Qiskit Fall Fest 2025 !

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Prof. Dr. **Jan De Beule**

VUB Fellow **Eric Michiels**

14th November 2025

Our (ambitious) Program of Today ...

- 09:00 hrs.: Lecture 1: A Holistic Introduction to Quantum Computing
- 09:30 hrs.: Lecture 2: An introduction to Qiskit
- 10:00 hrs.: **Lab 1: My first Qiskit Program**
- 10:30 hrs.: COFFEE BREAK
- 10:45 hrs.: **Lab 2: Diving deeper into a Quantum Algorithm**
- 11:30 hrs.: Lecture 3: An overview of Quantum Machine Learning
- **12:15 hrs.: LUNCH BREAK**
- 13:00 hrs.: Lecture 4: Challenge Description
- 13:30 hrs.: **Lab 3: Solve the Challenge with Quantum Machine Learning**
- 15:30 hrs.: Presentations of the Solutions to the Jury
- 16:30 hrs.: Announcement and Celebration of the Winning Team
- 16:45 hrs.: Fun Quantum Quiz
- **17:00 hrs.: NETWORKING**

Investment in Quantum Computing is accelerating at an *unprecedented pace*

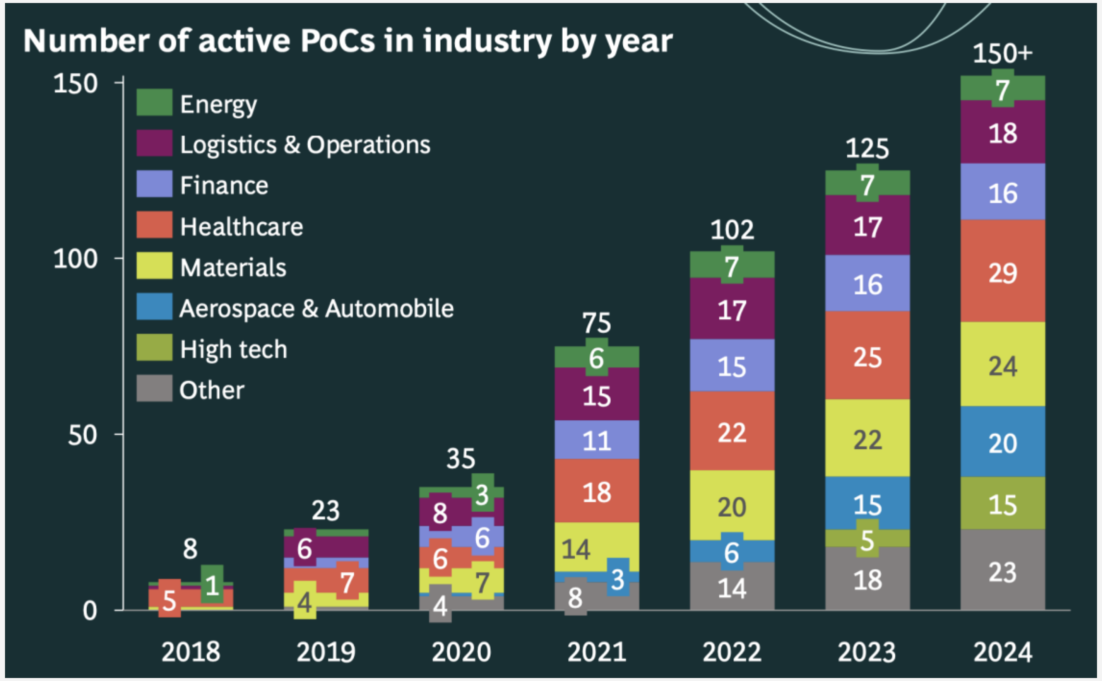
Accelerating adoption and usage

48% Customer spend CAGR[1]

$55B Global investment[2]

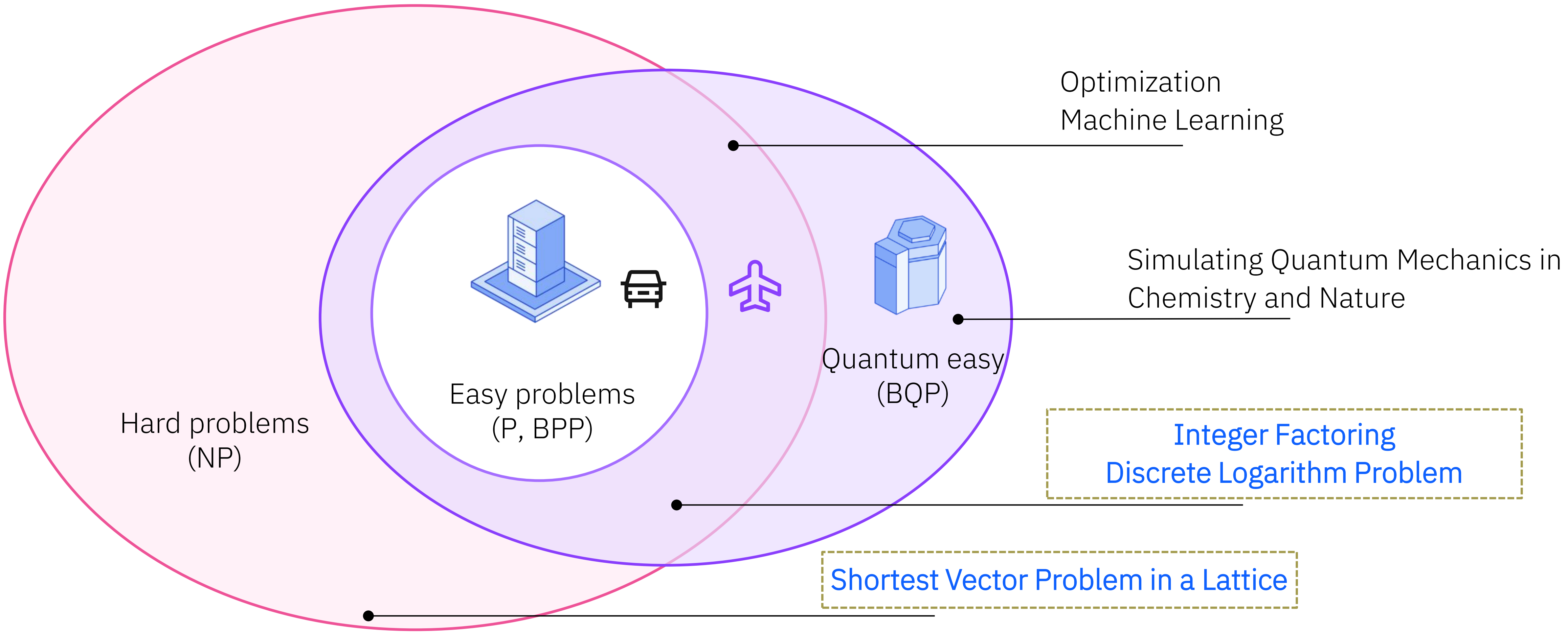
62% Early users spending $1M+ annually – 11% increase since 2022[3]

+50% Enterprise use case activity since 2022[4]



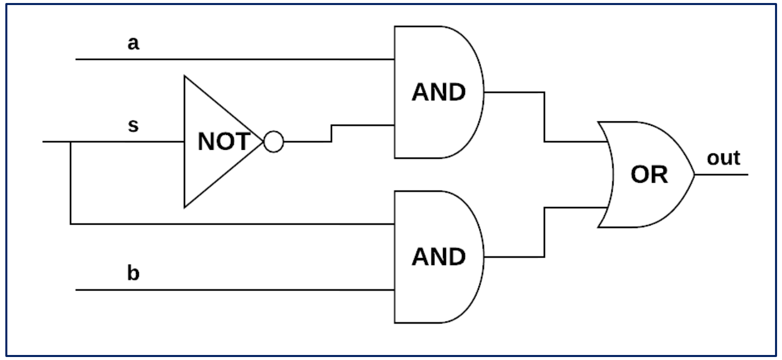
Source 1: IDC, IDC's Worldwide Quantum Computing Forecast: 2023–2027: Surfing the Next Wave of Quantum Innovation," IDC #US49198322, 2023.
Source 2: Sylvain Duranton (BCG), "Quantum Computing Takes Off With $55 Billion In Global Investments,"
Source 3: BCG, "Fantastic applications and where to find them," 2024.
Source 4: BCG, "Fantastic applications and where to find them," 2024.

Quantum Computing and Classical Computing ***complement*** each other



Classical versus Quantum Computing

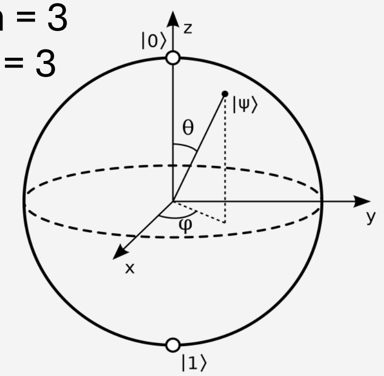
- CPUs and GPUs calculate with Bits
- **Bits are either 0 or 1**
- Enable our (amazing) Digital World
- Effective for (Generative) **AI**

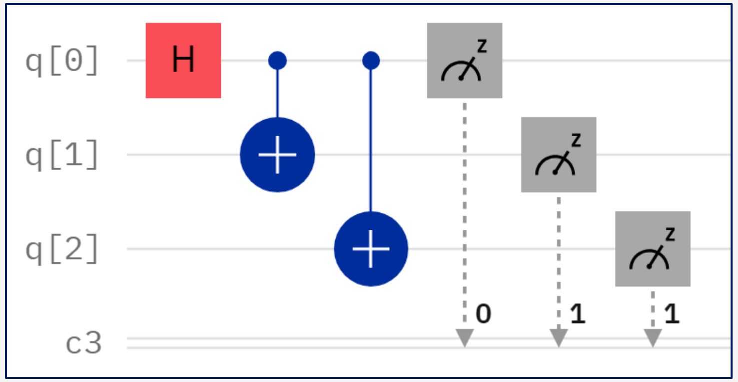


- Quantum Processing Units (QPUs) calculate with Qubits
- Apply principles of quantum mechanics
- Qubits can be in **more states than 0 and 1**
- Use new computational paradigm to obtain answers to **previously intractable** problems

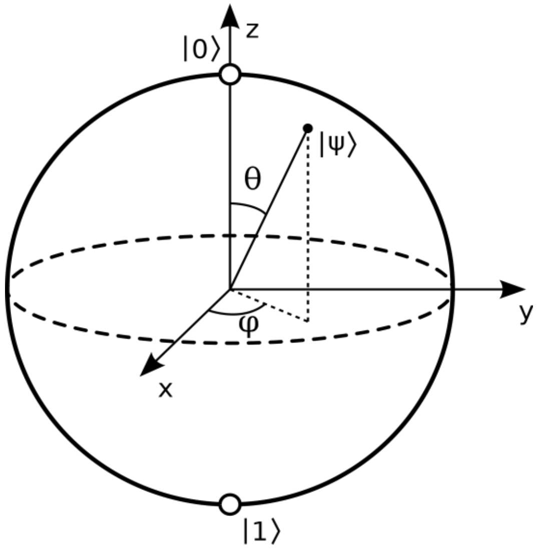
A Quantum Circuit is a set of Quantum Gate operations on Qubits and is the unit of computation

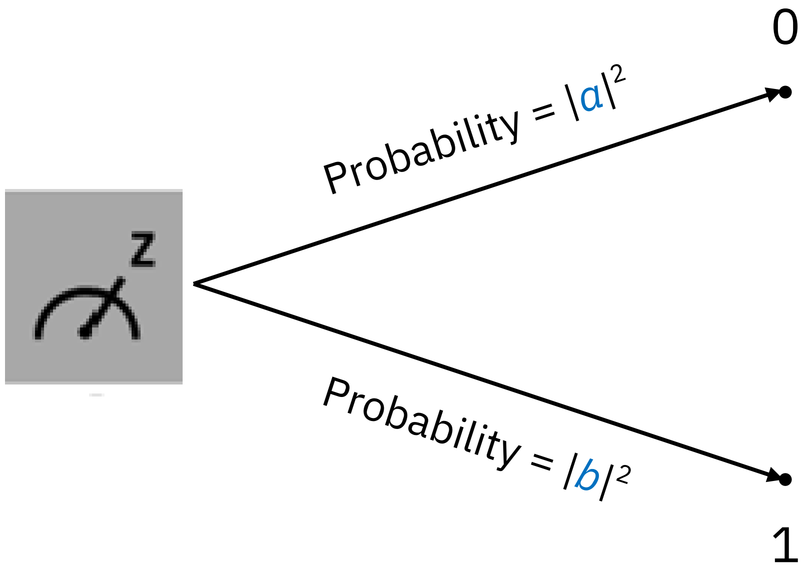
Example:
Depth = 3
Width= 3





Qubit Notation





A Qubit's State is a combination of $|0\rangle$ and $|1\rangle$:

$$a\,|0\rangle + b\,|1\rangle$$

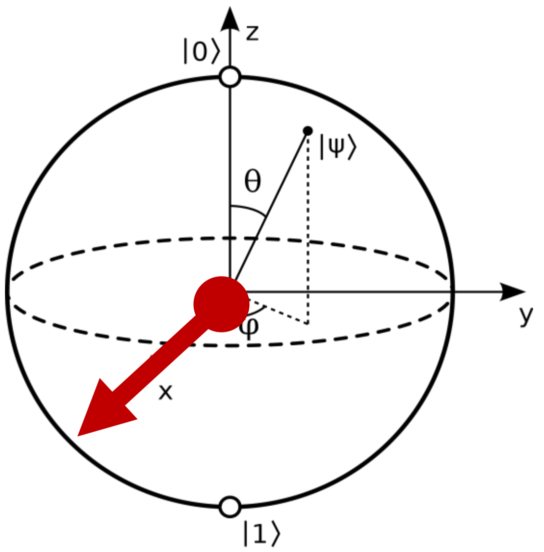
This means that a single Qubit contains two pieces of information.

When we measure a Qubit, it becomes **0** or **1** based on probability.

This also means that $|a|^2 + |b|^2 = 1$

Quantum Computing uses essentials from Quantum Mechanics and Mathematics

Superposition with Hadamard



This is what people mean when they say that a qubit can be "0 and 1 at the same time."

- $|0\rangle$ and $|1\rangle$ are vectors in the two-dimensional complex vector space $\mathbb{C}^2$:
  - $|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ and $|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$
- So, we can write any vector in $\mathbb{C}^2$ as:
  - $\begin{bmatrix} a \\ b \end{bmatrix} = a \begin{bmatrix} 1 \\ 0 \end{bmatrix} + b \begin{bmatrix} 0 \\ 1 \end{bmatrix} = a\,|0\rangle + b\,|1\rangle$
- We pronounce $|0\rangle$ and $|1\rangle$ as "ket zero" and "ket one." These are called the *computational basis*.

Quantum computing uses essentials from Quantum Mechanics and Mathematics (Cont.)

Entanglement

With tensor calculation in Mathematics,
you can immediately discover Entanglement

- ***Quantum Entanglement*** *is the phenomenon of a group of* ***particles*** *being generated or interacting in such a way that the* ***quantum state*** *of each particle of the group cannot be described independently of the state of the others, including when the particles are separated by a large distance.*
- *Quantum entanglement is at* ***the heart of the disparity between classical and quantum physics***
- *Entanglement is a primary feature of Quantum Mechanics not present in classical mechanics*
- ***EPR Paradox****: "impossible behavior", "spooky action at a distance", "violate local realism"*
- ***Verified in 2012-2013*** *by 3 teams of scientists*

We can write

$$\frac{\sqrt{2}}{2}|00\rangle + \frac{\sqrt{2}}{2}|01\rangle$$

as

$$|0\rangle \otimes \left(\frac{\sqrt{2}}{2}|0\rangle + \frac{\sqrt{2}}{2}|1\rangle\right)$$

but we cannot write

$$\frac{\sqrt{2}}{2}|00\rangle + \frac{\sqrt{2}}{2}|11\rangle$$

as the "tensor product" of two single Qubit states

They are entangled!

Once you measure the first Qubit,
the second is uniquely determined

Quantum computing uses essentials from Quantum Mechanics and Mathematics (Cont.)

Quantum Gates

Unlike many classical logic gates, Quantum Gates are reversible

Quantum gates are Unitary Operators and are described as unitary Matrices relative to some orthonormal basis.

In Linear Algebra, an invertible complex square matrix U is **unitary** if its matrix inverse U^{-1} equals its conjugate transpose U^*, that is, if

$$U^*U = UU^* = I$$

where I is the identity matrix

Some Examples:

- Pauli X Gate: $\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
- Pauli Y Gate: $\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$
- Pauli Z Gate: $\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$
- Hadamard Gate: $\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$
- S or $\sqrt{Z}$ Gate: $\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix}$ and T or $\sqrt[4]{Z}$: $\begin{bmatrix} 1 & 0 \\ 0 & e^{\frac{i\Pi}{4}} \end{bmatrix}$ and $P(\varphi) = \begin{bmatrix} 1 & 0 \\ 0 & e^{\varphi} \end{bmatrix}$
- CNOT Gate: $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$ SWAP Gate: $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Quantum Computing uses essentials from Quantum Mechanics and Mathematics (Cont.)

Combining Qubits

1 Qubit	→	2	dimensions
2 Qubits	→	4	dimensions
3 Qubits	→	8	dimensions
10 Qubits	→	1024	dimensions
…	→		…
n Qubits	→	2^n	dimensions

With two qubits we get combinations like

$$a\,|00\rangle + b\,|01\rangle + c\,|10\rangle + d\,|11\rangle$$

where:

$|01\rangle$ means that the first Qubit q_0 is $|1\rangle$ and the second Qubit q_1 is $|0\rangle$

a, b, c, and d are complex numbers with $|a|^2 + |b|^2 + |c|^2 + |d|^2 = 1$

In fact, the notation is a shortcut for the tensor product of the Qubits:

$$|00\rangle = |0\rangle \otimes |0\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}1\\0\end{bmatrix} = \begin{bmatrix}1\\0\\0\\0\end{bmatrix}$$

$$|01\rangle = |0\rangle \otimes |1\rangle = \begin{bmatrix}1\\0\end{bmatrix} \otimes \begin{bmatrix}0\\1\end{bmatrix} = \begin{bmatrix}0\\1\\0\\0\end{bmatrix}$$

$|q_2 q_1 q_0\rangle = |010\rangle = |0\rangle \otimes |1\rangle \otimes |0\rangle$ = … an 8-dimensional vector

Quantum computing uses essentials from Quantum Mechanics and Mathematics (Cont.)

