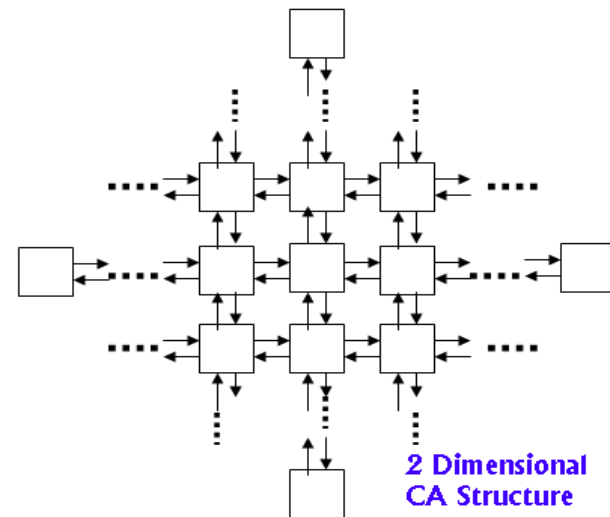


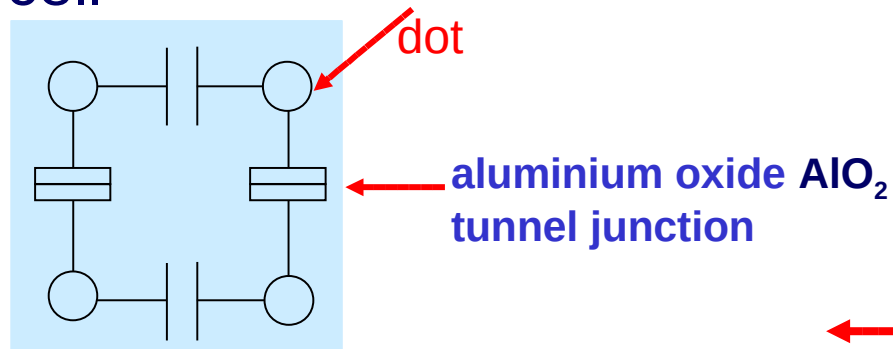
Quantum cellular Automata

- **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

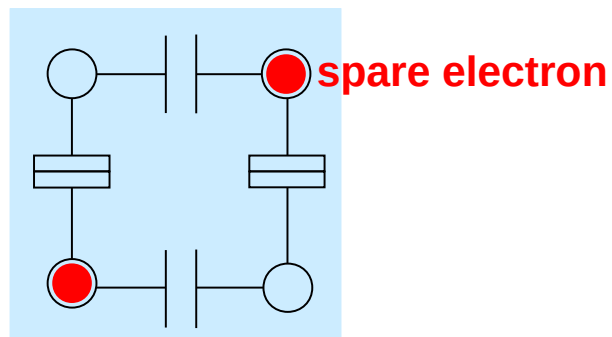


Quantum cellular Automata

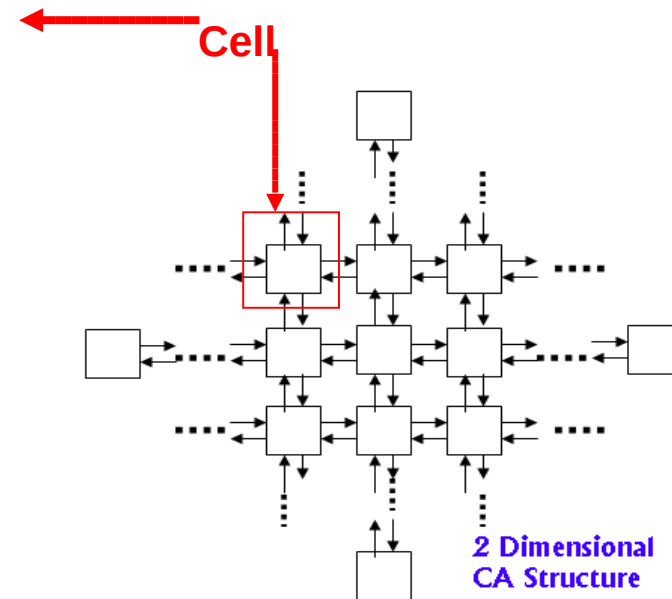
QCA cell



Four aluminium island on SiO_2 called dots



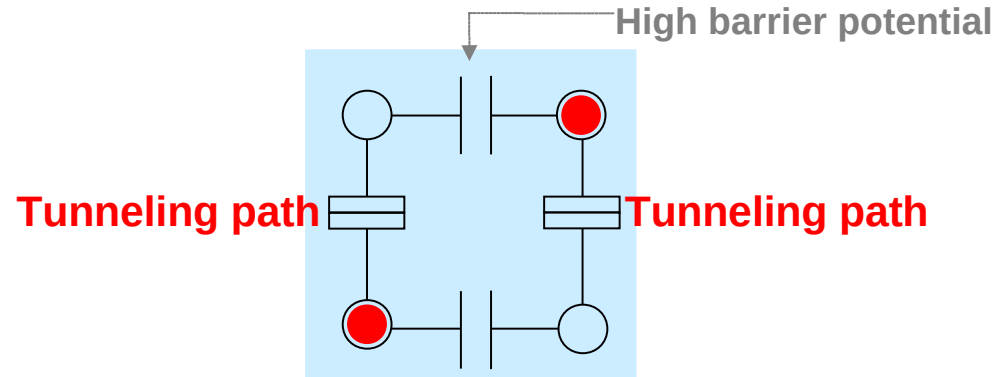
A QCA cell



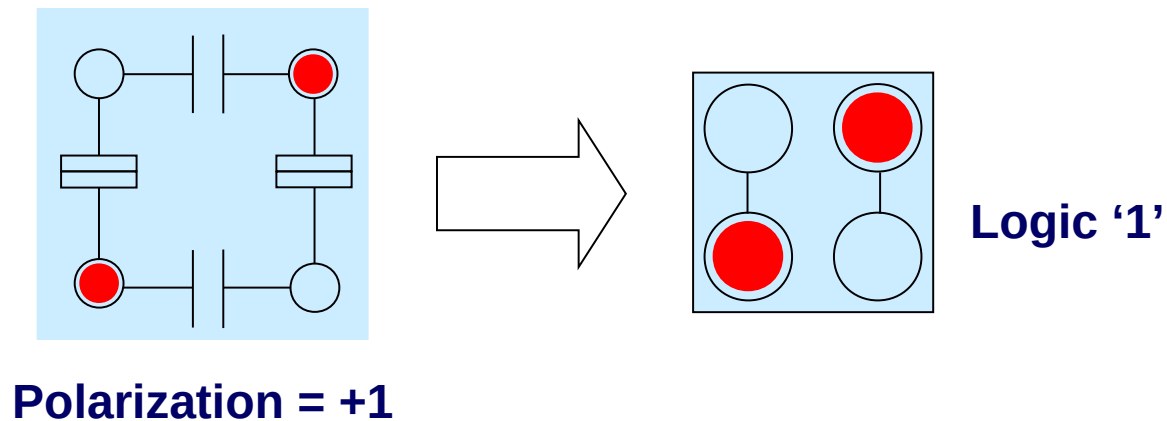
Information Representation

QCA cell

Electrons can tunnel through the path



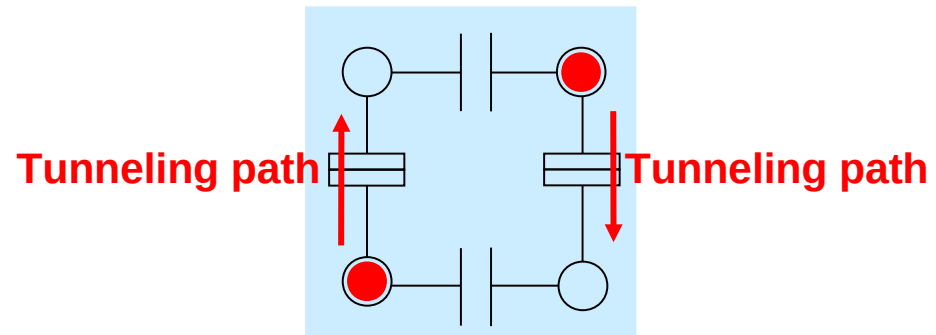
Polarization decides logic level



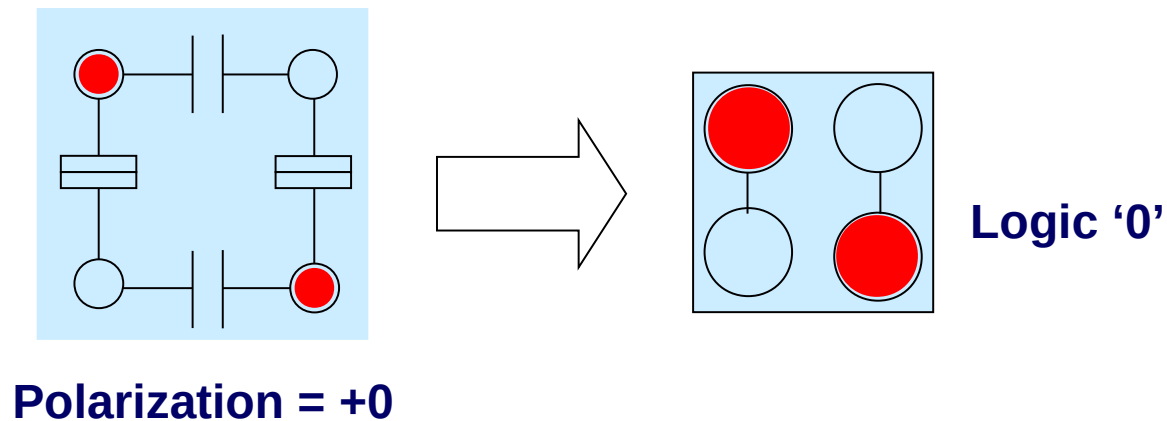
Information Representation

QCA cell

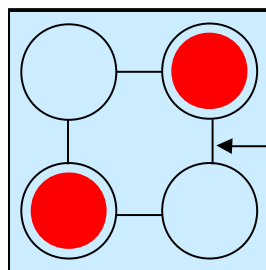
Electrons can tunnel through the path



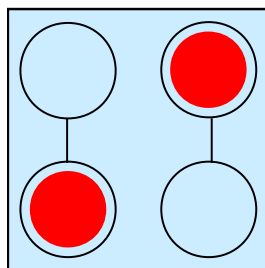
Polarization decides logic level



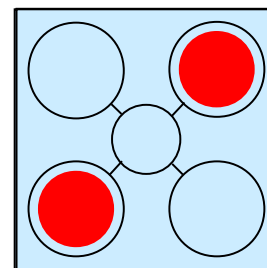
Variations of QCA Cell



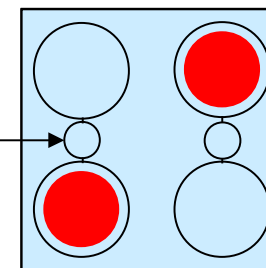
4-dot cell



2-dot cell



5-dot cell

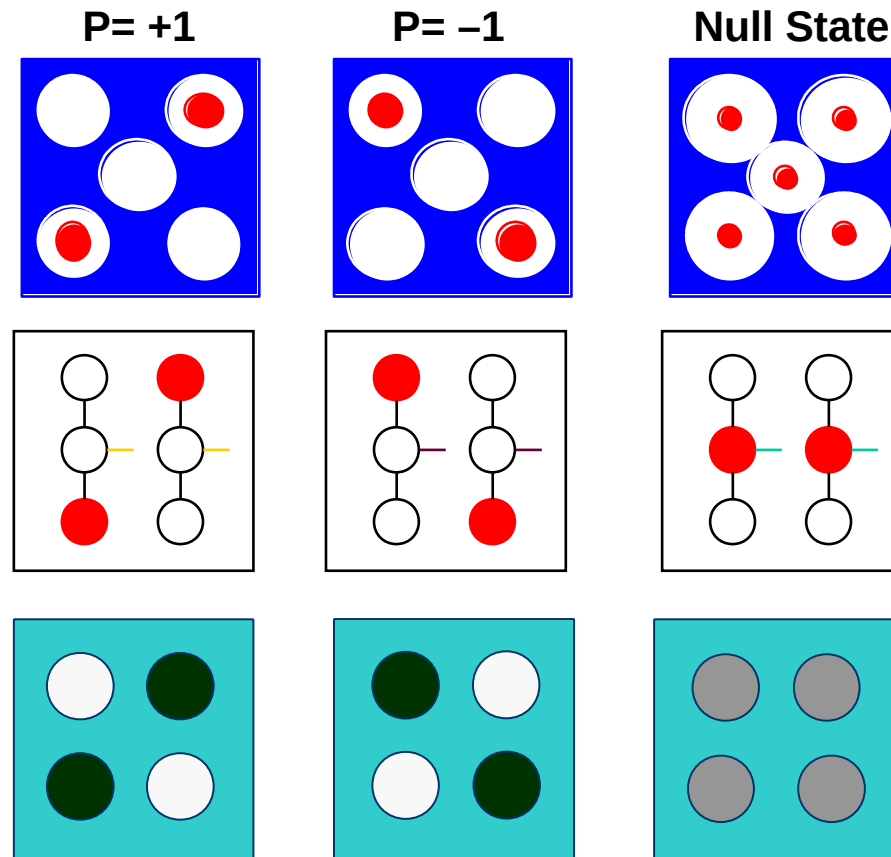


