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The Entropy Trajectory:
A Perspective to Classify Complex
Systems

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What are complex systems?

Having macroscopic properties which are not explicitly ascribed to the microscopic interactions between elements.

Empirically, the above definition is almost equal to

- 1) Difficult to predict the dynamics
- 2) Self-organized through long-term transient

Examples:

- Meteorological and oceanological systems
- Economical systems such as stock market
- Ecological systems such as animal population

Intelligence and complex systems

The organism is composed of millions of cells interacting one another, and an example of complex system.

In the organism, the microscopic interactions miraculously compose the **intelligence**, but complex systems are not always intelligent.

In an intelligent system, dynamics have a **purpose**

- Human tries to maximize the profit
- Even primitive bacteria try to survive and to prosper

Intelligence in computation

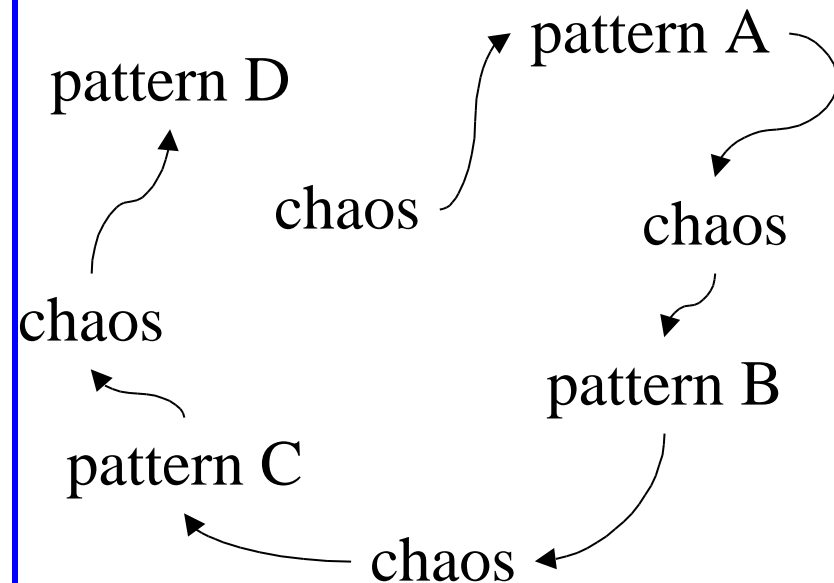
Synthesizing complex systems is easy, but synthesizing **intelligent** one (Artificial life: ALife) is not possible so far.

Open question

What kind of complex systems can lead to intelligent capacity?

A view of ALife

Systems must **adaptively** abandon and renew their self-organized pattern.



Objective and methodology of current work

OBJECTIVE

- **To establish a descriptor** to check if a complex system in computation is able to abandon and to renew the self-organized pattern.

METHODOLOGY

- Creating various complex systems using 2-dimensional Cellular Automata (CAs).
- Time-series analysis of **spatial and temporal entropy functions** of the CAs to observe the self-organizing itinerancy.

Cellular Automata (CAs)

- CA was created by von Neumann and Ulam to simulate self-replication process of biological system.
- CA is a dynamical system defined on **discrete space composed of 'cells'**.
- Each cell has **an integer state** which is updated every **discrete time step**.
- Update rule is local and homogenous.

EAMPLE

The state assumes 0, 1, 2 or 3. (Total rule entry number is 4^9 .)

0	1	2
0	3	0
2	1	2

time t

Next state is maximum of 8 outer neighbors

(periodic boundary condition)