Entanglement

State of a control Qubit influences the state of a target Qubit

For example:

- $\frac{\sqrt{2}}{2}|00\rangle + \frac{\sqrt{2}}{2}|01\rangle$ not entangled
- $\frac{\sqrt{2}}{2}|01\rangle - \frac{\sqrt{2}}{2}|10\rangle$ entangled
- $\frac{\sqrt{2}}{2}|00\rangle + \frac{\sqrt{2}}{2}|11\rangle$ entangled

<u>Example</u>: **CNOT Gate**

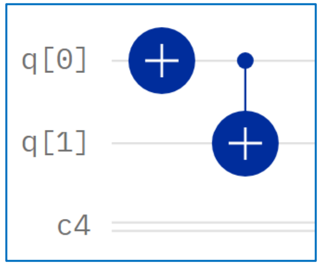
- Control = q_0
- Target = q_1

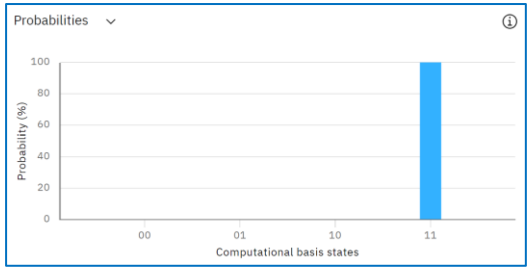
$|00\rangle \rightarrow |00\rangle$

$|01\rangle \rightarrow |11\rangle$

$|10\rangle \rightarrow |10\rangle$

$|11\rangle \rightarrow |01\rangle$





<u>Example</u>: **Toffoli Gate**

- Control = $q_0, q_1,$
- Target = q_2

$|000\rangle \rightarrow |000\rangle$

$|001\rangle \rightarrow |001\rangle$

$|010\rangle \rightarrow |010\rangle$

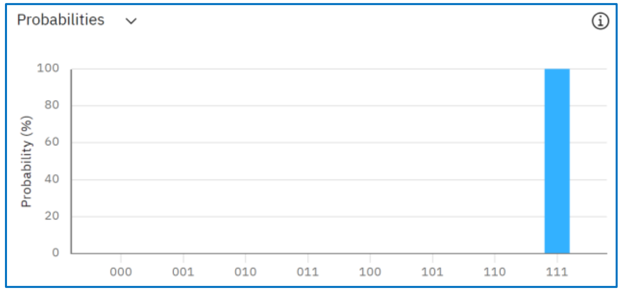
$|011\rangle \rightarrow |111\rangle$

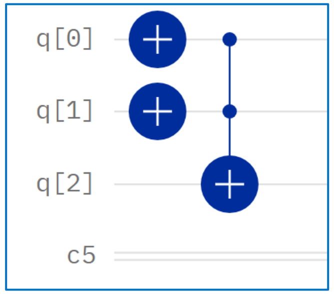
$|100\rangle \rightarrow |100\rangle$

$|101\rangle \rightarrow |101\rangle$

$|110\rangle \rightarrow |110\rangle$

$|111\rangle \rightarrow |011\rangle$





Linear Algebra and Quantum Computing Short Introduction

Bell State

Unitary Matrices

Be careful with the sequence!

$$CX.\left[(I \otimes H).|00\rangle\right]$$

$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} . \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \otimes \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$= \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} . \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 1 & 1 & -1 \end{bmatrix} . \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

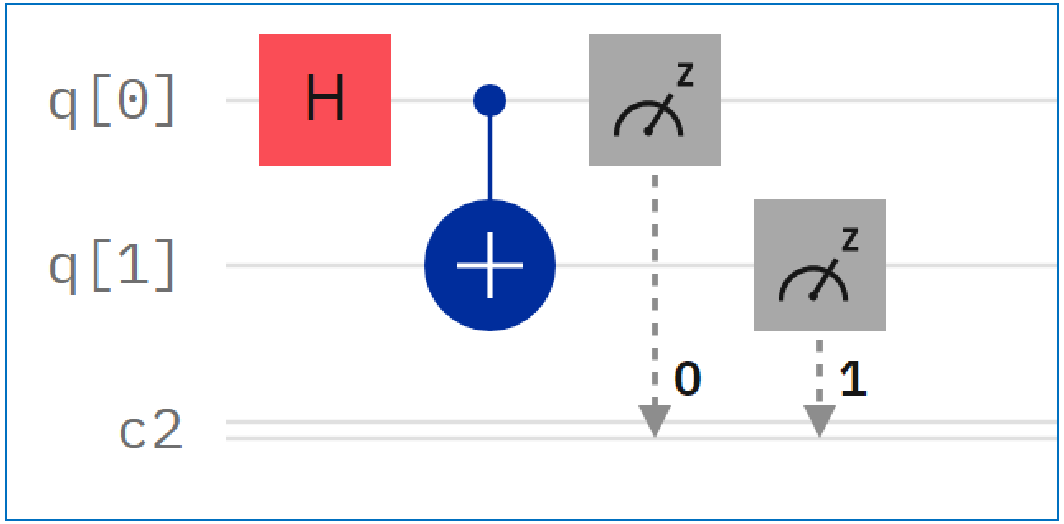
$$= \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 \\ 1 & -1 & 0 & 0 \end{bmatrix} . \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} = \frac{1}{\sqrt{2}} |00\rangle + \frac{1}{\sqrt{2}} |11\rangle$$

Linear Algebra and Quantum Computing
Short Introduction

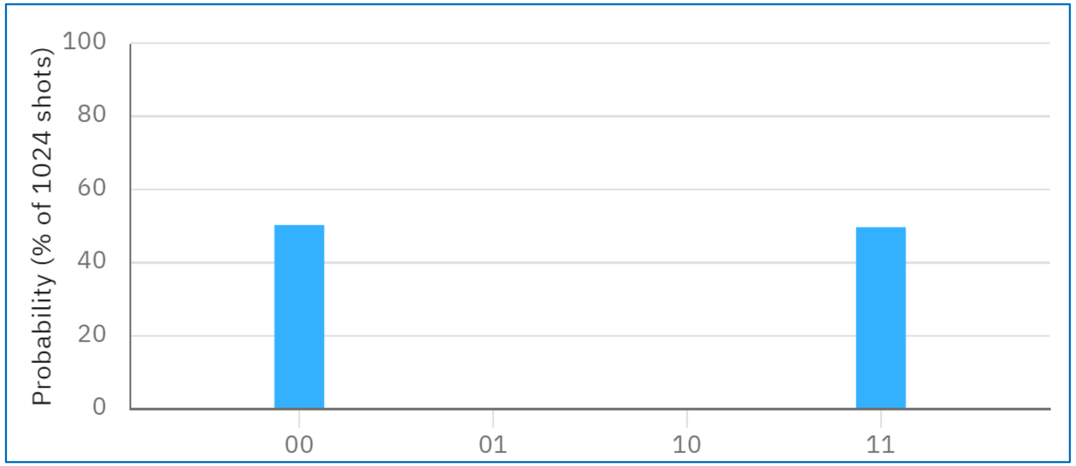
Bell State

Quantum Gates are Unitary Matrices

$CNOT\,.\,(I\ \otimes H)\,.\,|00\rangle$

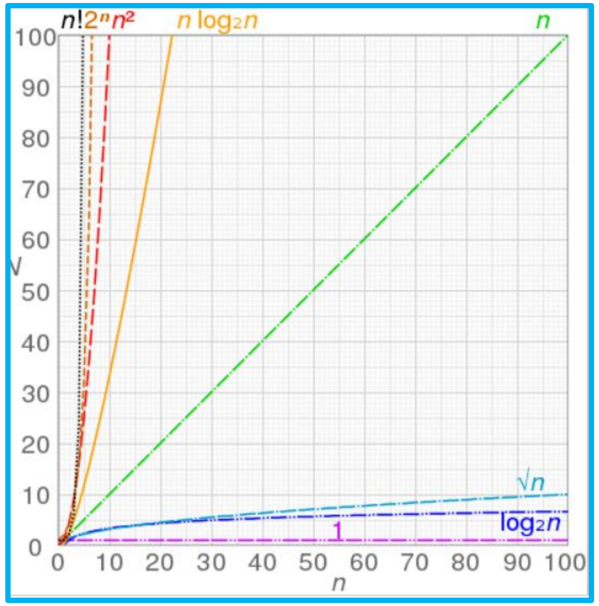


Probabilities after Measurement



Exponential growth

- 2^1
- 2^2
- 2^3
- …
- 2^n



The perfect dream …

1 qubit – 2 quantum state dimensions IBM **Quantum**

$a\,|0\rangle + b\,|1\rangle$

where *a* and *b* are complex numbers.

2 qubits – 4 quantum state dimensions

$a\,|00\rangle + b\,|01\rangle + c\,|10\rangle + d\,|11\rangle$

where *a, b, c,* and *d* are complex numbers.

3 qubits – 8 quantum state dimensions

$a\,|000\rangle + b\,|001\rangle + c\,|010\rangle + d\,|011\rangle +$
$e\,|100\rangle + f\,|101\rangle + g\,|110\rangle + h\,|111\rangle$

where *a, b, … , g,* and *h* are complex numbers.

2^{10} = 1,024

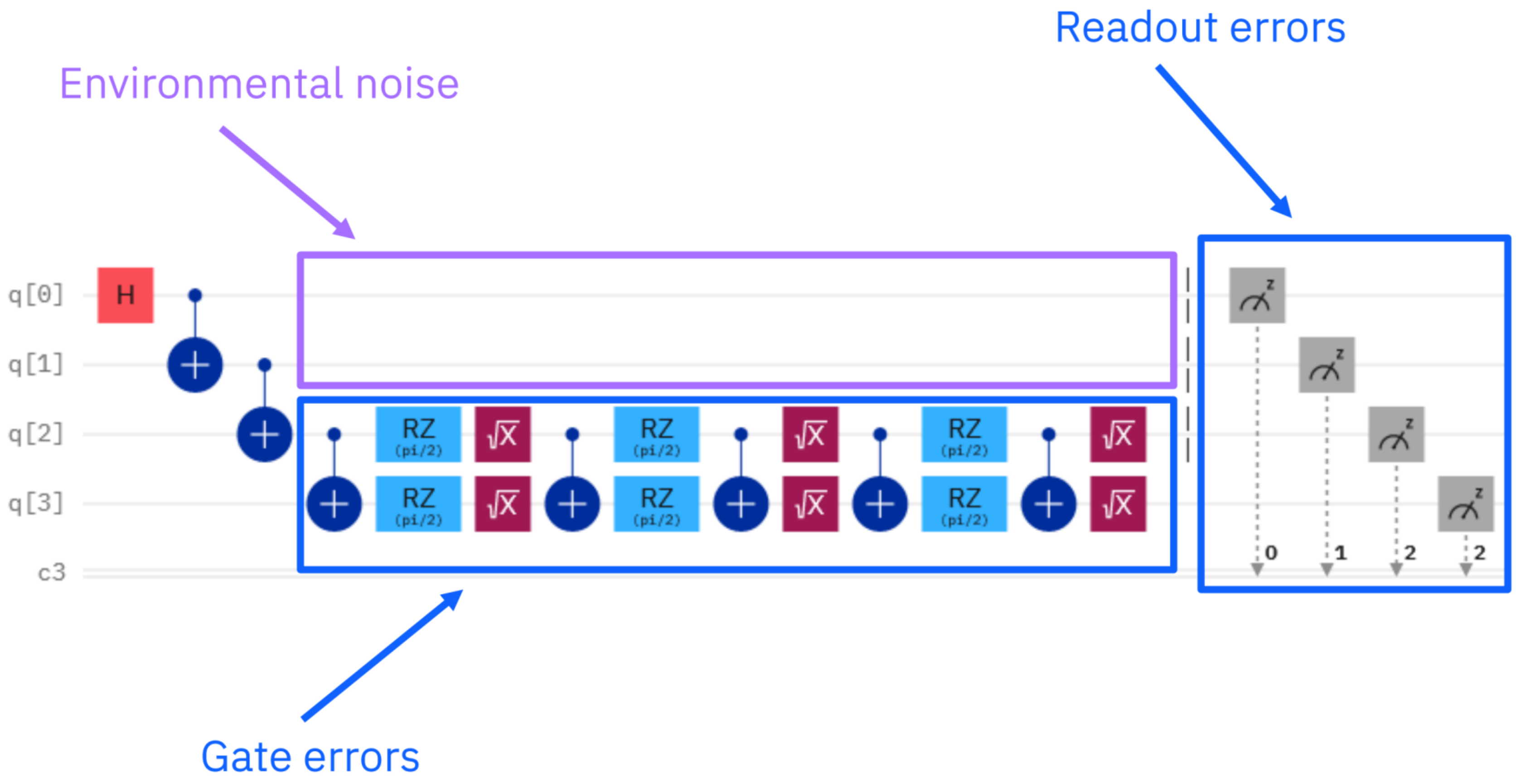
2^{20} = 1,048,576

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

Examples of Noise



Error Suppression

- Prevent noise before it occurs

Error Mitigation

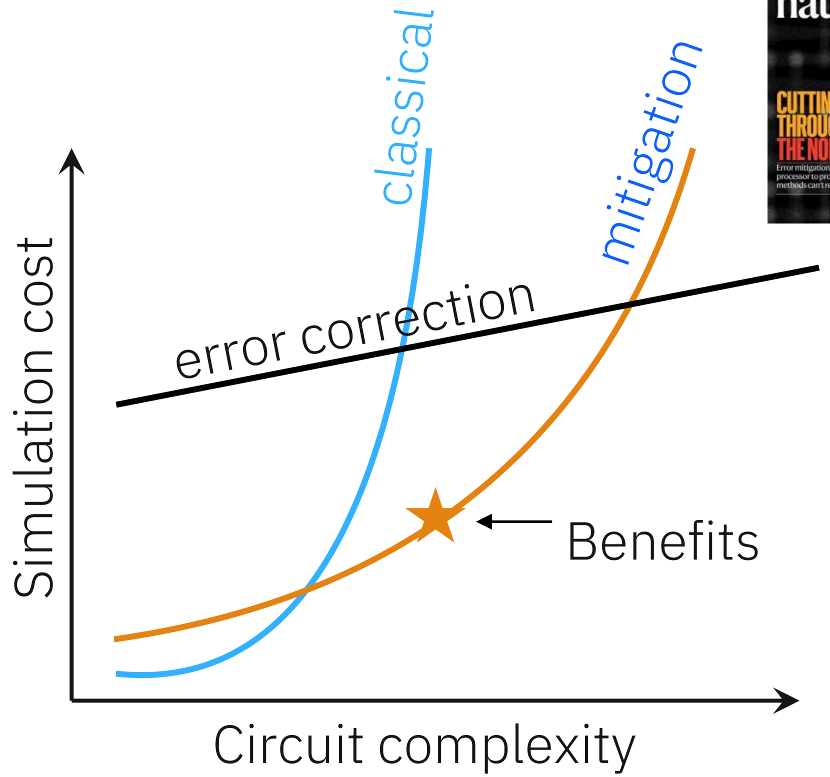
- Filter out noise after execution

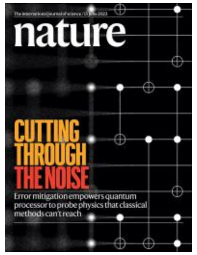
Error Correction

- Eliminate noise during execution

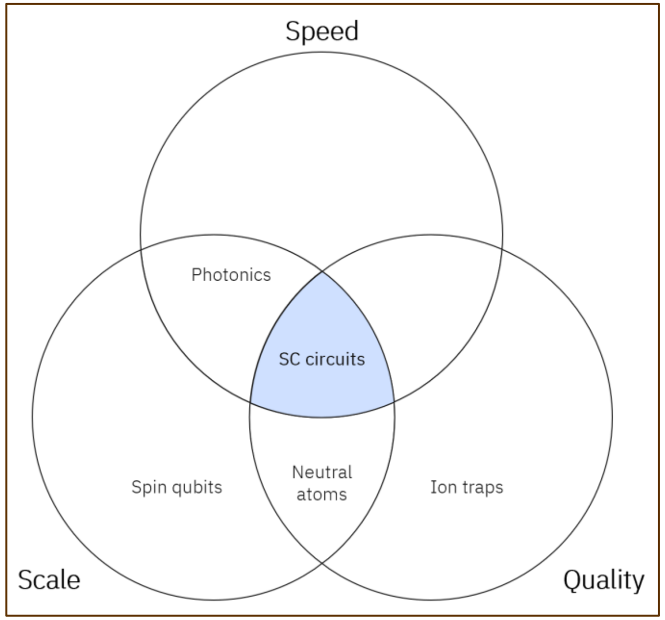
Quantum Utility Computing

Major advances in past 12 months

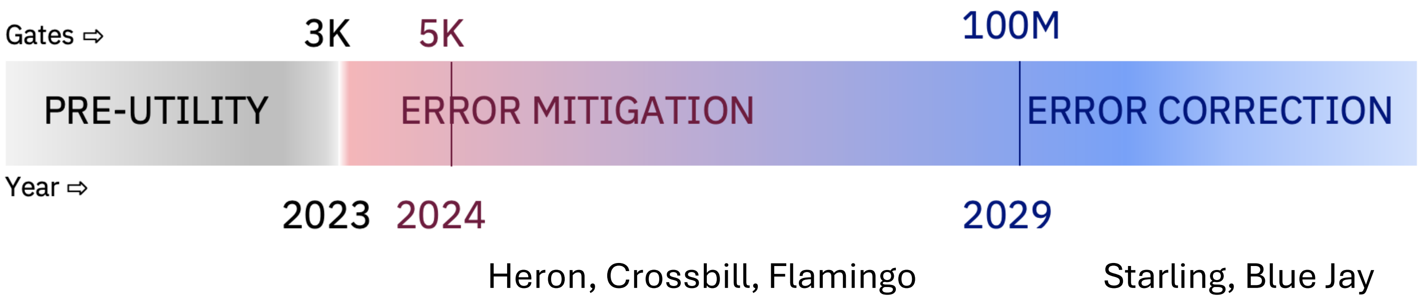




"If you're not using 100+ Qubits, you're not doing Quantum"



