Self-Repairing and Self-Replicating Hardware: The Embryonics Approach

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Caenorhabditis Elegans

11 December 1998
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C. elegans
Sequence to Biology
American Association for the Advancement of Science

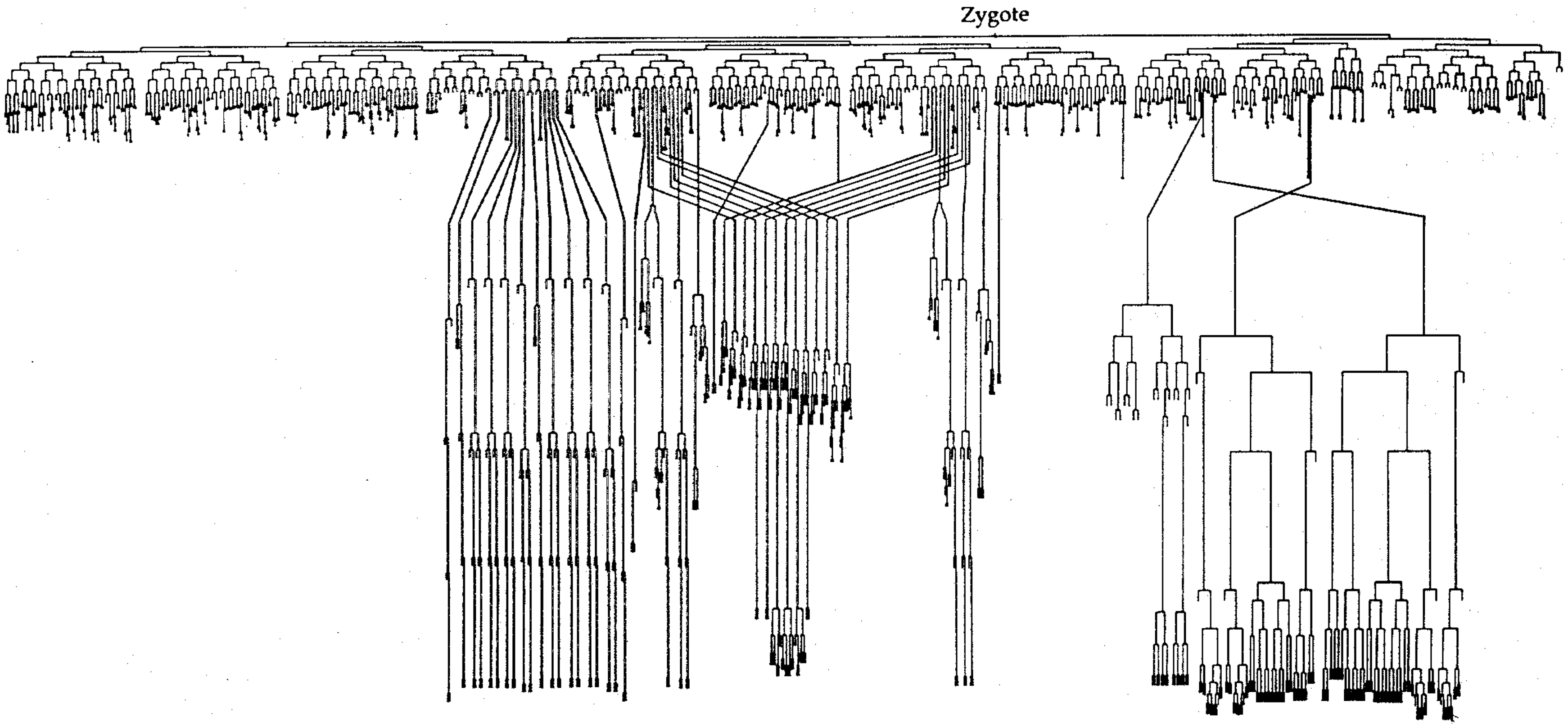
We understand completely the chromosome and role of the genes in the organism of the Elegans!

Model for studies in genetics

11 December 1998

Multicellular Organization

FIGURE 16
Entire cell lineage chart for C. *elegans*. Each vertical line represents a cell; each horizontal line represents a cell division. (From Sulston et al., 1983.)



959 somatic cells

Embryonics: Why?

Design of robust integrated circuits able to:

- self-repair (healing)
- self-replicate (cloning)

Embryonics: Why?

Today:

- space exploration
- nuclear plants
- avionics

Tomorrow:

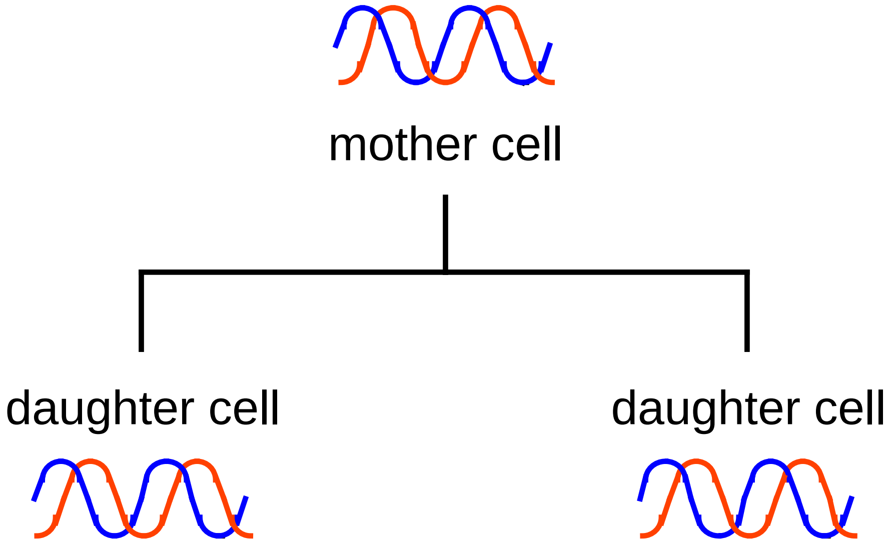
- molecular electronics

Embryonics: How?

Iterative electronic circuit based on 3 features:

- multicellular organization
- cellular division
- cellular differentiation

Cellular Division



mother cell

daughter cell

daughter cell

Cellular Differentiation

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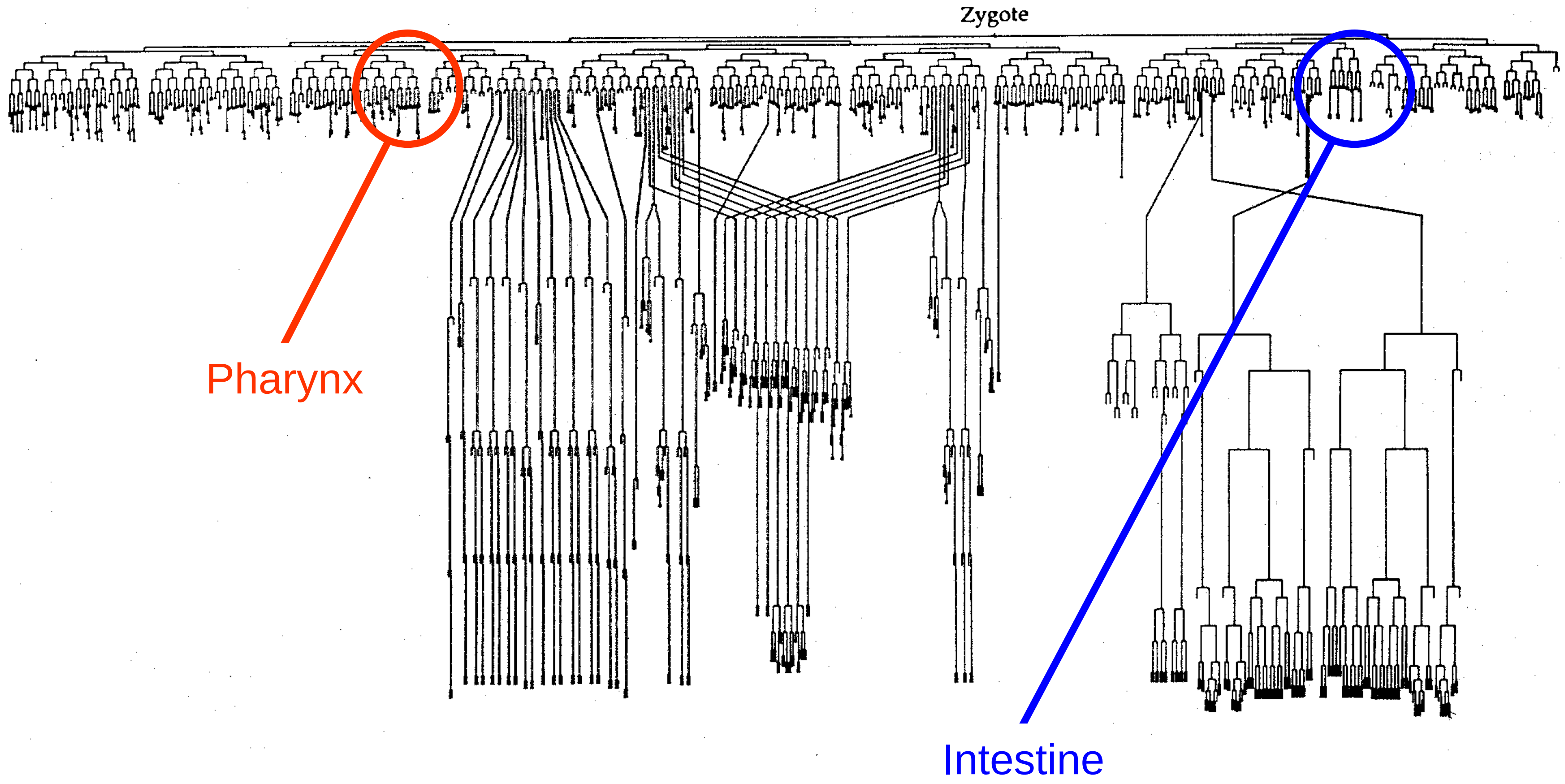
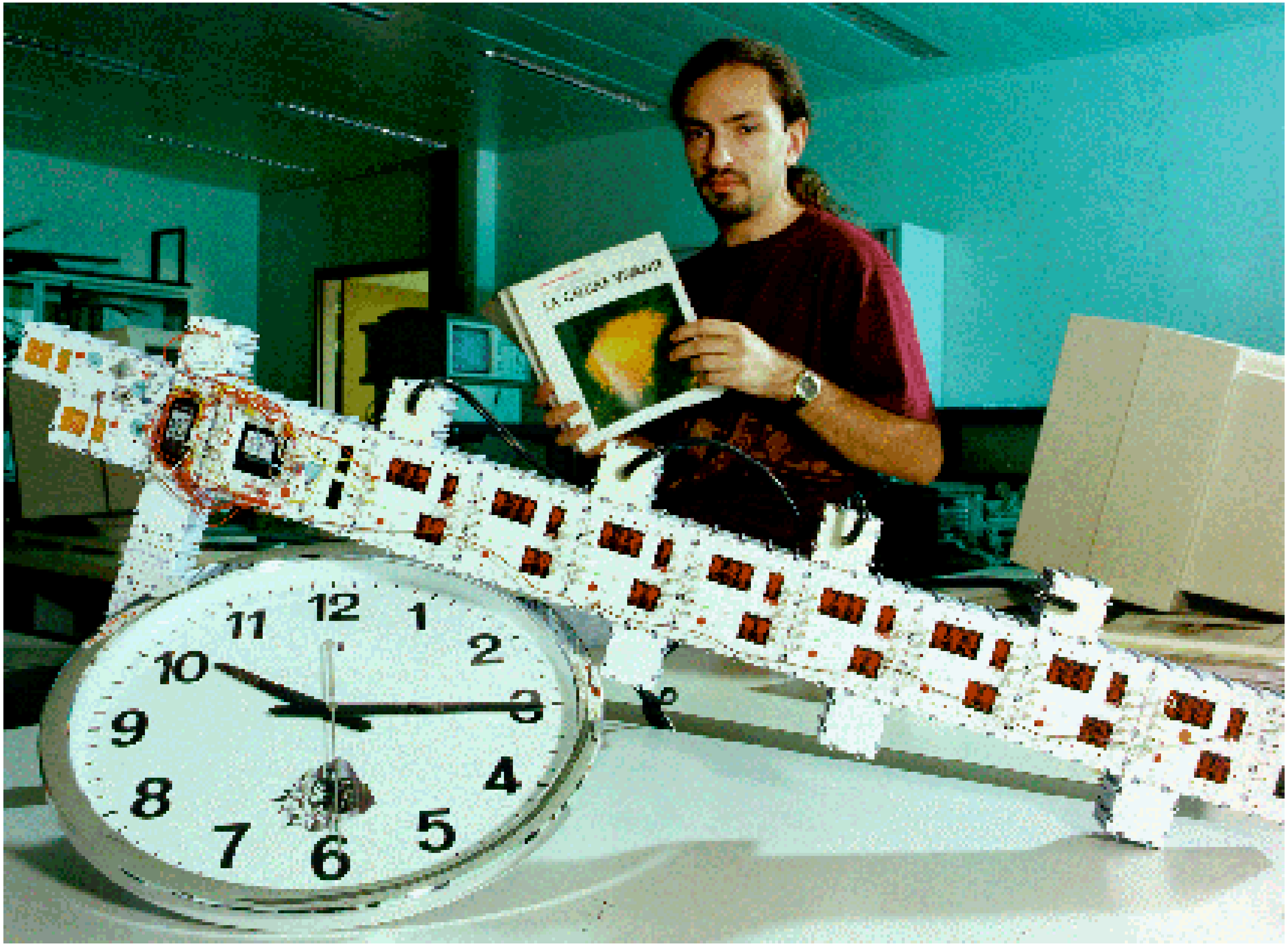
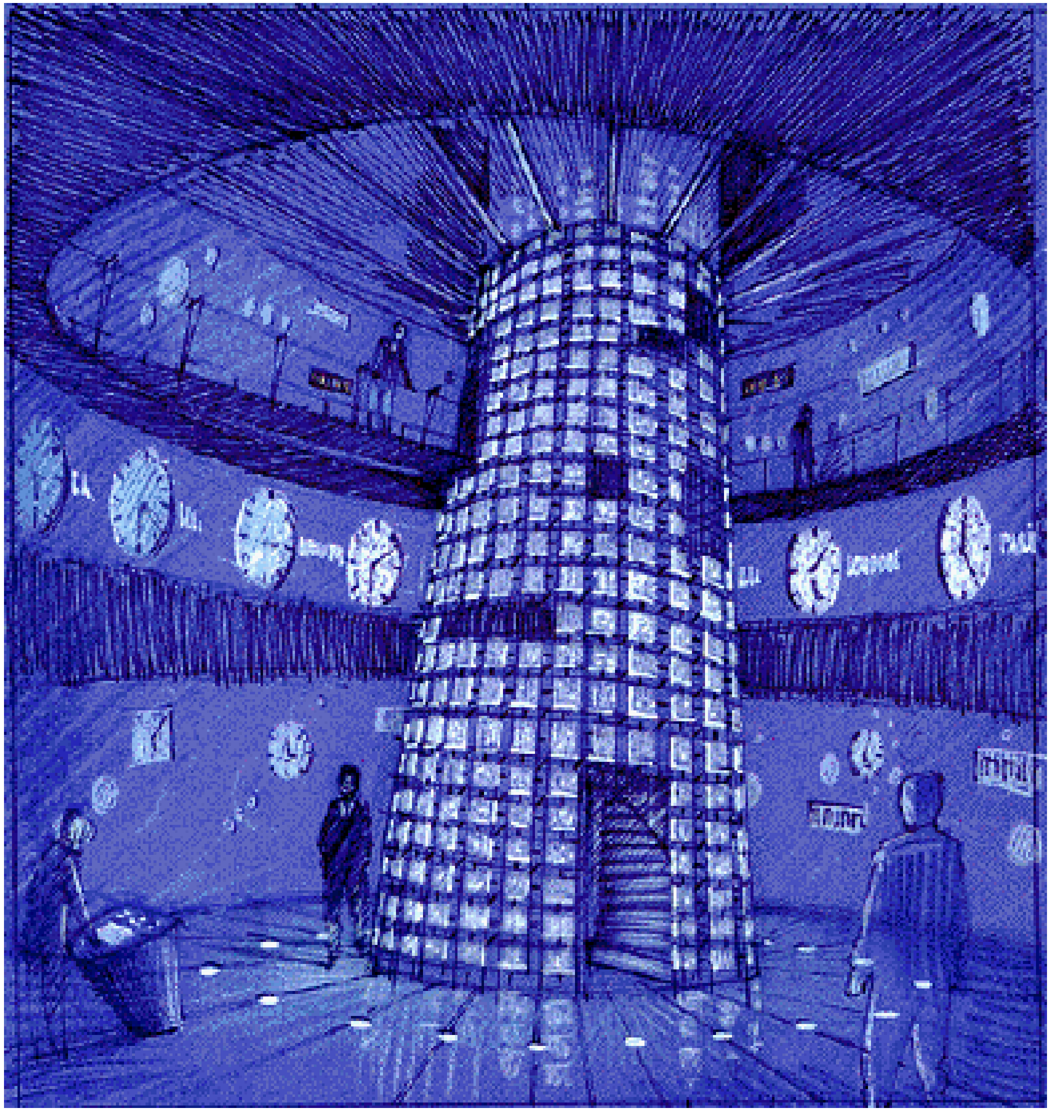


