Lecture
Evolutionary and Swarm Robotics

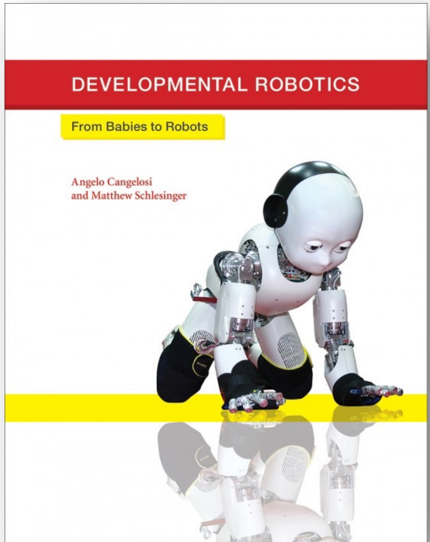
Angelo Cangelosi
Department of Computer Science, Kilburn Building,
The University of Manchester

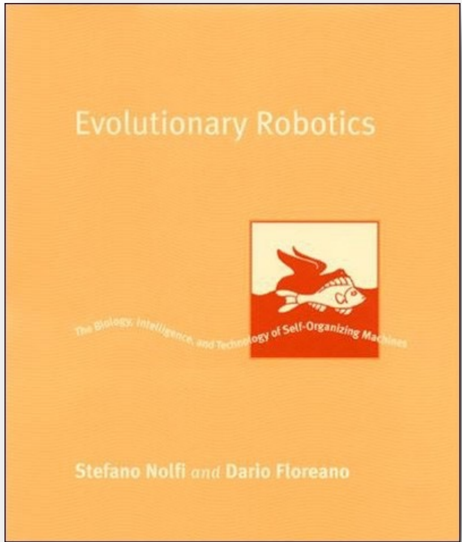
Content

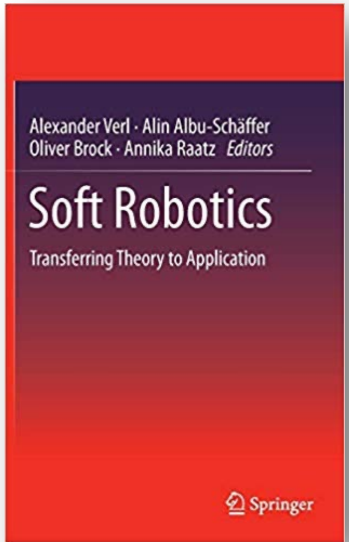
- Evolutionary Computation and GAs
  - GA
  - Khepera, iCub
  - Co-evolution and arms race
- Evolving morphologies
  - Kitano & Sims, Bongard & Lipson
- Swarm
  - Self-organization
  - Swarm applications
  - ACO Ant Colony Optimisation

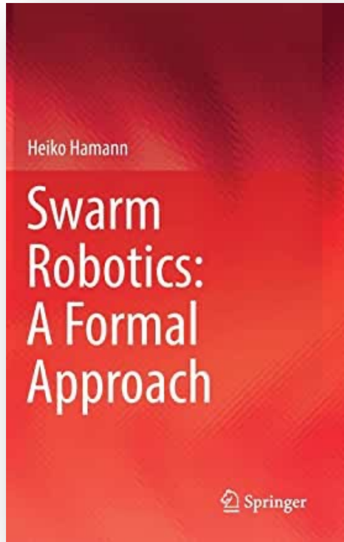
Terminology II

- Cognitive Robotics Approaches
  - Developmental Robotics (Cangelosi & Schlesinger 2015)
  - **Evolutionary Robotics** (Nolfi & Floreano 2002)
  - Swarm Robotics (Dorigo et al. 2014; Hamann 2018)
  - Soft Robotics (Laschi et al. 2016; Veri et al. 2015)







