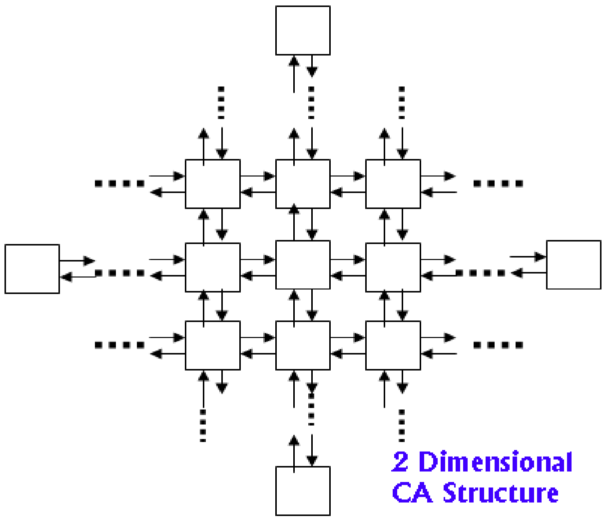
Quantum cellular Automata

- **QCA** is devised in analogy to conventional cellular automata (CA) introduced by von Neumann in 50's

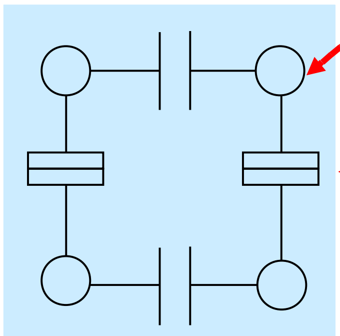
  - Dynamical System with Discrete space and Time
  - Simple, Regular and Modular Structure
  - Local Neighborhood

- Physical implementation of "classical" CA by exploiting quantum mechanical phenomena



Quantum cellular Automata

QCA cell

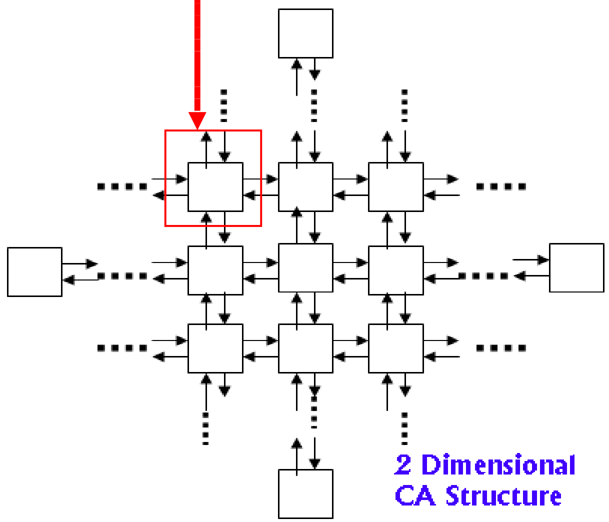


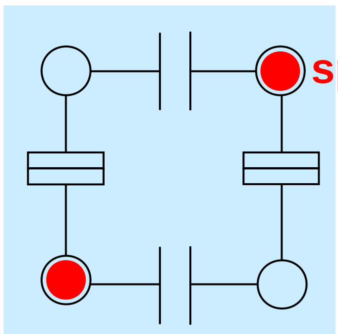
dot

aluminium oxide AlO$_2$
tunnel junction

Four aluminium island on **SiO$_2$** called dots

Cell





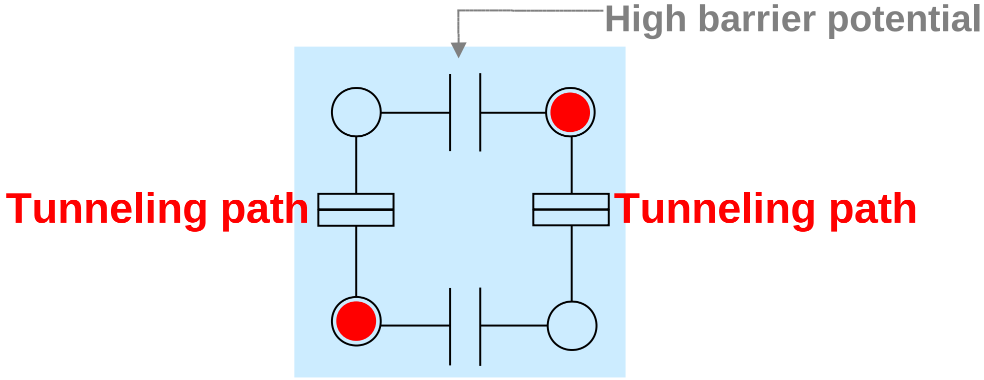
spare electron

A QCA cell

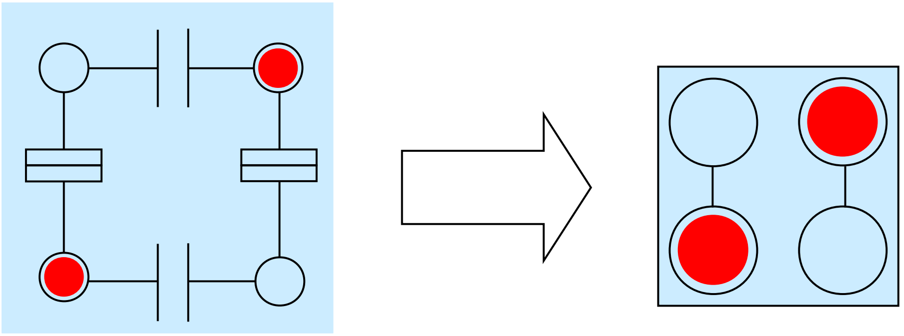
Information Representation

QCA cell

Electrons can tunnel through the path



Polarization decides logic level



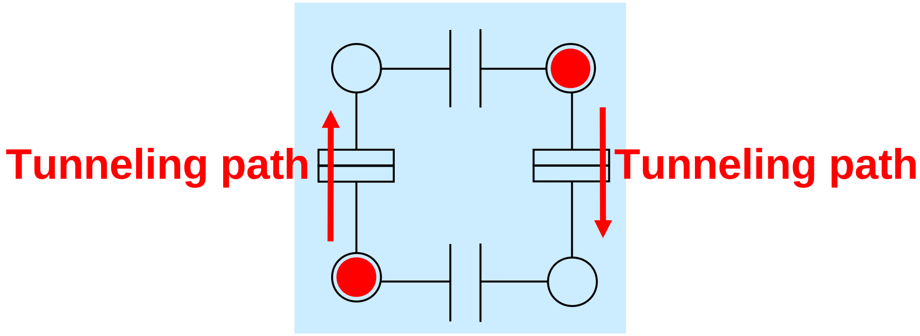
Logic ‘1’