BioWatch



The Future of Embryonics

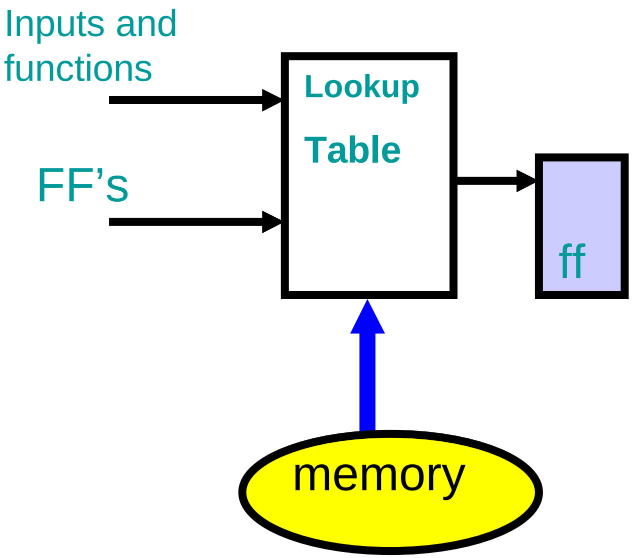


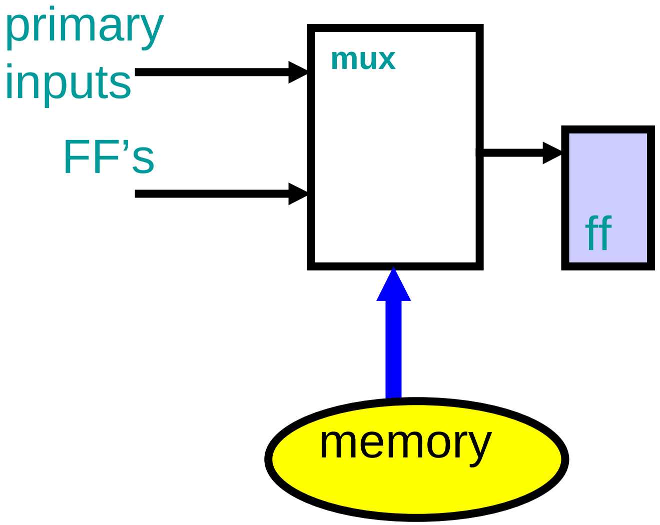
Two kinds of Programmable Arrays

Based on logic functions in cells

Based on switchboxes

Mixed

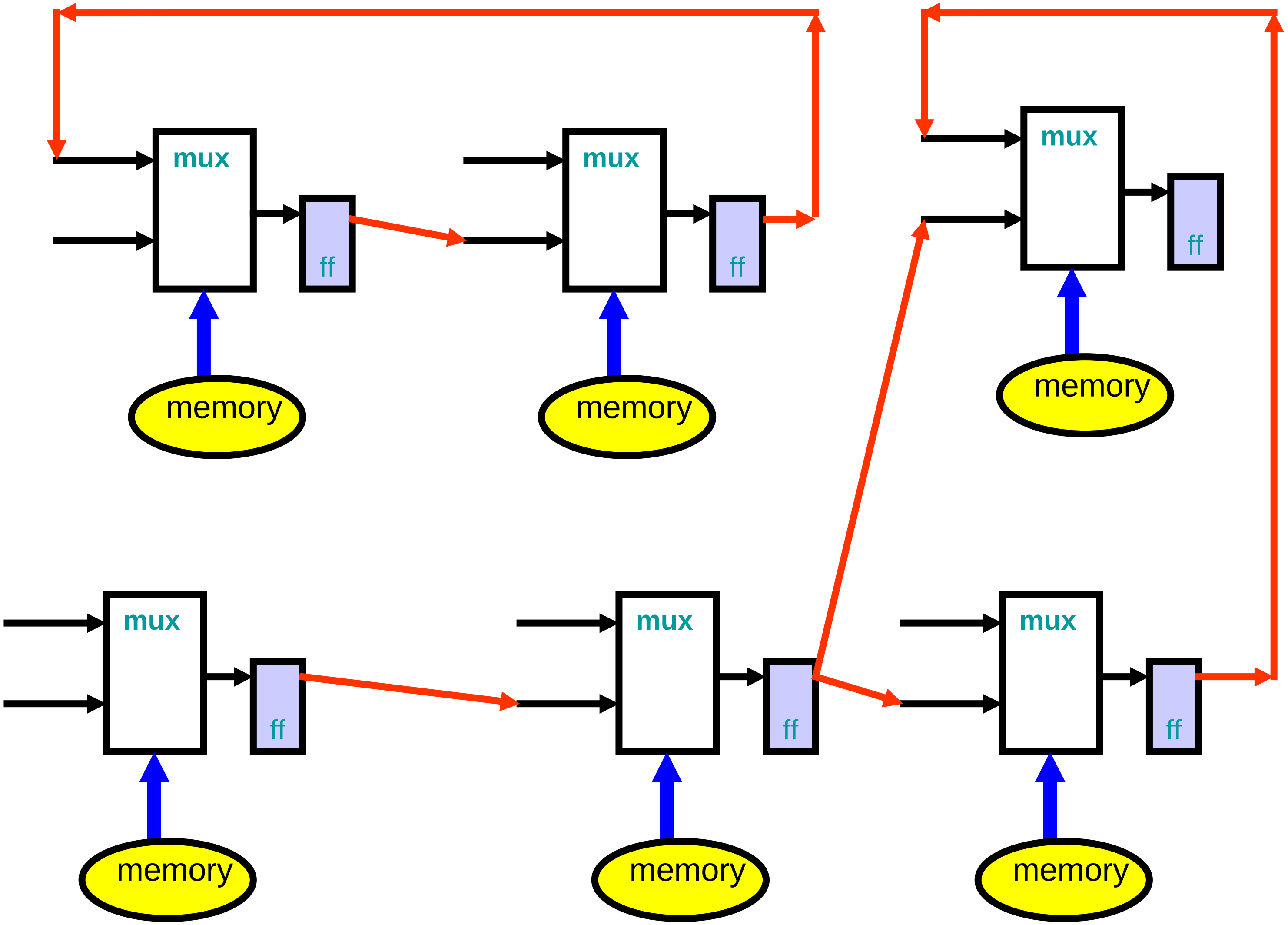


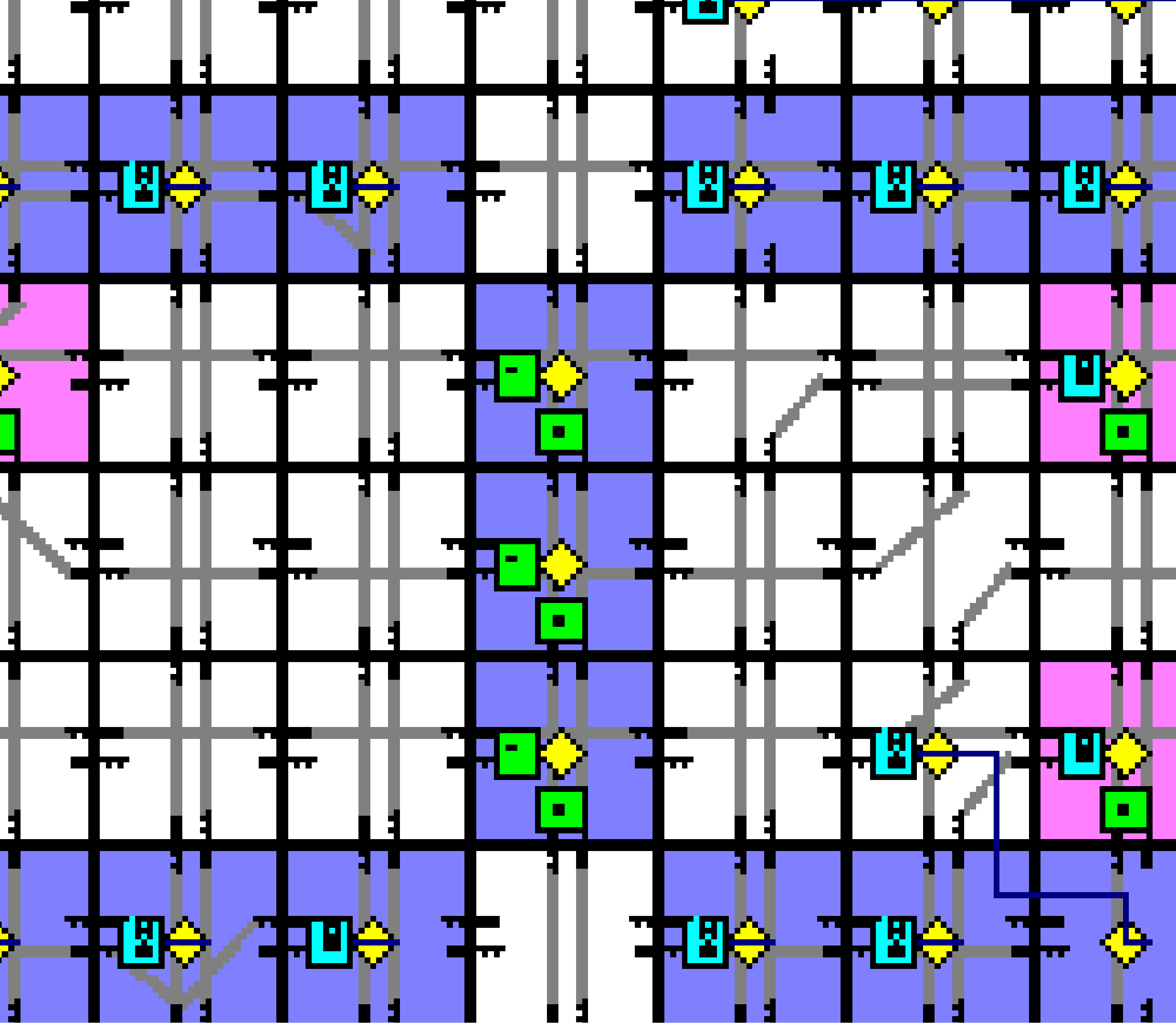


Based on logic functions

Based on switchboxes

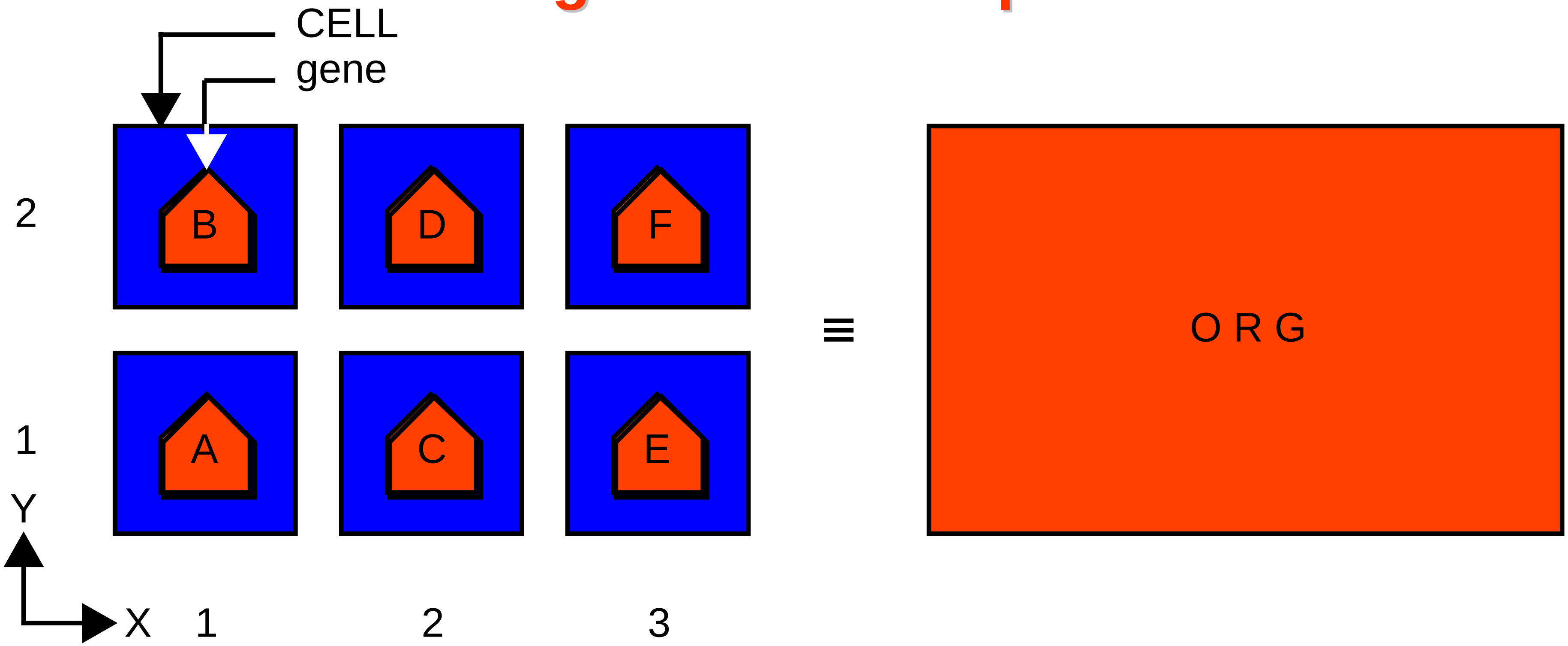
Based on switching





Multicellular Organization

Organism is composed of bio-cells



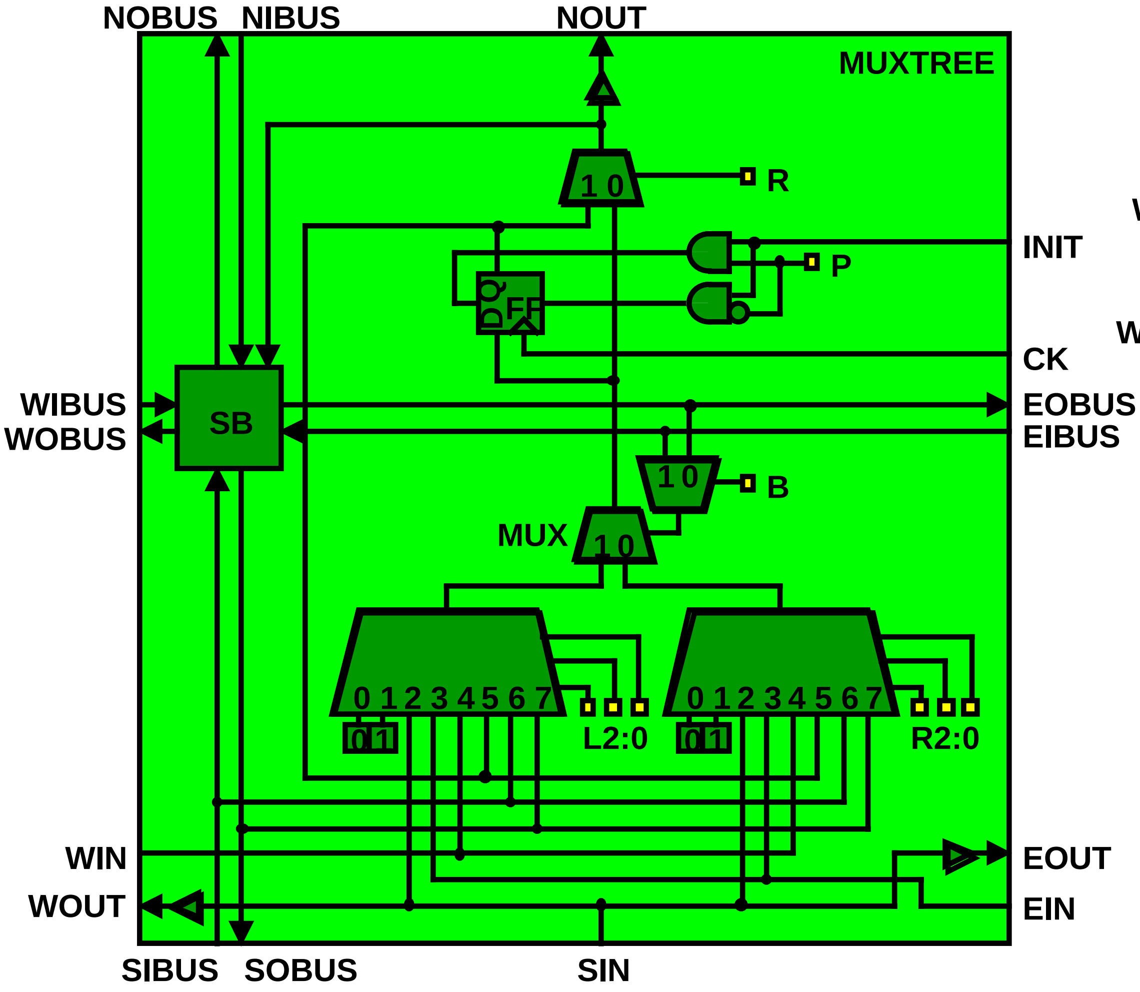
bio-cell = phenotype from genotype

bio-cell = logic circuit (virtual)

Chromosome = memory contents

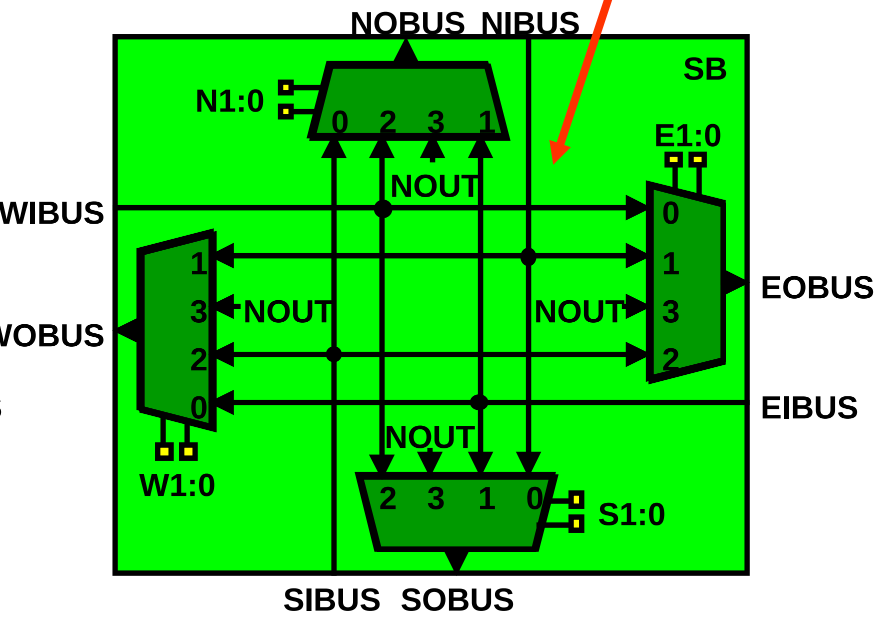
MUXTREE Molecule