- **11 Quantum Computers in the Cloud**
- 2 Cloud Quantum Computing **Centers**
- **4 Key Offerings**



Cloud Quantum ~~Data~~ Computing Centers

2

3T+

Circuits run on IBM systems

8

On premise dedicated Quantum Systems

IBM US Quantum Data Center

Poughkeepsie, USA
August 2019

10+ utility-scale Quantum Computers

IBM EU Quantum Data Center

Ehningen, Germany
October 2024

2+ utility-scale Quantum Computers

Quantum-Centric Supercomputing

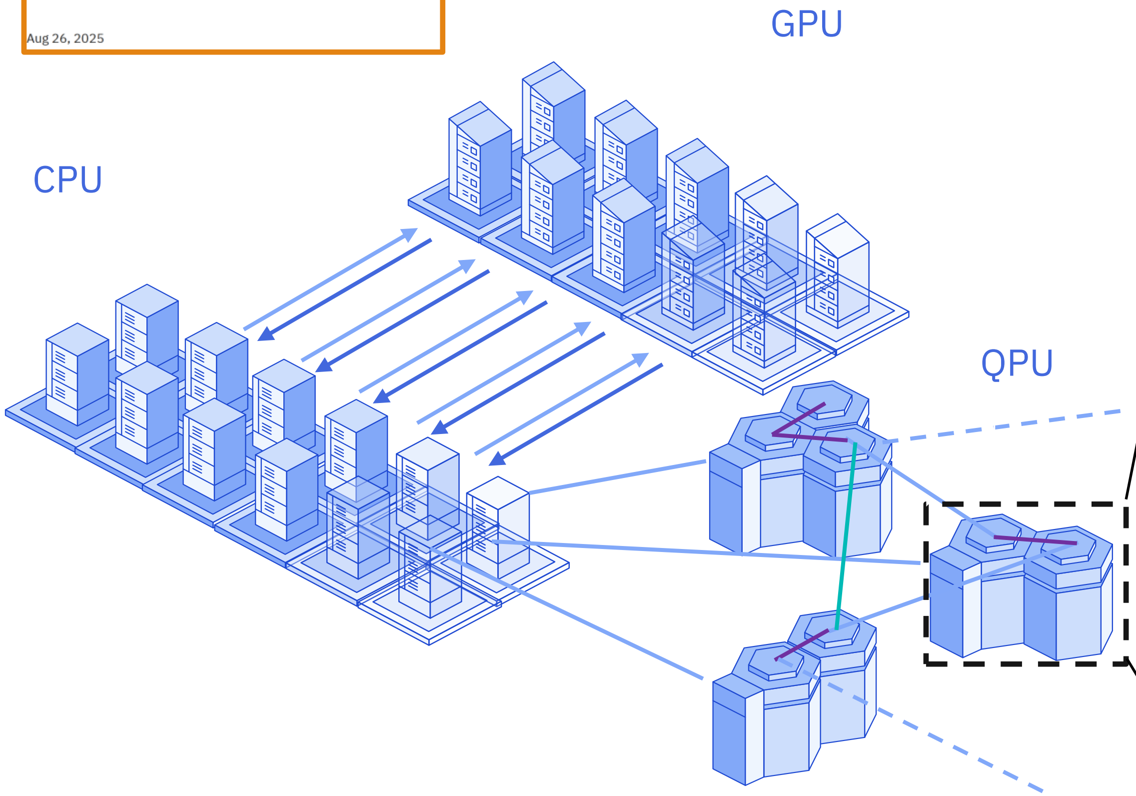
IBM and AMD Join Forces to Build the Future of Computing

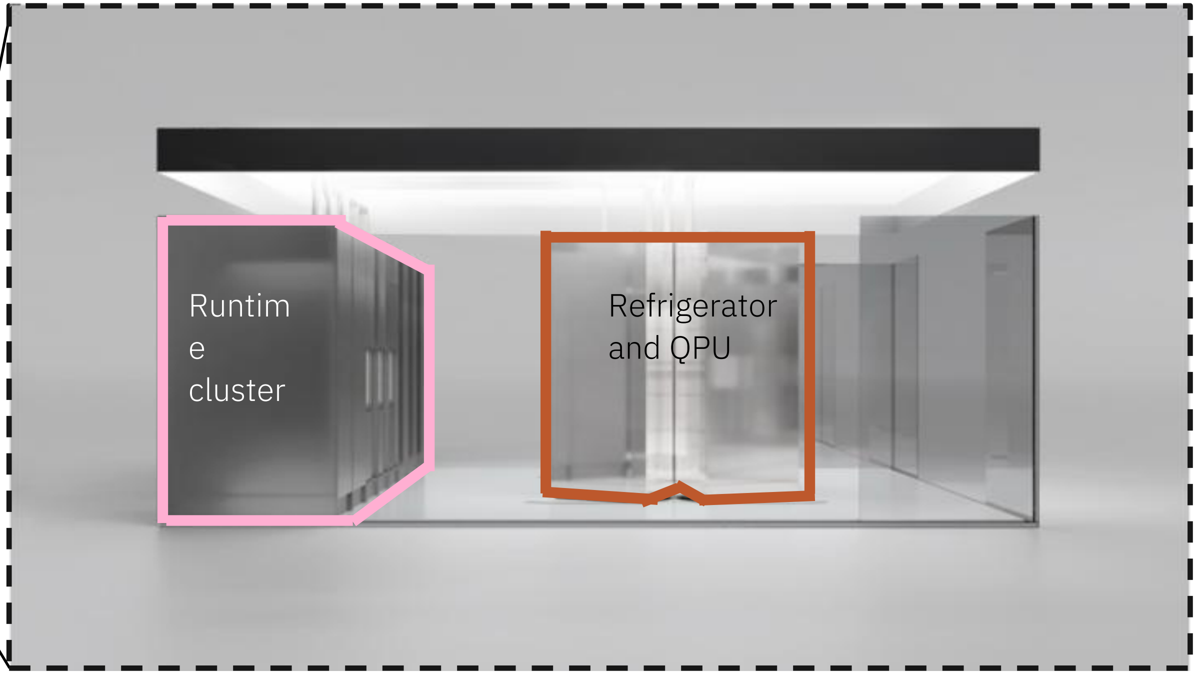
Companies aim to merge AI accelerators, quantum computers, and high-performance computing to help solve a wide range of the world's most difficult problems

Aug 26, 2025

Delivering impactful quantum computing requires the interplay of **Quantum** and **Classical** resources at scale

Quantum-Centric Supercomputing is the path toward industrial-scale applications





Development Roadmap

Scale + Speed + Quality + Stability

	2016–2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2033+
	Ran quantum circuits on IBM Quantum Platform	Released multi-dimensional roadmap publicly with initial focus on scaling	Enhanced quantum execution speed by 100x with Qiskit Runtime	Brought dynamic circuits to unlock more computations	Enhanced quantum execution speed by 5x with Quantum Serverless and execution modes	Demonstrated accurate execution of a quantum circuit at a scale beyond exact classical simulation (5K gates on 156 qubits)	Deliver quantum + HPC tools that will leverage Nighthawk, a new higher-connectivity quantum processor able to execute more complex circuits	Enable the first examples of quantum advantage using a quantum computer with HPC	Improve quantum circuit quality to allow 10K gates	Improve quantum circuit quality to allow 15K gates	Deliver a fault-tolerant quantum computer with the ability to run 100M gates on 200 logical qubits	Beyond 2033, quantum computers will run circuits comprising a billion gates on up to 2000 logical qubits, unlocking the full power of quantum computing
Hardware →	Early: Canary 5 qubits; Albatross 16 qubits; Penguin 20 qubits; Prototype 53 qubits	Falcon: Benchmarking; 27 qubits		Eagle: Benchmarking; 127 qubits		Heron (5K): Error mitigation; 5K gates; 133 qubits	Nighthawk (5K): Error mitigation; 5K gates; 120 qubits	Nighthawk (7.5K): Error mitigation; 7.5K gates; 120 qubits; Up to 120x3 = 360 qubits	Nighthawk (10K): Error mitigation; 10K gates; 120 qubits; Up to 120x9 = 1080 qubits	Nighthawk (15K): Error mitigation; 15K gates; 120 qubits; Up to 120x9 = 1080 qubits	Starling (100M): Fault-tolerant; 100M gates; 200 logical qubits	Blue Jay (1B): Fault-tolerant; 1B gates; 2000 logical qubits

Code assistant (2024, completed)

Applying algorithms to applications
- Functions (2024, completed)
- Use case benchmarking toolkit (2026)
- Computation libraries (2027+)

Discovering new algorithms for advantage
- Advanced classical transpilation tools (2024, completed)
- Advanced classical mitigation tools (2025, on target)
- Utility mapping tools (2026–2028)
- Circuit libraries (2029+)

Orchestrating workloads for quantum + HPC
- Resource Management
- Qiskit Serverless (2023, completed)
- Plugins for HPC (2024, completed)
- C API (2025, on target)
- Execution modes (2023, completed)
- Profiling tools (2026–2027)
- Workflow accelerators (2028+)

Accurately and efficiently executing on quantum computers
- Qiskit Runtime (2021+)
- IBM Quantum Experience (2016–2020, completed)
- OpenQASM 3 (2021, completed)
- Dynamic Circuits (2022, completed)
- Error mitigation (2023, completed)
- 200K CLOPS (2024, completed)
- Utility-scale dynamic circuits (2025, on target)
- Fault-tolerant ISA (2029+)

Completed
On target

Quantum Utility Computing

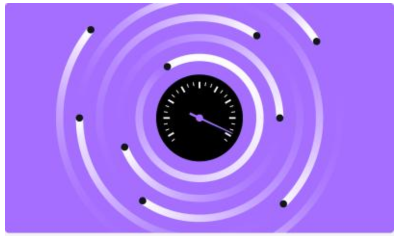
Quantum Advantage

Full Fault Tolerant Quantum Computers

Qiskit SDK

The **Lingua Franca** of Quantum Computing; write once and execute quantum circuits on **10+** different hardware providers

IBM Quantum
AQT
IQM
Azure Quantum
Alice & Bob
IonQ
Amazon Braket
Superstaq
Quantinuum
Rigetti



Benchpress

Quantum SDK Preferred
(2024 Unitary Foundation Survey)

74%

Qiskit contributors that are external to IBM

74%

Dependent Qiskit projects

4000+

Computationally Complex Problems exist in Every Industry

Banking
- Fraud monitoring
- Portfolio optimization
- Risk simulation
- Customer analytics
- Time series forecasting

Automotive
- Battery material design
- Material design
- Mobility as a Service
- Quality control
- Self-driving and ADAS
- Production optimization

Chemicals
- Sustainable products
- Low-carbon manufacturin g
- Resilient supply chains
- Process optimization
- Asset health

Life sciences
- Efficient drug research and development
- Clinical trials
- Tractable protein folding
- Call-centric therapeutics
- mRNA

Healthcare
- Accelerated diagnoses
- Personalized interventions
- Adherence to drugs
- Biomarkers
- Image processing

Logistics
- Global logistics optimization
- Disruption management
- Routing optimization
- Predictive maintenance
- Forecasting

Public services
- Security/safety
- Multimodal transport
- City resource planning
- Disaster management
- Fraud detection in tax and social

Insurance
- Catastrophe modeling
- Precise customer profiling
- Efficient risk management
- Optimized pricing of premiums

Electronics
- Faster product design
- Circuit defect identification
- Process optimization
- Production optimization
- Quality control

Airlines
- Forecasting and revenue
- Irregular operations
- Network planning
- Safety and maintenance
- Hyper-personalization

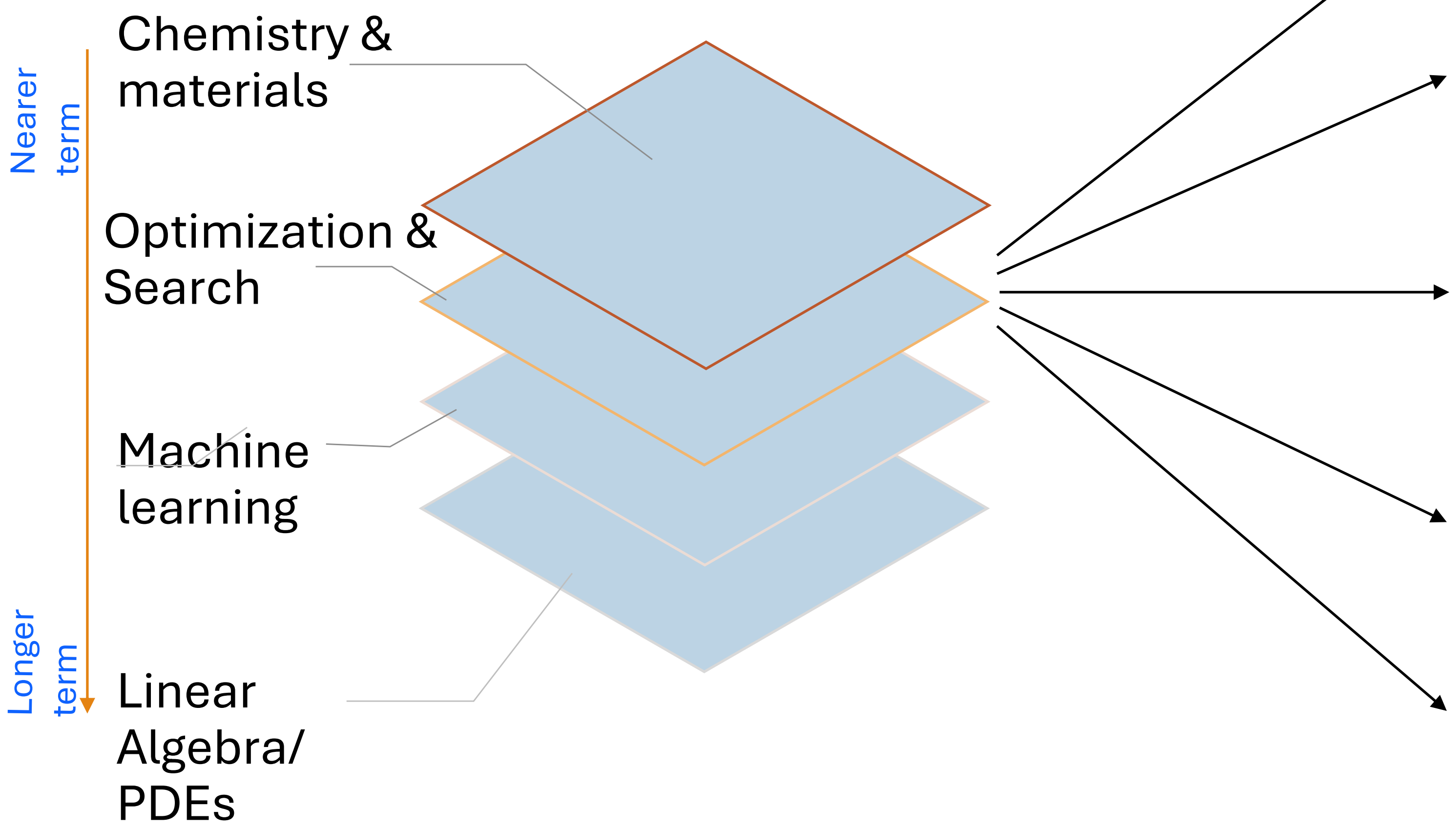
Energy and utilities
- Energy trading
- Optimization of energy grid
- Renewables system design
- Energy forecasting
- Hyper-personalization
- Asset health

Aerospace
- Material discovery
- Aircraft design
- Asset health
- Corrosion and material interaction
- Fuel efficiency

Oil and gas
- Emissions reduction
- Reservoir simulation
- Virtual flow meters
- Subsurface modeling
- Failure prediction

Telecom
- Network optimization
- Network anomaly detection
- Contextual customer segmentation
- Cybersecurity network

Quantum Computing Key Use Case Categories



Aerospace	High-performance materials Design optimization Aircraft design and simulation
Automotive	Advanced batteries Multi-objective vehicle routing optimization Auto design and simulation
Chemicals	Lower energy fertilizer manufacturing Efficient Catalysts Accelerated product development
Electronics & semiconductors	Product design Process development Finite element simulation
Energy	Risk of grid bottlenecks Grid optimization with EVs Carbon Sequestration
Financial Services	Portfolio optimization Derivatives/options pricing Anti-money laundering
Health Care & Life Sciences	Drug discovery and drug design optimization mRNA & protein structure predictions Disease target & biomarker discovery

IBM Quantum Network

A global community driving innovation

275+
Member organizations

40+
Quantum Innovation Centers, 8 with Dedicated Service

125+
Members of QICs
Includes research centers and universities

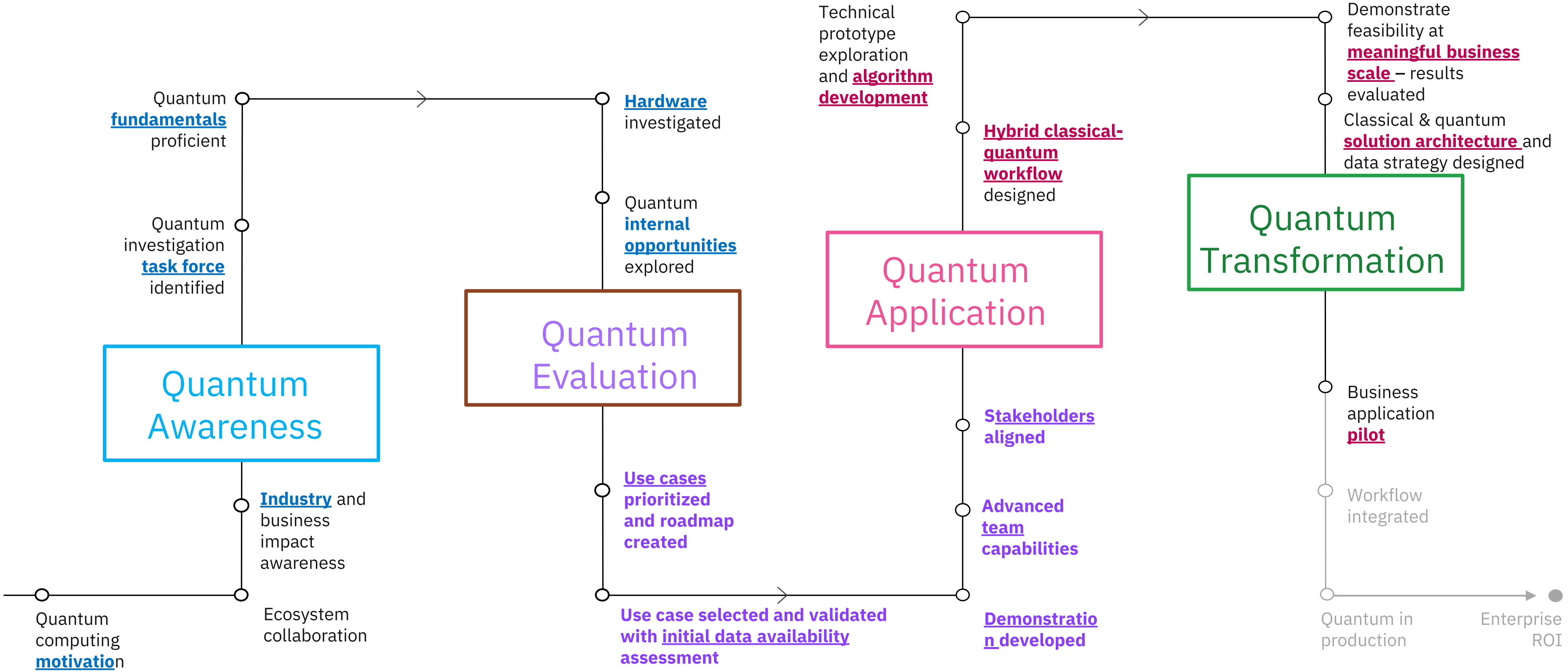
50+
Industry clients
Includes Quantum Accelerator, Premium Plan, and industry QIC members

