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THE NANO GROUP

Nanoscale Sensor Networks

DNA: A New Paradigm for Communication at the Bottom

Florian-Lennert Lau
Universität zu Lübeck
Institute of Telematics
May 25, 2021

Overview

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1. The Nanogroup
2. What We Do
3. Motivation
4. Applications
5. State of the Art
6. Prediction
7. Big Problems
8. The Nanoscale
9. DNA Basics
10. Message Molecules
11. Conclusion
12. Summary

The Speaker

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CV:

- Born 1990 in Lübeck
- Abitur in 2009
- Bachelor in 2013 on P2P systems
- Master in 2016 on competitive analysis
- Conceptualized DNA-based nanonetworks
- Doctor in 2020 on nanonetworks with magna cum laude
- Postdoctoral researcher since 2020
- Workshop organizer WoNaN
- Author of nanonetwork lectures & seminars

The Nanogroup

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Key Points:

- The Nanogroup was Founded in 2017
- We focus on:
  1. Nano-computation
  2. DNA-based nanonetworks
  3. Ethical, legal and social consequences
  4. Protocols
  5. Engineering aspects
  6. Simulation
  7. And many more topics




Mindmap

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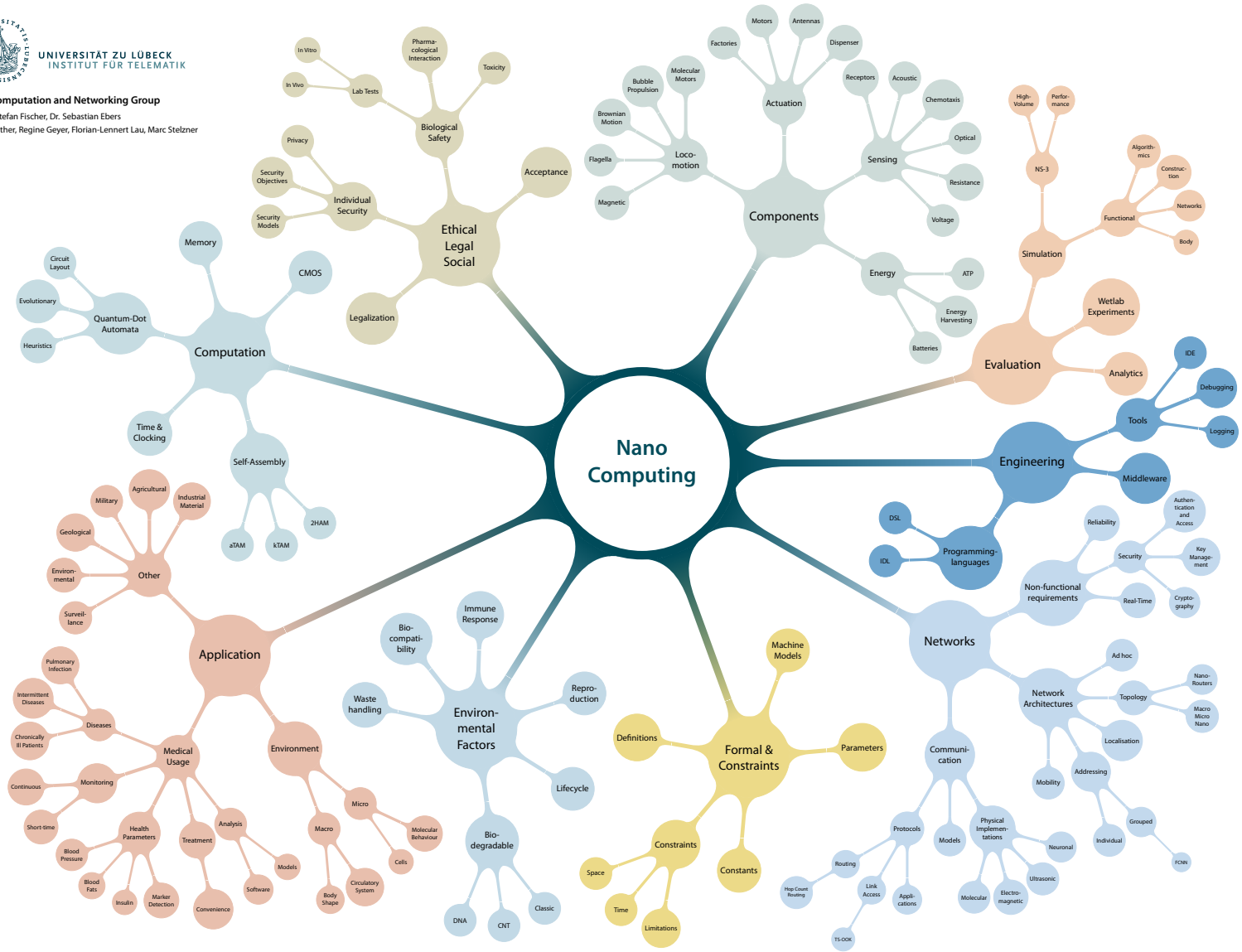
Nano Computation and Networking Group

Prof. Dr. Stefan Fischer, Dr. Sebastian Ebers
Florian Büther, Regine Geyer, Florian-Lennert Lau, Marc Stelzner

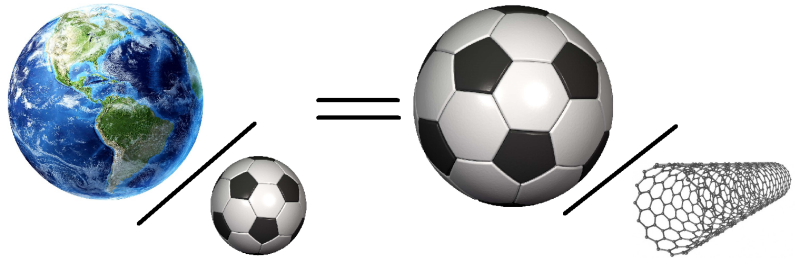


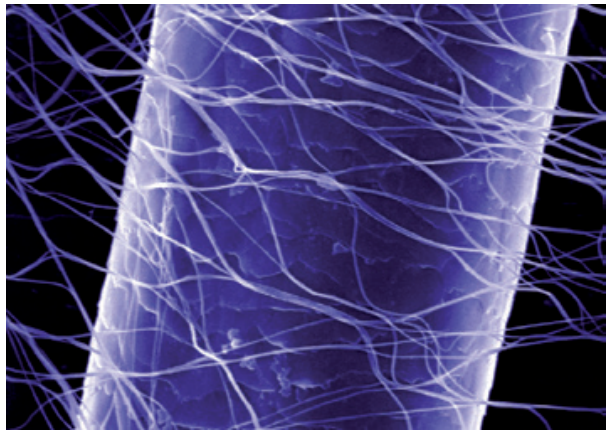
Motivation

Origin

Nanos = dwarf:

- ***Atom*** for the first time 500 BCE mentioned in Greece
- ***Kalapas*** 600 CE in Buddhist India
- 1–4000 nanometer = $1–4000^{-9}$m
- Hair: 20 000 nm–200 000 nm
- Cell: 10 000 nm
- DNA-helix: 2 nm





Hair vs. nano fibre.[1]

[1] Nau 2016.

Size

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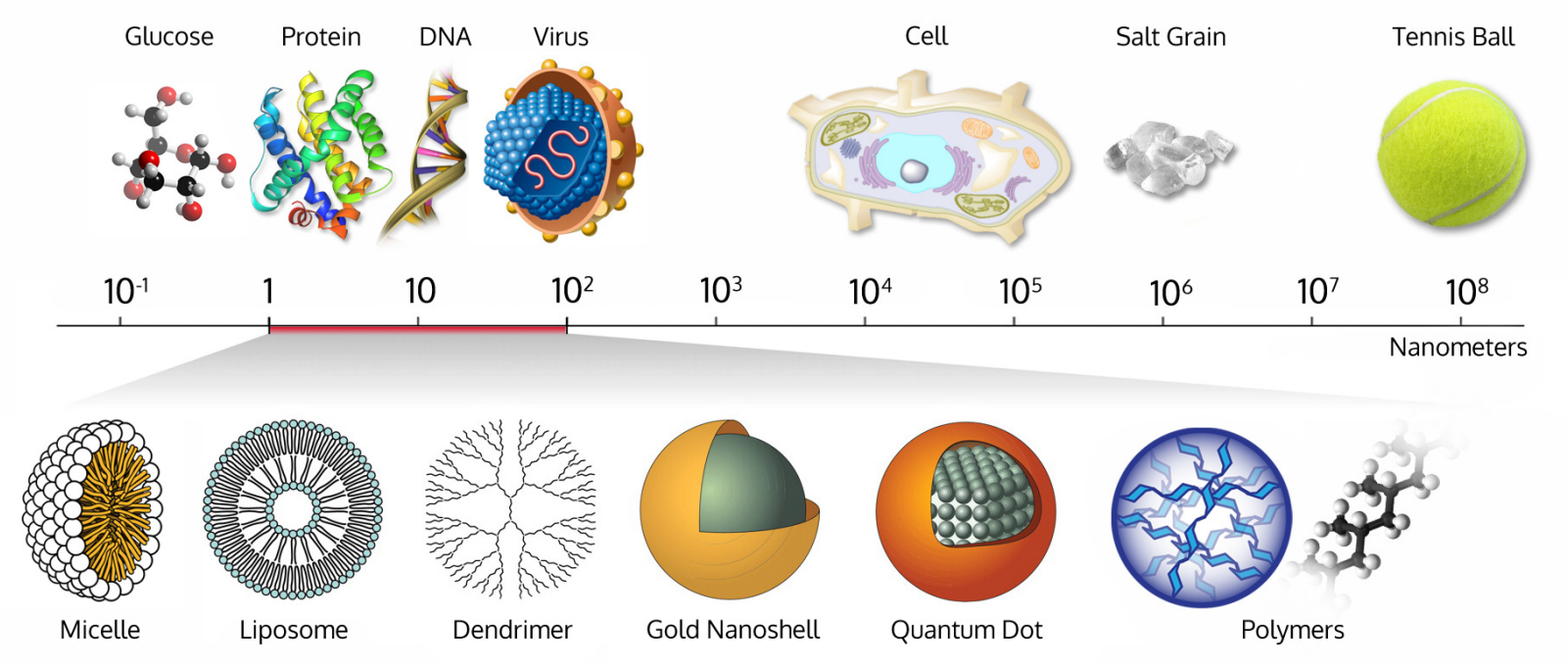


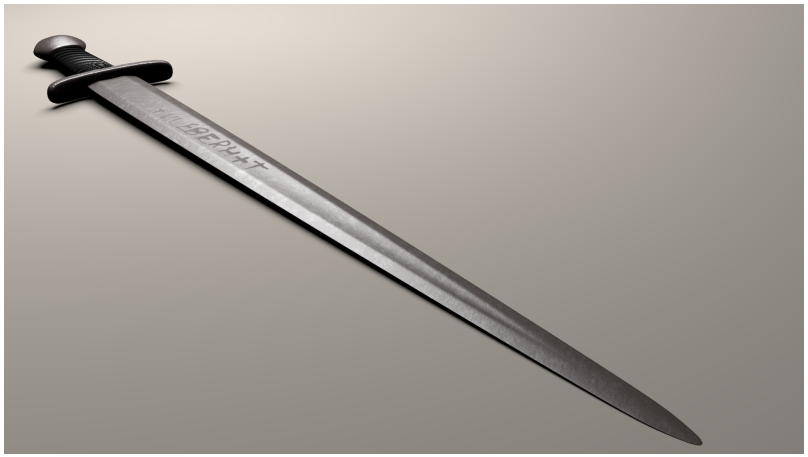
Size comparison of various nanoscale objects and particles[2].

[2] wichlab 2017.

Early Use

Germanic sword ***Ulfberht***:

- 800–1100 BC
- Carbon reinforced steel
- Carbon source: ***bones***
- ***Carbonnanotubes*** reinforcing steel
- ***Misbelief*** that the strength of animal or enemy passes from bones into the sword



Applications

Use Cases

- Medical surveillance of ***health parameters***
- Military ***communication monitoring***
- ***Agricultural*** efficiency enhancements through:
  - Destruents
  - Rhizomenetworks
  - Disease prevention or control
- Environmental control & regeneration
- Natural catastrophes warning systems

BAN

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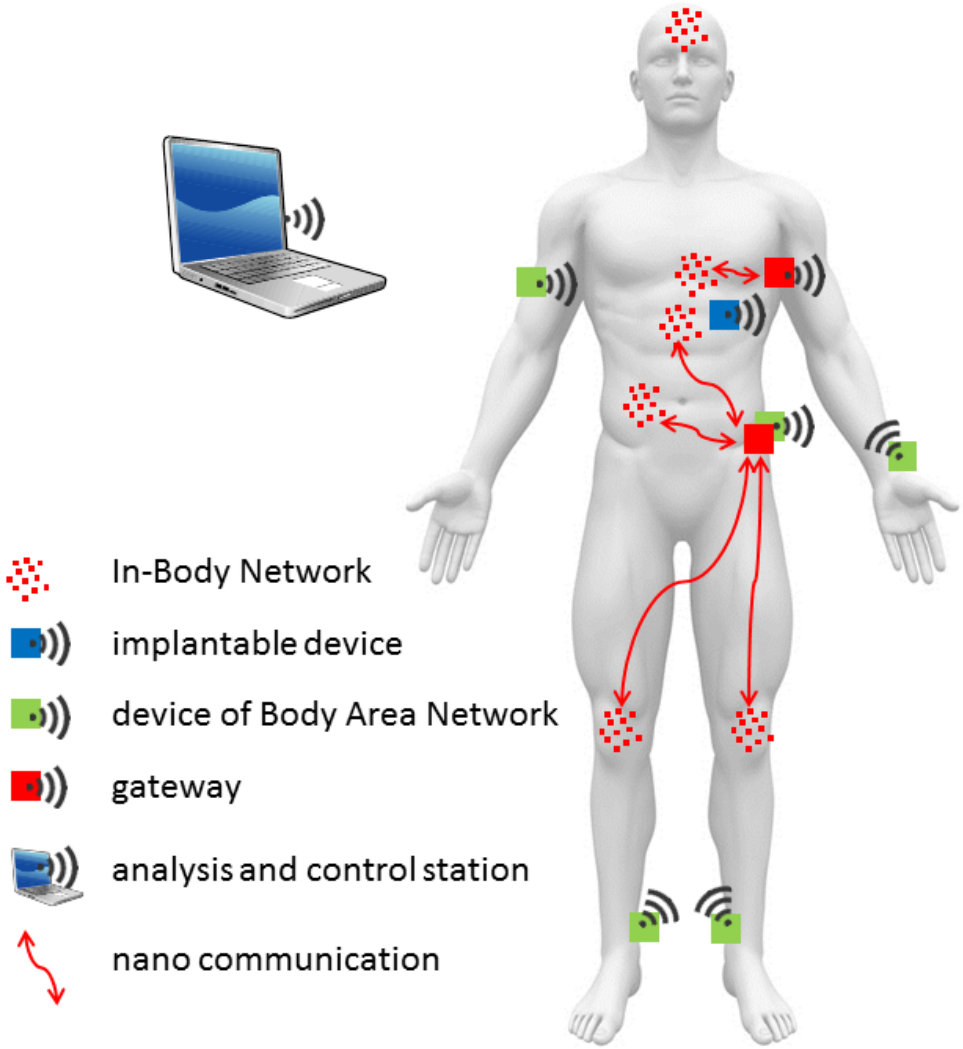

Pulmonary Inflammation

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Detection of pulmonary inflammation[3]:

- ***Discovery*** of disease markers through a Body Area Network (BAN)
- ***Communication*** of discoveries to other devices and to a ***gateway***
- ***Direct*** treatment during the ***emergence*** possible
- ***Local*** treatment without damaging of the surrounding tissue possible

[3] Stelzner et al. 2016.

State of the Art

Research With Carryover

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Interdisciplinary field of research:

- Sensor networks with ***protocols*** and ***algorithms***
- Mathematics with ***analytical tools*** and ***simulations***
- Medicine with clinical trials
- Pharmacy with exploring medication
- Bioengineering through construction of new nanostructures
- Biology by exploring natural adaptive processes
- Chemistry & Physics by particle research

Existing Nanostructures

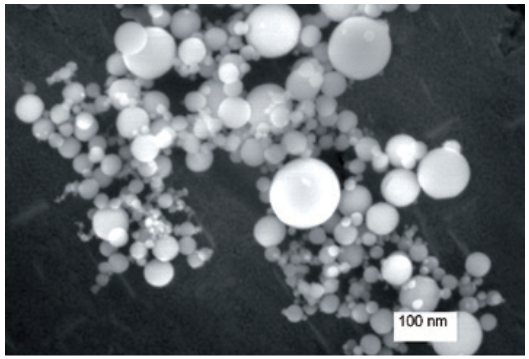
What can already be created?

- ***Nanoparticles*** for disease control
- Primitive ***microbots***
- Primitive ***transport structures***
  - Liposomes
  - DNA-boxes
  - „Dead" bacteria
- DNA-Origami structures

Gold Nanoparticles

For fighting cancer:

- „Coating" of nanoparticles by ***antibodies***
- ***Binding*** of nanoparticles to desired tissue
- ***Heating*** of nanoparticles via lasers
- Nanoparticles vibrate & ***heat up***
- The heat ***kills*** cancer tissue



Aluminum nanoparticles[4].

[4] Nau 2016.

Magnetic Nanoparticles

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Magnetic particle imaging:

- Uses *iron oxide particles* the size of about 10 nm
- Assists in *visualizing* biological processes
- Activation of particles by *magnetic fields*
- Calculation of locations from *resonance*

Microbots I

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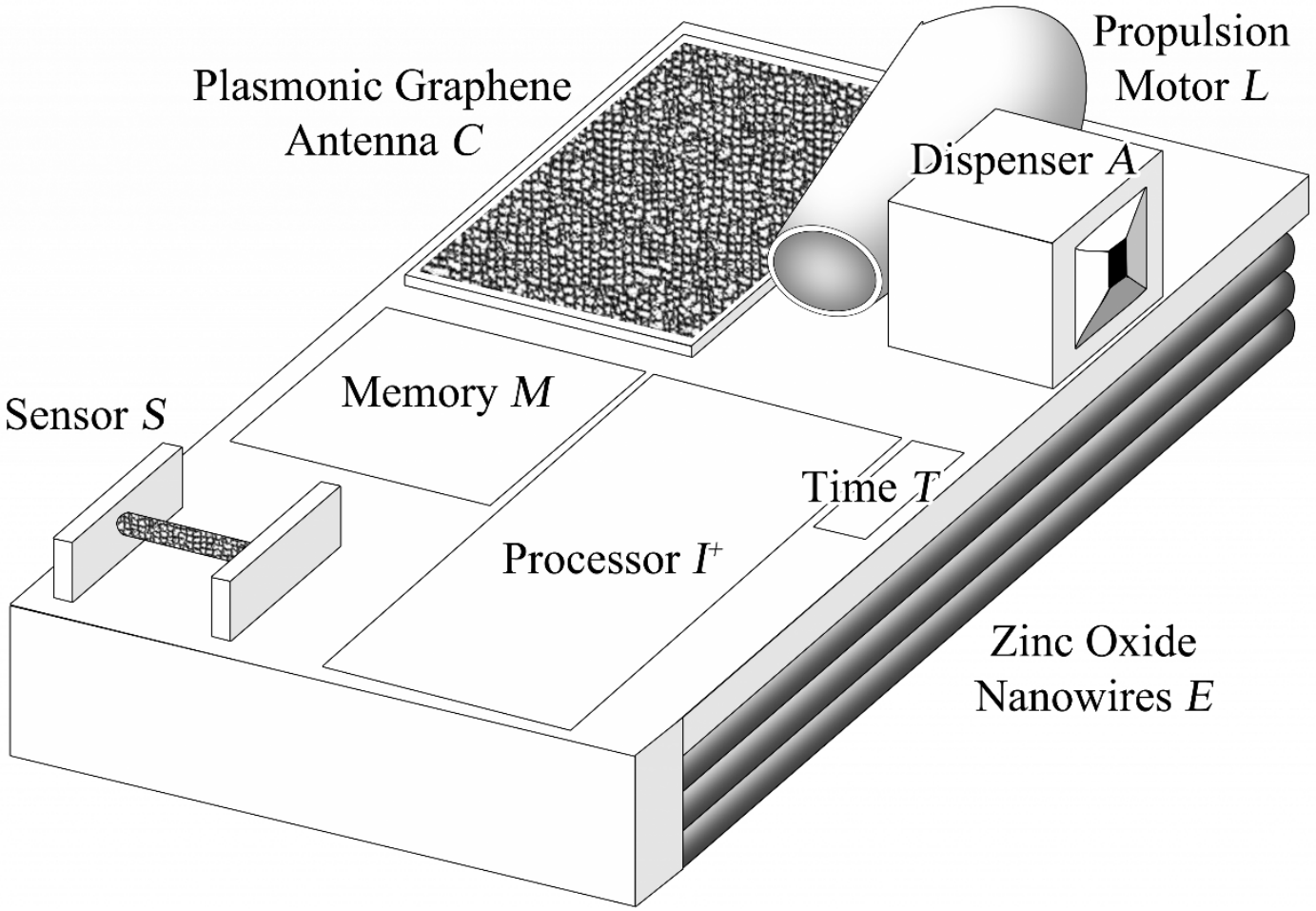

Cell Bots

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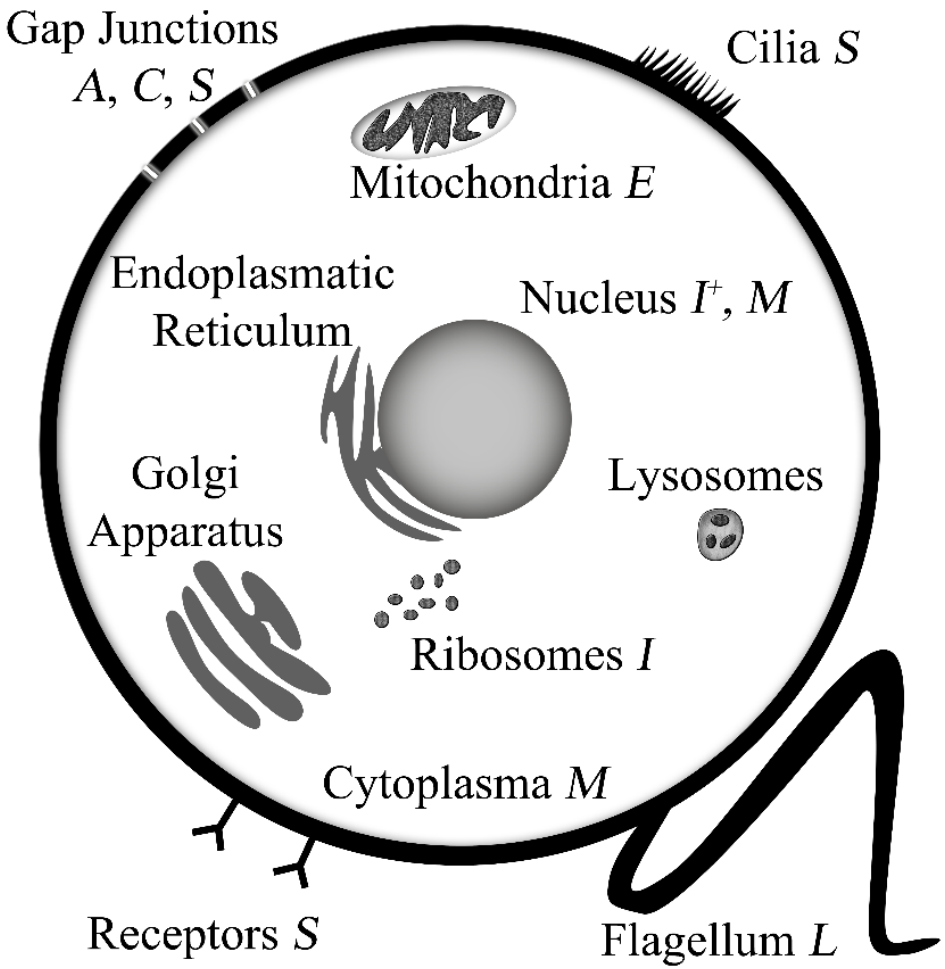

