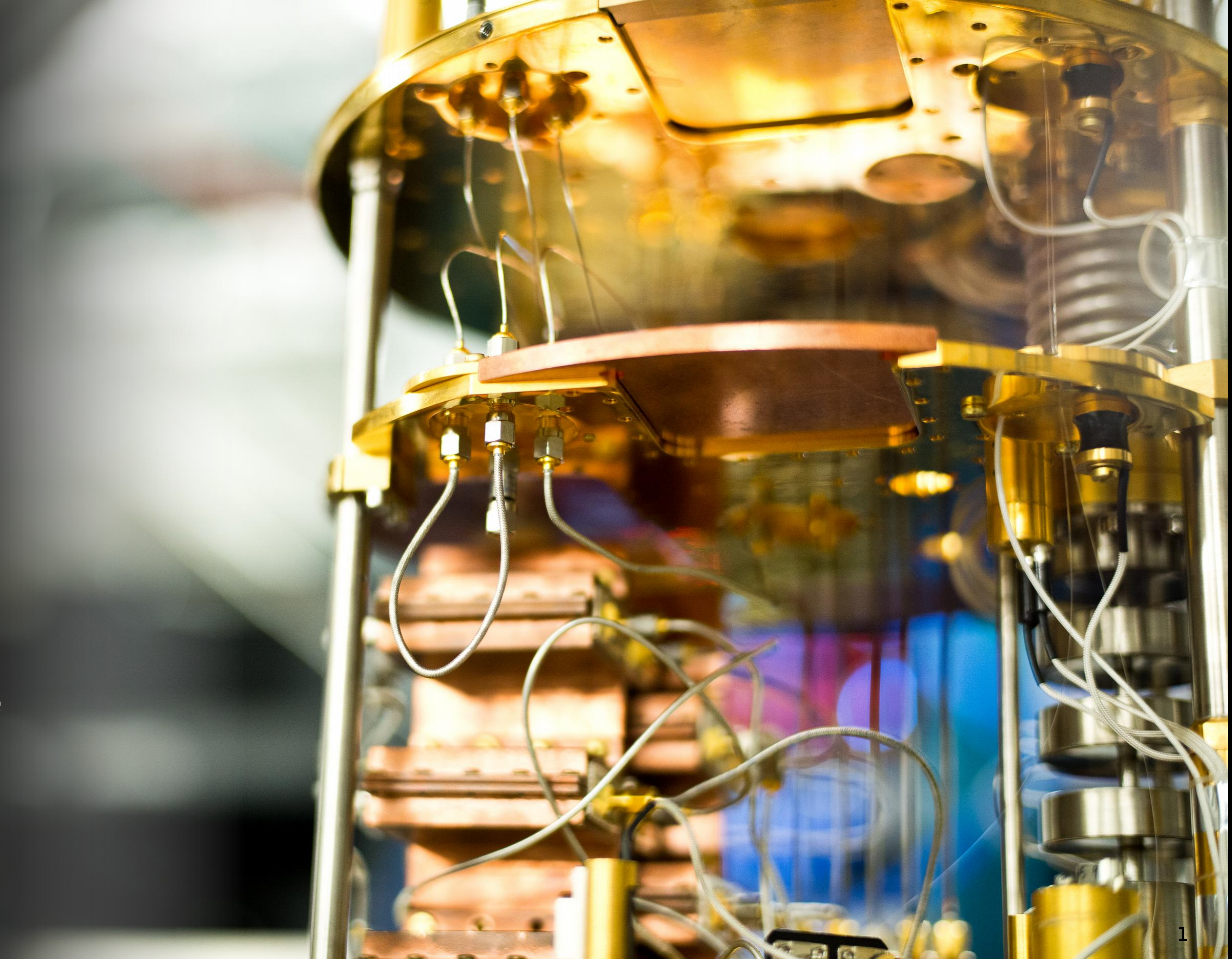
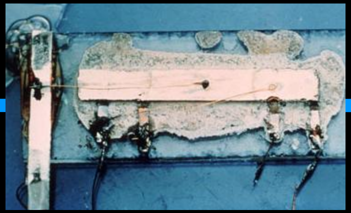
IBM Q



Ingolf Wittmann
Technical Director
Leader of HPC DACH & Europe
Leader of IBM Q Evangelist Europe

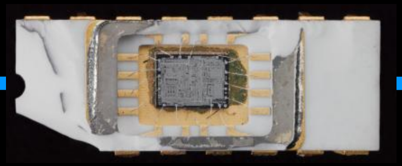
Why Quantum Computing? Why now?

1958



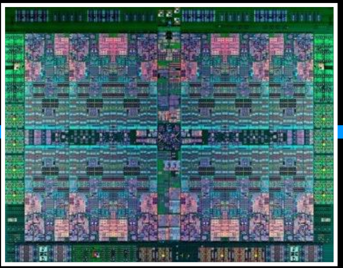
First integrated circuit
Size ~1cm^2
2 Transistors

1971

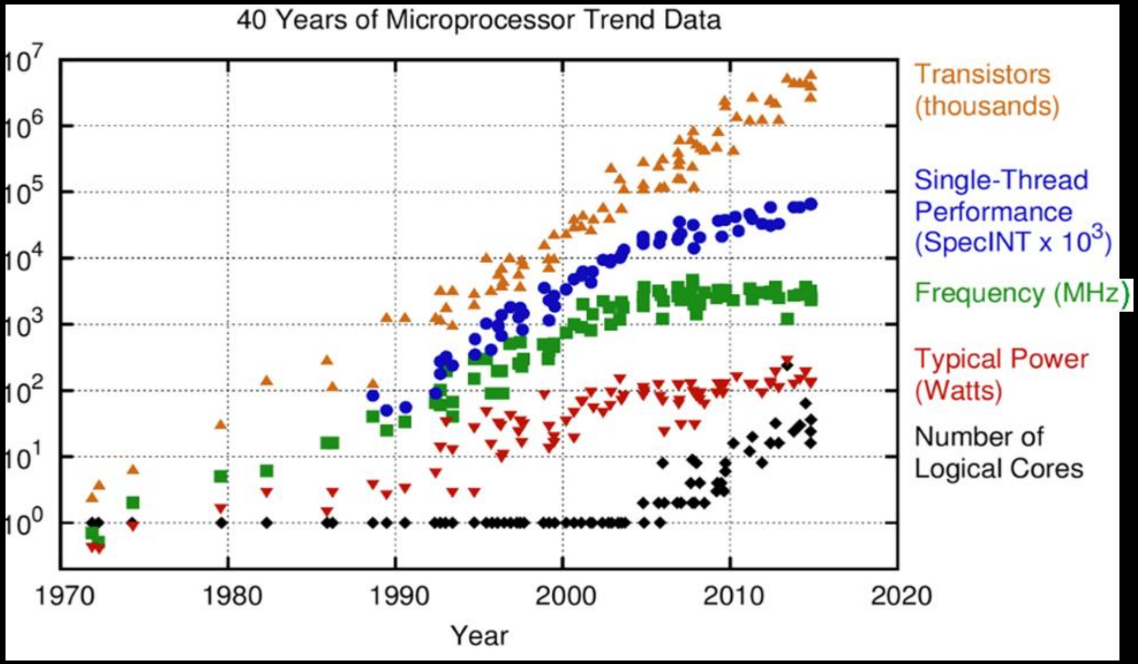


Moore's Law is Born
Intel 4004
2,300 transistors

2014

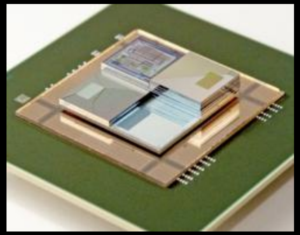


IBM P8 Processor ~ 650 mm^2
22 nm feature size, 16 cores
> 4.2 Billion Transistors



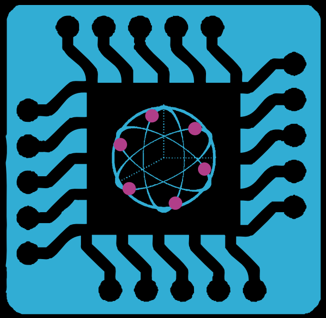
Alternative (co-existing) architectures:

next generation systems (3D/hybrid)



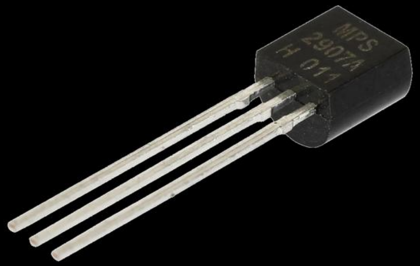
neuromorphic (cognitive)

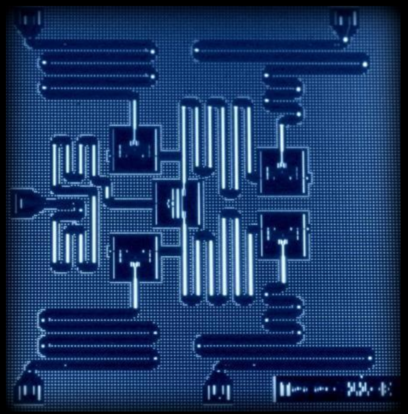
quantum computing



IBM

How to build the next evolution of computing?





?

History of Quantum Computing

Year	Event
1930er	Discovery of Quantum Mechanics
1970	Note on “quantum information theory” from Charlie Bennett (today IBM Fellow) and Stephen Wiesner
1981	Richard Feynman suggests to build a quantum computer
1984	Quantum key distribution Bennett/Brassard
1993	Quantum Teleportation Bennett
1994	Shor’s Factoring Algorithm
1995	Quantum Error Correction
1996	DiVincenzo Criterias to build an Quantencomputer
2001	Experimentally factoring the number 15
2004	Circuit QED
2007	The Transmon Superconducting Qubit is invented
2012	Qubit coherence time improvements
2014	Shor Algorithmus with NMR Steffen/Chuang/Vandersypen
2015	Error correction with superconductive Qubits
2016	IBM Quantum Experience & 5 Qubits
2017	The First Universal Quantum Computers for Business and Science with 20 Qubits

10 influential figures in the history of quantum mechanics. Left to right: Max Planck, Albert Einstein, Niels Bohr, Louis de Broglie, Max Born, Paul Dirac, Werner Heisenberg, Wolfgang Pauli, Erwin Schrödinger, Richard Feynman.

Source: https://en.wikipedia.org/wiki/History_of_quantum_mechanics

A Few Years Ago

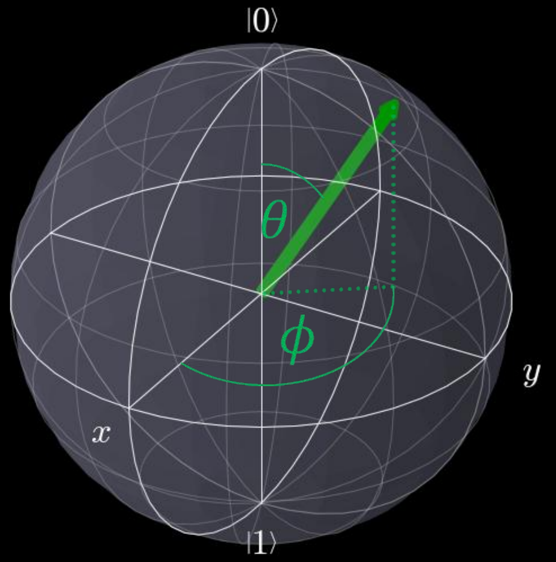
$$H_{eff} = \sum_i (\omega_i - \delta_{i/2}) b_i^+ b_i + \frac{\delta_i}{2} b_i^+ b_i b_i^+ b_i + J_{ij}(b_i^+ b_j + b_i b_j^+)$$

“I think I can safely say that nobody understands quantum mechanics.”

— Richard Feynman

A new model of computation

Quantum Applications is about working out how to use two principles, superposition and entanglement in a new model of computation



Superposition

A single quantum bit (qubit) can exist in a superposition of 0 and 1, and n qubits allow for a superposition all possible 2^n combinations

Entanglement

The states of entangled qubits cannot be described independently of each other

What are the basic units of information ?

