Robust computing over networks : Lessons from nature

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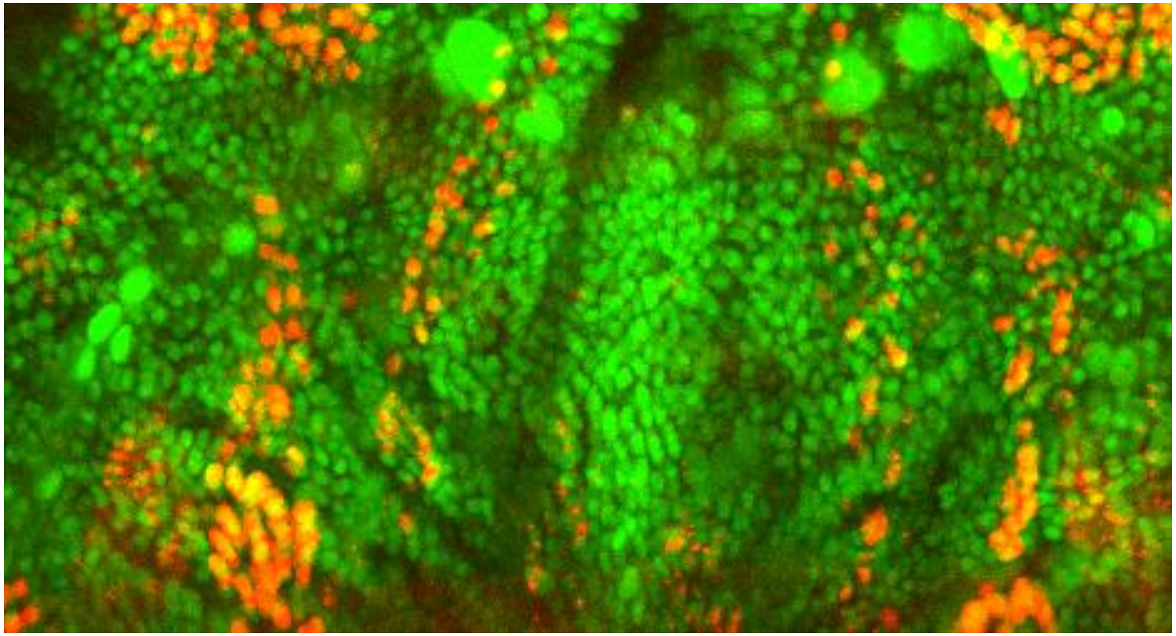
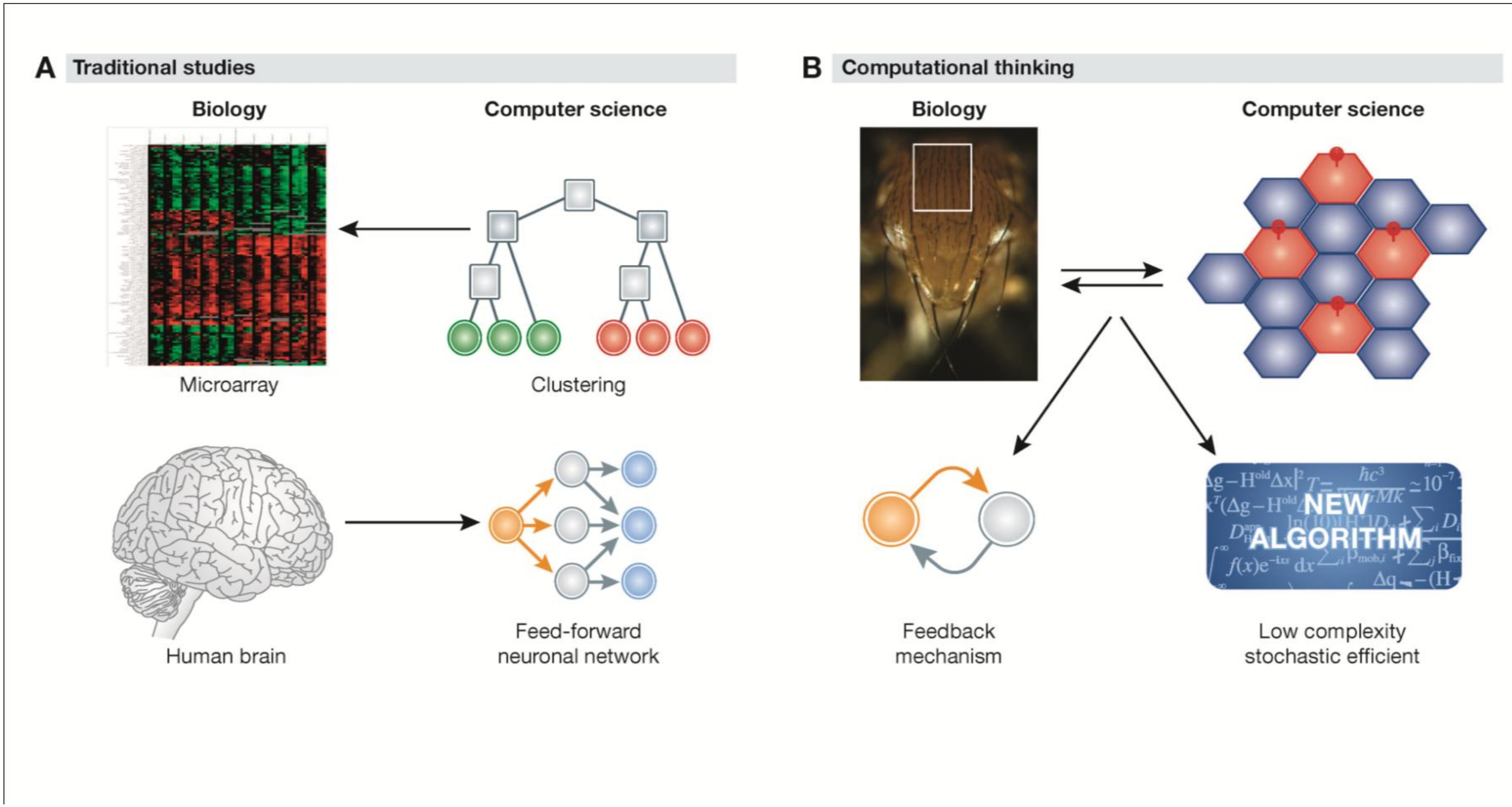


