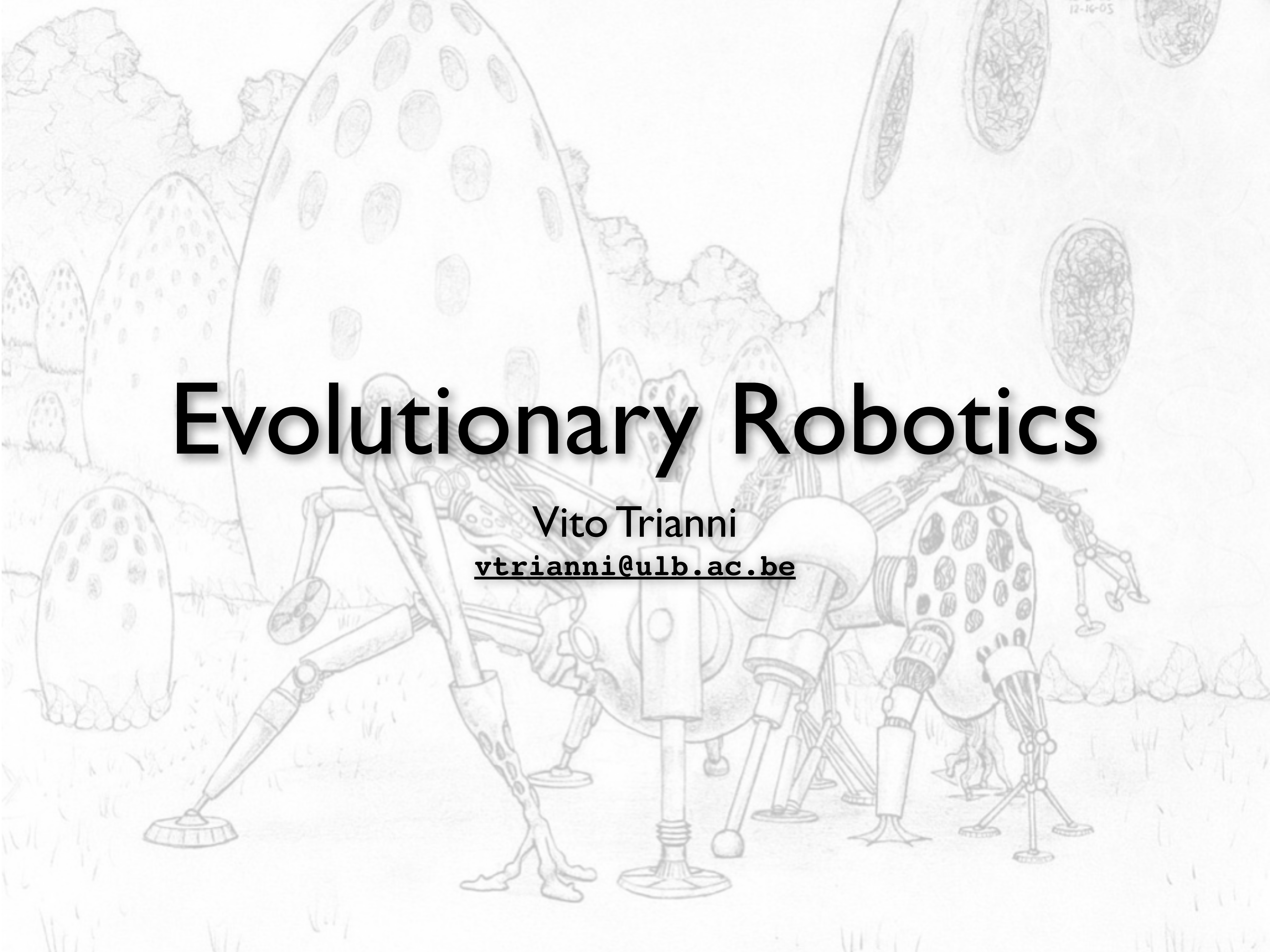

Evolutionary Robotics

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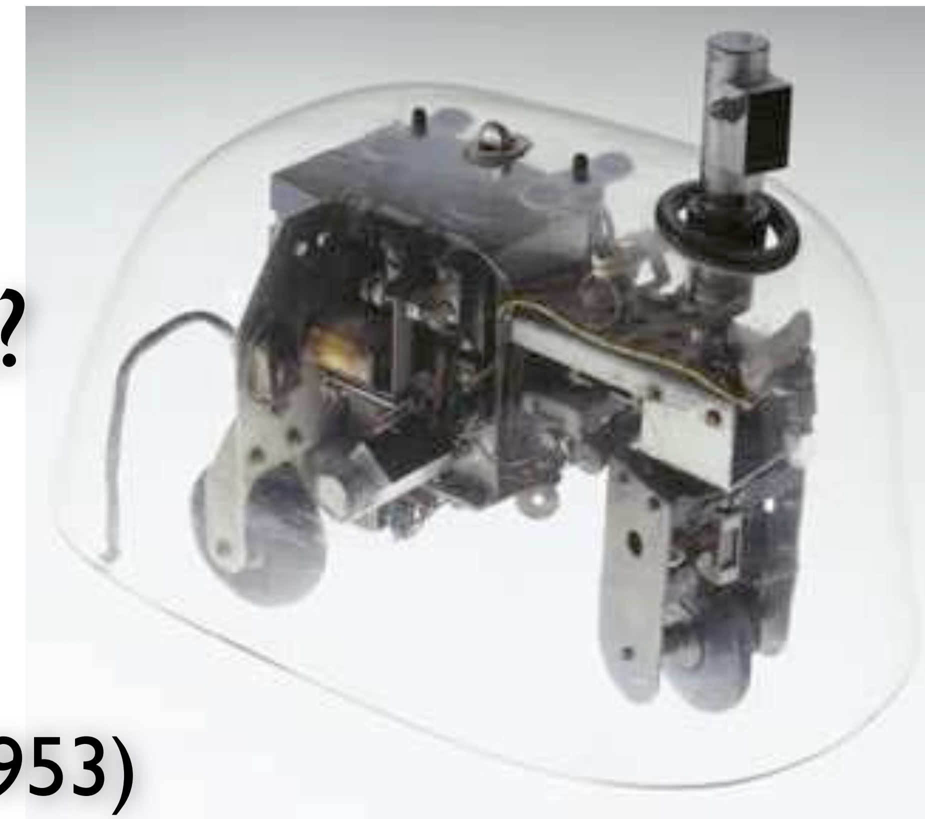
Contents

- Historical background (10’)
- Brief rehearsal about evolutionary computing (10’)
- Main features of Evolutionary Robotics (30’)
- Evolution of simple navigation (30’)
    - Break (20’)
- Reactive intelligence and active perception (20’)
- Beyond reactive intelligence (20’)
- Evolution of collective behaviours (35’)
- Conclusions (5’)

Historical Background

Artificial Intelligence

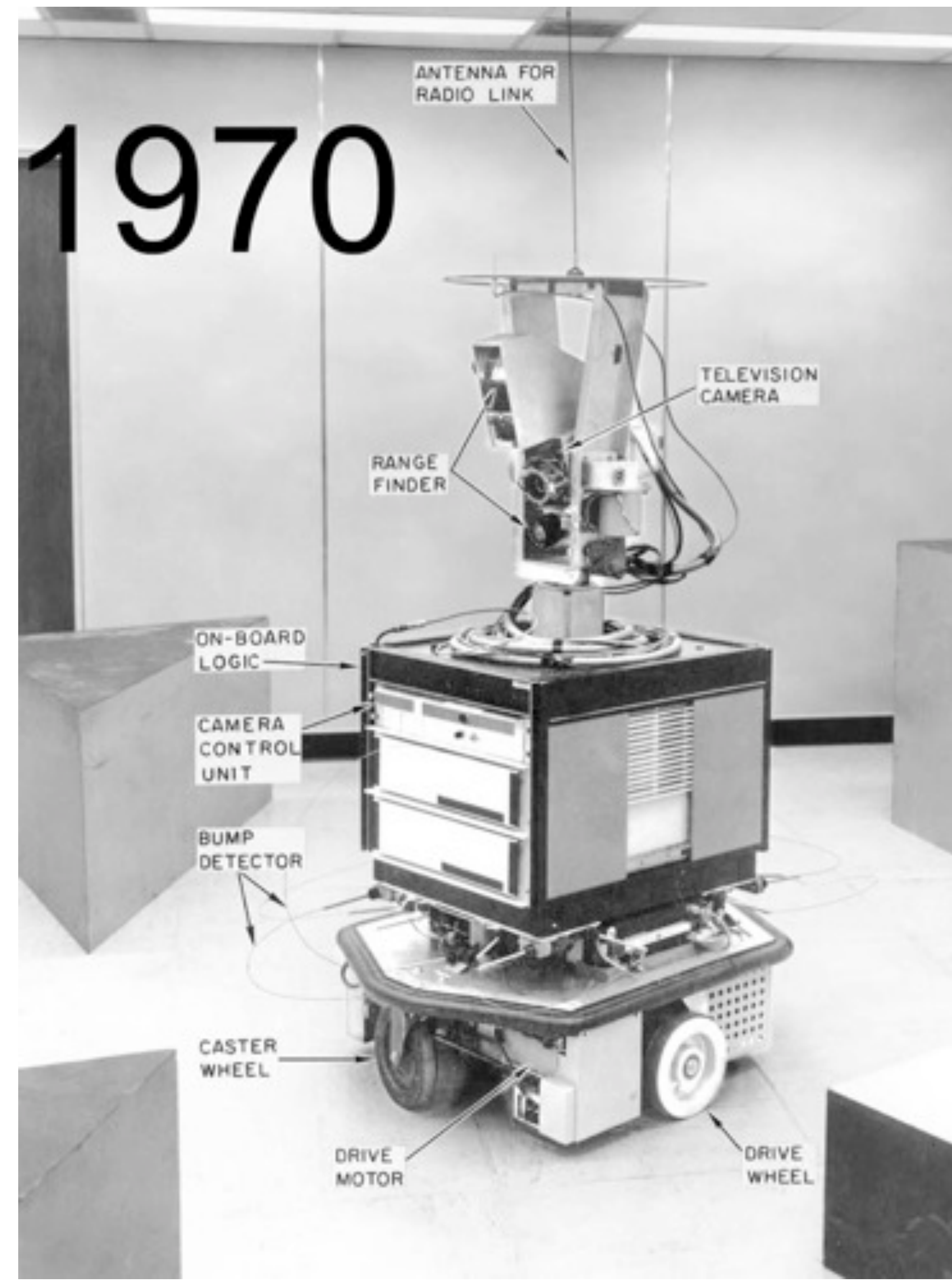
Back to the Origins



- What is *intelligence*?
  Can a machine be intelligent?
- Cybernetics: intelligence is behaving in the world
  - Elmer and Elsie, Grey Walter (1953)
- AI: intelligence is information processing
  - The Logic Theorist, Newell and Simon (1956)

(GOF)AI and Robotics

- Mental representations drive the behaviour
    - robots acquire information and build plans
    - *sense-think-act* approach
- Reasoning performed by manipulation of symbols
- Opponents' arguments
    - frame problem
    - chinese room



The Refusal of Symbols

- Connectionism tried to overcome limitations of symbolic systems
- Artificial Neural Networks (ANN) model mental and behavioural phenomena
    - Training through back-propagation (Rumelhart and McClelland, 1986)
- ANN as sub-symbolic representations

Embodied Cognitive Science

- Representations are rejected by the behaviour-based approach to robotics
- Situatedness and embodiment:
  being and acting in the world (Brooks, 1991)
  - no need of models and abstract representations: the world contains all the necessary information
  - the result of an action determines the following sensory stimuli
  - concepts are grounded in the dynamical coupling between robot and environment

Embodied Cognitive Science

- From *sense-think-act* to *sense-act-sense*
- Cognition results from agent-environment interactions
- Two possible interpretations:
  - reaction and adaptivity to environmental stimuli
  - maintenance of an equilibrium with respect to external perturbances

Evolutionary Robotics

- Cognitive systems are adapted to the environment in which they live
  - physical and behavioural capabilities develop by means of natural evolution
  - adaptation to the ecological niche
- Artificial evolution allows to study embodied cognition in artificial agents
  - minimal cognition
  - existence proofs

Evolutionary Robotics

- Artificial evolution is an optimisation method
- ER can automatically generate optimal solutions to robotic problems
    - no a priori assumptions
    - exploitation of dynamical coupling between robot and environment
    - bottom-up approach

ER in Brief

- Use artificial evolution to synthesise effective solutions to robotic problems
- Exploits agent-environment interactions: situatedness and embodiment
- Synthesise optimal solutions adapted to the (artificial) ecological niche

Brief Introduction to Evolutionary Computing

Evolutionary Computation

- Inspired by the natural evolution metaphor (Darwin, Mendel)
  - The characteristics of an organism determine its fitness within its ecological niche
  - The fittest organisms are more likely to reproduce (natural selection)
  - The genetic inheritance of traits from parents favours organisms that are fitter and fitter

Basic Ingredients

- A population of genotypes
- A genotype to phenotype mapping
- A fitness function
- A selection operator
- Sexual/asexual reproduction (recombination, mutation)

Basic Algorithm

1. Initialise population of genotypes
2. Evaluate fitness of the corresponding phenotypes
3. Check termination criteria
4. Select genotypes allowed to reproduce
5. Generate new population
    1. Recombination
    2. Mutation
6. go to 2.

Geno- and Phenotypes

- A genotype is a string of numbers (usually binary encoded: 0110001110010l...)
- The phenotype is a solution to the problem (e.g., a set of parameters of a neural network)
- The genotype to phenotype mapping is problem specific

Fitness and Termination

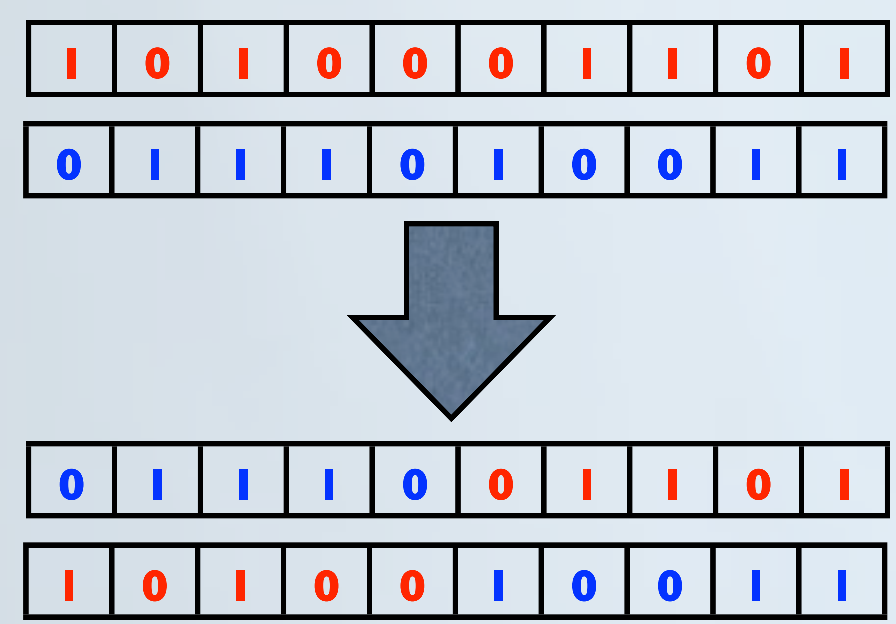
- Check the quality of the current solutions testing the fitness of the whole population
- Two main termination criteria:
  - a solution is found with fitness above a specified threshold
  - a maximum number of iterations (generations) has been performed

Selection of the Fittest

- Rank-based selection
  - select a given percentage of the individuals according to their fitness
- Roulette-wheel selection
  - genotypes are selected with probability proportional to the individual fitness
- Tournament selection
  - genotypes compete within randomly formed groups of k elements

Genetic Operators

- Crossover: a new genotype is created from 2 parents
  - single point
  - double point
  - uniform
- Mutation: a new genotype is created from one parent



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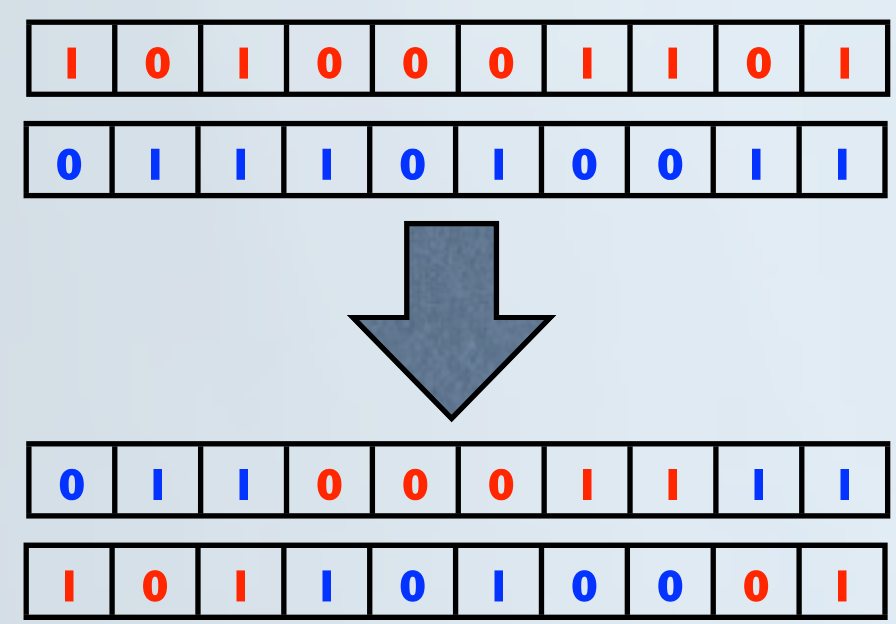

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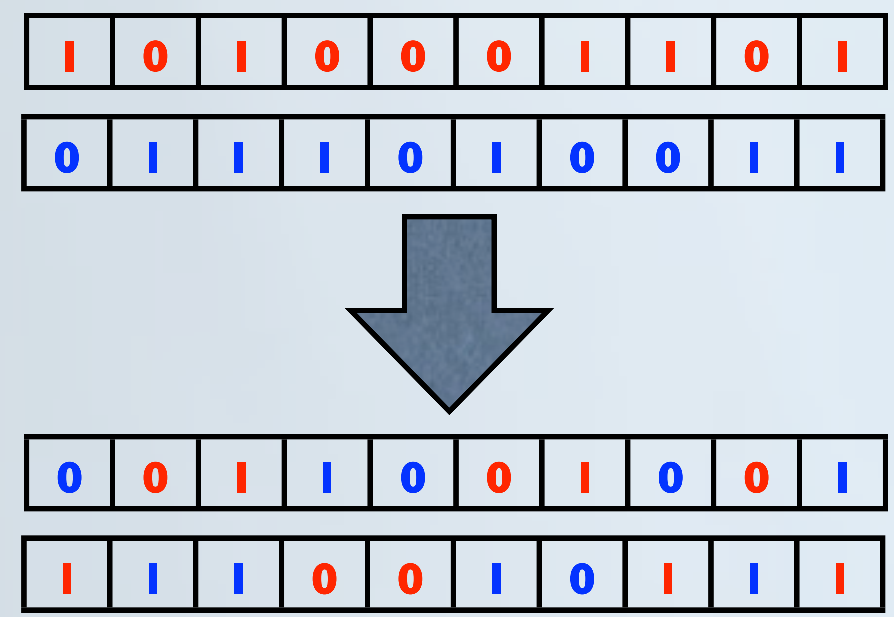

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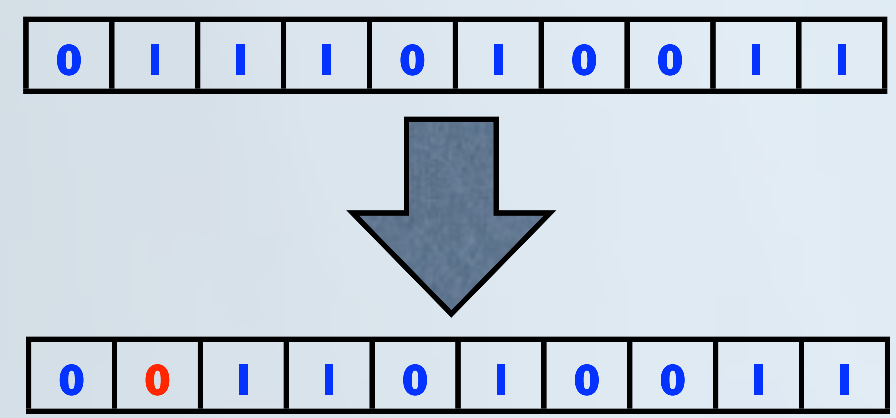
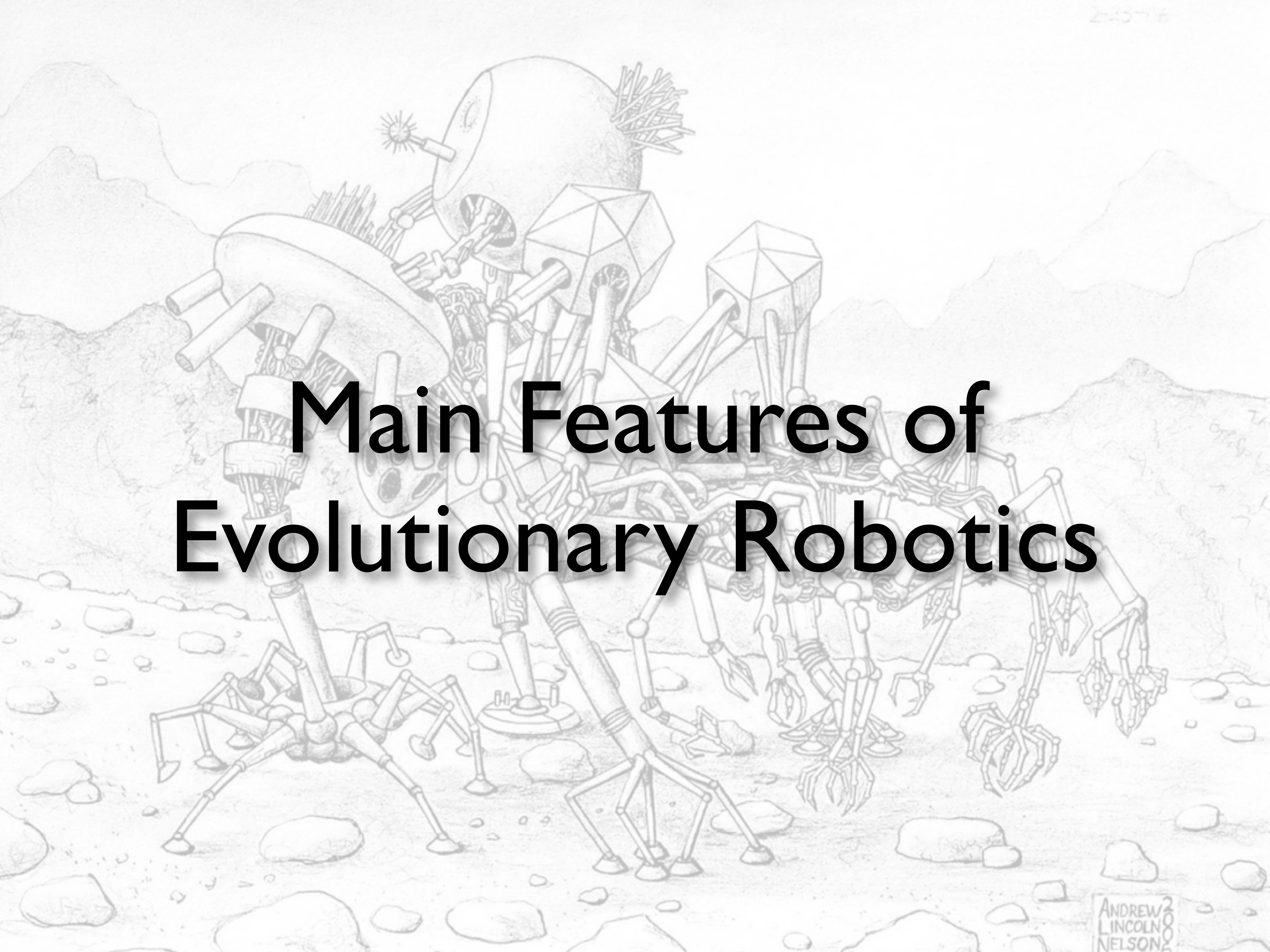


