Evolution, Self-Organisation and Swarm Robotics

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Self-Organisation in Action

- example: synchronisation
  - each metronome influences its neighbours
  - local interactions lead to global order
- synchronisation emerges thanks to self-organisation

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What is Self-Organisation?

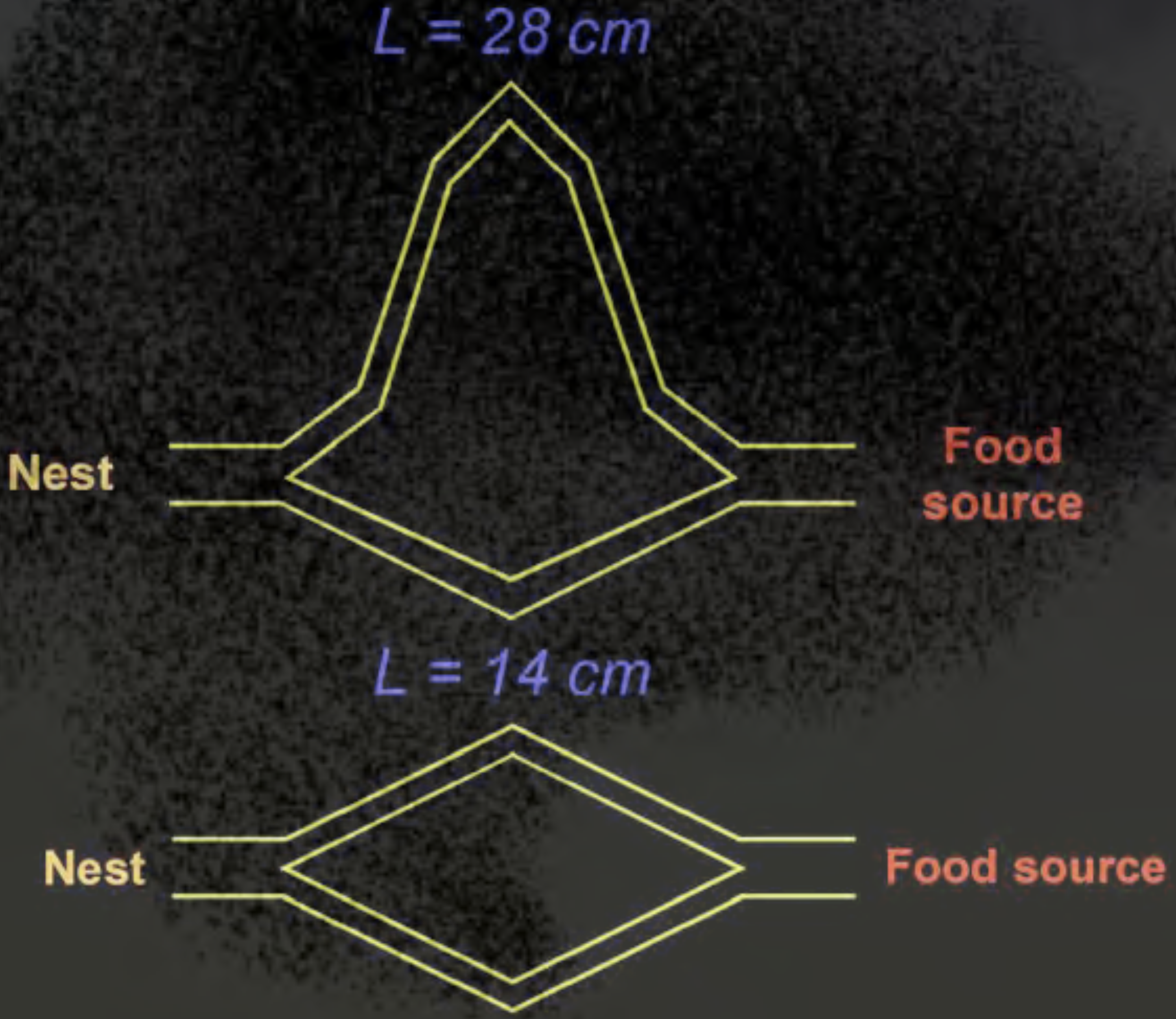
- emergence of global order in a system
- numerous interactions among the system components
- simple individual rules
- local information
- no reference to the global pattern

Engineering Self-Organisation

- Self-organising systems feature properties like robustness, flexibility and adaptivity
- Difficult to engineer systems having complex interacting entities
- Nature knows best: the Swarm Intelligence approach