6-dot cell

Indicates path for
tunneling

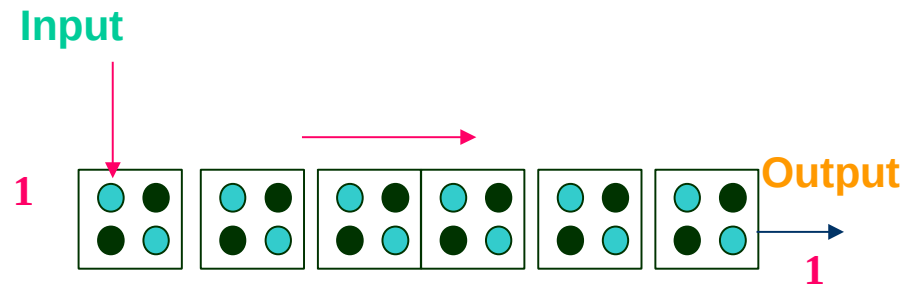
Middle dot acts as
variable barrier to
tunneling

Variations of QCA Cell



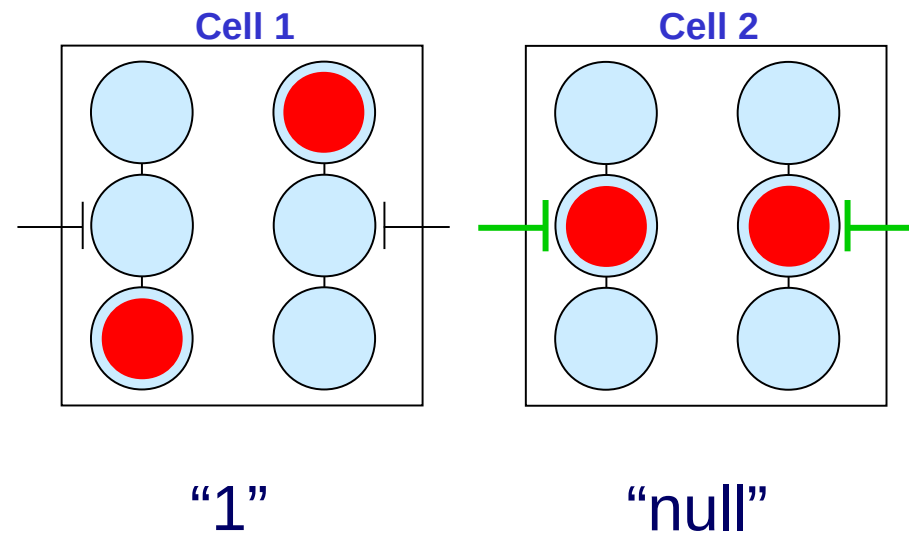
Clocked QCA circuits better utilizes tri-state 6 dot cells

Signal Propagation

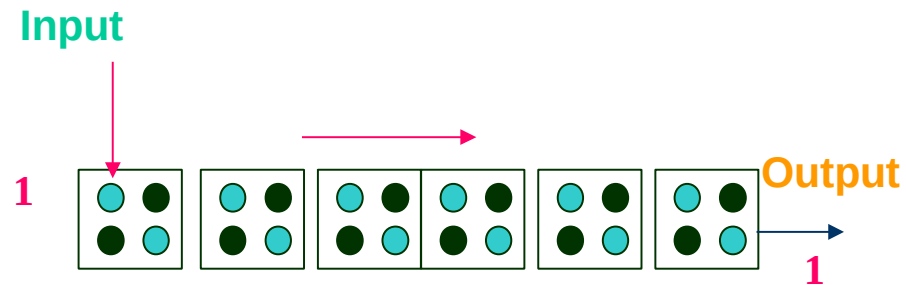


- Information flow on Coulombic interaction

Neighboring cells tend to align in the same state



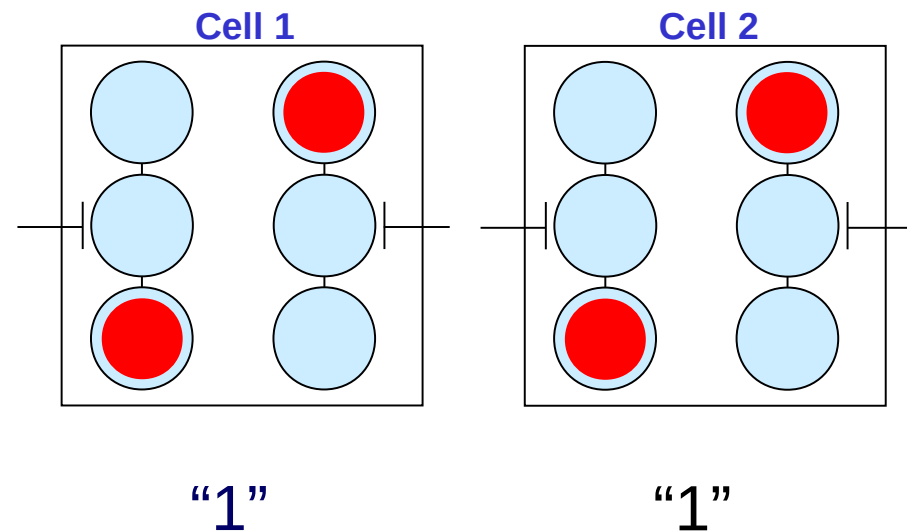
Signal Propagation



- Information flow on Columbic interaction

Neighboring cells tend to align in the same state

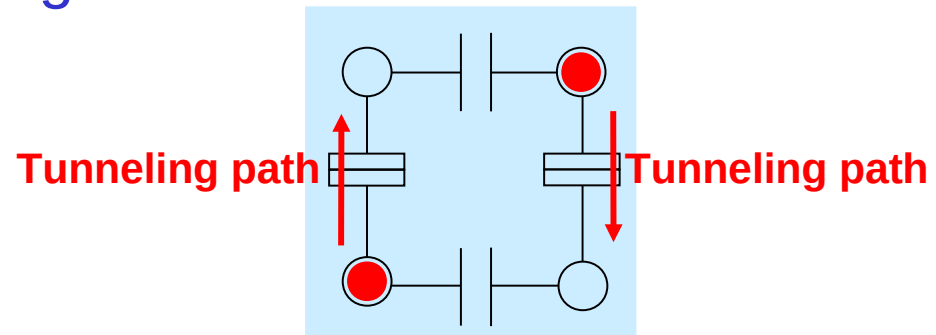
Ground state computing



Signal Propagation

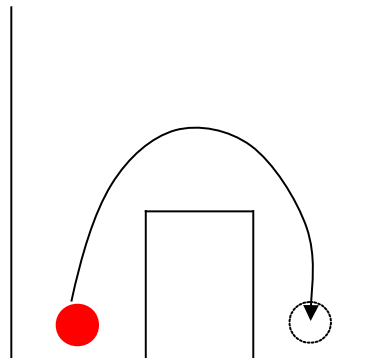
- Ground state computing

- Tunneling path barrier controlling

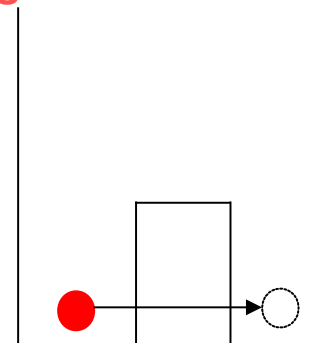


- Electron Traversing energy barrier dissipates no energy

Adiabatic switching



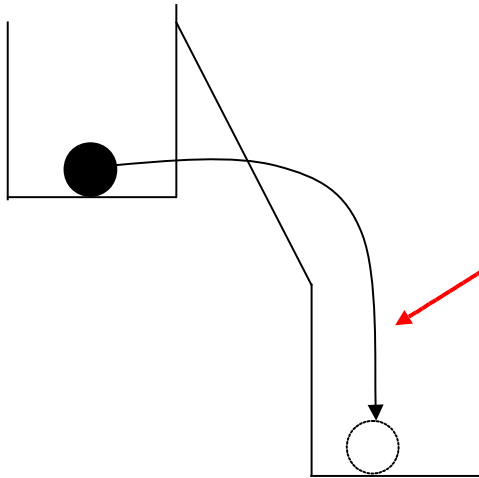
Thermal hop over barrier
dissipates no energy



