CSYS5010 Introduction to Complex Systems

Week 1b What are complex systems?

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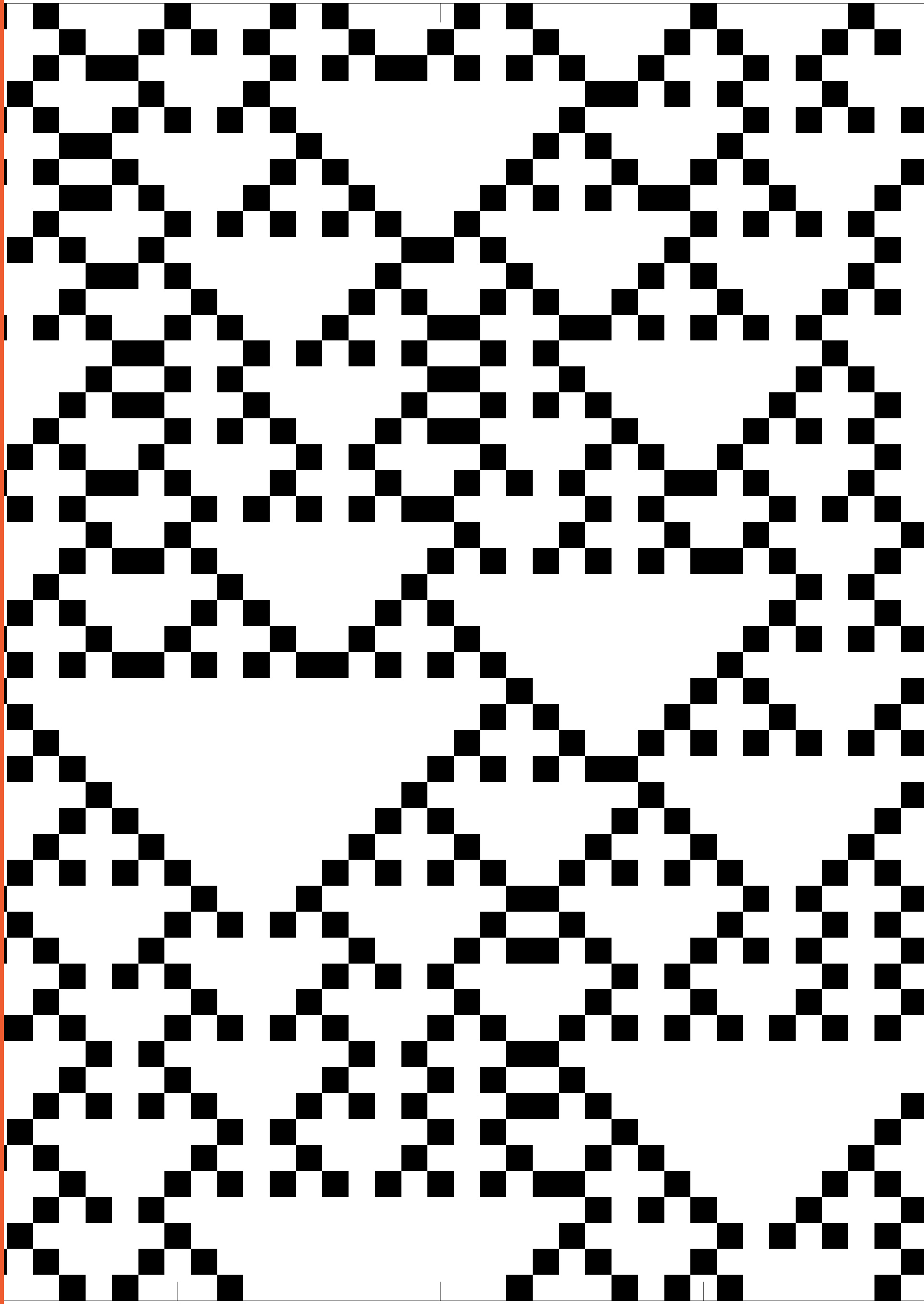
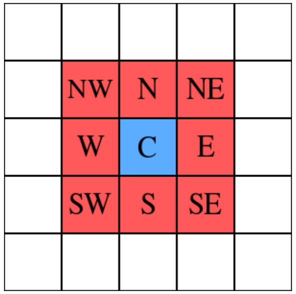