Swarm Intelligence

Iridomyrmex humilis



Deneubourg et al. (1990). Jour. Ins. Behav. 3:159-198

Swarm Intelligence

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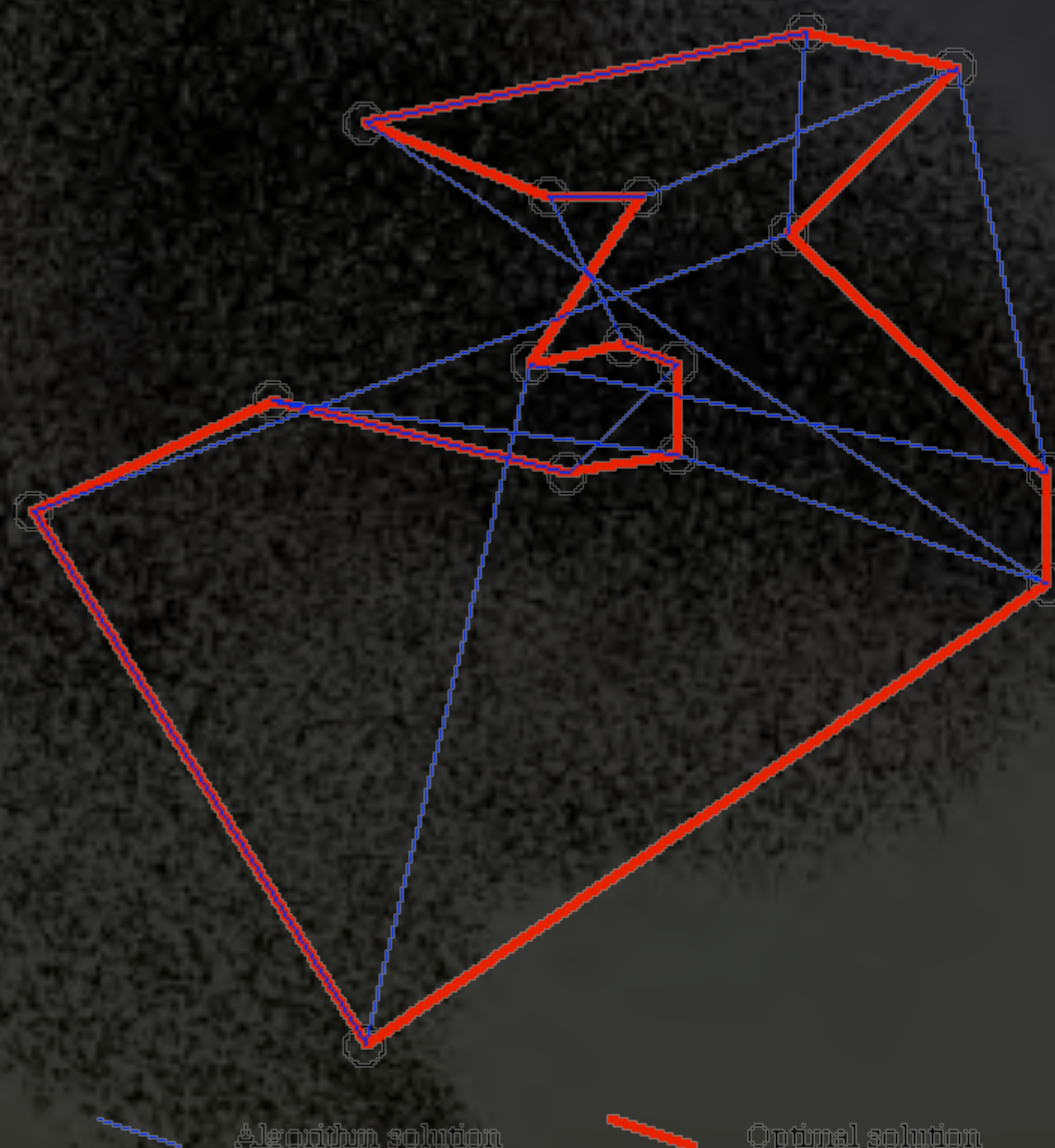
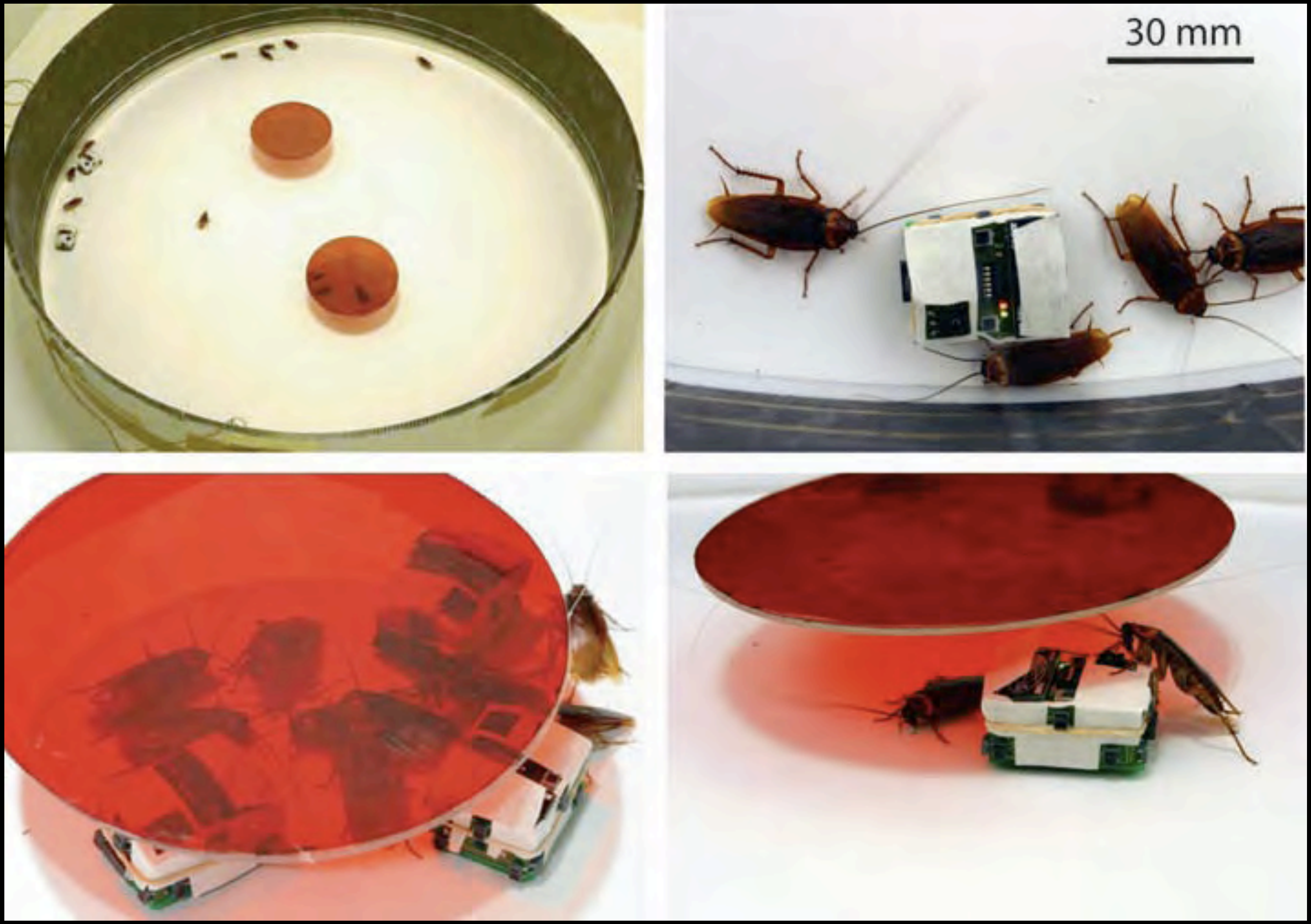


