Self-reference and Evolution of Evolvability

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Prof. Mikhail Prokopenko
Centre for Complex Systems
Faculty of Engineering

THE UNIVERSITY OF SYDNEY

Workshop “Evolution of Social Complexity”
Sydney, 13 February 2020

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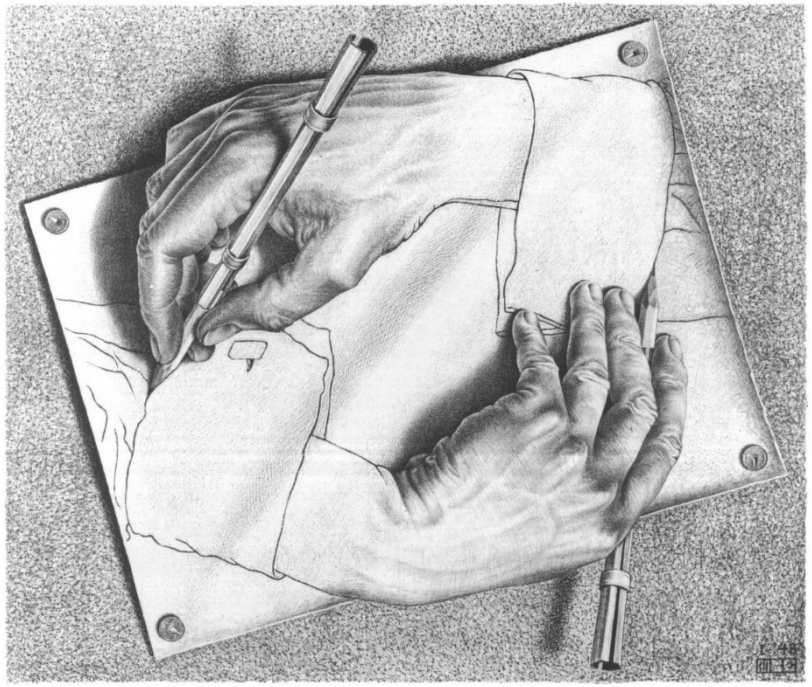
Outline

- Self-reference and “tangled hierarchies”
- The halting problem and The Liar paradox
- Edge of chaos, criticality and phase transitions
- Meta-simulation and novelty generation
- Emergence of functional self-descriptions

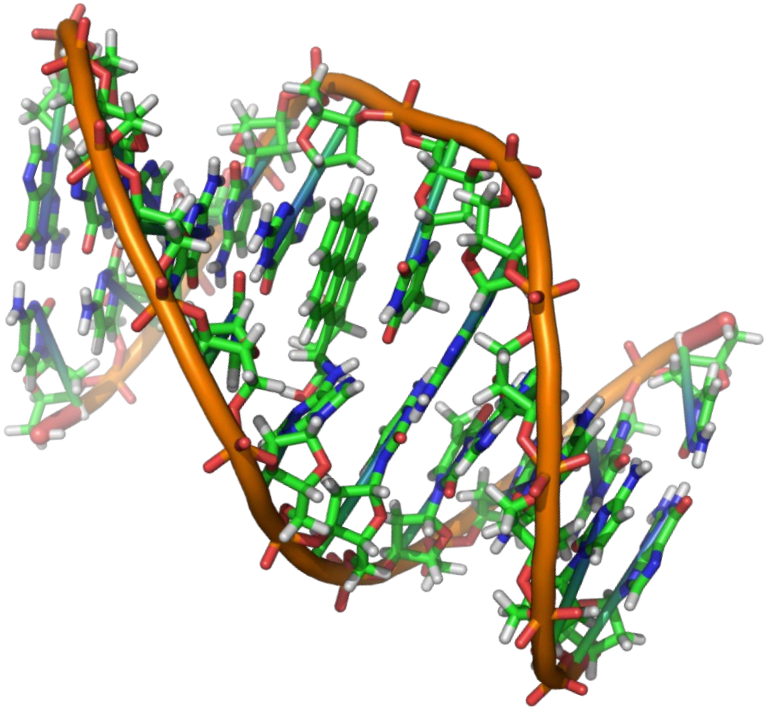
Self and a functional description of “self”



Drawing Hands:

the product, the hands, are undertaking the operation – the drawing of the hands

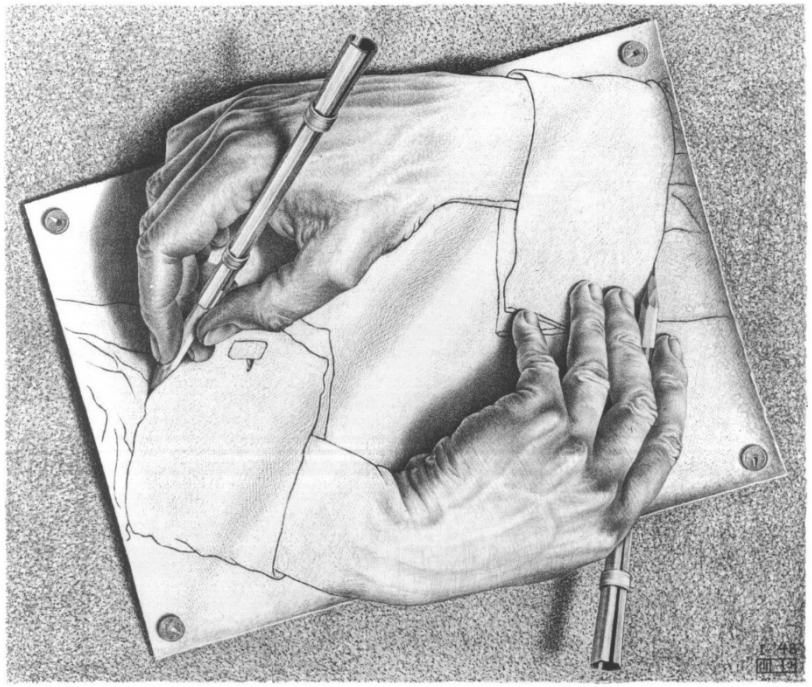
M. C. Escher, Drawing Hands, Wikipedia



DNA: genetic instructions (*sequence*) used in development and functioning of a living organism (*function and structure*) – a set of “blueprints” needed to construct other components of cells, and copy itself

Wikipedia

Self-reference



Drawing Hands:

the product, the hands, are undertaking the operation – the drawing of the hands

El Farol Bar Problem:

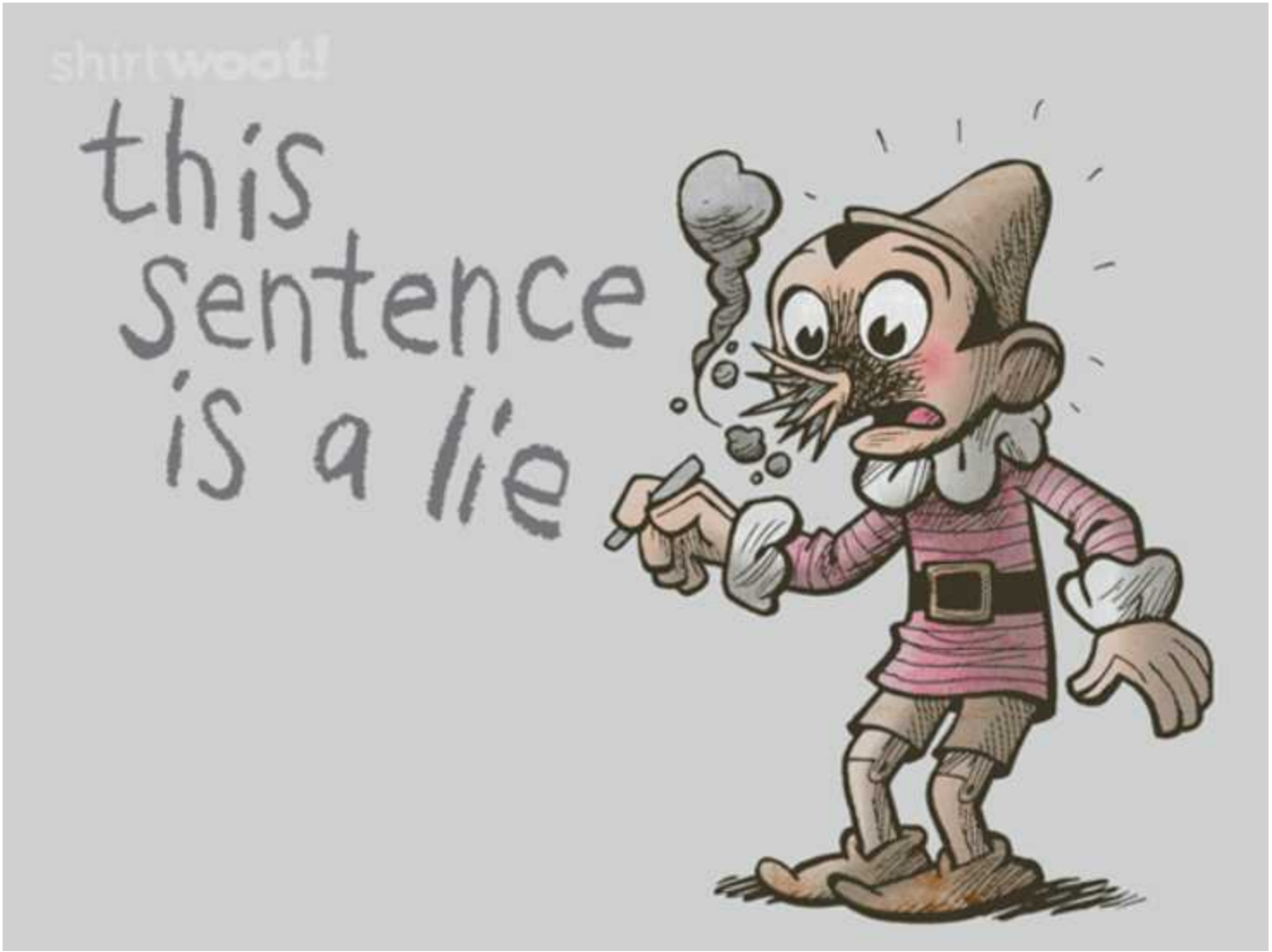
if less than 60% of the population go to the bar, then 🙂🙂🙂🙂