Bit state: 0 or 1
Multi-bit effects: none

0

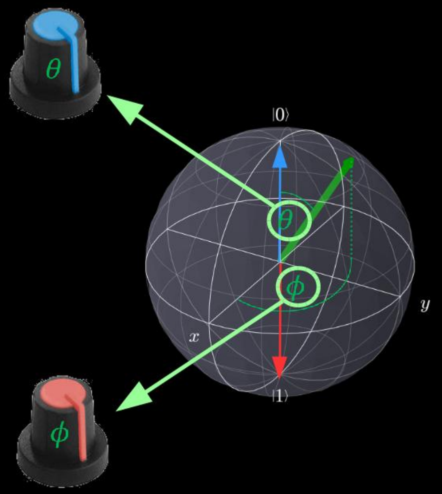
1

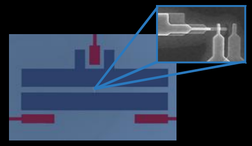
Silicon Structure
< 20 nm

∞

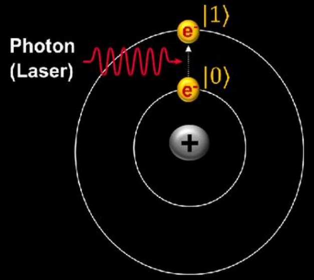
0 – 50° C

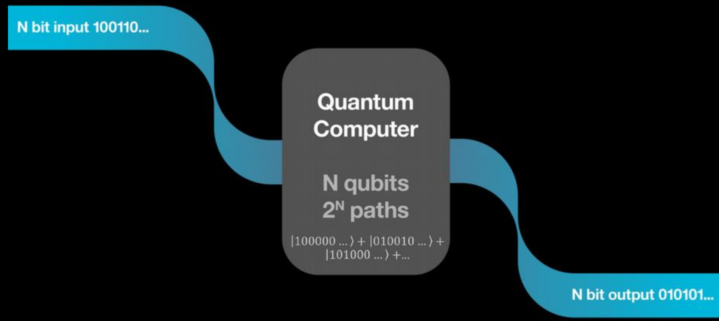
Qubit state: 0 and 1, at the same time (= superpostion)
represented by point on (Bloch-)Sphere
Multi-qubit effects: entanglement





Atoms
Electrons
Photons





100+ ms

20 mK

classical | *quantum*

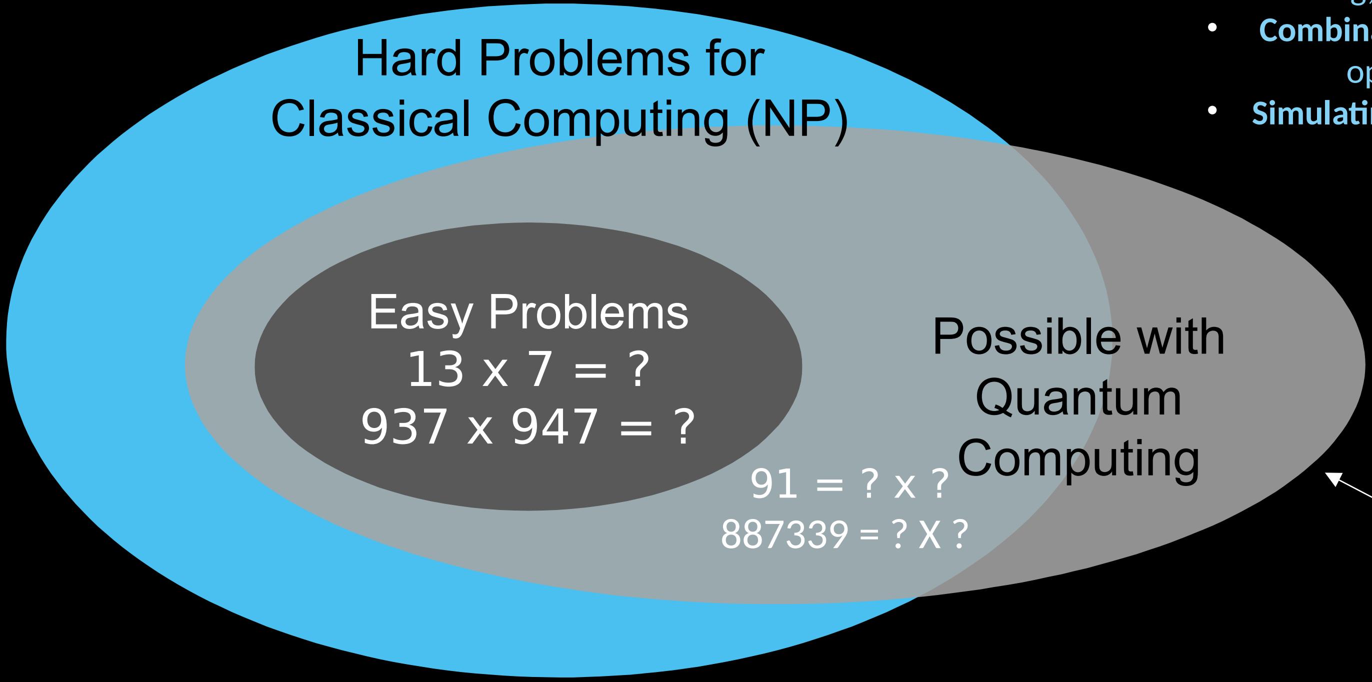
IBM

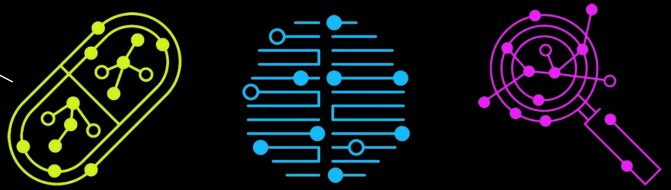
Quantum Computing as a path to solve intractable problems

Many problems in business and science are too complex for classical computing systems

“<u>hard</u>” / intractable problems:
(exponentially increasing resources with problem size)

- **Algebraic algorithms** (e.g. factoring, systems of equations) for machine learning, cryptography,...
- **Combinatorial optimization** (traveling salesman, optimizing business processes)
- **Simulating quantum mechanics** (chemistry, material science,...)





Material, Chemistry

Machine Learning

Optimization

Example: Shor's Algorithms

The problem of multiplication vs factoring:

937 x 947 = N (easy)

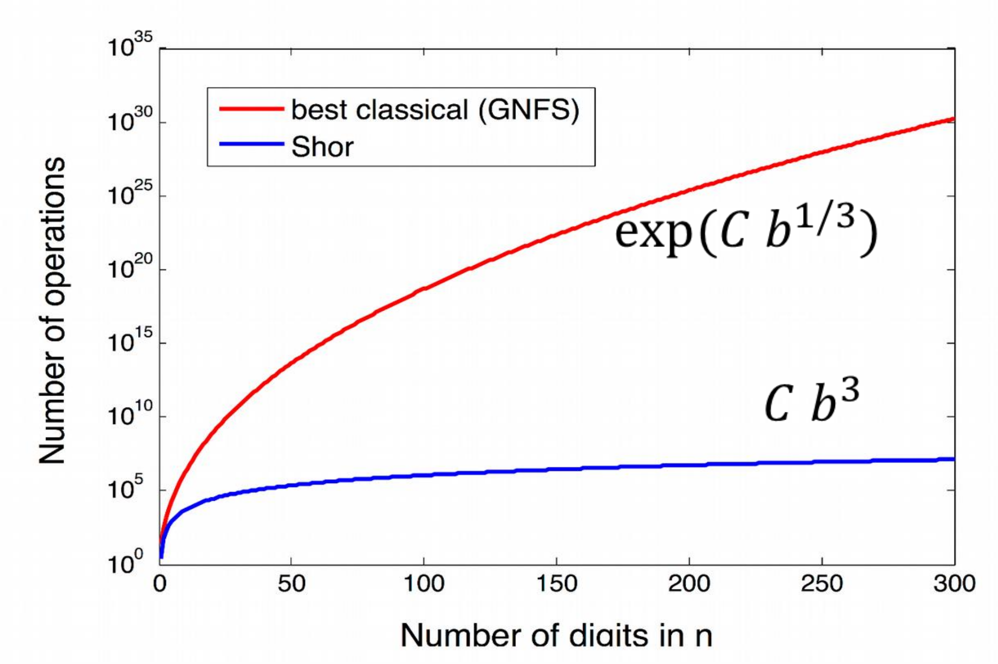
887339 = p x q (harder)

1024bit public key:

Modulus (1024 bits):
de b7 26 43 a6 99 85 cd 38 a7 15 09 b9 cf 0f c9
c3 55 8c 88 ee 8c 8d 28 27 24 4b 2a 5e a0 d8 16
fa 61 18 4b cf 6d 60 80 d3 35 40 32 72 c0 8f 12
d8 e5 4e 8f b9 b2 f6 d9 15 5e 5a 86 31 a3 ba 86
aa 6b c8 d9 71 8c cc cd 27 13 1e 9d 42 5d 38 f6
a7 ac ef fa 62 f3 18 81 d4 24 46 7f 01 77 7c c6
2a 89 14 99 bb 98 39 1d a8 19 fb 39 00 44 7d 1b
94 6a 78 2d 69 ad c0 7a 2c fa d0 da 20 12 98 d3

= p × q

→ just short of impossible



Classical Record: 320 digits (2^{1061}; >300 CPU years)

Exponential speed-up:
A task taking 300 years (2^{33} seconds) on a classical computer might take a minute (~ 30 seconds) on a quantum computer

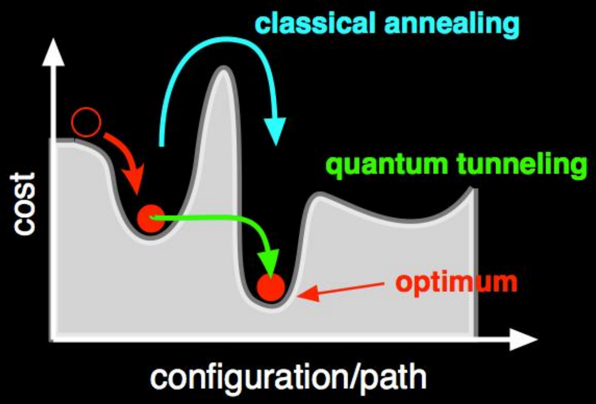
Shor's algorithm jumpstarted the interest in quantum computing

Types of Quantum Computing

Quantum Annealing

Optimization Problems

- Machine learning
- Fault analysis
- Resource optimization
- etc…

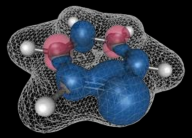


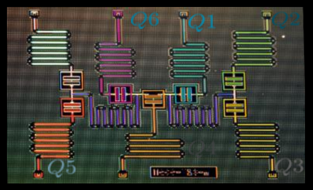
Many 'noisy' qubits can be built;
large problem class in optimization;
amount of quantum speedup unclear

Approximate Q-Comp.

Simulation of Quantum Systems, Optimization

- Material discovery
- Quantum chemistry
- Optimization (logistics, time scheduling,…)
- Machine Learning



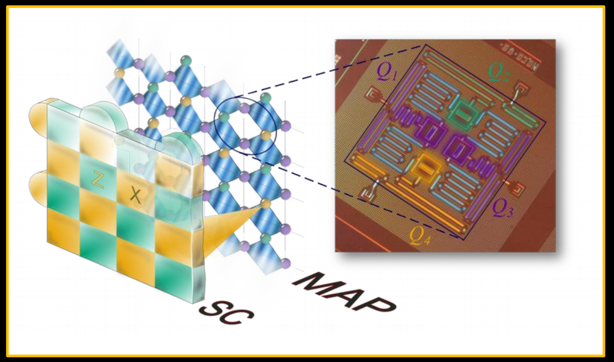


Hybrid quantum-classical approach;
already 50-100 "good" physical qubits could provide quantum speedup.

Fault-tolerant Universal Q-Comp.

Execution of Arbitrary Quantum Algorithms

- Algebraic algorithms (machine learning, cryptography,…)
- Combinatorial optimization
- Digital simulation of quantum systems



Surface Code: Error correction in a Quantum Computer

Proven quantum speedup;
error correction requires significant qubit overhead.