Ant Colony Optimisation

M. Dorigo & T. Stützle, Ant Colony Optimization, MIT Press, 2004

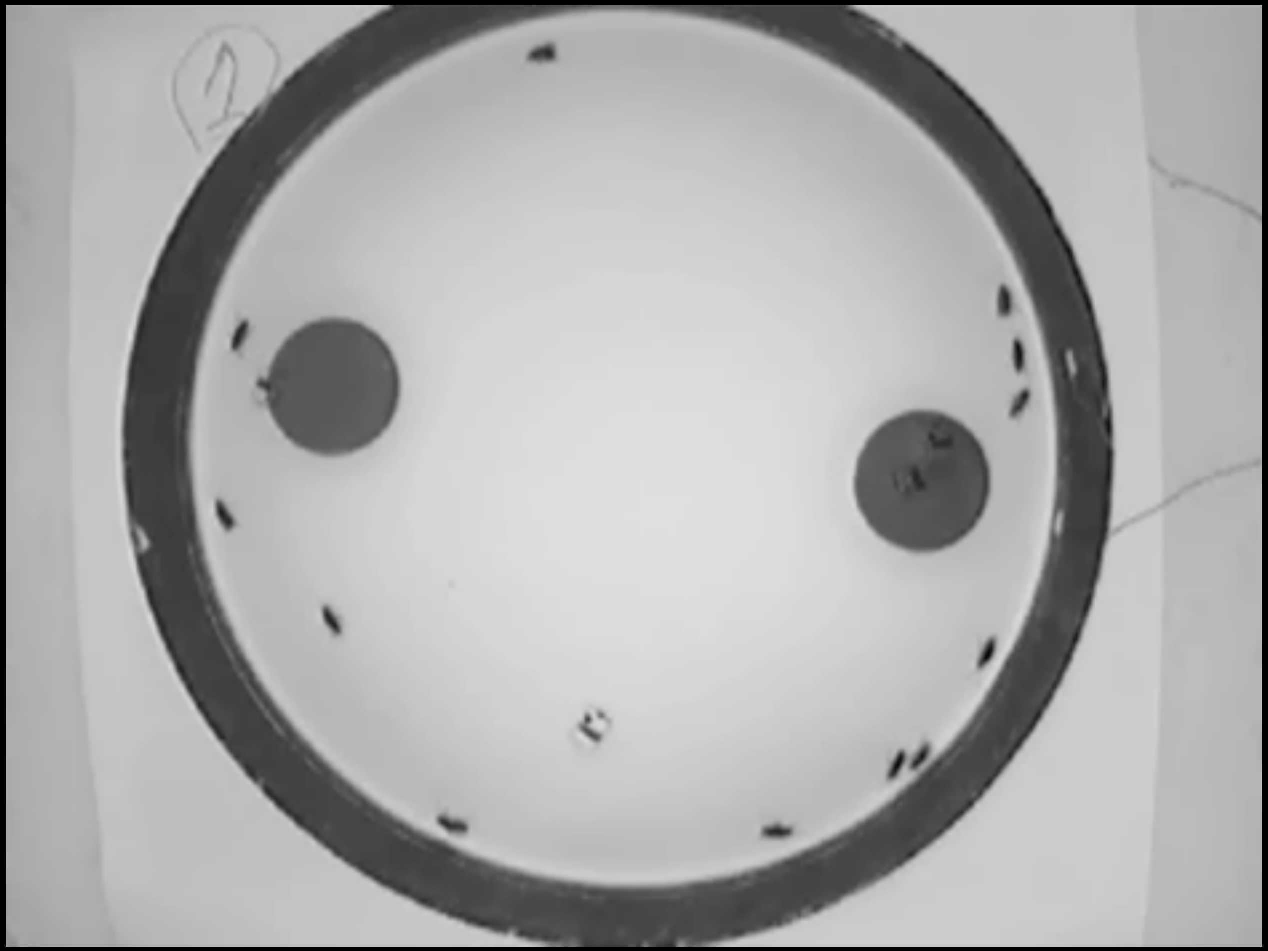
Steering Self-Organisation



Halloy et al., (2007). Science, 318:1155-1158

Steering Self-Organisation

1 minute



3 hours

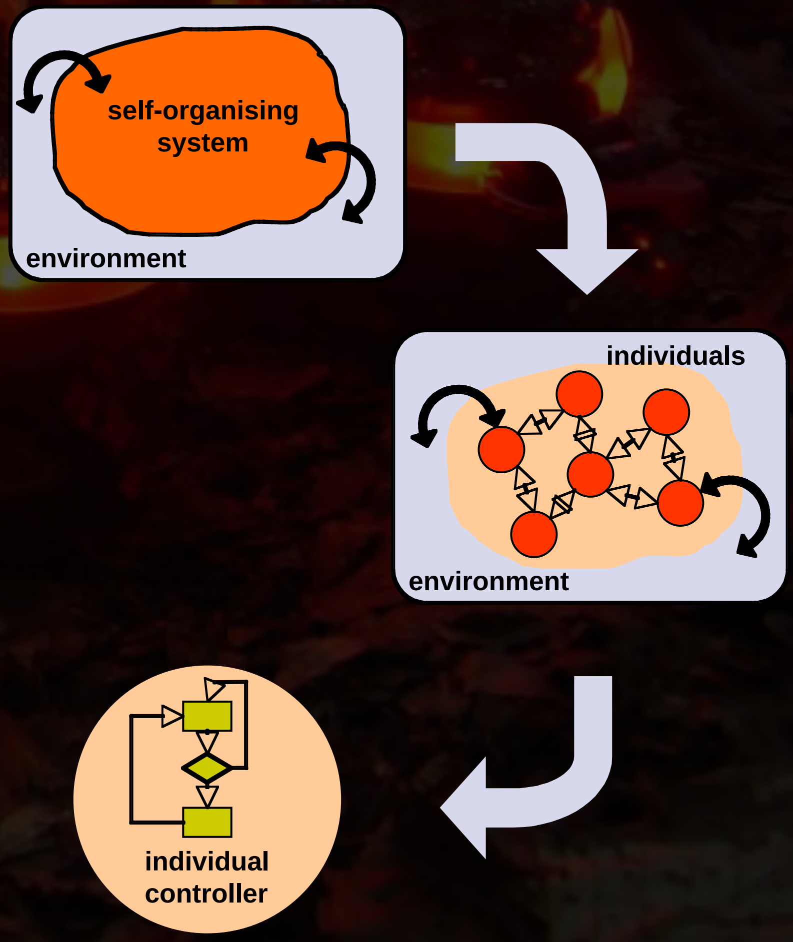
Halloy et al., (2007). Science, 318:1155-1158

From Swarms to Robots

- Swarm robotics: groups of robots having self-organising behaviour
  - distributed control of interacting and cooperating robots
  - limited individual abilities, complex group behaviours
- The problem:
  how to design the control system
  to obtain a self-organising behaviour?

Divide & Conquer

- Define the individual controllers to obtain a coherent group behaviour
- Two step decomposition
  - from global to individual behaviours
  - from individual behaviour to controller rules



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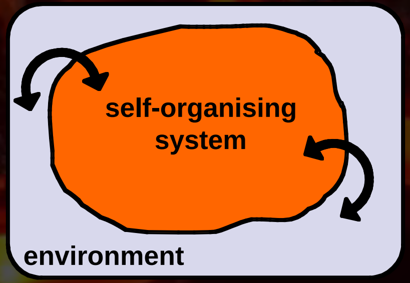
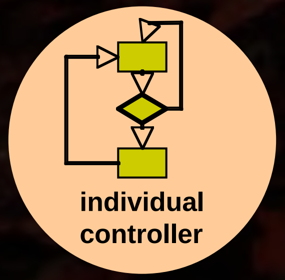


- Two step decomposition
  - from global to individual behaviours
  - from individual behaviour to controller rules

$$\dot{x} = xy + p(x)$$
$$\dot{y} = y^3 + q(x, y)$$



Iterative Design

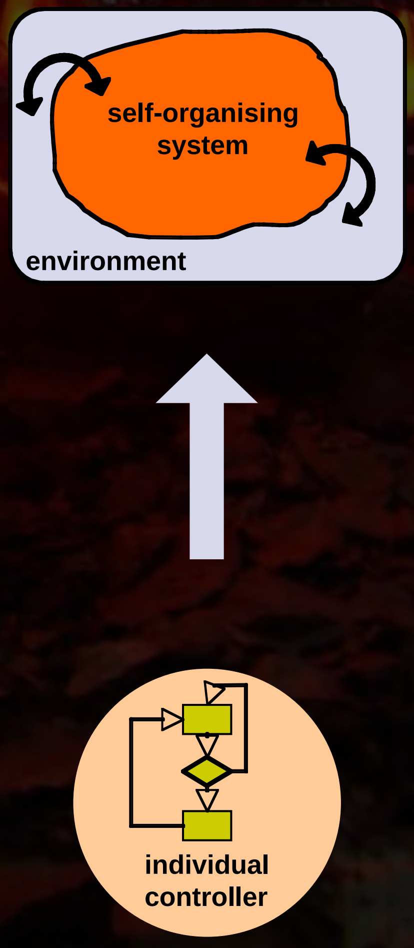
- **Design phase:**
  identify individual behaviours and
  relevant inter-individual interactions
- **Development phase:**
  encode the control rules for the individual agents
- **Analysis phase:**
  verify/validate the properties of the system

