Building the future of quantum computing

Dr. Fabio Scafirimuto

Workforce development, Education and Community
EMEA Lead

IBM Quantum

CINECA, Bologna – 15 Dec 2022

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IBM **Quantum**

Our mission

Bring useful quantum computing to the world

Make the world quantum safe

Our mission

Bring useful quantum computing to the world

Part I

IBM **Quantum** – On the cloud since May 2016

Over 460,000 registered users have run …

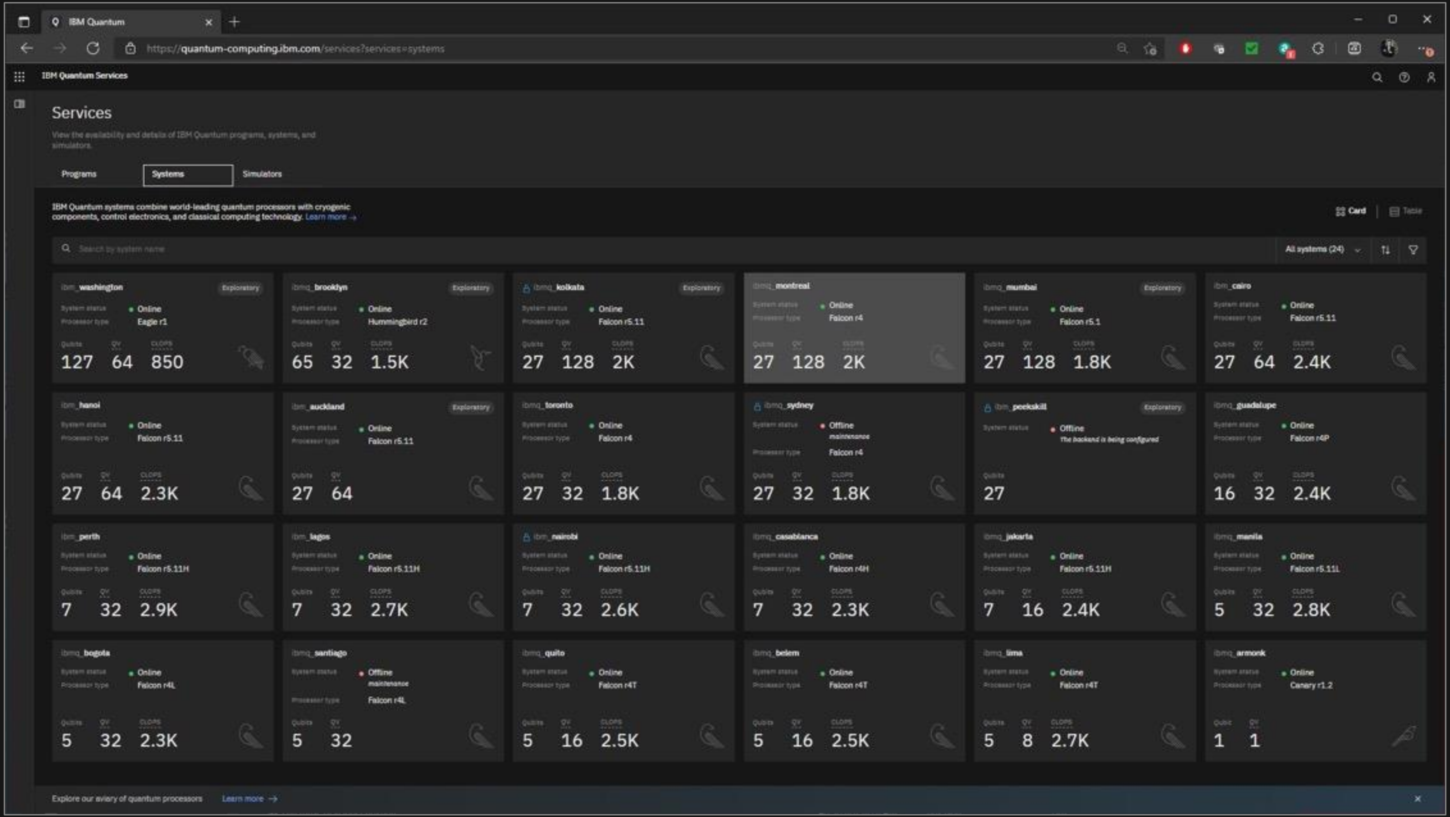
over 2 TRILLION hardware quantum circuits in total, and users run …

over 4 BILLION hardware quantum circuits on a typical day on …

more than 25 quantum computing systems on the IBM Cloud, and written over

1750+ scientific and research papers.

IBM Cloud quantum services



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

Building a Quantum Computing *Industry*

01

Advancing Quantum

↳ Technical working groups
↳ Open-source
↳ Open-science

02

Quantum Innovation Centers

↳ Access to leading-edge quantum compute services
↳ Research and development
↳ Education and workforce development
↳ Economic development

03

Industry Adoption

↳ Direct client interactions
↳ Scaling solutions with partner engagements

04

Application Services

↳ Access compute resellers
↳ Software providers
↳ Application integration

05

Quantum Safe

↳ Direct client interactions
  ↳ Prepare & Discover
  ↳ Assess & Plan Transformation
  ↳ Transform & Ongoing Observability

IBM Quantum Network Today

219 total

18 industry partners

24 hubs

60 members

52 startups

65 academic members and partners

Partners

BP
Boeing
Bosch
Capgemini SE
Credit Mutuel
Daimler
E.ON
Erste Group Bank AG
Exxon Mobil
Goldman Sachs
HSBC
JP Morgan Chase
JSR Corporation
LG Corporation
Samsung Advanced Institute of Technology
Tokyo Electron Limited
Wells Fargo
Woodside Energy Ltd

