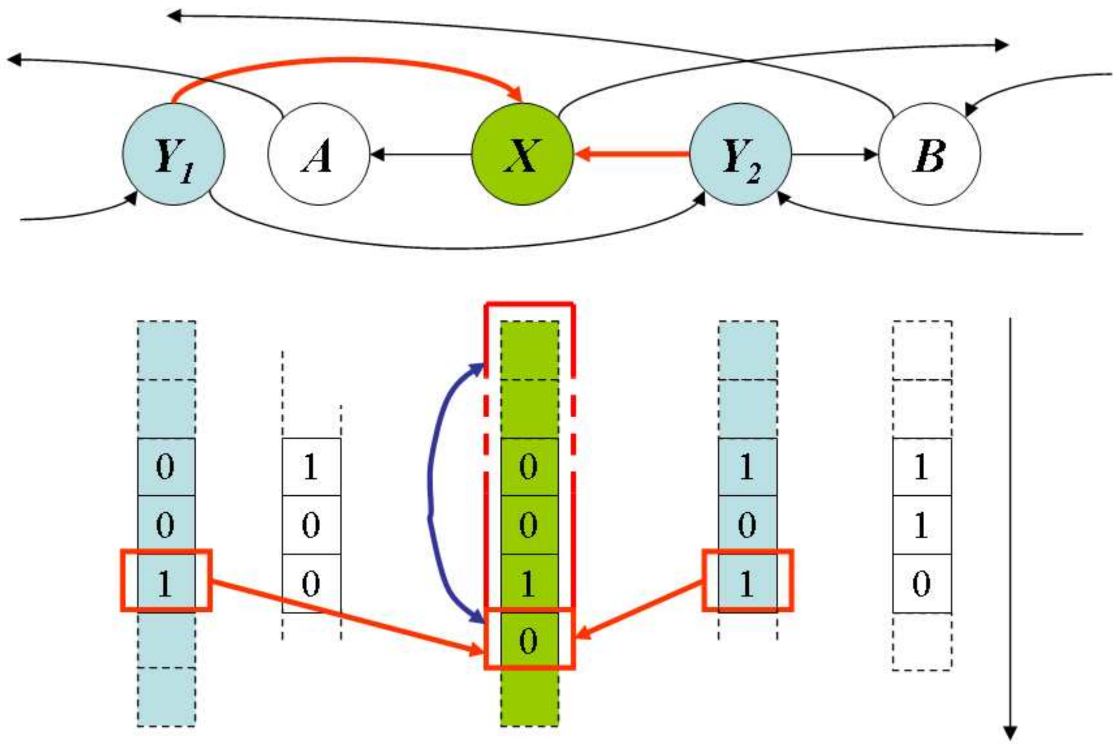

Coherent computation in biological networks

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Coherent computation in biological networks

- Hypothesis: That complex computation in biological systems is distinguished by the *coherence* of the underlying computation.
- Aim:
  1. To define and measure coherent structure in distributed biologically-inspired computation.
  2. To check whether the coherence of computation is a defining feature of such computation.
- Results:
  - A methodology which identifies clear and "hidden" coherent structure in complex computation.
  - Inference that coherent structure is maximised in an order-chaos phase-transition.

Contents

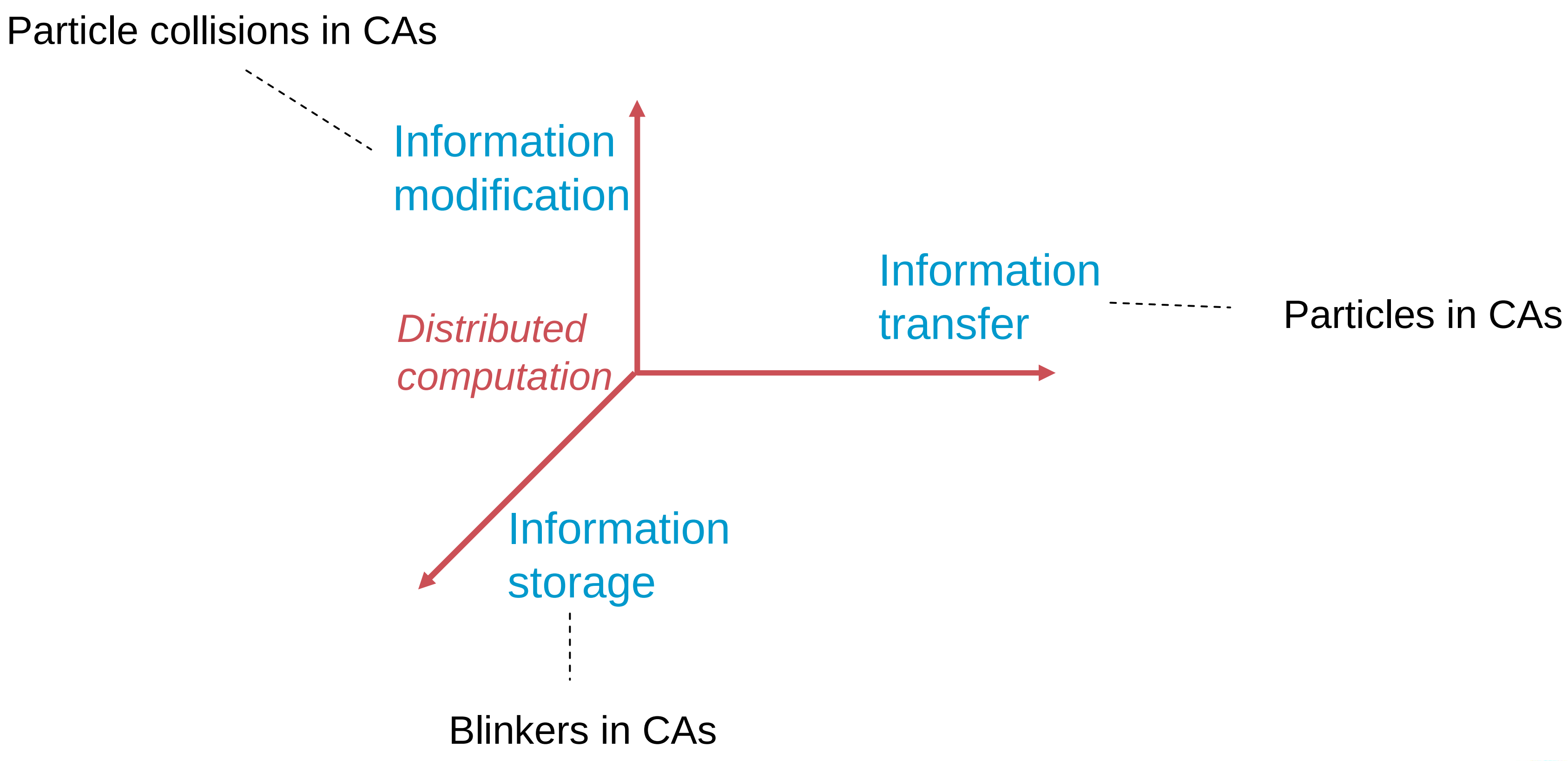
- Information dynamics of distributed computation
  - In Cellular Automata
  - In Random Boolean Networks
- Coherent computation
- Measurement of coherence of computation
- Experimental results in RBNs

What is distributed computation?