Bi-directional studies



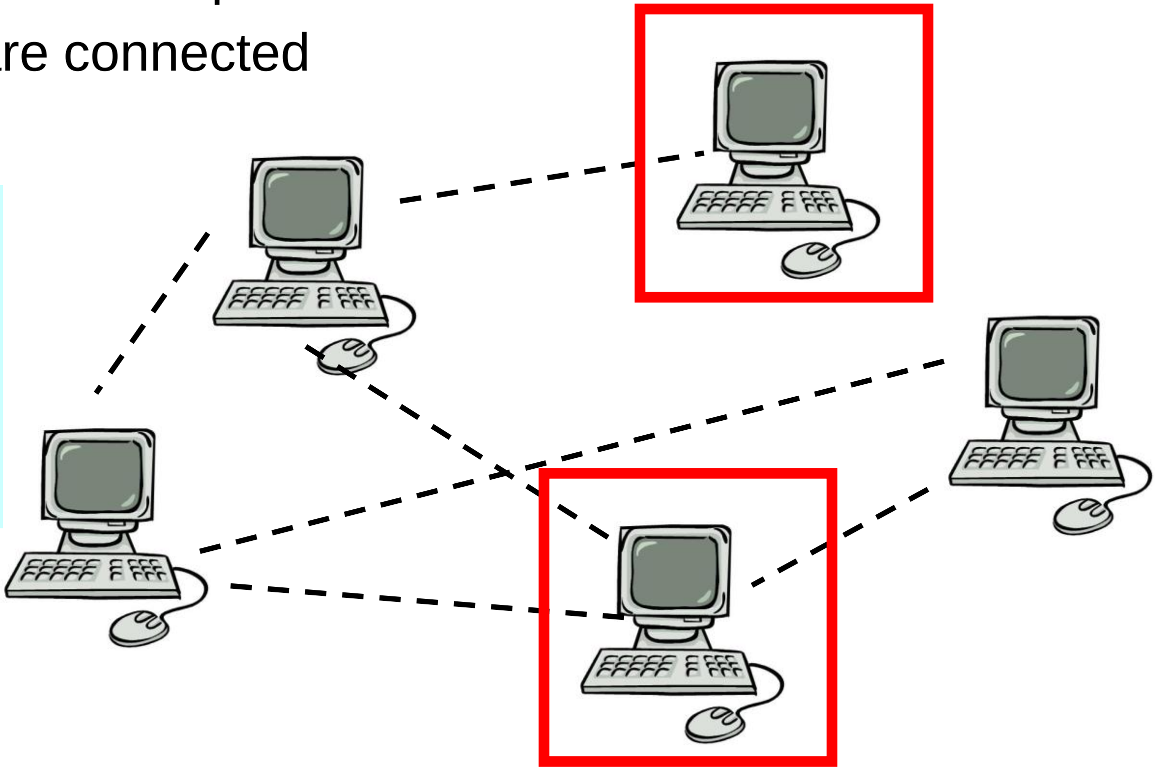
Navlakha and Bar-Joseph *Nature MSB* 2011

MIS and fly development

Maximal Independent Set (MIS)

