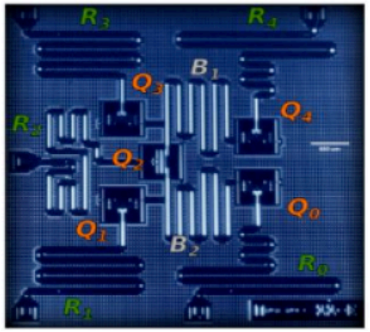
Quantum Lab: Enjoying the IBM quantum experience

Lecturers: Esperanza López and Germán Sierra

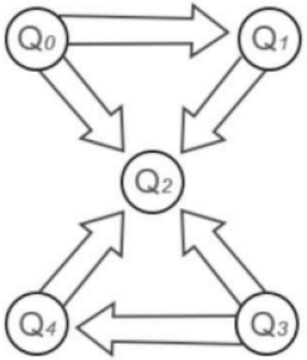
Abstract: In May 2016, the IBM company provided cloud access to a wide variety of quantum computers. They are still small and noisy, but can be used to learn the basic concepts and tools of quantum computing. In this lab we will show how to program and run them through several examples such as dense coding, quantum Fourier transform, prime state, quantum copying machine and variational quantum eigensolver.

Requirements: a laptop and a personal account at https://quantum-computing.ibm.com
Location: Instituto de Física Teórica UAM-CSIC

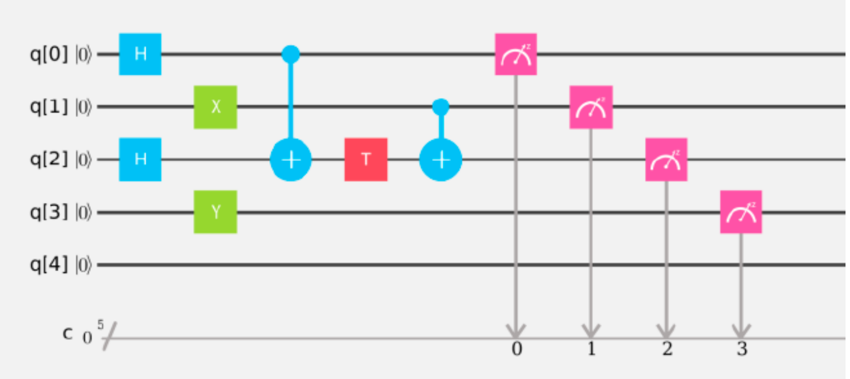


(a)

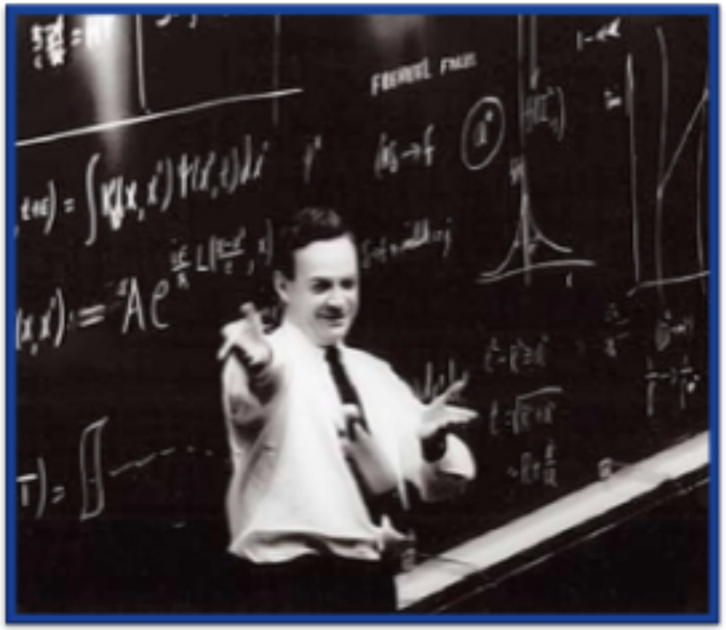
IBM-QX2

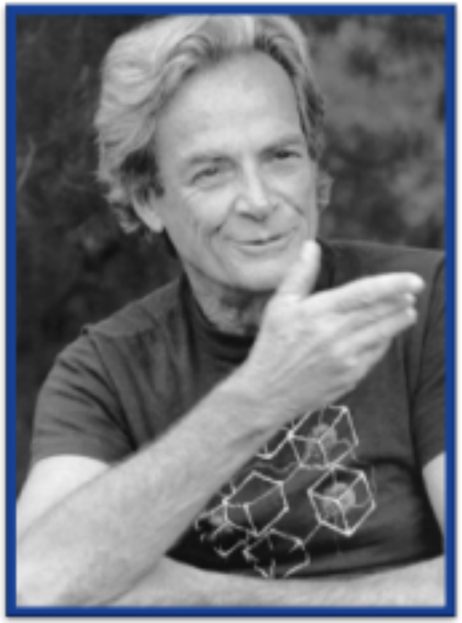


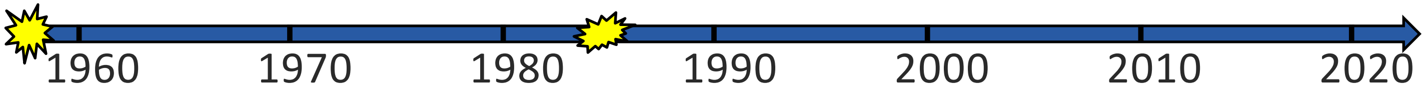
(b)