Bacteria Bots

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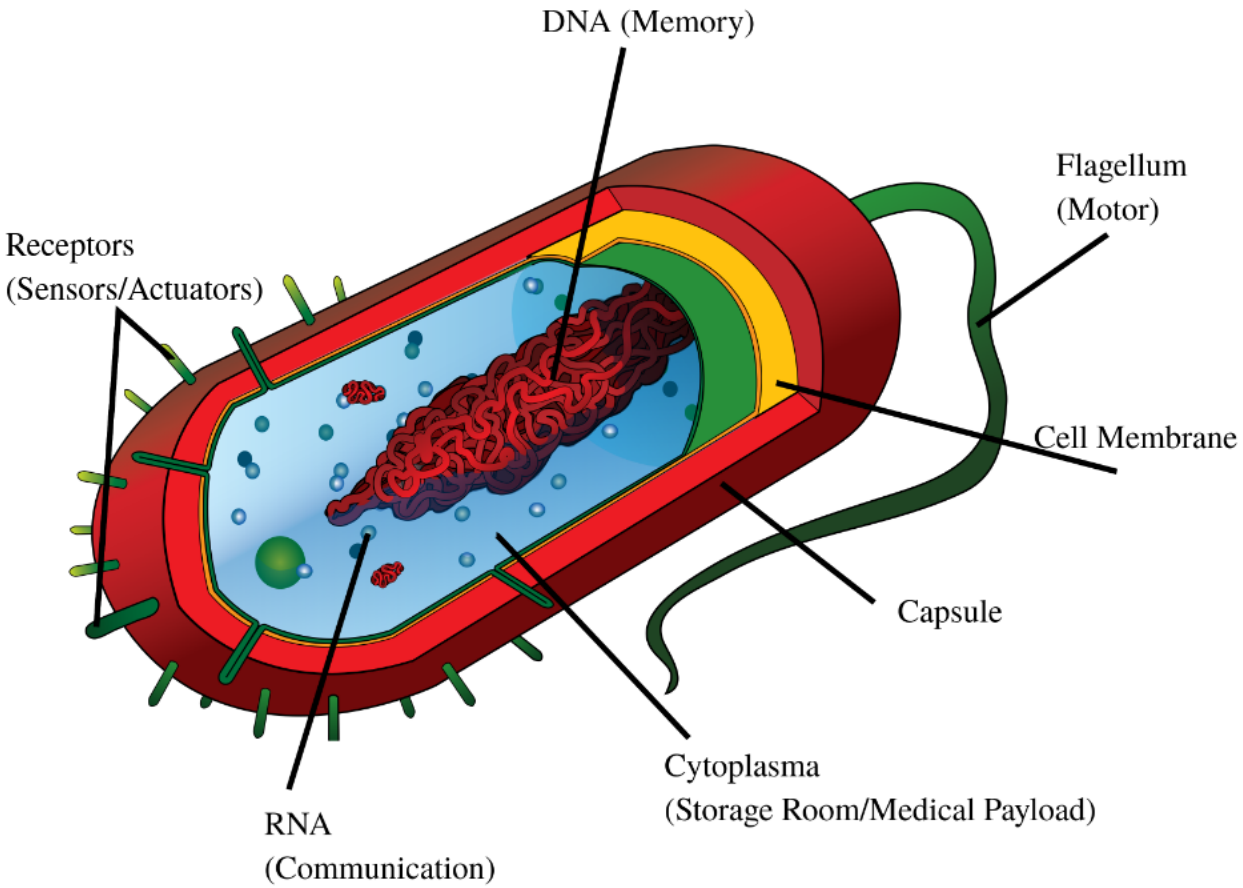

DNA Nanoscructures

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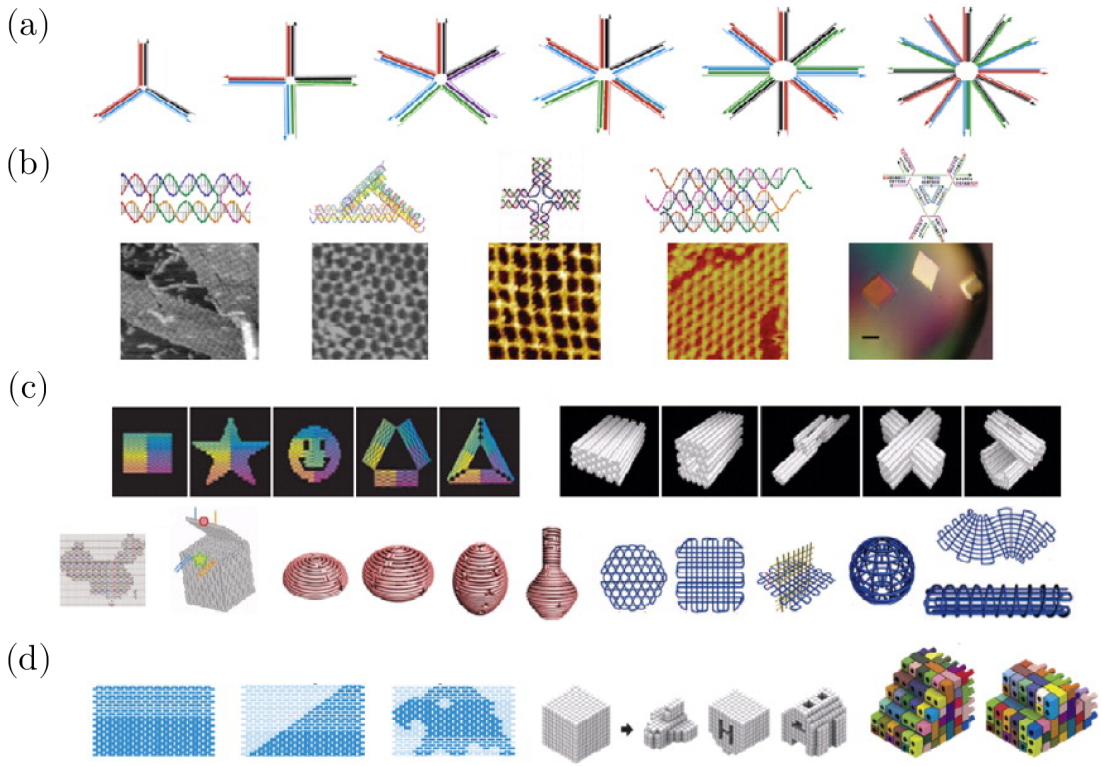

Collection of already produced nanostructures[5].

[5] Chao et al. 2015.

Prediction

Prognosis

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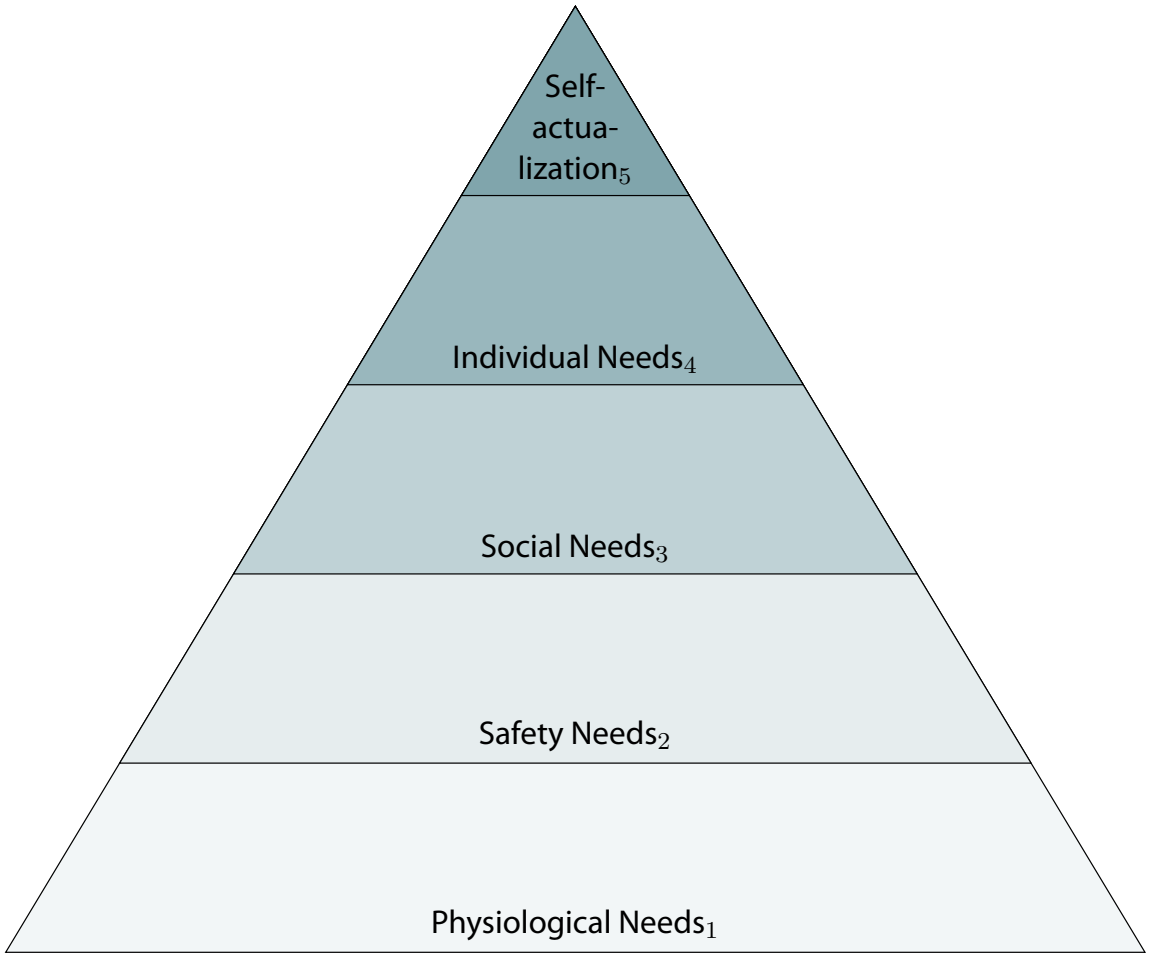

Economics

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Industry	GDP $	% of GDP	Maslow
Housing	1898	13 %	2
Local government	1336	9 %	2
Finance	1159	8 %	2
Health	1136	8 %	1
Durable products	910	6 %	4
Retail trade	905	6 %	4
Wholesale	845	6 %	4
State government	658	5 %	2
Data	646	4 %	4
Entertainment	591	4 %	3–5
Construction	529	4 %	2
Disposal	448	3 %	2
Others Services	447	3 %	4–5
Services	297	2 %	4–5
Mining	290	2 %	4
Administration	284	2 %	4–5
Education	174	1 %	1–5
Agriculture	173	1 %	1

Overarching Problems

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Great unresolved problems in nanoresearch:

- ***Construction*** of nanoscale, functional components for nanodevices or nanonetworks
- ***Communication*** and communication mechanisms at the nanoscale
- ***Computations*** that take the restrictions at the nanoscale into account
- ***Compatibility*** of all sub-solutions for holistic, nanoscale functional units or nanonetworks

The Nanoscale

Nanoscale Peculiarities

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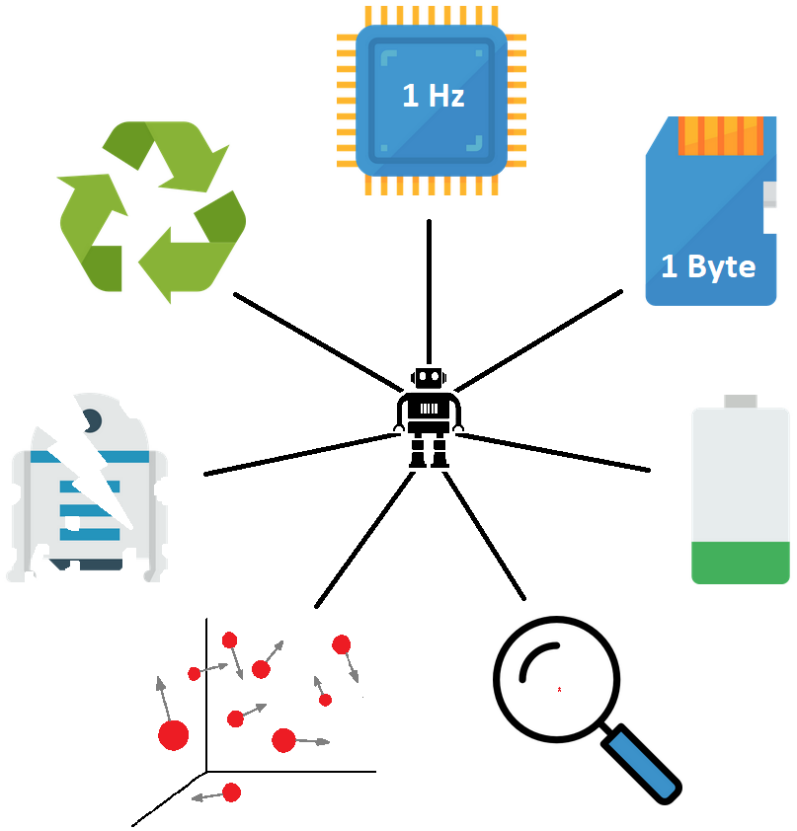
Unique Points:

- Extreme number of participants
- High topology dynamics
- Time/space restrictions
- Heterogeneity
- No central control instances
- No direct influence
- Biocompatibility
- Energy availability
- Waste disposal



Machine Models

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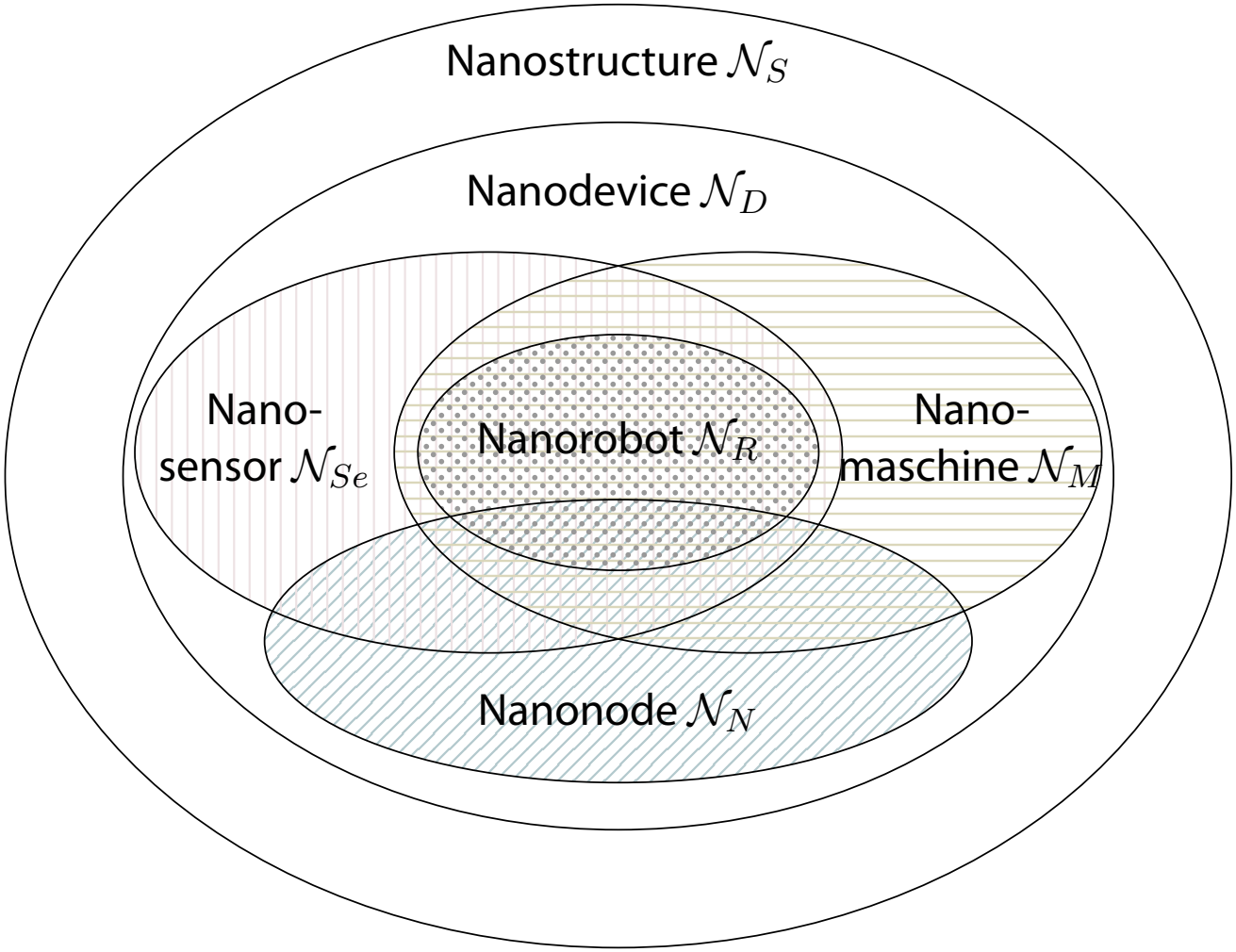

Storyboard

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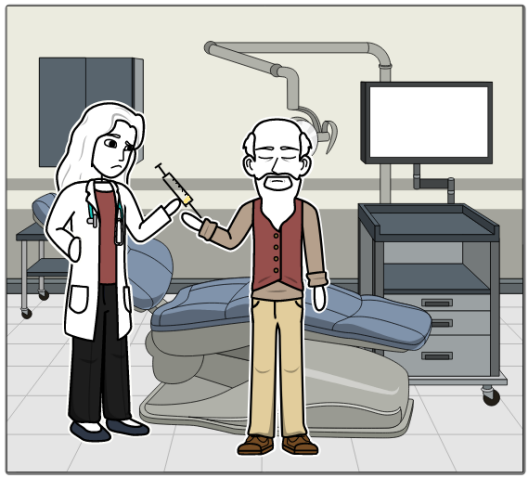
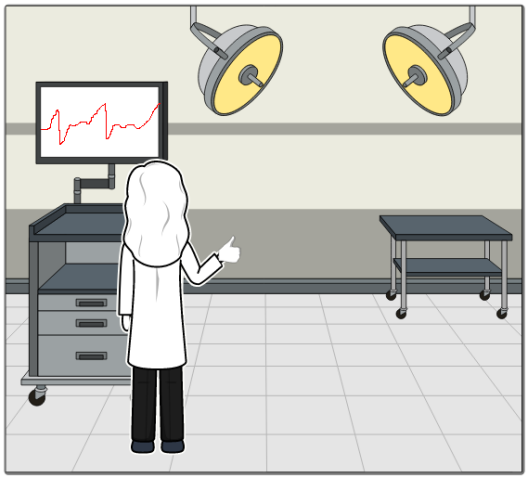
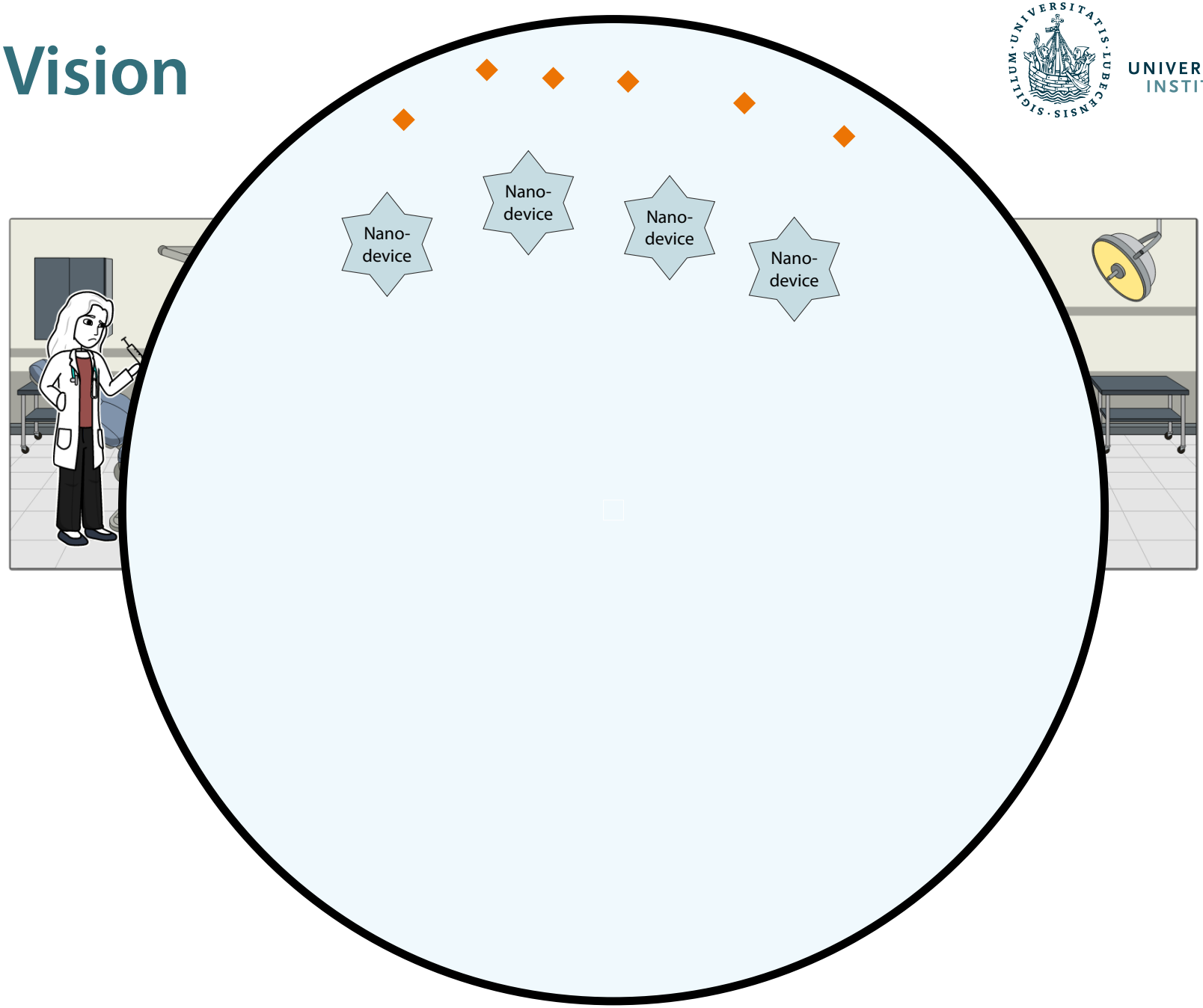




Vision



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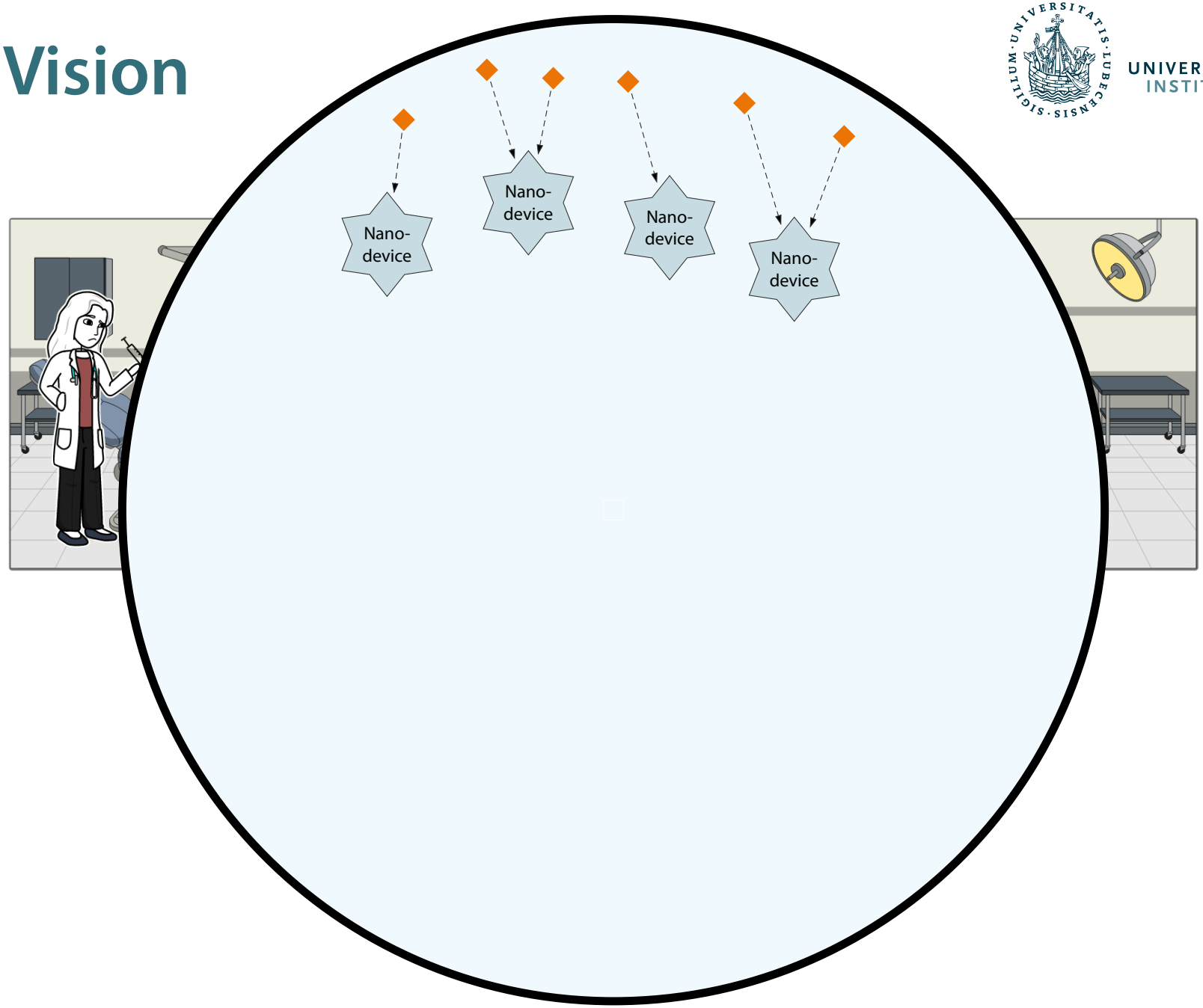