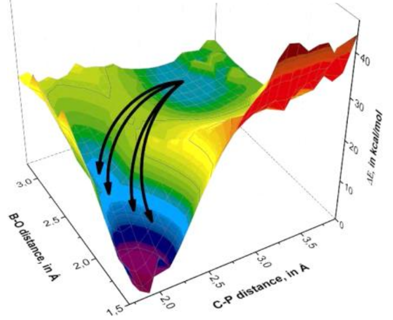
IBM

Applications and use cases

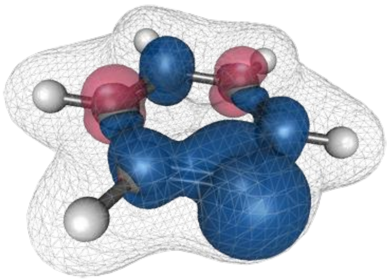
Initial applications will leverage algorithms that can tolerate or mitigate errors found in approximate quantum computers. Research & development for commercial use cases must be focused on selecting algorithms and determining how to best map problems to them.

Quantum Chemistry

Reaction pathways

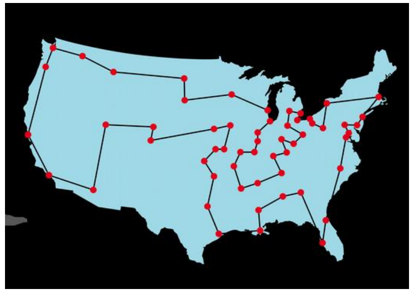


Molecule geometry

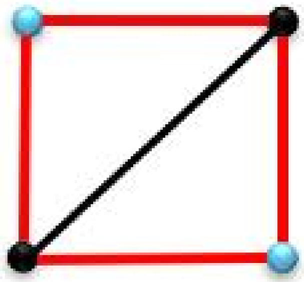


Optimization

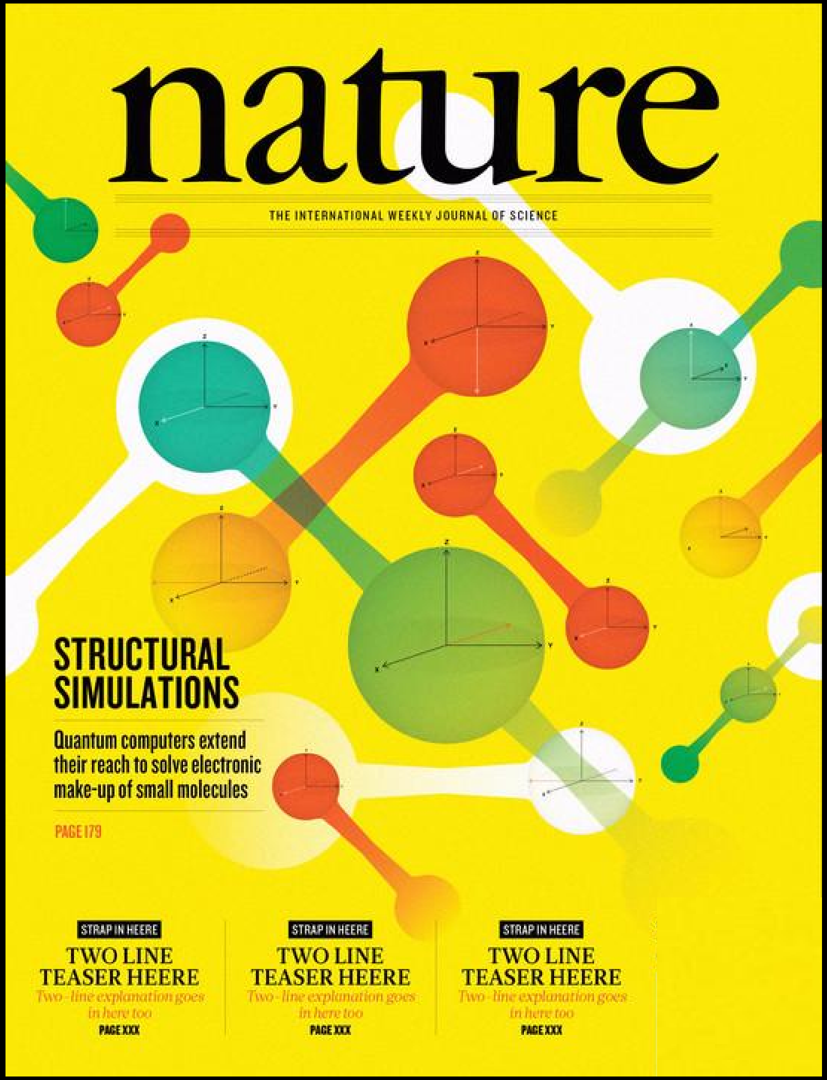
Traveling Salesman



Max Cut

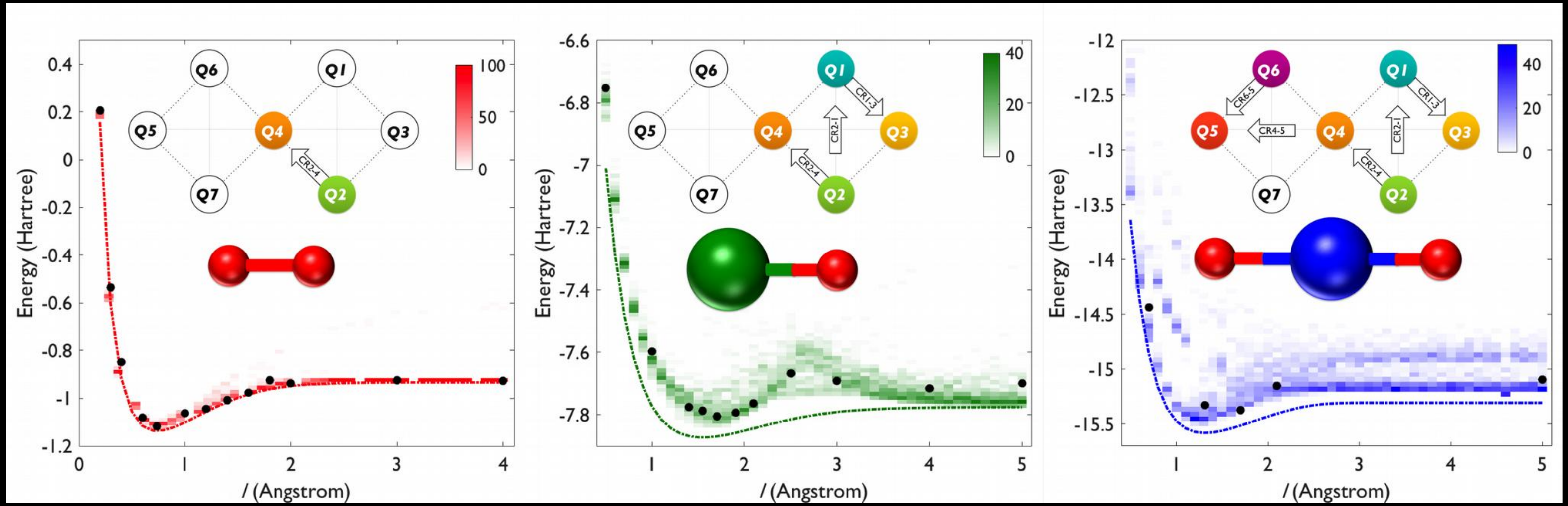


Algorithmic Building Blocks for Chemistry



World's first demonstration of modeling LiH and BeH2 using a quantum computer.

2 qubits | 4 qubits | 6 qubits



N electrons ~ N qubits

Potential Near Term Applications

Physical Sciences and Chemistry

- Electronic structure calculations (e.g. catalysts, fertilizers, battery chemistry)
- Compound chemical optimization (e.g. for drug-target interactions)
- Generation of small molecule drug candidates
- Reaction rates and reaction pathways analysis

Artificial Intelligence

- Support Vector Machine Classifier
- Eigenvalue decomposition
- Topological data analysis
- Quantum approximate Boltzmann machine
- Approximate Fourier Transform
- Quantum-assisted quantum process regression
- Quantum network analysis

Optimization

- Variational Monte Carlo
- Semi-definite programming
- Combinatorial optimization (Max Cut, Traveling Salesman, Graph Partitioning, etc.)

There are many difficult problems that classical computers can't solve well.

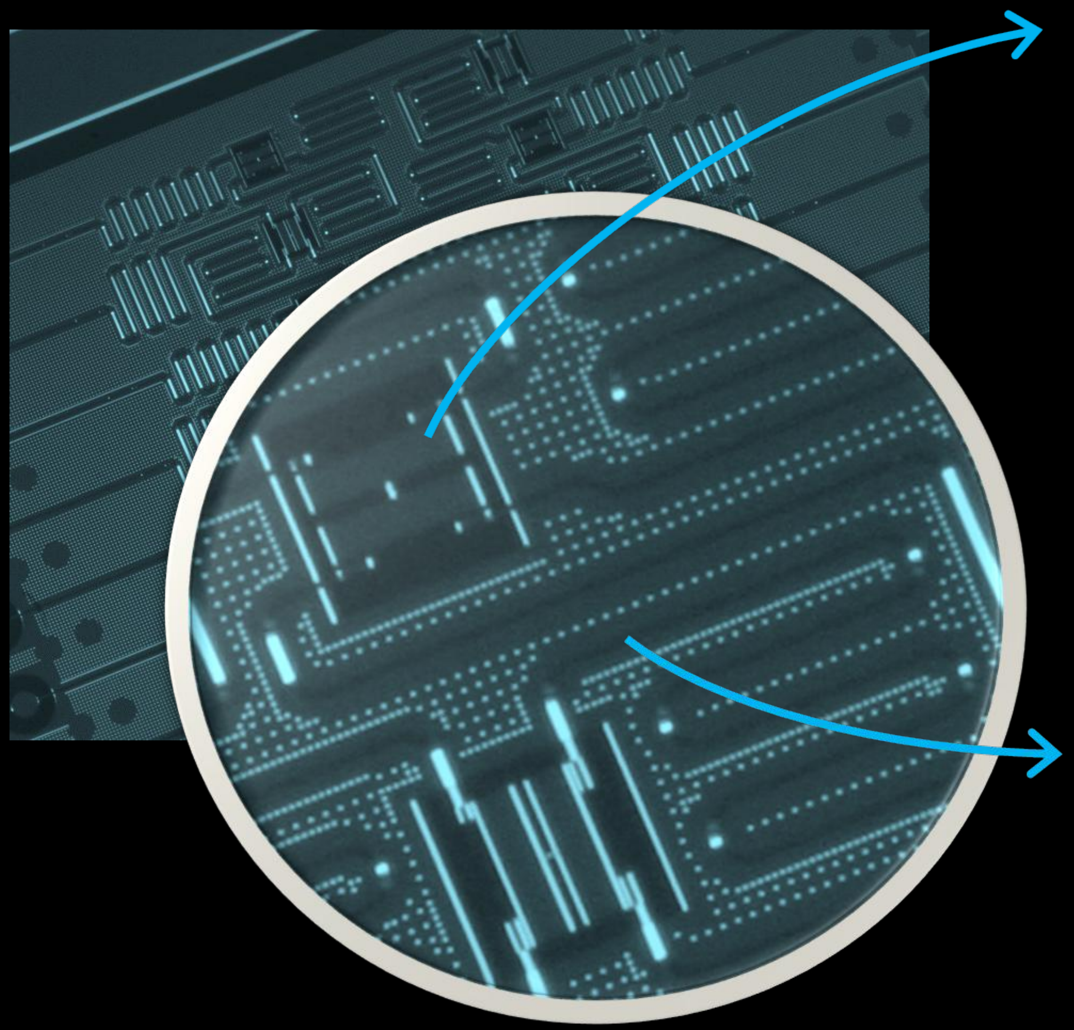
Some of these are good candidates for a quantum computer to solve.

We don't know what the first commercial applications will be.

But progress is rapid...and the race is on.

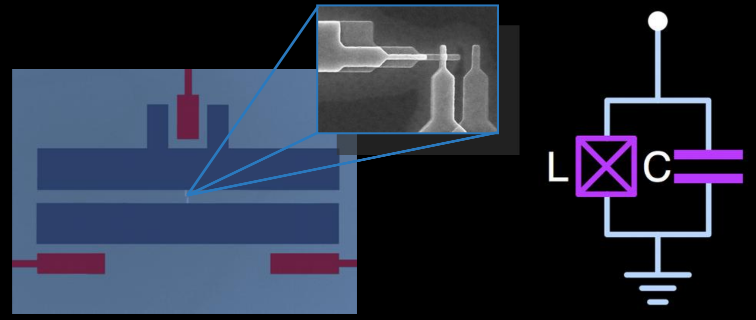
The winners may gain dominant commercial advantages in their industry.

