QUANTUM MACHINE LEARNING

THE NEXT BIG THING

By

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“Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.”

RICHARD FEYNMAN

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AGENDA

- Introduction
    - Machine Learning
    - Quantum Computing
    - Quantum Computer Architecture
- Why Quantum in Machine Learning ?
- Applications and Advantages
- Front Runners
- An exploration – An example !
- References

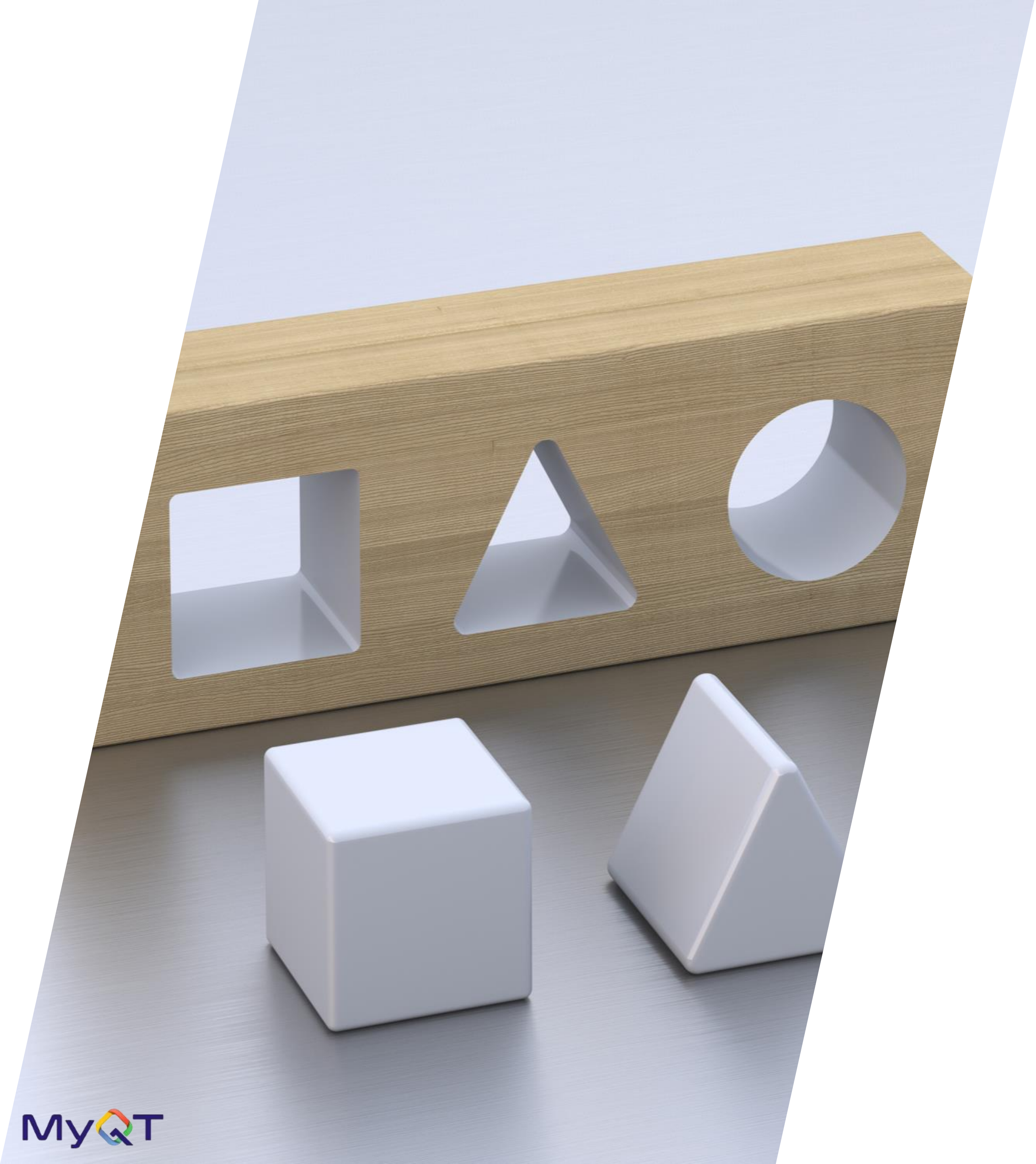
OpenAI's CEO Says the Age of Giant AI Models Is Already Over

Sam Altman says the research strategy that birthed ChatGPT is played out and future strides in artificial intelligence will require new ideas.

Megatron-Turing Natural Language Generation Model

- One of the largest AI model today.
- Has 530 billion parameters.
- 3 months to train on over 2K A100 GPUs on the NVIDIA Selene Supercomputer.
- Consuming over 3 million GPU hour.