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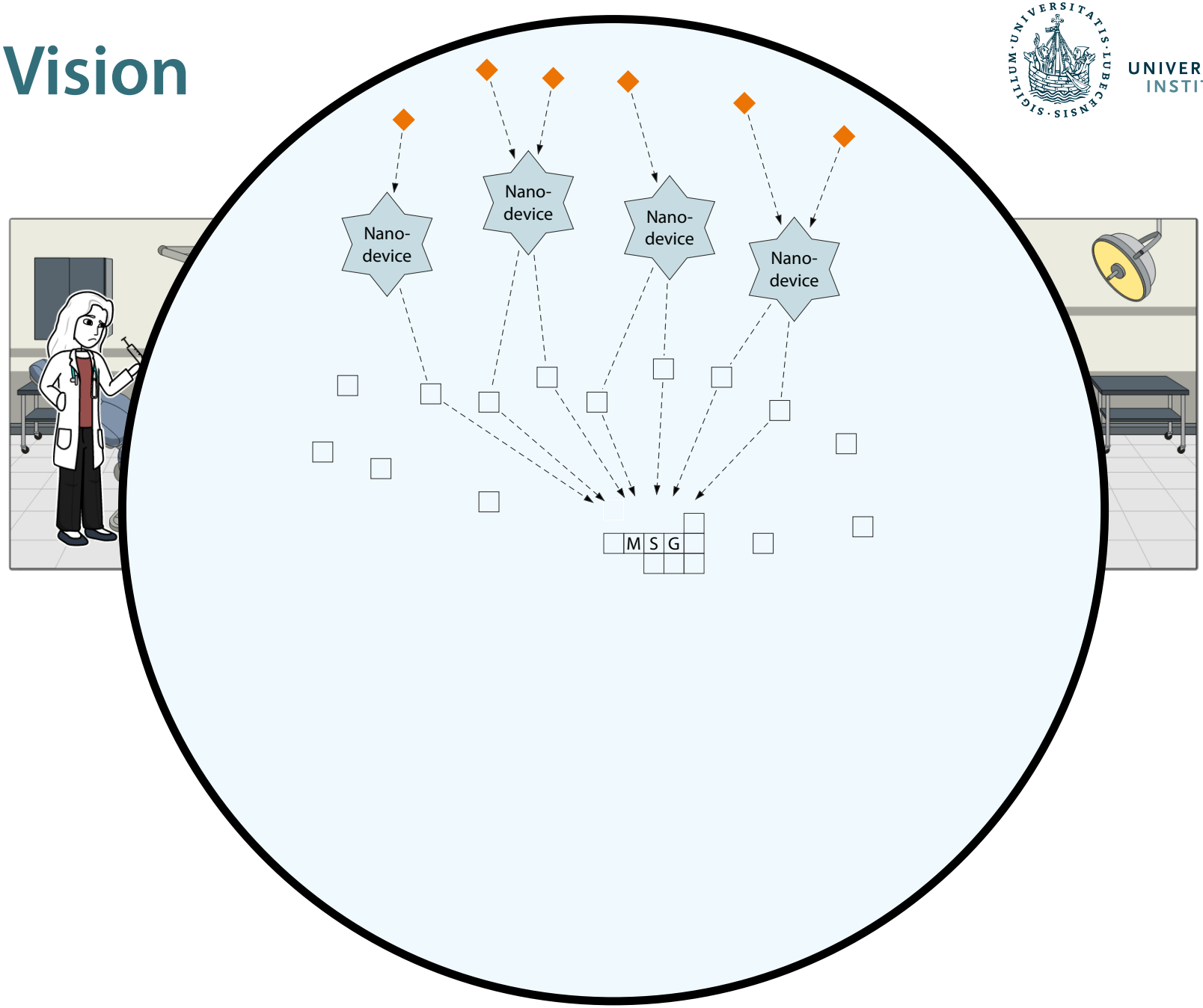

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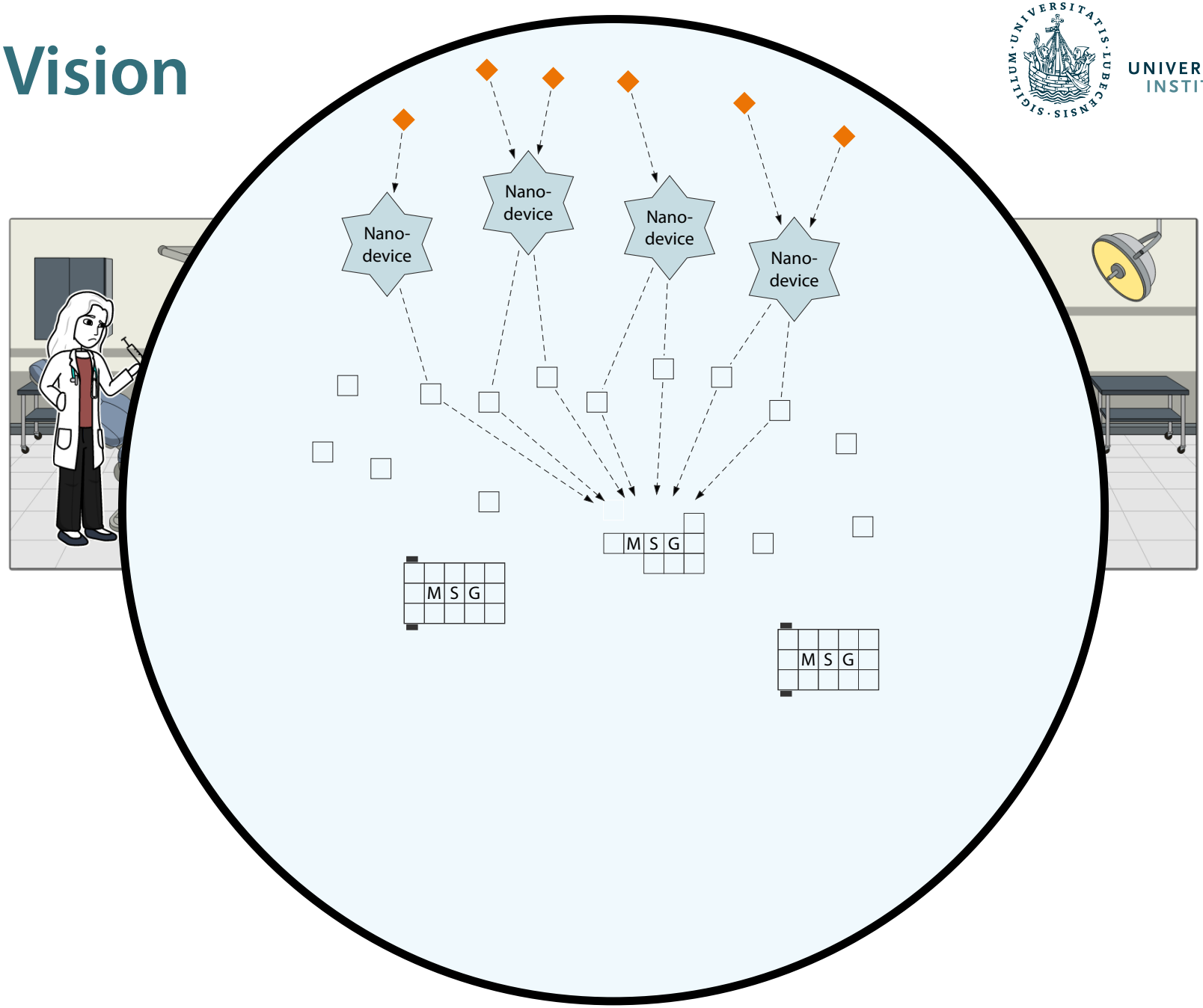

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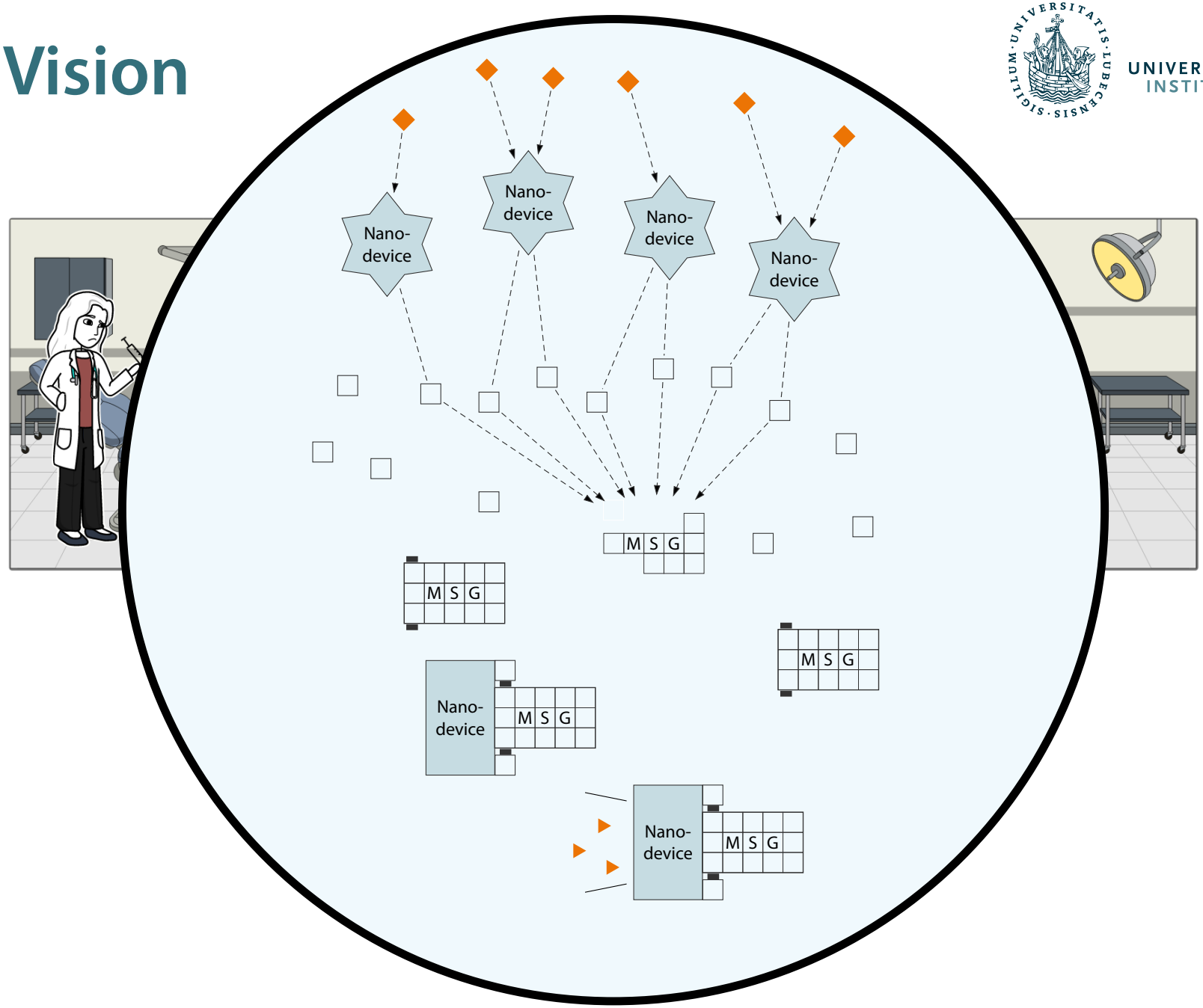

DNA-Tiles

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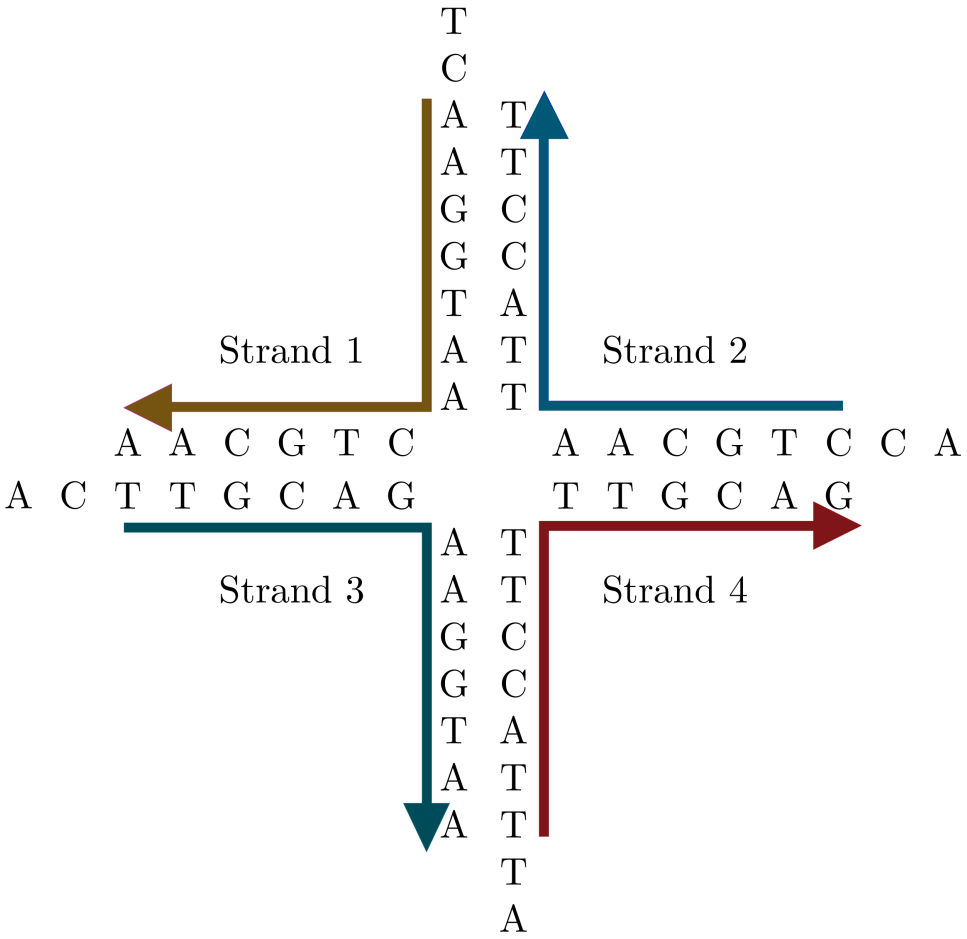

DNA-tile with glues in all directions

Model I

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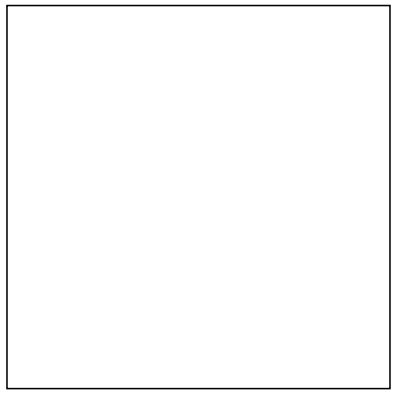
Formal definition of DNA-tiles [6]:

- Non-rotateable ***blocks***



[6] Lathrop, Lutz, and Summers 2007.

Model I

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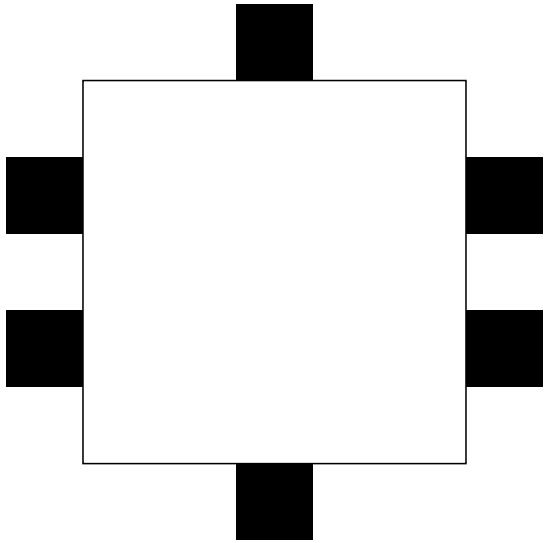
Formal definition of DNA-tiles [6]:

- Non-rotateable ***blocks***
- ***Glues*** on each side of different strength



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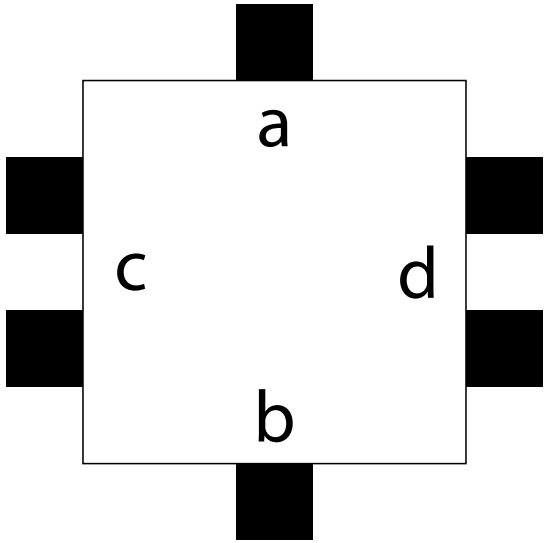
Model I

Formal definition of DNA-tiles [6]:

- Non-rotateable ***blocks***
- ***Glues*** on each side of different strength
- Glues have ***labels***



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Model I

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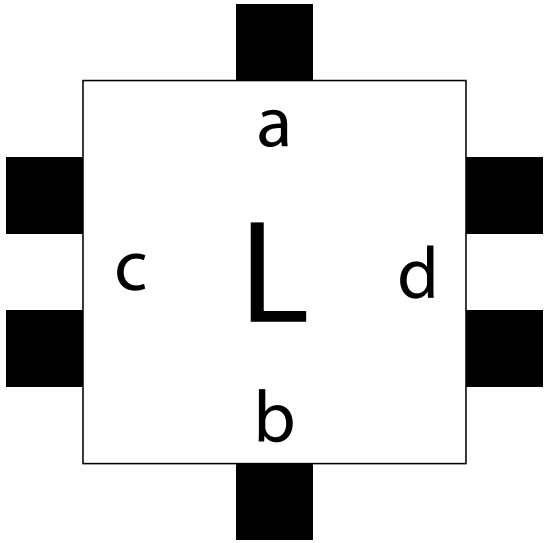
Formal definition of DNA-tiles [6]:

- Non-rotateable ***blocks***
- ***Glues*** on each side of different strength
- Glues have ***labels***
- ***Marker*** in the middle



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Model II

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Important properties:

- Tiles can ***compute*** – they are Turing-complete [3]
- Tiles can ***construct*** [4]
- Tiles can ***communicate*** in networks [5]

[7] Winfree et al. 1998.
[8] Patitz 2014.
[9] Lau, Büther, Geyer, et al. 2019.

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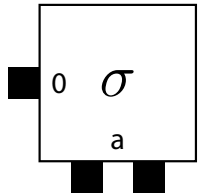

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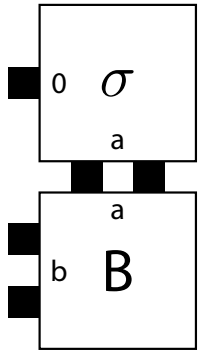

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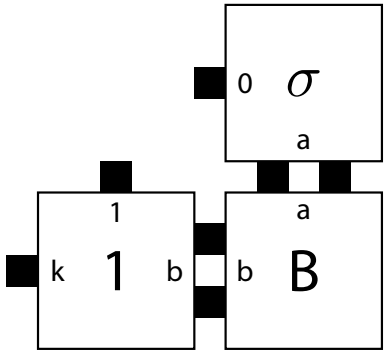

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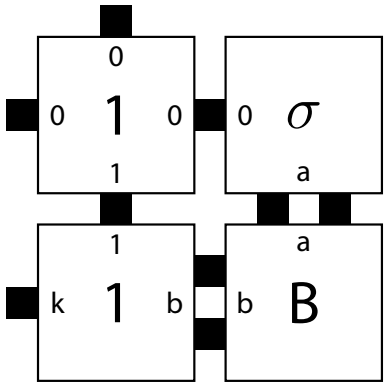

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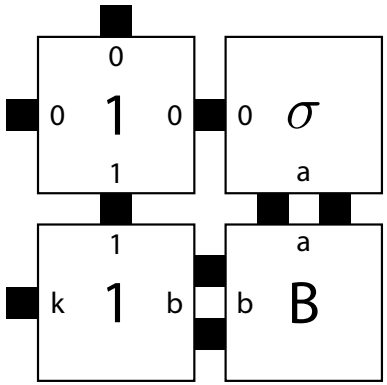

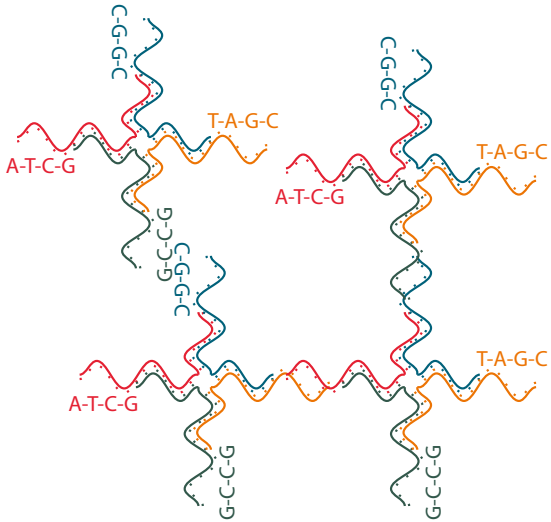

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From 2D- to 3D-tiles

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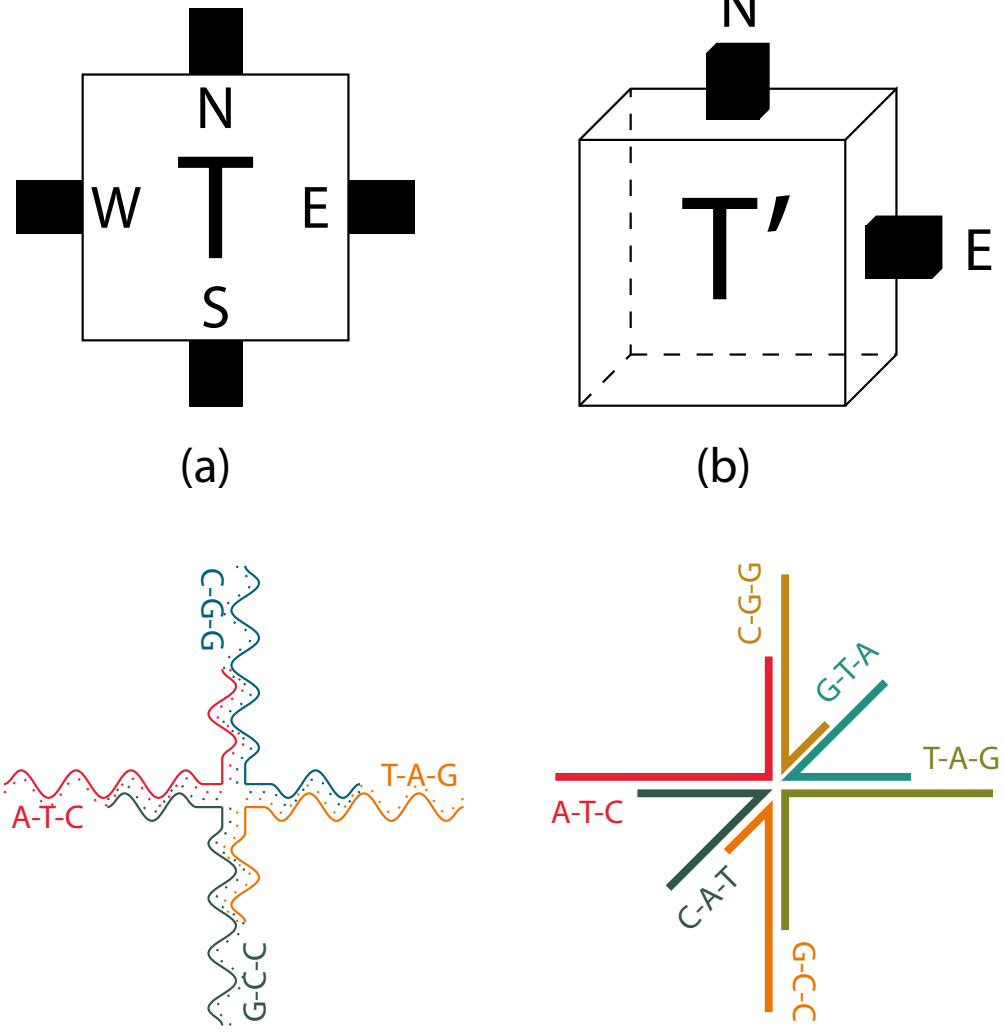

[10] Bende, Lau, and Fischer 2019.

DNA-Origami-Nanobots

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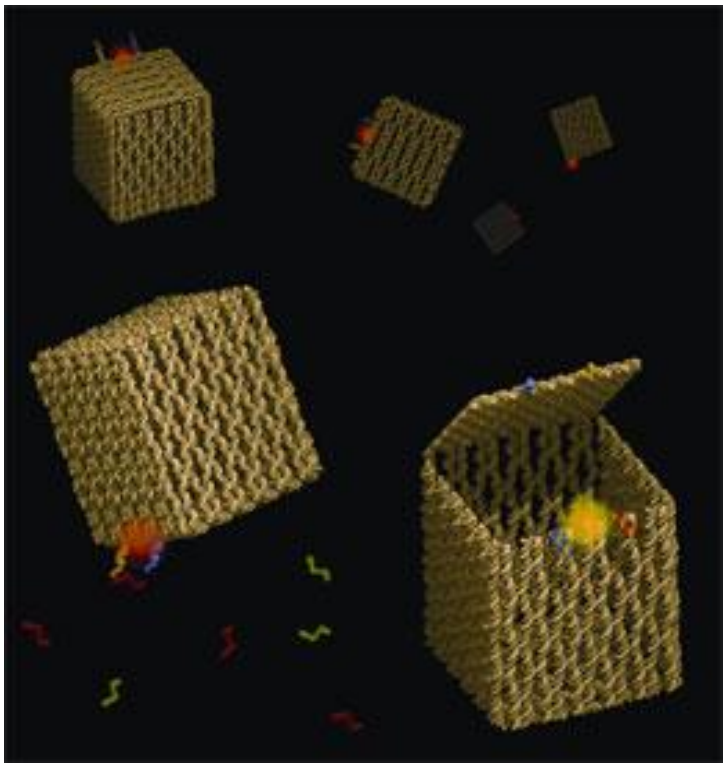

Schematic DNA-Box

Realistic DNA-Box [11]

[11] Andersen, Dong, Morten M. Nielsen, et al. 2009.