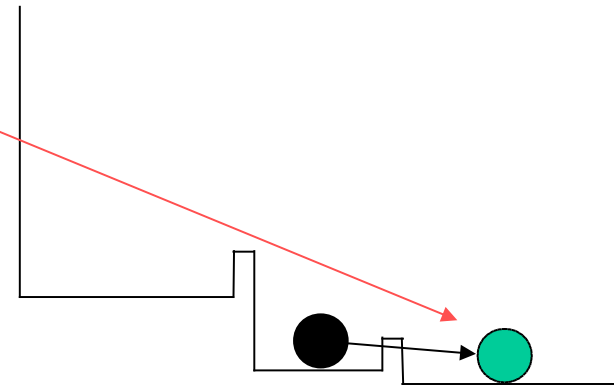
Tunneling through barrier
dissipates no energy

Signal Propagation

Fall downhill is not desirable



Breakdown of adiabaticity



Dissipates
energy

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

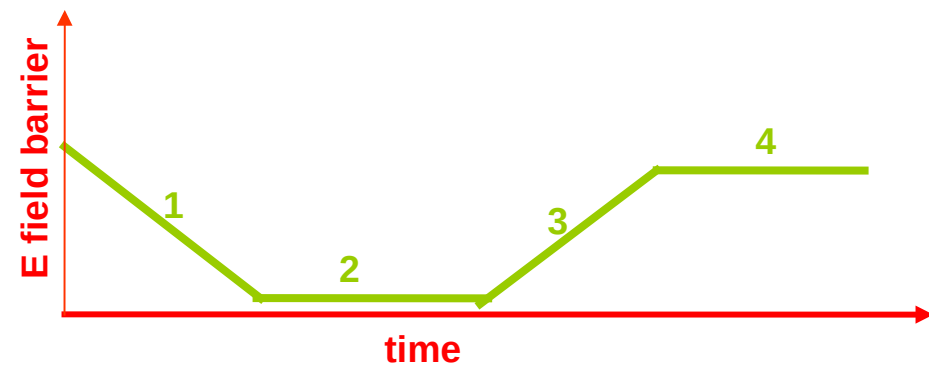
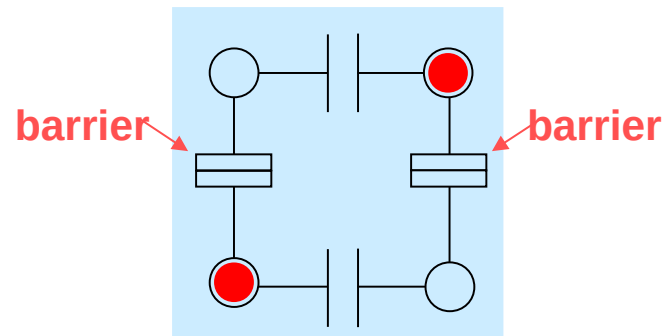
Adiabatic switching of a cell

1. Lowering the barrier

2. Removing the previous input

3. Applying the current input

4. Raising the barrier

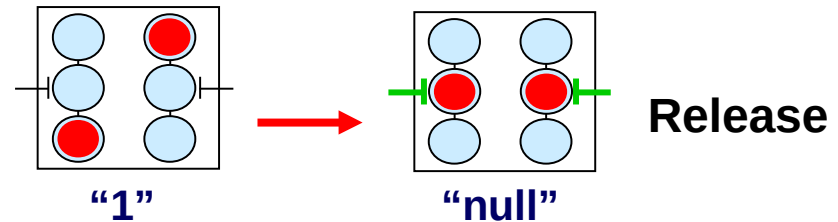


Signal Propagation

Adiabatic switching of a cell

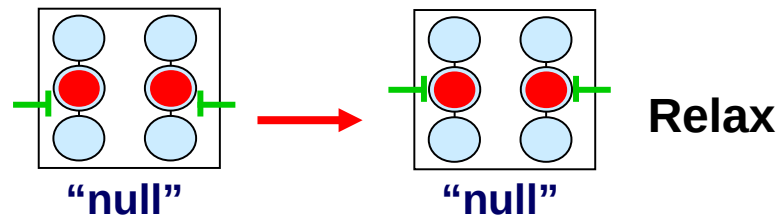
1. Lowering the barrier

Electrons are pulled into middle dots



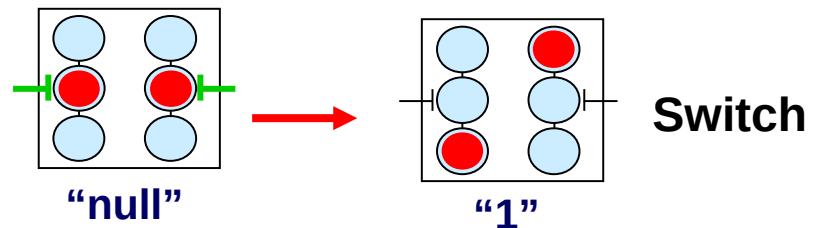
2. Removing the previous input

Cell is in null state



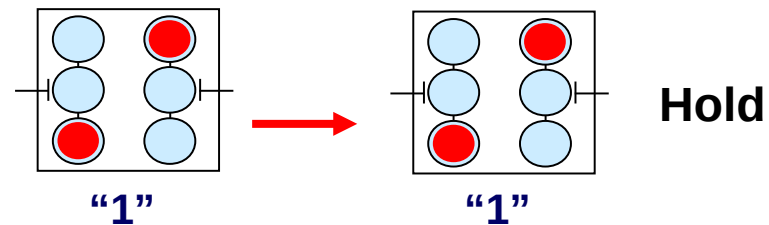
3. Applying the current input

inter dot barriers slowly raised



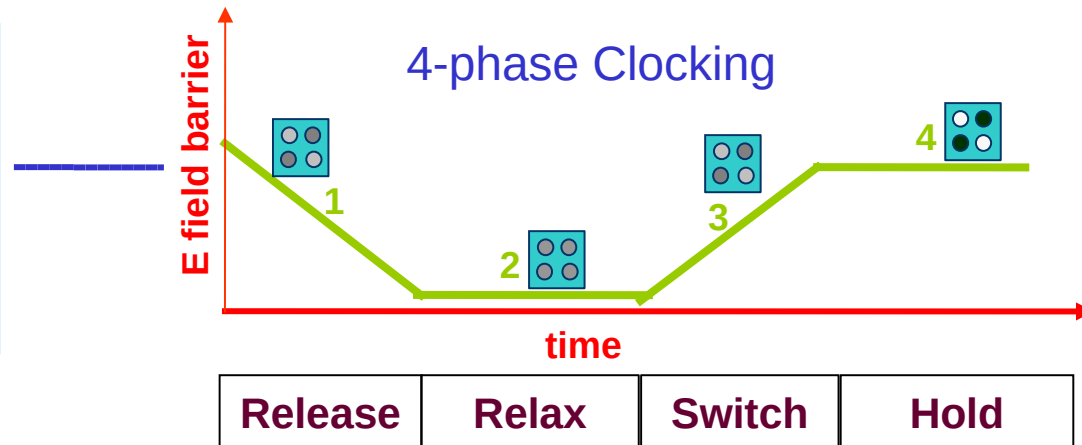
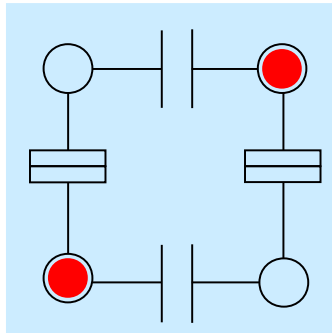
4. Raising the barrier

