Robustness, evolvability and complexity in Boolean network robots

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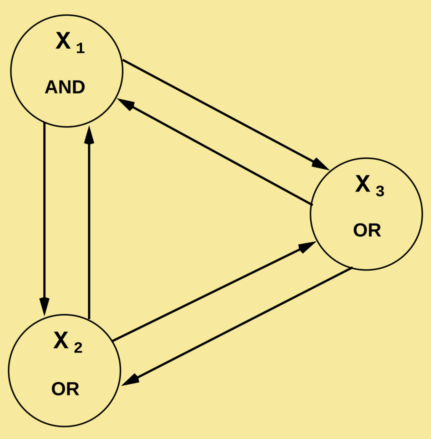
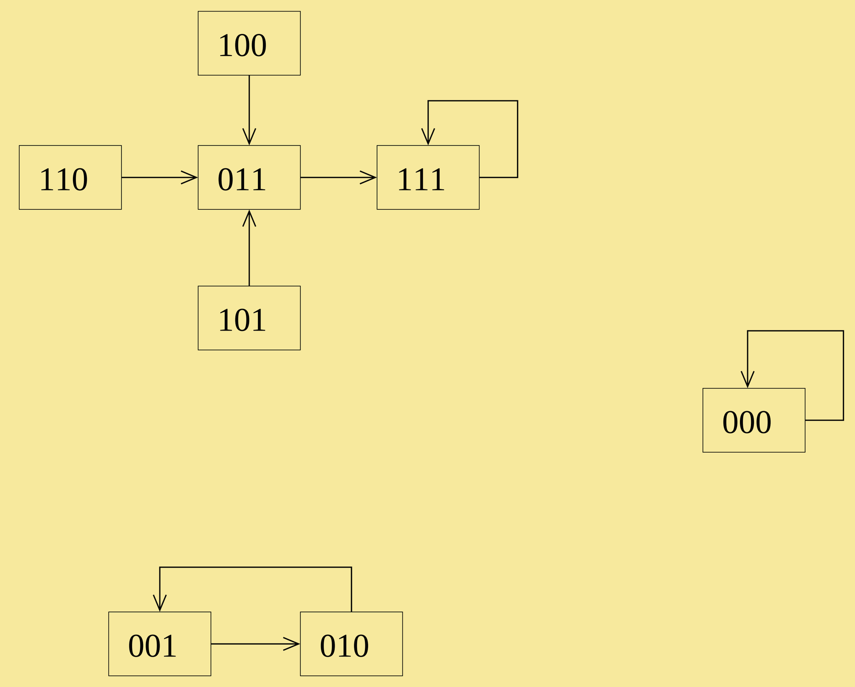
Boolean Networks

BN structure and transition table

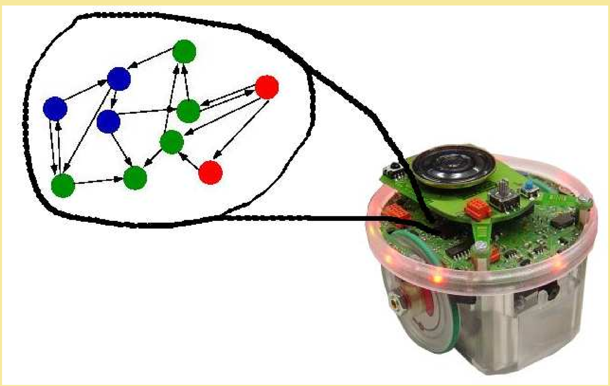


x_1 (t)	x_2 (t)	x_3 (t)	x_1 (t+1)	x_2 (t+1)	x_3 (t+1)
0	0	0	0	0	0
0	0	1	0	1	0
0	1	0	0	0	1
0	1	1	1	1	1
1	0	0	0	1	1
1	0	1	0	1	1
1	1	0	0	1	1
1	1	1	1	1	1

