



# Towards Nanoelectronics: Possible CNN Implementations using Nanoelectronic Devices

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**ABSTRACT:** We discuss novel nanoelectronic architecture paradigms based on cells composed of coupled quantum-dots. Boolean logic functions may be implemented in specific arrays of cells representing binary information, the so-called *Quantum-Dot Cellular Automata (QCA)*. Cells may also be viewed as carrying analog information and we outline a network-theoretic description of such *Quantum-Dot Nonlinear Networks (Q-CNN)*. In addition, we discuss possible realizations of these structures in a variety of semiconductor systems, rings of metallic tunnel junctions, and candidates for molecular implementations.

## 1. Introduction

Silicon technology has followed *Moore's Law* remarkably closely for more than three decades. However, there are indications now that this progress will slow, or even come to a standstill, as technological and fundamental limits are reached [1]. This slow-down of silicon ULSI technology may provide an opportunity for alternative device technologies. Among the chief technological limitations responsible for this expected slow-down of silicon technology are the interconnect problem and power dissipation [2]. However, these obstacles for silicon circuitry may present an opportunity for alternative device technologies which are designed for the nanometer regime and which are interconnected in an appropriate architecture.

In this paper, we describe our ideas of using nanostructures (more specifically, quantum dots) which are arranged in locally-interconnected cellular-automata-like arrays. We will demonstrate that suitably designed structures, the so-called "Quantum-Dot Cellular Automata" (QCA) [3], may be used for computation and signal processing. The fundamental idea for QCA operation is to encode information using the charge configuration in a cell, which is more naturally suited to nanostructures. This is an important break with the transistor paradigm, where binary information is encoded utilizing voltage-controlled current switches.

We envision that nanoelectronic implementations of QCA-type arrangements would result in extremely dense processor arrays, e.g. a complete processor behind each pixel in the prototypical array shown in Fig. 1. Even at the end of the *Roadmap*, conventional CMOS would not allow the realization of such structures.

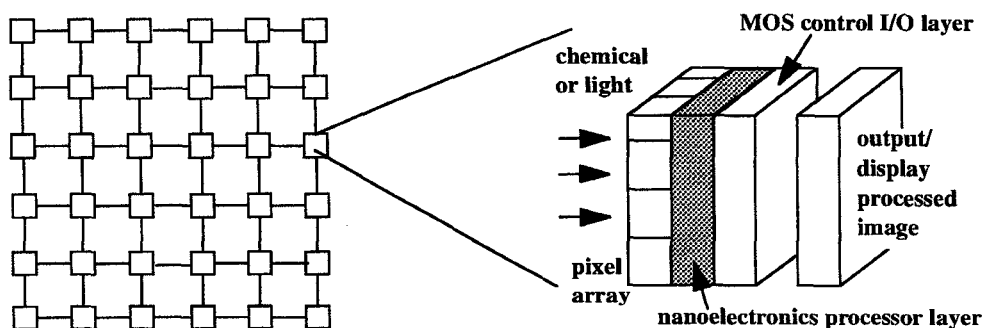


Figure 1: Schematic view of an image processing array, where each pixel also contains a nanoelectronic processor.

## 2. Quantum-Dot Cellular Automata

Based upon the emerging technology of quantum-dot fabrication, the Notre Dame *NanoDevices Group* has developed the QCA scheme for computing with cells of coupled quantum dots [3], which will be described below. To our knowledge, this is the first concrete proposal to utilize quantum dots for computing. There had been earlier suggestions that device-device coupling might be utilized in a cellular-automata scheme, alas, without an accompanying proposal for a specific implementation [4].

### 2.1 A Quantum-Dot Cell

The Quantum-Dot Cellular Automata (QCA) scheme is based on a cell which contains four quantum dots [3], as schematically shown in Fig. 2(a). The quantum dots are shown as the open circles which represent the confining electronic potential. In the ideal case, each cell is occupied by two electrons, which are schematically shown as the solid dots. The electrons are allowed to “jump” between the individual quantum dots in a cell by the mechanism of quantum mechanical tunneling. Tunneling is possible on the nanometer scale when the electronic wavefunction sufficiently “leaks” out of each dot, and the rate of these jumps may be controlled during fabrication by the physical separation between neighboring dots.