if more than 60% of the population go to the bar, then 😕😕😕😕😕😕😕😕

M. C. Escher, Drawing Hands, Wikipedia

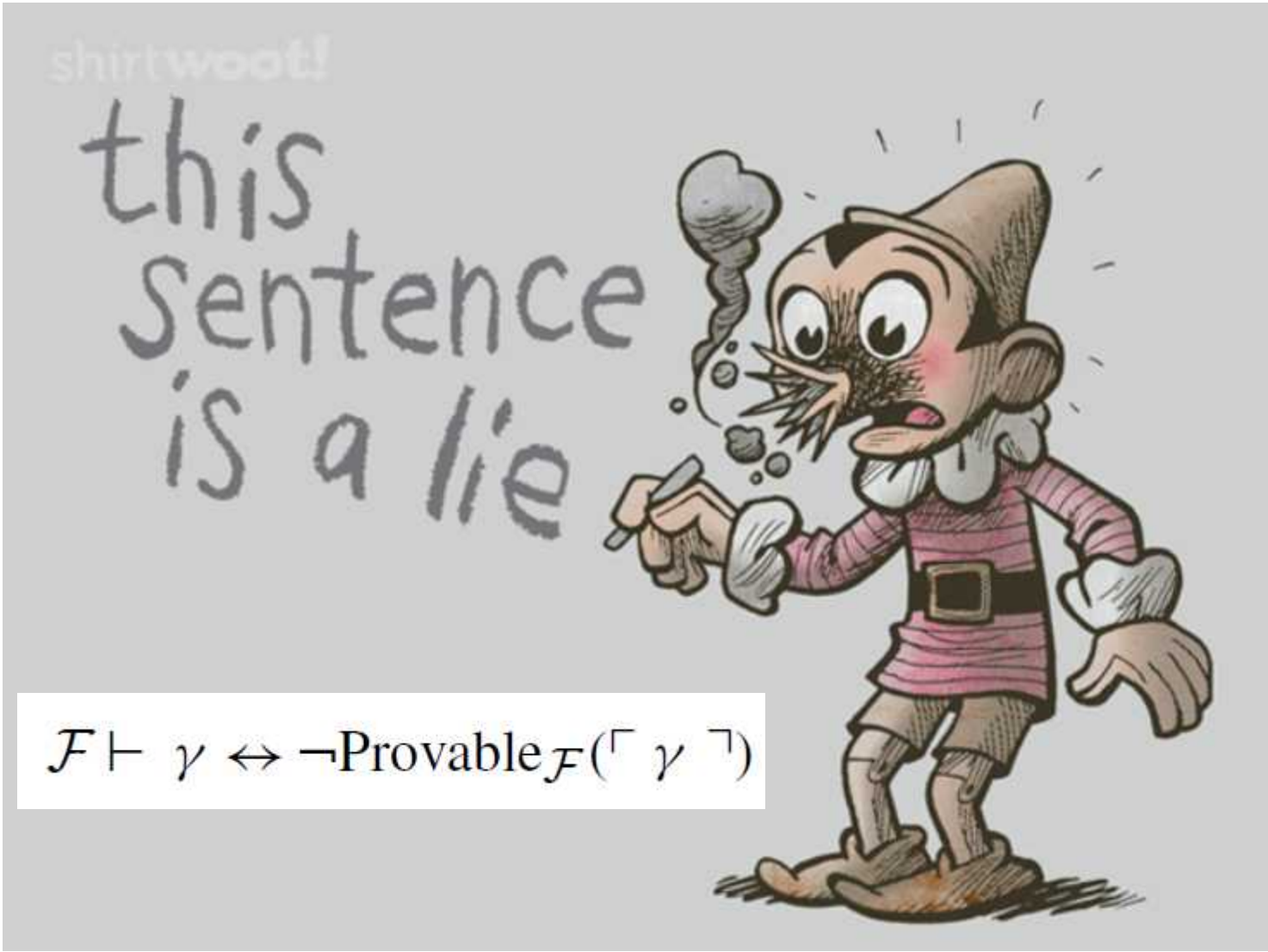
Kateryna Direnko: stylized human silhouettes

The Liar paradox



https://shirt.woot.com/offers/liars-paradox

The Liar paradox



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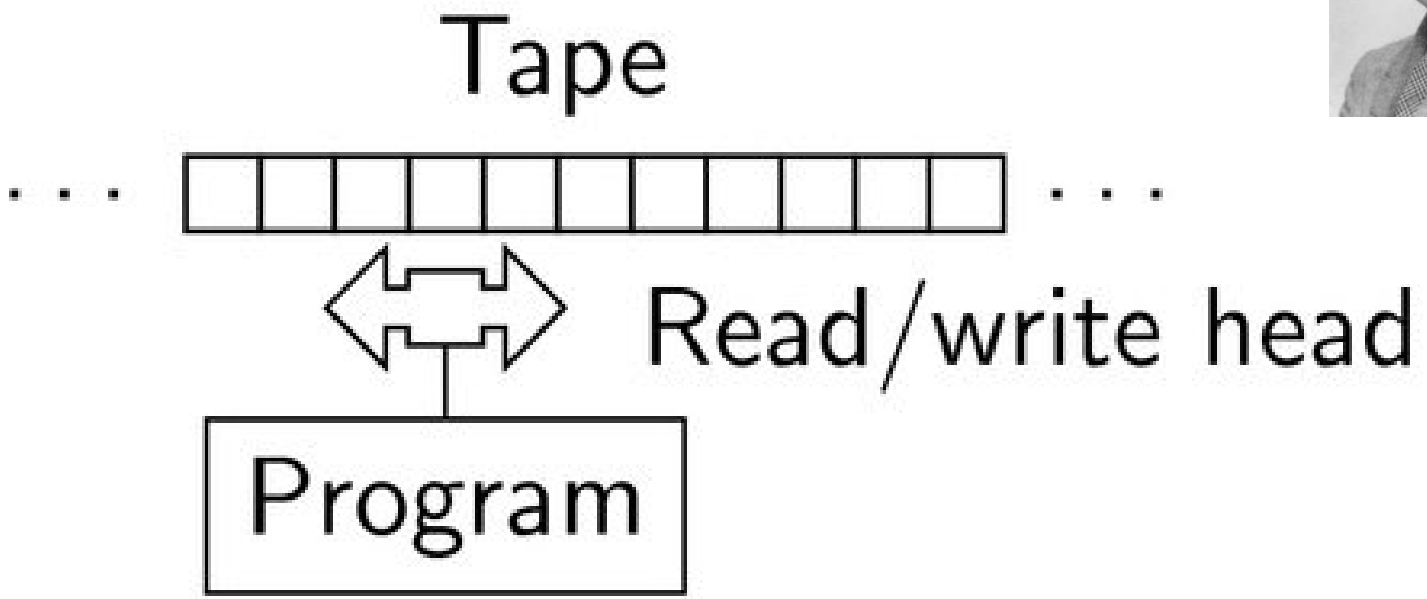
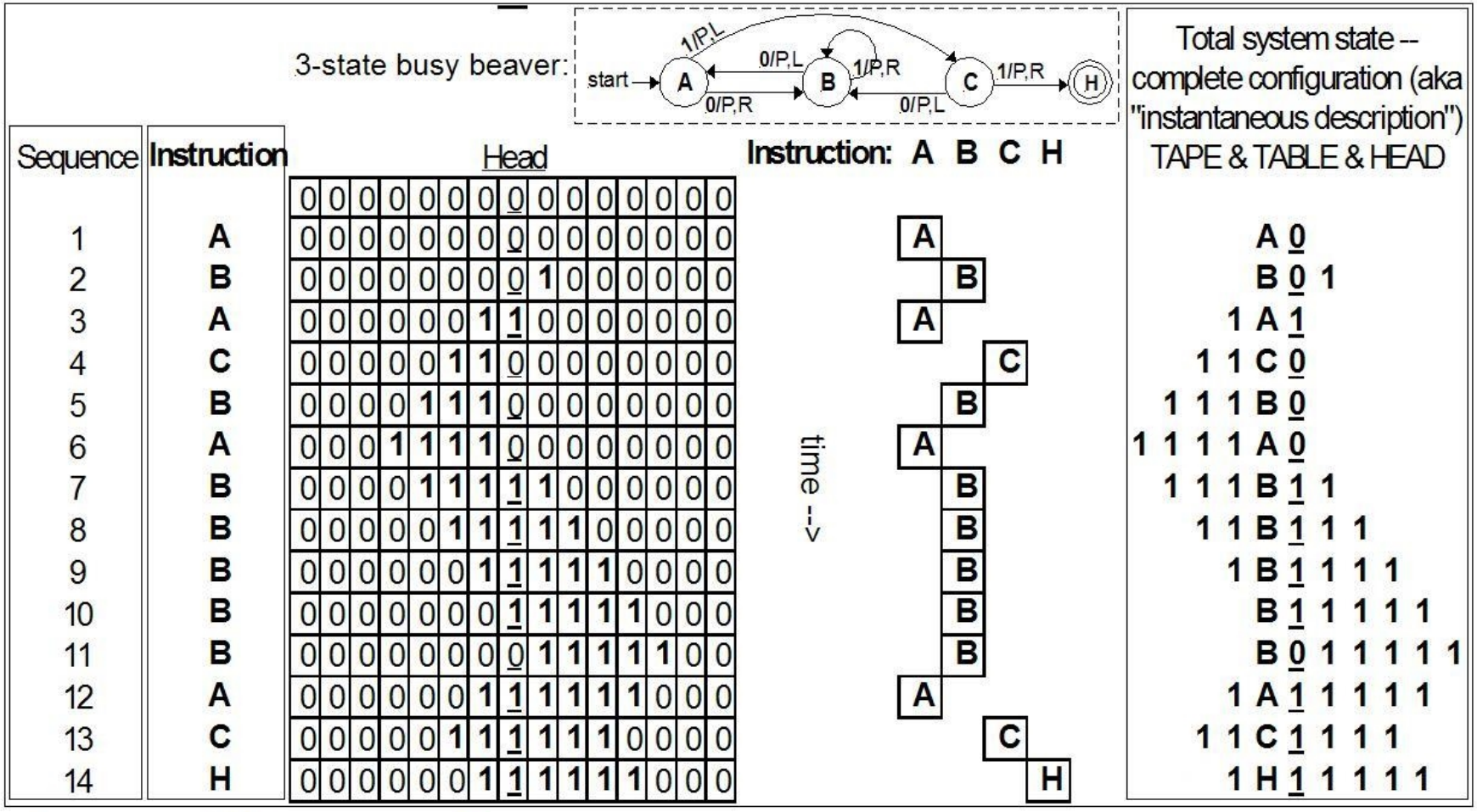
Turing Machine (…not that one)

