On DNA-based Gellular Automata

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Teijiro Isokawa, Ferdinand Peper and Katsunobu Imai

2014.07.16 UCNC 2014

Background — molecular robotics

- Molecular robot --- autonomous system consisting of sensor, computer and actuator

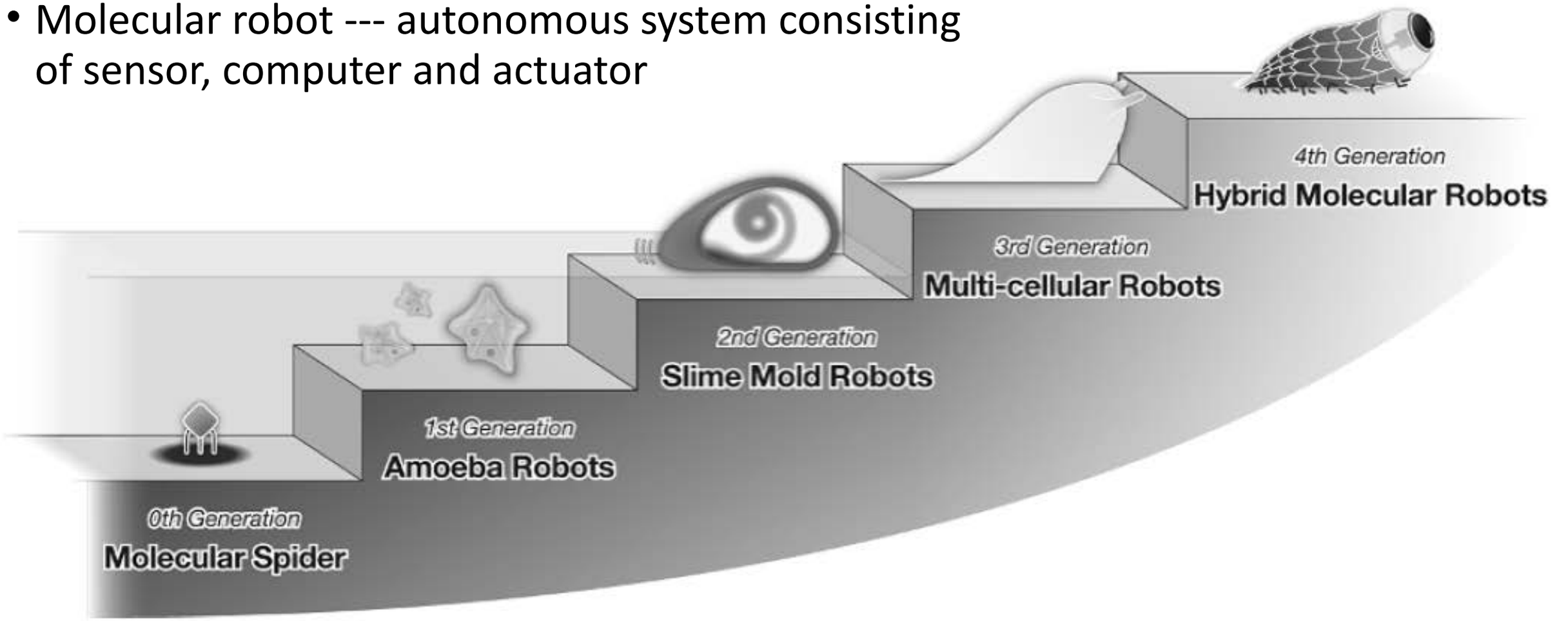
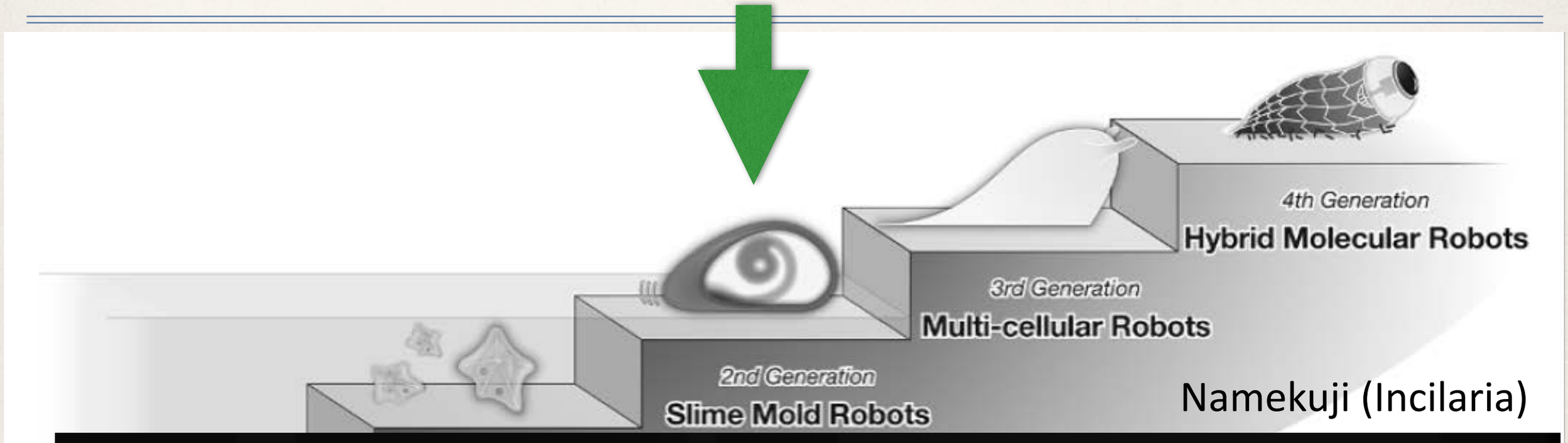


Fig. 1 Evolution of Molecular Robots

Background — molecular robotics

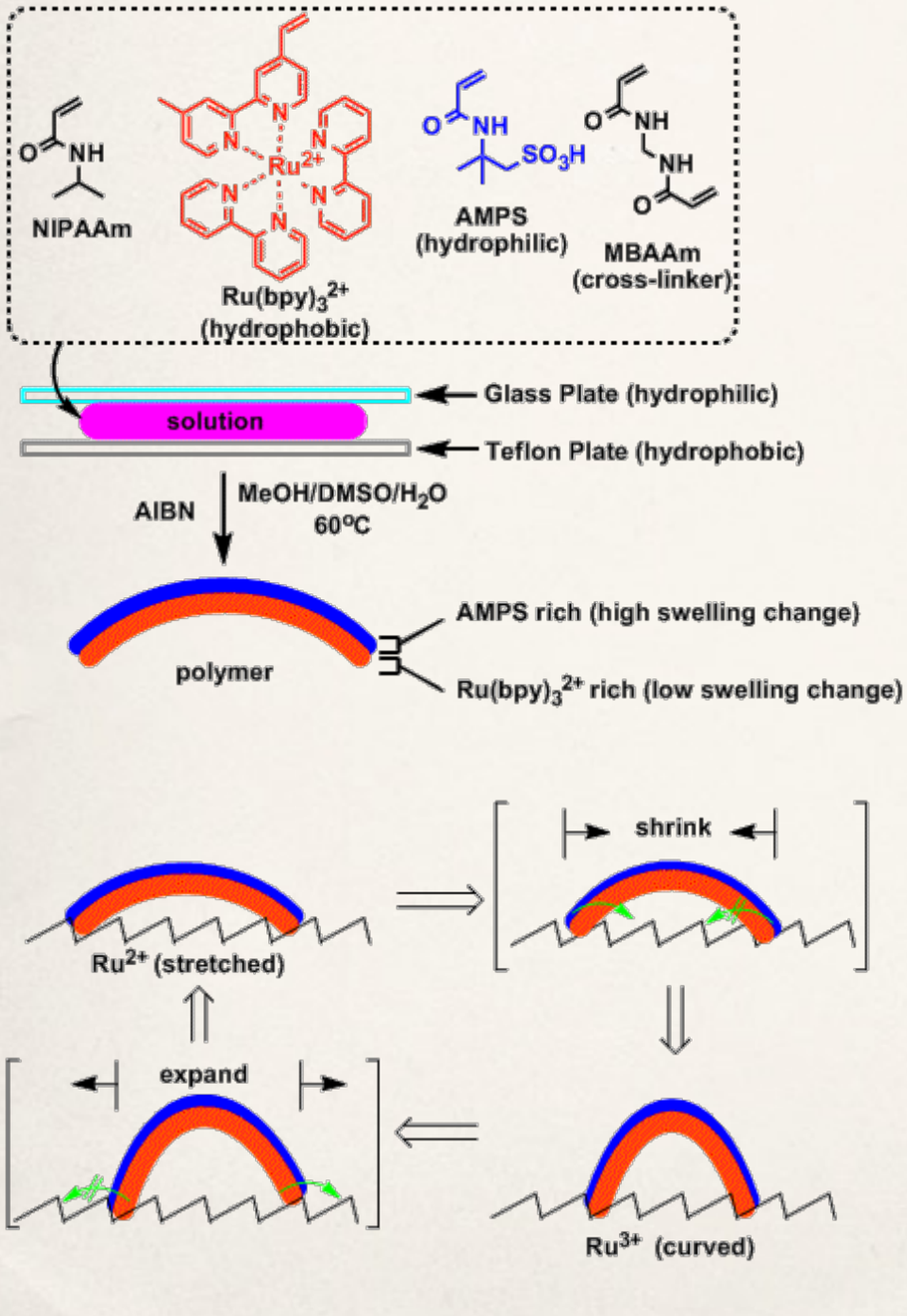


Namekuji (Incilaria)

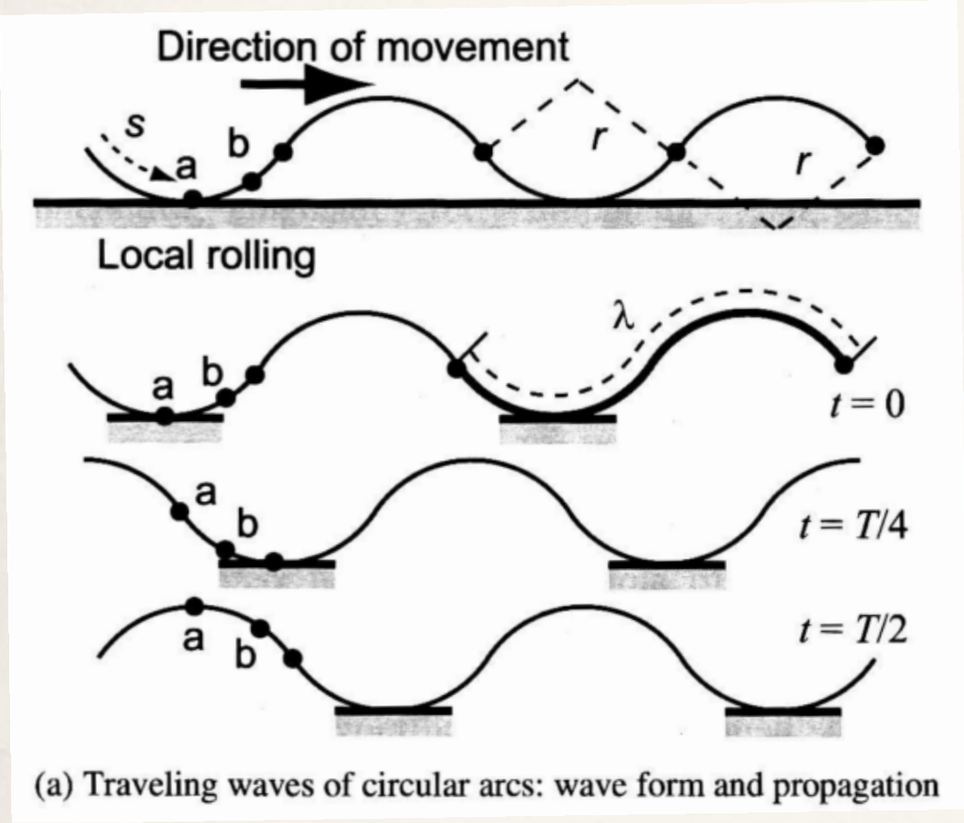
Inoue Laboratory, Kyoto University
http://cosmos.bot.kyoto-u.ac.jp/csm/movies-j.html

