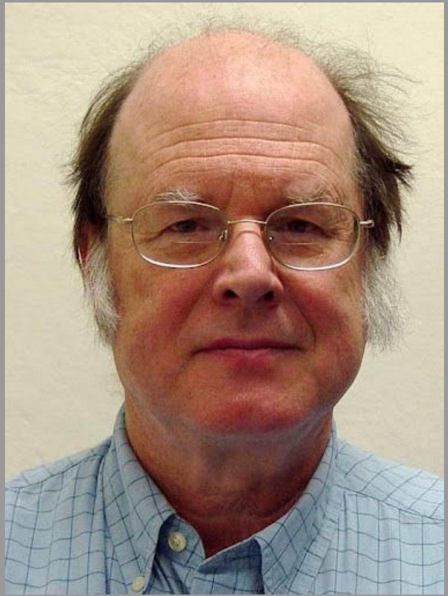




Stephen Wiesner. 1983. Conjugate coding. SIGACT News 15, 1 (Winter-Spring 1983), 78–88. DOI:https://doi.org/10.1145/1008908.1008920

Introduction

1927 1970 1973



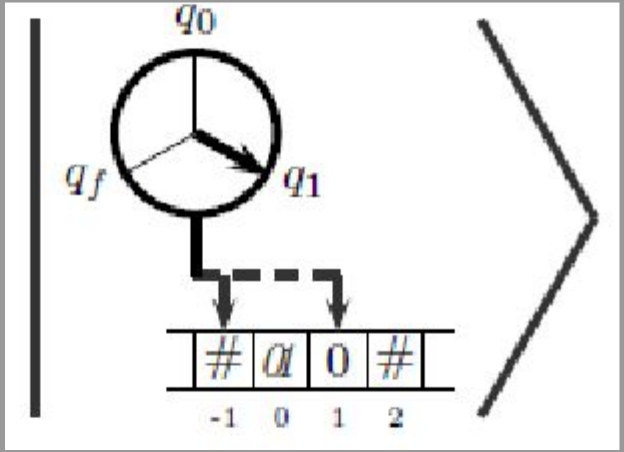
Bennett, C. (November 1973). "Logical Reversibility of Computation" (PDF). IBM Journal of Research and Development. 17 (6): 525–532. doi:10.1147/rd.176.0525.

Holevo, Alexander S. (1973). "Bounds for the quantity of information transmitted by a quantum communication channel". Problems of Information Transmission. 9: 177–183.

Introduction

1927 1970 1973 1980

Paul Benioff



"The Computer as a Physical System: A Microscopic Quantum Mechanical Hamiltonian Model of Computers as Represented by Turing Machines", Paul Benioff, Journal of Statistical Physics, 22, 563, 1980.

Introduction

1927 1970 1973 1980 1981

Physics of Computation Conference Endicott House MIT May 6-8, 1981

1 Freeman Dyson
2 Gregory Chaitin
3 James Crutchfield
4 Norman Packard
5 Panos Ligomenides
6 Jerome Rothstein
7 Carl Hewitt
8 Norman Hardy
9 Edward Fredkin
10 Tom Toffoli
11 Rolf Landauer
12 John Wheeler
13 Frederick Kantor
14 David Leinweber
15 Konrad Zuse
16 Bernard Zeigler
17 Carl Adam Petri
18 Anatol Holt
19 Roland Vollmar
20 Hans Bremerman
21 Donald Greenspan
22 Markus Buettiker
23 Otto Floberth
24 Robert Lewis
25 Robert Suaya
26 Stan Kugell
27 Bill Gosper
28 Lutz Priese
39 Madhu Gupta
30 Paul Benioff
31 Hans Moravec
32 Ian Richards
33 Marian Pour-El
34 Danny Hillis
35 Arthur Burks
36 John Cocke
37 George Michaels
38 Richard Feynman
39 Laurie Lingham
40 Thiagarajan
41 ?
42 Gerard Vichniac
43 Leonid Levin
44 Lev Levitin
45 Peter Gacs
46 Dan Greenberger

Introduction

1927 1970 1973 1980 1981 1982

“Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and it's a wonderful problem, because it doesn't look so easy.”

Simulating Physics with Computers

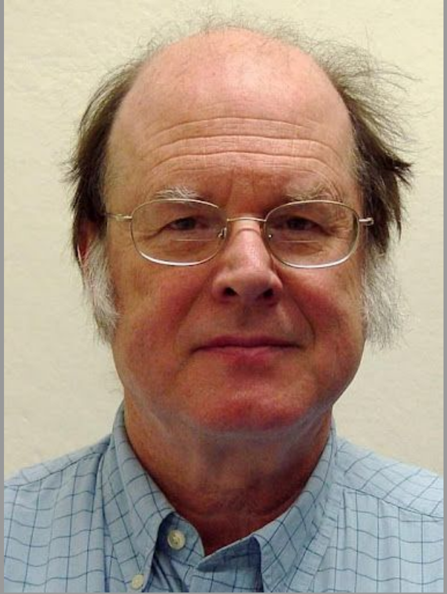
Richard P. Feynman

Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

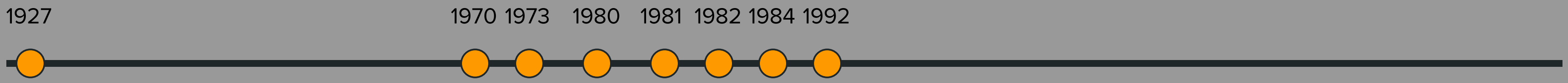
Introduction

1927 1970 1973 1980 1981 1982 1984



Bennett, Charles H.; Brassard, Gilles (1984). "Quantum cryptography: Public key distribution and coin tossing". Theoretical Computer Science. Theoretical Aspects of Quantum Cryptography – celebrating 30 years of BB84. 560: 7–11. doi:10.1016/j.tcs.2014.05.025.

Introduction



David Deutsch & Richard Jozsa (1992). "Rapid solutions of problems by quantum computation". Proceedings of the Royal Society of London A. 439 (1907): 553–558

Introduction

1927 1970 1973 1980 1981 1982 1984 1992 1994

Shor, Peter W. (1997), "Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer", SIAM J. Comput., 26 (5): 1484–1509

Introduction

1927 1970 1973 1980 1981 1982 1984 1992 1994 1995 2021

Egan, L., Debroy, D.M., Noel, C. et al. Fault-tolerant control of an error-corrected qubit. Nature 598, 281–286 (2021). https://doi.org/10.1038/s41586-021-03928-y

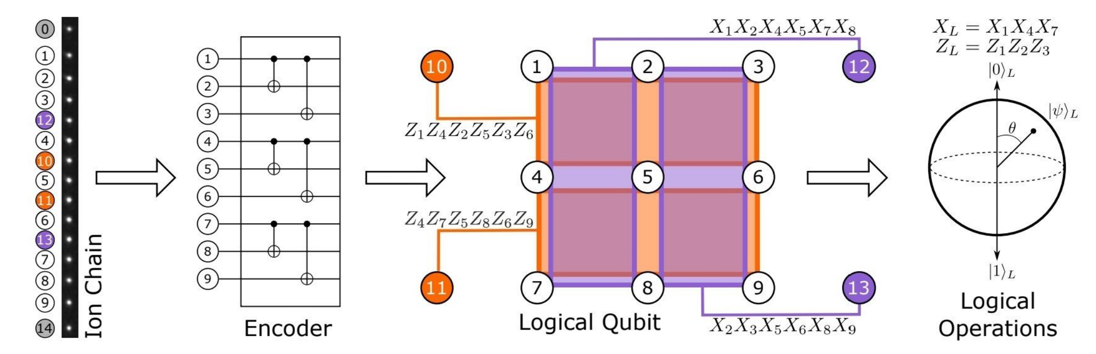
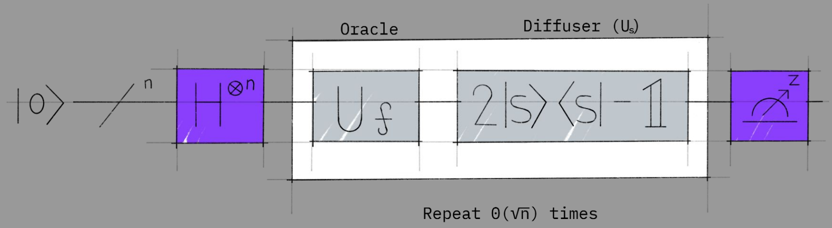