Mechanism DNA-Box

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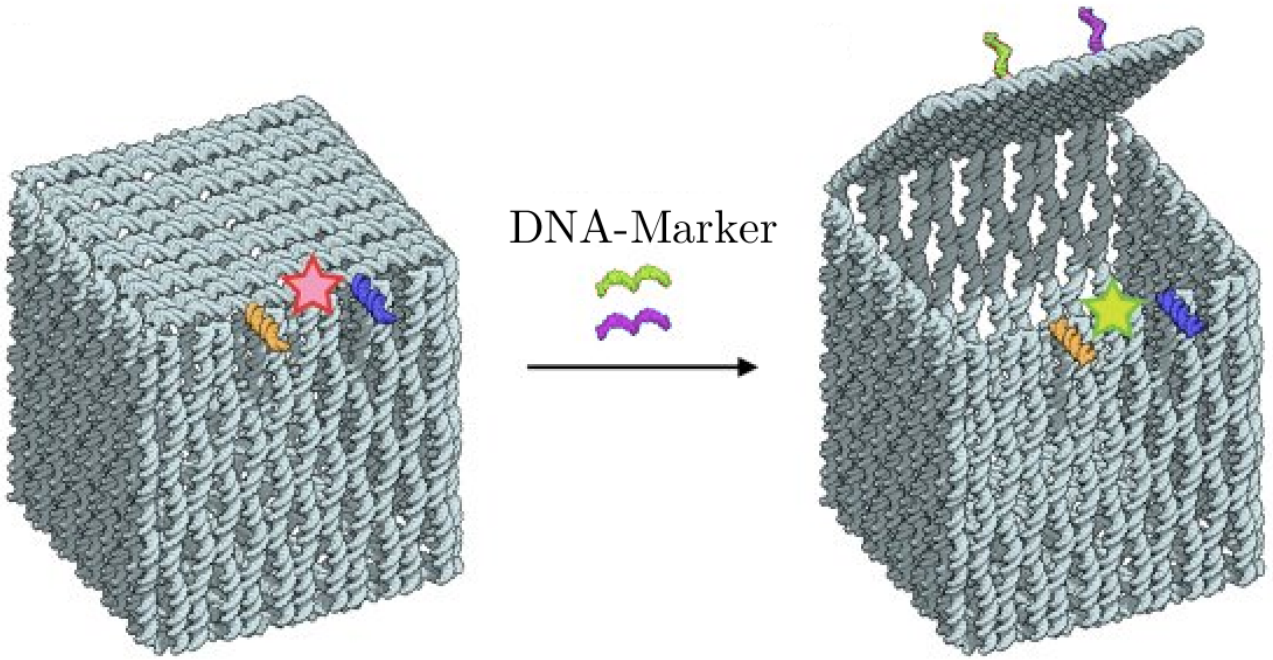


Mechanism of the DNA-Box

[11] Andersen, Dong, Morten M. Nielsen, et al. 2009.

Interim Conclusion

Results to far:

- Until now showed what is possible ***constructed***

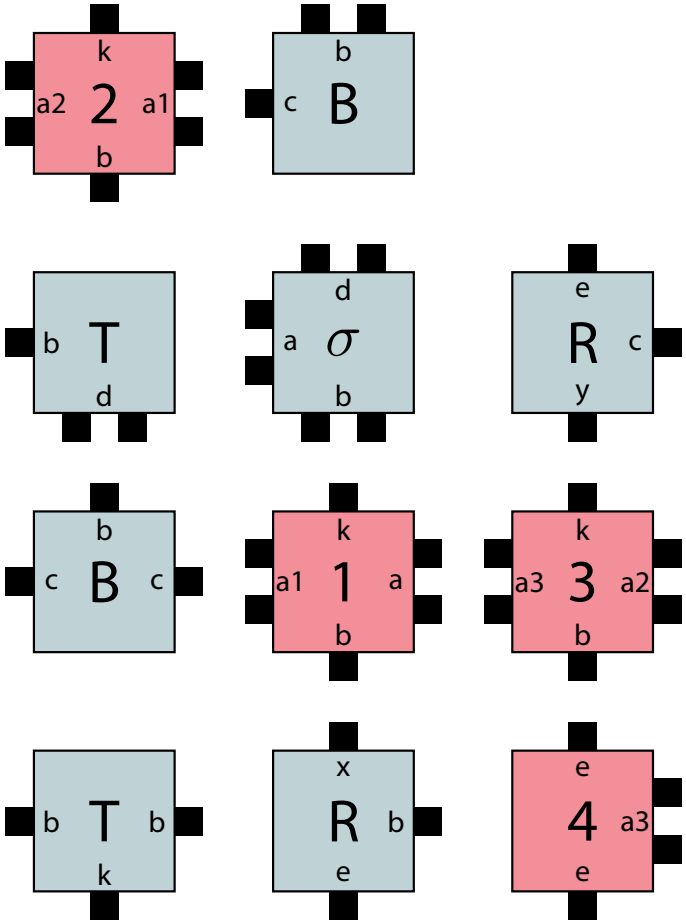
How do we ***compute*** and ***communicate***?

- Computations in ***messages*** instead of nanobots
- Computations via ***conditional*** assembly
- Input via ***event based*** release of specific tiles
- ***Formation of a ligand*** after a ***successful*** computation

$\Rightarrow$ Advantage: Fewer ***resource constraints*** in the channel![12]

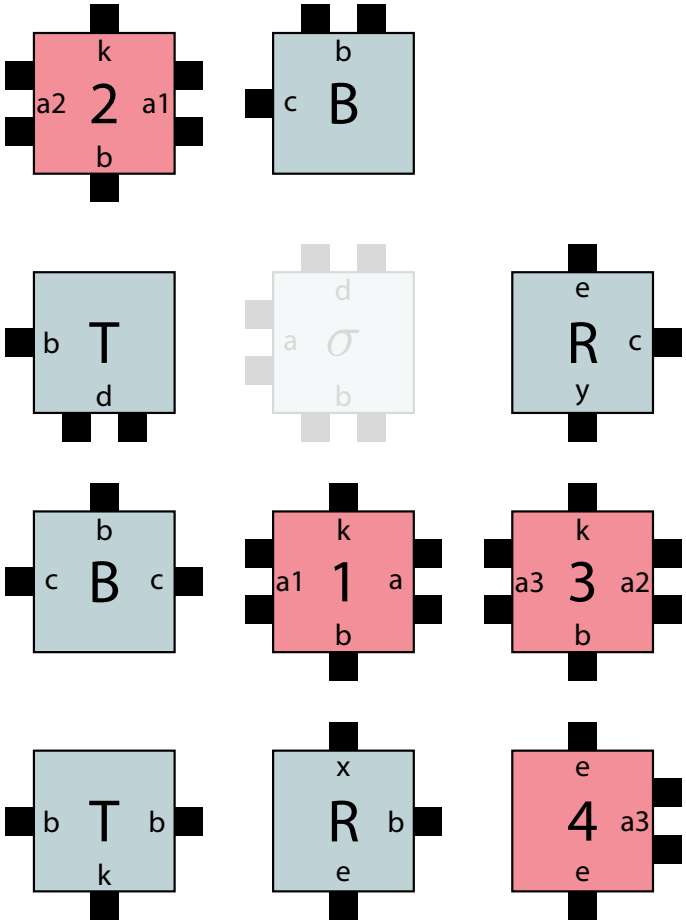
[12] Lau, Büther, Geyer, et al. 2019.

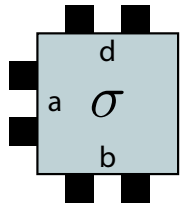
In-Message Computation



[12] Lau, Büther, Geyer, et al. 2019.

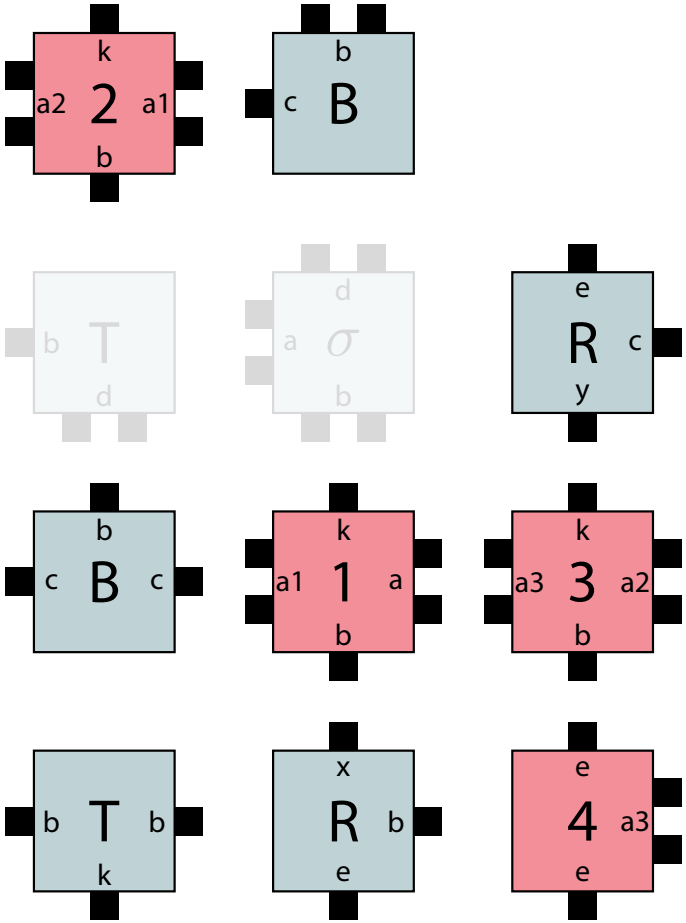
In-Message Computation

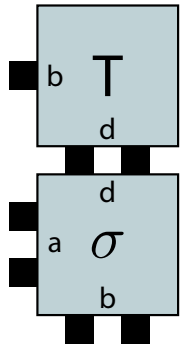




[12] Lau, Büther, Geyer, et al. 2019.

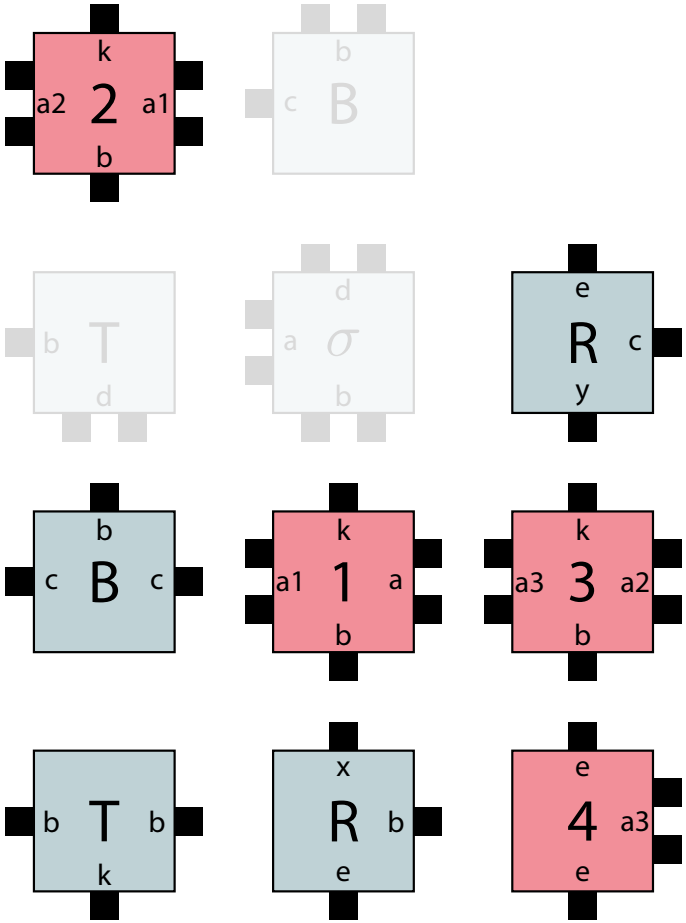
In-Message Computation



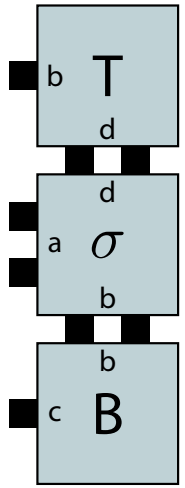


[12] Lau, Büther, Geyer, et al. 2019.

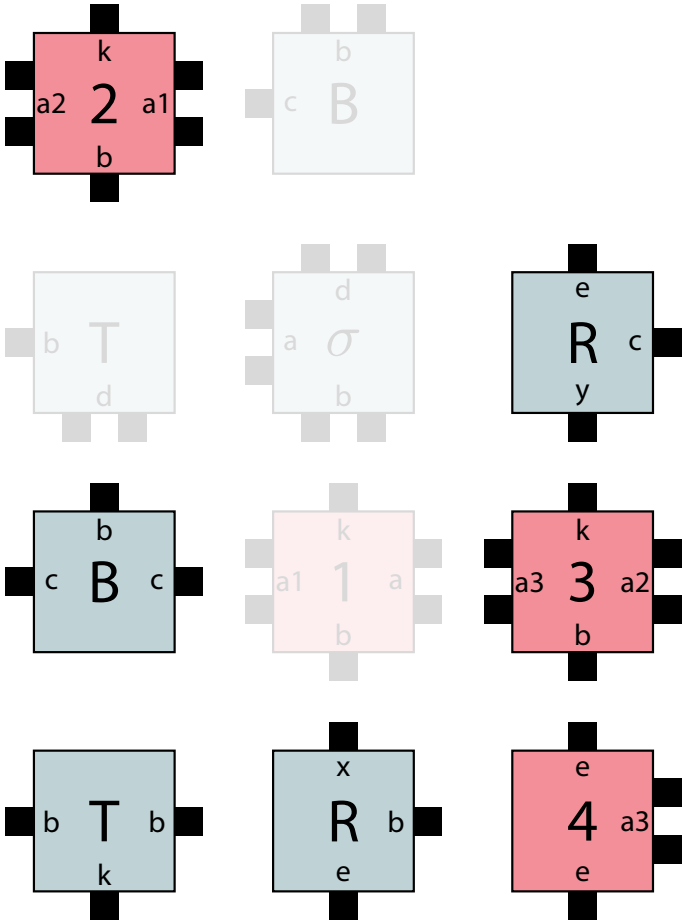
In-Message Computation

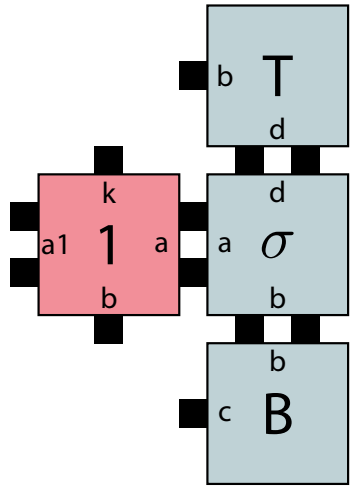


[12] Lau, Büther, Geyer, et al. 2019.



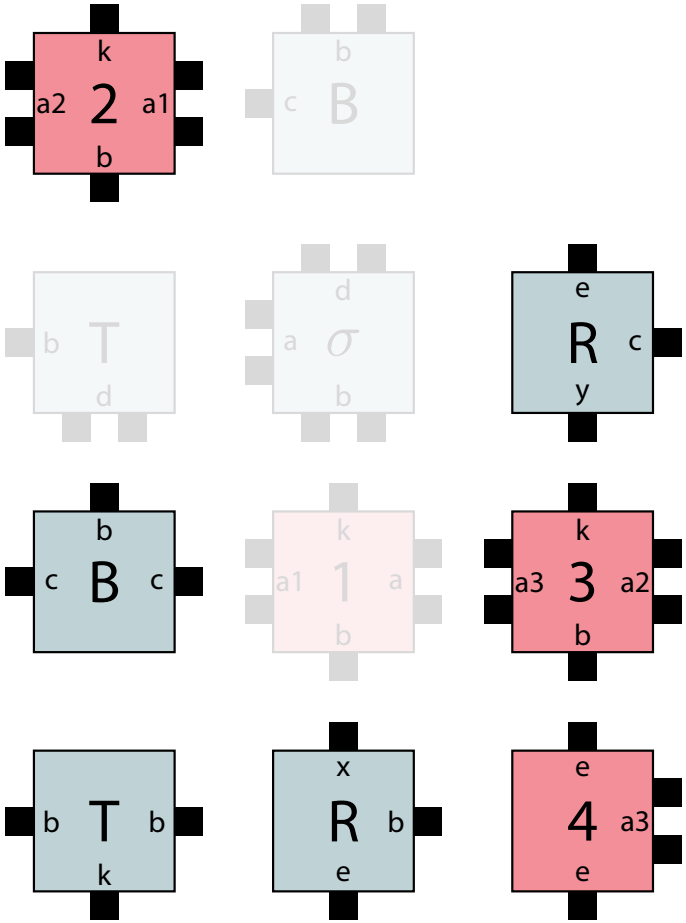
In-Message Computation

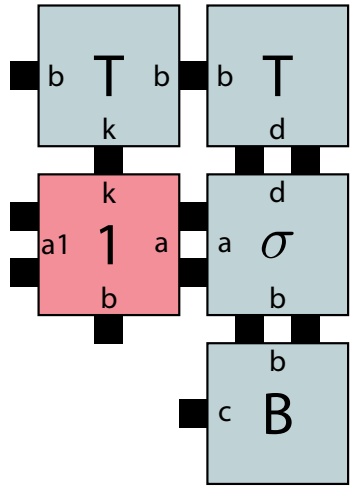




[12] Lau, Büther, Geyer, et al. 2019.

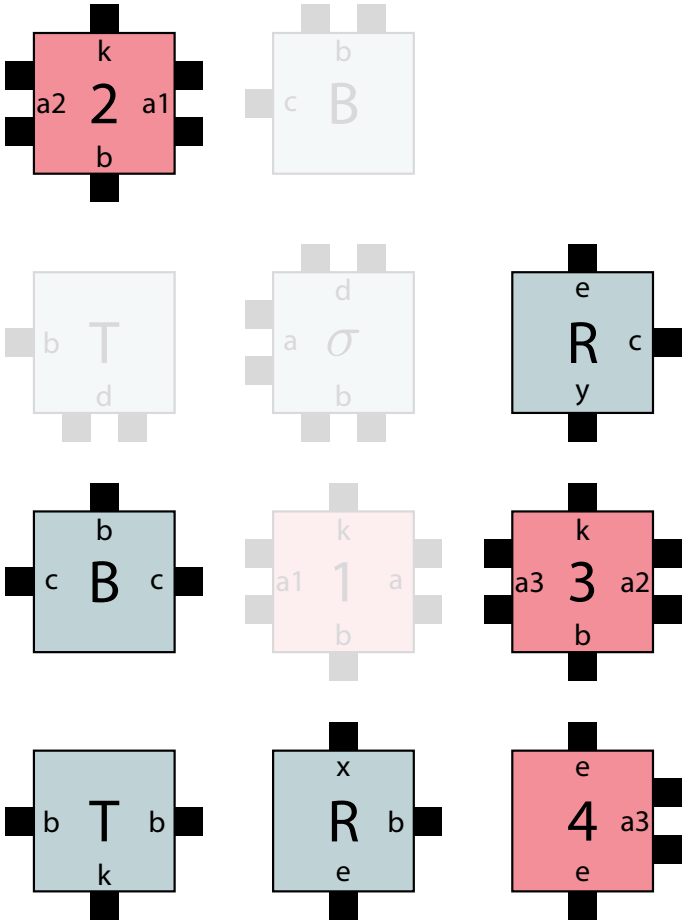
In-Message Computation

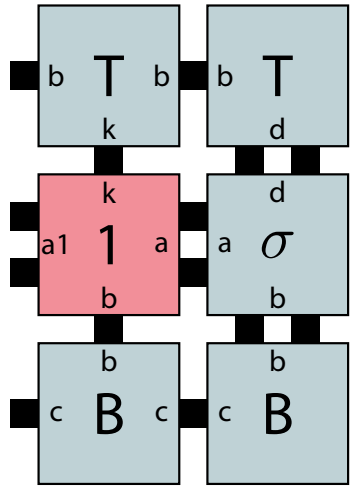




[12] Lau, Büther, Geyer, et al. 2019.

In-Message Computation





[12] Lau, Büther, Geyer, et al. 2019.

In-Message Computation

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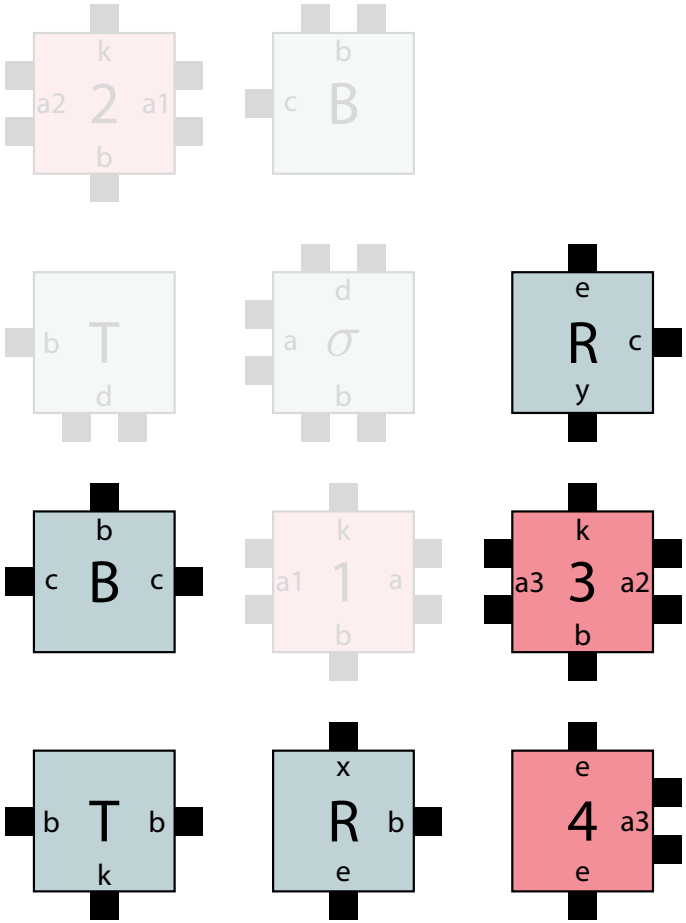

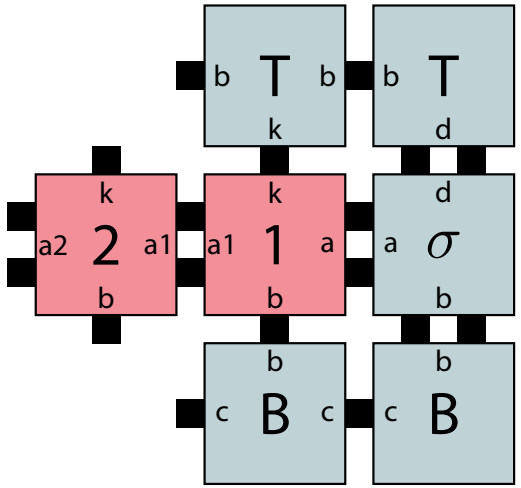

[12] Lau, Büther, Geyer, et al. 2019.

In-Message Computation

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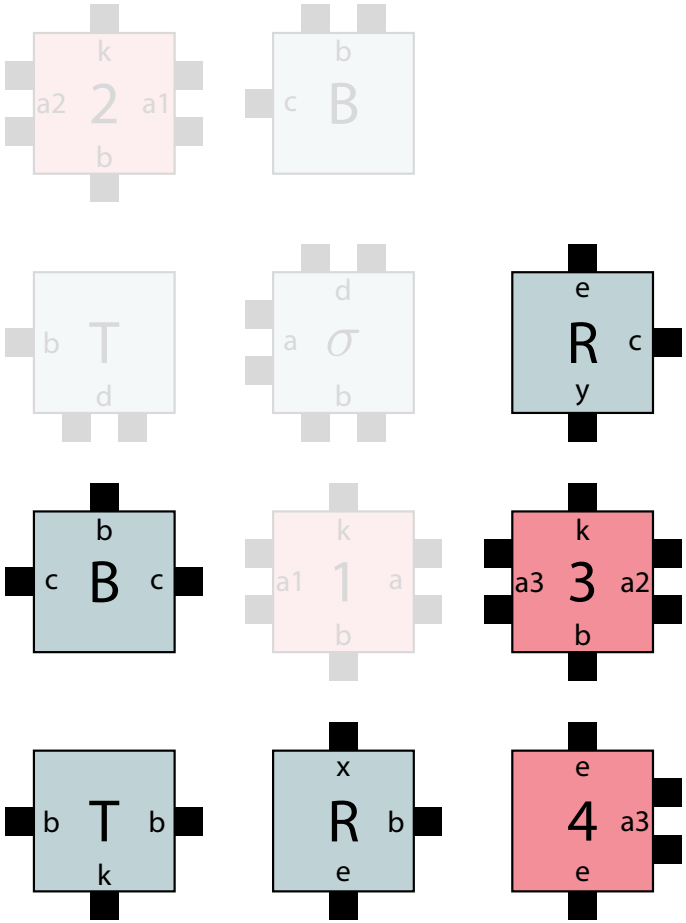
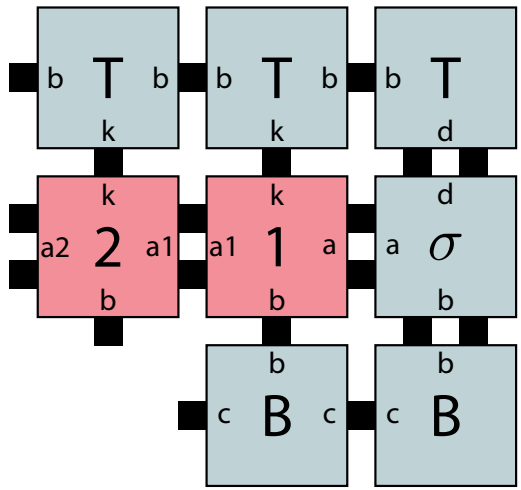
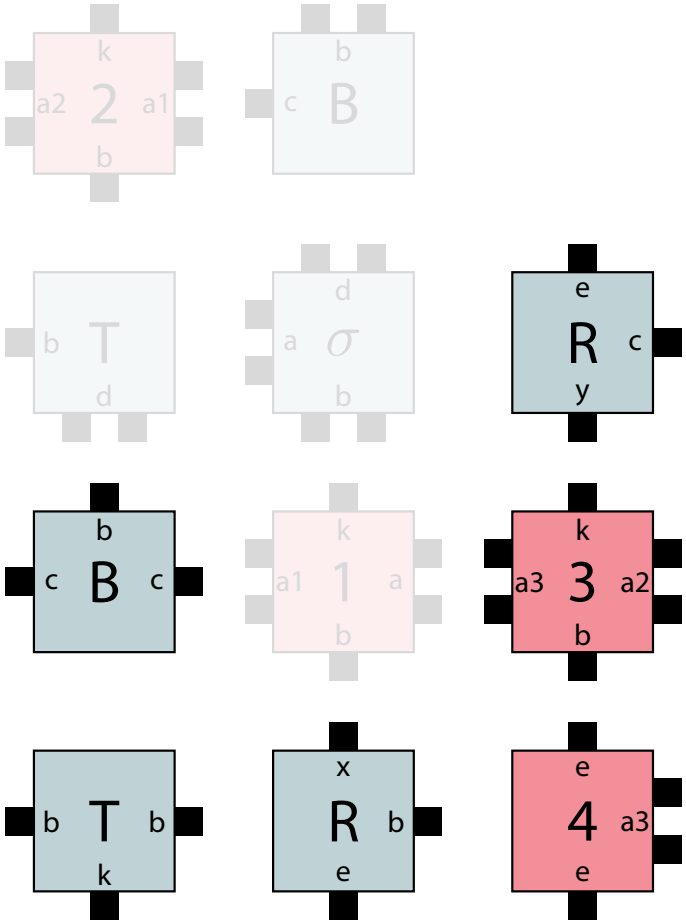
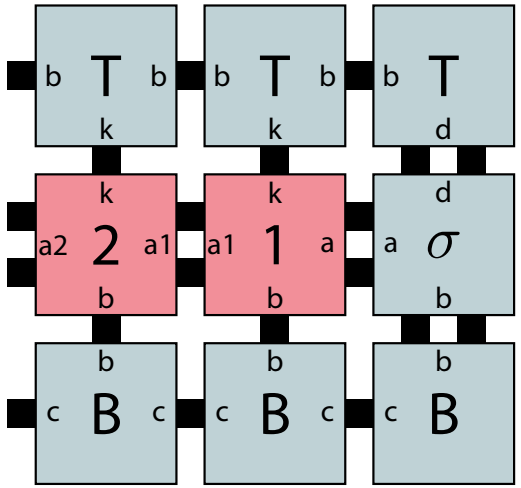




[12] Lau, Büther, Geyer, et al. 2019.