Richard Feynman – Proposed Quantum Computers in 1981



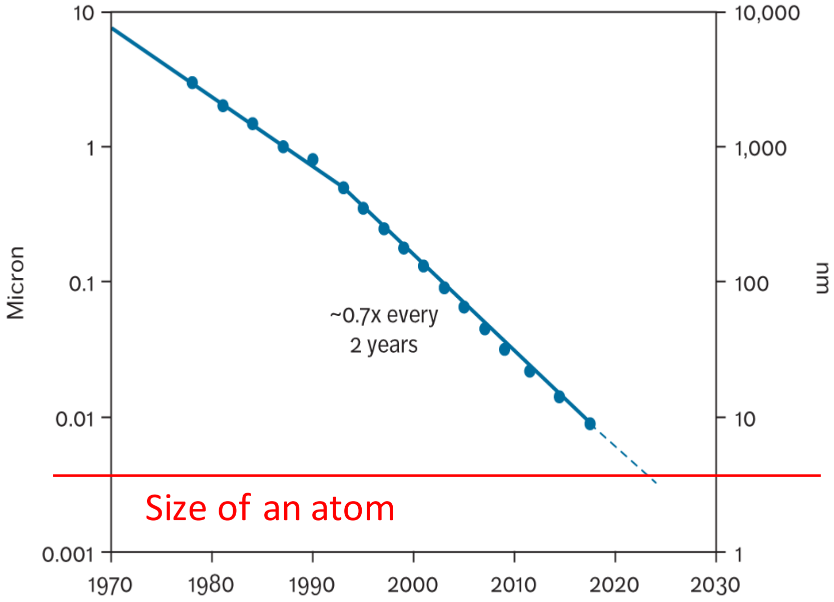




1959: There's Plenty of Room at the Bottom

1981: Simulating Physics with Computers

Why quantum Computing ?

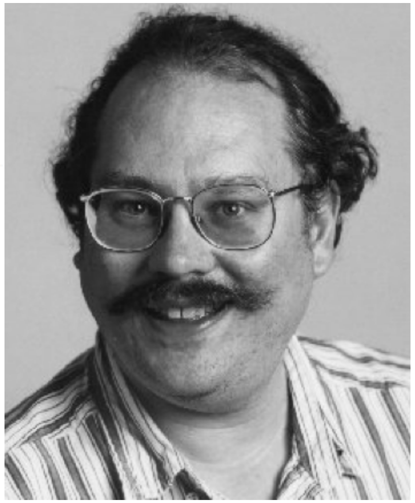


"Nature is quantum, goddamn it! So if we want to simulate it, we need a quantum computer."
R.Feynman, 1981

Is Quantum Computing a natural consequence of Moore's law?

Title:Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer

Authors:Peter W. Shor (AT&T Research) (1994)



Peter Shor 1959

Prime factorization can be done in polynomial time
In a quantum computer

N: integer, n = log N: number of digits

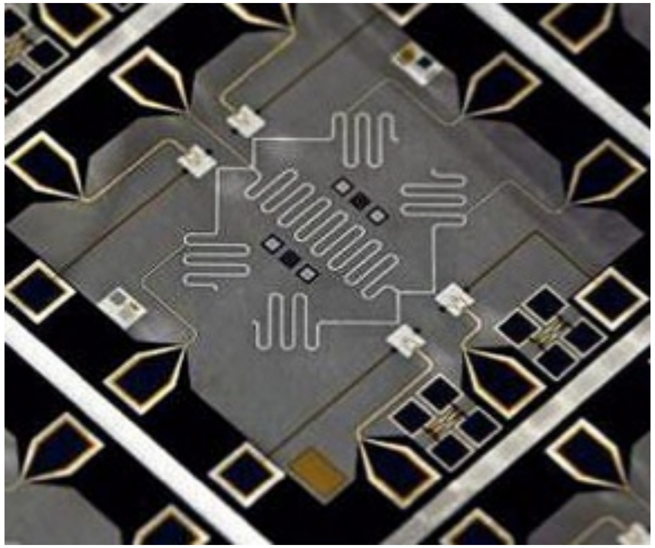
Best classical algorithm: $O\left(e^{1.9\,n^{1/3}(\log n)^{2/3}}\right)$