Figure 1. **The Bacon-Shor subsystem code implemented on a 15 ion chain.** Bacon-Shor is a [[9,1,3]] subsystem code that encodes 9 data qubits into 1 logical qubit. Four weight-6 stabilizers are mapped to ancillary qubits 10, 11, 12, and 13, for measuring errors in the X and Z basis. We demonstrate encoding of the logical qubit, with subsequent stabilizer measurements and logical gate operations.

W.Shor, Peter (1995). "Scheme for reducing decoherence in quantum computer memory". Physical Review A. 52 (4): R2493–R2496.

Introduction

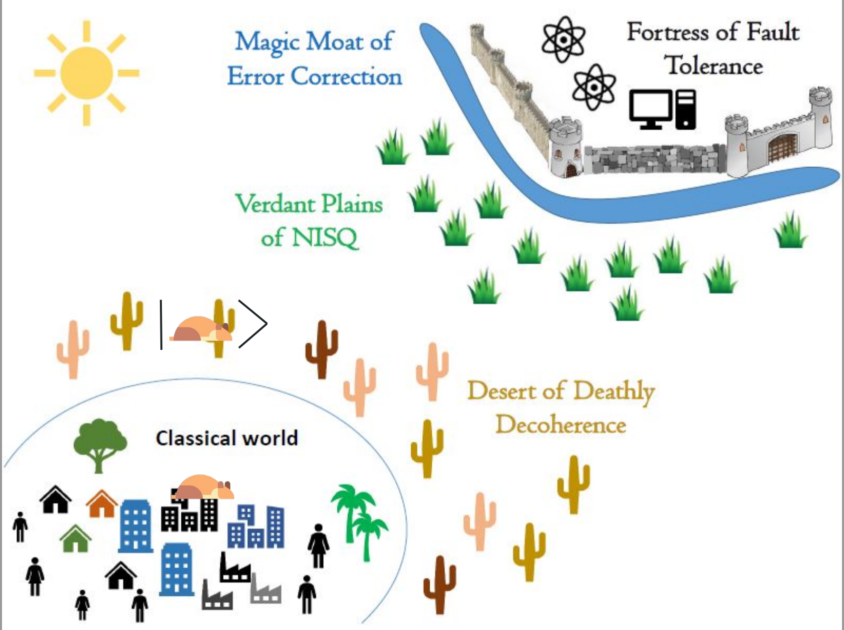
1927 1970 1973 1980 1981 1982 1984 1992 1994 1995 1996



Grover, Lov K. (1996-07-01). "A fast quantum mechanical algorithm for database search". Proceedings of the twenty-eighth annual ACM symposium on Theory of Computing. STOC '96. Philadelphia, Pennsylvania, USA: Association for Computing Machinery: 212–219.

Introduction

1927 1970 1973 1980 1981 1982 1984 1992 1994 1995 1996 1998



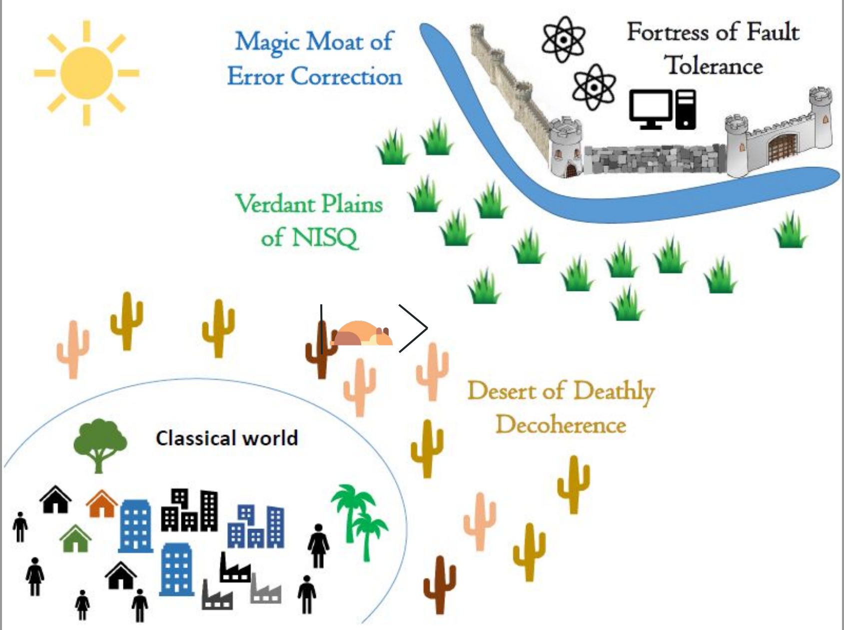
Source: http://quantumwa.org/quantum-computing-near-and-far-term-opportunities/

Experimental Implementation of Fast Quantum Searching

Isaac L. Chuang, Neil Gershenfeld, and Mark Kubinec
Phys. Rev. Lett. **80**, 3408 – Published 13 April 1998

Introduction

1927 1970 1973 1980 1981 1982 1984 1992 1994 1995 1996 1998



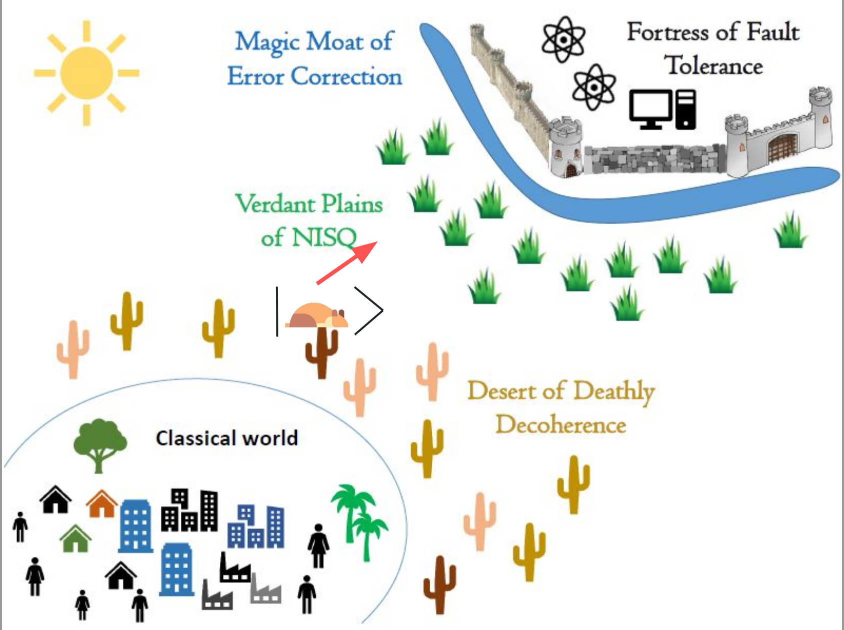
Source: http://quantumwa.org/quantum-computing-near-and-far-term-opportunities/