40+
Startups

10+
Ecosystem Partners
Includes re-sellers, GSIs, and ISVs

1Qbit Systems
Accelequant
Adam Mickiewicz University
Agnostiq Inc
Alabama A&M University
Alabama State University
Albany State University
Algorithmiq Oy
Aliro Quantum
American Express
Amgen
Anaqor
AngelQ
Ansys Inc
Applied Quantum Computing
Aqarios
Argonne National Lab
Arizona State University
Assured Information Security
Banco Bilbao Vizcaya Argentaria
Banco Bradesco
Basque Center for Applied Mathematics
Basque Center for Climate Change
Basque Center for Neuroscience (Achucarro)
Basque Center on Cognition, Brain and Language
Basque Center on Materials, Applications and Nanostructures
Beit
Biofisika Institute
BlueQubit
Boeing
Bosch
BosonQ Psi
Boston University
Bowie State University
Brookhaven National Lab
Bundesdruckerei GmbH
Bundeswehr University
ETH Zurich
ExxonMobil
EY Global
Fachhochschule Nordwestschweiz
Fermi National Accelerator Laboratory
Florida A&M University
Fraunhofer
GE Global Research
General Atomics
George Mason University
Georgia Institute of Technology
Global Data Quantum
Good Chemistry
Haiqu
Hampton University
Hanlim Pharm
Harvard University
Hitachi Ltd
Howard University
HQS Quantum Simulations
HSBC
Hydro-Quebec
Hyundai Motor Company
IBM-HBCU Quantum Center - Howard University
IBM-Illinois Discovery Accelerator Institute - University of Illinois Urbana Champaign
III Taiwan
Ikerbasque Foundation
Indian Institute of Technology Madras
Industrial Technology Research Institute
Infleqtion
Institute of Theoretical and Applied Informatics Polish Academy of Sciences
Instituto Nazionale di Fisica Nucleare
Israel Aerospace Industries
National Centre for Nuclear Research
National Energy Technology Laboratory
National Institute for Nuclear Physics
National Quantum Computing Centre
National Taiwan University
Naval Air Warfare Center Aircraft Division
Naval Air Warfare Center Weapons Div.
Naval Information Warfare Center Atlantic Command
Naval Information Warfare Center Pacific Command
Naval Surface Warfare Center
Netherlands eScience Center
Netherlands Organization for Applied Scientific Research
New Mexico State University
New York University
Norfolk State University
North Carolina AT State University
North Carolina Central University
North Carolina State University
Northeastern University
Northwestern University
Oak Ridge National Lab
OESIA
OVH Groupe SA
Pacific Northwest National Lab
Perimeter Institute for Theoretical Physics
Phasecraft
Plateforme d'Innovation Numerique et Quantique
Polymat
Poznan Supercomputing and Networking Center
Prairie View AM University
Spelman College
State Farm Insurance
Stellenbosch University
STFC Hartree Centre (UKRI)
Stony Brook University
Strangeworks
Sumitomo Mitsui Trust Bank Limited
Sungkyunkwan University
Suntory
Super Tech Labs
Surf
System Vertrieb Alexander GmbH
T-Systems International GmbH
Technical University of Denmark
TECNALIA Research & Innovation
Tecnologico de Monterrey
Tekniker
Tennessee State University
Texas Southern University
The University of Texas at San Antonio
Tokyo Electron Limited
Tokyo University of Agriculture and Technology
Toppan Inc
Toshiba
Toyota
Truist Financial Corp
Tuskegee University
Ulsan National Institute of Science and Technology
United States Air Force Research Lab
United States Naval Postgraduate Military University
United States Naval Research Laboratory
United States Naval Undersea Warfare Center

Typical Enterprise Journey to Quantum Business value



IBM Quantum Ecosystem

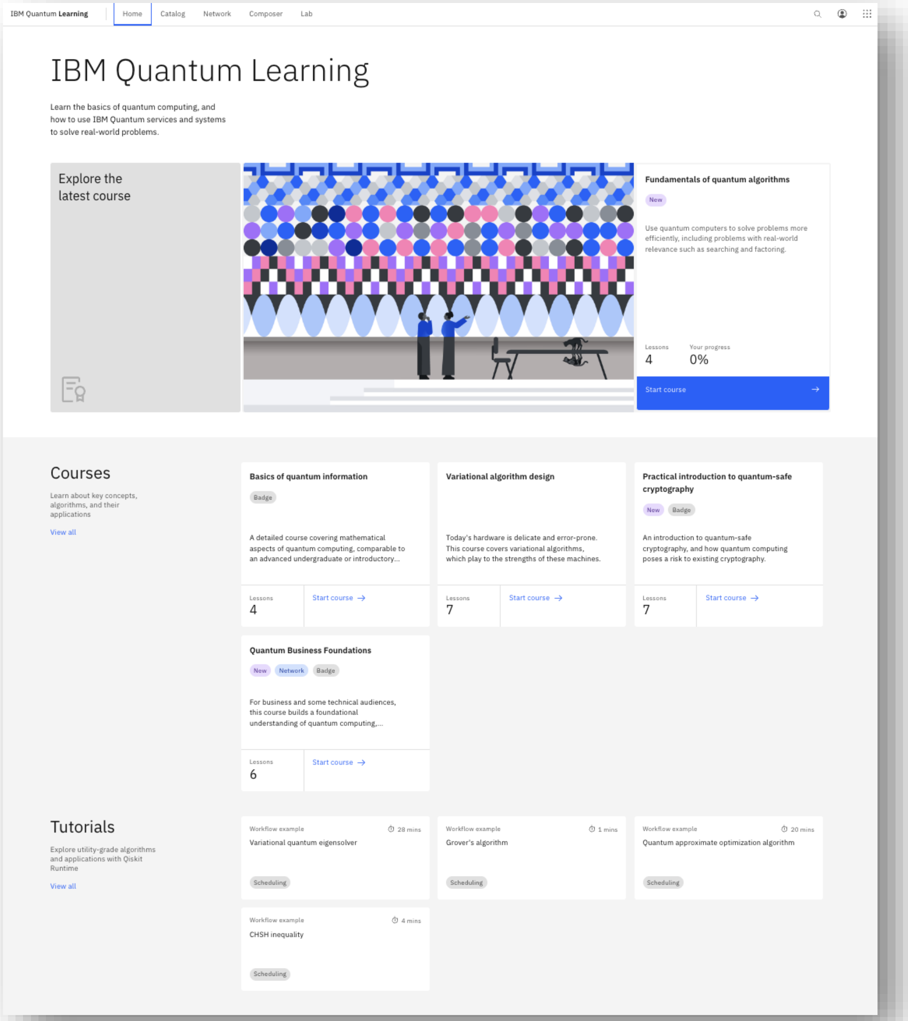
250+ — **IBM Quantum Network members**
The largest ecosystem across industries

600K+ — **Users**
The largest user base

2,800+ — **Papers**
The most innovative ecosystem

IBM Quantum Learning

- From Basic to Advanced topics
- Work with **real IBM Quantum Systems**
  - Courses, Tutorials, Badges
- Qiskit Global Summer School
- Quantum Challenge



Some useful links

- Quantum Platform
  - https://quantum.ibm.com/
- Quantum Learning Platform
  - https://learning.quantum.ibm.com/
- Qiskit
  - https://www.ibm.com/quantum/qiskit
- Quantum Research
  - https://www.ibm.com/quantum/research
- Qiskit Global Summer School 2025
  - https://github.com/qiskit-community/qgss-2025

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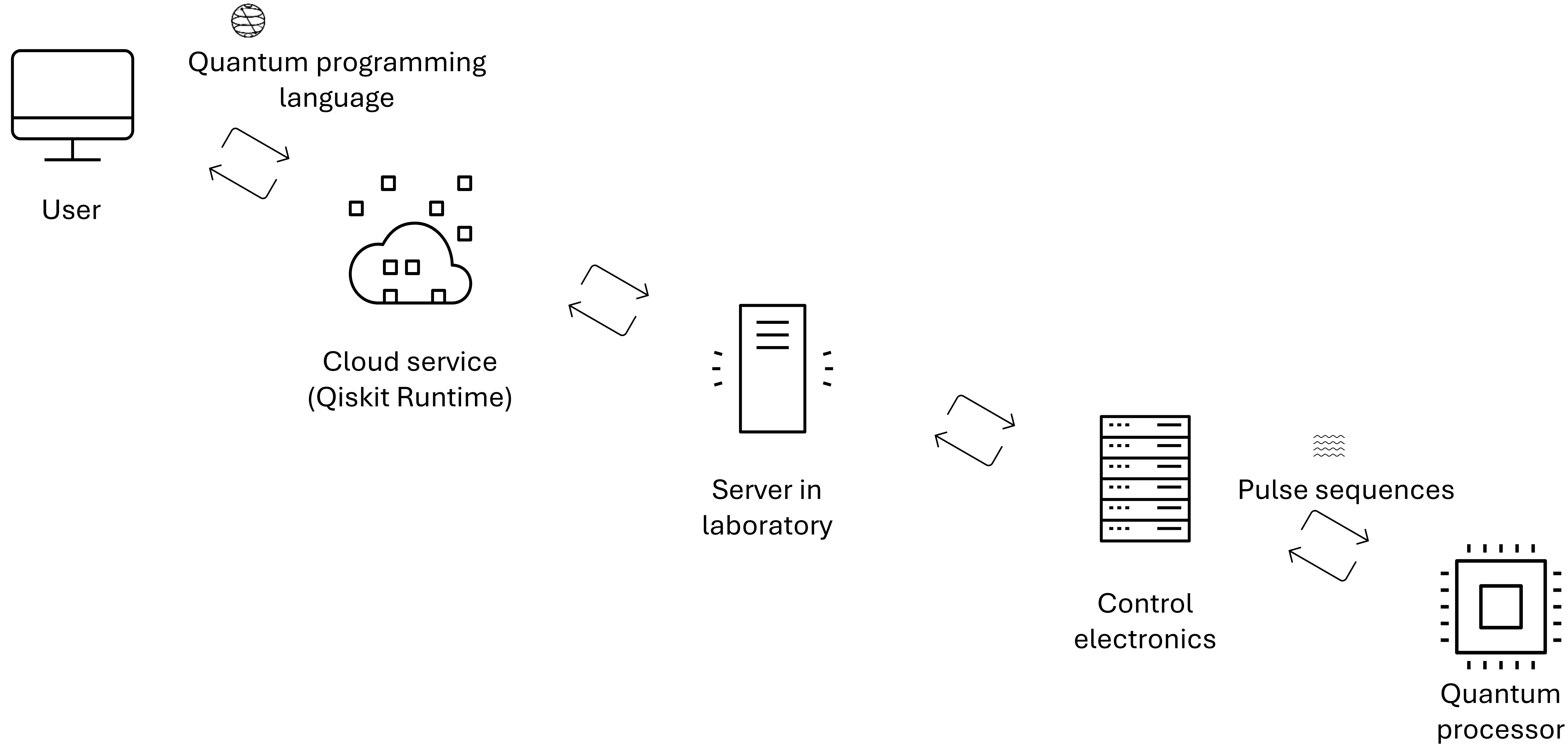
Anatomy of a Quantum Computing Service



Qiskit consists of 3 components

- The name "Qiskit" is a general term referring to a collection of software for executing programs on quantum computers.

- **Qiskit SDK** is an open-source SDK for working with quantum computers at the level of extended quantum circuits, operators, and primitives.
  - github.com/Qiskit/qiskit
  - quantum.cloud.ibm.com/docs

- **Qiskit Runtime** is a cloud service to execute workloads on IBM quantum processing units (QPUs)

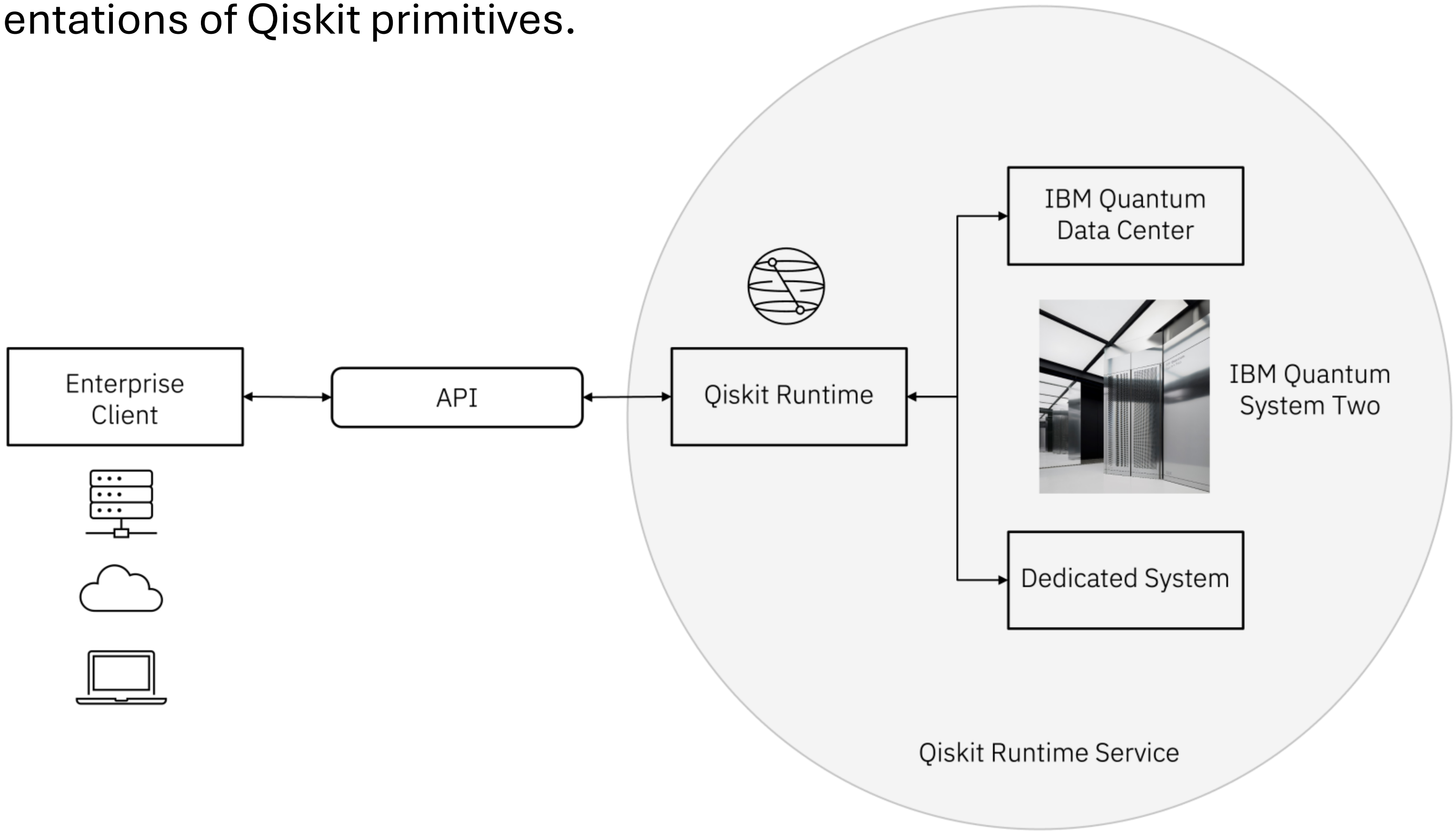
- The **Qiskit Ecosystem** is a collection of software and projects that build on or extend Qiskit.
  - qiskit.github.io/ecosystem

Qiskit Runtime

Qiskit Runtime is a **cloud-based service** for executing Quantum Computations on IBM Quantum hardware that streamlines quantum computations and provides optimal implementations of Qiskit primitives.

- Runs quantum programs on IBM Quantum hardware through IBM Quantum Platform or IBM Cloud
- Uses additional classical and quantum compute resources **including error suppression and error mitigation techniques**
- Offers three execution modes: **Job, Session, and Batch** for different use cases
- Simple installation via pip:

  `pip install qiskit-ibm-runtime`



How to import runtime primitives:

`from qiskit_ibm_runtime import EstimatorV2 as Estimator`
`from qiskit_ibm_runtime import SamplerV2 as Sampler`

Qiskit 2.0

Released April 2025

- Qiskit 2.0 is the first release to introduce a C API beyond the usual Python interface, marking the beginning of multi-language support. This sets the foundation for accessing Qiskit from C directly and building bindings for other programming languages on top of C interface.

Two modes of operation:

- **Standalone C** usage (no Python runtime dependency) - Installation Guide
- Embedded extension, for **calling the C API from a Python context** - Extension Guide
- Currently, the **C interface is minimal but growing**: C API Reference

- **Other Qiskit 2.0 highlights:**
- **Rust-powered** performance boosts: Up to 2× faster **circuit construction** and ~20% **faster transpilation**.
- Support for abstract/deferred timing in dynamic circuits: enables use of stretches for complex timing logic.
- New 'Box' support: **Atomic blocks for the transpiler**; useful for twirling, noise learning, and more.