Polarization = +1

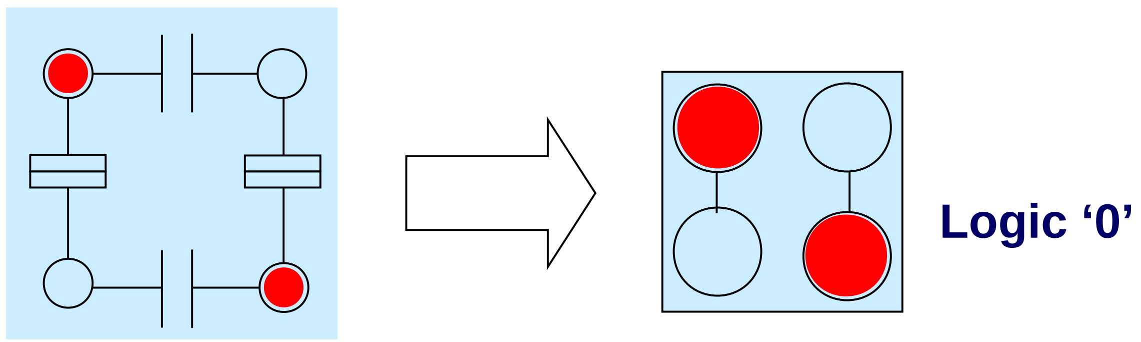
Information Representation

QCA cell

Electrons can tunnel through the path

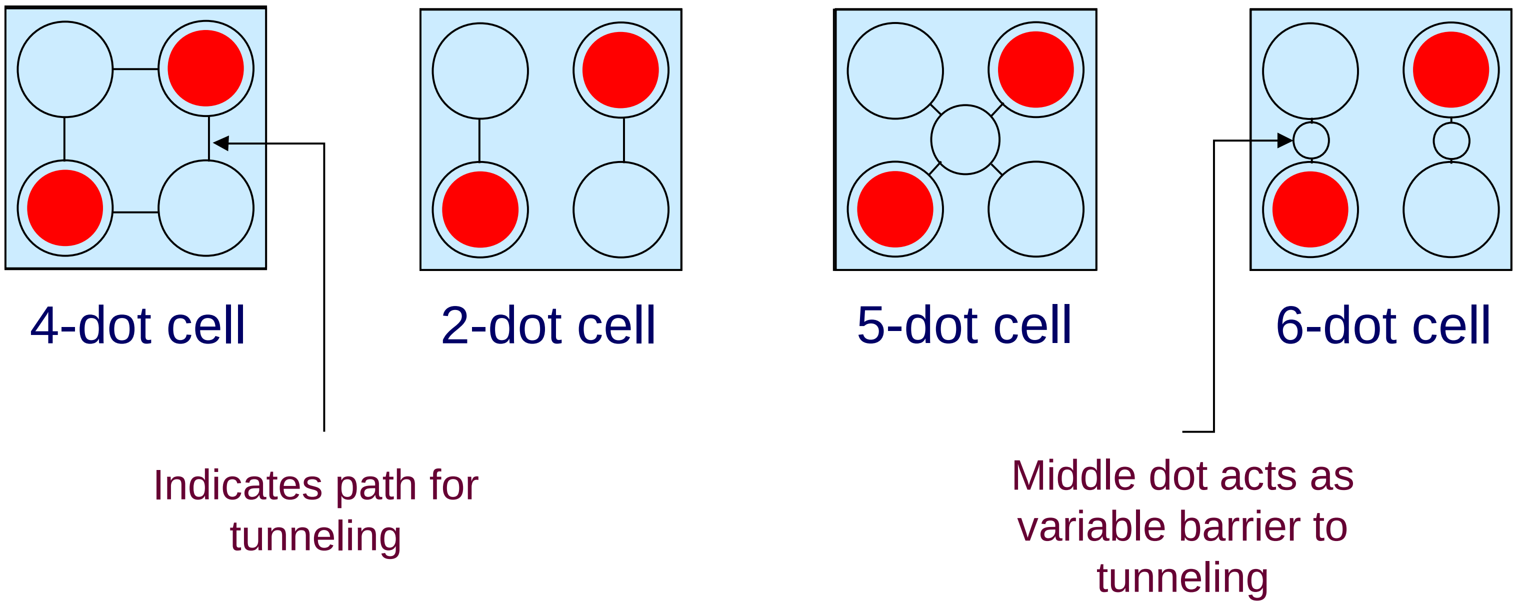


Polarization decides logic level

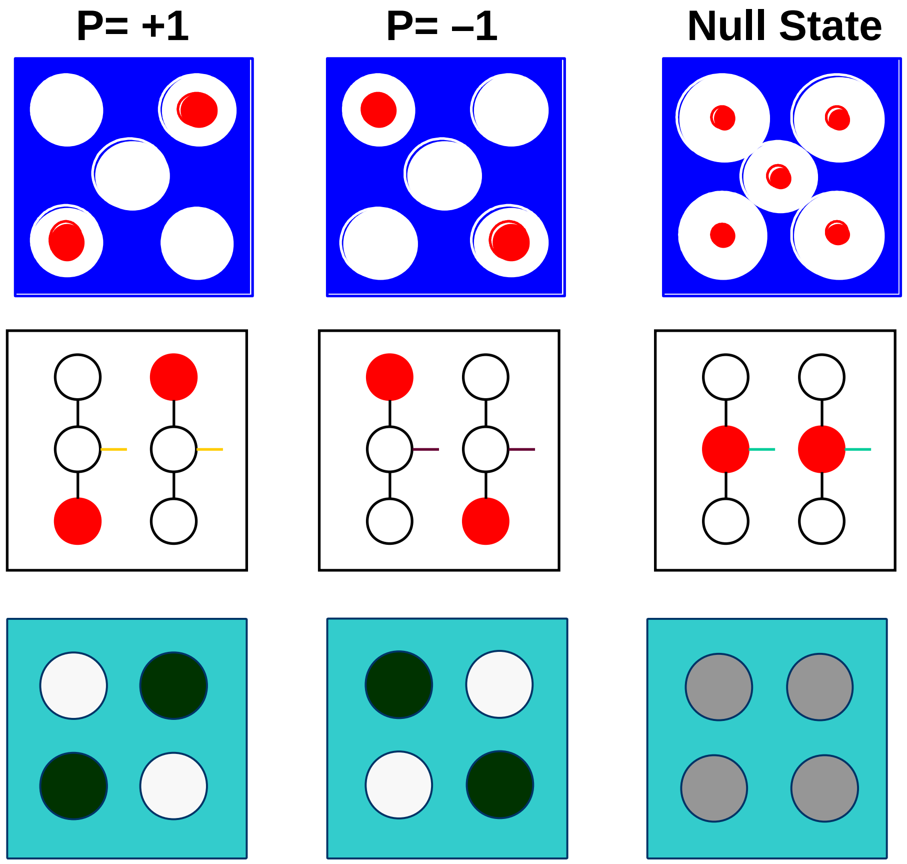


Polarization = +0

Variations of QCA Cell

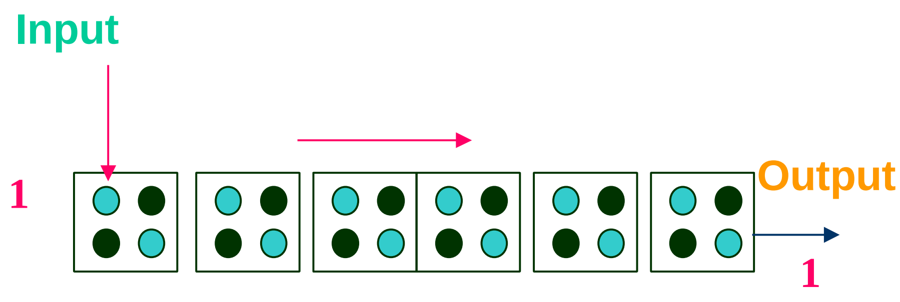


Variations of QCA Cell



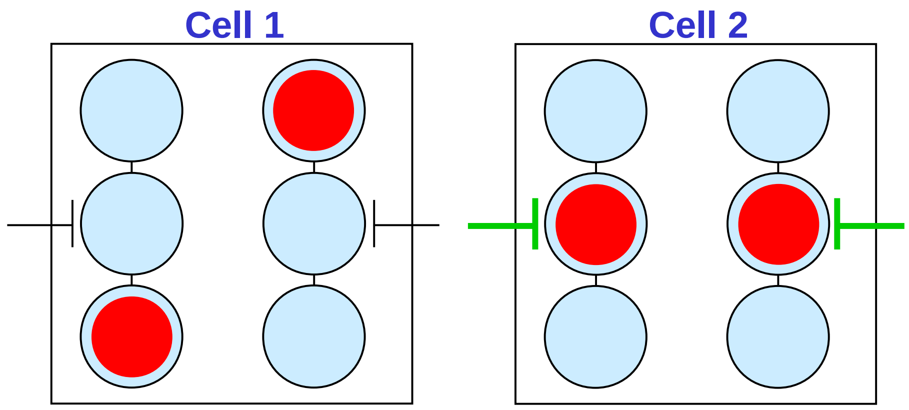
Clocked QCA circuits better utilizes tri-state 6 dot cells

Signal Propagation



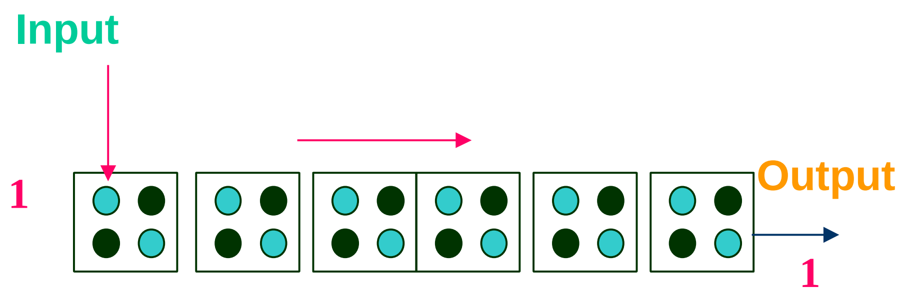
- Information flow on Coulombic interaction

Neighboring cells tend to align in the same state



"1" "null"

