Quantum Support Vector Machines (QSVMs) are the quantum version of classical Support Vector Machines (SVMs), which are used for tasks like classifying data into different categories. Classical SVMs try to find a line or hyperplane that separates data points of different classes with the largest margin. QSVMs use **quantum computers** to handle data in much higher dimensions, which can make it easier to find patterns that are hard for classical computers. In QSVMs, regular data is converted into **quantum states** using a process called a **quantum feature map**, which represents the data in a special way that a quantum computer can work with.

QSVMs use something called a **quantum kernel** to measure how similar two data points are. This is done by calculating the inner product of their quantum states:

$$K(x_i, x_j) = |\langle \phi(x_i) | \phi(x_j) \rangle|^2$$

This kernel is then used in the SVM framework to classify data points. Using quantum kernels allows QSVMs to handle complex patterns and very large datasets more efficiently than classical SVMs.

QSVMs are useful in many areas, such as **image and speech recognition, drug discovery, molecular simulations, and financial predictions**. By combining classical SVM ideas with quantum computing, QSVMs can process data faster and find patterns more effectively. Overall, QSVMs show how **quantum computing can improve machine learning** for difficult and high-dimensional problems.

Quantum Boosting is the **quantum version of classical boosting algorithms**, which are widely used in machine learning to improve the performance of weak learners. Boosting works by combining multiple weak models (which perform slightly better than random guessing) into a **strong model** that makes accurate predictions. Quantum Boosting uses **quantum computers** to speed up computations and handle high-dimensional data efficiently.

Quantum Boosting Concept:

- In Quantum Boosting, **quantum algorithms** are used to accelerate the training of weak classifiers and the combination process.

- Quantum states can represent **superpositions of many possible data points**, allowing parallel processing of multiple possibilities at once.

- A **quantum oracle** is often used to evaluate weak classifiers efficiently on the dataset.

Key Steps in Quantum Boosting:

1. **Prepare the quantum states** representing the training data.

2. **Train weak classifiers** using quantum operations, focusing on misclassified examples.

3. **Compute weights** for weak classifiers to combine them into a strong classifier.

4. **Measure the final quantum state** to obtain the classification result.

- Minimal math example: If $h_t(x)$ is the weak classifier at step t and α_t is its weight, the final classifier is:

$$H(x) = \text{sign}(\sum_t \alpha_t h_t(x))$$

Advantages of Quantum Boosting:

- Can handle **large and high-dimensional datasets** more efficiently than classical boosting.

- Potential **speedup** due to quantum parallelism and superposition.

- Can improve accuracy of weak classifiers faster, especially in complex problems.

Applications:

- Image recognition and computer vision

- Fraud detection in finance

- Drug discovery and molecular modeling

- Any problem where **boosting algorithms** are used classically

Quantum Neural Networks (QNNs) are the quantum version of classical neural networks. They combine **quantum computing** with machine learning to process **complex and high-dimensional data** more efficiently than classical networks.

Concept:
In QNNs, **quantum bits (qubits)** replace classical neurons, and **quantum gates** act like neuron operations. Data is encoded into quantum states, processed through layers of quantum gates, and finally measured to produce outputs. Qubits can exist in **superposition**, representing multiple states simultaneously, and can be **entangled**, creating correlations that are difficult for classical networks to replicate.

Minimal Math:
A simple quantum neuron can be represented by a **parameterized quantum gate** $U(\theta)$ acting on a qubit:

$$|\psi_{\text{out}}\rangle = U(\theta) |\psi_{\text{in}}\rangle$$

This output is obtained by measuring the qubit. Multiple qubits and gates form layers, similar to classical neural network layers.

Advantages:
QNNs can handle **high-dimensional data efficiently**, learn **complex patterns faster**, and leverage **quantum parallelism and entanglement** to create richer data representations than classical neural networks.

Applications:
QNNs are useful in **image and speech recognition**, **quantum chemistry and drug discovery**, and solving **optimization problems** in finance and logistics. They are particularly promising for tasks where classical networks face computational limitations.

Variational Quantum Algorithms (VQAs) are a class of quantum algorithms that combine **quantum computing** with **classical optimization** to solve problems efficiently. They are especially useful for tasks that are hard for classical computers, such as **optimization, machine learning, and quantum chemistry**.

Concept:

- VQAs use a **parameterized quantum circuit** (also called an ansatz) to prepare quantum states.

- A **classical optimizer** adjusts the parameters to **minimize or maximize a cost function** based on measurements from the quantum circuit.

- This process is repeated iteratively until the optimal solution is found.

Advantages:

- Can work on **current noisy intermediate-scale quantum (NISQ) devices**.

- Efficiently handles problems in **high-dimensional spaces**.

- Flexible and applicable to **optimization, machine learning, and quantum simulations**.

Applications:

- Finding **ground-state energies of molecules** in quantum chemistry.

- Solving **combinatorial optimization problems**.

- Quantum-enhanced **machine learning models**.

Conclusion:
VQAs are a promising approach in quantum computing, using a hybrid **quantum-classical loop** to solve complex problems that are difficult for classical algorithms alone.

Quantum Nearest Neighbour Search is the **quantum version** of classical nearest neighbour search. It aims to find the **most similar data points** to a given query in a dataset using **quantum computing**, which can provide **speedups** over classical methods, especially for large and high-dimensional datasets.

2. Concept:

- Classical NNS calculates distances between a query and all dataset points to find the nearest neighbour.

