Quantum Computing:
An Introduction for the perplexed

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Our mission

Bring useful quantum computing to the world

Make the world quantum safe
Our mission

Bring useful quantum computing to the world

Make the world quantum safe
Our modern digital world depends on public key cryptography. This is now a problem.
The problem with quantum computers

Shor’s algorithm (1994) shows a quantum computer can factor large numbers—at least 2048 bits long (that’s 617 decimal digits).

On a classical computer, this would take millions of years.

On a *cryptographically relevant quantum computer*, this would take a few hours.

Shor’s algorithm breaks RSA and other public-key cryptosystems, where security is based on the difficulty of mathematical *trapdoor* functions (factoring large numbers or taking discrete logarithms).¹

Grover’s algorithm (1996) theoretically affects AES, but probably won’t in our lifetimes.²

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² “A fast quantum mechanical algorithm for database search” 29 May 1996.
Today’s classical security protocols will be obsolete tomorrow

Prime factors $= p \times q$

2048-bit composite integer

Expected computation time

The most powerful computer today:
Millions of years

Shor’s quantum algorithm:
Hours

Public key encryption • Digital signatures • Key exchange algorithms

RSA • DSA • ECC • ECDSA • DH
Journey to Quantum Safe

U.S. National Institute of Standards and Technology announced the first quantum-safe cryptography protocol standards for cybersecurity (July 2022), three of which were created by IBM in collaboration with industry and academic partners.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Algorithm</th>
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<tbody>
<tr>
<td>Public-key Encryption and Key establishment Algorithms</td>
<td>CRYSRALS-Kyber</td>
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<tr>
<td>Digital Signature Algorithms</td>
<td>CRYSRALS-DILITHIUM</td>
</tr>
<tr>
<td>DSA (alternate)</td>
<td>Falcon</td>
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<tr>
<td>DSA (alternate)</td>
<td>SPHINCS+</td>
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NIST Selected Algorithms, July 5th 2022. NIST recommended two primary algorithms to be implemented for most use cases: CRYSRALS-KYBER (key-establishment) and CRYSRALS-Dilithium (digital signatures).

US Government establishes timeline for transition to CNSA 2.0-compliant algorithms

GSMA Telco Consortium
Support industry transition to quantum-safe cryptography

IBM Quantum Safe
Support client transition to quantum-safe cryptography

z16
First Quantum-safe platform
IBM Quantum Safe

- Understand, Prepare & Plan
- Discover & Classify Data
- Create a Crypto Inventory
- Implement with Crypto Agility
The future of computing

Mathematics + Information
Today’s computers and HPC

Biology + Information
AI Systems

Physics + Information
Quantum Systems

Hybrid Cloud
Secure heterogeneous computational fabric

Intelligent Automation
Automated programming and AI

Intelligent Applications

bits
neurons
qubits
The limit of bits

For decades we’ve been simplifying nature into 1s and 0s because that was the only way we could manage to create a useful and scalable system of computation.

But the future isn’t just 1s and 0s.
Quantum computers are the only novel hardware that changes the game.

Quantum computing is not just a faster or better version of classical systems. It is an entirely new branch of computing.

Quantum computing follows the laws of nature to represent data in ways that mimic the randomness and unpredictability of the natural world. Ultimately, GPUs and classical hardware are not built for this.
We are in the early stages of a rapidly advancing new computing technology

Computer: 1944

Quantum Computer: 2019
Superconducting qubits need to be really COLD

Refrigerator to cool qubits to 10 - 15 mK with a mixture of $^3$He and $^4$He.

0.015 Kelvin – colder than space.

Deep space (2.7K, -270°C)
Quantum Particles

There are 10 kinds of people: those who understand binary and those who don't.
A quantum bit or **qubit** is a controllable quantum object that is the unit of information.

A **quantum circuit** is a set of quantum gate operations on qubits and is the unit of computation.
Quantum computing uses essential ideas from quantum mechanics

Superposition is creating a quantum state that is a combination of $|0\rangle$ and $|1\rangle$.