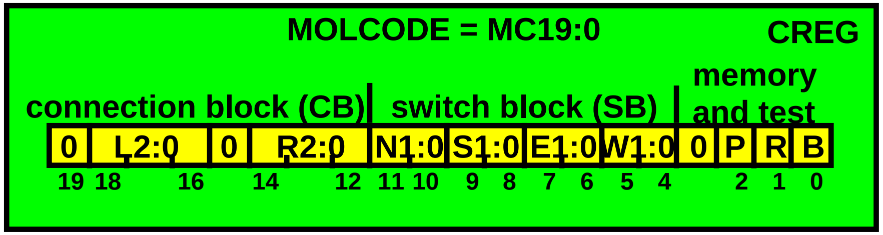
Bio-cell has several molecule cells like this



8 memory cells

Block SB





MOLCODE = MC19:0

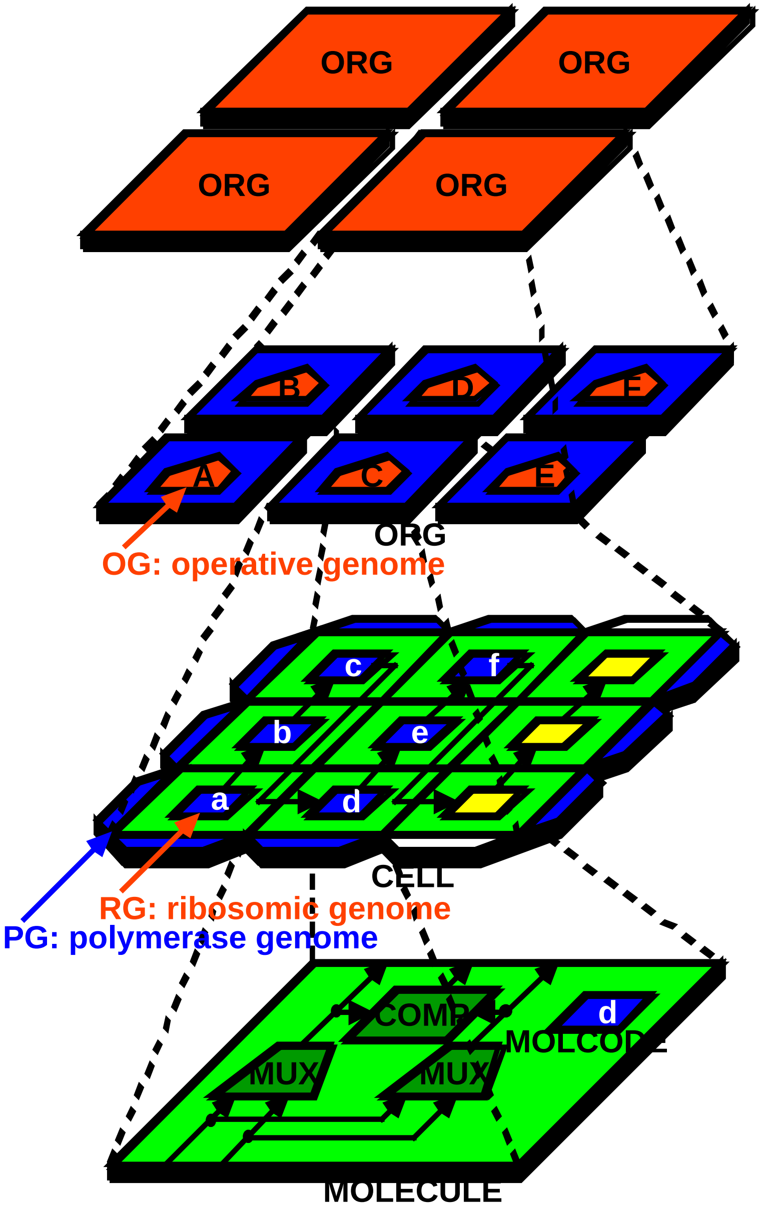
connection block (CB)				switch block (SB)				memory and test			
0	L2:0	0	R2:0	N1:0	S1:0	E1:0	W1:0	0	P	R	B
19	18 16	14	12	11 10	9 8	7 6	5 4		2	1	0

9 memory cells

9+8+3=20 memory cells

20 programming bits in memory of the molecule cell

Embryonics Landscape



Population level
(population = Σ organisms)

Organismic level
(organism = Σ cells)

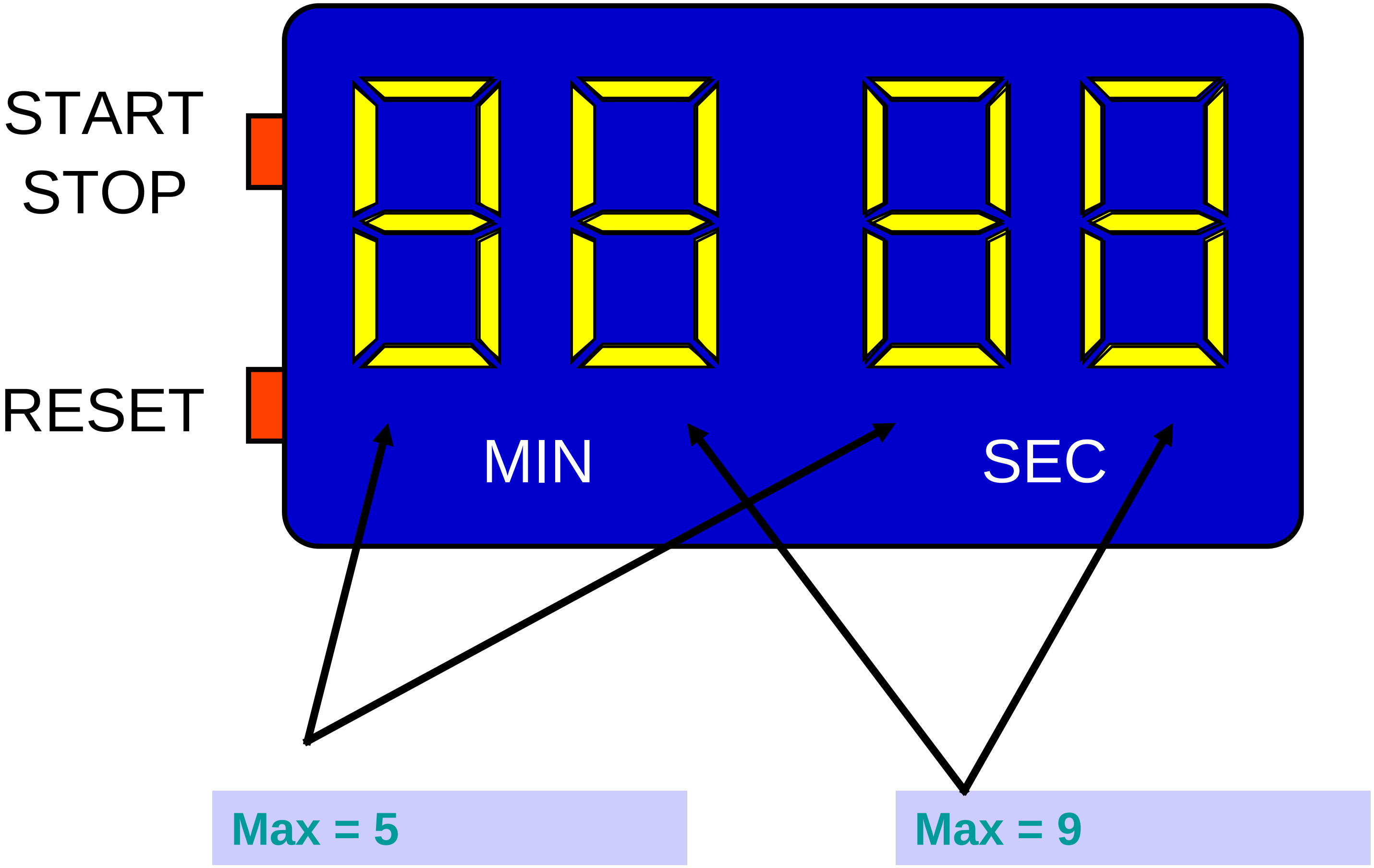
Operative genome is the same as chromosome in previous lectures

Cellular level
(cell = Σ molecules)

Molecular level
(basic FPGA's element)