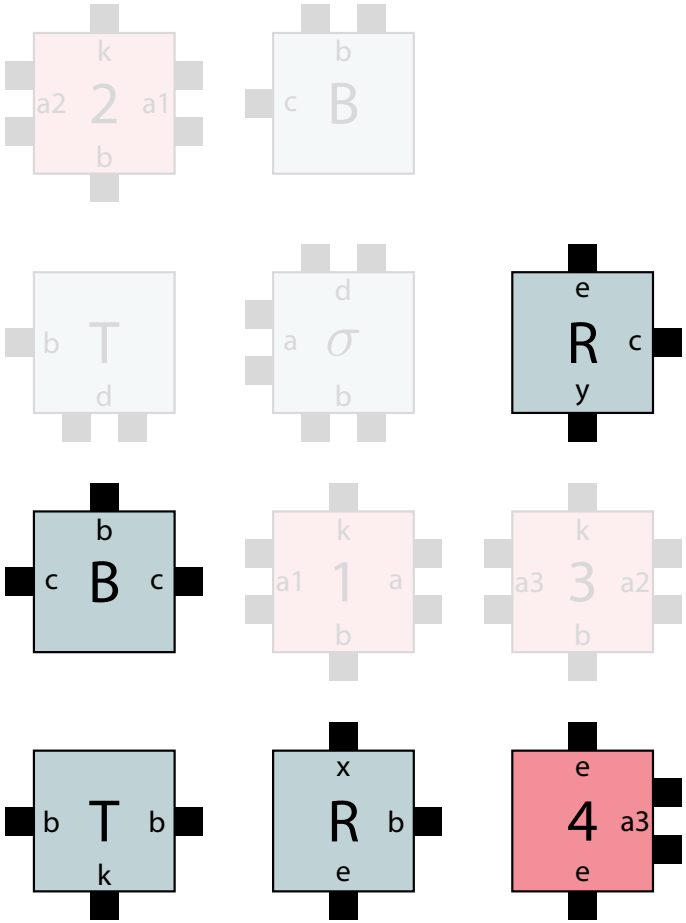
In-Message Computation

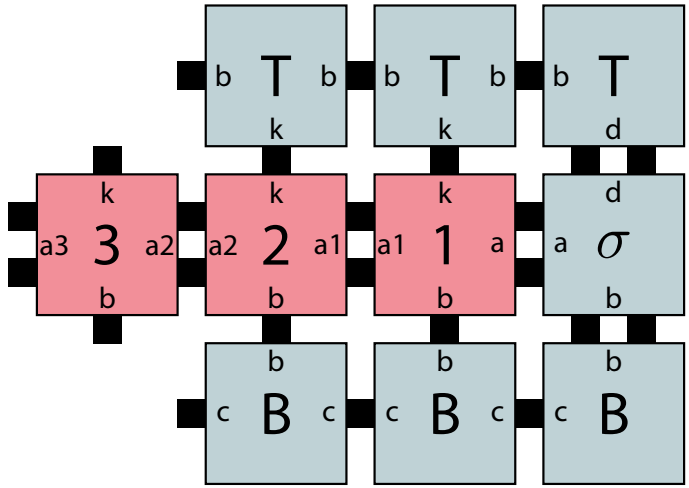




[12] Lau, Büther, Geyer, et al. 2019.

In-Message Computation





[12] Lau, Büther, Geyer, et al. 2019.

In-Message Computation

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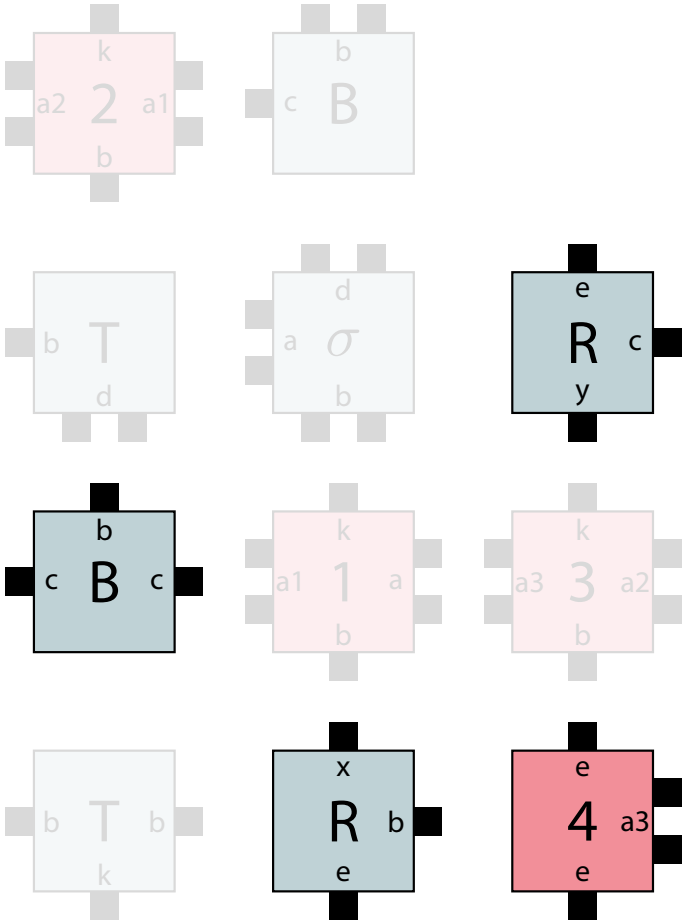

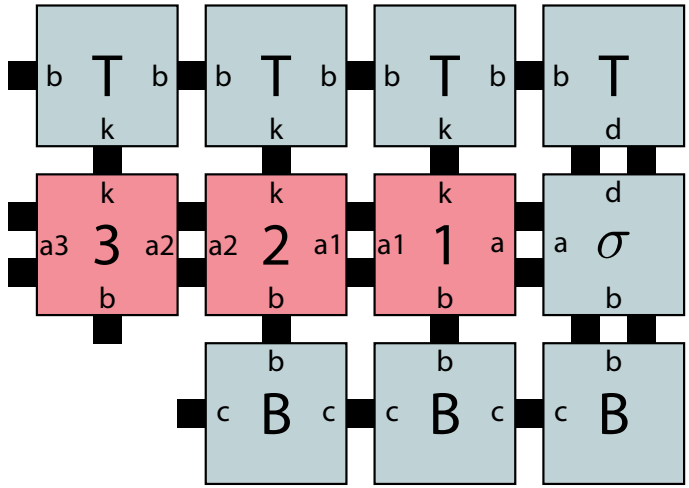

[12] Lau, Büther, Geyer, et al. 2019.

In-Message Computation

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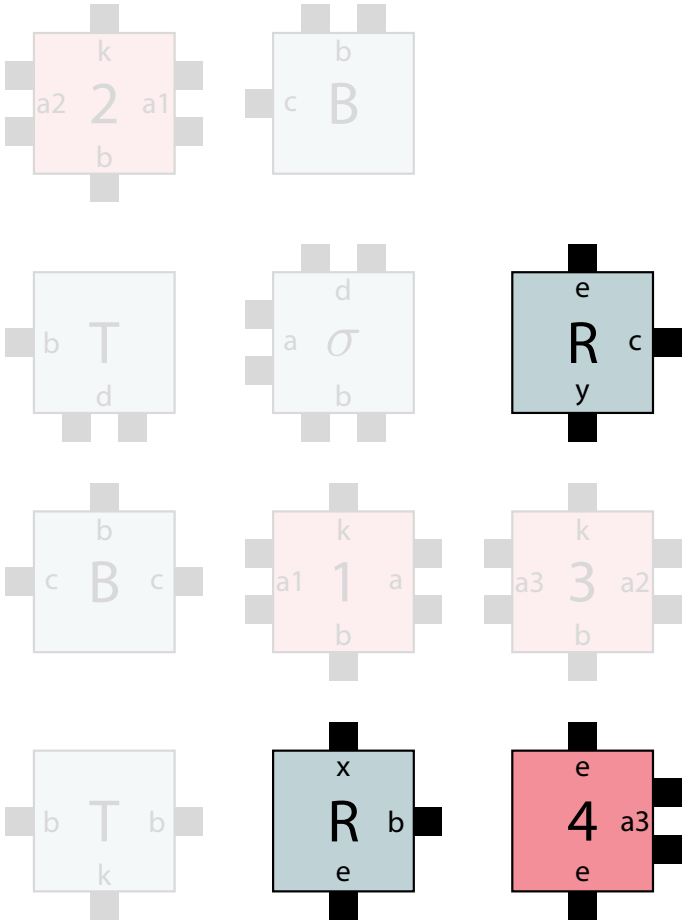
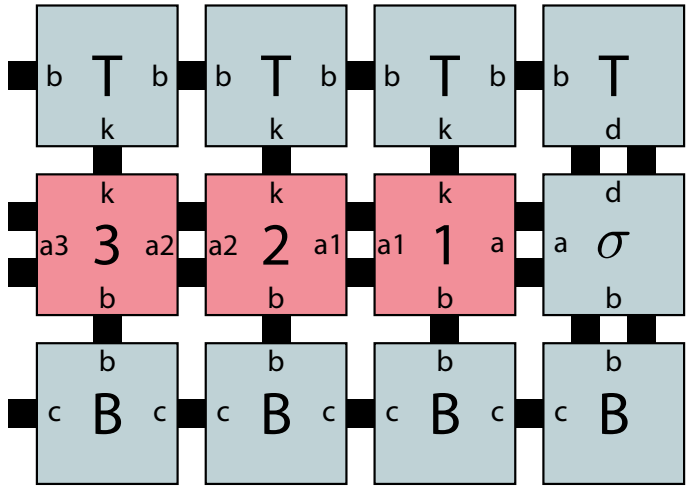
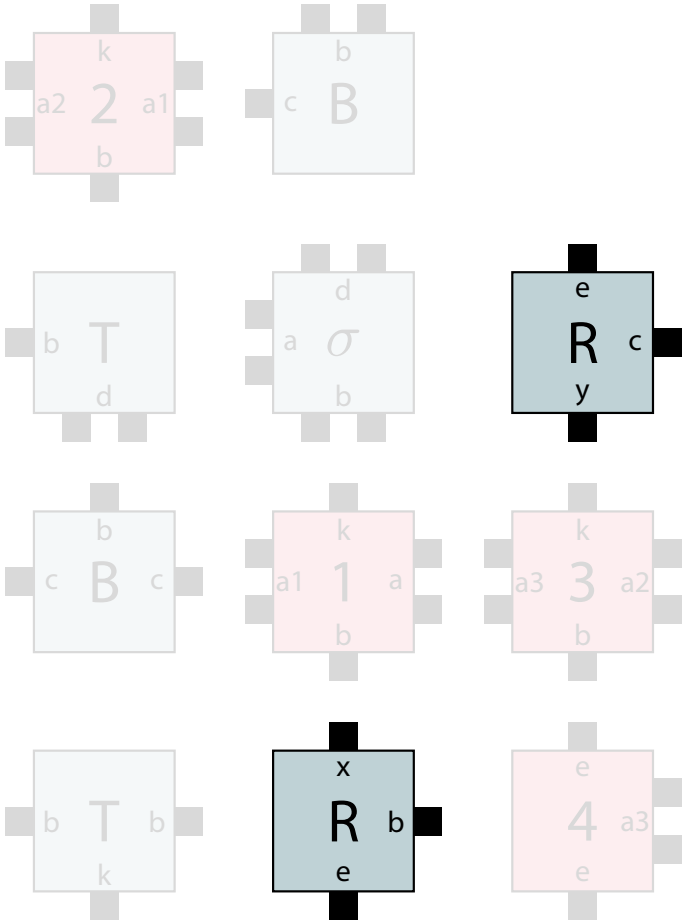
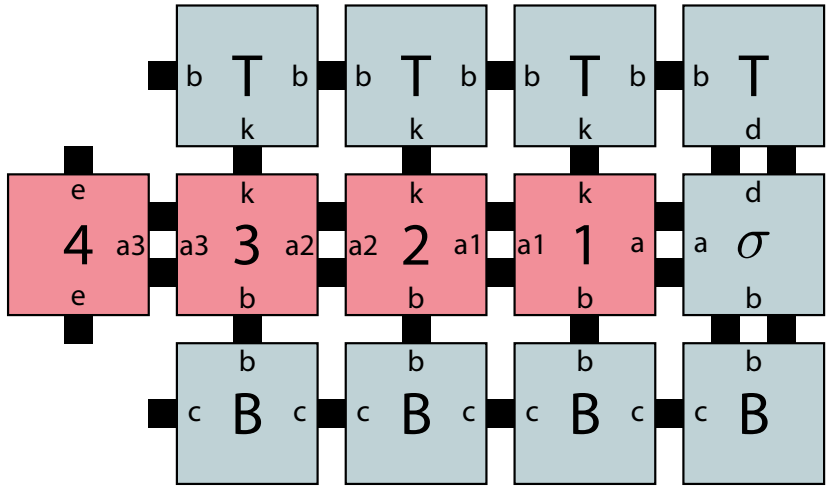




[12] Lau, Büther, Geyer, et al. 2019.

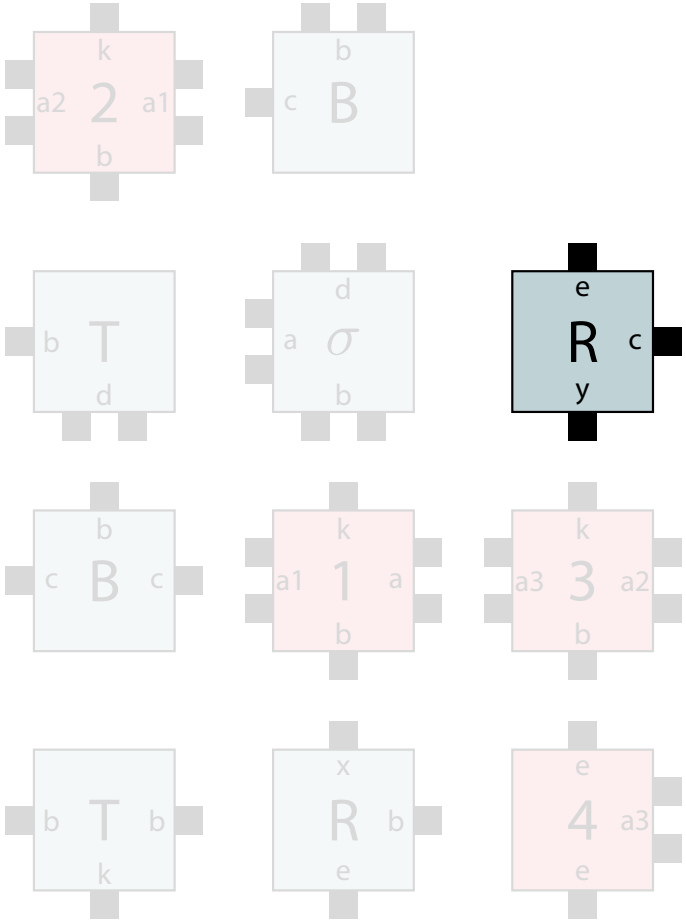
In-Message Computation

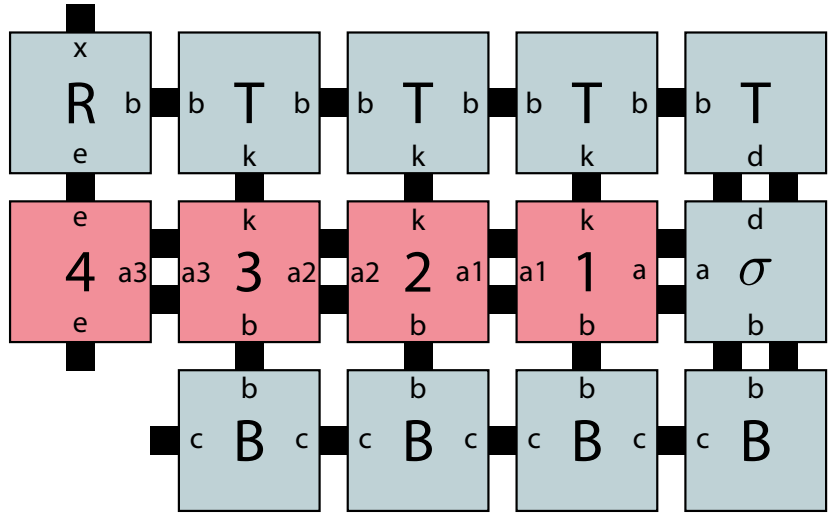




[12] Lau, Büther, Geyer, et al. 2019.

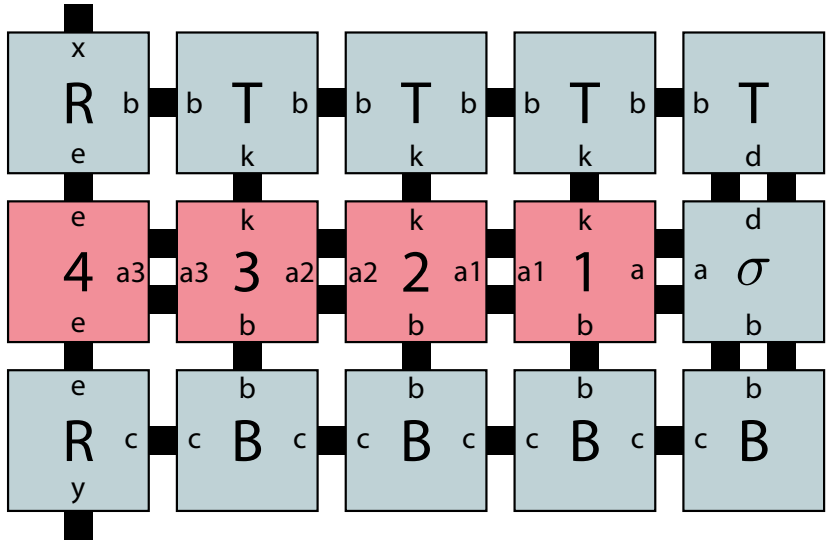
In-Message Computation





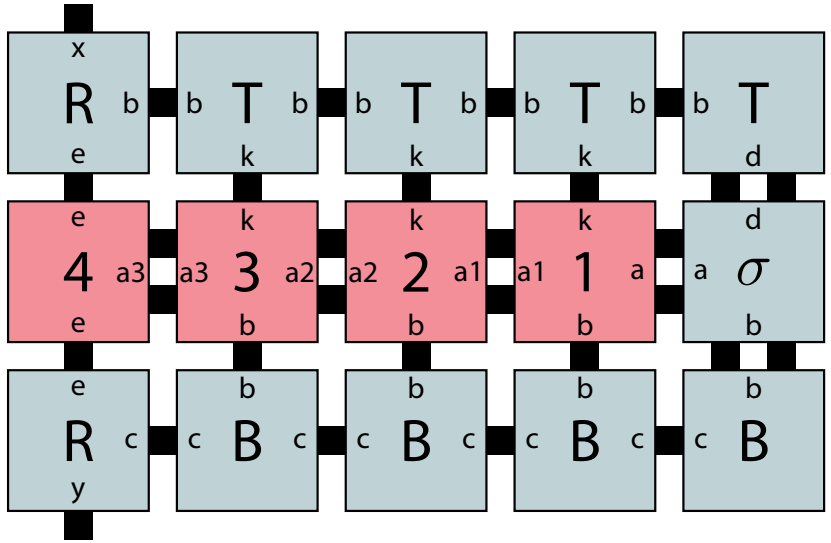
[12] Lau, Büther, Geyer, et al. 2019.

In-Message Computation



[12] Lau, Büther, Geyer, et al. 2019.

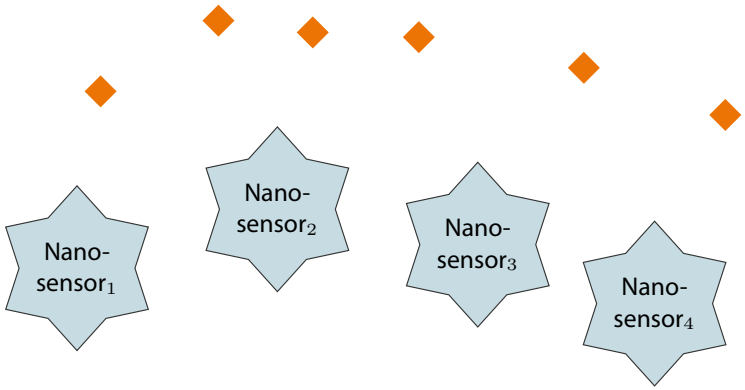
In-Message Computation



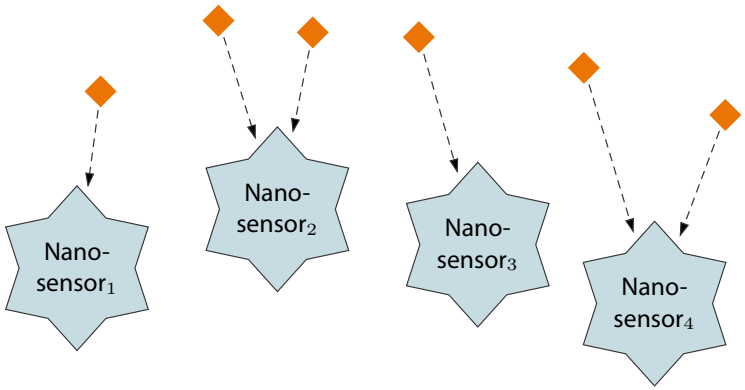
⇒ Full assembly ***only*** when tiles 1–4 are present

[12] Lau, Büther, Geyer, et al. 2019.