To make significant advancements and achieve larger breakthroughs in AI, it is crucial to harness increased computational power while simultaneously optimizing AI algorithms.



UNCONVENTIONAL COMPUTING

- **Quantum Computing**
- Neuromorphic Computing
- Analog Computing
- Edge Computing
- DNA Computing
- Optical Computing
- Neuromorphic Photonics

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INTRODUCTION

- Quantum Machine learning, an **amalgamation** of Quantum computing and classical Machine learning.

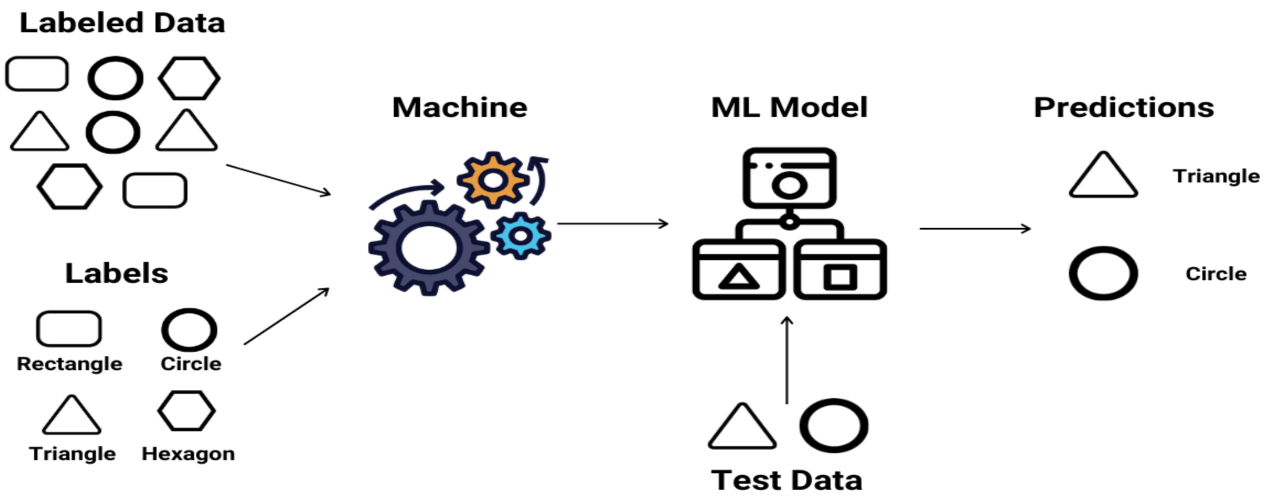
- We might want to find out whether **Quantum Computers can speed up** the time it takes to train or evaluate a machine learning model.

- We can leverage techniques **from machine learning to help us uncover quantum** error-correcting codes, estimate the properties of quantum systems, or develop new quantum algorithms.

- Quantum machine learning **extends the pool of hardware for machine learning** by an entirely new type of computing device—the quantum computer.