Bio-cell is one or more FPGA cells

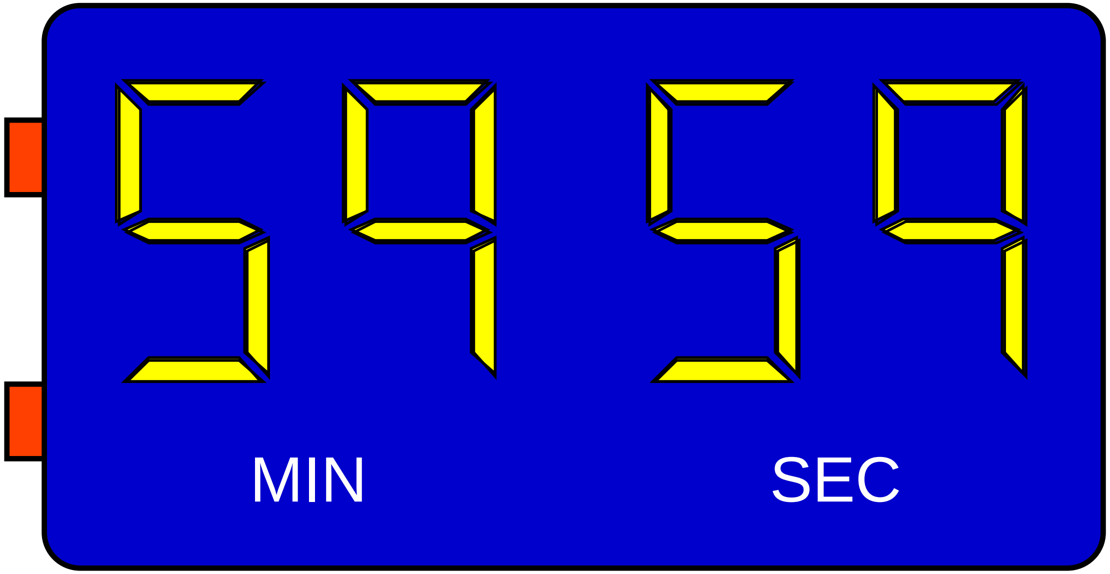
StopWatch



Max = 5

Max = 9

StopWatch

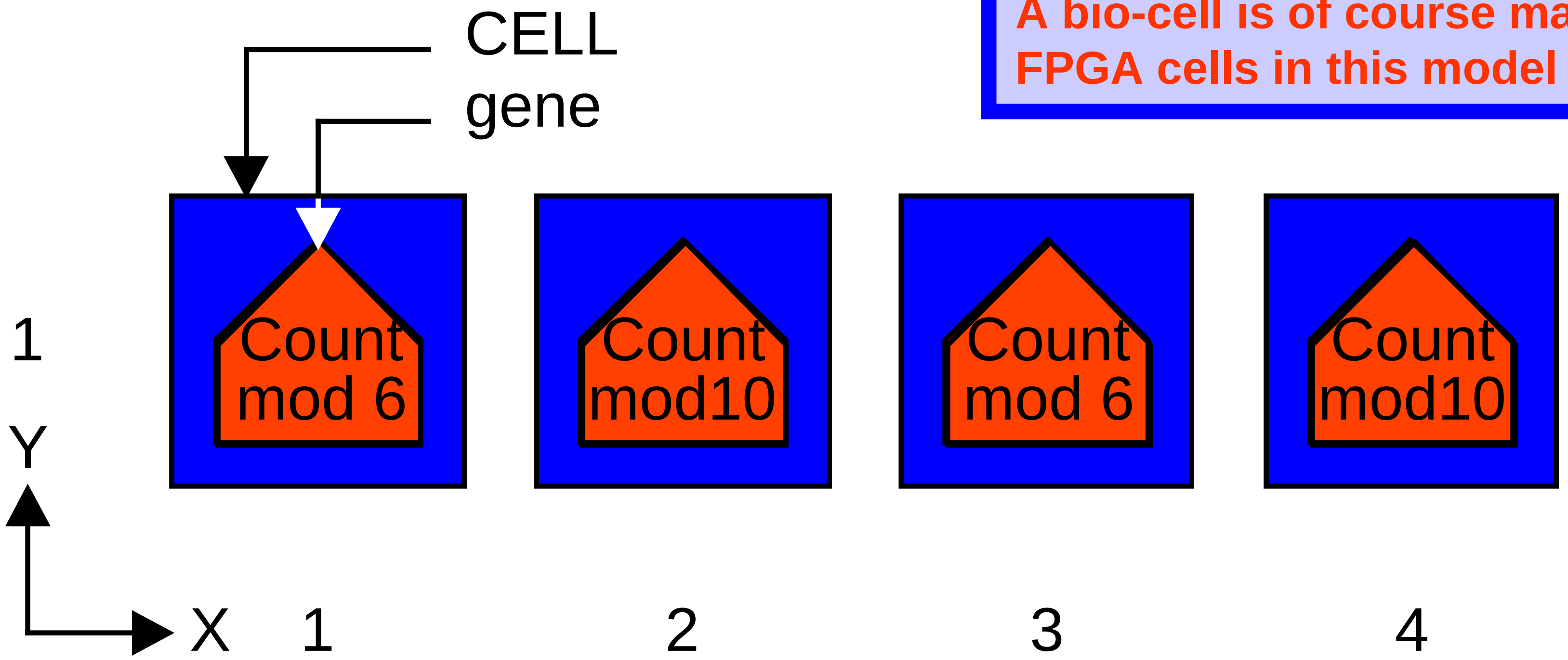


StopWatch

The whole counter is an organism

The component module 6 or module 10 counter is a bio-cell

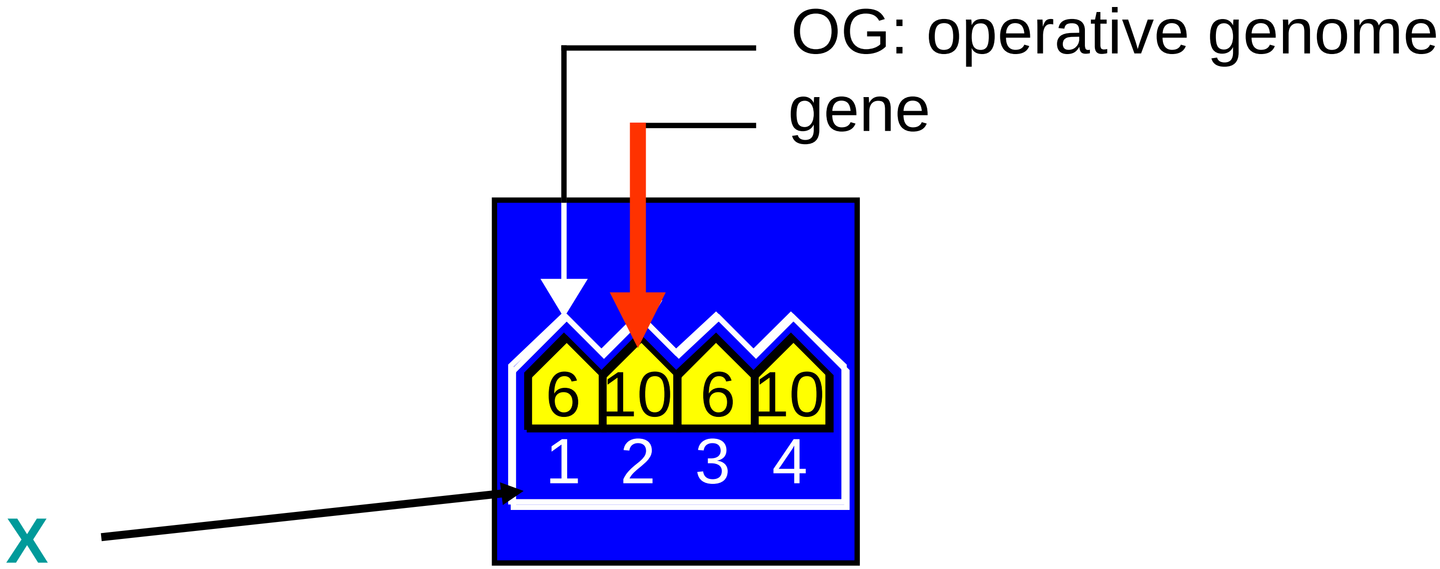
A bio-cell is of course many FPGA cells in this model



- The organizm is one-dimensional
- It has four bio-cells

- There are two types of bio-cells:
  - Count mod 6
  - Count mod 10

StopWatch



Operative genome => for organism

gene => for bio-cell of the organism

4 genes

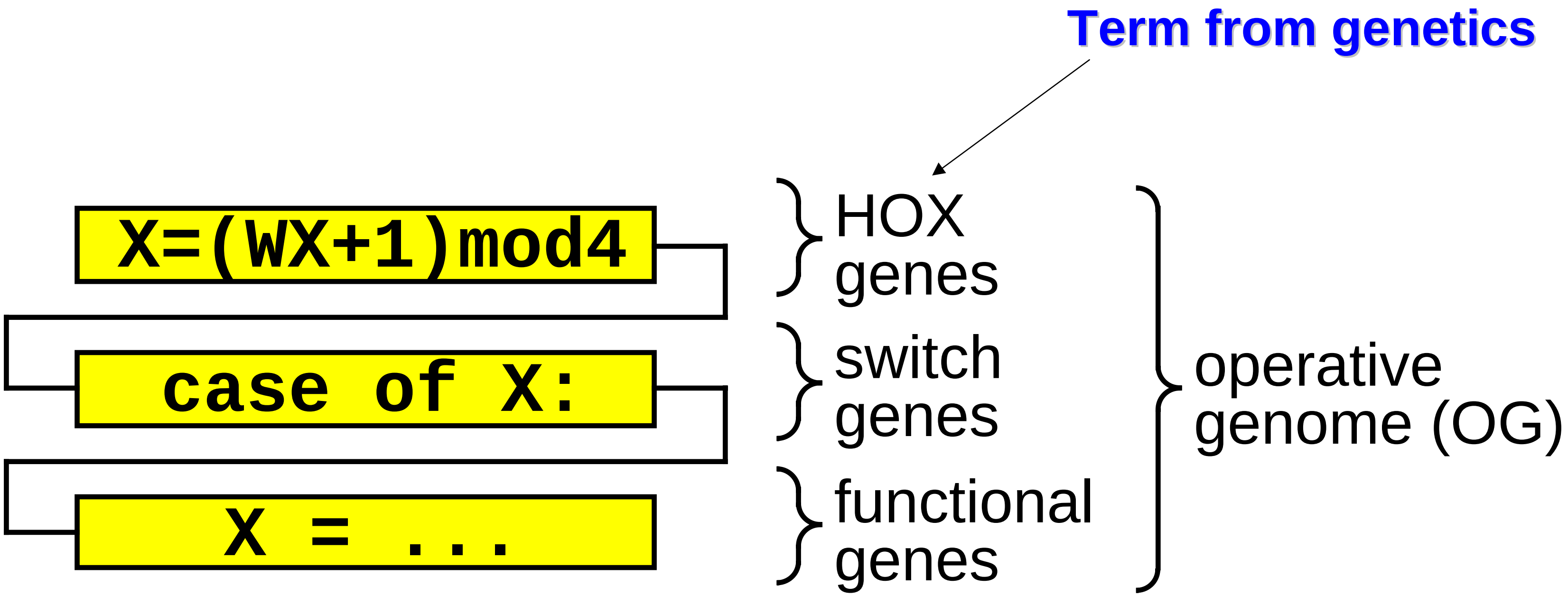
genes responsible for two types of bio-cells in the phenotype

StopWatch

```
OG: operative genome

case of X:
   X = 1: Countmod 6  (10 minutes)
   X = 2: Countmod 10 (minutes)
   X = 3: Countmod 6  (10 seconds)
   X = 4: Countmod 10 (seconds)
```