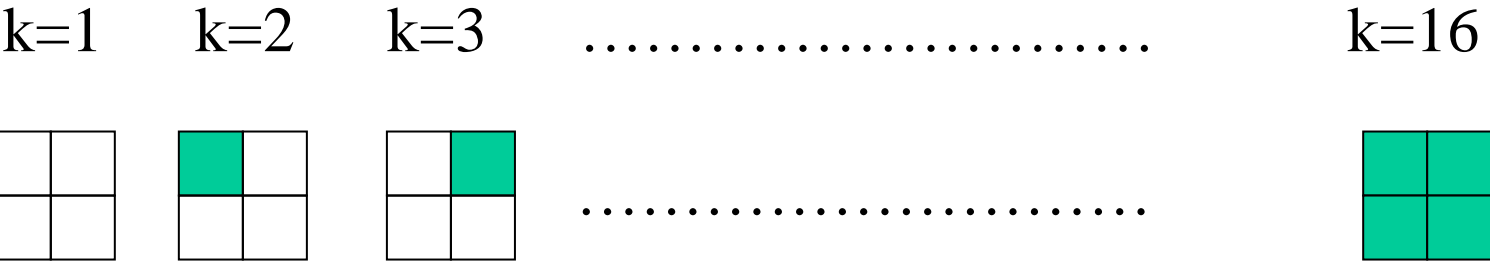
3	3	3
3	2	3
3	3	3

time $t+1$

Spatial Pattern Entropy

$$H_s(\tau) = - \sum_k P_s^k(\tau) \log_{16}(P_s^k(\tau))$$

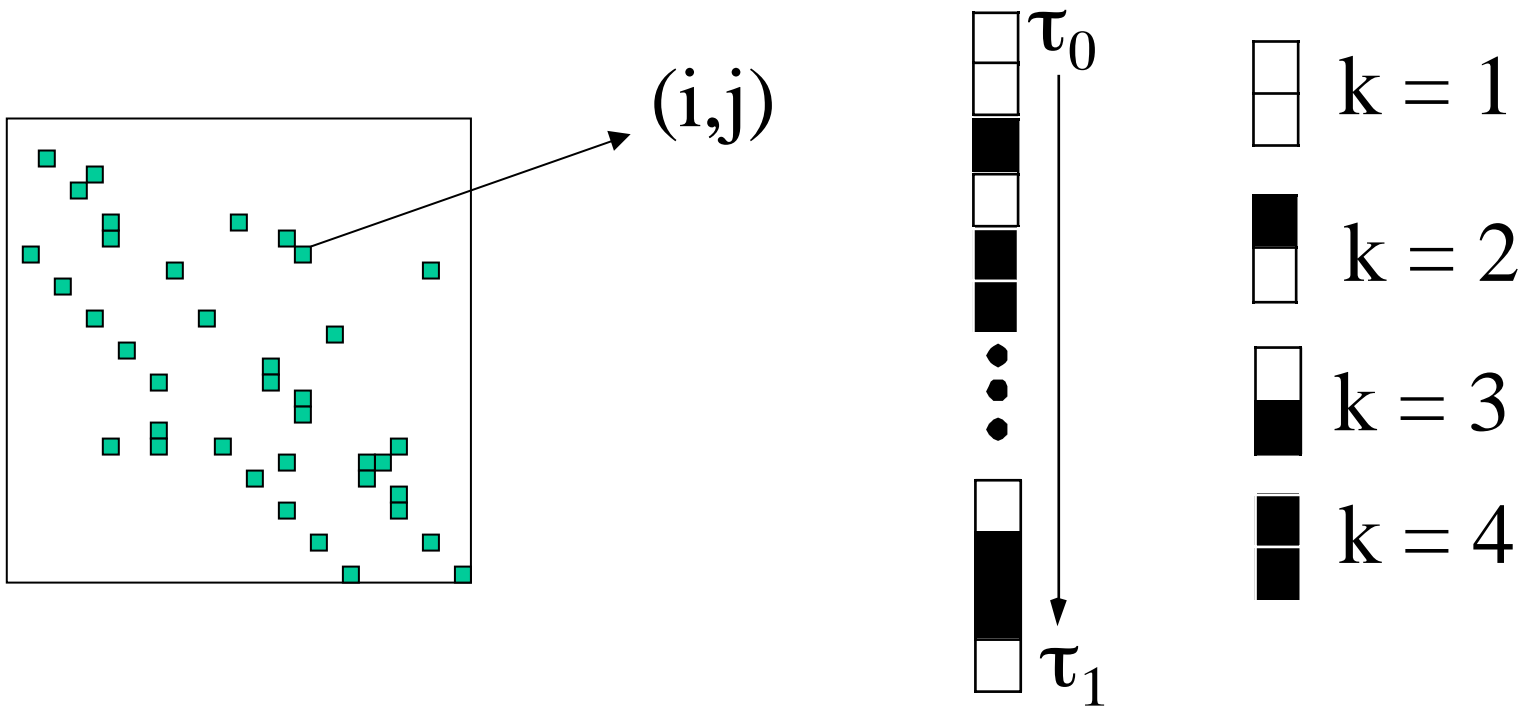
$P_s^k(\tau)$ is the probability for a particular spatial pattern of local patch at the time step τ .