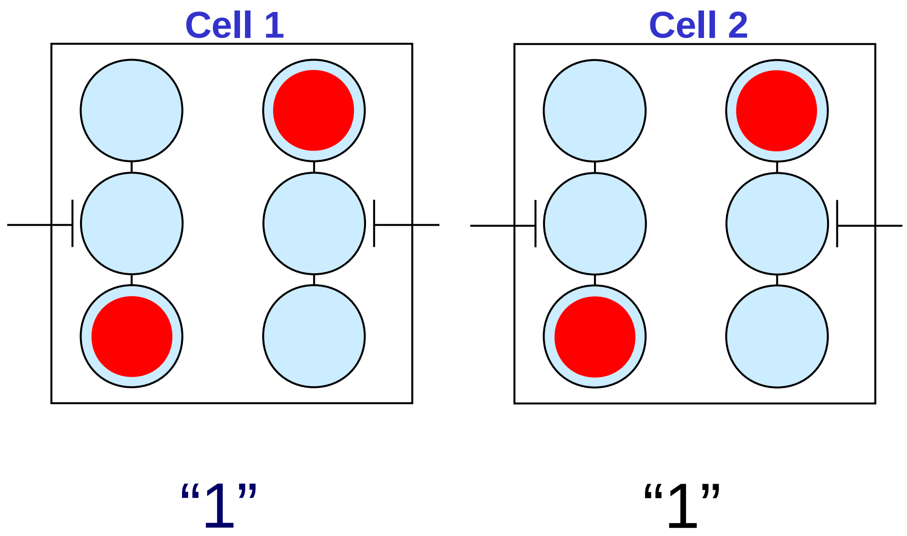
Signal Propagation



- Information flow on Columbic interaction

Neighboring cells tend to align in the same state

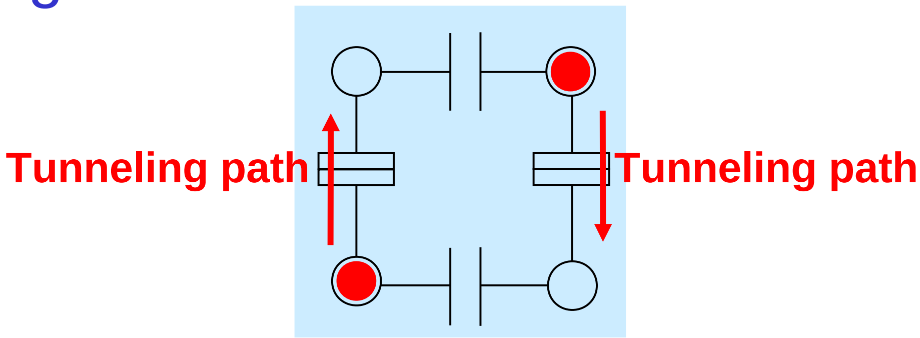
Ground state computing



Signal Propagation

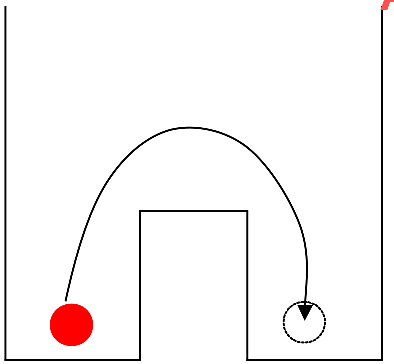
- Ground state computing

  - Tunneling path barrier controlling

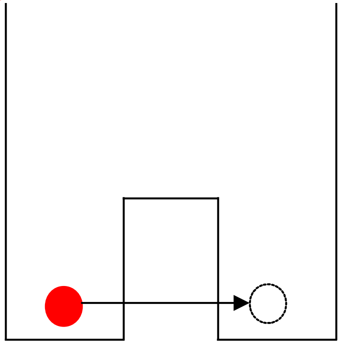


- Electron Traversing energy barrier dissipates no energy

Adiabatic switching

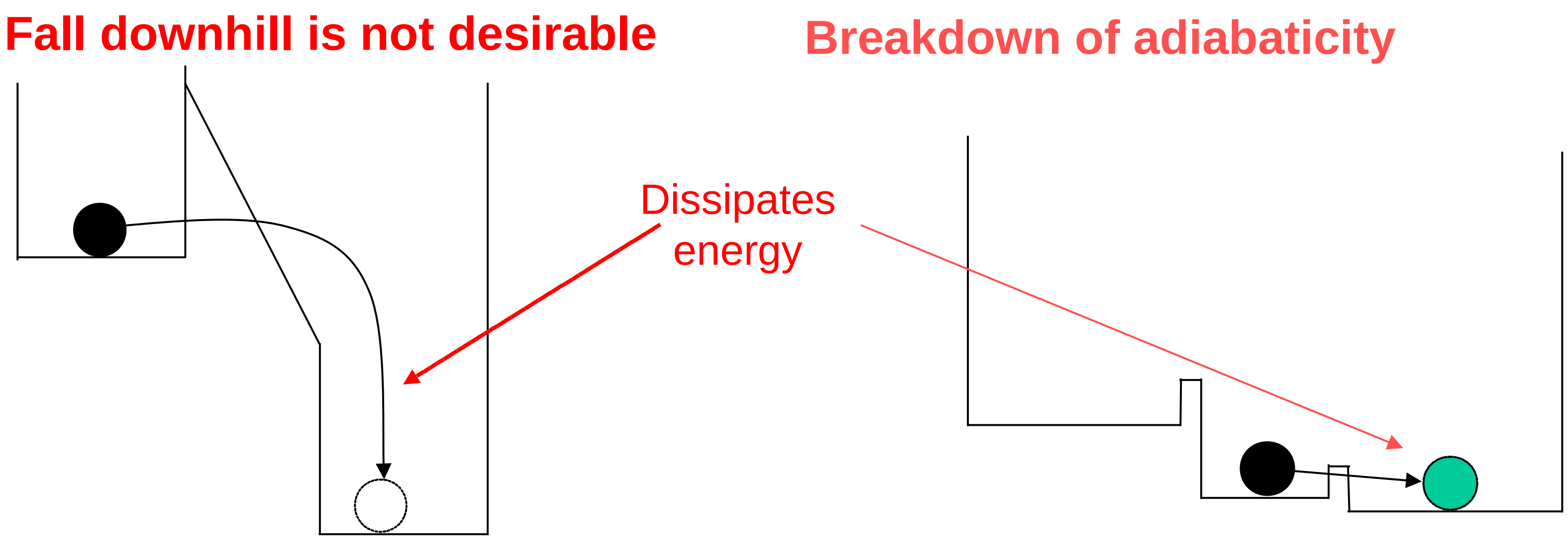


Thermal hop over barrier dissipates no energy



Tunneling through barrier dissipates no energy

Signal Propagation



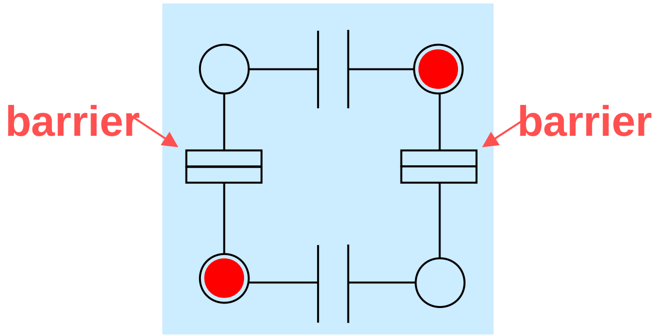
Energy dissipation is determined by energy difference between initial and final state – not the barrier height

Adiabatic switching in QCA keeps system always very close to ground state

Signal Propagation

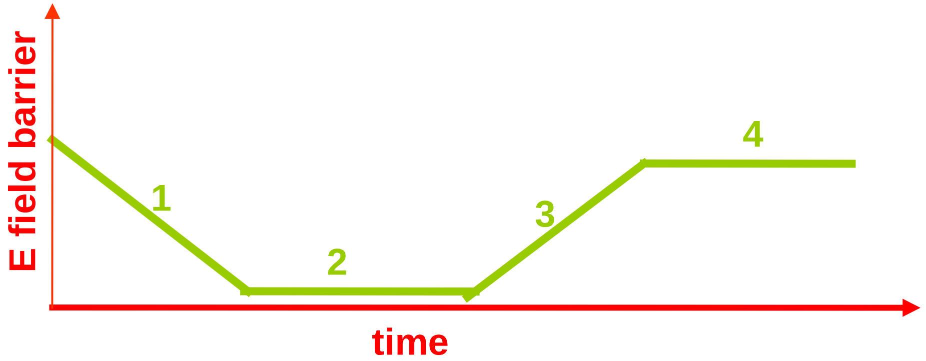
Adiabatic switching of a cell

1. Lowering the barrier



2. Removing the previous input

3. Applying the current input



4. Raising the barrier

Signal Propagation

<u>Adiabatic switching of a cell</u>

1. Lowering the barrier

Electrons are pulled into middle dots

Imagine lowering walls between rooms so people (electrons) can move freely. No memory of where they came from.

2. Removing the previous input

Cell is in null state

The room is now empty and waiting for new guests.

3. Applying the current input

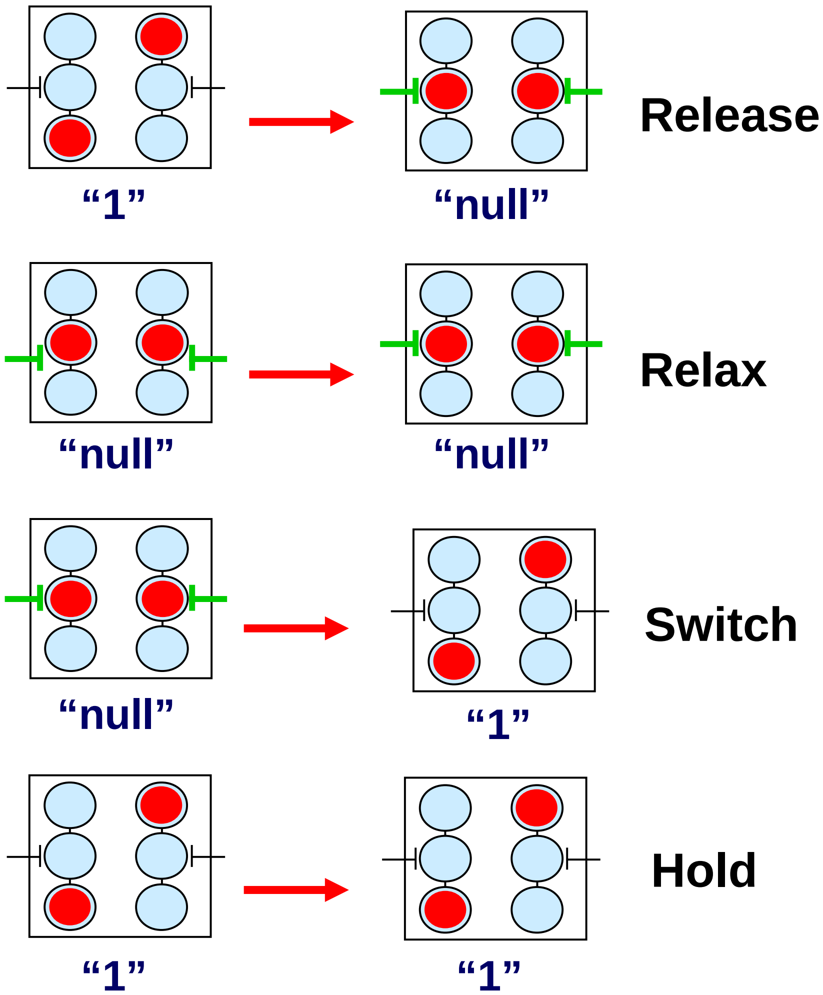
<u>inter dot barriers slowly raised</u>

New guests (electrons) enter and slowly settle into specific rooms based on preference (input).

4. Raising the barrier

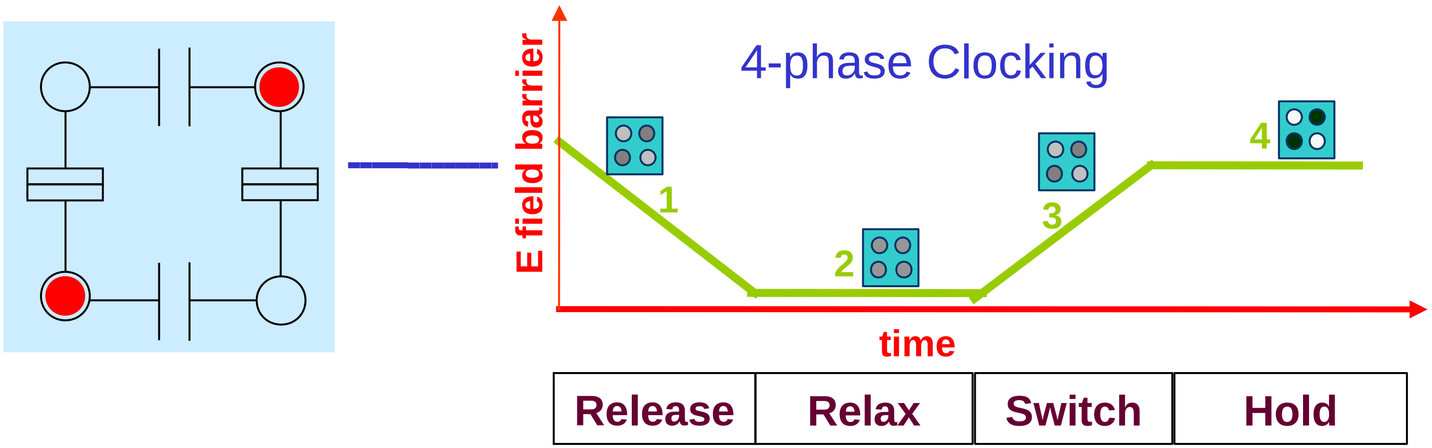
Barriers high, cell retains its polarity

Doors are now locked. Guests can't move — the state is frozen until the next release.

