ECE 497NC:
Unconventional Computer Architecture

Lecture 16:
Computing With Nanotech –
Quantum Cellular Automata

Outline/Objectives

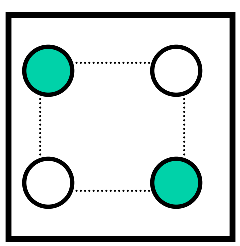
- Introduction to Quantum-Dot Cellular Automata
- Computing System that Uses QCA

Quantum Dots

- Regions of low potential surrounded by ring of high potential
  - Particles (such as electrons) tend to stay within the dot because they can't cross the potential barrier
  - Can create "tunnel junctions" that allow electrons to pass between dots.
- Many ways to implement
  - Metal
  - "molecular implementations" (vague term from paper)
- Paper used metal-based system
  - "islands" of Aluminum used as the dots
  - $Al/AlO_x/Al$ structures used as tunnel junctions

Quantum Cellular Automata

- 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



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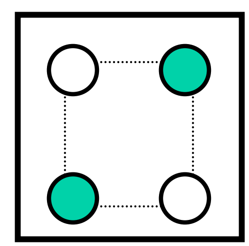

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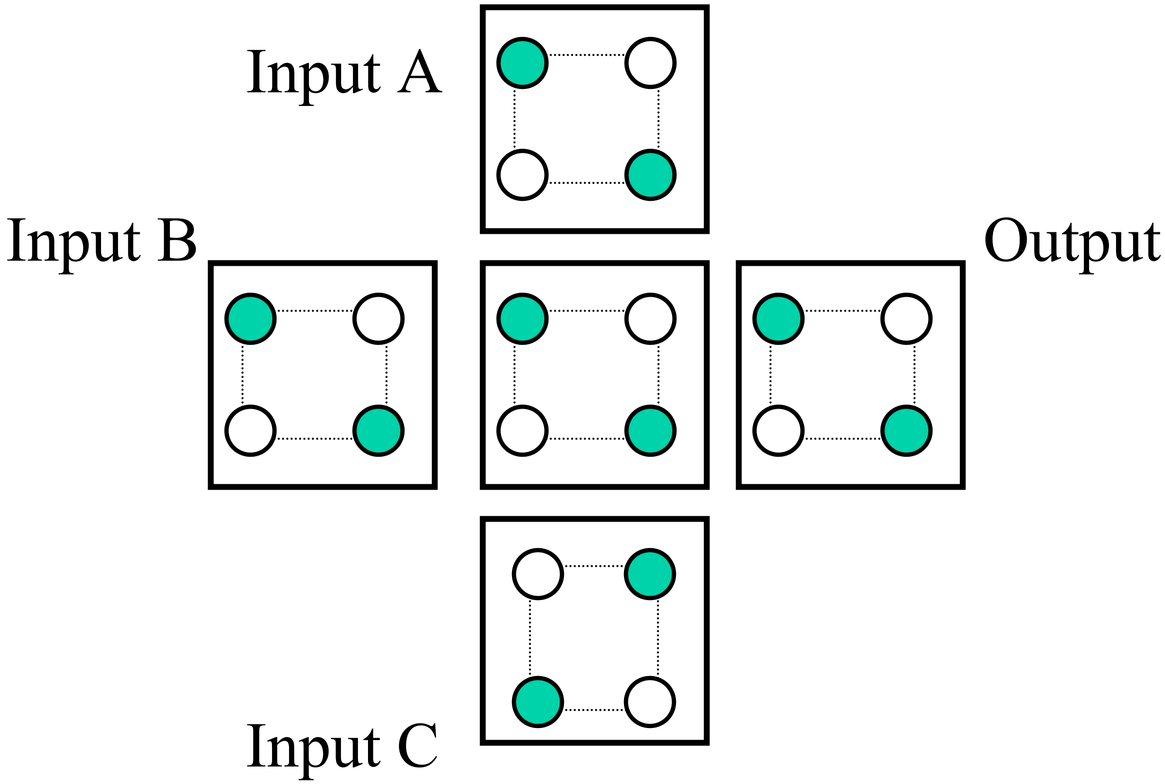
Basic QCA Gate – Majority



