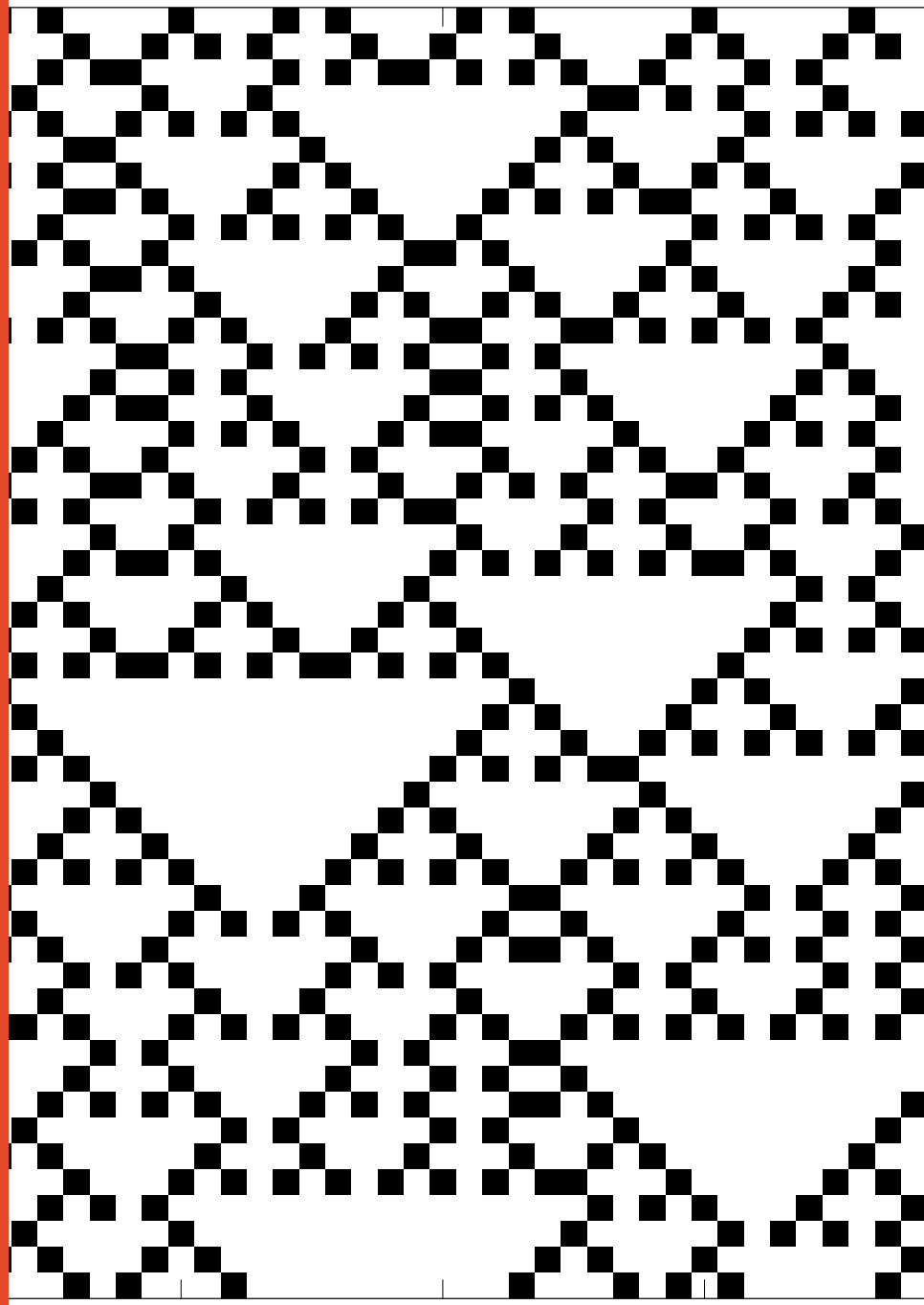
Information theory, self-organisation and complex systems

Dr. Joseph Lizier



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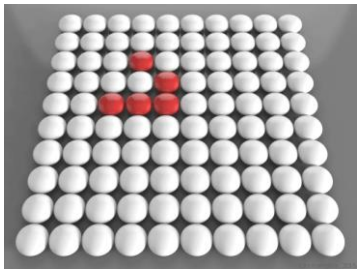
Self-organisation: session outcomes

- Understand concept of self-organisation;
- Understand candidate approaches to measure it directly at system level, and within a system.