Qiskit Installation Instructions

- `To Install Qiskit:`
- You can use an online jupyter lab environment (quantum.cloud.ibm.com/docs/en/guides/online-lab-environments) or install Qiskit locally.
- Follow the Qiskit installation guide (docs.quantum.ibm.com/guides/install-qiskit) to complete the following steps:
- 1. Install python
- 2. Install Qiskit
    - Create a virtual environment and activate it
    - Install qiskit including the visualization extra packages : `pip install qiskit[visualization]`
    - Install qiskit-ibm-runtime: `pip install qiskit-ibm-runtime`
    - Install jupyter: `pip install jupyter`
- `To Access Hardware:`
- Follow this guide (docs.quantum.ibm.com/guides/setup-channel) to setup an IBM Quantum account
- 1. Register IBM Quantum account using your institutional email
- 2. Save token to your local computer

qisk.it/install

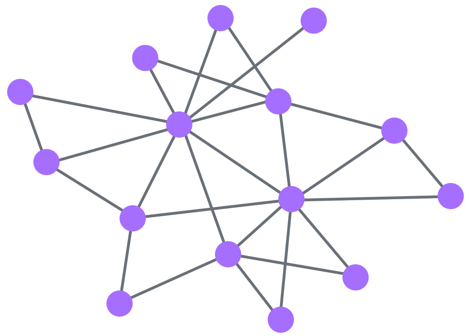
We use qBraid today

qBraid https://www.qbraid.com/

Qiskit Patterns

Step 1

- Map classical inputs to a quantum problem



55% decrease in memory usage

Step 2

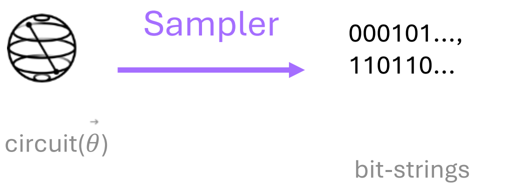
- Optimize problem for quantum execution.

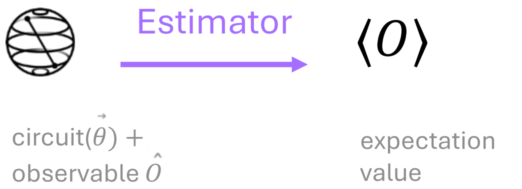
```
PassManager([UnitarySynthesis(),
             BasisTranslator(),
             EnlargeWithAncilla(),
             AISwap(),
             Collect1qRuns(),
             Optimize1qGates(),
             Collect2qBlocks(),
             ConsolidateBlocks()])
```

16x faster binding & transpiling
23% fewer 2Q Gates
Reinforcement Learning

Step 3

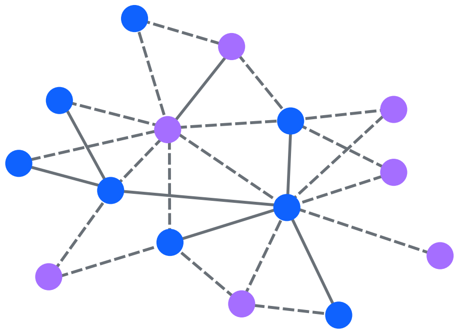
- Execute using Qiskit Runtime Primitives.





Step 4

- Post-process, return result in classical format.



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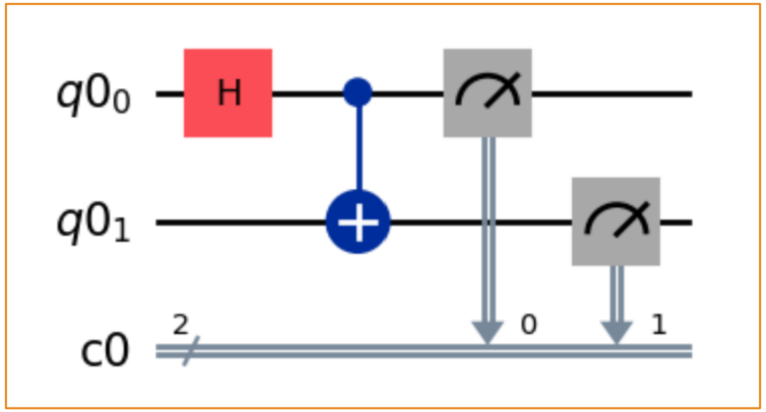
On Lab 1 – My First Qiskit Program

We will develop a Qiskit Application, known as “**Hello World**” from scratch



Simulator > Participants

Fake Device > Demonstration

Real Device > Demonstration

QML Preparation Steps !

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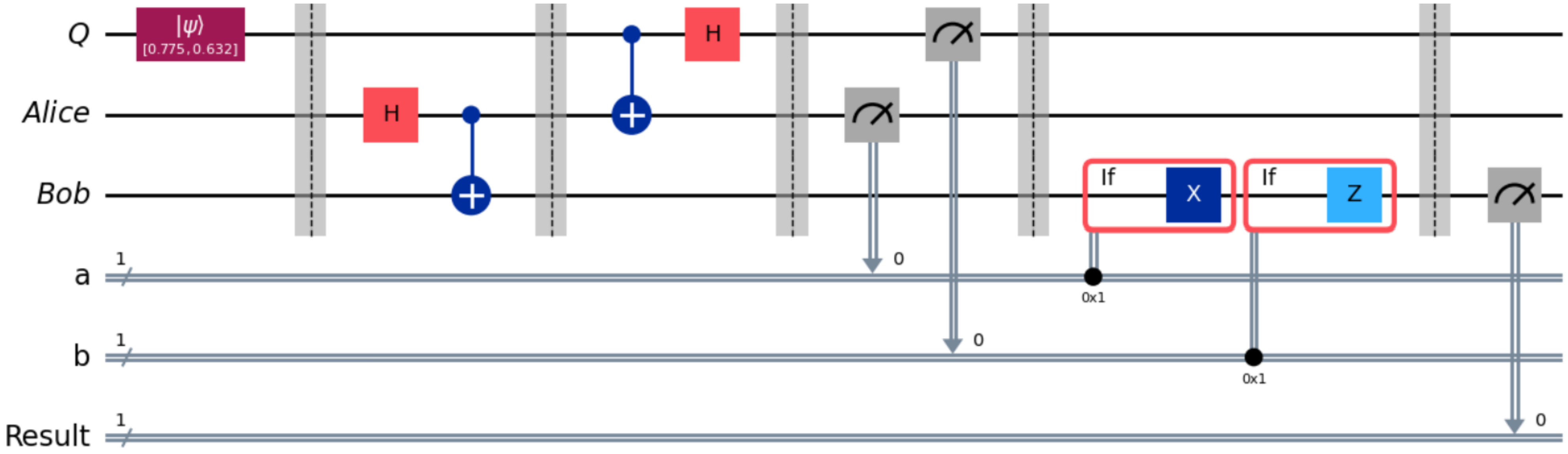
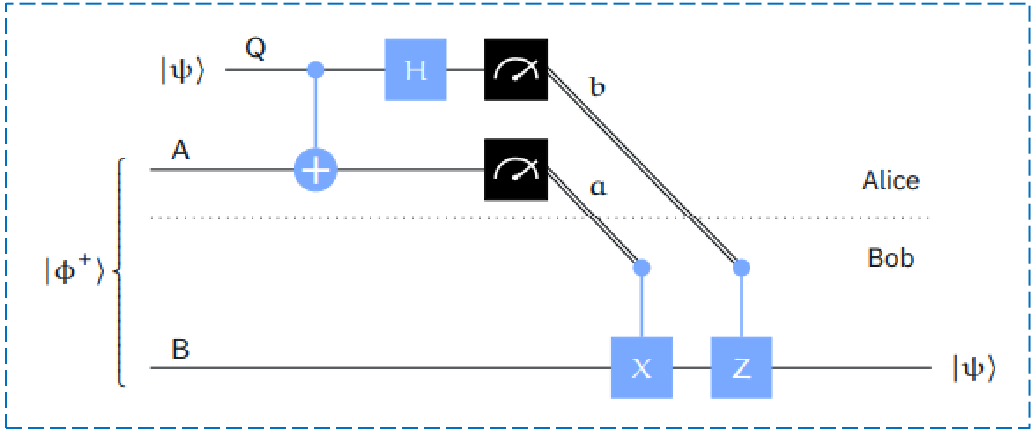
Lab 2: Diving Deeper into a Quantum Algorithm

We will develop a Qiskit Application, known as the "**Quantum Teleportation Algorithm**"



Teleportation – Protocol



Operations performed by Bob

- I if ab $= 00$
- Z if ab $= 01$
- X if ab $= 10$
- ZX if ab $= 11$

Protocol

1. Alice performs a controlled-NOT operation, where Q is the control and A is the target
2. Alice performs a Hadamard operation on Q
3. Alice measures A and Q, obtaining binary outcomes a and b, respectively.
4. Alice sends a and b to Bob.
5. Bob performs these two steps:
   1. If a $= 1$, then Bob applies an X operation to the qubit B.
   2. If b $= 1$, then Bob applies a Z operation to the qubit B

Qubit B will be in **whatever state Q was** prior to the protocol being executed, including whatever correlations it had with any other systems ≡ Q has been teleported into B

Teleportation – Quantum Information Theory

<u>Quantum Gates</u>

$X\,|0\rangle = |1\rangle$

$X|1\rangle = |0\rangle$

$Z\,|0\rangle = |0\rangle$

$Z\,|1\rangle = -|1\rangle$

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

$H|1\rangle = |-\rangle = \frac{\sqrt{2}}{2}\,(|0\rangle - |1\rangle)$

<u>Matrices and Column Vectors</u>

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

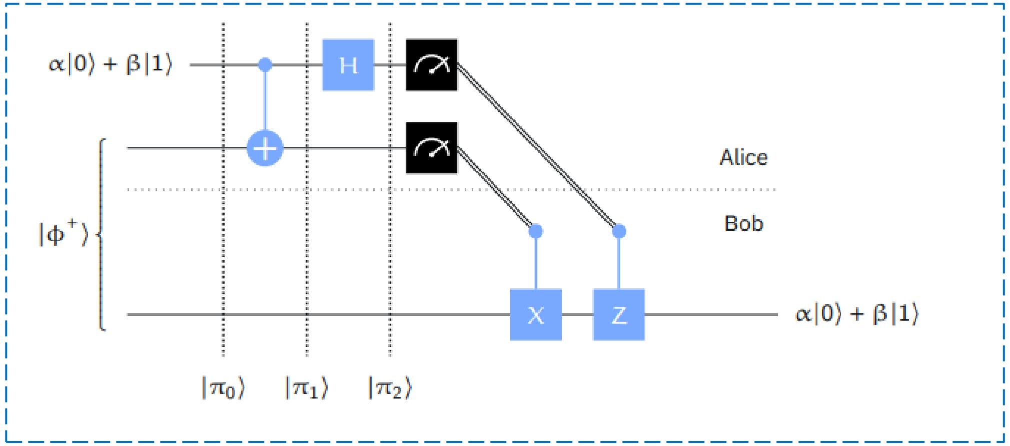
$$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \end{bmatrix} = -\begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

$$\frac{\sqrt{2}}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} 1 \\ 0 \end{bmatrix} = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 \\ 1 \end{bmatrix} = = \frac{\sqrt{2}}{2}\left(\begin{bmatrix} 1 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix}\right)$$

$$\frac{\sqrt{2}}{2}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}\begin{bmatrix} 0 \\ 1 \end{bmatrix} = \frac{\sqrt{2}}{2}\begin{bmatrix} 1 \\ -1 \end{bmatrix} = = \frac{\sqrt{2}}{2}\left(\begin{bmatrix} 1 \\ 0 \end{bmatrix} - \begin{bmatrix} 0 \\ 1 \end{bmatrix}\right)$$

Teleportation – Analysis



$$\frac{1}{\sqrt{2}}|00\rangle + \frac{1}{\sqrt{2}}|11\rangle$$

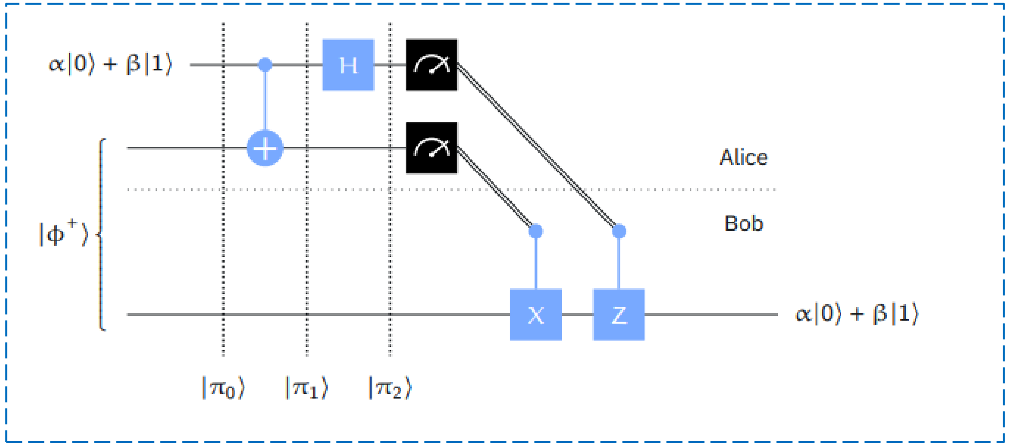
$$|\pi_0\rangle = |\phi^+\rangle \otimes (\alpha|0\rangle + \beta|1\rangle)$$

$$|\pi_0\rangle = \frac{\alpha|000\rangle + \alpha|110\rangle + \beta|001\rangle + \beta|111\rangle}{\sqrt{2}}$$

$$|\pi_1\rangle = \frac{\alpha|000\rangle + \alpha|110\rangle + \beta|011\rangle + \beta|101\rangle}{\sqrt{2}}$$

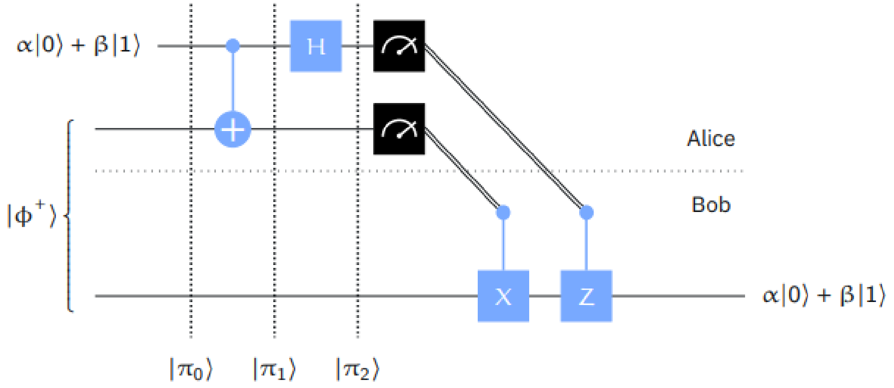
$$|\pi_2\rangle = \frac{\alpha|00\rangle|+\rangle + \alpha|11\rangle|+\rangle + \beta|01\rangle|-\rangle + \beta|10\rangle|-\rangle}{\sqrt{2}}$$

Teleportation – Analysis



$$
\begin{aligned}
|\pi_2\rangle &= \frac{\alpha|00\rangle|+\rangle + \alpha|11\rangle|+\rangle + \beta|01\rangle|-\rangle + \beta|10\rangle|-\rangle}{\sqrt{2}} \\
&= \frac{\alpha|00\rangle(|0\rangle + |1\rangle) + \alpha|11\rangle(|0\rangle + |1\rangle) + \beta|01\rangle(|0\rangle - |1\rangle) + \beta|10\rangle(|0\rangle - |1\rangle)}{2} \\
&= \frac{\boxed{\alpha|000\rangle} + \boxed{\alpha|001\rangle} + \boxed{\alpha|110\rangle} + \boxed{\alpha|111\rangle} + \boxed{\beta|010\rangle} - \boxed{\beta|011\rangle} + \boxed{\beta|100\rangle} - \boxed{\beta|101\rangle}}{2} \\
&= \frac{1}{2}(\alpha|0\rangle + \beta|1\rangle)|00\rangle + \frac{1}{2}(\alpha|0\rangle - \beta|1\rangle)|01\rangle + \frac{1}{2}(\alpha|1\rangle + \beta|0\rangle)|10\rangle + \frac{1}{2}(\alpha|1\rangle - \beta|0\rangle)|11\rangle
\end{aligned}
$$

Teleportation – Analysis



- At the end of the protocol, Alice no longer has the state $\alpha\,|0\rangle+\beta\,|1\rangle$, which is expected by the no-cloning theorem
- Irrespective of $\alpha\,|0\rangle+\beta\,|1\rangle$, the probability for each of the 4 possible measurements is ¼: Bob obtains the state without it being disturbed

$$|\pi_2\rangle = \frac{1}{2}(\alpha|0\rangle + \beta|1\rangle)\,|00\rangle + \frac{1}{2}(\alpha|0\rangle - \beta|1\rangle)\,|01\rangle + \frac{1}{2}(\alpha|1\rangle + \beta|0\rangle)\,|10\rangle + \frac{1}{2}(\alpha|1\rangle - \beta|0\rangle)\,|11\rangle$$

ab	Probability	Conditional state of (B, A, Q)	Operation on B	Final state of B
00	$\frac{1}{4}$	$(\alpha|0\rangle + \beta|1\rangle)|00\rangle$	$\mathbb{1}$	$\alpha|0\rangle + \beta|1\rangle$
01	$\frac{1}{4}$	$(\alpha|0\rangle - \beta|1\rangle)|01\rangle$	Z	$\alpha|0\rangle + \beta|1\rangle$
10	$\frac{1}{4}$	$(\alpha|1\rangle + \beta|0\rangle)|10\rangle$	X	$\alpha|0\rangle + \beta|1\rangle$
11	$\frac{1}{4}$	$(\alpha|1\rangle - \beta|0\rangle)|11\rangle$	ZX	$\alpha|0\rangle + \beta|1\rangle$