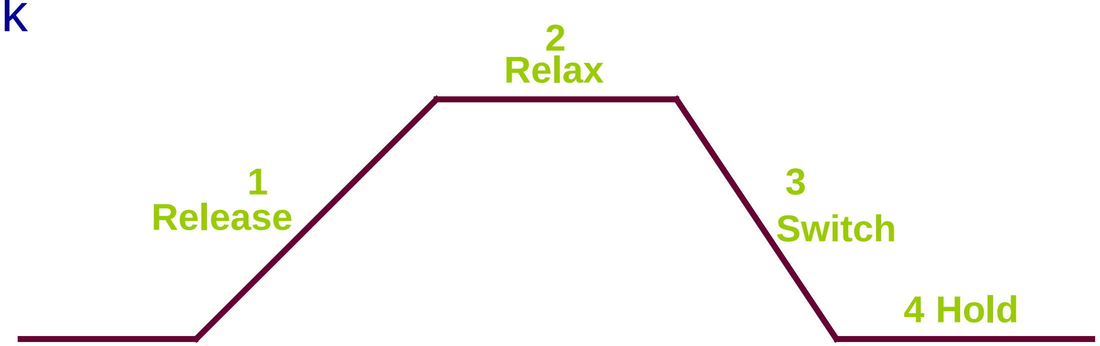


Realizes with 4-phase Clocking

Signal Propagation

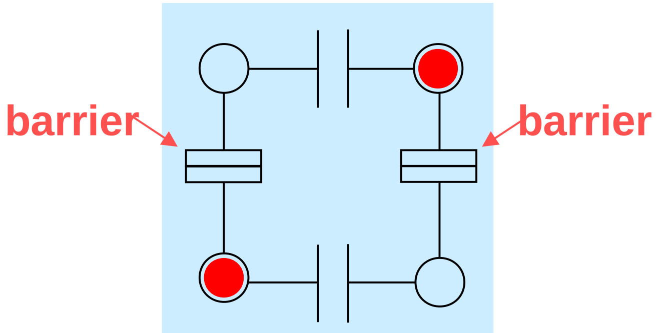


4-phase Clock



Signal Propagation

- Barrier low implies non-polarization
- Barrier high - cells are not allowed to change state



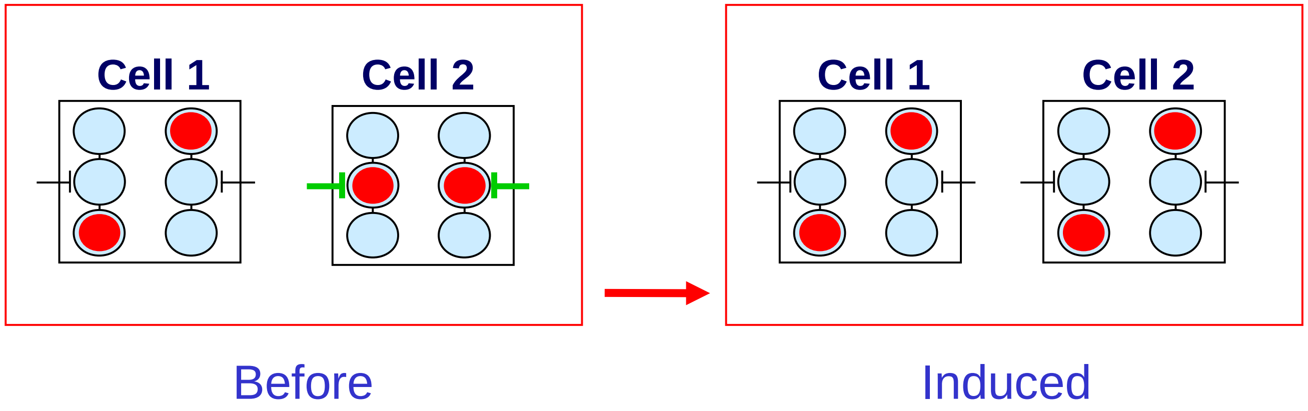
- Clocking control information flow
- Needed for both combinational and sequential circuits
- Clocks supplied by CMOS wire/CNTs

Signal Propagation

Cell-to-cell responses

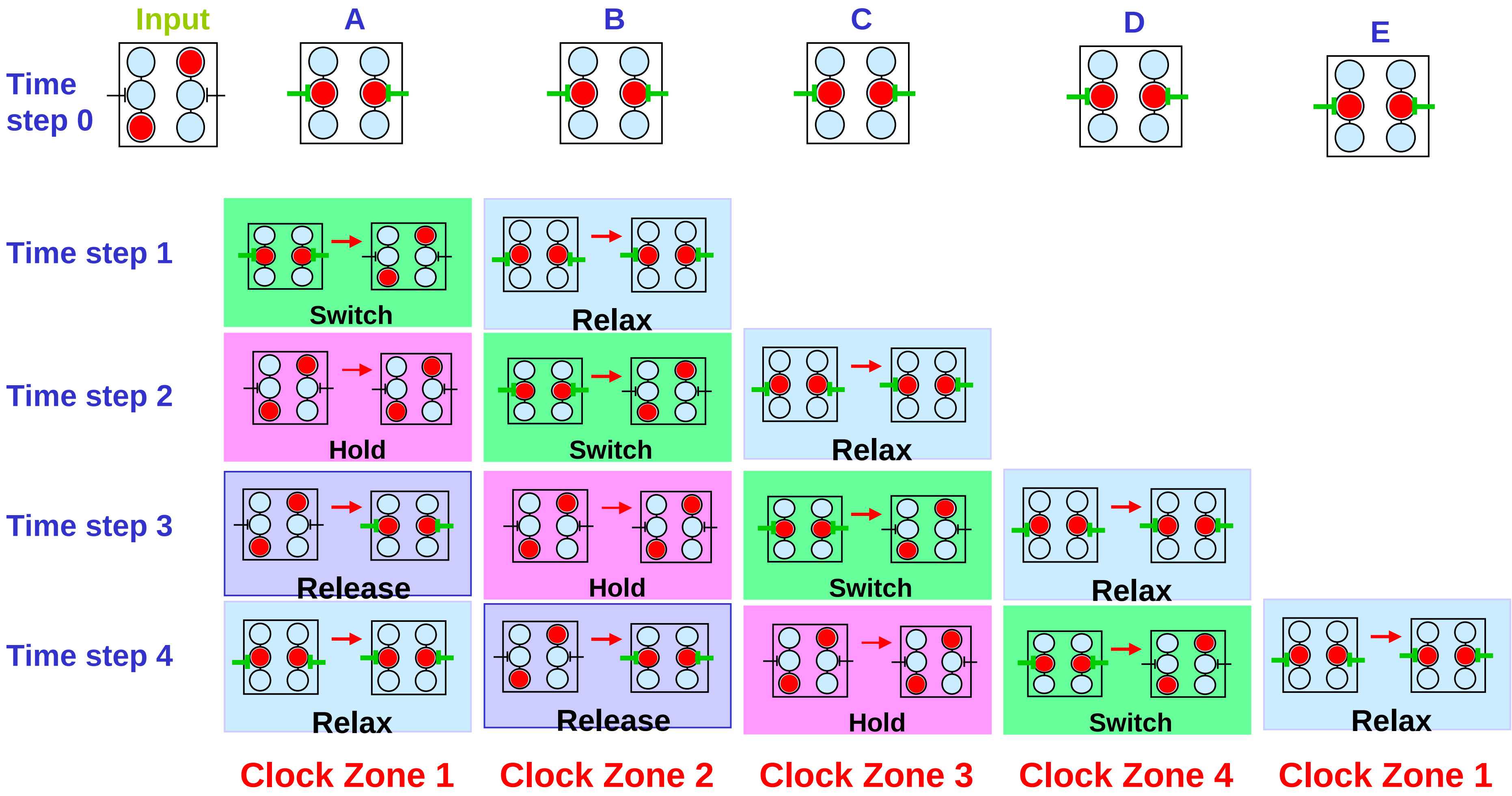
Polarization P2 of Cell2 is induced by neighbor Cell1 with polarization P1

A slightly polarized input Cell1 may fully polarize Cell 2



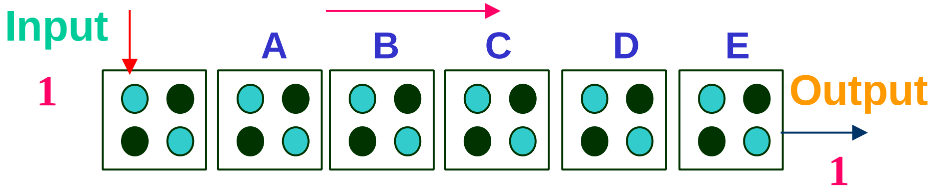
Cell-to-cell response is computed by solving two particle Schrodinger equation

