Quantum Dots and Quantum Dot Cellular Automata

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2.1 What are Quantum Dots?

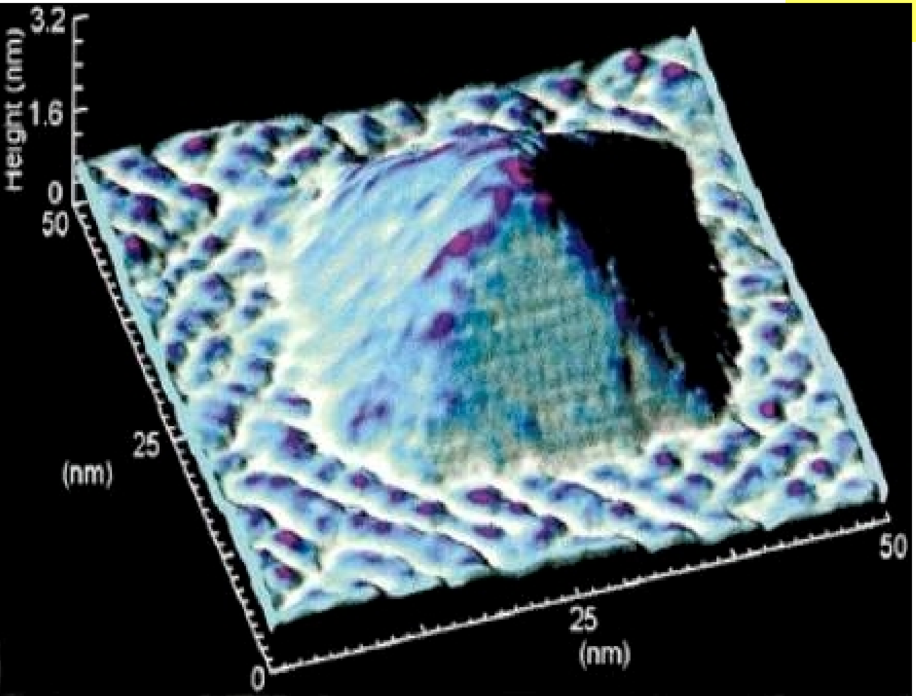
- In order to implement a system that encodes information in the form of electron position it becomes necessary to construct a vessel in which an electron can be trapped and "counted" as there or not there.
- A quantum dot does just this by establishing a region of low potential surrounded by a ring of high potential.
- See Figure 1.
- Such rings are able to trap electrons of sufficiently low energies/temperature and are sometimes called potential wells.
- There are several ways to implement quantum dots but apparently the most common, and the ones used in [1] are metal.
- Nanometer-scale dots are constructed from Aluminum using electron beam lithography techniques.

WHAT ARE QUANTUM DOTS?

- The logic unit in QCA is the QCA cell which was proposed by researchers at the University of Notre Dame.
- The QCA cell is composed of 4 or 5 quantum dots.
- Before we examine the potential functionality of these cells we need to know a few basic facts about quantum dots.
- A quantum dot is a nanometer sized structure that is capable of trapping electrons in three dimensions.
- Quantum dots are made by creating an island of conductive material surrounded by insulating material.
- Electrons that enter the quantum dot will be confined because of the high potential required to escape.

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

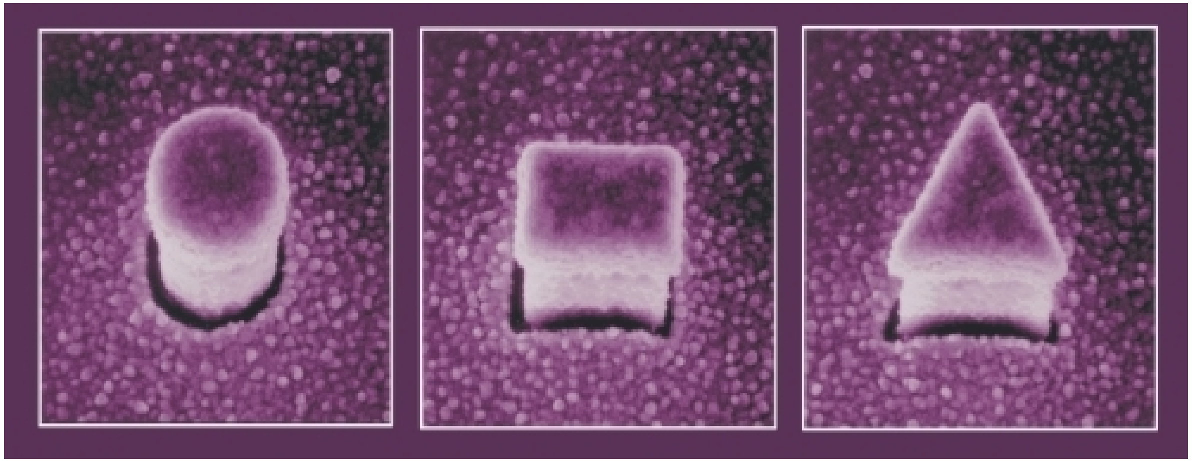


What are their Applications?

- Neuro-quantum structures
- Single-electron devices, for instance transistors
- Tunable lasers
- Photodetectors
- Sensors
- Quantum Computing: Quantum Cellular Automata

Mass production of Quantum Dots?

- Producing dots of small positional and size variability usually involves the use of electron beam lithography, which is similar to conventional lithography except that patterns are traced out using an electron beam rather then using a mask and light.
- Conventional lithography is not capable of creating devices at that scale since the wavelength of light used is greater then the required feature size.
- The image below shows three different quantum dot structures:



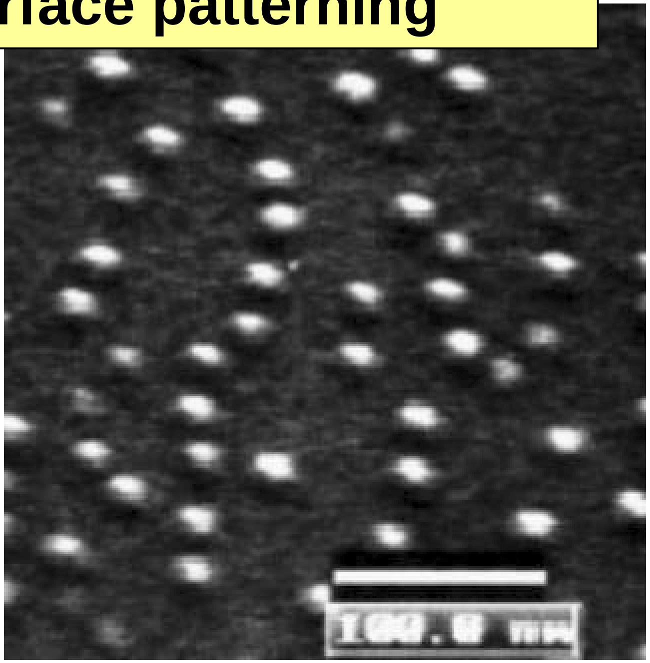
- As we can see the shape of a quantum dot is not necessarily round and varies depending on the process and application.

mass production?