Barriers high, cell retains its polarity

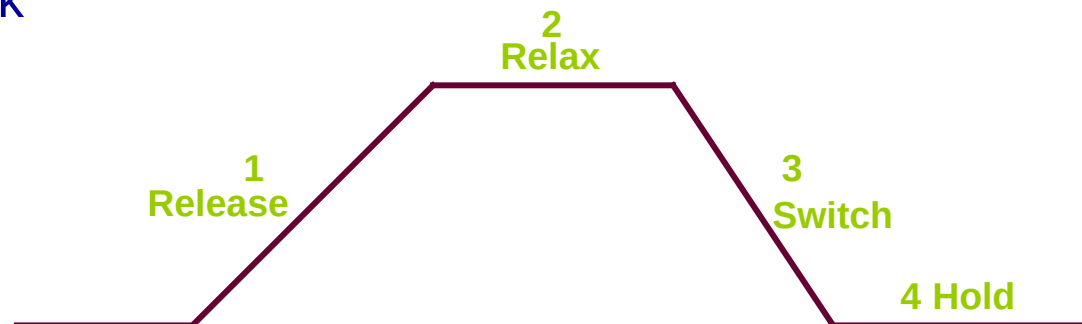


Realizes with 4-phase Clocking

Signal Propagation

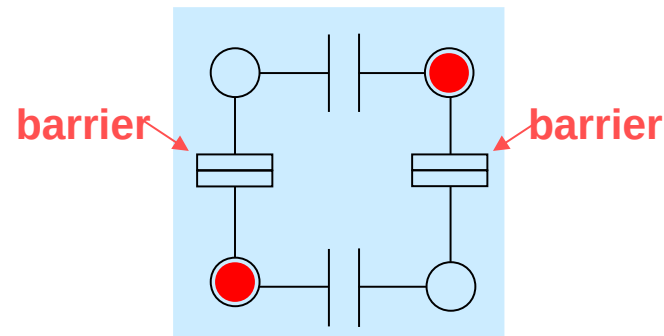


4-phase Clock



Signal Propagation

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



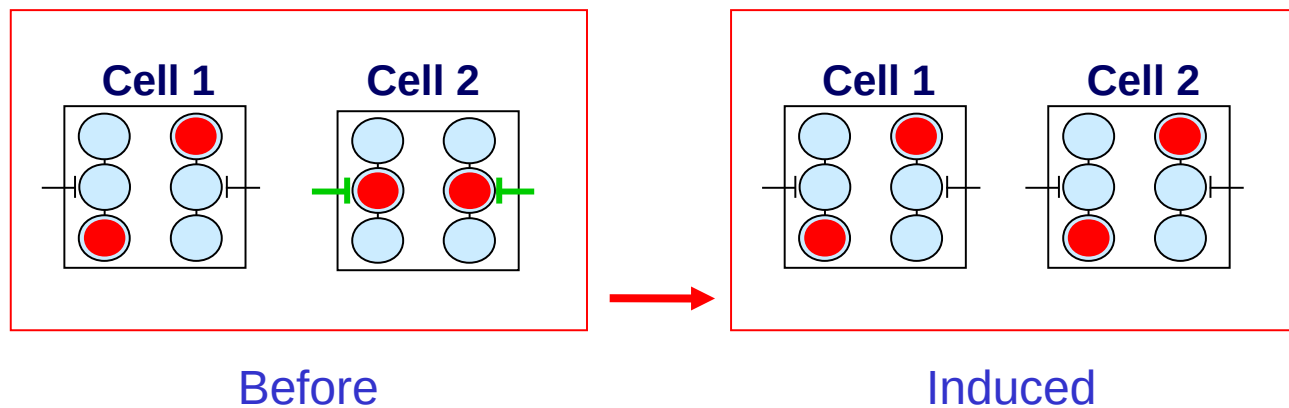
- Clocking control information flow
- Needed for both combinational and sequential circuits
- Clocks supplied by CMOS wire/CNTs

Signal Propagation

Cell-to-cell responses

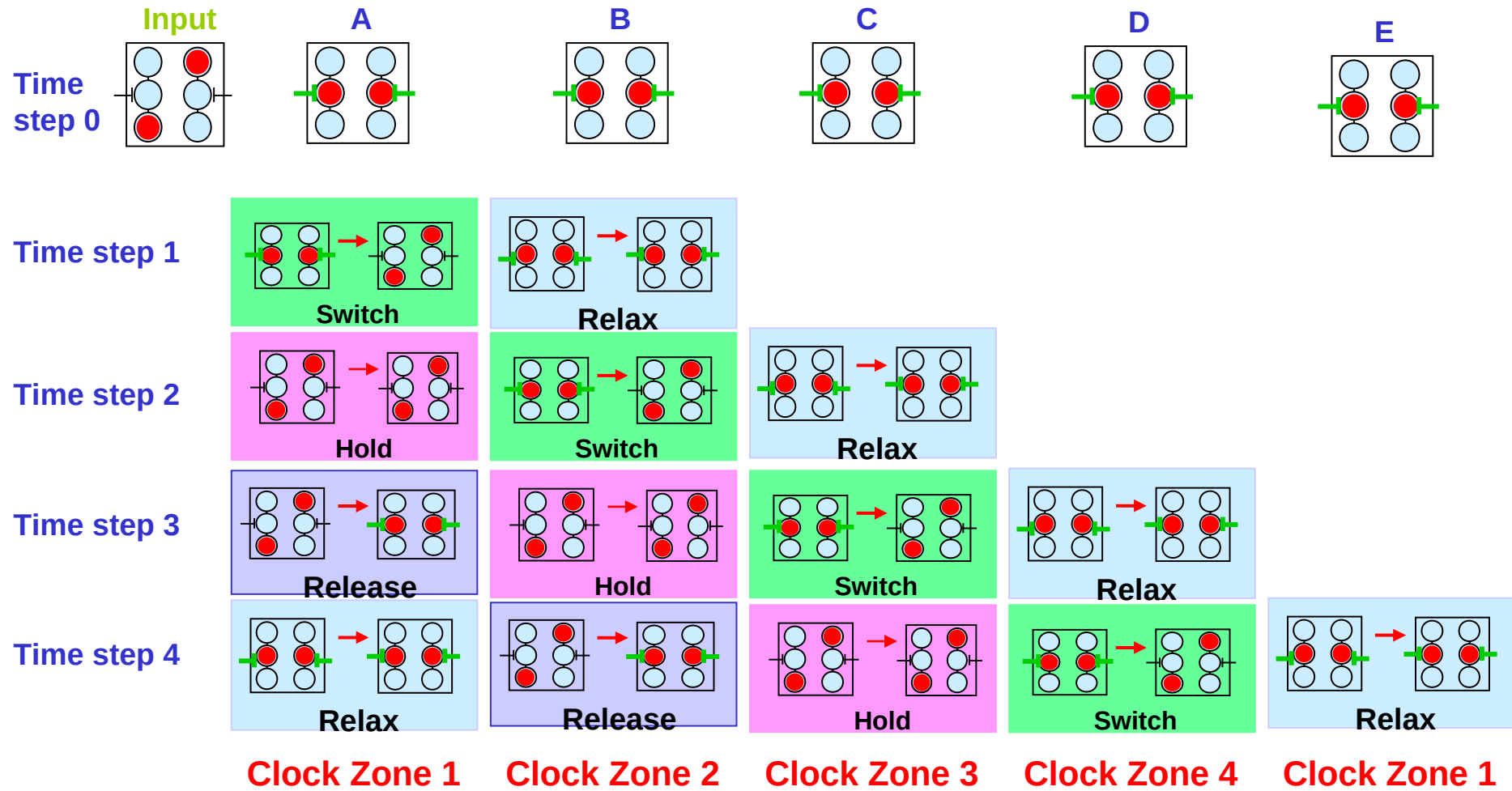
Polarization P2 of Cell2 is induced by neighbor Cell1 with polarization P1

A slightly polarized input Cell1 may fully polarize Cell 2



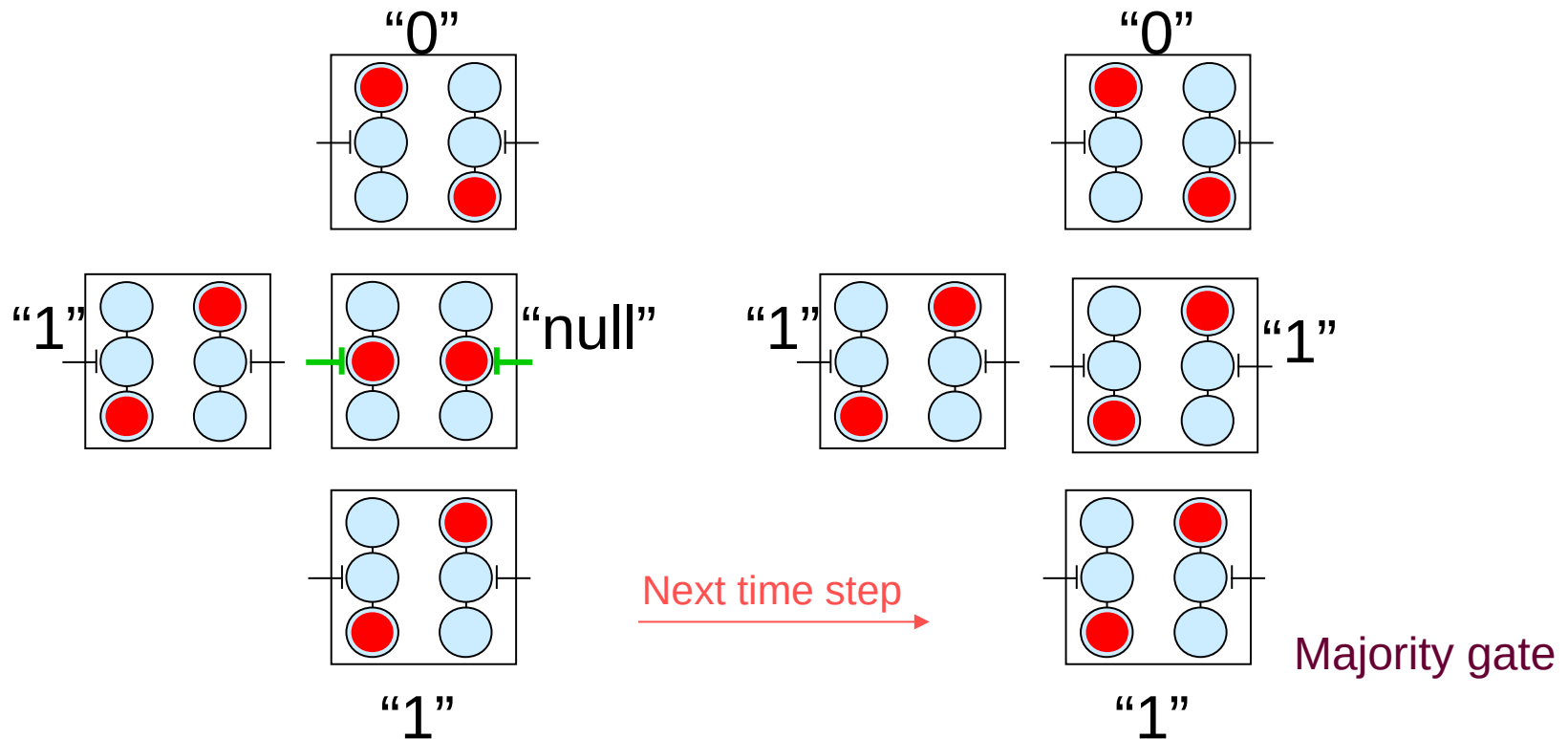
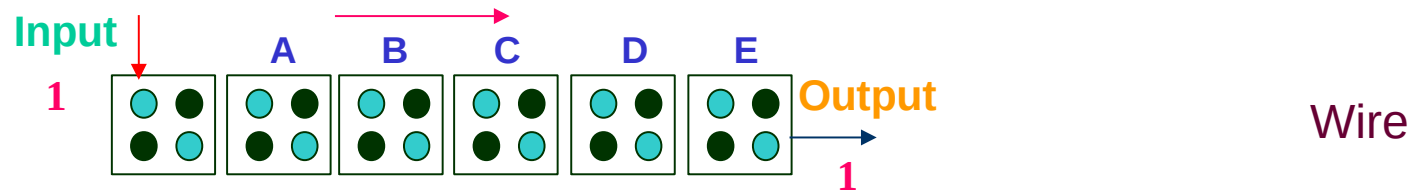
Cell-to-cell response is computed by solving two particle Schrodinger equation

