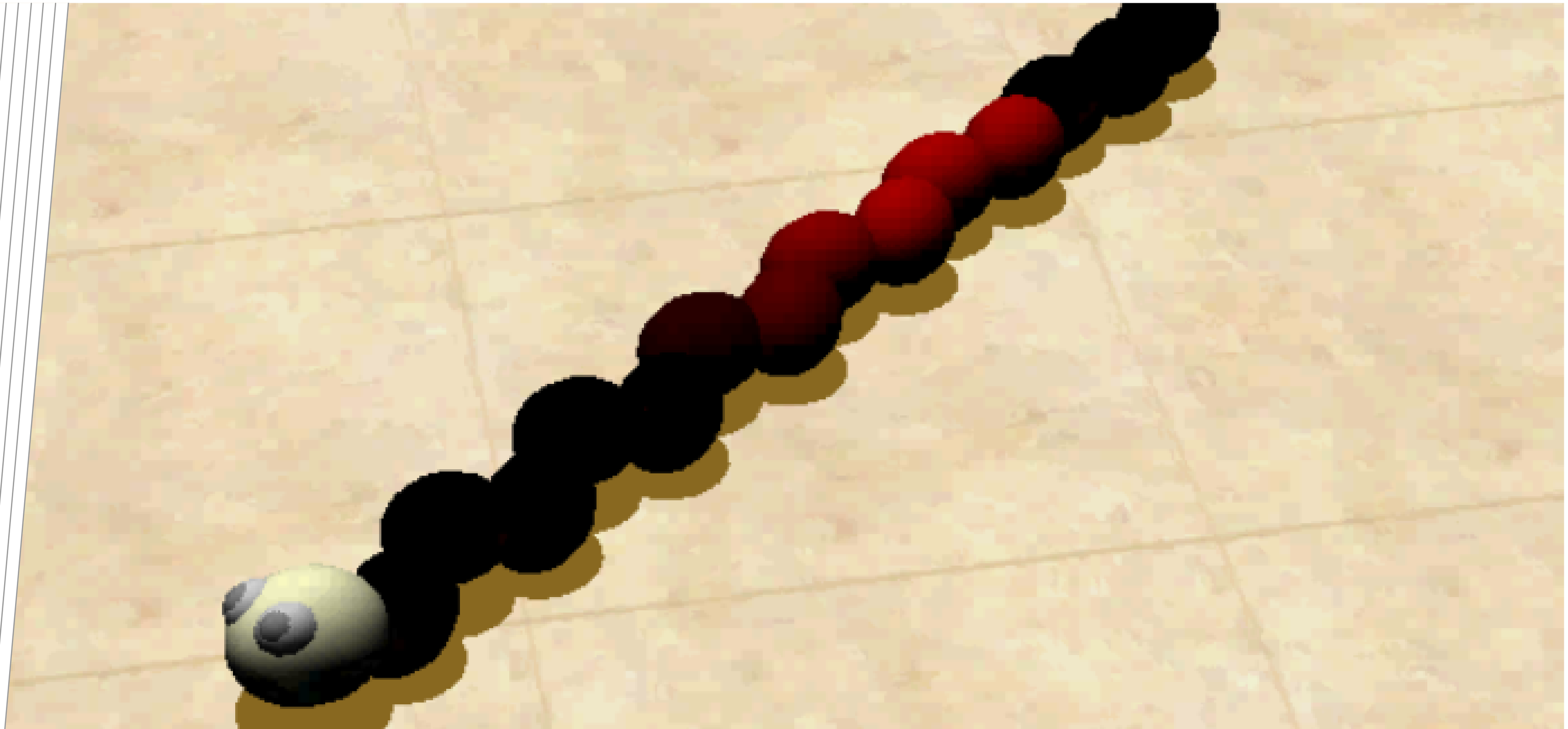

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Emergence of Glider-like Structures in a Modular Robotic System