The Imitation Game, 2014

Turing Machine



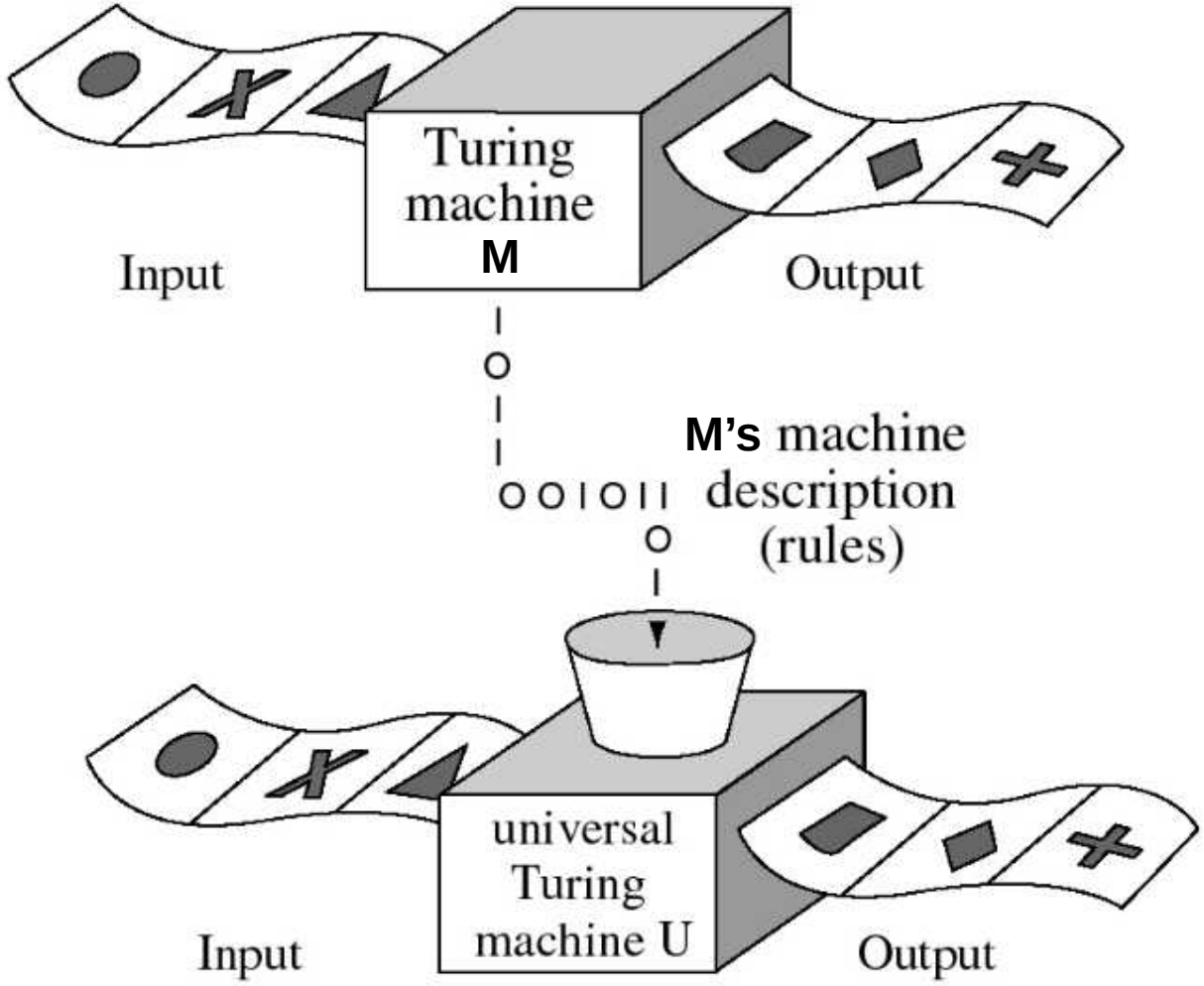
Turing Machine



Progress of the computation (state-trajectory) of a 3-state busy beaver

Wikipedia

Universal Turing Machine: can simulate any other machine



Glenn D. Blank et al., 2003

http://www.cse.lehigh.edu/~glennb/um/1intro.pdf

Universal Decider Turing Machine: does it exist?

$$P([M, w]) = \begin{cases} accept & \text{if } M \text{ accepts } w \\ reject & \text{if } M \text{ does not accept } w \end{cases}$$

M. Prokopenko, M. Harré, J. Lizier, F. Boschetti, P. Peppas, S. Kauffman, Self-referential basis of undecidable dynamics: from The Liar Paradox and the halting Problem to the edge of chaos, *Physics of Life Reviews*, 31: 134-156, 2019.

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Universal Decider Turing Machine: does it exist?

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$$V([M]) = \begin{cases} reject & \text{if } M \text{ accepts } [M] \\ accept & \text{if } M \text{ does not accept } [M] \end{cases}$$

Universal Decider Turing Machine: does not exist!

$$P([M, w]) = \begin{cases} accept & \text{if } M \text{ accepts } w \\ reject & \text{if } M \text{ does not accept } w \end{cases}$$

$$V([M]) = \begin{cases} reject & \text{if } M \text{ accepts } [M] \\ accept & \text{if } M \text{ does not accept } [M] \end{cases}$$

$$V([V]) = \begin{cases} reject & \text{if } V \text{ accepts } [V] \\ accept & \text{if } V \text{ does not accept } [V] \end{cases}$$

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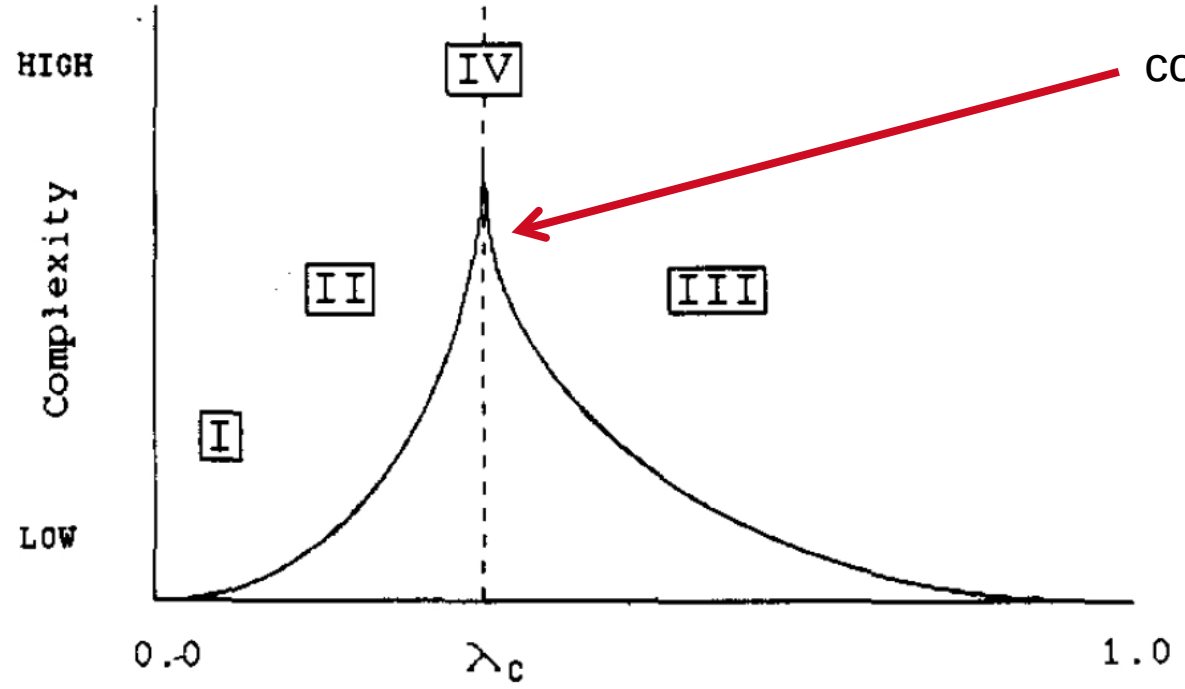
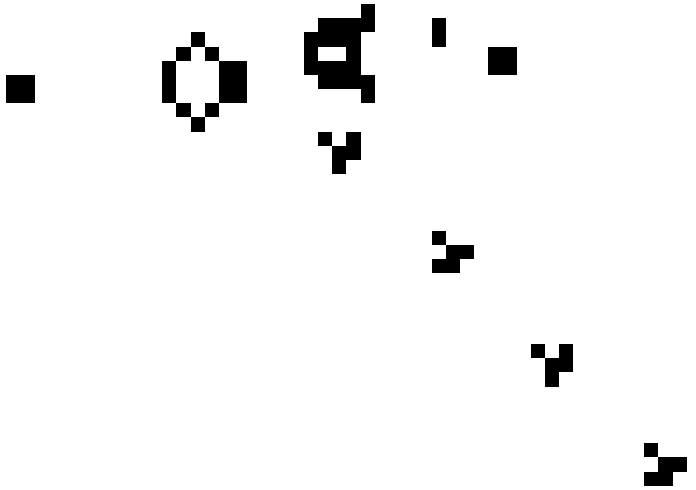
Motivation: dynamics of computation

Chris Langton, "Computation at the edge of chaos: Phase transitions and emergent computation" (1991):

- how can emergence of computation be explained in a *dynamic* setting?
- how is it related to *complexity* of the system in point?

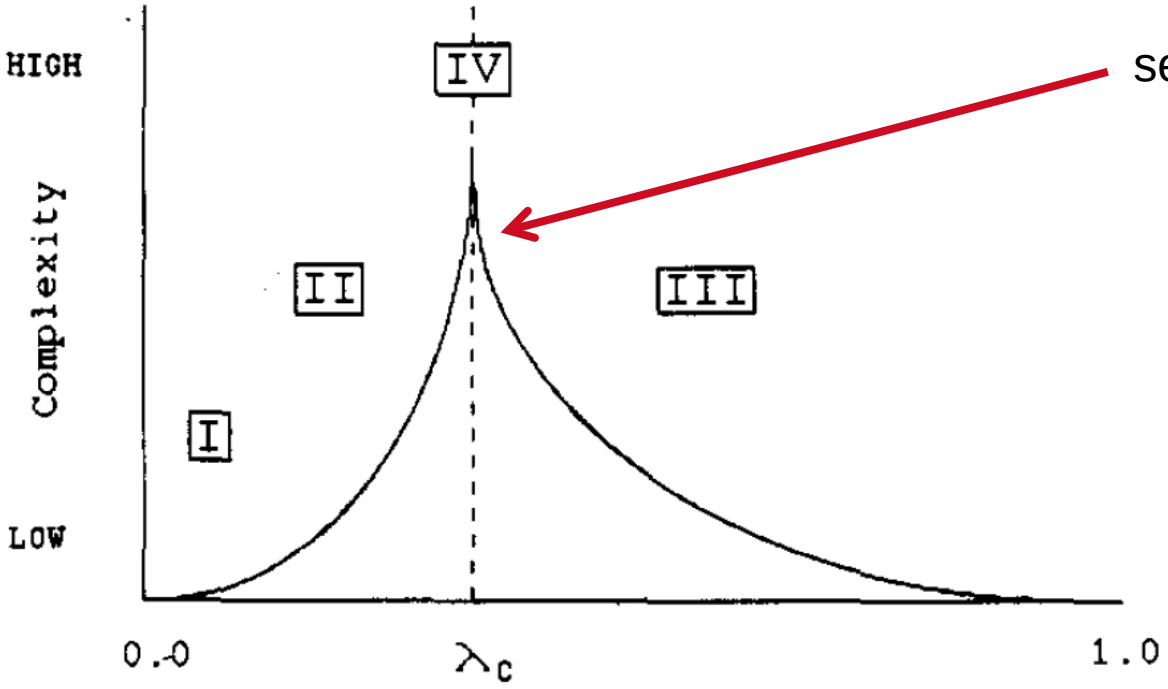


complex high-level structures

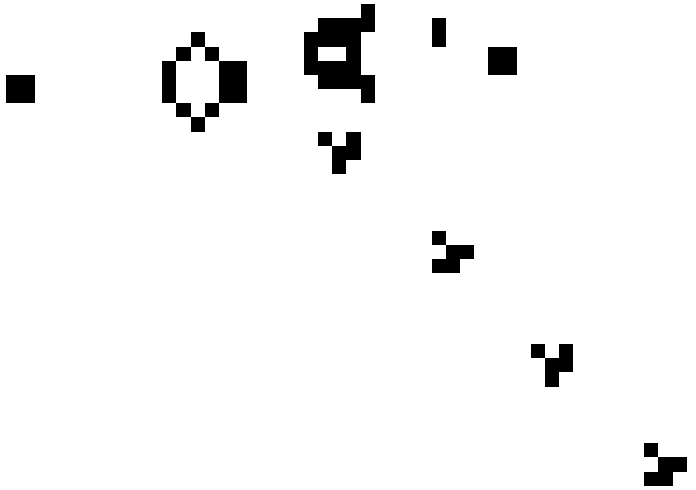


Game of Life

1. Deaths. Any live cell with fewer than two or more than three live neighbours dies.
2. Survivals. Any live cell with two or three live neighbours lives on to the next generation.
3. Births. Any dead cell with exactly three live neighbours becomes a live cell.