Experimental Implementation of Fast Quantum Searching

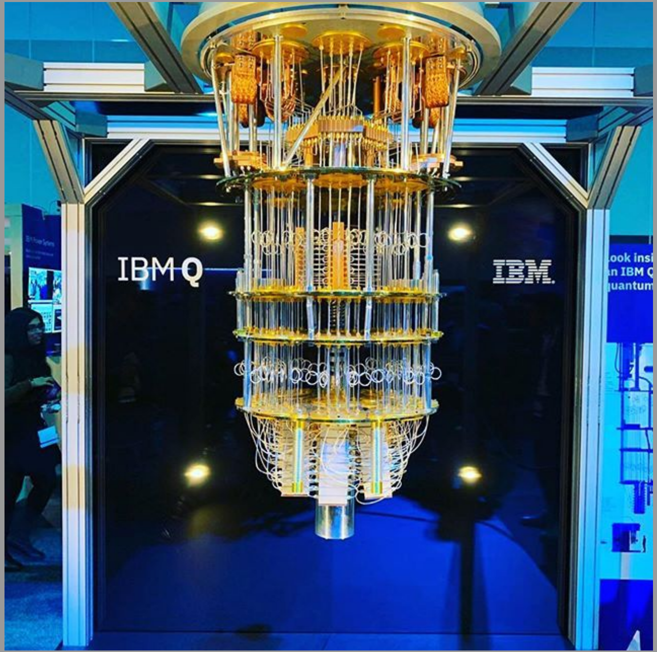
Isaac L. Chuang, Neil Gershenfeld, and Mark Kubinec
Phys. Rev. Lett. **80**, 3408 – Published 13 April 1998

Introduction

1927 1970 1973 1980 1981 1982 1984 1992 1994 1995 1996 1998 2000 - 2010 2016

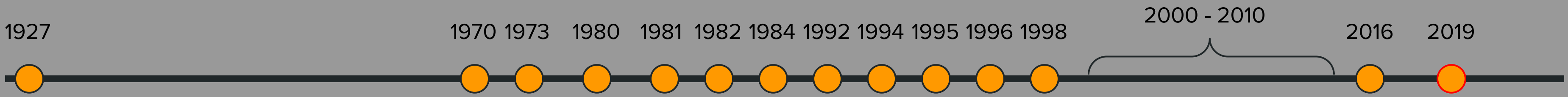


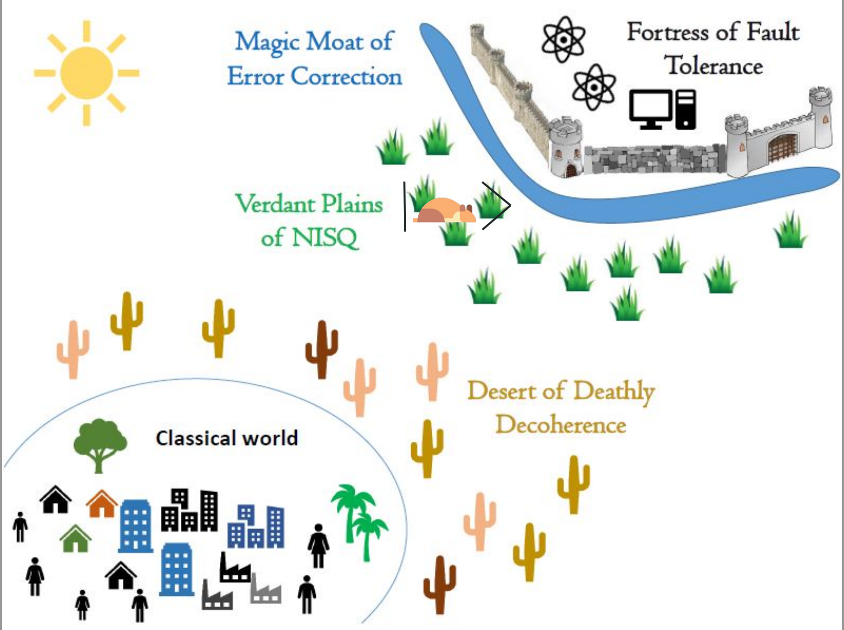
Source: http://quantumwa.org/quantum-computing-near-and-far-term-opportunities/



September 29, 2016, Devitt, S. J (2016). "Performing quantum computing experiments in the cloud". Physical Review A. 94 (3): 032329.

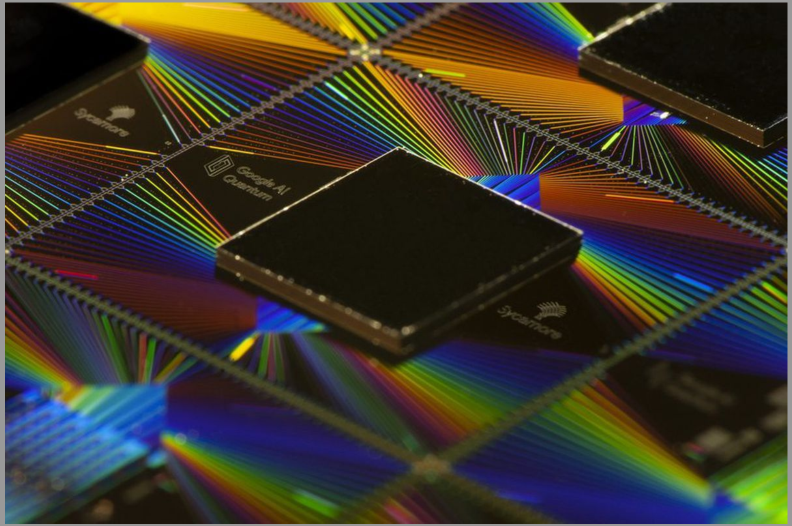
Introduction





Source: http://quantumwa.org/quantum-computing-near-and-far-term-opportunities/

Arute, F., Arya, K., Babbush, R. et al. Quantum supremacy using a programmable superconducting processor. Nature 574, 505–510 (2019). https://doi.org/10.1038/s41586-019-1666-5

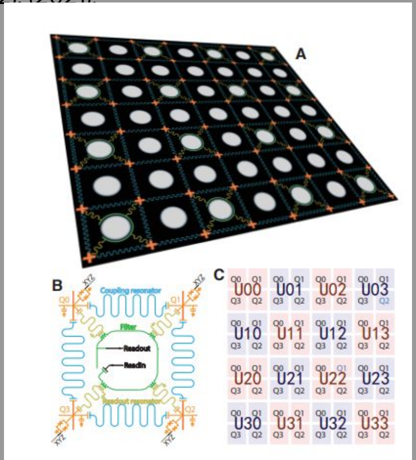


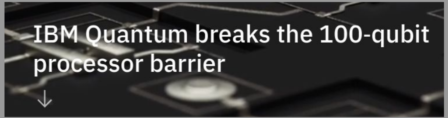
Introduction

1927 1970 1973 1980 1981 1982 1984 1992 1994 1995 1996 1998 2000 - 2010 2016 2019 2020 2021

Zhong, Han-Sen, et al. "Quantum computational advantage using photons." Science 370.6523 (2020): 1460-1463.