Exponential speedup

Shor's algorithm: $O(n^2 \log n \log\log n)$

15 = 3 x 5

Proof of principle



University of California at Santa Barbara 2001

A theoretical estimation (Fowler et al 2012)

n=2000 bits -> 4000 logical qubits -> 2 x 10^8 physical qubits -> 1 day


HEY, GROVER
WHAT'S THE BEST WAY TO FACTOR A REALLY LARGE NUMBER WITH A STRONG QUANTUM COMPUTER?
SORRY-
I'M NOT SHOR

Quantum Computing: Key Concepts

Superposition

Classical Physics Quantum Physics

Heads <u>or</u> Tails Heads <u>and</u> Tails

Entanglement

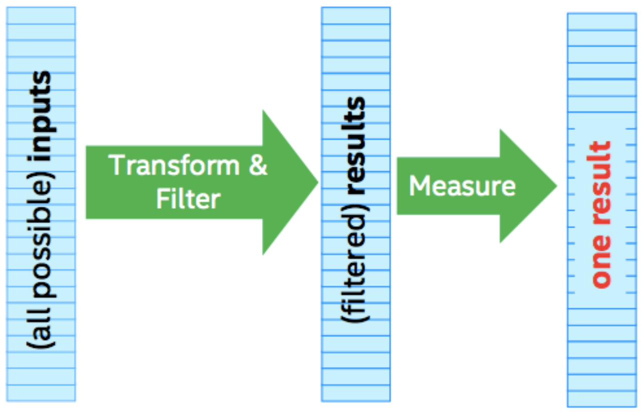
N Quantum Bits or **Qubits** = 2^N States

- 50 Entangled Qubits = more states than any possible supercomputer
- 300 Entangled Qubits = more states than atoms in the universe
- Fragility will require error correction and likely millions of qubits

Fragility

Observation or noise causes loss of information

The promise of quantum computing



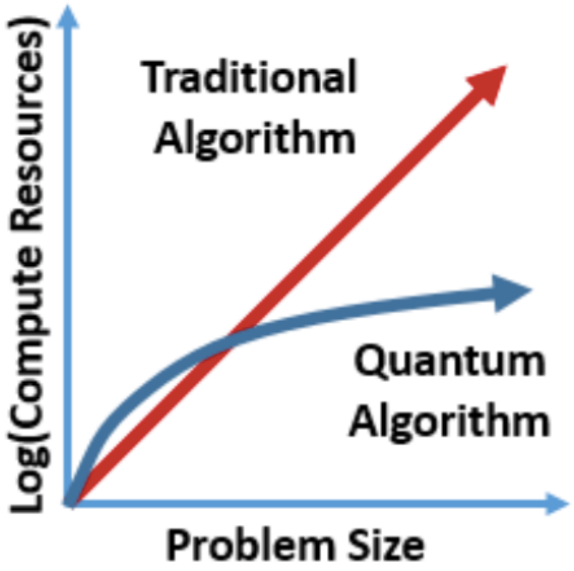
(all possible) **inputs**

Transform & Filter

(filtered) **results**

Measure

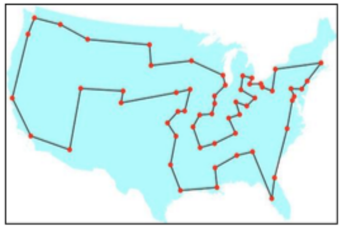
one result



Exponential speedup ←→ surpassing the limits of scaling

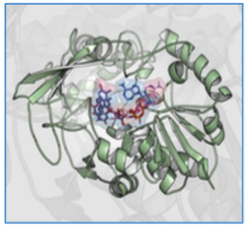
Changing the World

TIME
“Quantum Will Change Everything”