A Simple Example

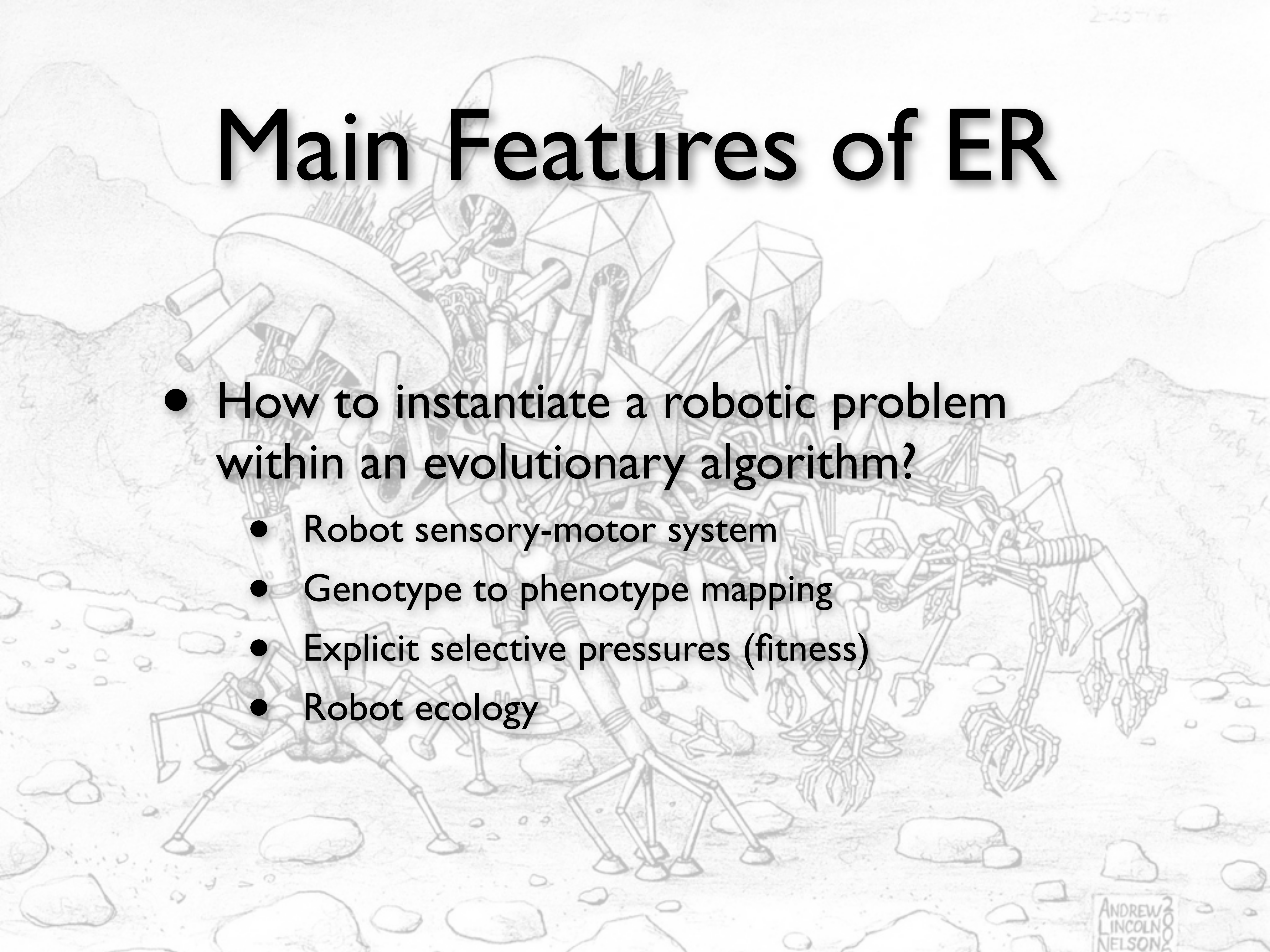
- Problem: maximise an integer number within the interval [0:1023]
- Genotype: a 10 bit string
- Phenotype: the corresponding integer
- Fitness: $F(n) = n$

Main Features of Evolutionary Robotics



Main Features of ER

- How to instantiate a robotic problem within an evolutionary algorithm?
  - Robot sensory-motor system
  - Genotype to phenotype mapping
  - Explicit selective pressures (fitness)
  - Robot ecology



Sensory-Motor System

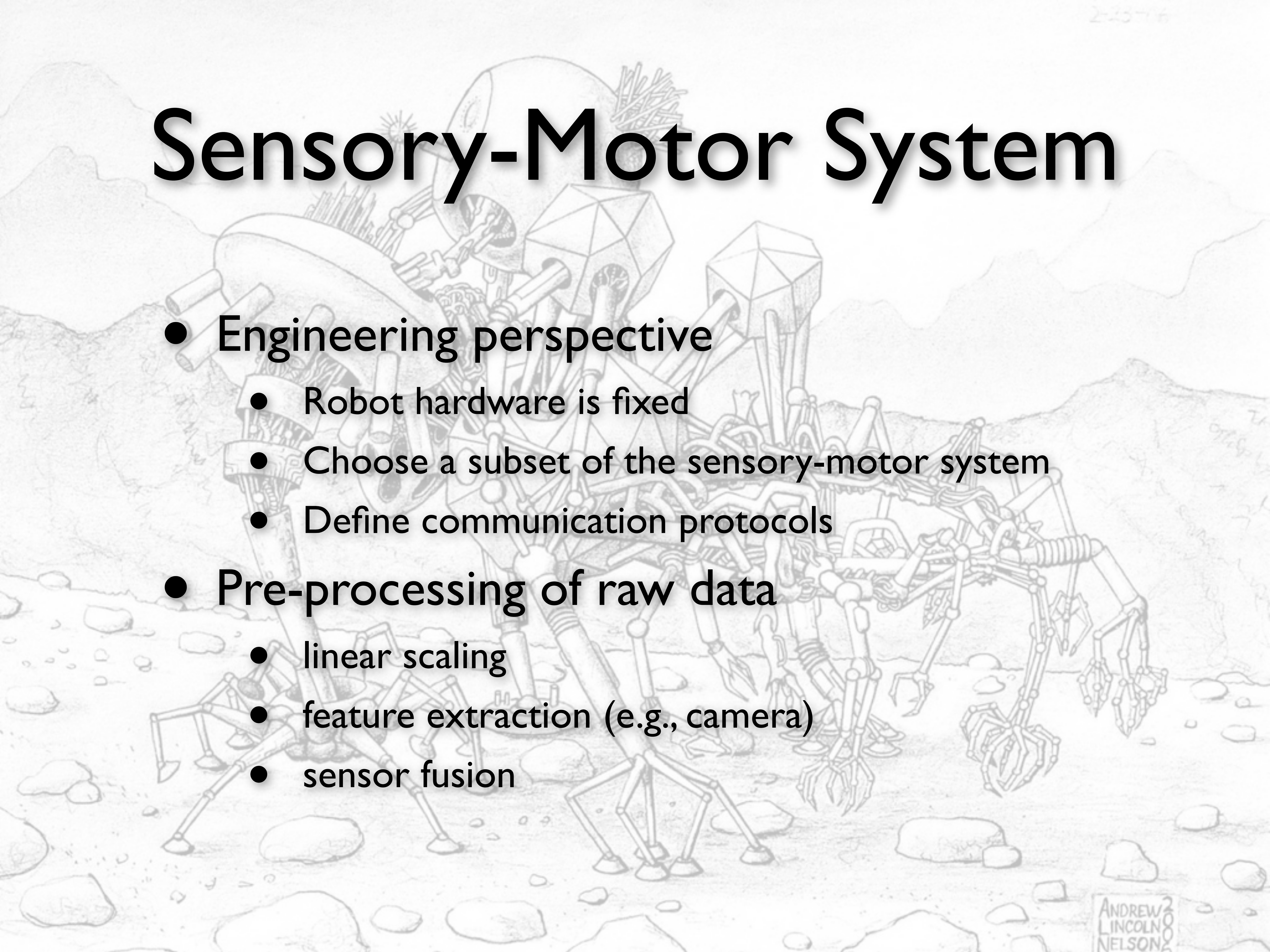
- Body and sensory-motor systems define the interaction with the environment
- Need to define sensory-motor abilities
- Possibility to evolve in parallel both morphology and behaviour

Evolved Virtual Creatures

Karl Sims

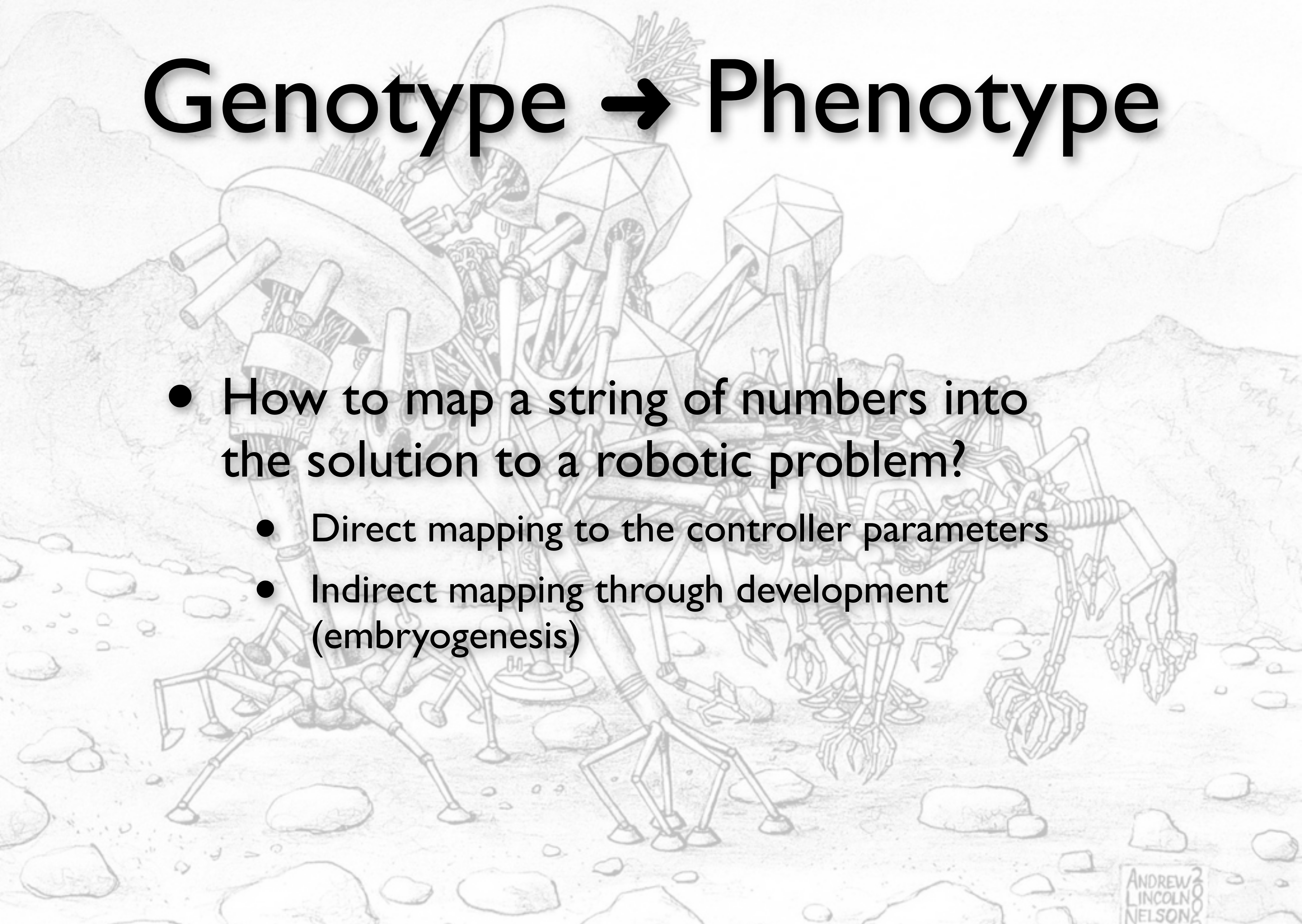
Sensory-Motor System

- Engineering perspective
  - Robot hardware is fixed
  - Choose a subset of the sensory-motor system
  - Define communication protocols
- Pre-processing of raw data
  - linear scaling
  - feature extraction (e.g., camera)
  - sensor fusion

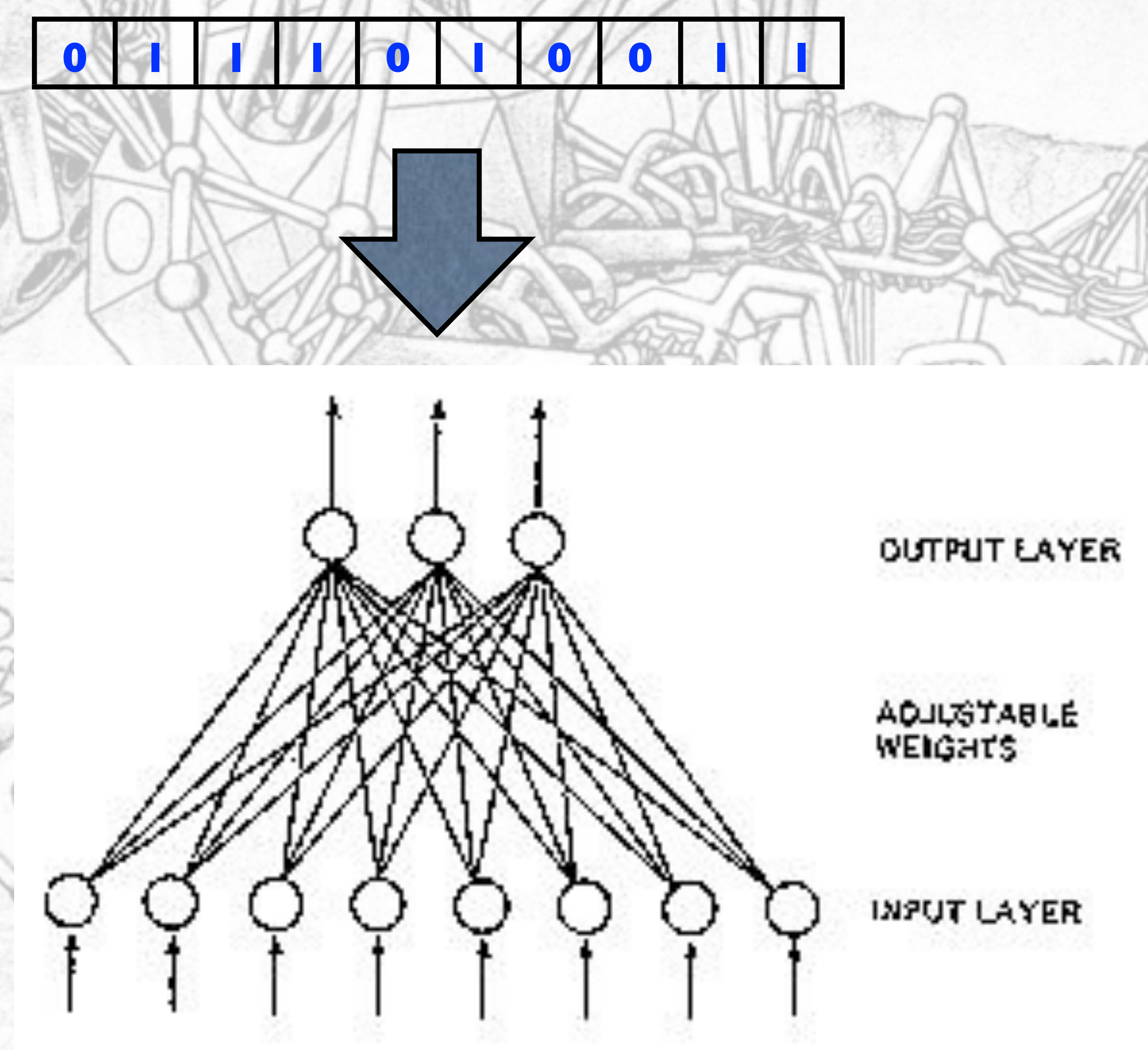


Genotype ➜ Phenotype

- How to map a string of numbers into the solution to a robotic problem?
  - Direct mapping to the controller parameters
  - Indirect mapping through development (embryogenesis)



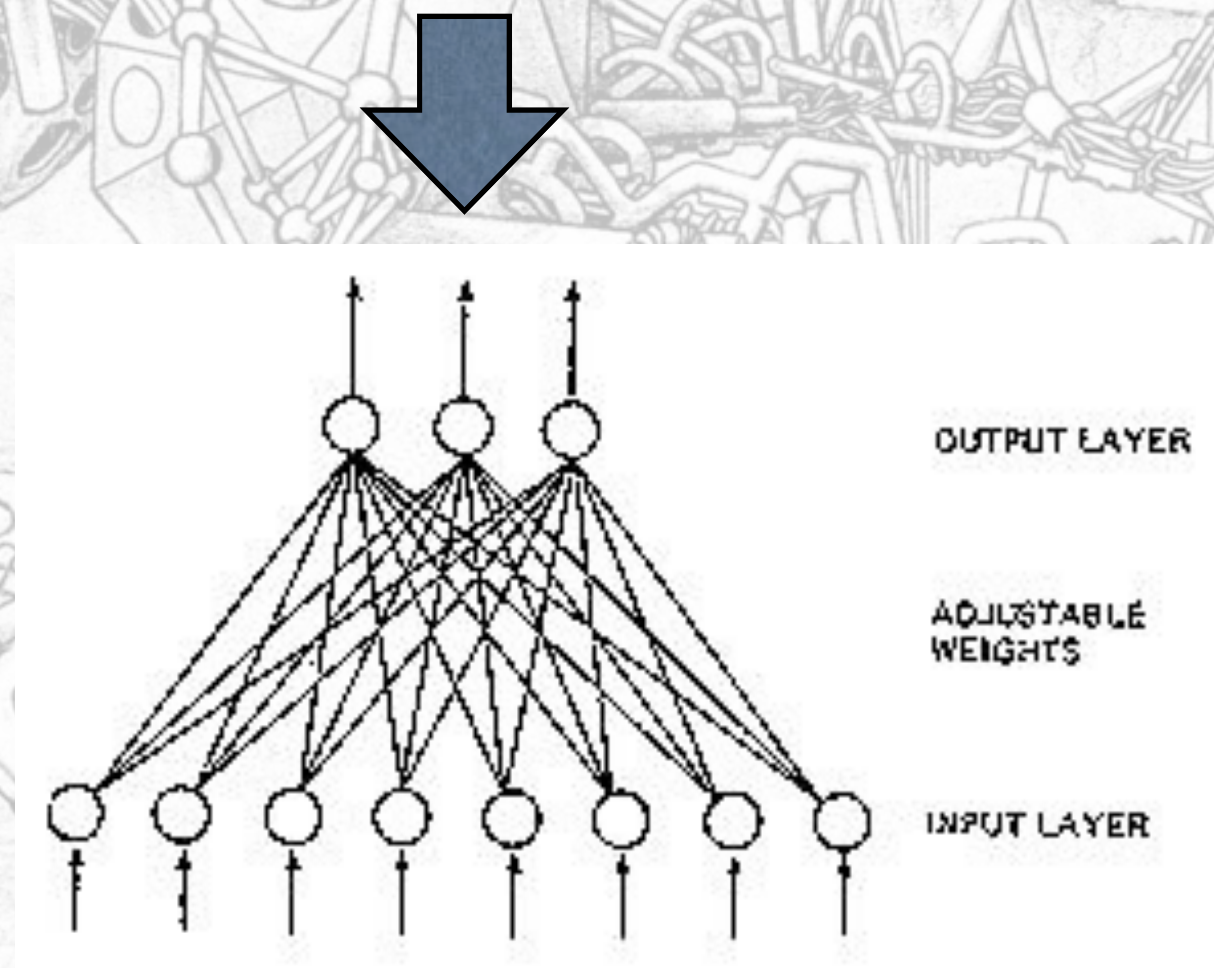
Controller Architecture



Controller Architecture

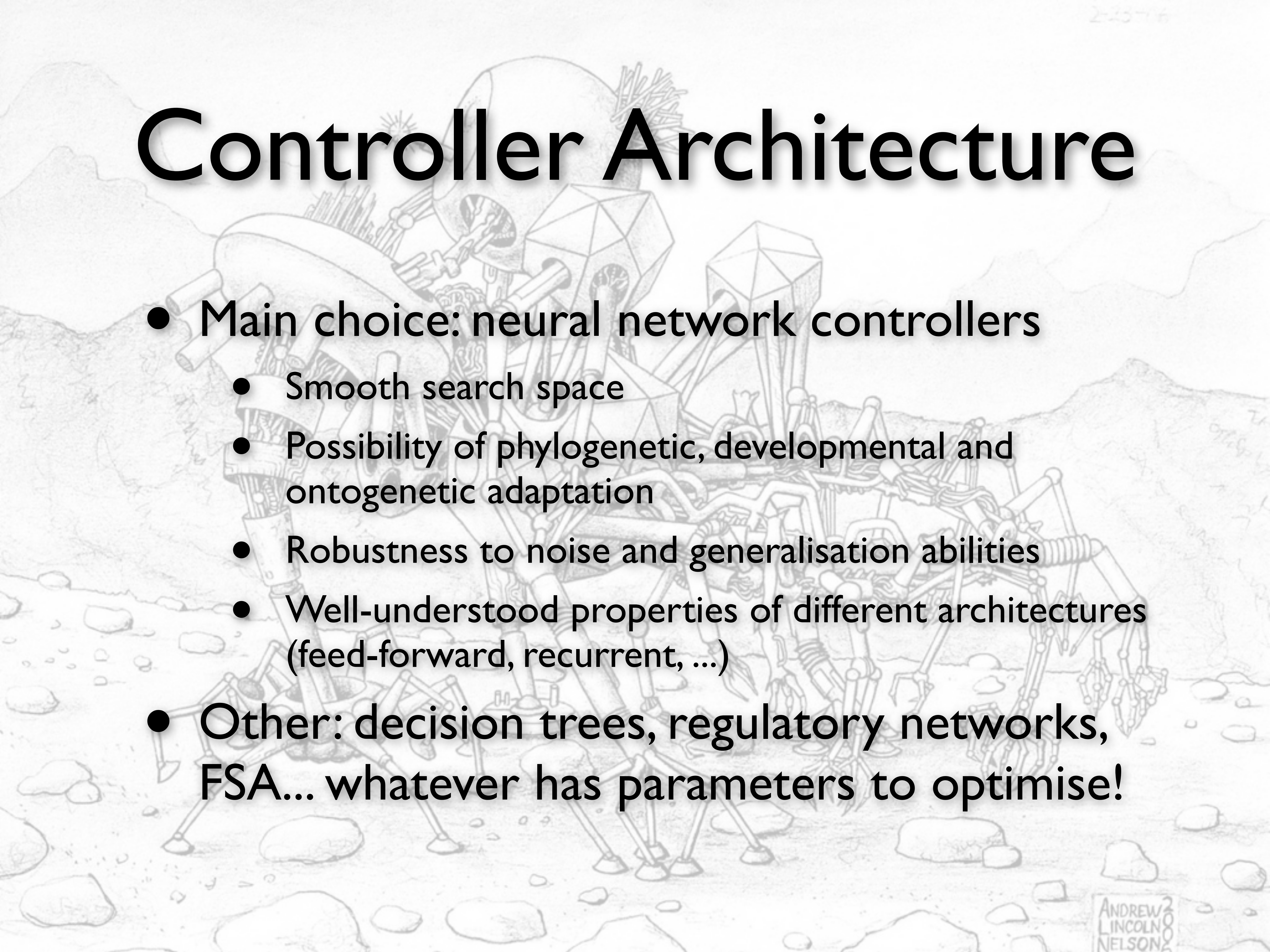
- Main choice: neural network controllers

0	1	1	1	0	1	0	0	1	1



Controller Architecture

- Main choice: neural network controllers
    - Smooth search space
    - Possibility of phylogenetic, developmental and ontogenetic adaptation
    - Robustness to noise and generalisation abilities
    - Well-understood properties of different architectures (feed-forward, recurrent, ...)