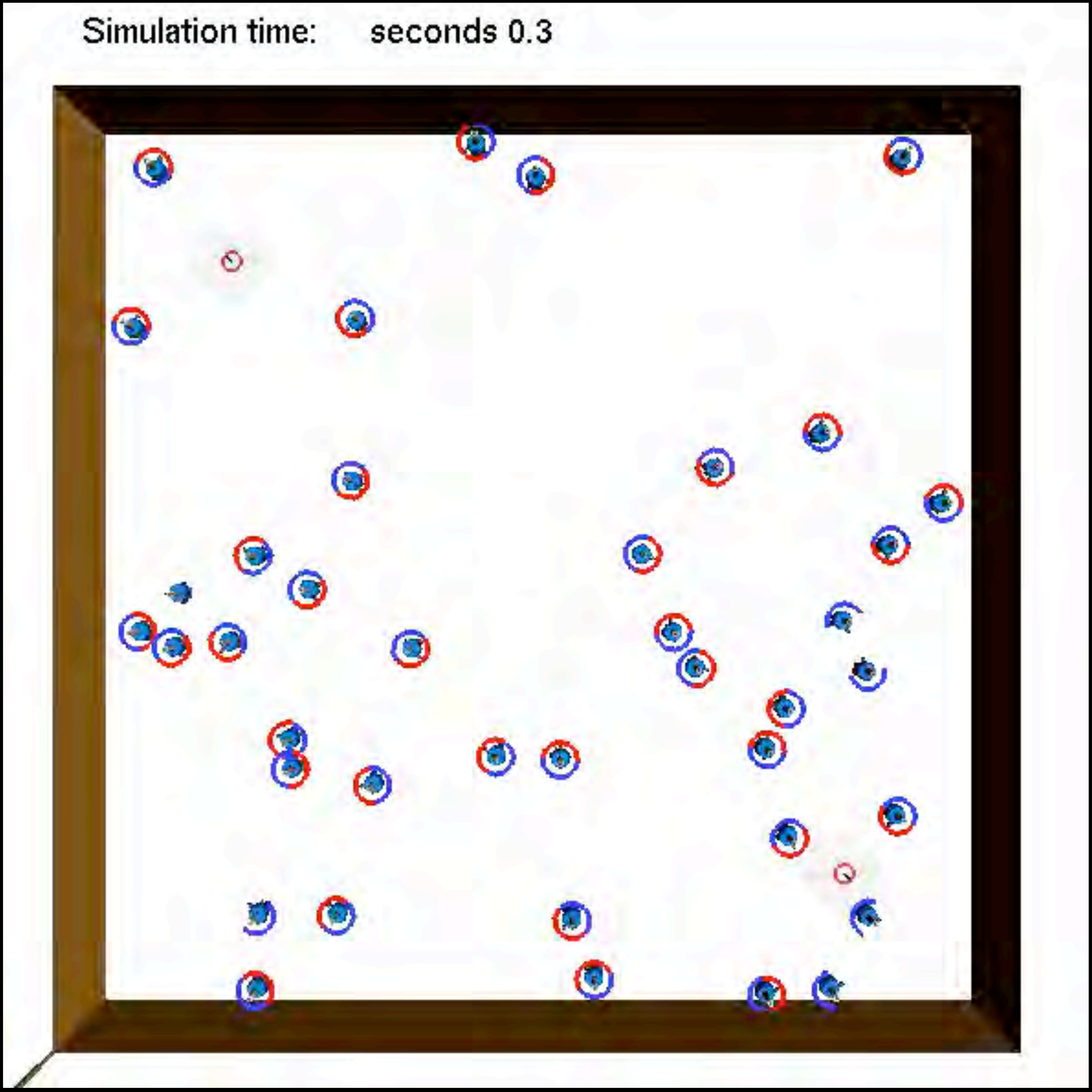
The Design Problem

- Difficult to decompose the global behaviour into individual controllers
- Strongly non-linear indirect relationship between individual rules and group behaviour
- The details matter!

Artificial Evolution

- automatic design process based on the natural evolution metaphor
- evaluate controllers for their ability to produce self-organisation
  - evaluation of the system as a whole
  - exploitation of the fine-grained dynamical interactions




Simulation time: seconds 0.3

Evolutionary Design

- Design phase:
  define the genotype-to-phenotype mapping,
  define the interfaces with the (social) environment,
  define the selective pressures (explicit or implicit)
- Development phase:
  run the evolutionary machinery
- Analysis phase:
  verify/validate the properties of the system,
  identify the evolved mechanisms

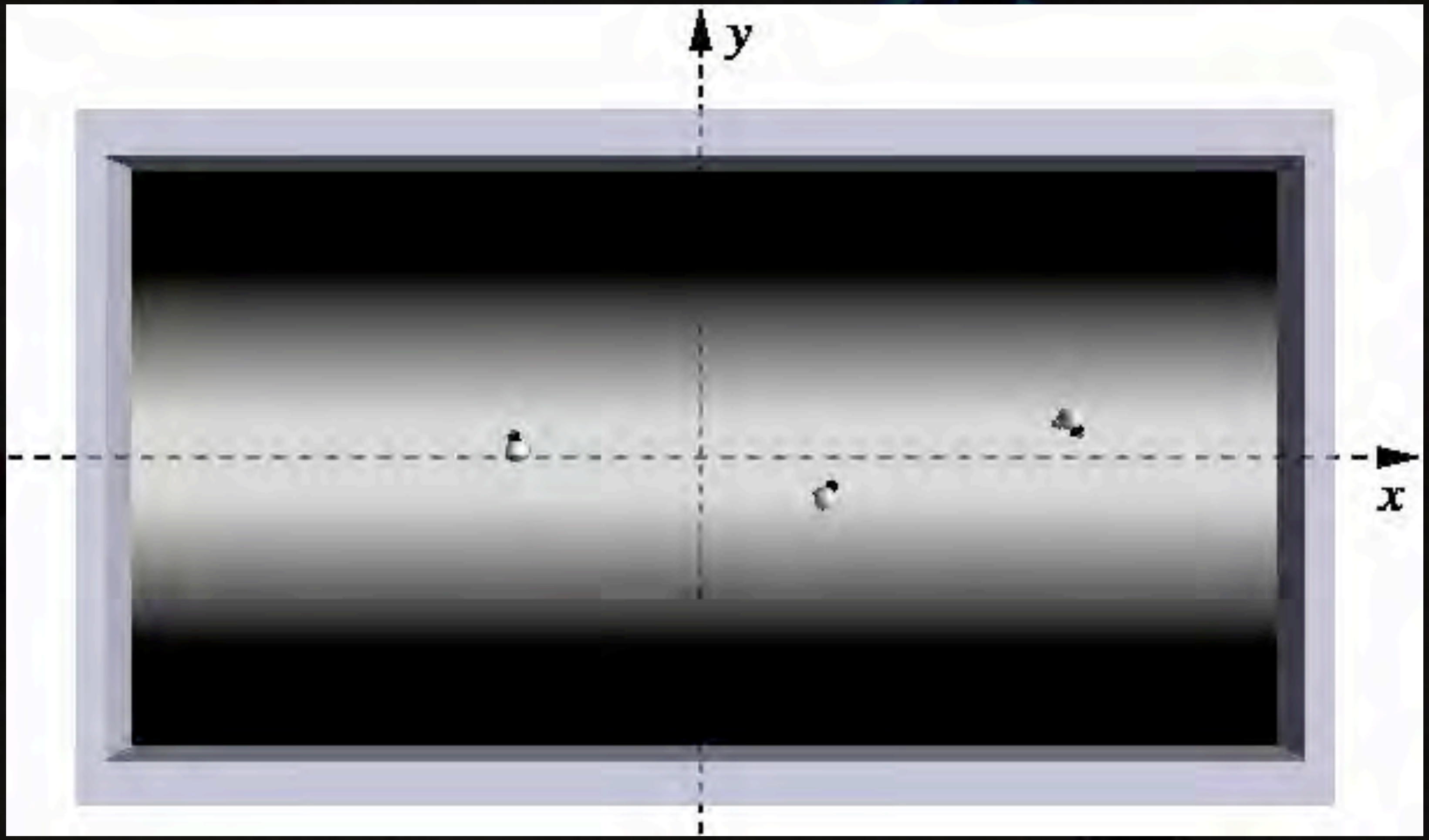
Summary

- Seek for self-organisation in artificial systems
    - decentralisation
    - simple individual behaviour, complex group patterns
    - flexibility, robustness and adaptivity
- Artificial evolution as a viable tool for the synthesis of self-organising behaviours
- Exploit dynamical system theory to analyse and predict the features of the evolved behaviours

A Case Study: Synchronisation

- the goal is investigating synchronisation in a swarm of autonomous robots
  - evolution of minimal behavioural and communication strategies
- synchronisation of the individual periodic behaviour
  - individual oscillations over a grey gradient
  - coupling among robots through communication

Simulation Environment



- rectangular arena surrounded by walls
- symmetric gradient in shades of grey painted on the ground
- oscillatory movements parallel to the *y* axis