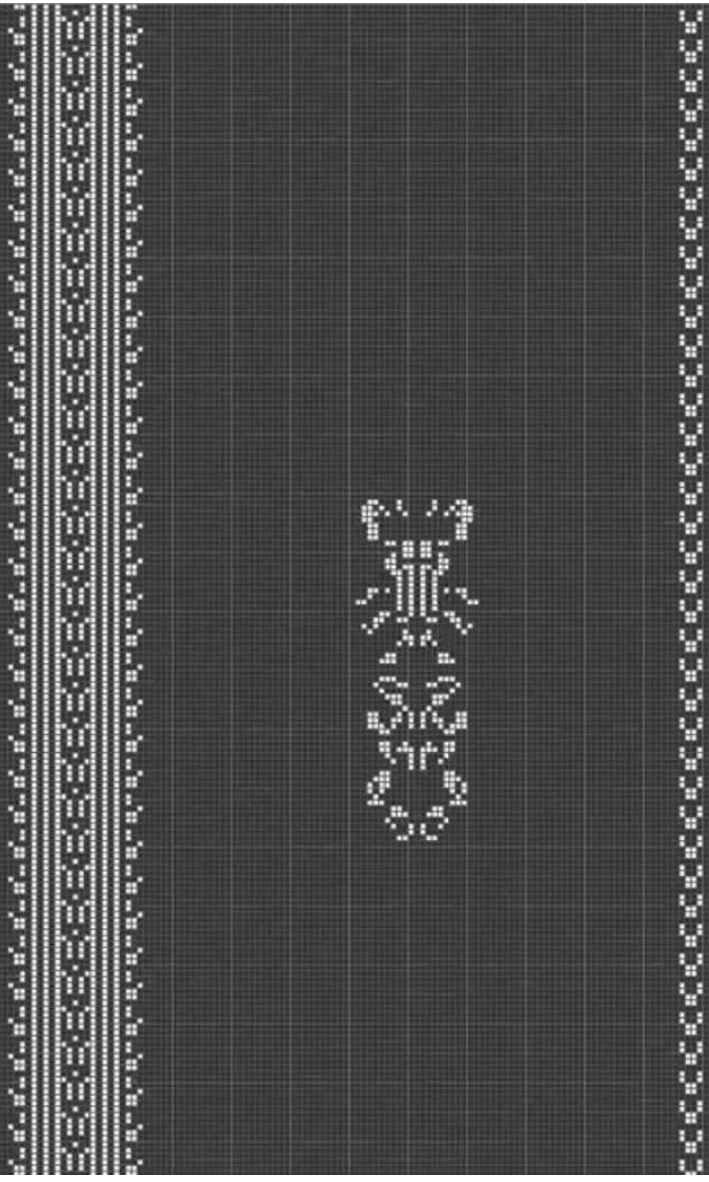


self-organising structures



Game of Life: convergence?

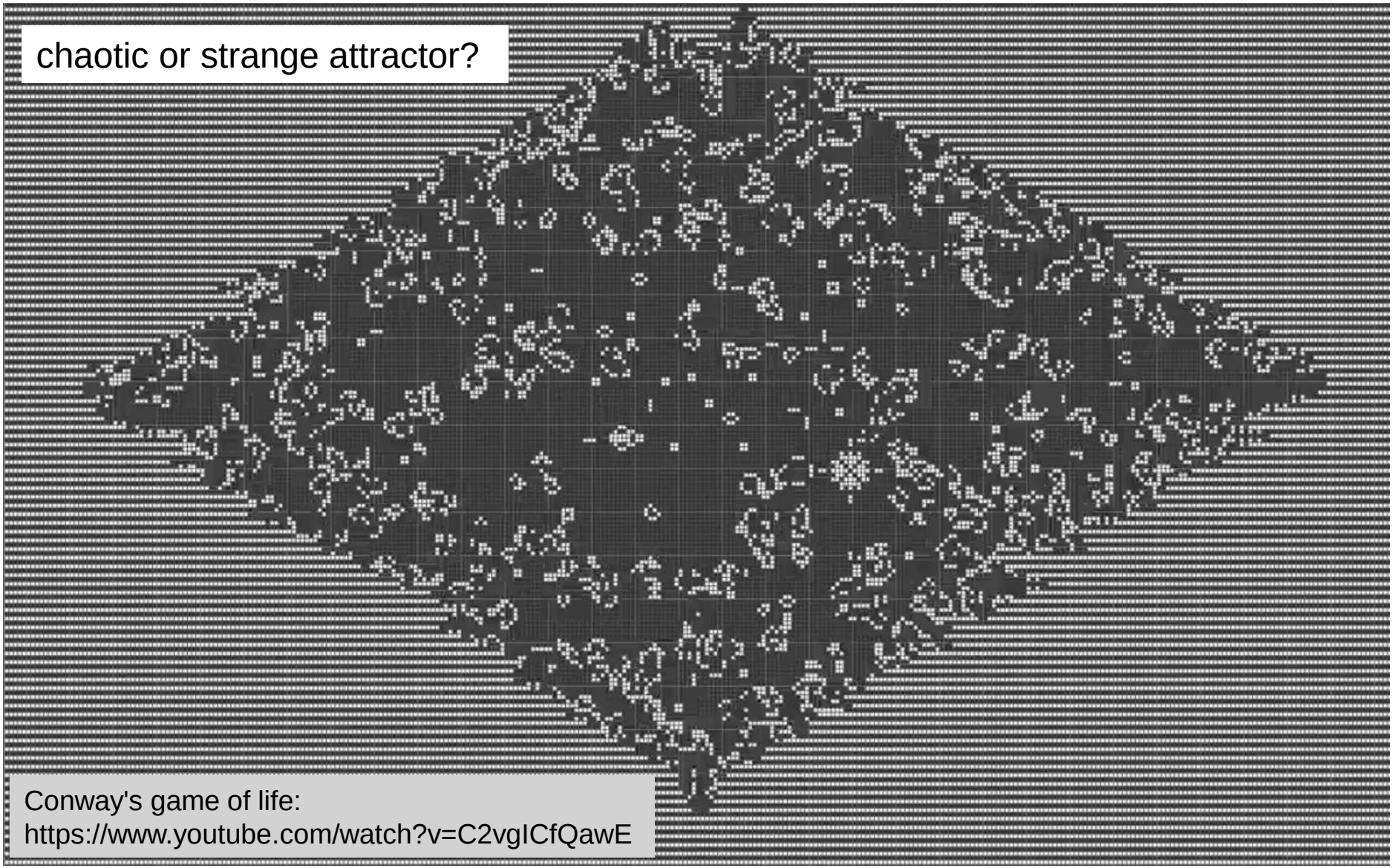
fixed point or limit cycle ?



Conway's game of life:
https://www.youtube.com/watch?v=C2vgICfQawE

Game of Life: convergence?

chaotic or strange attractor?



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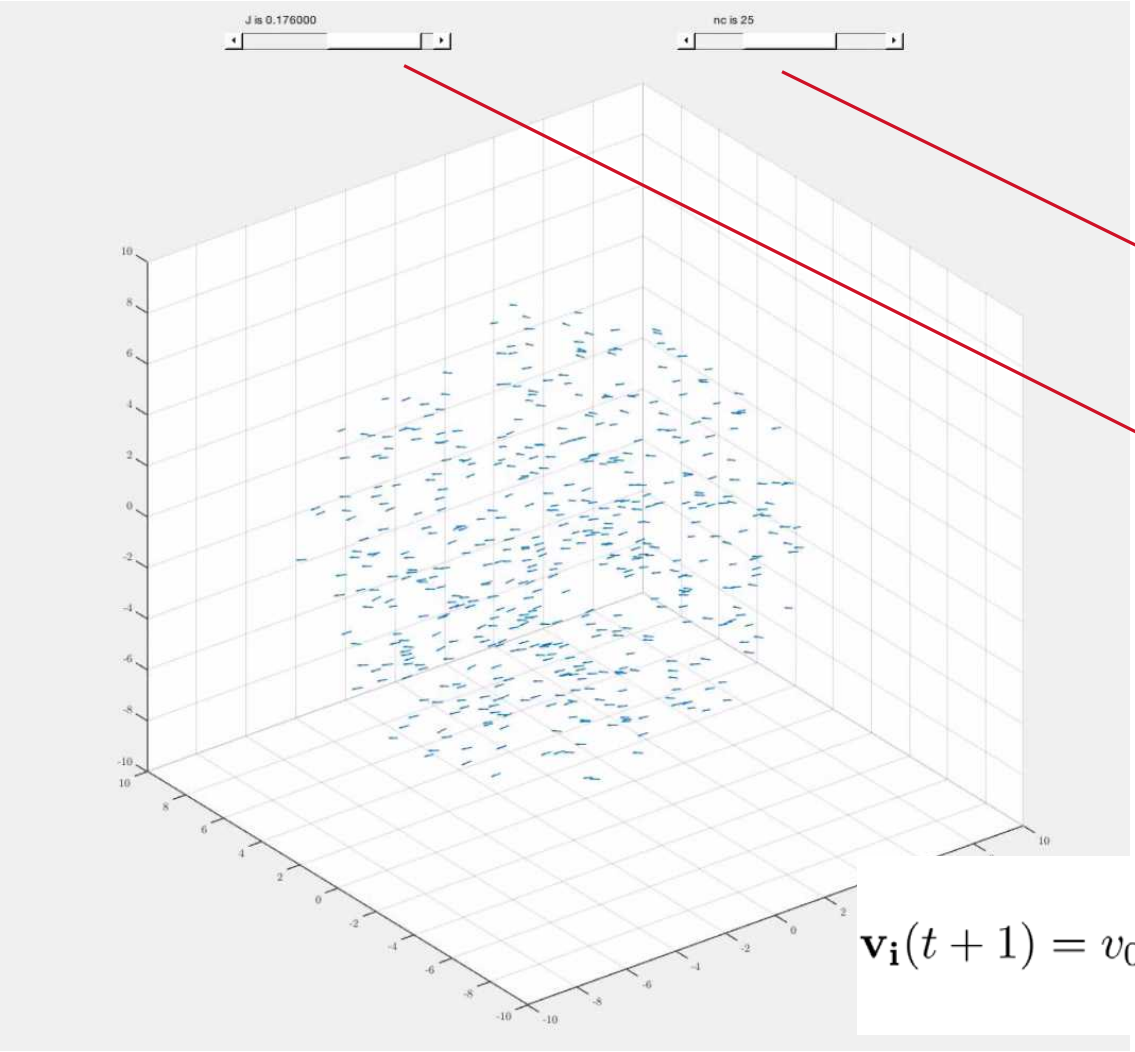
Swarming (collective) motion