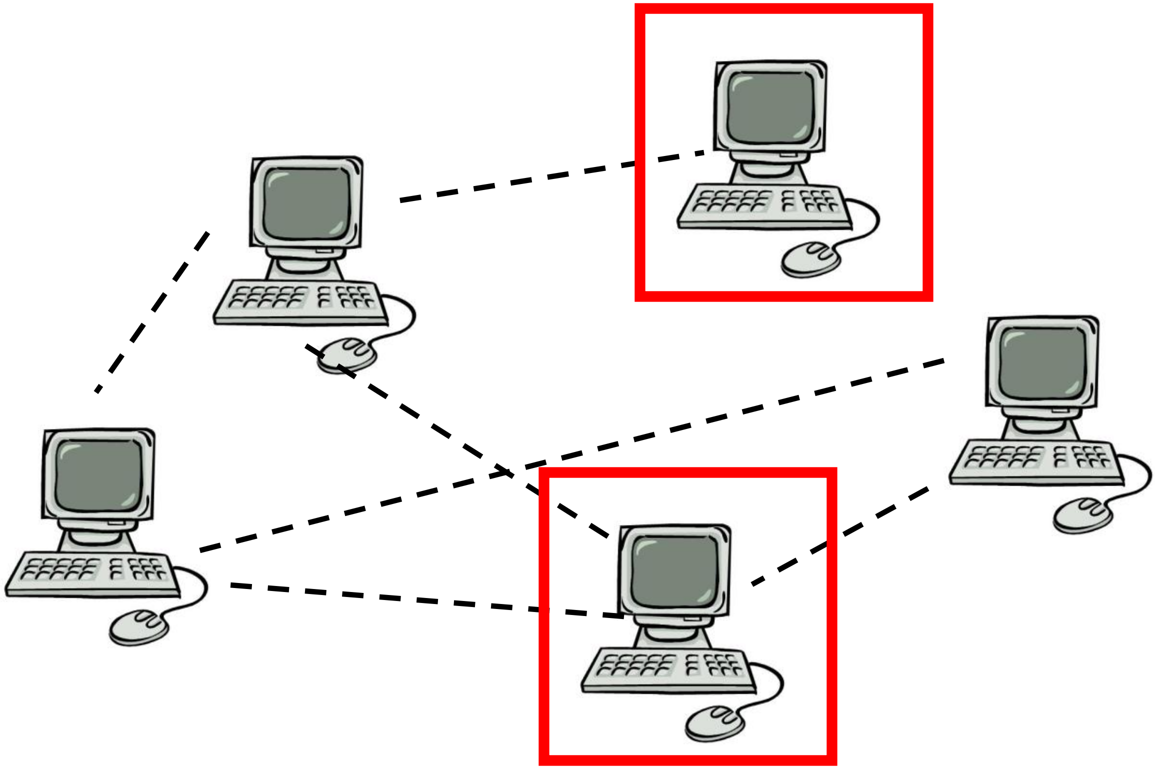
- A fundamental problem in distributed computing:
  - Often required to establish wireless networks
  - Used for routing messages, grouping sensors etc.
- For a set of nodes select a subset *A* such that:
  - Each processor is connected to a processor in *A*
  - No two processors in *A* are connected

"it is difficult to see how this problem can be solved in substantially fewer stages such as O(√*n*) …" (Valiant 1982)



Maximal Independent Set (MIS)

- Fast algorithms (e.g. Luby and Alon et al) exist for distributively selecting the MIS set but:
  - They Assume nodes know the status of their neighbors and also the topology of the graph (which is changing)
  - Use large messages



Algorithm for MIS

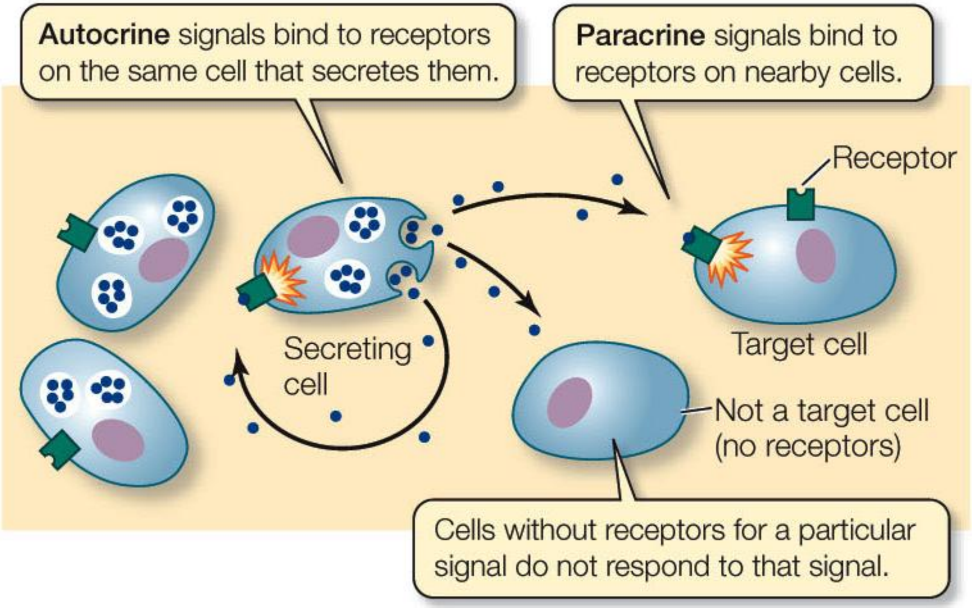
Each process needs to know how many neighbors it has