Temporal Pattern Entropy

$$H_t(i, j) = - \sum_k P_t^k(i, j) \log_4(P_t^k(i, j))$$

$P_t^k(i, j)$ is the probability for a particular temporal pattern of local patch at the cell (i, j) .

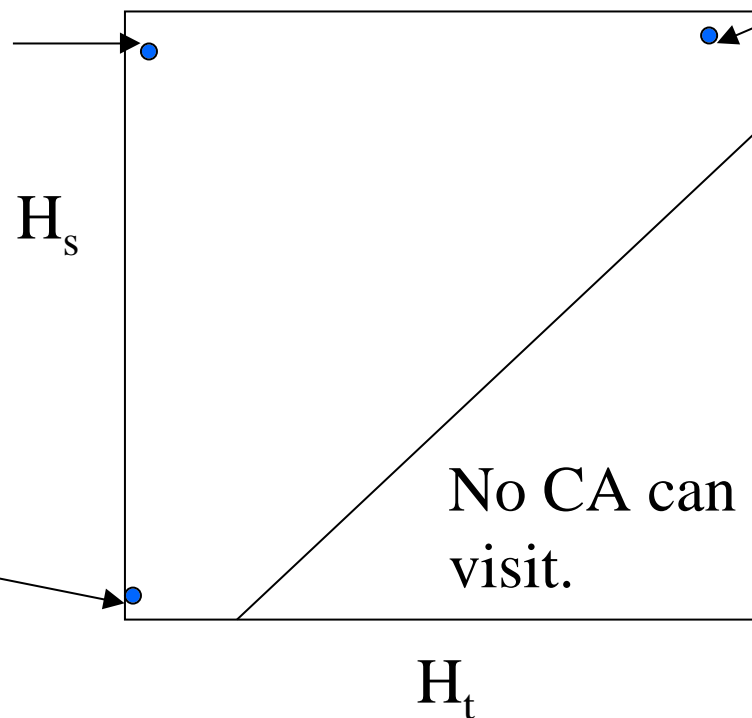


Classification of non-complex CA

Non-complex CAs have a fixed point entropy trajectory

static random
spatial pattern
(amorphous)

homogeneous
or localized



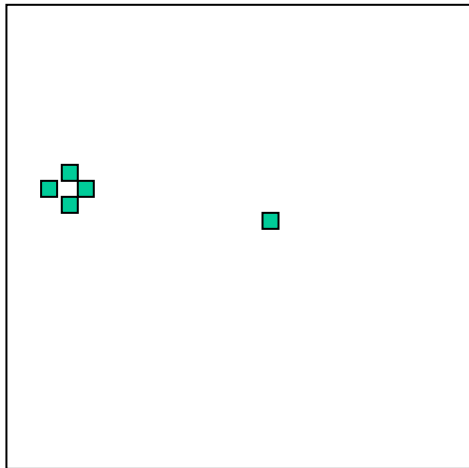
Complex CA : GOL Type

$$\lambda = \frac{N-n}{N}$$

N : Total rule entry number

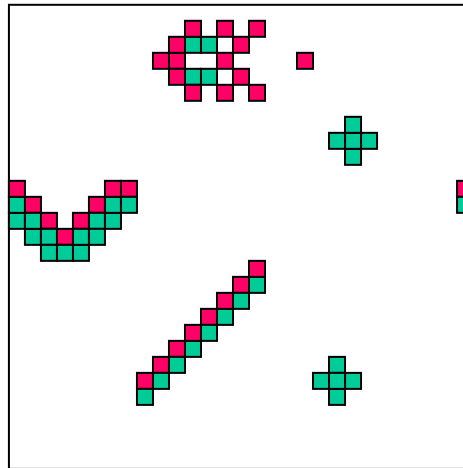
n : Number of entries outputting zero state