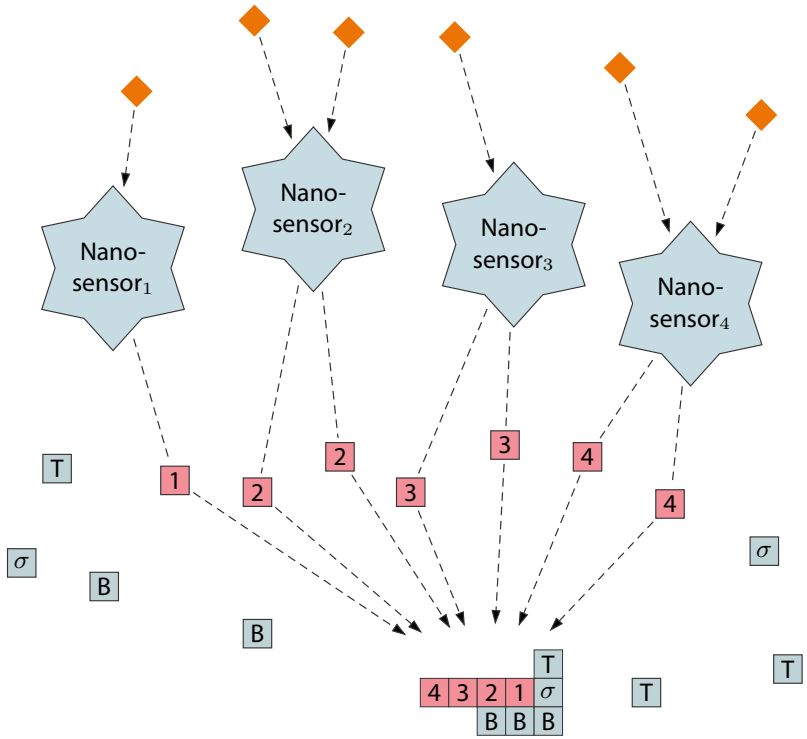
And-Nanonetwork



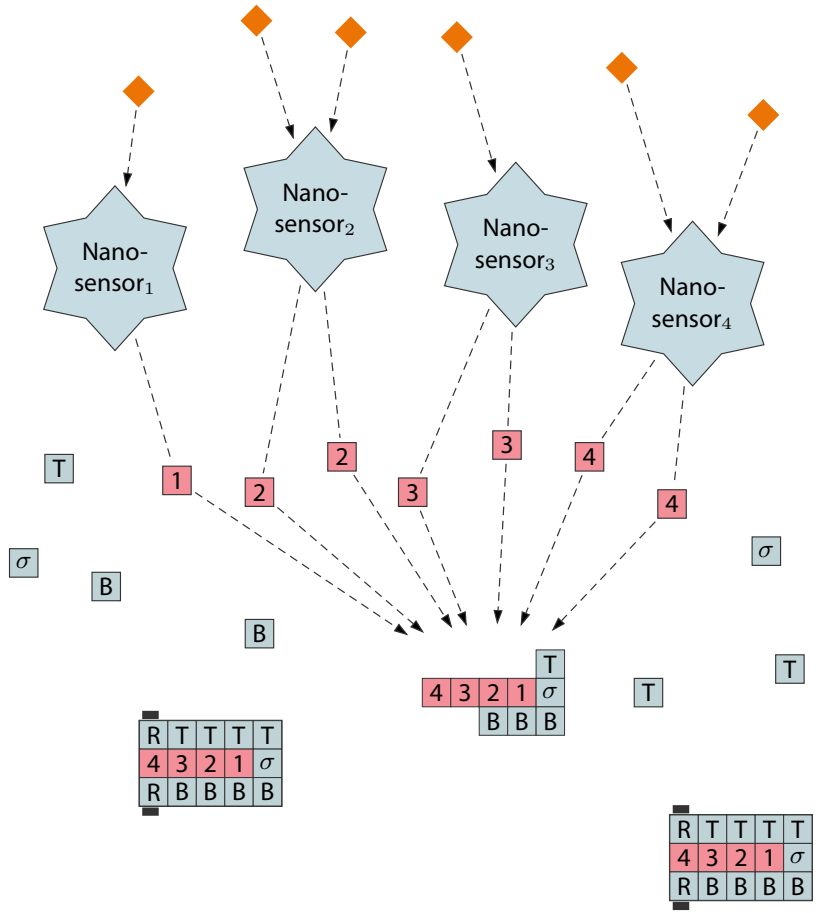
And-Nanonetwork



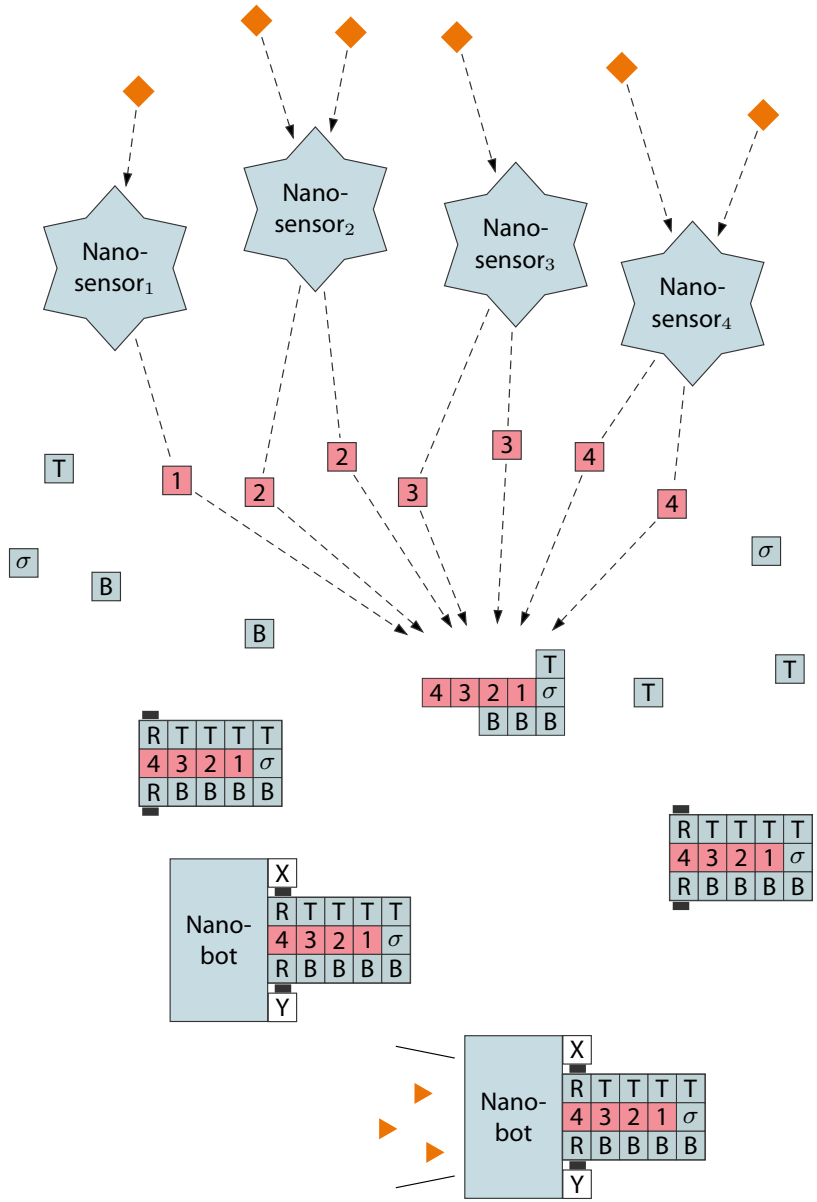
And-Nanonetwork



And-Nanonetwork



And-Nanonetwork



And-Reference Architecture

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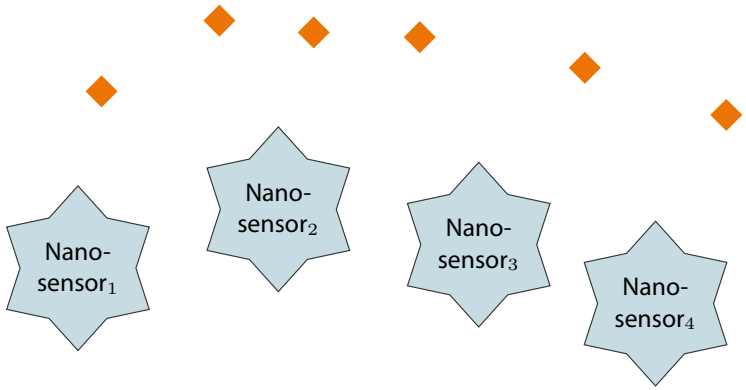
1. Marker detection

2.Tile release



3. Message assembly

4. Receptor binding

5. Medication release

And-Reference Architecture

UNIVERSITÄT ZU LÜBECK
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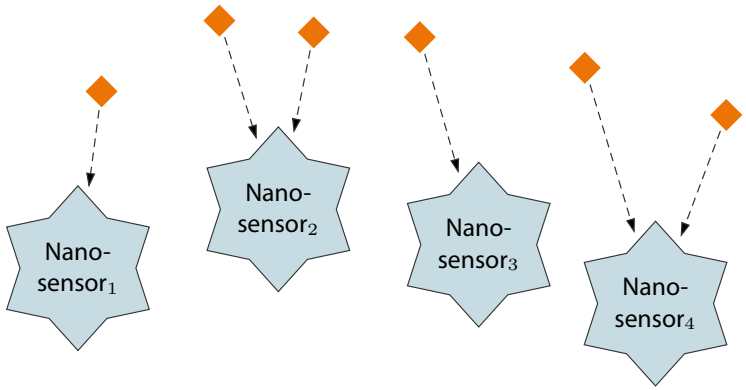
1. Marker detection

2.Tile release



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And-Reference Architecture

UNIVERSITÄT ZU LÜBECK
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1. Marker detection

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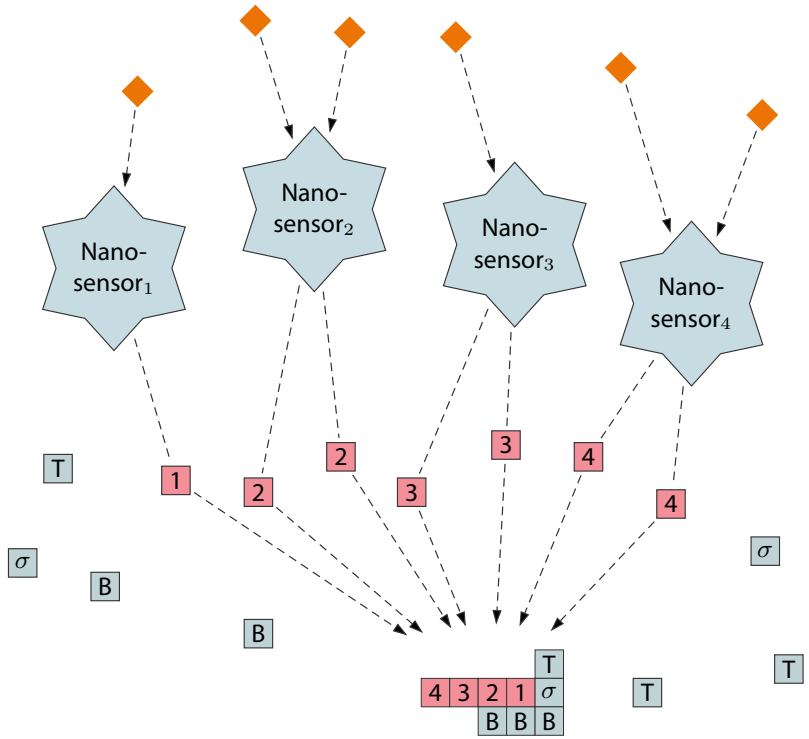

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And-Reference Architecture

UNIVERSITÄT ZU LÜBECK
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1. Marker detection

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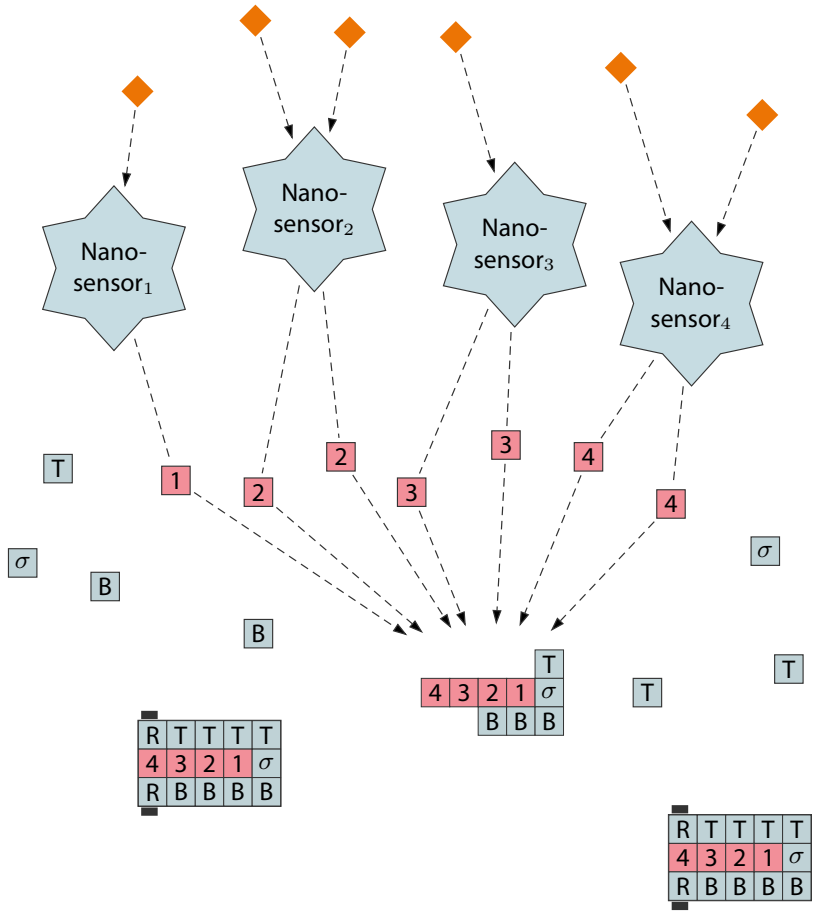

And-Reference Architecture

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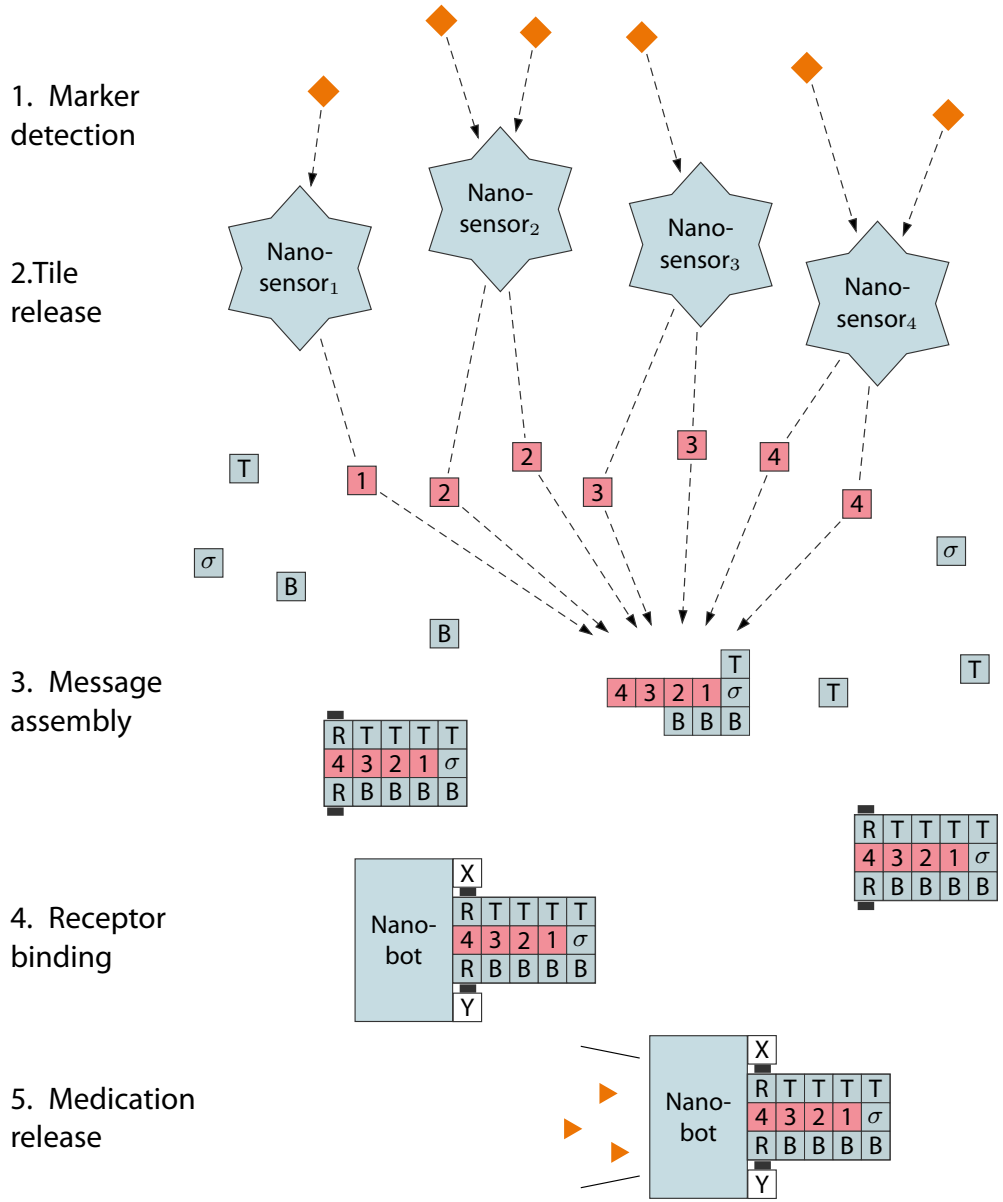

Modularization

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The following realizable ***modules*** exist:

1. Detecting a ***arbitrary marker*** through a nanosensor. Li et al. have already shown that medication can be released after the detection of markers[13].
2. The ***storage*** of tiles and drugs in nanostructures[14].
3. ***Assembly*** of message molecule in the laboratory[15].
4. The attachment of message molecule to a nanobot[16].
5. The ***release*** of tiles or drugs, see 1.[17].

[13] Li et al. 2018; Benenson et al. 2004.
[14] Li et al. 2018; Andersen, Dong, Morten M Nielsen, et al. 2009.
[15] Lee et al. 2004.
[16] Cheng et al. 2005.
[17] Li et al. 2018.

Add

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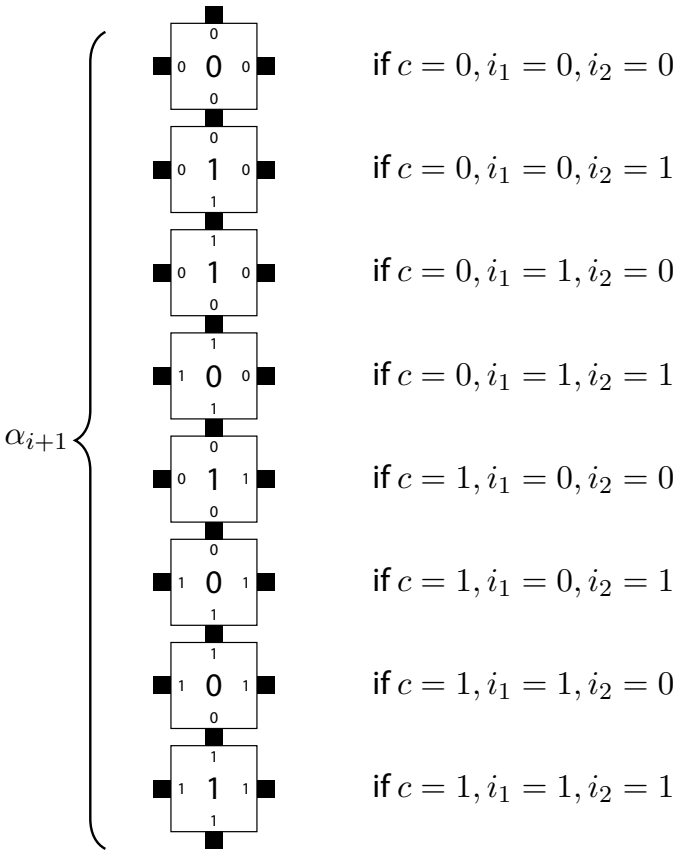
Behavior ADD:



Function Problem Add

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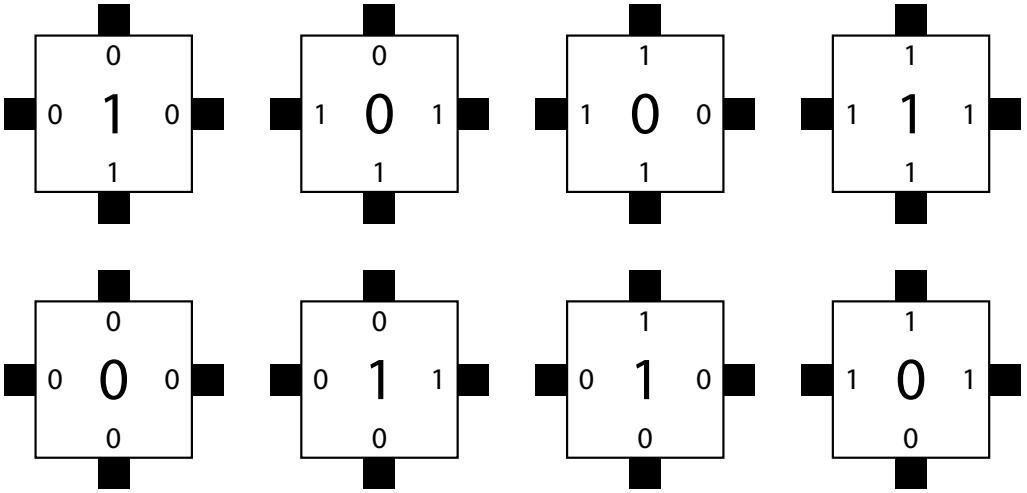

Function Problem Add

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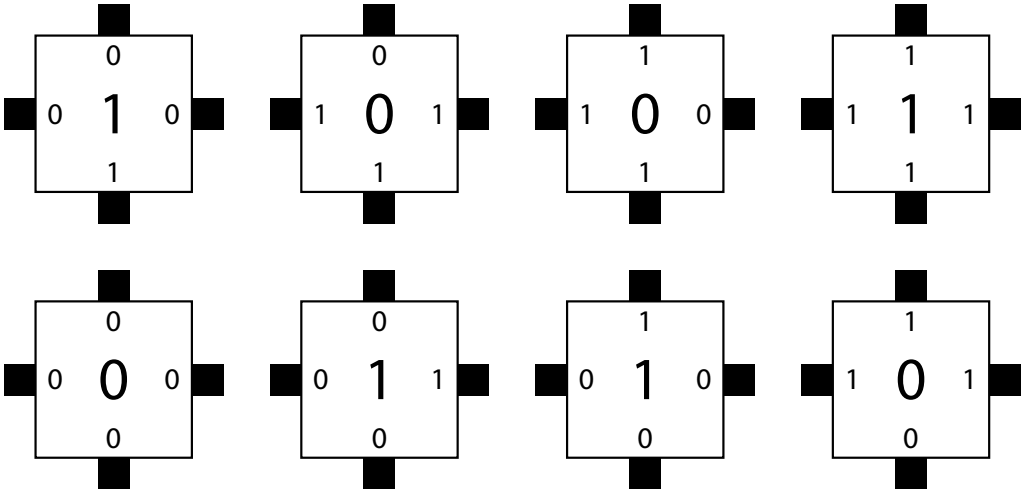

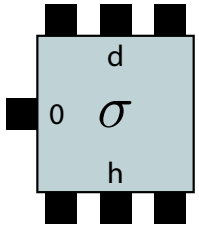

Function Problem Add

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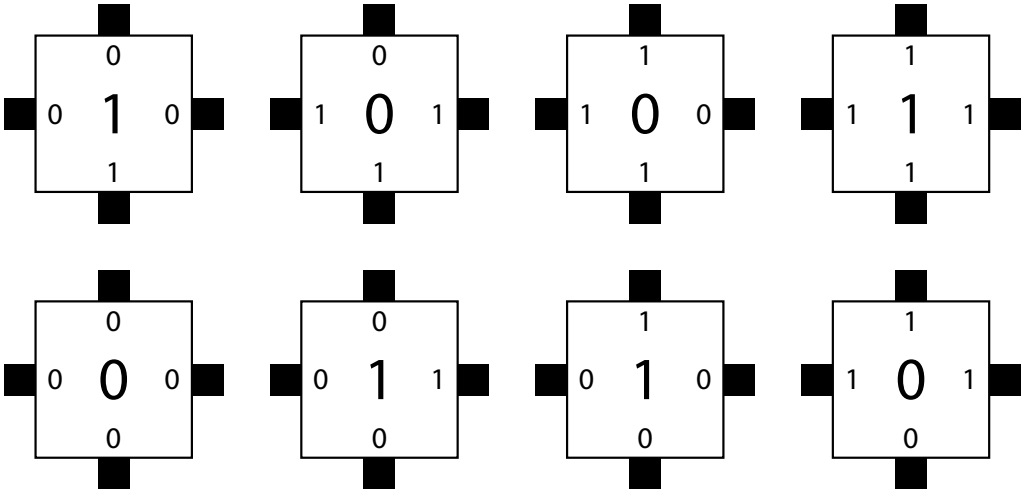

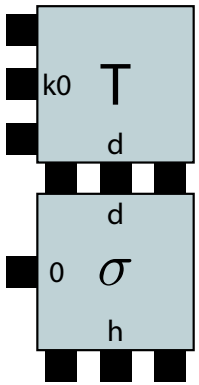

Function Problem Add

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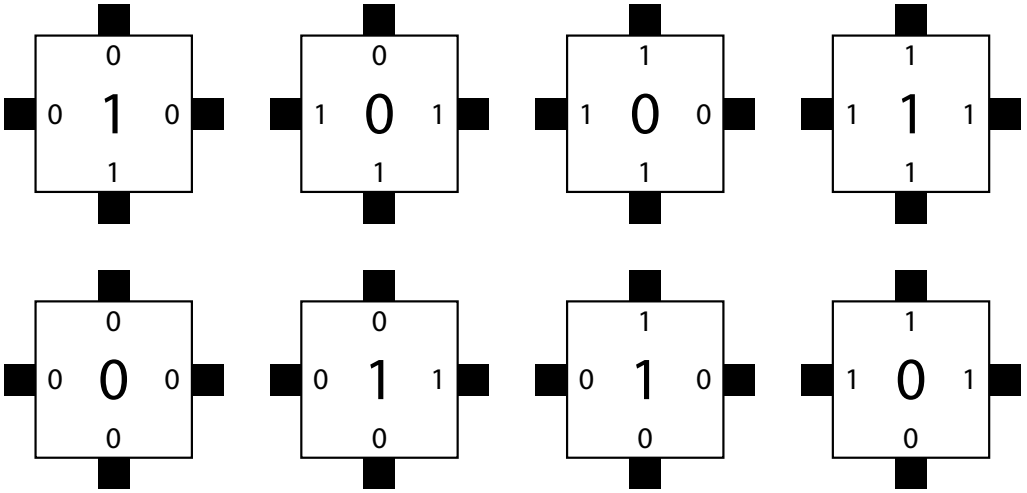