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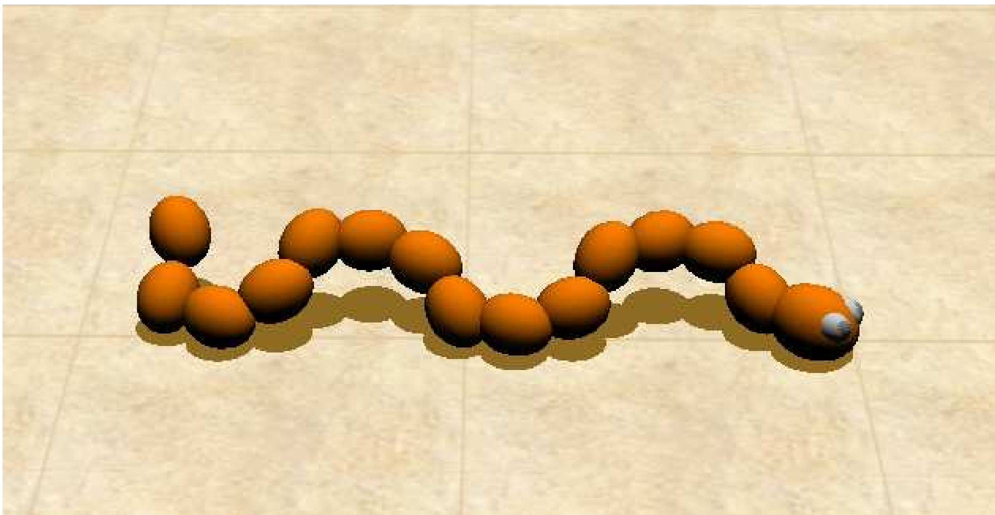
Emergence of Glider-like structures

- Aim: To test information transfer as a generic fitness function for information-driven self-organisation.
  - Use transfer entropy to drive evolution of a snake-like robot
  - Check whether this results in interesting behaviour and useful structure.
- Results: Emergence of glider-like structures transferring information across space and time in the snakebot.



Contents

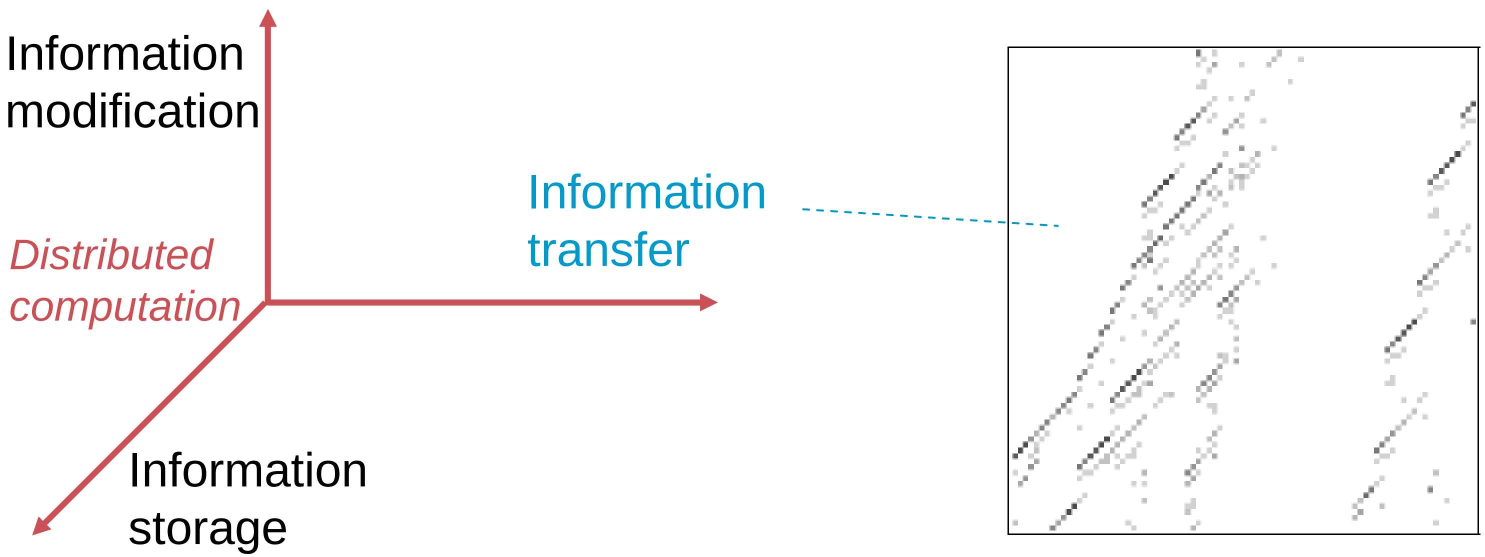
- Information-driven self-organisation
- Measuring information transfer with transfer entropy
- Evolving snakebot with transfer entropy
- Results: emergence of glider-like structures