Self-walking gel

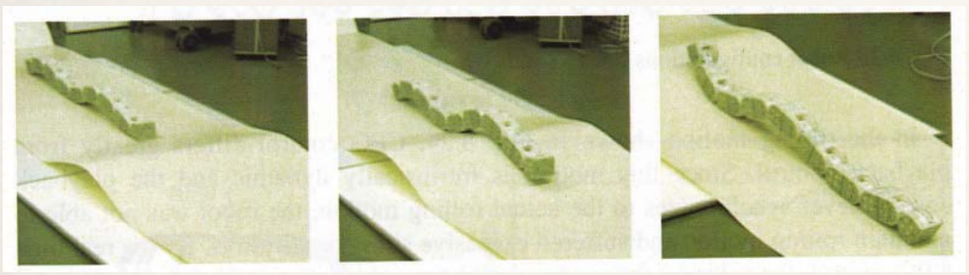
Maeda et al. 2007

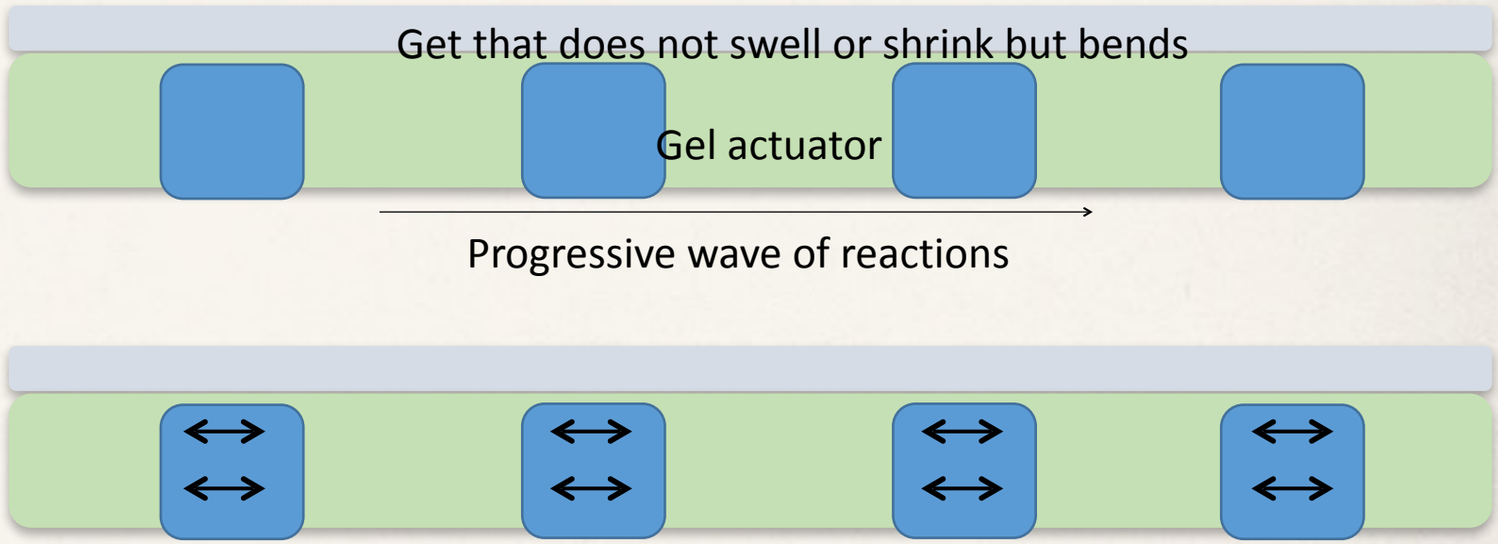


Movement by progressive wave

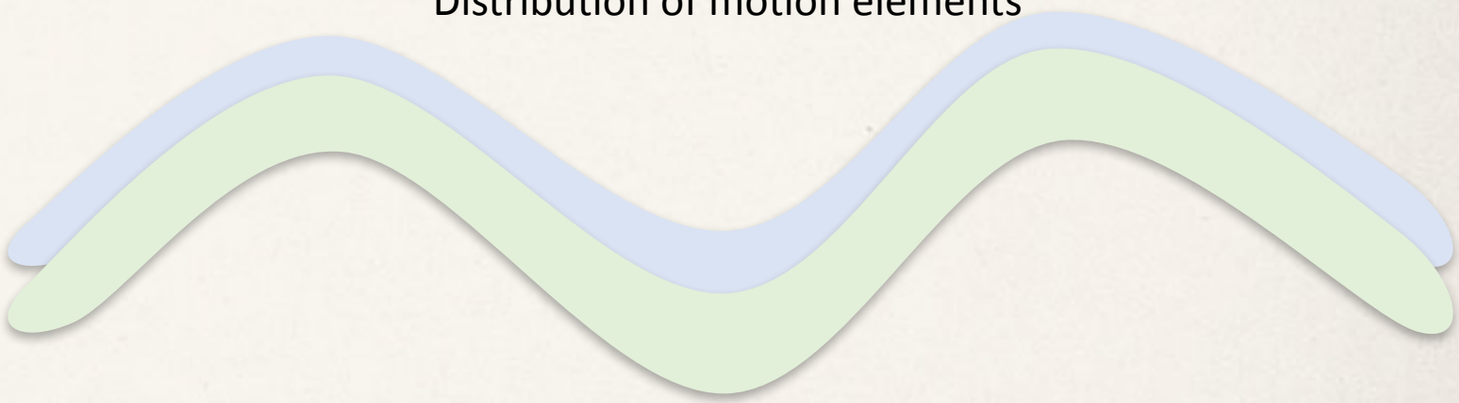


(a) Traveling waves of circular arcs: wave form and propagation





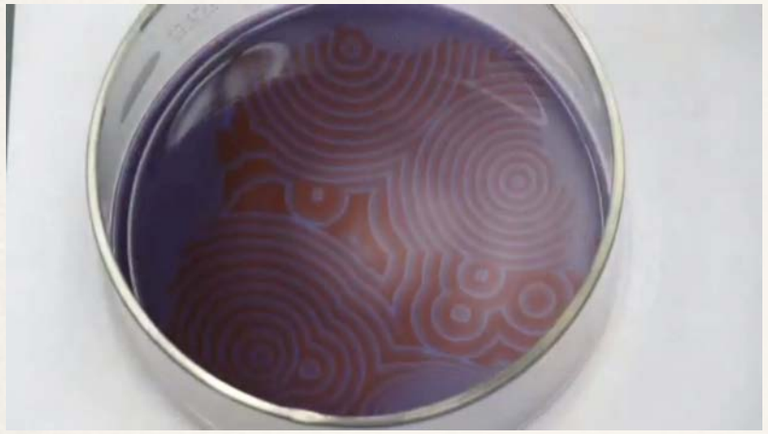
Distribution of motion elements



S.Murata, H.Kurokawa, Self-Organizing Robots, 2011

Implementation of progressive wave

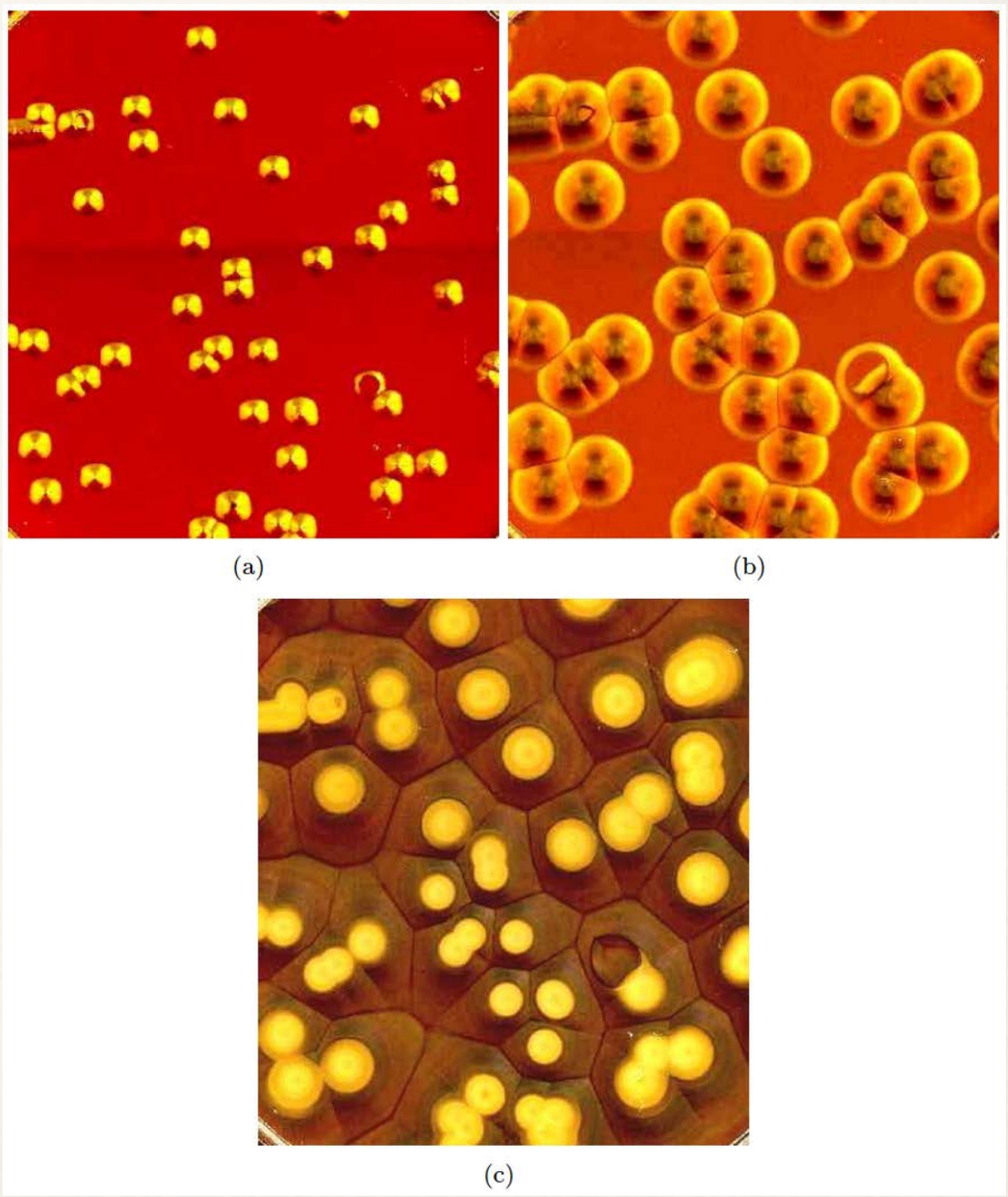
Reaction-diffusion computing



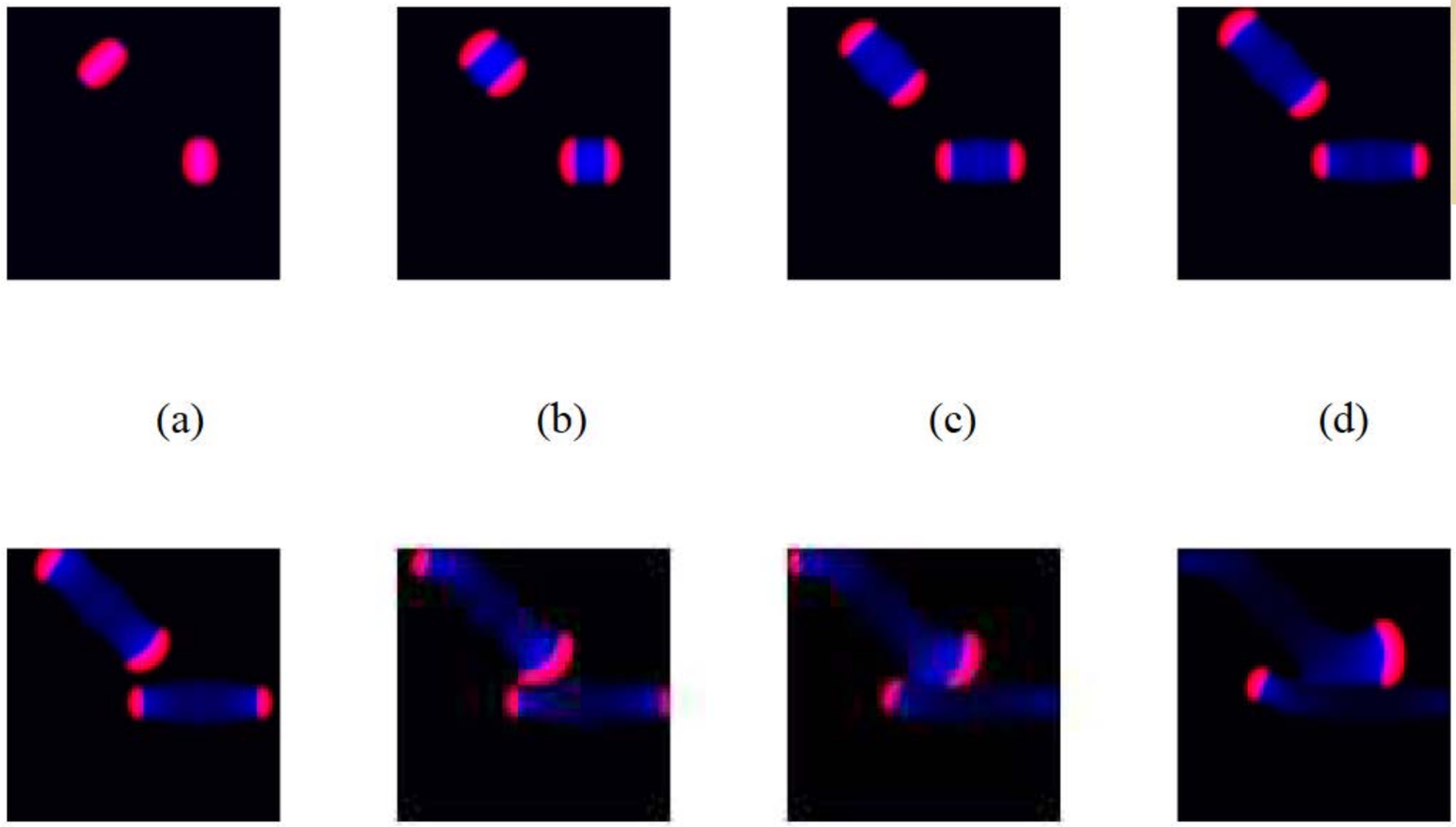
Belousov-Zhabotinsky reaction
(Belousov 1951, Zhabotinsky 1961)

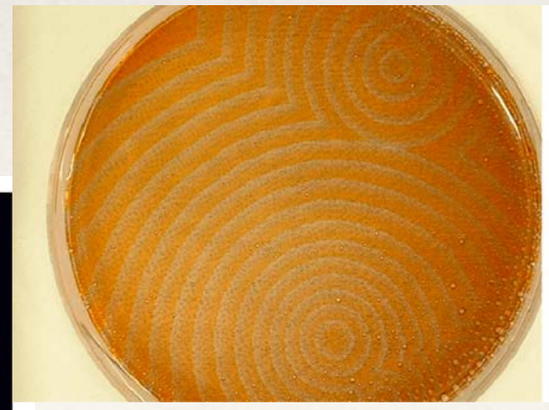
Employing oscillating chemical reactions to computing.

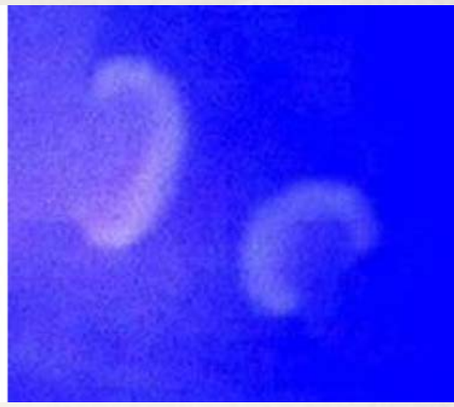
An important candidate for gel based computation.



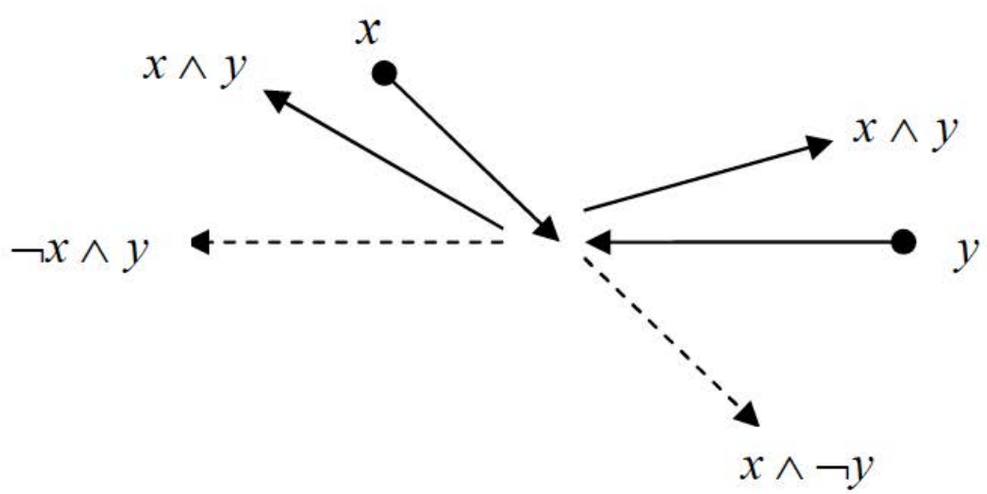
Adamatzky et, al. 2006, 2008







localized wave



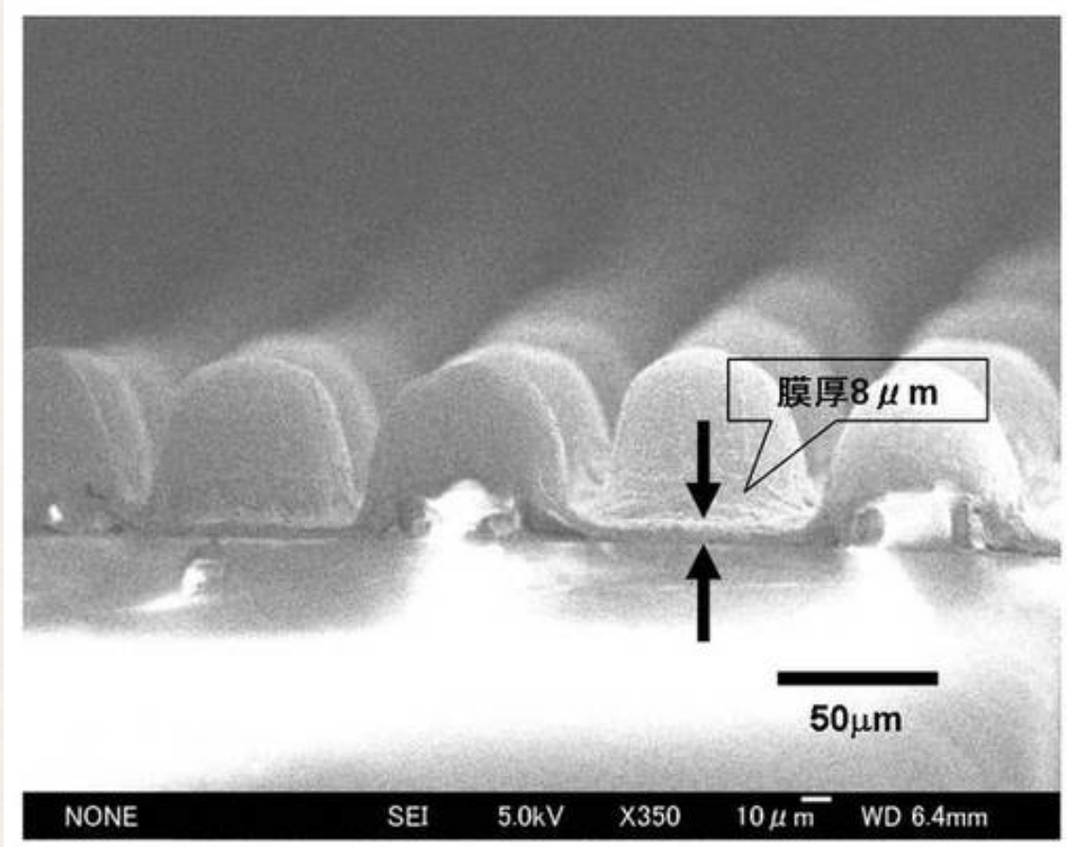
Adamatzky et, al. 2008

Might be simulate any logical gate circuit effectively...

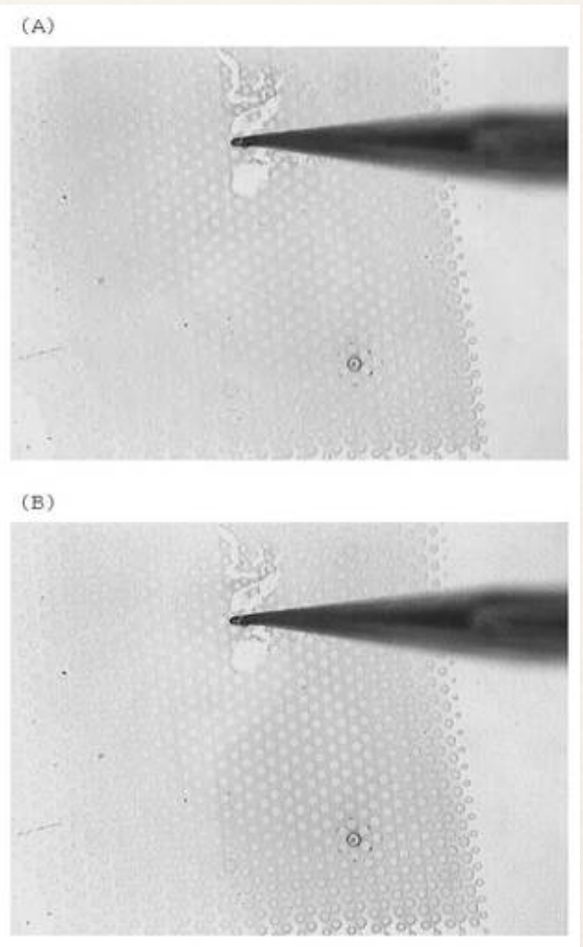
BZ reaction based cellular automaton made by autonomic responsive gel

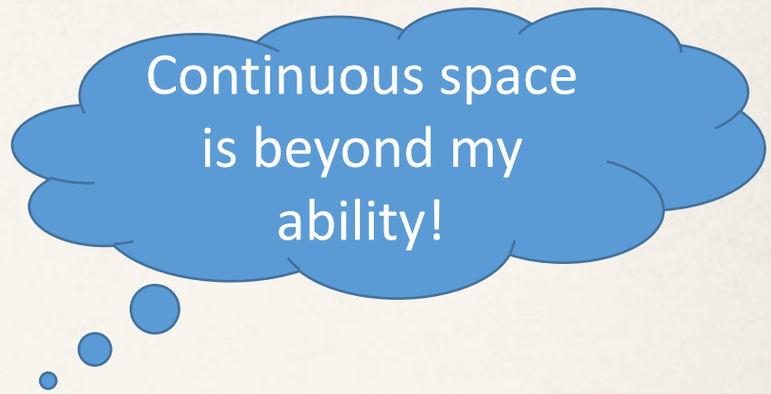
Kansai Univ. and Toyota research lab. (JP Patent 2009-70922)