Robot configuration

- Simple neural network for controlling the robot
  - Configuration for the individual behaviour:
    - ground sensors for ground colour perception
    - infrared proximity sensors for obstacle avoidance
    - two wheels for differential drive motion
  - Configuration for synchronisation:
    - coupling through a user-defined communication protocol

Communication

- Minimal communication
  - global signals → perceived everywhere
  - binary signals → either 0 or 1
- Each robot can produce a binary signal $S_r(t)$
- The signal $s(t)$ is perceived by all robots in the arena

$$s(t) = \max_r S_r(t) \in \{0, 1\}$$

Evolutionary Setup

- Evolution of homogeneous groups
- The fitness of a trial is the average of:
  - movement component
    → fast motion parallel to the y axis
  - synchronisation component
    → cross-correlation of y position
- Results: evolution of synchronising behaviours successful in 20 different evolutionary runs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Synchronisation Behaviour

- The analysis revealed that synchronisation is the result of the robot’s reaction to perceived signals
    - robots can be considered embodied oscillators
    - phase modulation through sensory-motor coordination

Trianni V. and S. Nolfi, *Self-Organising Sync in a Robotic Swarm. A Dynamical System View.* IEEE Transactions on Evolutionary Computation. 13(4):722-741, 2009

Synchronisation Behaviour

- The analysis revealed that synchronisation is the result of the robot's reaction to perceived signals
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- How do the robots perform with larger groups?

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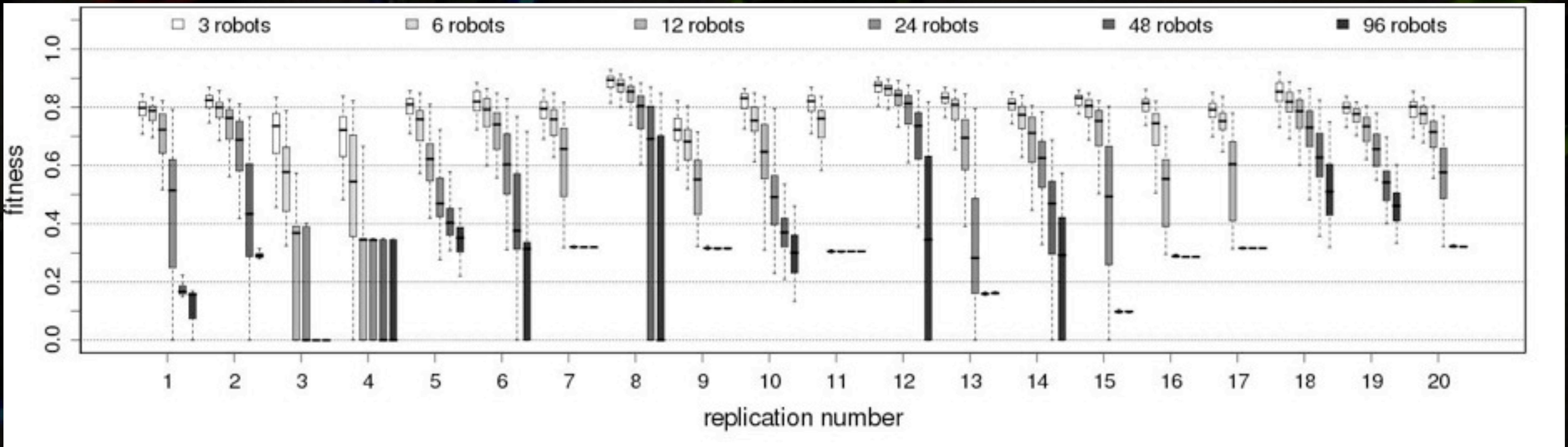
Scalability

- We test how controllers perform with more than 3 robots
  - we compare groups of 3, 6, 12, 24, 48 and 96 robots
  - same experimental conditions used during evolution
  - constant uniform density of robots in the arena