small λ -parameter



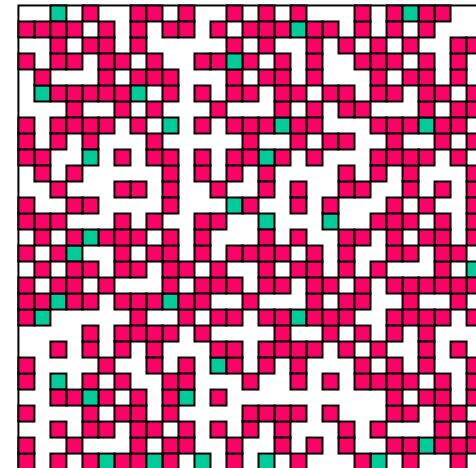
homogeneous
or localized

critical



unpredictable
such as GOL

large λ -parameter



chaotic

- Newly born non-zero cell
- Other non-zero cell

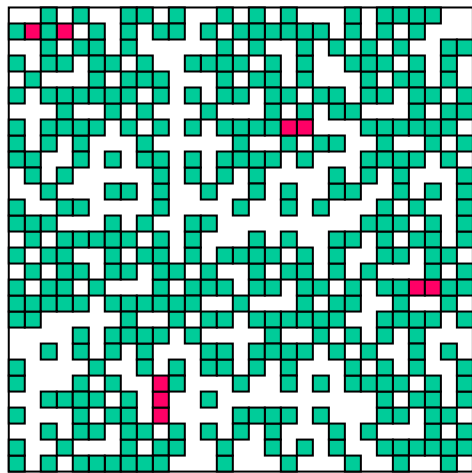
Complex CA : Crystal Type

$$\mu = \frac{N - m}{N}$$

N : Total rule entry number

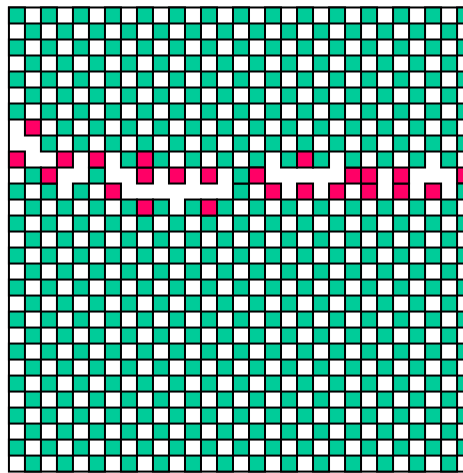
m : Number of entries not changing state

small μ -parameter



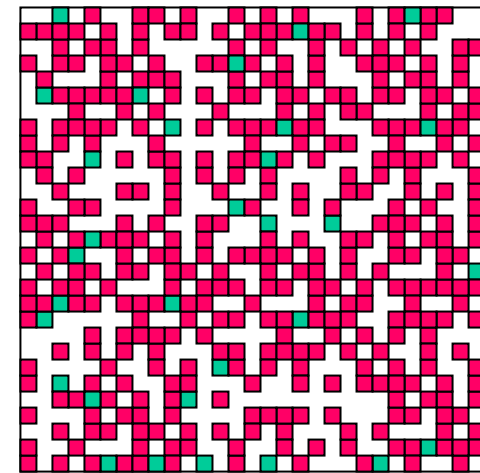
amorphous

critical μ



crystal-like

large μ -parameter

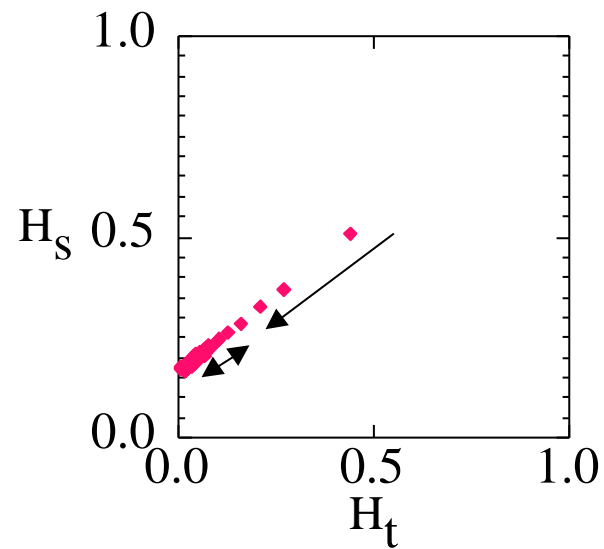
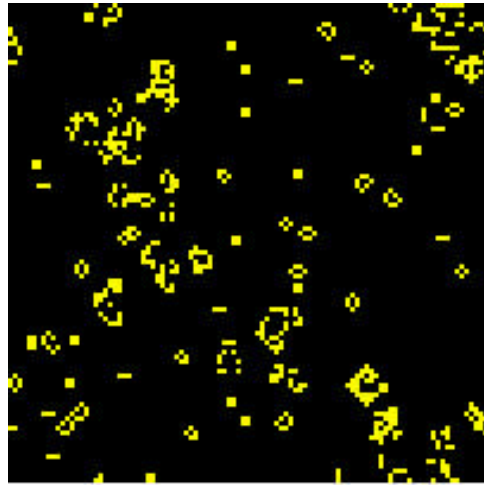