Hubs

Arizona State University
Brookhaven National Lab
Bundeswehr University Munich
CERN
Cleveland Clinic Foundation
Deutsches Elektronen Synchrotron
Fraunhofer
KEIO University
Korea Quantum Computing Corporation
Lantik SA
Los Alamos National Laboratory
National Taiwan University
North Carolina State University
Oak Ridge National Lab
Pacific Northwest National Lab
Poznan Supercomputing and Networking Center
Quebec PINQ2
Science and Technology Facilities Council Daresbury
Sungkyunkwan University
United States Air Force Research Lab
University of Melbourne
University of Sherbrooke
University of Tokyo
Yonsei University

Members

Amgen
Anthem
Argonne National Lab
Assured Information Security
CMC Microsystems
Carnegie Mellon Software Engineering Institute
Cognizant
Consiglio Nazionale delle Ricerche - Istituto di calcolo e reti ad alte prestazioni
DIC Corporation
Deloitte
Fermi National Accelerator Laboratory
Fidelity Investments
Flightprofiler
Fraunhofer members
GE Global Research
General Atomics
Hitachi Ltd
III Taiwan
Industrial Technology Research Institute
Infosys
Istituto Italiano di Tecnologia
Lawrence Berkeley National Laboratory (Berkeley Lab)
Lockheed Martin
Mitsubishi Chemical Corporation
Mitsubishi UFJ Financial Group
Mizuho Bank
Molecular Forecaster Inc
National Institute for Nuclear Physics
RIKEN National Research and Development Agency
Sandia National Labs
Sony
Sumitomo Mitsui Trust Bank Limited
System Vertrieb Alexander GmbH
TNO
Tech Mahindra Limited
Toshiba
Toyota
Toyota Central RD Labs
United States Naval Research Laboratory
Yokogawa Electric Corporation

Startups

1Qbit Systems
AIQTECH Inc
Agnostiq Inc
Aliro Quantum
Applied Quantum Computing
Apply Science
Beit
Blueqat
Boxcat Inc
Cambridge Quantum Computing
Classiq
ColdQuanta
ColibriTD
Entangled Networks Ltd.
Entropica Labs
Equal1
First Quantum
HQS Quantum Simulations
Horizon Quantum Computing
JoS Quantum
Keysight
Kipu Quantum
Max Kelsen
Menten AI
Miraex
Multiverse Computing
NetraMark Corp
Nordic Quantum Computing Group
Opacity
Phasecraft
ProteinQure
Q-Ctrl
QC Ware
QEDMA Quantum Computing
Qu & Co
Quantfi
Quantum MADS
Quantum Machines
Quantum South
Quantum Technology Foundation of Thailand
QuantumNET
Qunasys
Rahko
SoftwareQ
Solid State AI
SpinUp AI
Strangeworks
Super Tech Labs
Xanadu
Zapata Computing Inc
Zurich Instruments
qBraid Co

Academic

Aalto University
Boston University
Bowie State University
Centrum Wiskunde & Informatica
Chalmers University of Technology
Clemson University
Cornell University
ETH Zurich
Florida State University
Georgia Institute of Technology
Hampton University
Hanyang University
Harvard University
Howard University
Indian Institute of Technology - Madras IIT
Johns Hopkins University
Korea Advanced Institute of Science and Technology
Korea University
Maastricht University
Massachusetts Institute of Technology
Morehouse College
Morgan State University
National University of Singapore
Netherlands Organization for Applied Scientific Research
Netherlands eScience Center
New Mexico State University
New York University
North Carolina AT State University
Northeastern University
Northwestern University
Pohang University of Science and Technology
Prairie View AM University
Princeton University
Purdue University
Saarland University
Seoul National University
Southern University and A&M College
Stanford University
Stony Brook University
Surf
Swiss Federal Institute of Technology Lausanne
The University of Texas at Austin
Turku University
Tuskegee University
Ulsan National Institute of Science and Technology
United States Naval Postgraduate Military University
University of Amsterdam
University of Basque Country
University of Chicago
University of Georgia
University of Illinois at Urbana Champaign
University of Innsbruck
University of Madrid
University of Minho
University of Montpellier
University of New Mexico
University of Oxford
University of South Carolina
University of Southern California
University of Tennessee
University of Washington
University of Waterloo
University of Witwatersrand Johannesburg
University of the District of Columbia Community College
Virginia Tech

Strategic partnerships to accelerate regional quantum ecosystems

IBM **Quantum**

IBM Quantum datacenter in NY

Fraunhofer
Jan 2021

University of Tokyo
July 2021

Cleveland Clinic
1Q23

Yonsei University
Projected 2023

Quebec
Projected 2023

A snapshot of global collaboration within the IBM Quantum Network

IBM Quantum

Publishes algorithm paper on Amplitude Estimation.

Zurich, Switzerland

Keio University

Advances method, publishes with Mizuho and MUFG.

Tokyo, Japan

JPMorgan Chase

Applies the method to options pricing and publishes.

New York, USA

Qiskit

Contributed code into open source Qiskit for all to use.