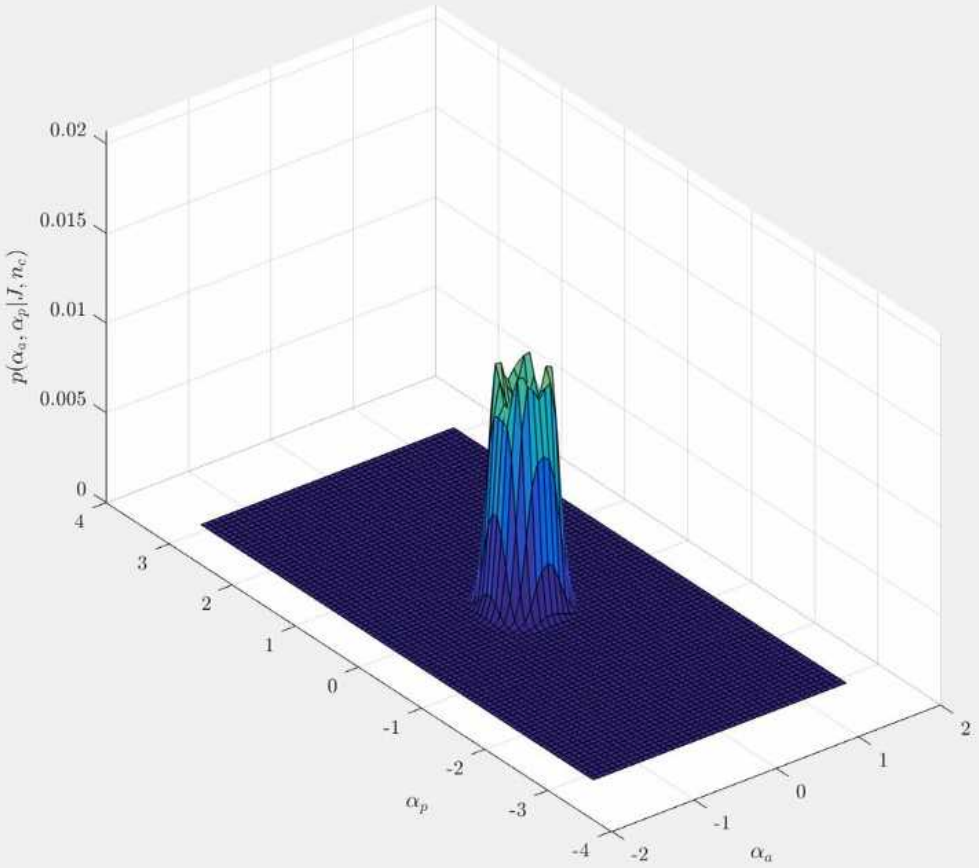
a kinetic phase transition driven by

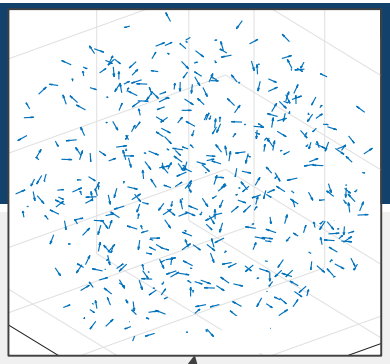
- nearest neighbours N_c
- alignment strength $J = v_0 a$

$$\mathbf{v_i}(t+1) = v_0 \Theta \left[a \sum_{j \in n_c^i} \mathbf{v_j}(t) + b \sum_{j \in n_c^i} f_{ij} + n_c \boldsymbol{\eta_i} \right]$$

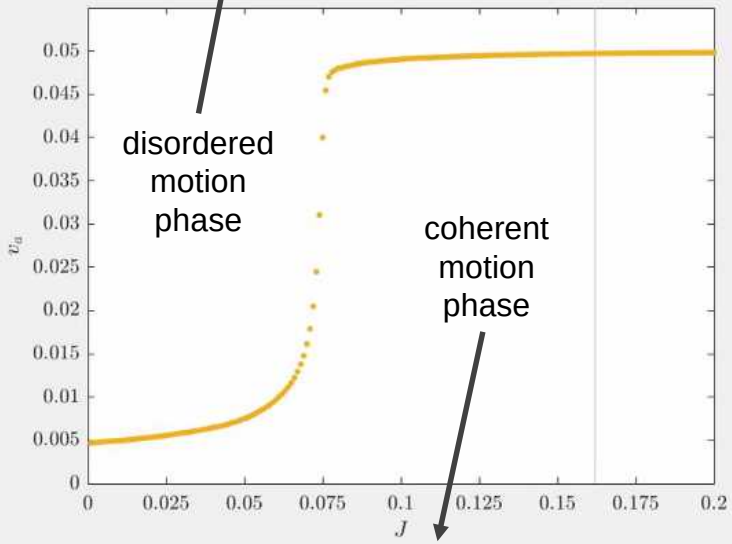
E. Crosato, R. Spinney, R. Nigmatullin, J. T. Lizier, M. Prokopenko, Thermodynamics of collective motion near criticality, *Physical Review E,* 97, 012120, 2018.