IBM: Superconducting Qubit Processor



Superconducting qubit

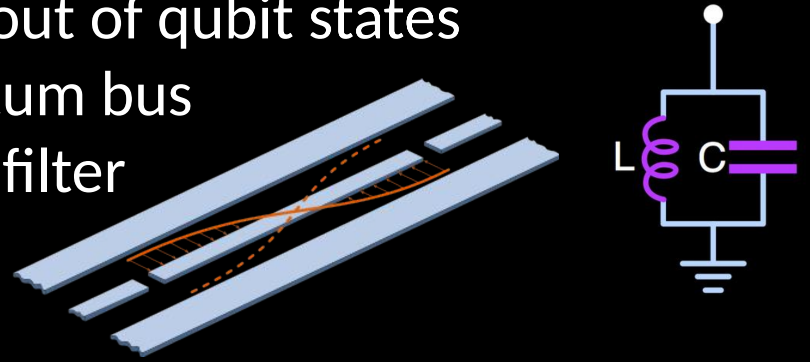
- quantum information carrier



$E_{01} \approx 5\ GHz \approx\ 240\ mK$

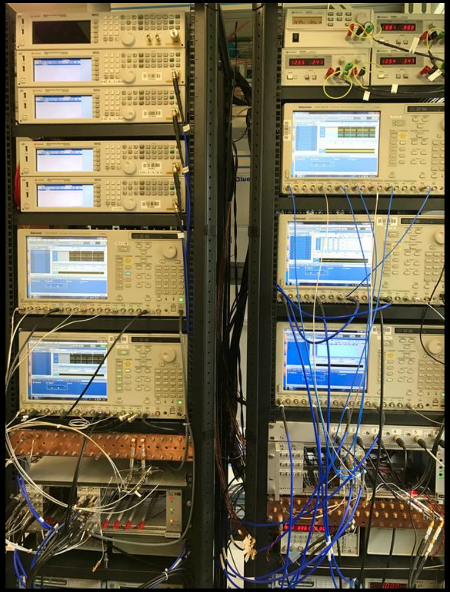
Microwave resonator:

- read-out of qubit states
- quantum bus
- noise filter

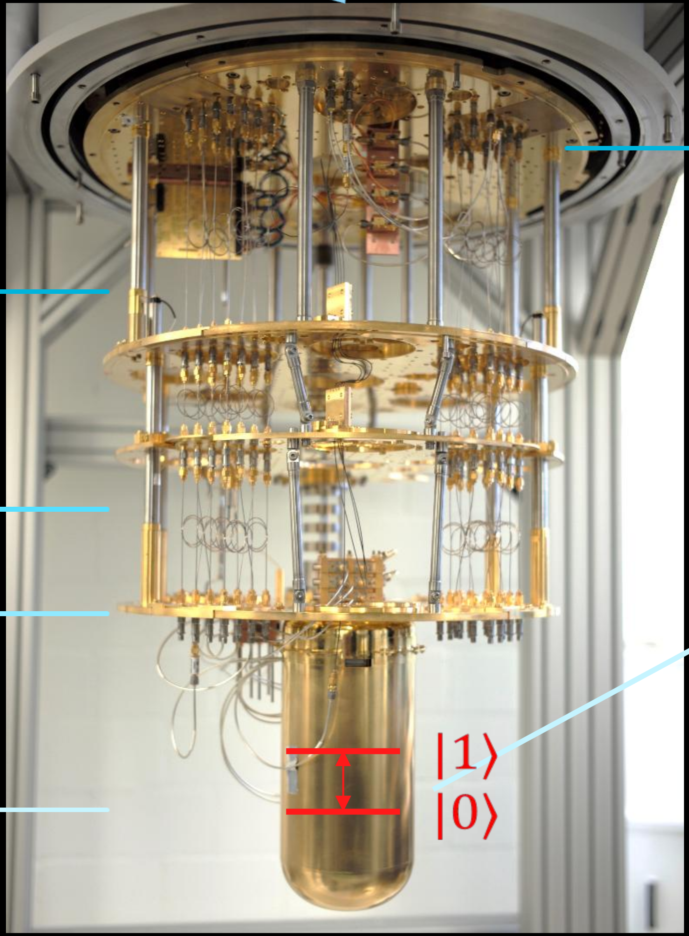


IBM

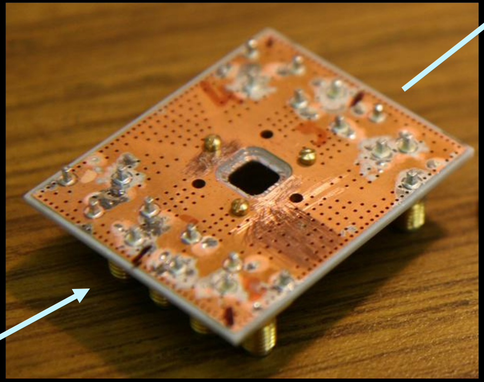
Measurement setup



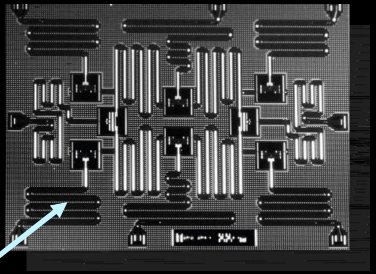
Microwave electronics



Dilution cryostat

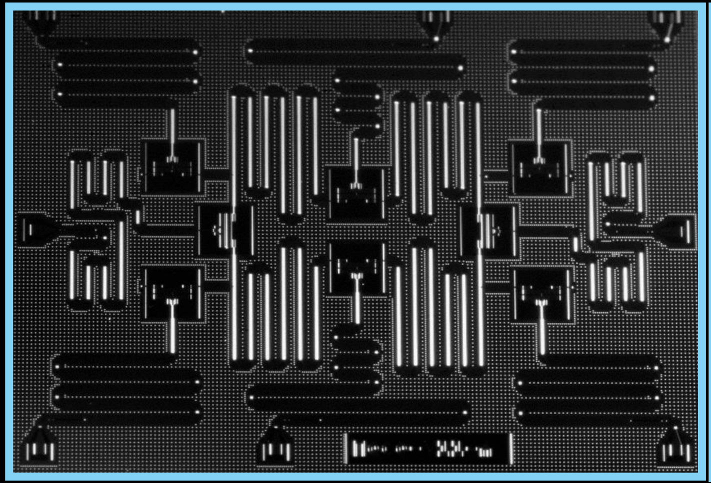


PCB with the qubit chip at 20mK
Protected from the environment by multiple shields

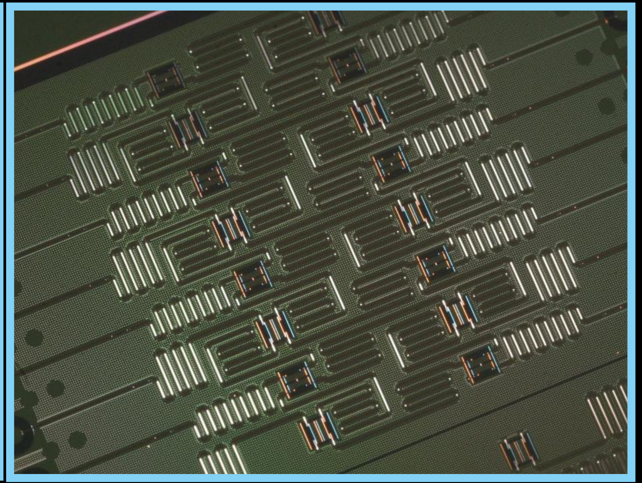


Chip with superconducting qubits and resonators

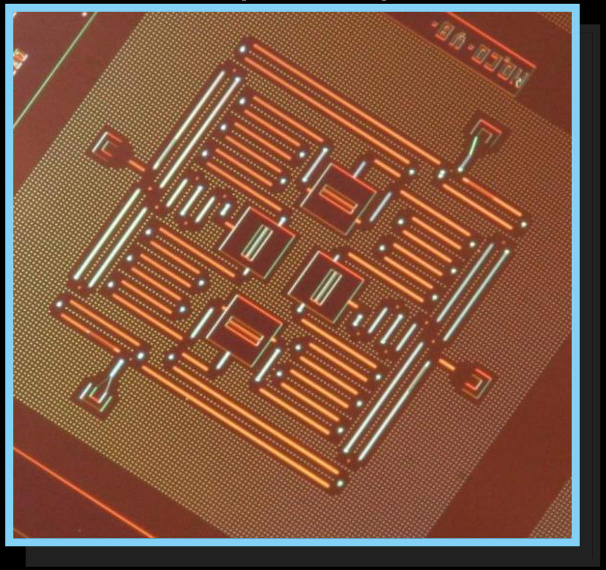
8 Qubits (2016)



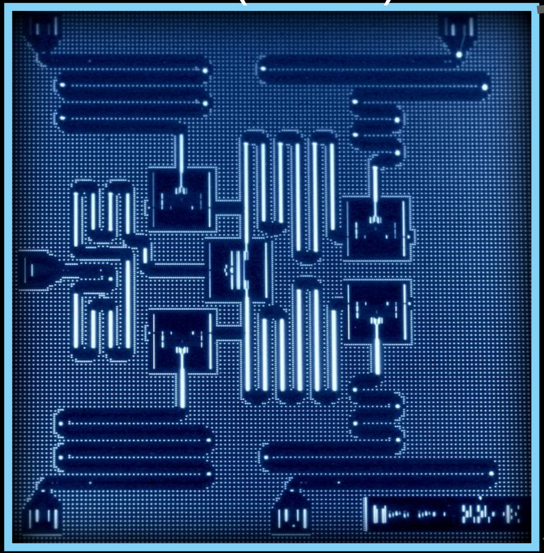
16 Qubits (2017)