This quantum-dot cell represents an interesting dynamical system. The two electrons experience their mutual Coulombic repulsion, yet they are constrained to occupy the quantum dots. If left alone, they will seek, by hopping between the dots, the configuration corresponding to the physical ground state of the cell. It is clear that the two electrons will tend to occupy different dots because of the Coulomb energy cost associated with bringing them together in close proximity on the same dot. It is easy to see that the ground state of the system will be an equal superposition of the two basic configurations with electrons at opposite corners, as shown in Fig. 2(b).

### 2.2 Cell-Cell Coupling

The properties of an isolated cell were discussed above. The two polarization states of the cell will not be energetically equivalent if other cells are nearby. Here, we study the interactions between two cells, each occupied by two electrons. The electrons are allowed to tunnel between the dots in the same cell, but not between different cells. Coupling between the two cells is provided by the Coulomb interaction between electrons in different cells.

Figure 3 shows how one cell is influenced by the state of its neighbor. The inset shows two cells where the polarization of cell 1 ( $P_1$ ) is determined by the polarization of its neighbor ( $P_2$ ). The  $P_2$  is presumed to be fixed at a given value, corresponding to a certain arrangement of charges in cell 2, and this charge distribution exerts its influence on cell 1, thus determining its polarization  $P_1$ . The important finding here is the strongly non-linear nature of the cell-cell coupling. Cell 1 is almost completely polarized even though cell 2 might only be partially polarized.

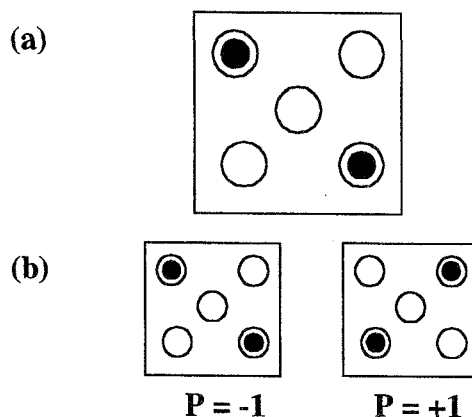


Figure 2: (a) A quantum-dot cell consisting of five dots is occupied by two electrons. (b) The two distinct ground-state configurations with their polarizations.

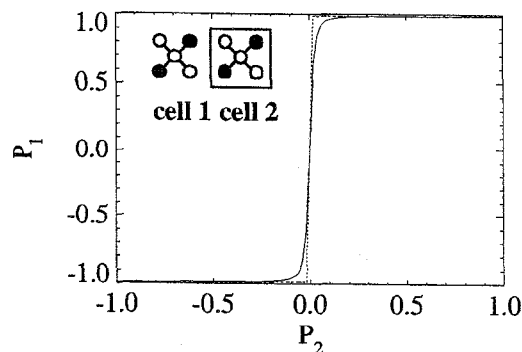


Figure 3: (a) Cell-cell coupling characteristics.

### 2.3 QCA Logic

Based upon the bistable behavior of the cell-cell coupling, the cell polarization can be used to encode binary information. We have demonstrated that the physical interactions between cells may be used to realize elementary Boolean logic functions [5]. Figure 4 shows examples of simple arrays of cells. In each case, the polarization of the cell at the edge of the array is kept fixed; this is the so-called driver cell and it is plotted with a thick border. We call it the driver since it determines the state of the whole array. Without a polarized driver, the cells in a given array would be unpolarized in the absence of a symmetry-breaking influence that would favor one of the basis states over the other. Each figure shows the cell polarizations corresponding to the physical ground state configuration of the whole array. Fig. 4(a) shows that a line of cells allows the propagation of information, thus realizing a binary wire. Note that only information but no electric current flows down the line, which results in low power dissipation. Information can also flow around corners, as shown in Fig. 4(b), and fan-out is possible, shown in Fig. 4(c). Cells which are positioned diagonally from each other tend to anti-align. This feature is employed to construct an inverter as shown in Fig. 4(d). In each case, electronic motion is confined to within a given cell, but not between different cells. Only information, and not charge, is allowed to propagate over the whole array.