StopWatch



Term from genetics

```
X=(WX+1)mod4
case of X:
X = ...
```

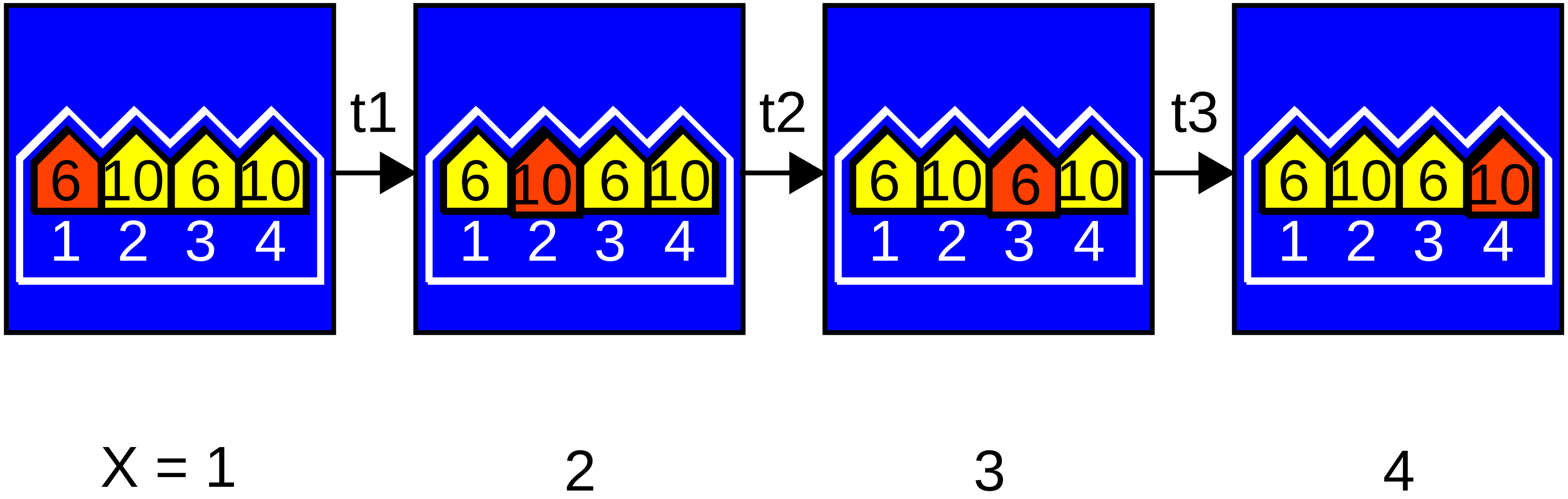
HOX genes

switch genes

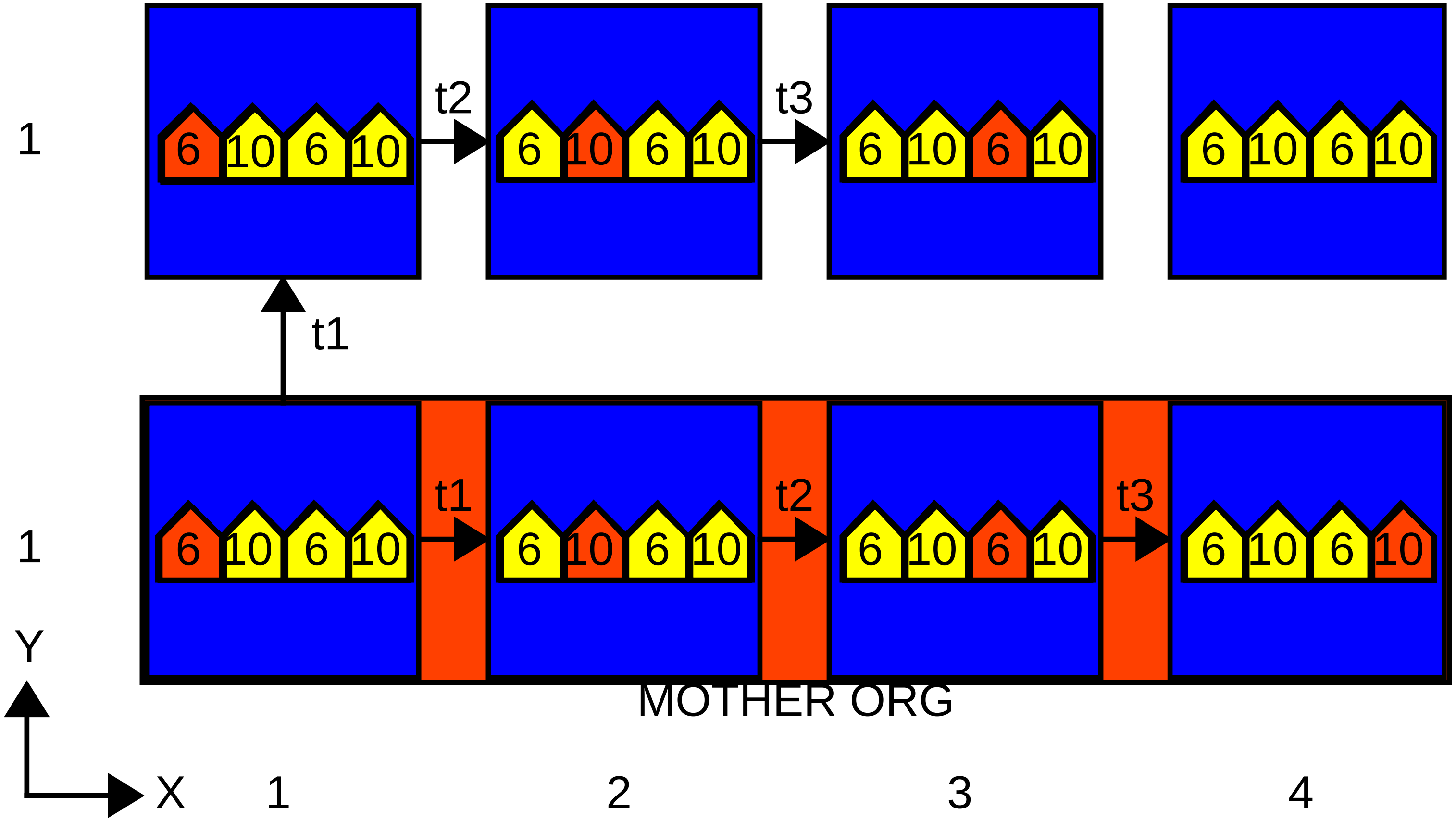
functional genes

operative genome (OG)

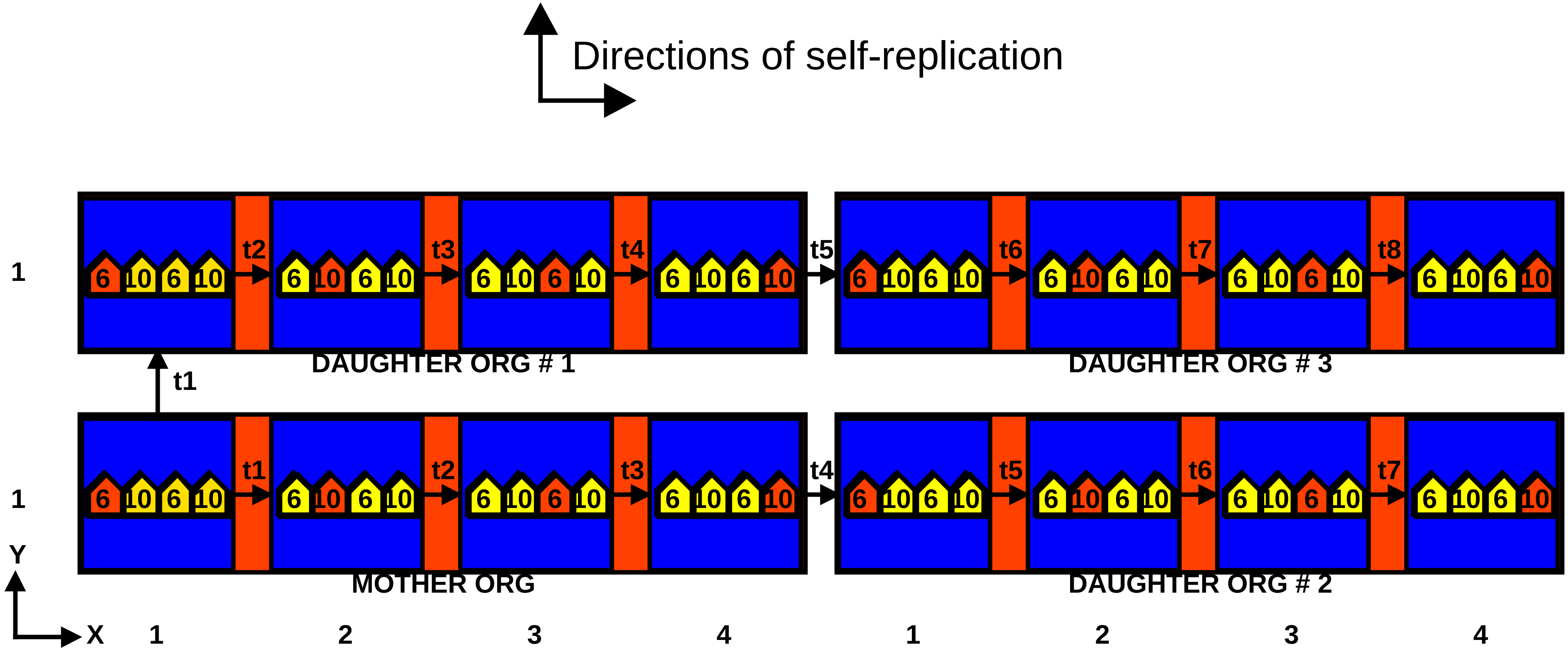
Cellular Differentiation



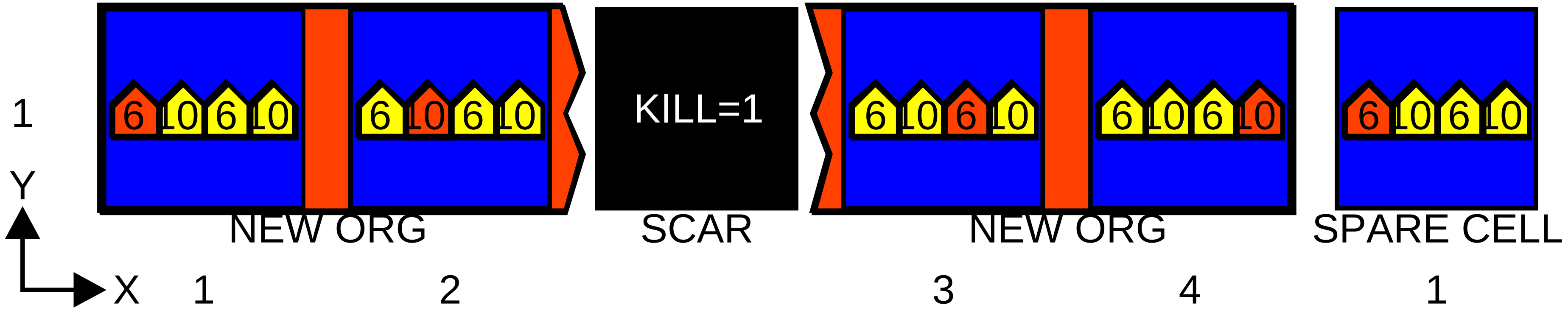
Self-Replication



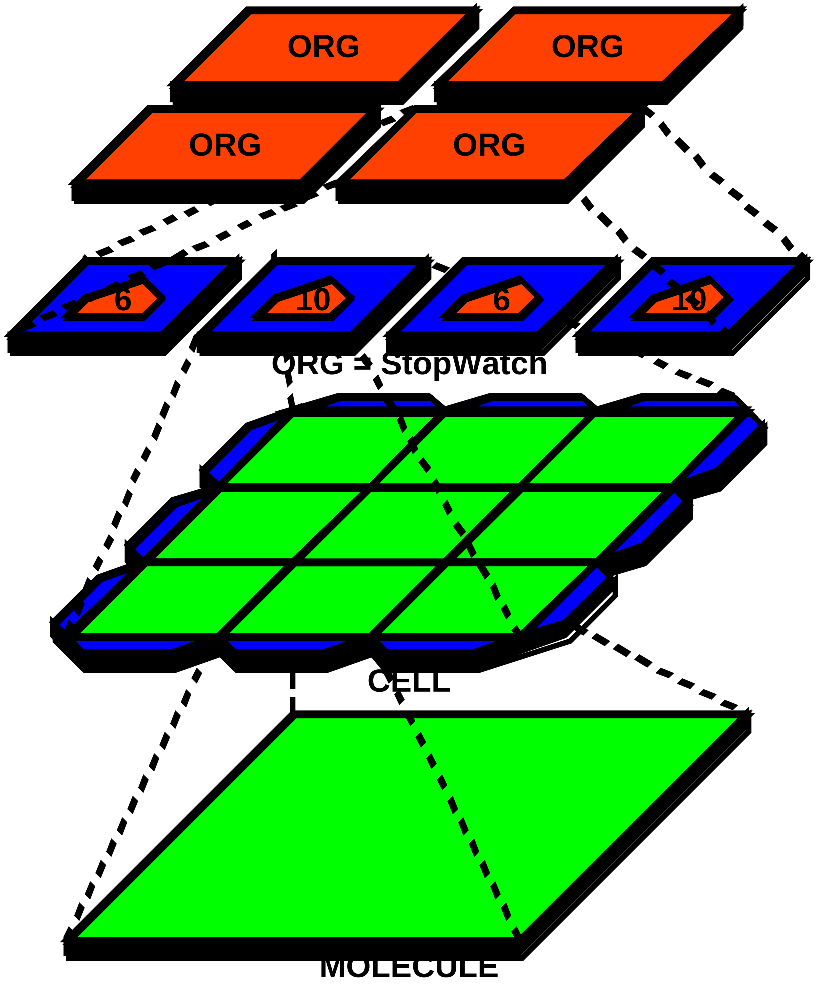
Self-Replication



Self-Repair


1
Y
X
6 10 6 10
6 10 6 10
KILL=1
6 10 6 10
6 10 6 10
6 10 6 10
NEW ORG
SCAR
NEW ORG
SPARE CELL
1
2
3
4
1

Embryonics Landscape



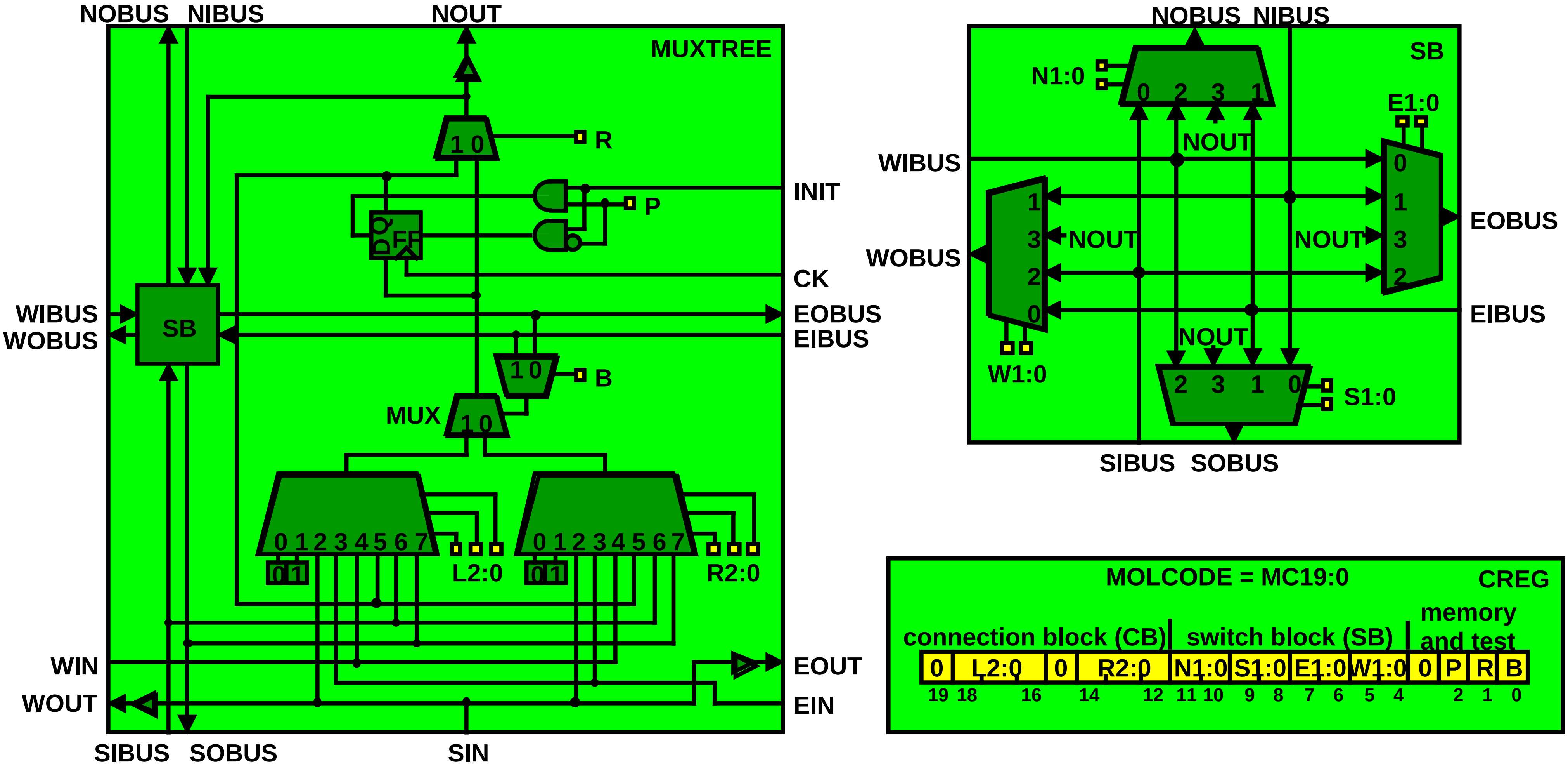
Population level
(population = Σ organisms)