Global

Quantum applications span three general areas

Simulating Quantum Systems		Artificial Intelligence	Optimization / Monte Carlo	
Improved battery materials	Accelerated Diagnosis	Fraud detection	Irregular Operations	Freight Forecasting
Manufacturing defect identification	Genomic Analysis	Risk analysis	Network Optimization	Irregular Operations
Semiconductor materials	Chemical product design	Options pricing	Product Portfolio Optimization Process Planning	Fabrication Optimization
Chemical property prediction	Catalyst discovery	Derivatives Pricing	Quality Control	Manufacturing Supply Chain
Drug Discovery	Chemical process optimization	Investment Risk Analysis	Vehicle Routing	Fluid Dynamics
Protein Structure Predictions	High energy physics classification	Portfolio Management	Raw materials shipping	
Disease Risk Predictions	Transaction classification	Transaction Settlement	Refining Processes	
	Product recommendation	Finance Offer Recommender	Seismic imaging	
		Credit/Asset Scoring	Disruption Management	
		Airline Scheduling		

and many more …

Mercedes-Benz

Quantum Computing for Materials Discovery and Manufacturing Optimization

Mercedes-Benz and IBM have recently published a series of papers demonstrating progress toward using quantum computers to model material systems including Lithium-sulfur that are relevant to advancing the performance of batteries. The teams have also demonstrated applications in manufacturing defect analysis and product recommendation.

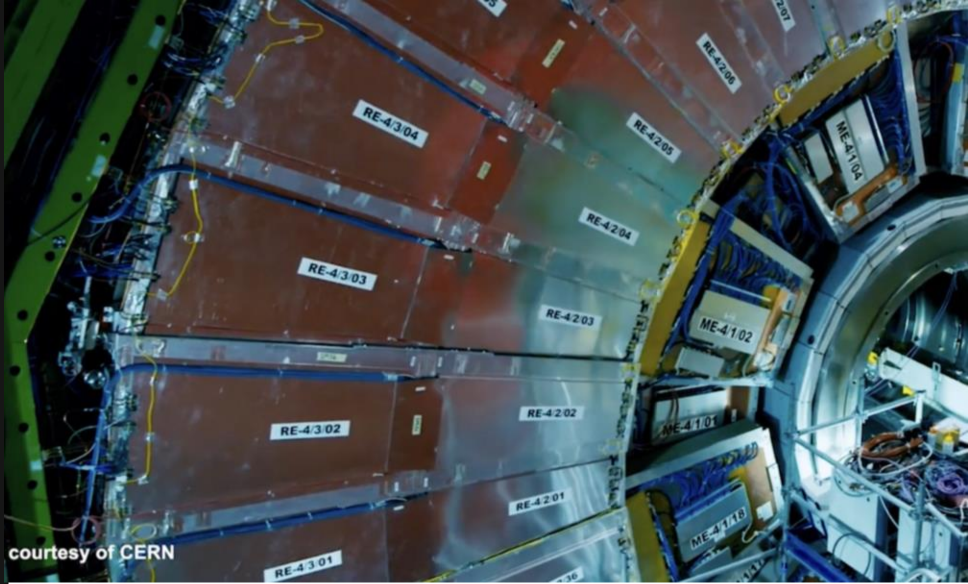
"Developing and perfecting these hypothetical batteries could unlock a billion-dollar opportunity."

Benjamin Boeser
[Former] Director of Innovation Management, Silicon Valley at Mercedes-Benz R&D North America

CERN

Quantum Machine Learning to understand what sews the universe together

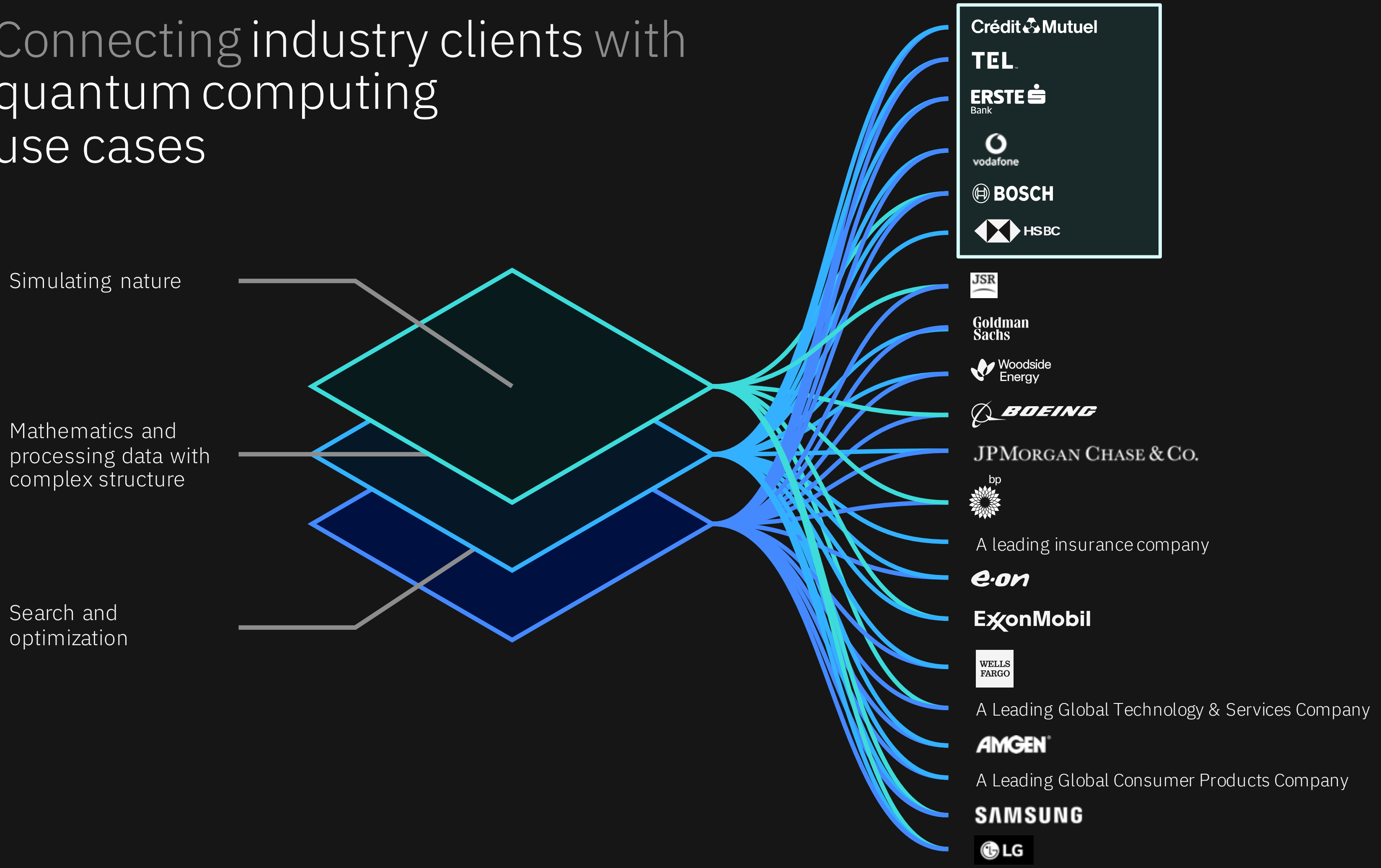
CERN’s partnership with IBM Quantum seeks new ways of finding patterns in data of the Large Hadron Collider. A recent collaboration with IBM scientists involves the detection and analysis of the Higgs boson, a recently discovered particle that helps explain the origin of mass. Sifting through raw data to find occurrences of Higgs behavior is a knotty problem that stretches classical computers to their limit.