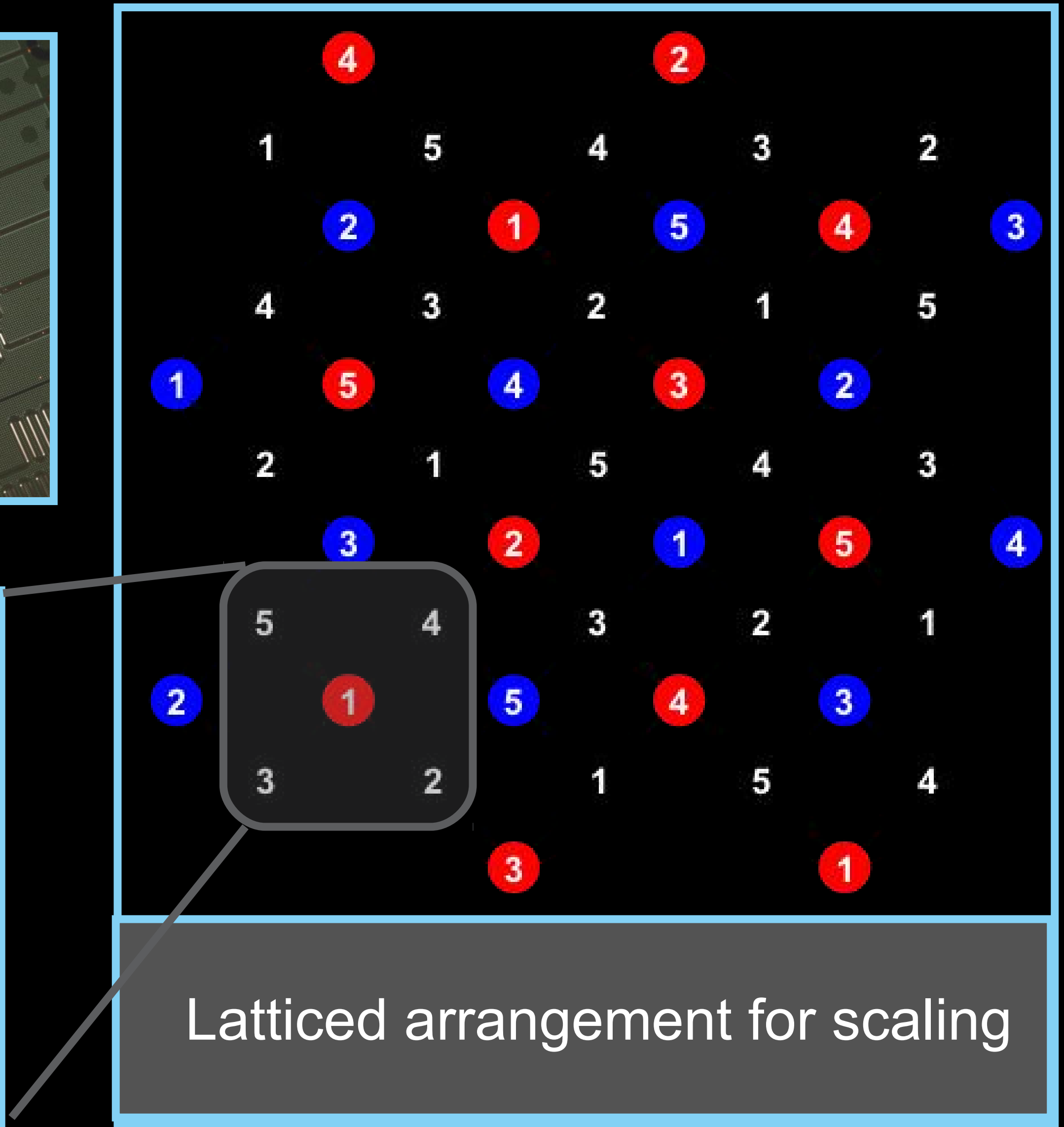


4 Qubits (2015)



5 Qubits (2016)





Latticed arrangement for scaling

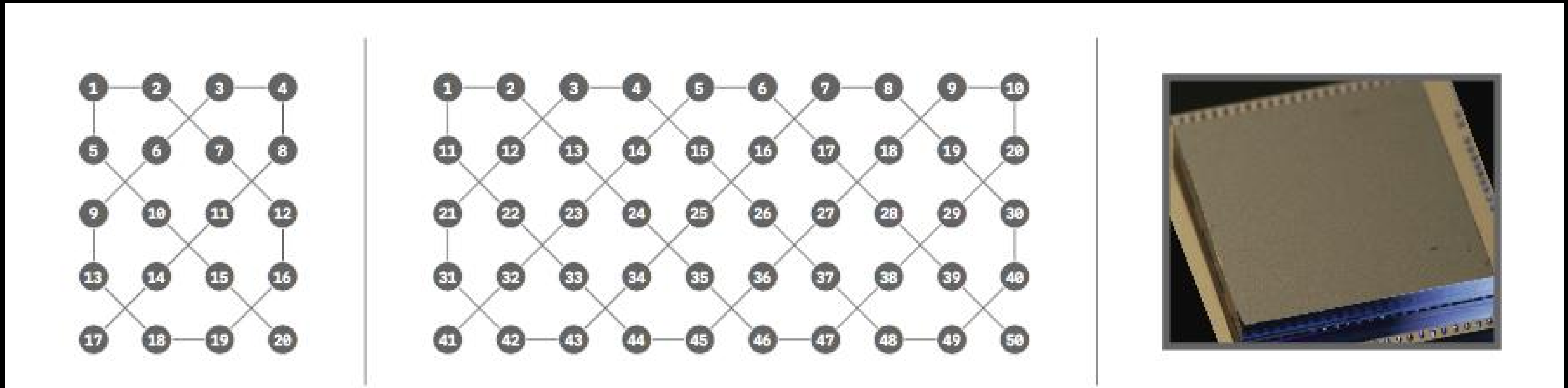
05/2016: 5 Qubits hosted on IBM Quantum Experience
05/2017: 16 Qubits on Quantum Experience; next generation: 17 Qubits on IBMQ (commercial)
11/2017: 20 Qubits on IBMQ

IBM

IBM Q Systems

IBM Q

50 qubit system operational
20 qubit systems ready for use

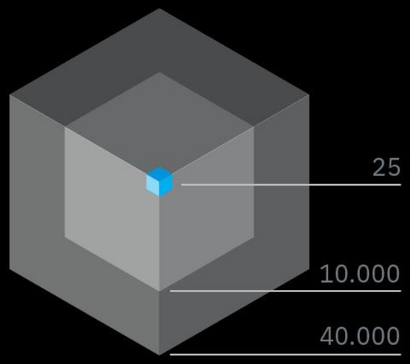


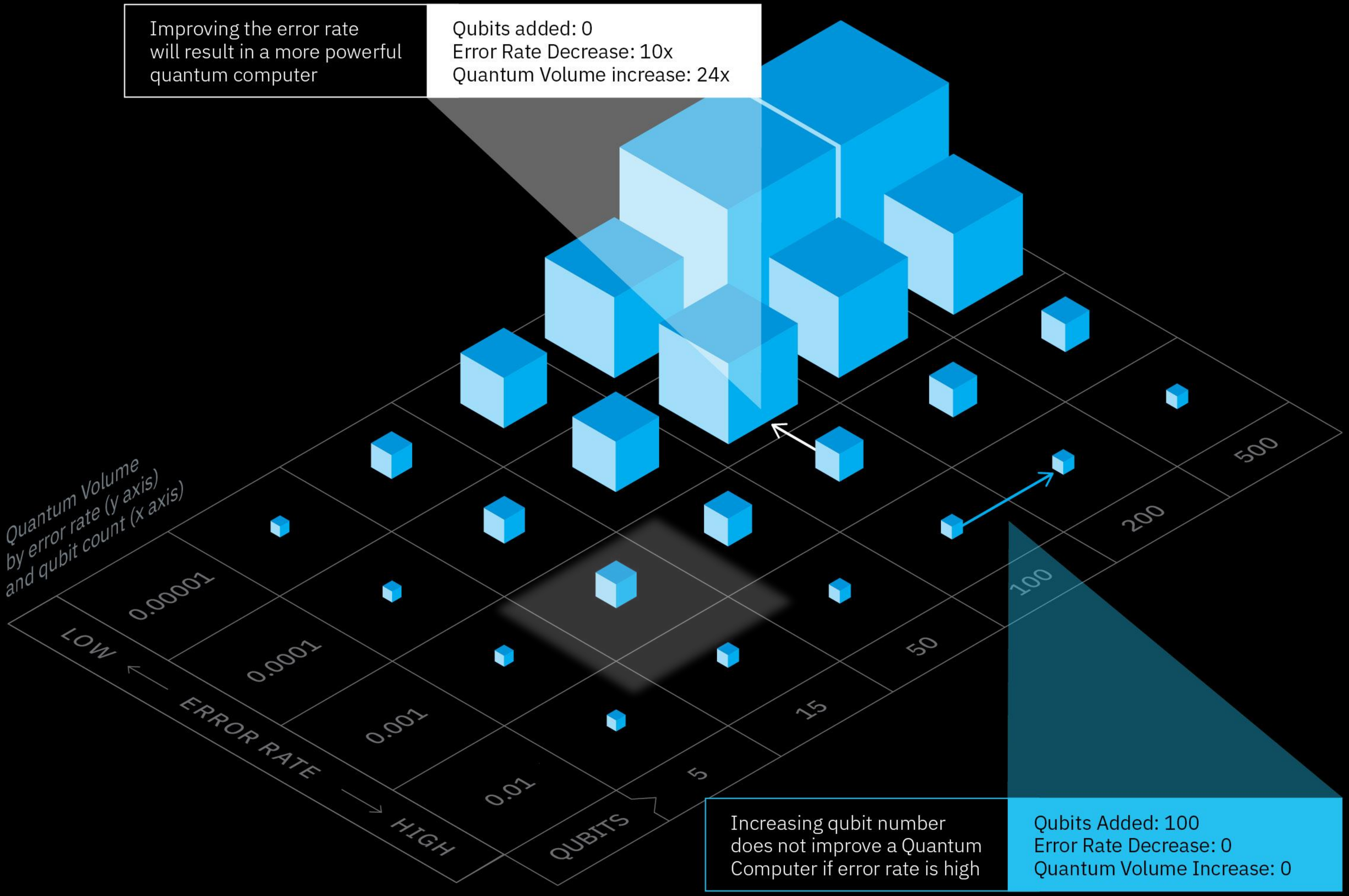
Average coherence ~90 microseconds and high fidelity

IBM Q Systems are the next more advanced generation of universal quantum computers. This new generation of systems will form the basis for applied research that will lead to commercial advantage.

Quantum Volume

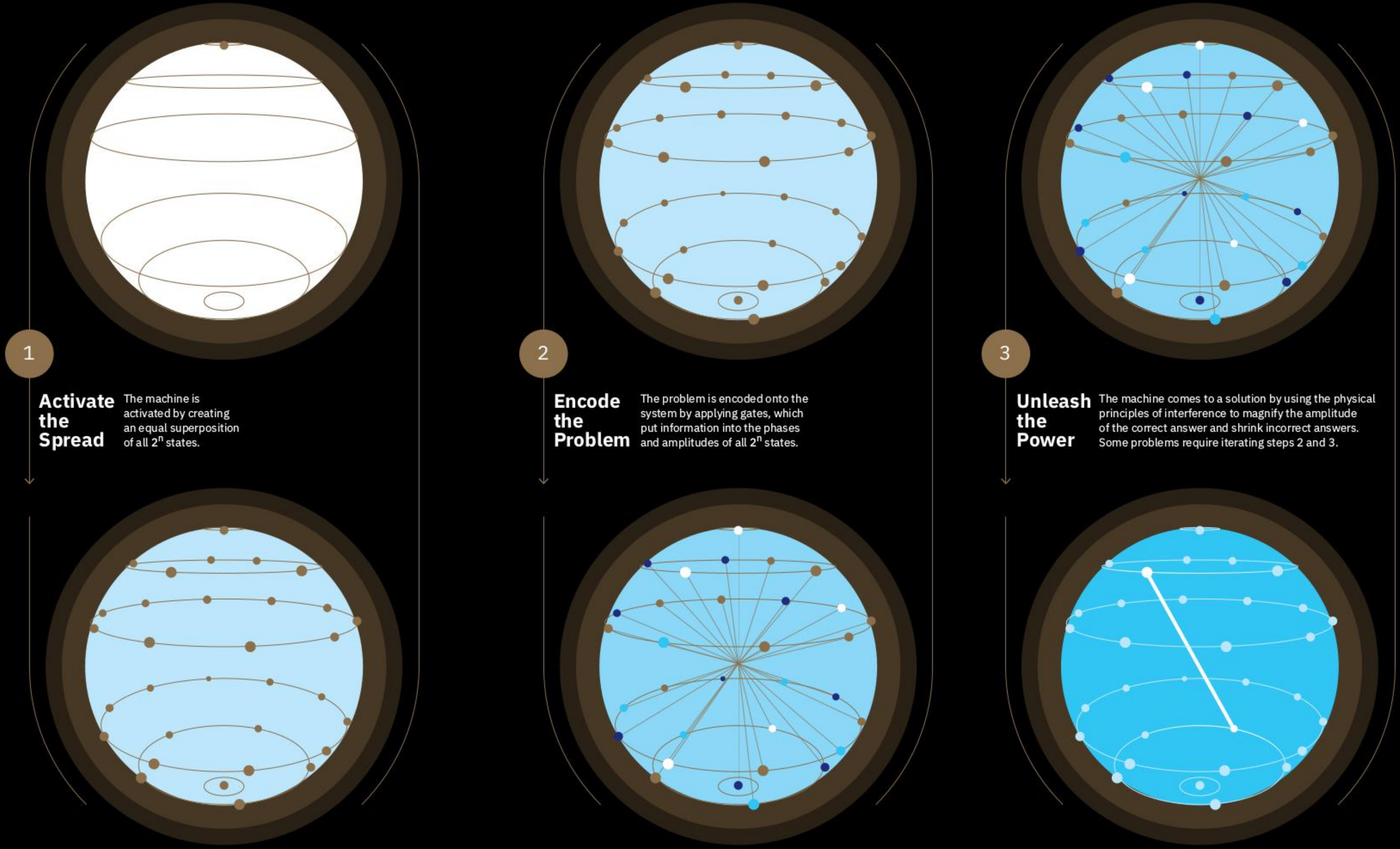
Volume of cube proportional to useful quantum computing that can be done





Source:
IBM Research

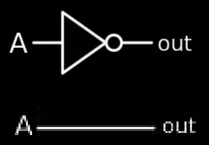
How does Quantum Computer compute?