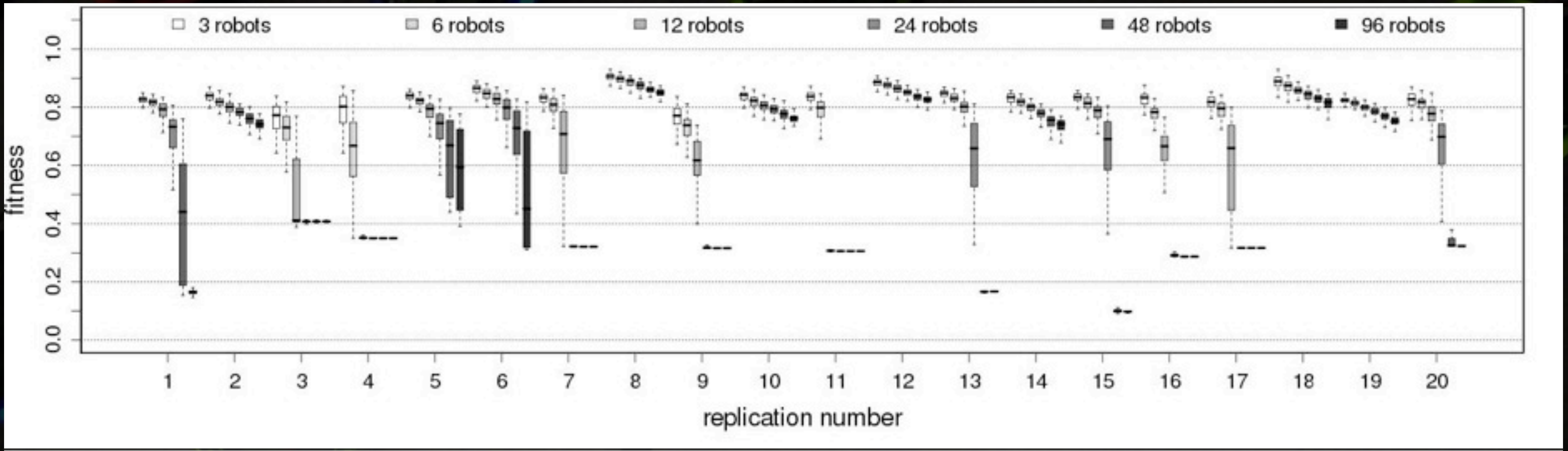


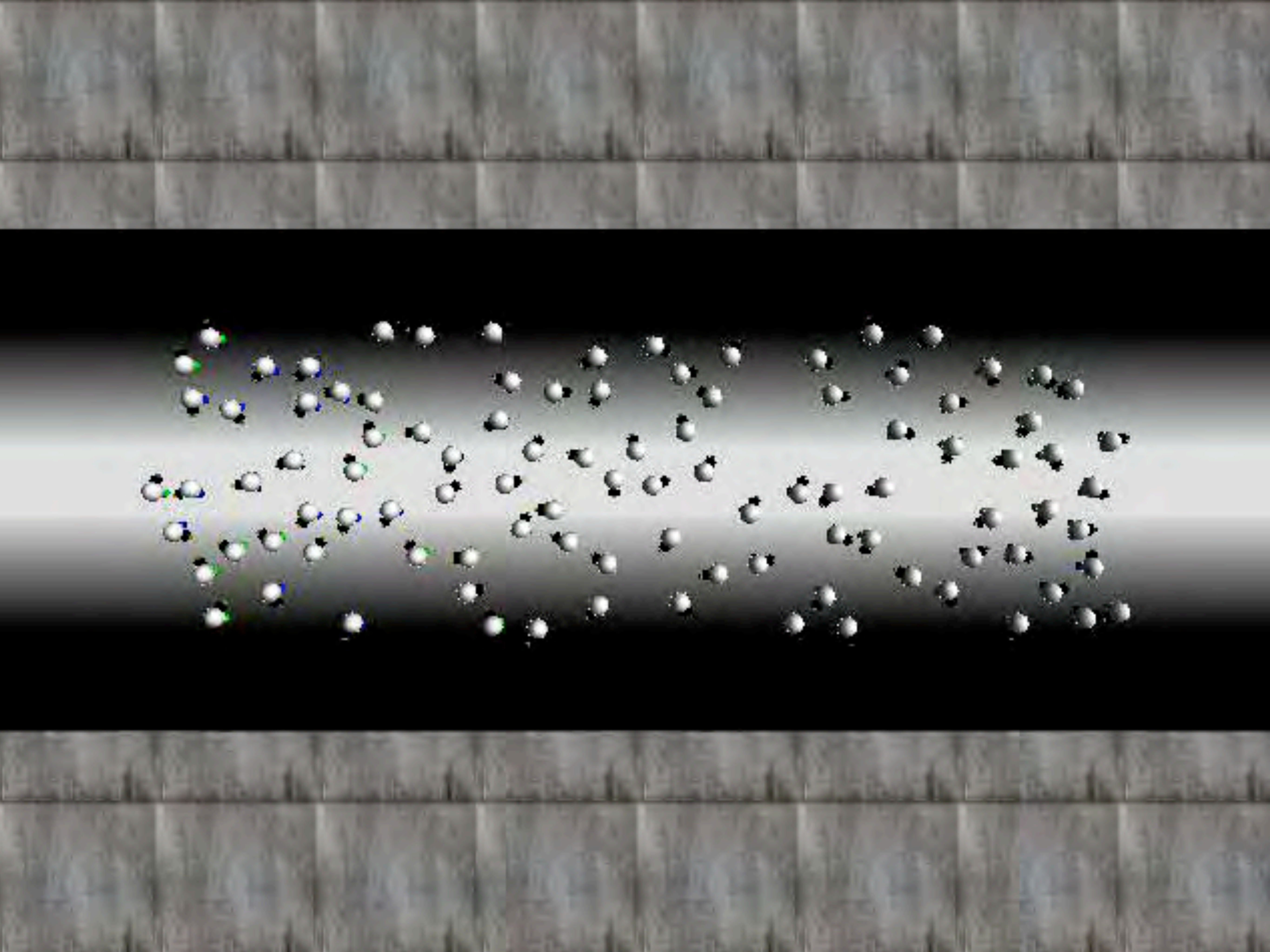
Scalability

- Scalability not always achieved
- Performance drop is a consequence of
  - longer transitory phase to achieve synchronisation
  - the larger number of collisions for larger groups
  - collision avoidance leads to de-synchronisation
  - global communication influences the whole group

Sync Scalability

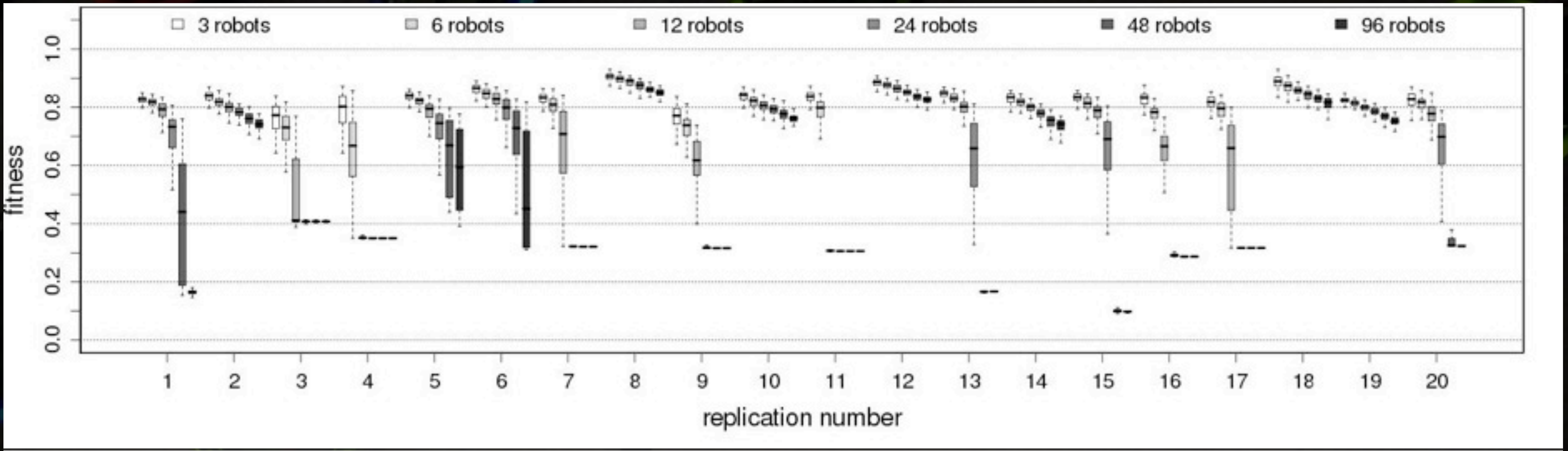
- We test the scalability of the synchronisation mechanism
  - neglect physical interactions
  - perform scalability analysis with the same modalities