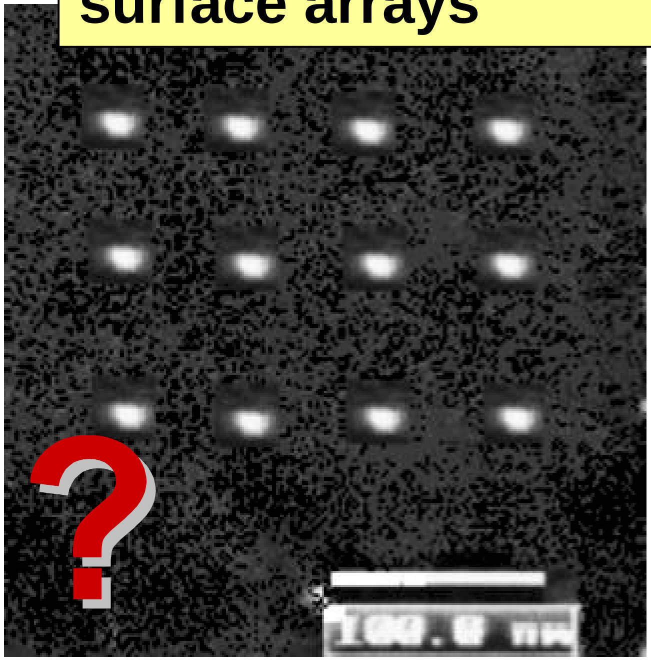
- The consistent and mass production of these devices at such scales is one of the main challenges.
- There are techniques available to produce quantum dots at extremely small scales, one of these is the self organization process.
- Self organization occurs when molecules of one crystal structure are deposited on top of another.
- The difference in lattice structure results in high stresses at the point of contact.
- As a result the deposited material tends to clump up in a manner that is analogous to depositing oil on water.
- Self organization processes can produce dots of incredibly small sizes.
- There is an important problem with trying to design with self organizing structures and that is the high variation in the final location of the resulting dots.
- Currently there is no self organizing process capable of creating quantum dots at precisely controlled locations.

Patterning of Quantum Dots

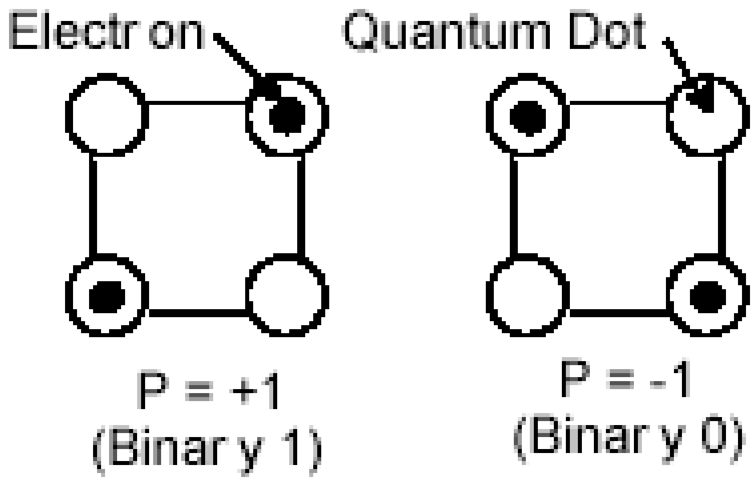
CURRENT: random surface patterning



FUTURE: patterned surface arrays



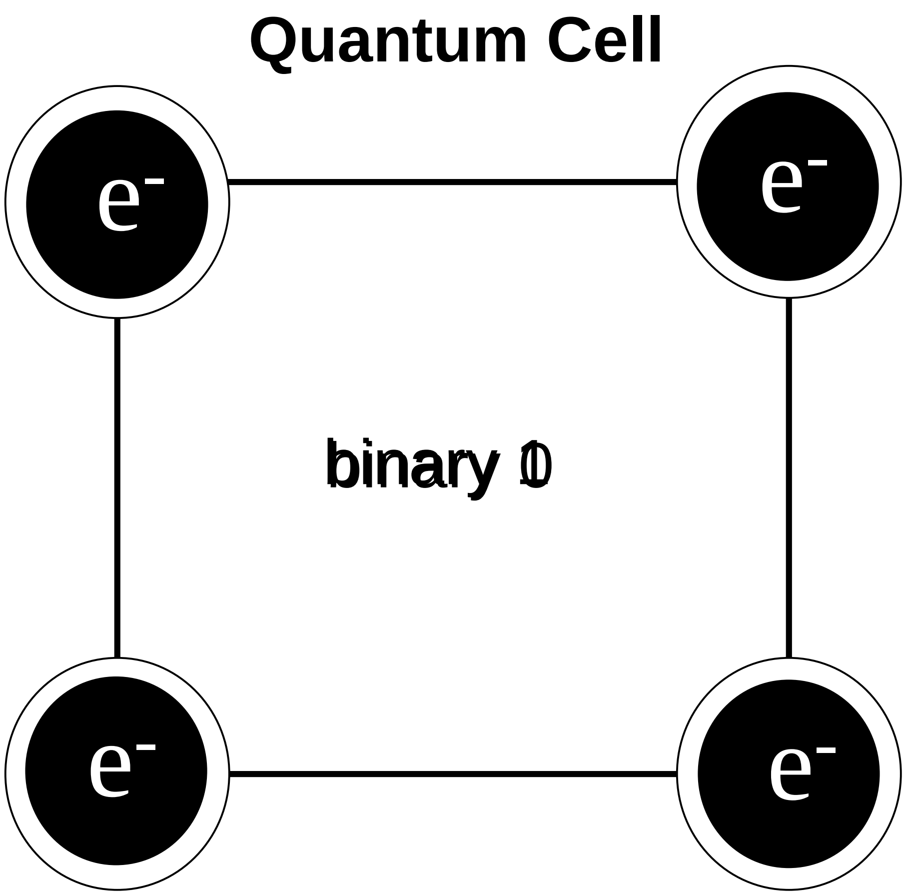
QCA – The Four Dot Device



- Uses electrons in cells to store and transmit data
  - Electrons move between different positions via electron tunneling
- Logic functions performed by Coulombic interactions

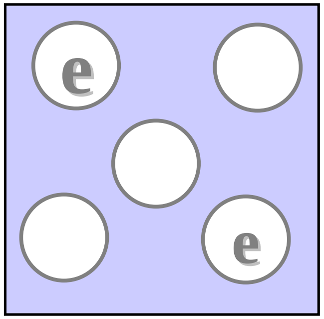
Quantum Dots operate as Cellular Automata

- 2 extra electrons are introduced to the quantum cell
- Electrons have the ability to tunnel from one quantum dot to the next
- Repelling force of electrons moves the charge to opposite corners of the quantum cell, resulting in two possible arrangements, representing binary 0 and 1