Information-driven self-organisation (IDSO)

- Self-organised multi-agent systems are typically designed using some task-based fitness function.
- IDSO is proposed as an alternative:
  - Possibly enhance benefits of adaptability, robustness and scalability.
  - Based on theory that information structure is vital to emergence of self-organised intelligence (Polani et al, 2007).
  - Proposes a consistent framework with template-based evolution of required computational tasks.

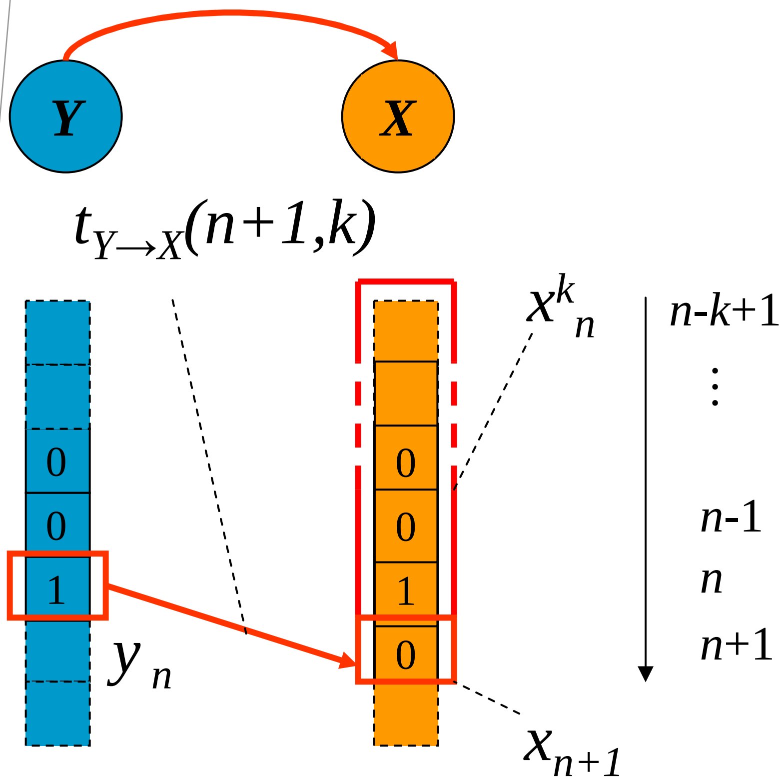
Information transfer as a fitness function

- Information transfer suggested as an important fitness function:
  - Conjectured to be maximised in an order-chaos phase transition
  - Related concept of empowerment (Klyubin et al, 2005)
  - Fundamental component of distributed computation:



e.g. Gliders in CAs

Information transfer



- **Transfer entropy** is:
  - the average information provided by a source
  - about the destination's next state
  - that was not contained in the past of the destination.
- Equivalent to the mutual information between source and destination conditioned on the past of the destination, i.e. $T_{Y\to X}(k)=I(Y,X';X^{(k)})$