chaotic

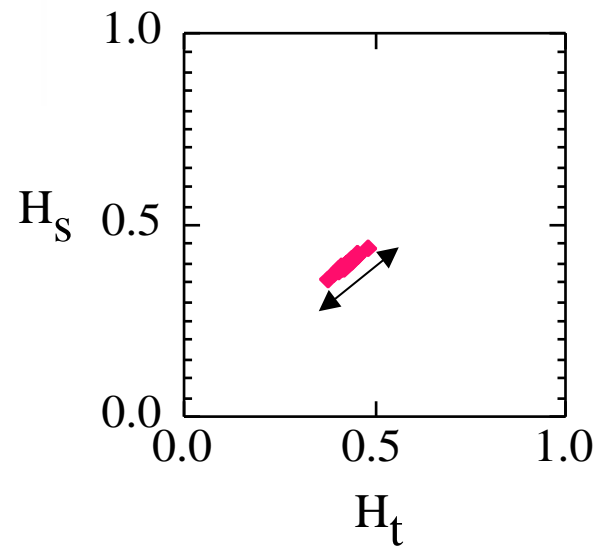
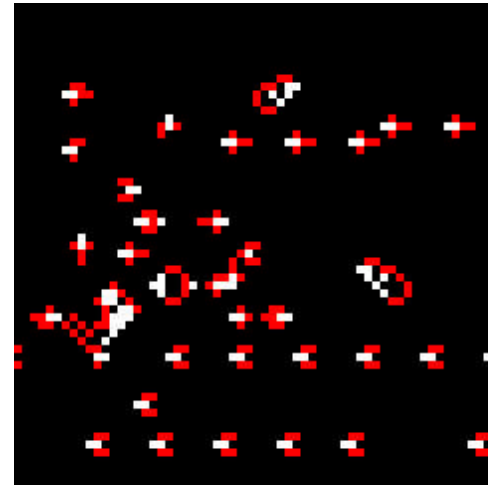
- Newly born non-zero cell
- Other non-zero cell

Example of Complex CA (1): GOL Type

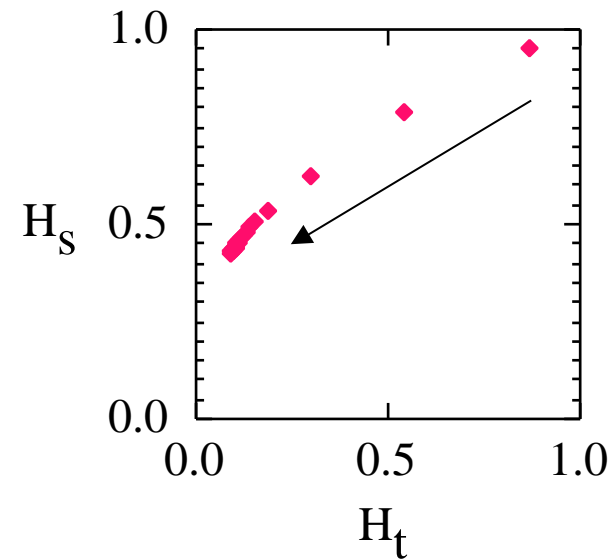
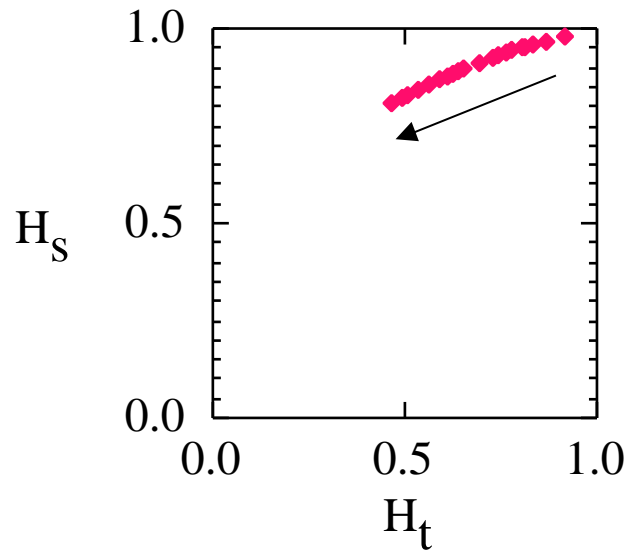
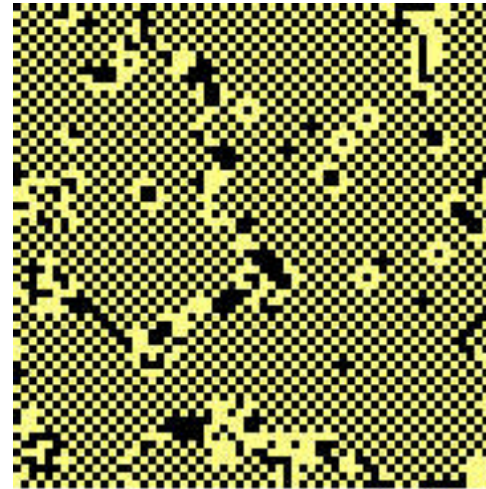
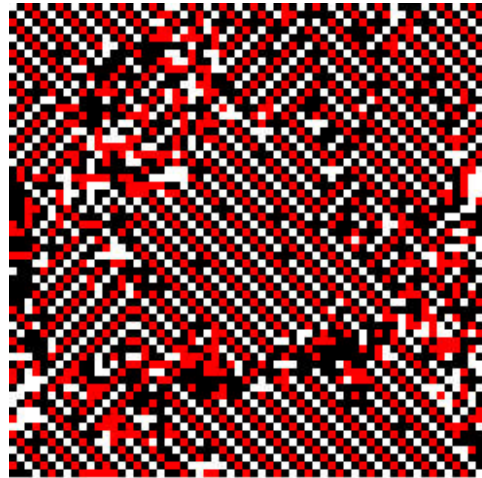
GOL