- Algorithm (proceed in rounds)
  - Each processor flips a coin with probability *1/d* where *d* is the number of its neighbors
  - If result is 0, do nothing
  - If result is 1, send to all other processors
    - If no collisions, Leader; all processes exit
    - Otherwise process with highest number of neighbors wins and becomes leader

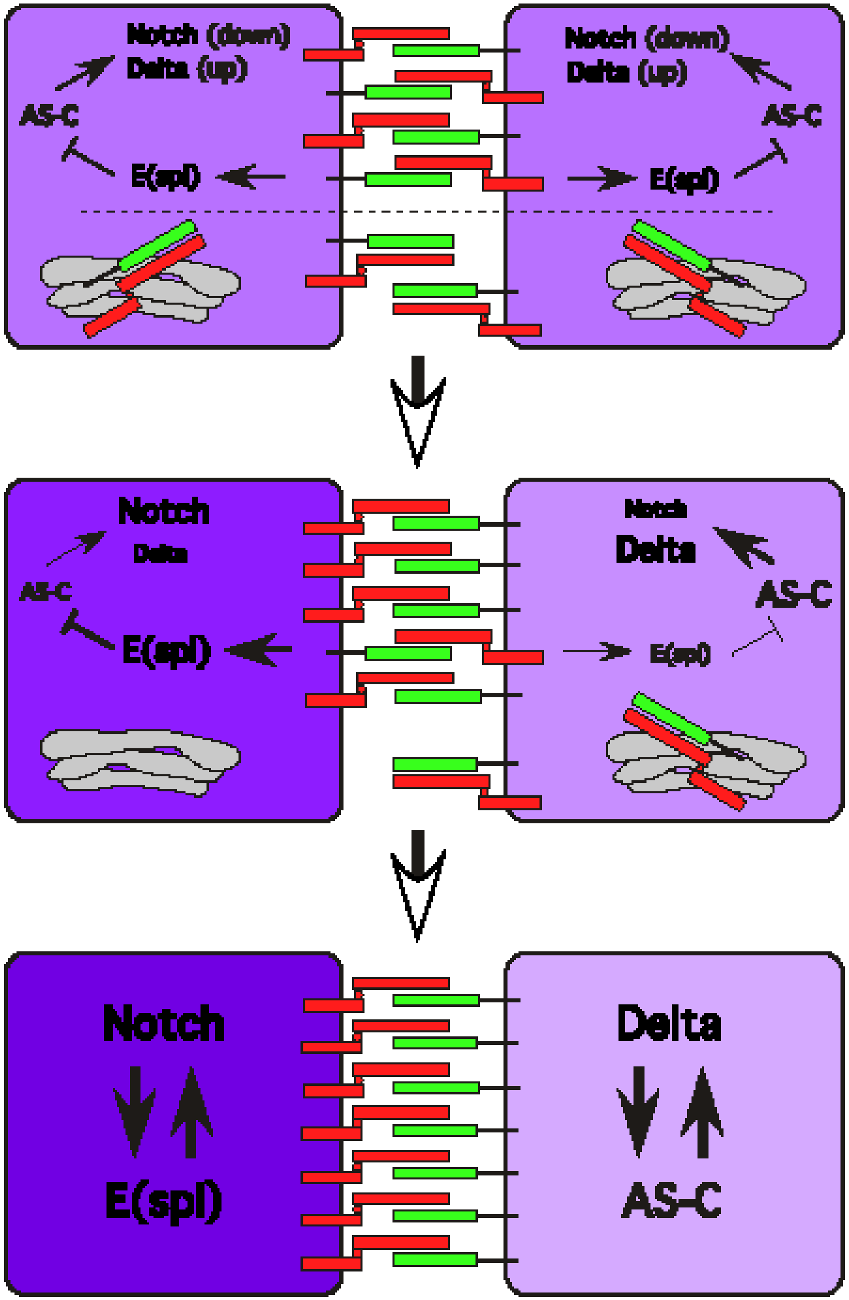
Each process needs to know how many neighbors its neighbors have