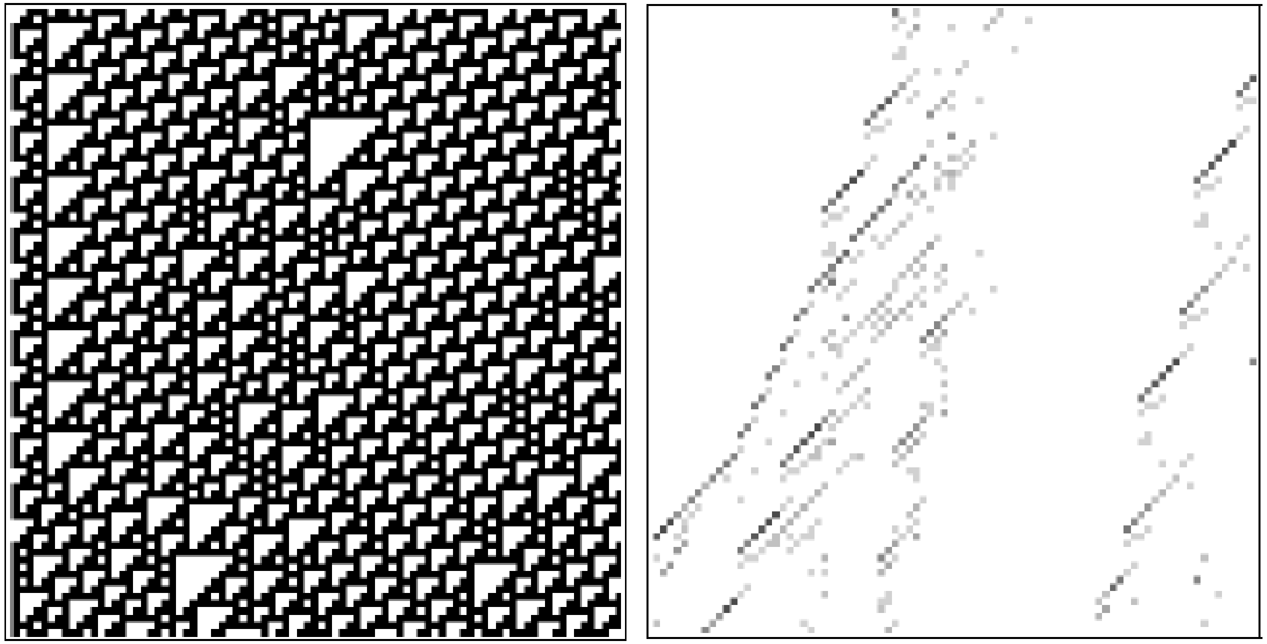
$$T_{Y\to X} = \sum_{x_{n+1},x_n^{(k)},y_n^{(l)}} p(x_{n+1},x_n^{(k)},y_n^{(l)}) \log_2 \frac{p(x_{n+1}|x_n^{(k)},y_n^{(l)})}{p(x_{n+1}|x_n^{(k)})}$$

Local transfer entropy

- TE is also an average over a **local transfer entropy**:

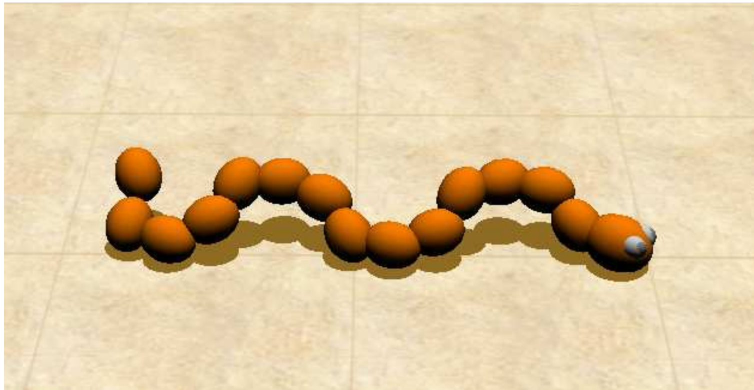
$$T_{Y\rightarrow X}(k) = \langle t_{Y\rightarrow X}(n,k) \rangle \qquad t_{Y\rightarrow X}(n+1,k) = \log_2 \frac{p(x_{n+1}|x_n^{(k)}, y_n)}{p(x_{n+1}|x_n^{(k)})}$$