“Quantum computing may play a significant role in (…) exploring the many open questions related to issues such as dark matter, dark energy, (…) and more.”

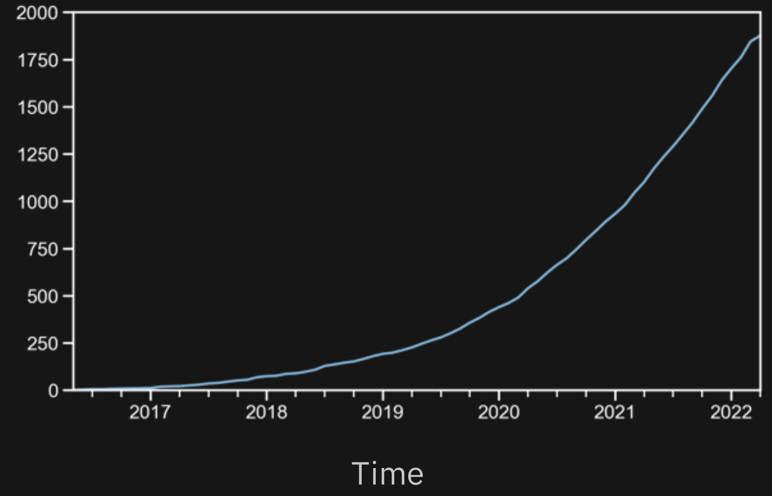
Alberto Di Meglio
Head of CERN openlab

Connecting industry clients with quantum computing use cases



Advancing Quantum

Cumulative Research papers using IBM Quantum & Qiskit



1,750

published research papers since 2016

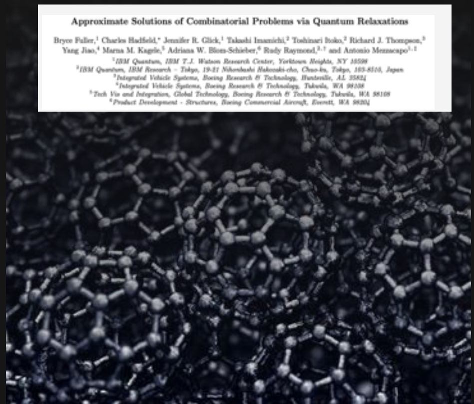
Gravitational Wave Detection

Quantum encoding is suitable for matched filtering

Doğa Veske,[1,*] Cenk Tüysüz,[2,3] Mirko Amico,[4] Nicholas T. Bronn,[4] Olivia T. Lanes,[4] Zsuzsa Márka,[5] and Szabolcs Márka[1]

[1] *Department of Physics, Columbia University in the City of New York, New York, NY 10027, USA*
[2] *Deutsches Elektronen-Synchrotron (DESY), Platanenallee 6, 15738 Zeuthen, Germany*
[3] *Institüt für Physik, Humboldt-Universität zu Berlin, Newtonstr. 15, 12489 Berlin, Germany*
[4] *IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, NY, USA*
[5] *Columbia Astrophysics Laboratory, Columbia University in the City of New York, New York, NY 10027, USA*

Ply Composite Optimization

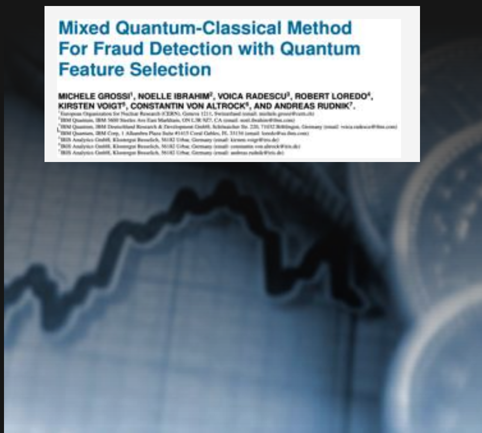


Approximate Solutions of Combinatorial Problems via Quantum Relaxations

Bryce Fuller,[1] Charles Hadfield,* Jennifer R. Glick,[1] Takashi Imamichi,[2] Toshinari Itoko,[2] Richard J. Thompson,[3] Yang Jiao,[4] Marna M. Kagele,[5] Adriana W. Blom-Schieber,[6] Rudy Raymond,[2,†] and Antonio Mezzacapo[1,‡]

