

Neuromorphic computation using Quantum dot cellular Automata

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Neuromorphic Computation

What is Neuromorphic Computing?



Neuromorphic computing, also known as neuromorphic engineering, is a computer engineering method that is inspired by the the structure and function of the human brain. It is an application of Artificial Intelligence and uses artificial neurons and synapses to process information, allowing computers to:

- Solve problems
- Recognize patterns
- Make decisions more quickly and efficiently
- Perform parallel processing
- Learn in real-time

Neuromorphic Computing vs Traditional Computing Methods

- **Power Efficiency:** Traditional computers use a lot of power, especially when dealing with complex tasks like artificial intelligence and machine learning. Neuromorphic computing mimics the brain's structure, which is highly efficient in terms of power consumption due to its parallel processing capabilities.
- **Speed:** Neuromorphic computing can process information in parallel, similar to how the brain works, leading to faster processing times for certain types of tasks compared to sequential processing in traditional computers.
- **Scalability:** Traditional computing architectures face challenges in scaling up to handle increasingly complex tasks and large datasets. Neuromorphic systems, with their interconnected neurons and synapses, are inherently scalable and can adapt to varying computational requirements.
- **Adaptability and Learning:** Neuromorphic systems have the potential for adaptive learning, allowing them to improve and learn from experience without the need for explicit programming or reprogramming. This contrasts with traditional computers that rely on predefined algorithms and instructions.



Quantum dot cellular Automata

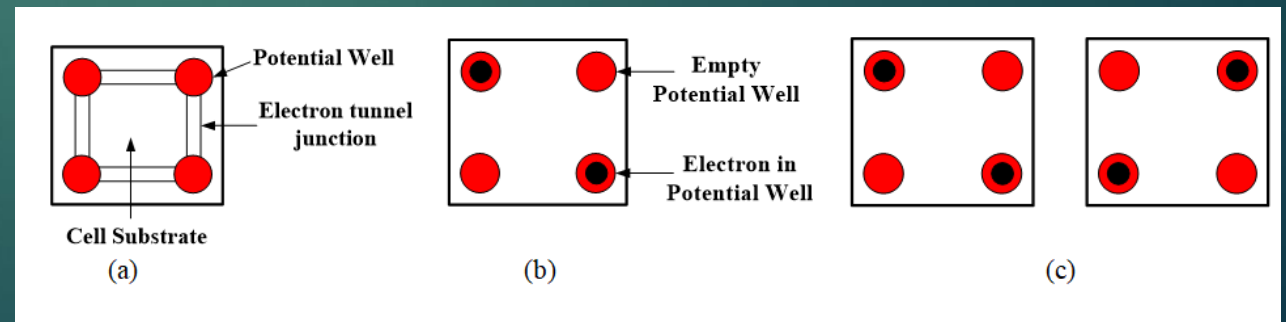
Quantum dot cellular Automata

Quantum-dot cellular automata (QCA) is a nanoscale computing technology that represents binary information based on the spatial distribution of electron charge configuration in chemical molecules.

It is a promising computing paradigm that leverages principles from quantum mechanics and nanotechnology to build ultra-compact and energy-efficient computing devices

Importance of QCA Technology:-

- 1) QCA Cells
- 2) QCA Wire
- 3) QCA Inverter

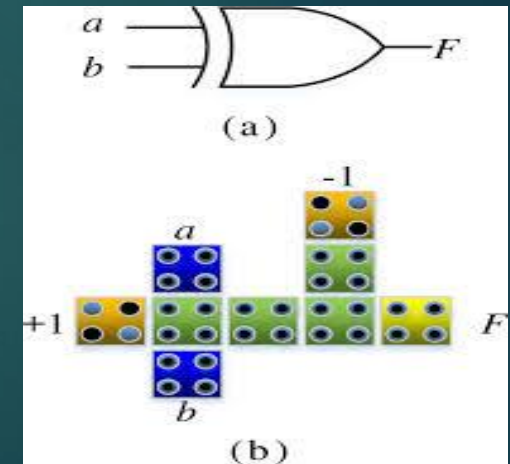


Features of Quantum dot cellular Automata

- a) **Basic Principle:** QCA relies on the behavior of quantum dots, which are nanoscale semiconductor particles. These dots can be charged or uncharged, representing binary states (0 and 1), and they interact with neighboring dots through quantum tunneling effects.
- b) **Cellular Automata:** QCA operates on the concept of cellular automata, where each quantum dot acts as a "cell" in a grid. The arrangement and charge of these dots determine the computational state of the system.
- c) **Computational Elements:** In QCA, logical operations are performed by arranging quantum dots into specific configurations. For example, XOR and AND gates can be constructed using carefully designed layouts of charged and uncharged dots.