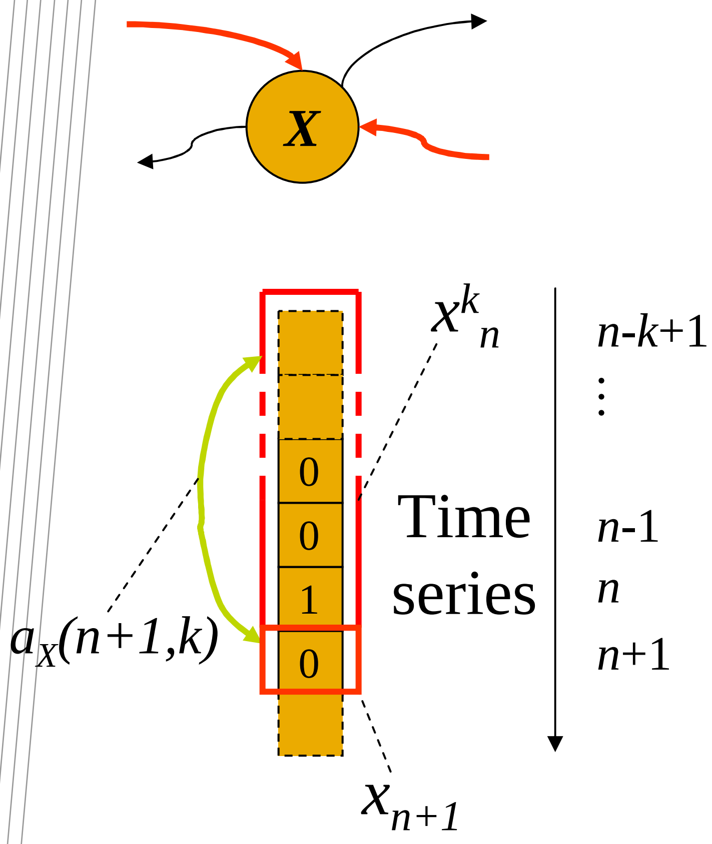
- We talk about computation as:
  - Memory
  - Communication
  - Processing
- We quantify computation in terms of:
  - Information storage
  - Information transfer
  - Information modification
- Distributed computation is any process that involves these features, e.g.:
  - Time evolution of cellular automata
  - Information processing in the brain
  - Gene regulatory networks computing cell type
  - Flocks computing their collective heading
  - Ant colonies computing the most efficient routes to food sources
  - The universe is computing it's own future!
- Many conjectures about distributed computation in these systems, e.g.:
  - ✓ Computation by gliders in cellular automata
  - ~ Maximisation of computational capabilities in order-chaos phase transitions

Information dynamics

- Information dynamics of distributed computation in terms of 3 components of Turing universal computation:



Information storage



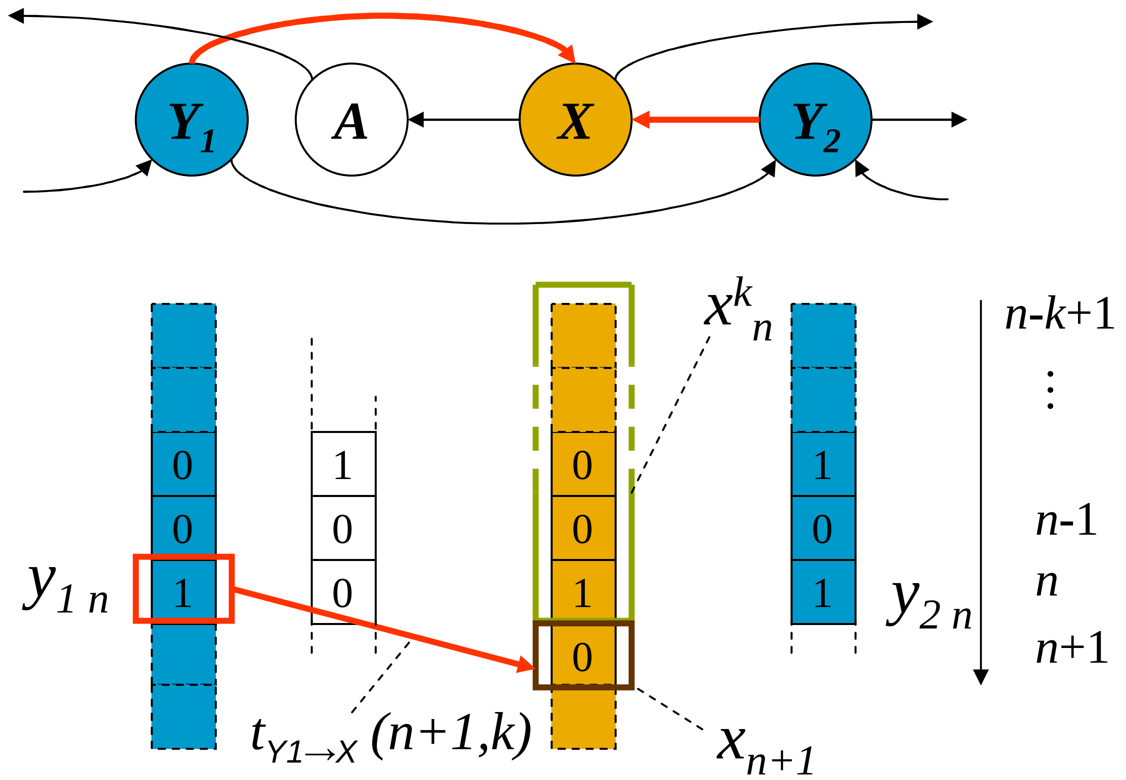
- Information storage: info in past of an agent relevant to predicting its future.
- Active info storage = mutual info between past and next step:

  $A_X(k) = I(X', X^{(k)})$

- Is the average of a local active information storage at each time point:

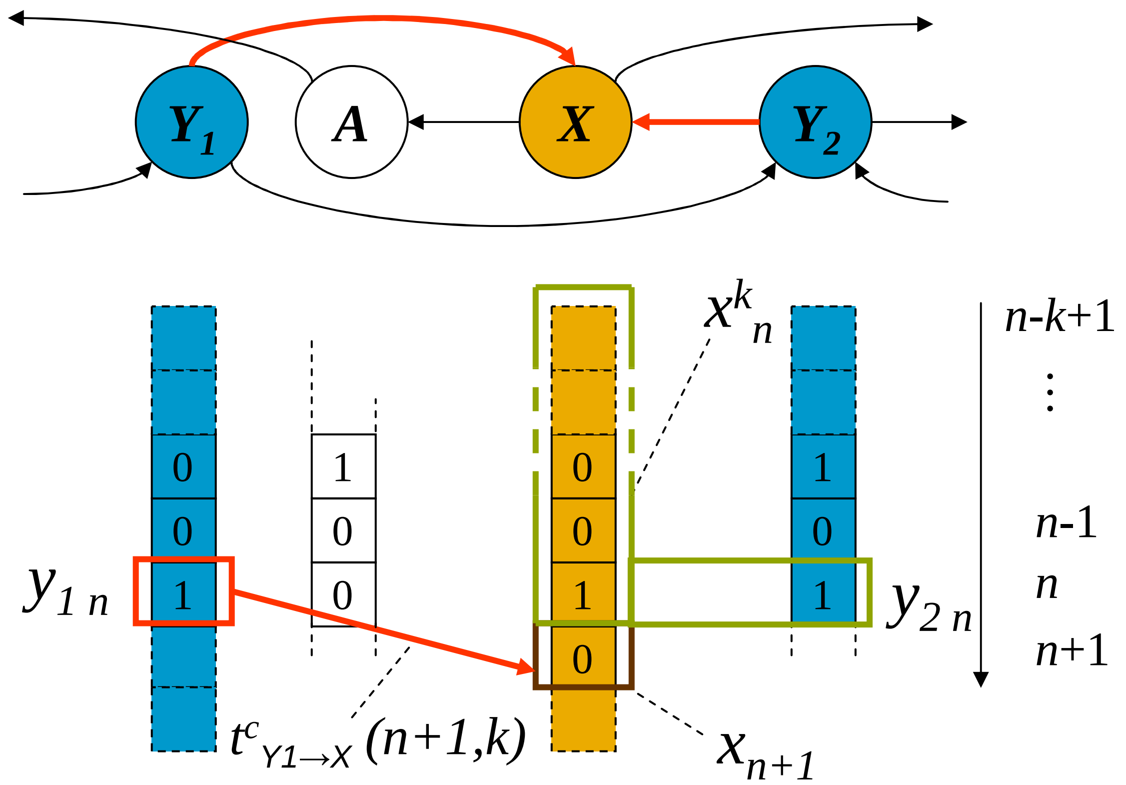
  $A_X(k) = \langle a_X(n,k) \rangle$

Information transfer



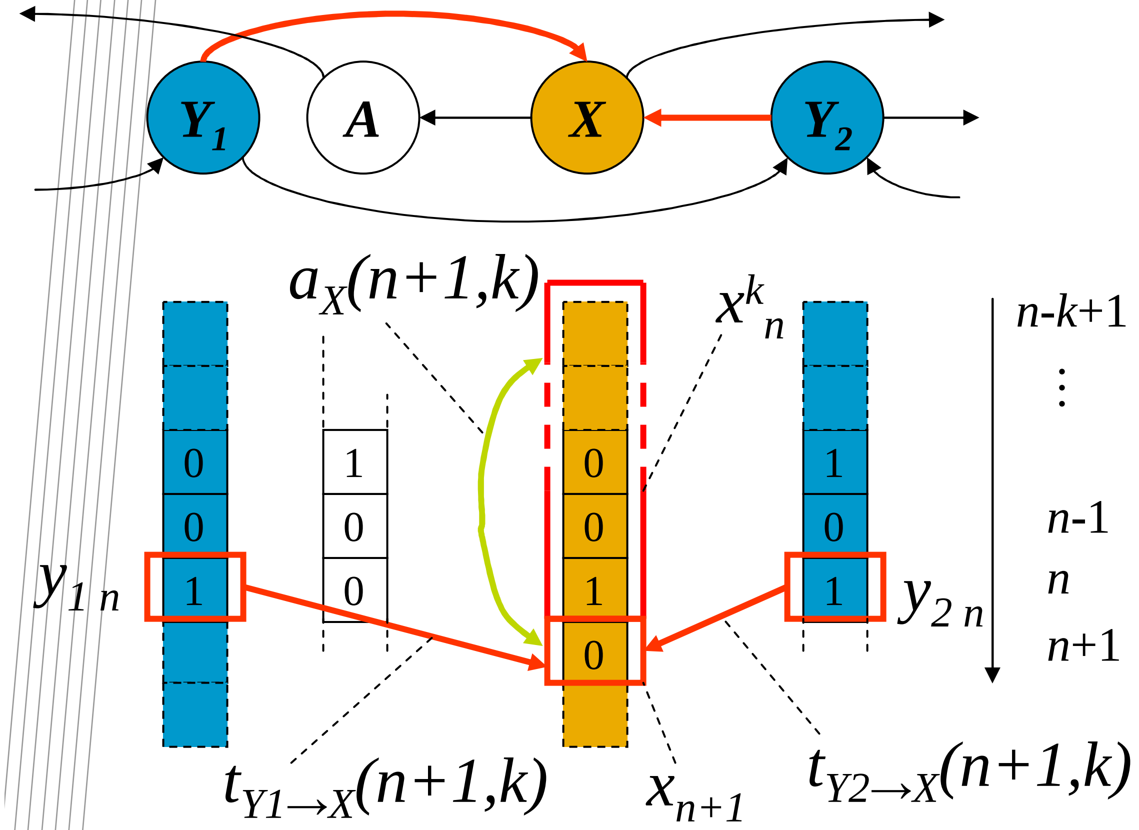
- **Apparent** transfer entropy: mutual information between **source** and **destination** conditioned on the **past** of the destination, e.g. $T_{Y1 \to X}(k) = I(Y_1, X'; X^{(k)})$

Information transfer



- **Complete** transfer entropy also conditions on other causal information sources, e.g. $T^{C}_{Y1\rightarrow X}(k)=I(Y_1,X';X^{(k)},Y_2)$

Information modification



- Define **Local Separable Information** as:

$$s_X(n) = a_X(n) + \sum_{Y \in V, Y \neq X} t_{Y \rightarrow X}(n)$$

- s > 0: trivial info modification.
- s < 0: non-trivial info modification, where sources interact.
- Average over all time steps to get $S_X(k)$ and over all nodes to get $S_X(k,/K)$.

Also record positive components of the averages $S^+_X(k)$ and $S^+_X(k,/K)$ and negative components $S^-_X(k)$ and $S^-_X(k,/K)$ such that:

$S_X(k) = S^+_X(k) + S^-_X(k)$

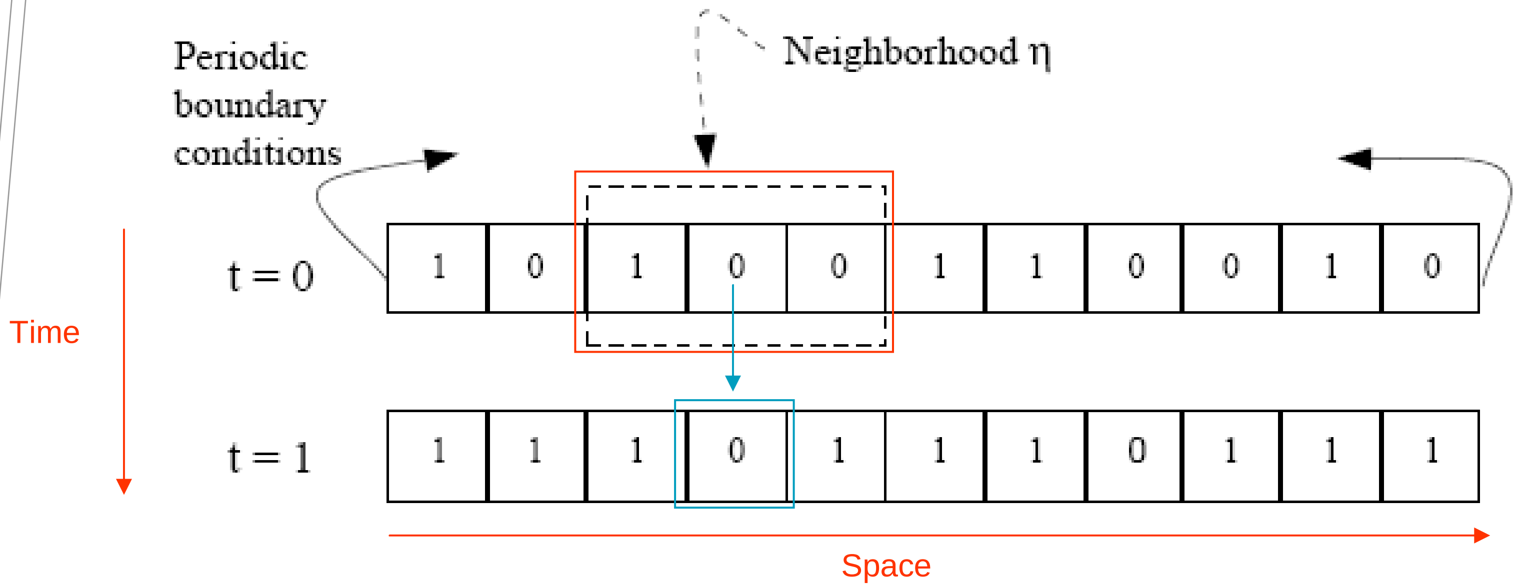
Cellular Automata

Rule table φ:

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

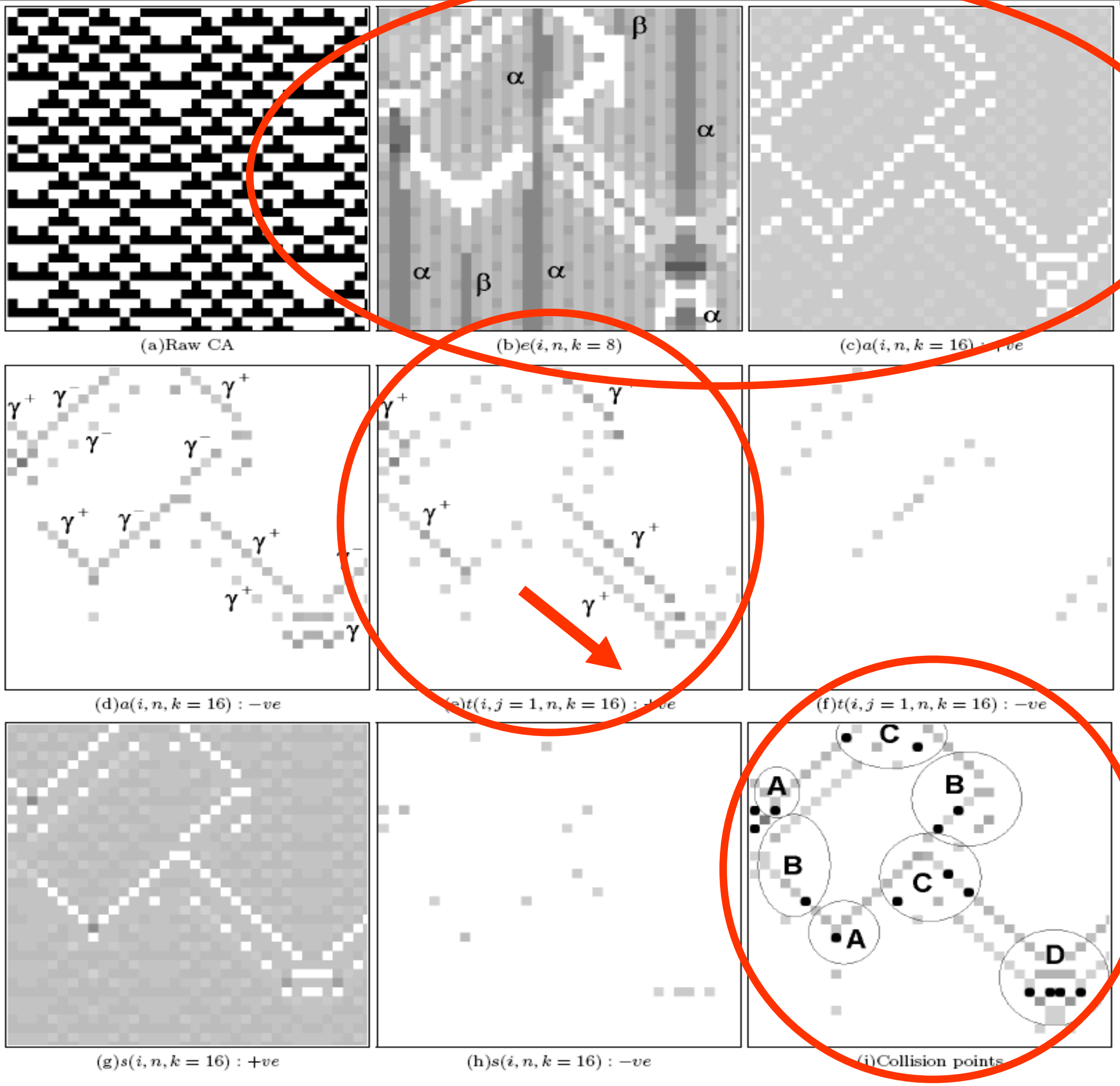
= Rule 0x6e = Rule 110

Lattice:



- "Computation in Cellular Automata: A selected review", Mitchell, 1998

Local information dynamics in CAs: rule 54

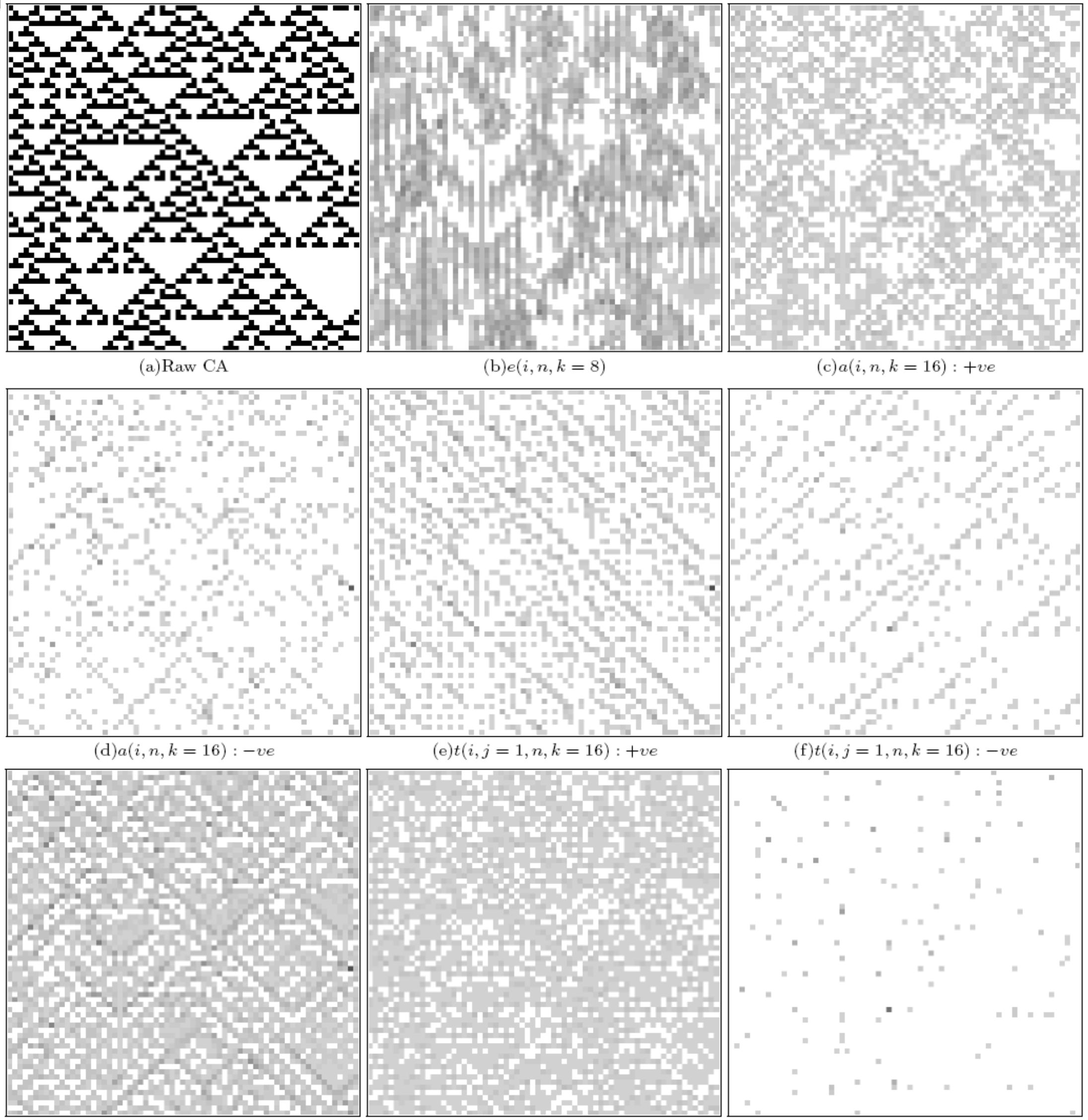


← Information storage

← Information transfer

← Information modification

Local information dynamics in CAs: rule 22


(a)Raw CA (b)$e(i,n,k=8)$ (c)$a(i,n,k=16):+ve$
(d)$a(i,n,k=16):-ve$ (e)$t(i,j=1,n,k=16):+ve$ (f)$t(i,j=1,n,k=16):-ve$
(g)$h_\mu(i,n,k=16)$ (h)$s(i,n,k=16):+ve$ (i)$s(i,n,k=16):-ve$

← Information storage

← Information transfer

← Information modification

Coherent computation

- We conjecture that coherent structure is a defining feature of complex computation, particularly computation which solves human-understandable tasks.
- OED says that *coherence* implies a property of sticking together or a logical relationship.
- We apply it here to describe a *logical relationship between values in local information dynamics profiles*.
- But before we go on:
  - “Tell me more about why *coherent* computation is important?”

Exhibit A: Coherent computation in CAs

- Obviously the known complex rules exhibit coherent structures
- So too do CA rules *evolved* to solve human understandable computational tasks, e.g. density classification by *Mitchell et al (1994, 1996)*:

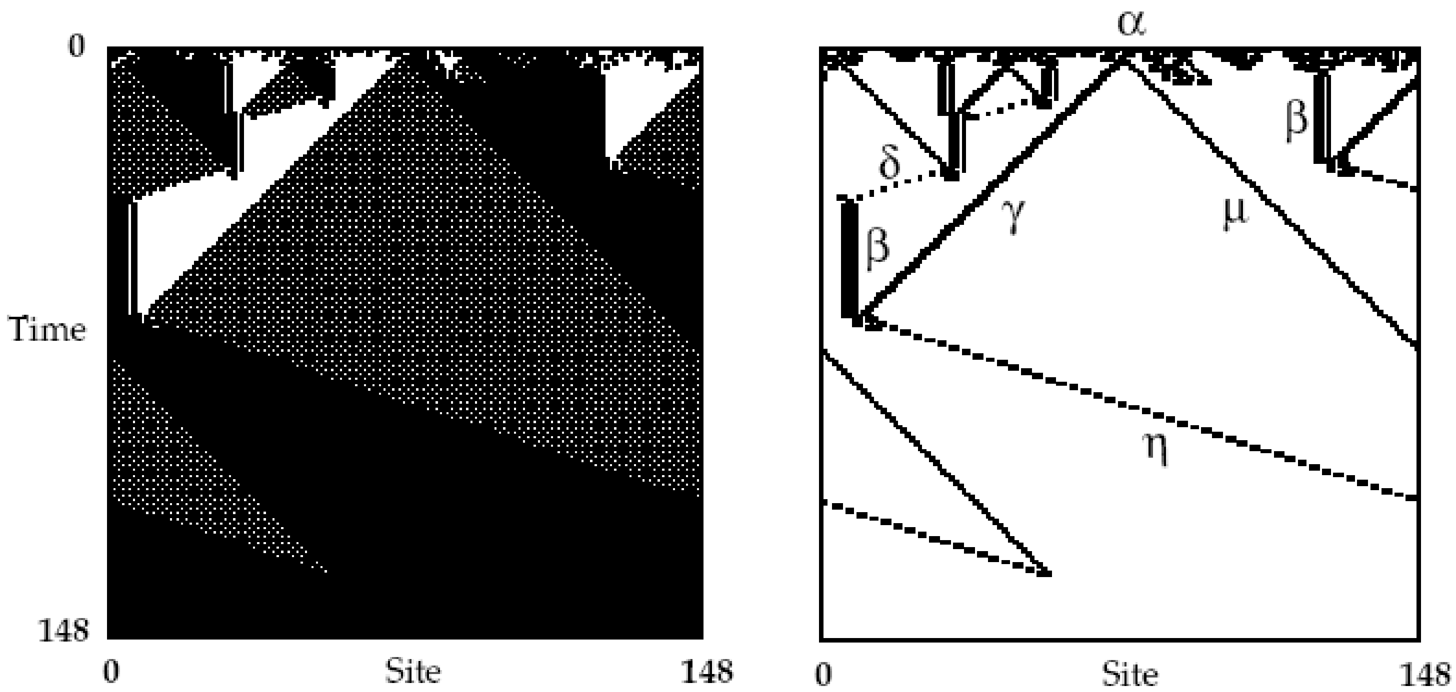
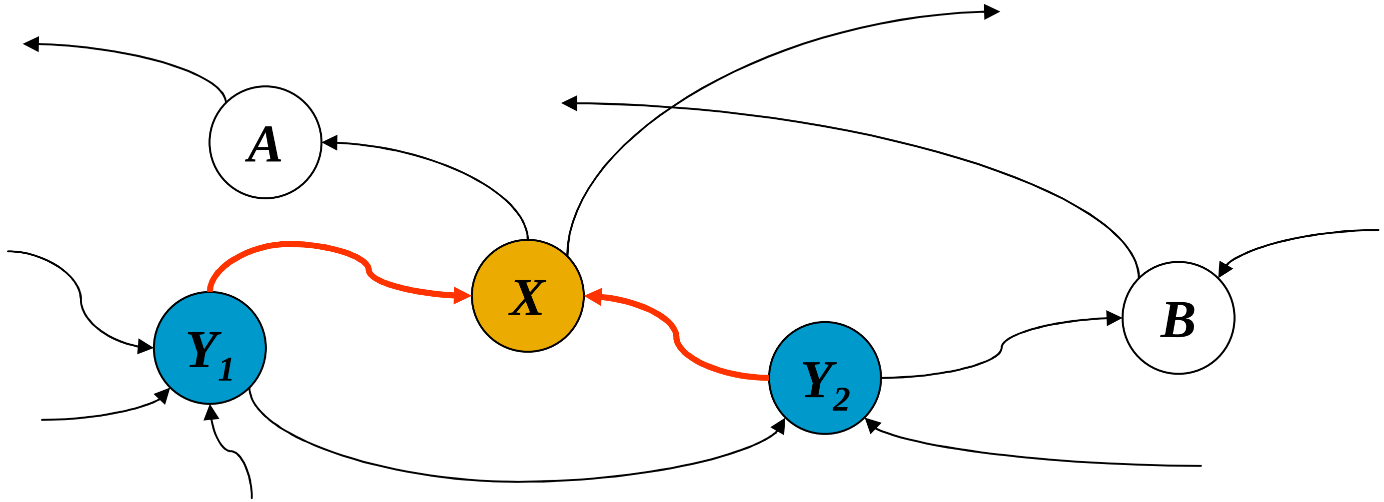


Exhibit B: Coherent biological computation

- In cell signalling networks:
  - Much talk about signalling cascades and maximal unpredictability in cascade size
- Coherent wave structures in neural computation:
  - e.g. Gong (2008), even in spontaneous activity

- It appears that nature evolves coherent computation as well!
  - Coherent structures provide *stable* mechanisms for:
    1. Storing information
    2. Transferring information
    3. Facilitating non-trivial information modification when required.