The two kinetic phases

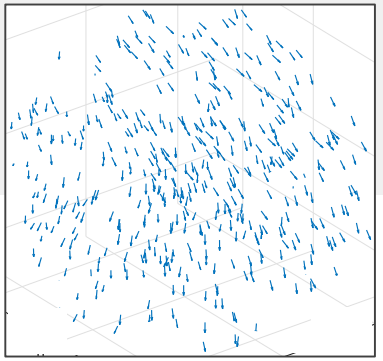




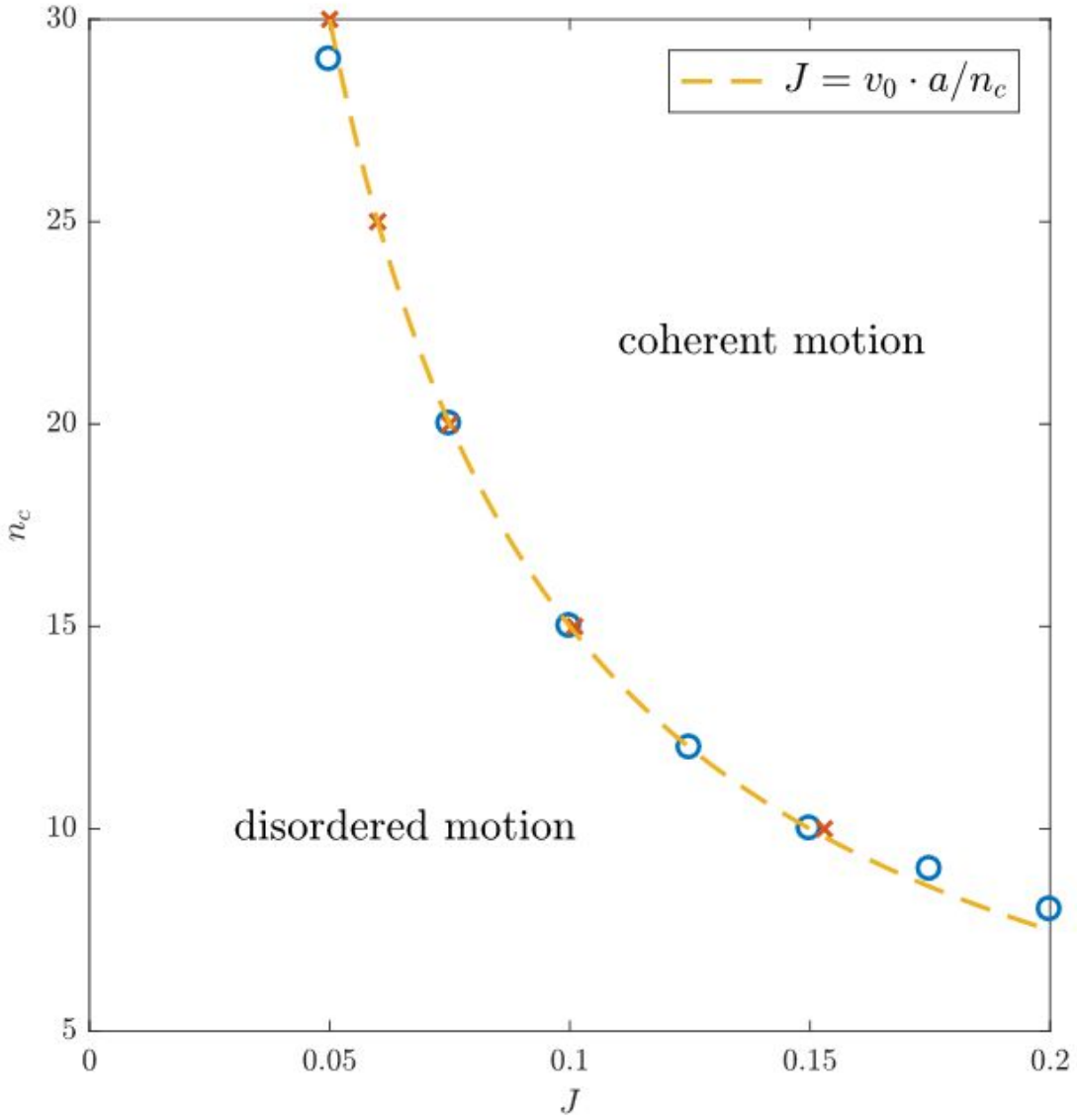
disordered motion phase



coherent motion phase



Edge of chaos in collective motion



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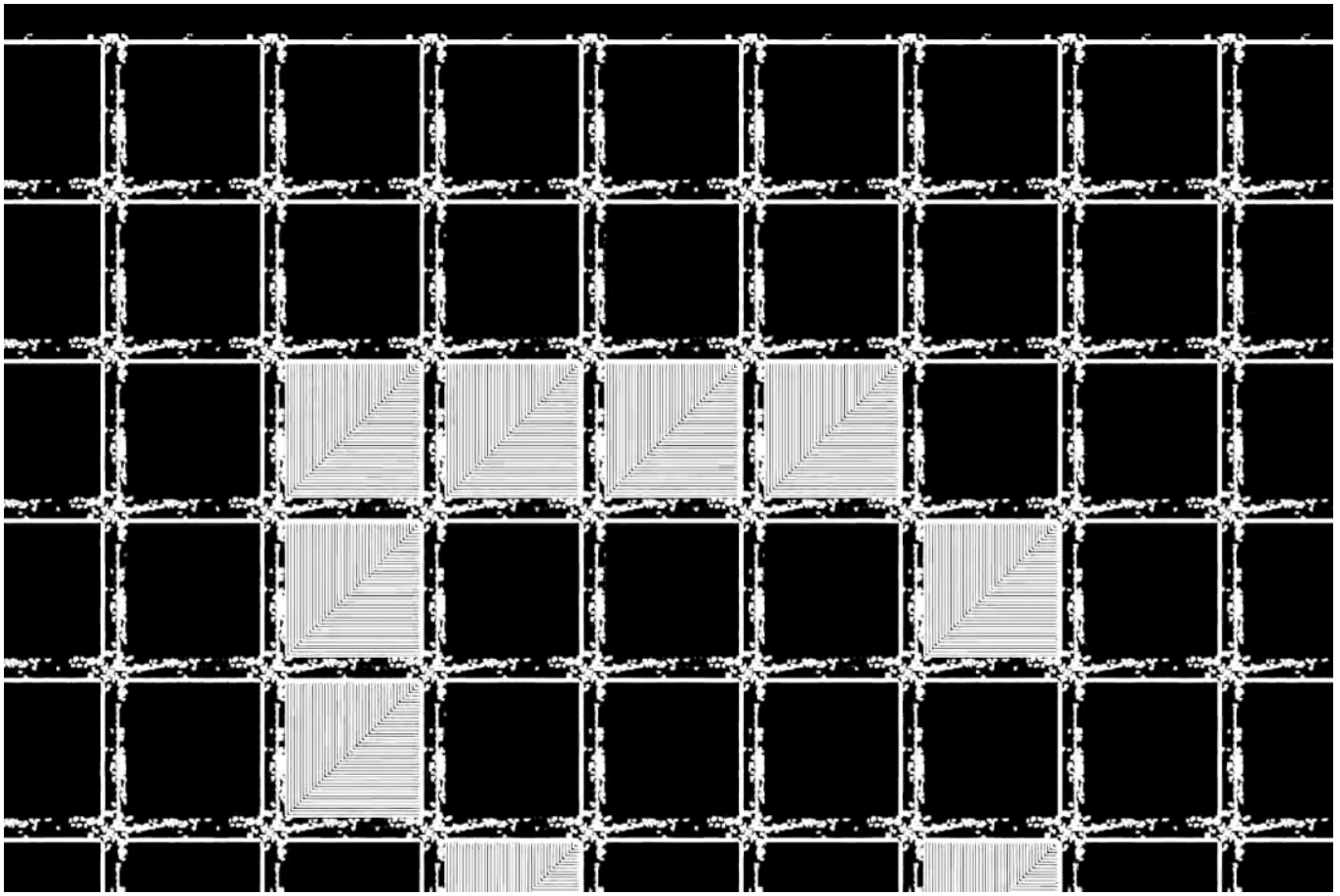
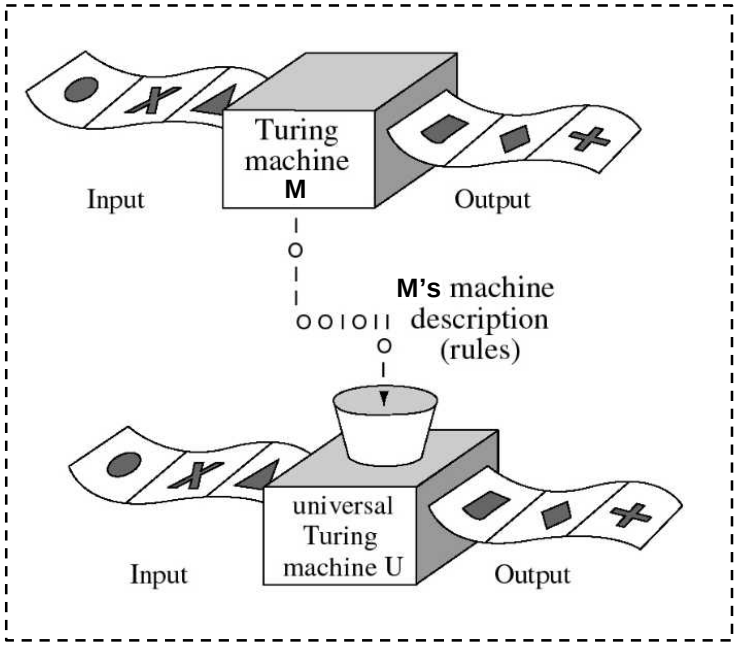
Universal Cellular Automata: a Metapixel



“Life in Life” by Phillip Bradbury: https://www.youtube .com /watch ?time _continue =4 &v =xP5 -iIeKXE8

Three-way equivalence

$$\mathcal{F} \vdash \gamma \leftrightarrow \neg \text{Provable}_{\mathcal{F}}(\ulcorner \gamma \urcorner)$$



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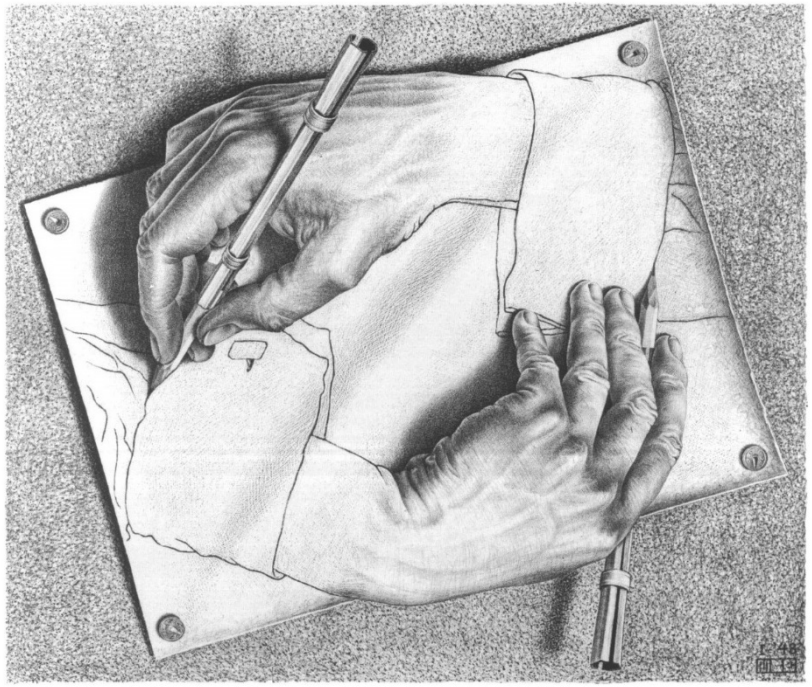

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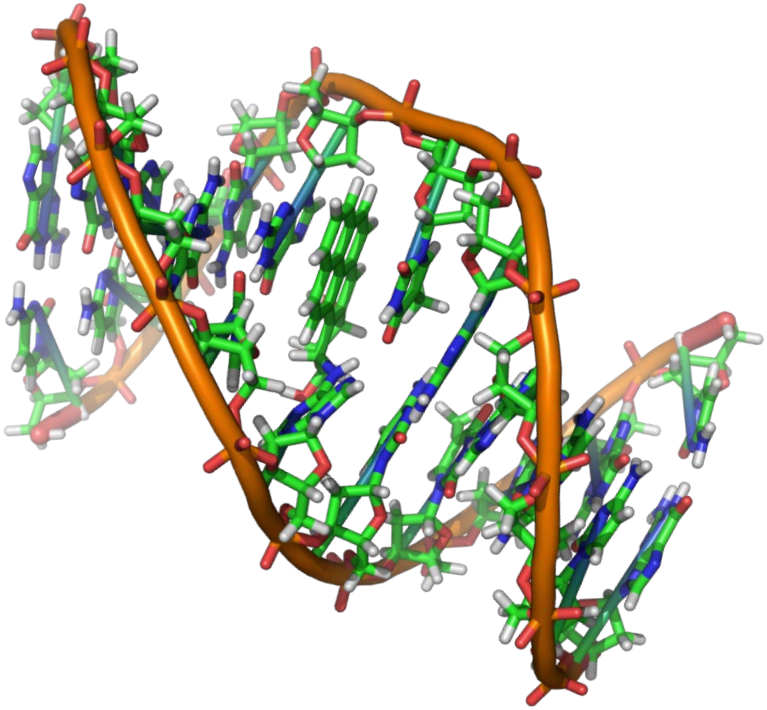