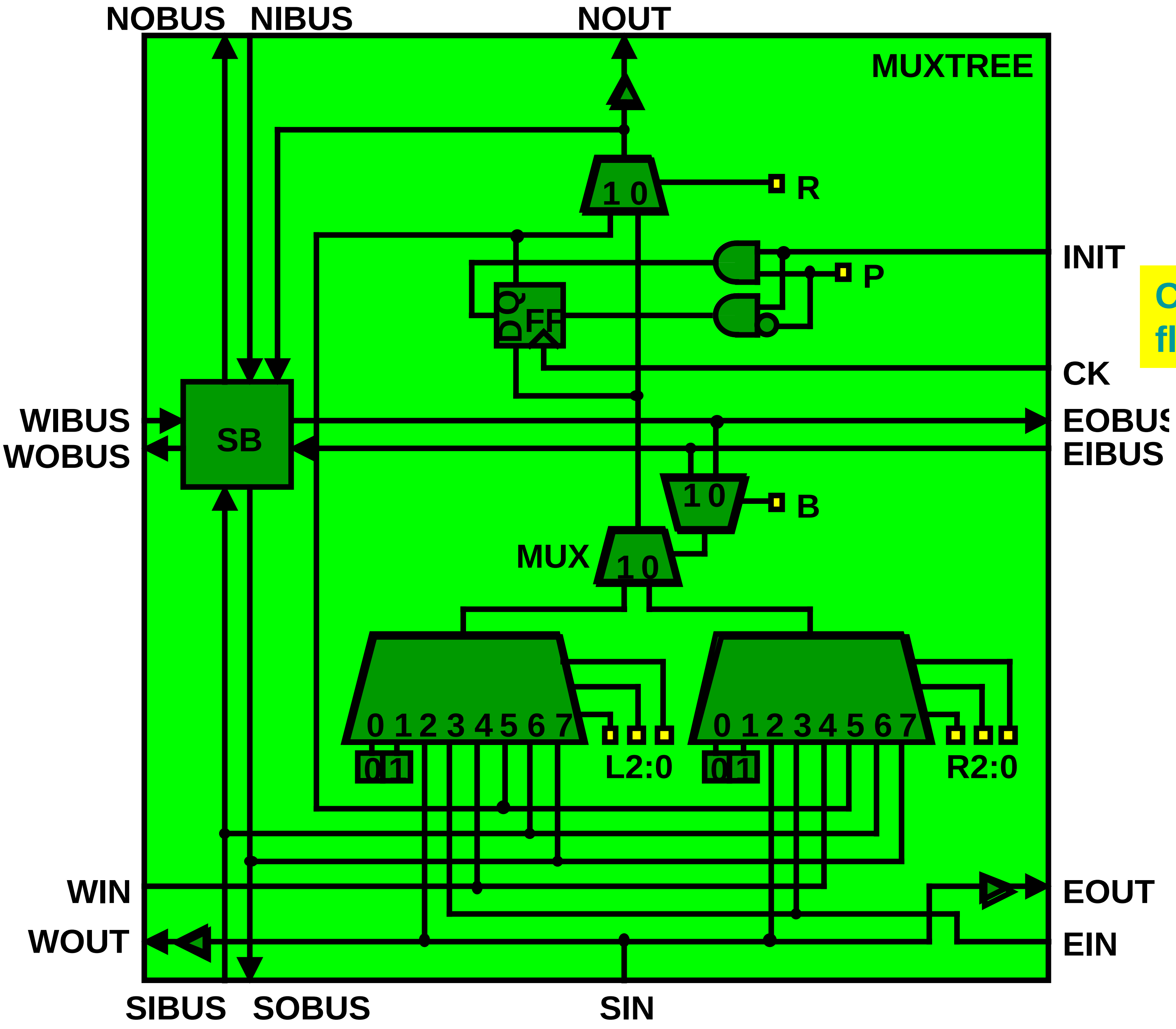
Organismic level
(organism = Σ cells)

Cellular level ???
(cell = Σ molecules)

Molecular level ???
(basic FPGA's element)