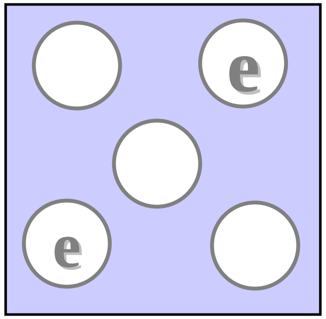


Quantum Dot Wireless Logic: five dot model of Lent and Porod

- Lent and Porod of Notre Dame proposed a wireless two-state quantum dot device called a "cell"
  - Each cell consists of 5 quantum dots and two electrons



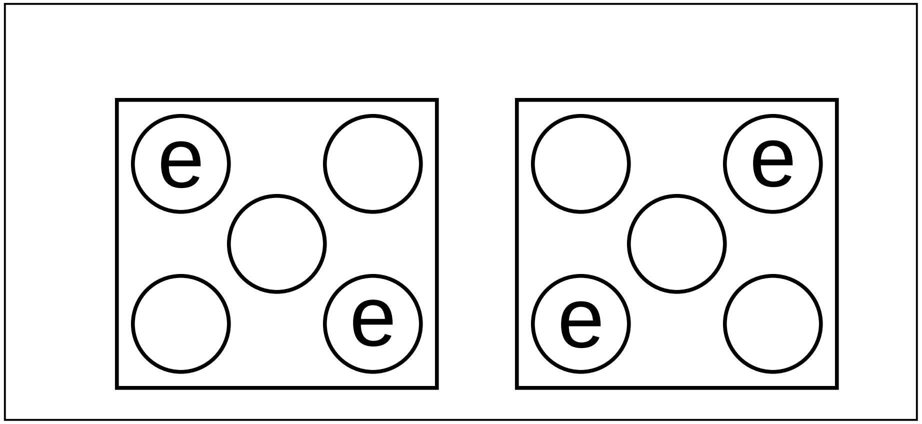
State "1"



State "0"

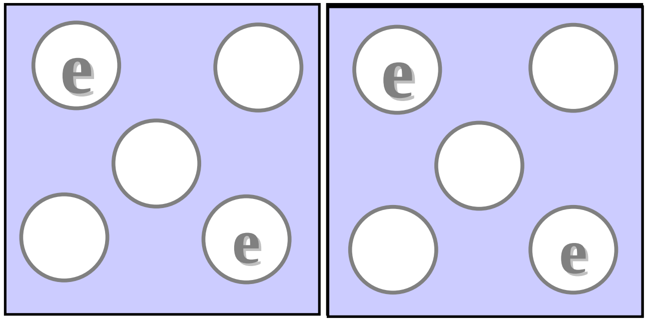
Quantum Dots: Five dot Model

- Very similar to four-dot model
- The two electrons repel each other, causing them to move to opposite corners of the device
- This yields two states of equal energy in the cell



Quantum Dot Wire

- By placing two "cells" adjacent to each other and *forcing the first cell into a certain state,* the second cell will assume the same state in order to lower its energy



The net effect is that a "1" has moved on to the next cell

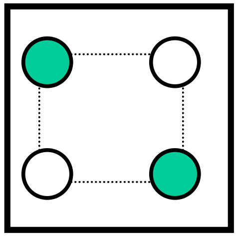
By stringing cells together in this way, a "pseudo-wire" can be made to transport a signal

In contrast to a real wire, however, no current flows

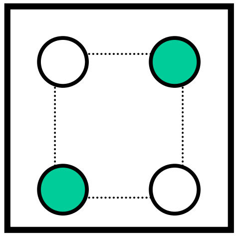
Quantum Cellular Automata: A four-dot model

- Basic cell: four quantum dots connected by tunnel junctions
  - Can control voltage of tunnel junctions to freeze state of device
    - Allows clocking
- Add two excess electrons to cell to contain state
  - Repulsion between electrons will push them to opposite corners
  - One configuration indicates 0, the other 1
- Capacitatively-coupled gates allow electrons to be forced into one configuration or the other
- Capacitatively-coupled electrometers allow position of electrons, and thus bit state, to be read

0

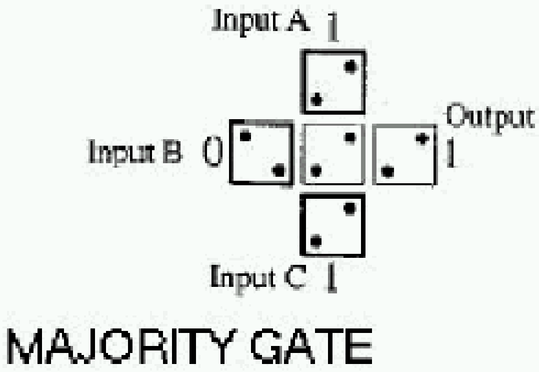


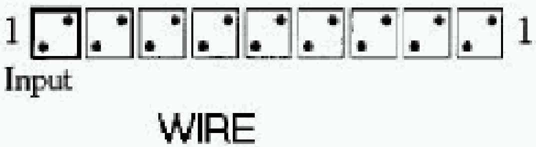
1

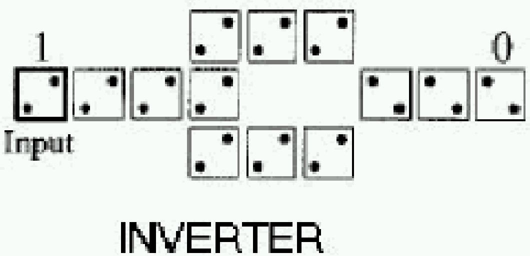


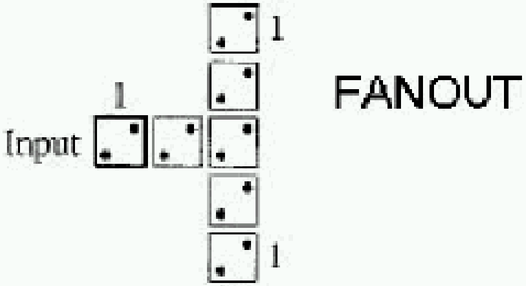
Example of a complete geometrical-logical system for QD