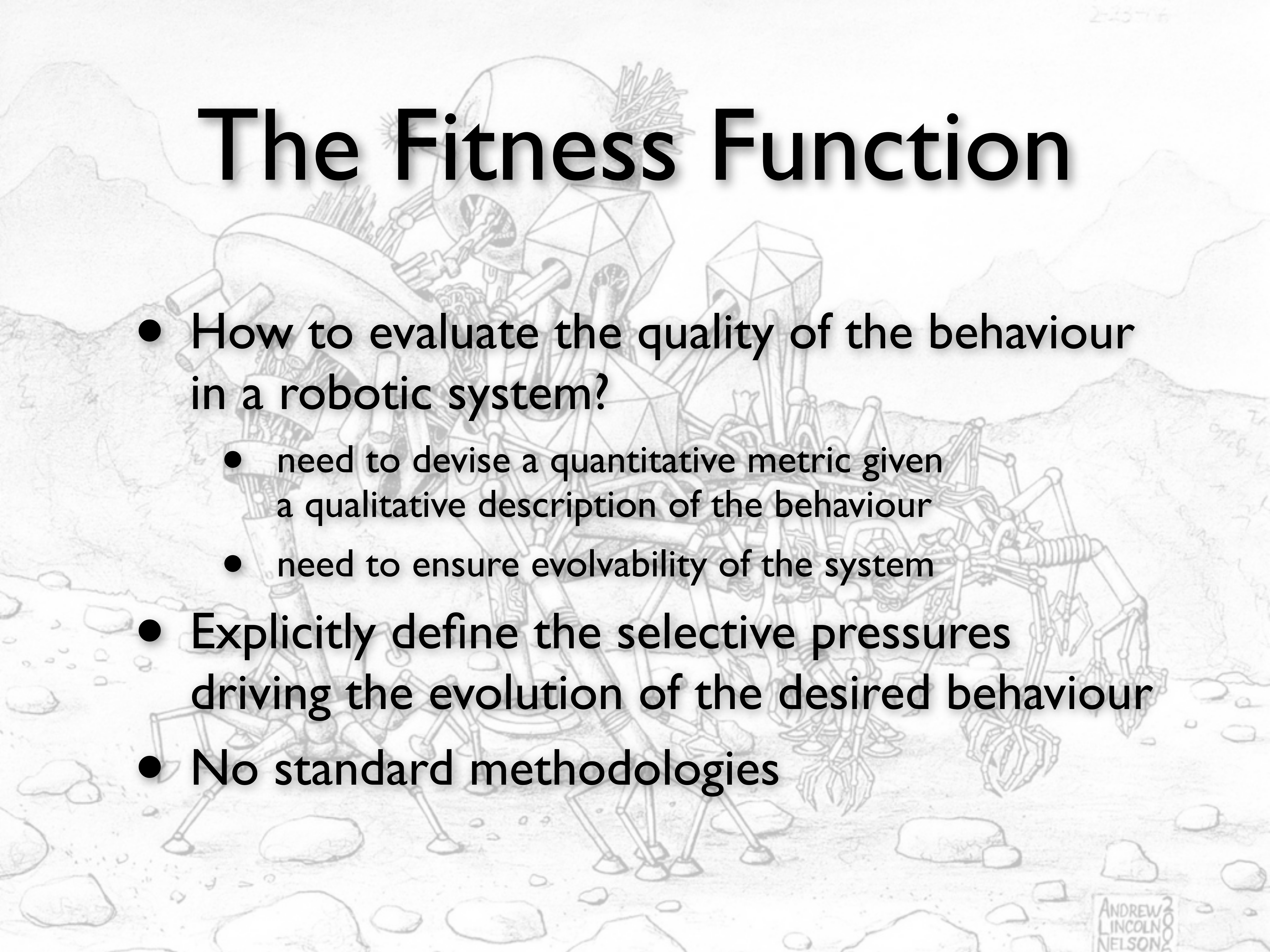


Controller Architecture

- Main choice: neural network controllers
  - Smooth search space
  - Possibility of phylogenetic, developmental and ontogenetic adaptation
  - Robustness to noise and generalisation abilities
  - Well-understood properties of different architectures (feed-forward, recurrent, ...)
- Other: decision trees, regulatory networks, FSA... whatever has parameters to optimise!

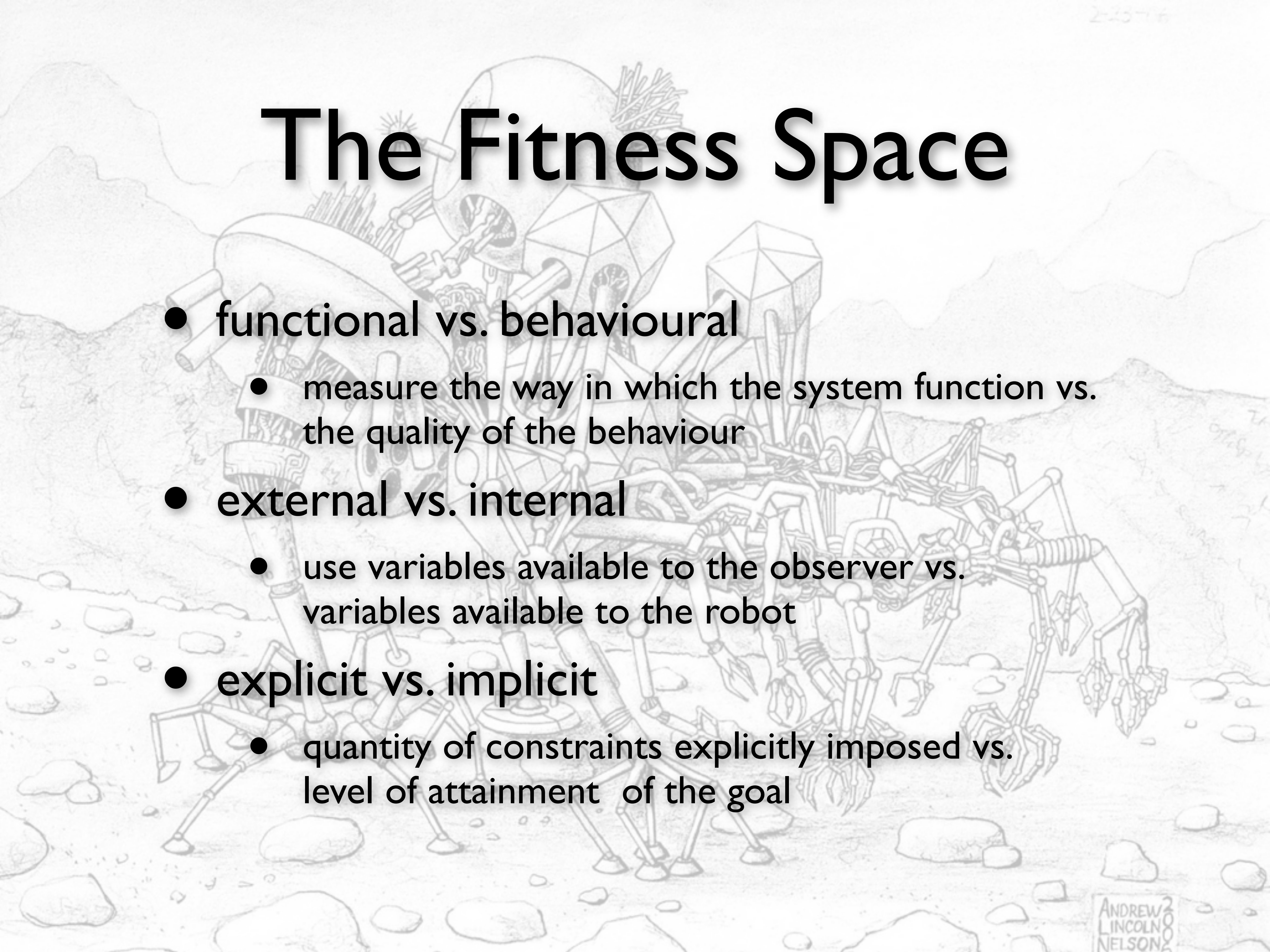
The Fitness Function

- How to evaluate the quality of the behaviour in a robotic system?
  - need to devise a quantitative metric given a qualitative description of the behaviour
  - need to ensure evolvability of the system
- Explicitly define the selective pressures driving the evolution of the desired behaviour
- No standard methodologies

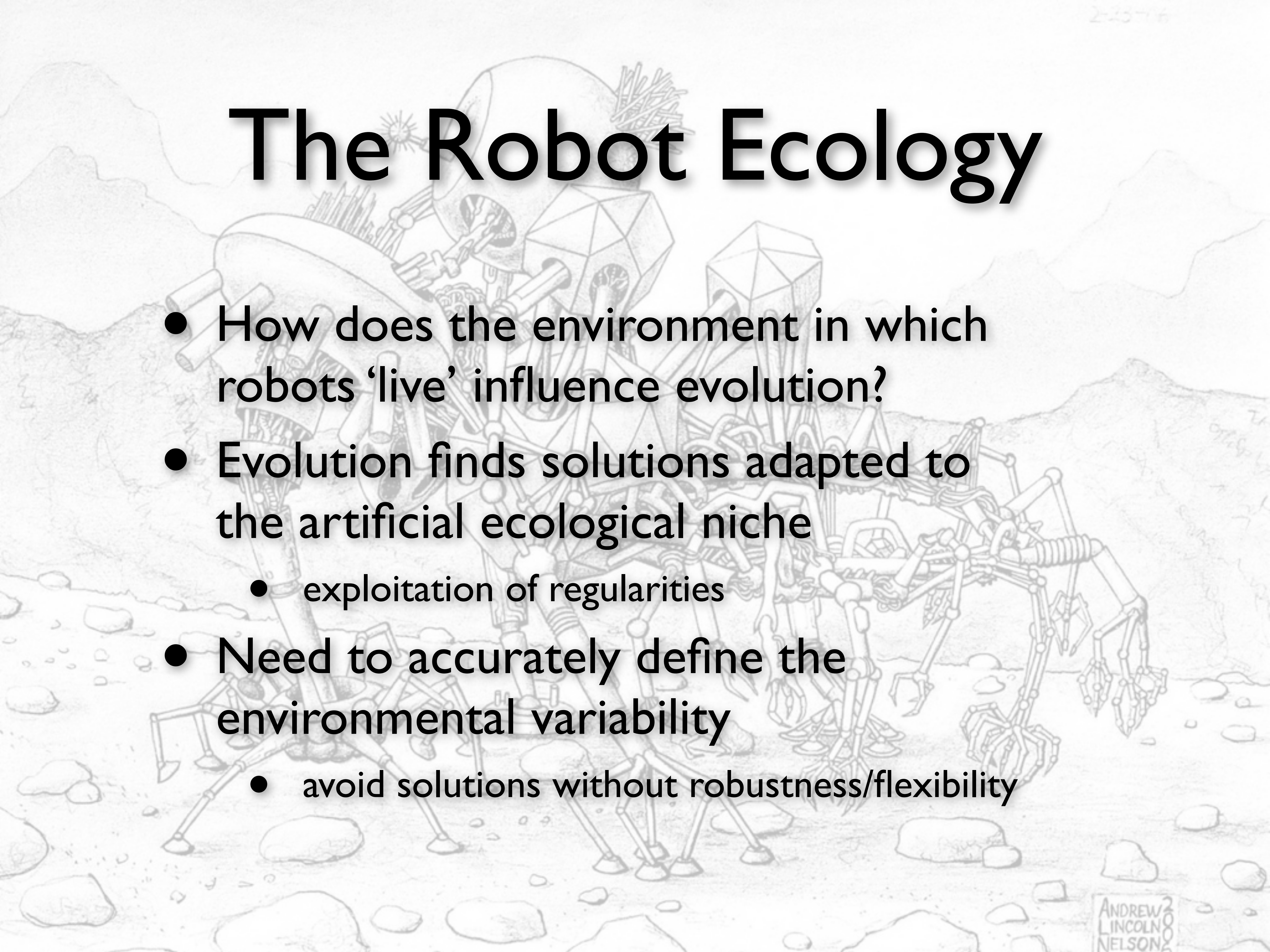


The Fitness Space

- functional vs. behavioural
  - measure the way in which the system function vs. the quality of the behaviour
- external vs. internal
  - use variables available to the observer vs. variables available to the robot
- explicit vs. implicit
  - quantity of constraints explicitly imposed vs. level of attainment of the goal



The Robot Ecology



- How does the environment in which robots ‘live’ influence evolution?
- Evolution finds solutions adapted to the artificial ecological niche
  - exploitation of regularities
- Need to accurately define the environmental variability
  - avoid solutions without robustness/flexibility

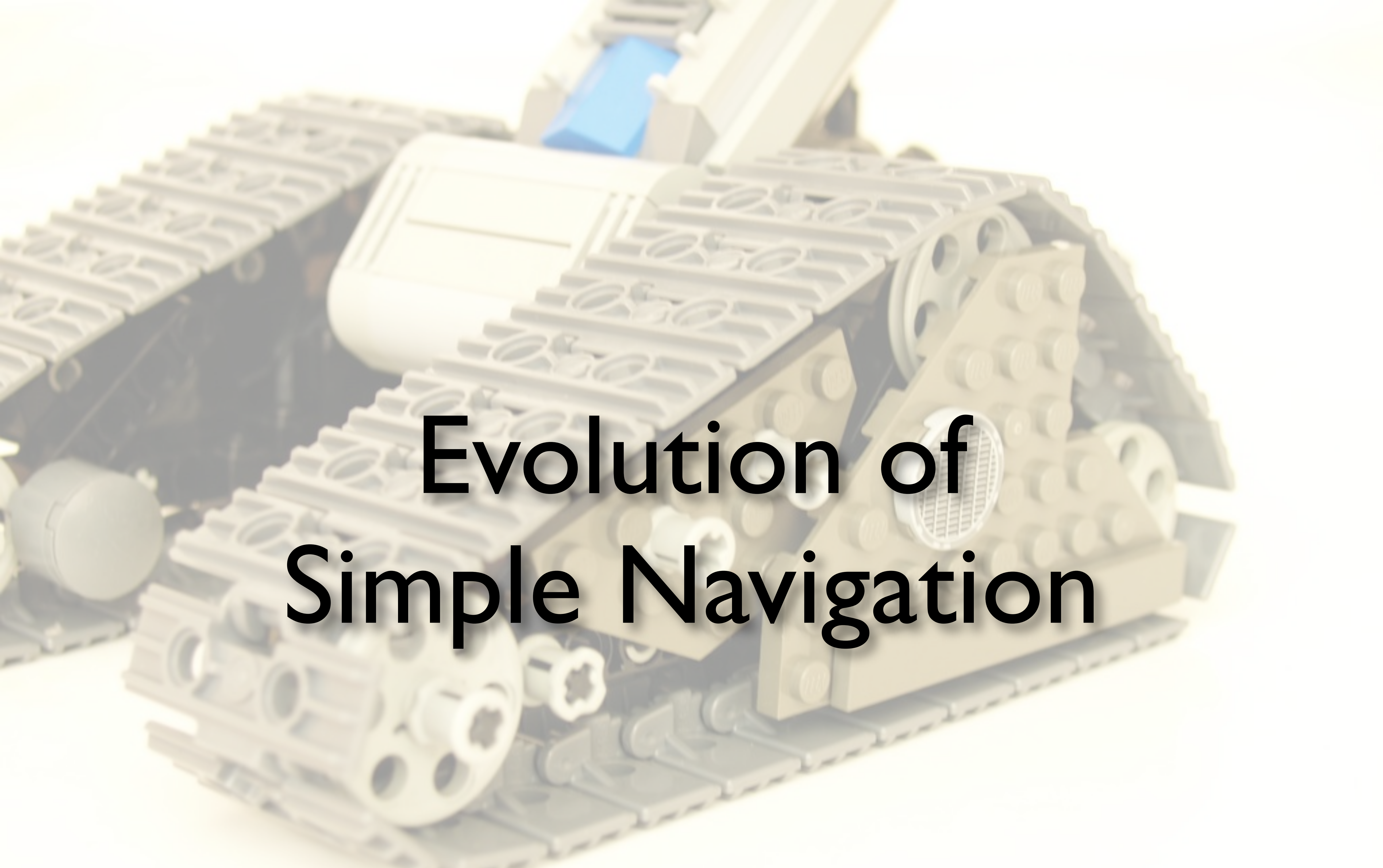
Estimation of the Fitness

- Not practical/possible to test the fitness in every single ecological condition
  - varying initial positions and orientations
  - varying environmental features (arena size, obstacle positions, ...)
- Need of sampling to estimate the fitness
- Creation of indirect selective pressures

Summary

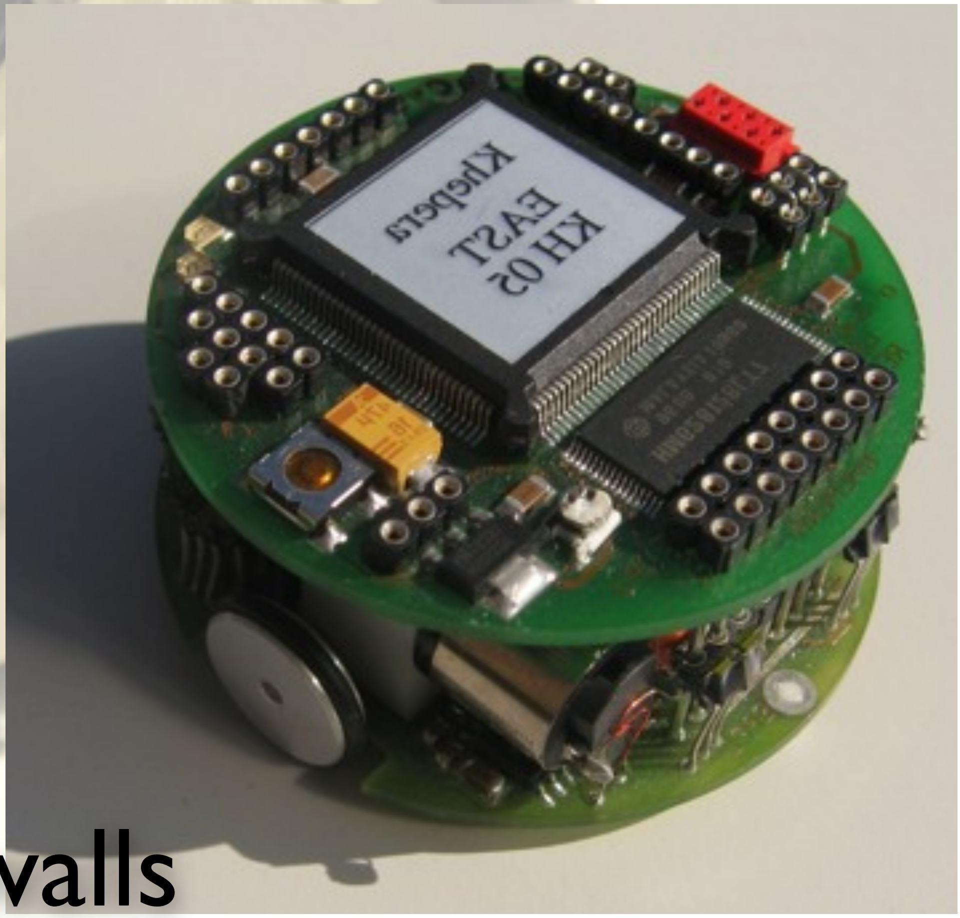
- Basic steps to design an ER experiment
  - choose a subset of the sensory-motor configuration
  - map the genotype in a suitable control structure
  - define the fitness function
  - define the environment in which robots evolve

Evolution of Simple Navigation



Simple Navigation

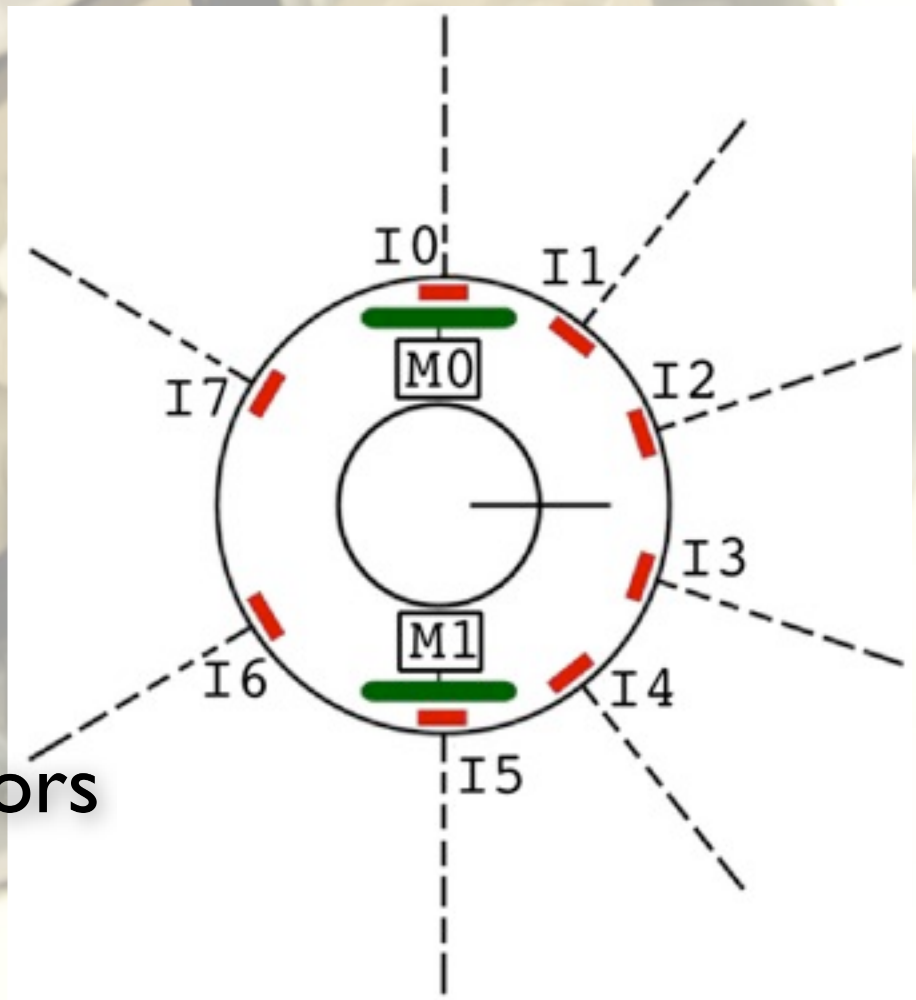
- Problem: navigation and obstacle avoidance with a simple robot (Floreano and Mondada, 1994)
  - *Kephera* developed at EPFL
- Goal: move as fast as possible while avoiding to collide with walls