BZ-reaction based communications between neighborhood cells



A cross-sectional image of aligned cells by gel





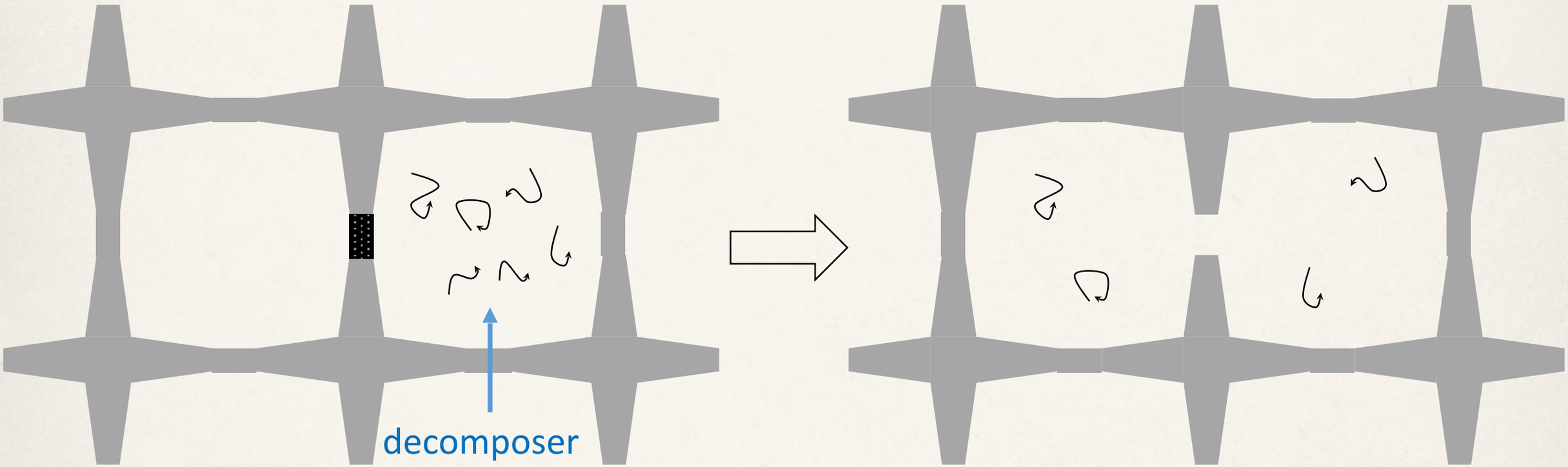
- Motivation
  - It is not easy to design and control a reaction-diffusion field
  - DNA reactions can simulate almost any reaction networks and their processing speeds but diffusion of DNA in a gel is extremely slow

Gellular Automata

DNA & Gel for simulating cellular automaton

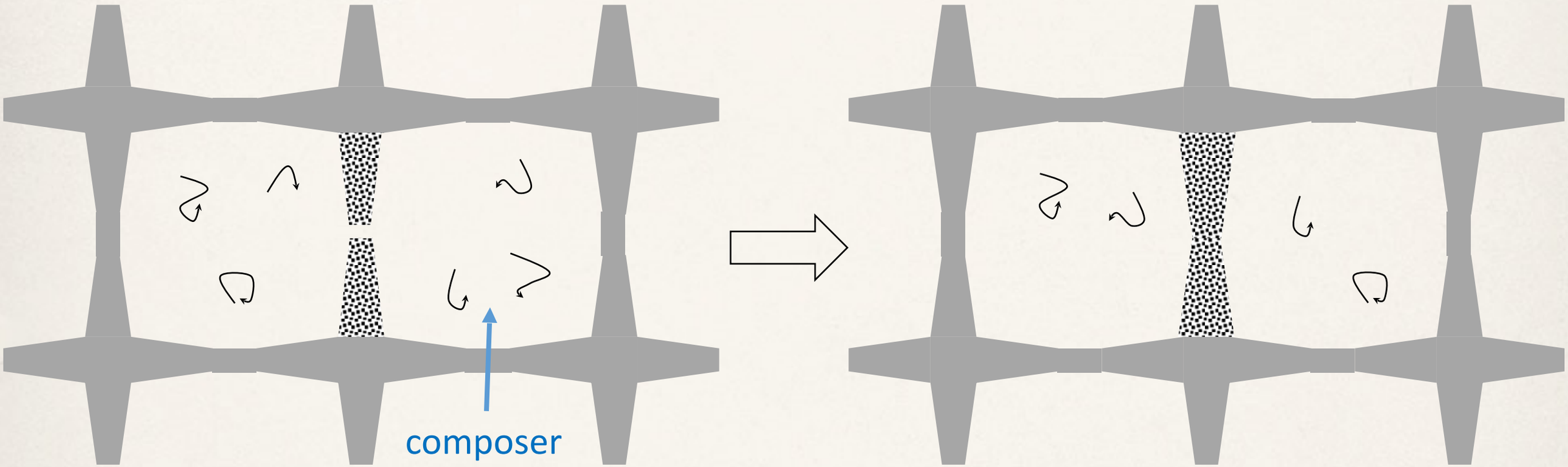
- Approach
  - Go **discrete** --- adopt cellular automata
  - Use gels to make **walls to separate space into cells**
    - Each cell is filled with a **solution**
    - Reactions in a solution produce decomposers and composers of walls
      - A **wall is dissolved** by its decomposer
      - A **wall is (re)constructed** by its composer
    - Solutions in cells are mixed and separated
- Use 3D gel printers in future

Dissolution of a wall



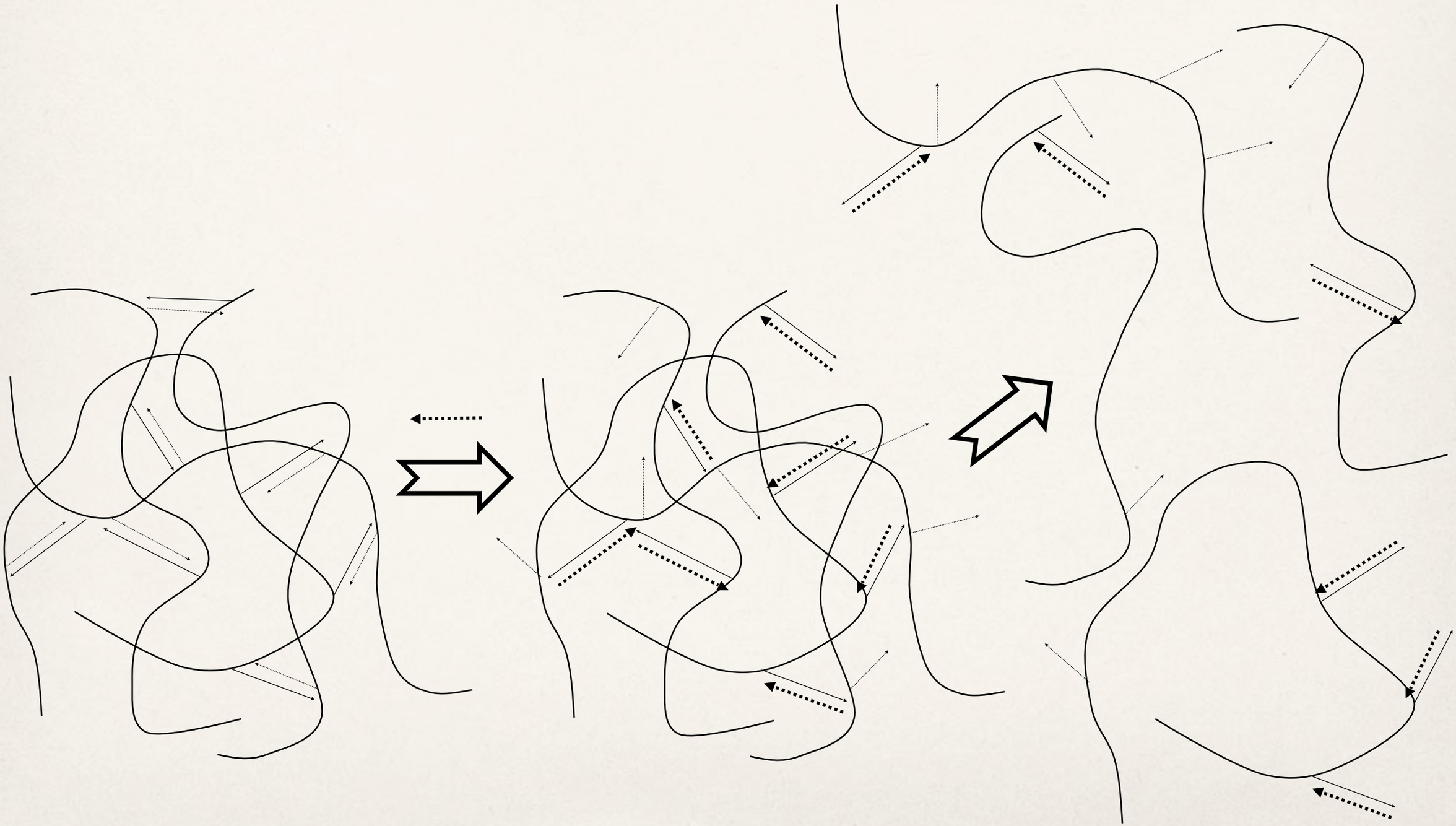
Walls may have some variations, i.e, they contain several distinct kinds of DNA crosslinks.

Construction of a wall



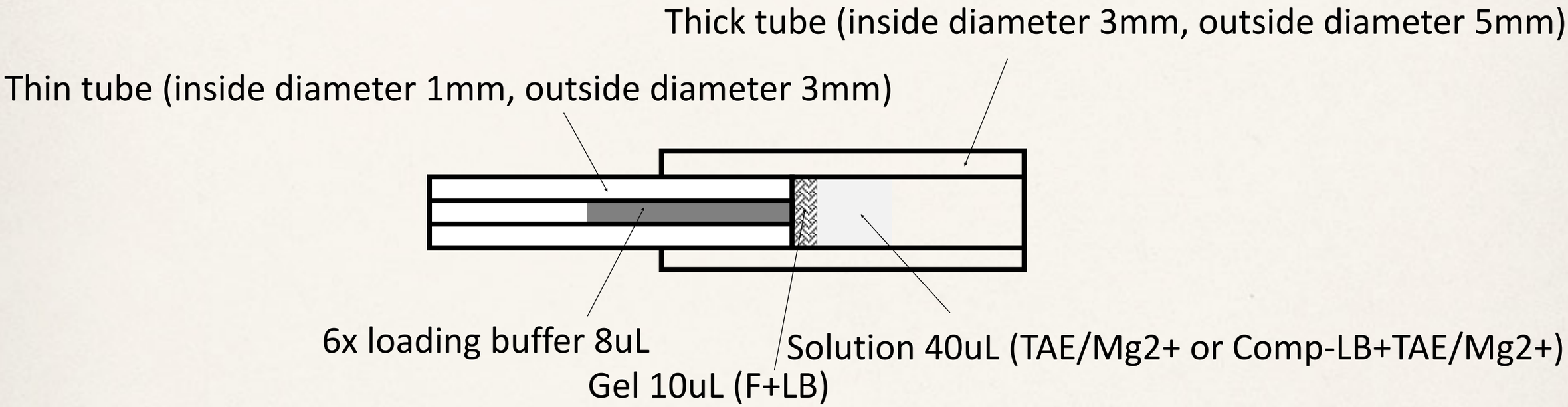
Preliminary experiments

AAm+DNA dissolvable gel



Preliminary experiment

Dissolution of a wall



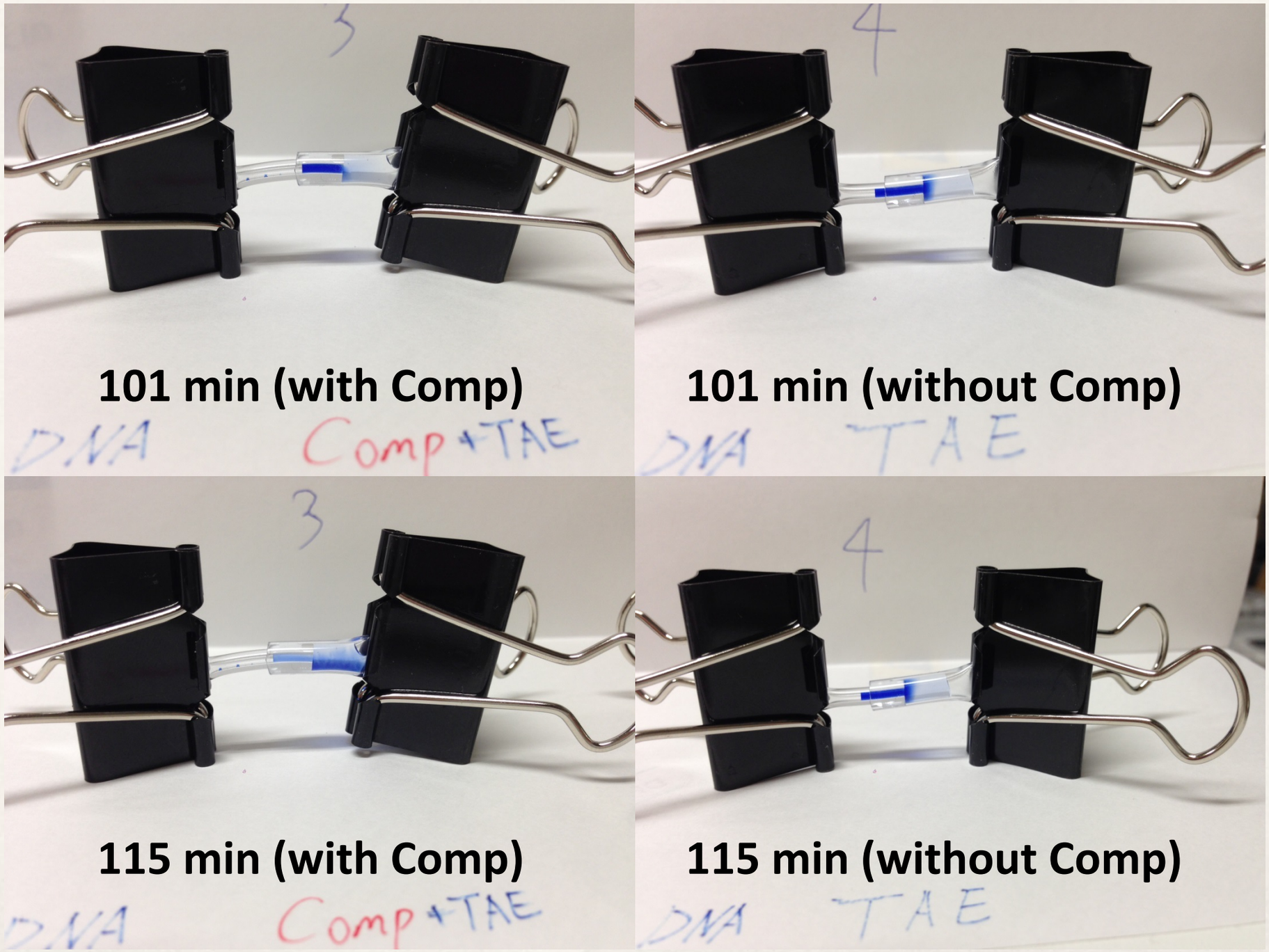
Dissolution of a wall

Dissolution of a wall

Dissolution of a wall

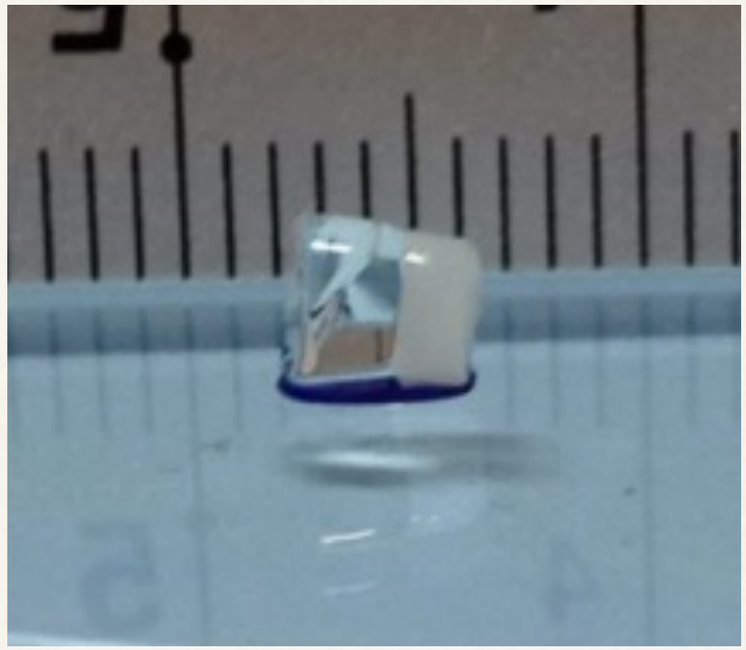
Dissolution of a wall

Experiment: dissolution



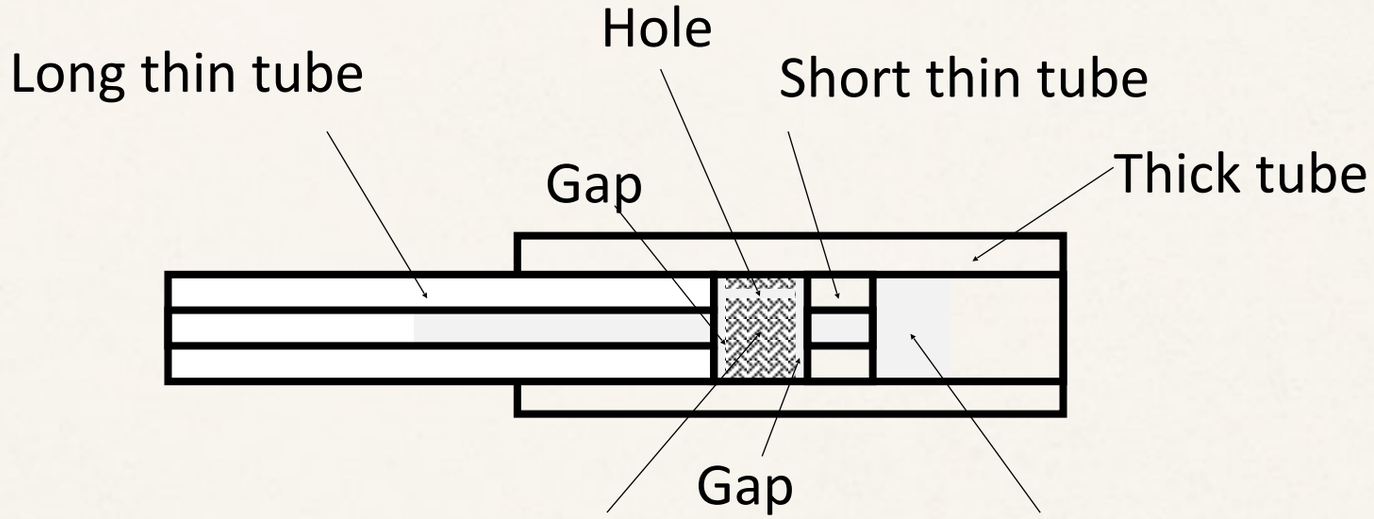
Preliminary experiment

AAm+DNA+bis swelling gel



The gel absorbs water and swells when it looses DNA crosslinks and consists of only crosslinks by bis.