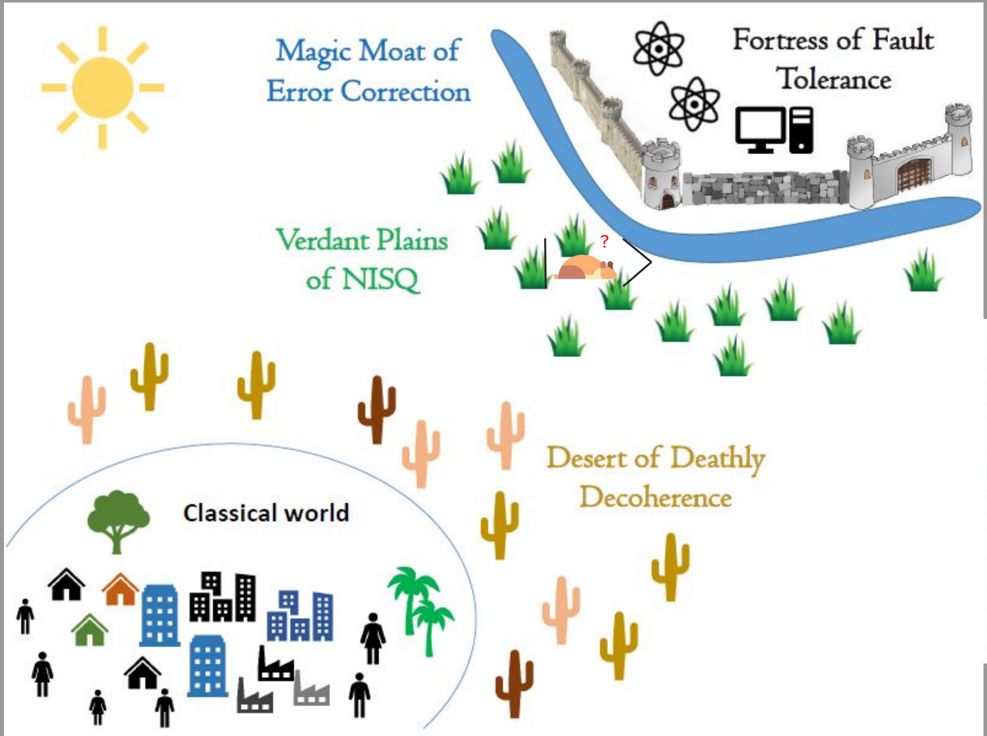
Ming Gong,Shiyu Wang,Chen Zha,Ming-Cheng Chen,He-Liang Huang,Yulin Wu,Qingling Zhu,Youwei Zhao,Shaowei Li,Shaojun Guo,Haoran Qian,Yangsen Ye,Fusheng Chen,Chong Ying,Jiale Yu,Daojin Fan,Dachao Wu,Hong Su,Hui Deng,Hao Rong,Kaili Zhang,Sirui Cao,Jin Lin,Yu Xu,Lihua Sun,Cheng Guo,Na Li,Futian Liang,V. M. Bastidas,Kae Nemoto,W. J. Munro,Yong-Heng Huo,Chao-Yang Lu,Cheng-Zhi Peng,Xiaobo Zhu,Jian-Wei Pan, Quantum walks on a programmable two-dimensional 62-qubit superconducting processor, Science, 372, 6545, (948-952), (2021).





https://research.ibm.com/blog/127-qubit-quantum-processor-eagle

Introduction



Source: http://quantumwa.org/quantum-computing-near-and-far-term-opportunities/

Exponential suppression of bit or phase errors with cyclic error correction

https://doi.org/10.1038/s41586-021-03588-y Google Quantum AI*

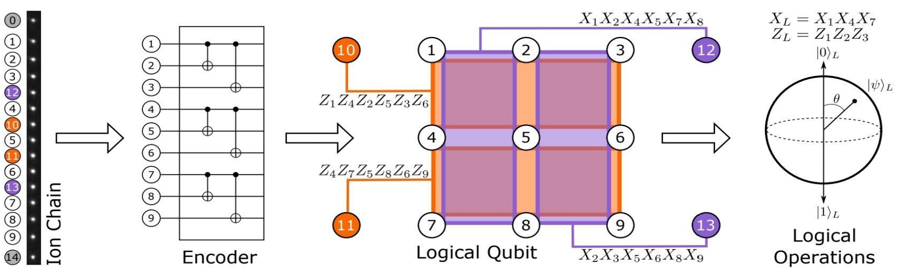
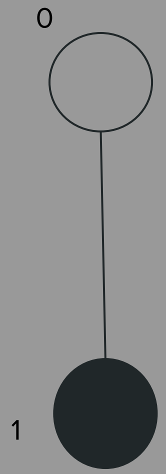


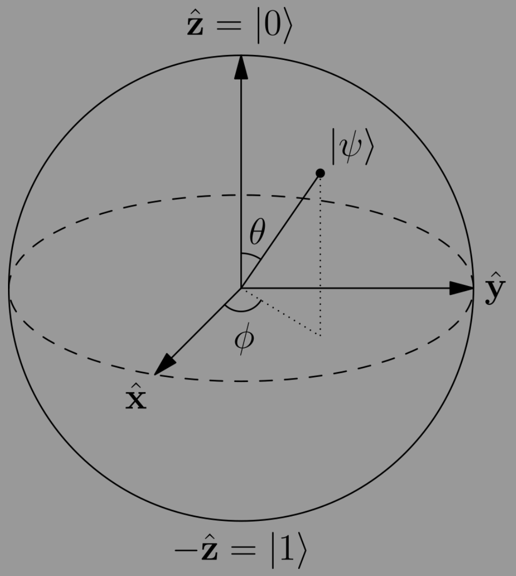
Figure 1. **The Bacon-Shor subsystem code implemented on a 15 ion chain.** Bacon-Shor is a [[9,1,3]] subsystem code that encodes 9 data qubits into 1 logical qubit. Four weight-6 stabilizers are mapped to ancillary qubits 10, 11, 12, and 13, for measuring errors in the X and Z basis. We demonstrate encoding of the logical qubit, with subsequent stabilizer measurements and logical gate operations.

Egan, L., Debroy, D.M., Noel, C. et al. Fault-tolerant control of an error-corrected qubit. Nature 598, 281–286 (2021). https://doi.org/10.1038/s41586-021-03928-y