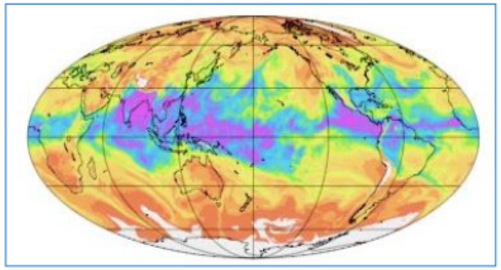


Travel and Logistics

Image Processing



Pharmacology



Improved Forecasting

Improved Stock ROI

Cryptography

Source: Google Images

Companies developping QC

IBM

Google

Dwave

Microsoft

Intel

Rigetti

Alibaba …

QUP (Quantum processors) from Wikipedia

Manufa	Name/Codename/Des	Architecture	Fidelity	Qubits	Release date
Google	N/A	Superconducting	99.5%[1]	20 qb	2017
Google	N/A	Superconducting	99.7%[1]	49 qb[2]	Q4 2017 (planned)
Google	Bristlecone	Superconducting	99% (readout) 99.9% (1 qubit) 99.4% (2 qubits)	72 qb[3][4]	5 March 2018
Google	Sycamore	Nonlinear supercon	N/A	54 transmon qb 53 qb effective	2019
IBM	IBM Q 5 Tenerife	Superconducting	99.897% (average gate) 98.64% (readout)	5 qb	2016[1]
IBM	IBM Q 5 Yorktown	Superconducting	99.545% (average gate) 94.2% (readout)	5 qb	
IBM	IBM Q 14 Melbourne	Superconducting	99.735% (average gate) 97.13% (readout)	14 qb	
IBM	IBM Q 16 Rüschlikon	Superconducting	99.779% (average gate) 94.24% (readout)	16 qb[5]	17-may-1 (Retired: 26 September 2018)[6]
IBM	IBM Q 17	Superconducting	N/A	17 qb[5]	17-may-1
IBM	IBM Q 20 Tokyo	Superconducting	99.812% (average gate) 93.21% (readout)	20 qb[7]	10 November 2017
IBM	IBM Q 20 Austin	Superconducting	N/A	20 qb	(Retired: 4 July 2018)[6]
IBM	IBM Q 50 prototype	Superconducting	N/A	50 qb[7]	
IBM	IBM Q 53	Superconducting	N/A	53 qb	October 2019
Intel	17-Qubit Superconduc	Superconducting	N/A	17 qb[8][9]	10 October 2017
Intel	Tangle Lake	Superconducting	N/A	49 qb [10]	9 January 2018
Rigetti	8Q Agave	Superconducting	N/A	8 qb	4 June 2018[11]
Rigetti	16Q Aspen-1	Superconducting	N/A	16 qb	30 November 2018[11]
Rigetti	19Q Acorn	Superconducting	N/A	19 qb[12]	17 December 2017
IBM	IBM Armonk[13]	Superconducting	N/A	1 qb	16 October 2019
IBM	IBM Ourense[13]	Superconducting	N/A	5 qb	03 July 2019
IBM	IBM Vigo[13]	Superconducting	N/A	5 qb	03 July 2019
IBM	IBM London[13]	Superconducting	N/A	5 qb	13 September 2019
IBM	IBM Burlington[13]	Superconducting	N/A	5 qb	13 September 2019
IBM	IBM Essex[13]	Superconducting	N/A	5 qb	13 September 2019

Quantum Manifesto

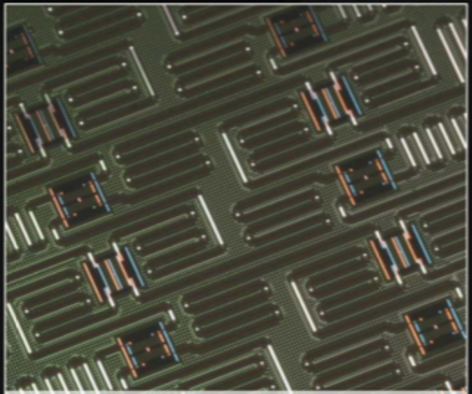
A New Era of Technology

May 2016

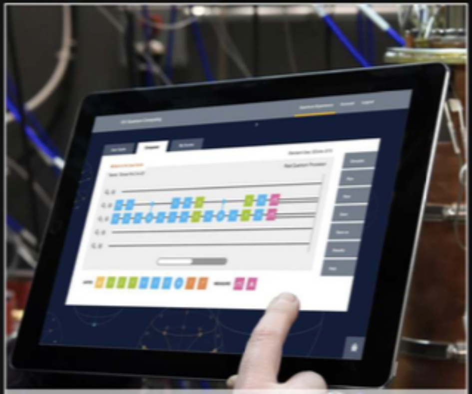
2ND QUANTUM REVOLUTION

IBM released the IBM **Q** Experience in 2016

Quantum computer at IBM Research



IBM quantum bit device



IBM Quantum Experience

In May 2016, IBM made a quantum computing platform available via the IBM Cloud, giving students, scientists and enthusiasts hands-on access to run algorithms and experiments

IBM released the IBM **Q** Experience in 2016

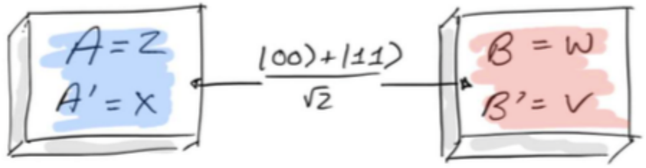
QX is a fantastic tool for teaching.

Proving Bell's inequality using IBM QX is a few minutes task.