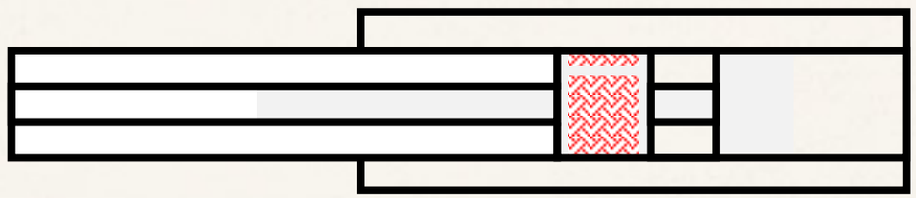
Construction of a wall



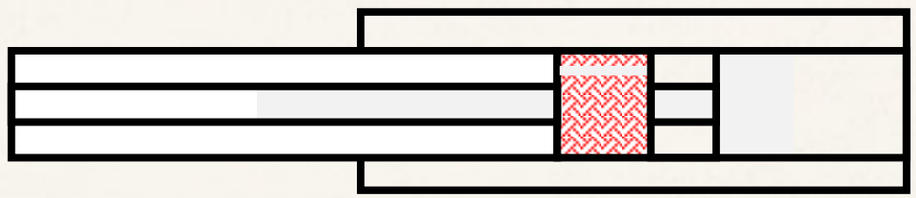
Gel 20uL (BIS+S+B8) with a hole

Solution 30uL (P18+TAE/Mg2+)

Construction of a wall

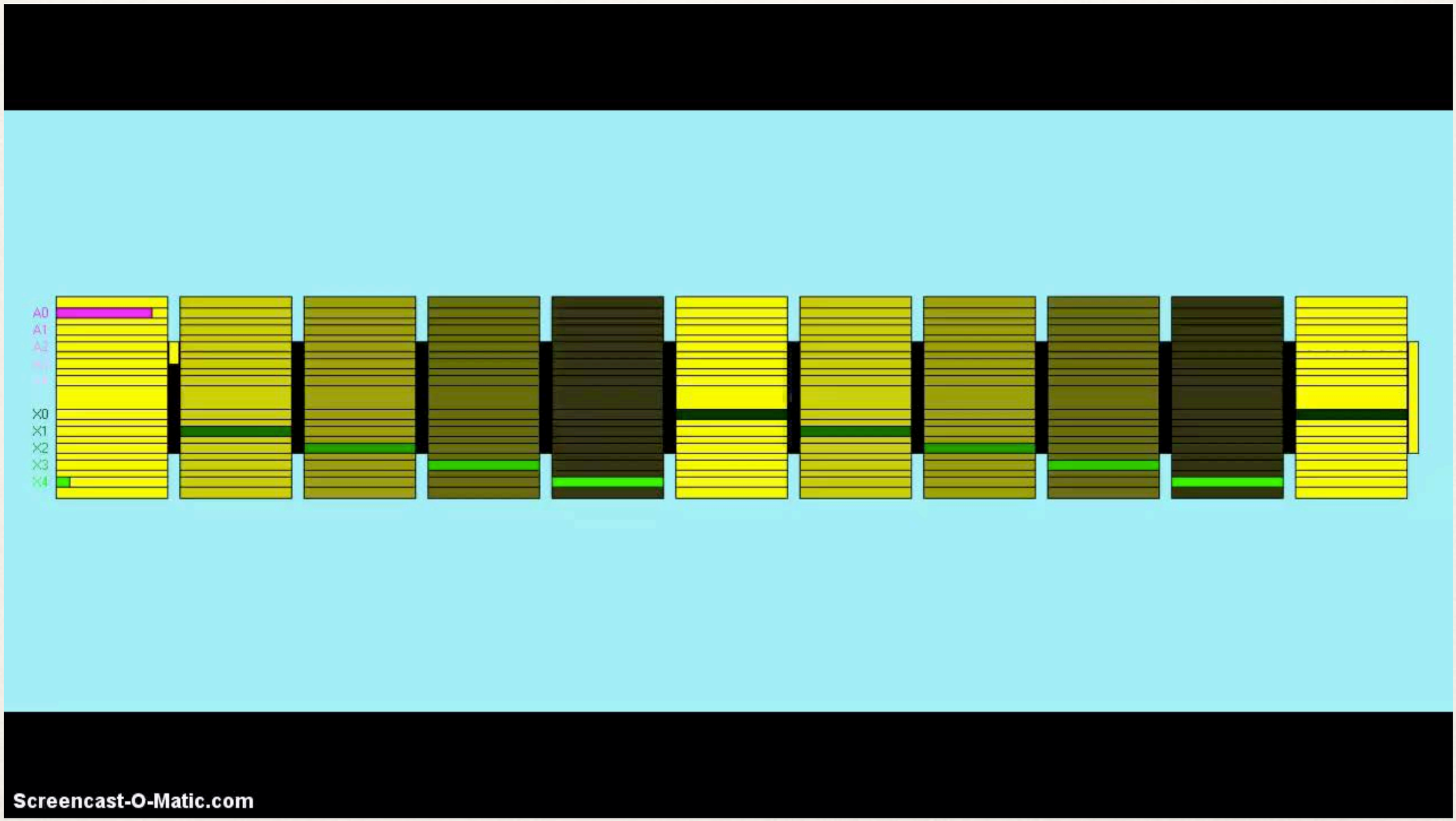


Construction of a wall



Experiment: construction

Simulation of a propagating signals



Evolution example

A, W	Y	Z	V	W
A, W, Y		Z	V	W
B, X		Z	V	W
B, X	B, X	Z	V	W
B, X	B, X, Z		V	W
X	C, Y		V	W
X	C, Y	C, Y	V	W
X	C, Y	C, Y, V		W
X	Y	D, Z		W

A, Y → B, B
W, Y → B, B
B → X

B, Z → C, C
X, Z → C, C
C → Y

C, V → D, D
Y, V → D, D
D → Z

A becomes W
A interacts only with Y
B interacts only with Z
X interacts with Z, E, V
Y interacts with A, W, V
W interacts with Y, D, Z

D, W → E, E
Z, W → E, E
E → V

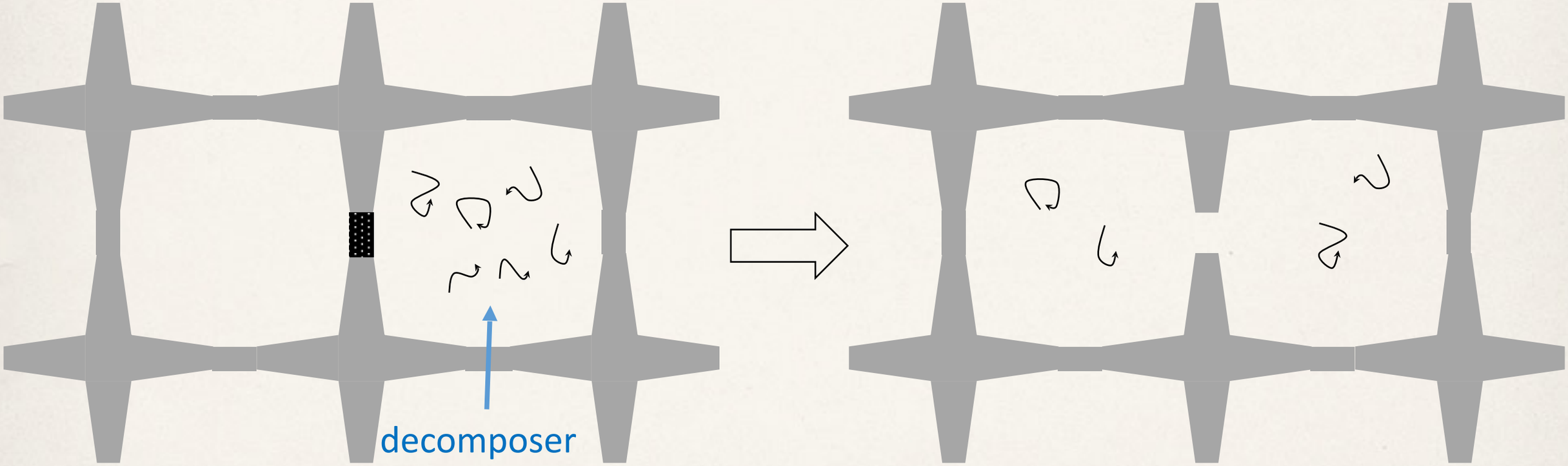
E, X → A, A
V, X → A, A
A → W

Parameters

- A, Y → B, B0.1
- W, Y → B, B 0.2
- B → X 0.01
- The total concentration in each cell is 1.0
- A variable (w) is assigned to each wall
- Dissolution of a wall: dw/dt = -0.03[A]
  - w goes down from 1.0 to 0.0 and then the wall is dissolved
- Construction of a wall: dw/dt = 0.03[B]
  - w goes up from 0.0 to 1.0 and then the wall is reconstructed

Gellular automata without wall reconstruction

Solutions are always diluted when walls are dissolved.

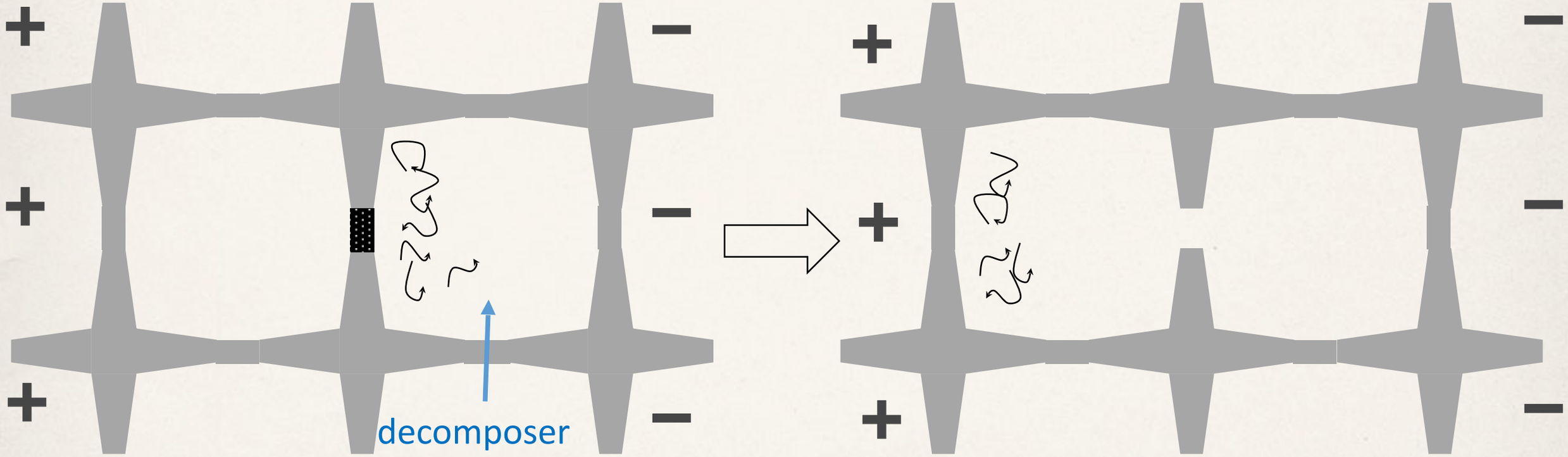


Reconstruction is more difficult than dissolution.

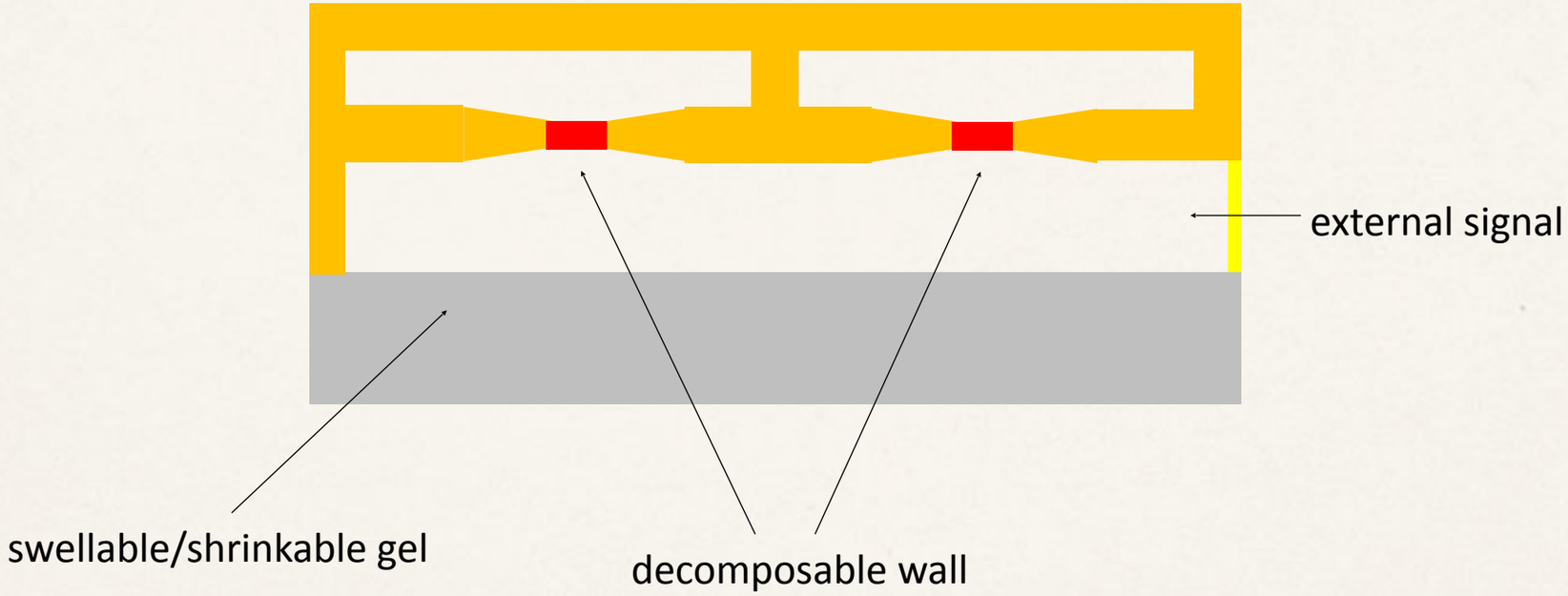
Gellular automata without wall reconstruction

Adding voltage gradient

circuits without feedback may be embeddable.



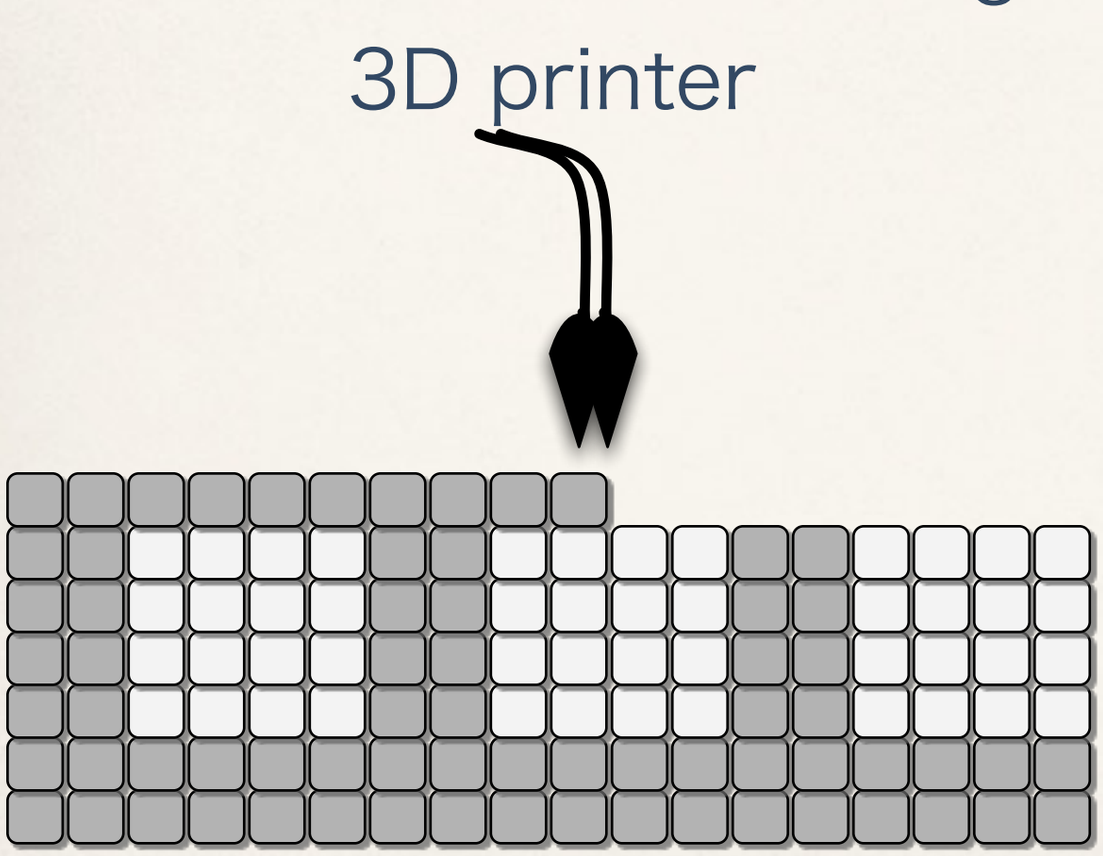
More prototypical gel machine



Printing gellular automata

Printing gellular automata cells

Additive manufacturing



- gel ink for walls
- gel ink for internal solutions
  which causes solation at a high (but not so high) temperature. cf. gelatin

Keeping a low temperature when printing. Raise the temperature after the structure is printed.