- **Majority Gate can function as 2 input AND/OR**

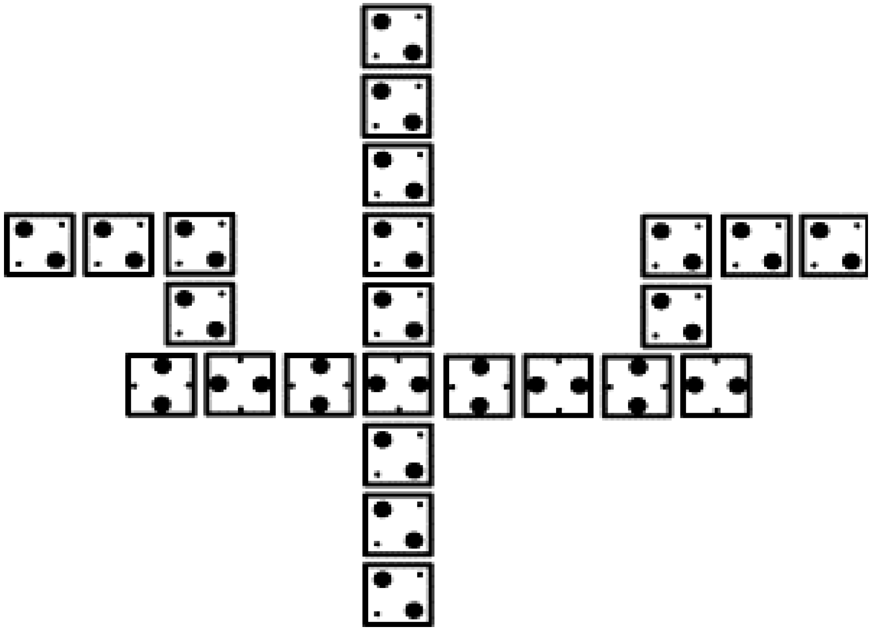








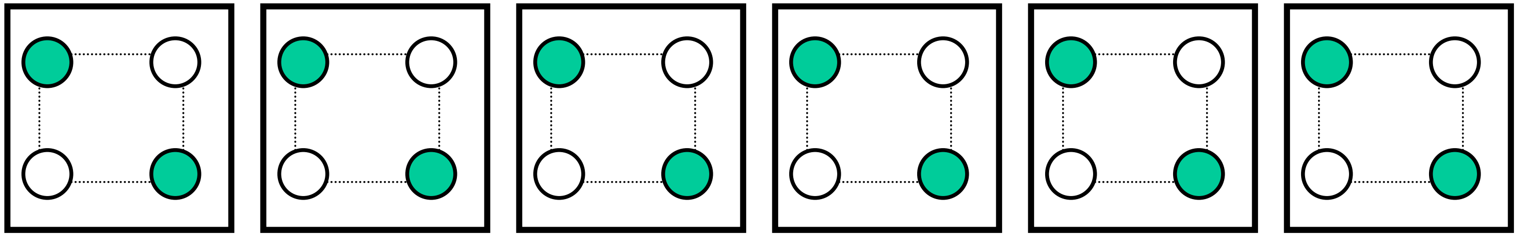
- Remember about the difficulty of equal time delays.
- Special CAD needed.



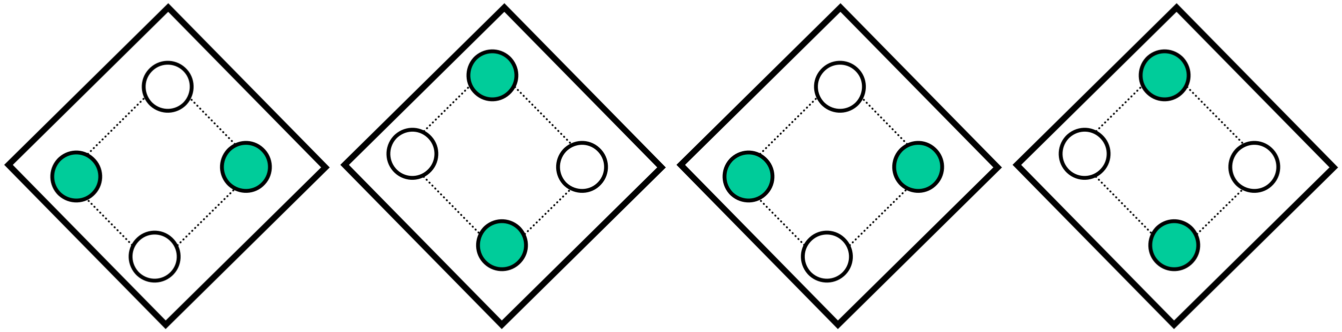
- This is a feature that is not available in conventional microelectronics.
- Actually the fact that there is no co-planer crossing in microelectronics is causing significant problems.
- Many layers of metal have to be created in order to connect the high density of devices on today's chips.
- These layers of metal interconnect cause large parasitic capacitances that slow the chip down.

Other QCA Structures-- Wires

- 90-degree wire



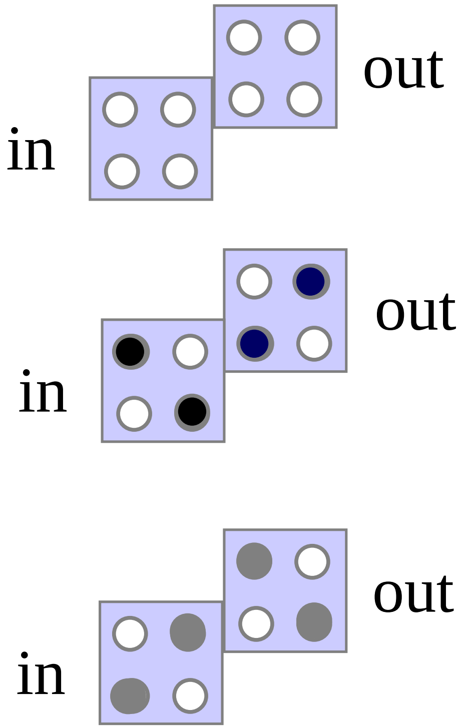
- 45-degree wire
  - Normal and inverted signal available on the same wire



Observe that in this logic an inverter costs nothing!

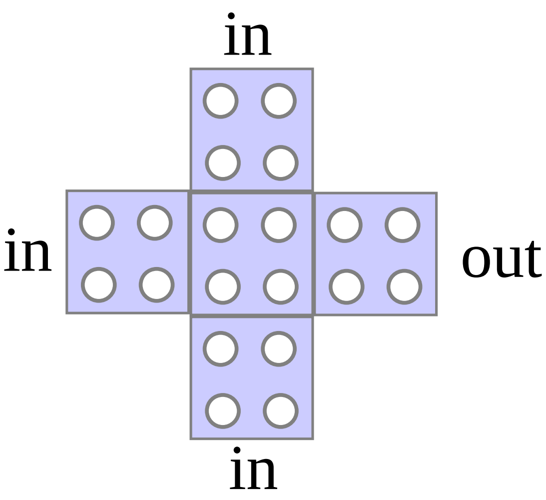
Quantum Dot Inverter

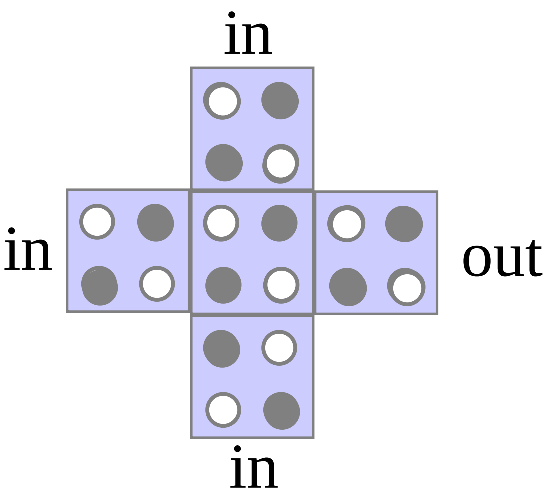
- Two cells that are off center will invert a signal