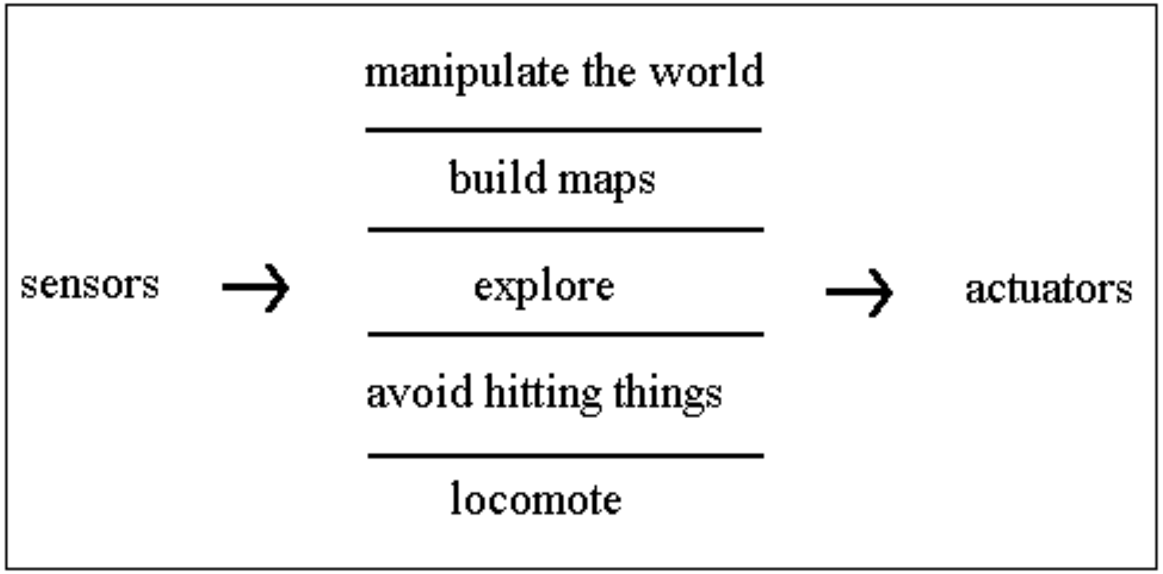


Classical Robotics

- Engineering problem: Functional breakdown in separated modules *(Divide and Conquer)*
  - Perception (Artificial Vision, NLP)
  - Planning (Knowledge Bases, Spatial Models)
  - Action (Robotics Arms, Mobile robots)
- Problems
  - High levels of complexity
  - Integration of modules

Behaviour-Based Robotics

- Radically different approach (Brooks 1991)
  - the division is accomplished at the **level of behaviour** (not human-centred)



Problem: Integration of behaviours

Brooks (1991), New Approaches to Robotics, *Science*, 253, 252-257

Bio-Inspired Approaches

- Look at Natural/Biological solutions to evolving complexity
  - **Psychology and development** (Developmental Robotics)
  - **Natural selection** for evolving complex organisms and complex behaviours