Luby ,*SIAM J. Comput.* 1986
Alon et al *J. Algorithms* 1986

Cell signaling



Lateral inhibition: Notch-Delta signaling

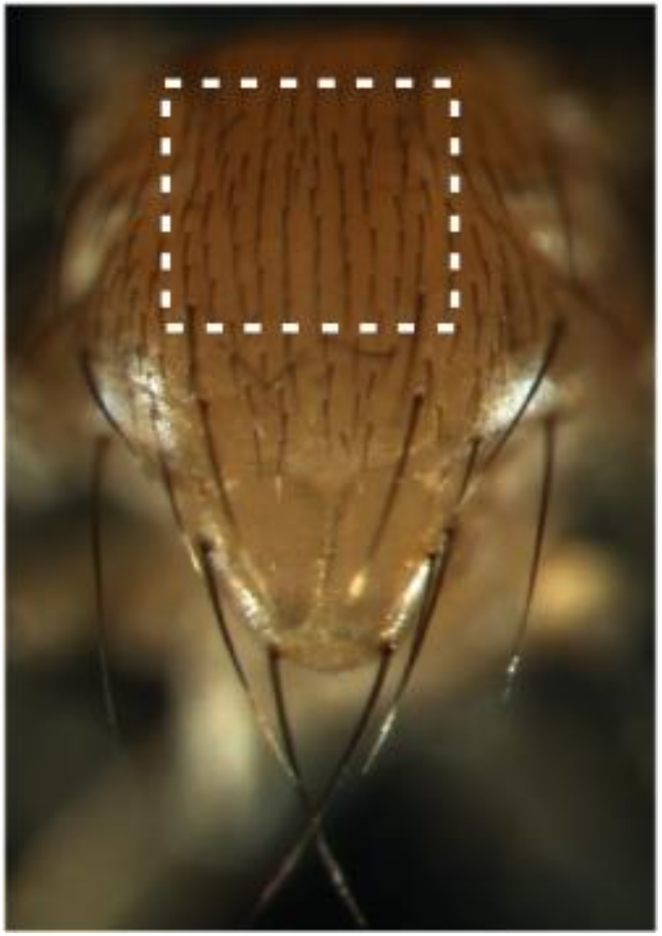


SOP selection in flies

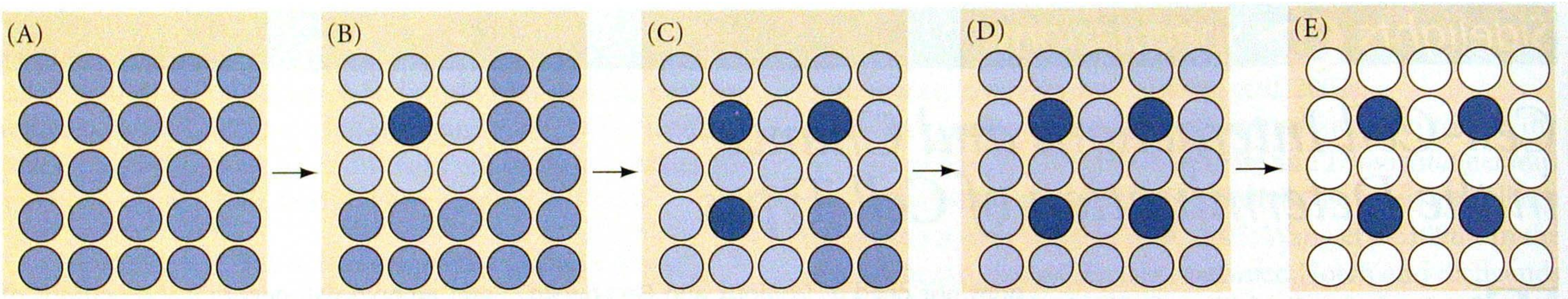
- When the fly’s nervous system develops several cells are selected as sensory organ precursors (SOPs)
- These cells are later attached to the fly's sensory bristles
- Similar to the MIS requirements, in a highly accurate process each cell in a predefined cluster is either:

  - Selected as a SOP

  - Laterally inhibited by a neighboring SOP so it cannot become a SOP



Generation of regular patterns of cells from equivalence groups



Similarities between MIS and SOP selection

- Both are performed using a stochastic processes

  - Proven for MIS, experimentally validated for SOP
- Both are constrained by time

  - A cell that is not inhibited by certain time becomes a SOP
- Both only send messages if a node (cell) decides to join *A*

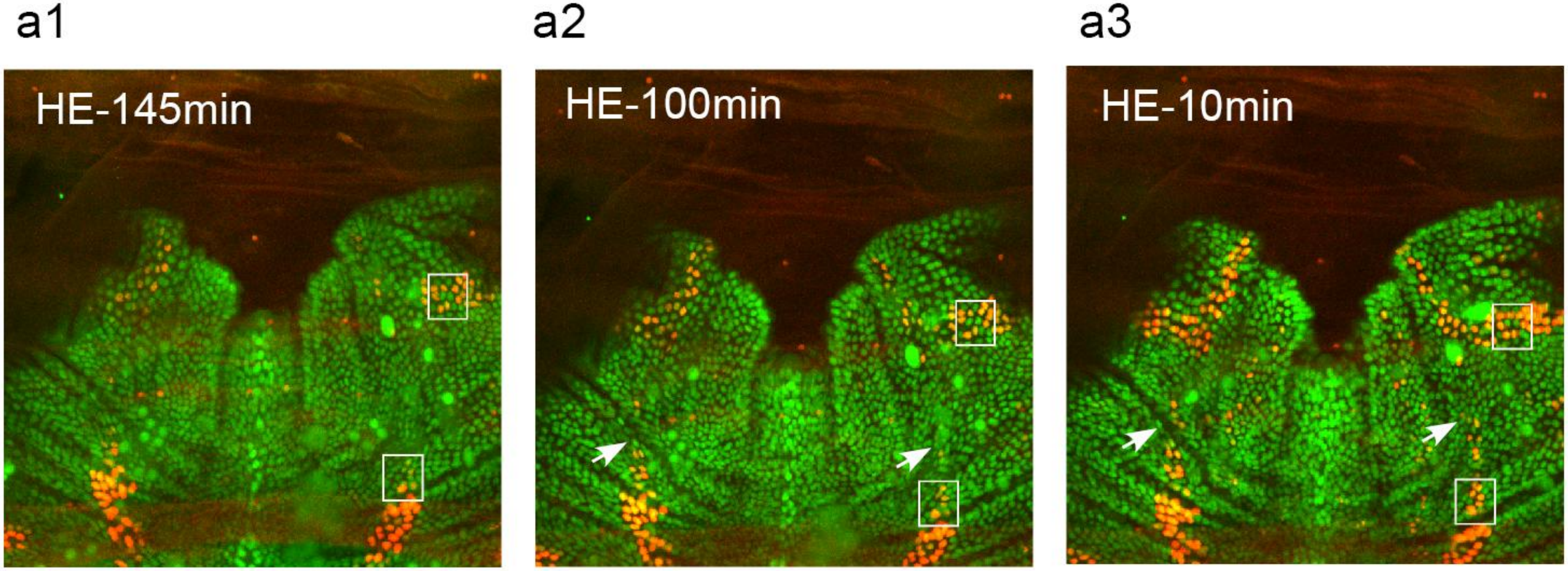
  - Reduces communication in computational systems, based on *cis* interactions for cells