Measurement is an action that forces a qubit to either $|0\rangle$ or $|1\rangle$ based on probability.

Entanglement strongly connects two or more qubits so that their quantum states are no longer independent.

Quantum gates perform the basic computational operations on qubits (think of as counterparts to classical $\text{and}$, $\text{+}$, and so on).

Interference allows us to increase the probability of getting the right answer and decrease the chance of getting the wrong one.
Entanglement: “Spooky action at a distance”

We can also combine qubits to cause a correlation of results when observed.

Is the system observed as 1 or 0?

A: 50% of the time the answer is 1
   50% of the time the answer is 0
B: Gives the same random answers as qubit A

Yet we can still perform deterministic operations on the two qubits.
The power of quantum computing

Classical Computers
The potential power of a classical computer doubles every time you double the number of transistors.

Quantum Computers
The potential power of a quantum computer doubles every time you add one additional qubit.

IBM Power 9 24-Core

IBM Q 16 Qubit Device
Exponential growth

\[ 2^n \]

**n qubits** – \( 2^n \) quantum state dimensions.

\[
\begin{align*}
2^{10} &= 1,024 \\
2^{20} &= 1,048,576 \\
2^{50} &= 1,125,899,906,842,624 \\
2^{65} &= 36,893,488,147,419,103,232 \\
2^{127} &= 170,141,183,460,469,231,731,687,303,715,884,105,728
\end{align*}
\]
Exponential growth

$2^{275}$

275 qubits – more quantum state dimensions than there are atoms in the observable universe.

$60,708,402,882,054,033,466,233,184,588,234,965,832,575,213,720,379,360,039,119,137,804,340,758,912,662,765,568 \approx 6.1 \times 10^{82}$
The path to useful quantum computing

Run quantum circuits faster on quantum hardware

Chart a path to develop quantum technology (hardware + software) that runs noise-free estimators of quantum circuits faster than can be done using classical hardware alone.

Map interesting problems to quantum circuits

We need applications that can be solved only with quantum circuits that are known to be difficult to simulate. This must be done in partnership with our clients and users.
The three key metrics for measuring quantum computing performance

**Scale**
Measured by **number of qubits** which indicates the amount of information we can encode in the quantum system.

- High coherence, high reliability, lower cost

<table>
<thead>
<tr>
<th>Year</th>
<th>Qubits</th>
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<tbody>
<tr>
<td>2020</td>
<td>65 qubits</td>
</tr>
<tr>
<td>2021</td>
<td>127 qubits</td>
</tr>
<tr>
<td>2022</td>
<td>433 qubits</td>
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</table>

**Quality**
Measured by **Quantum Volume** which indicates quality of circuits and how faithfully circuits are implemented in hardware.

- Need low operation errors, meaning large Quantum Volume

<table>
<thead>
<tr>
<th>Year</th>
<th>Quantum Volume</th>
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<tbody>
<tr>
<td>2020</td>
<td>32 QV</td>
</tr>
<tr>
<td>Today</td>
<td>512 QV</td>
</tr>
<tr>
<td>2022</td>
<td>1024 QV</td>
</tr>
</tbody>
</table>

**Speed**
Measured by **CLOPS (Circuit Layer Operations Per Second)** which indicates how many circuits can run on hardware in a given time.