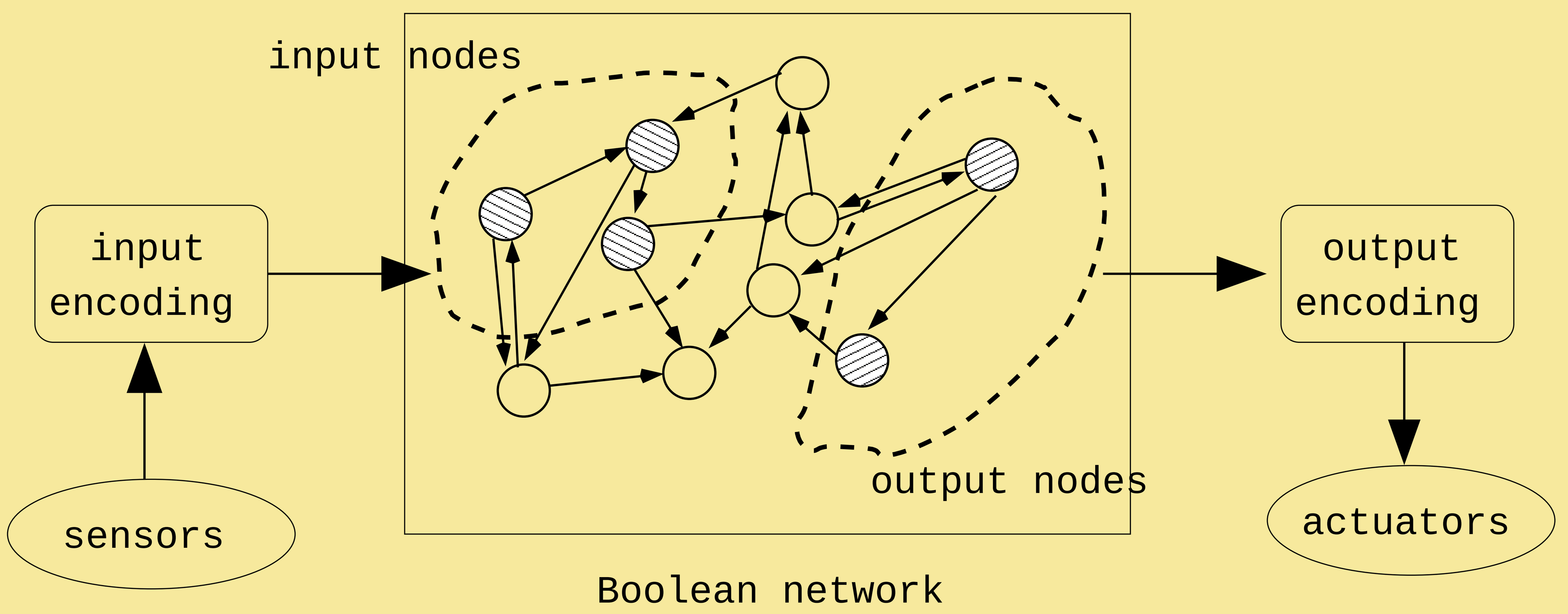


BN state space

Boolean Network robot

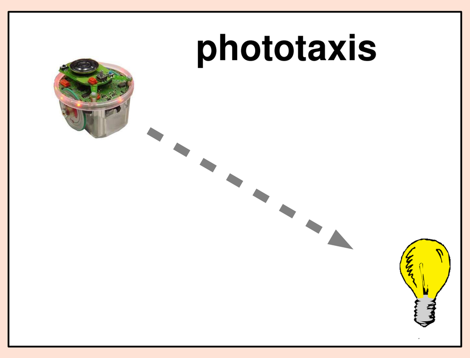


Robot controlled by a Boolean network

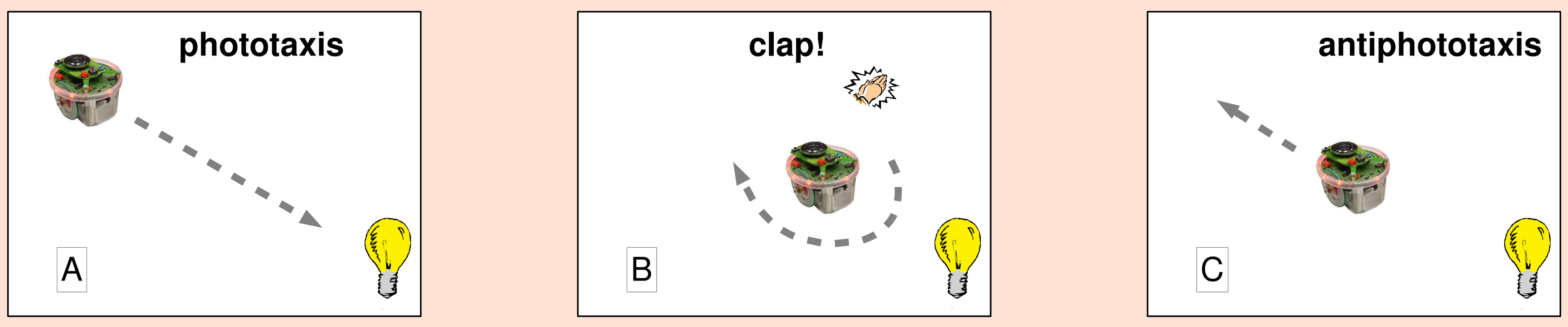


The robot's goal

Task 1 The robot is trained to perform phototaxis



Task 2 The robot is trained to perform **phototaxis first, then antiphototaxis**



- Besides being **evolvable**, the robot must also be **robust**, i.e., able to correct its trajectory in case of noise and external perturbations

Learning algorithm

- **Adaptive walk** (a.k.a. stochastic descent)
- Mutation: one flip in one function's truth table (randomly chosen)
- BNs with random topology

Incremental training:

- Task1 (phototaxis), until iteration 5×10^3
- Task2 (phototaxis + antiphototaxis), from iteration $5 \times 10^3 + 1$

Symbolic dynamics analysis

- Analysis of trajectories in the BN state space
- Trajectory features: number of states visited, number of fixed points, statistical complexity, etc.
- Same results in simulation and real testing

100 evolved robots divided into three classes

Good: successfully accomplishes both Task1 and Task2 ($\approx$ 30%)
Bad: attains only Task1 ($\approx$ 55%)
Worst: can not even perform Task1 ($\approx$ 15%)

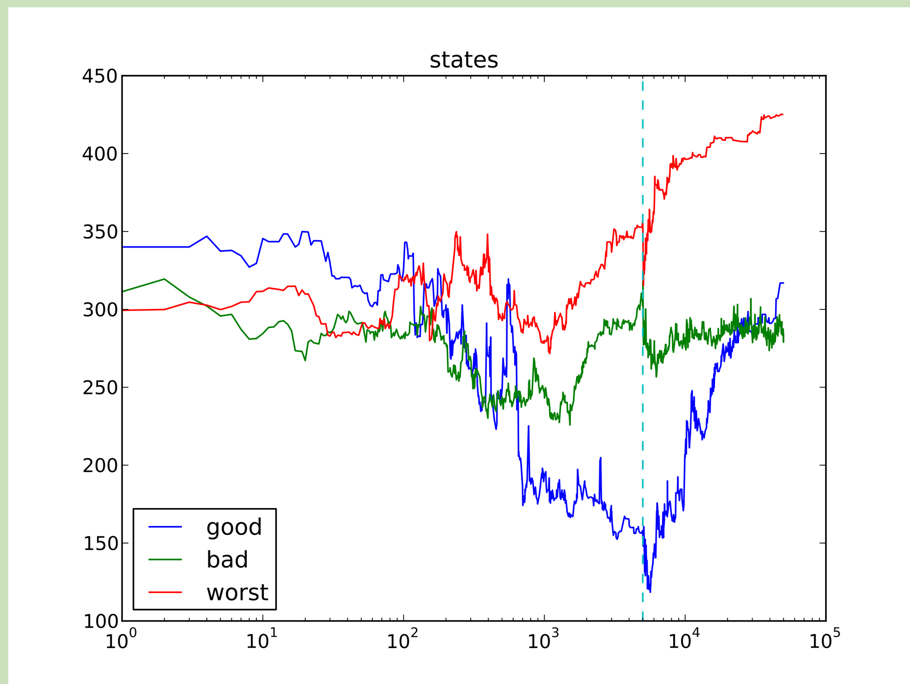
"Good" robots optimally balance robustness and evolvability

Results

Averages over "good" robots (in blue):