Quantum logic … foundation for a programming model

Bit

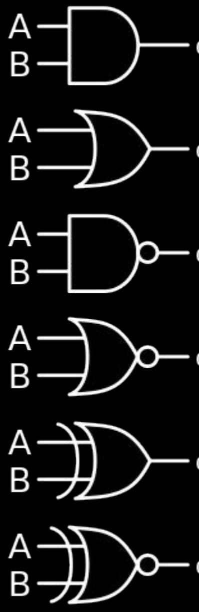
1 Bit Gates



NOT

ID

2 Bit Gates



AND

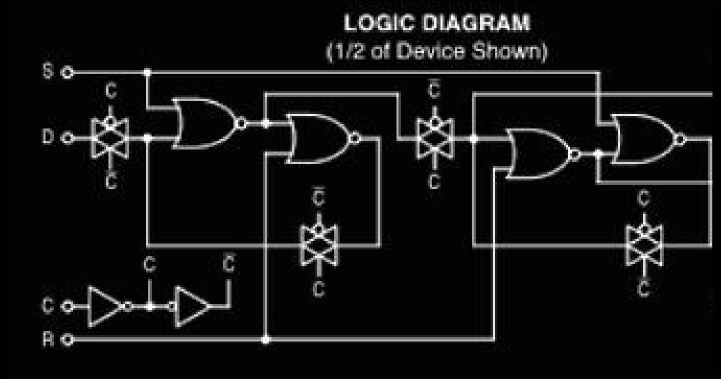
OR

NAND

NOR

XOR

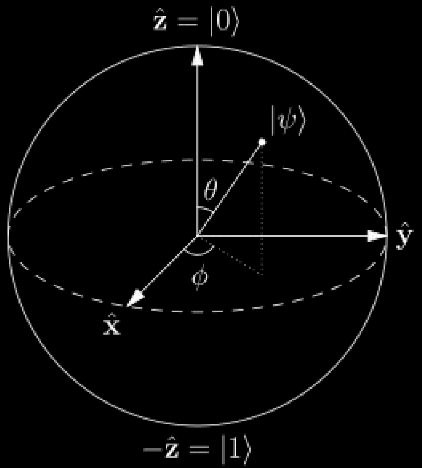
XNOR



Qubit

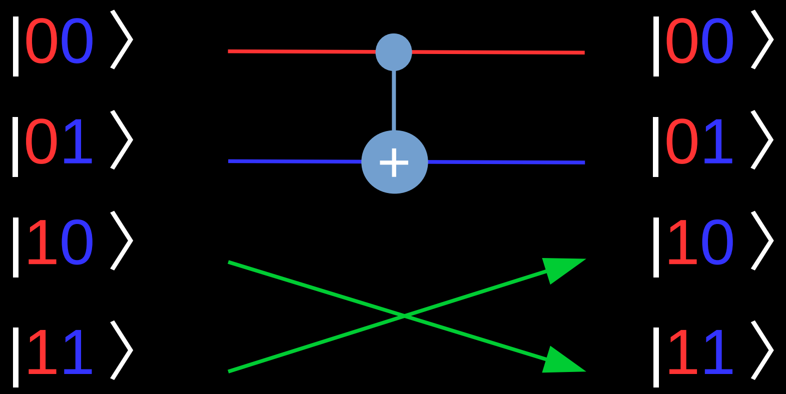
IN

OUT



1-qubit Gate
→ Rotation of Bloch-Sphere
→ Adding to length and latitudee

2-qubit Gate: CNOT
→ Controlled NOT
→ Exchange of $|10\rangle$ and $|11\rangle$



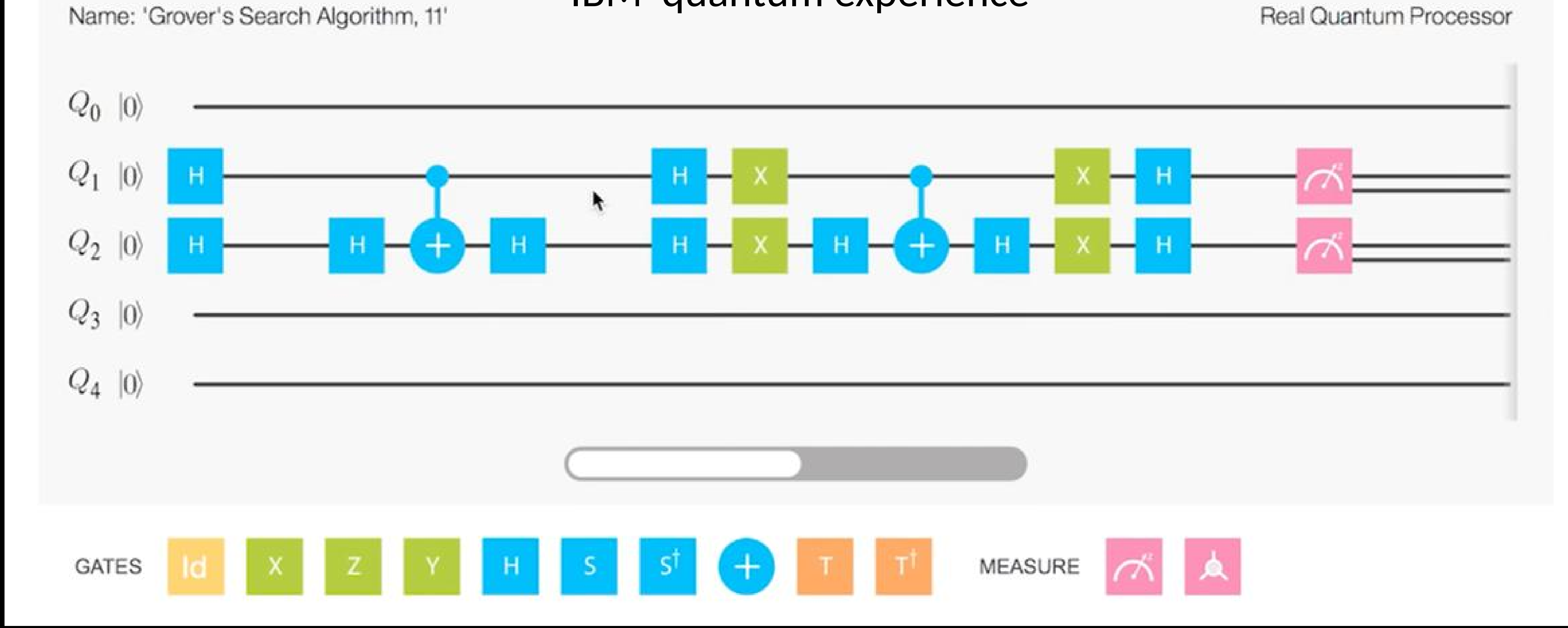
The Road to Commercial Applications

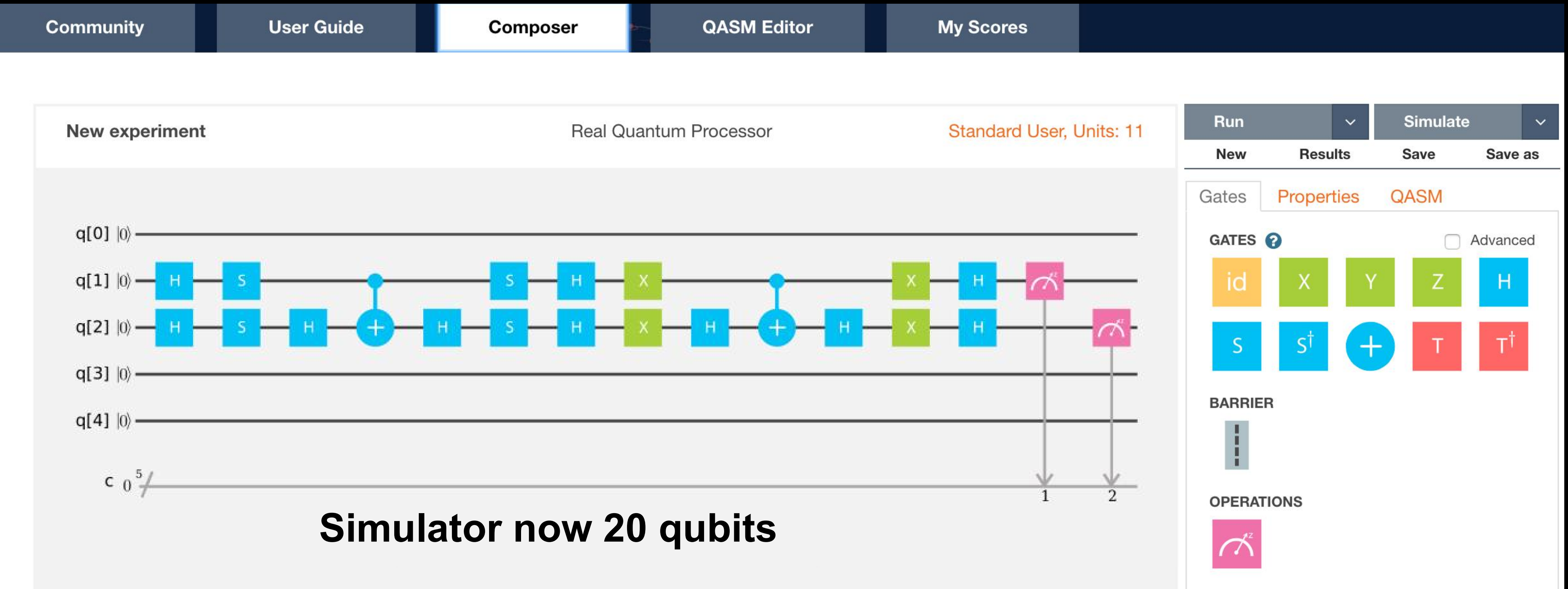
Quantum ready means applying rapidly advancing fundamental quantum computing capabilities to **specific problems in business and science** to find the first commercial applications.

Gate based quantum computing

evolve initial states via discrete gates towards final state, the solution

IBM ‘quantum experience’

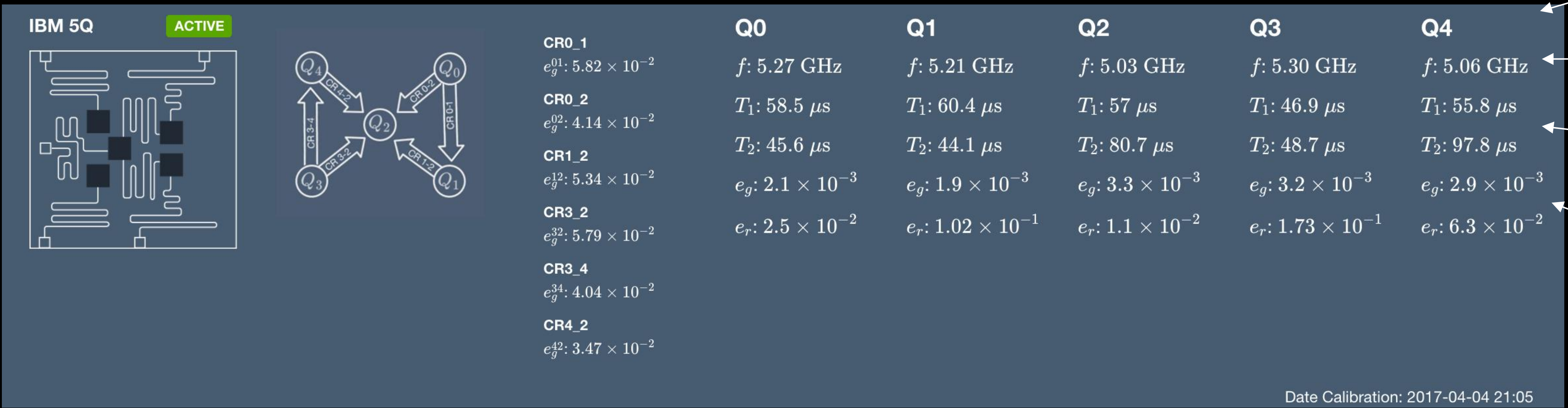




Simulator now 20 qubits

Quantum gates

5-qubits



Each a diff. freq.