Signal Propagation

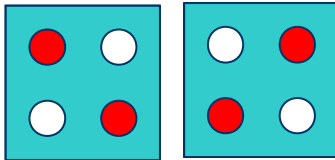


Circuit partitioned into Clock Zones. Cell A and E are in same Zone

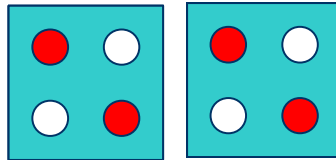
Signal Propagation



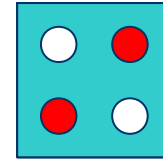
Signal Propagation



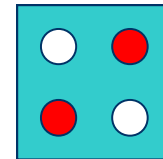
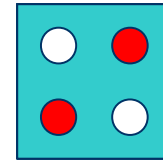
Unstable



Stable

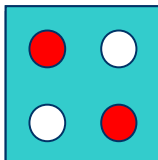
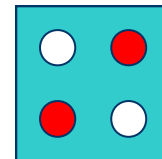
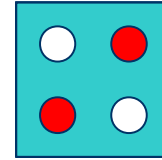
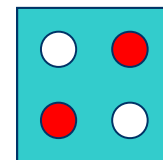


Stable

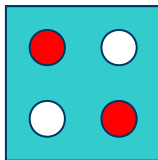


Unstable

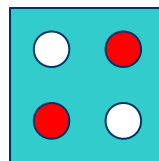
Stable



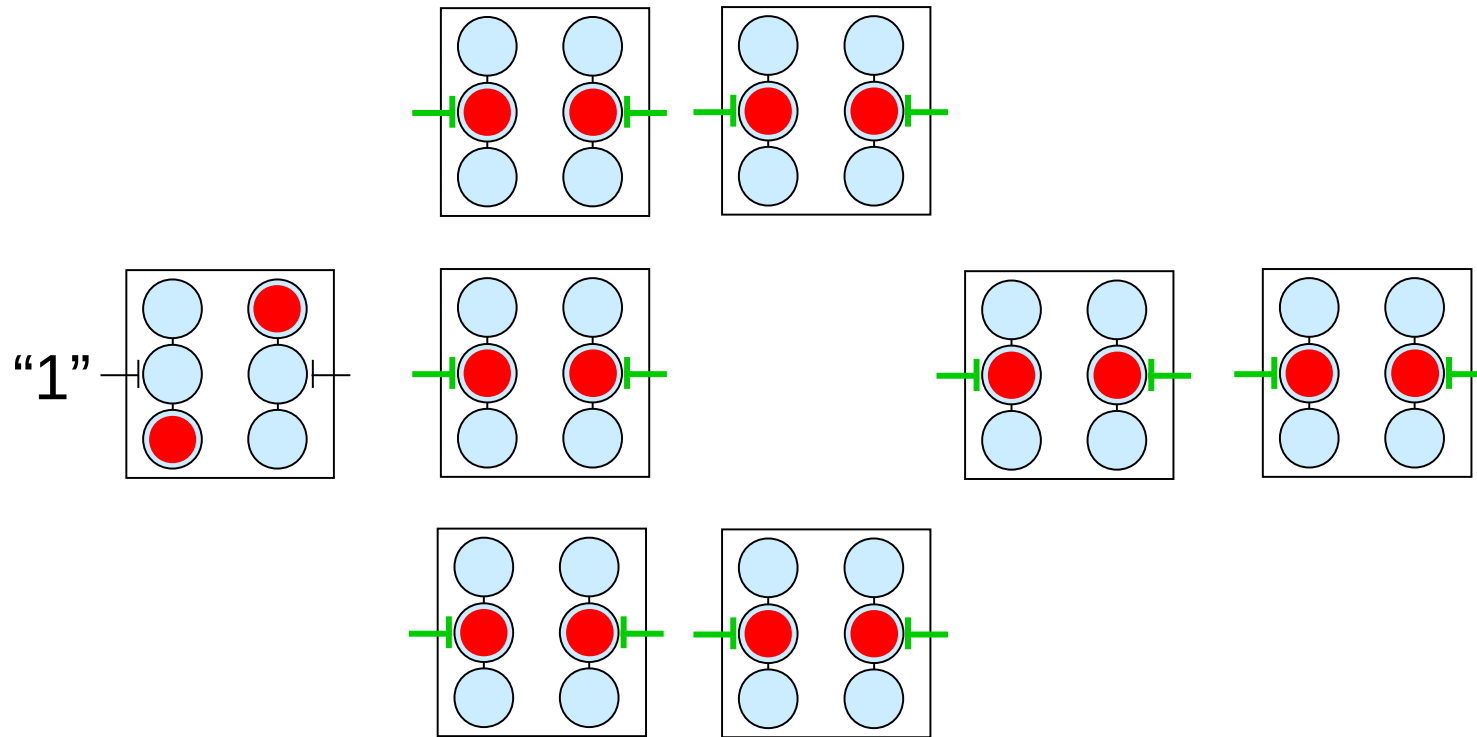
Unstable



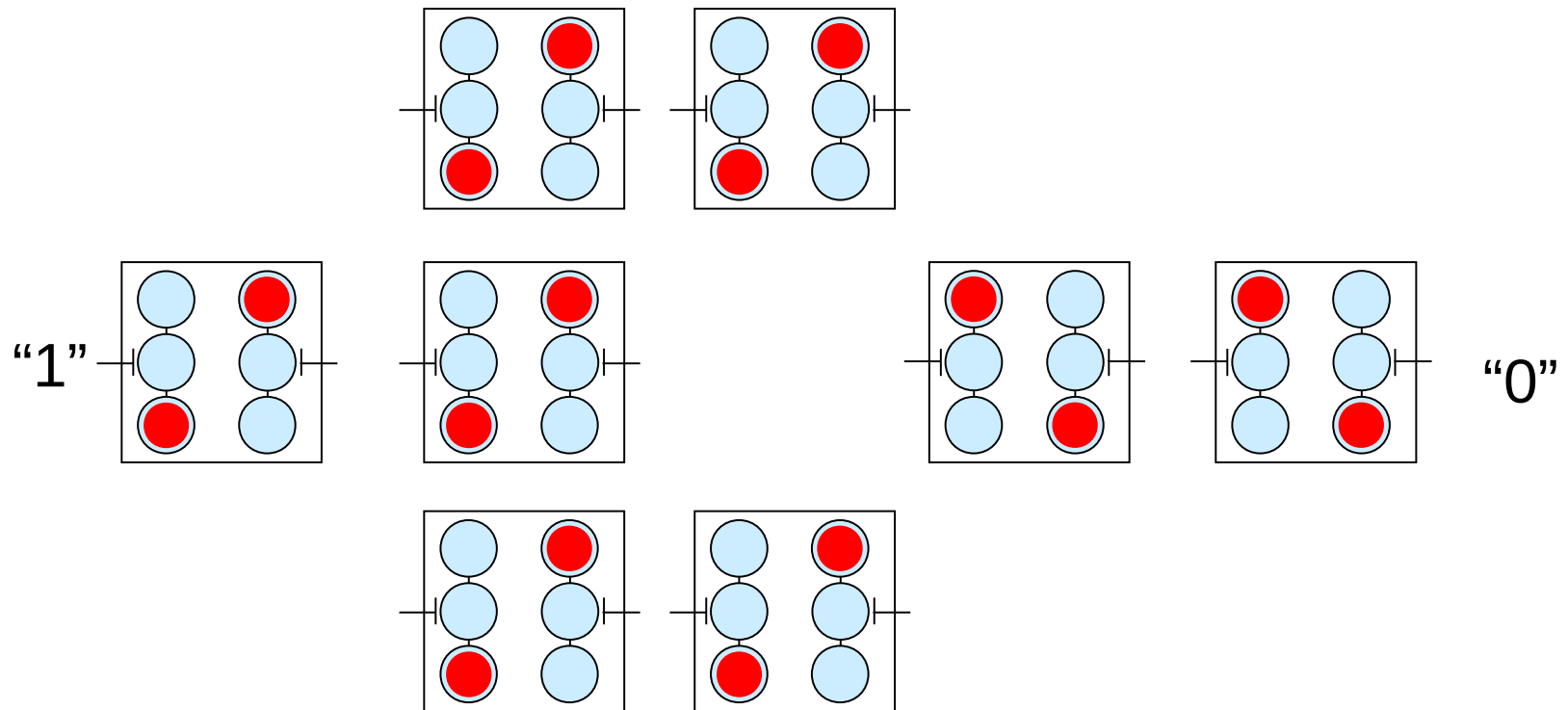
Stable



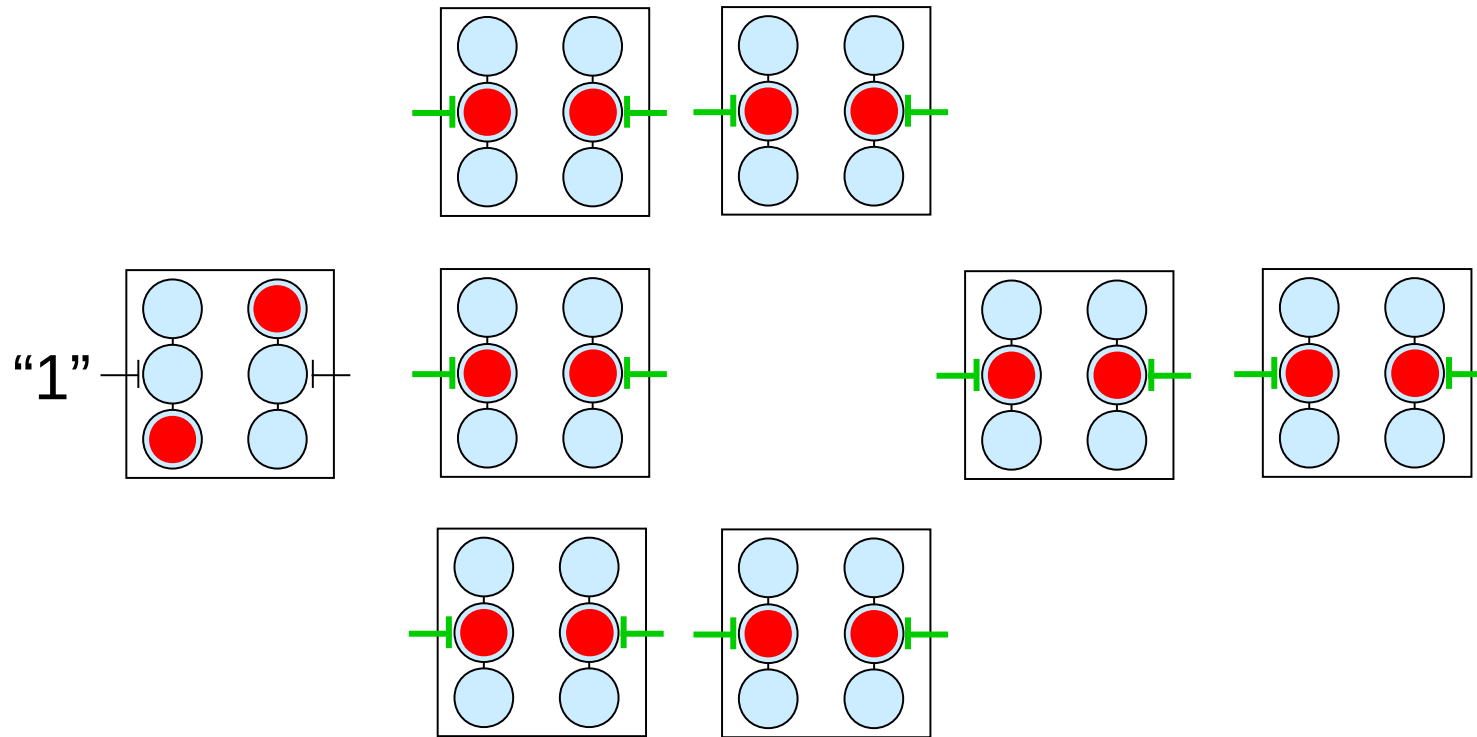
Signal Propagation



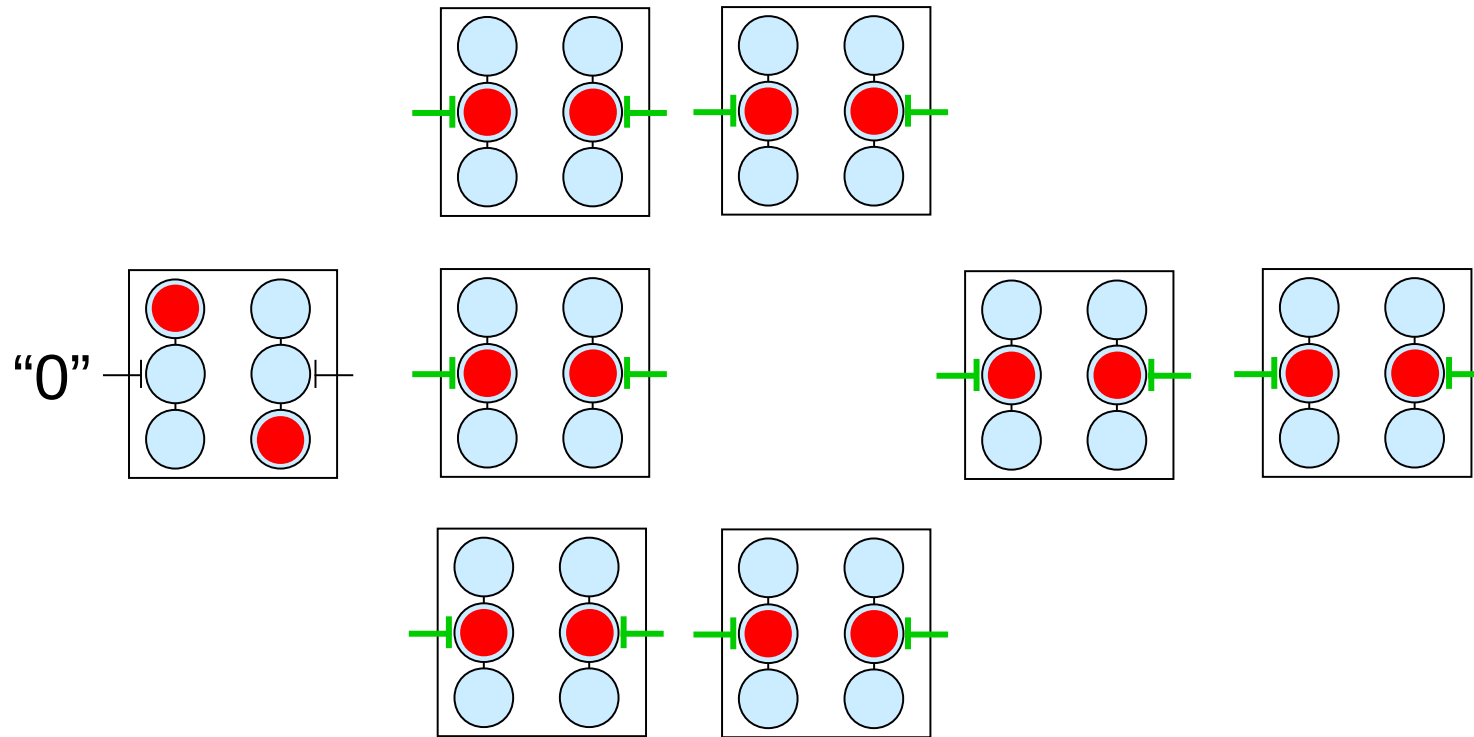
Signal Propagation



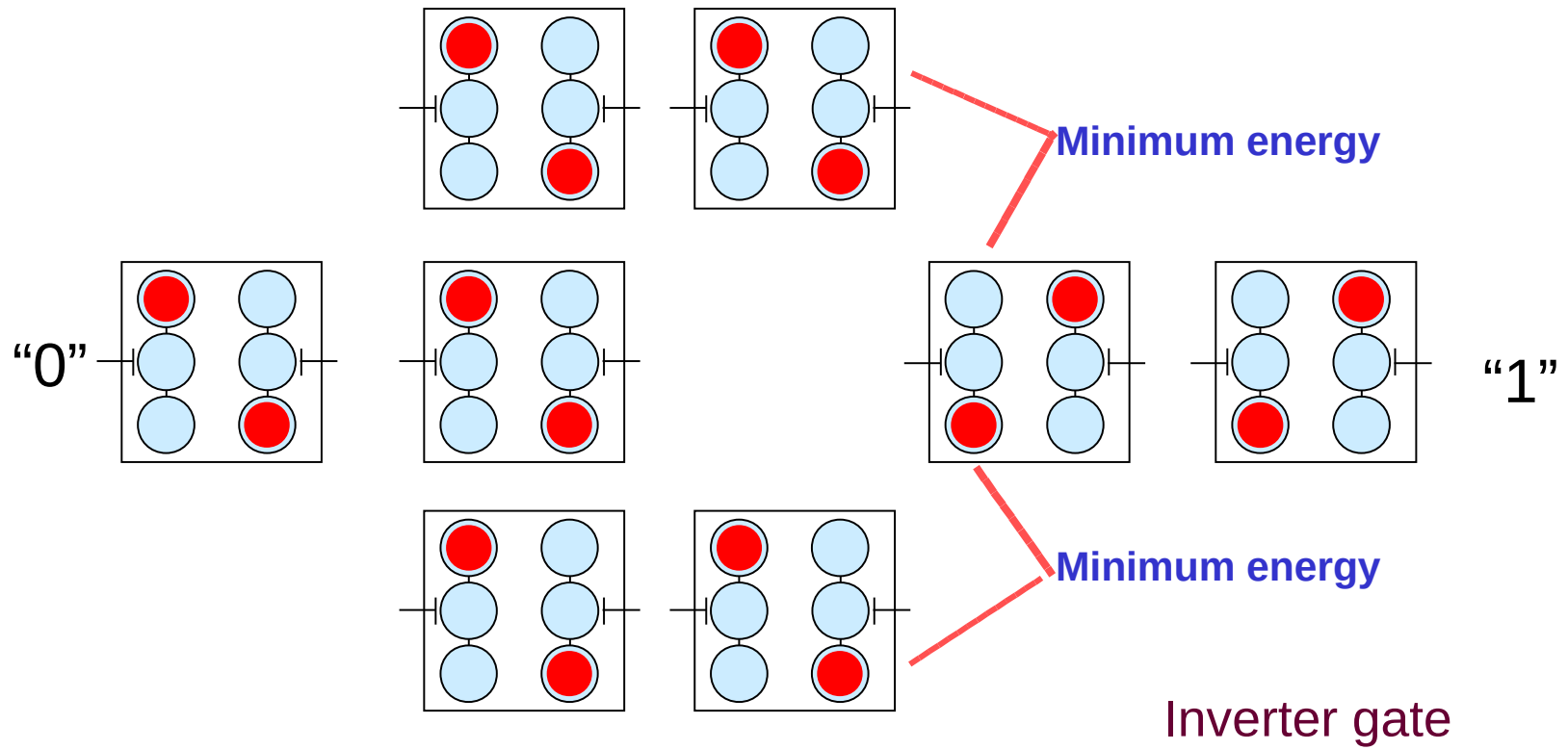
Signal Propagation



Signal Propagation

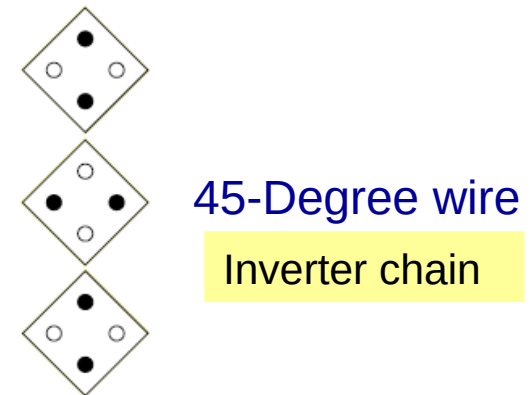
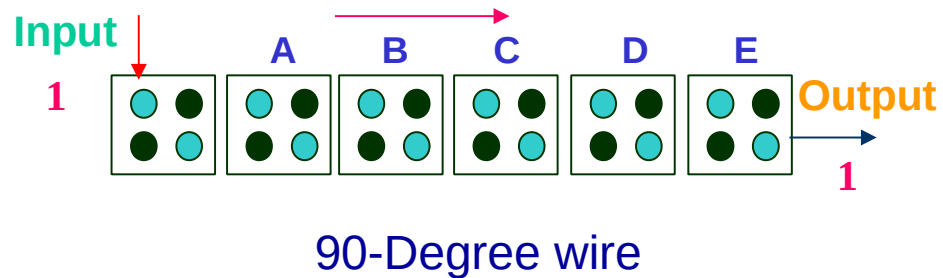


Signal Propagation