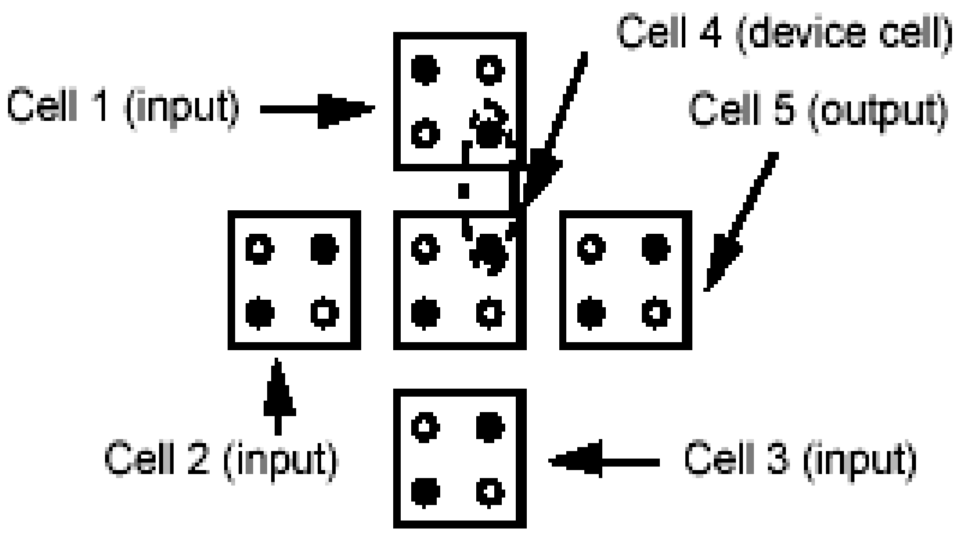
Quantum Dot Majority Gate

- Logic gates can be constructed with quantum dot cells
  - The basic logic gate for a quantum dot cell is the majority gate



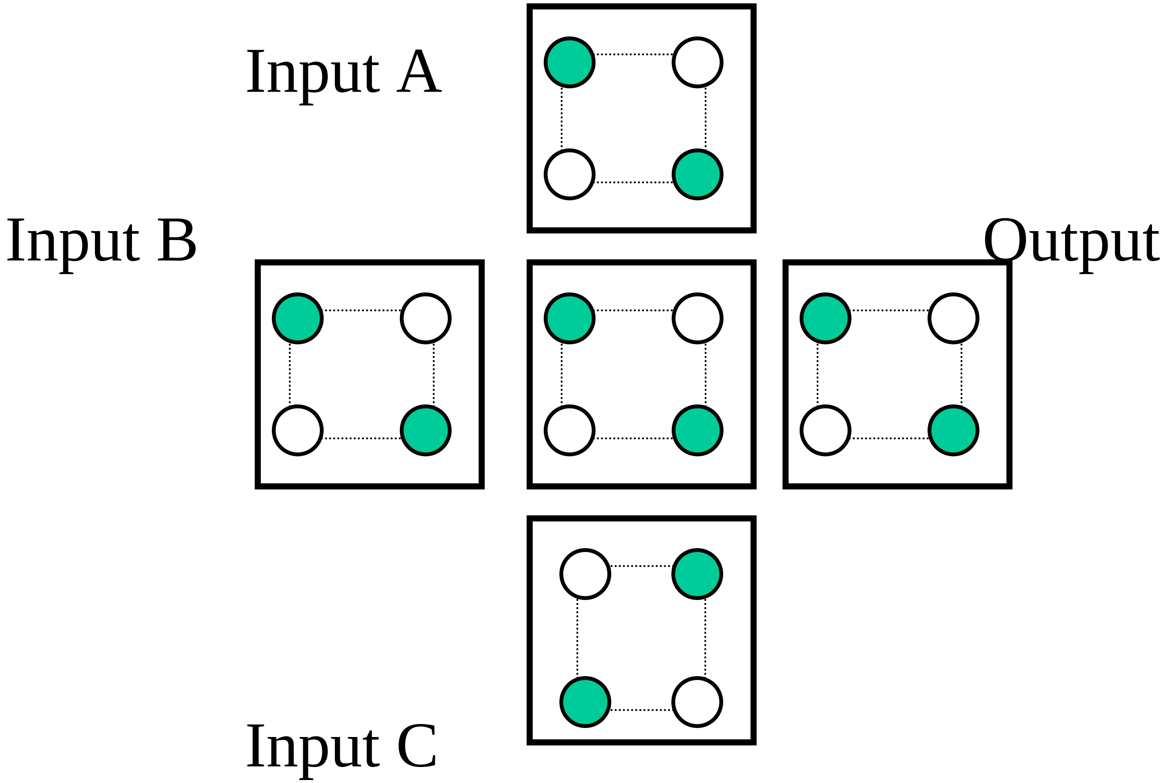


QCA – The Circuit



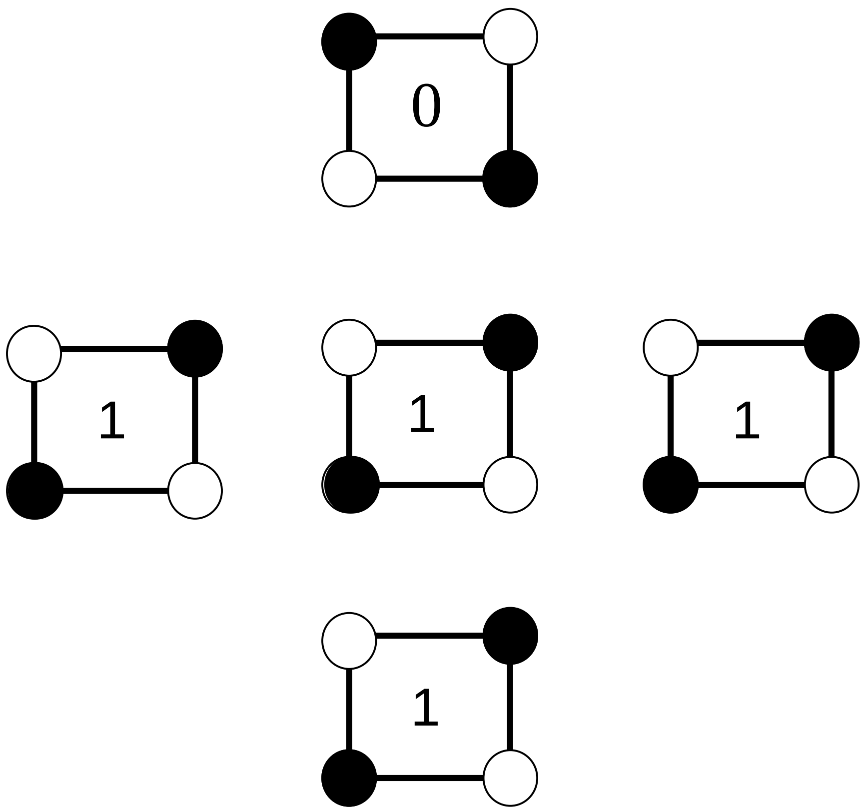
- Fundamental circuit is shown above
  - This is a 90-degree wire
  - 45-degree wires can also be constructed
    - Binary value alternates between polarization +1 and –1 as it travels down the wire
    - Ripper cells can be placed to get the actual binary value or complemented value from the wire