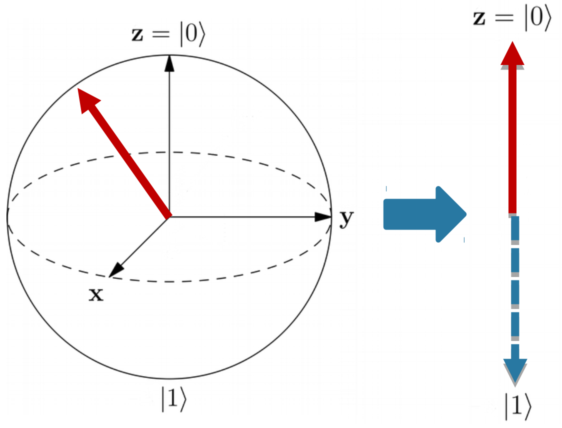
Good coherence

Low error rates

Quantum gates

measurement

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

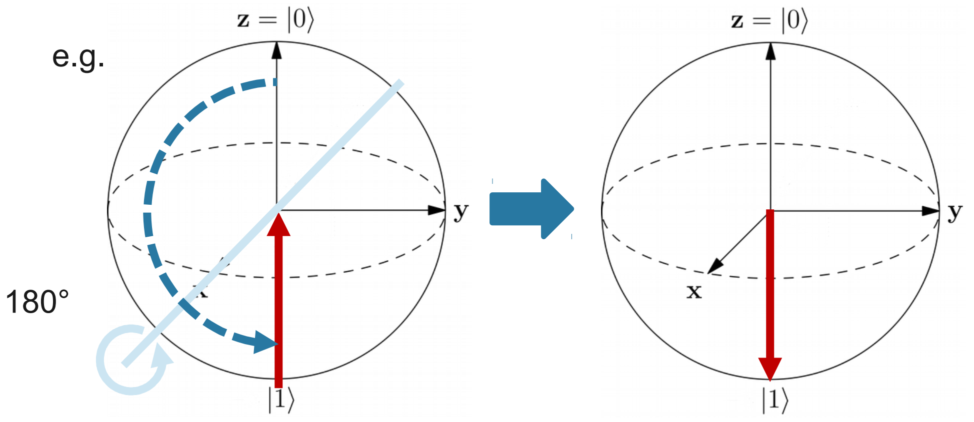


probability

either $|\alpha|^2$

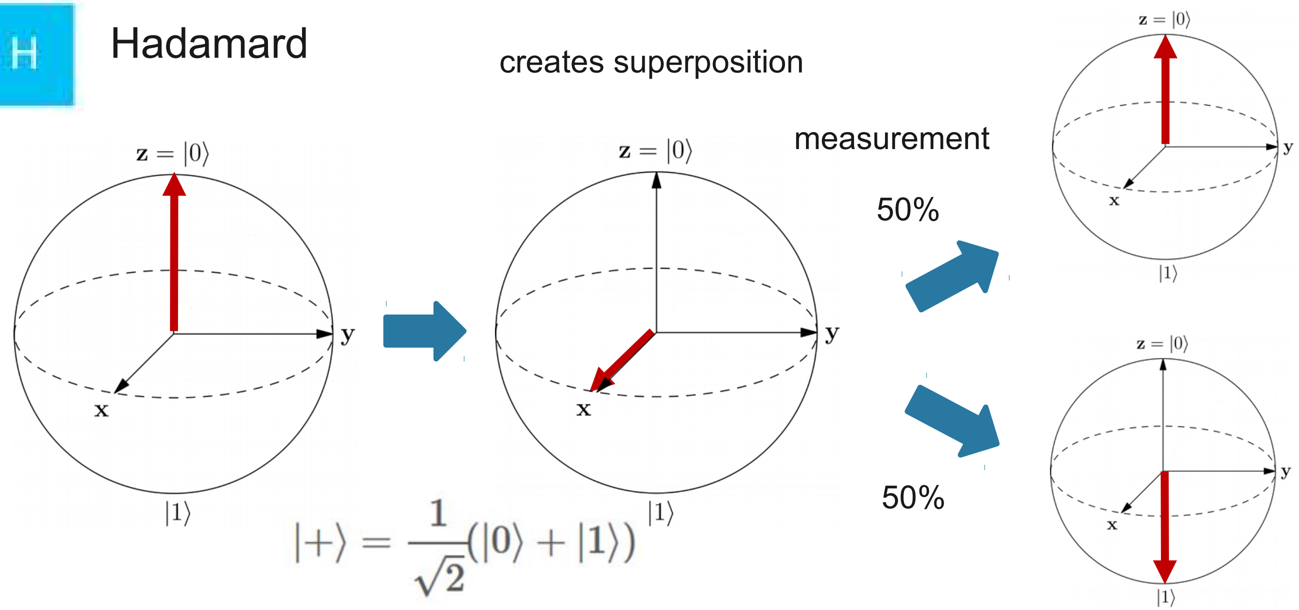
or $|\beta|^2$

X Z Y rotations



H Hadamard

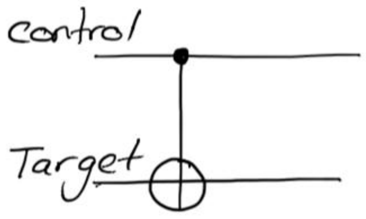
creates superposition



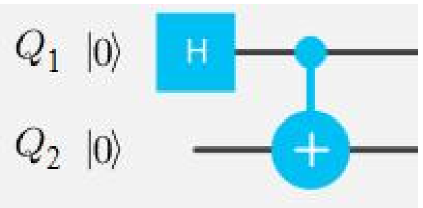
$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$$

controlled-NOT

for entanglement



e.g.



→ no classical equivalent exists

Today: IBM QISKit - an SDK for

jupyter Superposition+Entanglement+Bell+States+and+the+CHSH+inequality (unsaved changes) Logout

File Edit View Insert Cell Kernel Widgets Help Python 3

Markdown CellToolbar

IBM Quantum

Superposition, Entanglement, Bell states, and the C with the Python Interface for the Web API of the IBM Quantum Experience

© IBM Research

The latest version of this notebook is available on https://github.ibm.com/QuantumSD

For more information about how to use the Quantum Experience consult the IBM Qua the community.

Introduction

Many people tend to think quantum physics is hard math. This is actually not true, qua algebra classes you probably did in first year university or even at high school. What is no simple underlying theory. Instead you need to accept counter-intuitive ideas and in together we feel that these can be distilled into two principles.

1. A physical system in a perfectly definite state can still behave randomly.
2. Two systems that are too far apart to influence each other can nevertheless behav random, are somehow strongly correlated.

In [26]:

```
from IBMQuantumExperience import IBMQuantumExperience
from IPython.display import Image, display
import matplotlib.pyplot as plt
import numpy as np
import scipy as sp
import scipy.linalg
%matplotlib inline

config = {"url": 'https://quantumexperience.ng.bluemix.net/api'} # base url for the
import Qconfig
api = IBMQuantumExperience.IBMQuantumExperience(Qconfig.APIemail,Qconfig.APIpasswor

def plotHistogramData(values, labels):
    """Plot a histogram of data"""
    N = len(values)
    ind = np.arange(N)  # the x locations for the groups
    width = 0.35       # the width of the bars
    fig, ax = plt.subplots()
    rects1 = ax.bar(ind, values, width, color='r')
    # add some text for labels, title and axes ticks
    ax.set_ylabel('Probabilities')
    ax.set_xticks(ind + (width/2.))
    ax.set_xticklabels(labels)
    def autolabel(rects):
        # attach some text labels
        for rect in rects:
            height = rect.get_height()
            ax.text(rect.get_x() + rect.get_width()/2., 1.05*height,
                    '%f' % float(height),
                    ha='center', va='bottom')
    autolabel(rects1)
    plt.show()
```