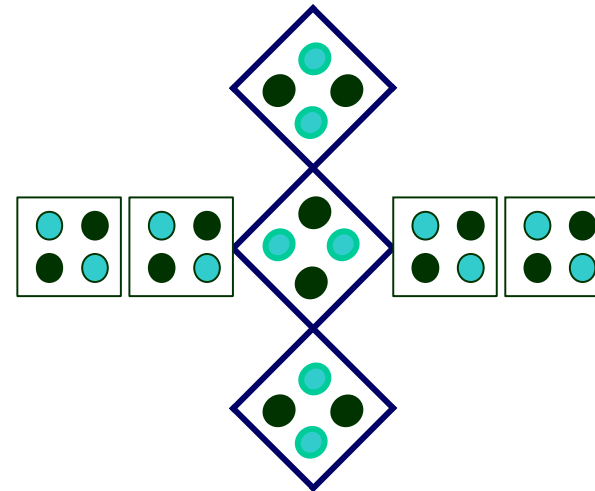


Basic QCA Devices

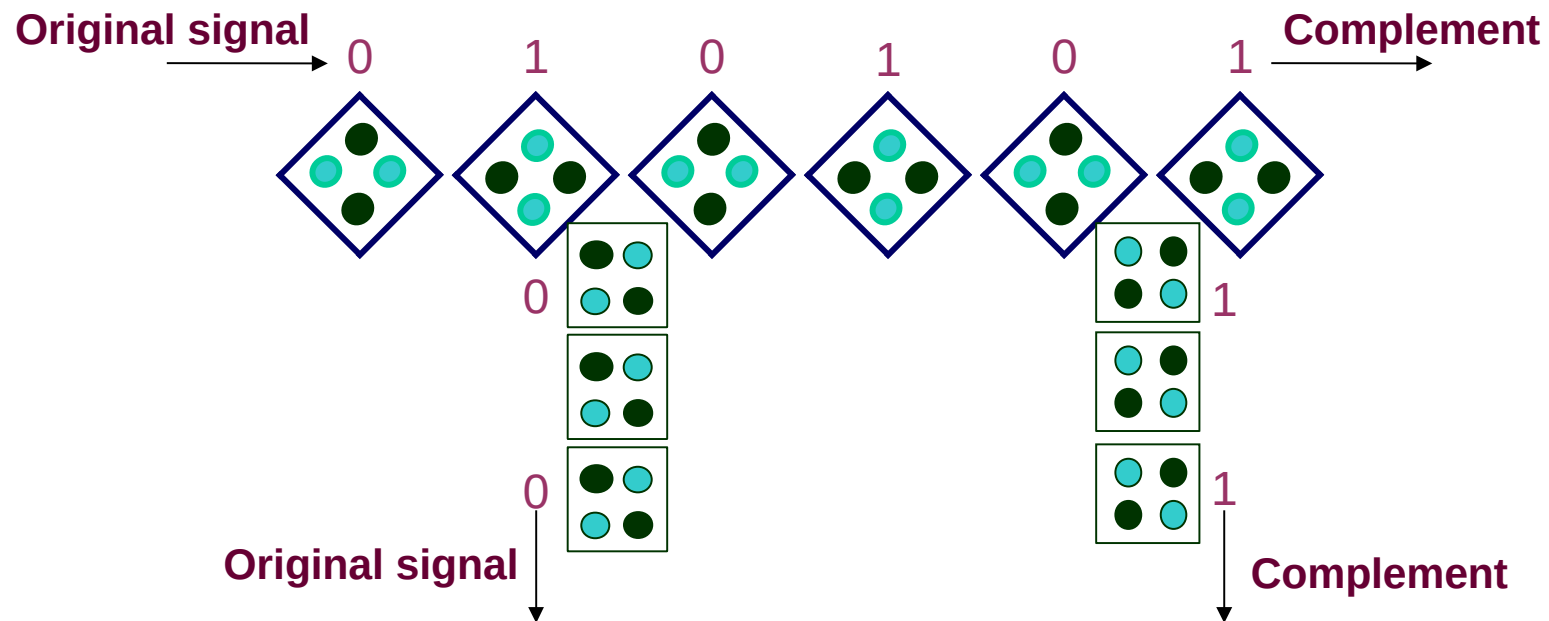
- Wires are the string of QCA cells



- Coplanar wire-crossing



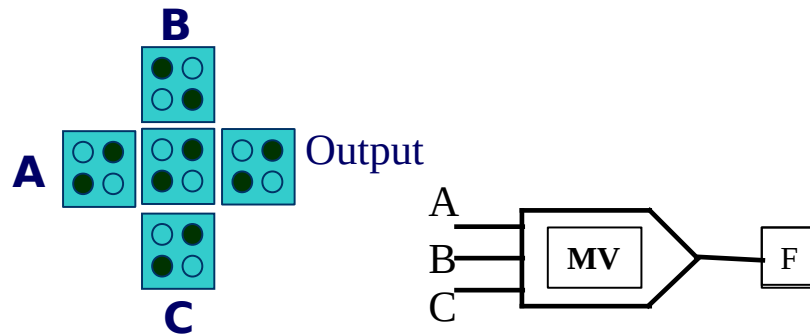
Basic QCA Devices



Processing-By-Wire (PBW)

Basic QCA Devices

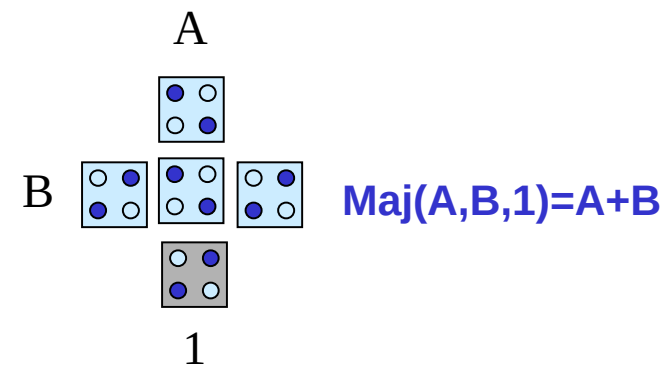
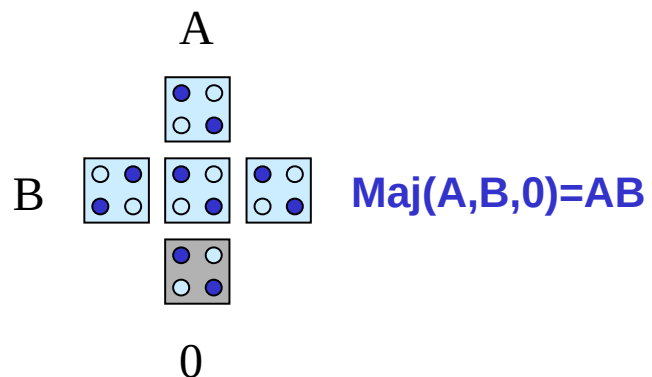
QCA Majority Gate



The basic logic gate in QCA

$$\text{Maj}(A,B,C)=AB+BC+CA$$

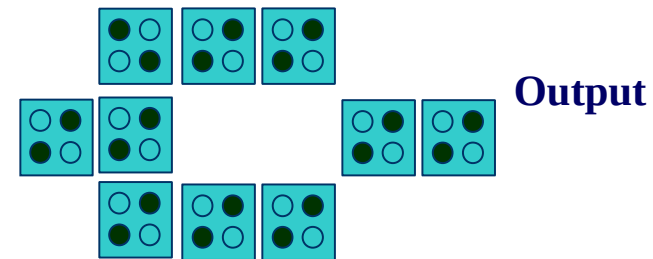
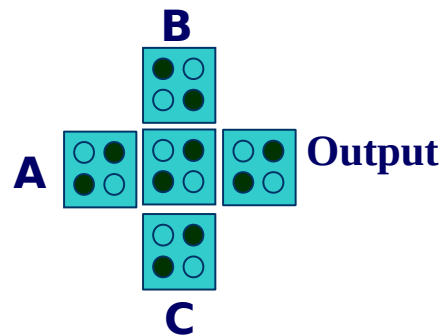
No built-in VDD or ground lines