- Primary references:
  - J.T. Lizier, "The local information dynamics of distributed computation in complex systems", Springer, Berlin/Heidelberg, 2013. Section 2.1.2 (pre-print)
  - M. Prokopenko, F. Boschetti, A.J. Ryan, "An Information-Theoretic Primer on Complexity, Self-Organization, and Emergence", Complexity, 15(1), pp. 11-28, 2009.

Self-organisation



Glider

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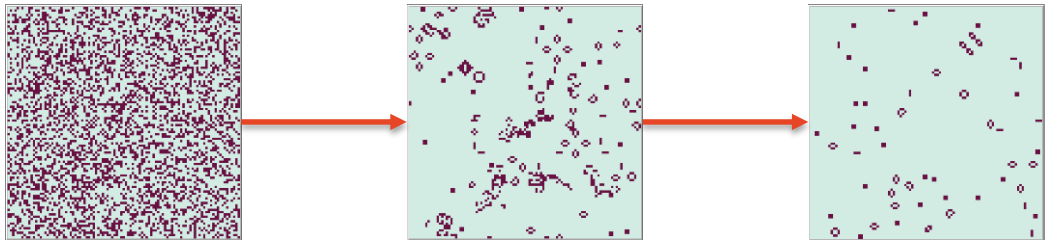
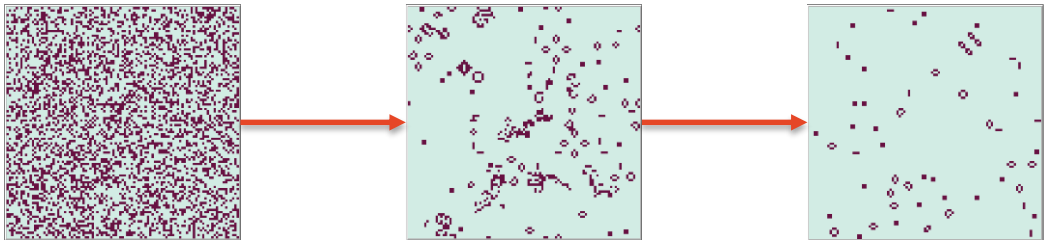
- Game of Life – a canonical complex system
- Run it:
  - In NetLogo (`Models library | Sample Models | Computer Science | Cellular Automata | Life`), or
  - Directly on the NetLogo website



- From your observations:
  - Describe the intermediate and final states in contrast to the initial random state?
  - Did it organise? In what way?
  - How did that happen? Was there any central control?
  - What happens to the density, and does the original density matter?
- Other examples of self-organisation?

Self-organisation



- Sayama, p. 6: "*Self-organization is a dynamical process by which a system spontaneously forms nontrivial macroscopic structures and/or behaviors over time.*"
- More specifically [2,3 in 4,5], must have 2 key features:
  - "*An increase in organisation over time*"
  - "*Dynamics not guided by any centralised or external control agent*"

[1] H. Sayama, "*Introduction to the Modeling and Analysis of Complex Systems*", Geneseo, NY: Open SUNY Textbooks, 2015; chapter 1
[2] C.R. Shalizi, K.L. Shalizi, R. Haslinger, "*Quantifying self-organization with optimal predictors*", Phys. Rev. Lett. 93(11), 118701 (2004)
[3] D. Polani, "*Foundations and formalizations of self-organization*", in Advances in Applied Self-organizing Systems, ser. Advanced Information and Knowledge Processing, ed. by M. Prokopenko (Springer, London, 2008), pp. 19–37
[4] J.T. Lizier, "*The local information dynamics of distributed computation in complex systems*", Springer: Berlin/Heidelberg, 2013
[5] M. Prokopenko, F. Boschetti, A.J. Ryan, "An Information-Theoretic Primer on Complexity, Self-Organization, & Emergence", Complexity, 15(1), pp. 11-28, 2009.