Today: IBM Q Experience

First QC on the cloud

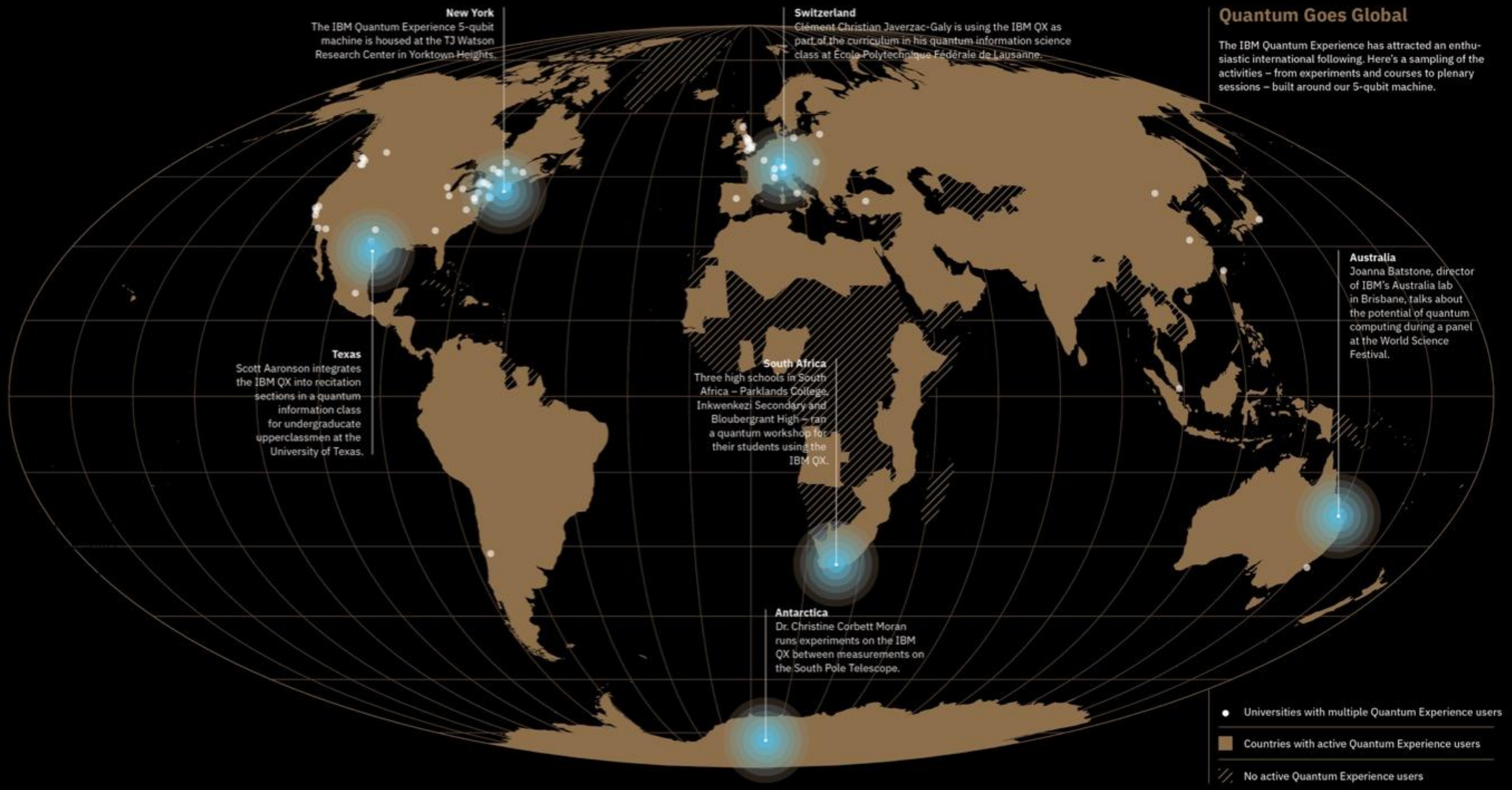
> 60,000 users

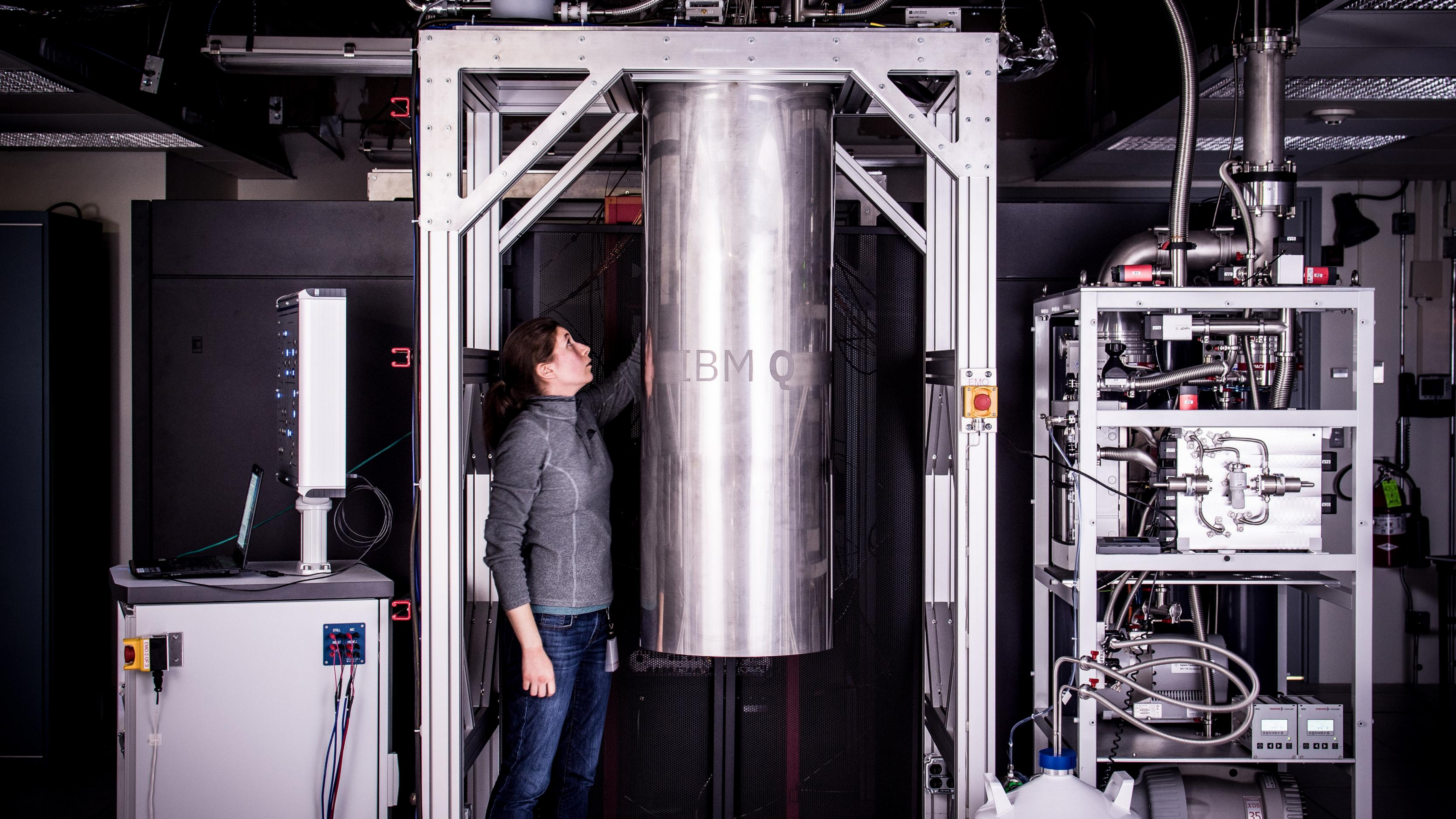
All 7 continents

> 1.7 million experiments

35+ external papers

>150 colleges and universities




IBM Q

IBM **Q** Systems

IBM Q Systems are the world’s most advanced and first commercially available universal quantum computing systems for business and science applications.

Grand Challenge: Quantum Computing

Goal:

Build computers based on quantum physics to solve problems that are otherwise intractable

Roadmap:

Small-scale (Demonstration of Quantum advantage)

- Research level demonstrations
- Verify chemistry and error correction principles
- Infrastructure & community building
- Demonstrate ‘Quantum advantage’

Medium-scale (Commercializing approximate QC)

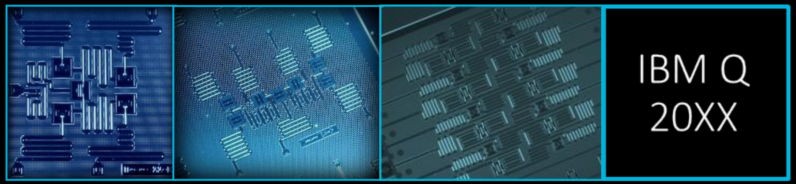
- Develop “Hardware-efficient” apps
  - Chemical configurations
  - Optimization
  - Hybrid quantum-classical computers
- No full error correction available

Large-scale (Fault-tolerant Universal QC)

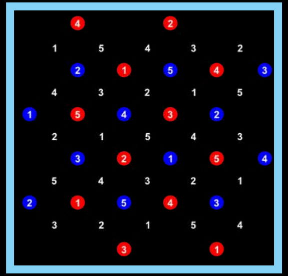
Known and proven speed-up:

- Factoring
- quantum molecular simulations
- Speed-up machine learning

Enable secure cloud computing



5-8 qubits 16 qubits 50+100 qubits

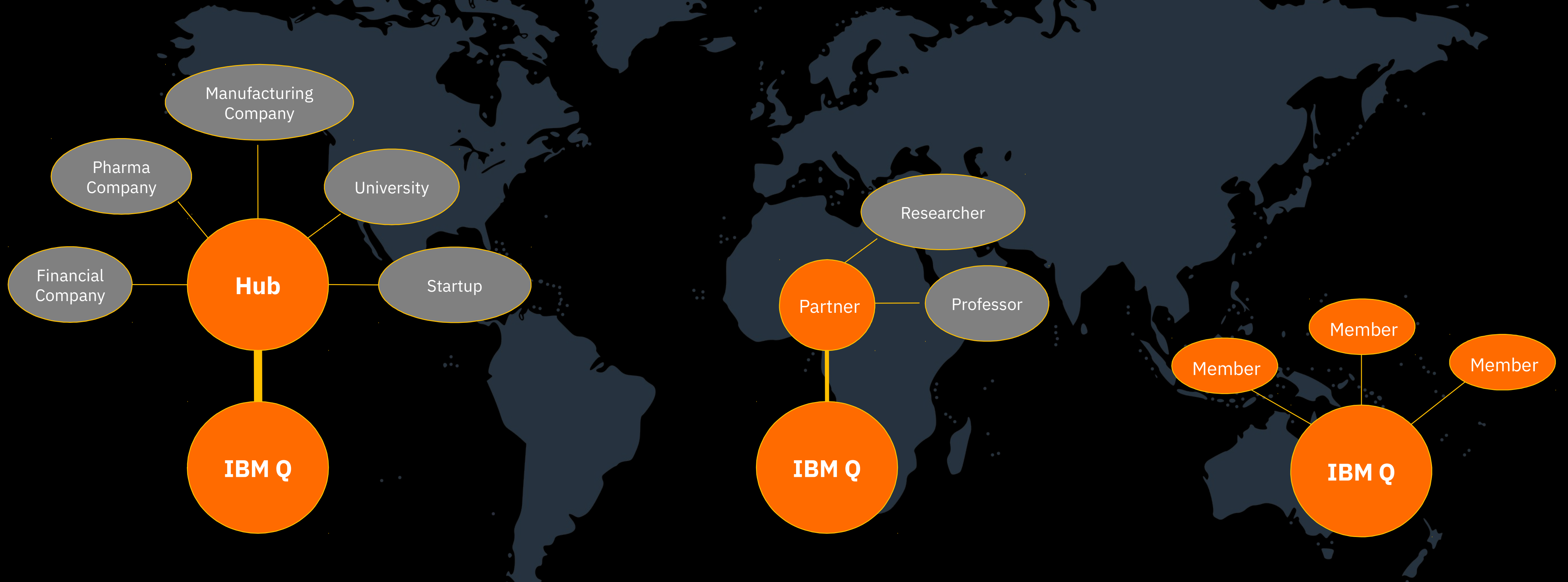


100-1000+ qubits

10^6-10^7 qubits

IBM Q Network

IBM Q Network is a **worldwide organization** of hubs, members, and partners **enabled by IBM Q systems** with the shared mission of advancing quantum computing and launching the **first commercial applications.**



Hubs

Regional centers of quantum computing R&D and ecosystem

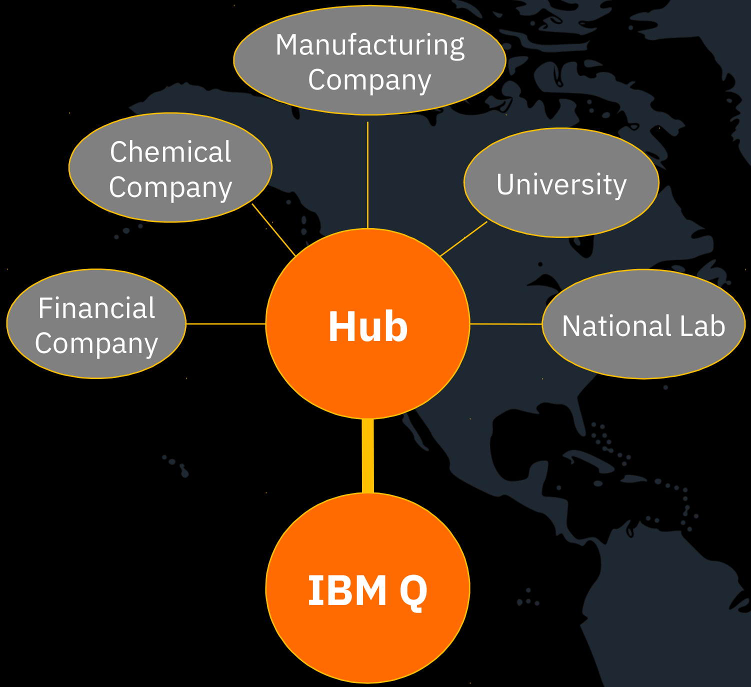
Partners

Pioneers of quantum computing in a specific industry or academic field

Members

Develop expertise and a strategy for getting quantum ready.

IBM Q Network Hubs



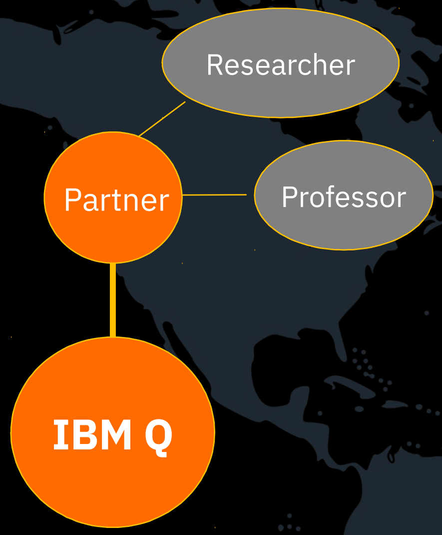
Hubs
Engage broadly and foster a large ecosystem.

IBM Q Network Hubs are organizations that are regional centers of quantum computing education, research, development, and commercialization.

Hubs deploy a hub and spoke model of engagement to scale access and enablement to many organizations and create a regional center of excellence in quantum computing.

Hubs provide access to IBM Q systems, technical support, educational and training resources, community workshops and events, and opportunities for joint work.

IBM Q Network Partners



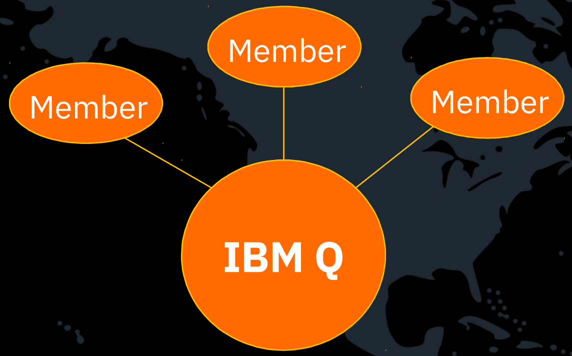
Partners
Go deep into a particular subject area with IBM.

IBM Q Network Partners are organizations that are pioneers of quantum computing in a specific industry or academic field.

Partners work closely with IBM and select individual collaborators and commit to shape how quantum computing will transform the future of their industry or field.

Partners have direct access to IBM Q systems and work closely with IBM on joint development and creation and training of an in-house team of quantum experts within the Partner organization.

IBM Q Network Members



Members

Build general knowledge and expertise working with IBM, in particular before a hub is set up in their region.

IBM Q Network Members are organizations that seek to build their general knowledge of quantum computing and to develop a strategy for getting quantum ready.

Members work with IBM directly on small projects and to build their understanding and skills base and a quantum strategy.

IBM itself acts as a hub for these Members. Members can access the resources of IBM Q and the IBM Q Network community.

IBM Q Network Launch

The founding organizations of the IBM Q Network include Fortune 500 companies and research institutions in the United States, Europe, and Asia. They include:

Hubs
- University of Oxford in the UK
- Oak Ridge National Laboratory in the USA
- Keio University in Japan
- University of Melbourne in Australia

Partners
- Daimler AG
- JPMorgan Chase
- Samsung
- JSR

Members
- Barclays
- Honda
- Hitachi Metals
- Nagase

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