What are complex systems? Session outcomes

- Understanding of examples of complex systems
- Ability to define complex systems
- Understanding of features of complex systems, such as emergence and self-organisation

- Primary references:
  - M. Mitchell, "*Complexity: A guided tour*", New York: Oxford University Press, 2009 – chapter 1
  - H. Sayama, "*Introduction to the Modeling and Analysis of Complex Systems*", Geneseo, NY: Open SUNY Textbooks, 2015 – chapter 1

My favourite complex system: cellular automata



Moore neighbourhood
(Image by MorningLemon (Own work) [CC BY-SA 4.0])

- **Cellular automata (CA)** consist of :
  - A regular (spatially embedded) lattice or array of cells,
  - Connected in a regular pattern amongst some nearest neighbours.
  - Cells have discrete states,
  - Which update synchronously in discrete time,
  - As a homogeneous function of their neighbours current states.

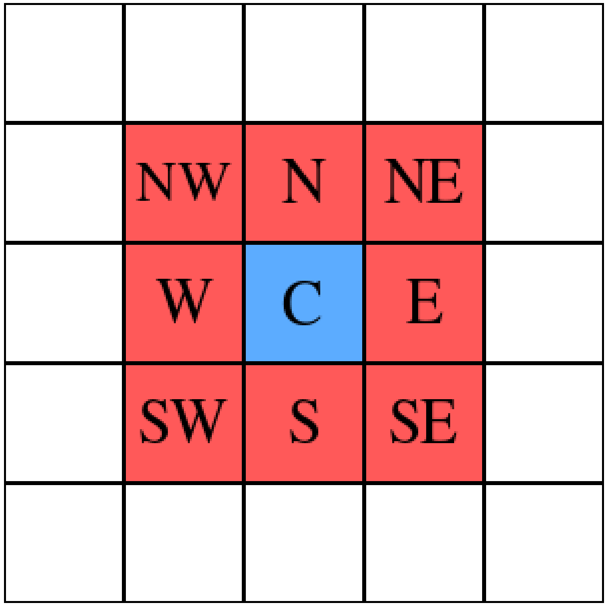
- Why are we interested in them?
  - Very simple spatio-temporal system model
    - Examples: fireflies, forest fires, fluid flows, earthquakes, etc.
  - You may recognise features of complex systems above
    - They generate apparently complex dynamics!

H. Sayama, "*Introduction to the Modeling and Analysis of Complex Systems*", Geneseo, NY: Open SUNY Textbooks, 2015; Ch. 11
M. Mitchell, "*Complexity: A guided tour*", New York: Oxford University Press, 2009 – chapter 10

Game of Life

- A CA created by John Conway, popularised by Martin Gardner
- Sought to mimic life-like behaviour

- Cells are alive (1) or dead (0).
- L(C) = number of alive neighbours of C
- Rule: cell C updates via:
  - **Birth**: dead -> alive if L(C) = 3
  - **Survival**: alive -> alive if L(C) = 2 or 3
  - **Loneliness**: alive -> dead if L(C) < 2, and
    dead -> dead if L(C) < 3
  - **Overcrowding**: alive/dead -> dead if L(C) > 3



Moore neighbourhood

(Image by MorningLemon (Own work) [CC BY-SA 4.0])

H. Sayama, "*Introduction to the Modeling and Analysis of Complex Systems*", Geneseo, NY: Open SUNY Textbooks, 2015; p. 191-197
M. Mitchell, "*Complexity: A guided tour*", New York: Oxford University Press, 2009 – chapter 10
M. Gardner, "*Mathematical games: The fantastic combinations of John Horton Conway's new solitaire game of 'life'*," Scientific American, vol. 223, no. 4, pp. 120–123, 1970

Game of Life – NetLogo

– Let's take a look in NetLogo:

1. Start NetLogo
2. Open the Models Library (`File | Models Library`) then browse to `Sample Models | Computer Science | Cellular Automata | Life` and click `Open`
3. Click "`setup-random`" button.
   a. What do you think will happen when you click "`Go-forever`"?
   b. Click "`Go-forever`" and observe
4. Play around and observe the results (make hypotheses before you do):
   a. Try again with a new random initial condition
   b. Try changing the initial density slider
   c. Try turning the draw-cells button on while the simulation is running and adding some live cells in random positions
   d. Try setup-blank, then make some cells live, then run.
   e. **Challenge**: can you construct a self-sustaining moving object?

Game of Life – NetLogo

Reflect:

- Do the Game of Life dynamics appear life-like?
- Would you say the Game of Life is a complex system?
  - Why?

Name some examples of complex systems

- Show the photographs of complex systems from your pre-work
  - Why did you choose these?
  - Why do you say these are complex systems?

- Let's list examples of complex systems …

Why are we interested in studying complex systems?

- They don’t yield to reductionist approaches
  - Emergent properties surprise us
- Can find universal features across disciplines
- So many examples around us that:
  - We don’t have a full understanding of, and
  - That have a significant impact on society.
- We could harness the power of collective intelligence
- …

How do you define complex systems?

How do experts define complex systems?

– Melanie Mitchell asks "what is your definition of a complex system?" (~12 min) –

Complexity Explorer – Introduction to Complex Systems, module 1.5: "What are Complex Systems? The Experts Weigh In"

How do experts define complex systems?

– What did you think of their definitions?
  – Did it change your thoughts? Which resonated with you?
  – Was there a consensus?

Wordl cloud from the transcript (removing “complex” “system*”, “definition”)

Definitions of complex systems that I like

- Mitchell, p.4, on complex systems science:
  - *"An interdisciplinary field of research that seeks to explain how large number of relatively simple entities organize themselves, without the benefit of any central controller, into a collective whole that creates patterns, uses information, and, in some cases, evolves and learns."*
- Mitchell, p. 13, on complex systems:
  - *"A system in which large networks of components with no central control and simple rules of operation give rise to complex collective behaviour, sophisticated information processing, and adaptation via learning or evolution."*
- Sayama, p. 3:
  - *"Complex systems are networks made of a number of components that interact with each other, typically in a nonlinear fashion. Complex systems may arise and evolve through self-organization, such that they are neither completely regular nor completely random, permitting the development of emergent behavior at macroscopic scales."*

M. Mitchell, "*Complexity: A guided tour*", New York: Oxford University Press, 2009 – chapter 1

H. Sayama, "*Introduction to the Modeling and Analysis of Complex Systems*", Geneseo, NY: Open SUNY Textbooks, 2015; chapter 1

Definitions of complex systems that I like

- Mitchell, p. 13:
  - *"A system in which large networks of components with no central control and simple rules of operation give rise to complex collective behaviour, sophisticated information processing, and adaptation via learning or evolution."*
- Simpler:
  - Mitchell, p. 13: *"A system that exhibits nontrivial emergent and self-organising behaviors"*
  - JL, p. 3: *"the study of large collections of (generally simple) entities, where the global behaviour is a non-trivial result of the local interactions of the individual elements"*

M. Mitchell, "*Complexity: A guided tour*", New York: Oxford University Press, 2009 – chapter 1
J.T. Lizier, "*The local information dynamics of distributed computation in complex systems*", Springer: Berlin/Heidelberg, 2013

Key features of the definition

1. Large collections of interacting elements
2. Global behaviour is a non-trivial result of these interactions
   - Difference between:
     - Simple systems (fixed coin tosses, precisely defined engineered systems)
     - Complicated systems (ideal gases), and
     - Complex systems

– Q: is there a continuum of complexity?