MUXTREE Molecule



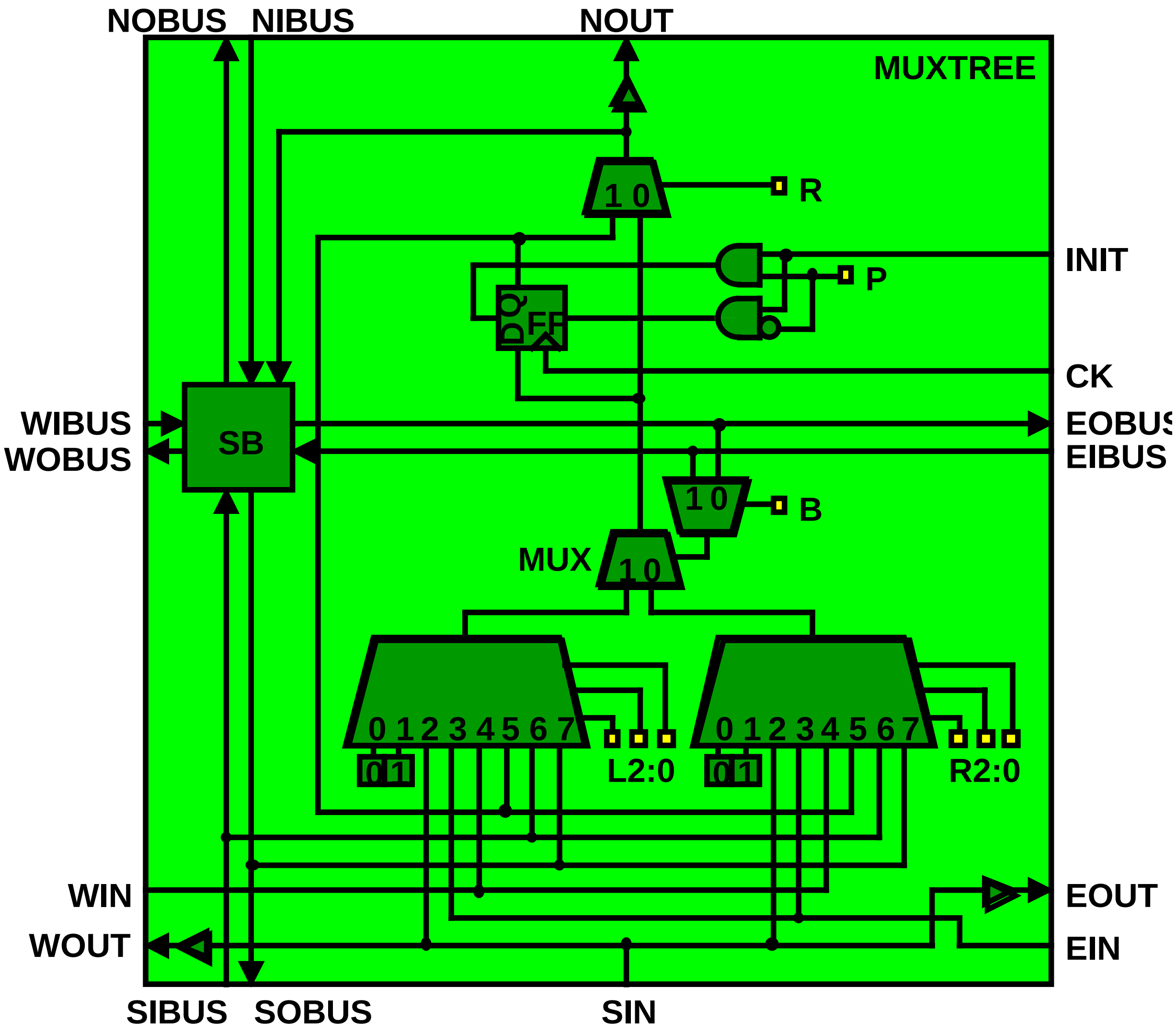


Cell has only one flip-flop

This is programmable hardware

Is programmed to virtual hardware

Virtual hardware is a FSM



NOBUS
NIBUS
NOUT
north

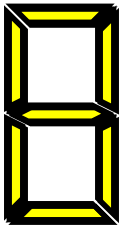
R
P
INIT

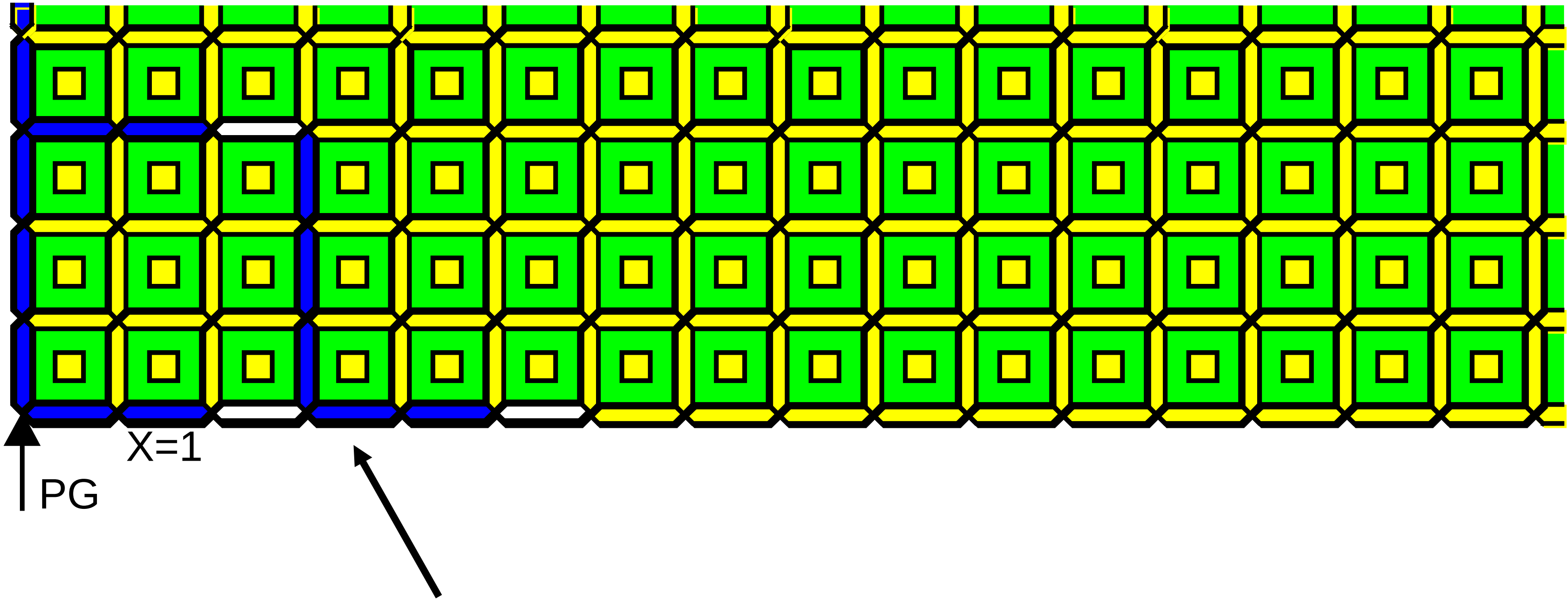
EOBUS
EIBUS
EOUT
EIN
east

WIN
WOUT
WIBUS
WOBUS
west

SIBUS
SOBUS
SIN
south

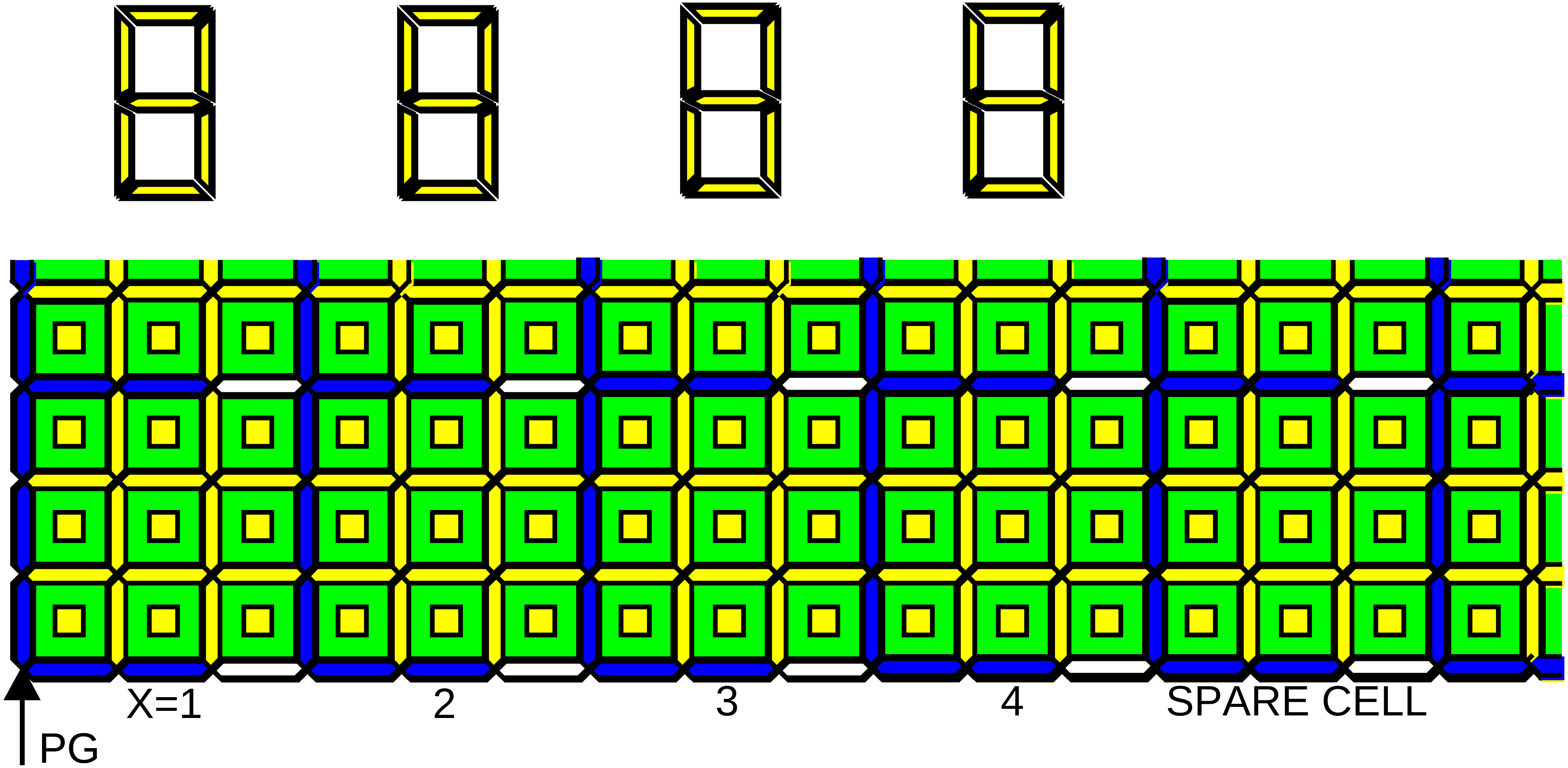
Space Divider



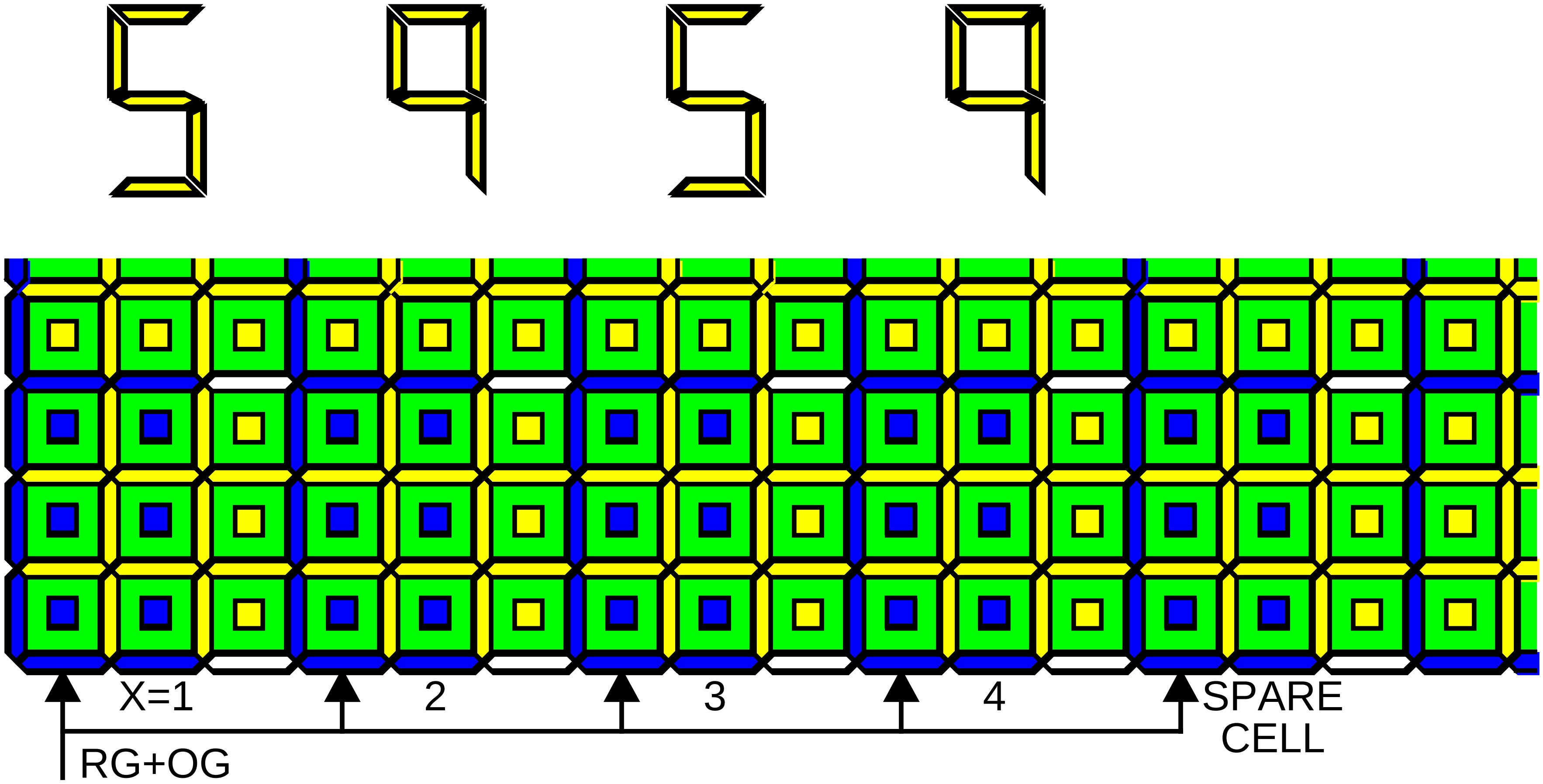


Separation concerns only some signals

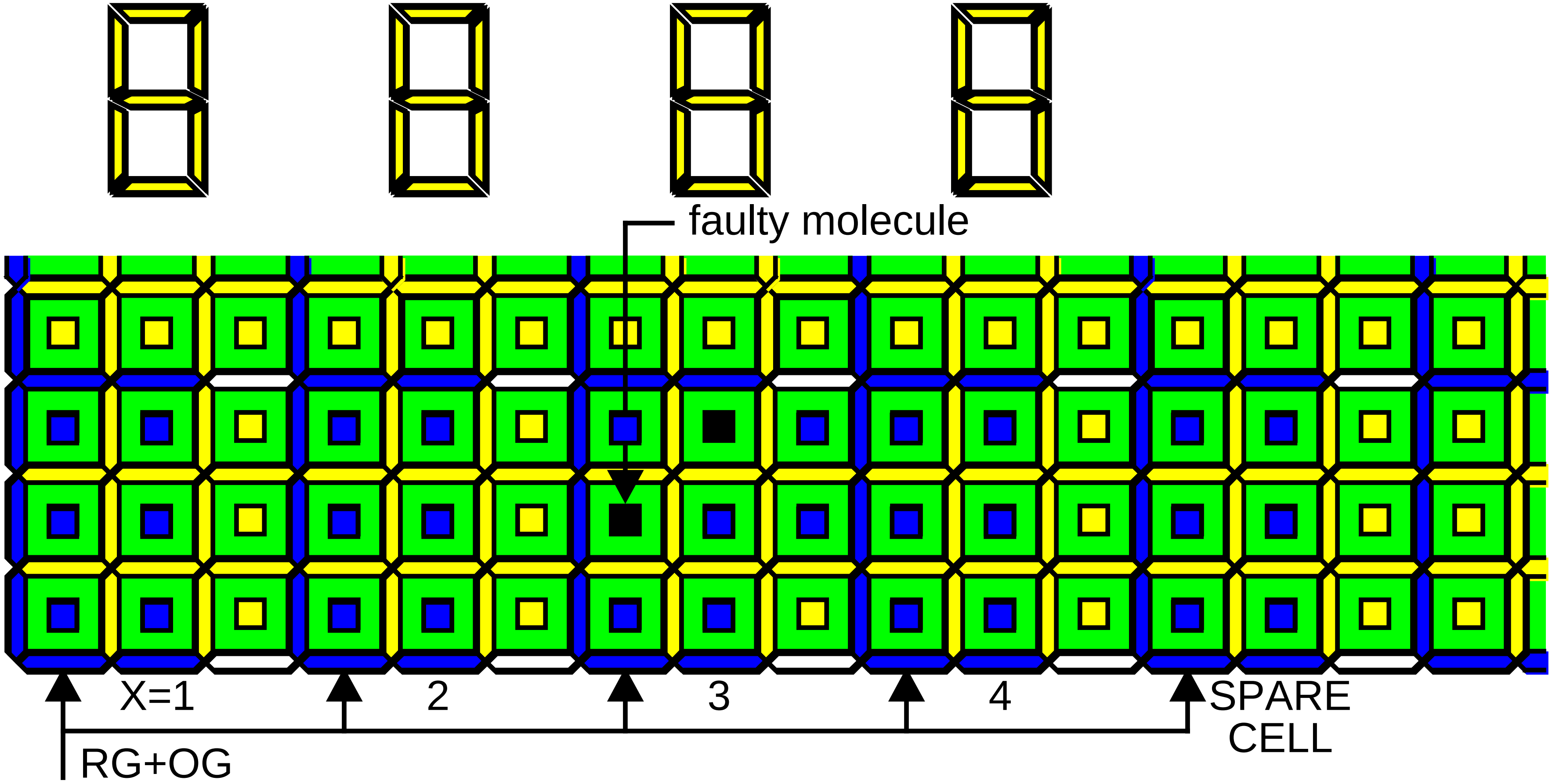
Space Divider



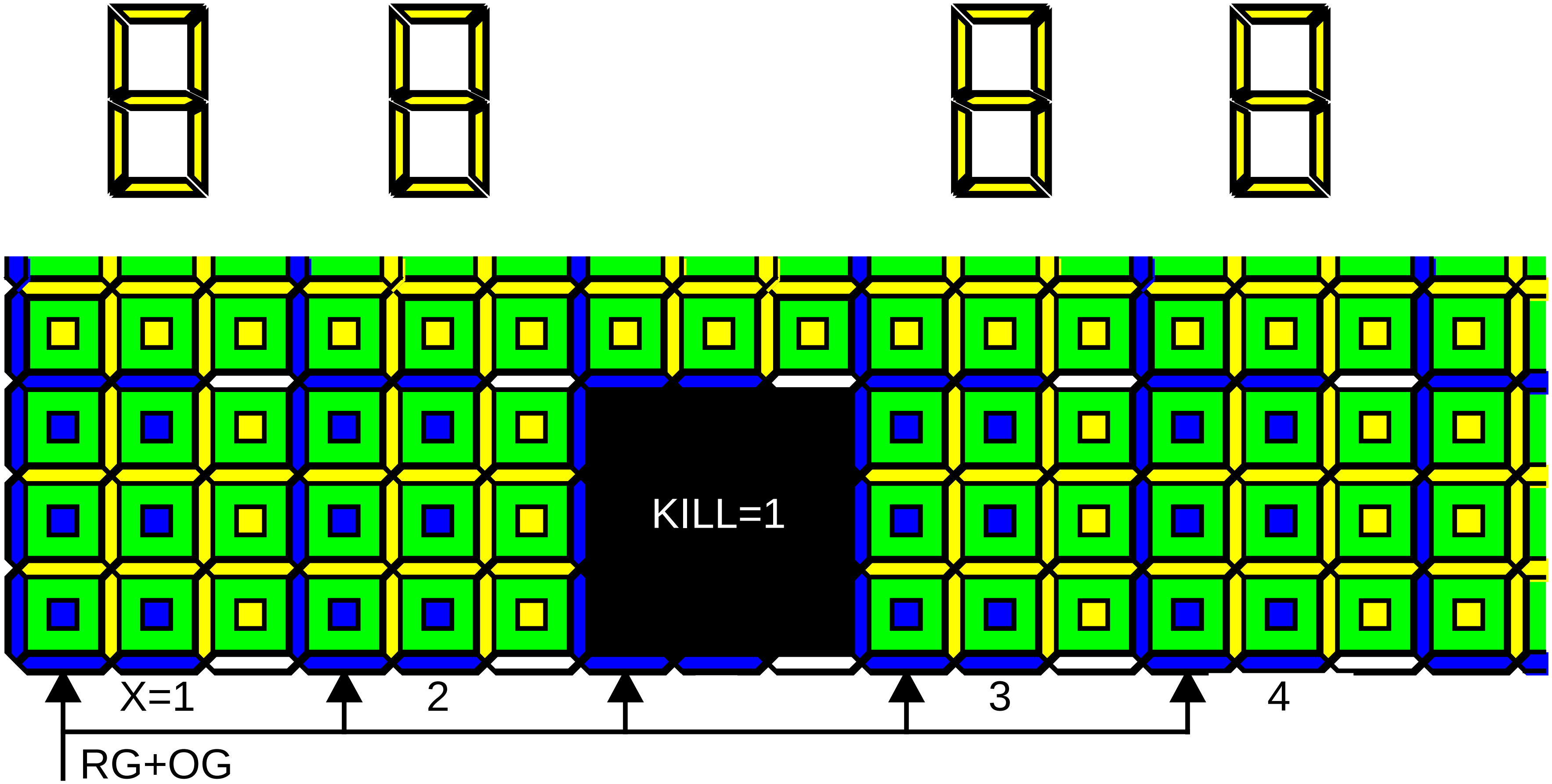
Cellular Self-Replication



Cellular Self-Repair

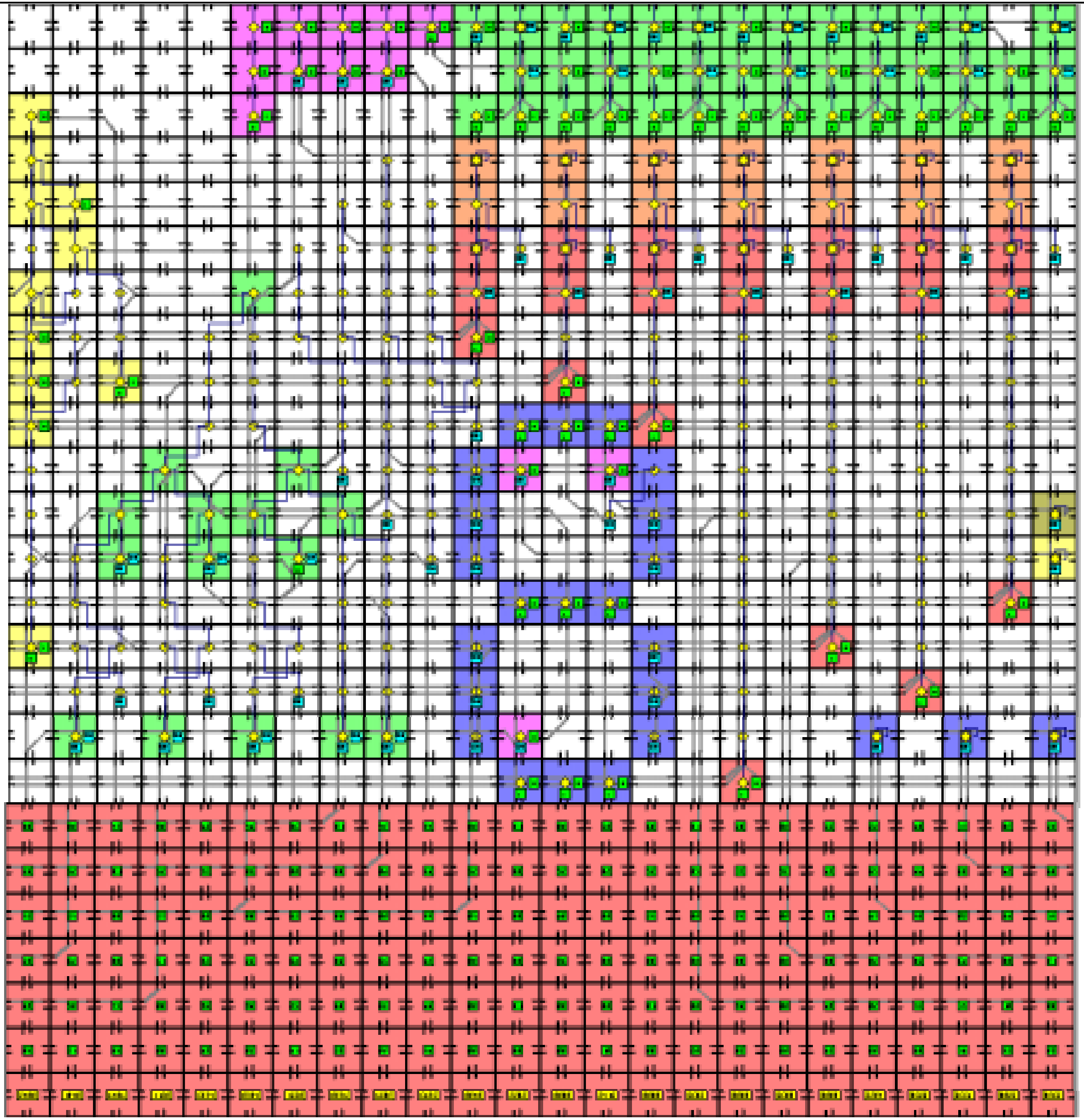


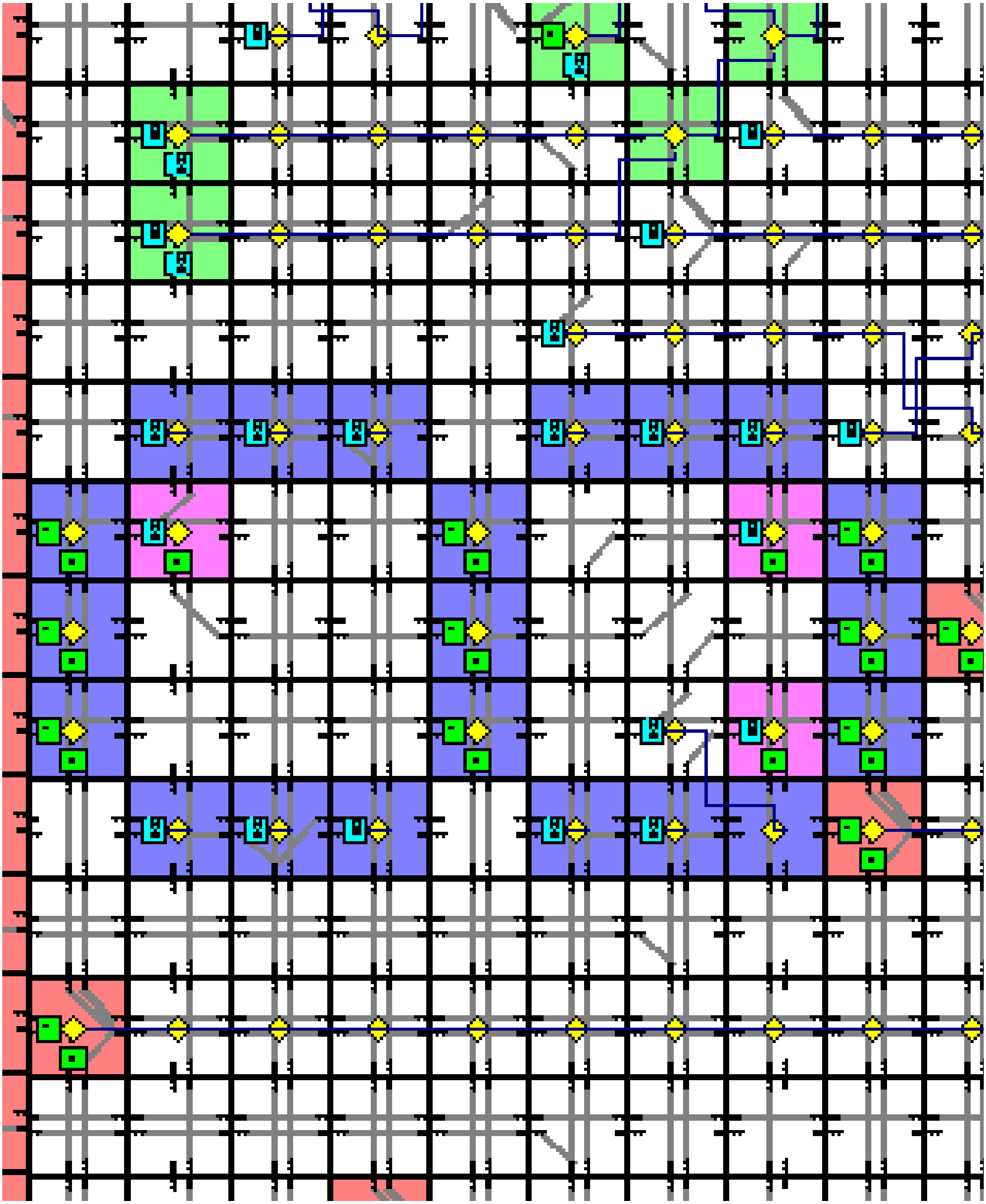