Simple Navigation

Sensory-Motor System

- Actuators
  - 2 wheels providing differential drive motion
- Sensors
  - 2 motor encoders
  - 8 infrared proximity sensors
  - 8 ambient-light sensors



Simple Navigation

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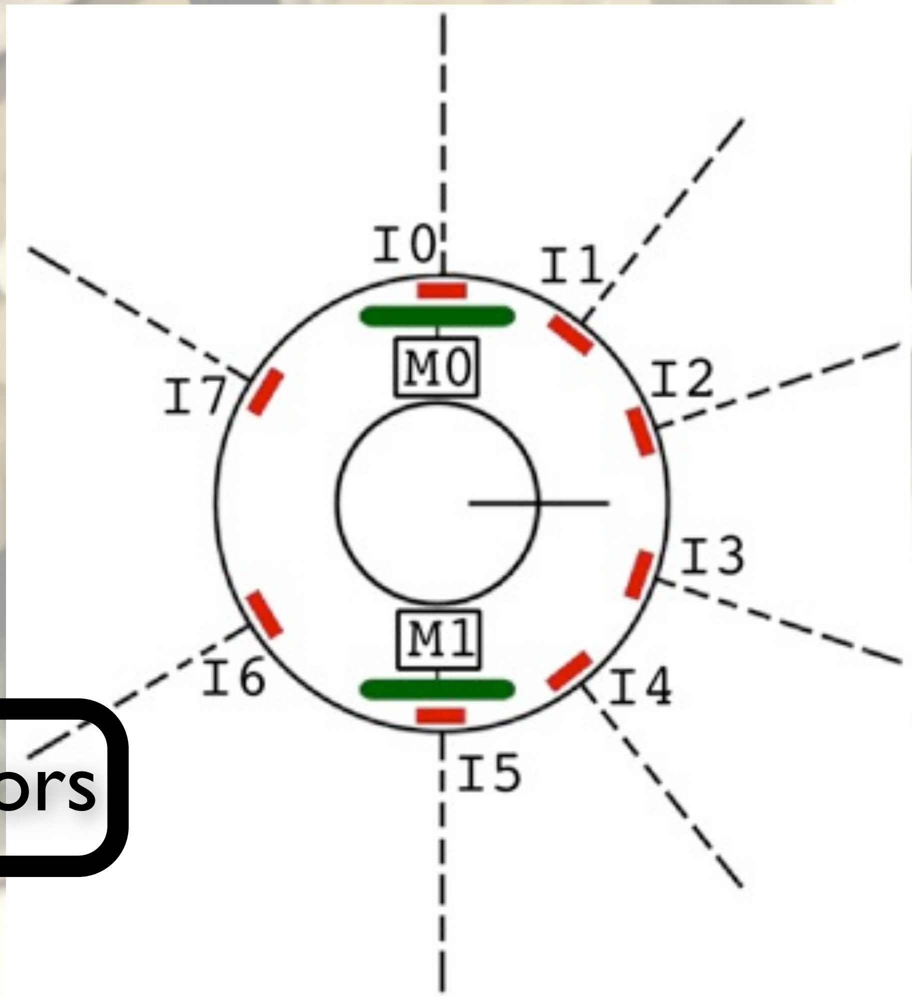


Simple Navigation

Genotype ➜ Phenotype

- The controller is a simple Elman network
  - layer of 8 input units from IR sensors
  - layer of 2 output units to the motors
  - recurrent connections within the output layer
- Direct encoding of the genotype into the phenotype (synaptic weights and thresholds)
  - each parameter represented by a real number
  - the chromosome contains 22 genes

Simple Navigation

Fitness Function

- What should be the fitness function?
- The fitness evaluates the ability of the robot to move
    - fast
    - straight
    - away from obstacles

$$\Phi = V\left(1 - \sqrt{\Delta v}\right)(1 - i)$$

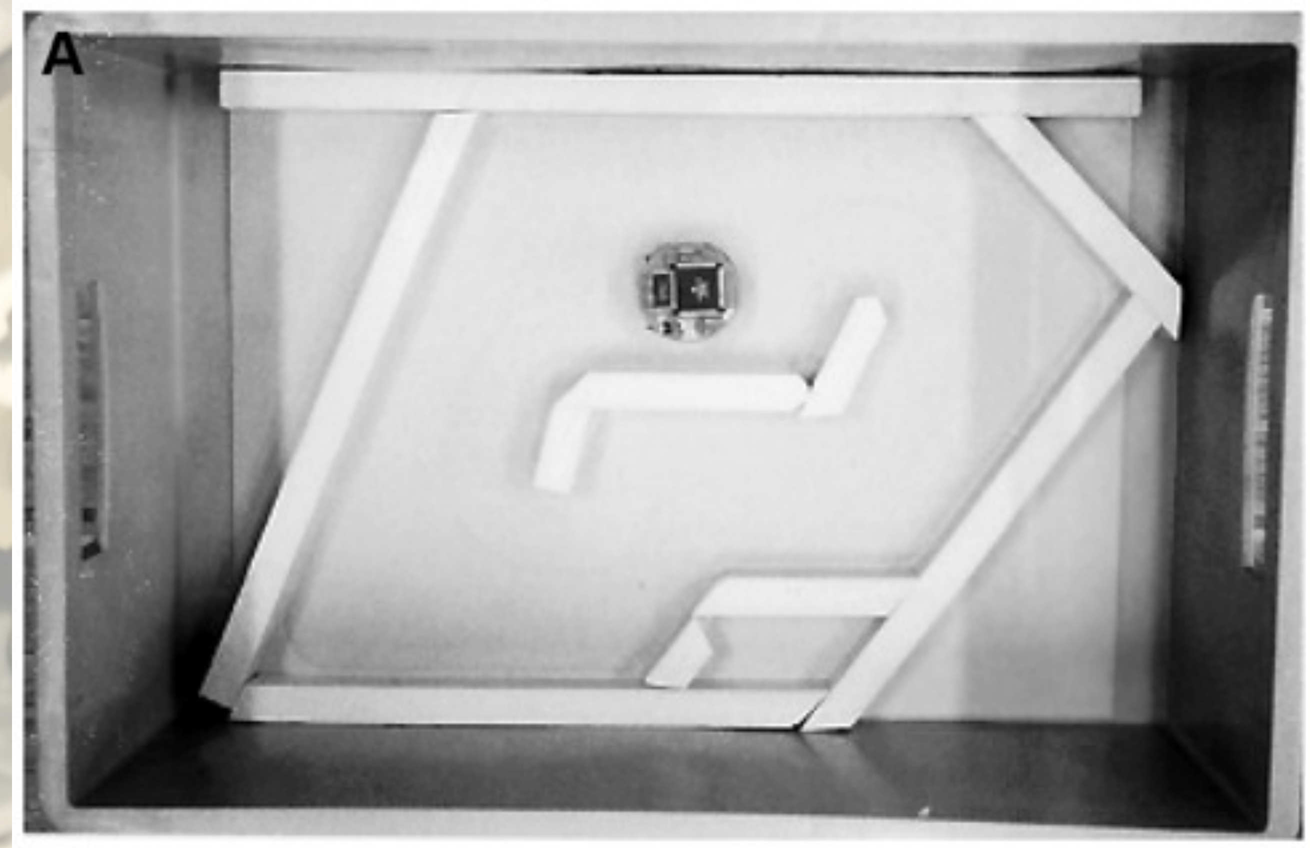
$$V = \frac{|\omega_r| + |\omega_l|}{2\omega_M} \qquad \Delta v = \frac{|\omega_r - \omega_l|}{2\omega_M}$$

- Behavioural, internal and implicit function!

Simple Navigation

Robot Ecology

- The environment is a looping maze
  - corridors
  - narrow passages
- Different starting positions and orientation



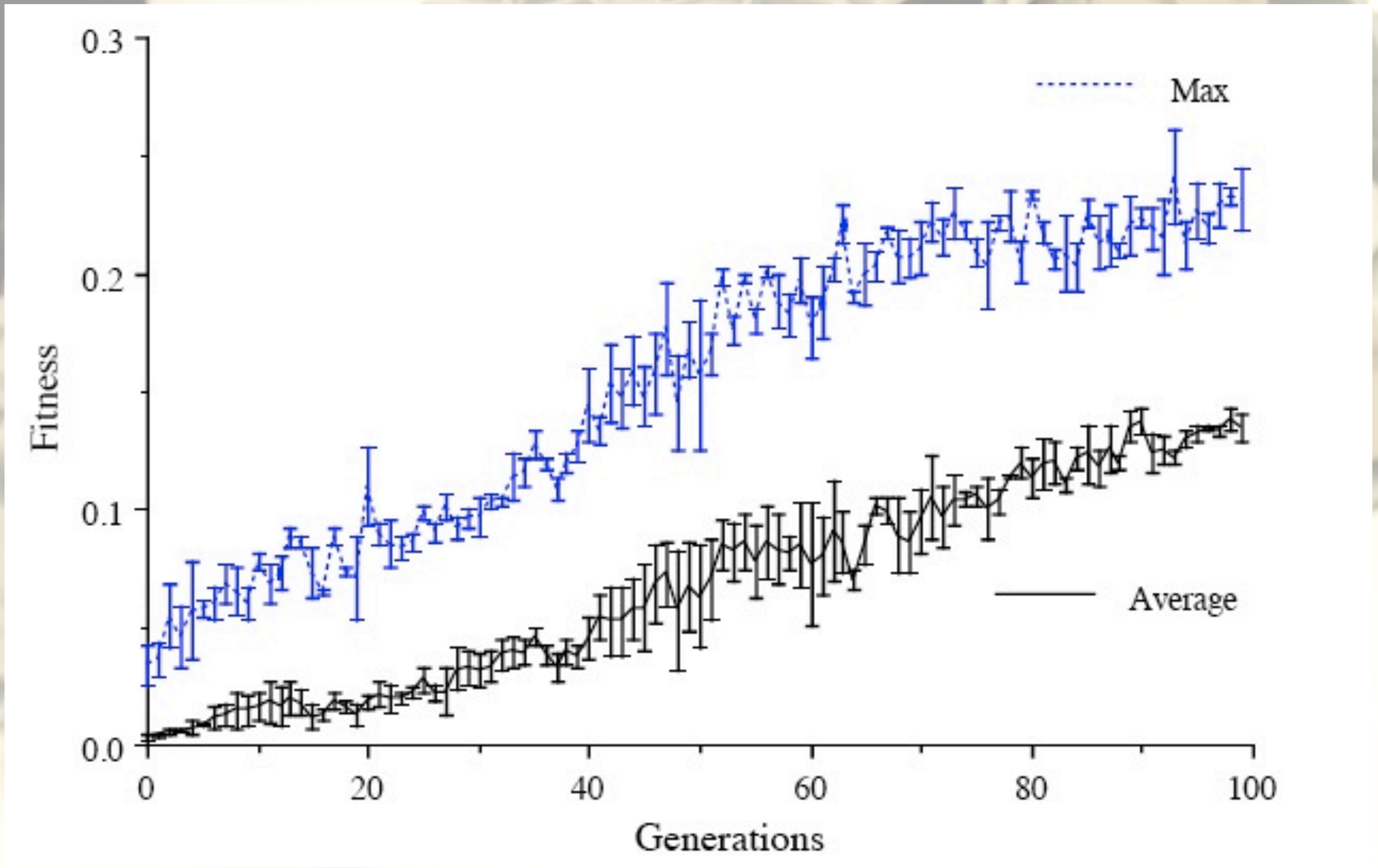
Simple Navigation

Evolutionary Setup

- Population of 50 individuals
- 100 generations
- Roulette-wheel selection
- Mutation (P = 0.2)
- One-point crossover (P = 0.1)

Simple Navigation

Obtained Results



Reactive Intelligence and Active Perception

Reactive Systems

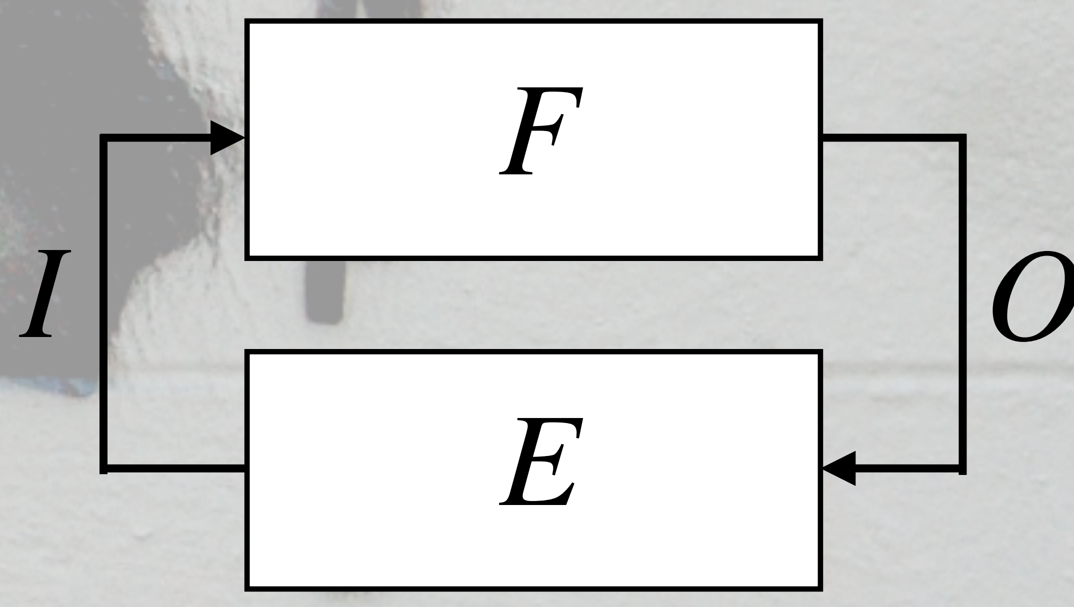
- Reactive systems directly map inputs to outputs, and have no internal state
  - simple coupling of sensations to actions
  - no internal dynamics
- A reactive controller is modelled as a function:

$$O = F(I)$$

- Apparently, no “intelligent” behaviour can be produced

Dynamical Coupling

- Embodiment provides a dynamical coupling with the environment
- Actions partially determine the future sensations
- Robot and environment form a dynamical system
- Even reactive behaviour can display complex dynamics



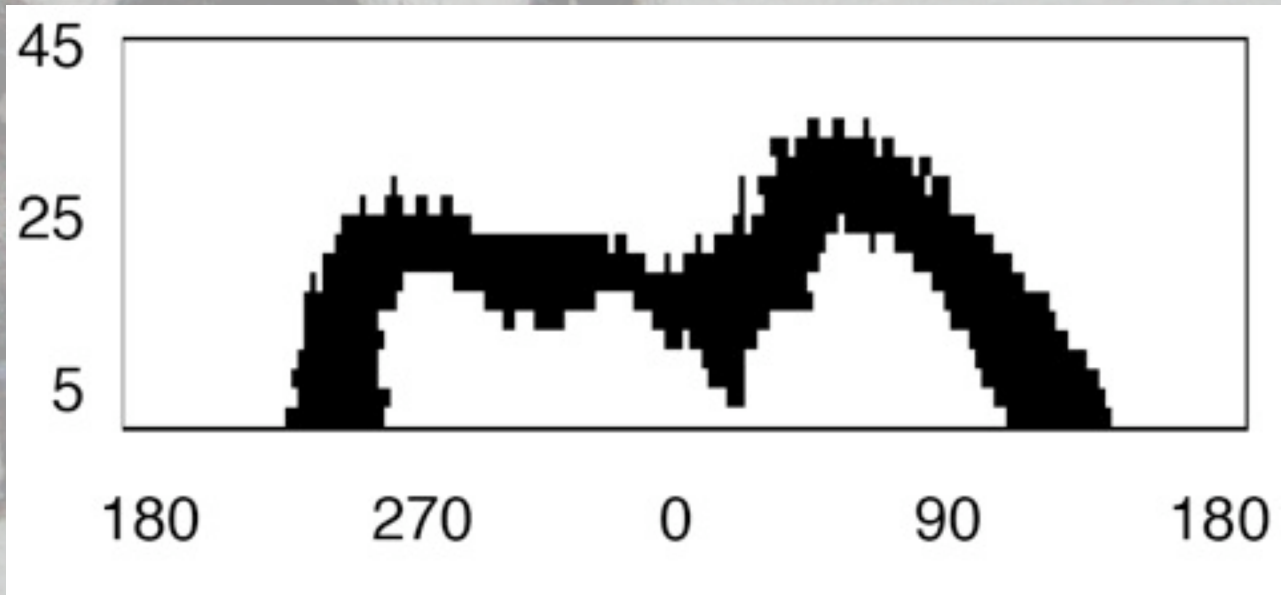
Recognising Cylinders

- Problem:
  search and remain close to small cylinders in a arena surrounded with walls (Nolfi, 1997)
- Tools: Kephera robot
- Sensory-motor system
  - 6 infrared proximity sensors
  - 2 wheels
- Goal: recognise cylinders from walls

Recognising Cylinders

Disembodied System

- Train a perceptron network through back-propagation
- Test all combinations of distance and angle
- Result:
  poor discrimination



Recognising Cylinders

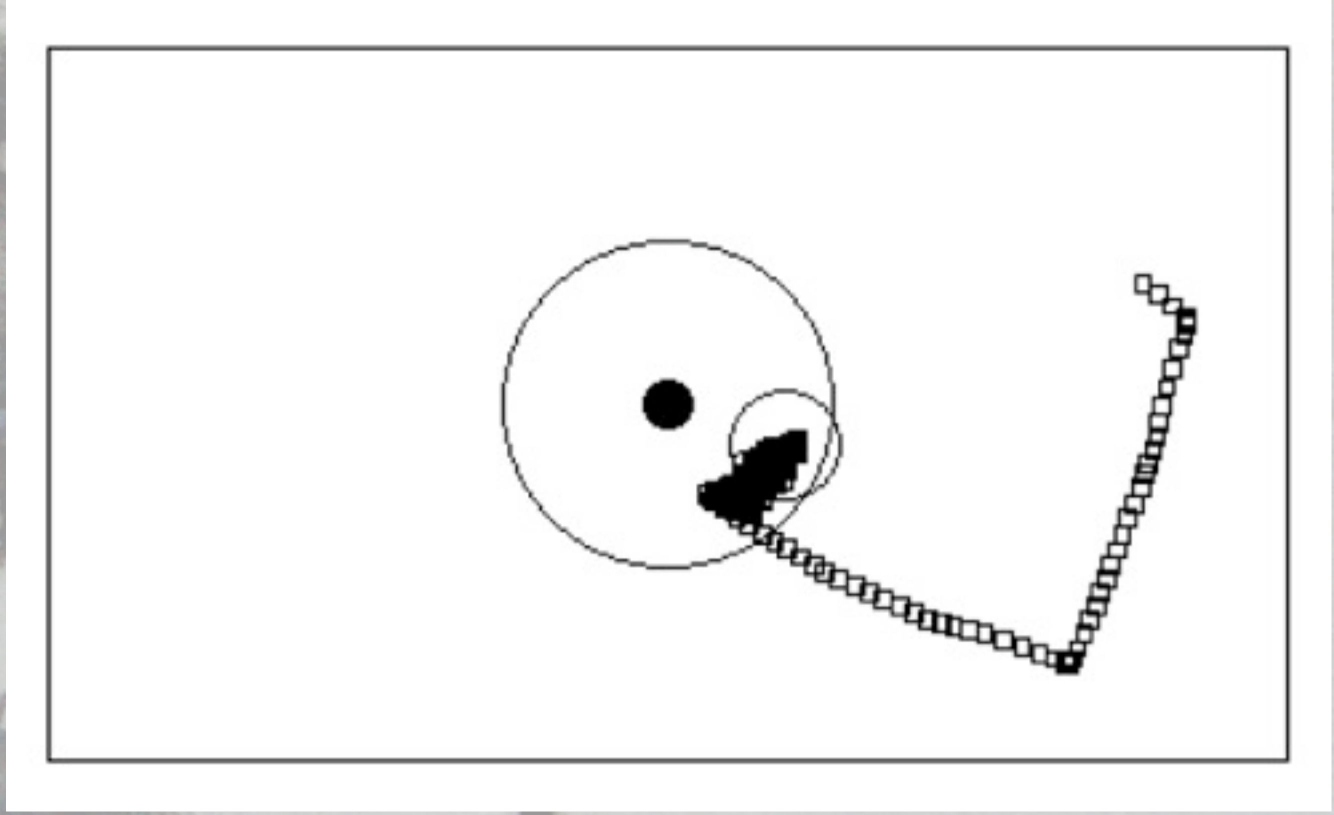
Evolving Embodied Systems

- Controller: reactive perceptron network
- Fitness: percentage of time-steps spent in an area close to the cylinder
- Ecology:
  - a rectangular arena containing a single cylinder
  - random initial positions and orientations