d) **Advantages:**

- **Miniaturization:** QCA enables the creation of extremely small computing components, potentially leading to denser and more powerful integrated circuits.
- **Low Power:** Due to its quantum nature, QCA consumes very little power compared to traditional CMOS-based circuits, making it suitable for energy-efficient computing.
- **High Speed:** QCA devices can operate at very high speeds, offering excellent performance for certain types of computations.



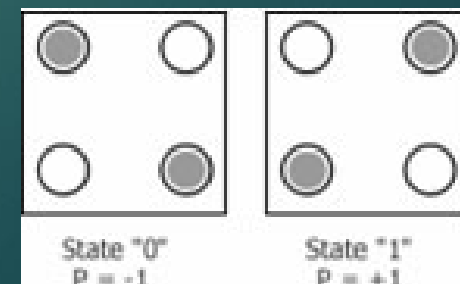
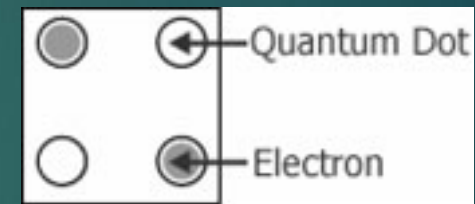
Quantum Dot Cellular Automata

- ▶ QCA

- ▶ proposed models of quantum computation
- ▶ analogous to conventional CAs
 - ▶ but based on quantum mechanical phenomenon of “tunneling”

- ▶ Quantum dots

- ▶ 4-dot cell
 - ▶ basic unit of storage and computation
 - ▶ two polarization states: -1 and +1
 - ▶ electrostatic repulsion



Quantum Dot Cellular Automata

In Quantum dot Cellular Automata (QCA), the states of a cell are characterized by polarization (P) and activation (A). Here's an explanation of the key elements in the context of a **six-dot QCA cell**:

- **Polarization (P):** Polarization refers to the alignment of electron spins within the quantum dots. In QCA, polarization can be either "up" or "down," corresponding to values of "1" or "-1", respectively. This polarization state is represented by the presence or absence of a mobile electron (red disc) in each quantum dot.
- **Activation (A):** Activation refers to the state of the cell, whether it is in an active state (either "1" or "0") or in a neutral state (null). In the diagram, an active state is represented by the presence of a mobile electron in certain quantum dots, indicating a binary value of either "1" or "0." The null state occurs when there are no mobile electrons present in the quantum dots.
- **Tunneling Paths:** Tunneling paths are represented by white connecting lines between the quantum dots. Tunneling allows electrons to move between quantum dots even though they are physically separated. In this context, tunneling between active states ("0" or "1") requires an intermediate tunneling through the null state. This means that to transition from one active state to another, the cell must pass through the null state.
- **Clocking:** Clocking is a crucial operation in QCA that controls the movement of electrons within the cell. Clocking involves applying voltages to specific dots in the cell to manipulate the polarization and activation states.

In summary, the described six-dot QCA cell operates based on the polarization and activation states of its quantum dots.