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H. Sayama, "*Introduction to the Modeling and Analysis of Complex Systems*", Geneseo, NY: Open SUNY Textbooks, 2015; chapter 1
M. Prokopenko, F. Boschietti, A.J. Ryan, "*An information-theoretic primer on complexity, self-organization, and emergence*", Complexity 15(1), 11–28 (2009)

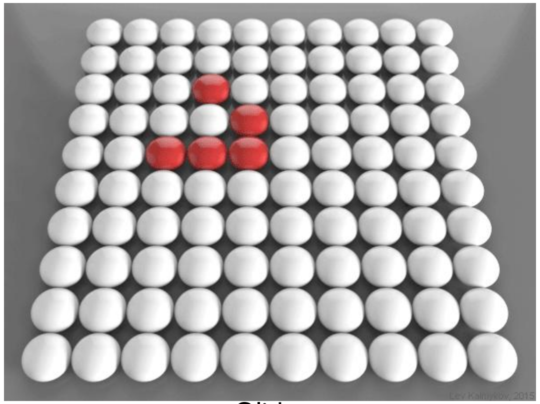
Key concepts

- Emergence, and behaviour at multiple scales
- Self-organisation, and dynamics
- Order-chaos interplay

- Go back to the Game of Life. Take note of what examples you might observe of these phenomena?

Emergence

– Game of Life?
  – What did you expect when you first pressed Go?
  – Gliders, blinkers, glider guns, etc. Many more
  – *Emergent structure*

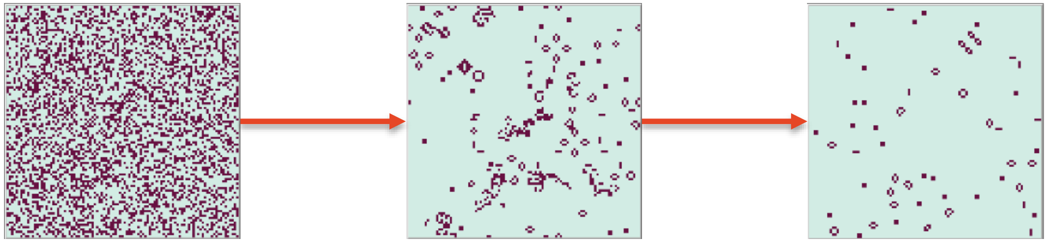


Glider
(Image By Lev Kalmykov (Own work) [CC BY-SA], via Wikimedia Commons

– Sayama, p. 6: *"Emergence is a nontrivial relationship between the properties of a system at microscopic and macroscopic scales. Macroscopic properties are called emergent when it is hard to explain them simply from microscopic properties."*
– Simple rules produce hard to predict complex behaviour.
– Increase in order over (physical) scale
– Quantitatively, Shalizi: *Emergence occurs where predictive efficiency (ratio of how much can be predicted versus difficulty of prediction) increases with scale*
– Complex systems involve behaviour at multiple scales – e.g. Life in Life
– Other examples of emergence?

H. Sayama, "*Introduction to the Modeling and Analysis of Complex Systems*", Geneseo, NY: Open SUNY Textbooks, 2015; chapter 1
M. Prokopenko, F. Boschietti, A.J. Ryan, "*An information-theoretic primer on complexity, self-organization, and emergence*", Complexity 15(1), 11–28 (2009)
C. Shalizi, "*Causal architecture, complexity and self-organization in time series and cellular automata*", PhD thesis, University of Michigan, 2001

Self-organisation



– Game of Life?
  – Describe the final state 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?
– 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], must have 2 key features:
  – *"An increase in organisation over time"*
  – *"Dynamics not guided by any centralised or external control agent"*
– Other examples of self-organisation?