Recognising Cylinders

Dynamic Solution

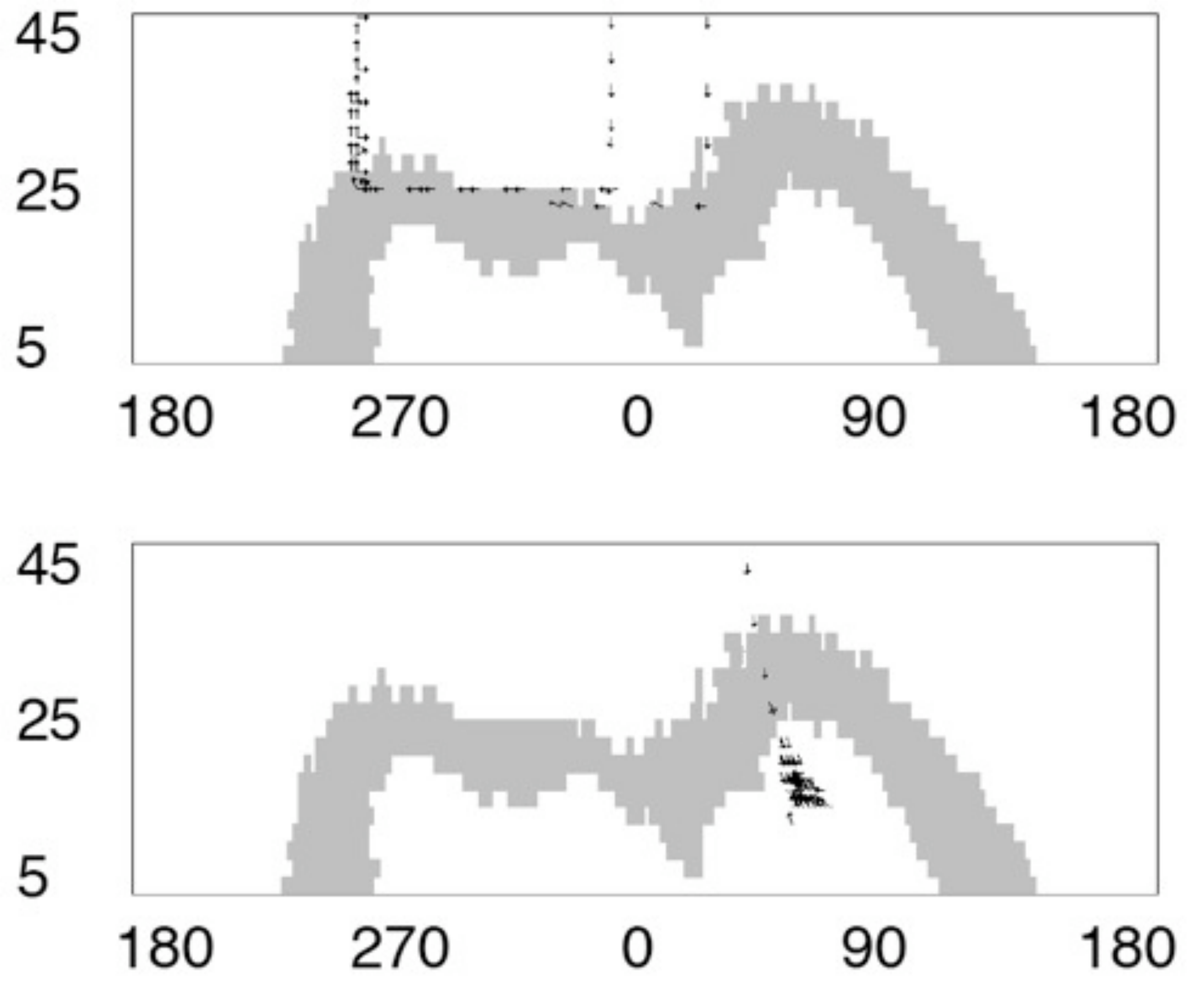
- The robot exploits the dynamical coupling with the environment



Recognising Cylinders

Dynamic Solution

- The robot exploits the dynamical coupling with the environment
- The difference between cylinder and wall resides in the interactions
    - turn in presence of walls
    - oscillations close to the cylinder

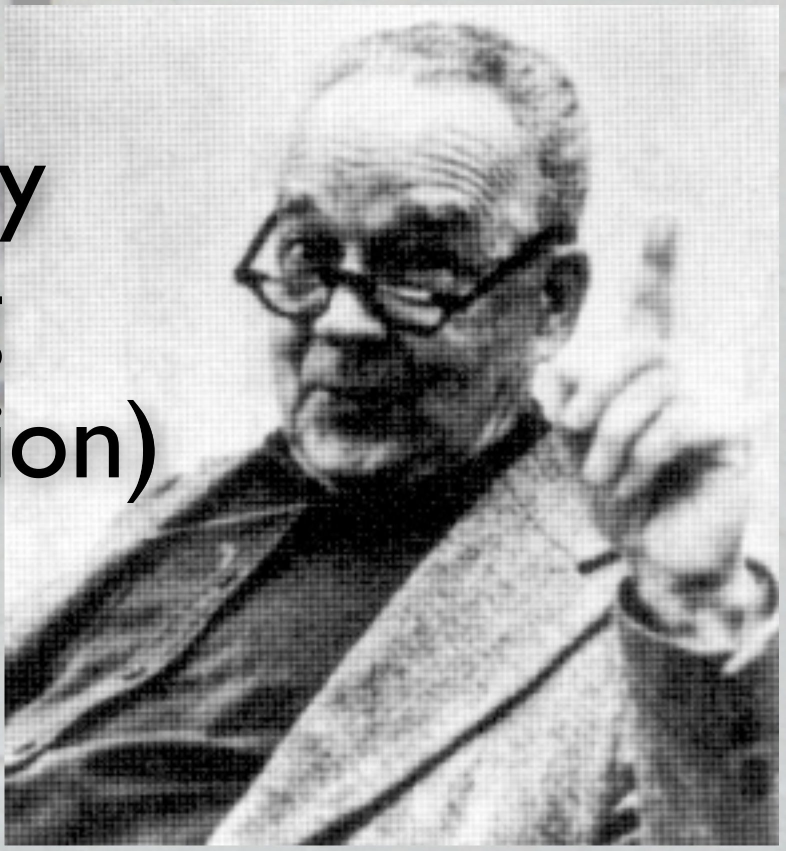


Perception-in-Action

- Perception and movement are tightly linked
- Intelligent agents perceive the world according to the actions to be performed

Perception-in-Action

- Perception and movement are tightly linked
- Intelligent agents perceive the world according to the actions to be performed
- Affordances (Gibson, 1977): opportunities of actions given by the agent-environment coupling (e.g., a chair affords a sitting action)



Active Vision

- Perception and action are interconnected also in vision
- Overt attention: directing sense organs towards a stimulus source
- Information is acquired through a sequence of saccadic movements that depend on the context
  - Alfred L. Yarbus investigated the nature of eye movements

Ilya Repin. The Unexpected Return. 1884

...freely examine the painting

Ilya Repin. The Unexpected Return. 1884

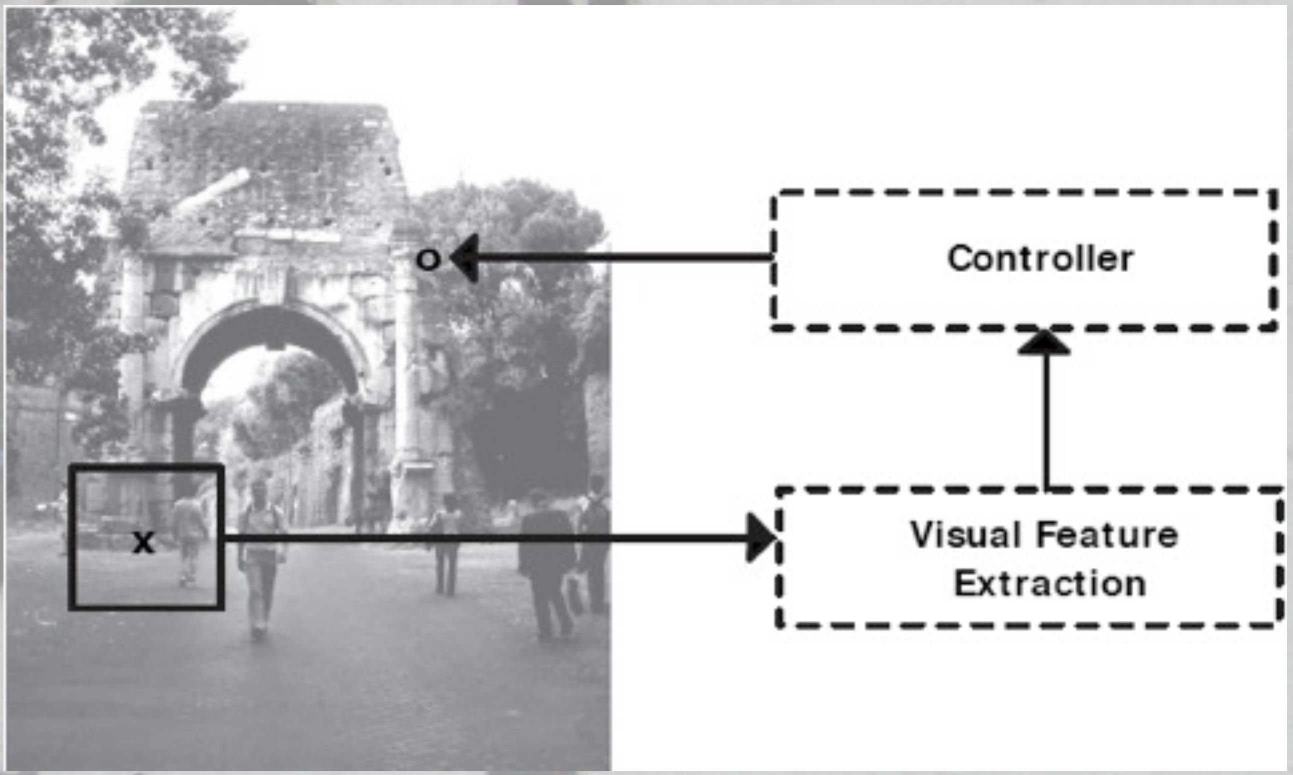
...estimate the age of the people

Ilya Repin. The Unexpected Return. 1884

Ilya Repin. The Unexpected Return. 1884

Gaze Control

- How to exploit active vision in artificial setups? (de Croon, 2008)
  - Analyse images, recognise and categorize objects
  - Use gaze control for driving action



Let’s try again!

Gaze Control

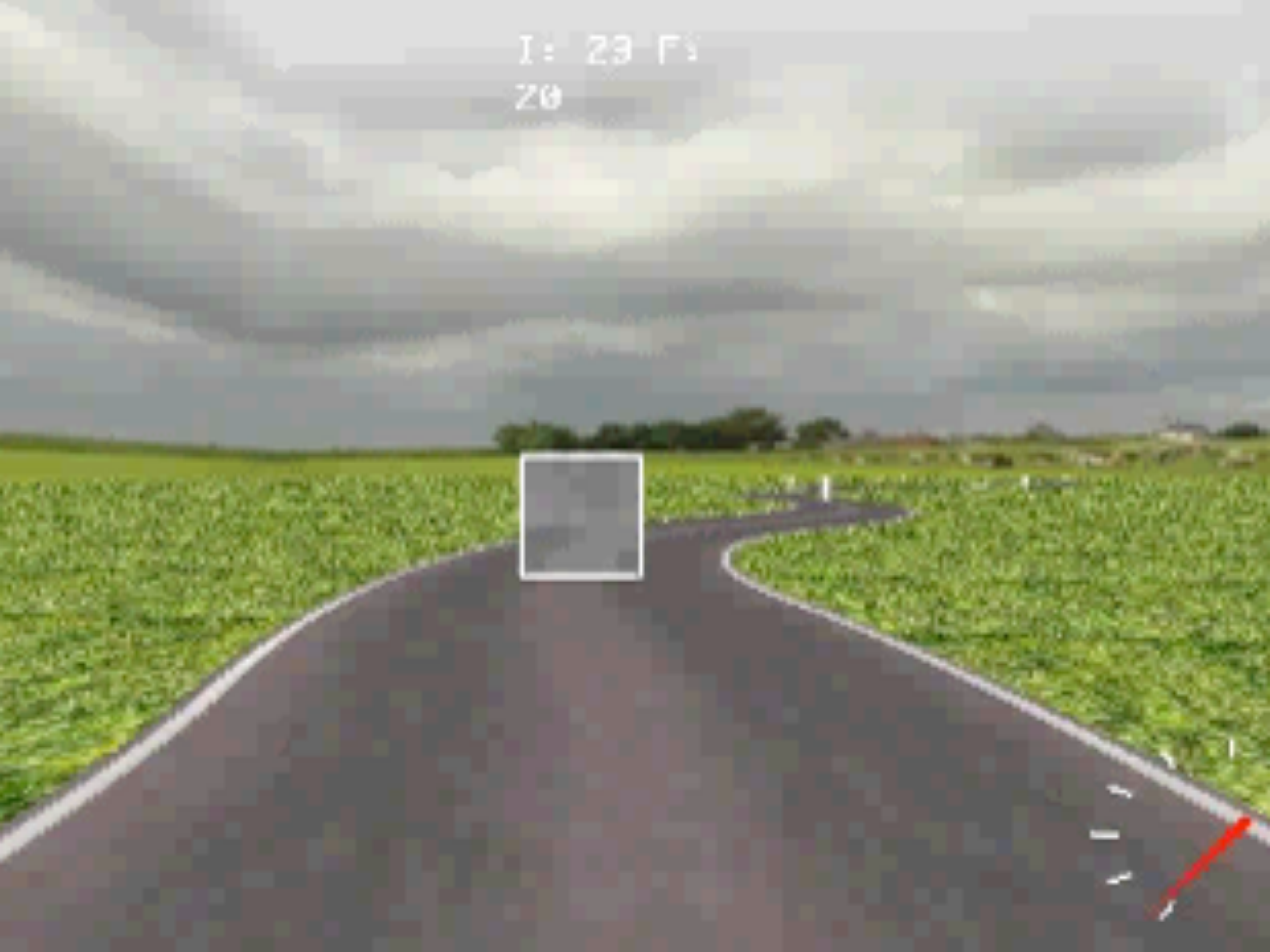
Object Recognition

- A virtual retina must foveate over objects
- Evolution performed on a finte image set
  - recognise faces in an office environment
  - recognise cars in outdoor scenes

Gaze Control

Car Driving

- A virtual retina extracts features used for driving
  - recognise curves
  - avoid obstacles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Beyond Reactive Intelligence

Beyond Reactive Intelligence

- Reactive strategies present several limits
  - perform a single behaviour
  - work only on readily available information
- Need to accumulate information over time
- Initiate alternative actions on the basis of previous experiences

Dynamic Neural Nets

- A very powerful architecture is the Continuous Time Recurrent Neural Network

$$\tau \dot{y}_j = -y_j + \sum_{j=1}^{n} w_{ij}\, \sigma(y_j + \beta_j) + gI_i$$

- CTRNN can produce rich internal dynamics
- CTRNN can approximate any finte-time trajectory of a dynamical system

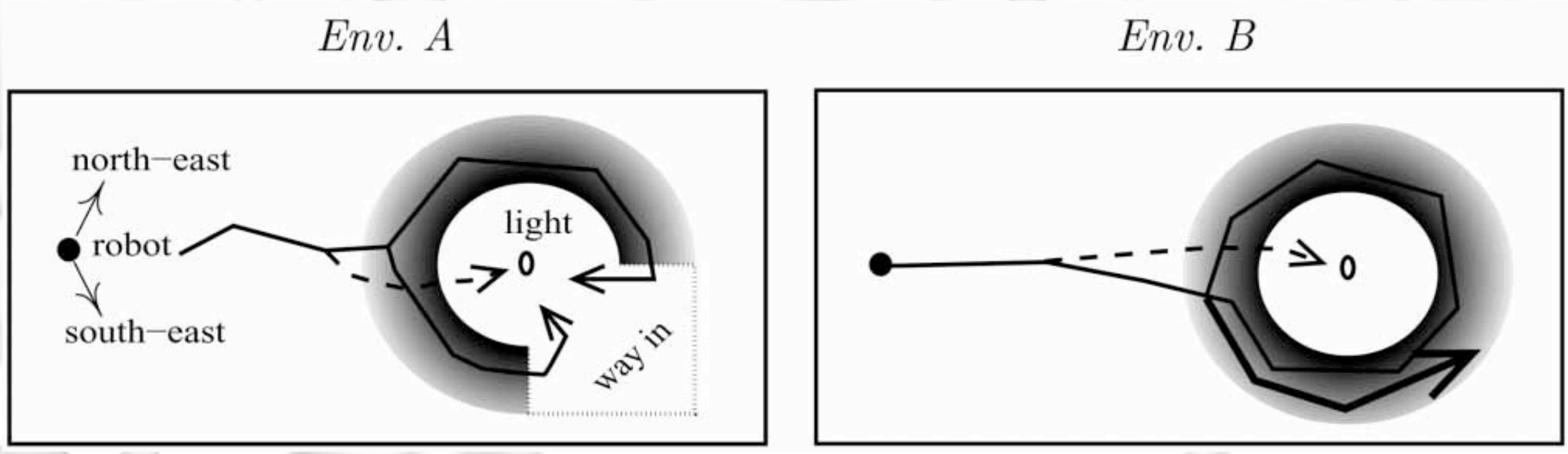
Feeling the Flow of Time

- Problem:
  decide wether to continue with unsuccessful attempts or leave for good (Tuci et al., 2004)
- Tools: kephera robot
- Sensory-motor system
  - 2 ambient light sensors
  - 1 ground sensor
  - 2 wheels
- Goal: integrate perceptual flux over time

Feeling the Flow of Time

Binary-Choice Setup

- Reach a light positioned in the center, while avoiding crossing the black barrier
- Local perception forces to search the way in
- Emit a signal when there is no way in

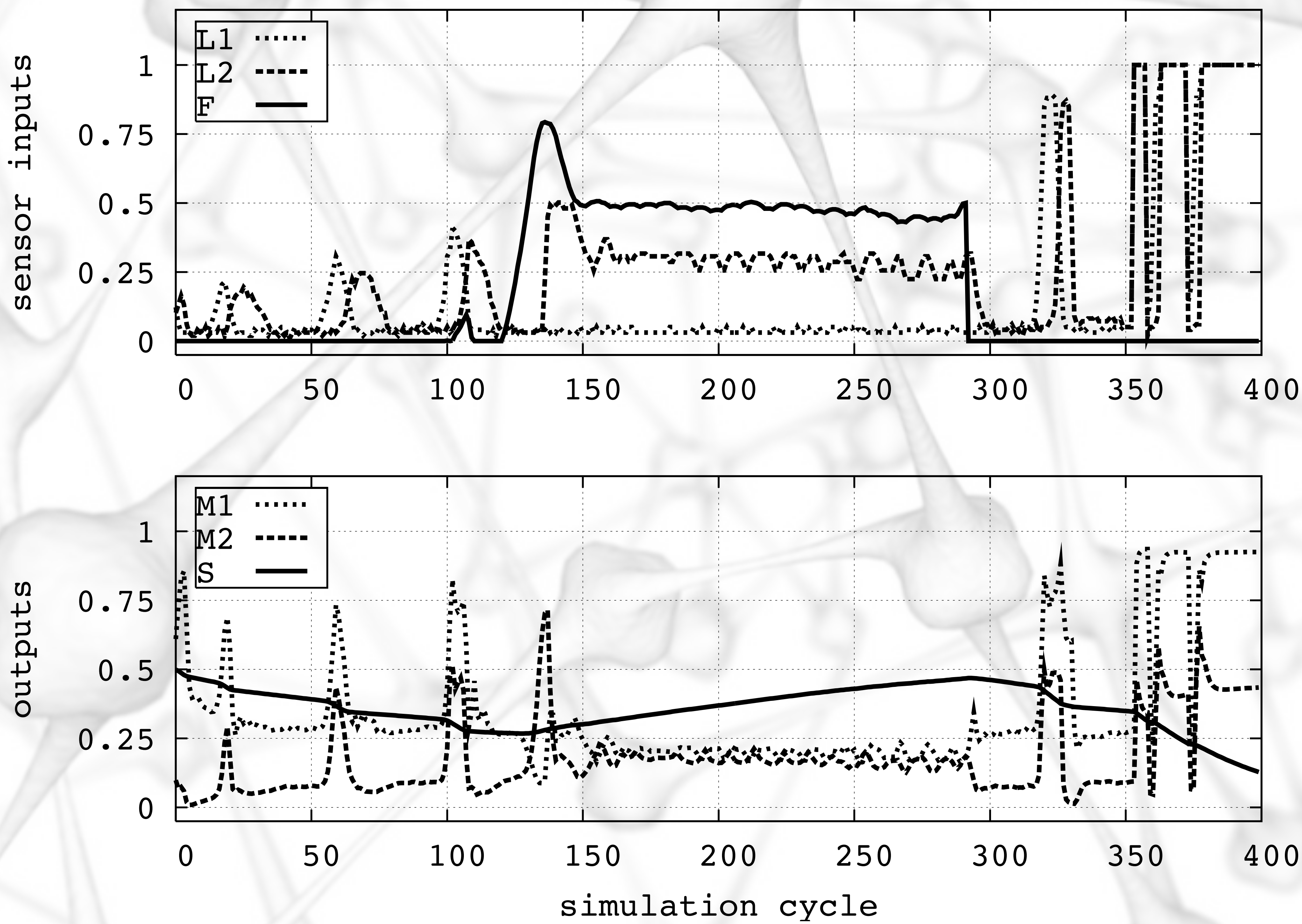


Perception and Decision

- The following steps are necessary:
  - develop sensory-motor coordination to search for the way in
    → provide a constant perceptual flux
  - develop the ability to integrate information over time
    → feel the flow of time through the flux of perception
  - develop the ability to signal when enough time is passed
    → take decisions on the basis of the cumulated information

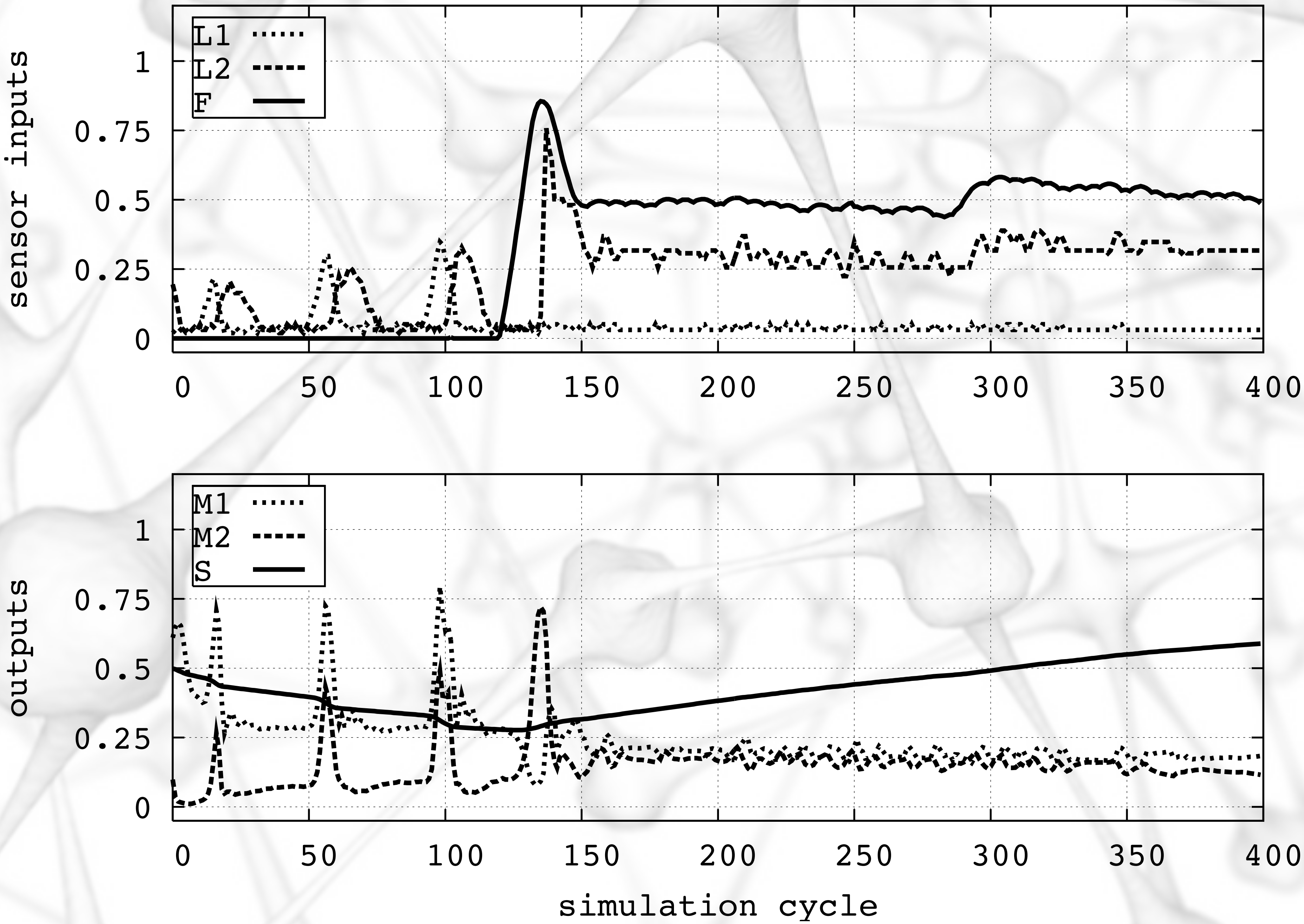
Feeling the Flow of Time

Evolved Solution



Feeling the Flow of Time

Evolved Solution

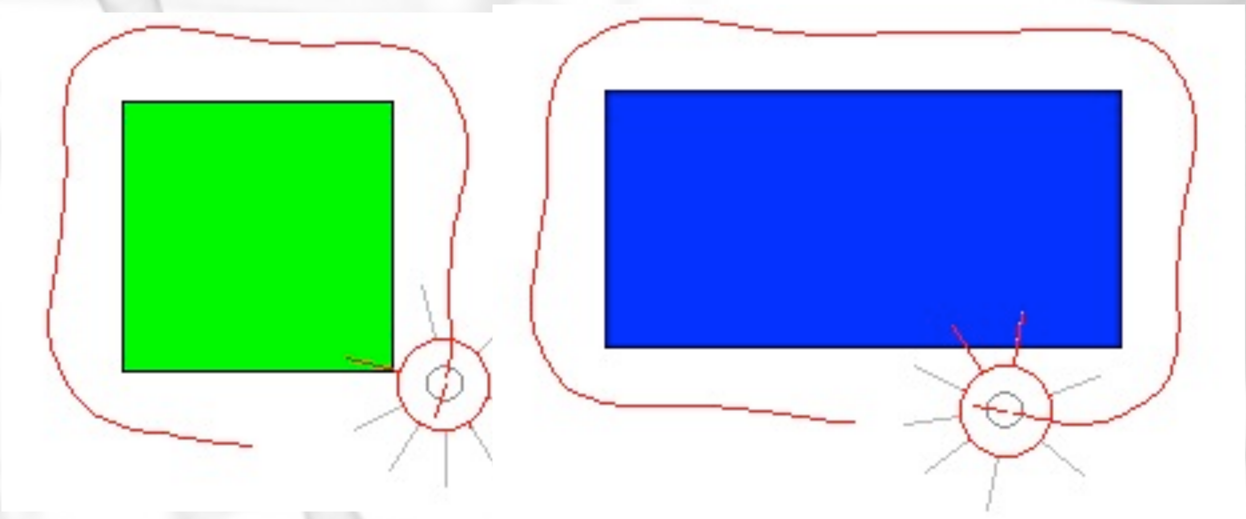


Abstract Categories

- Problem:
  categorise objects in squares or rectangles (Morlino et al., 2009)
- Tools: kephera robot
- Sensory-motor system
  - 8 IR proximity sensors
  - 2 wheels
- Goal: recognise objects from noisy data and repeated interactions through time