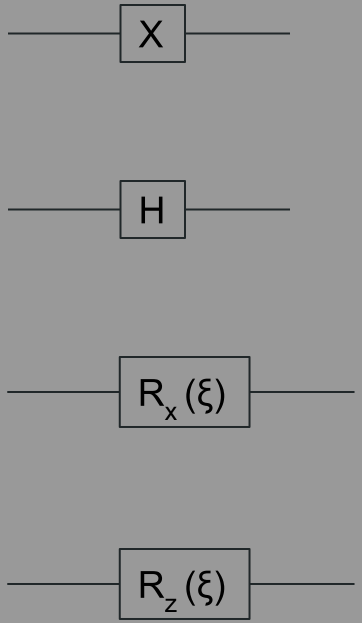
From bits to qubits

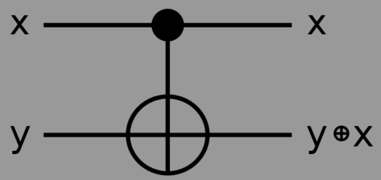


$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$$

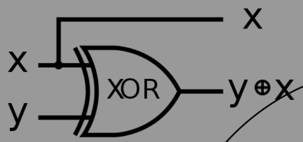


Quantum Circuits

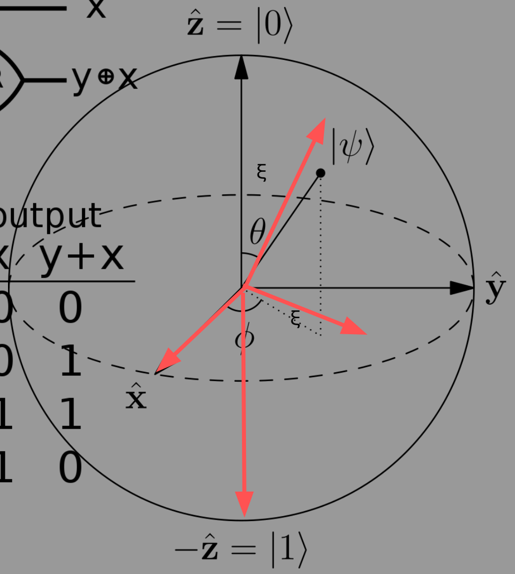




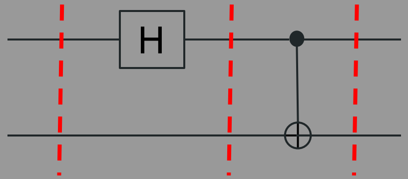
input		output	
x	y	x	y+x
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$



input		output	
x	y	x	y+x
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0



Quantum Circuits: Constructing a bell state



$$|\psi_0\rangle \qquad |\psi_1\rangle \qquad |\psi_2\rangle$$

$$|\psi_0\rangle = |0\rangle \otimes |0\rangle$$

$$|\psi_1\rangle = H \otimes I\,|\psi_0\rangle = \frac{1}{\sqrt{2}}\Big(|0\rangle + |1\rangle\Big) \otimes |0\rangle$$

$$|\psi_2\rangle = CNOT|\psi_1\rangle = \frac{1}{\sqrt{2}}\Big(|00\rangle + |11\rangle\Big)$$

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad CNOT = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \quad H = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

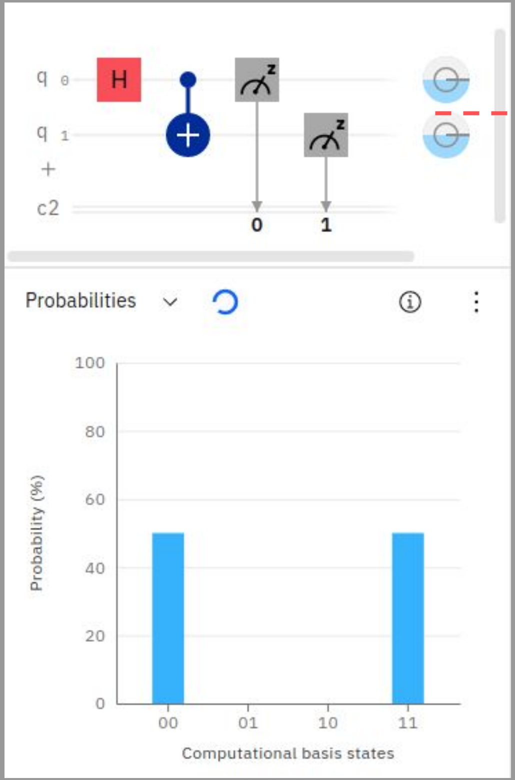
$$\begin{pmatrix} a \\ b \end{pmatrix} \otimes \begin{pmatrix} c \\ d \end{pmatrix} = \begin{pmatrix} a\begin{pmatrix} c \\ d \end{pmatrix} \\ b\begin{pmatrix} c \\ d \end{pmatrix} \end{pmatrix} = \begin{pmatrix} ac \\ ad \\ bc \\ bd \end{pmatrix}$$

$$\vdots$$

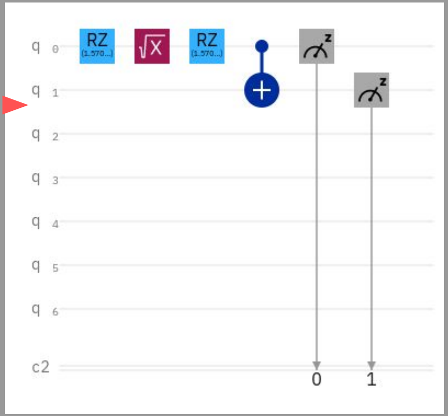
$$|\psi_2\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

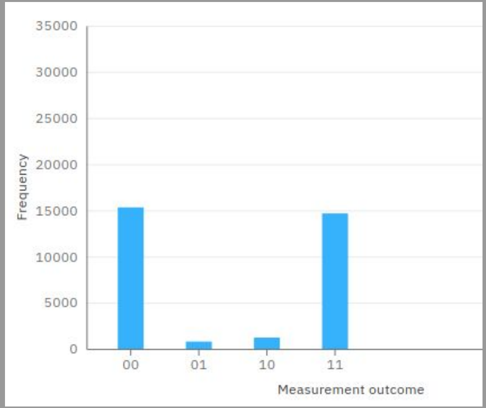
Running Quantum Circuits on real devices