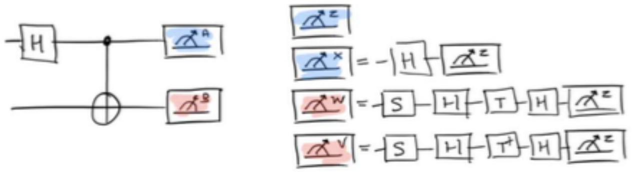
With QX you have access to a 'quantum laboratory' from home.

Test simple quantum algorithms without the need to learn any programming language.

... but you may need more ....



$$C = \langle AB\rangle - \langle AB'\rangle + \langle A'B\rangle + \langle A'B'\rangle$$



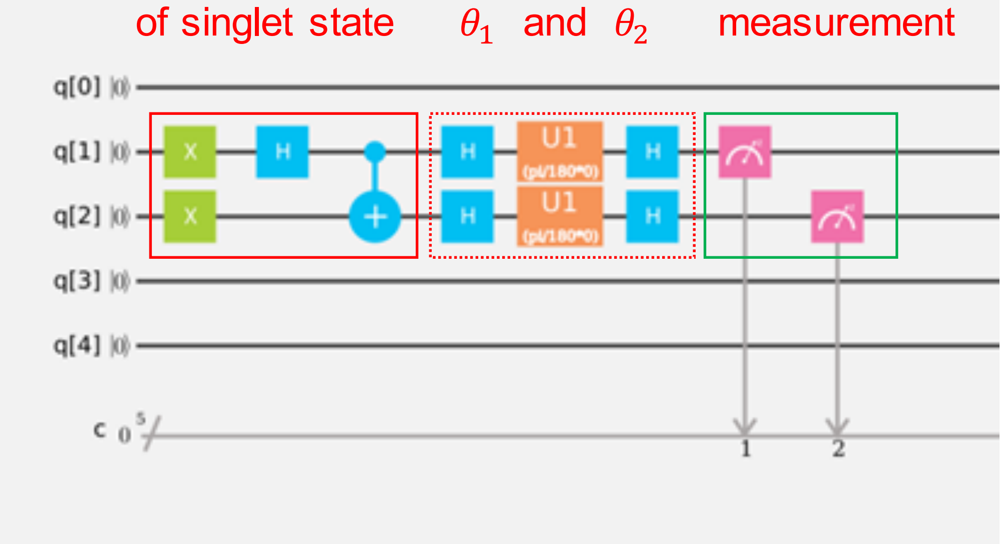
Belltest: 8192 shots May 2nd 11:44pm

	P(00)	P(11)	P(01)	P(10)	⟨AB⟩
ZW	0.434	0.380	0.070	0.116	0.629
ZV	0.409	0.415	0.100	0.076	0.648
XW	0.452	0.375	0.090	0.083	0.654
XV	0.110	0.077	0.451	0.36	-0.626

$|C| = 2.56 \pm 0.03$

Simulation on IBM Quantum Experience (IBM QX)

IBM QX, Yorktown Heights, USA



Preparation of singlet state

Rotation by θ_1 and θ_2

Readout measurement

X X-gate:
$X|0\rangle = |1\rangle$
$X|1\rangle = |0\rangle$

H Hadamard gate:
$H|0\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$
$H|1\rangle = (|0\rangle - |1\rangle)/\sqrt{2}$

U1 phase-gate:
$U1|0\rangle = |0\rangle$, $U1|1\rangle = e^{i\theta}|1\rangle$

CNOT gate: $C_{01}|0_1 0_0\rangle = |0_1 0_0\rangle$
$C_{01}|0_1 1_0\rangle = |1_1 1_0\rangle$
$C_{01}|1_1 0_0\rangle = |1_1 0_0\rangle$
$C_{01}|1_1 1_0\rangle = |0_1 1_0\rangle$

Possible application areas for quantum computing

We believe the following areas might be useful to explore for the early applications of quantum computing:

Chemistry

Material design, oil and gas, drug discovery

Artificial Intelligence

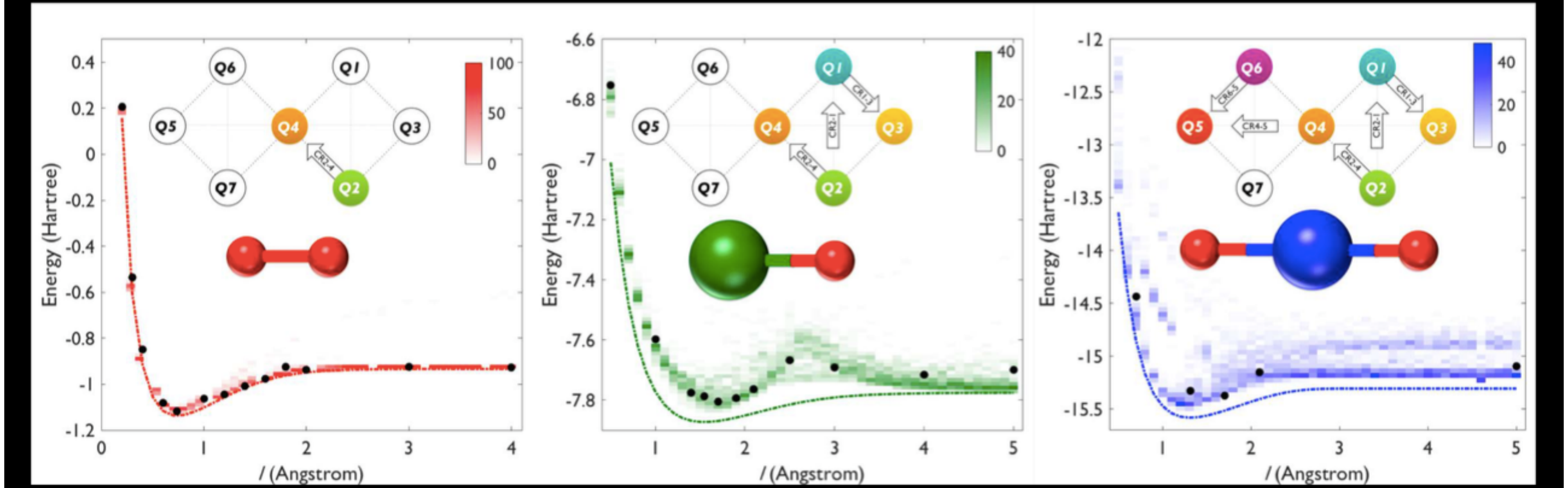
Classification, machine learning, linear algebra

Financial Services

Asset pricing, risk analysis, rare event simulation

Quantum chemistry – the VQE approach

Ground state-energy of simple molecules



H_2: 2 qubits
5 Pauli terms, 2 sets

LiH: 4 qubits
100 Pauli terms, 25 sets

BeH_2: 6 qubits
144 Pauli terms, 36 sets

[A. Kandala et al. **Nature 549**, 242-246, 2017]