Possible application:

3D printed

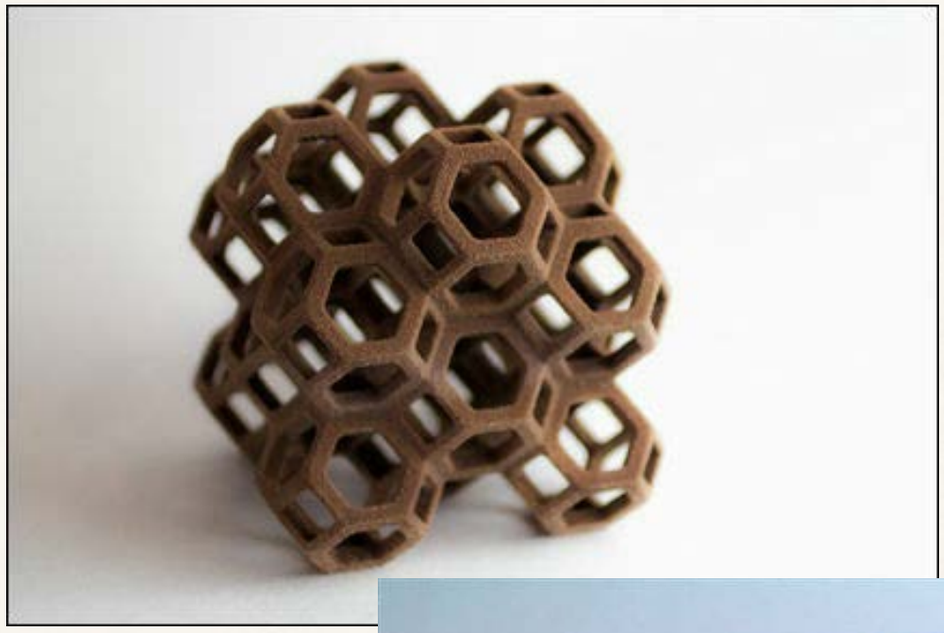
Gellular automata based

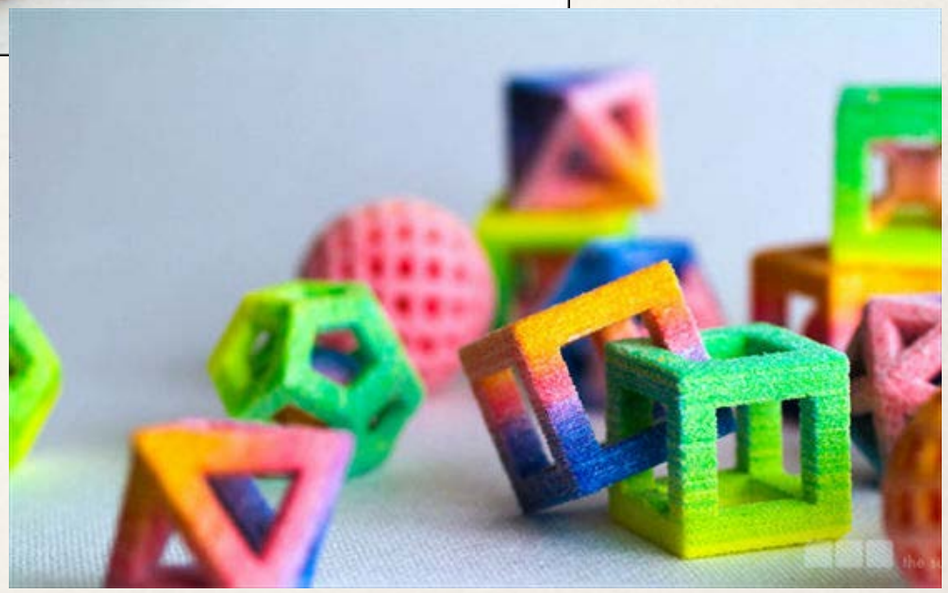
“programmable foodstuff”

Use edible gels (agarose, arginine, DNA, etc.) instead of acrylamid

ChefJet™ 3D

3D Systems



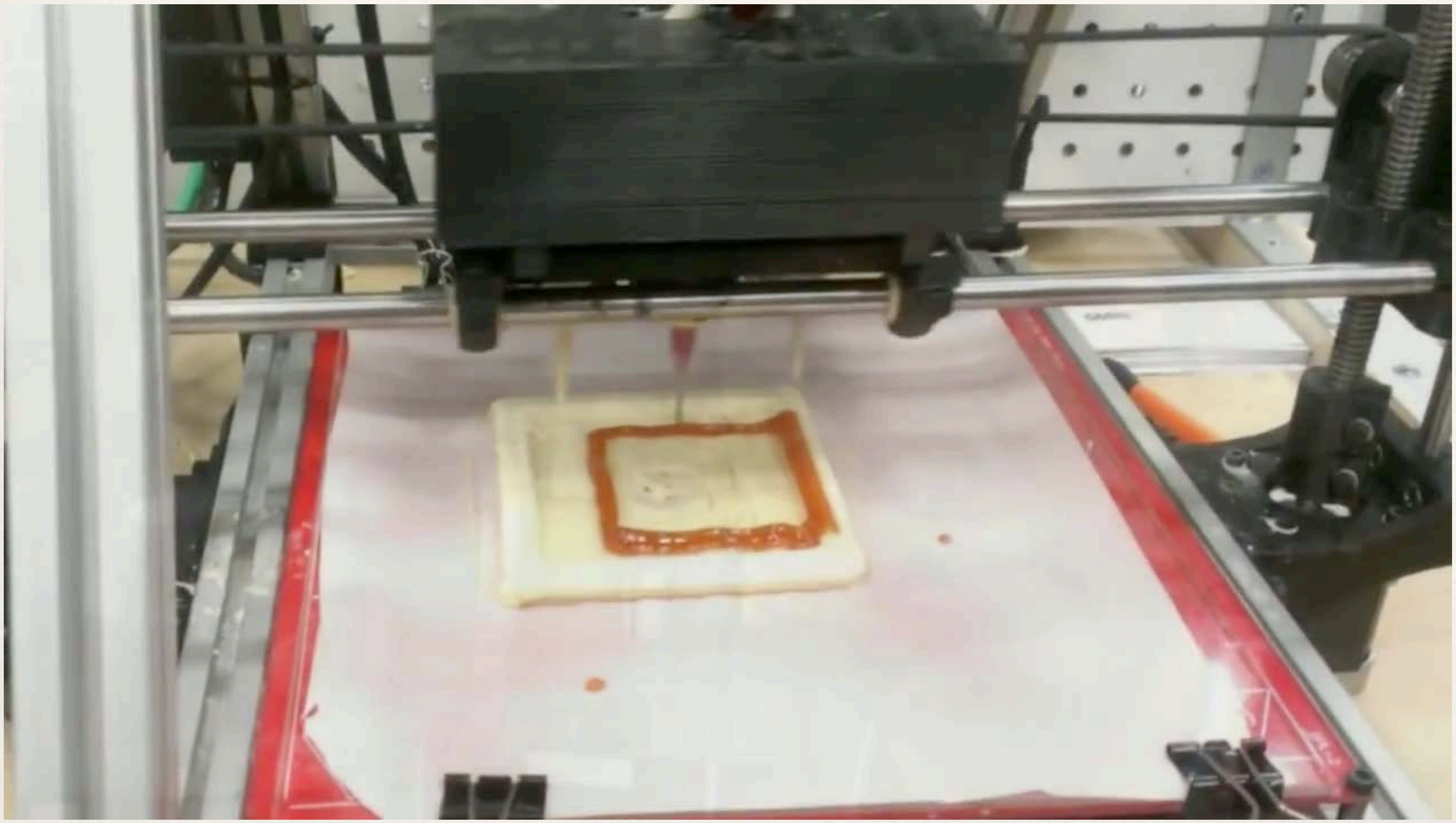


http://www.gizmag.com/3d-chocolate-printer/19121/
http://3dimensions-printer.com/?p=3620

3D Systems & Hershey

Pizza printing

Systems and Materials Research Consultancy and NASA



https://www.youtube.com/watch?v=uphIwHFz0no

How should a computing foodstuff be?

Computing tablets?

Do you want to eat Turing universal foodstuff?

http://takeuke3.up.n.seesaa.net/takeuke3/image/whiteshot-innerlock-811e2.JPG?d=a2

http://google.co.jp/#q=Programmable+food

PUBLIC HEALTH

Coming Soon: Kraft Programmable Food

by JOSH UMBEHR on Jan 7, 2008 • 3:14 am

Thanks to the wonders of nanoscience, you may soon be able to customize drinking water into your favorite double shot espresso diet soy cafe mocha something-or-other…

The processed-food giant Kraft and a group of research laboratories are busy working towards 'programmable food'. One product they are working on is a colourless, tasteless drink that you, the consumer, will design after you've bought it. You'll decide what colour and flavour you'd like the drink to be, and what nutrients it will have in it, once you get home. You'll zap the product with a correctly-tuned microwave transmitter – presumably Kraft will sell you that, too.
This will activate nano-capsules – each one about 2,000 times smaller than the width of a hair – containing the necessary chemicals for your choice of drink: green-hued, blackcurrant-flavoured with a touch of caffeine and omega-3 oil, say. They will dissolve while all the other possible ingredients will pass unused through your body, in their nano-capsules.

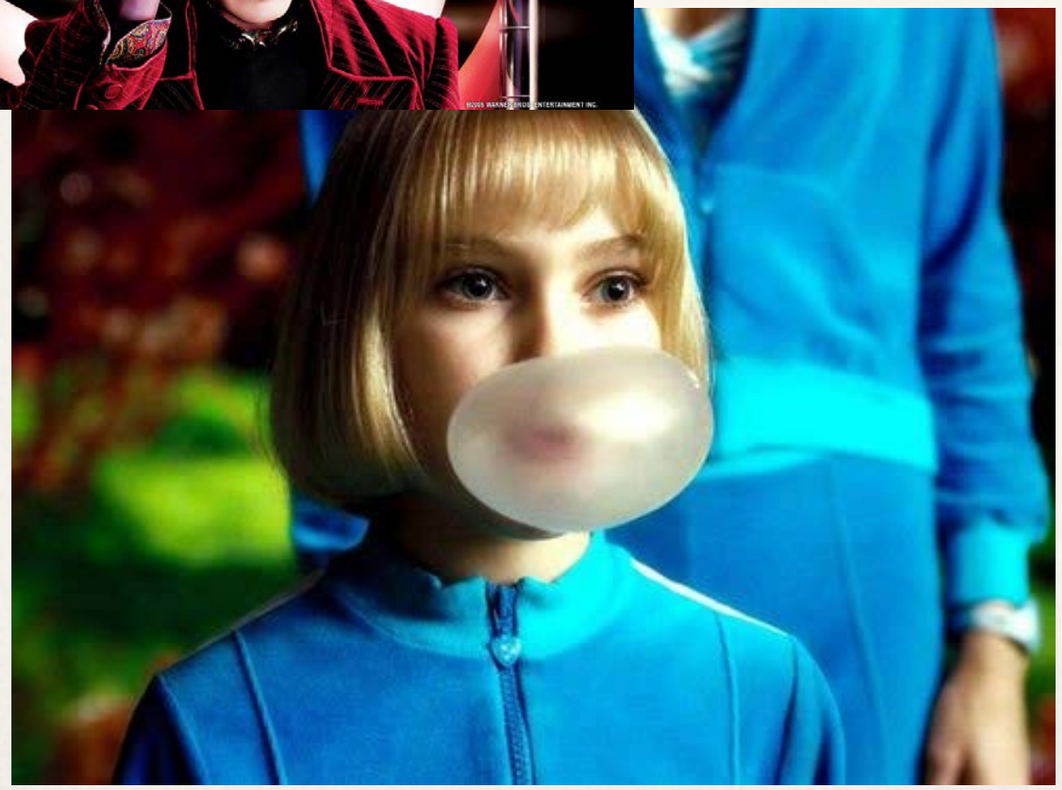
http://www.medgadget.com/2008/01/coming_soon_kraft_programable_food.html

Flavor trapped nano-capsules are selectively destroyed by a specially tuned microwave oven.

From a news site

Three-course-meal gum

In Dahl's Charlie and the Chocolate Factory



Dave Hart (Institute of Food Research)

"Professor Hart and his team are exploring whether nanotechnology could encapsulate and release such diverse flavours in a precisely controlled way...

http://www.forteantimes.com/strangedays/science/4588/threecoursemeal_gum.html

Universal foodstuff

Foodstuff is universal ...

- taste
- flavor
- texture
- temperature
- color
- shape

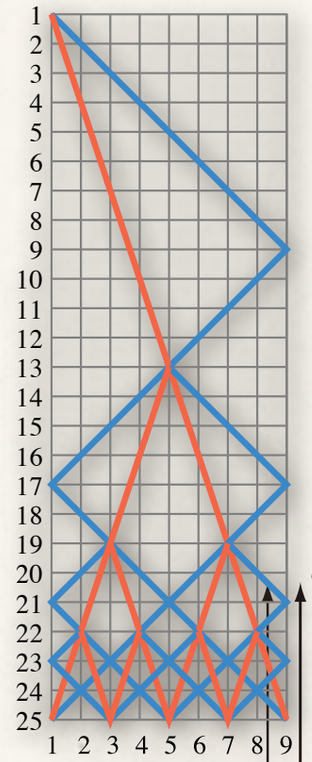
http://ysmart.up.n.seesaa.net/ysmart/js/10091119.jpg?d=a1

can be controlled in the time and space domain

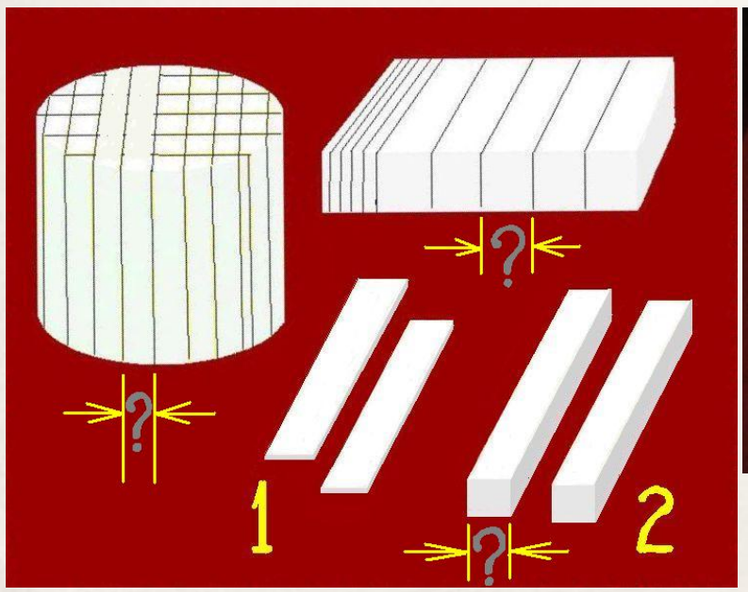
cf. construction-universality

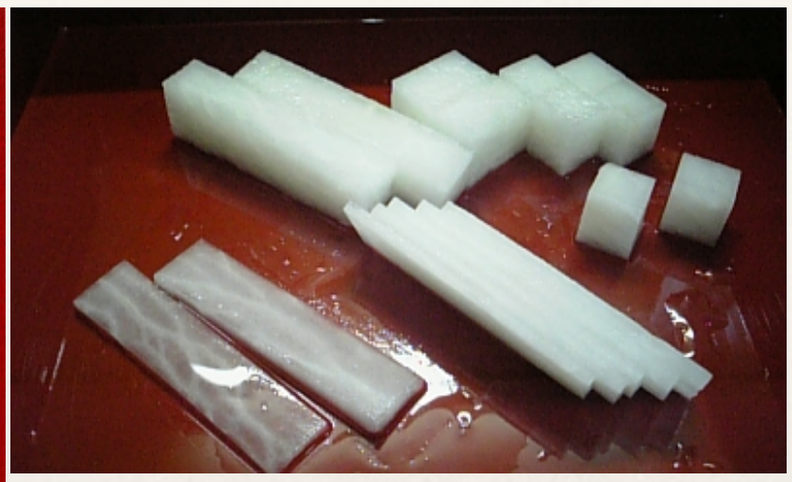
Shape

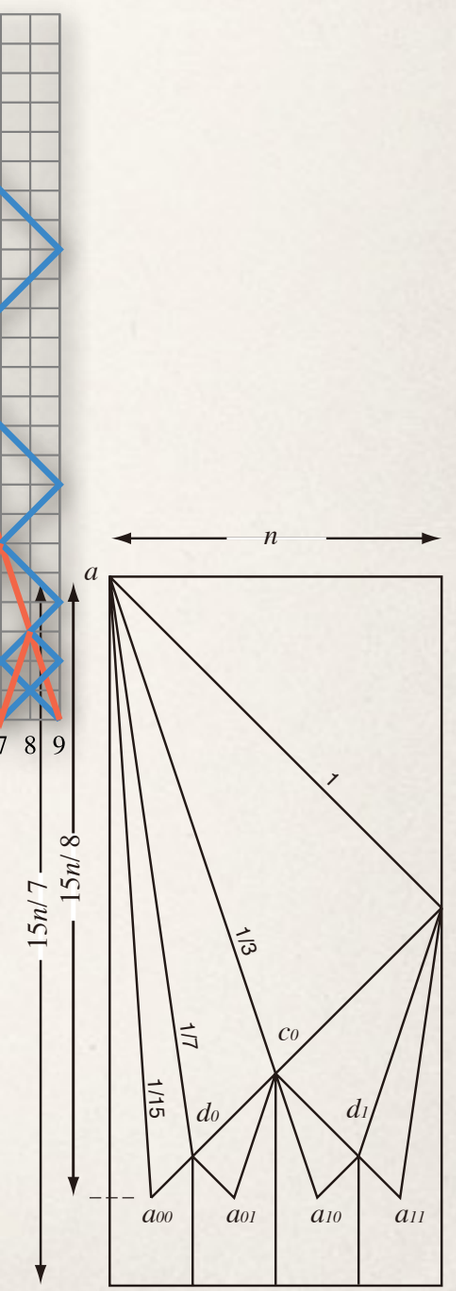
Let's cut a gellular automaton by a firing squad synchronization solution.