Differences between SOP and MIS selection

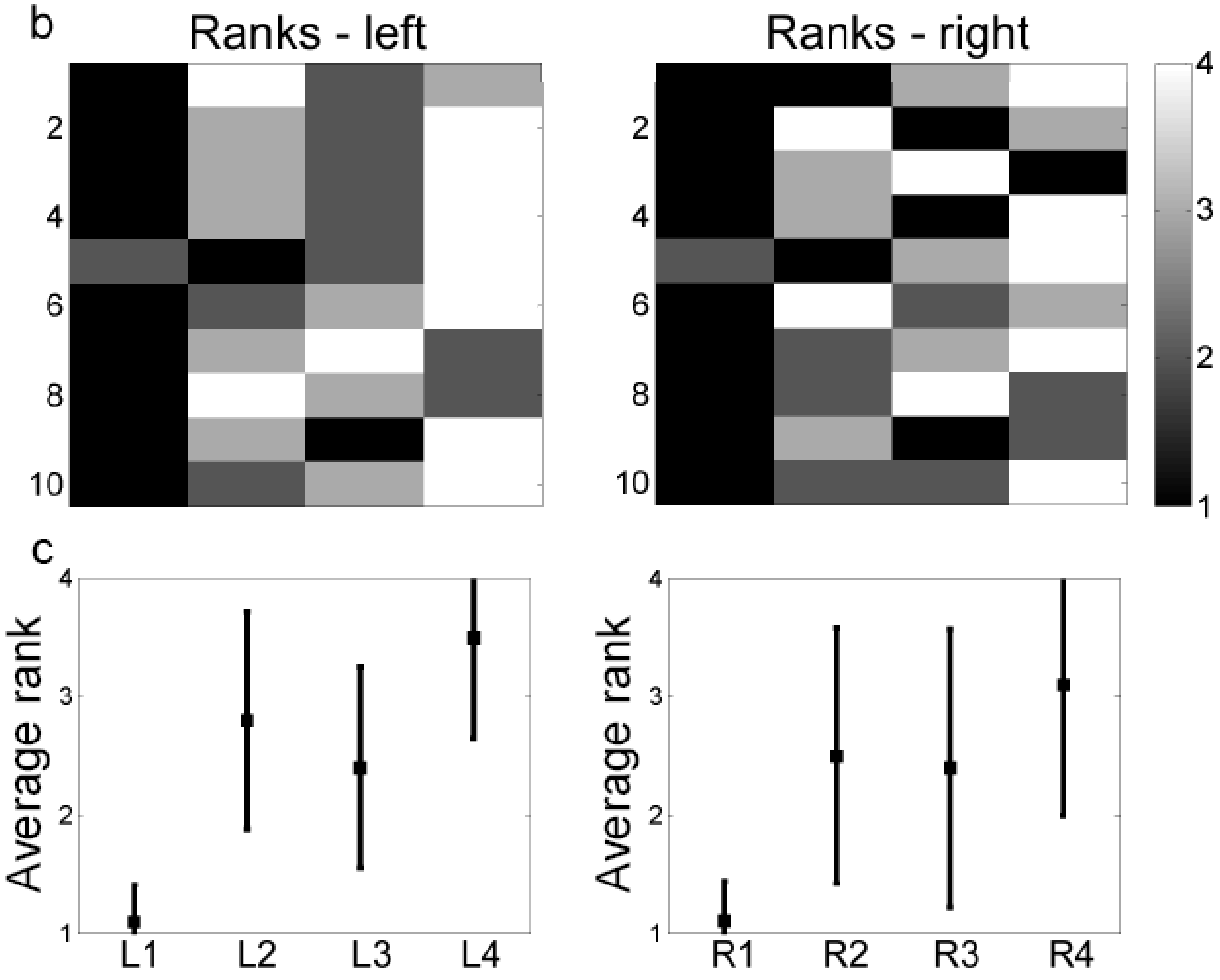
- In SOP selection cells do not know the status of their neighbors and the overall topology
- Messages in SOP selection are binary

Can we improve current algorithms for MIS by understating how the biological process is performed?