- Seamless synchronization of quantum and classical circuits increases execution rate

<table>
<thead>
<tr>
<th>Year</th>
<th>CLOPS</th>
</tr>
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<tbody>
<tr>
<td>2020</td>
<td>200 (Inferred)</td>
</tr>
<tr>
<td>Today</td>
<td>1.4K CLOPS</td>
</tr>
<tr>
<td>2022</td>
<td>10K CLOPS</td>
</tr>
</tbody>
</table>
Quantum volume

- QV 512 — Prague
- QV 256 — Prague
- QV 128 — Montreal
- QV 64 — Montreal
- QV 32 — Paris
- QV 16 — Johannesburg
- QV 8 — Tokyo

Quality
Coherence
Improved control
New architectures
Development Roadmap

2016–2019
- Run quantum circuits on the IBM Quantum Platform
- Release multi-dimensional roadmap publicly with initial aim focused on scaling

2020
- Enhancing quantum execution speed by 10X with Qiskit Runtime

2021
- Bringing dynamic circuits to unlock more computations

2022
- Enhancing quantum execution speed by 5X with quantum synthesizers and execution modes

2023
- Improving quantum circuit quality and speed to allow 5K gates with parametric circuits

2024
- Enhancing quantum execution speed and parallelization with partitioning and quantum modularity

2025
- Improving quantum circuit quality to allow 7.5K gates

2026
- Improving quantum circuit quality to allow 10K gates

2027
- Improving quantum circuit quality to allow 15K gates

2028
- Improving quantum circuit quality to allow 100K gates

2029
- Beyond 2033, quantum-centric supercomputers will include 1000’s of logical qubits unlocking the full power of quantum computing

Innovation Roadmap

Software Innovation
- IBM Quantum Experience
- Qiskit Circuit and operator API with compilation to multiple targets
- Application modules: Modules for domain-specific application and algorithm workflows
- Qiskit Runtime: Performance and abstract through precompiled
- Serverless: Demonstrate concepts of quantum-classical supercomputing
- AI enhanced quantum: Prototype demonstrations of AI enhanced circuit transcription
- Resource management: System partitioning to enable parallel execution
- Scalable circuit modules: Demonstration of a quantum system with real-time error correction decoder

Hardware Innovation
- Early
  - Canary 11 qubits
  - Albacore 16 qubits
  - Penguine 20 qubits
  - Prototype 13 qubits
- Falcon: Demonstrating scaling with multiplanar modules
- Hummingbird: Demonstrating scaling with multiplanar modules
- Eagle: Demonstrating scaling with 160 qubits with TSV
- Osprey: Demonstrating scaling with high-fidelity signal integrity
- Condor: Demonstrating scaling with modular connectivity
- Flamingo: Demonstrating scaling with non-local coupler
- Kookaburra: Demonstrating path to improved quality with logical connectivity
- Cockatoo: Demonstrating path to improved quality with logical connectivity
- Starling: Demonstrating path to improved quality with logical connectivity

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Condor

Pushing the limits of scale & yield

1,121
Superconducting qubits

50%
Increase in qubit density

1 mile +
Of flex cabling
Introducing Heron

133 qubit systems

Tunable coupler architecture

<table>
<thead>
<tr>
<th></th>
<th>ibm_sherbrooke Eagle</th>
<th>ibm_montecarlo (Heron)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate Error (best system)</td>
<td>0.6-0.7%</td>
<td>0.3% - Best ~ 0.1%</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>High (qubit-qubit collisions)</td>
<td>Almost zero!</td>
</tr>
<tr>
<td>Gate time</td>
<td>500-600ns</td>
<td>90-100ns</td>
</tr>
</tbody>
</table>
New error correction codes and system modularity

**C-coupler** enables long-range on-chip connections for high-rate LDPC codes

**L-coupler** enables joining multiple logical memories to create large-scale systems

**M-coupler** enables joining multiple short-range chip-to-chip connections
Run quantum circuits faster on quantum hardware

Chart a path to develop quantum technology (hardware + software) that runs noise-free estimators of quantum circuits faster than can be done using classical hardware alone.