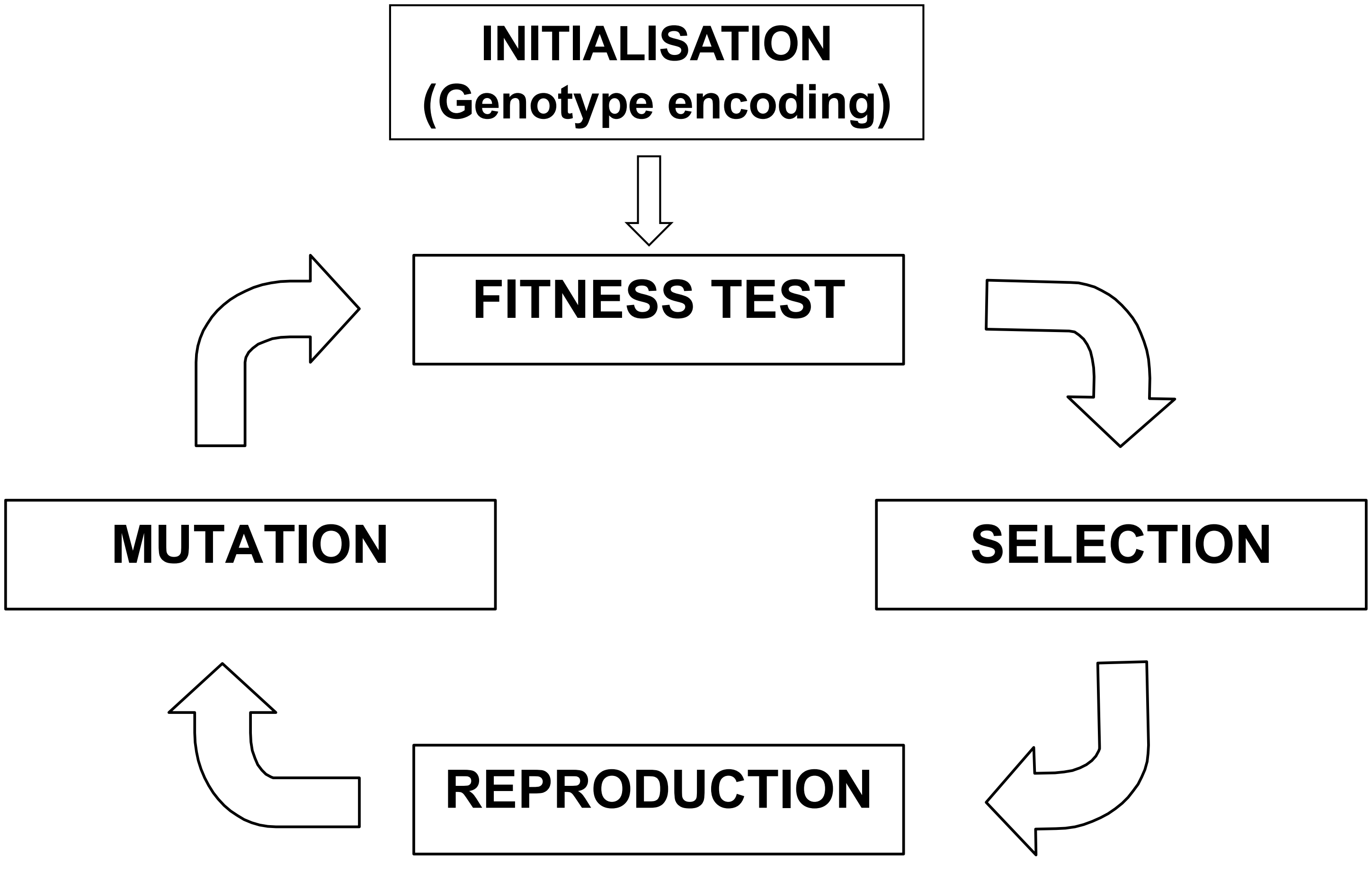
EvoRobot: Evolutionary Robotics

Evolutionary Robotics is the ***automatic design*** *of robots and of their sensorimotor control systems through an* ***evolutionary computation*** *process*