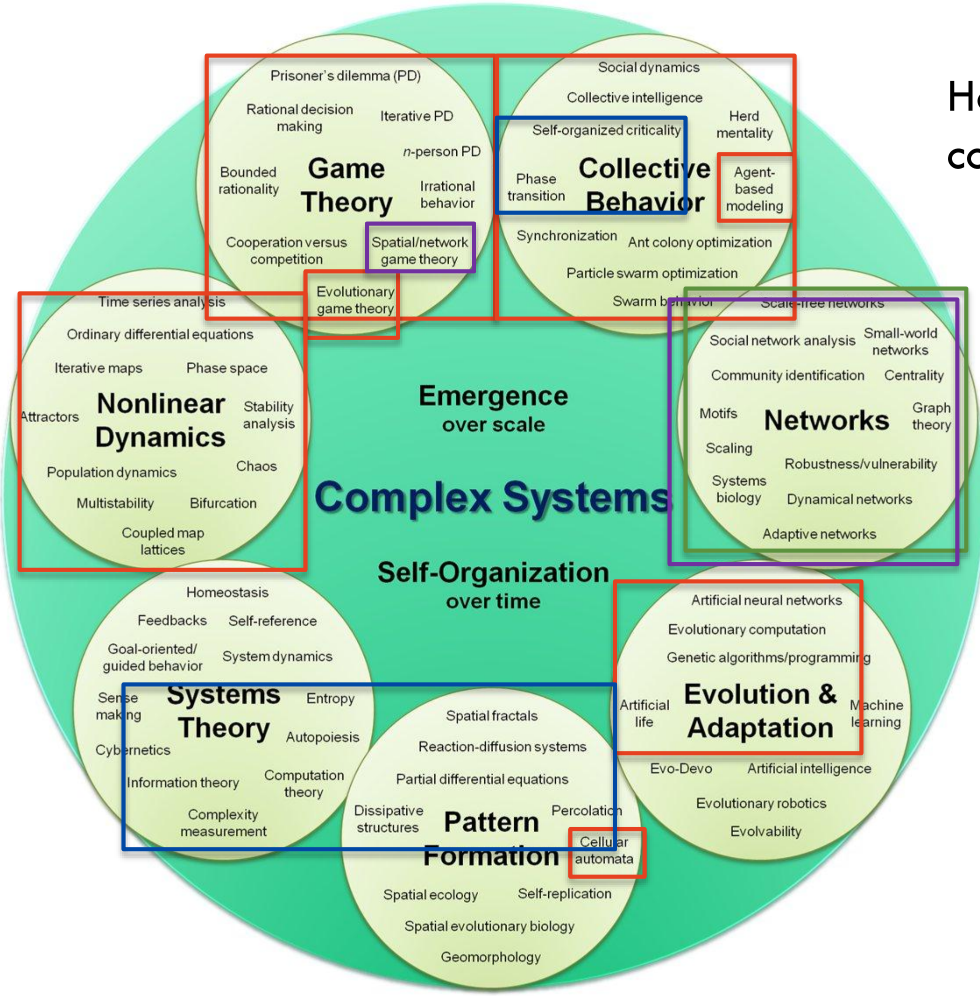
[1] H. Sayama, "*Introduction to the Modeling and Analysis of Complex Systems*", Geneseo, NY: Open SUNY Textbooks, 2015; chapter 1
[2] C.R. Shalizi, K.L. Shalizi, R. Haslinger, "*Quantifying self-organization with optimal predictors*", Phys. Rev. Lett. 93(11), 118701 (2004)
[3] D. Polani, "*Foundations 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

Interplay of order and chaos

- Game of Life?
  - What forms of order and chaos did you see?
  - What happens if we "insert life" into a given cell?
  - What happens if we change the rules?
- Do these aspects remind you of properties of other systems?
- What might be the advantages for biological systems in exhibiting aspects of both order and chaos?
- Langton: "*Computation at the edge of chaos*" – an incredibly seductive idea, though various aspects disproven and others elusive to quantification.

C.G. Langton, "*Computation at the edge of chaos: phase transitions and emergent computation*", Physica D 42(1–3), 12–37 (1990)

Topical areas of Complex Systems



How can we study complex systems?

CSYS5010

CSYS5030

COMP5313

CSYS5020

Image By Hiroki Sayama, D.Sc. [CC BY-SA], via Wikimedia Commons
H. Sayama, "*Introduction to the Modeling and Analysis of Complex Systems*", Geneseo, NY: Open SUNY Textbooks, 2015; p. 5

Summary

- Defining "Complex systems" is a contested question to some extent, but researchers agree on various important aspects:
  - Interaction amongst many simple elements;
  - Non-trivial emergence of global behaviour.
- Related concepts of self-organisation and emergence.