- Application to cellular automata highlights gliders/particles as coherent information transfer agents:



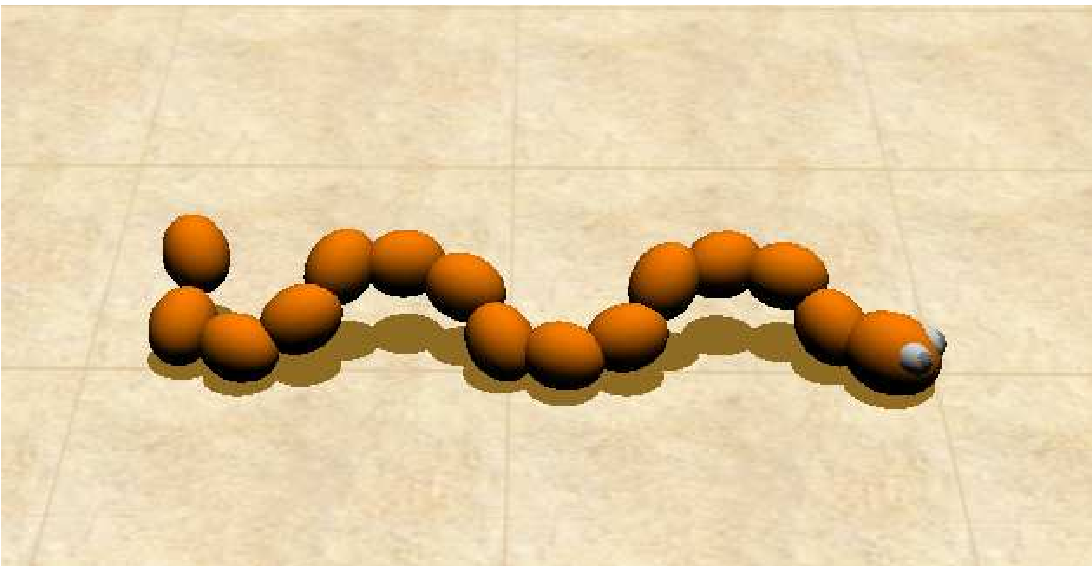
Snakebot

- Snakebot is a snake-like modular robot simulated in Open Dynamics Engine (ODE) (Tanev et. al, 2005)
- Genome is algebraic expression for patterns of desired turning angles of the segments.
- Actual turning angles result from interactions between segments and with the terrain
- Snakebot evolves in a flat environment here.