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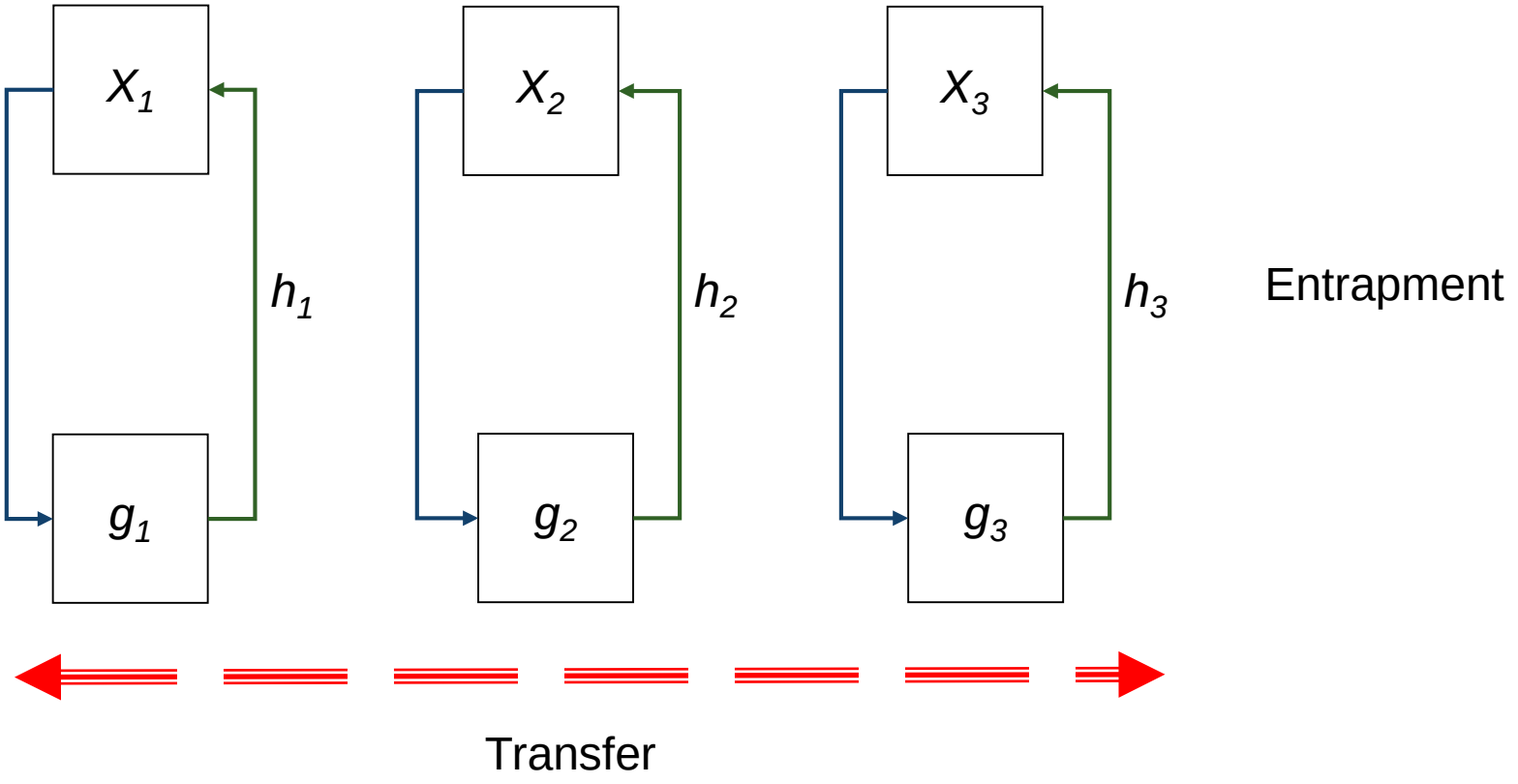
Wikipedia

Coding threshold

- genotype-phenotype mapping: a self-referential relationship between an encoded description of a living organism (data) and the organism itself (program)
- “how the genotype-phenotype relationship had come to be?”
- how a functional self-description (“encoding”) could evolve?
- “Coding threshold” separates an earlier evolutionary stage and the RNA world with the capacity to represent nucleic acid life symbolically, in terms of amino acid sequences

Woese, C.R., A new biology for a new century, *Microbiology and Molecular Biology Reviews*, 68(2):173–186, 2004

Entrapment and Horizontal Gene Transfer



M. Prokopenko, D. Polani, M. Chadwick. Stigmergic gene transfer and emergence of universal coding, *HFSP Journal*, 3(5): 317-327, 2009.

Selection pressure: information preservation

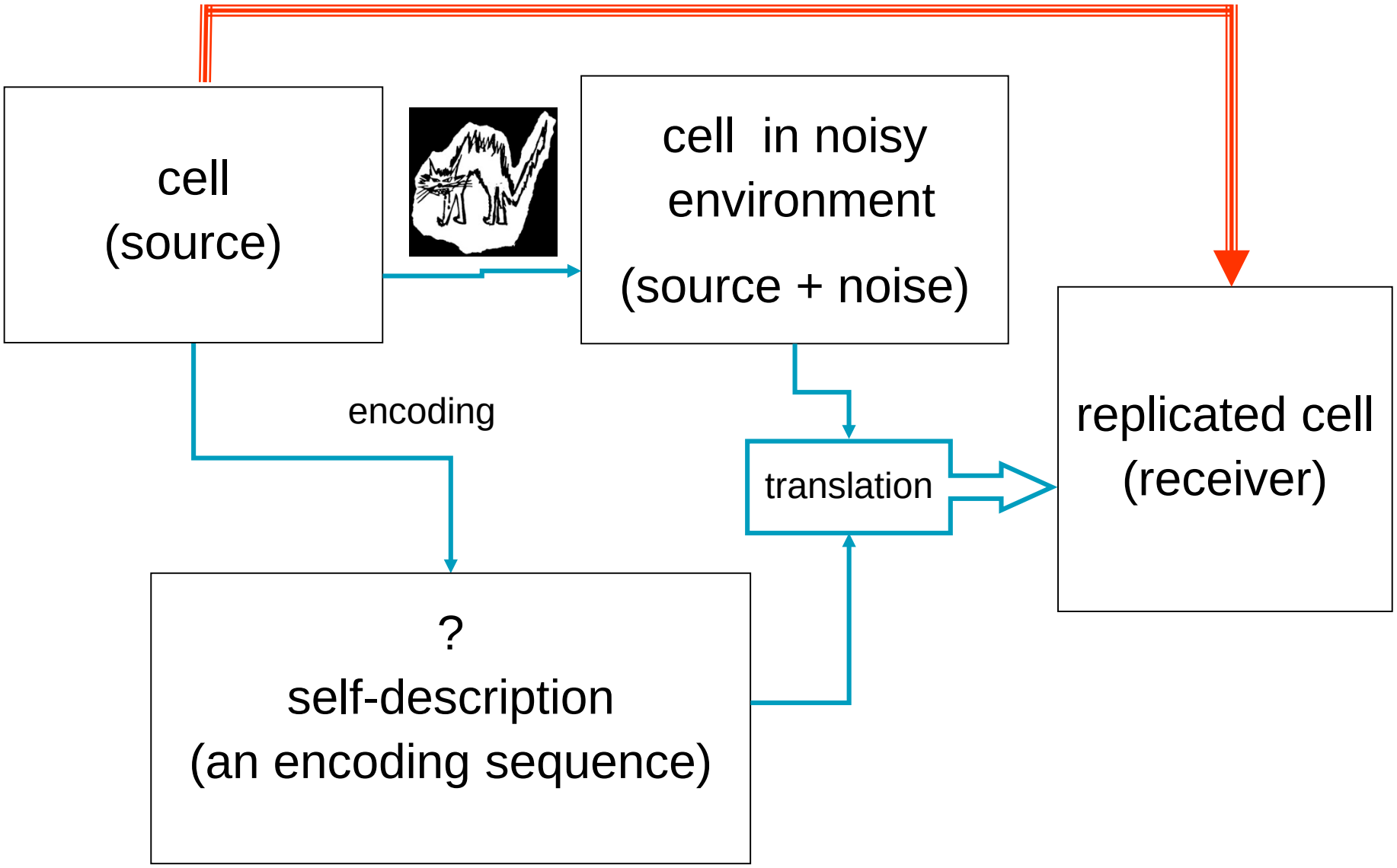
- how a functional self-description ("encoding") could evolve?

- hypothesis: maximisation of information preservation through selected channels is one of the main evolutionary pressures

- information preservation is a consistent motif in biology:
  - evolution extracts valuable information and stores it in the genes
  - this process is relatively slow and noisy

  $\longrightarrow$ a selective advantage: to preserve this information, once captured