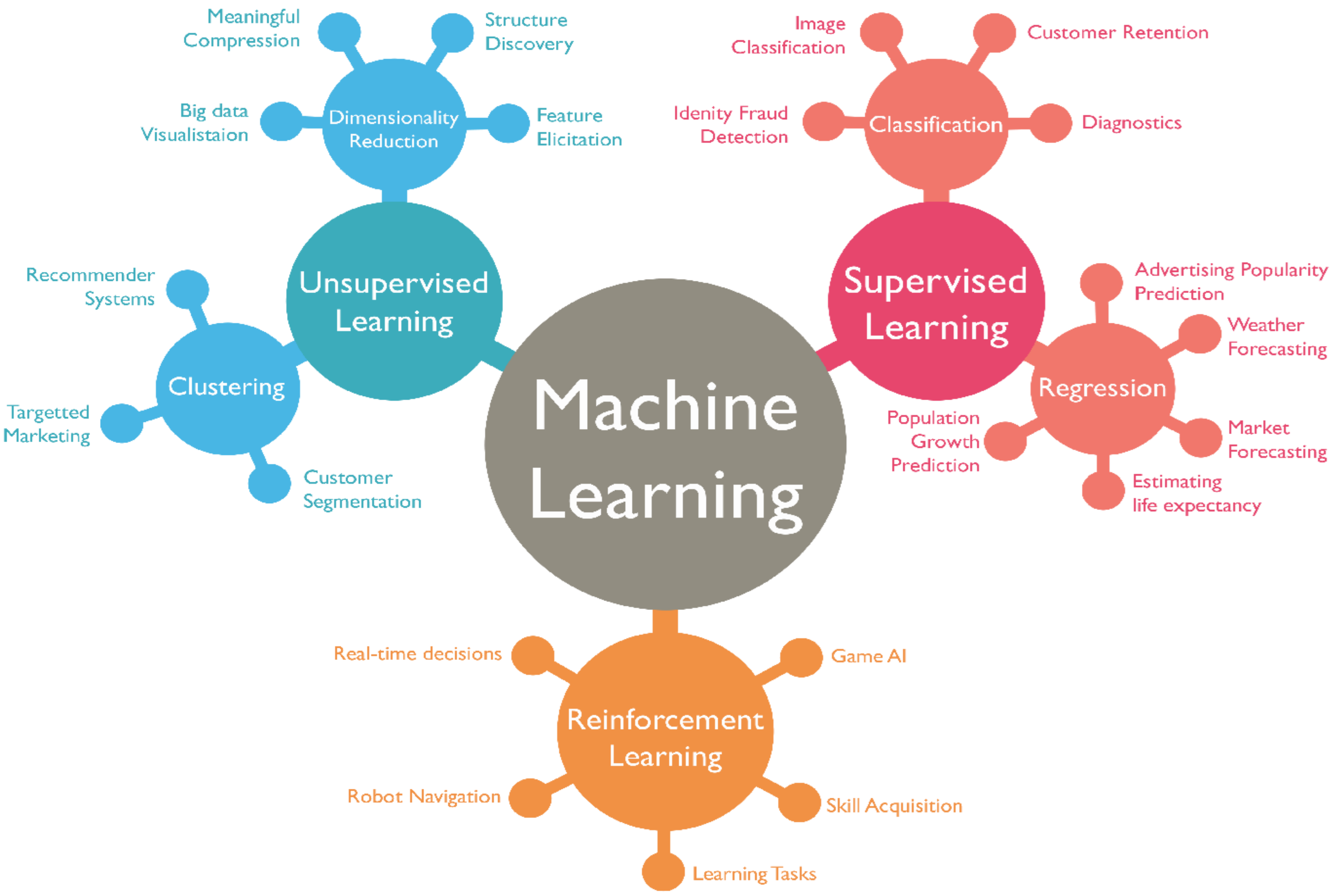
INTRODUCTION - MACHINE LEARNING

- The area of computational science that focuses on analyzing and interpreting patterns and structures in data using algorithms to enable learning, reasoning, and decision making the way that humans do and beyond that.



An Example of Supervised ML model

INTRODUCTION - MACHINE LEARNING



INTRODUCTION - MACHINE LEARNING

Achievements

- According to a study published in **Nature** (January 2020), AI is more accurate than doctors in diagnosing breast cancer from mammograms.
- Language Models to generate HTML code, guitar nodes, and webpages in addition to being a language generating model
- DeepMind’s Alpha Fold – Highest Accuracy Drug Protein Folding AI.
- CurialAI – First AI algorithm to detect potential COVID-19 infected patients.
- Google Waymo Self-Driving Cars, Tesla Autopilots

INTRODUCTION - MACHINE LEARNING

Advantages

- Easily identifies trends and patterns
- Automation
- Continuous Improvement
- Handling multi-dimensional and multi-variety data
- Wide Applications

Challenges

- Data Acquisition
- Time and Resources
- Interpretation of Results
- High error-susceptibility

INTRODUCTION – QUANTUM COMPUTING

- An area of study focused on the development of computer-based technologies ***centered around the principles of quantum theory***.
- Quantum theory explains the nature and behavior of energy and matter on the quantum (atomic and subatomic) level.

- The quantum computer gains much of its processing power through the ability of the qubits to be in ***Superposition*** states (0 & 1) .
- For the mathematically inclined, we can say that if you have “n” qubits, you can **simultaneously** represent 2^n states.
- In comparison to classical (0 | 1), quantum computing counts as ***true parallel processing***.

INTRODUCTION – QUANTUM COMPUTING

- **Entanglement** is a quantum mechanical effect that correlates the behavior of two separate things. When two qubits are entangled, changes to one qubit directly impact the other.
- Quantum algorithms leverage those relationships to find solutions to complex problems.