Signal Propagation

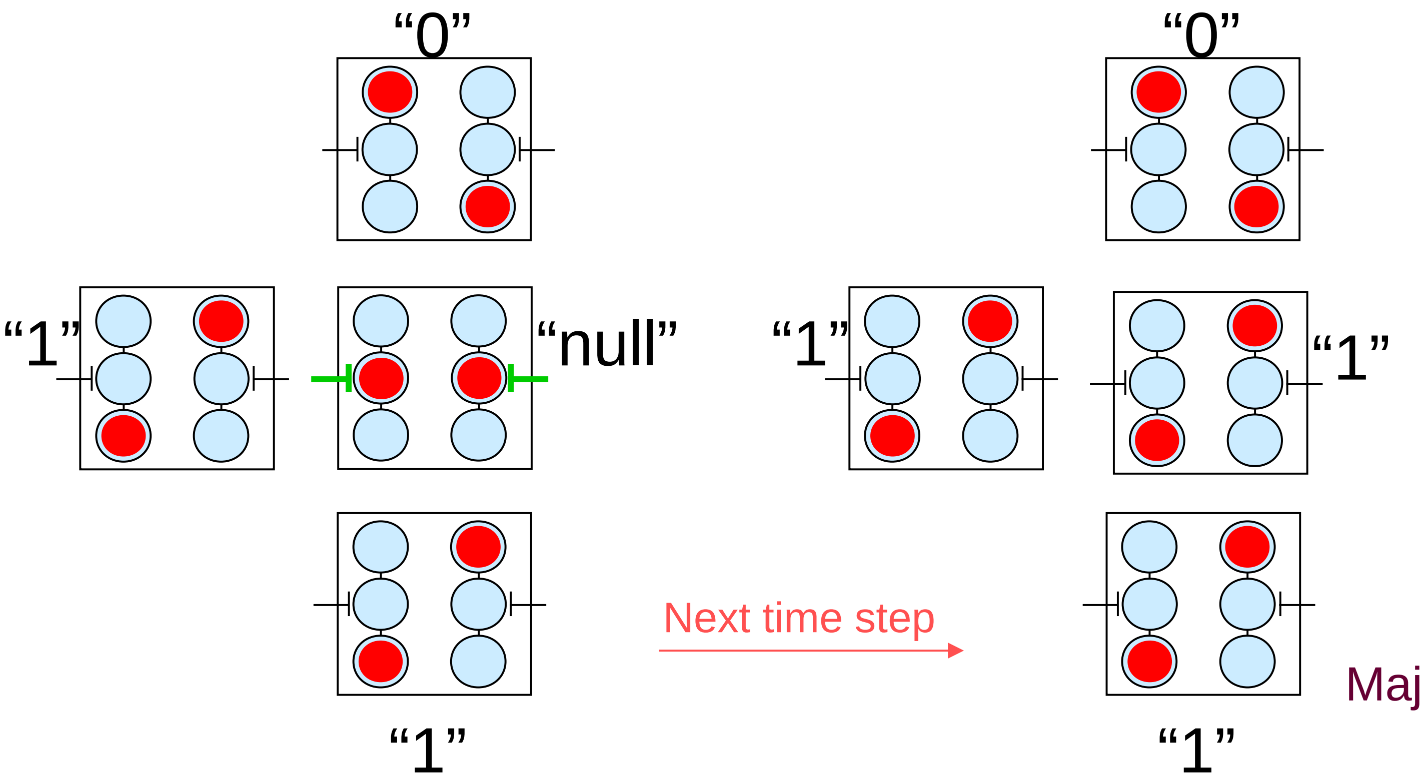


Circuit partitioned into Clock Zones. Cell A and E are in same Zone

Signal Propagation

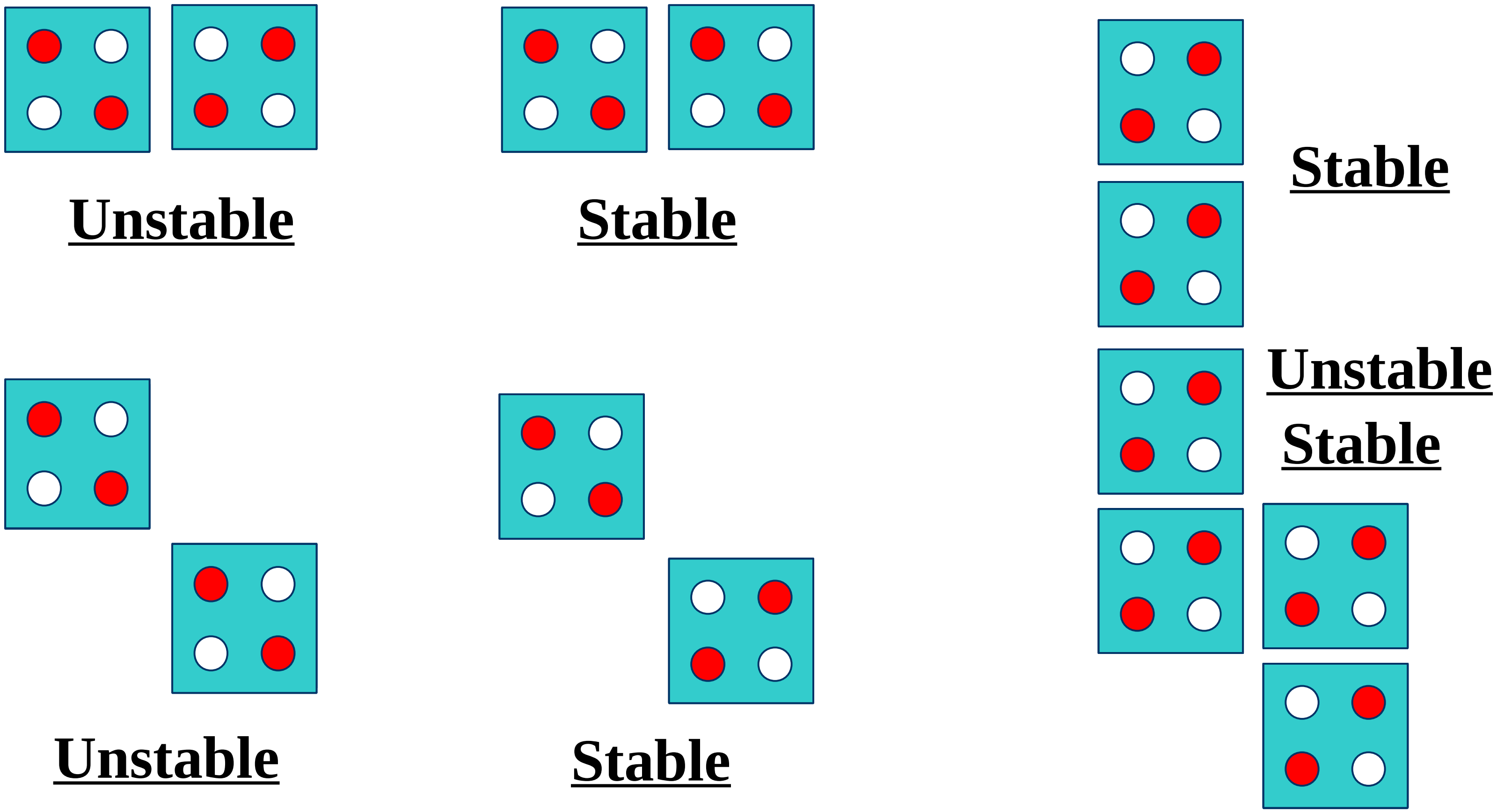


Wire

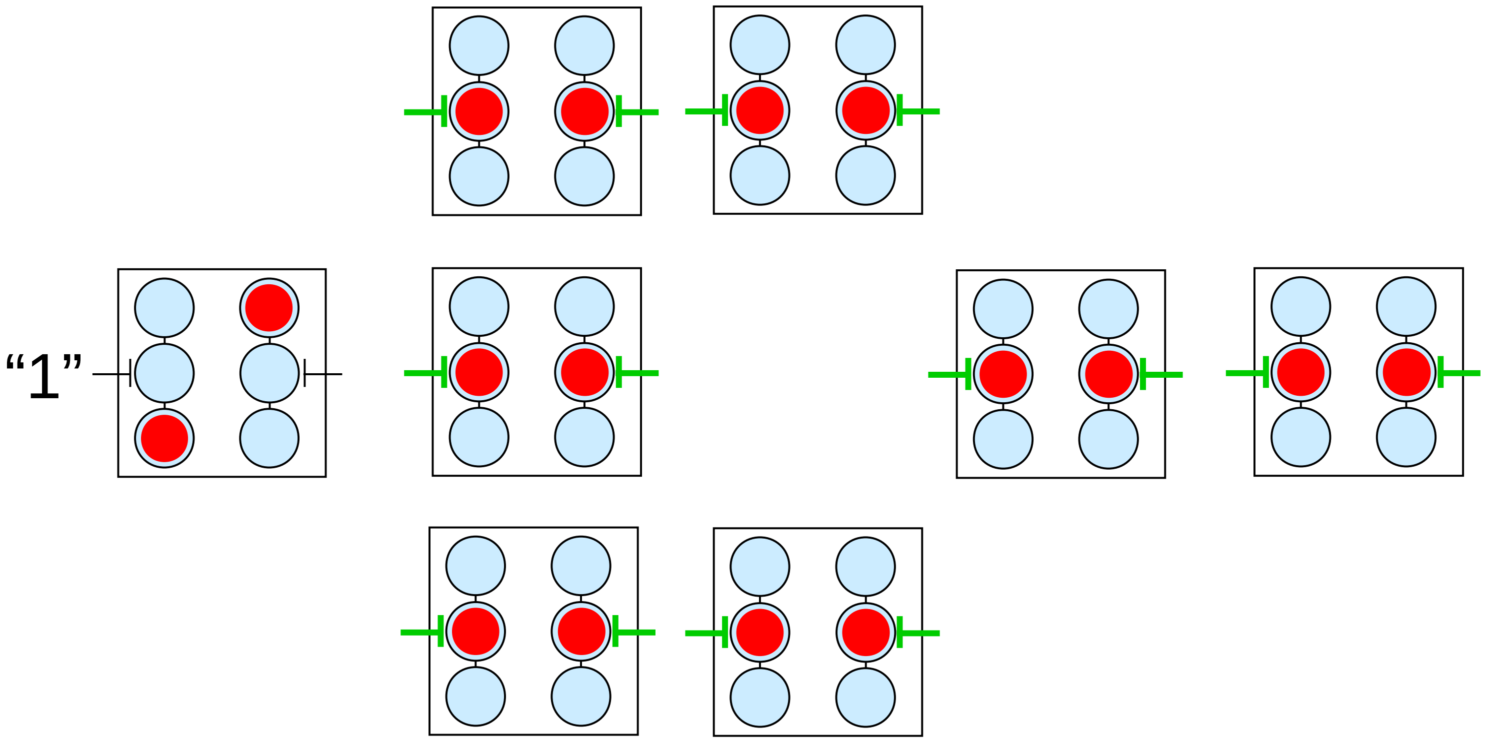


Majority gate

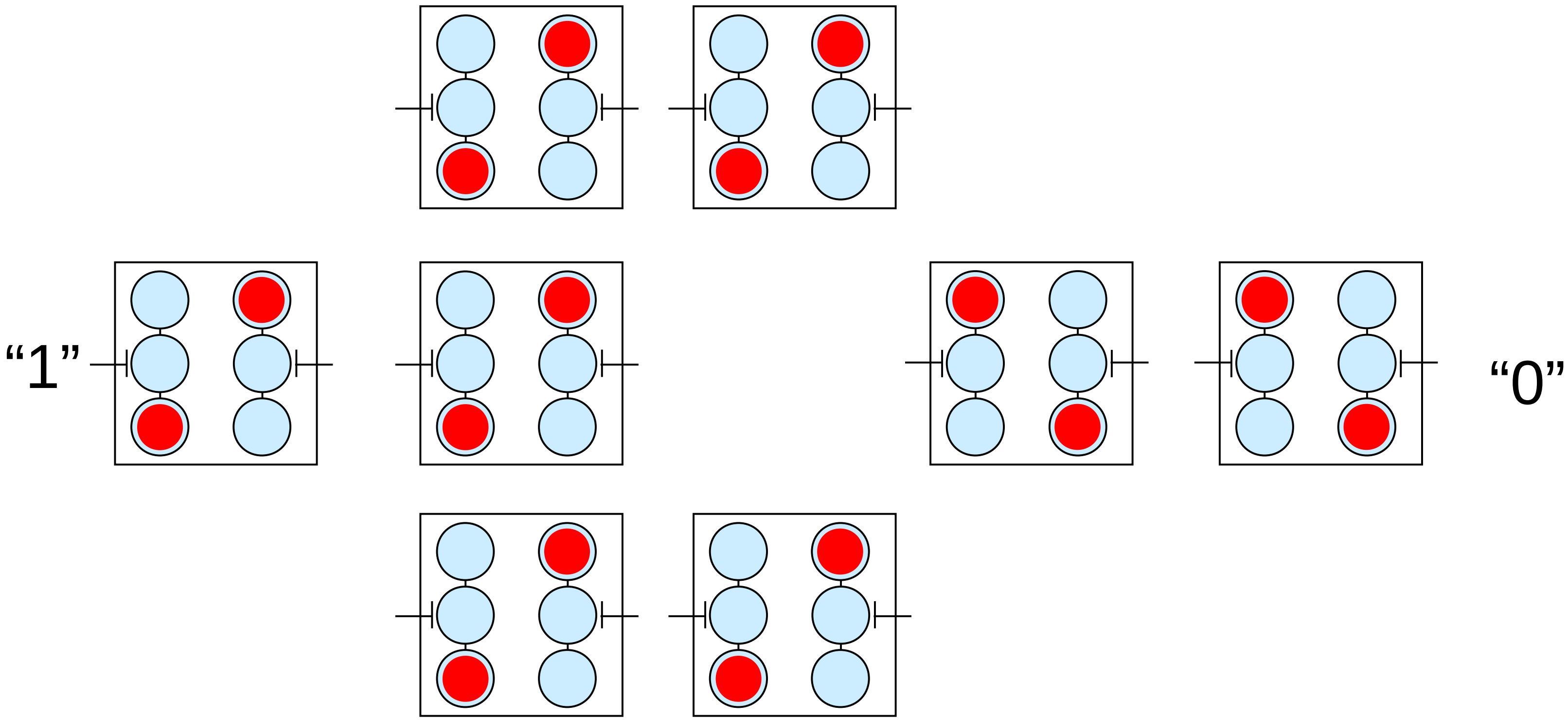
Signal Propagation