Cellular Self-Repair

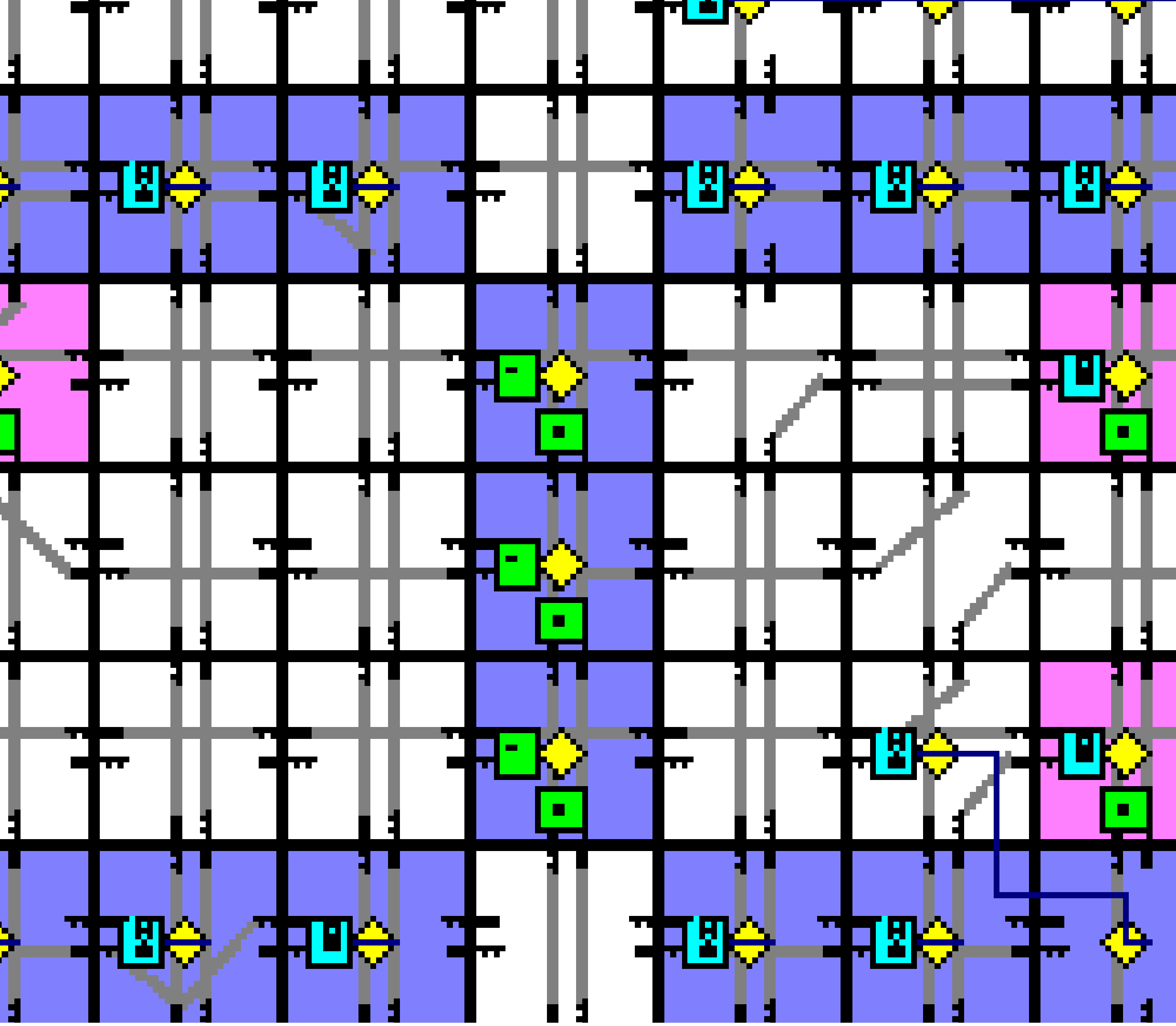


Stuck-at-one, stuck-at-zero fault models

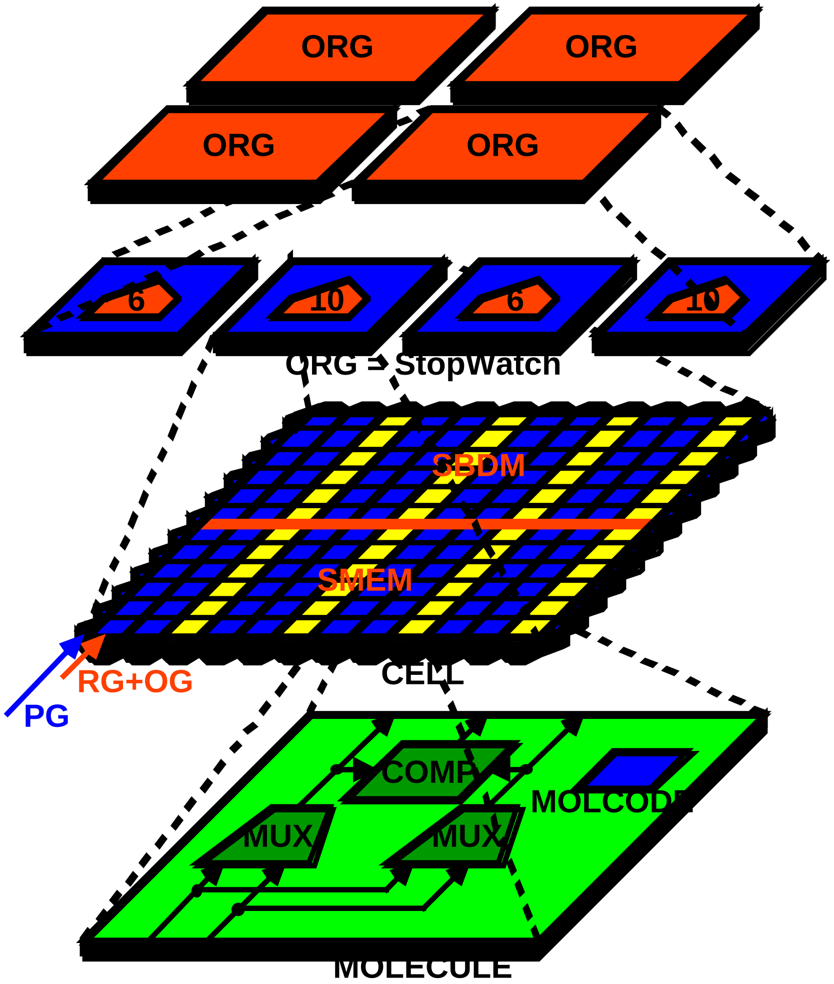
Molecular Implementation







Embryonics Landscape



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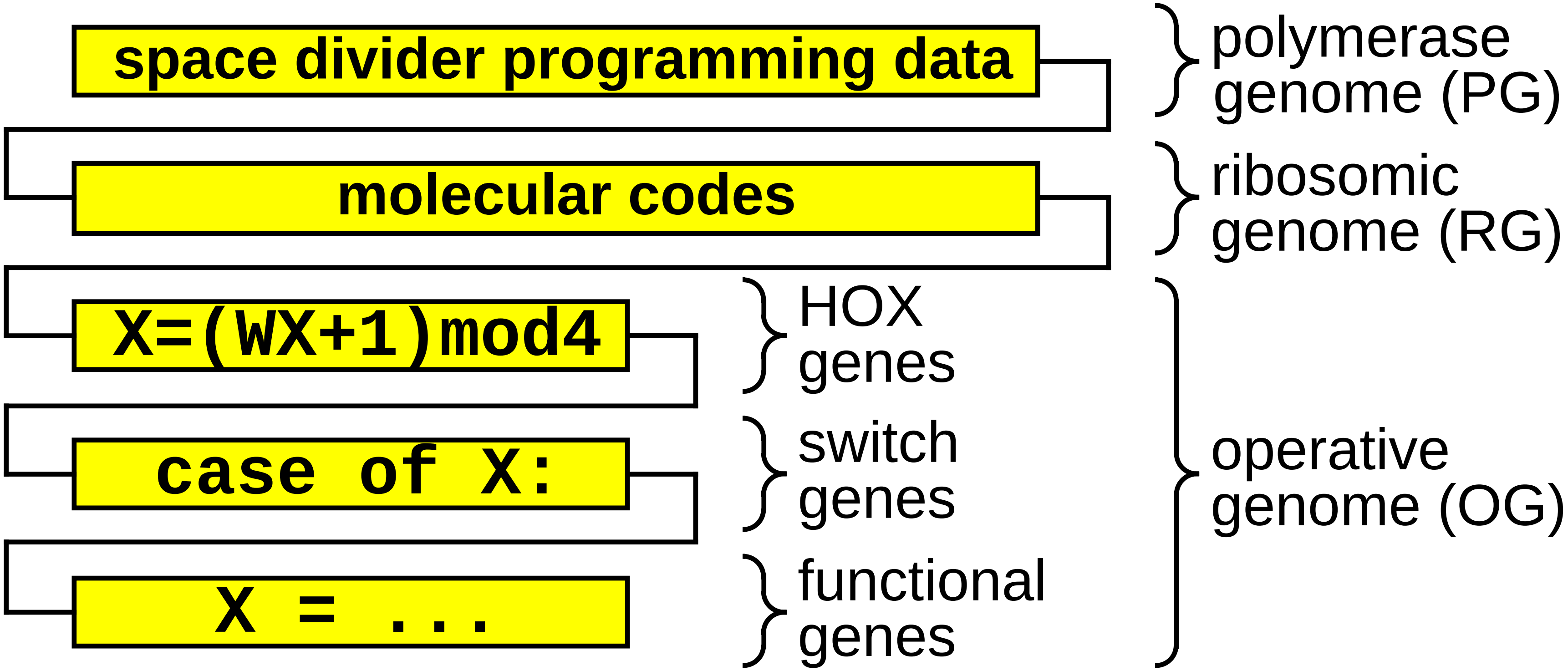
Molecular level
(basic FPGA's element)

Artificial Genome



Problems to solve

- Draw a modulo 6 counter using only flip-flops and multiplexed constants
- Do the same for module 10 counter.
- Design a complete watch, as in this lecture from such elements.
- Explain a methodology of realizing arbitrary autonomous machines in the switch/constant cellular model
- Explain how to realize arbitrary state machine with single input in this model