Compute all cutting positions by employing diffusion signals of several distinct speeds and dissolve all related walls.



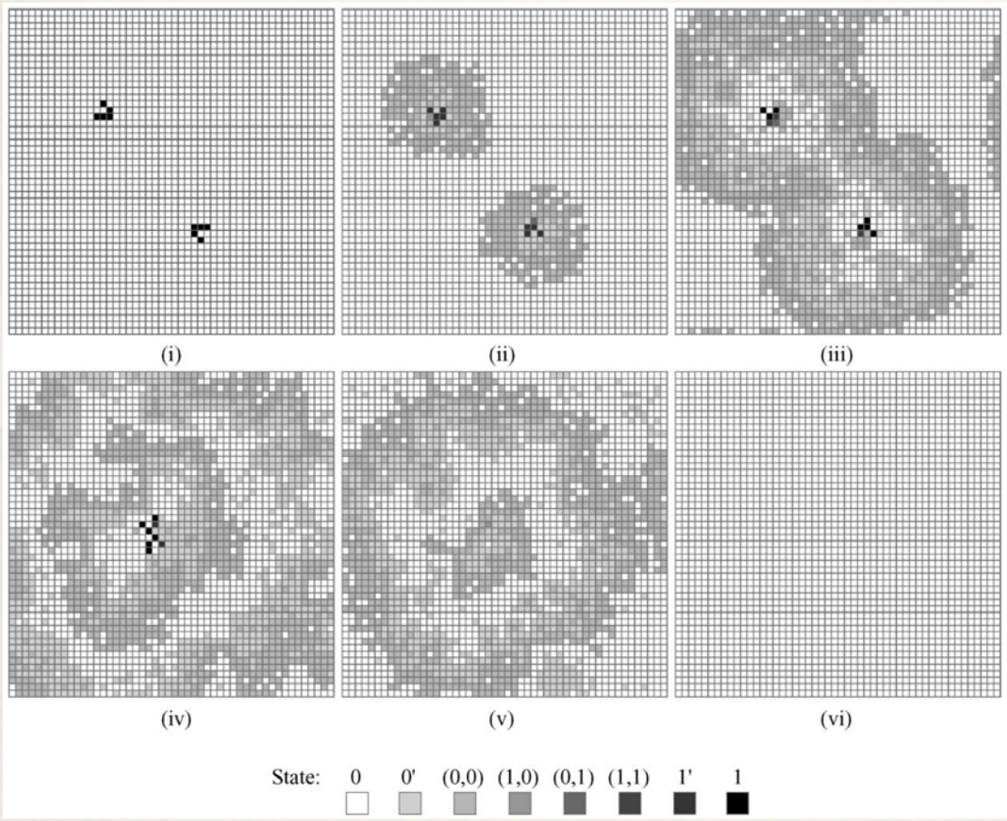




http://tujigahana88.seesaa.net/article/134221853.html

Although gellular automata are asynchronous cellular automata...

A synchronous cellular automaton can effectively be simulated by an asynchronous one.



8-state asynchronous Life

Lee et, al. 2004

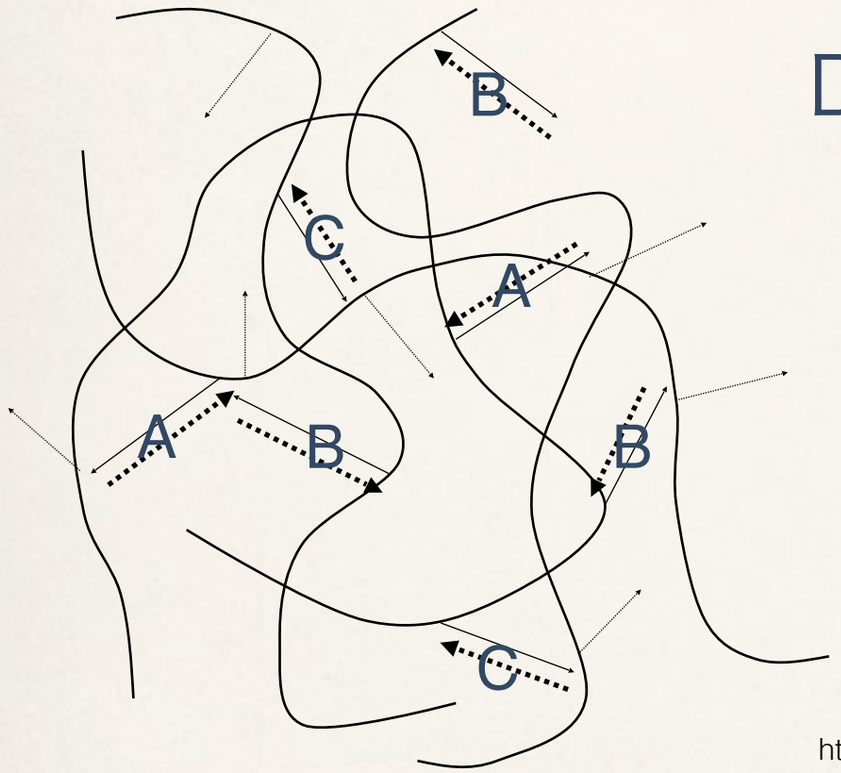
Actually....

accuracy may not be a big problem.

http://arstechnica.com/civis/viewtopic.php?f=23&t=125445

Texture

Change the **stiffness** of walls by controlling the level of dissolution.



Dissolve several kinds of cross-links according to a desired hardness.

http://s130636984.online.de/wp-content/uploads/2011/03/31.jpg http://megetemoe.blog.fc2.com/blog-entry-13.html

Change the **texture of surface** by dissolving the walls of surface cells selectively.

Tastes and flavors

Tastes:

sweetness, bitterness, umami

saltiness、sourness、calcium

Flavors:

aromatic series, ester, lactone, …

Too difficult to understand.
Are there any approximative base flavors set?

Trap molecules into liposomes.

Free molecules by destroying liposomes

Tastes and flavors

~~**Recipe Protocol** 1~~:

1. Each column contains liposomes (molecules such as Na+, sucrose, ..., and charged iron oxide nanoparticles in it.)
2. Dissolve all walls of cells in each column in which contain unused liposomes and extract them out of gels by a voltage gradient.
3. Lower the temperature for gellation of internal solutions.
4. Destroy remained liposomes by **induction heating** when you want to eat.

Temperature

If an induction heating is employed in the last stage, you do not need so worry about heating, but universal foodstuff should be **self-heatable**.

self-heatable retort food

http://userdisk.webry.biglobe.ne.jp/002/443/15/1/yasyoku1.jpg

Pulling the strap and wait a few minutes → hot food!

Temperature

If an induction heating is employed in the last stage, you do not need so worry about heating, but universal foodstuff should be **self-heatable**.

Oxidation reaction of iron powder
cf. disposable body warmer

Huge waste remained!

If such an **exothermal reaction** can be safely invoked and controlled somehow in a liposome...

"Look Ma, (heat dissipative) but no garbage!"

Temperature

If an **endothermic reaction** can be invoked in a gellular automaton, it might be possible to cool it down.

http://haijikg7.exblog.jp/15721825/

Gellular automata seems to be good for cold desserts.

e.g. barium hydroxide + ammonium chloride

Discussion

- Processing speed is still too slow.
- Can molecules be trapped and freed properly?
- Is it actually possible to print with a gel 3D printer?
- Expiration date : Gellular automata seems to be 'die' soon.
  I want to keep them in my freezer!
- Safety: useful molecules are usually harmful.

We are looking for self-organizing gels.

Does anyone know?

Our goal may be...

Self-reproducing gellular automata (as programmable foodstuffs)

Universal foodstuff

Foodstuff is universal ...

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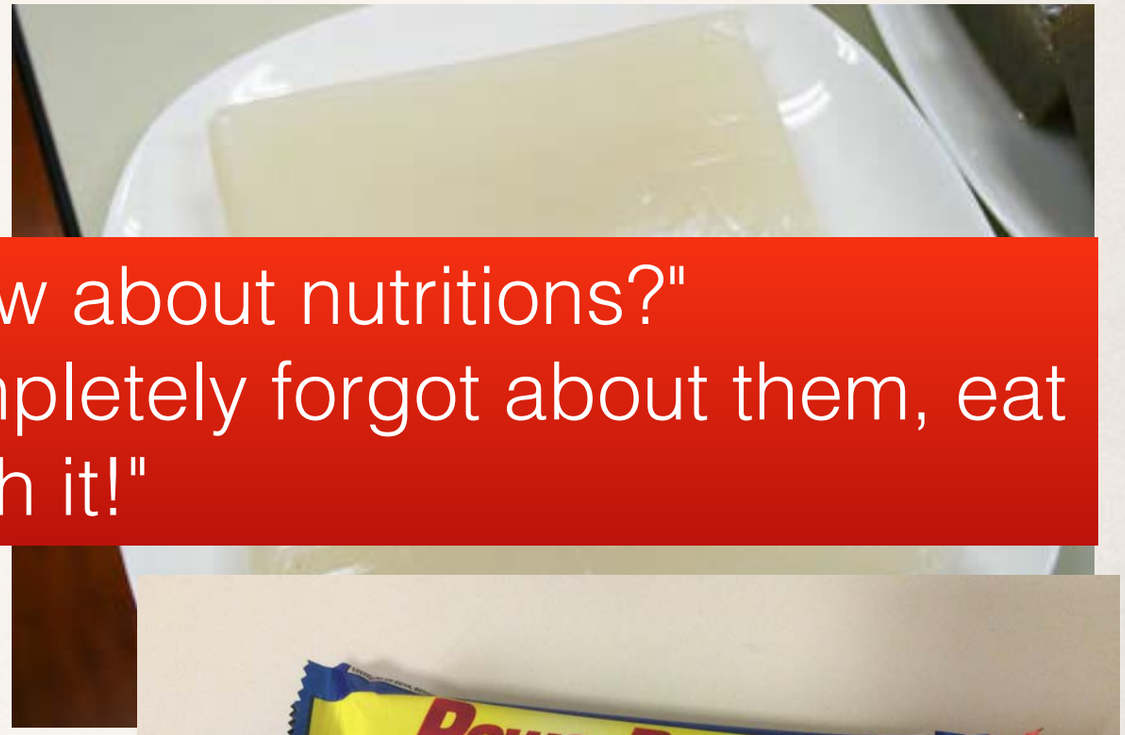
- flavor
- texture
- temperature
- color
- shape

can be controlled in the time and space domain

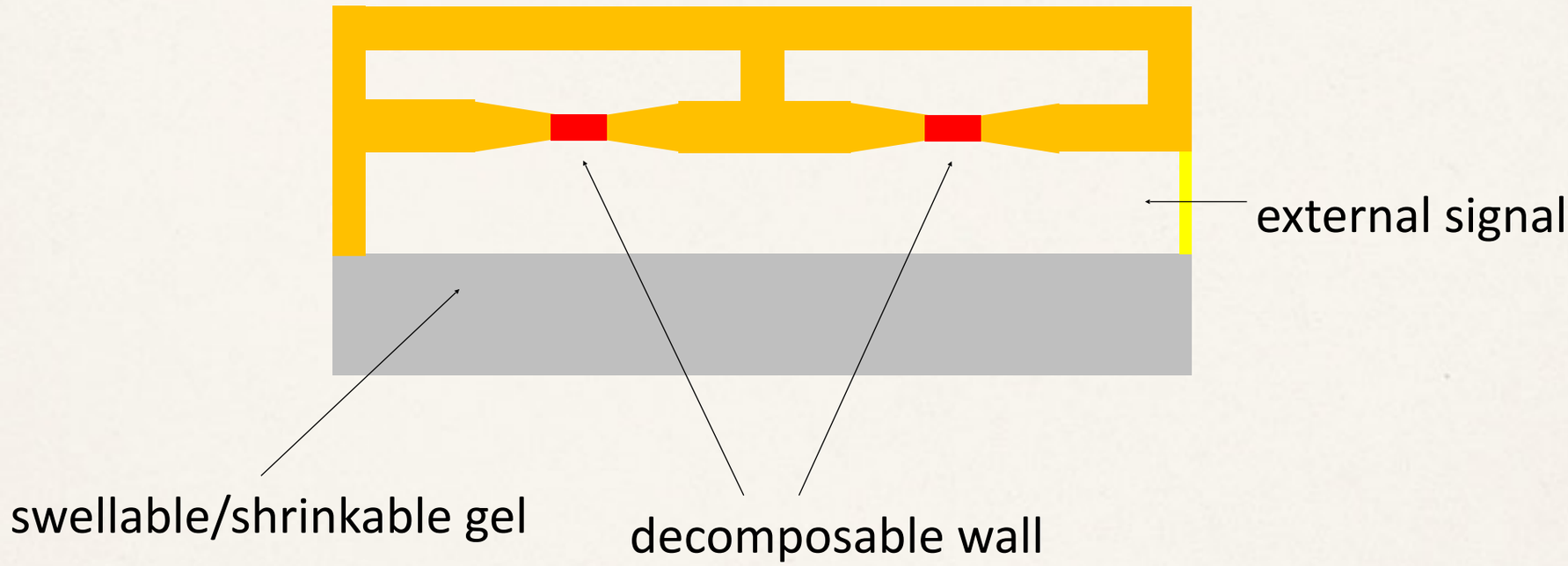
cf. construction-unniversality



Q: "By the way, how about nutritions?"
A: "Oh, I have completely forgot about them, eat a PowerBar with it!"

(Might be) useful edible gellular automata

Sensing the existence of some intraoral molecules and selecting one of walls to dissolve.



e.g. A gummi candy of which taste reflects a specific health condition.

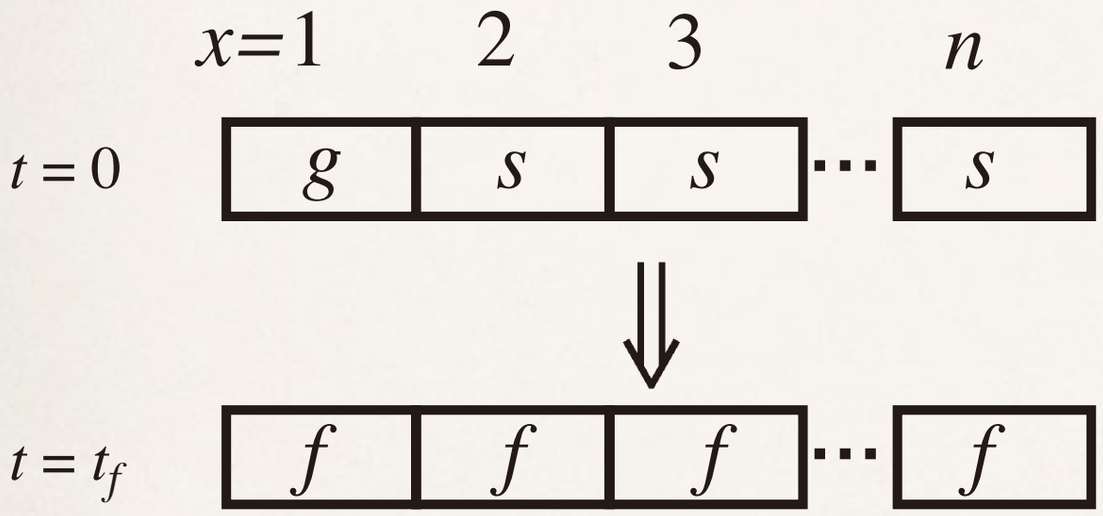
But processing speed is too slow so far.

Let's recall

Cellular automata programming

Example: Firing squad synchronization problem (FSSP)

Synchronize all quiescent soldier cells by a starting signal from the left side general cell.



g: general, *s*: soldier, *f*: firing state

1964～ Minsky & McCarthy 3n time
1966 Goto, optimal (2n-2) time
1967 Balzar 8-state, opt. time
1987 Mazoyer 6-state, opt. time

There is no 4-state solution
5-state, open.