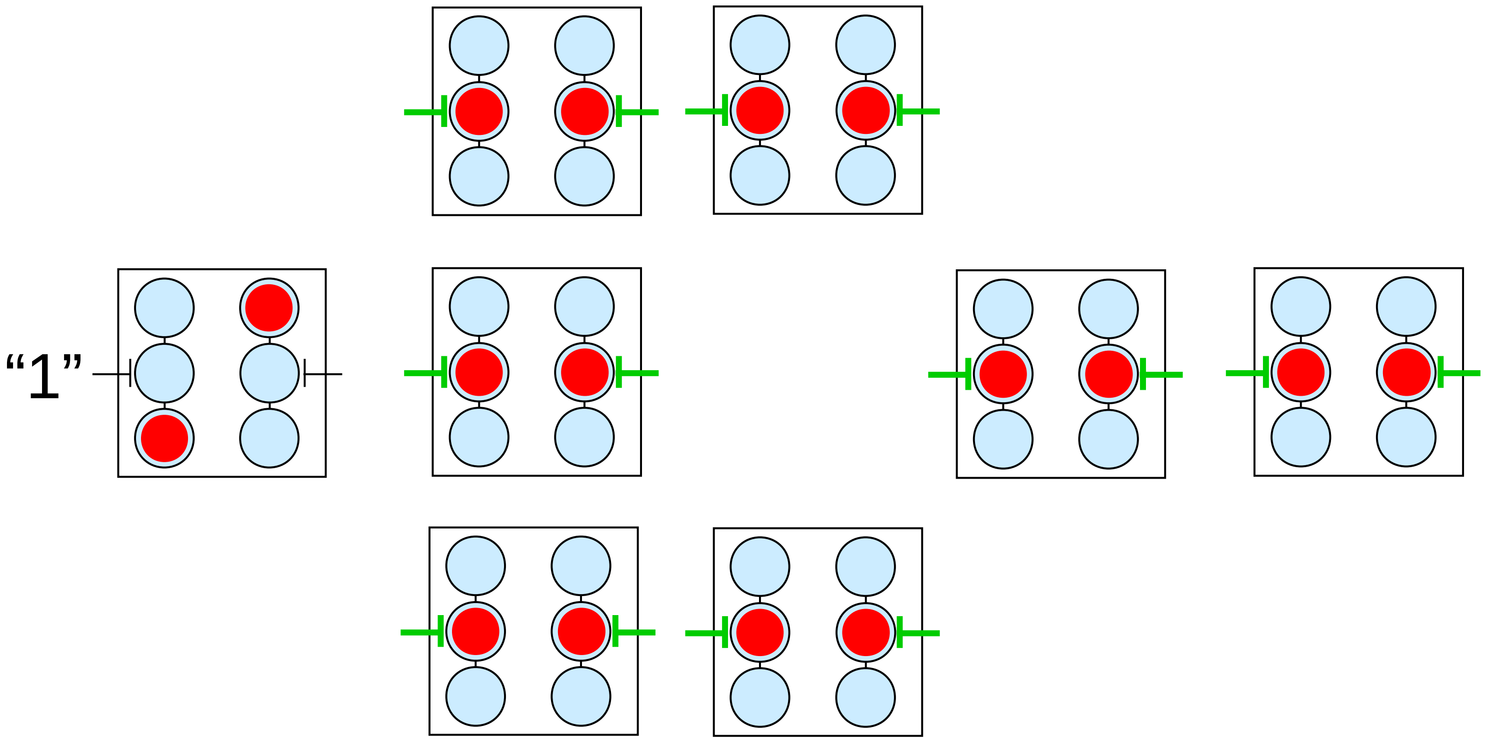
Signal Propagation



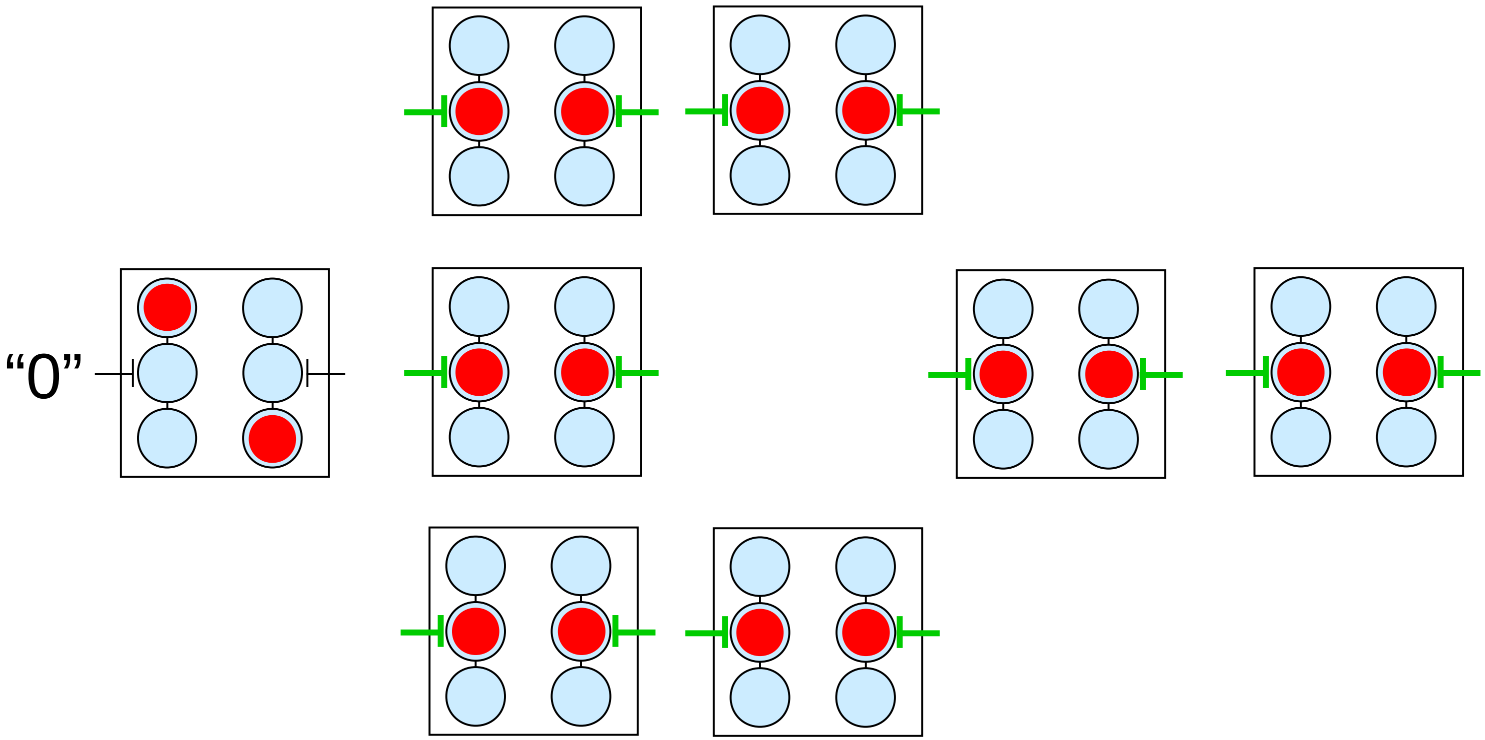
Signal Propagation



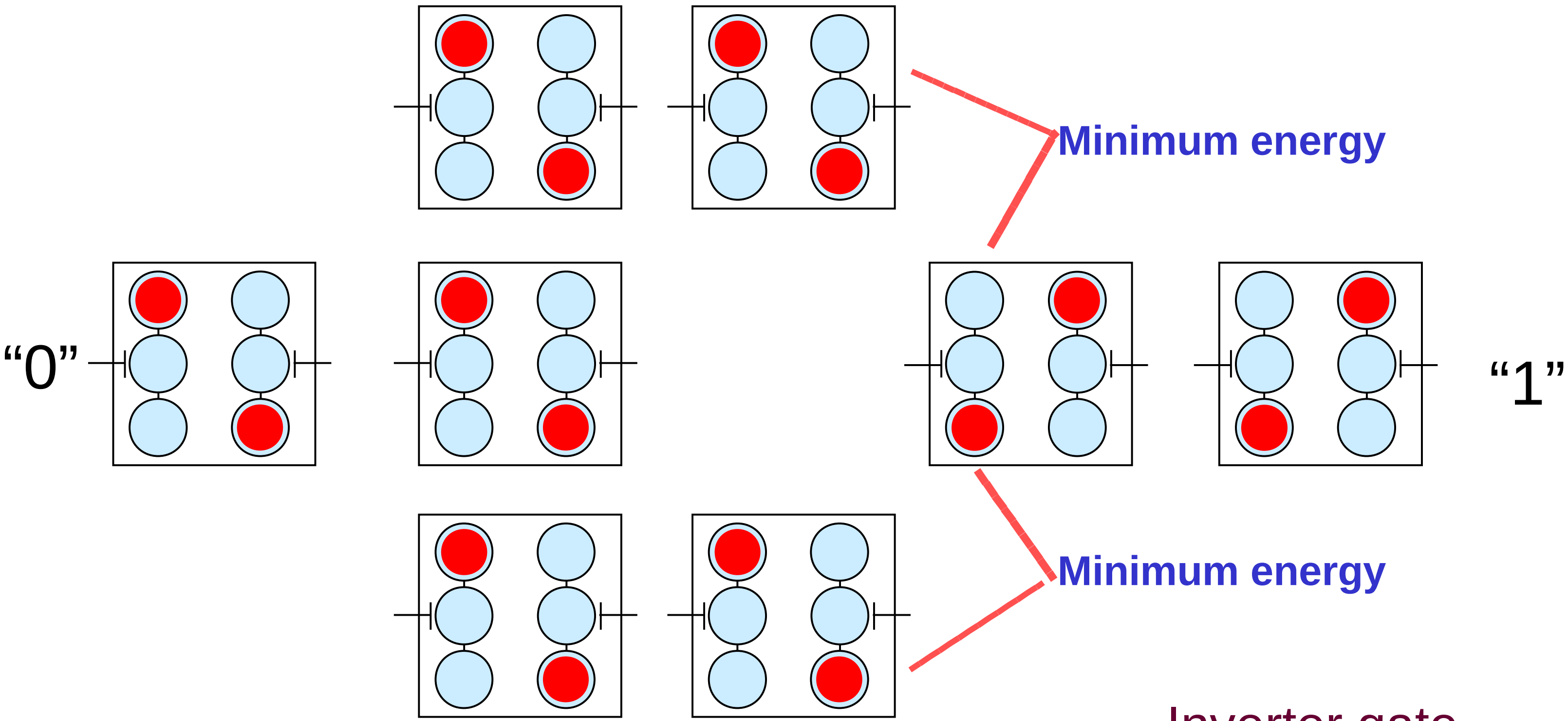
Signal Propagation



Signal Propagation



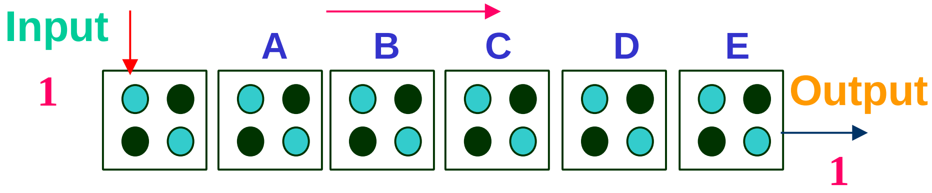
Signal Propagation



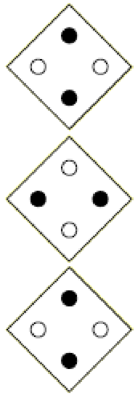