Quantum-dot Cellular Automata

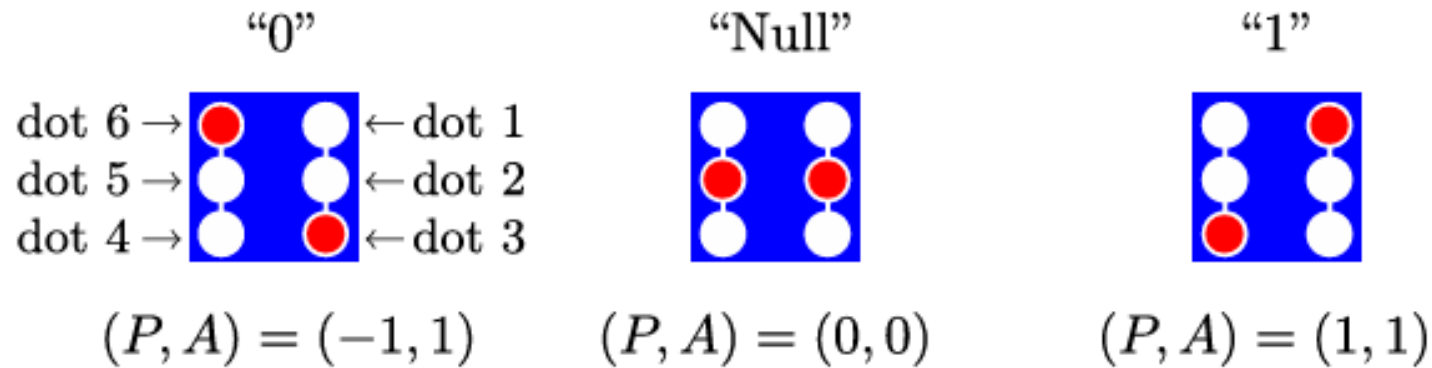


Fig. 1. The states of a six-dot QCA cell are characterized by polarization (P) and activation (A). Here, each white disc represents a quantum dot, and each red disc represents one mobile electron. White connecting lines between dots indicate tunneling paths, with the consequence that tunneling between active states (“0” or “1”) requires an intermediate tunneling through the “Null” state. The cell can be clocked to the Null state by applying a positive voltage ($V_{clk} > 0$) to dots 2 and 5 (“null” dots), or to an active state by applying a negative voltage ($V_{clk} < 0$) to the null dots. Clocking leads connected to the null dots are not shown here.

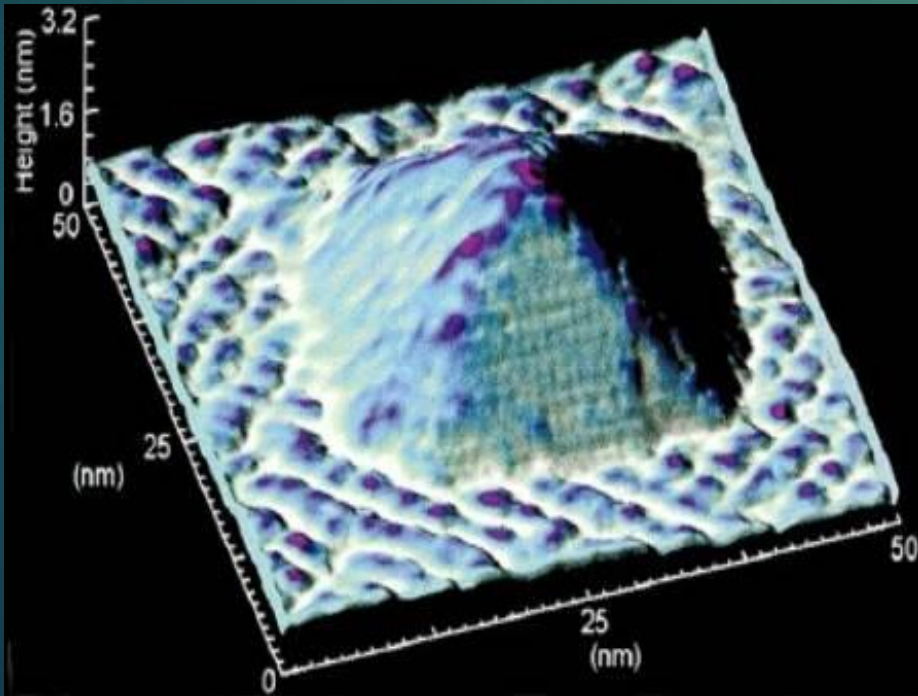
Quantum-dot Cellular Automata

$$P = \frac{q_1 + q_4 - q_3 - q_6}{Q}, \quad \text{and} \quad A = 1 - \frac{q_2 + q_5}{Q} \quad (1)$$

The valid ranges for P and A are $[-1, 1]$ and $[0, 1]$, respectively. Here, $Q = \sum_{k=1}^6 q_k = 2q$ is the total mobile charge on all six dots, and q is the electronic charge. A bit is encoded on the sign of P , and signal strength can be measured by taking the absolute value of P . A weak bit has $|P| < 1$, and a full-strength bit has $|P| \simeq 1$.