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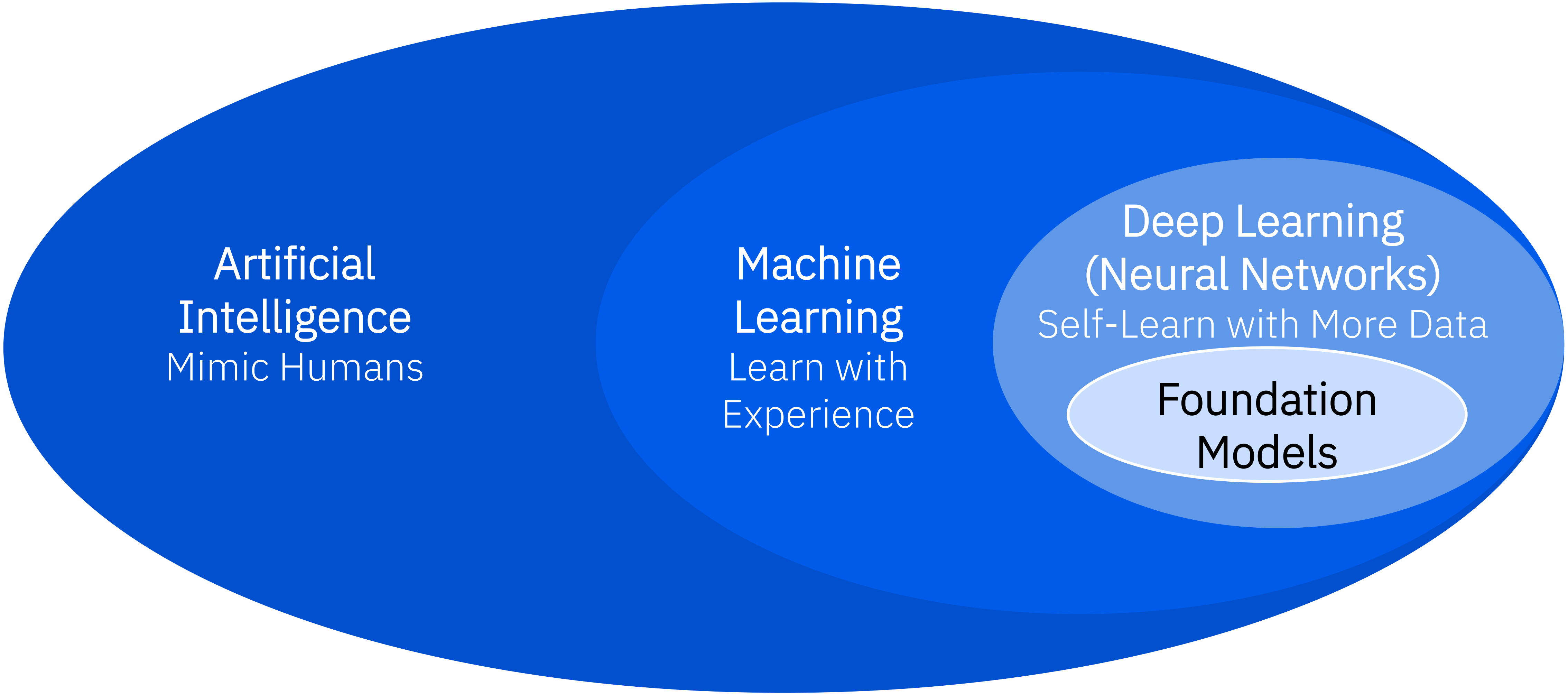
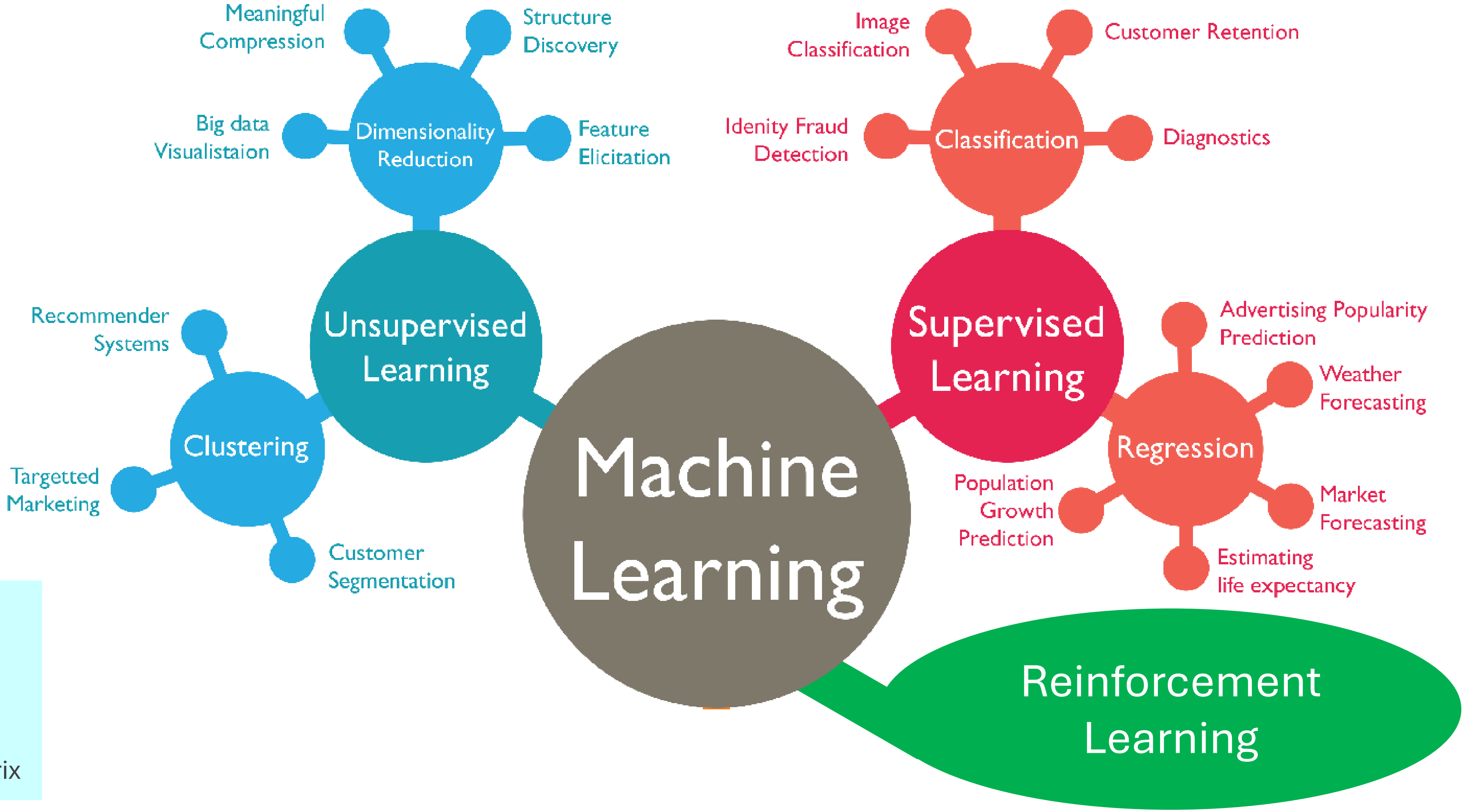
Artificial Intelligence



Machine Learning



KPIs

- Precision
- Recall
- F1 Score
- Accuracy
- Confusion Matrix

Quantum Computing and AI – 4 areas of Synergy

GenAI as a tool for the Quantum Developer

E.g.: Qiskit Code Assistant

Train LLMs in support of Quantum Computing Research

E.g. Ansatz in VQC for Chemistry

Integrated Application Workflow thru GenAI, using a Quantum Algorithm

E.g.: GenAI transforms speech into Boolean Expression. This is the input for a Boolean SAT Problem, solved with Grover's Algorithm

Quantum Computing for improving AI, GenAI and Agentic AI outcomes

- Faster training
- Real Time Learning
- Save resources
- More complex models

Positioning Quantum Machine Learning (QML)

Type of Algorithm
Processing Device

Type of Data
Data Generating System

	Classical	Quantum
Classical	CC	**CQ**
Quantum	QC	QQ

Maria Schuld, Francesco Petruccione
Machine Learning with Quantum Computers", Page 7

Considerations beyond "the straightforward"

- **CC**: *Machine Learning can be based on methods borrowed from Quantum Information research, or "Quantum-Inspired"*
- **QC**: *how can Machine Learning help in Quantum Computing Systems?*
- **CQ**: *synonym for QML. Data come from classical systems like text, images, time series, macro-economic variables*
- ***Requires Quantum-Classical interface***
- **QQ**: *closely related to CQ. Data can be measured from Quantum System or dataset can be Quantum States*

Near-Term and Fault-Tolerant Methods

Emerging Approach - Third Wave

- Based on deeper understanding of ML Potential of Quantum phenomena
- Combine the CML knowledge with Quantum Information Theory
- Train Quantum Models we cannot simulate any more ...
- **QUANTUM INSPIRED METHODS**

> 2021

Near Term Approach - Second Wave

- “What type of ML Model fits the physical characteristics of a small-scale Quantum Device?”
- New Models and Algorithms derived
- “Empirical” and “Heuristic” mindset
- ISSUE: IS A CLASSICAL ML MINDSET SUFFICIENT... ?

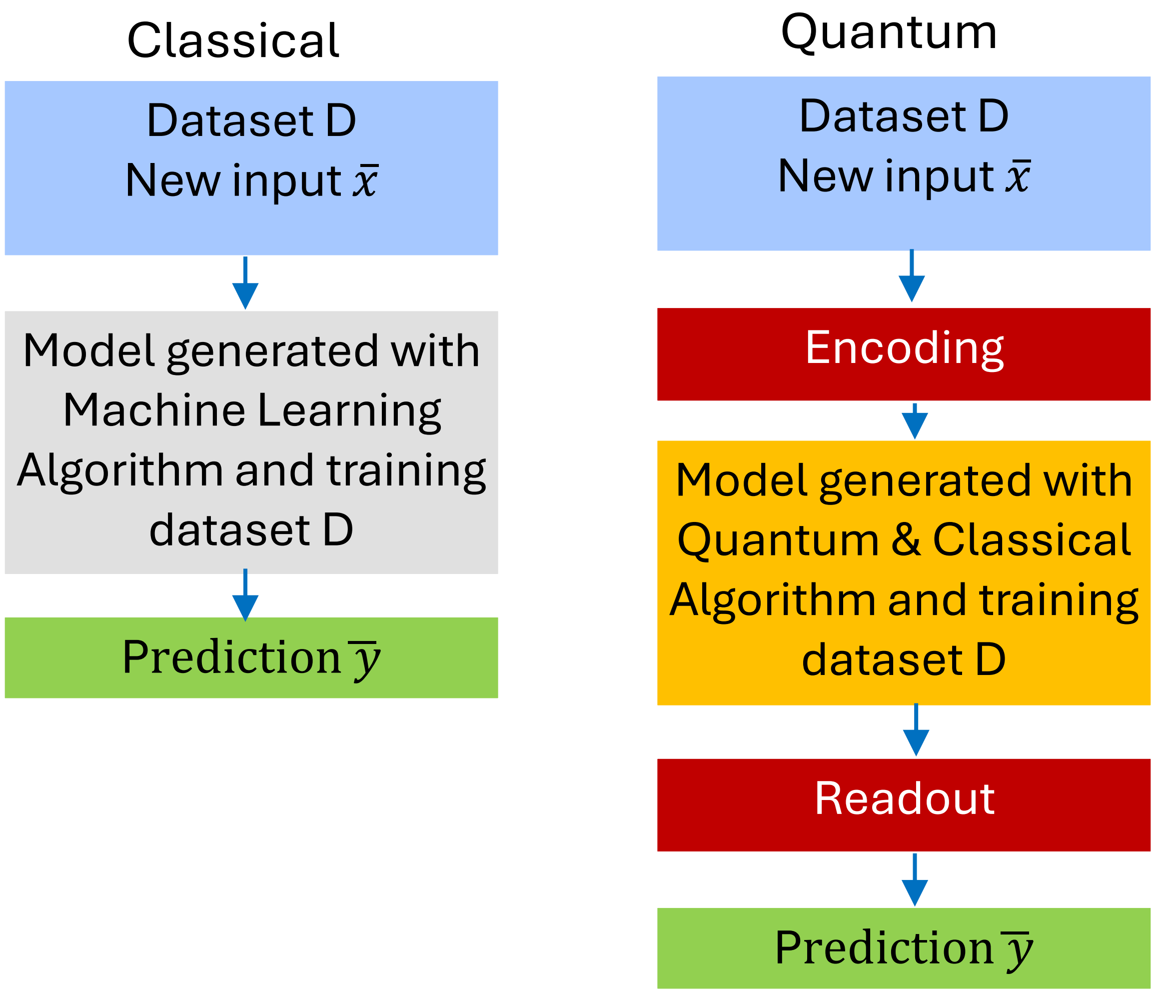
> 2017

Long Term Benefit – First Wave

- Assumes Fault-Tolerant Quantum Computers
- Rather “Academic” and “Mathematical” mindset
- ISSUE: WE ONLY HAVE NISQ TODAY ...

> 2013

The Key Challenge in QML



M. Schuld, F. Petruccione: Supervised Learning with Quantum Computers
M. Schuld, N. Killoran: arxiv 1803.07128

Data Encoding

One of the most important parts of a QML approach...

*Frameworks, software and hardware that address the **interface** between classical memory and Quantum Device*

Encoding strategies

- Qubit-Efficient State Preparation
- Resource-Efficient State Preparation

Sample encoding methods

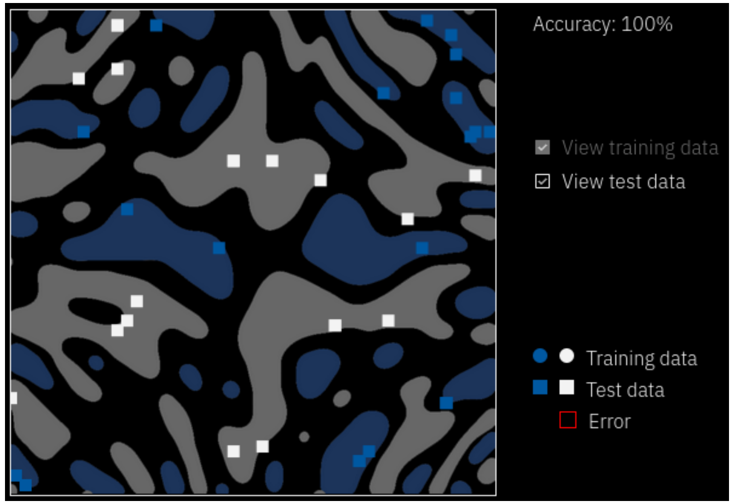
- Basis encoding
- Amplitude encoding
- Angle encoding
- Encode dataset via *Hamiltonian*
- Data Encoding as a *Feature Map*
- ... *(ongoing innovation)*

Near-term QML Algorithms – Key Flavours

Quantum SVM

- Classification, Regression
- Quantum Kernel Estimation method
- Benefit: Quantum Feature Space

Key paper: Havlíček et al, *Nature* 567, pp 209–212 (2019)

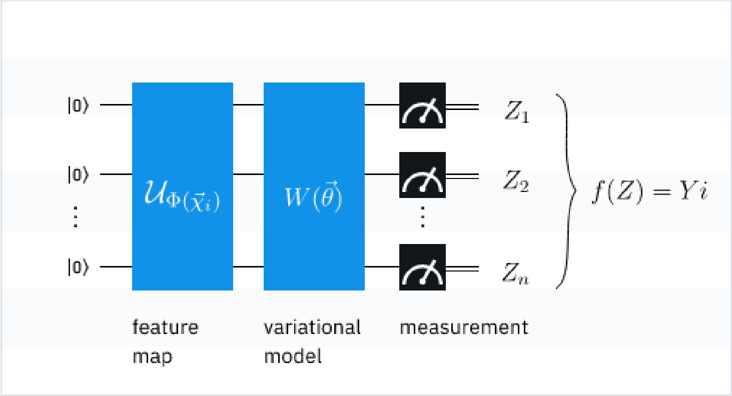


https://www.nature.com/articles/s41586-019-0980-2

Quantum Neural Networks

- Classification, Regression
- Variational Quantum Circuits
- Benefits: model expressiveness, resilience to Barren Plateaus

Key paper: Abbas et al, *Nature Comp. Sci.* 1, pp 403–409 (2021)

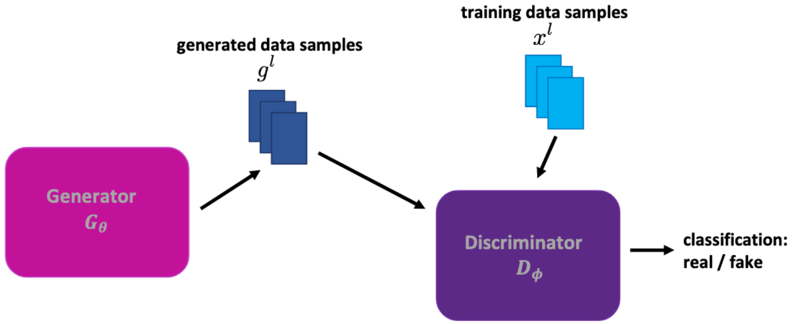


https://arxiv.org/abs/2011.00027

Quantum GANs

- Data Generation
- Quantum and Classical Neural Networks
- Benefits: efficient data sampling

Key paper: Zoufal et al, *npj Quant. Info*. 5, no: 103 (2019)



https://export.arxiv.org/abs/1904.00043

Encoding Data - Summary

M = Number of features
n = number of bits per feature
$N = \lceil log_2 n \rceil$

Example: [6, 8, 0] : 6 km. walk/day, 8 hrs. sleep/day ➔ no cancer

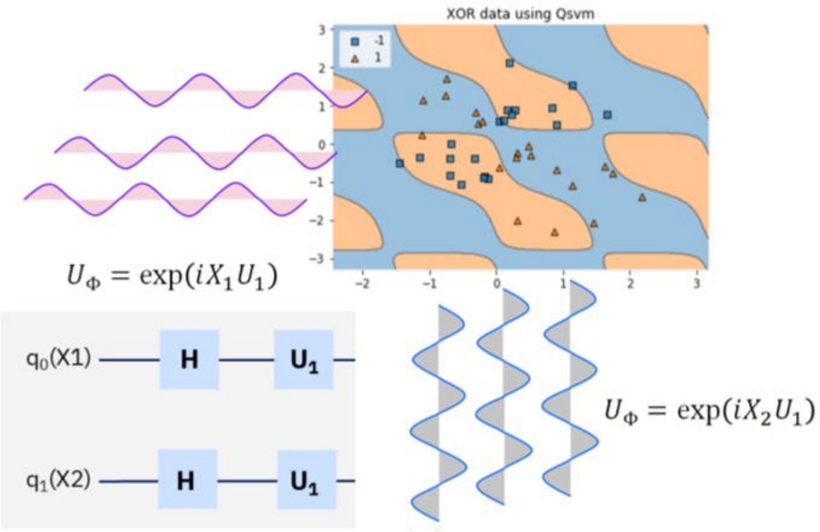
- Basis Encoding
  Encode each n-bit feature into n qubits
  $$x = (b_{n-1}, \dots, b_1, b_0) \quad \rightarrow \quad |x\rangle = |b_{n-1}, \dots, b, b_0\rangle$$
  $\frac{\sqrt{3}}{3}(\,|0110\rangle + |1000\rangle + |0000\rangle)$ ➔ 4 Qubits
- Amplitude Encoding
  Encode into quantum state amplitudes
  $$x = \begin{bmatrix} x_0 \\ \vdots \\ x_{N-1} \end{bmatrix} \quad \rightarrow \quad |\psi_x\rangle = \sum_{j=0}^{N-1} x_j |j\rangle$$
  $(\frac{3}{5}|00\rangle + \frac{4}{5}|01\rangle + 0\,|10\rangle + 0\,|10\rangle)$ ➔ 2 Qubits
- Angle Encoding (and Phase Encoding)
  Encode values into qubit rotation angles
  $$|x\rangle = \bigotimes^{N} \cos(x_i)\,|0\rangle + \sin(x_i)\,|1\rangle$$
  $(\cos\frac{6\pi}{7}\,|0\rangle + \sin\frac{6\pi}{7}\,|1\rangle) \otimes\ (\cos\frac{8\pi}{7}\,|0\rangle + \sin\frac{8\pi}{7}\,|1\rangle) \otimes$
  $(\cos 0\,|0\rangle + \sin 0\,|1\rangle)$ ➔ 3 Qubits

- Arbitrary Encoding (Feature Map)
  Encode N features in constant-depth circuit with n qubits
  $$x = \begin{bmatrix} x_0 \\ \vdots \\ x_{N-1} \end{bmatrix} \quad \rightarrow \quad |\psi_x\rangle = \mathcal{U}_{\Phi(x)}|0\rangle$$

Encoding	#Qubits	State Preparation Time
Basis	n	$O(n)$
Amplitude	N	$\frac{O(n)}{O(N)}$
Angle	M	$O(n)$
Feature Map	N	?