Inverter gate

Basic QCA Devices

- Wires are the string of QCA cells



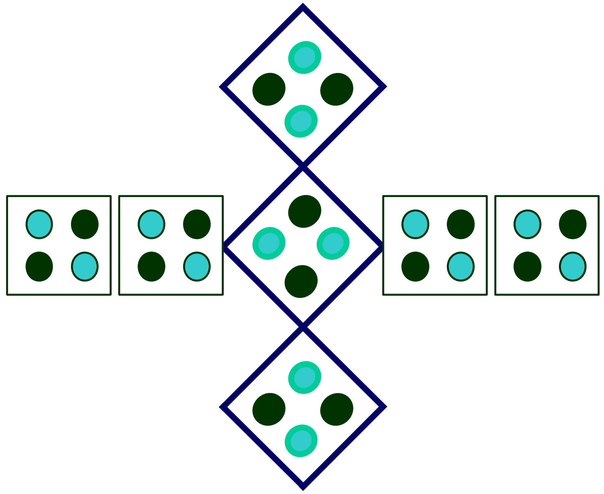
90-Degree wire



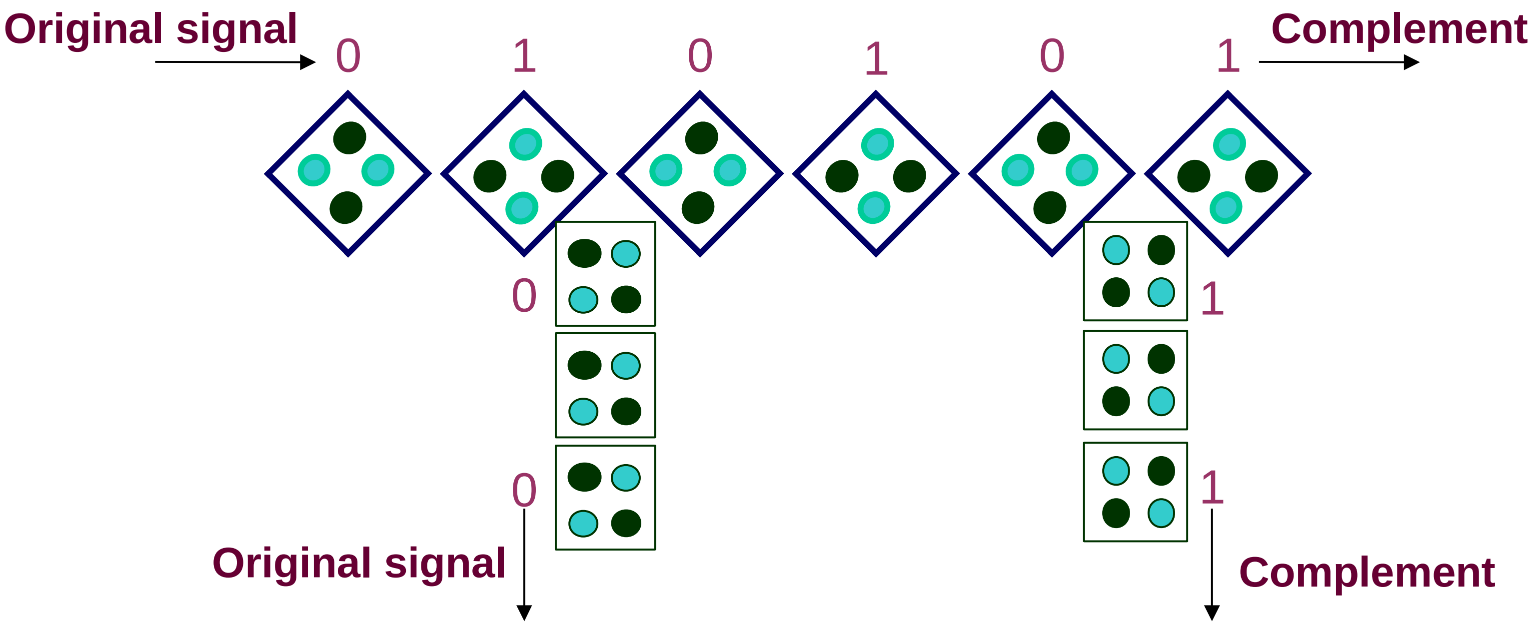
45-Degree wire

Inverter chain

- Coplanar wire-crossing



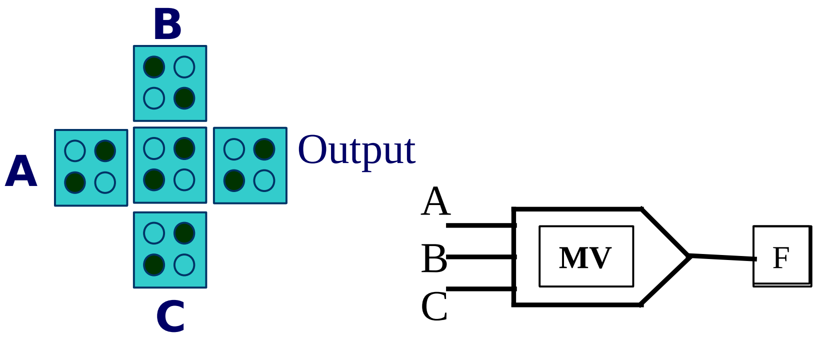
Basic QCA Devices



Processing-By-Wire (PBW)