Why are Quantum Dots important?

- ▶ Quantum dots will become the backbone of future microelectronic and photonic devices:
 - ▶ because of their unique properties due to *quantum confinement of electrons in 3-dimensions*
 - ▶ this results in interesting electronic and optical properties



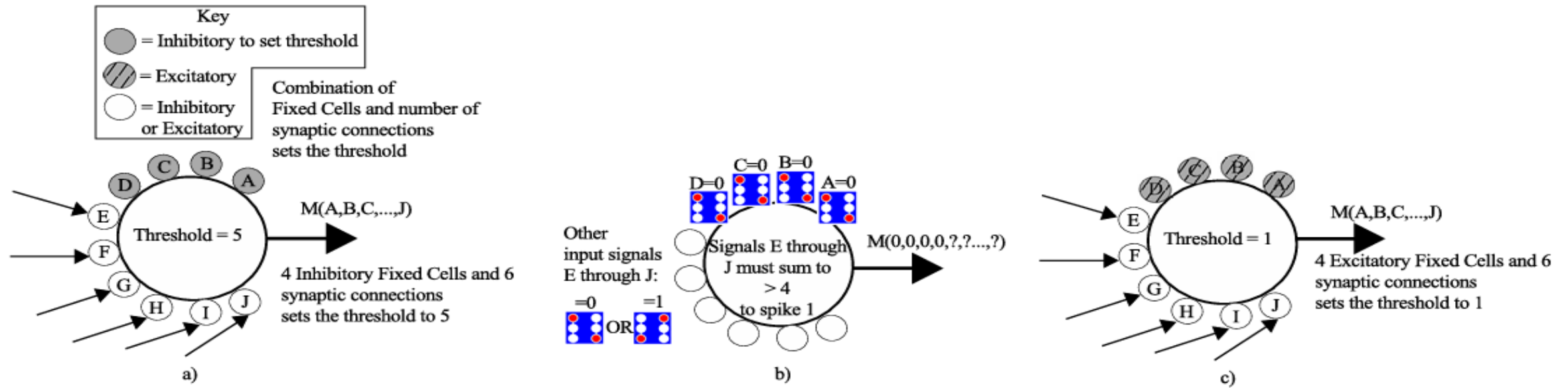
What are their Applications?

- Neuro-quantum structures
- Single-electron devices, for instance transistors
- Tunable lasers
- Photodetectors
- Sensors

Neuromorphic Computation using Quantum dot Cellular Automata

Quantum dot cellular automata (QCA) is a promising technology for neuromorphic computing due to its potential for low-power, high-density computation and its ability to mimic certain aspects of neural networks. Here's how QCA can be used in neuromorphic computing:

- **Energy Efficiency:** QCA operates at the nanoscale level and uses electron tunneling between quantum dots, which can lead to extremely low power consumption. This energy efficiency is crucial for designing neuromorphic systems that aim to mimic the energy-efficient operation of biological brains.
- **Parallel Processing:** QCA enables parallel processing at a very high density. In neuromorphic computing, this parallelism can be leveraged to simulate large-scale neural networks efficiently. Each quantum dot can represent a neuron or synapse, allowing for massive parallelism in neural network computations.
- **Neuron and Synapse Emulation:** By configuring QCA cells in specific patterns, it's possible to emulate neurons and synapses. Neurons can be represented by QCA cells that integrate inputs, perform activation functions, and generate outputs. Synaptic connections between neurons can be simulated using QCA cells that modulate the strength of connections based on activity.



The diagram depicts an abstract model of how quantum dot cellular automata can be configured to perform computations that mimic the behaviour of biological neurons. In biological brains, neurons communicate with each other through electrical signals. The quantum dot cellular automata emulate this by using electrical fields to manipulate the state of the QDs.