https://quantum-computing.ibm.com/

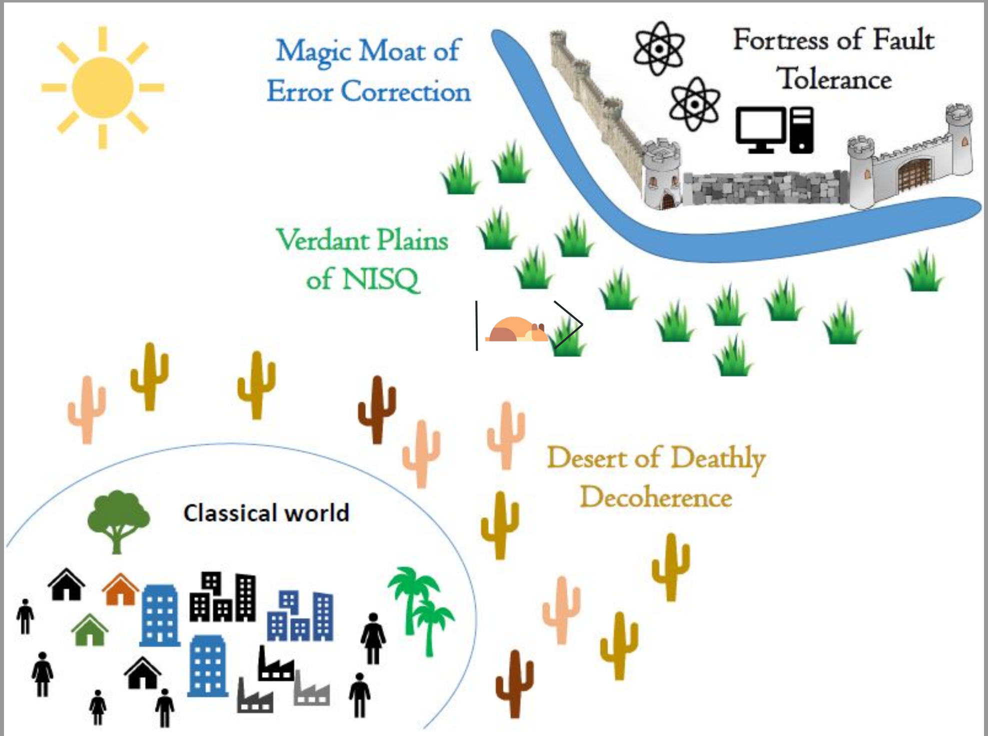


Transpilation



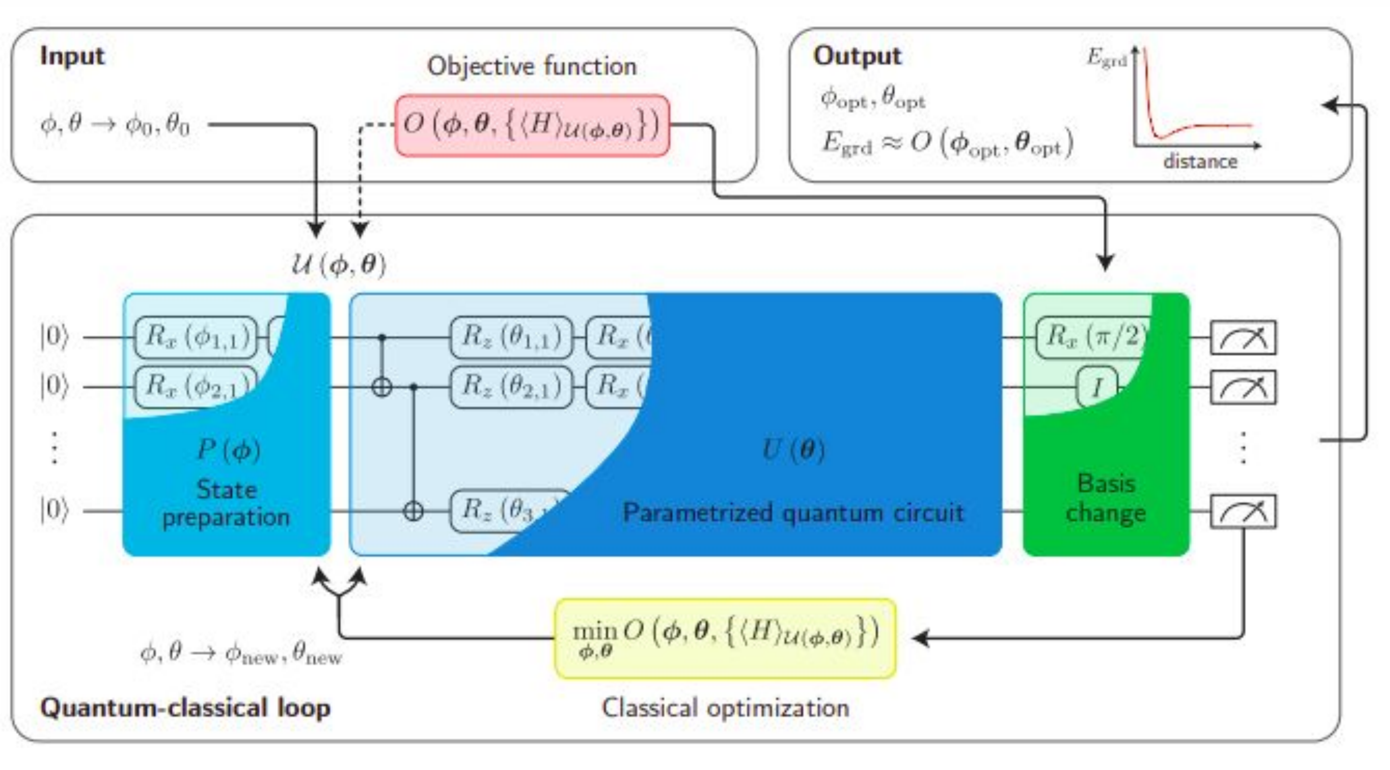


Variational Quantum Algorithms



Source: http://quantumwa.org/quantum-computing-near-and-far-term-opportunities/

Variational Quantum Algorithms



Source: Arxiv:2101.08448

VQE: Stating the problem

We want to solve the following problem:

Given a Hamiltonian H, we want to approximate the ground state energy by solving the following optimization problem:

$$\mathbf{min}_{\theta}\langle\psi(\theta)|\mathcal{H}|\psi(\theta)\rangle$$

Using the variational principle, we have that:

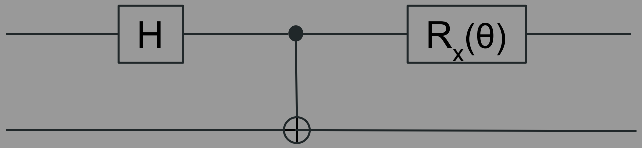
$$\lambda_{\theta} = \langle\psi(\theta)|\mathcal{H}|\psi(\theta)\rangle \geq \lambda_{\min} = E_{gs}$$

So by minimizing this value, we get an approximation of the minimum eigenvalue of the Hamiltonian.

VQE: Algorithm

1) Decompose the Hamiltonian into Pauli Strings of polynomial size $\mathcal{H} = \sum_\alpha h_\alpha P_\alpha$ $\quad P_\alpha = \sigma^{\alpha_1} \otimes \ldots \sigma^{\alpha_N}$

2) Create an Ansatz $|\psi(\theta)\rangle$



3) Evaluate the Hamiltonian using the chosen ansatz $\langle \mathcal{H} \rangle(\theta) = \langle \psi(\theta) | \mathcal{H} | \psi(\theta) \rangle \quad = \sum_\alpha h_\alpha \langle \psi(\theta) | P_\alpha | \psi(\theta) \rangle$

4) Using the value of the first step, minimize the expectation value with respect to the parameter θ using a classical optimizer.

Example

Suppose that you want to find the minimum eigenvalue of the following matrix:

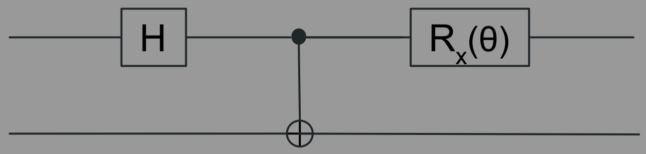
$$A = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

1) Decompose the Hamiltonian into Pauli Strings of polynomial size $\mathcal{H} = \sum_\alpha h_\alpha P_\alpha$ $\quad P_\alpha = \sigma^{\alpha_1} \otimes \dots \sigma^{\alpha_N}$

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \qquad A = \frac{1}{2^2} \sum_{ij} h_{ij} \sigma_i \otimes \sigma_j \qquad h_{ij} = \frac{1}{2^2} \mathrm{Tr}\left[(\sigma_i \otimes \sigma_j) \cdot A\right]$$

$$A = \frac{1}{2}\left(I \otimes I - \sigma_x \otimes \sigma_x - \sigma_y \otimes \sigma_y + \sigma_z \otimes \sigma_z\right)$$

2) Constructing the Ansatz



Example

3) Evaluate the Hamiltonian using the chosen ansatz $\langle\mathcal{H}\rangle(\theta) = \langle\psi(\theta)|\mathcal{H}|\psi(\theta)\rangle \quad = \sum_\alpha h_\alpha \langle\psi(\theta)|P_\alpha|\psi(\theta)\rangle$

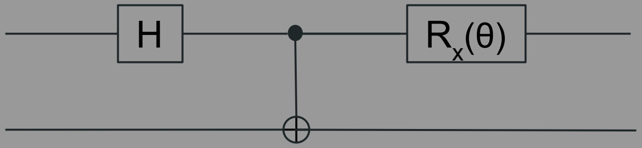
$$\langle\psi(\theta)|A|\psi(\theta)\rangle = \frac{1}{2}\left(\underbrace{\boxed{\langle\psi(\theta)|I\otimes I|\psi(\theta)\rangle}}_{1} - \boxed{\langle\psi(\theta)|\sigma_x\otimes\sigma_x|\psi(\theta)\rangle} - \boxed{\langle\psi(\theta)|\sigma_y\otimes\sigma_y|\psi(\theta)\rangle} + \boxed{\langle\psi(\theta)|\sigma_z\otimes\sigma_z|\psi(\theta)\rangle}\right)$$