Movie



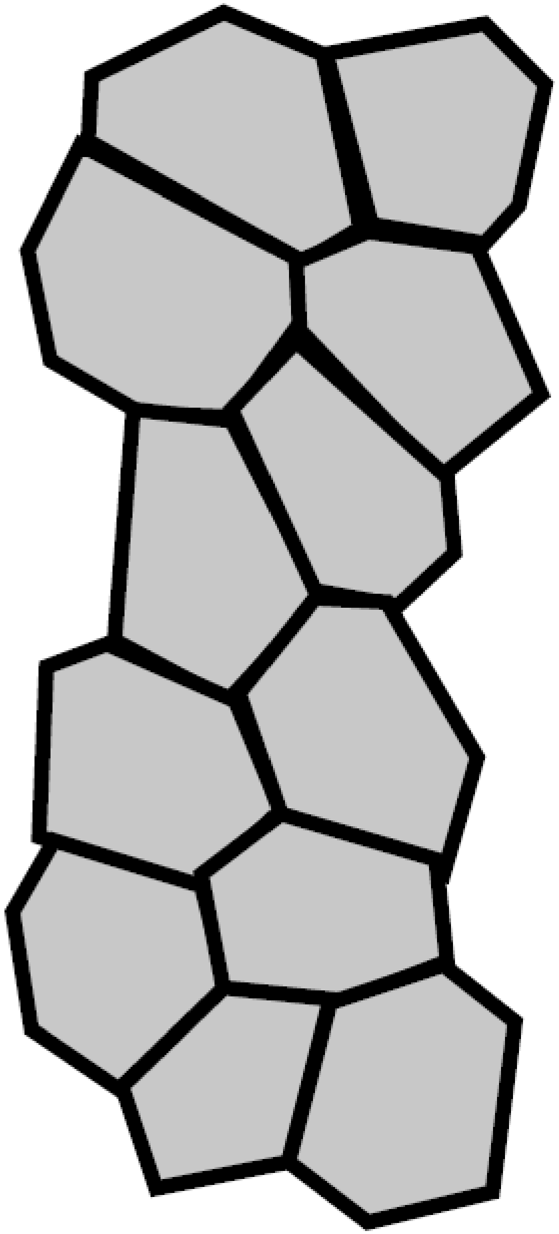
Observation 1: SOP selection is stochastic



Simulations

• 2 by 6 grid (also tried 2 by 7)

• Each cell touches all adjacent and diagonal neighbors



Simulations

- All models assume a cell becomes a SOP by accumulating the protein Delta until it passes some threshold

Four different models:

1. Accumulation

   - Accumulating Delta based on a Gaussian distribution

2. Fixed Accumulation

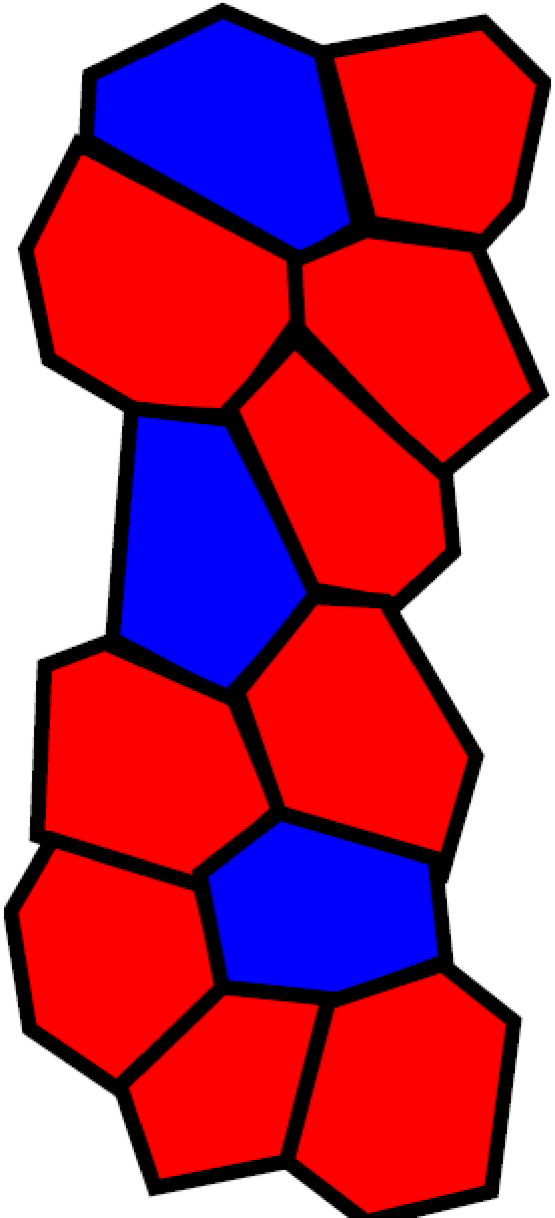
   - Randomly select an accumulation rate only once