In the image, each coloured circle represents a quantum dot (QD), the basic unit of the QCA. The QDs are arranged in a specific pattern to create cells, which are interconnected by lines representing electrical connections. These connections influence the state of the QDs, which can be either 0 or 1.

The image explains how the arrangement of QDs and the connections between them determines the threshold required for a specific QD to switch states. The threshold is a number that represents the minimum number of excitatory inputs a QD needs to receive to switch from a 0 state to a 1 state. Likewise, it's the number of inhibitory inputs required to prevent a QD from switching to a 1 state.

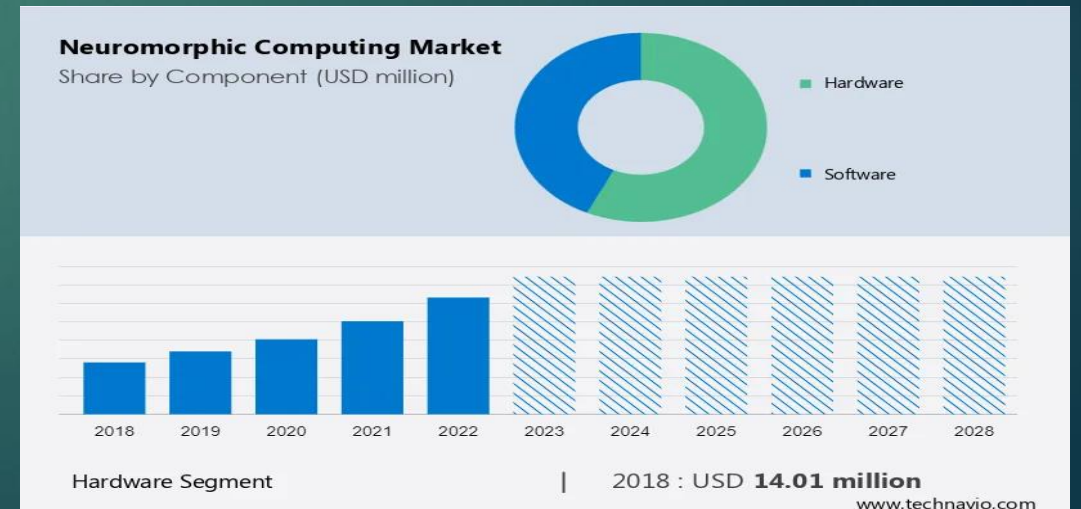
The signals E through J represent external input signals that can be applied to the circuit.

Applications

- **Pattern Recognition:** QCA-based neuromorphic systems can be used for pattern recognition tasks such as image and speech recognition. The parallel processing capability of QCAs, coupled with their low-power operation, makes them suitable for real-time processing of large datasets, enabling applications in computer vision, surveillance systems, and natural language processing.
- **Healthcare and Biomedical Applications:** QCAs in neuromorphic systems can be used in healthcare for tasks like medical image analysis, disease diagnosis, and personalized medicine. They can process large biomedical datasets efficiently, identify patterns indicative of diseases or conditions, and adapt their algorithms based on patient-specific data, leading to more accurate and timely healthcare interventions.

Future of Neuromorphic Computing

Neuromorphic computing is expected to have a significant impact on **artificial intelligence (AI)** and **data analysis**, and could **potentially reshape the landscape of future technological advancements**. The neuromorphic chip market is expected to reach USD **5.83 billion** by 2029, with a compound annual growth rate (CAGR) of 104.70% from 2024 to 2029



Conclusion

- **Advantages:** Neuromorphic computing offers potential advantages over traditional computing methods. Its ability to mimic the brain's structure and operation could lead to significant improvements in energy efficiency, parallel processing capabilities, and computational speed for specific tasks.
- **Applications:** Neuromorphic computing has promising applications in various fields such as artificial intelligence, robotics, pattern recognition, and sensor networks. Its ability to process data in a brain-like manner makes it suitable for tasks that require real-time processing, adaptive learning, and complex pattern recognition.

Bibliography

Source:

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THANK YOU