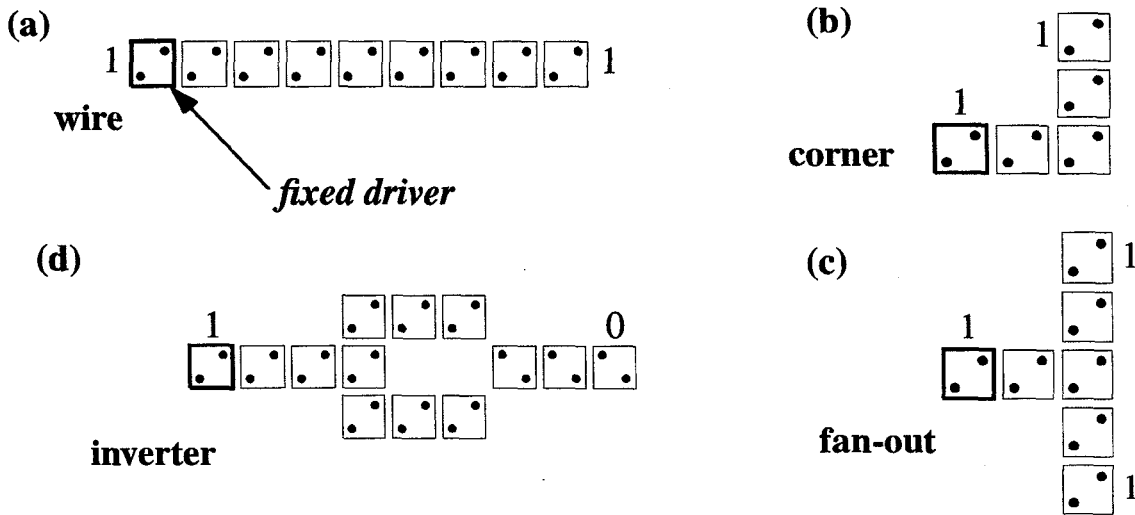


Figure 4: Examples of simple QCA arrays for Boolean logic.

These quantum-dot cells are an example of quantum-functional devices. Utilizing quantum-mechanical effects for device operation may give rise to new functionality. Figure 5 shows the fundamental QCA logical device, a three-input majority gate, from which more complex circuits can be built. The central cell, labeled the device cell, has three fixed inputs, labeled A, B, and C. The device cell has its lowest energy state if it assumes the polarization of the majority of the three input cells. The difference between input and outputs cells in this device, and in QCA arrays in general, is simply that inputs are fixed and outputs are free to change. The inputs to a particular device can come from previous calculations or be directly fed in from array edges. Using conventional circuitry, the design of a majority logic gate would be significantly more complicated, being composed of some 26 MOS transistors. It is possible to “reduce” a majority logic gate by fixing one of its three inputs in the 1 or 0 state. In this way, a reduced majority logic gate can also serve as a programmable AND/OR gate. The new physics of quantum mechanics gives rise to new functionality, which allows a rather compact realization of majority logic.

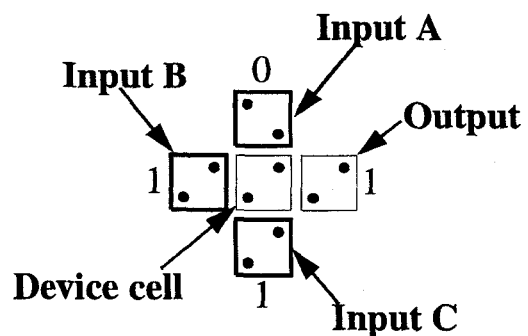


Figure 5: QCA Majority Logic gate.

### 3. Quantum-Dot Cellular Neural Networks

In addition to employing QCA cells to encode binary information, these cells may also be used in an analog mode. As schematically shown in Fig. 6, each cell interacts with its neighbors within a certain range, thus forming what we call a *Quantum-Dot Cellular Nonlinear Network* (Q-CNN) [6]. This way of viewing coupled cells as a nonlinear dynamical system is similar to *Cellular Nonlinear (or, Neural) Networks* (CNN), which are locally-interconnected structures implemented using conventional circuitry [7]. Each cell is described by appropriate state variables, and the dynamics of the whole array is given by the dynamical law for each cell, which includes the influence exerted by the neighbors on any given cell.