- In Quantum Machine Learning, **data is encoded into quantum states** using a **quantum feature map**.

- Similarity between the query and dataset points is computed using **quantum measurements**, often via **inner products** or **quantum kernels**:

$$K(x_i, x_j) = |\langle \phi(x_i) \mid \phi(x_j) \rangle|^2$$

- Quantum parallelism allows computation of similarities between the query and **all data points simultaneously**, reducing computation time.

3. Minimal Math:

- Let $| \phi(q) \rangle$ be the quantum state of the query and $| \phi(x_i) \rangle$ the quantum state of dataset points.

- The nearest neighbour is:

$$x_{NN} = \arg \max_{x_i} \ | \langle \phi(q) \ | \ \phi(x_i) \rangle \ |^2$$

- This corresponds to finding the dataset point **most similar** to the query in the quantum Hilbert space.

4. Advantages:

- Can handle **large and high-dimensional datasets** more efficiently due to **quantum parallelism**.

- Reduces the number of **distance computations** compared to classical brute-force NNS.

- Can be integrated with **quantum kernels** for richer similarity measures.

5. Applications in Quantum Machine Learning:

- **Quantum recommendation systems** – finding similar users or items faster.

- **Quantum image and pattern recognition** – finding similar images in large datasets.

- **Quantum clustering** – identifying clusters based on nearest neighbour relationships.

- **Anomaly detection** in quantum datasets.

1. Introduction:

Quantum Cryptography is a technique that uses **quantum mechanics principles** to achieve **secure communication**. Unlike classical cryptography, which relies on mathematical complexity (like factoring large numbers), quantum cryptography leverages **quantum phenomena** such as **superposition** and **entanglement** to ensure that any eavesdropping can be detected. Its main goal is to provide **unconditional security** in data transmission.

2. Key Principles:

- **Superposition:** A quantum bit (qubit) can exist in multiple states simultaneously, allowing information to be encoded in a quantum state.

- **No-Cloning Theorem:** Quantum states **cannot be copied perfectly**, ensuring that an eavesdropper cannot duplicate quantum information without detection.

- **Measurement Disturbs State:** If someone tries to measure a quantum state, it **changes the state**, which can be detected by the communicating parties.

3. Concept:

The most widely known application of quantum cryptography is **Quantum Key Distribution (QKD)**. The **BB84 protocol**, introduced by Bennett and Brassard in 1984, works as follows:

1. The sender (Alice) encodes bits using **polarized photons** in random bases.

2. The receiver (Bob) measures the photons in randomly chosen bases.

3. Alice and Bob publicly compare the bases (not the actual bits) and keep only the bits where the bases match.

4. If an eavesdropper (Eve) tries to intercept the photons, she will **disturb the states**, introducing detectable errors.

This allows Alice and Bob to share a **secret key securely**, which can then be used for encryption using classical methods like the **One-Time Pad**, ensuring **unbreakable encryption**

4. Advantages:

- Provides **provably secure communication** based on the laws of physics, not computational hardness.

- Detects **any eavesdropping** automatically.

- Resistant to **quantum attacks**, unlike classical cryptography.

5. Applications:

- **Secure communication networks**

- **Banking and financial transactions**

- **Military and government communication**

- **Quantum Internet** (future secure global networks)

Quantum Dense Coding is a **quantum communication protocol** that allows two parties to transmit **more classical information than is possible classically** using **entanglement**. In classical systems, sending one bit of information requires one bit of physical transmission. In contrast, QDC uses **entangled qubits** to send **two classical bits by sending just one qubit**. It demonstrates the **information-enhancing power of quantum entanglement**.

2. Entanglement Basics:

- Entanglement is a quantum phenomenon where two qubits share a **correlated state**, such that the measurement of one qubit instantly affects the other, no matter the distance.

- Commonly used entangled states are **Bell states**, for example:

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

- In QDC, Alice and Bob each hold **one qubit** of an entangled pair.

3. The Protocol:

1. **Preparation:**

   o Alice and Bob share an entangled pair (Bell state).

   o Alice wants to send **2 classical bits** (00, 01, 10, 11) to Bob.

2. **Encoding (Alice's Operation):**

   o Alice applies **one of four quantum operations** (Pauli gates) on her qubit to encode 2 bits:

   ▪ 00 → Identity I

   ▪ 01 → X(bit flip)

   ▪ 10 → Z(phase flip)

   ▪ 11 → $Y = iXZ$(bit + phase flip)

3. **Transmission:**

   o Alice sends her qubit to Bob through a **quantum channel**.

4. **Decoding (Bob's Measurement):**

   o Bob now has **both qubits**.

   o He performs a **Bell-state measurement**, which can distinguish all four Bell states.

   o Each measurement outcome corresponds uniquely to the **2 classical bits** Alice encoded.

4. Why It Works:

- **Quantum entanglement** allows **more information to be encoded per qubit**.

- The transmitted qubit alone **does not reveal the information**; Bob needs both qubits to decode.

- This ensures **security and efficiency**.

5. Advantages:

- **Doubles communication efficiency** (2 classical bits per qubit).

- Demonstrates the **power of quantum entanglement** in communication.

- Can be combined with **quantum cryptography** for **secure data transmission**.

- Lays the foundation for **advanced quantum protocols** like quantum teleportation.

6. Applications:

- **Quantum communication networks** – transmit more information with fewer qubits.

- **Quantum cryptography** – enhanced key distribution and secure messaging.