Modelling evolutionary dynamics



Objective (fitness) function

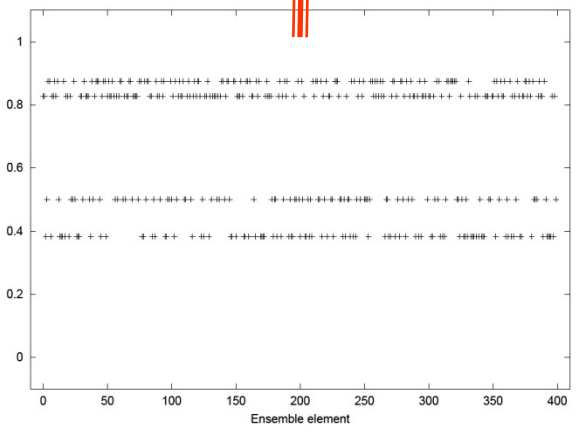
$$\max_{g} \; I_g(X_{t_0}; X_{t^*})$$

$$\min_{g} \; d_g(X_{t_0}, X_{t^*}) = H(X_{t_0}|X_{t^*}) + H(X_{t^*}|X_{t_0})$$

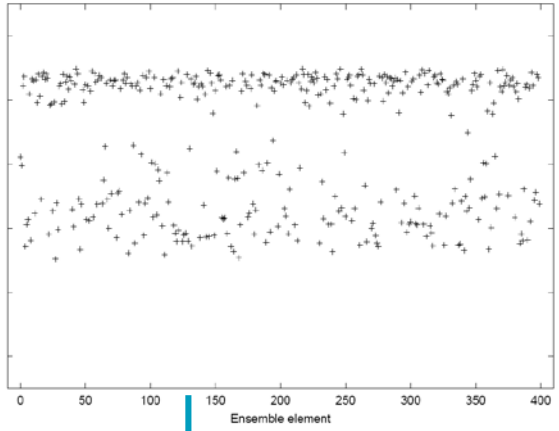
subject to

$$\varphi$$

Recovery of structure



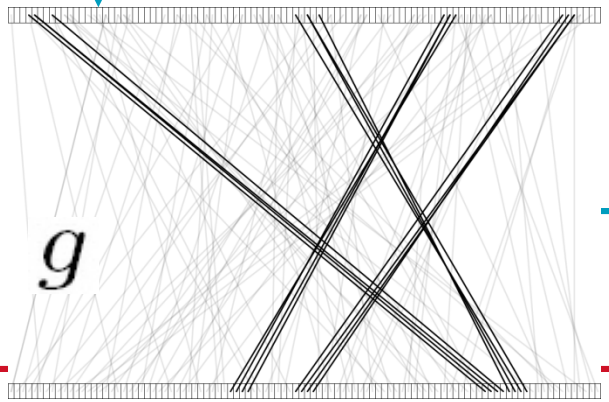
φ

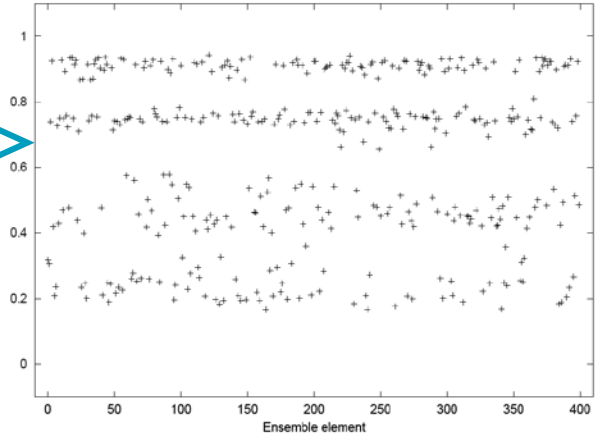


$d_g(X_{t_0}; X_{t^*})$

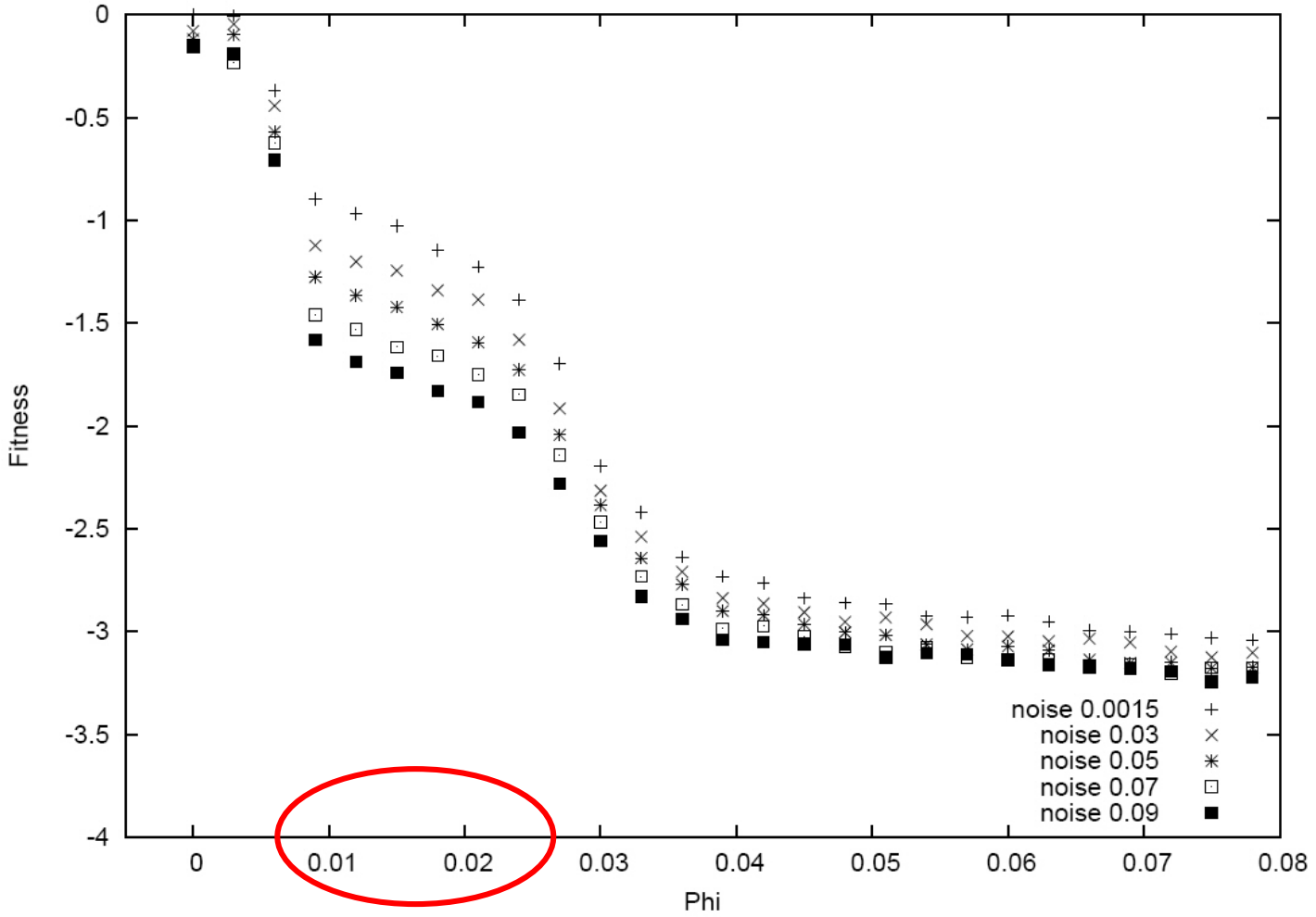
encoding

translation
h





“Error interval”



Fitness *d* over external noise

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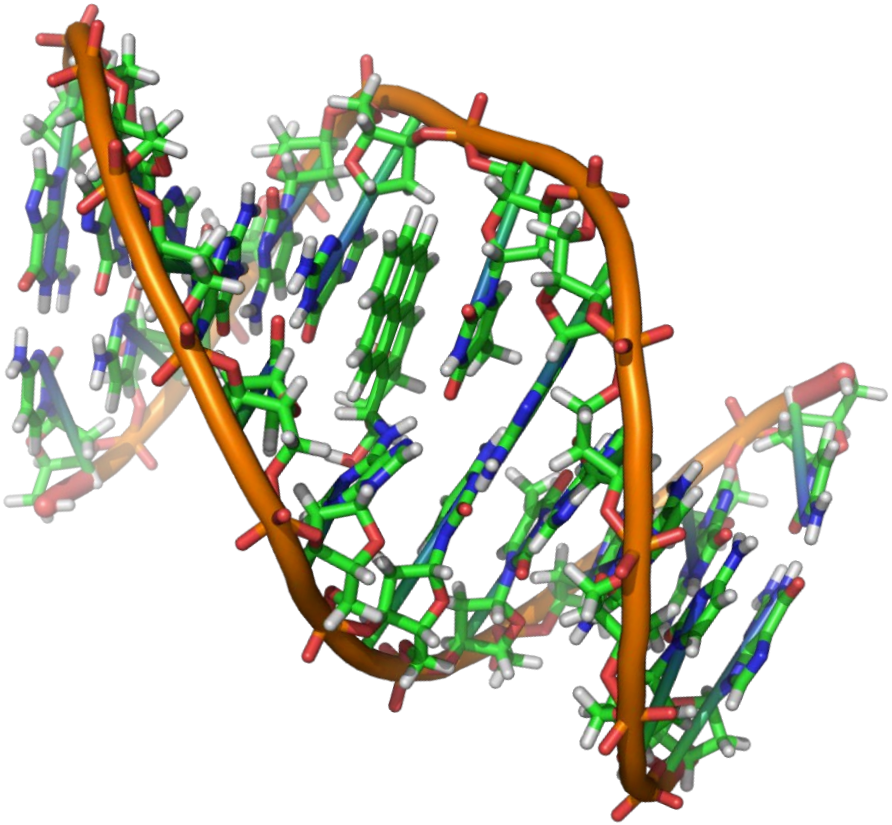
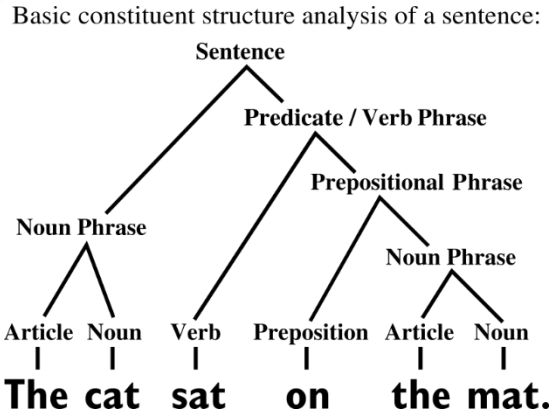
Genetic code: a functional self-description



DNA: genetic instructions (*sequence*) used in development and functioning of a living organism (*function and structure*) – a set of “blueprints” needed to construct other components of cells, and copy itself

Wikipedia

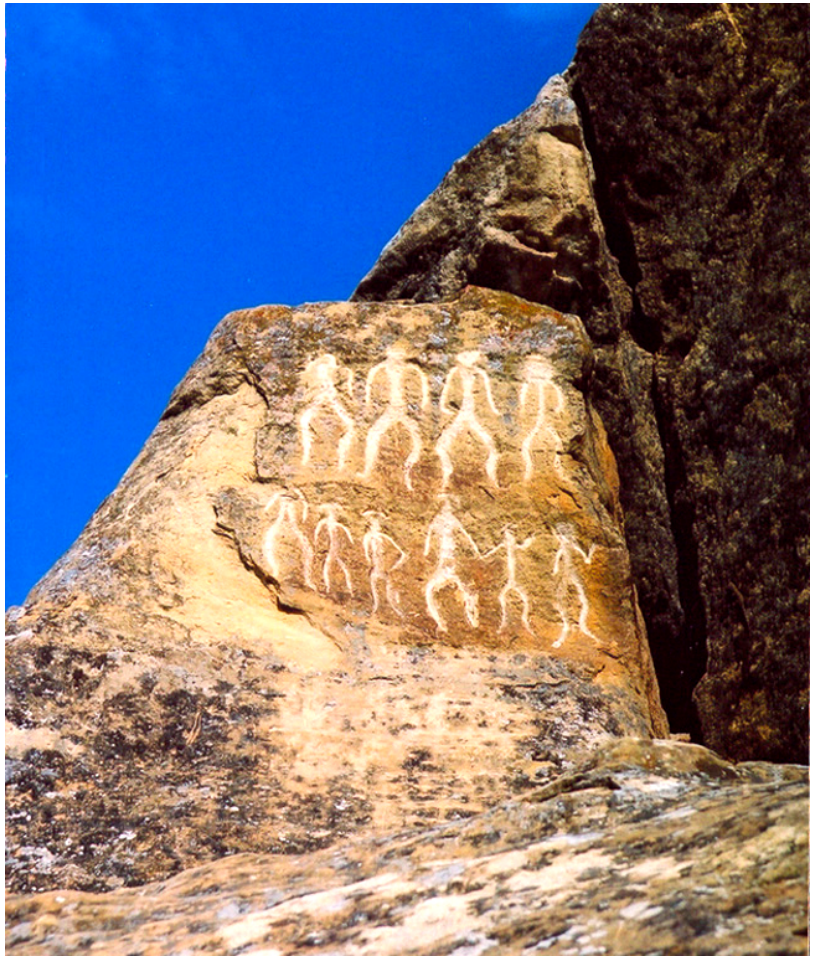
Language: a functional self-description



Speech, language, grammar: A mural in Teotihuacan, Mexico (c. 2nd century) depicting a person emitting a speech scroll from his mouth, symbolizing speech

Wikipedia

Culture: a functional self-description



Culture: Petroglyphs in modern-day Gobustan, Azerbaijan, dating back to 10,000 BCE

The Tower of Babel
by Pieter Bruegel the Elder,1563.

Wikipedia

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Conclusions

- universal computation and undecidable dynamics
- undecidability is generated by self-reference, infinite computation and negation
- computational novelty can be created by agents with universal computation and functional self-description
- information preservation via functional self-description drives novelty generation across major transitions (genetic, linguistic, cultural)
- complex systems are dynamical systems with undecidable dynamics

Acknowledgements

HFSP Journal

ARTICLE

Stigmergic gene transfer and emergence of universal coding

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(Submit 10 April 2009; accepted 21 June 2009; published online 6 August 2009)

Acknowledgements

PHYSICAL REVIEW E **97**, 012120 (2018)

Thermodynamics and computation during collective motion near criticality

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(Received 15 August 2017; published 16 January 2018)

Acknowledgements

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Physics of Life Reviews 31 (2019) 134–156

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Review

Self-referential basis of undecidable dynamics: From the Liar paradox and the halting problem to the edge of chaos

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[c] *Center for AI, School of Software, FEIT, University of Technology Sydney, NSW 2007, Australia*
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[e] *University of Pennsylvania, Philadelphia, PA 19104, USA*

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