Binary Categorisation

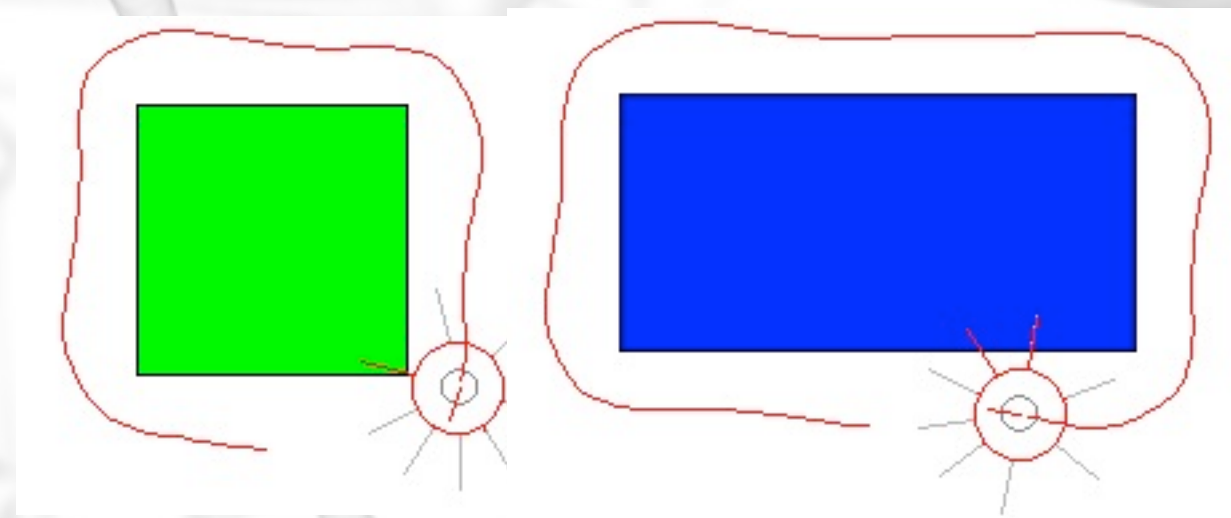
- The system must categorise shapes
  - side length varies
  - need to extract high level information

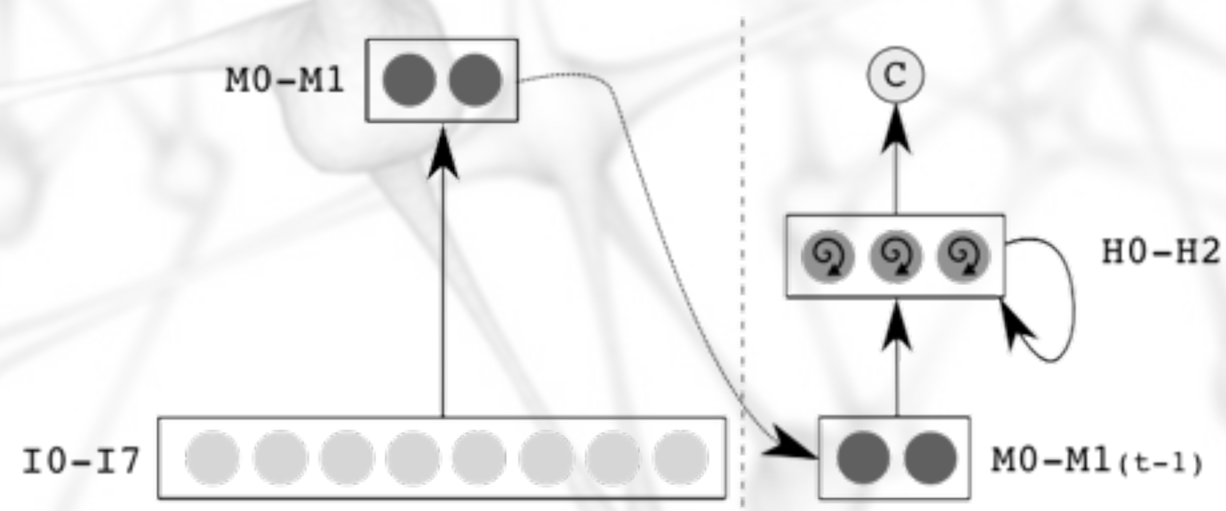


Abstract Categories

Binary Categorisation

- The system must categorise shapes
  - side length varies
  - need to extract high level information
- The dynamic part of the controller outputs a categorisation signal





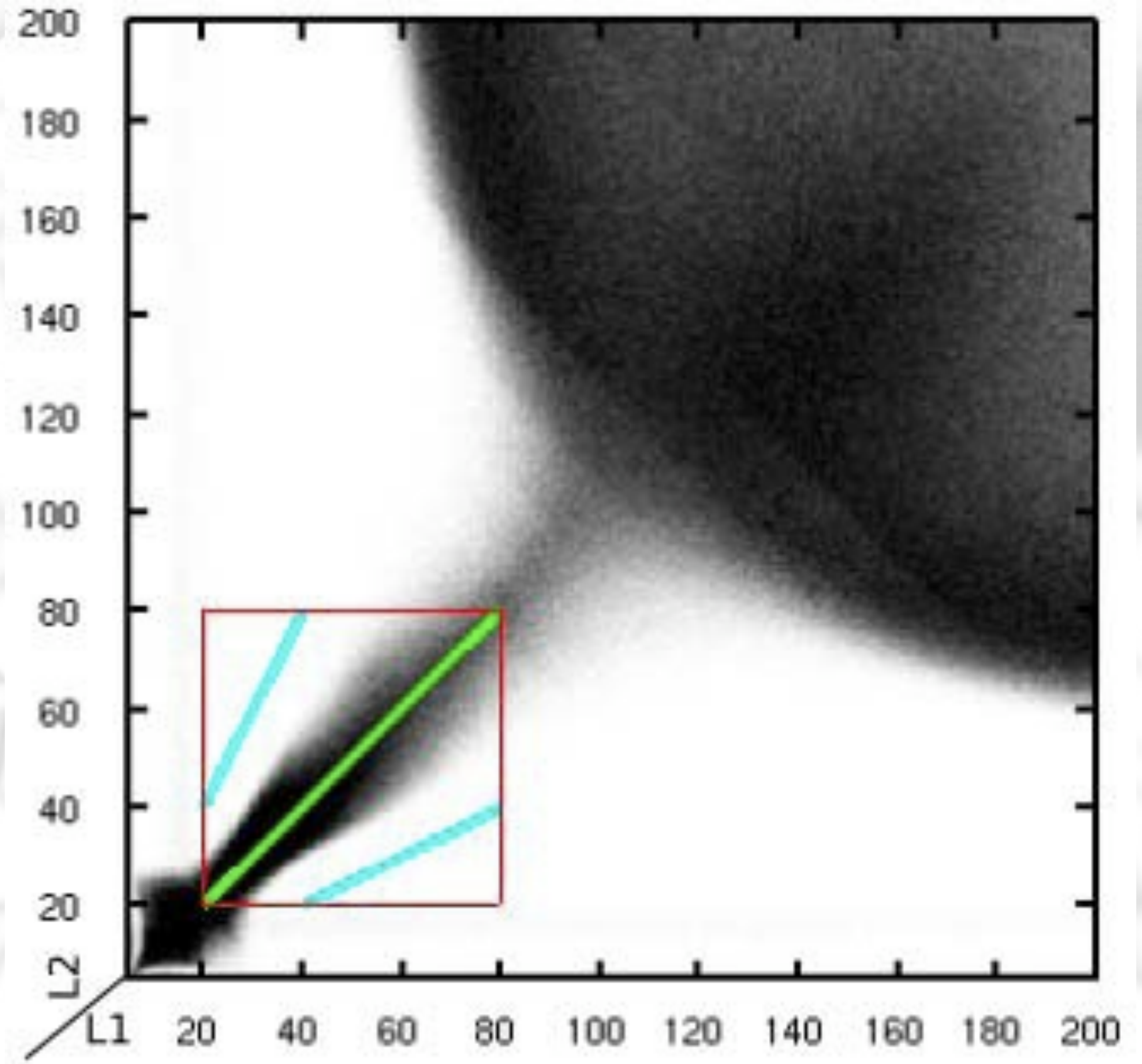
Two-Step Evolution

- First step: exploration
  → evolve the ability to circle around objects
- Second step: categorisation
  → exploit the flux of motor commands
  to decide between squares and rectangles

Abstract Categories

Analysis

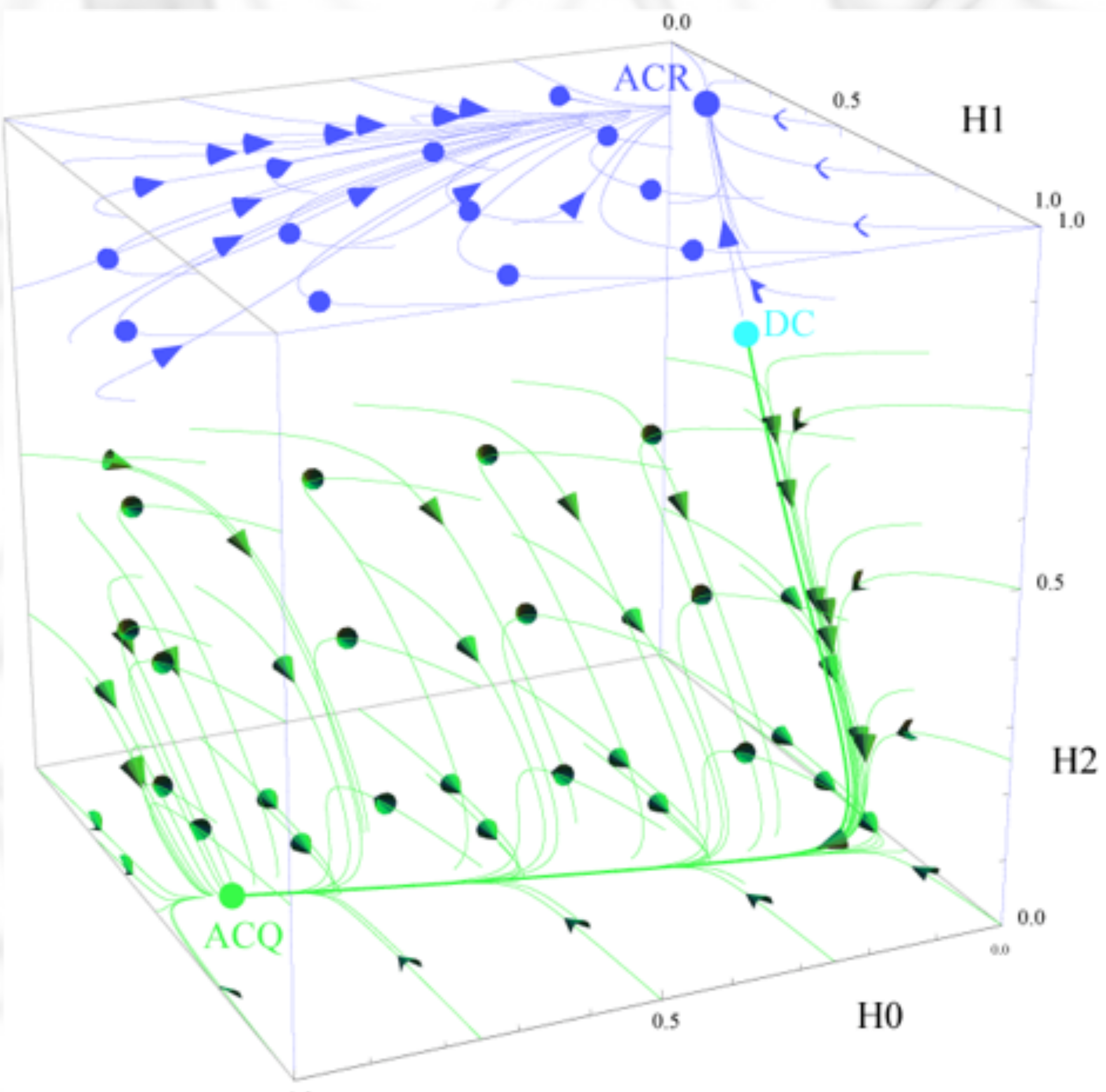
- Evolved robots recognise shapes efficiently
- Good generalisation to different conditions
- Study the dynamics of categorisation



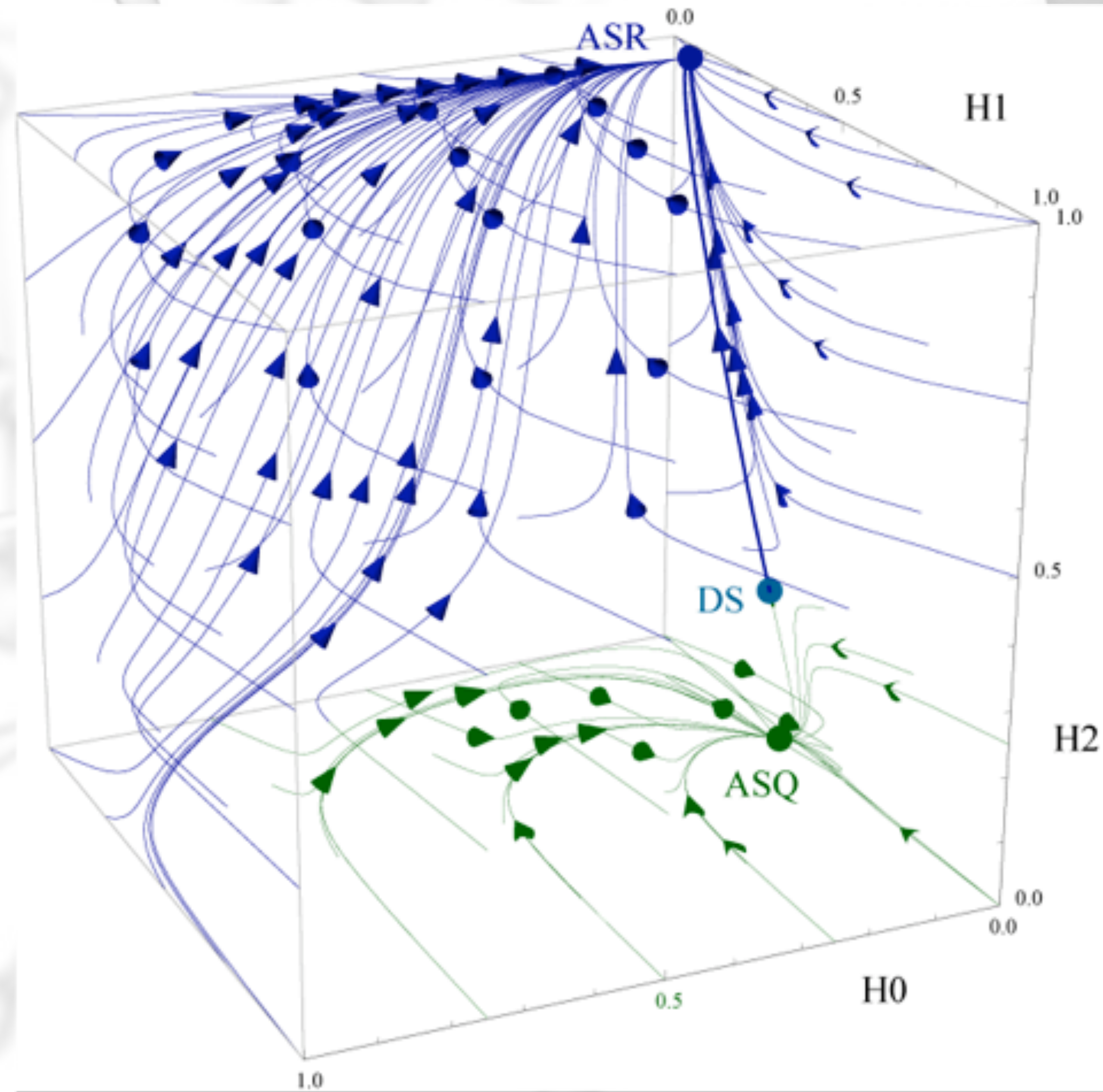
Abstract Categories

Controller Dynamics

Corner crossing (C)



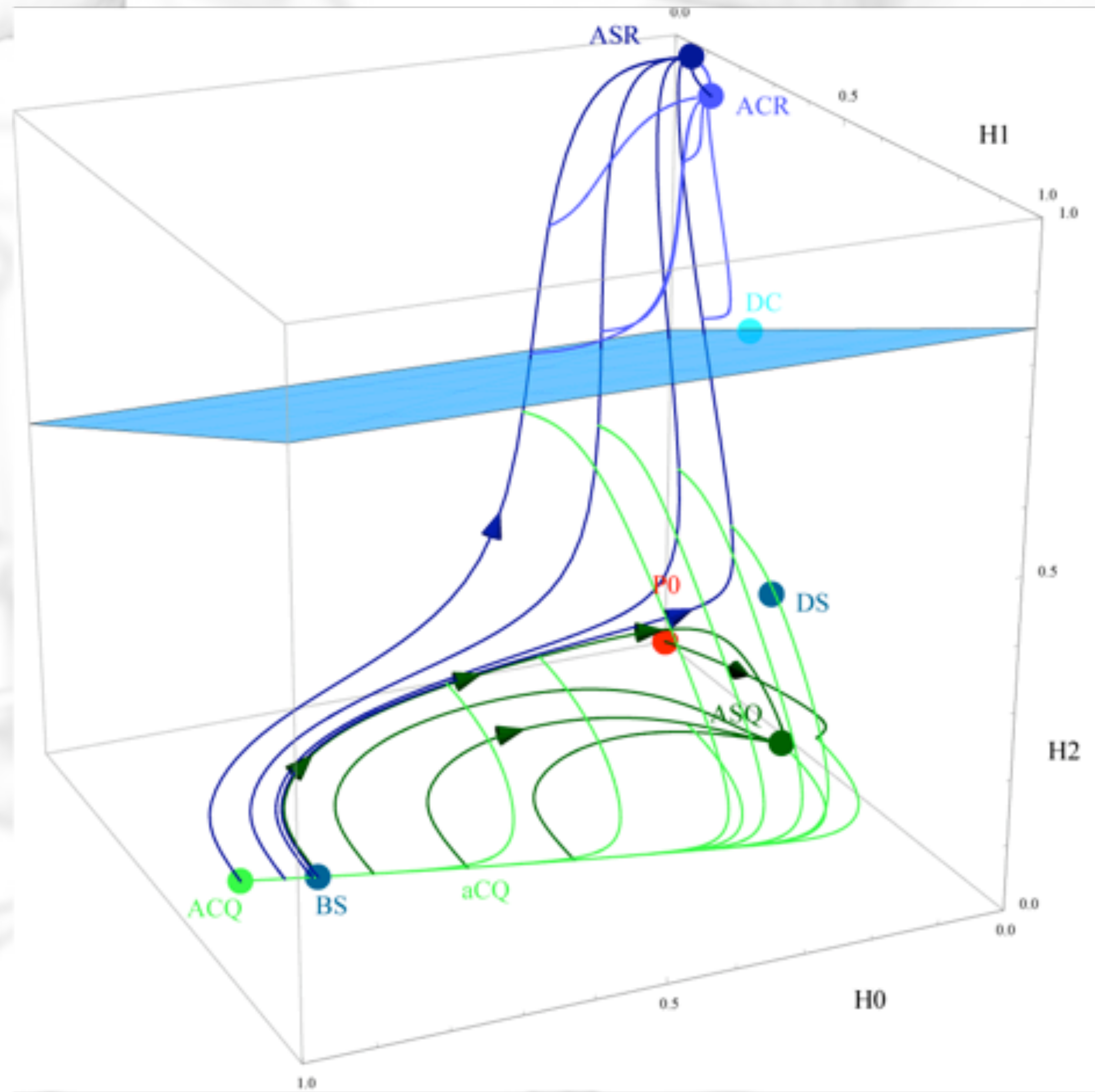
Side walking (S)