- Q: Can we measure complexity, self-organisation and emergence?
  - Complexity: many measures (Lloyd, 2001)
  - Self-organisation / emergence – rely on measures of order/structure (see CSYS5030)

- *Next*: how to model complex systems?

S. Lloyd, "Measures of complexity: A non-exhaustive list", IEEE Control Systems Magazine, 7-8, August, 2001

Questions

Elementary CA rule 110

Rule table ϕ:

neighborhood:	000	001	010	011	100	101	110	111
output bit:	0	1	1	1	0	1	1	0

= Rule 0x6e = Rule 110

Lattice:

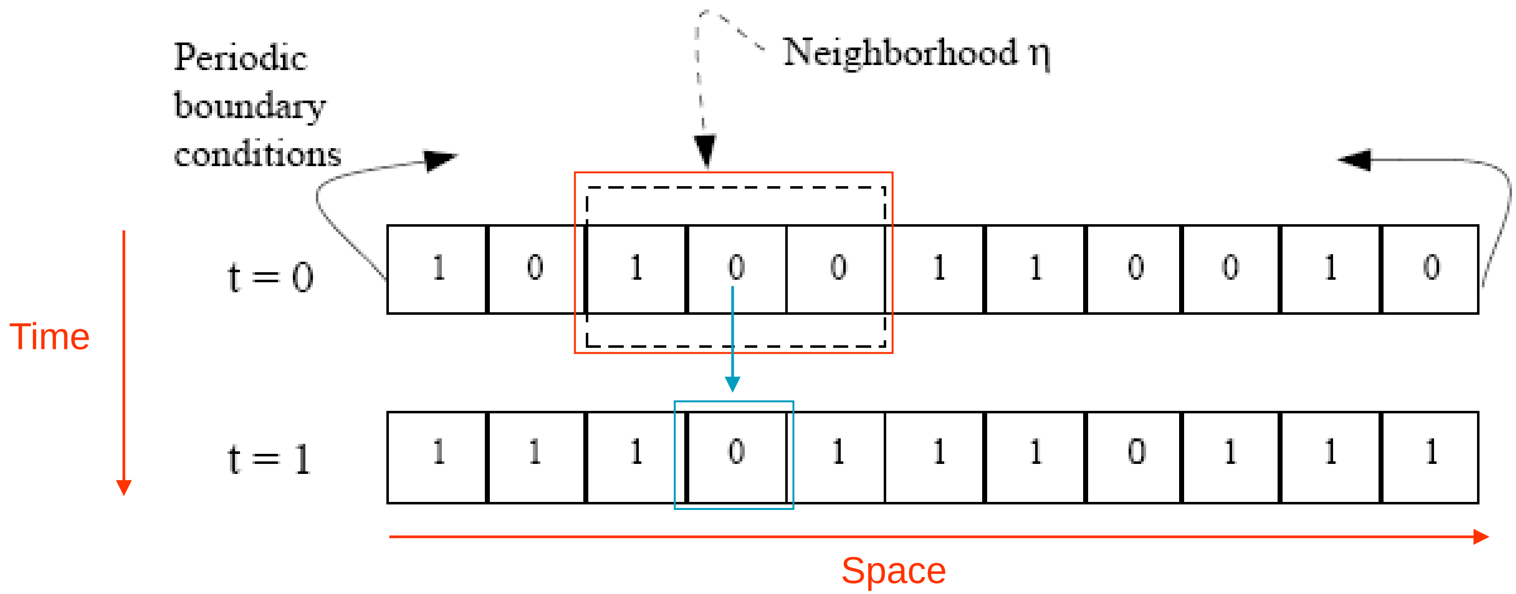


Diagram from: M. Mitchell, "Computation in Cellular Automata: A selected review", in Non-Standard Computation, T. Gramss, S. Bornholdt, M. Gross, M. Mitchell, and T. Pellizzari, Eds. Weinheim: VCH Verlagsgesellschaft, 1998, pp. 95–140.