[1] *IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, NY 10598*
[2] *IBM Quantum, IBM Research – Tokyo, 19-21 Nihonbashi Hakozaki-cho, Chuo-ku, Tokyo, 103-8510, Japan*
[3] *Integrated Vehicle Systems, Boeing Research & Technology, Huntsville, AL 35824*
[4] *Integrated Vehicle Systems, Boeing Research & Technology, Tukwila, WA 98108*
[5] *Tech Vis and Integration, Global Technology, Boeing Research & Technology, Tukwila, WA 98108*
[6] *Product Development - Structures, Boeing Commercial Aircraft, Everett, WA 98204*

Fraud Detection



Mixed Quantum-Classical Method For Fraud Detection with Quantum Feature Selection

MICHELE GROSSI[1], NOELLE IBRAHIM[2], VOICA RADESCU[3], ROBERT LOREDO[4], KIRSTEN VOIGT[5], CONSTANTIN VON ALTROCK[6], AND ANDREAS RUDNIK[7].

Our mission

Bring useful quantum computing to the world

Part II

Bring useful quantum computing to the world

A path towards quantum computing

„IBM's point of view and goal is a computational quantum advantage, where a computational task of business or scientific relevance can be performed more efficiently, cost-effectively, or accurately using a quantum computer than with classical computations alone."

Value =

Performance

\+ Frictionless

\+ Capabilities

Performance =

Scale — Number of qubits

\+ Quality — Circuit fidelity

\+ Speed — Circuit execution speed

Performance =

Scale — Number of qubits

+ Quality — Circuit fidelity

+ Speed — Circuit execution speed

2019
Falcon
27 Qubits

2020
Hummingbird
65 Qubits

2021
Eagle
127 Qubits

2022
Osprey
433 Qubits

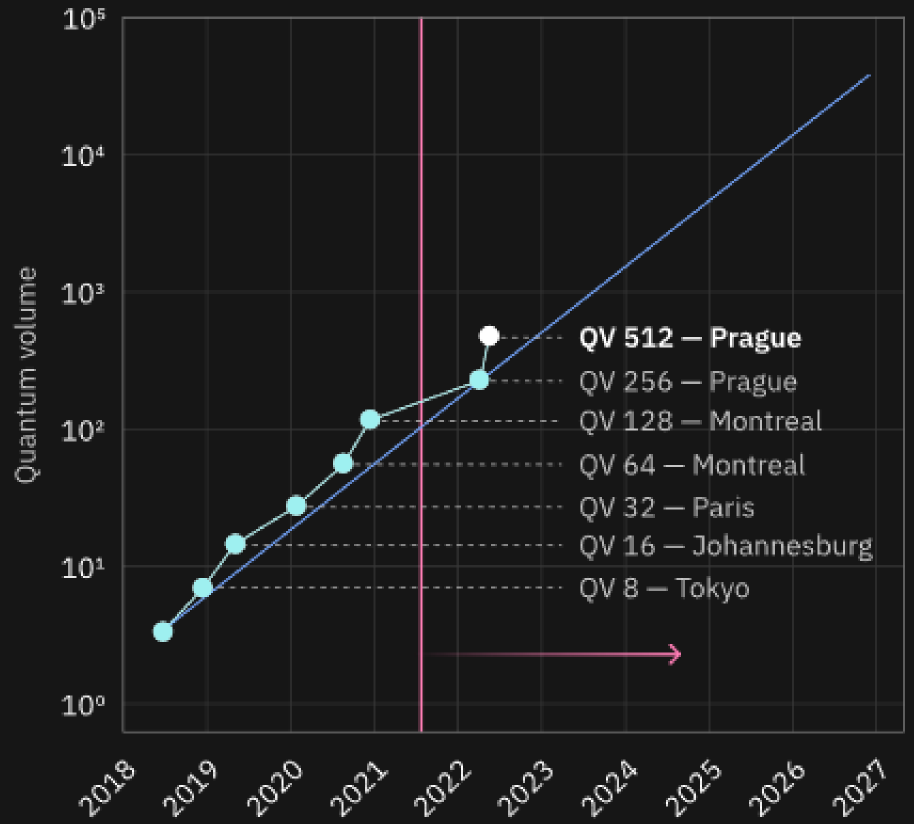
Performance =

Scale — Number of qubits

\+ Quality — Circuit fidelity

\+ Speed — Circuit execution speed

Quantum volume

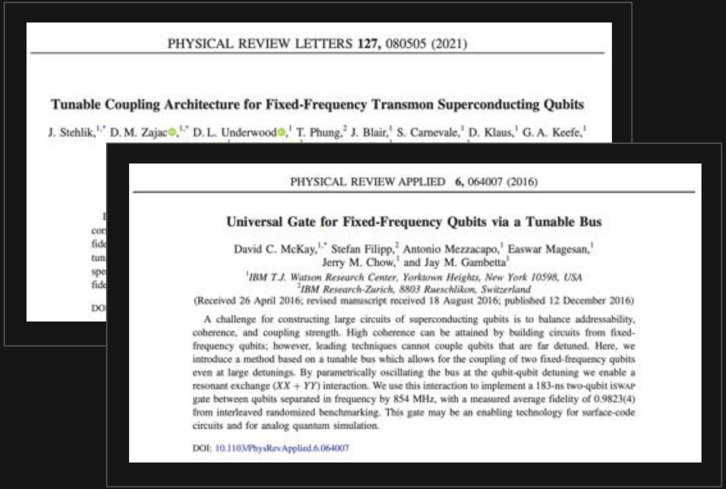


Quality

Coherence

Improved control

New architectures



PHYSICAL REVIEW LETTERS **127,** 080505 (2021)