Random Boolean Networks



RBNs used here have:

- N nodes in a directed structure,
- which is determined at random from an average in-degree $\overline{K}$.

Each node has:

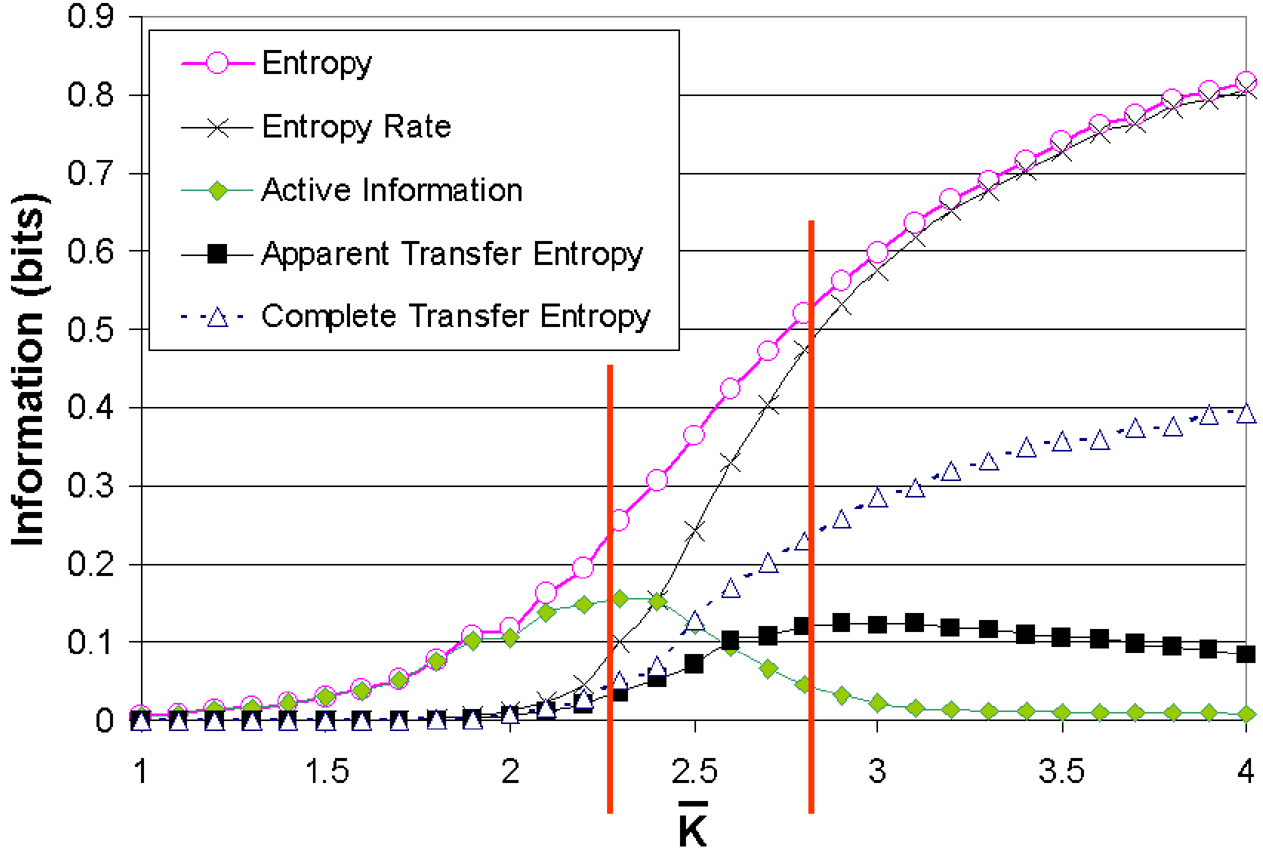
- Boolean states updated synchronously in discrete time.
- Update table determined at random.

- See Kauffman "Origins of order" (1993) or Gershenson (2004).

Phase transitions in RBNs

Connectivity	Low $\overline{K} < 2$	Intermediate $\overline{K} \approx 2$	High $\overline{K} > 2$
Phase	Ordered	Critical	Chaotic
Sensitivity to initial conditions	Low $\delta < 0$	Critical $\delta \approx 0$	High $\delta > 0$
Convergence of similar macro states	Strong	Uncertain	Highly divergent

Average info dynamics through phase transition in RBNs



- Information storage peaks slightly within the ordered regime.
- Apparent transfer entropy slightly within chaotic regime.
- Complete transfer entropy continues to rise in chaotic regime.

Exhibit C: Averages of info dynamics measures

- A set of circumstantial evidence of features of complex computation associated with coherence …

- Significant amounts of information storage and apparent TE.
- Apparent TE as a high proportion of complete TE for more than one channel.
  - Propagation of coherent effects from distinct sources.
- Very low proportion of non-trivial information modification events
  - Few information collisions allows coherent computation, but high impact associated with each collision.

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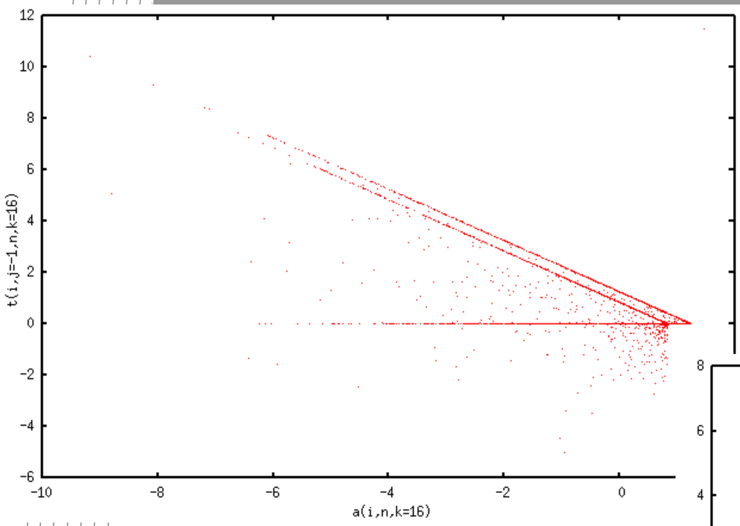
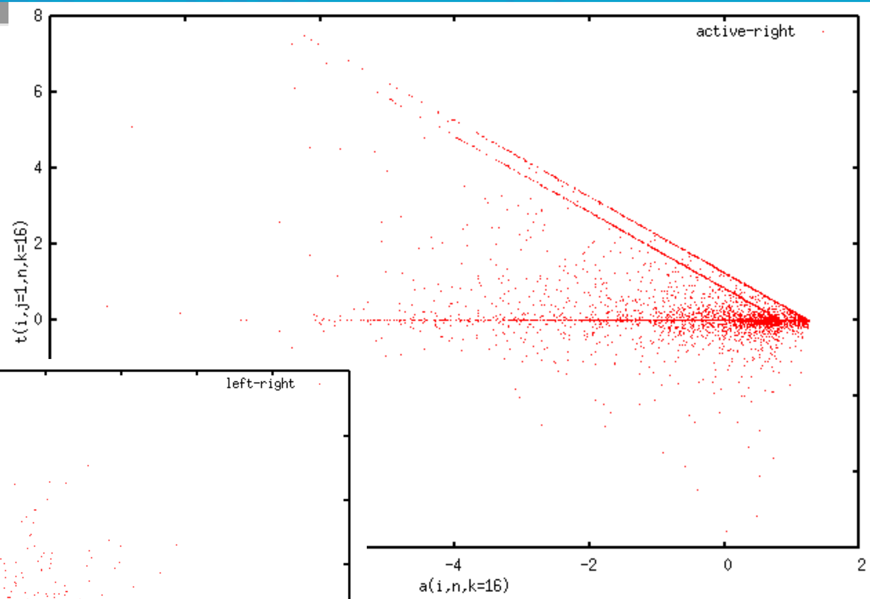
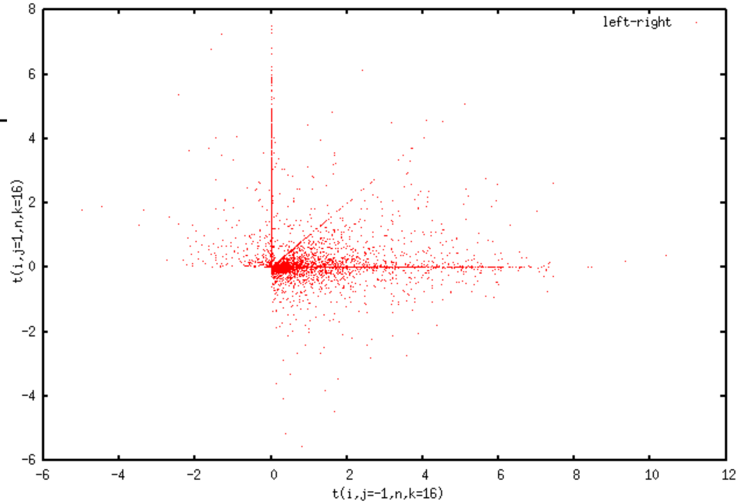
Exhibit D: structure between local measures