Basic QCA Gate – Majority



- Can be used to implement AND, OR by setting one input to 0, 1

Special cases of Majority

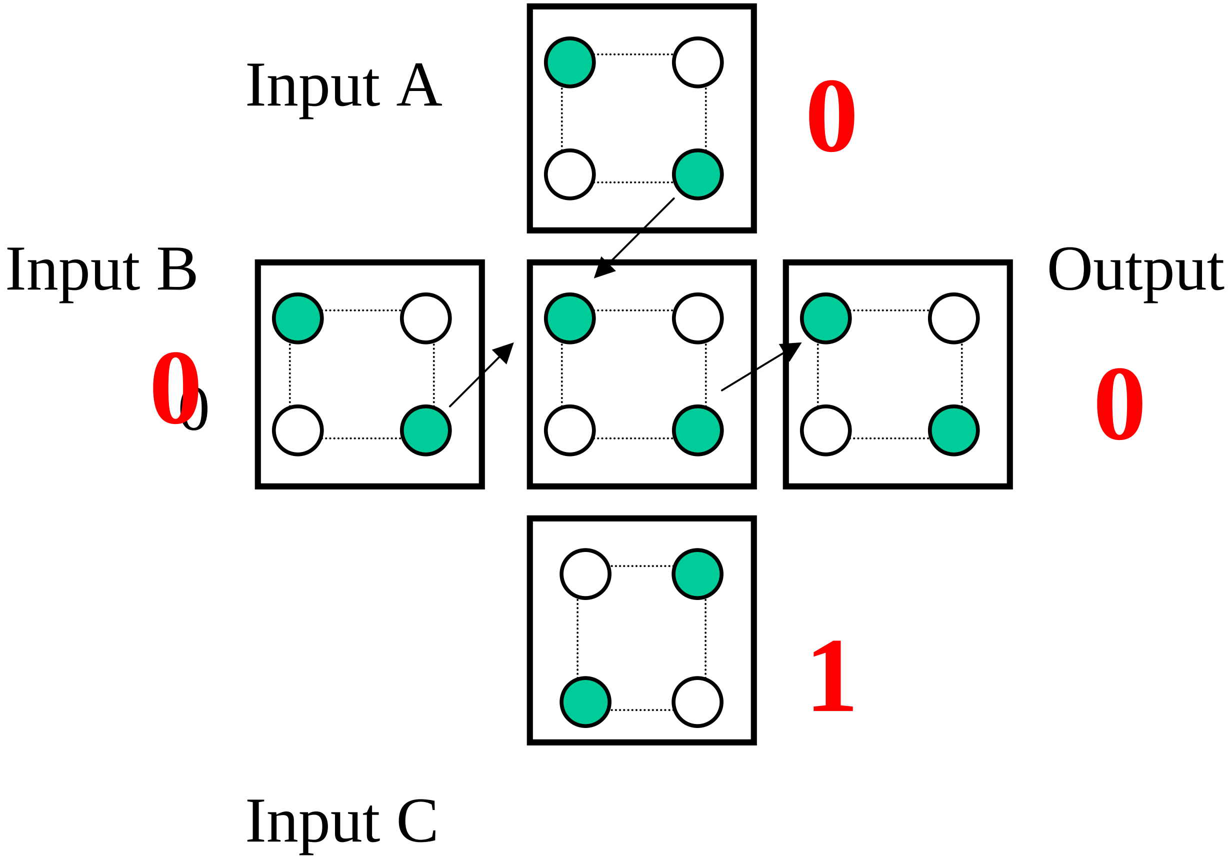


AND Gate (Program Line = 0)

A	B	OUT
1	1	1
1	0	0
0	1	0
0	0	0

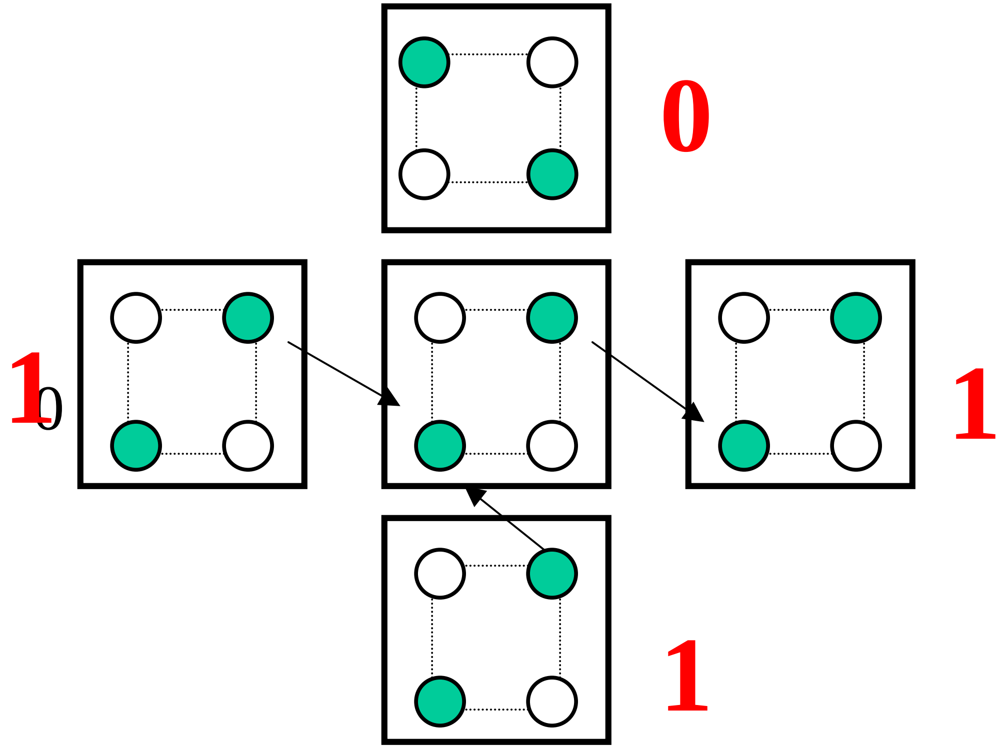
*by simply changing the program line to 1, the device is transformed to an OR gate