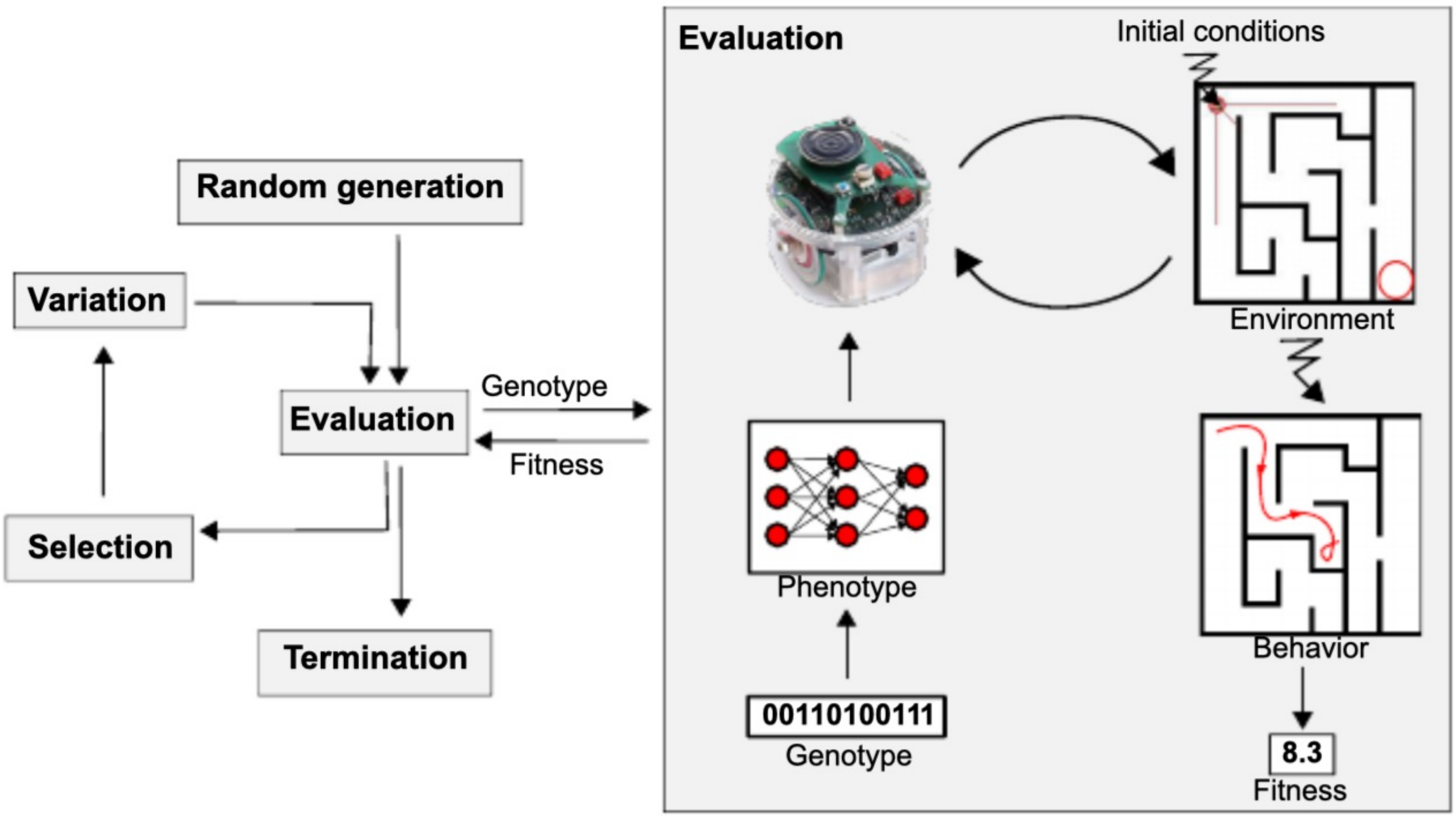
(Nolfi & Floreano, 2000)

GA: Genetic Algorithm

A computational model of Darwin's Natural Selection (Holland 1975; Goldberg 1989)