- **Quantum Coherence is** the ability of a quantum state to maintain its entanglement and superposition in the face of interactions and the effects of thermalization.
- It can outperform the best-known classical algorithms. This phenomenon is called the **Quantum Speedup.**

INTRODUCTION – QUANTUM COMPUTING

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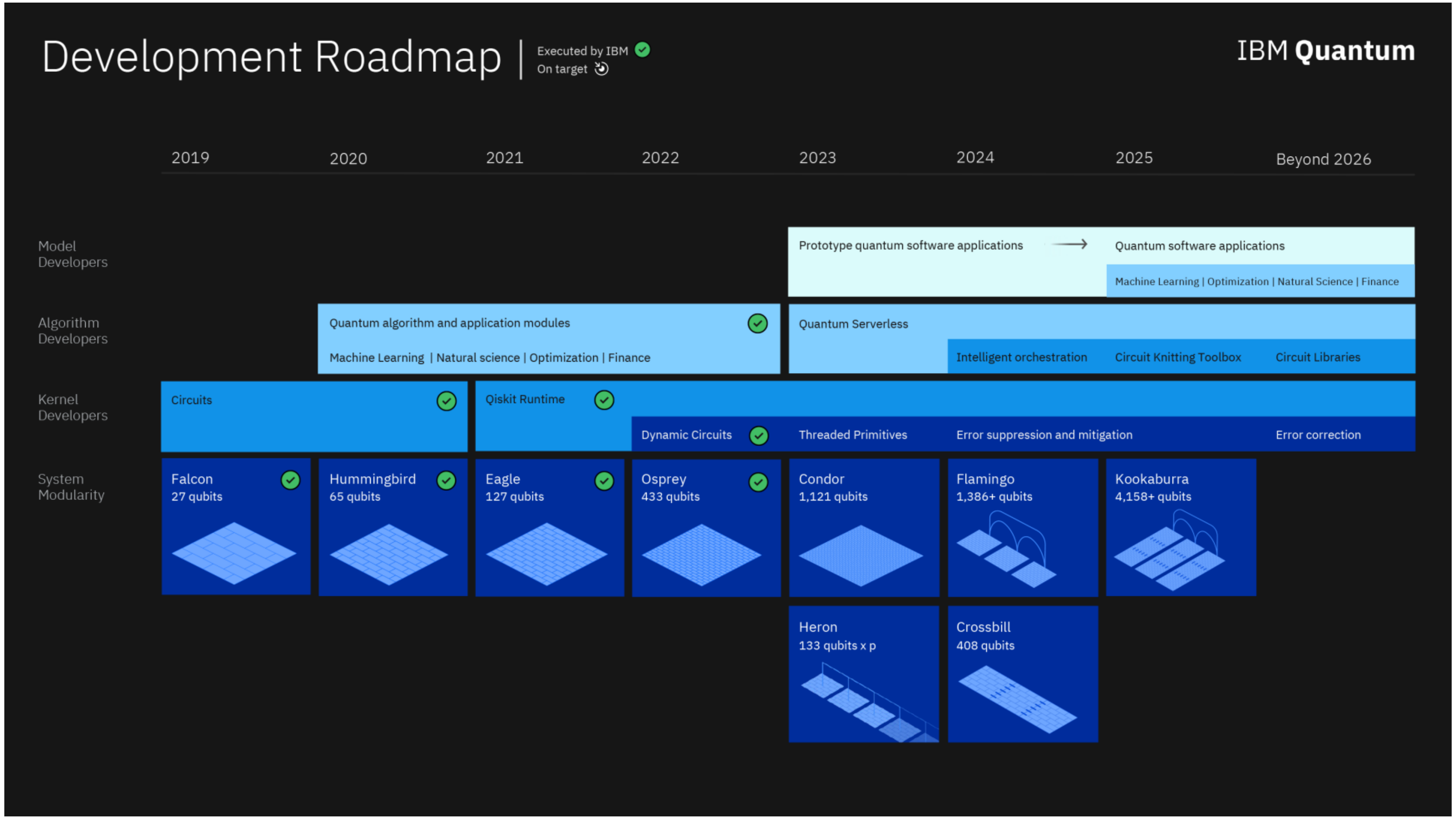
INTRODUCTION – QUANTUM COMPUTING

Performance Metrics

- **Scale** - Measured by ***number of qubits*** which indicates the amount of information we can encode in the quantum system.
- **Quality** - Measured by ***Quantum Volume*** which indicates quality of circuits and how faithfully circuits are implemented in hardware.
- **Speed** - Measured by ***CLOPS*** (Circuit Layer Operations Per Second) which indicates how many circuits can run on hardware in each time.