t(i,j=-1,n) vs a(i,n)



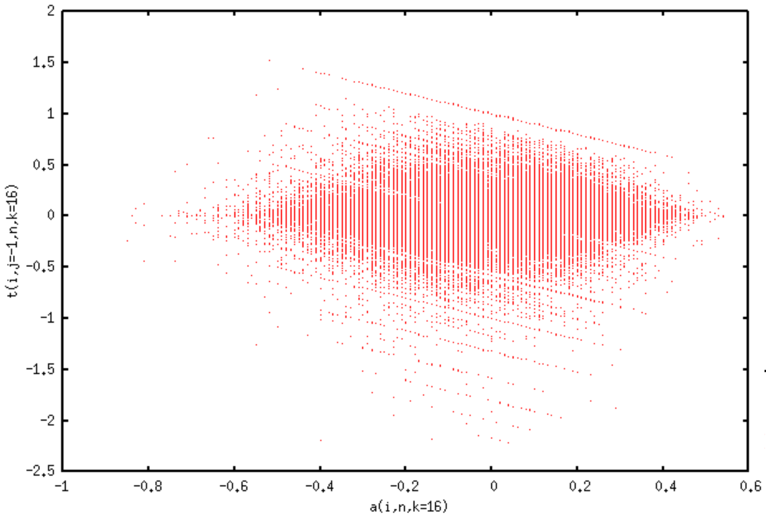
t(i,j=+1,n) vs a(i,n)



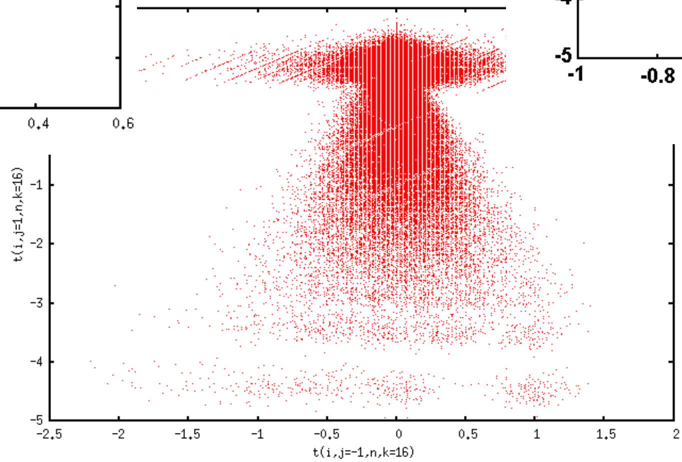
t(i,j=+1,n) vs t(i,j=-1,n)

- Rule **110** – clear structure seen in local information dynamics.
  - Structure appears to imply coherence of computation.
- What about other rules?

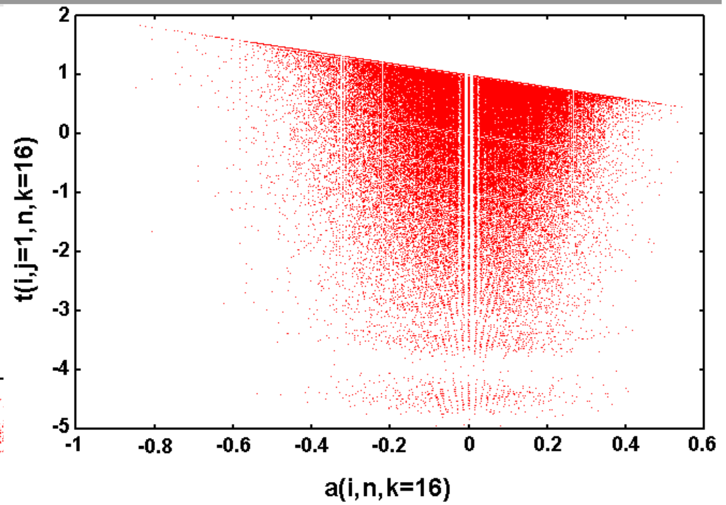
Exhibit D: structure between local measures



t(i,j=-1,n) vs a(i,n)



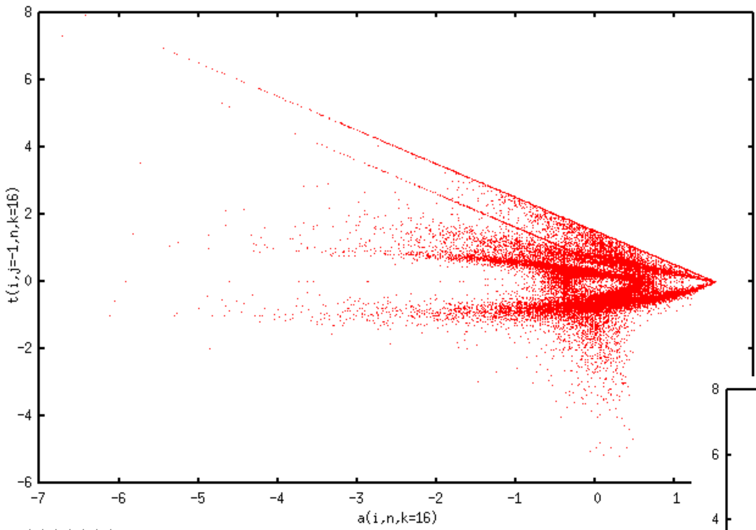
t(i,j=+1,n) vs t(i,j=-1,n)