Map interesting problems to quantum circuits

We need applications that can be solved only with quantum circuits that are known to be difficult to simulate. This must be done in partnership with our clients and users.
Structure of a typical workload

Real workloads are not purely quantum, but rather require interaction between quantum and classical compute resources.
Quantum applications span three general areas:

- **Simulating Quantum Systems**
  - Quantum chemistry
  - Material science
  - High energy physics

- **Artificial Intelligence**
  - Better model training
  - Pattern recognition
  - Fraud detection

- **Optimization / Monte Carlo**
  - Portfolio optimization
  - Risk analysis
  - Loans & credit scoring
  - Monte Carlo-like applications
Quantum applications span three general areas

**Simulating Quantum Systems**
- Improved battery materials
- Manufacturing defect identification
- Semiconductor materials
- Chemical property prediction
- Drug Discovery
- Protein Structure Predictions
- Disease Risk Predictions
- Accelerated Diagnosis
- Genomic Analysis
- Chemical product design
- Catalyst discovery
- Chemical process optimization
- High energy physics classification
- Transaction classification
- Product recommendation

**Artificial Intelligence**
- Fraud detection
- Risk analysis
- Options pricing
- Derivatives Pricing
- Investment Risk Analysis
- Portfolio Management
- Transaction Settlement
- Finance Offer
- Recommender
- Credit/Asset Scoring
- Airline Scheduling

**Optimization / Monte Carlo**
- Irregular Operations
- Network Optimization
- Product Portfolio Optimization Process Planning
- Quality Control
- Vehicle Routing
- Raw materials shipping
- Refining Processes
- Seismic imaging
- Disruption Management
- Freight Forecasting
- Irregular Operations
- Fabrication Optimization
- Manufacturing Supply Chain
- Fluid Dynamics
- and many more...

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Connecting industry clients with quantum computing use cases

- Simulating nature
- Mathematics and processing data with complex structure
- Search and optimization
• Wells Fargo + IBM Quantum have published more than 10 quantum research papers in recent years.

• These papers explore new kinds of algorithms and new ways of thinking about problems in the financial services industry.

• Research focus on training quantum systems to mimic the probability distributions seen in the real world, then use that system for predictive modeling.
• JSR + IBM are experimenting with chemical simulations to help improve the development and manufacture of photoresists.

• We’ve already demonstrated that we can simulate small molecules that mimic parts of the photoresist.

• We hope that simulations like these will help us realize even faster chips.
Boeing + IBM demonstrated a way to create larger computational spaces for simulating new materials.

The simulations that the team ran are among the most complex quantum optimizations ever run.

Boeing hopes these simulations will let them design lighter and stronger materials so planes can fly further with less fuel.
• ExxonMobil + IBM are modeling maritime inventory routing on quantum devices.

• By analyzing different strategies for vehicle and inventory routing they’re laying the foundation for constructing practical solutions for their operations.

• More efficient shipping routes could help us transport fuel more efficiently around the globe.
IBM Quantum Network