Majority 0,0,1→0

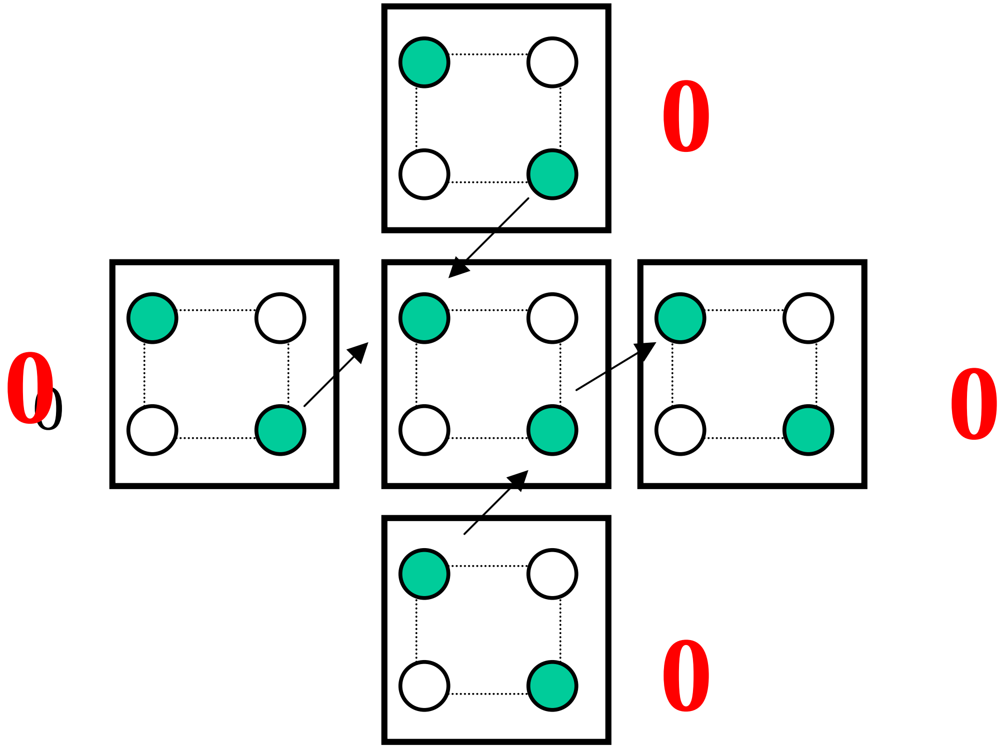


Stronger wins!