Tunable Coupling Architecture for Fixed-Frequency Transmon Superconducting Qubits

J. Stehlik,[1,*] D. M. Zajac,[1,*] D. L. Underwood,[1] T. Phung,[2] J. Blair,[1] S. Carnevale,[1] D. Klaus,[1] G. A. Keefe,[1]

PHYSICAL REVIEW APPLIED **6,** 064007 (2016)

Universal Gate for Fixed-Frequency Qubits via a Tunable Bus

David C. McKay,[1,*] Stefan Filipp,[2] Antonio Mezzacapo,[1] Easwar Magesan,[1]
Jerry M. Chow,[1] and Jay M. Gambetta[1]
[1]*IBM T.J. Watson Research Center, Yorktown Heights, New York 10598, USA*
[2]*IBM Research-Zurich, 8803 Rueschlikon, Switzerland*
(Received 26 April 2016; revised manuscript received 18 August 2016; published 12 December 2016)

A challenge for constructing large circuits of superconducting qubits is to balance addressability, coherence, and coupling strength. High coherence can be attained by building circuits from fixed-frequency qubits; however, leading techniques cannot couple qubits that are far detuned. Here, we introduce a method based on a tunable bus which allows for the coupling of two fixed-frequency qubits even at large detunings. By parametrically oscillating the bus at the qubit-qubit detuning we enable a resonant exchange ($XX + YY$) interaction. We use this interaction to implement a 183-ns two-qubit iSWAP gate between qubits separated in frequency by 854 MHz, with a measured average fidelity of 0.9823(4) from interleaved randomized benchmarking. This gate may be an enabling technology for surface-code circuits and for analog quantum simulation.

DOI: 10.1103/PhysRevApplied.6.064007

Performance =

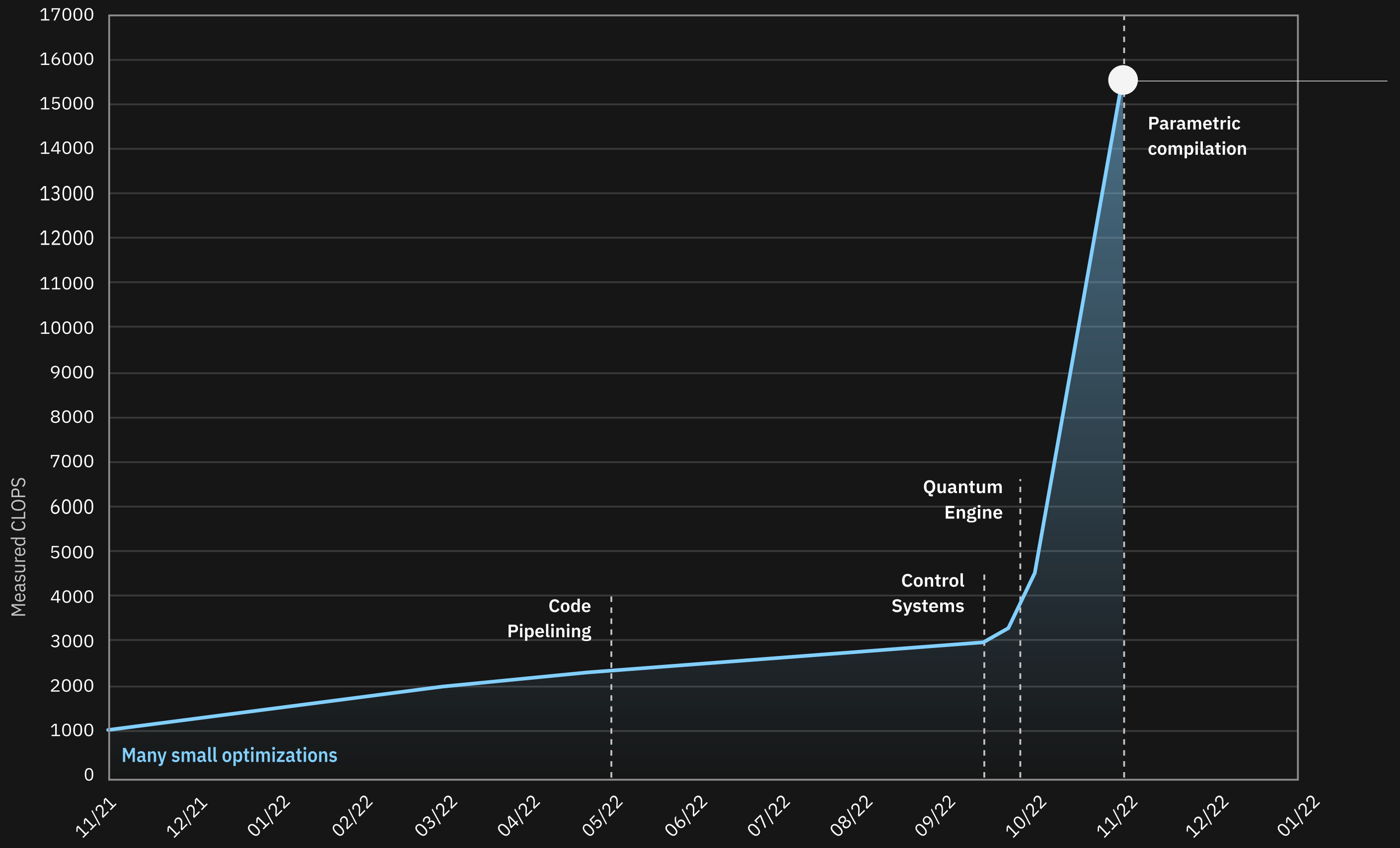
Scale — Number of qubits

\+ Quality — Circuit fidelity

\+ Speed — Circuit execution speed

Circuit Layer Operations per Second (CLOPS) is a measure of how many parallel and parameterized quantum operations a QPU can execute per unit of time.