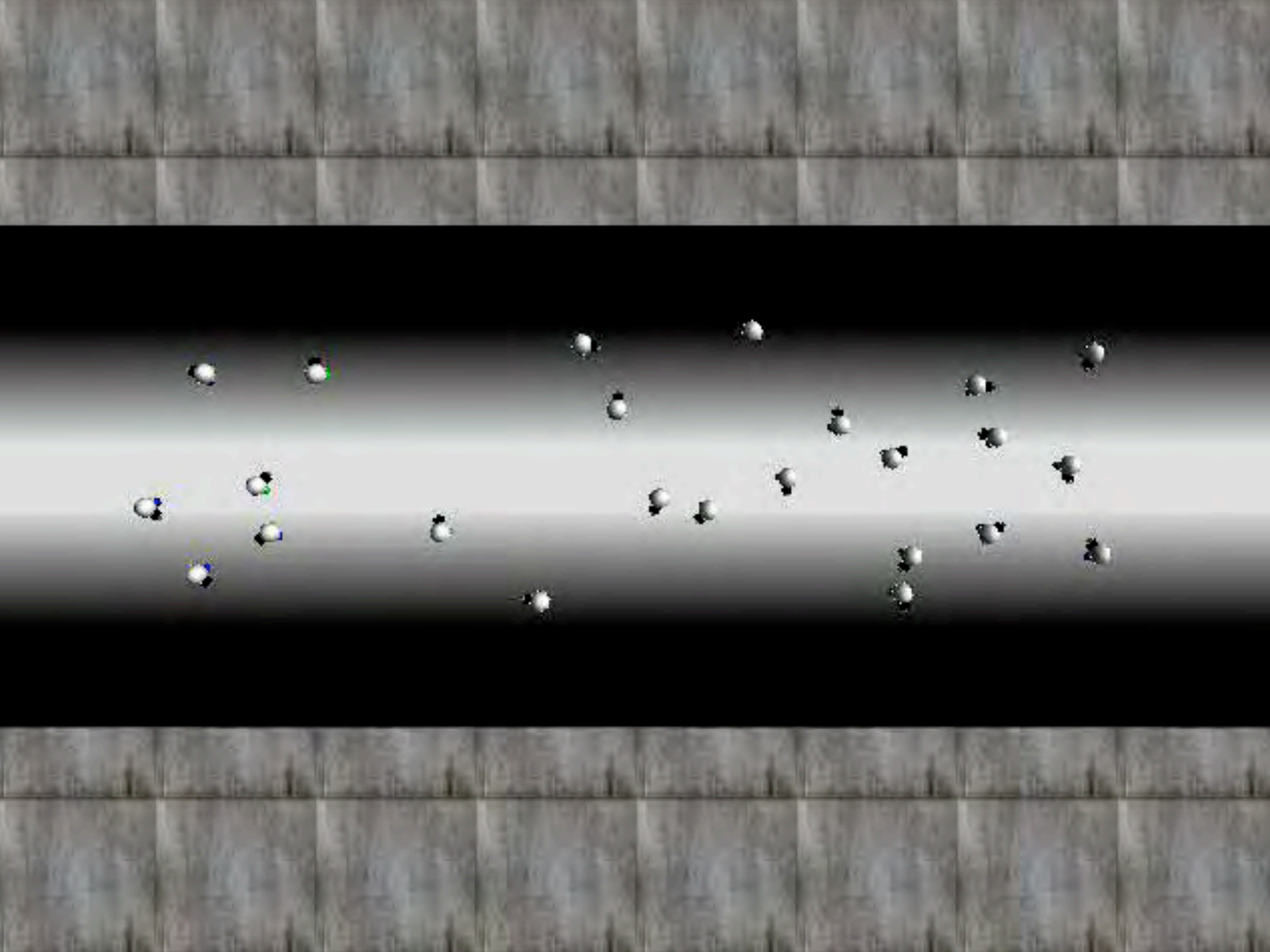




Sync Scalability

- some controllers present a strange behaviour
  - scalability up to a certain size
  - low constant performance for large groups
  - signals overlap in time and are perceived as a single signal





Re-Engineering Evolution

- The selected communication protocol has a strong impact on the system scalability
  - a single robot can influence the whole group
  - communicative interference prevent scalability
- The behavioural analysis identified two causes:
  - lack of locality
  - lack of additivity
- We decided to re-engineer the experimental setup to obtain better results

Additive Communication

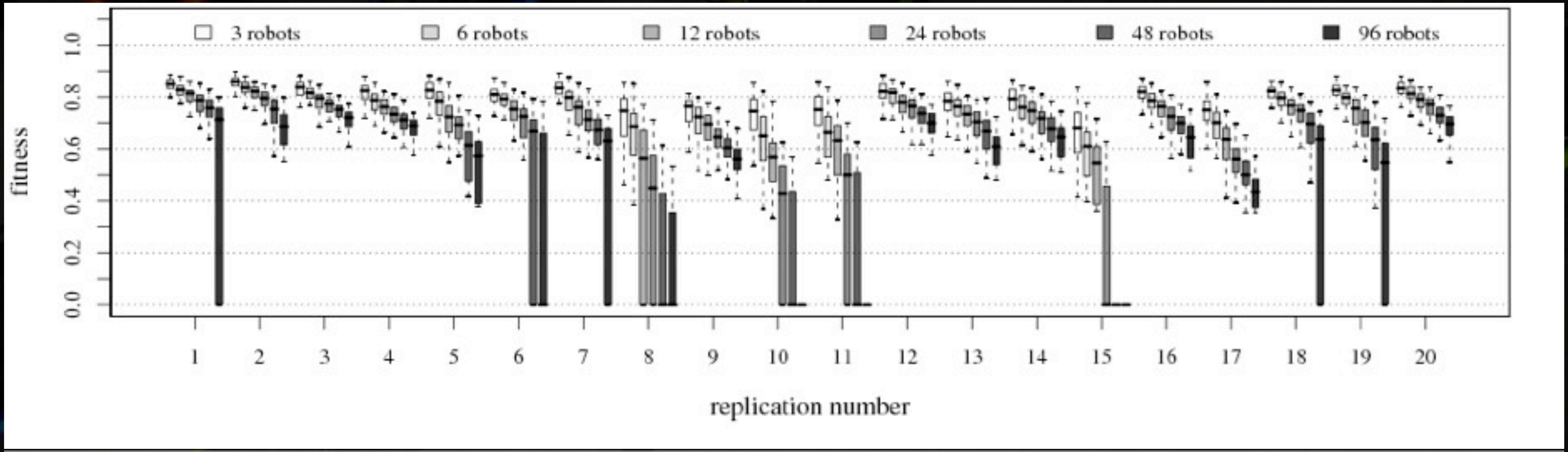
- We implement a new additive communication protocol
- Robots emit and perceive continuous signals

$$s(t) = \max_r S_r(t) \in \{0,1\} \quad \longrightarrow \quad \tilde{s}(t) = \frac{1}{N}\sum_{r=1}^{N} \tilde{S}_r(t) \in [0,1]$$

- We evolve new synchronisation behaviours

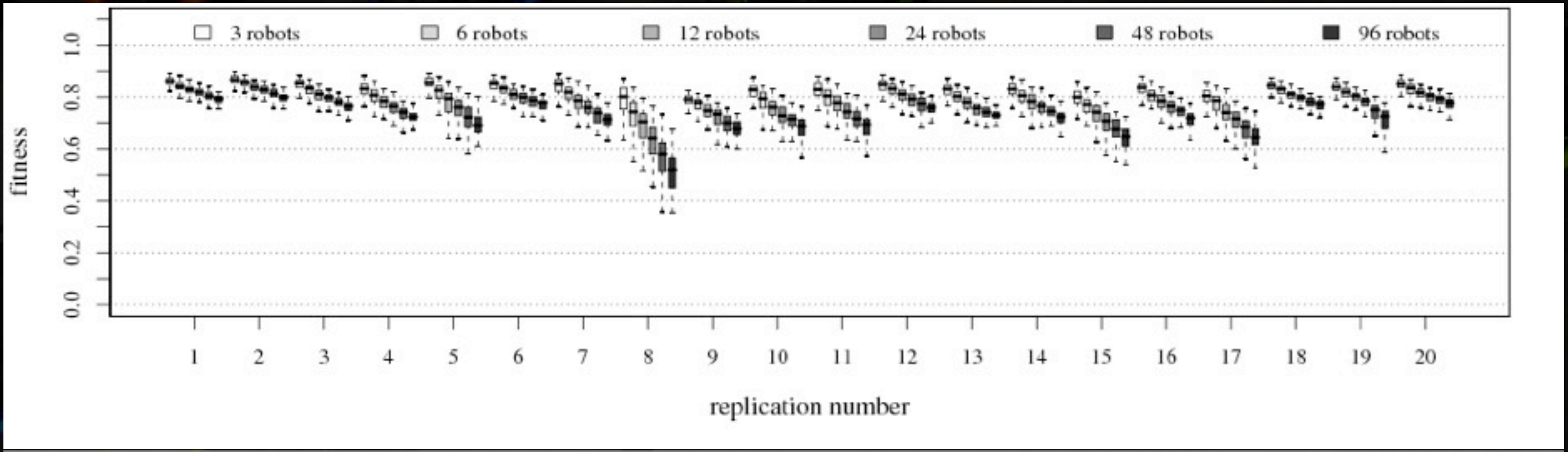
Scalability Analysis

- The usage of an additive communication protocol leads to better performance even with large groups
  - physical interactions and collisions do not have a severe impact on performance



Sync Scalability Analysis

- Additive communication results in the scalability in all cases
    - no more communicative interferences
    - all evolved controllers properly scale