3. Rate Change

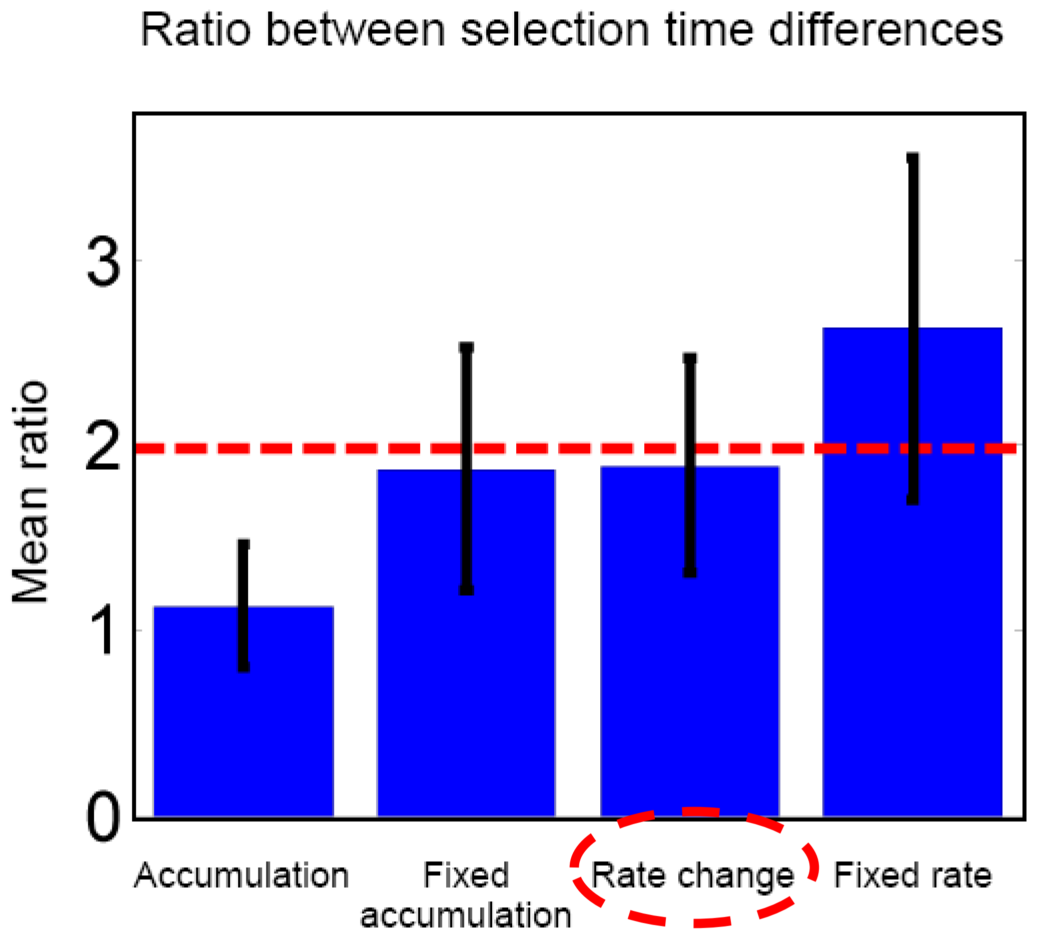
   - Increase accumulation probability as time goes by usind feedback loop

4. Fixed rate

   - Fix accumulation probability, use the same probability in all rounds



Observation 2: Comparing the time of experimental and simulated selection



MIS Algorithm (revised)

MIS Algorithm (n,D) // n – upper bound on number of nodes

D - upper bound on number of neighbors

- *p = 1/D*
- round = round +1
- if round > log(n)

  *p = p * 2* ; round = 0 // we start a new phase
- Each processor flips a coin with probability *p*
  - If result is 0, do nothing
  - If result is 1, send to all other processors
    - If no collisions, Leader; all processes exit
    - Otherwise

Afek et al *Science* 2011, Afek et al DISC 2011

Why does it work?

- Can show that by phase *i* there are no processes with more $n/2^i$ neighbors
- Overall running time is O(log (n) log(D)) where D is an upper bound on the number of neighbors
- For grids this is as fast as the best known algorithm for this problem.
- Message complexity is also extremely low: O(n)

Can be extended to:

1. Continuous probability increases
2. Unsynchronized settings
3. Cases where no upper bound is given on degree
4. No collision detection

(several) open problems

- Can we learn how to protect important nodes from the way cells rely on redundancy?
- Can we improve coordination among agents (or robots) based on bacterial quorum sensing?
- What other specific biological problems can gain from the information processing prescriptive, and how insights into these will improve computational algorithms?

Thanks

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