Not universal. Not favourable for synthesis by existing tools

Basic QCA Devices

QCA Majority Gate + QCA inverter = Universal Gate



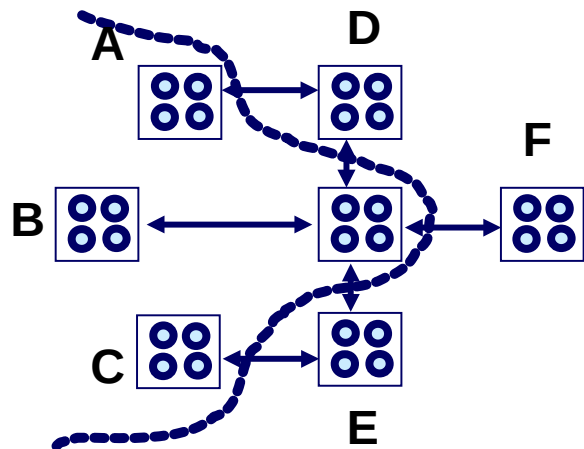
QCA Inverter is costly

Employed for QCA logic design

Universal gate structures are desirable

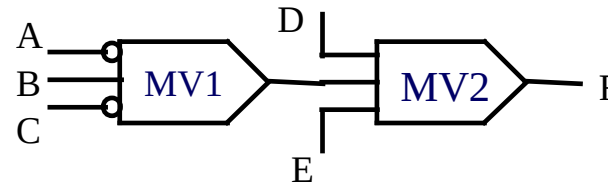
Basic QCA Devices

AOI Gate: Universal Gate



Cell B has stronger effect on device

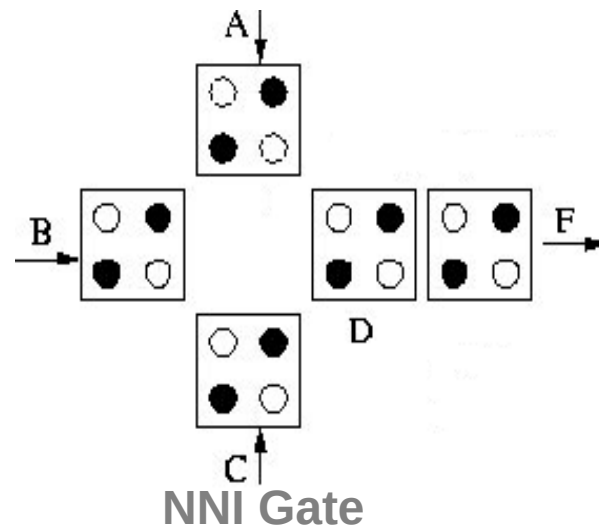
1. Five input cells
2. A & C have inverting effect
3.
$$F = DE + (D + E)(A'C' + A'B + BC')$$
$$= \text{Maj}(D, E, \text{Maj}(A', B, C'))$$



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

Basic QCA Devices

Nand Nor Inverter [NNI] Gate



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

- Universal gate
- More stable than the AOI

QCA Tiles

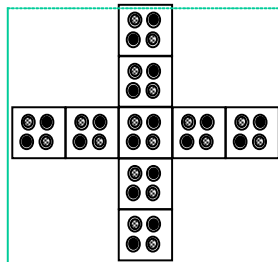
- Molecular implementation of QCA has been proposed

[Lieberman et. al, 2002 & 2003]

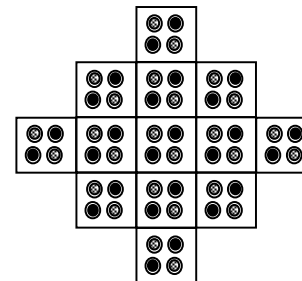
- Molecular implementation targets modular design

SQUARES (5X5 grid)

[Fountain et.al GLSVLSI, 1999]

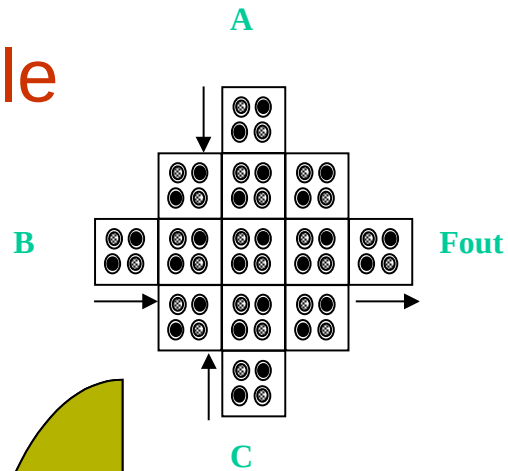


Tiles (3X3 grid) [J. Huang et. al, Nanotechnology Conf 2005]

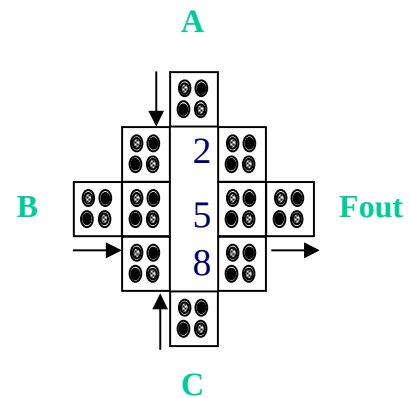


Tiles implementing universal logic gate functions are of interest

NNI Tile

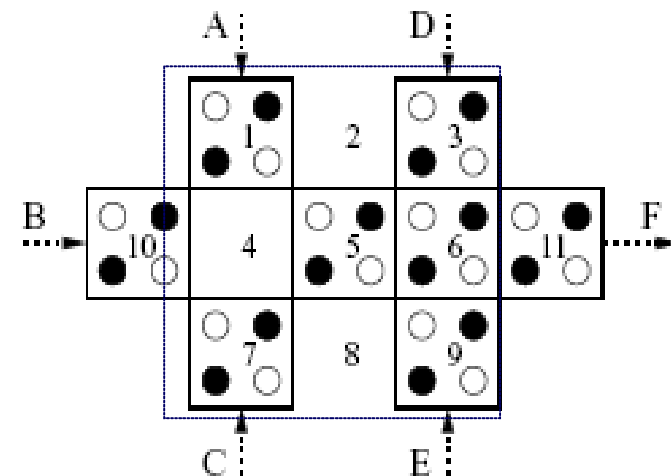
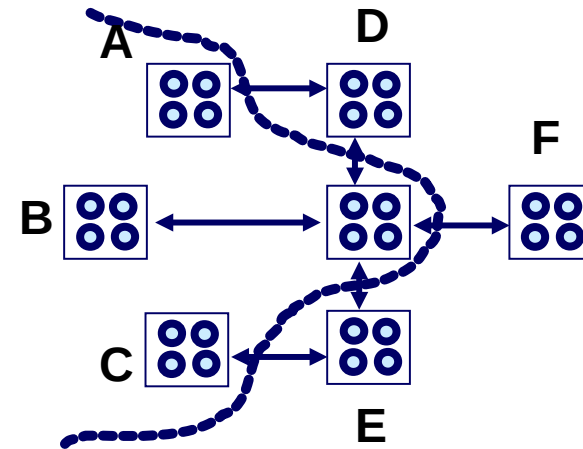


Orthogonal Tile



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

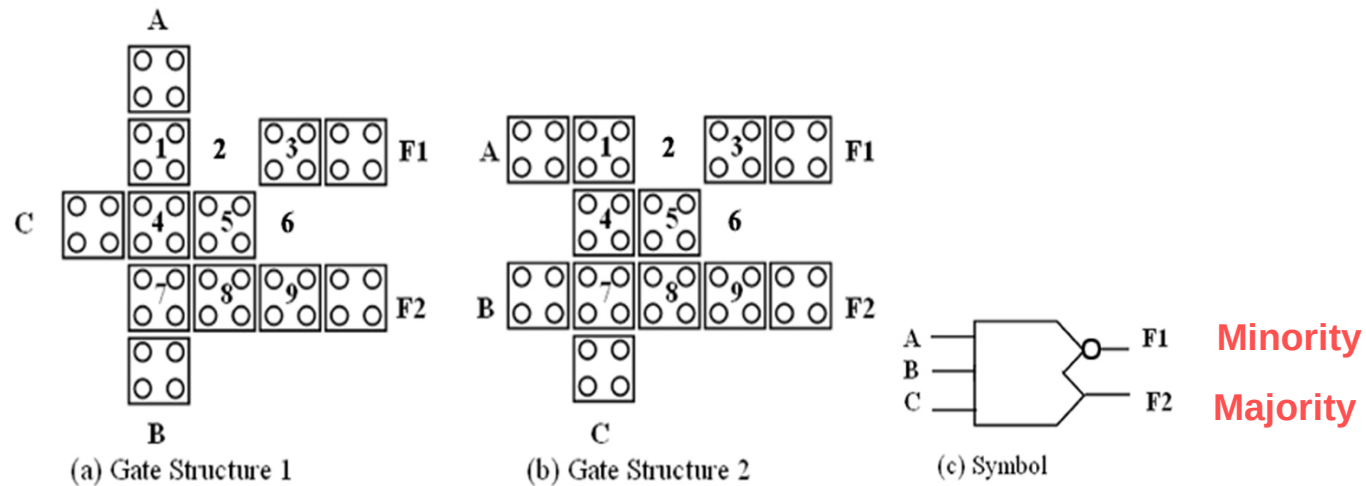
AOI Tile



New stable AOI gate structure

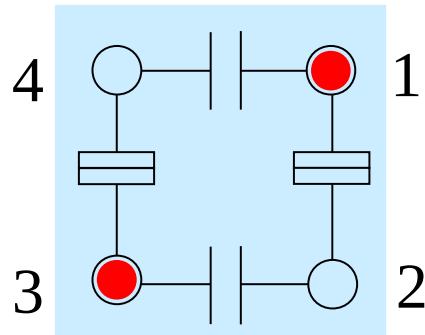
Coupled Gate

CMVMIN gate structure [Ditti, VDAT, 2008]



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

$C=0$ $F1 = (A+B)'$:**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 $P = -1$