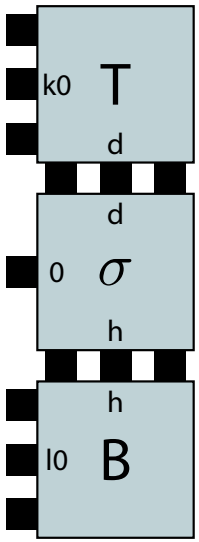

Function Problem Add

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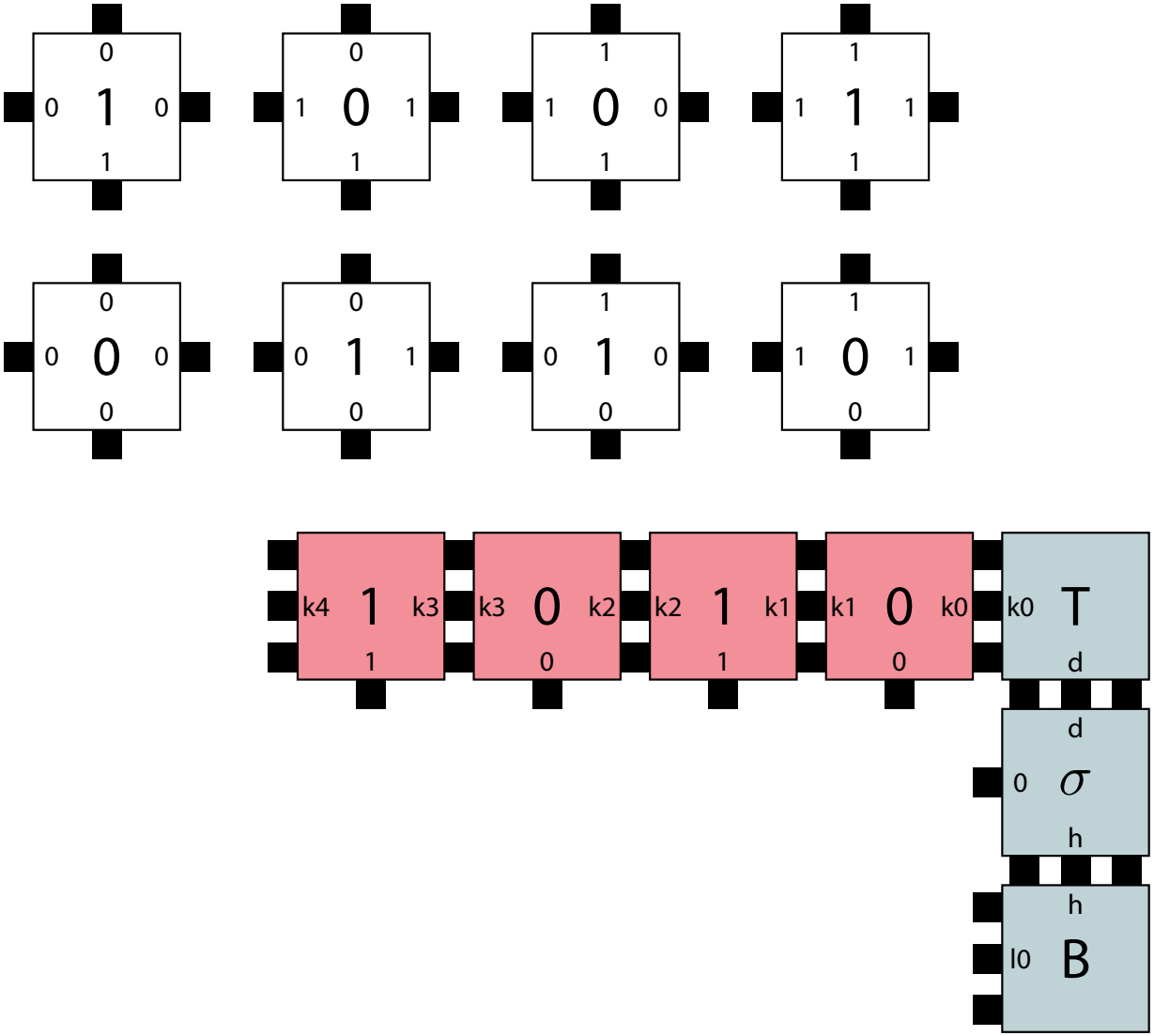

Function Problem Add

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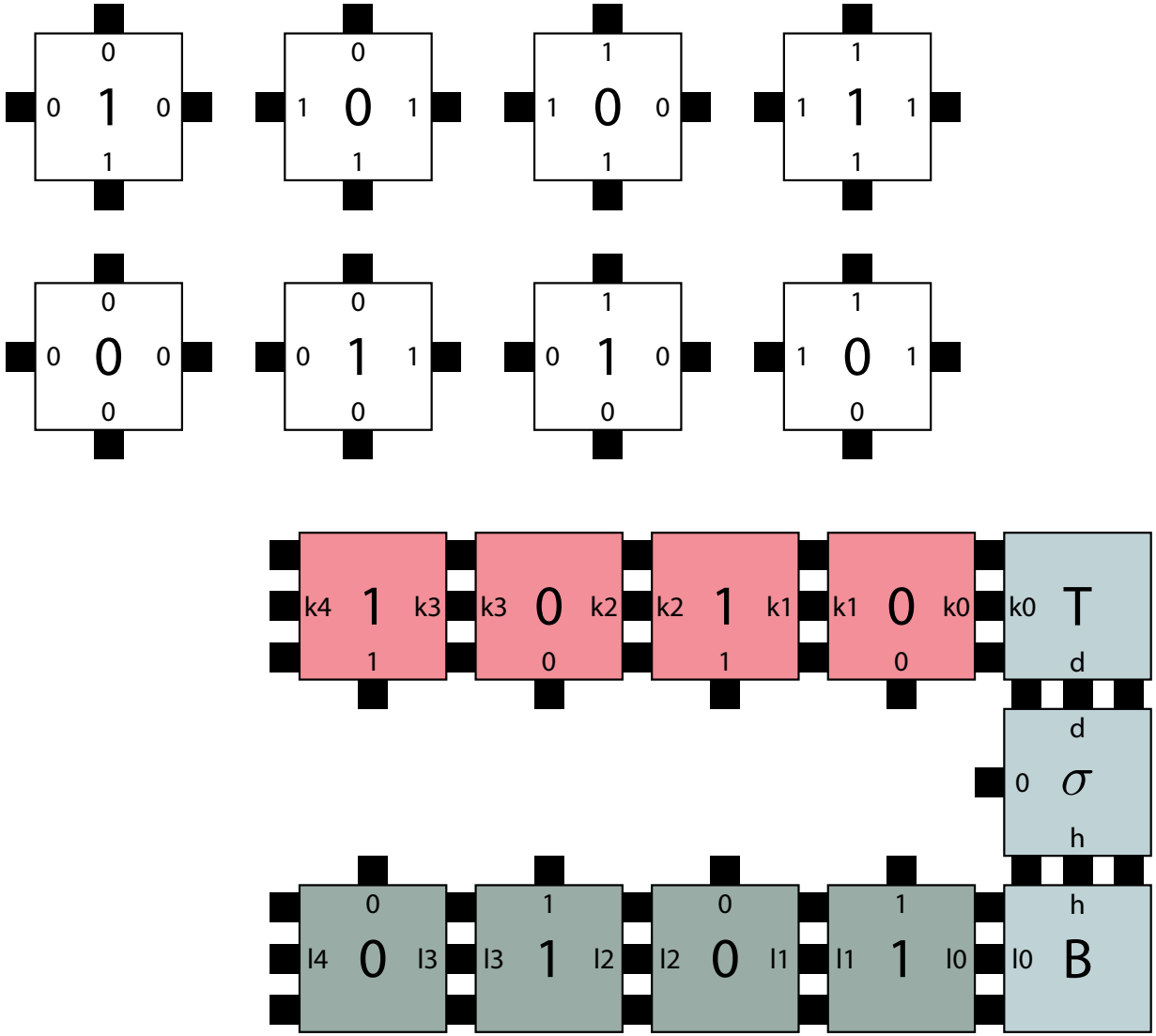

Function Problem Add

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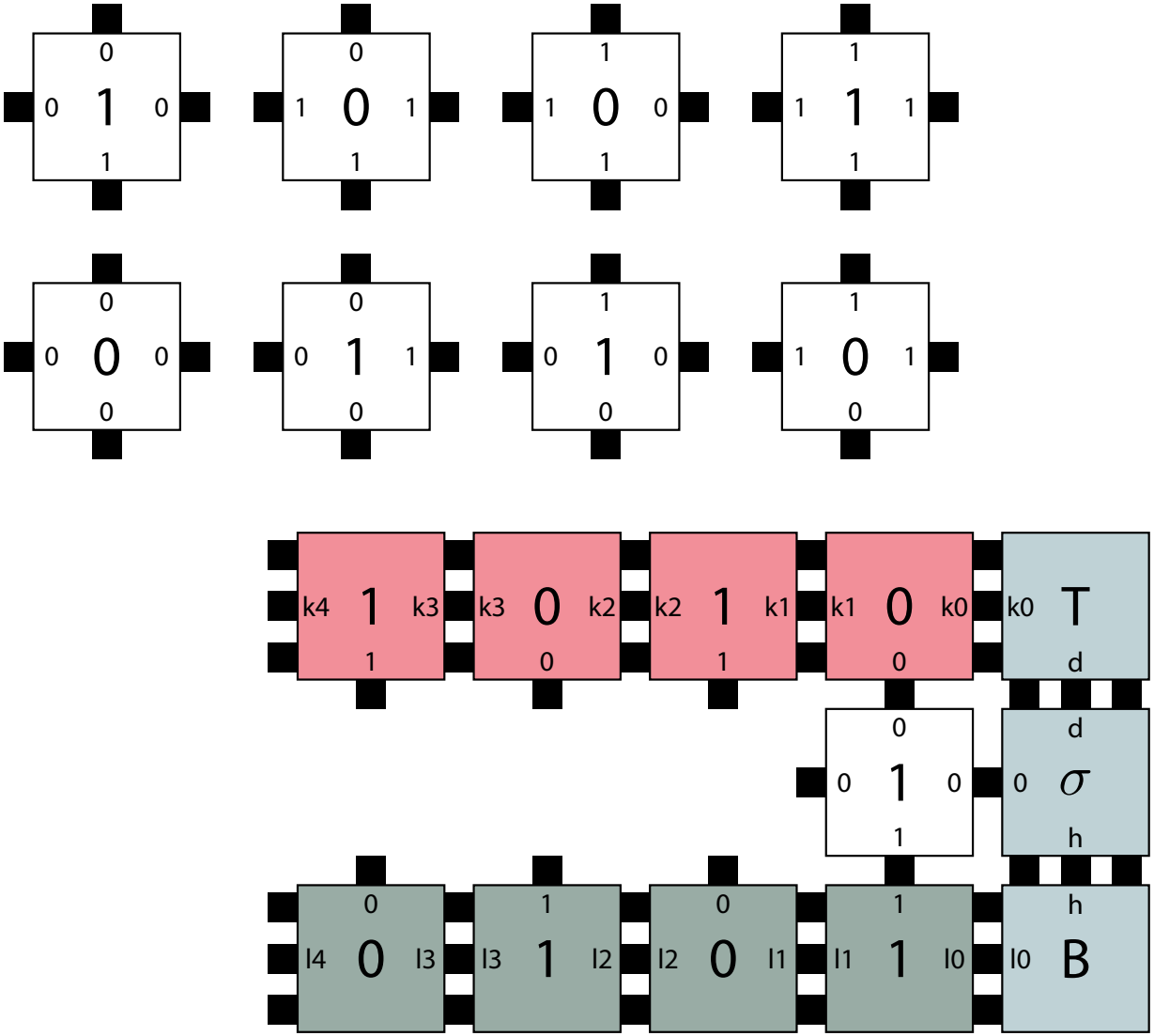

Function Problem Add

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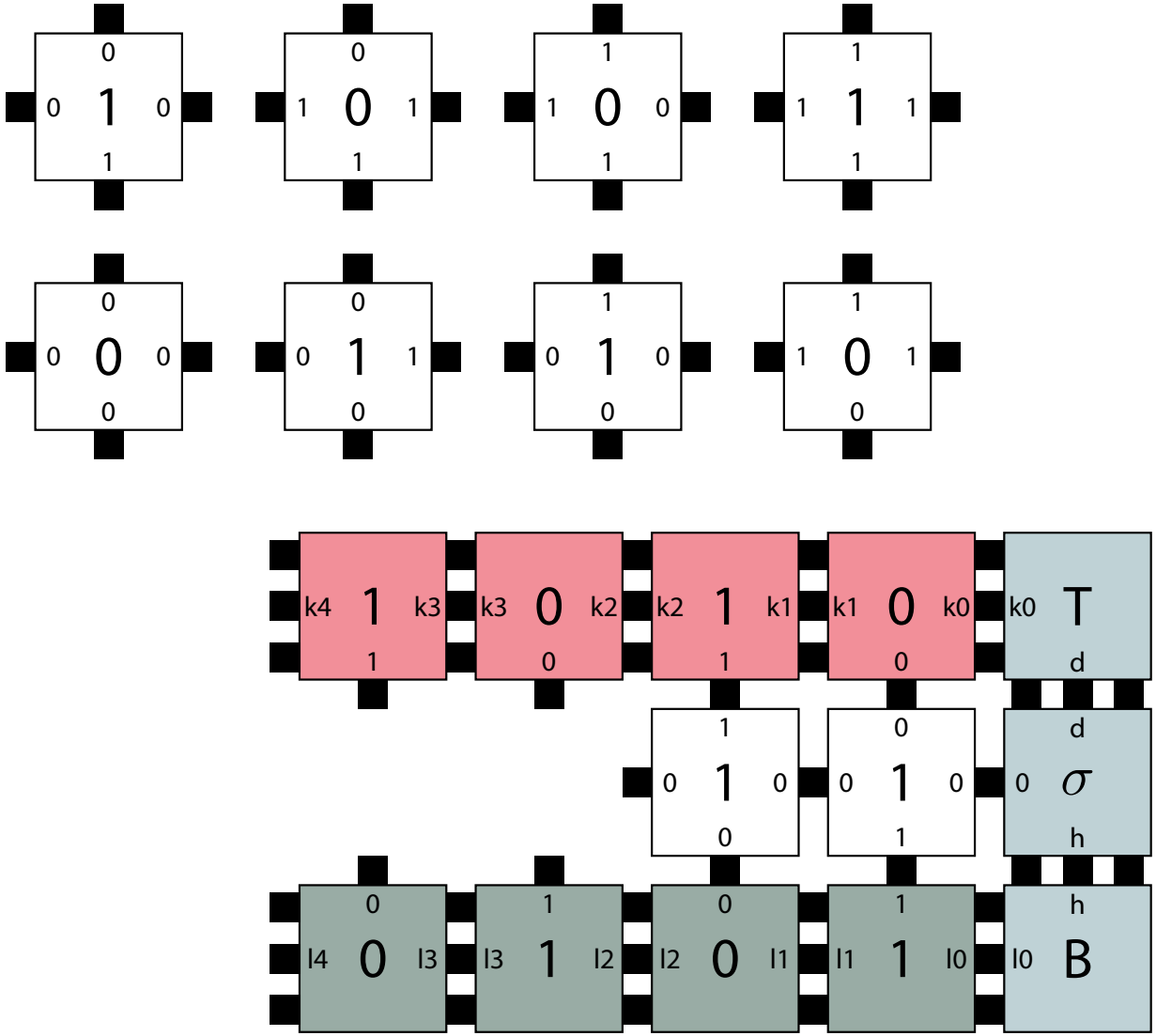

Function Problem Add

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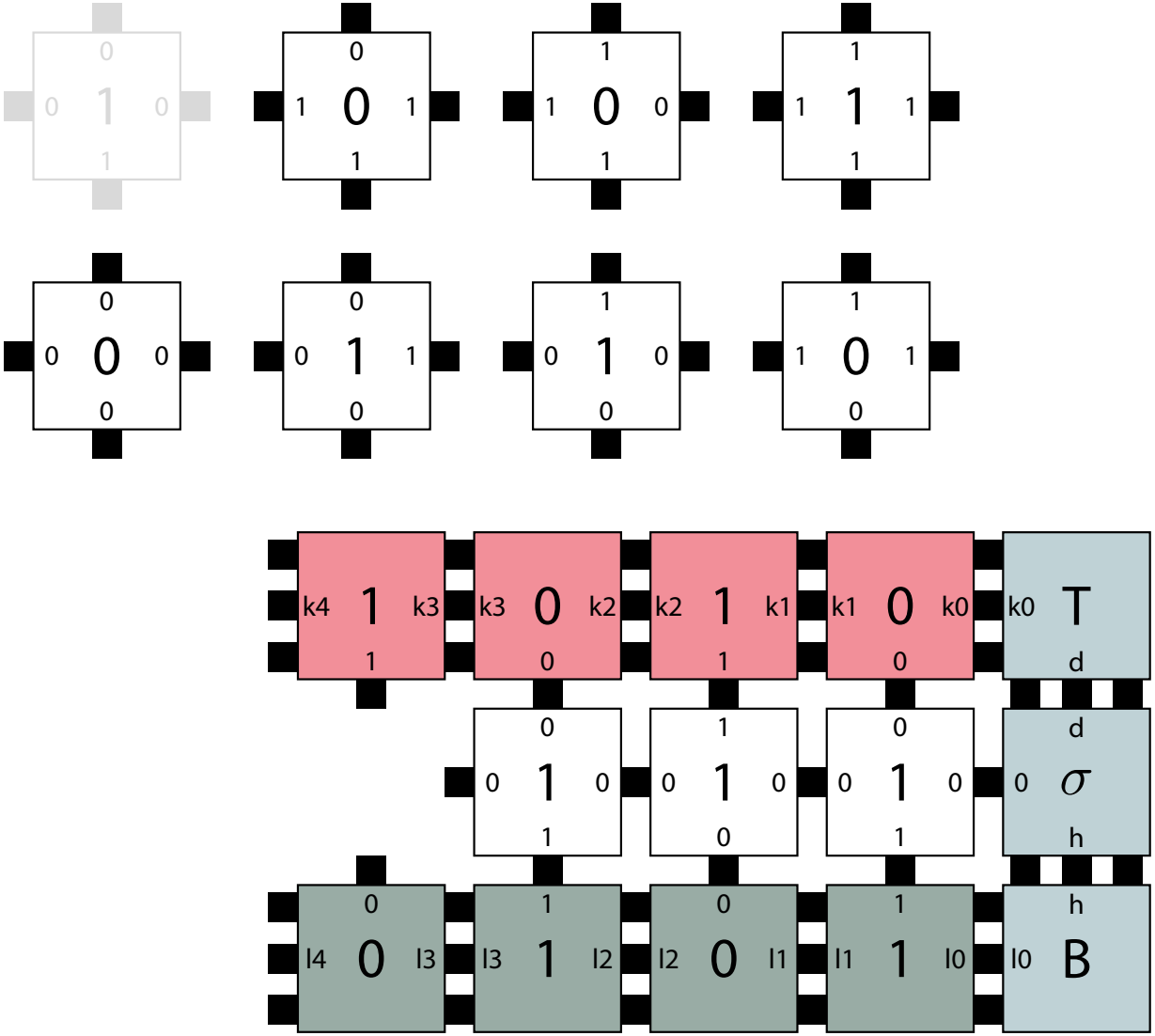

Function Problem Add

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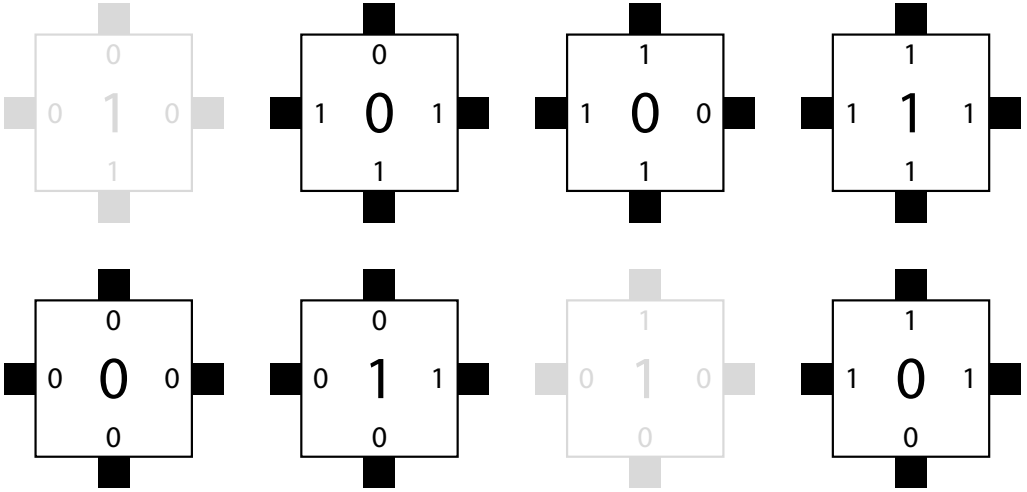

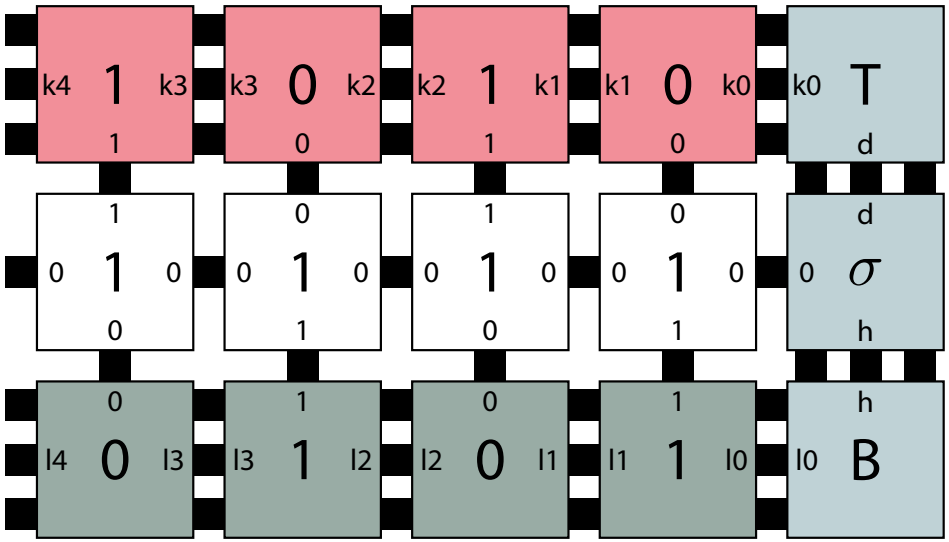

Function Problem Add

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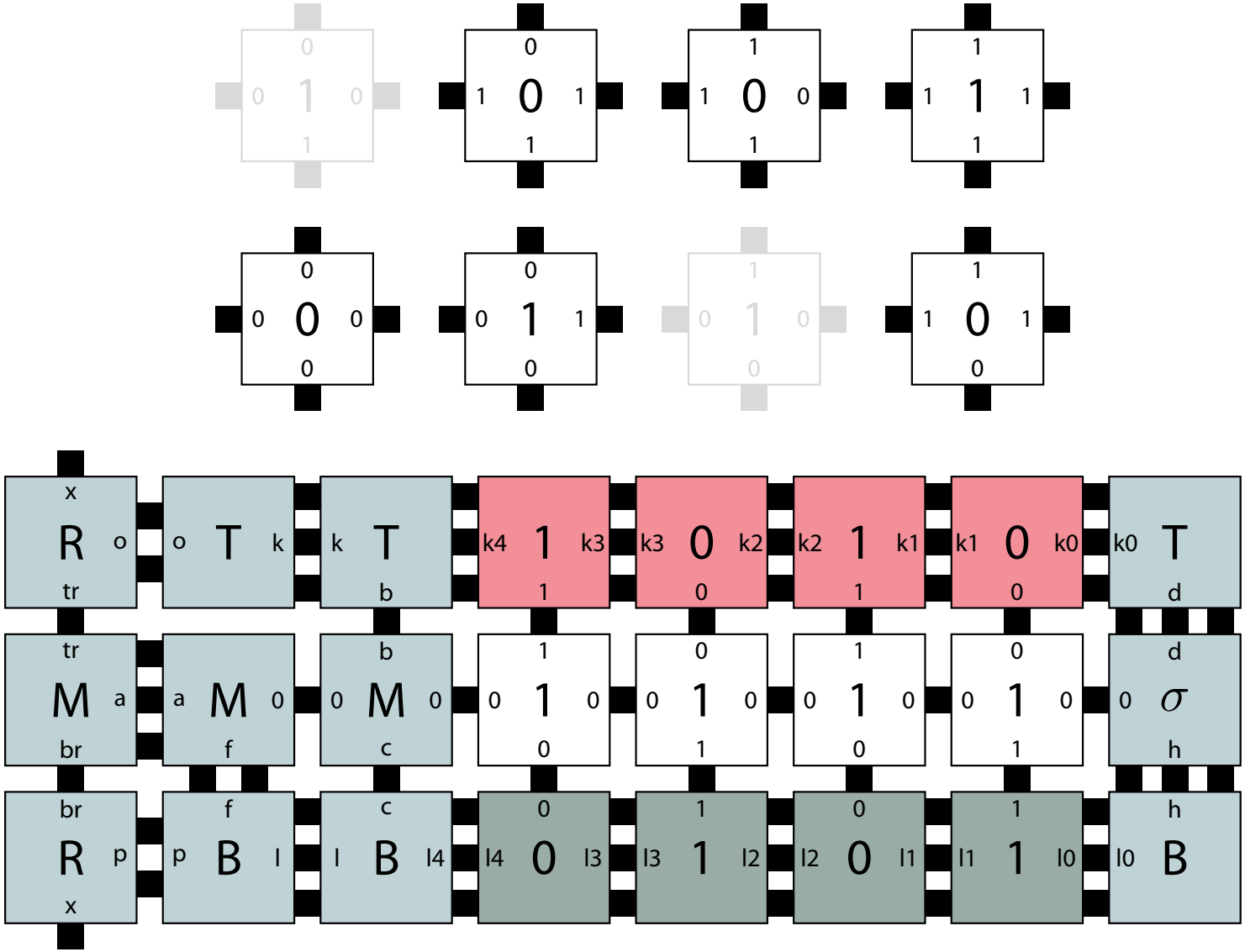
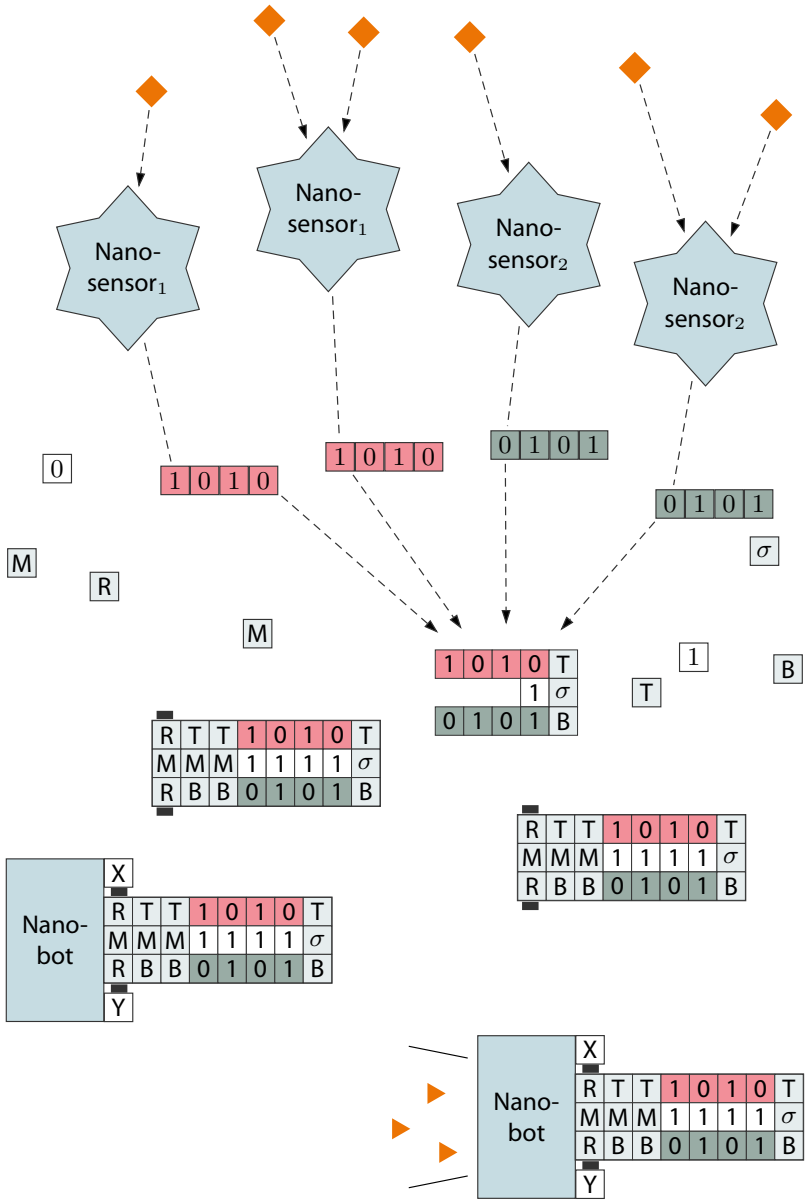