Signal design

propagating signals

Speed 1 signal:

time ↓

s	s	R	s	s	s	s	s	s	s
s	s	s	R	s	s	s	s	s	s
s	s	s	s	R	s	s	s	s	s

rules $(s, s, s) \to s$

$(s, s, R) \to s$
$(s, R, s) \to s$
$(R, s, s) \to R$

Speed 1/3 signal:

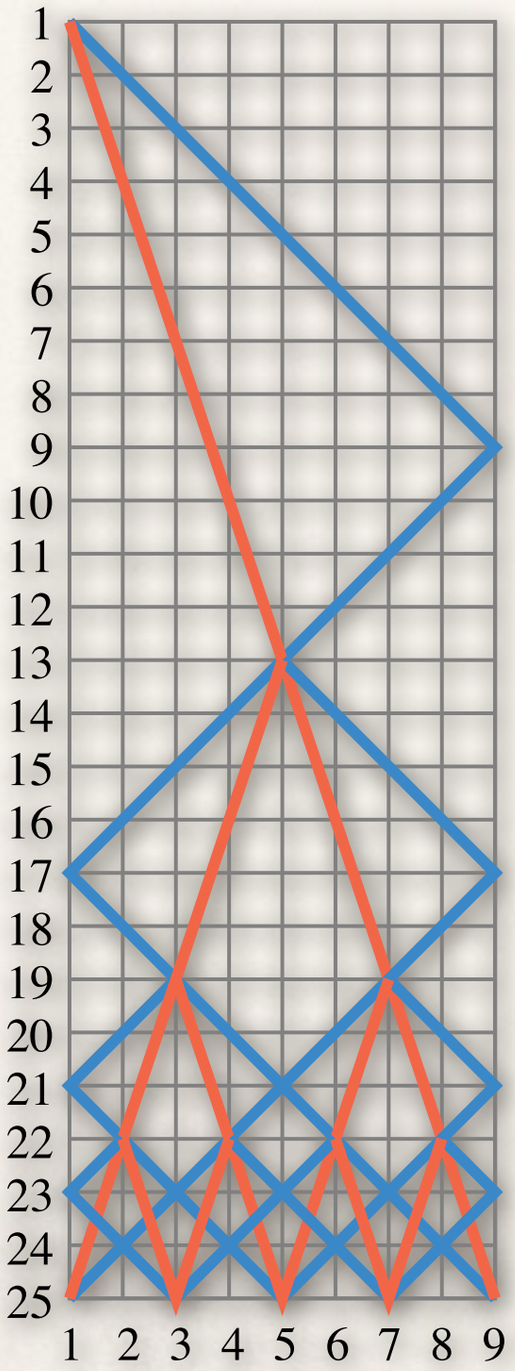
time ↓

s	s	A	s	s	s	s	s	s	s
s	s	B	s	s	s	s	s	s	s
s	s	C	s	s	s	s	s	s	s
s	s	s	A	s	s	s	s	s	s
s	s	s	B	s	s	s	s	s	s
s	s	s	C	s	s	s	s	s	s

$(s, s, A) \to s$
$(s, s, B) \to s$
$(s, s, C) \to s$
$(s, A, s) \to B$
$(s, B, s) \to C$
$(s, C, s) \to s$
$(A, s, s) \to s$
$(B, s, s) \to s$
$(C, s, s) \to A$

A solution for firing squad problem

Minsky & McCarthy 1964



G	s	s	s	s	s	s
X	R	s	s	s	s	s
X	s	R	s	s	s	s
s	A	s	R	s	s	s
s	B	s	s	R	s	s
s	C	s	s	s	R	s
s	s	A	s	s	s	R
s	s	B	s	s	s	L
s	s	C	s	s	L	s
s	s	s	A	L	s	s
s	s	s	G	s	s	s
s	s	L	G	R	s	s
s	L	s	G	s	R	s
L	s	a	G	A	s	R
R	s	b	s	B	s	L
s	R	c	s	C	L	s
s	G	G	s	G	G	s
L	G	G	X	G	G	R
R	G	G	Y	G	G	L
F	F	F	F	F	F	F

Divide and conquer

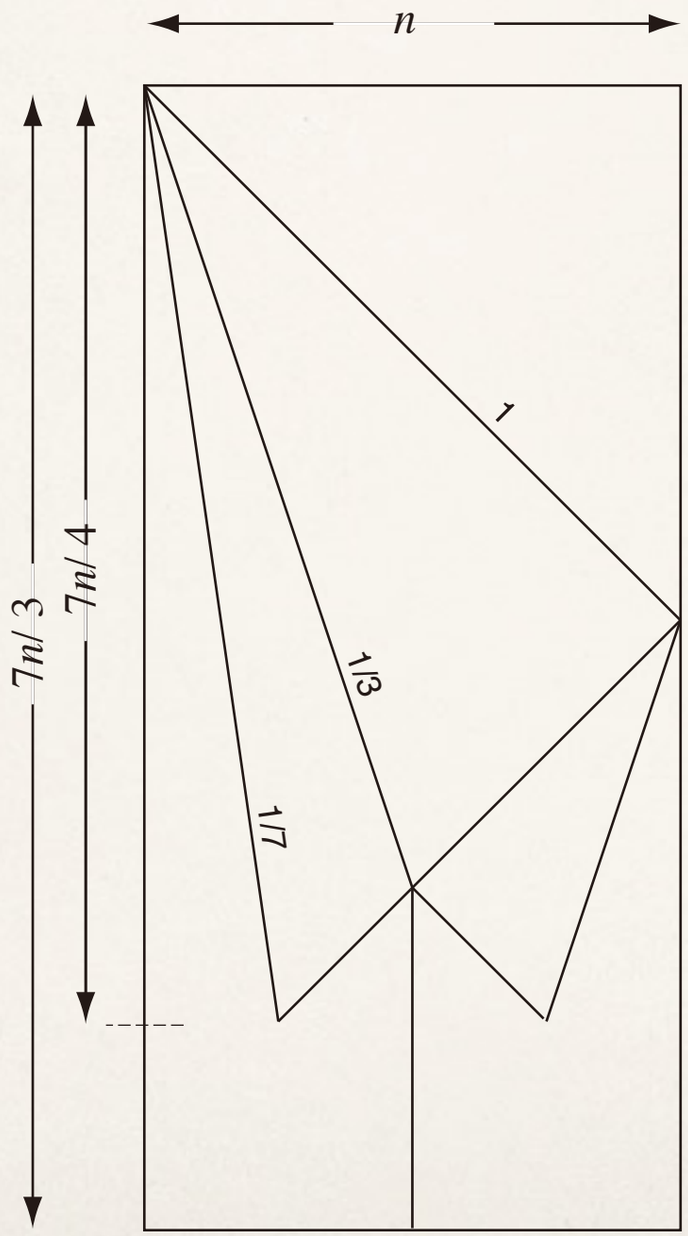
Generate speed 1 and 1/3 signals.

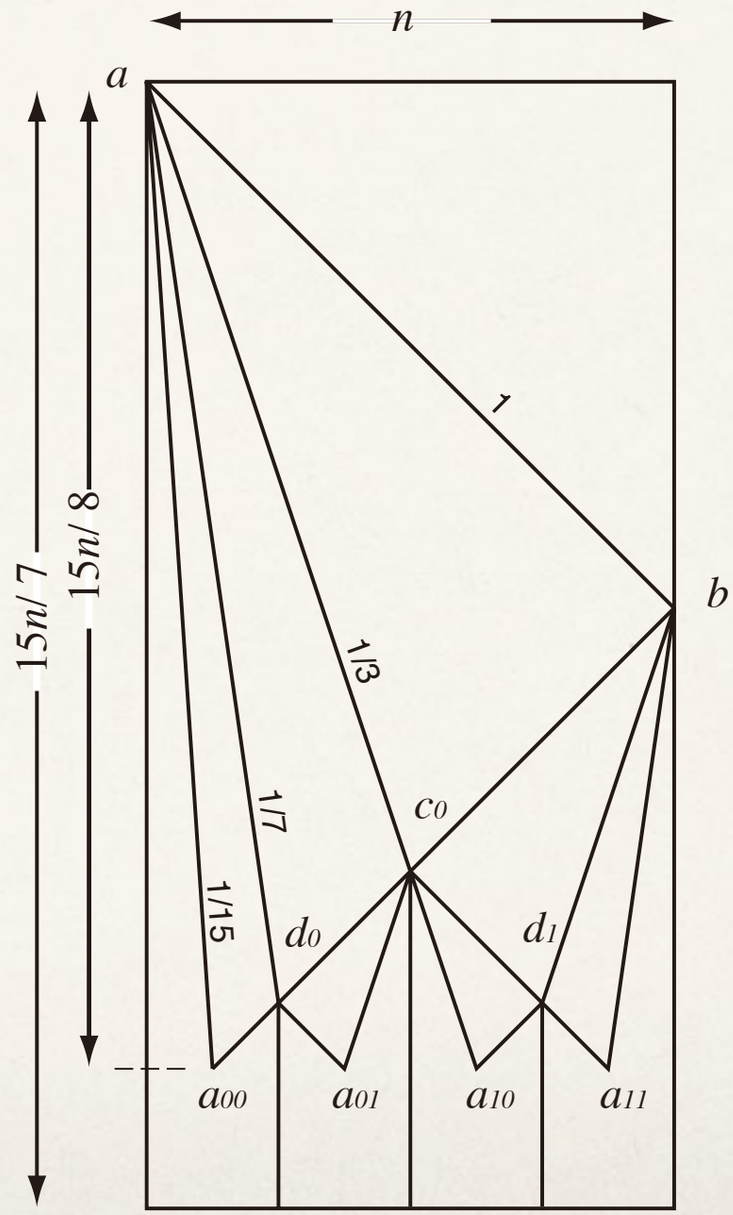
Divide into two subproblems at the collision (center) point.

Invoke subproblems recursively.

7-state 3n time solution (Yunes 1997)

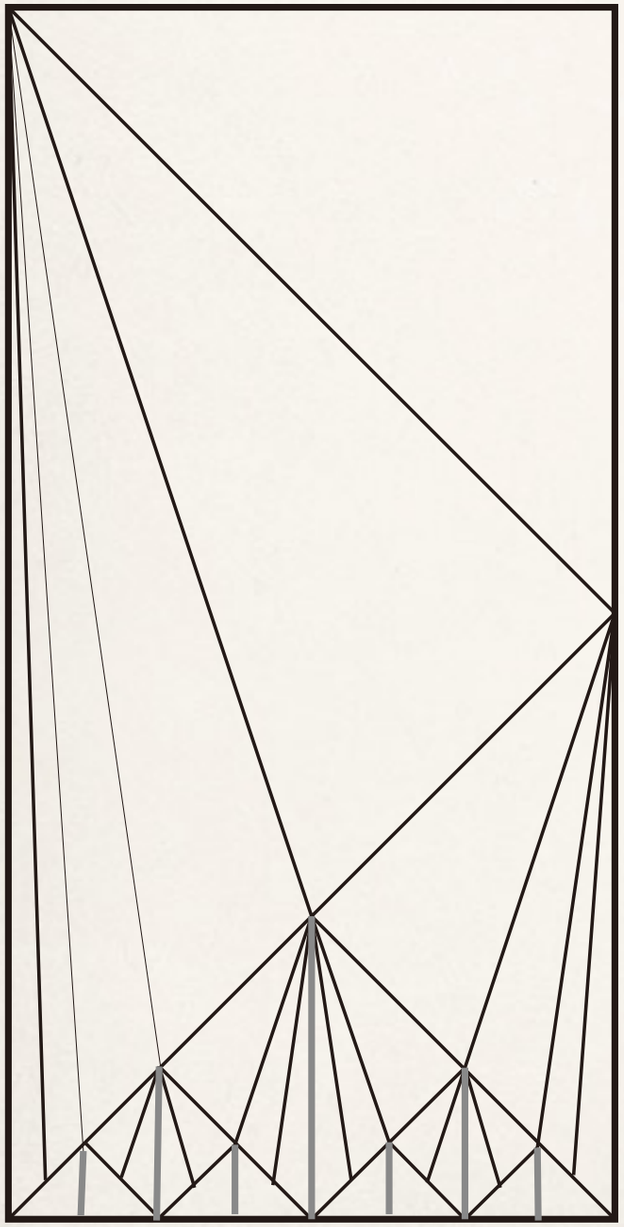
How to divide the cells in FSSP



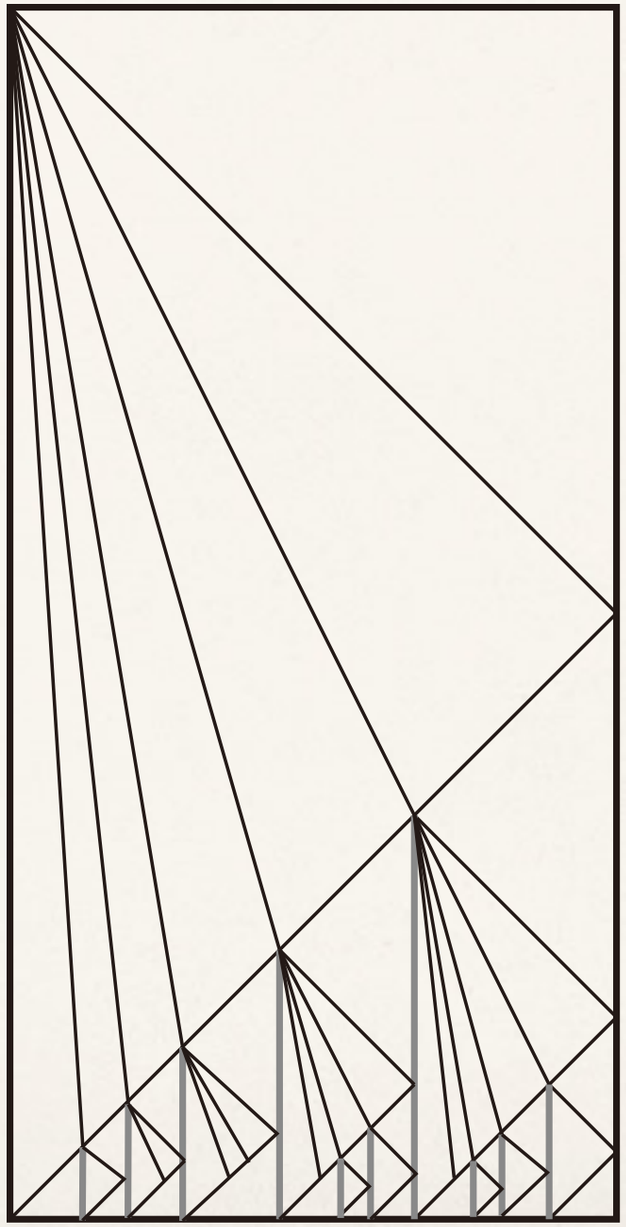


As the limit of divide and conquer algorithm

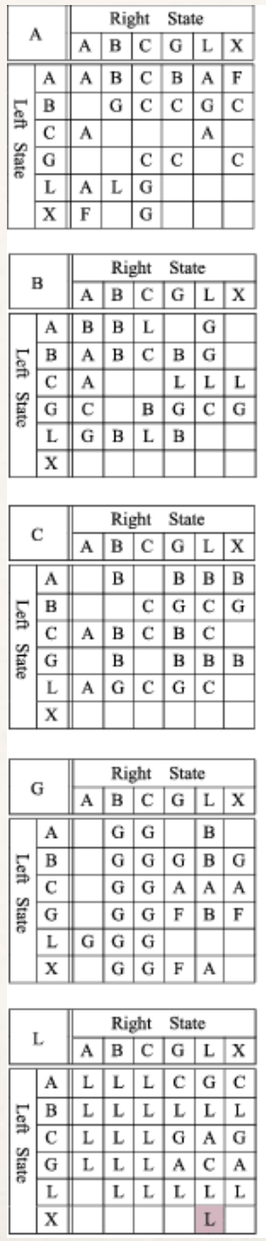
Optimal time solution to FSSP



(a) Waksman-Balzer type solution



(b) Mazoyer type solution



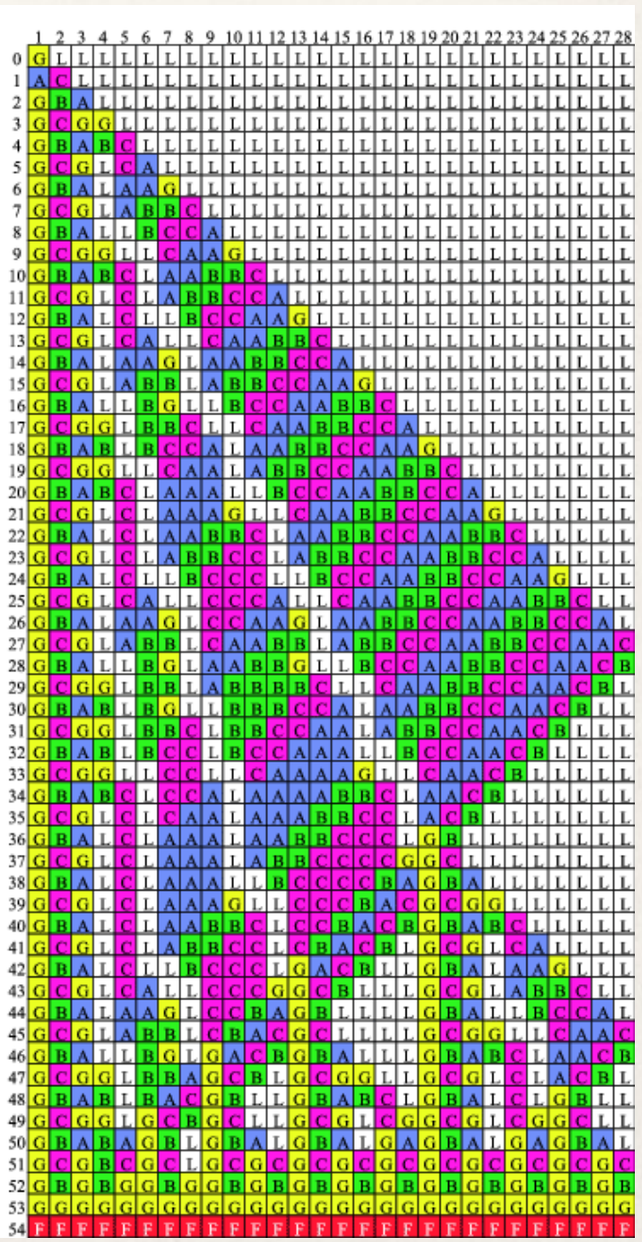
A	Right State					
	A	B	C	G	L	X
Left State A	A	B	C	B	A	F
Left State B		G	C	C	G	C
Left State C	A				A	
Left State G			C	C		C
Left State L	A	L	G			
Left State X	F		G			