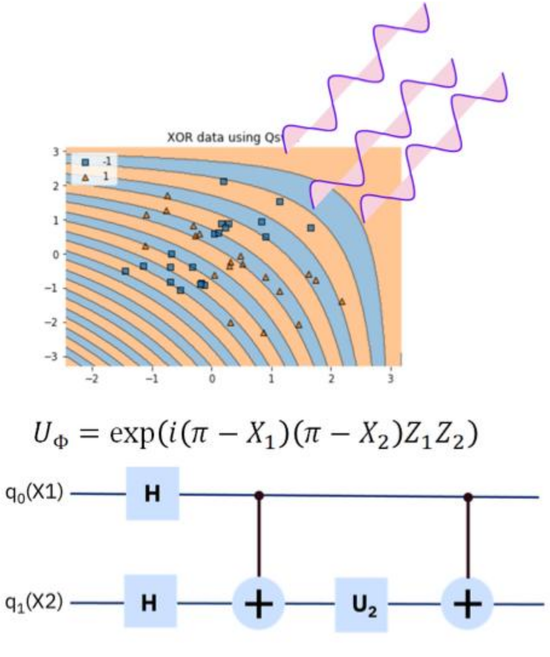
The impact of Entanglement in the Quantum Feature Map *(Outcome)*

Simple rotations



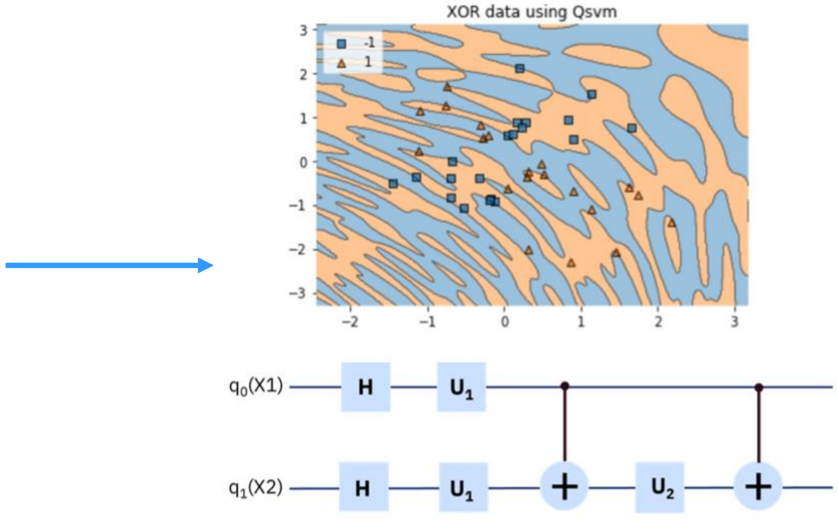
(a)

Entangled unitary rotations



(b)

Simple and Entangled unitary rotations

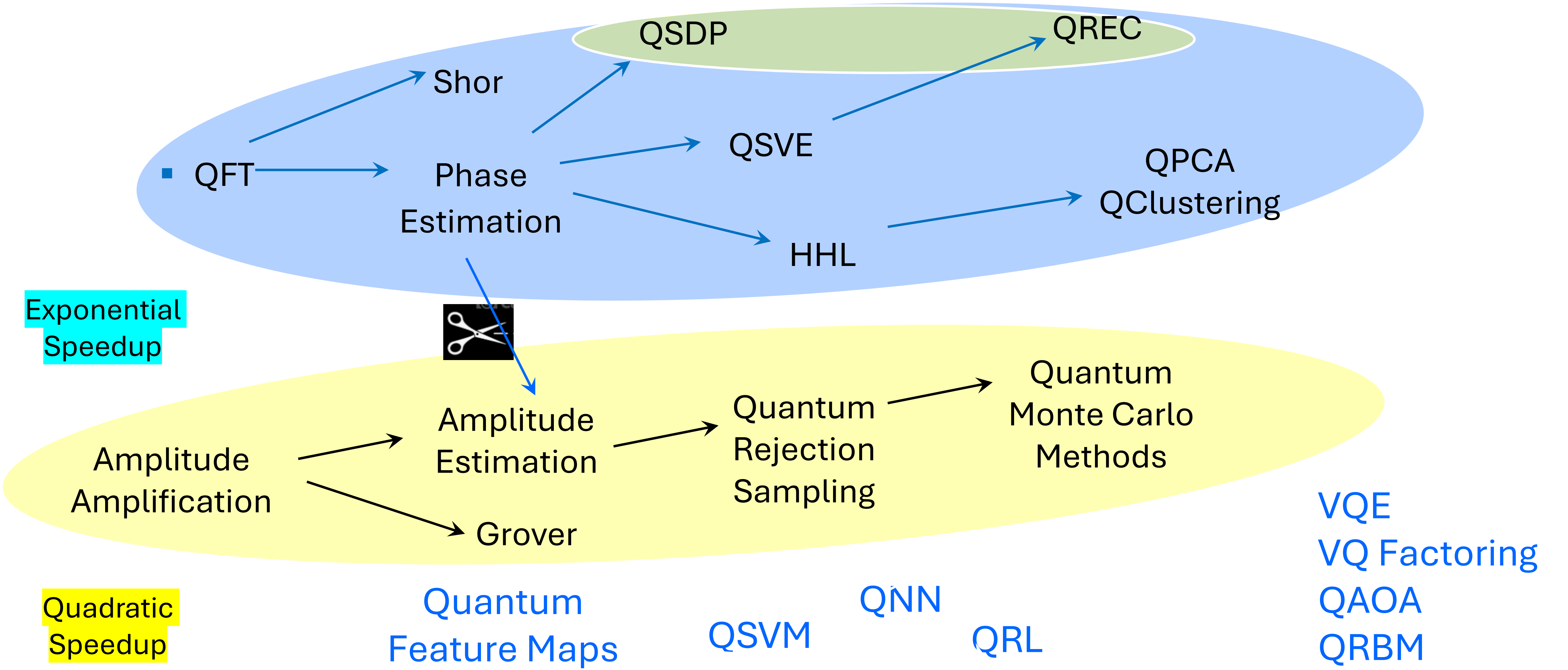


Z Feature Map: H+R
ZZ Feature Map: H+R+CNOT
Efficient SU2 Feature Map: R+CNOT

Park et al, arXiv: 2012.07725v1

https://arxiv.org/abs/2012.07725

QML Dependencies

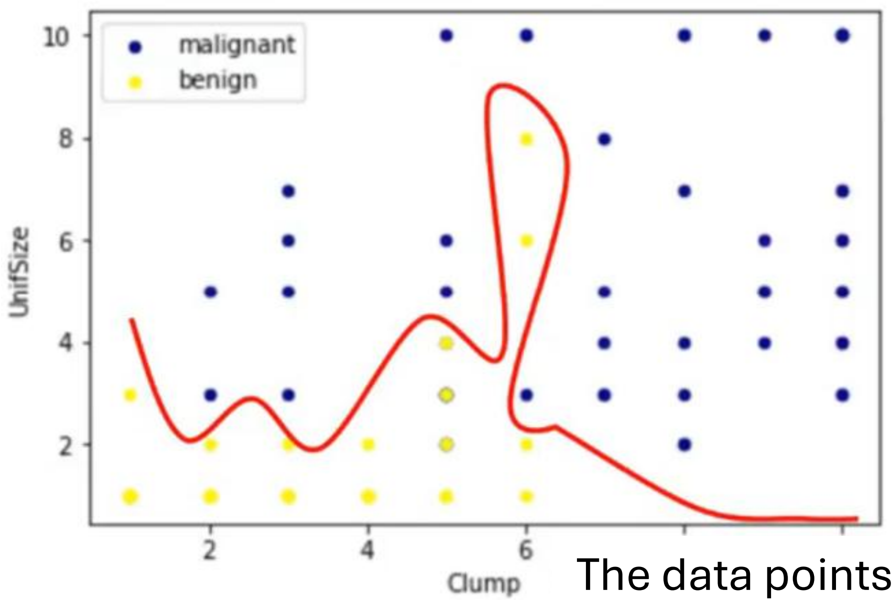


What is an SVM?

An SVM is a supervised algorithms that classifies cases by finding a separator

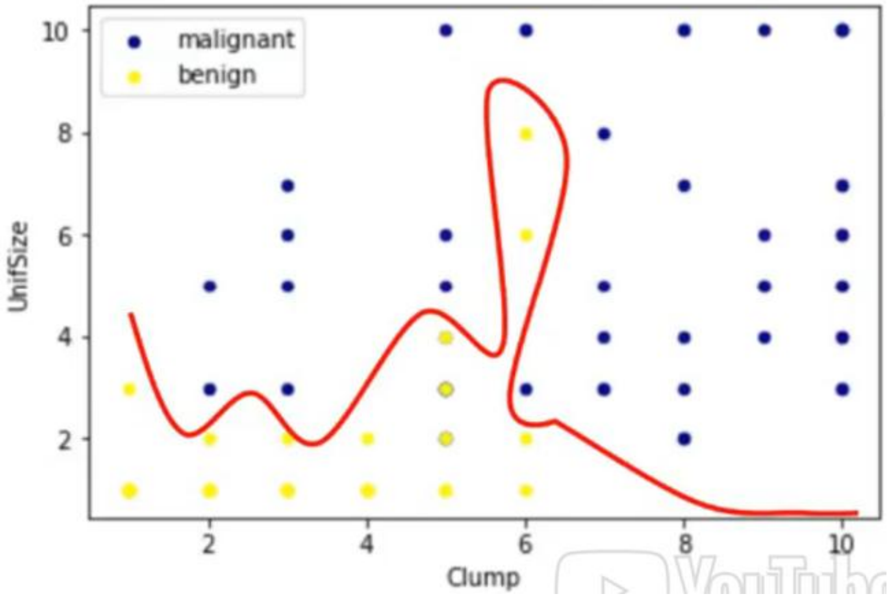
1. Map data to a higher dimensional feature space if necessary
2. Find a separator

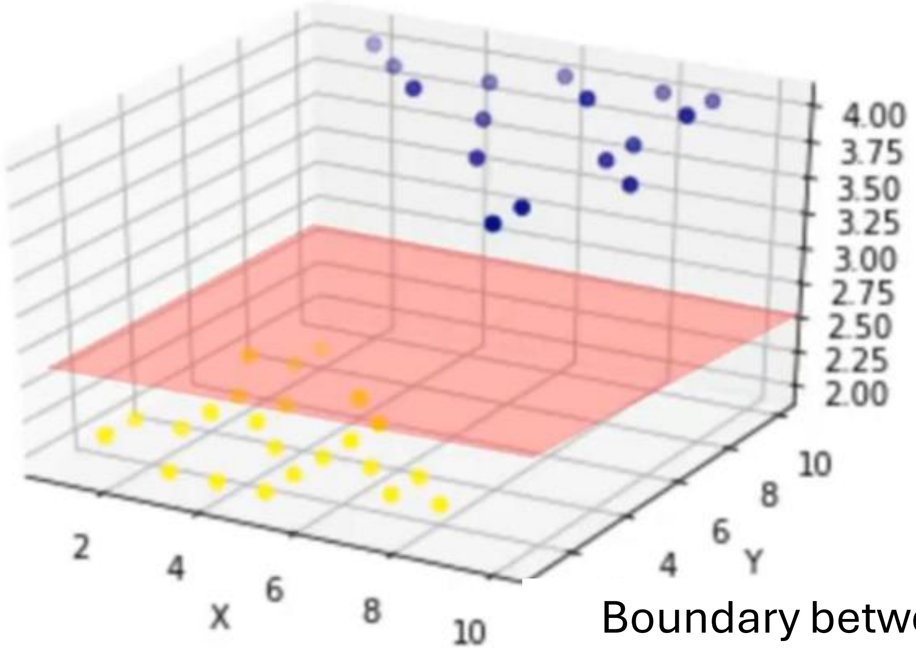
Clump	UnifSize	UnifShape	MargAdh	SingEpiSize	BareNuc	BlandChrom	NormNucl	Mit	Class
5	1	1	1	2	1	3	1	1	benign
5	4	4	5	7	10	3	2	1	benign
3	1	1	1	2	2	3	1	1	malignant
6	8	8	1	3	4	3	7	1	benign
4	1	1	3	2	1	3	1	1	benign
8	10	10	8	7	10		7	1	malignant
1	1	1	1	2	10	3	1	1	benign
2	1	2	H	2	1	3	1	1	benign
2	1	1	1	2	1	1	1	5	benign
4	2	1	1	2	1	2	1	1	benign



The data points are not linearly separable

SVM Approach

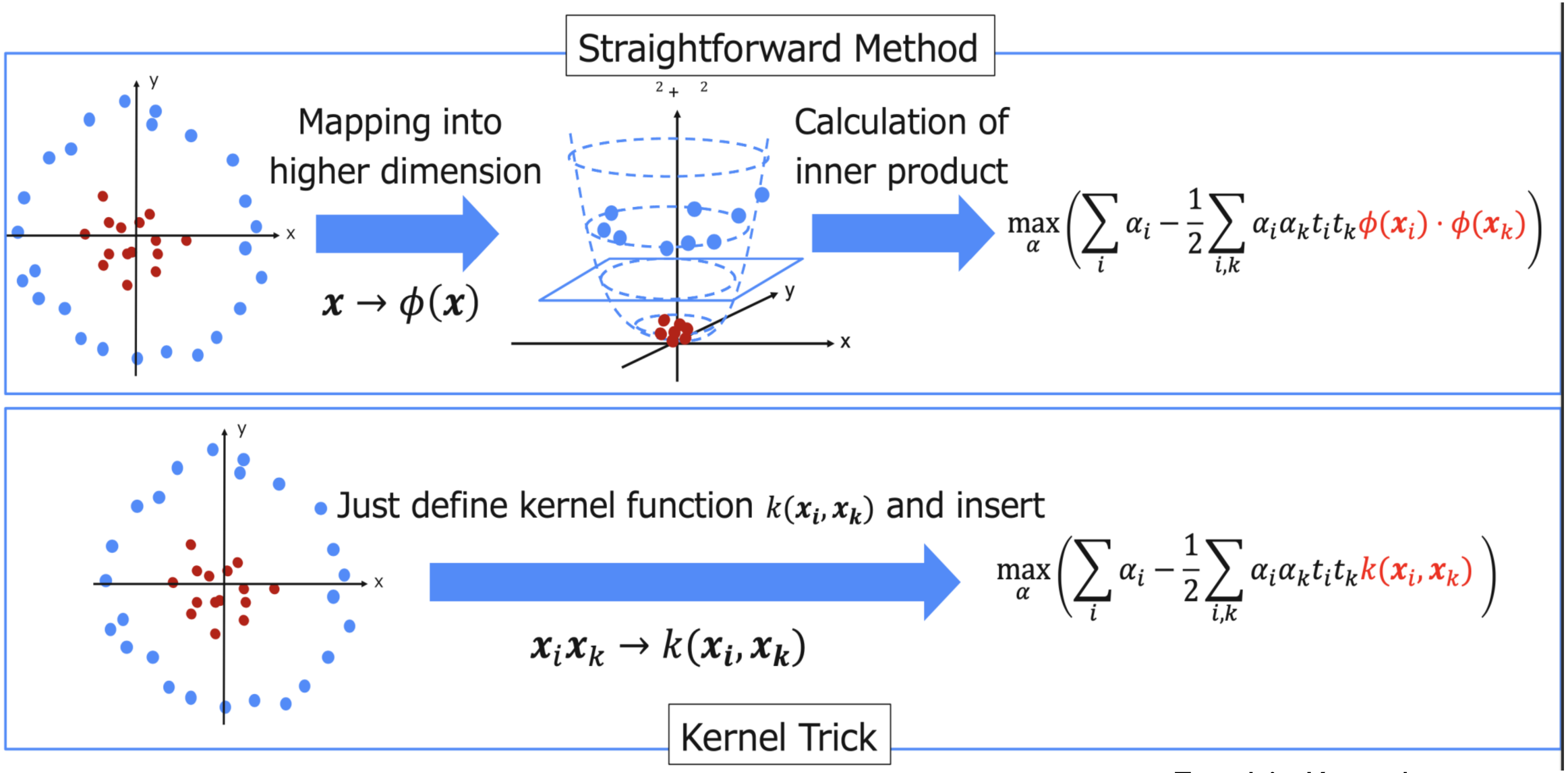




Boundary between categories with a Hyperplane allows to classify unknown cases

- Q1: How do we transform the data in such a way that a separator can be drawn as a hyperplane?
- Q2: How can we find the best optimized hyperplane?