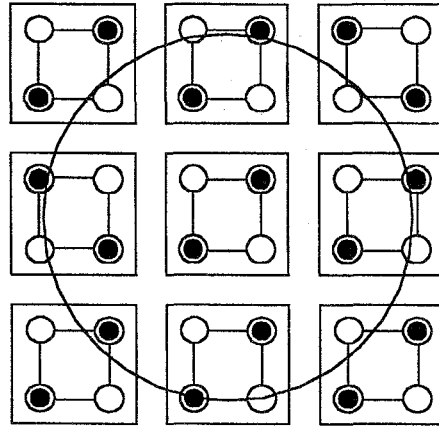


Figure 6: Schematic view of a locally-connected cellular QCA array. The circle indicates the range of interaction for the central cell.

In the literature [6, 8], we have developed a simple two-state model for the quantum states in each cell and show how the quantum dynamics of the array can be transformed into a CNN-style description by choosing appropriate state variables. The general features of this model are: (1) Each cell is a quantum system, characterized by both classical and quantum degrees of freedom. (2) The interactions between cells only depends upon the classical degrees of freedom; the precise form of the “synaptic input” is determined by the physics of the intercellular interactions. (3) The state equations are derived from the time-dependent Schrödinger equation; one state equation exists for each classical and quantum degree of freedom.

For the case of a two-dimensional array, each Q-CNN cell possesses an equivalent CNN-cell model described by the differential equations given below. We may thus think of such a quantum-dot cell array as a special case of cellular nonlinear networks [9]. The equivalent circuit describing a cell is composed of two linear capacitors, four nonlinear controlled sources and eight linear controlled sources representing the interactions between the cell and its eight neighbors [10].

Our quantum model is a special case of a general formalism for “quantum networks” developed by Mahler [11]. As schematically shown in Fig. 7, a quantum network consists of subsystems which are special quantum objects denoted as “network nodes” and the interaction channels between them are denoted as “network edges.” In his book, Mahler develops the theoretical study of small (coherent) quantum networks by means of the density matrix theory: the network node is taken as a finite local state space of dimension  $n$ . The network might be a regular lattice or an irregular array of nodes. The network is coupled to external driving fields and dissipative channels, which are required for measurement. This approach provides a system-theoretic tool adaptable to situations where a finite quantum mechanical state space is controlled by a classical environment. In other words, this formalism also includes dissipation, which we have not yet incorporated in our Q-CNN model, but this work is in progress.

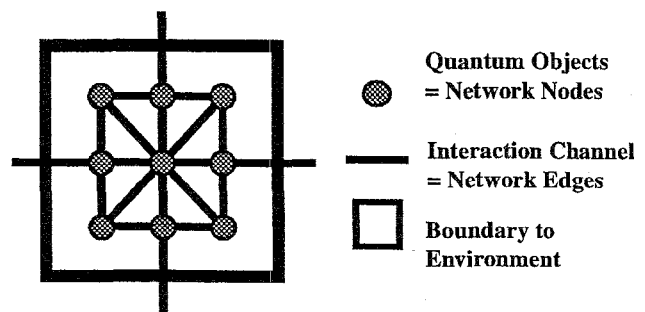


Figure 7: Quantum Network: the subsystems of the network are special quantum objects denoted as “network nodes” and the interaction channels are denoted as “network edges” [11].

## 4. Possible Quantum-Dot Cell Implementations

### 4.1 Gate-controlled quantum dots

The fabrication of a QCA cell by split-gate technology is a challenging problem, yet appears to be within reach of current lithographic capability. Figure 8 shows a possible physical realization which is based on electrostatic confinement provided by a top metallic electrode. The key implementation challenges are (i) to gain sufficient gate control in order to define quantum dots in the few-electron regime, and (ii) to place these dots sufficiently close to each other in order to make coupling possible. Using these techniques, it is conceivable that coupled-dot cells may be realized in a variety of materials systems, such as III-V compound semiconductors, Si/SiGe heterolayers, and Si/SiO<sub>2</sub> structures.

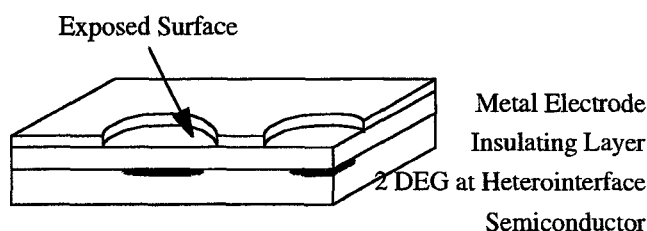


Figure 8: Schematic view of gate-confined quantum dots.