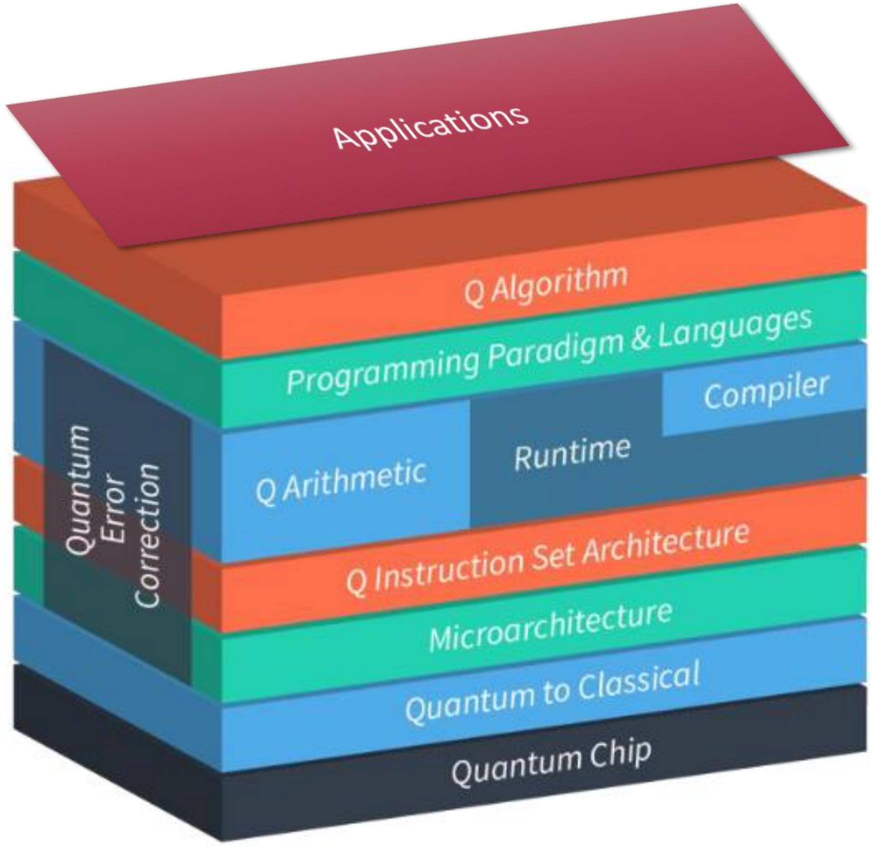
Rose's Law suggests quantum computing qubits should double every two years and is close to or already moving faster than Moore's Law.

INTRODUCTION – QUANTUM COMPUTING



INTRODUCTION – QUANTUM COMPUTER ARCHITECTURE

Applications - Software application-specific modules for natural science, optimization, machine learning, and finance



A simple Architecture of Quantum Computer

Algorithm - Quantum Serverless, Orchestration, Circuit Knitting

Kernel - Dynamic Circuits, Runtime primitives, Error suppression techniques

WHY QUANTUM FOR MACHINE LEARNING ?

❑ **Matrix Operation on Higher dimensional space**

- The quantum state of the qubits is a vector in a 2^a-dimensional complex vector space.
- Quantum Computers can solve common ***linear algebraic problems*** such as the Fourier Transformation, finding eigenvectors and eigenvalues, and solving linear sets of equations (eg: **HHL algorithm**).
- The execution is exponentially faster than classical computers due to the **Quantum Speedup**.

WHY QUANTUM FOR MACHINE LEARNING ?

- **Random Vectors to form Covariance Matrix in PCA.**
  - Quantum Computers can calculate **eigenvectors** and **eigenvalues** of the higher dimensional inputs very efficiently and at a very high speed by using ***Quantum Random Access Memory*** (QRAM) to choose a data vector at random.
  - It maps that vector into a quantum state using qubits.
  - The chosen random vector forms a dense matrix which is actually the covariance matrix.
  - By *repeatedly sampling* with the **quantum phase estimation algorithm**, we can take the quantum version of any data vector and decompose it into its principal components.
  - Both the **computational** complexity and **time** complexity is thus reduced **exponentially**.

WHY QUANTUM FOR MACHINE LEARNING ?

- **Iterative Optimization to minimize the loss function**
  - **Quantum optimization algorithms** suggest improvement in solving optimization problems in machine learning.
  - The property of **quantum superposition and entanglement** enables to produce multiple copies of the present solution, encoded in a quantum state.
  - They are used to improve that solution at each step of the machine learning algorithm.

WHY QUANTUM FOR MACHINE LEARNING ?

- **New Framework for Neural Network**
    - Quantum computing can be combined with deep learning **to reduce the time** required to train a neural network.
    - A qubit can act as a neuron that constitutes the basic unit of a neural network.
    - We can systematically adapt the **physical control parameters**, such as an electromagnetic field strength or a laser pulse frequency, to solve a problem.
    - For example, a trained circuit can be used to **classify** the content of images, by encoding the image into the physical state of the device and taking measurements.