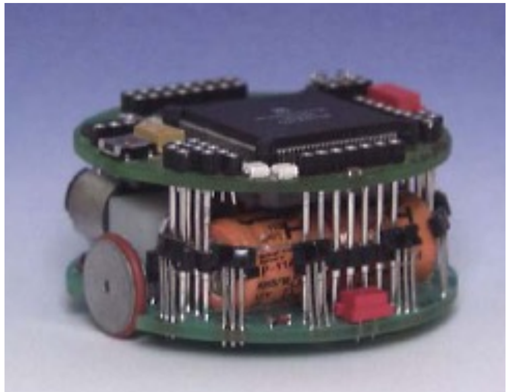
GA and EvoRobot

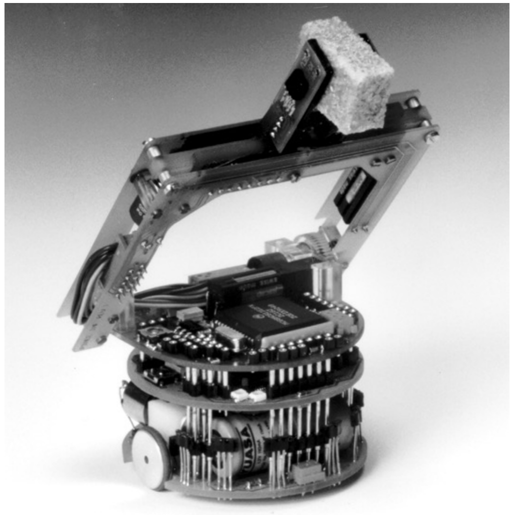


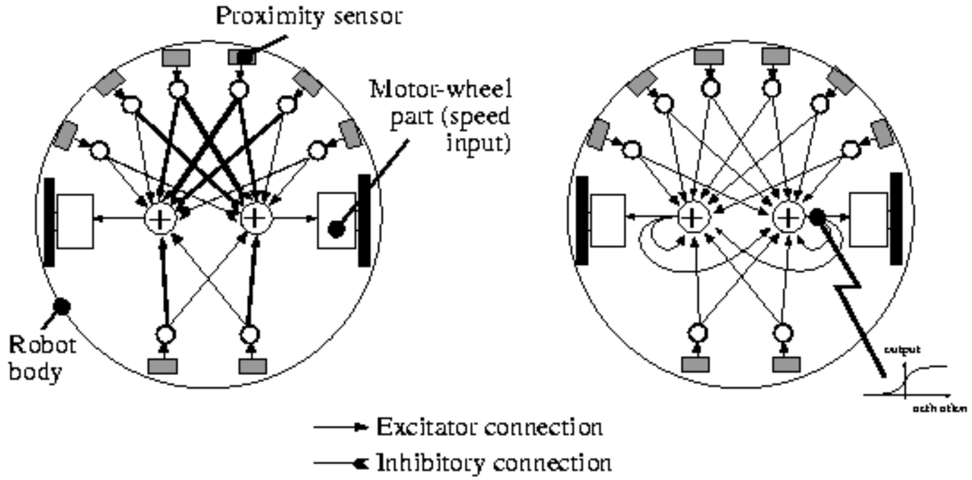
[Doncieux et al. 2017, Evolutionary robotics: what, why, and where to. *Frontiers Robotics*]

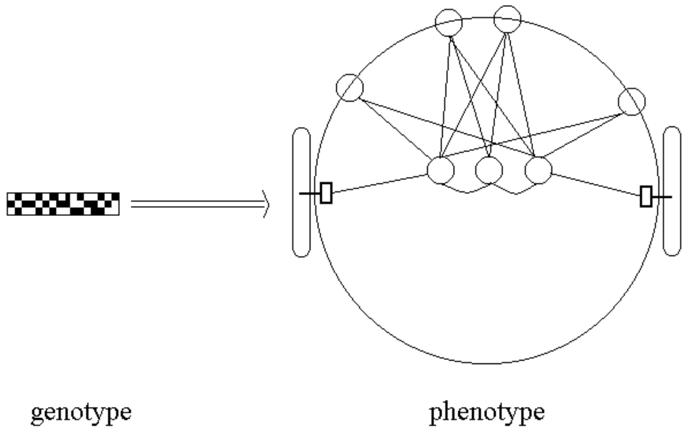
Khepera's Body & Brain

- Neural networks with evolving weights





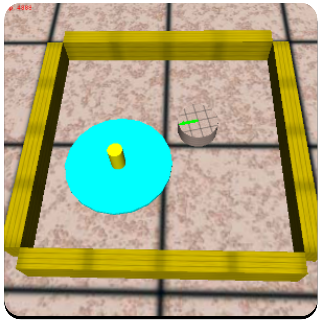




FARSA: iCub EvoRobot

- FARSA simulator
  - integrated open-source C++ libraries for evolutionary experiments with robots (iCub, Khepera, e-puck)

Discrimination Experiment with Khepera



A Khepera robot provided with infrared sensors evolved for the ability to find and remain close to a cylindrical object randomly located in the environment. The discrimination of the two type of objects (walls and cylinders) is realized by exploiting the limit cycle oscillatory behaviour, produced by the robot near the cylinder, that emerges from the robot/environmental interactions (i.e. by the interplay between the way in which the robot react to sensory stimuli and the perceptual consequences of the robot actions).

More information and videos

Nolfi S. (2009). *Behavior and cognition as a complex adaptive system: Insights from robotic experiments.* In C Hooker (Ed.), Handbook of the Philosophy of Science. Volume 10: Philosophy of Complex Systems. General editors: Dov M. Gabbay, Paul Thagard and John Woods. Elsevier. PDF

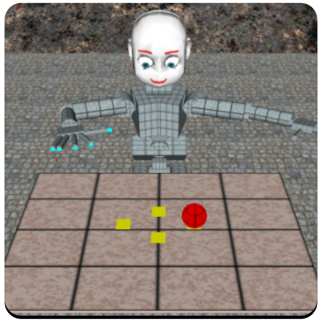
Reaching Experiment with iCub

An iCub robot able to reach with its left arm any arbitrary target position in its peripersonal space by controlling 6 actuated joints (2 joints of the iCub's torso and 4 joints of the iCub's left arm). The connection weights of the robots' neural controller are adapted through an evolutionary method on the basis of an evaluation criterion calculated on the basis of the distance between the left hand of the robot and the target location averaged over several trials in which the robot has to reach different target positions.