POND

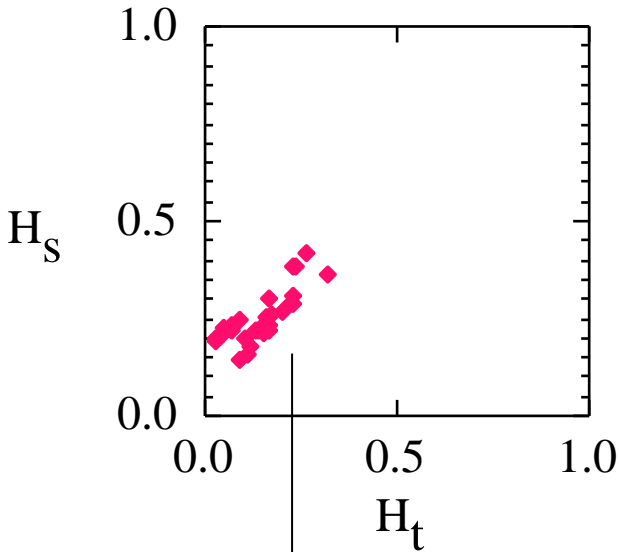
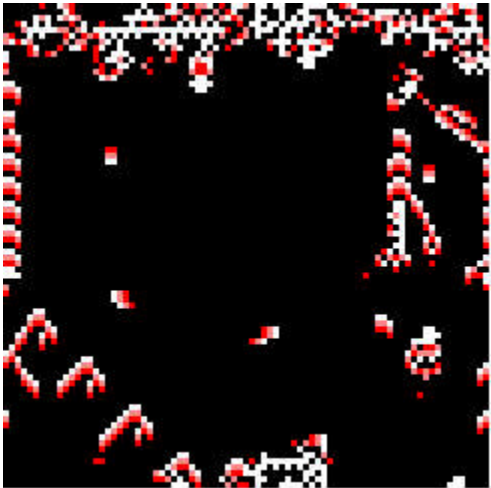


Example of Complex CA (2): Crystal Type



Example of Complex CA (3): Crossover Type

StarWars by M. Wojtowicz



↓
irregular trajectory

Concluding Remarks

Both GOL and Crystal types of CAs have **simple** entropy trajectory and **do not** renew their self-organized pattern.

The crossover type has an **irregular** entropy trajectory and **do** renew the self-organized pattern.



The entropy trajectory is a useful descriptor to measure the variety of self-organized patterns.

Could it be a descriptor of intelligence?