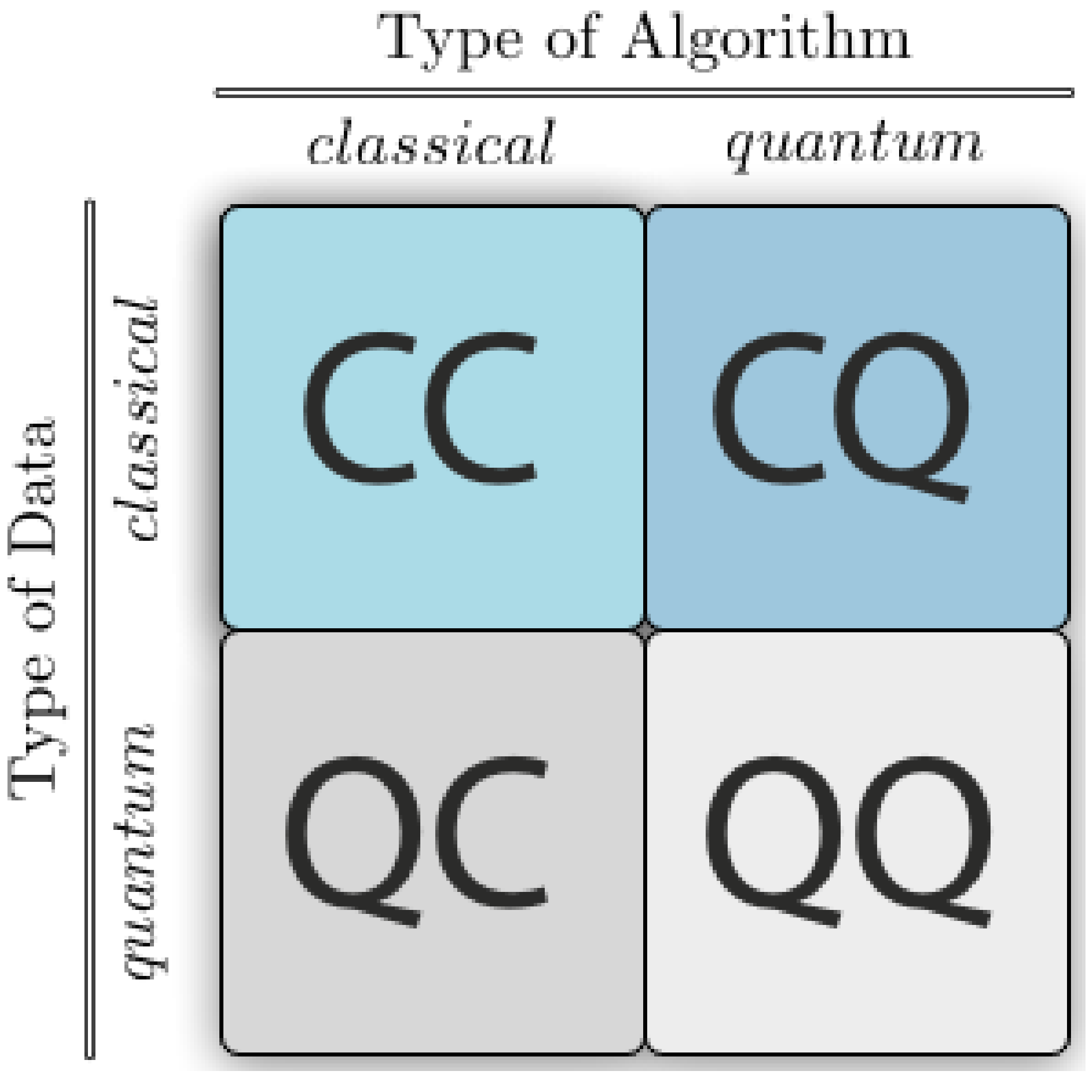
BENEFITS OF QML

- **Sustainability** – The Q4Climate collective showed that running a well-published calculation on Google's Sycamore quantum computer required 557,000-times less energy than if the same calculation had been performed on a classical supercomputer.
- **Powerful** - 158 million times faster than the most sophisticated supercomputer we have in the world today.
- **Reduced Complexity**
- **Optimization**
- **Enhanced Pattern Recognition**
- **Expanded Data Analysis**
- **Potential for Breakthrough Discoveries**

QML ALGORITHMS

- **Quantum Support Vector Machines (QSVM)**
- Hybrid quantum autoencoders (HQA)
- Quantum multiclass classifier
- Quantum neural networks QRNN
- Hybrid k-neighbours-nearby model
- Orthogonal neural networks
- Quantum fully self-supervised neural networks
- CNOT neural networks
- Quantum convolutional deep convolutional neural networks (QCNN)
- Quantum backpropagation neural networks (QBNN)
- Quantum Generative adversarial networks (QGAN)
- QLSTM, QRNN……..

APPLICABILITY OF QUANTUM ML



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FRONT RUNNERS!

XANADU

- A full-stack quantum machine learning company, provide a **leading resource hub** for quantum computing education and research.