Majority 0,1,1→1

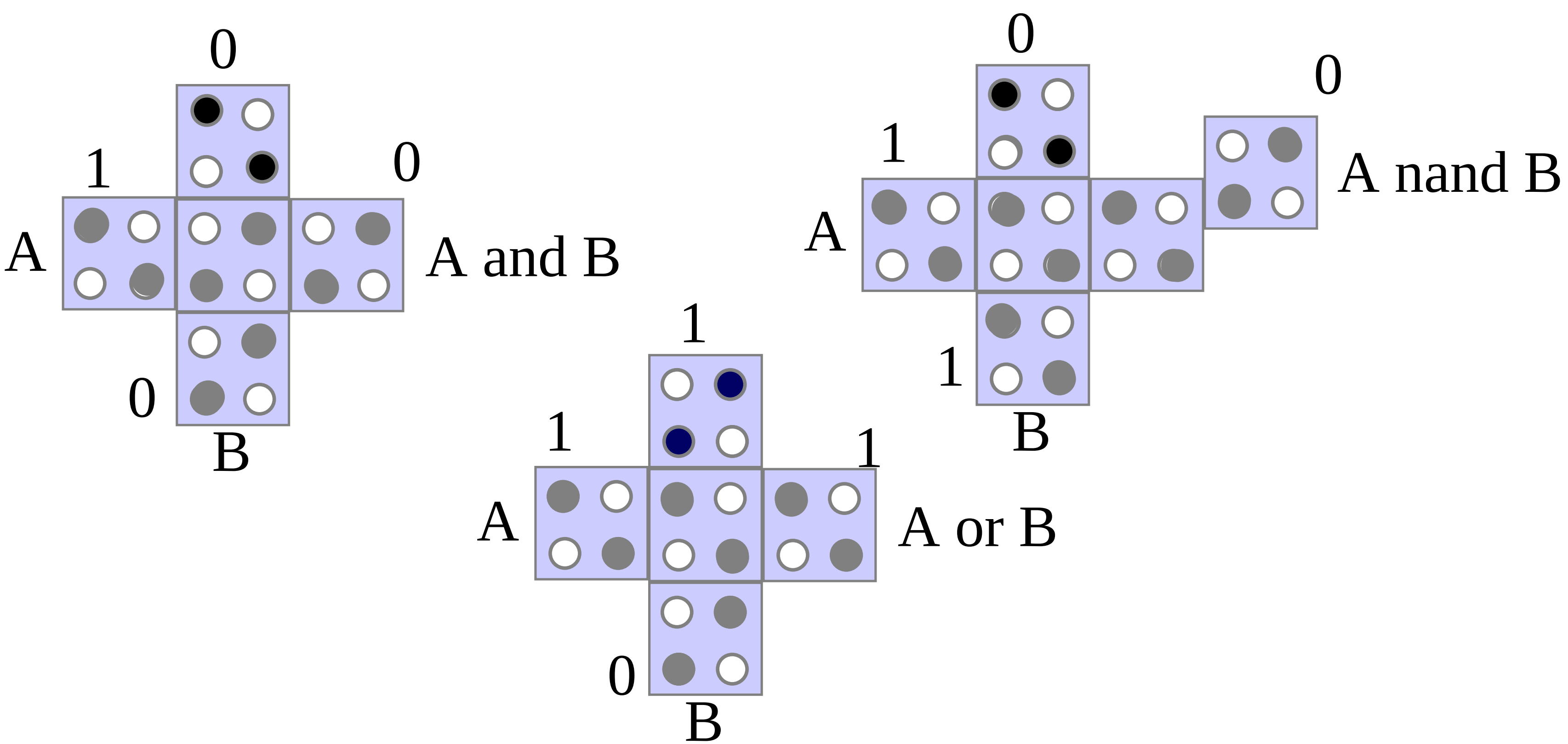


Majority 0,0,0→0



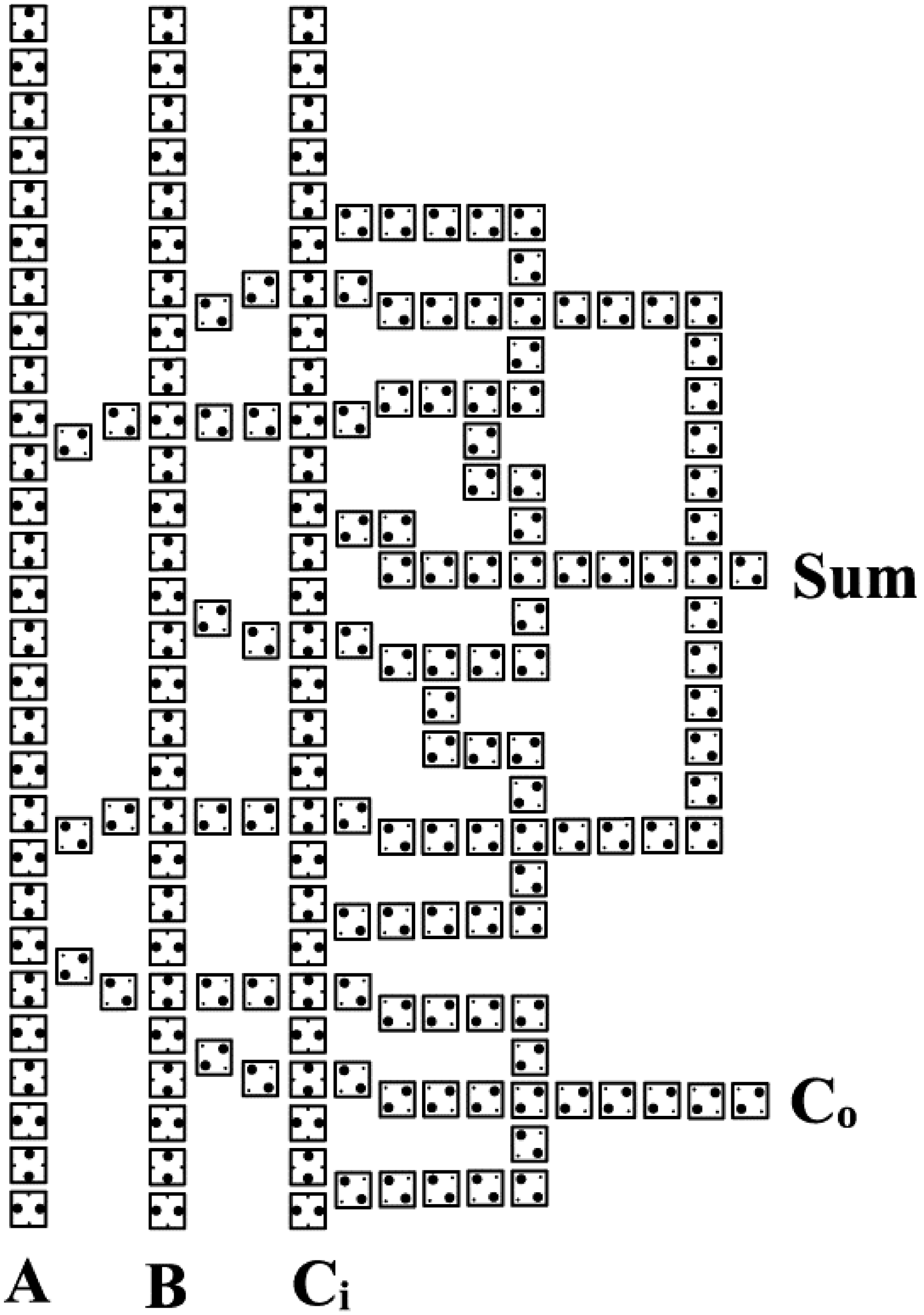
Quantum Dot Logic Gates that use NOT

- AND, OR, NAND, etc can be formed from the NOT and the MAJ gates



QCADesigner

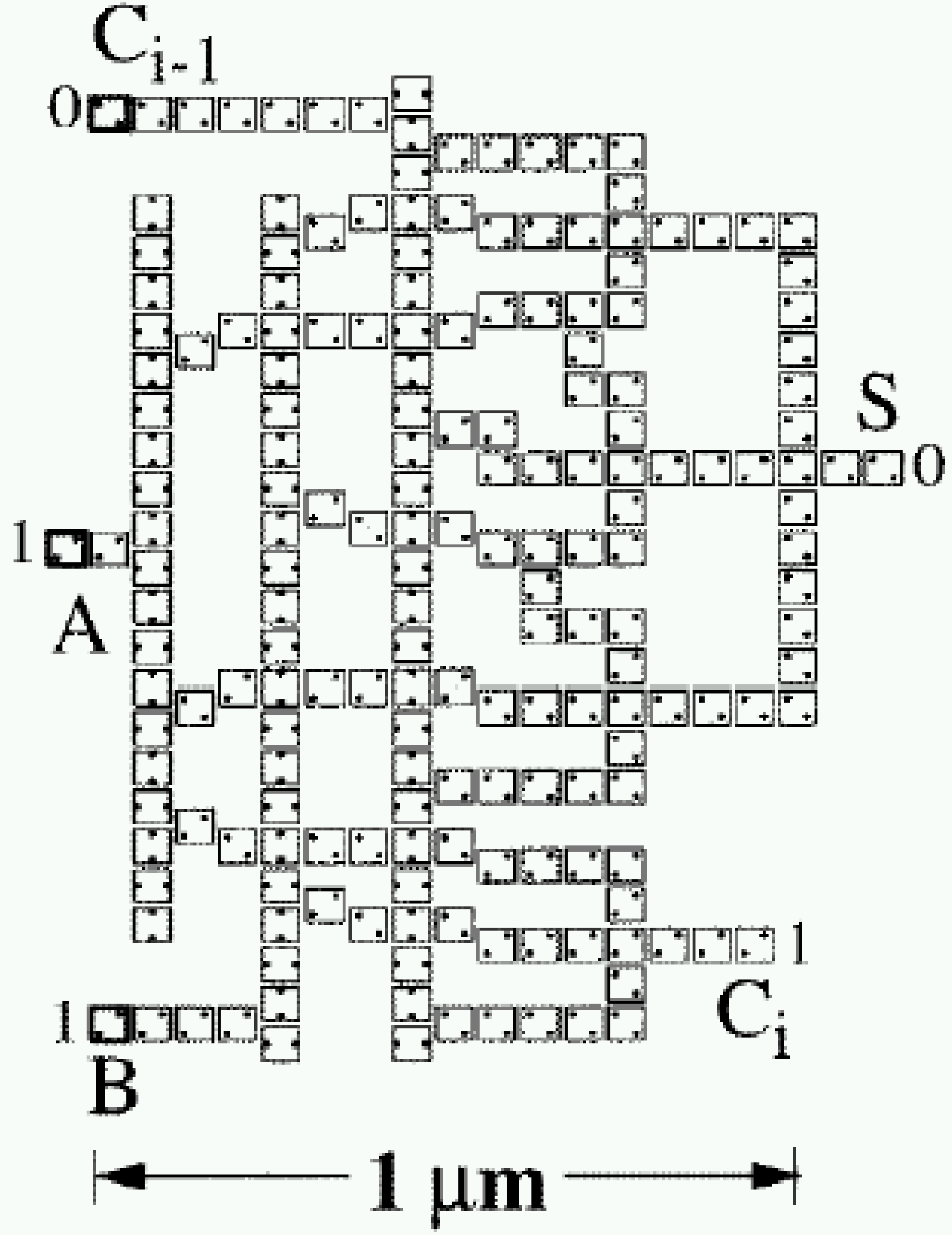
- Using QCADesigner we will easily create and simulate such designs.
  If you have any questions please contact:
  Konrad Walus
  walus@atips.ca



QCA Circuits

- 1 -Bit Full Adder (Lent, et al, 1994) Bit Full Adder (Lent, et al, 1994)
- For a dot size of 10 nm, area For a dot size of 10 nm, area required is less than 1.5 µm2 and replaces about 30 transistors
- Very Low Power
- No power is directly supplied to the interior of the array the interior of the array
- Theoretical Switching Frequency in THz range!!!

- **Possible Research Projects:**
  - adaptation of DDs
  - adaptation of Lattices
  - adaptation of PLAs
  - adaptation of FPGA structures
  - adaptation of Net Structures
  - reversibility
  - Reversible CA
  - •Universal CA, life, reproduction, Billiard Ball model
  - pipelined, systolic, etc.
  - Three - dimensional?



A QCA 1-Bit Full Adder