Basic QCA Devices

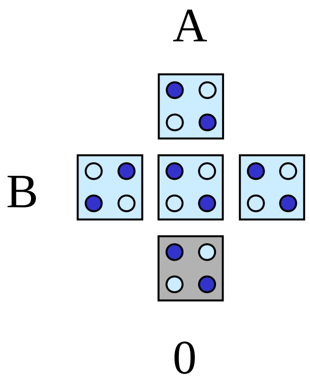
QCA Majority Gate



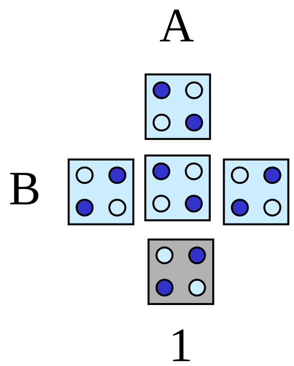
The basic logic gate in QCA

Maj(A,B,C)=AB+BC+CA

No built-in VDD or ground lines



Maj(A,B,0)=AB

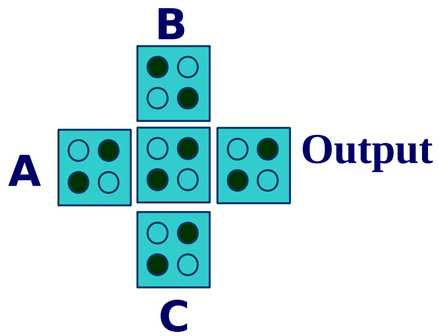


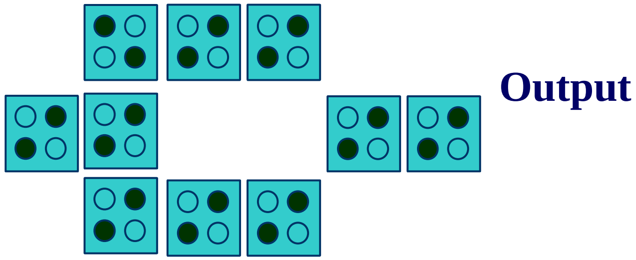
Maj(A,B,1)=A+B

Not universal. Not favourable for synthesis by existing tools

Basic QCA Devices

QCA Majority Gate + QCA inverter = Universal Gate





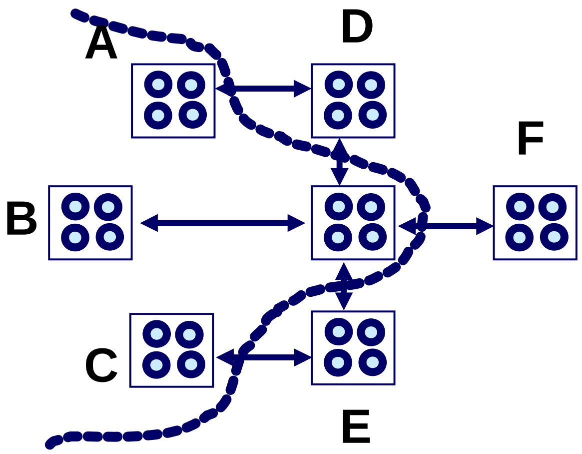
QCA Inverter is costly

Employed for QCA logic design

Universal gate structures are desirable

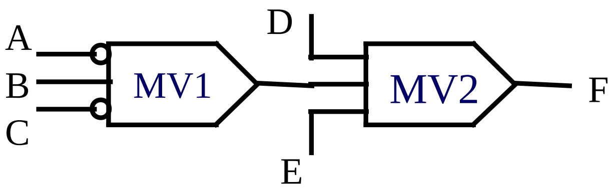
Basic QCA Devices

AOI Gate: Universal Gate



Cell B has stronger effect on device

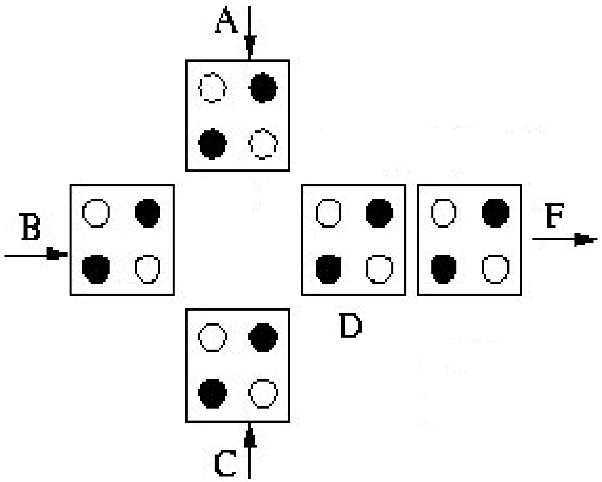
1. Five input cells
2. A & C have inverting effect
3. F=DE+(D+E)(A'C'+A'B+BC')
   =Maj (D, E, Maj (A',B,C'))



This AOI structure is very sensitive to proper separation of input/output wires

Basic QCA Devices

Nand Nor Inverter [NNI] Gate



NNI Gate

F=A'B+BC'+C'A'

- Universal gate
- More stable than the AOI

QCA Tiles

- Molecular implementation of QCA has been proposed

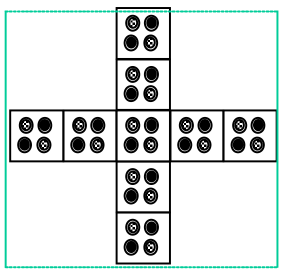
[Lieberman et. al, 2002 & 2003]

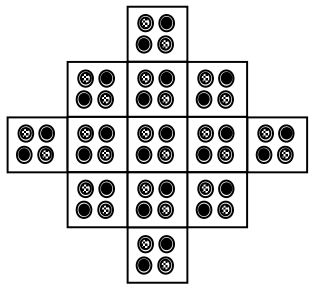
- Molecular implementation targets modular design

SQUARES (5X5 grid)

[Fountain et.al GLSVLSI, 1999]

Tiles (3X3 grid) [J. Huang et. al, Nanotechnology Conf 2005]

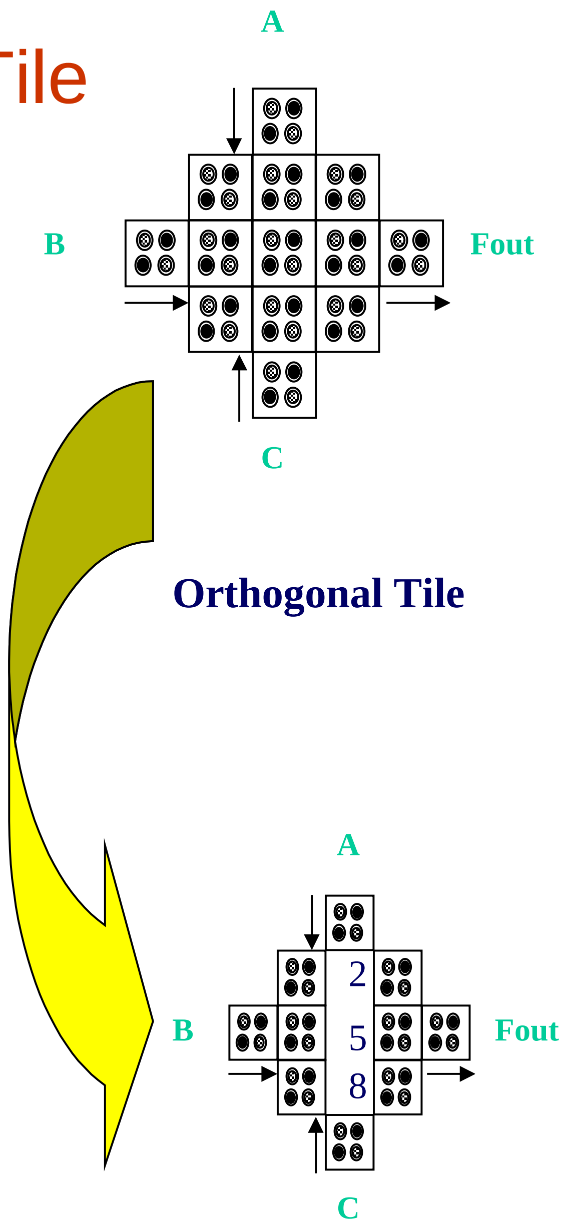


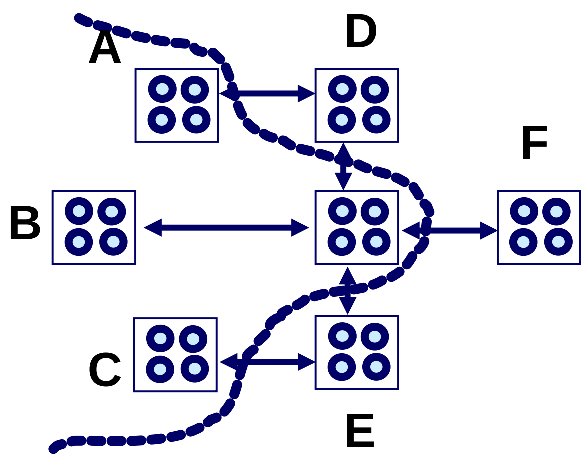


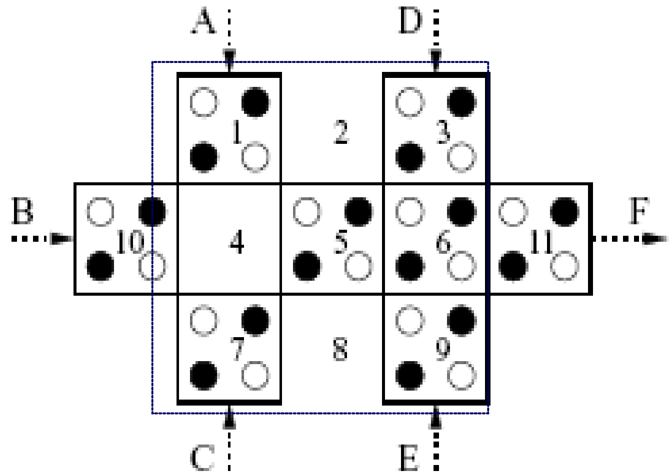
Tiles implementing universal logic gate functions are of interest

NNI Tile

AOI Tile





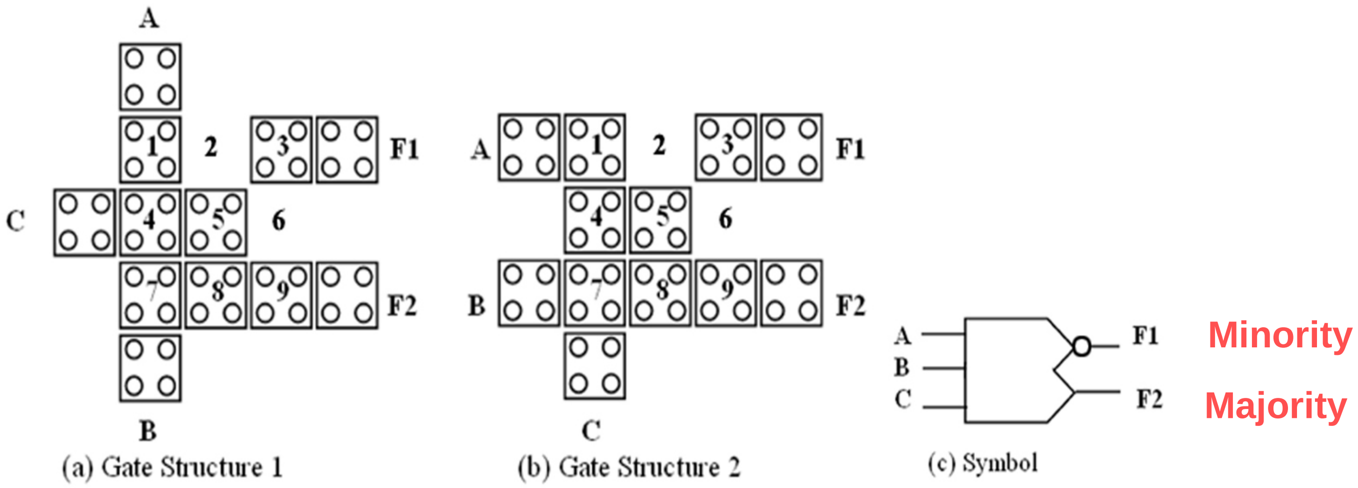


New stable AOI gate structure

Realizes universal logic function $F = A'B + BC' + C'A'$

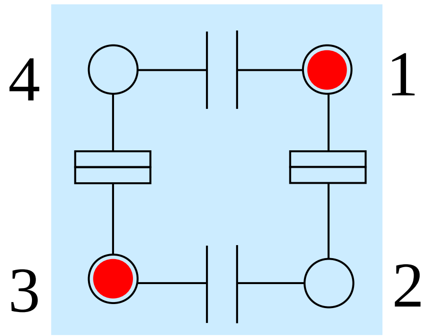
Coupled Gate

CMVMIN gate structure [Ditti, VDAT, 2008]



C=-1 F1 = (AB)' :*NAND*; F2 = AB :*AND*

C=1 F1 = (A+B)' :*NOR*; F2 = A+B :*OR*



Numbering of dots in the cell goes clockwise starting from the dot on top right.

A polarization P in a cell, which measures the extent to which the electronic charge is distributed among four dots is

$$P = \frac{(\rho 1 + \rho 3) - (\rho 2 + \rho 4)}{\rho 1 + \rho 2 + \rho 3 + \rho 4}$$

Two most likely polarization states of QCA can be P = +1 and P = −1