The SVM Kernel Trick



For this Kernel,
Quantum Computing is applied

Mapping data into a higher dimensional space is called "kernelling"

There are different mapping or transformation functions

Most of them are implemented in Data Science programming languages

General Quantum Neural Networks (QNN)

- QNN is Parameterized Quantum Circuit (PQC)
- Variational Ansatz in multiple repetitions of similar layers:

$$U_{QNN} = \prod_{L}^{1} S_i(x) U_i(\theta_i)$$

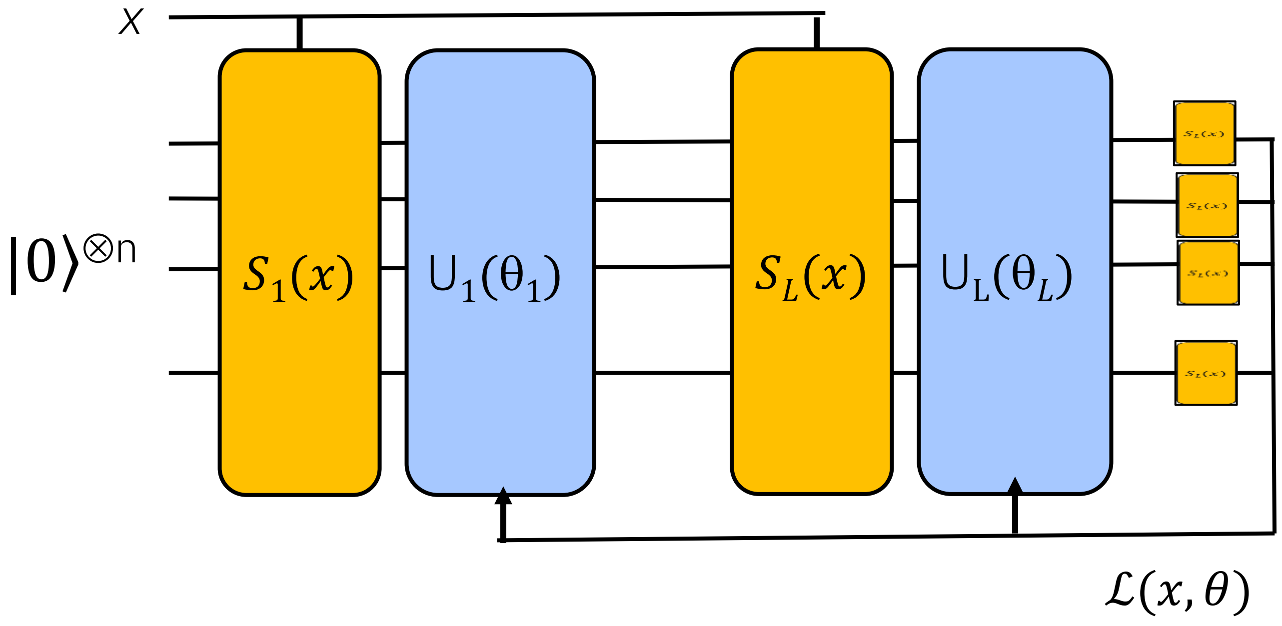
where:

$U_i(\theta_i)$: variational gate layers = “Ansatz”

$S_i(x)$: *data encoding procedure = “Feature Map”*

L: number of layers

Data re-uploading procedure



The more often data are re-uploaded, *the more expressive the QML model becomes*

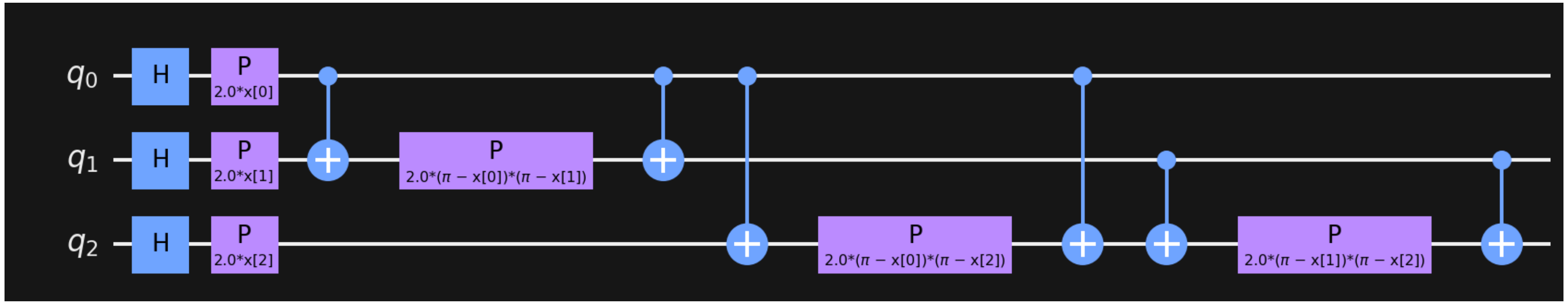
VQC = Variational Quantum Classifier
VQR = Variational Quantum Regressor

Examples of components of a QNN Circuit

- Data encoder
- Feature Map

$S_1(x)$

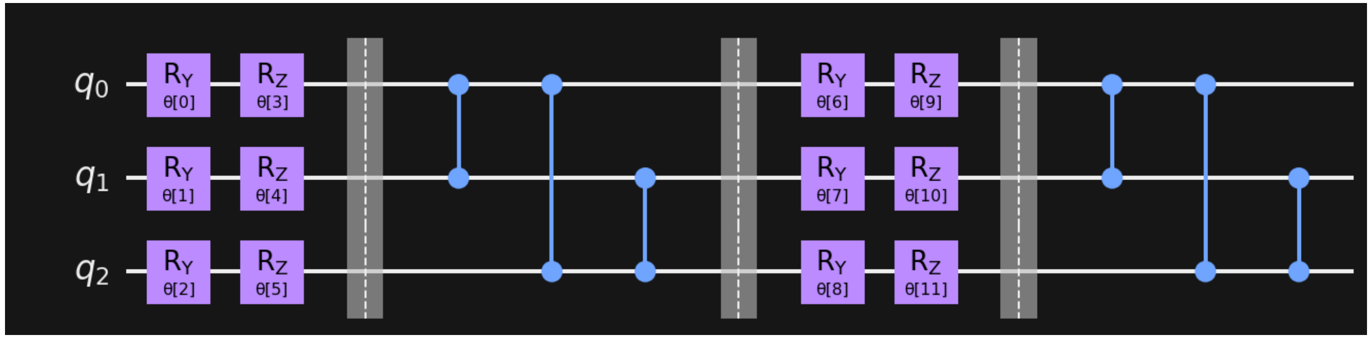
ZZ feature map



- Parameterized circuit
- Ansatz

$U_1(\theta_1)$

Two-local (R_Y and R_Z)



The Challenge of the Barren Plateaus

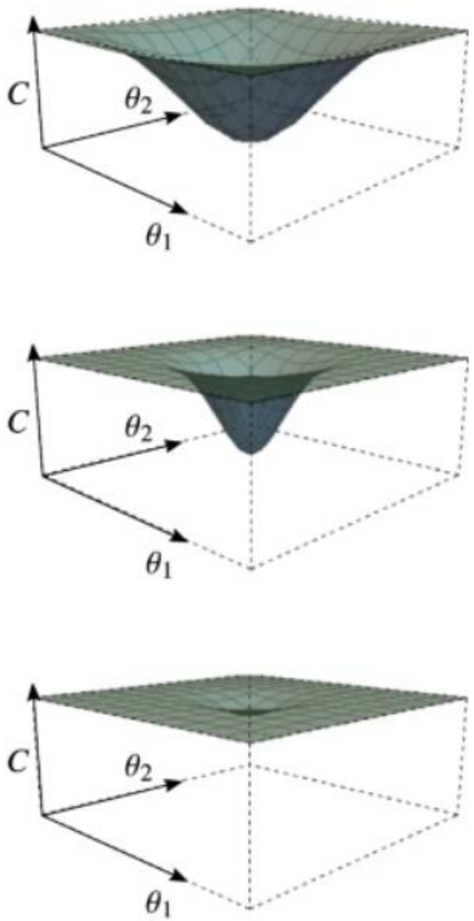
Key "Victims"

- **Noisy** Near-Term Quantum Computers
- **Highly expressive** Circuits and large Hilbert Spaces
- **Deep** Quantum Circuits
- Circuits with **global measurements**
- **High entanglement** entropy
- **Dissipative** Quantum Neural Networks

Convolutional QNNs are **resilient** to Barren Plateaus

[See: Pesah et al., Phys Rev X, 2021]

https://journals.aps.org/prx/pdf/10.1103/PhysRevX.11.041011



Some strategies to avoid or mitigate Barren Plateaus

- Initialize and train parameters in batches
- Reduce depth of circuit by randomly initializing a subset of the total number of parameters
- Introduce correlations between the parameters in multiple layers of the QNN to reduce the overall dimensionality of the parameter space
- Leverage Classical recurrent NNs to find good parameter initializing heuristics such that the network starts close to a minimum
- Choice of local cost functions and specific entanglements between hidden and visible units

Key take-aways on QML

- Potential dimensions of QML Quantum Advantage: Quality (e.g. accuracy), speed and efficiency
- Pay attention to Data Encoding of classical data into a quantum computer
- Near-term QML algorithms like QSVM, QNN and QGANs may provide benefits in terms of quantum enhanced feature space, model expressibility, resilience to barren plateaus and efficient data sampling
- Exponential and quadratic speedups are expected on Fault-Tolerant Quantum Computers (FTQC)

Learn more

https://quantum.cloud.ibm.com/learning/en/courses/quantum-machine-learning

Continuous Research

[Submitted on 9 Sep 2021]

Quantum Machine Learning for Finance

Marco Pistoia, Syed Farhan Ahmad, Akshay Ajagekar, Alexander Buts, Shouvanik Chakrabarti, Dylan Herman, Shaohan Hu, Andrew Jena, Pierre Minssen, Pradeep Niroula, Arthur Rattew, Yue Sun, Romina Yalovetzky

The power of quantum neural networks

Amira Abbas[1,2], David Sutter[1], Christa Zoufal[1,3], Aurelien Lucchi[3], Alessio Figalli[3], and Stefan Woerner[1,*]

[1] IBM Quantum, IBM Research – Zurich
[2] University of KwaZulu-Natal, Durban
[3] ETH Zurich

Qiskit | Ecosystem

Qiskit Machine Learning 0.7.2

[Submitted on 28 Nov 2016 (v1), last revised 10 May 2018 (this version, v2)]

Quantum Machine Learning

Jacob Biamonte, Peter Wittek, Nicola Pancotti, Patrick Rebentrost, Nathan Wiebe, Seth Lloyd

Challenges and Opportunities in Quantum Machine Learning

M. Cerezo, Guillaume Verdon, Hsin-Yuan Huang, Lukasz Cincio, Patrick J. Coles

(Submitted on 16 Mar 2023)

[Submitted on 10 Sep 2014]

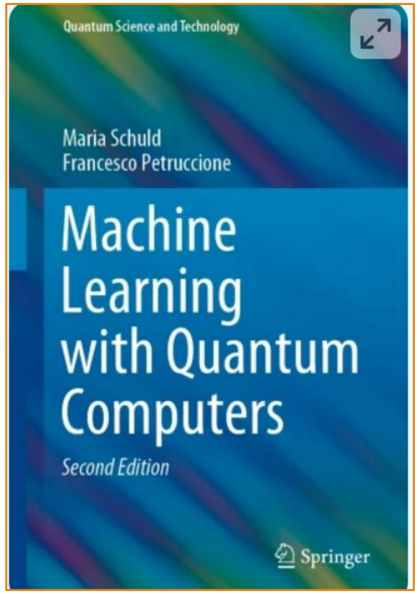
An introduction to quantum machine learning

M. Schuld, I. Sinayskiy, F. Petruccione

[Submitted on 4 Jan 2023 (v1), last revised 6 Mar 2023 (this version, v2)]

Quantum Machine Learning: from physics to software engineering

Alexey Melnikov, Mohammad Kordzanganeh, Alexander Alodjants, Ray-Kuang Lee



A rigorous and robust quantum speed-up in supervised machine learning

Yunchao Liu,[1,2,*] Srinivasan Arunachalam,[2,†] and Kristan Temme[2,‡]

[1] Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720
[2] IBM Quantum, IBM T.J. Watson Research Center, Yorktown Heights, NY 10598
(Dated: October 6, 2020)

Applications of Quantum Machine Learning for Quantitative Finance

Piotr Mironowicz, Akshata Shenoy H., Antonio Mandarino, A. Ege Yilmaz, Thomas Ankenbrand

[Submitted on 21 Jan 2024 (v1), last revised 31 Mar 2024 (this version, v2)]

A comprehensive review of Quantum Machine Learning: from NISQ to Fault Tolerance

Yunfei Wang, Junyu Liu

Top References

- M. Schuld, F. Petruccione: Machine Learning with Quantum Computers
- Stefan Woener et al.: The power of quantum neural networks: https://arxiv.org/abs/2011.00027v1
- Krista Teme et al.: A rigorous and robust quantum speed-up in supervised machine learning: https://arxiv.org/abs/2010.02174
- Stefani Mangini et al.: Quantum computing models for artificial neural networks: https://arxiv.org/abs/2102.03879
- M. Schuld, N. Killoran: Quantum machine learning in feature Hilbert spaces: https://arxiv.org/abs/1803.07128
- Park et all.: Practical application improvement to Quantum SVM: theory to practice: https://arxiv.org/abs/2012.07725
- S. Lloyd et al.: Quantum algorithms for supervised and unsupervised machine learning: https://arxiv.org/abs/1307.0411
- V. Havlicek et al.: Supervised learning with quantum-enhanced feature spaces: Nature 567, 209 (2019)
- IBM Research YT, Almaden: Covariant Quantum Kernels for Data with group Structure: https://arxiv.org/abs/2105.03406
- Qiskit Machine Learning Ecosystem: https://qiskit-community.github.io/qiskit-machine-learning/migration/01_migration_guide_0.5.html

Demo

- Quantum Neural Network
- **Iris Flower Dataset**

Iris setosa

Iris versicolor

Iris virginica

4 Features
Petal Length
Petal Width
Septal Length
Sepal Width

1 Label
Species

150 Rows

QML Preparations

Our (ambitious) Program of Today …

- 09:00 hrs.: Lecture 1: A Holistic Introduction to Quantum Computing
- 09:30 hrs.: Lecture 2: An introduction to Qiskit
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- **17:00 hrs.: NETWORKING**

Juryleden
Stickers
Quiz boek

Challenge Description - Introduction

In this challenge, you will train a Quantum Machine Learning (QML) model to solve a classification problem.
You are provided with a **Dataset** containing information about several students.

1. Irrelevant feature (to be excluded from the QML model):
Student Number – serves only as an identifier. (Note: student names are omitted for privacy reasons.)

2. Target label:
Degree – indicates whether the student successfully obtained the Master's Degree in Mathematics and Data Science:

0 → the student did not achieve the Master's Degree
1 → the student did achieve the Master's Degree

3. Input features (from the first semester of the Bachelor's program in Mathematics and Data Science): These variables are considered independent predictors that may influence the label "Degree":

- Average number of weekly study hours
- Average number of weekly class attendance or participation hours
- Score on the course "Discrete Mathematics"
- Number of secondary school hours per week dedicated to Mathematics in the final year
- Average number of weekly hours of sports practice
- Average number of weekly hours of collaboration with other students
- Average number of weekly hours of sleep

Challenge Description

The challenge is to create a **Quantum Neural Network** or QNN Model
that can classify or **predict for new Students**
their **final achievement**
at the end of their Study Career in **Mathematics and Data Science,**
using **data that are collected**
at the **end of the first semester**
in the first phase of the **Academic Bachelor**.

Some hints and tips – but you are free!

- Let inspire you by the Iris Flowers Dataset case …

- Try out several Feature Maps: ZZFeatureMap, ZFeatureMap, ..
- Try out different parameter settings for the Feature Maps

- Try out several Ansatzes: EfficientSU2, RealAmplitudes, …
- Try out different parameter settings for the Ansatzes

- Try out different optimizers: COBYLA, SPSA, …
- Try out different number of iterations

- Reduce the number of features to improve the model?
- Apply PCA to reduce the number of features?

- Compare with classical Machine Learning?

- Use the Qiskit Documentation

Evaluation Criteria

1. Technical Understanding (20%)

How well do participants demonstrate understanding of QML principles?
Can they clearly explain what their QNN does?

2. Implementation & Correctness (20%)

How effectively did the team translate their idea into working Qiskit code?
Does the code run without errors?
Does it actually train and make reasonable predictions on the dataset?

3. Creativity & Design (20%)

Do they design their own circuit architecture (feature map, ansatz) or creatively modify known ones?
Do they show initiative in combining classical preprocessing or hybrid methods?

4. Presentation & Communication (20%)

How clearly and confidently do they present their solution to the jury?
Can they explain *why* they chose this method and *what they learned*?
Are visualizations, slides, or demonstrations used effectively?
Is teamwork and role distribution clear during the pitch/demo?

5. Results & Potential Impact (20%)

What is the overall value and promise of the solution?
Does it achieve meaningful results on the dataset?
Does the team reflect on limitations and possible improvements?

5 = Excellent
4 = Good
3 = Fair
2 = Week
1 = Poor

Finally

Success !

Be ready to present and demonstrate
as from
15:30 hrs.

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Announcement of the Winning Team

1. Team ...

2. Team ...

3. Team ...

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Quantum Quiz

https://dashboard.blooket.com/my-sets

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Qiskit Fall Fest 2025 !

$\langle 10|Q \rangle$ for your efforts!

Prof. Dr. **Ann Dooms**

Prof. Dr. **Jan De Beule**

VUB Fellow **Eric Michiels**