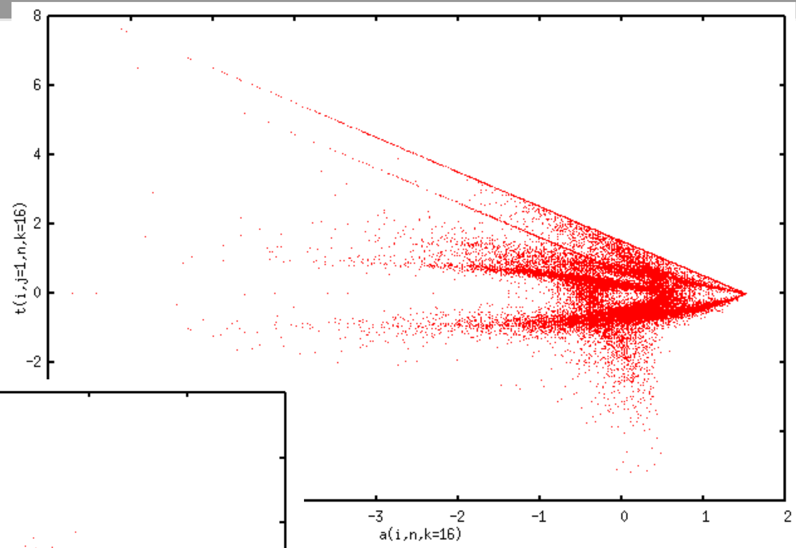
t(i,j=+1,n) vs a(i,n)

- Rule **30** – had no structure seen in local information dynamics.
- What do we expect for rule 22?

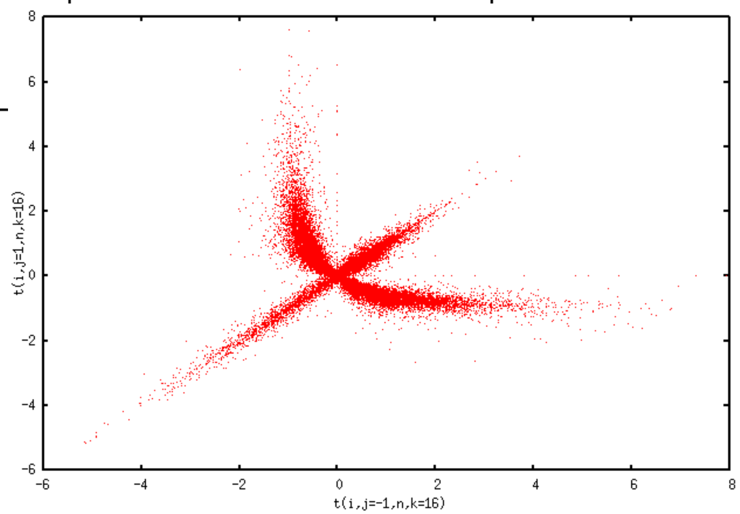
Exhibit D: structure between local measures



t(i,j=-1,n) vs a(i,n)



t(i,j=+1,n) vs a(i,n)



t(i,j=+1,n) vs t(i,j=-1,n)

- Rule 22 – has structure in **between** the local dynamics which was not obvious from their individual profiles!
- These two views from the same framework provide new insights into debate on the nature of rule 22.

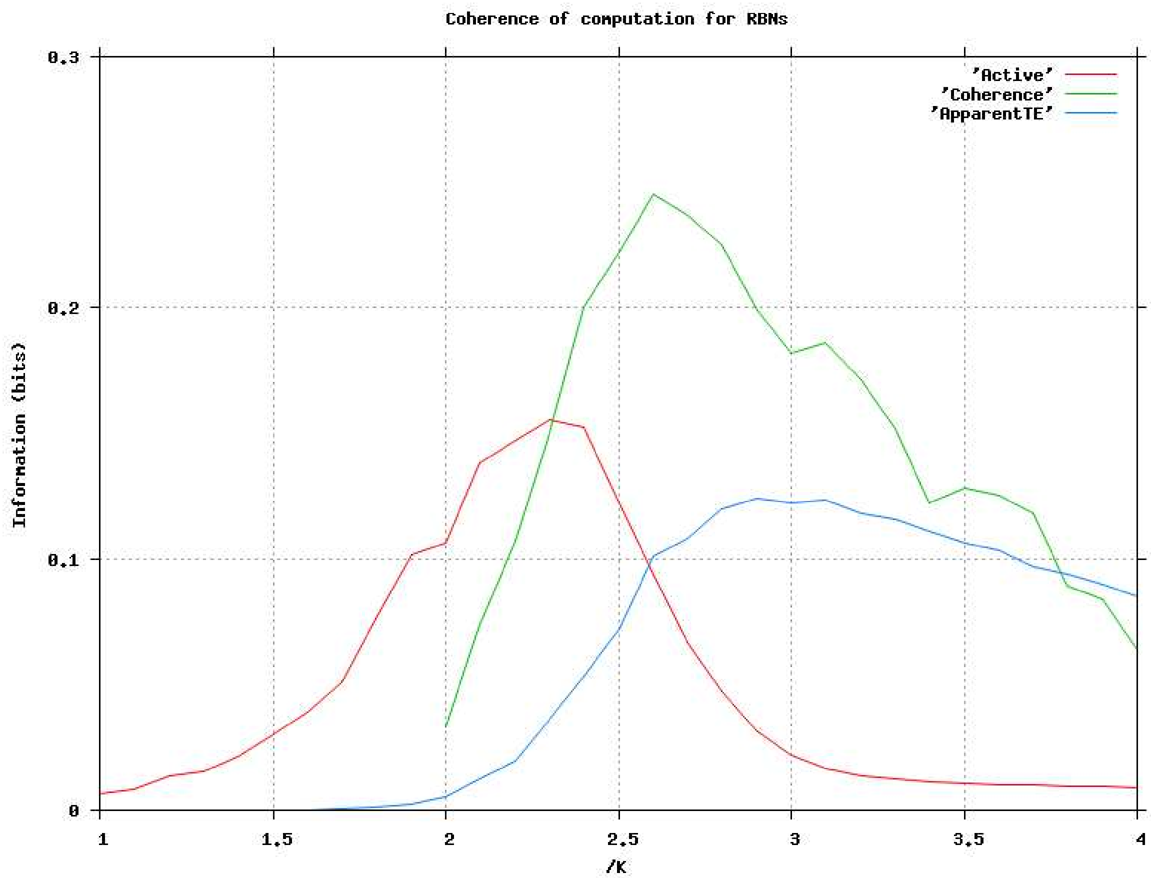
Measure for coherent computation

- Recall our definition: *a logical relationship between values in local information dynamics profiles*.
- So we refine this as the amount of structure in the state-space of the local information dynamics.
  - Spatiotemporal proximity taken into account via transfer entropy
- Measure this using the multi-information of this space:

$$C_{cX} = I(a_X; t_{Y1 \rightarrow X}; t_{Y2 \rightarrow X}; \ldots; t_{Ym \rightarrow X})$$

where $Y_1..Y_m$ are the causal information contributors to X.

Exhibit E: Coherent computation in RBNs



- Coherence is maximised in between the maximisations of information storage and transfer, directly in the vicinity of the critical point.

Conclusions

- Coherent structure appears to be a defining feature of complex computation, particularly in biological systems.
- We have presented a methodology, consistent with the information dynamics of distributed computation, for exploring the coherence of such computation.
- This methodology:
  - Captures otherwise hidden structure in the computation
  - Suggests that the coherence of computation is maximised in an order-chaos phase transition.
- Future work:
  - Refine measurement of multi-info here.
  - Explore relationship of coherence to other measures (e.g. convergence/divergence parameter).
  - Guiding self-organisation with coherent computation.

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Thank you