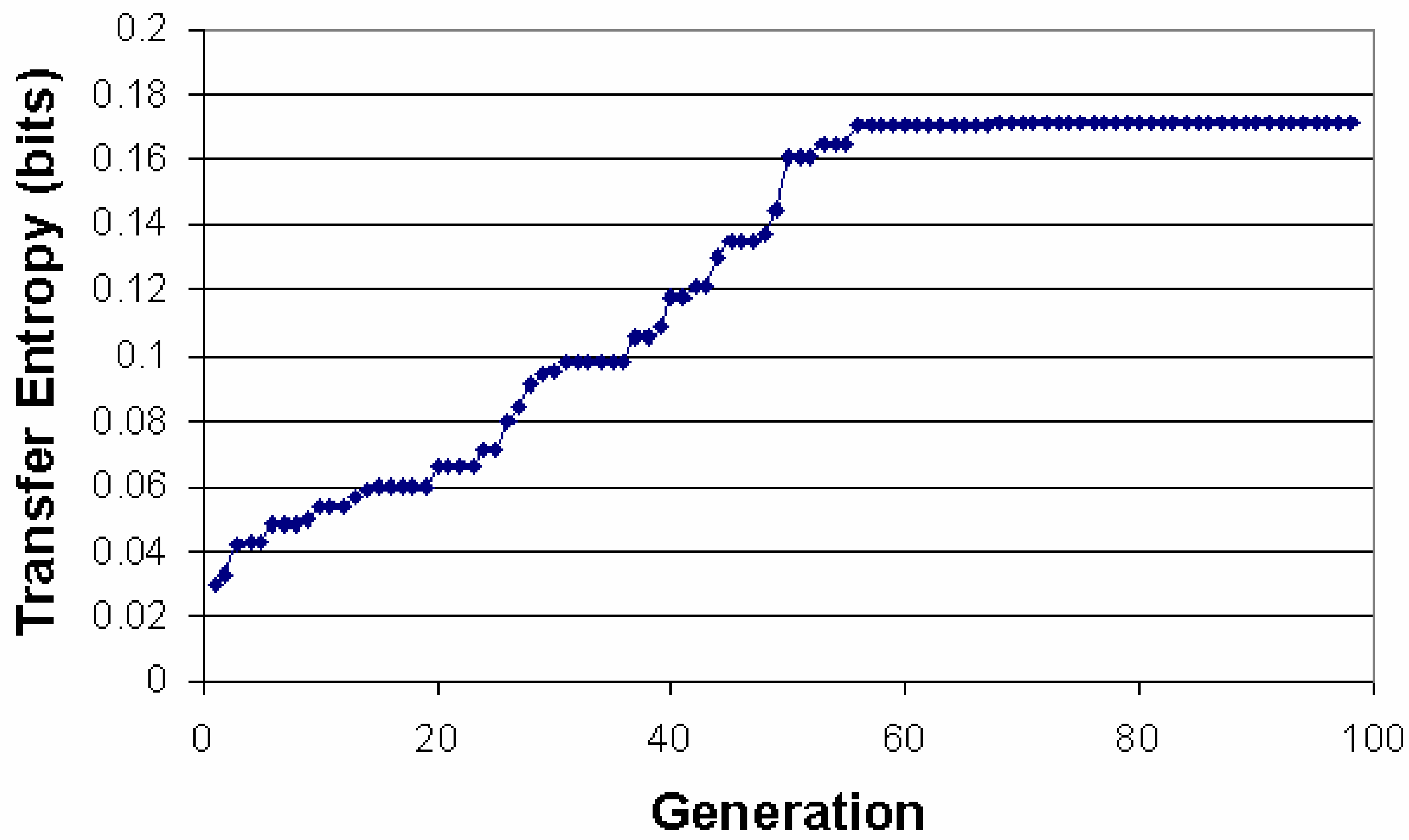
Applying transfer entropy to snakebot

- 1800 time steps were simulated for each genome.
- **Fitness function**:
  - Analyses actual horizontal turning angles
  - Average transfer entropy is measured between adjoining modules, in the direction from the tail to the head,
    - Using kernel estimation (for continuous-valued variables).
  - Then averaged over all module pairs.