Critical elements for speed



15,700
CLOPS

Value =

Performance

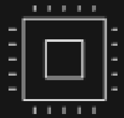
+Frictionless

+Capabilities

We now deliver these optimizations through the Qiskit Runtime Primitives

Primitives are predefined programs that provide a simplified interface for defining near-time quantum-classical workloads required to efficiently build and customize applications.

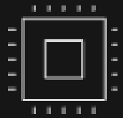
Sampler



Circuit → $\tilde{p}(\hat{x})$

Quasi-probability distribution

Estimator



Circuit + Observable $\tilde{O}$ → $\langle \tilde{O} \rangle$

Expectati
on value

sampler Primitive

Generates quasi-probabilities by sampling quantum circuits.

Last updated	Jul 19, 2022
Max execution time	10000 seconds

estimator Primitive

Calculates expectation values of quantum operators.

Last updated	Jul 19, 2022
Max execution time	18000 seconds

Value =
Performance
+ Frictionless
+ Capabilities

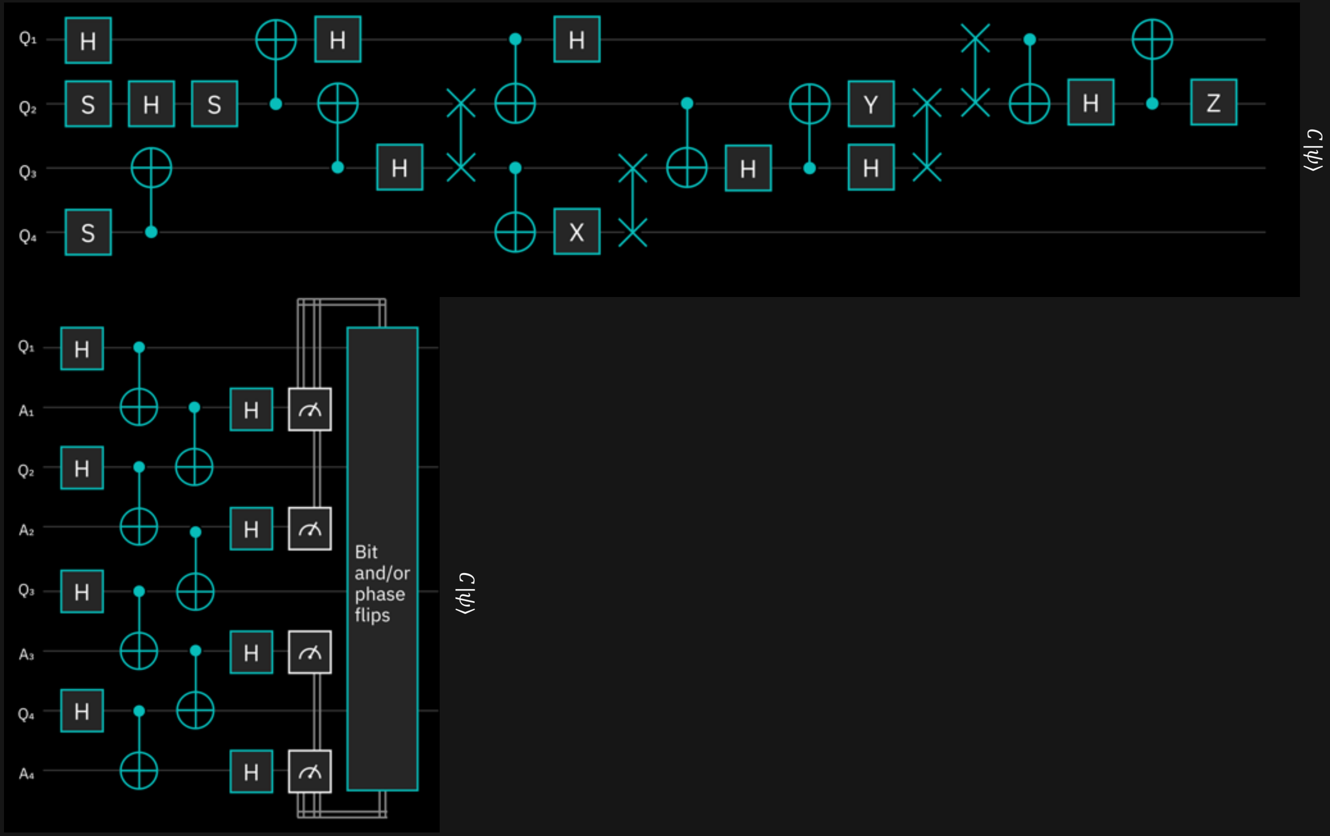
Power of Dynamic Circuits

Reducing Circuit Depth

E.g. a static n-qubit Clifford circuit of depth $2n + O(\log^2 n)$

Can become a dynamic circuit of constant depth[1].