Abstract Categories

Coupled System

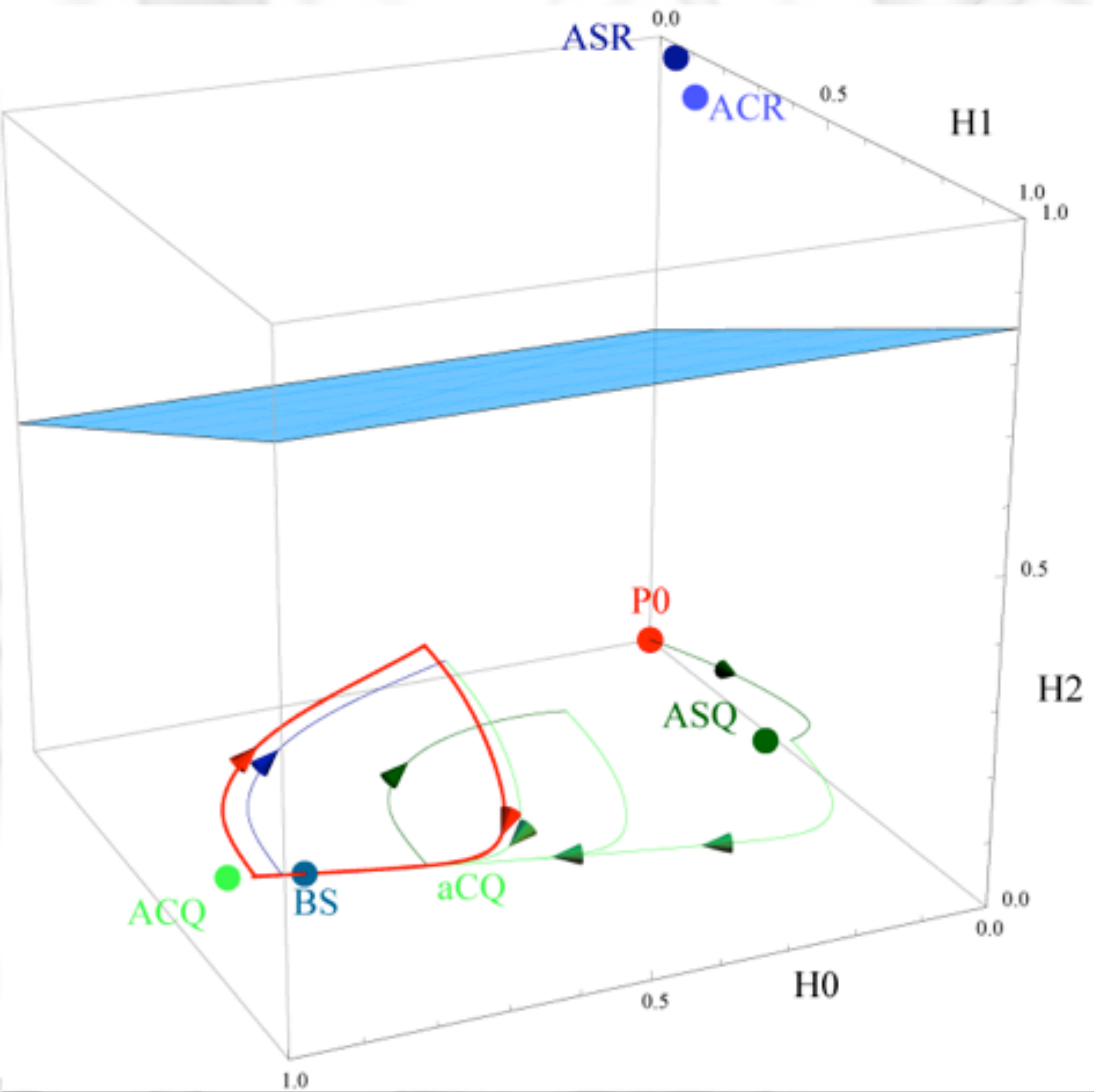
- Alternate dynamics produced while coping with corners and sides
- The blue plane represents a decision boundary
  - prejudice towards squares
  - unbalanced sides shift the interaction dynamics
  - categorise rectangles when crossing the blue plane



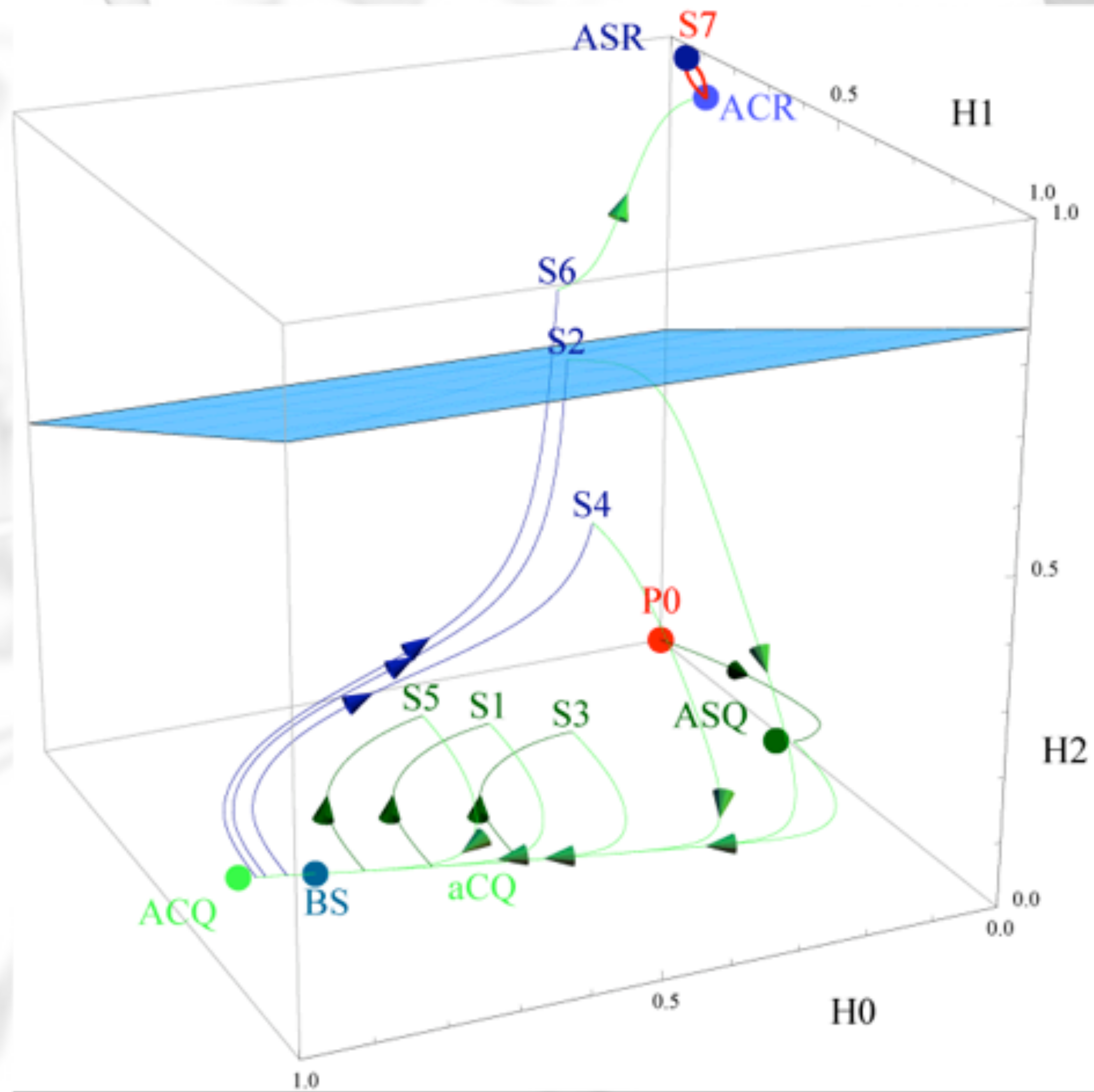
Abstract Categories

Squares vs. Rectangles

Square (40x40cm)



Rectangle (21.5x43cm)

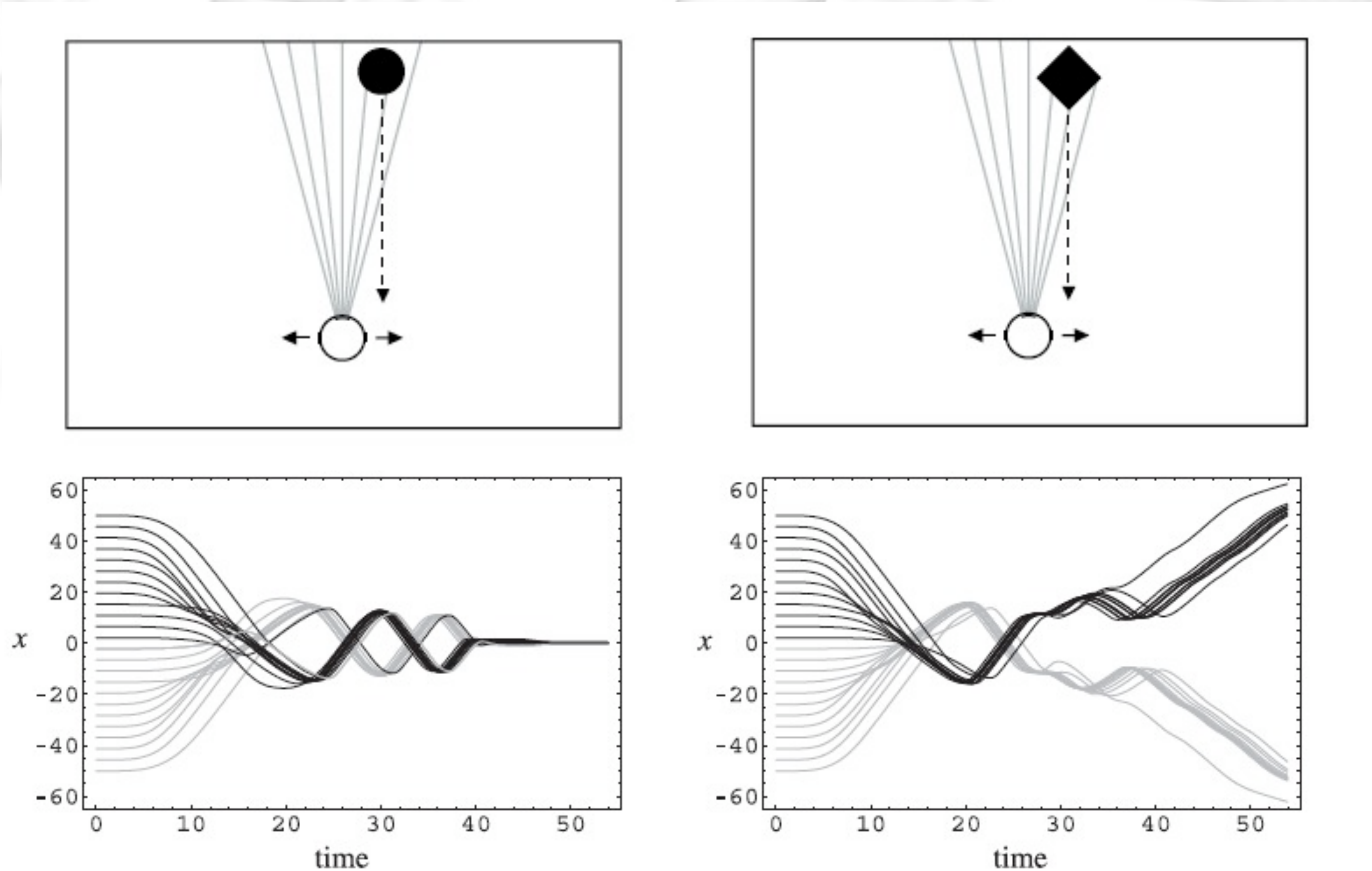


Minimally Cognitive Behaviours

- Study the simplest behaviours that raise questions of cognitive interest (Beer, 2003)
  - detailed experimental and theoretical analysis
  - a powerful strategy for exploring the implications of a dynamical approach to the study of cognition
- focus on trajectory that unfolds over time, rather than on the physical nature of the underlying mechanisms

Minimally Cognitive Behaviours

Circles vs. Diamonds



Minimally Cognitive Behaviours

Dynamic Representations

- Situatedness and embodiment imply the view about cognition as dynamical interaction
  - Inputs and external forces serve as perturbations of the intrinsic dynamics
  - Internal states not necessarily correspond to representations of external entities
- Cognition extends beyond an agent's brain including the external (social) environment

Evolution of Collective Behaviours

Swarm Robotics

- Multi-robot systems that present some form of swarm intelligence
  - Inspiration from the abilities of social insects and other group-living animals
  - Focus on distributed, self-organising behaviours

Main Features

- Decentralisation
  - distributing coordination and decision making
  - no single point of failure
- Locality
  - actions performed exploiting local information only
  - no reference to the global pattern
- Flexibility and robustness
  - adapting to novel working conditions
  - resiliency to individual failures through redundancy
- Emergence

The Design Problem

- Definition of the individual controllers to obtain a coherent group behaviour
- *Divide & conquer* approach
  - from global to individual behaviours
  - from individual behaviour to controller rules
- Problem: indirect relationship between individual rules and group behaviour

ER and Swarm Robotics

- Bottom-up approach
  - Limit a priori assumptions by the experimenter
- Evaluate individual controllers for their ability to produce self-organisation
  - Evaluate the system as a whole
  - Exploit the fine-grained dynamical interactions
- How to apply ER in swarm robotics?

Sensory-Motor System

Communication Issues

- Robots may be provided with different communication devices
- Choosing the communication channel might affect the evolutionary process
    - define the way in which robots interact and exchange information
    - influence the properties of the evolved behaviour

Genotype ➜ Phenotype

Group Structure

- Define the genetic relatedness of the group
- Homogeneous groups
  - all robots are identical
  - suitable for self-organising behaviours
- Heterogeneous groups
  - different robots are not genetically identical
  - larger search space
  - well differentiated roles

The Fitness Function

Group Evaluation

- The fitness should be behavioural, external and implicit
  - functional measures are related to the (unknown) mechanisms underpinning the behaviour
  - purely internal measures are possible only in the single robot case
  - explicit measures may overly constrain evolution

The Fitness Function

Group Evaluation

- The genetic relatedness of the group influences the fitness evaluation
  - No problem with a single genotype per group
- Heterogeneous genotypes
  - Evaluate individual contributions
  - Average over multiple groups
- Risk of competition between different genotypes

Swarm Ecological Niche

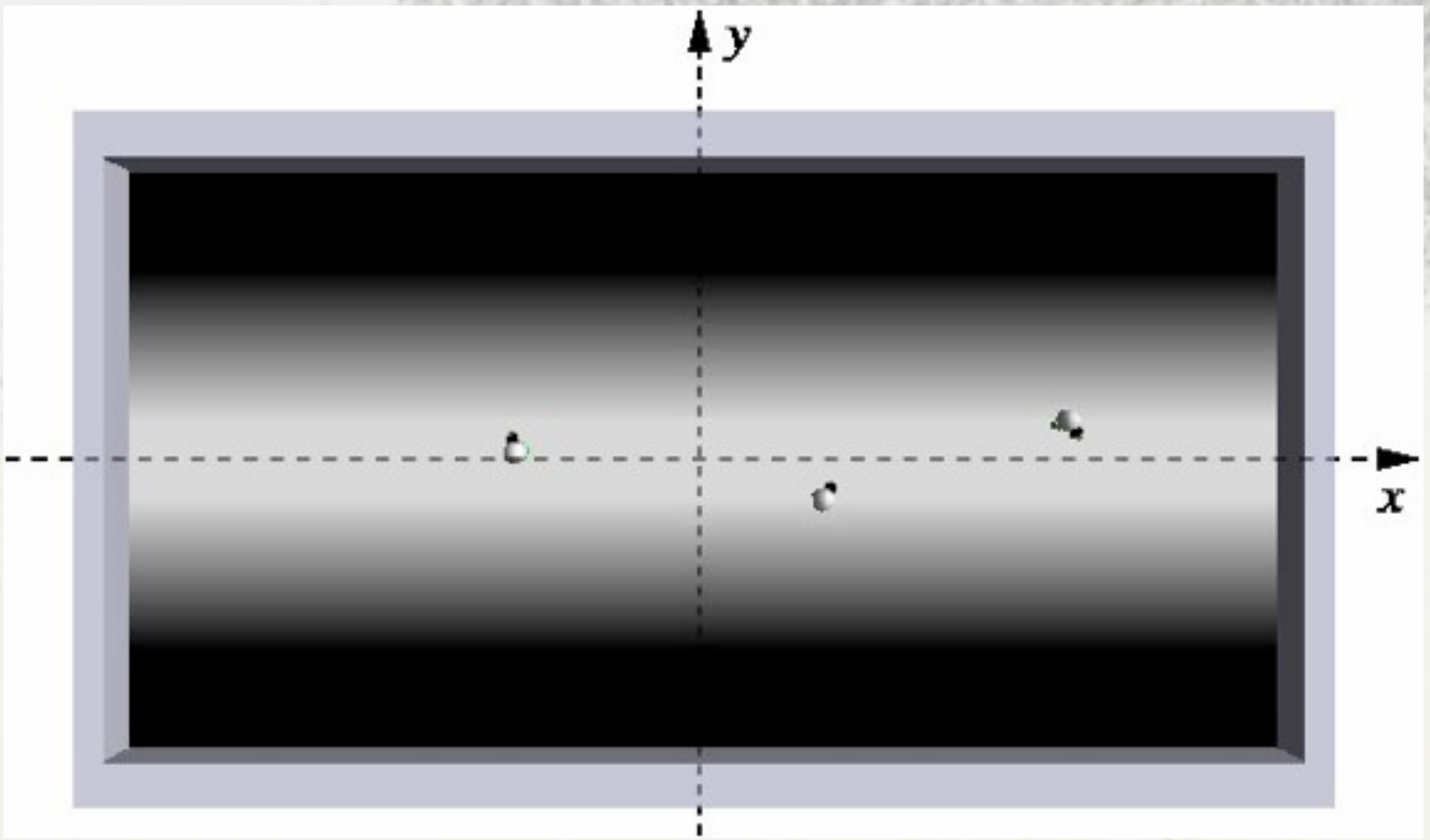
- Multiple robots increase the variability of the ecological niche
  - Interaction among individuals
  - Physical interferences
  - Collisions among robots
- Allow the group to experience the relevant interaction patterns
  - Explicitly consider symmetry breaking

Synchronisation

- The goal is investigating synchronisation in a swarm of autonomous robots (Trianni and Nolfi, 2009)
  - 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
- Oscillatory movements parallel to the y axis



Synchronisation

The s-bot

- Autonomous robot designed for self-assembly
- Many sensors, actuators and communication devices
    - 4 ground sensors
    - 8 infrared proximity sensors
    - 2 wheels
    - speaker and microphones

Synchronisation

Communication Channel

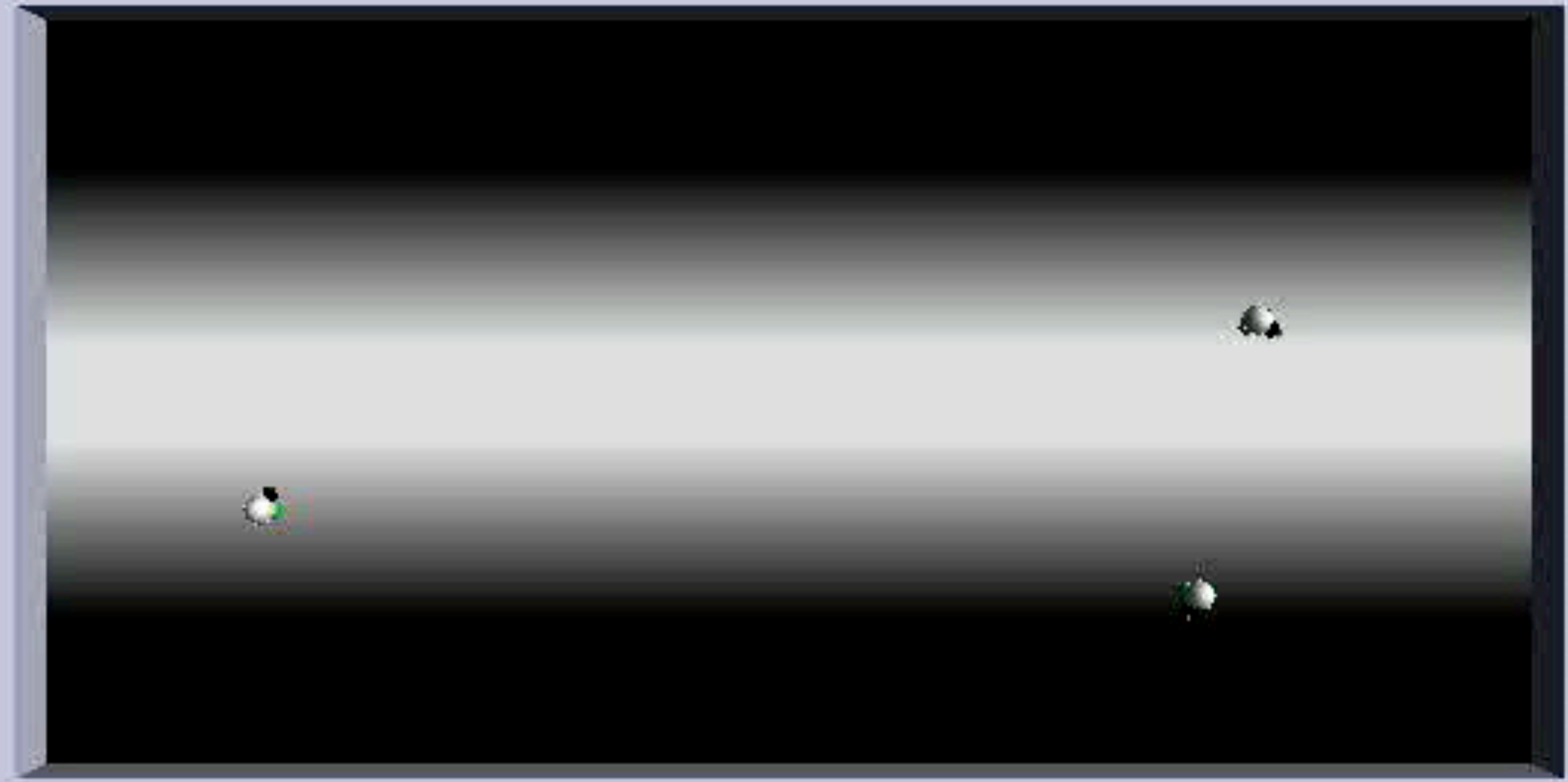
- Large freedom in choosing the protocol
- Minimal communication
  - Global signals → perceived everywhere
  - Binary signals → either 0 or 1
- Each robot can produce a binary signal
- The signal is perceived by all robots

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

Synchronisation

Evolutionary Setup

- Homogeneous group with reactive network
- Fitness is the average of two components
    - Movement component:
      → fast motion parallel to the y axis
    - Synchronisation component:
      → cross-correlation of y position

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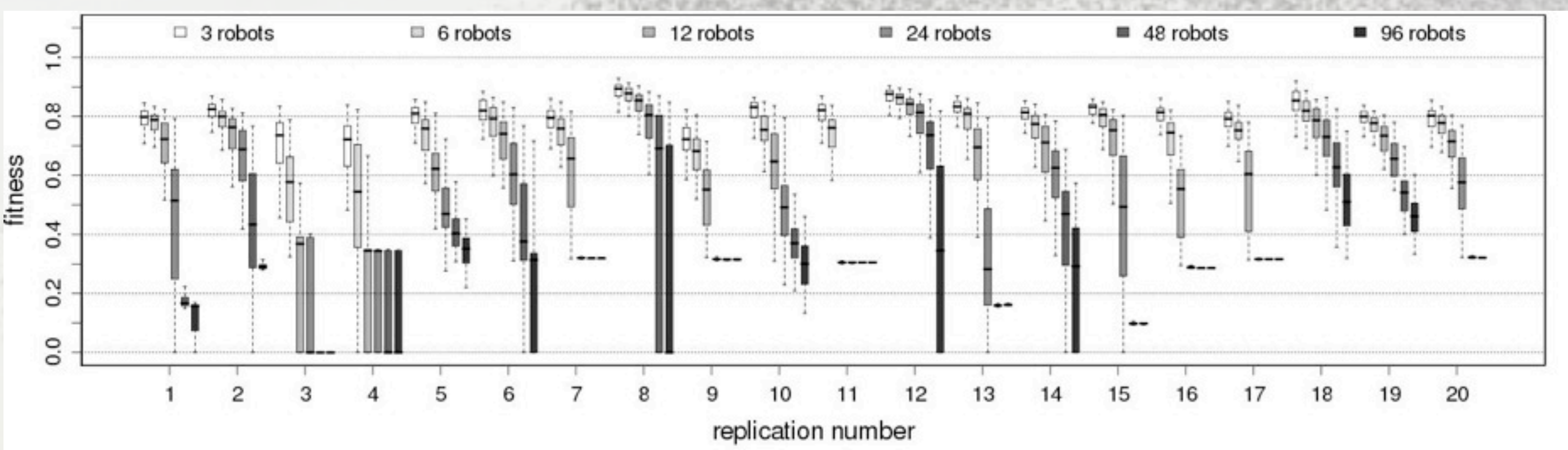
Behavioural Analysis

- Synchronisation is the result of robot's moves in reaction to perceived signals
    - Robots can be considered embodied oscillators
    - Phase modulation through sensory-motor coordination
- How do the robots perform with larger groups?