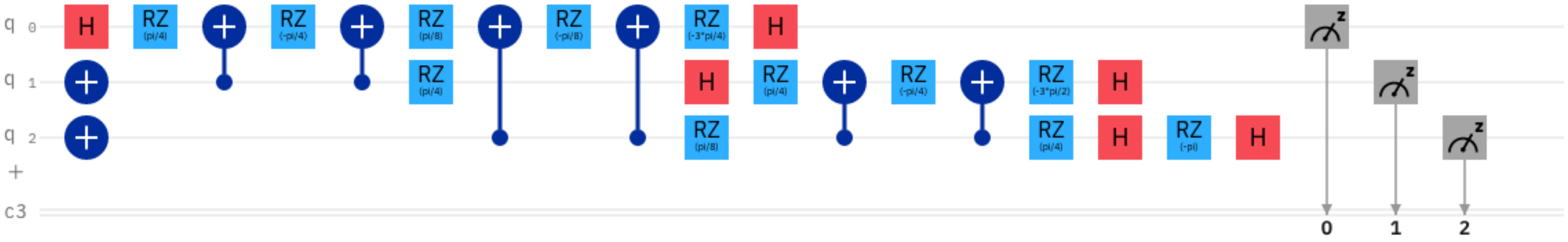
Ivano Tavernelli - ita@zurich.ibm.com

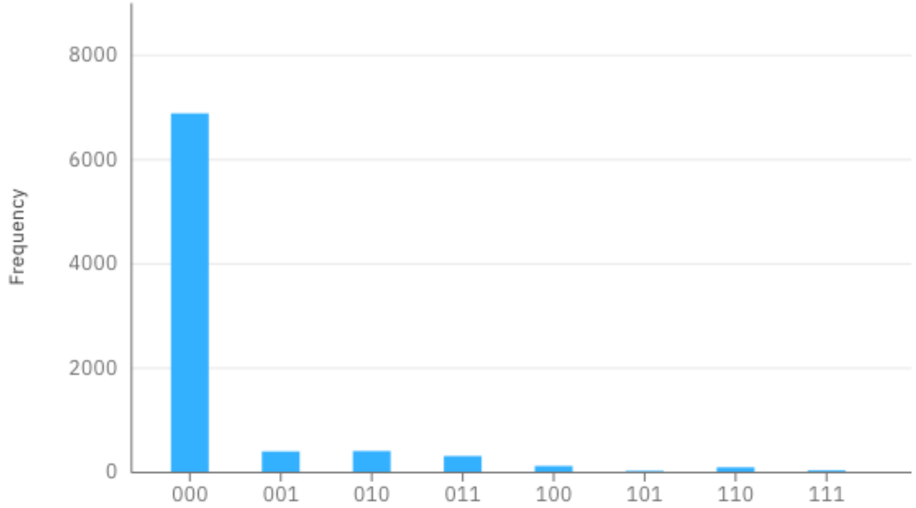
INFIERY QUANTUM LAB

Program and run five experiments using IBMQ

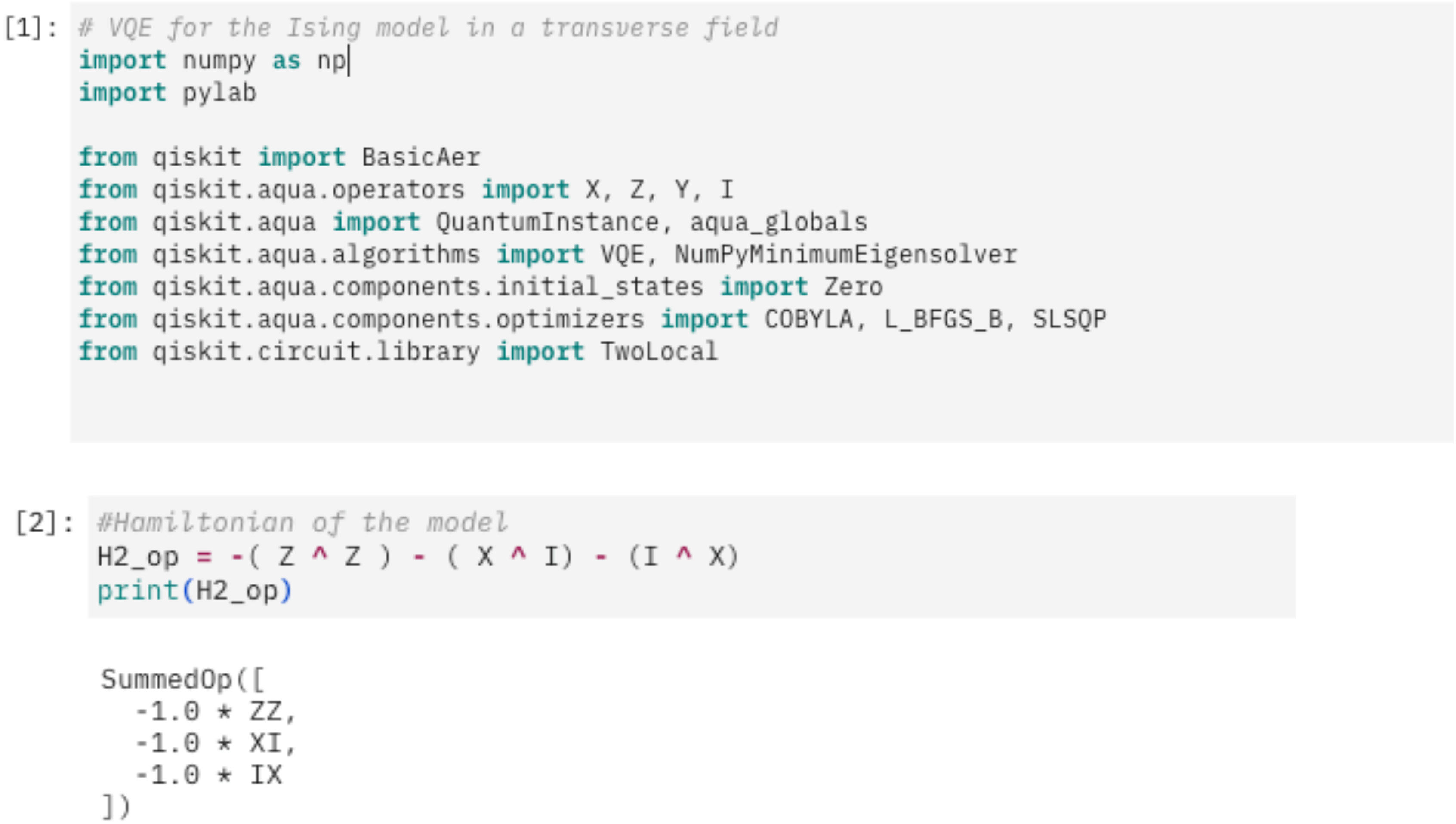
- Dense coding : 2 classical bits <-> 1 qubit
- Quantum Fourier Transform
- Prime state : quantum superposition of prime numbers
- Quantum copying machine : imperfect copies of states
- Variational quantum eigensolver : find the ground state of a Hamiltonian