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- They pursuit quantum advantage to solve practical problems especially applications that benefit from quantum machine learning or that require modeling and simulation of quantum-mechanics (such as **materials science** and **chemistry** problems)

ZAPATA

- Zapata is developing quantum-ready solutions today for industry-leading enterprises.

D-Wave
The Quantum Computing Company™

- Developed applications of quantum ML based on quantum-assisted ML algorithms, quantum Boltzmann machine. Additionally, working with CPUs, quantum processing units is likely to advance ML in a quantum-inspired way.

IBM Q

aws
Amazon Braket

Google AI Quantum

Azure Quantum

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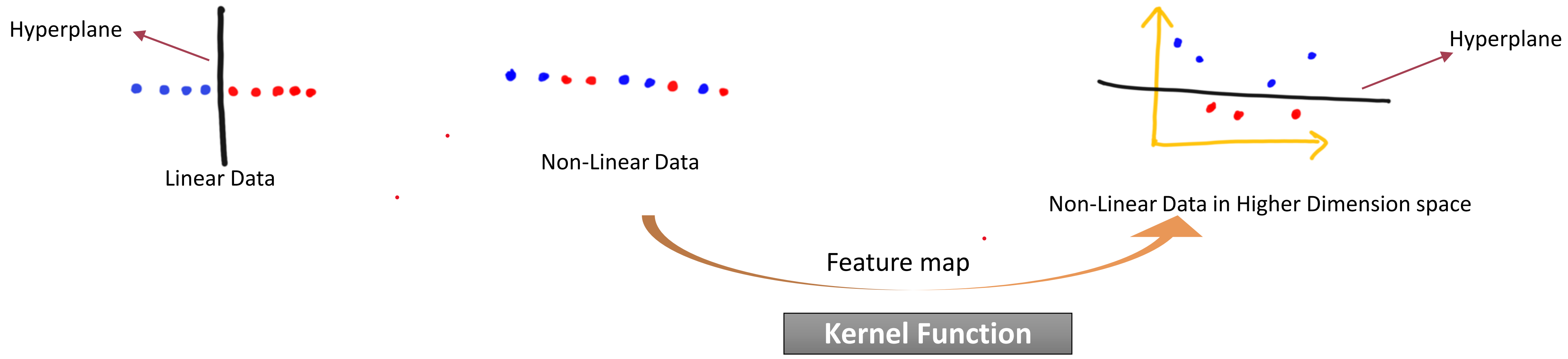
AN EXPLORATION – AN EXAMPLE !

Support Vector Machine

- The objective of classical SVM algorithm is **to find a hyperplane** in an N-dimensional space that distinctly classifies the data points with maximum margin.
- Data cannot typically be separated by a hyperplane in its original space.
- A common technique used to find such a hyperplane consists of applying **a non-linear transformation function** to the data.
- This function is called a **feature map**, as it transforms the raw features.



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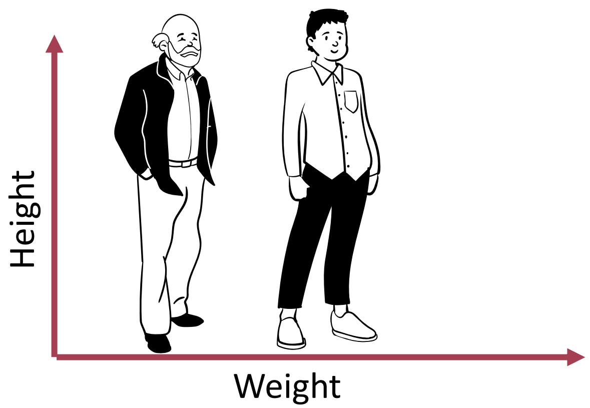
AN EXPLORATION – AN EXAMPLE !

Support Vector Machine - **What is in Higher Dimension space!!**

Eg: Problem- Classify Strength of the person – Weak/Strong

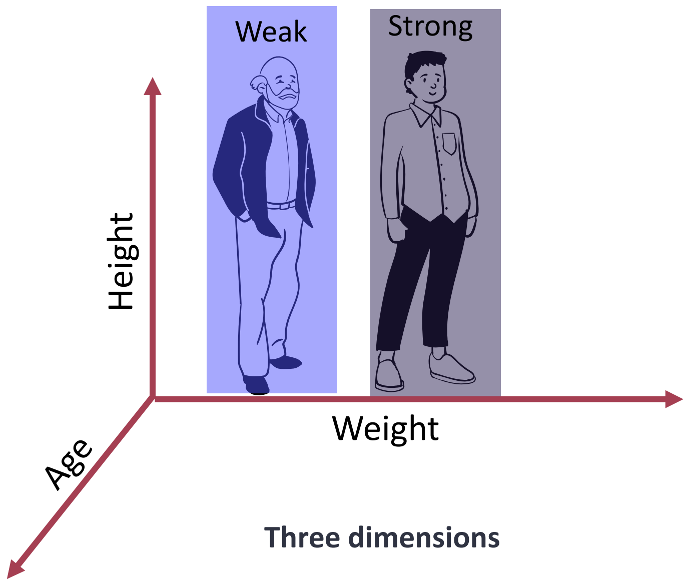
One dimension

What if the height is same for both



Two dimensions

Still need more characteristic parameters !!!