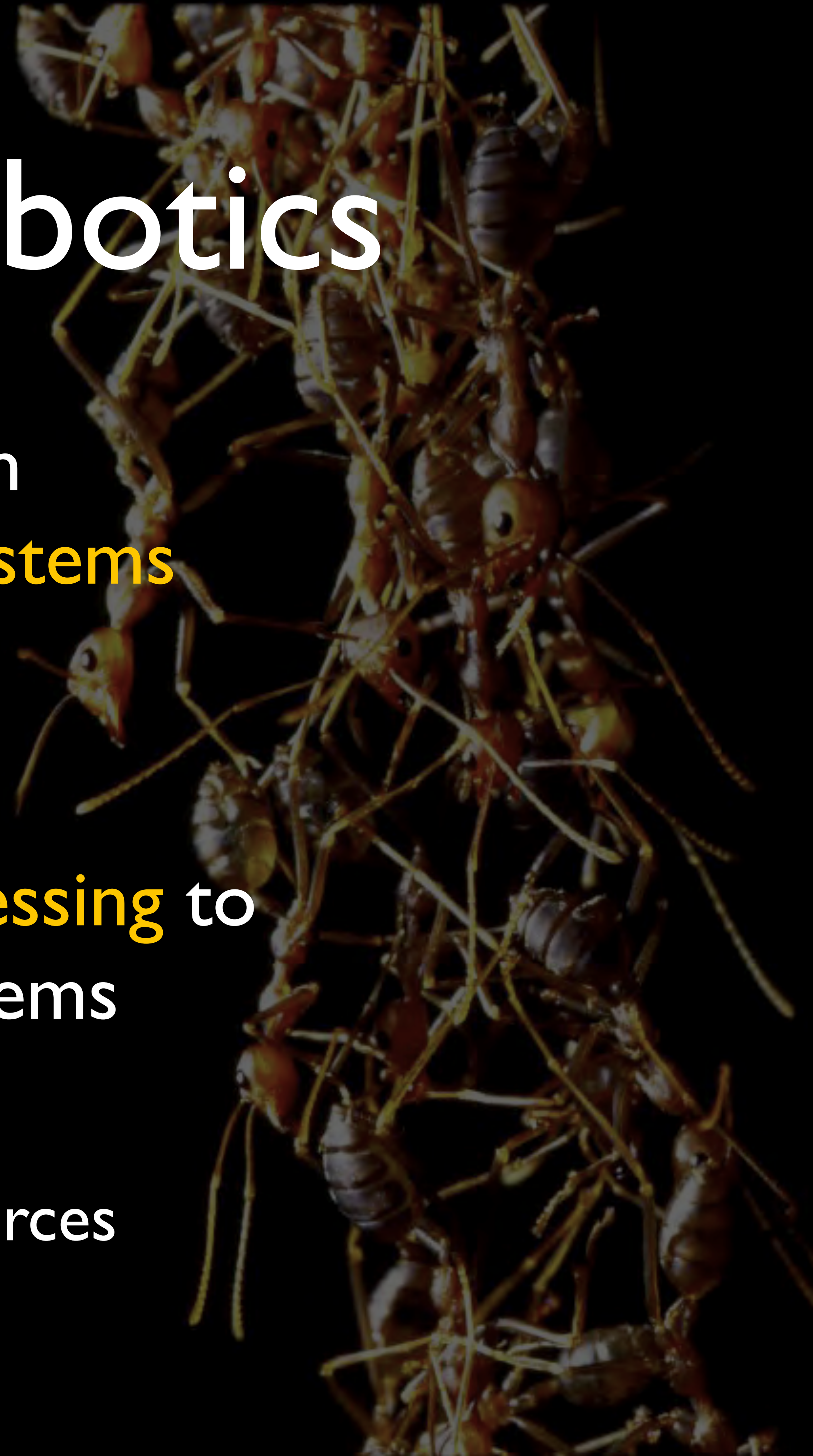


Conclusions

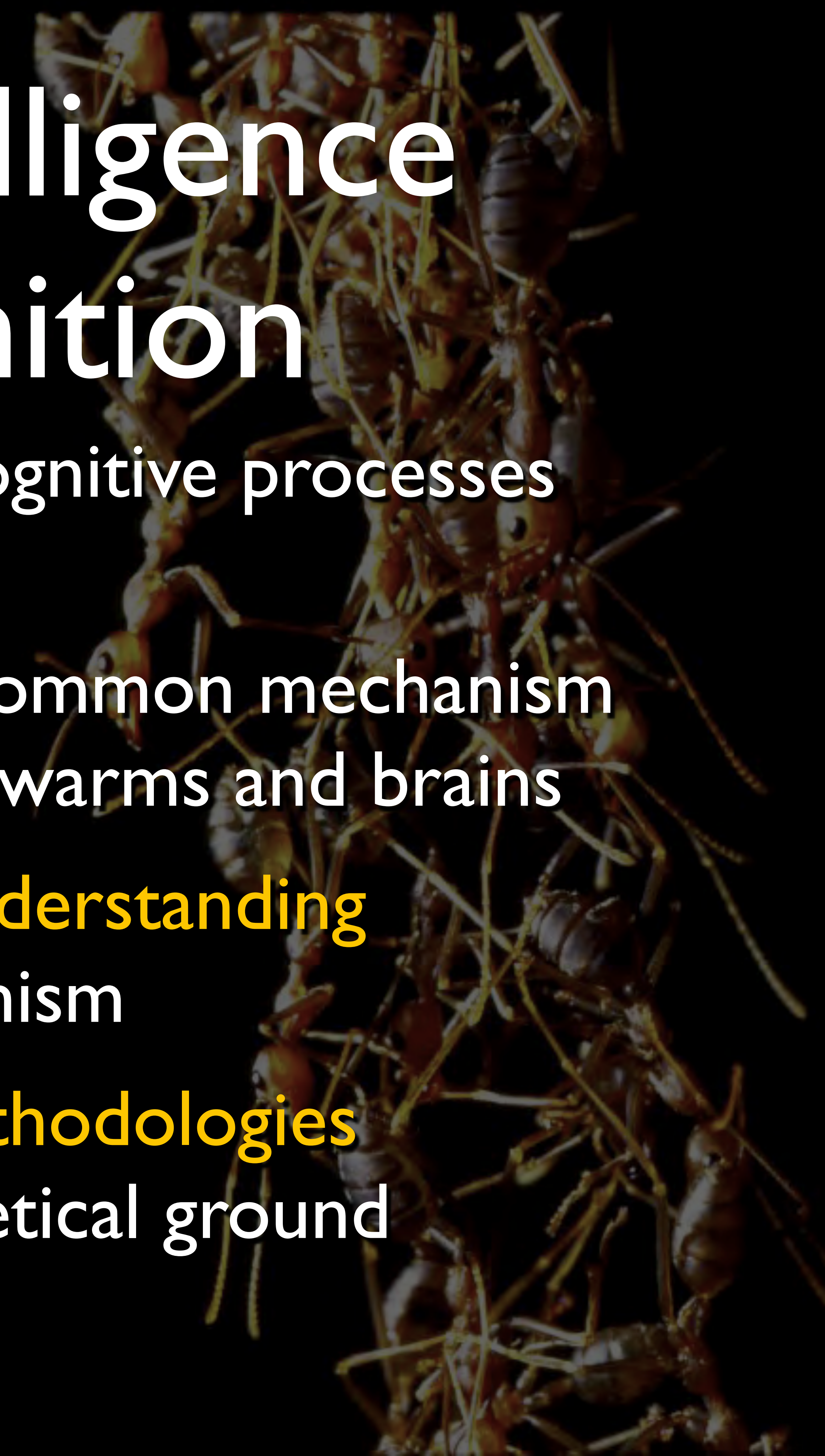
- Artificial evolution can synthesise self-organising behaviours for robot groups
- The analysis of the obtained results
  - uncovers the mechanisms underlying self-organisations
  - conveys knowledge on how to re-engineer the system for evolving better solutions

Beyond Robotics

- Engineering emergence in large scale distributed systems
  - Swarm intelligence
  - Evolutionary design
- Providing cognitive processing to complex distributed systems
  - optimal decision-making
  - optimal allocation of resources



Swarm Intelligence and Cognition



- Colony behaviour and cognitive processes are functionally similar
- Self-organisation is the common mechanism supporting cognition in swarms and brains
- Need for a principled understanding of the underlying mechanism
- Develop engineering methodologies based on a strong theoretical ground

thanks for your attention