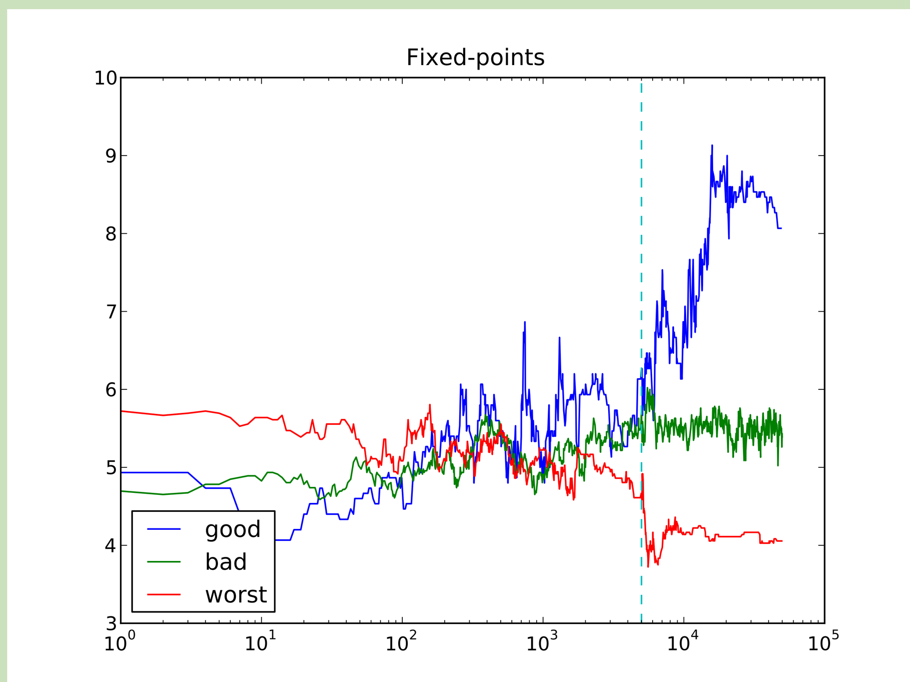
Generalisation

- The number of **visited states** decreases during evolution (Task1);
- then, it increases to take into account also the new task (Task2);
- finally, it converges.



Adaptive walk iterations
(Task1: until 5×10^3, then Task2)

Emergence of micro-behaviours

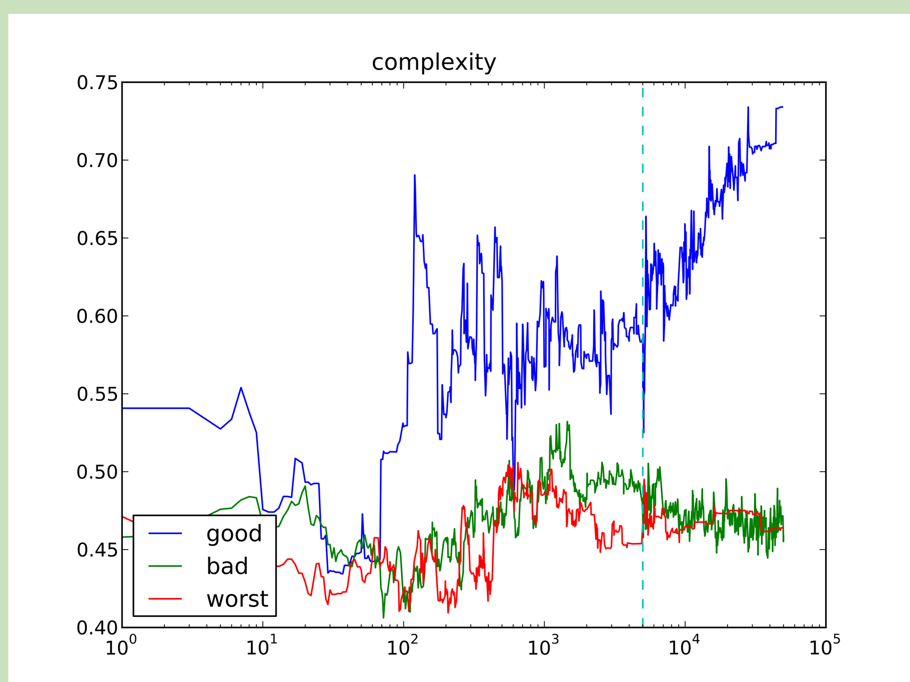


Adaptive walk iterations
(Task1: until 5×10^3, then Task2)

- The number of **fixed points** increases and then saturates at the end of evolution
- Fixed points represent micro-behaviour (e.g., "go straight", "turn left")

Complexity

- **Complexity = Entropy** $\times$ **Disequilibrium**
- the complexity steadily increases



Adaptive walk iterations
(Task1: until 5×10^3, then Task2)

BN Robotics website: http://iridia.ulb.ac.be/bn-robotics/

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