Add-Nanonetwork



Thres

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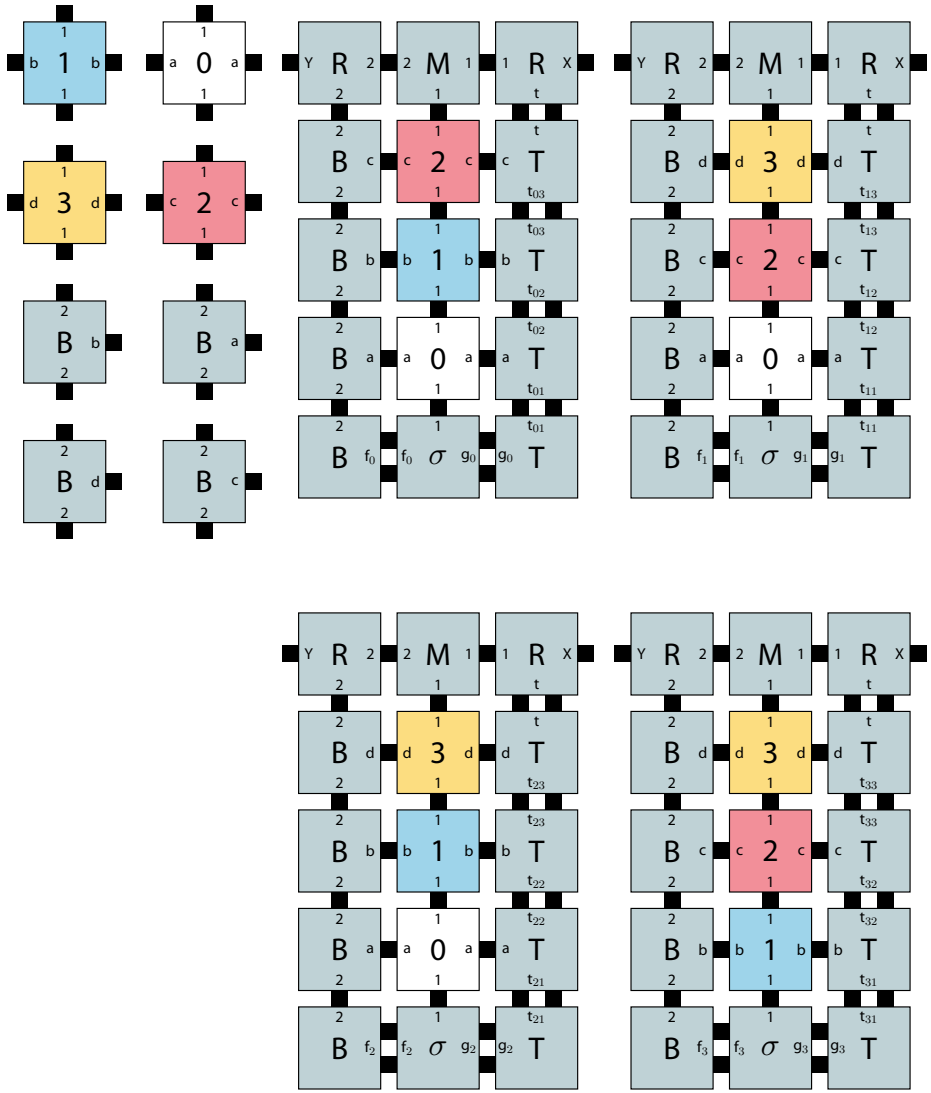
Behavior THRES:

- Algorithm and input are identical
- Various molecules are formed
- These correspond to all ***combinations*** of a threshold size k
- In the example, a threshold value of 3 out of 4 input bits is calculated
- Message molecules are ***different versions*** of a AND molecule

Decision Problem Thres



Thres-Nanonetwork

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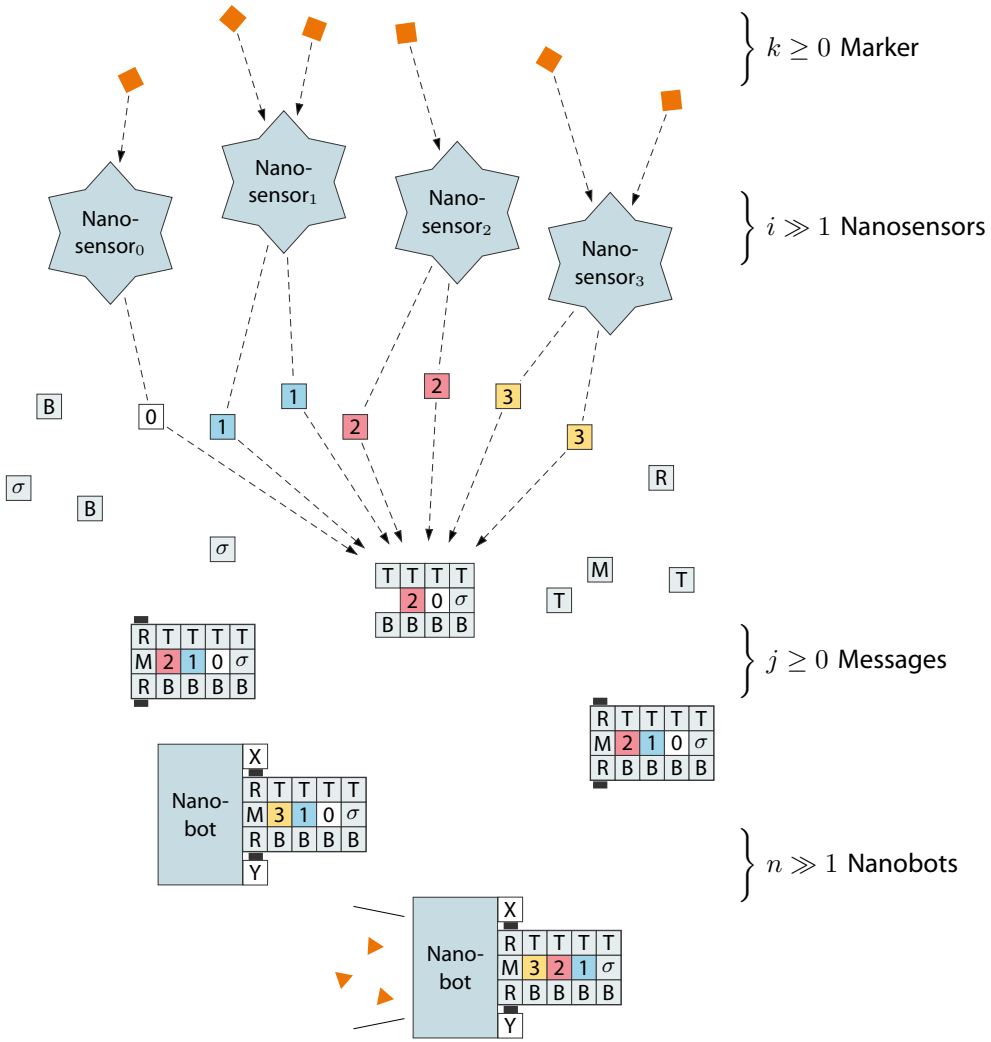

General Procedure

Description:

1. Transformation of a ***computation problem*** into a ***Boolean formula*** Φ (if possible)
2. Creation of a ***truth table***
3. Computation of the ***disjunctive normal form*** Φ
4. Creation of a ***message molecule*** for each clause

$\Rightarrow$ The Boolean formula is successfully evaluated once a single message molecule is fully assembled.

Φ-Tileset

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ϕ_1	ϕ_2	...	Φ
1	1		1
1	0		1
		⋮	
0	1		0
0	0		1

Example truth table of the formula Φ

Φ-Tileset

ϕ_1	ϕ_2	…	Φ
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1	0		1
		⋮	
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Φ-Tileset

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Example truth table of the formula Φ

- i-***th*** row with „1”
- n-***th*** Literal

Φ-Tileset

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ϕ_1	ϕ_2	…	Φ
1	1		1
1	0		1
		⋮	
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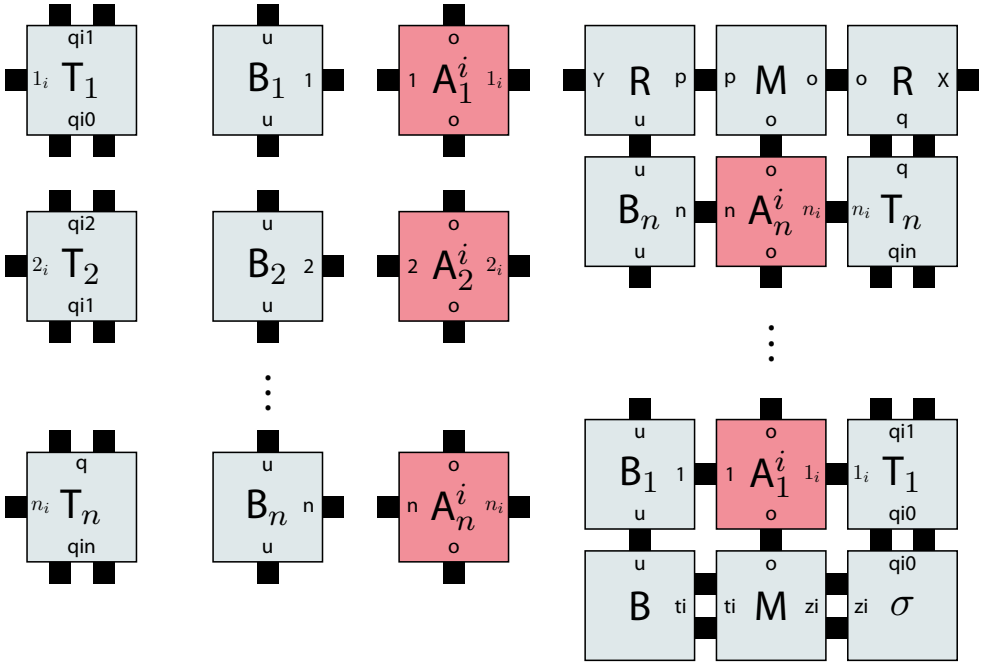
0	0		1

Example truth table of the formula Φ



- i-***th*** row with „1”
- n-***th*** Literal

Φ-Nanonetwork

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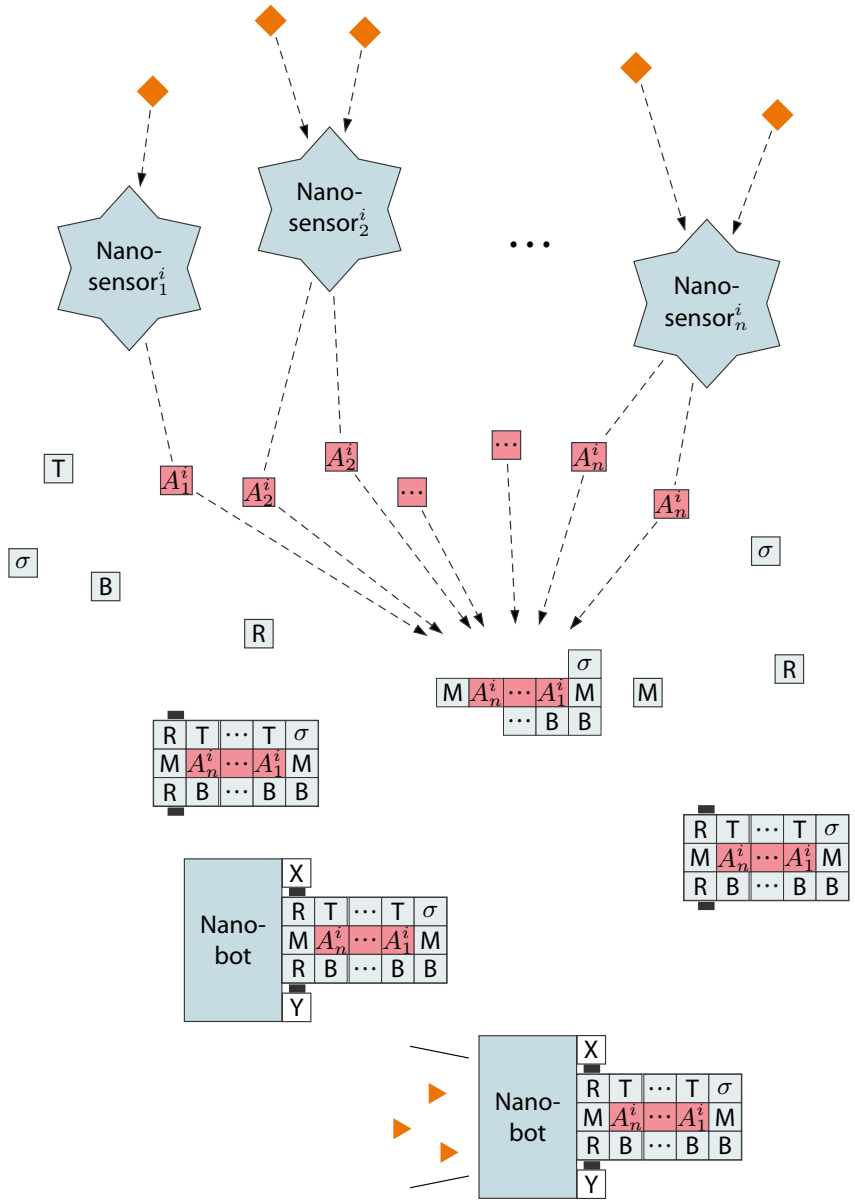

Turing Proof I

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Proof sketch:

- Turing machine is a ***Tupel*** $M = (Q, \Sigma, \Gamma, \delta, q_0, q_\square)$
- ***State space*** coonsists of ***tape***, ***head position***, ***state automata***…
- Simulation of a Turing Machine by a self-assembly systems
- Encoding of the machine states by ***rows from tiles***
- Creation of Tiletypes for ***transition function***, ***tape***, ***terminal state***
- Tile-stack of rows of Turing Machine states self-assembles
- Intuitively corresponds to a traversal of the ***Configuration graph*** of the Turing machine

Turing Proof II

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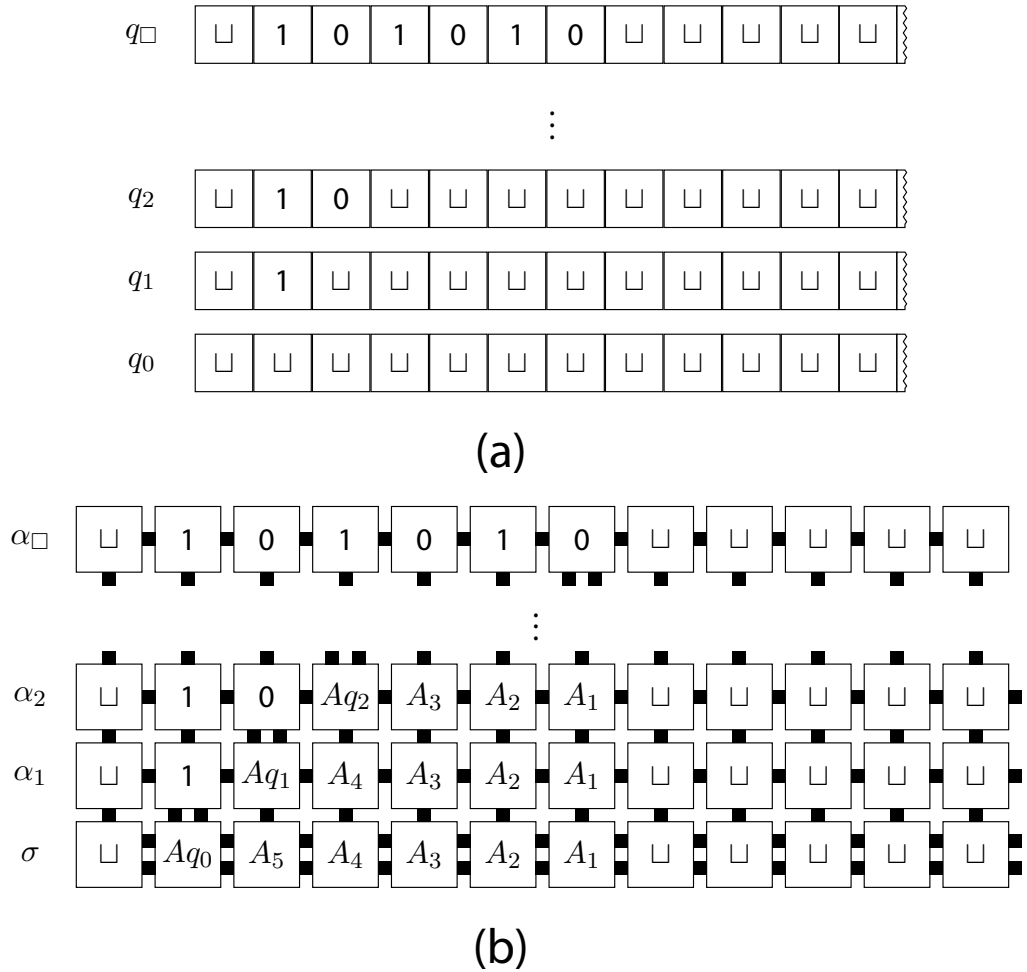

Turing-Network

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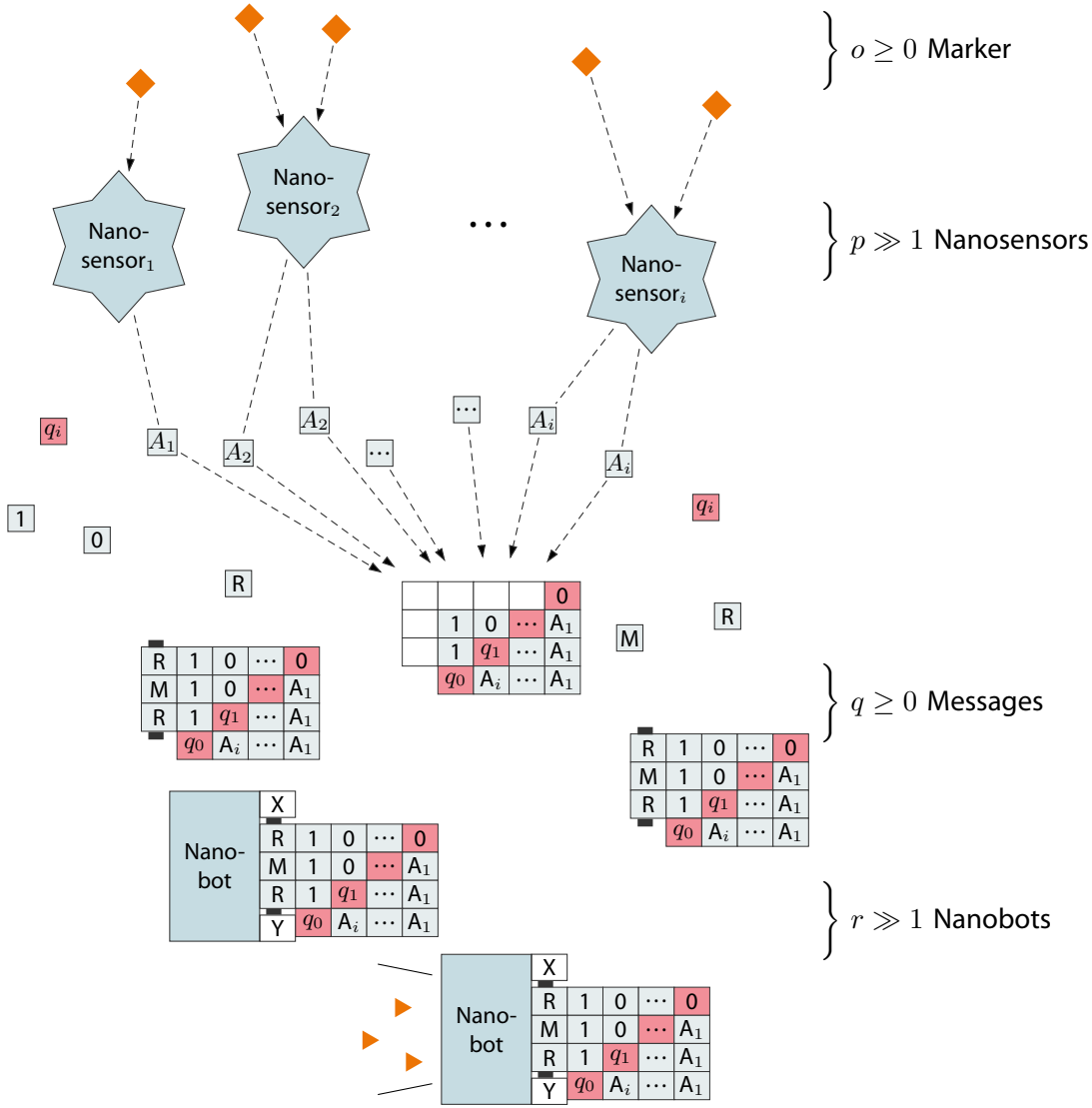

Efficient Solvable Problems

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	Medical Problems	Additional Problems
AC^0-Message:	ADD	ODD/EVEN
	SUB	DIV_2
	SIGN	MOD_2
	INC	INV
	AND/OR	LOG_2
NC^1-Message:	MULT	MIN/MAX
	DIV	PARITY
	EXP	AVG
	MAJOR	MOD
	THRES	IT-MULT
	IT-ADD[18]	

⇒ Less ***overhead*** than Turing-based tile systems, ***fewer errors*** and ***realistic binding*** at a nanobots because of ***size restrictions*** of the message molecules.

[18] Lau, Büther, and Gerlach 2017.

New Solvable Scenarios

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- ***Continuous medical monitoring without quality of life limitations***. Currently, this is only possible in a stationary environment under considerable deprivation.
- ***„Immediate treatment " during emergence***. So far, it almost always has to come to the outbreak of illness and associated symptoms before being intervened.
- ***Local treatment without systemic consequences***. So far, drugs are almost always given ***systemic*** and thus relate to the whole organism.

Novel Contributions

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- ***Fingerprinting*** by detecting specific tissues via DNA markers
- Fast alternative DNA-detection mechanism compared to ***PCR***
- Arbitrarily ***programmable*** and ***error resistant***
- ***Biocompatible***
- ***Multi-parameter*** diagnosis possible
- Can be created from ***already existing*** materials

Summary

What do DNA-based nanonetworks achieve?

- DNA is a suitable material for ***construction***, ***computation*** and ***communication***
- It is possible to create fully-functional nanonetworks from just DNA as a building block
- It is possible to compute any ***Boolean formula*** at the nanoscale via message molecules

$\Rightarrow$ DNA-based nanonetworks only rely on already available technologies and can be used to perform ***complex*** and ***arbitrary*** computation!

Thank you for your attention!

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