Checking F|011>





VQE circuit for the Ising model in a transverse field



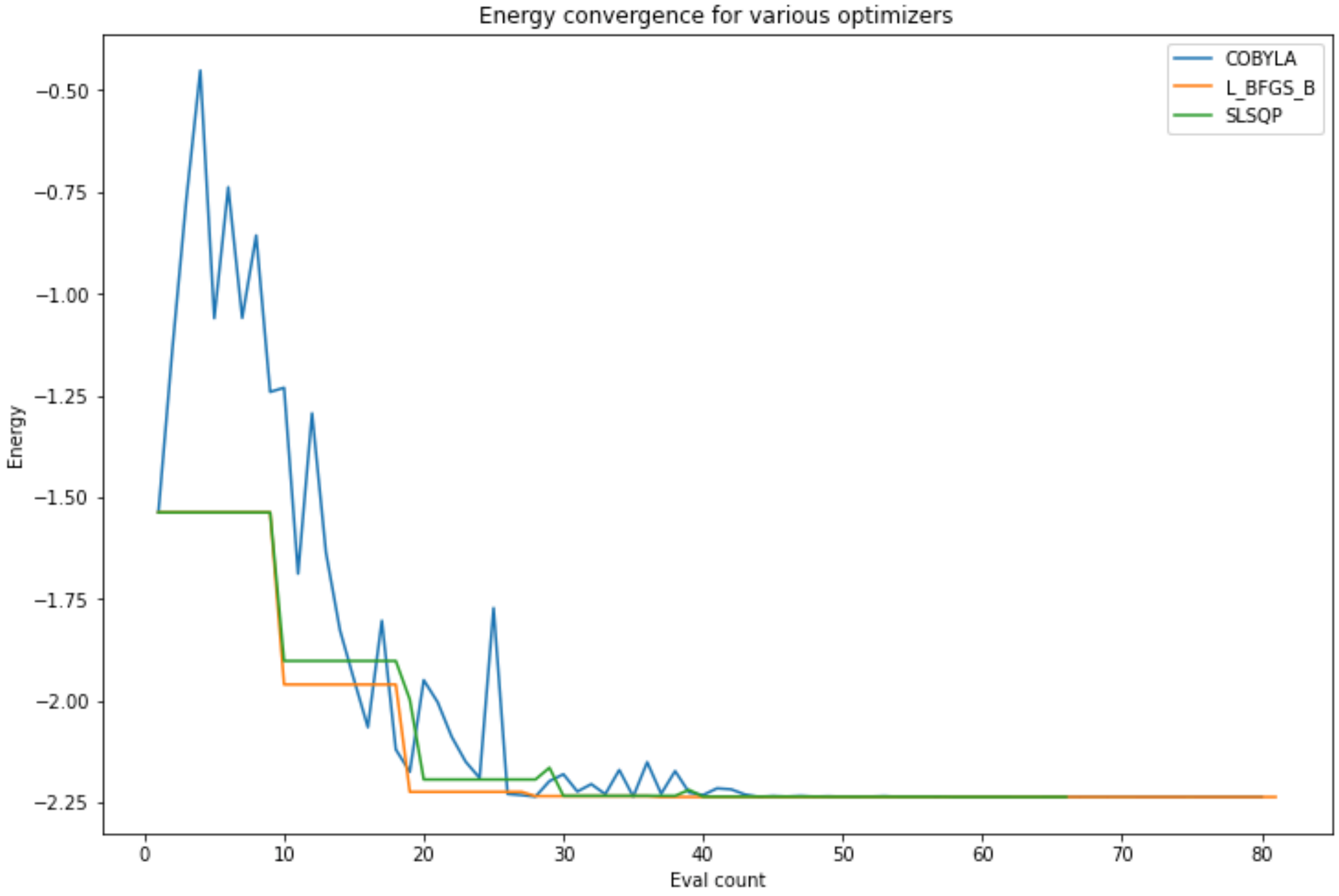
```
[1]: # VQE for the Ising model in a transverse field
     import numpy as np
     import pylab

     from qiskit import BasicAer
     from qiskit.aqua.operators import X, Z, Y, I
     from qiskit.aqua import QuantumInstance, aqua_globals
     from qiskit.aqua.algorithms import VQE, NumPyMinimumEigensolver
     from qiskit.aqua.components.initial_states import Zero
     from qiskit.aqua.components.optimizers import COBYLA, L_BFGS_B, SLSQP
     from qiskit.circuit.library import TwoLocal
```

```
[2]: #Hamiltonian of the model
     H2_op = -( Z ^ Z ) - ( X ^ I) - (I ^ X)
     print(H2_op)
```

```
SummedOp([
  -1.0 * ZZ,
  -1.0 * XI,
  -1.0 * IX
])
```

```
[6]: pylab.rcParams['figure.figsize'] = (12, 8)
     for i, optimizer in enumerate(optimizers):
         pylab.plot(converge_cnts[i], converge_vals[i], label=type(optimizer).__name__)
     pylab.xlabel('Eval count')
     pylab.ylabel('Energy')
     pylab.title('Energy convergence for various optimizers')
     pylab.legend(loc='upper right');
```



Thanks for your attention