A collaborative community of discovery

Educate and Train

Accelerate Research

Develop Applications
IBM Quantum Network members worldwide

1Qbit Systems
AIOTECH Inc
Aalto University
Agnostix Inc
Airo Quantum
Ampere
Anthem
Applied Quantum Computing
Apply Science
Argonne National Lab
Arizona State University
Assured Information Security
BP
Belt
Blueqat
Boeing
Bosch
Boston University
Bowie State University
Boxcat Inc
Brookhaven National Lab
Bundeswehr University Munich
CERN
CMC Microsystems
Cambridge Quantum Computing
Capgemini SE
Carnegie Mellon Software Engineering Institute
Centrum Wiskunde & Informatica
Chalmers University of Technology
Classiq
Clemson University
Cleveland Clinic Foundation
Cognizant
ColdQuanta
ColdTID
Consortium Nationali della Ricerca - Istituto di calcolo e reti ai alte prestazioni
Cornell University
Credit Mutuel
DCI Corporation
Daimler
Deloitte
Deutsches Elektronen Synchrotron
E.ON
ETH Zurich
Entangled Networks Ltd.
Entropica Labs
Equal1
Erste Group Bank AG
ExxonMobil
Fermi National Accelerator Laboratory
Fidelity Investments
First Quantum
Flight proffer
Florida State University
Fraunhofer
Fraunhofer members
GE Global Research
General Atomics
Georgia Institute of Technology
Goldman Sachs
HiQS Quantum Simulations
HSCC
Hampton University
Harang University
Harvard University
Hitachi Ltd
Horizon Quantum Computing
Howard University
III Taiwan
Indian Institute of Technology - Madras
IIT
Industrial Technology Research Institute
Infosys
Istituto Italiano di Tecnologia
JP Morgan Chase
JSR Corporation
JetQuantum
Johns Hopkins University
KEIO University
Keysight
Kisu Quantum
Korea Advanced Institute of Science and Technology
Korea Quantum Computing Corporation
Korea University
LG Corporation
Lantik SA
Lawrence Berkeley National Laboratory (Berkeley Lab)
Lockheed Martin
Los Alamos National Laboratory
Maastricht University
Massachusetts Institute of Technology
Max Kelsen
Menten AI
Miraex
Mitsubishi Chemical Corporation
Mitsubishi UFJ Financial Group
Mizuho Bank
Molecular Forecaster Inc
Morehouse College
Morgan State University
Multiverse Computing
National Institute for Nuclear Physics
National Taiwan University
National University of Singapore
Netherlands Organization for Applied Scientific Research
Netherlands eScience Center
NetraMark Corp
New Mexico State University
New York University
Nordic Quantum Computing Group
North Carolina AT State University
North Carolina State University
Northeastern University
Northwestern University
Oak Ridge National Lab
Qacity
Pacific Northwest National Lab
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Pohang University of Science and Technology
Poznan Supercomputing and Networking Center
Praine View AM University
Princeton University
ProteinQure
Purdue University
Q-CTRL
QC Ware
QEDMA Quantum Computing
Qiu & Co
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Quantum MADS
Quantum Machines
Quantum South
Quantum Technology Foundation of Thailand
QuantumNET
Quebec PINQ2
Quansys
RIKEN National Research and Development Agency
Rakhi
Saarland University
Samsung Advanced Institute of Technology
Sandia National Labs
Science and Technology Facilities Council Daresbury
Seoul National University
SoftwareQ
Solid State A1
Sony
Southern University and A&M College
SpinUp AI
Stanford University
Stony Brook University
Strangeworks
Sumitomo Mitsui Trust Bank Limited
Sungkyunkwan University
Super Tech Labs
Surf
Swiss Federal Institute of Technology Lausanne
System Vertrieb Alexander GmbH
TNO
Tech Mahindra Limited
The University of Texas at Austin
Tokyo Electron Limited
Toshiba
Toyota
Toyota Central RD Labs
Turku University
Tuskegee University
Ulsan National Institute of Science and Technology
United States Air Force Research Lab
United States Postal Service
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University of California
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University of Colorado
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University of Edinburgh
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What builds a quantum workforce?

**OPEN ACCESS**
IBM is the only company to offer our real quantum computers available for public and premium access via the cloud.

**OPEN SOURCE**
Written in Python and maintained on GitHub, Qiskit is designed to make quantum computing software tools and frameworks available to everyone.

**EDUCATION**
Now is the opportunity for us all to give back and support building a diverse community of researchers, students, educators, and developers.
Chapters:

0. Prerequisites
1. Quantum States and Qubits
2. Single Qubits and Multi-Qubit Gates
3. Quantum Algorithms
4. Quantum Algorithms for Applications
5. Investigating Quantum Hardware Using Qiskit
6. Implementations of Recent Quantum Algorithms
2016 - 2023
2023 → Utility
We have entered the era of Quantum Utility.
Definition of Quantum Utility

High-fidelity quantum computation outside the reach of exact classical simulation methods

It is the first major milestone on the path to Quantum Advantage.

Useful quantum computation requires utility-scale hardware and co-designed scalable software capabilities.

This means systems larger than 100 qubits, where simulations are not a viable alternative.
If you’re not using 100+ qubits, you’re not doing quantum.
IBM Quantum

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