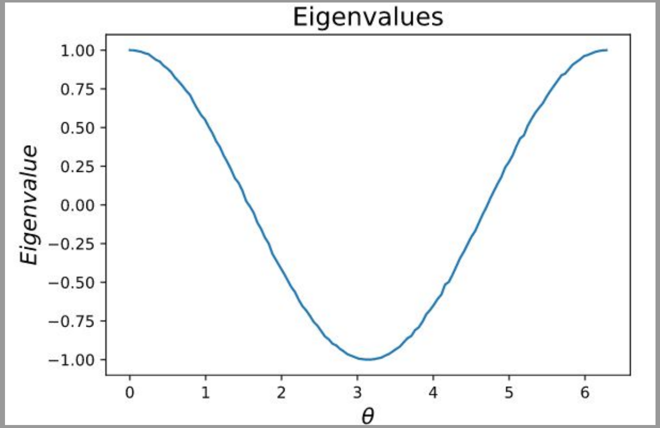
$$\sigma_z\otimes\sigma_z(a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle)$$
$$= a|00\rangle - b|01\rangle - c|10\rangle + d|11\rangle$$

$$\langle\psi|\sigma_y|\psi\rangle = \left(\langle\psi|(HS^\dagger)^\dagger\right)Z\left(HS^\dagger|\psi\rangle\right) \equiv \langle\tilde{\psi}|Z|\tilde{\psi}\rangle$$

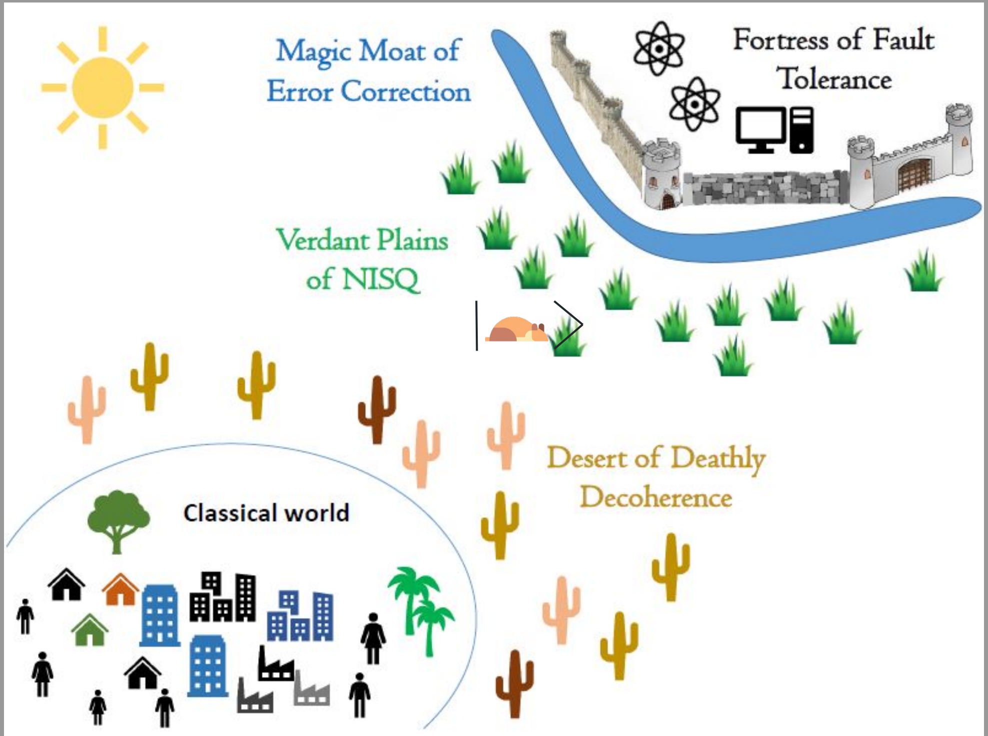
$$\langle\psi|\sigma_x|\psi\rangle = \left(\langle\psi|(H)^\dagger\right)Z\left(H|\psi\rangle\right) \equiv \langle\tilde{\psi}|Z|\tilde{\psi}\rangle$$

$$\langle\psi|\sigma_z\otimes\sigma_z|\psi\rangle = Pr(00) - Pr(01) - Pr(10) + Pr(11)$$





Applications



Source: http://quantumwa.org/quantum-computing-near-and-far-term-opportunities/

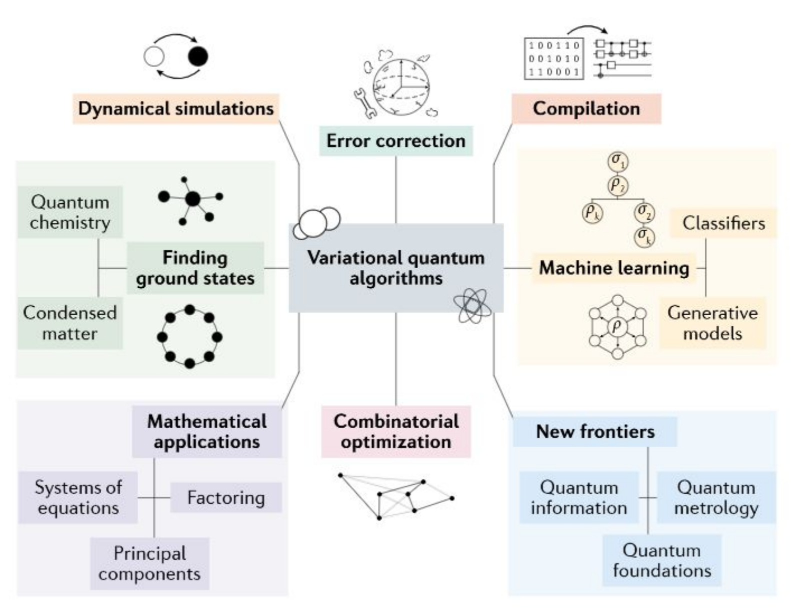
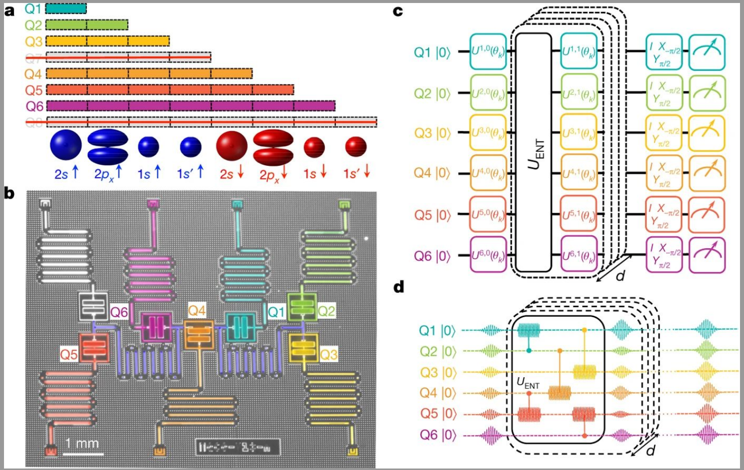
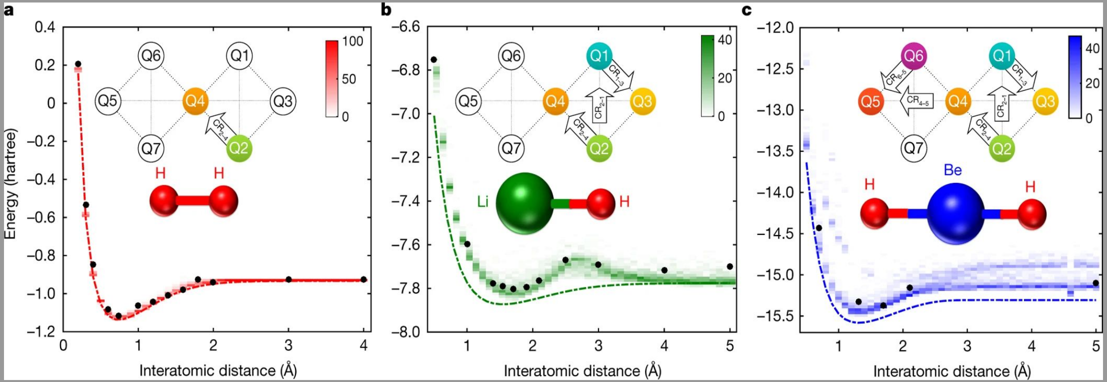