How to directly measure order/organisation?

Several options:

1. Complement of randomness / entropy [1]

2. Mutual information between parts of the system [2]
   - Integration/multi-information:

$$\mathrm{I}(X_1; \ldots; X_k) = \left(\sum_{i=1}^{k} \mathrm{H}(X_i) \right) - \mathrm{H}(X_1; \ldots; X_k)$$

   - Implemented in JIDT (`infodynamics.measures.*.*.MultiInfoCalculator[TYPE]`)

[1] C. Gershenson, N. Fernández, "*Complexity and information: Measuring emergence, self-organization, and homeostasis at multiple scales*", Complexity, 18(2), pp. 29-44, 2012
[2] D. Polani, "*Foundations and formalizations of self-organization*", in Advances in Applied Self-organizing Systems, ser. Advanced Information and Knowledge Processing, ed. by M. Prokopenko (Springer, London, 2008), pp. 19–37

How to directly measure order/organisation?

Several options:

1. Complement of randomness / entropy [1]

2. Mutual information between parts of the system [2]

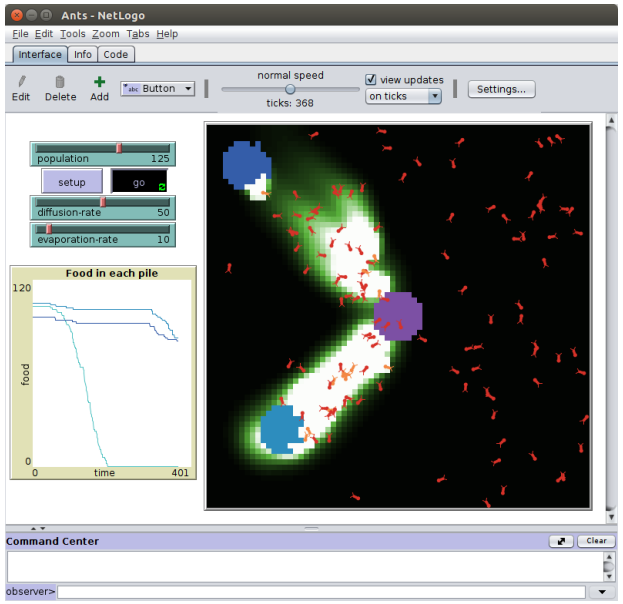
3. Statistical complexity* [3]

- I prefer approach 3 as a measure of organisation (*subjective*);
- Approach 2 is more accessible to the reader and to compute.

[1] C. Gershenson, N. Fernández, "*Complexity and information: Measuring emergence, self-organization, and homeostasis at multiple scales*", Complexity, 18(2), pp. 29-44, 2012
[2] D. Polani, "*Foundations and formalizations of self-organization*", in Advances in Applied Self-organizing Systems, ser. Advanced Information and Knowledge Processing, ed. by M. Prokopenko (Springer, London, 2008), pp. 19–37
[3] C.R. Shalizi, K.L. Shalizi, R. Haslinger, "*Quantifying self-organization with optimal predictors*", Phys. Rev. Lett. 93(11), 118701 (2004)
* Not covered in this course!

Alternative: measure various aspects of order/organisation

- Self-organisation is about *information structuring* (see Sayama).
- May be multiple aspects of information structure/organisation that we wish to investigate, e.g.
  - Temporal structure
  - Relationships between variables
  - Spatial structure
  - Information storage
  - Information transfer
  - Aspects that correlate with task



- Our approach:
  - To use information theory to characterise information processing structure in complex systems and their self-organisation, and how this changes over time.

Self-organisation: summary

- Self-organisation is an increase in order over time (without external control).
  - The key to measuring it is measuring order/organisation/structure in the system;
  - There are several options for doing so:
    - Directly, at system level; or
    - Examining multiple aspects of information structuring.

- *Coming up*: Information processing in complex systems.

Questions

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