### 4.2 Rings of Metallic Tunnel Junctions

Single-electron tunneling phenomena may also be observed in metallic tunnel junctions, schematically shown in Fig. 9. The tunnel junctions are represented by the capacitor symbols, indicating that they are characterized by their capacitance and tunnel resistance. The metallic droplets themselves are the “wires” between the tunnel junctions. Consider now that two extra electrons are added to such a cell, as schematically shown in part (b). This cell exhibits precisely the same two distinct ground state configurations as the semiconductor cell discussed above. In addition, the cell-cell coupling, which is purely capacitive, also shows the same strongly non-linear saturating characteristic [XX]. The metallic tunnel-junction cell may be used as a building block for more complicated structures, in a fashion completely analogous to the semiconductor implementations.

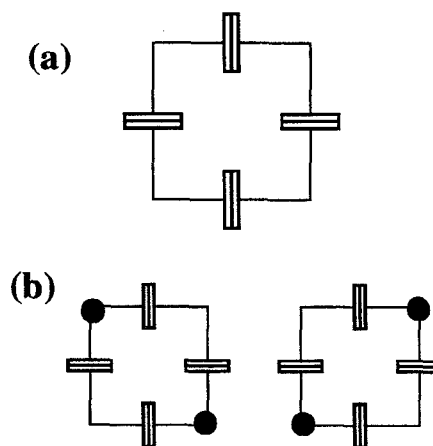


Figure 9: Schematic view of a ring of tunnel junctions representing a QCA cell.

### 4.3 Possible Molecular Implementation

QCA room temperature operation would require molecular-scale implementations of the basic cell. In previous work by Fehler and co-workers, a candidate for such a prototypical molecular cell has been synthesized and crystallographically characterized [XX]. As schematically illustrated in Fig. 10, these molecular substances with the formula  $M_2\{(CO)_9Co_3CCO_2\}_4$ , where  $M=Mo, Mn, Fe, Co, Cu$ , consist of square arrays of transition metal clusters, each containing three cobalt atoms. It is remarkable that the four clusters are arranged in a (flat) square, as opposed to a (three-dimensional) tetrahedron, which one might have expected. The reason for this behavior lies in the two metallic atoms at the center which form a “spindle” and the clusters attach themselves in the plane perpendicular to this axis.

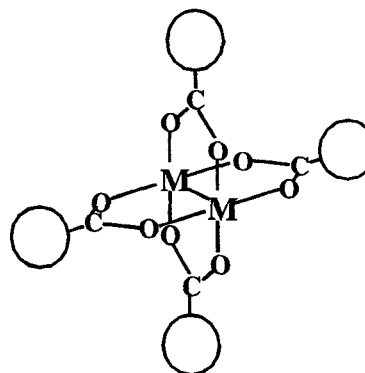


Figure 10: Schematic view of a candidate molecule for a QCA cell [13].

## 5. Conclusion

We have developed a novel nanoelectronic scheme for computing with coupled quantum dots, where information is encoded by the arrangement of single electrons. We have shown that such structures, the so-called Quantum-Dot Cellular Automata, may be used for binary information processing. In addition, an analog version is also possible, the so-called Quantum-Dot Cellular Nonlinear Networks, which exhibit wave phenomena. We have discussed possible realizations of these structures in a variety of semiconductor systems (including GaAs/AlGaAs, Si/SiGe, and Si/SiO<sub>2</sub>), rings of metallic tunnel junctions, and candidates for molecular implementations.

Note that our scheme is not a quantum computer in the sense of the “quantum computing” community, as reviewed by Spiller [14]. QCA’s do not require quantum mechanical phase coherence over the entire array; phase coherence is only required inside each cell, and the cell-cell interactions are classical. This limited requirement of quantum mechanical phase coherence makes QCA’s a more attractive candidate for actual implementations.

QCA operation has been recently demonstrated in experiments, using the system of metallic tunnel junctions.[15]. These are the first studies to demonstrate the control of a single electron by single electrons.

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