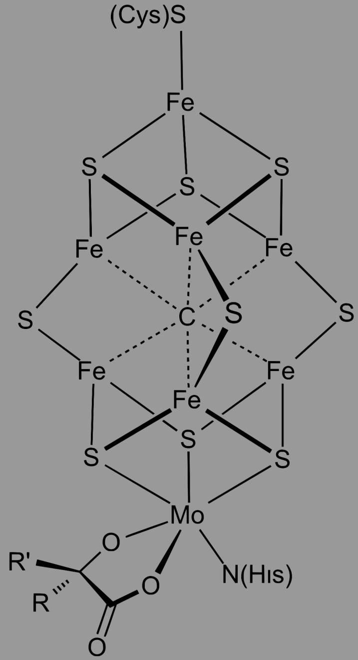
Fig. 1 | **Applications of variational quantum algorithms.** Many applications have been envisaged for variational quantum algorithms. Here we show some of the key applications that are discussed in this Review.

Source: Cerezo, M., Arrasmith, A., Babbush, R. et al. Variational quantum algorithms. Nat Rev Phys (2021). https://doi.org/10.1038/s42254-021-00348-9

Applications







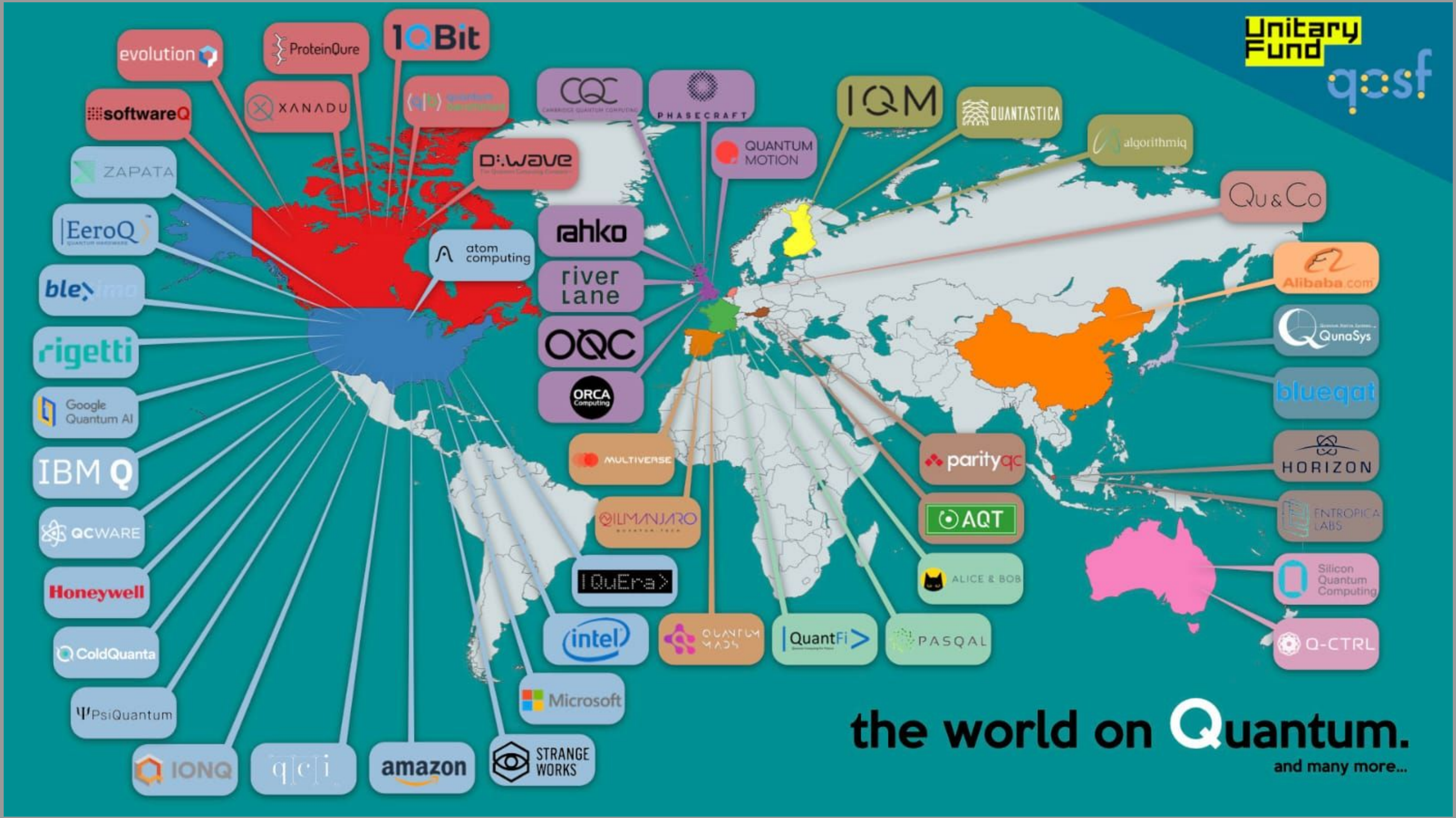
FeMoco
(aprox. 111 qubits)

Source: Nature volume 549, pages242–246(2017)

Applications

https://refikanadol.com/works/quantummemories/

Quantum World



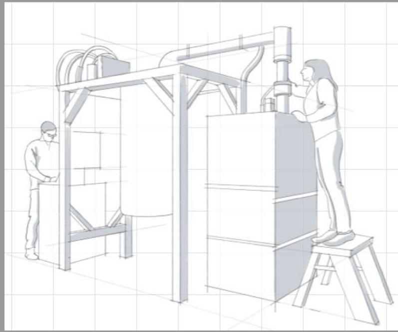
Learning Tools

https://docs.microsoft.com/pt-br/azure/quantum/tutorial-qdk-intro-to-katas

https://codebook.xanadu.ai

https://nahumsa.github.io/n-blog/

https://qiskit.org/textbook



https://github.com/nahumsa/Notes-on-Quantum-Computing

How can you contribute?

Qiskit

Unitary Fund

QuTiP

Quantum Toolbox in Python

PENNYLANE

XANADU

STRAWBERRY FIELDS

Thank You !