Synchronisation

Scalability

- We test groups of 3, 6, 12, 24, 48 and 96 robots
  - Same experimental conditions used during evolution
  - Constant uniform density of robots in the arena



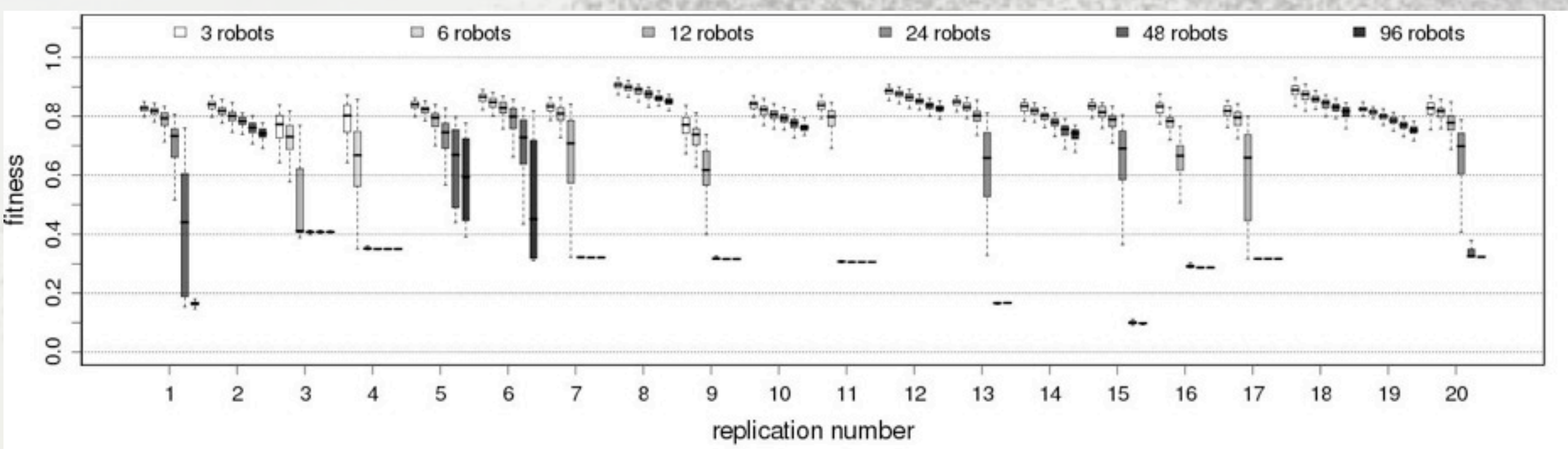
Synchronisation

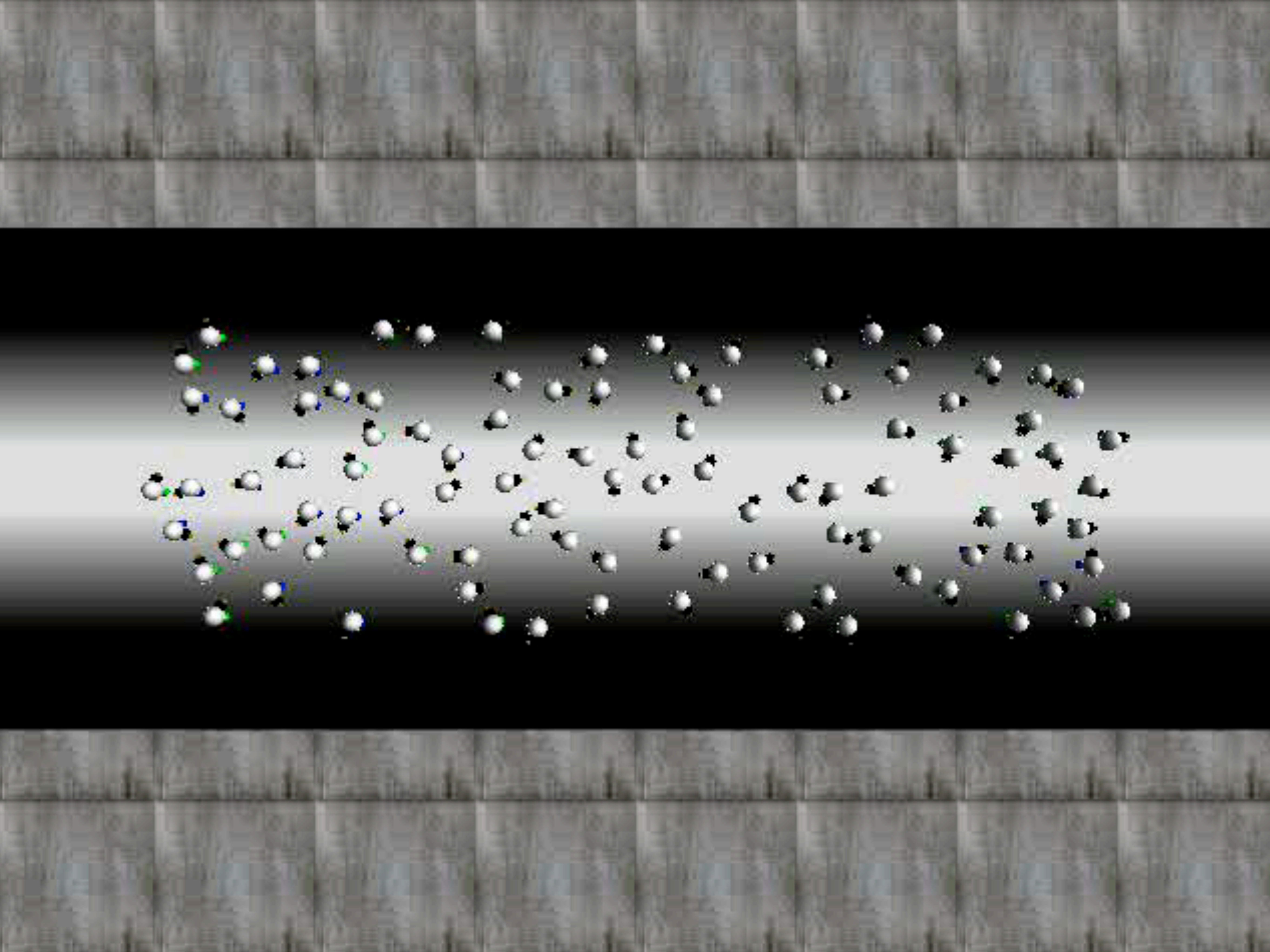
Scalability

- 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

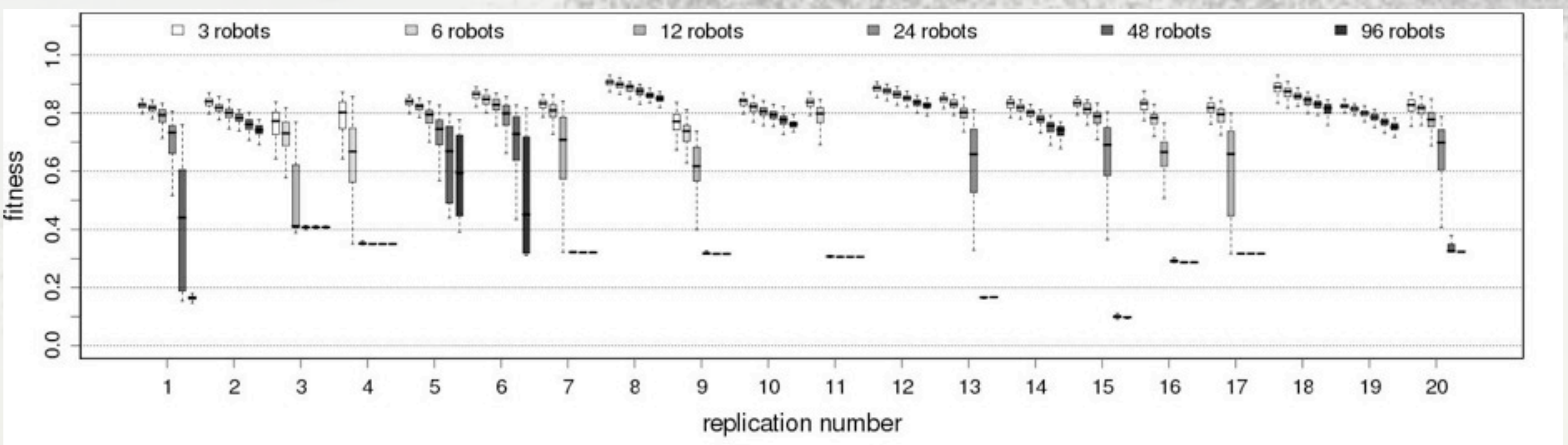
- Scalability of the synchronisation mechanism
  - Neglect physical interactions
  - Perform scalability analysis with the same modalities

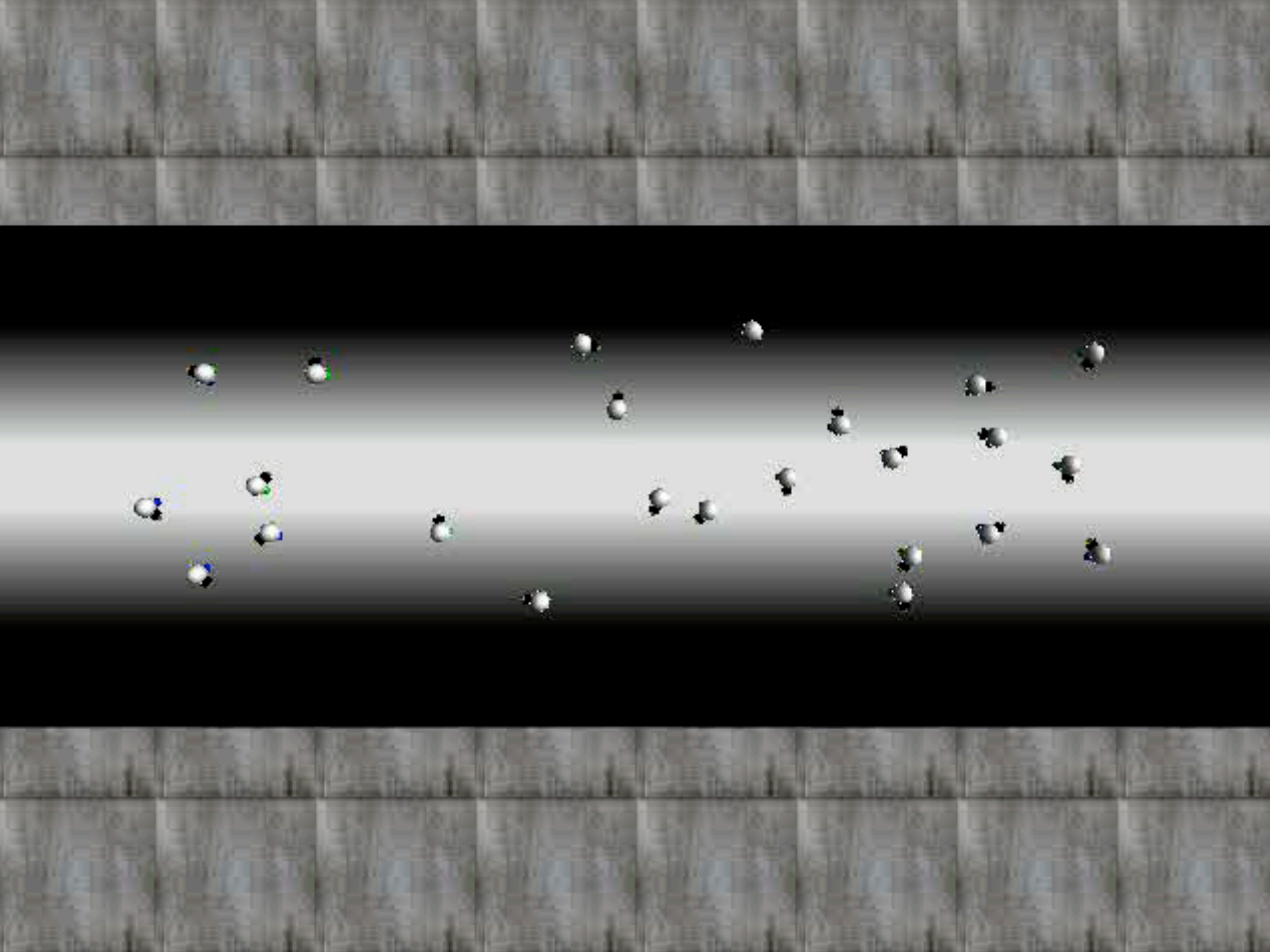




Sync Scalability

- 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





Synchronisation

Re-Engineering Evolution

- The communication protocol hinders 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 experiment to obtain better results

Additive Communication

- A new additive communication protocol
- S-bots emit and perceive continuous signals

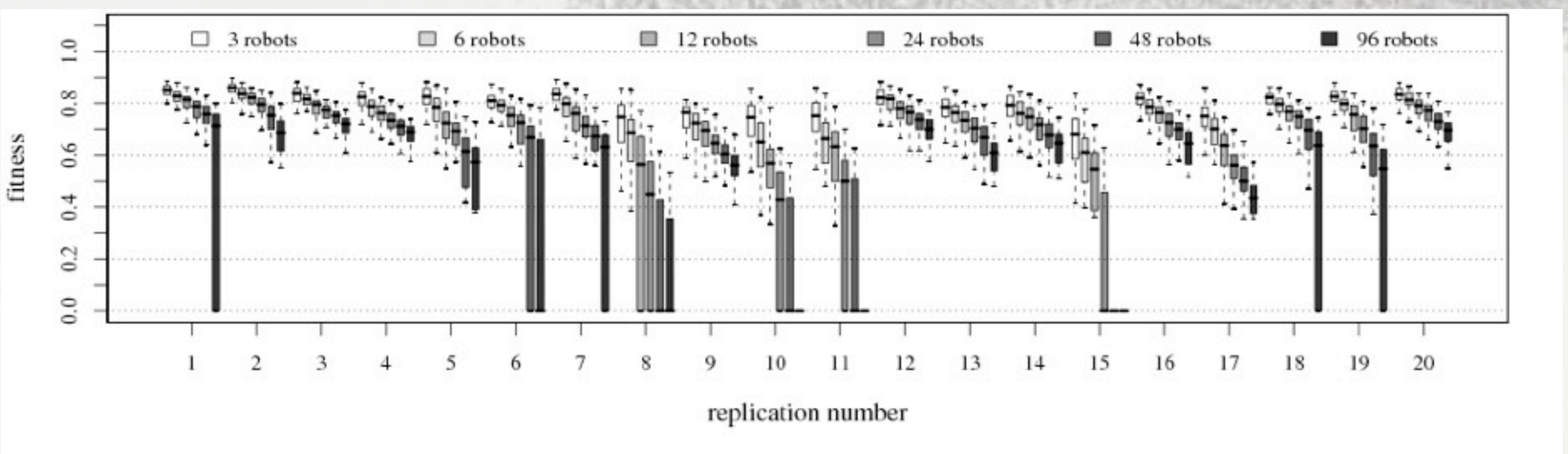
$$s(t) = \max_r S_r(t) \in \{0,1\} \longrightarrow s(t) = \frac{1}{N}\sum_{r=1}^{N} S_r(t) \in [0,1]$$

- Evolve new synchronisation behaviours
  - Focus on global synchronisation
  - Minor changes to experimental setup
  - Compare effects of re-engineering

Synchronisation

Scalability Analysis

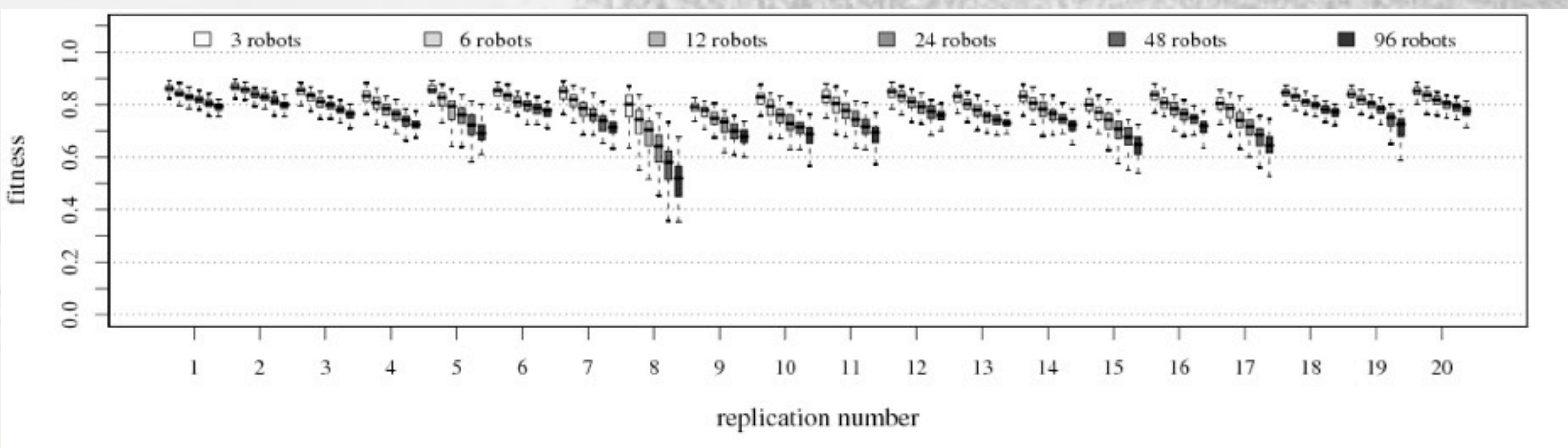
- Additive communication improves performance
  - Physical interactions and collisions do not have a severe impact on performance



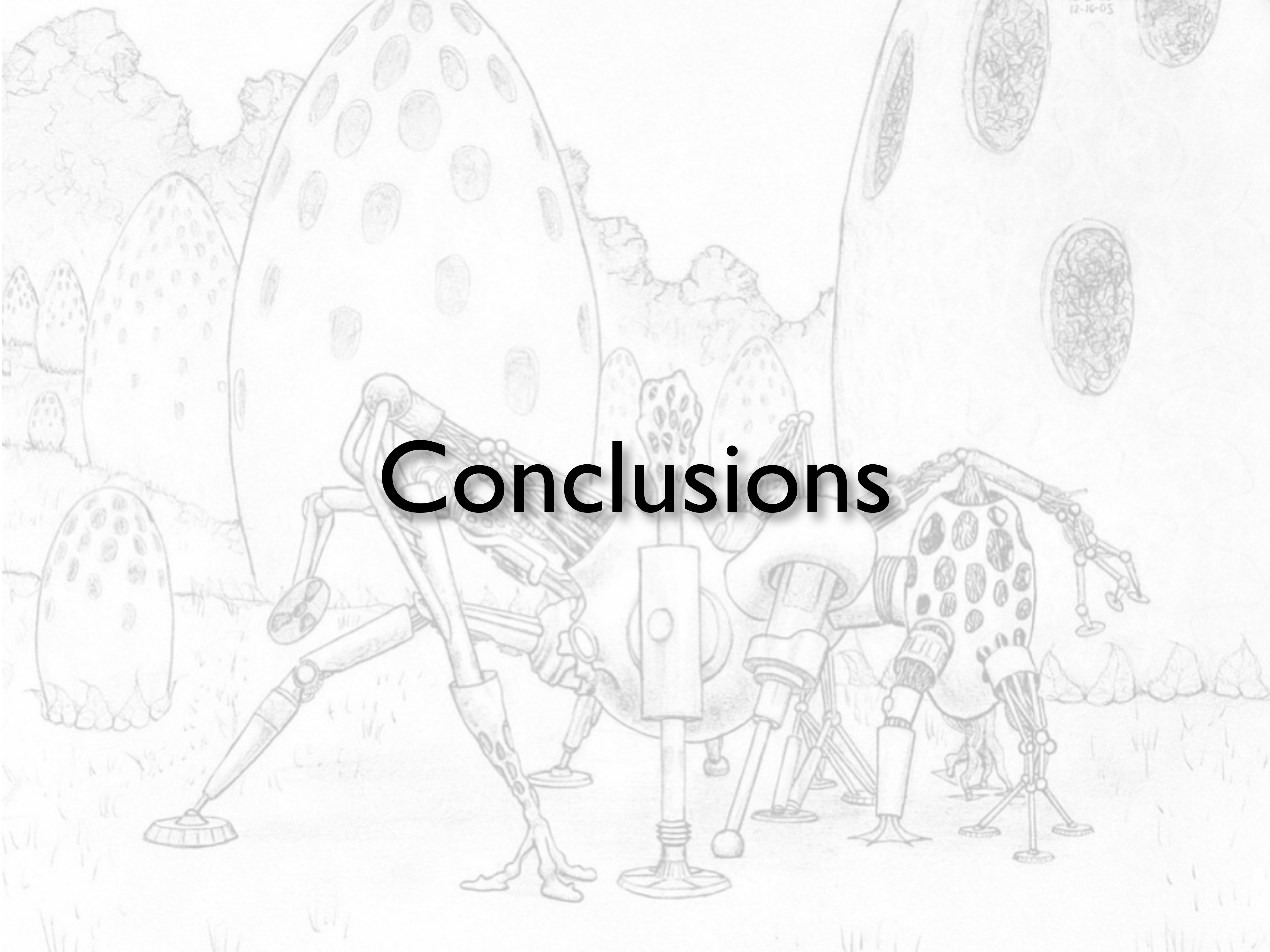
Synchronisation

Sync Scalability Analysis

- Additive communication always produces scalability
  - No more communicative interferences
  - All evolved controllers properly scale



Conclusions



Summary

- ER is a powerful methodology for synthesising robot behaviours
  - situatedness and embodiment
  - neural networks as powerful controllers
- ER contributes to the study of cognition
  - dynamical systems approach
  - intuition pump
  - proof-of-concepts
- ER can be applied to a variety of problems

Topics not Covered

- Study on the evolutionary algorithm (MOER)
- Relation between evolution and learning
- Relation between evolution and development
- Competitive co-evolution
- Open-ended evolution
- On-board, on-line evolution

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