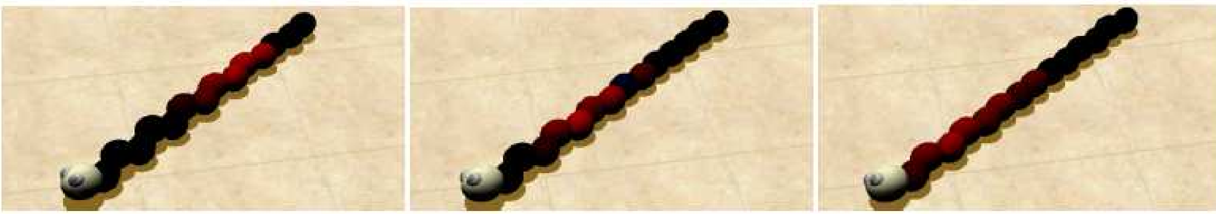
Results: preliminaries

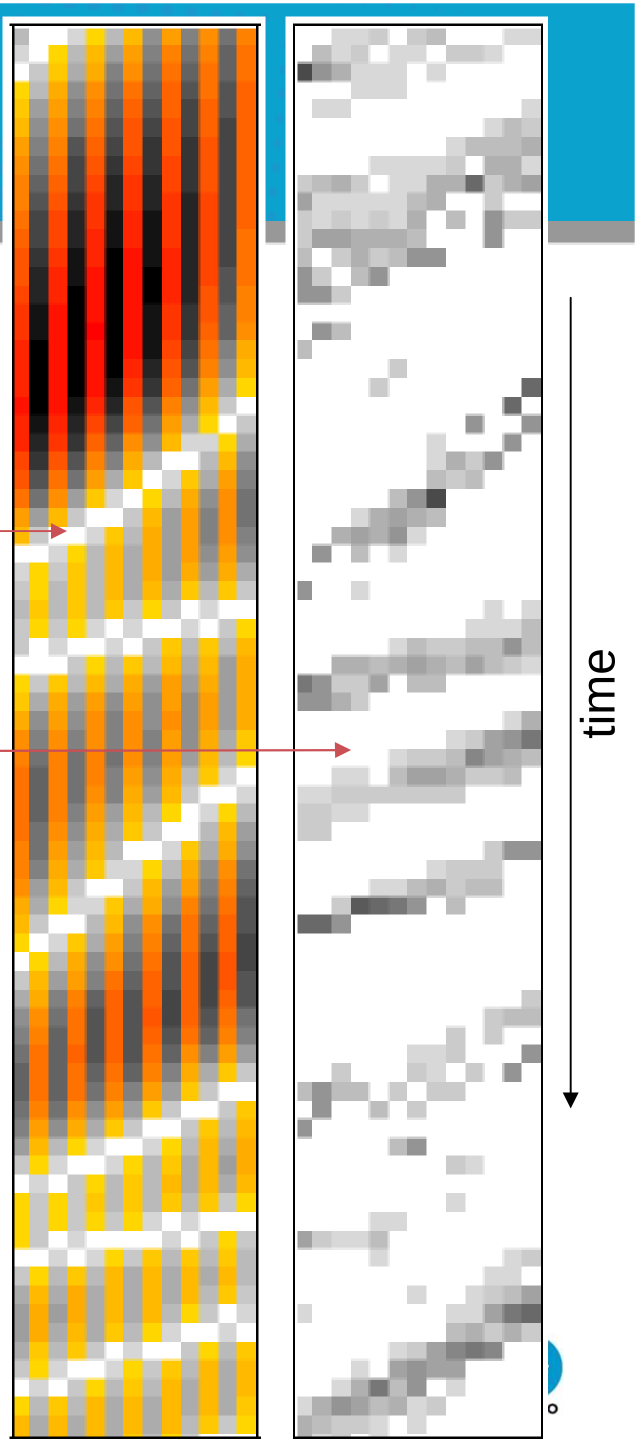
- Highly coordinated snakebots had very low transfer entropy.
- Growth in fitness through the experiment:



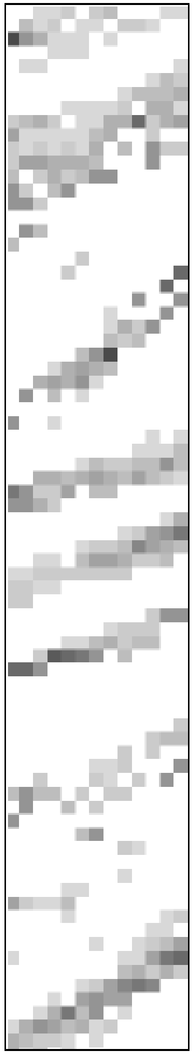
Results: most fit snakebot

- Raw motion is *not* fast, well-coordinated side-winding locomotion.
- Dynamics are more clear from examining actuator angles
- Analogy to gliders is made clear by the plot of local transfer entropies
- and highlighting the snake with the local transfer entropy values.
- Local values tell us much more than the raw states or average TE.