B	Right State					
	A	B	C	G	L	X
Left State A	B	B	L		G	
Left State B	A	B	C	B	G	
Left State C	A			L	L	L
Left State G	C		B	G	C	G
Left State L	G	B	L	B		
Left State X						

C	Right State					
	A	B	C	G	L	X
Left State A		B		B	B	B
Left State B			C	G	C	G
Left State C	A	B	C	B	C	
Left State G		B		B	B	B
Left State L	A	G	C	G	C	
Left State X						

G	Right State					
	A	B	C	G	L	X
Left State A		G	G		B	
Left State B		G	G	G	B	G
Left State C		G	G	A	A	A
Left State G		G	G	F	B	F
Left State L	G	G	G			
Left State X		G	G	F	A	

L	Right State					
	A	B	C	G	L	X
Left State A	L	L	L	C	G	C
Left State B	L	L	L	L	L	L
Left State C	L	L	L	G	A	G
Left State G	L	L	L	A	C	A
Left State L		L	L	L	L	L
Left State X					L	

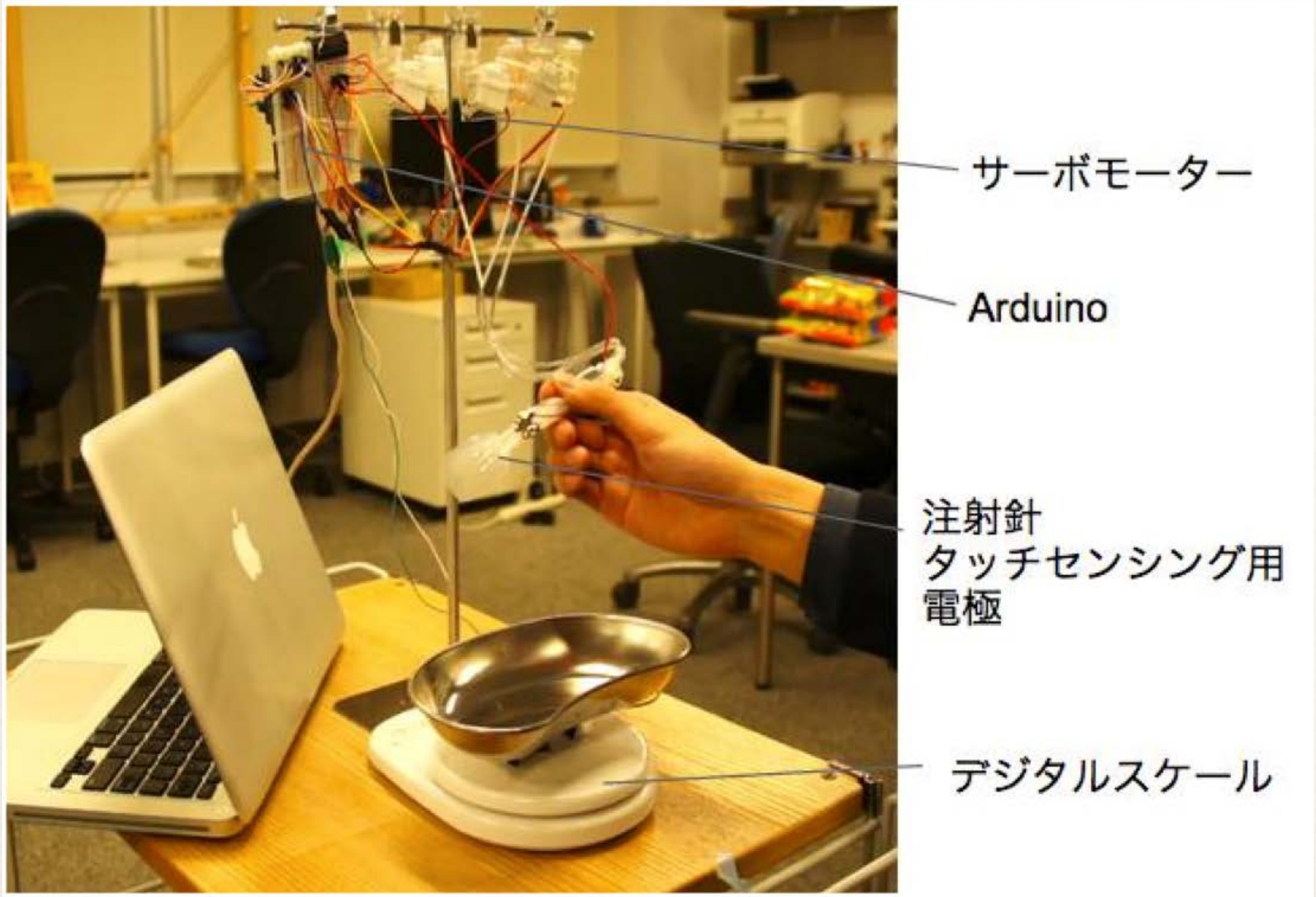


Mazoyer 1987

http://link.springer.com/static-content/images/642/chp%253A10.1007%252F978-1-4614-1800-9_70/MediaObjects/978-1-4614-1800-9_70_Fig7_HTML.gif

http://google.co.jp/#q=プログラマブルフード

Yet another programmable food —Adding seasoning by a program—

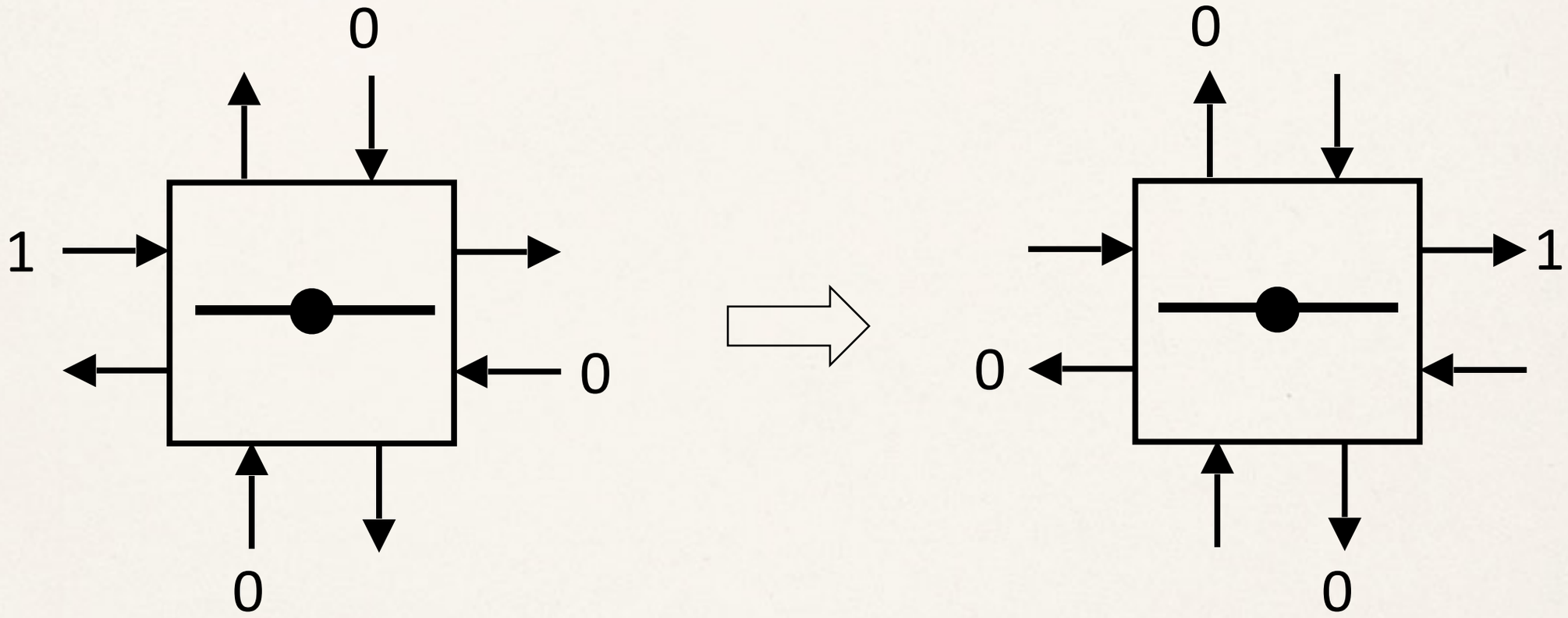


Kita (2012「未踏IT人材発掘・育成事業」accepted project)

万能ネギ！

ゲルオートマトンで“万能ネギ”を作れば
九条ネギも下仁田ネギもシミュレート
出来るんじゃないかな？

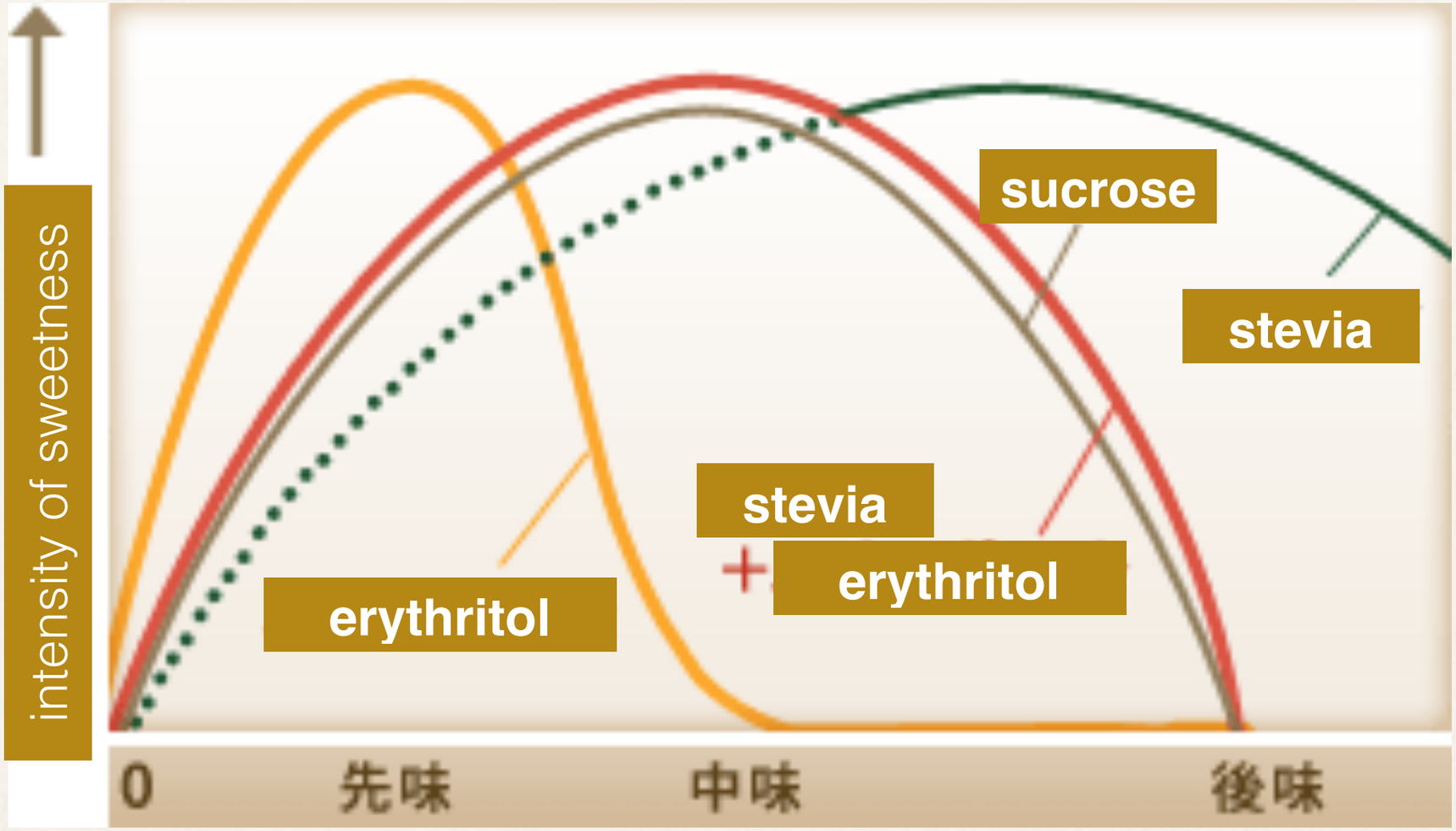
Implementation of a rotary element



Things to be computed...

e.g. Intensity of sweetness

Sucrose can be simulated by stevia+erythritol.



statistically scheduled so far...

三菱化学フーズ　http://www.mfc.co.jp/product/tourui/erisuri/apply.html

Gel based toy foods

Kracie co., ltd.

Neruneruneruneru

http://rainbowdevil.jp/?p=167

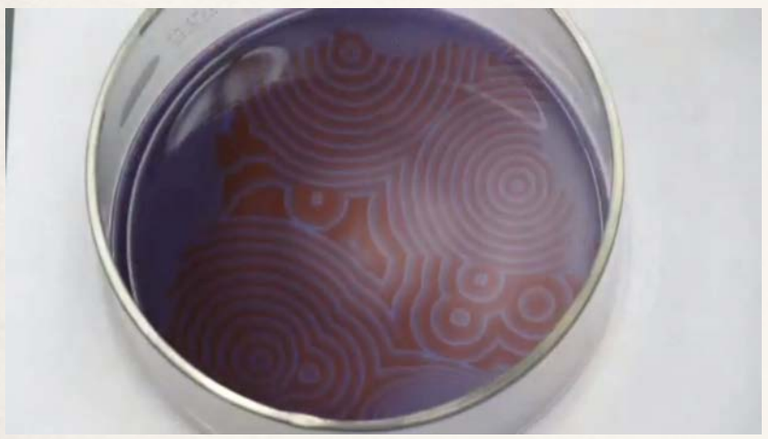
Narunarumininaru

http://girlschannel.net/topics/7028/

カレーセット

How to compute with a gel based media

Excitable media



Belousov-Zhabotinsky reaction

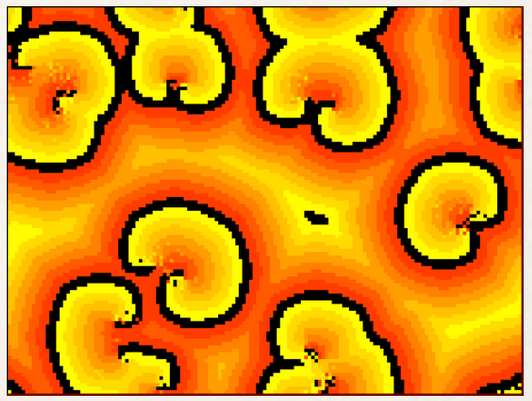
(Belousov 1951, Zhabotinsky 1961)

Cellular automata models of excitable media

cyclic cellular automata

Greenberg-Hastings

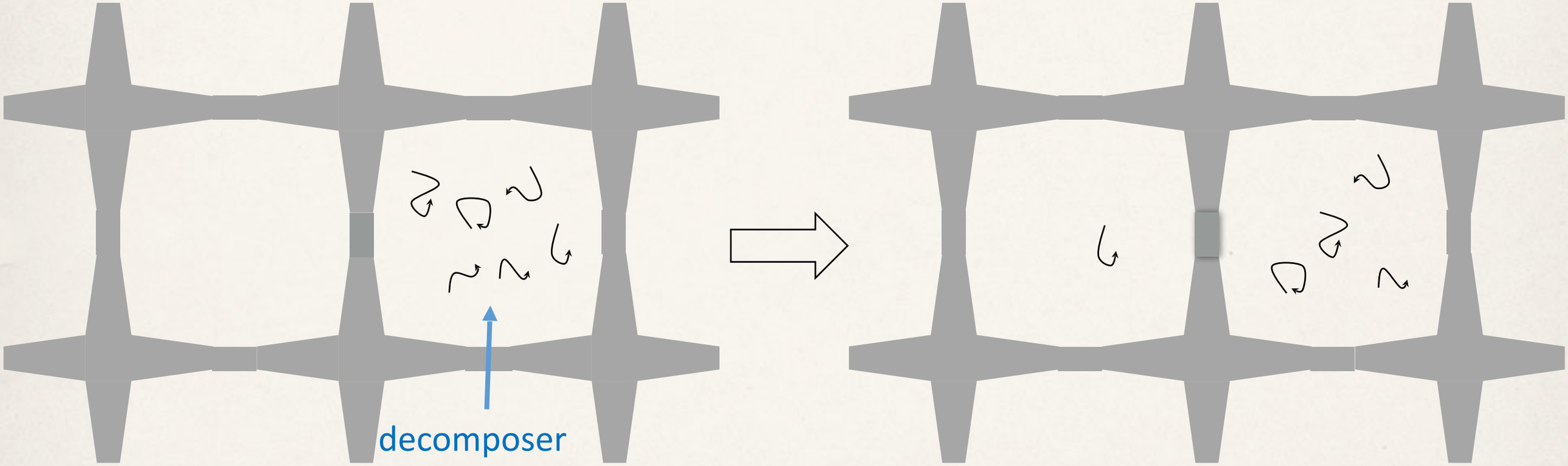
http://psoup.math.wisc.edu/mcell/rullex_cycl.html



Cellular automaton for simulating gel

Gellular automata without wall dissolution

It might even possible to evolve employing the difference of diffusion speed of distinct DNA fragments.



Thinning walls -> Faster execution but the life-span of a gellular automaton turn to be short.