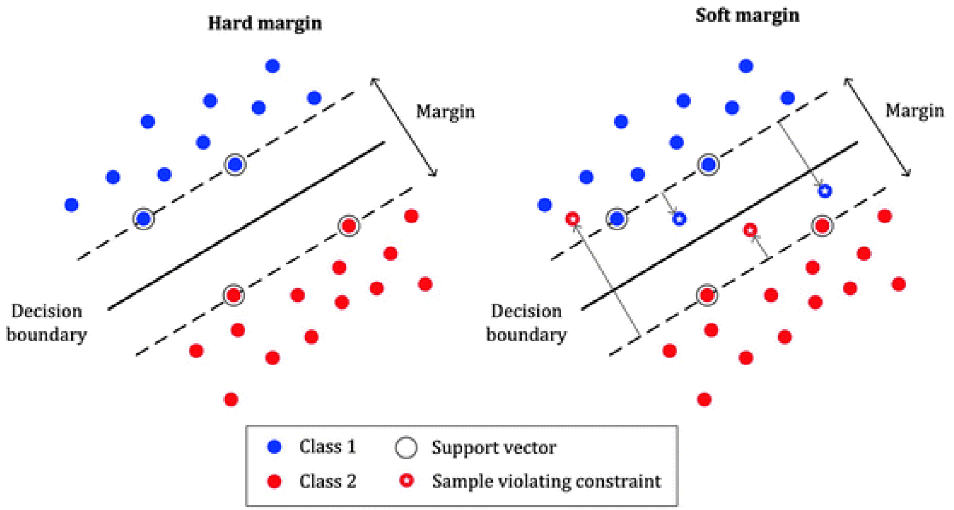


Three dimensions

AN EXPLORATION – AN EXAMPLE !

Support Vector Machine

- **Linearly** separable data is the **hard** margin whereas **non-linearly** separable data poses a **soft** margin.



- The hyperplane constraint will be simple but in cases of **non-linear** data with three or more classes the **Power of SVM is really challenged** and training complexity of SVM is highly dependent on the size of data set.

AN EXPLORATION – AN EXAMPLE !

Quantum Enhanced Supervised Learning

1. Quantum Algorithm on Quantum Data

- The **quantum variational classifier** builds on and operates through using a variational quantum circuit to classify a training set in direct analogy to conventional SVMs.
- Steps as follow,
  1. The classical data is mapped nonlinearly to a quantum state of N qubits by applying a **feature map quantum circuit** to the initial state |0>.
  2. A **short depth quantum circuit** is applied to the feature state.
  3. For a two-label classification problem, a **binary measurement** is applied to the state, this measurement is implemented by measurements in the **Z- basis** and feeding the output bit-string.
- **IBMQ(Qiskit) - QSVC** uses a **Quantum processor** to solve this problem by **direct estimation of the kernel** in the feature space. In the training phase, the kernel is estimated or calculated, and support vectors are obtained.

AN EXPLORATION – AN EXAMPLE !

Quantum Enhanced Supervised Learning

2. Classical Algorithm on Quantum Data

- Rather than using a variational quantum circuit to generate the separating hyperplane, A **quantum kernel estimator** estimates the kernel function and optimize the classifier(SVM) directly.
- But in applying the Quantum Kernel function directly, **we should transform** our training data and test data into **appropriate quantum states.**
- We can encode the training instances in a superposition in a register, and the test instances in another register using **Amplitude Encoding.**
- These two registers are put into entanglement.

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AN EXPLORATION – AN EXAMPLE !

Quantum Enhanced Support Vector Classifier (QSVC)

Dataset used – Ad hoc data

- A toy dataset that can be fully transformed to quantum states with ``qiskit.circuit.library.ZZ_Feature_Map``
- contains 2 features and 2 classes.
- 20 training sample and 5 test sample for each class.
- **Classical SVC on Classical Data - Score = 0.6**

	SVC with QKernel_score	QSVC_score
TRAIL1	1.0	0.9
TRAIL2	0.9	1.0
TRAIL3	0.9	1.0

- **Exponentially faster than Classical SVC.**

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DEMONSTRATION

LET'S EXECUTE…

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LET'S DISCUSS…

THANK YOU

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