[1] Jozsa arXiv:quant-ph/0508124 (2005)



IBM Quantum System Two *Design*

https://www.youtube.com/watch?v=AQjKUN8PORM

Development Roadmap | Executed by IBM ✓ On target

IBM **Quantum**

	2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023	2024	2025	Beyond 2026
	Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime
Model Developers					Prototype quantum software applications →		Quantum software applications Machine learning | Natural science | Optimization	
Algorithm Developers		Quantum algorithm and application modules ✓ Machine learning | Natural science | Optimization			Quantum Serverless	Intelligent orchestration	Circuit Knitting Toolbox	Circuit libraries
Kernel Developers	Circuits ✓		Qiskit Runtime ✓	Dynamic circuits ✓	Threaded primitives	Error suppression and mitigation		Error correction
System Modularity	Falcon 27 qubits ✓	Hummingbird 65 qubits ✓	Eagle 127 qubits ✓	Osprey 433 qubits ✓	Condor 1,121 qubits	Flamingo 1,386+ qubits	Kookaburra 4,158+ qubits	Scaling to 10K-100K qubits with classical and quantum communication
					Heron 133 qubits x p	Crossbill 408 qubits		

IBM Quantum
State of the Union
@ IBM Quantum Summit 2022
by Jay Gambetta

Our mission

Bring useful quantum computing to the world

Part III

Education and Workforce enablement

460k+

Registered users have run 2.36 trillion circuits since 2016

12,000

Students attend QubitxQubit Intro to Quantum Computing

375+

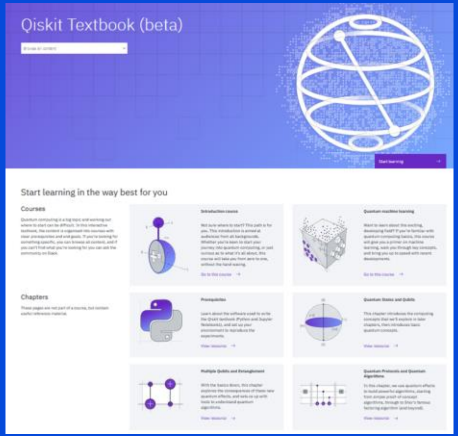
Quantum computing courses using Qiskit

5M+

Learners accessing digital content

Education and Workforce enablement

Qiskit Textbook



An online textbook to learn about quantum computing and Qiskit, with multiple learning paths and content for all levels.

Qiskit Developer Certification

A certification meant to assess your proficiency with Qiskit.

Understanding Quantum Information and Computation

A free, university-level course on quantum computing.

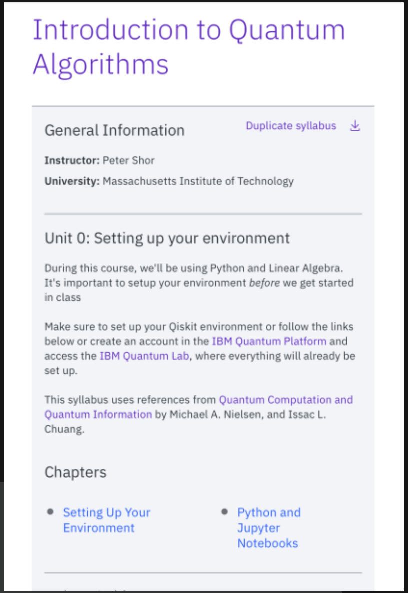
And many more …

- Qiskit Global Summer Schools
- Internship Program
- Qiskit hackathons
- Qiskit Bootcamp
- QubitxQubit
- Qiskit YouTube
- IBM Quantum Challenge
- …

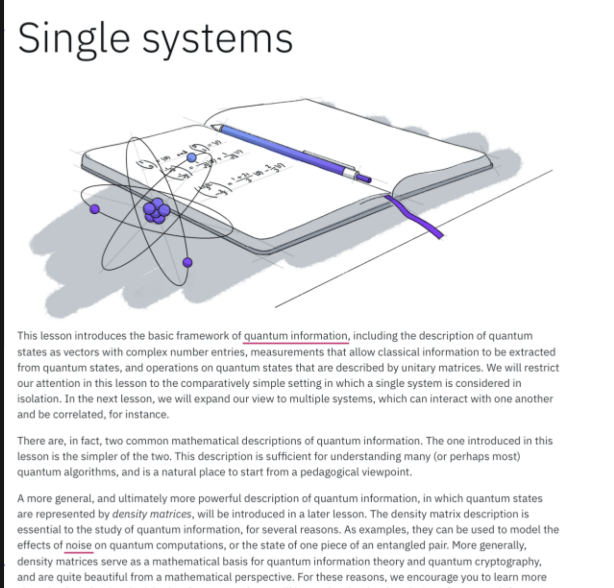
Enabling educators to create, teach, and assess

IBM **Quantum**

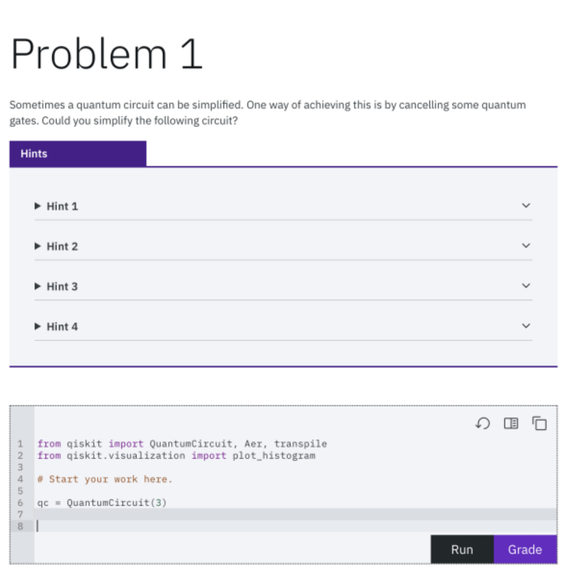
Create a custom syllabus



Teach using IBM Quantum resources



Assess with custom auto-graded problem sets



IBM **Quantum**

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