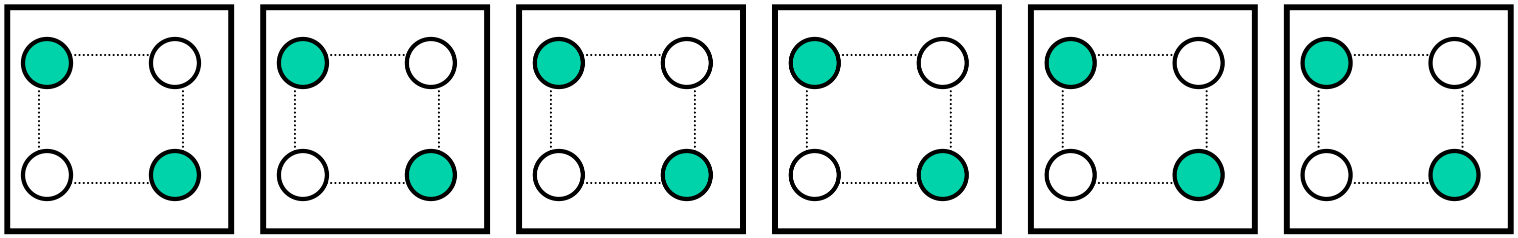
- Can be used to implement AND, OR by setting one input to 0, 1

Experimental Results

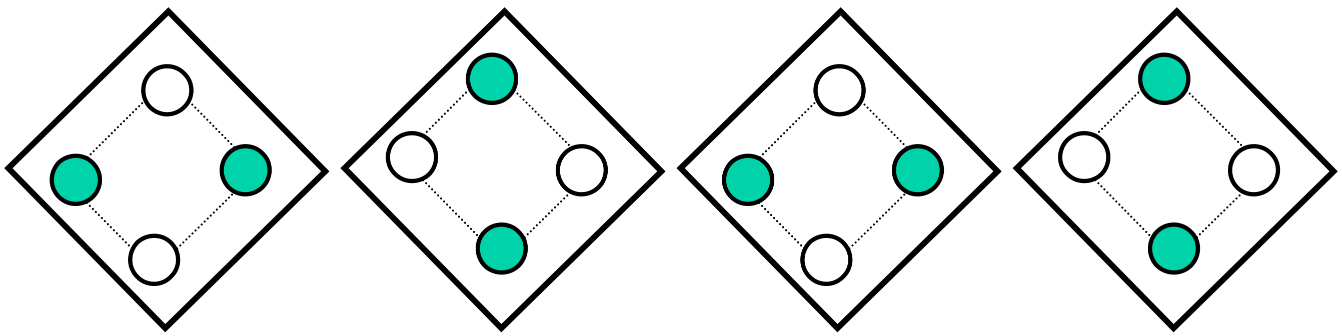
- QCA cells and gate implemented using Al quantum dots
  - 70 mK temperature
- System displays correct digital switching behavior when inputs set by external stimulus
  - Switching times in seconds
- Authors predict that molecular implementation of quantum dots would allow operation at room temperature

Other QCA Structures-- Wires

- 90-degree wire



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



From Gates to Systems

- Know how to build:
  - Non-inverting logic gates
  - Inverting and non-inverting wires
- Need:
  - Large-scale clocking scheme to break delays and allow pipelining
- Key differences between QCA and VLSI
  - Wire delay much more explicitly visible/computable
    - Simple function of number of cells a signal travels through
    - Seems like wire/gate delay ratio would be easy to compute, though authors don't discuss this explicitly
  - Signal propagation is probabilistic, not definite
    - The further a signal travels from a fixed input node, the lower the chance the signal will propagate correctly
      - Fabrication processes will probably specify a maximum signal travel distance in a single clock cycle

Clocking Strategy

- Four-phase system:
  - Switch phase (evaluate output based on input)
    - Tunneling barriers low
  - Hold phase (output stable)
    - Tunneling barriers high
    - Next stage evaluates based on this stage's output
  - Release phase (return system to unpolarized state)
    - Tunneling barriers low
  - Relax phase (cell stays in unpolarized state)
    - Tunneling barriers low
- Built-in latching in pipeline stages
- Can have multiple cells in a single stage
  - In fact, assume this because of the difficulty involved in wiring clock signals to individual QCA cells.

System Examples

- Bit-slice datapath for a 12-bit CPU
- Various FSM designs
  - Problem: getting all state bits to change in the same clock phase
  - Trade-off between functionality and keeping wires short
- Layout for more complete CPU

Implementation Issues

- Metallic QCA cells not ready for prime time
  - Demonstrated: 70mK operating temperature
  - Need: Room-temperature operation
    - Completely new implementation technology required for room-temperature operation
  - Demonstrated: multiple-second switching time
  - Conjectured: terahertz+ switching times

- Molecular implementations show much more promise
  - Nanometer-scale molecules simulated that display QCA behavior
  - Current experimental issues are finding ways to attach these molecules to substrates and apply clocking fields.