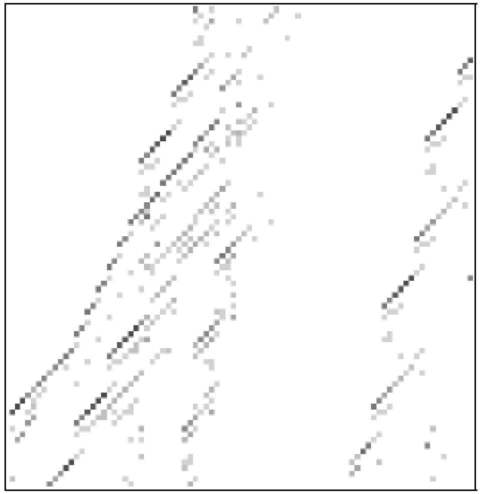


Results: gliders in the snakebot



Snakebot

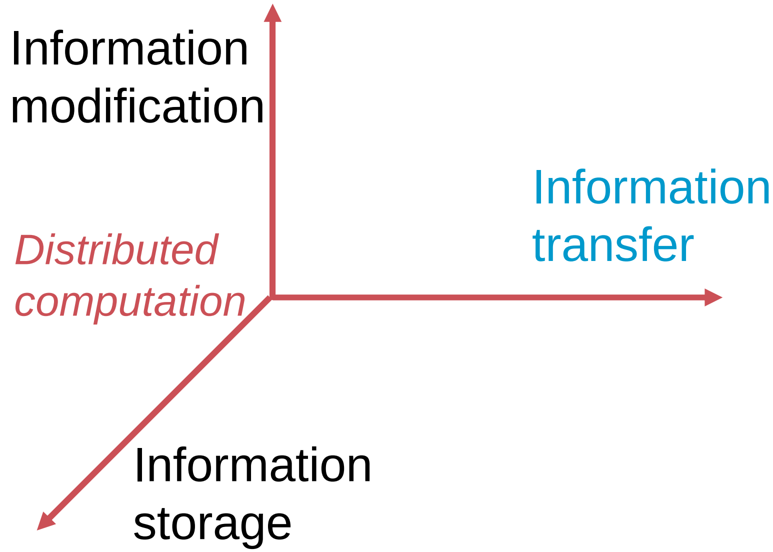
CA



- Coherent travelling info structures are analogous to gliders in CAs.
- **Significant** because gliders play a vital role in distributed computation in CAs.
- **Emergent** because we specified high average TE, not coherent local TE structures.
  - Local coherent structures possibly require less evolutionary steps to design.
- Biological systems exploit glider-like structures.

Conclusions

- First known application of a direct measure of information transfer to evolve a system.
- Maximising transfer entropy can lead to coherent propagating information structures.
- Future work
  - Investigate how to optimally fit information transfer with information storage and modification in order to achieve complex computation.



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Thank you

Transfer entropy: continuous variables

1. Average $T_{Y \rightarrow X}(k)$ over each observation (i.e. average of local transfer entropies) rather than all possible observations
2. Use **kernel estimation** for probability distribution functions by counting similar tuples:

$$\hat{p}_r(u_n) = \frac{1}{N} \sum_{n'} \Theta \left(\left| \begin{pmatrix} x_{n+1} - x_{n'+1} \\ x_n^{(k)} - x_{n'}^{(k)} \\ y_n - y_{n'} \end{pmatrix} \right| - r \right)$$

- Max distance for the norm
- Step kernel

- i.e. computation for continuous variables is necessarily an average over local values.