More information and videos

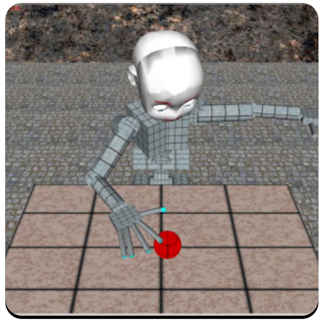
Massera G., Ferrauto T., Gigliotta O., Nolfi S. (2013). *Designing adaptive humanoid robots through the FARSA open-source framework.* CNR-ISTC: Technical Report

Grasping Experiment with iCub



An evolved iCub robot displaying integrated reaching and grasping capabilities that enable it to reach a ball located in varying positions over a table, grasp it, and handle and elevate it. Beside the difficulties concerning the need to control an articulated arm with many DOFs, this represents a rather challenging task since it requires to interact with a spherical object, that can easily roll away from the robot's peripersonal space, and requires to

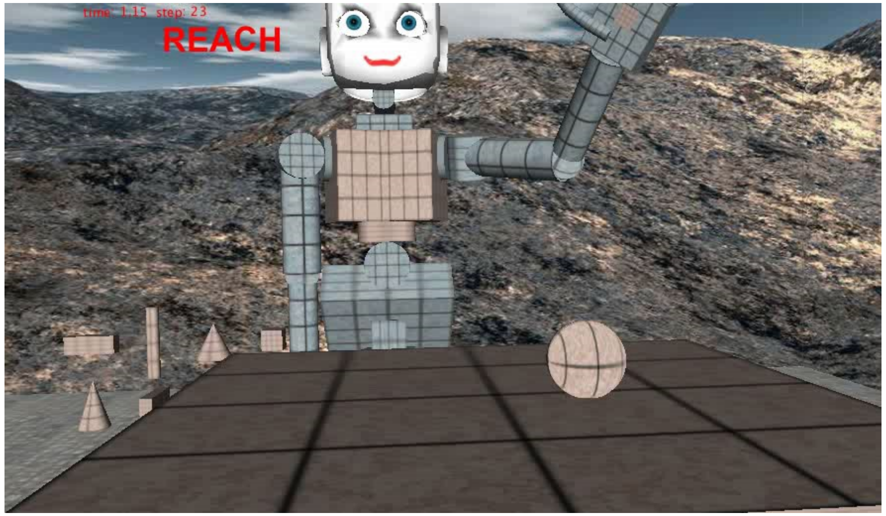
Grasping Experiment with Kinesthetic Learning

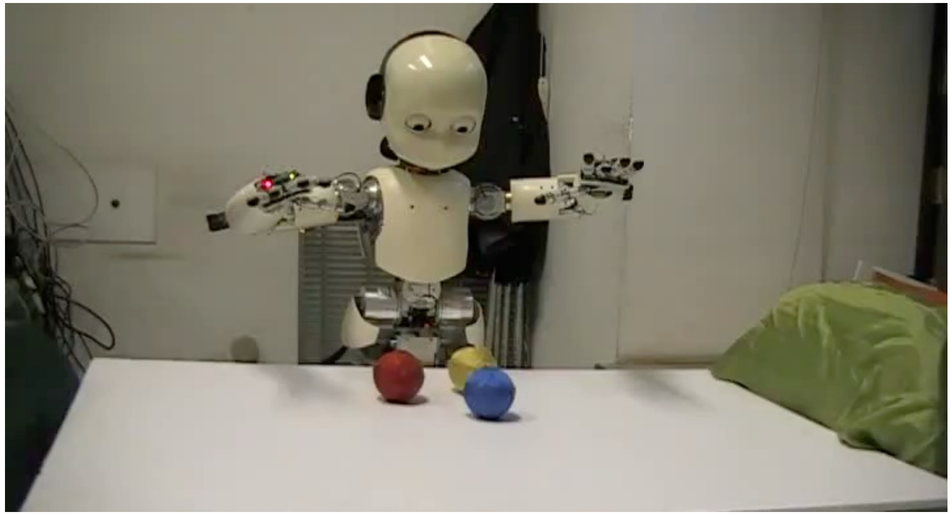


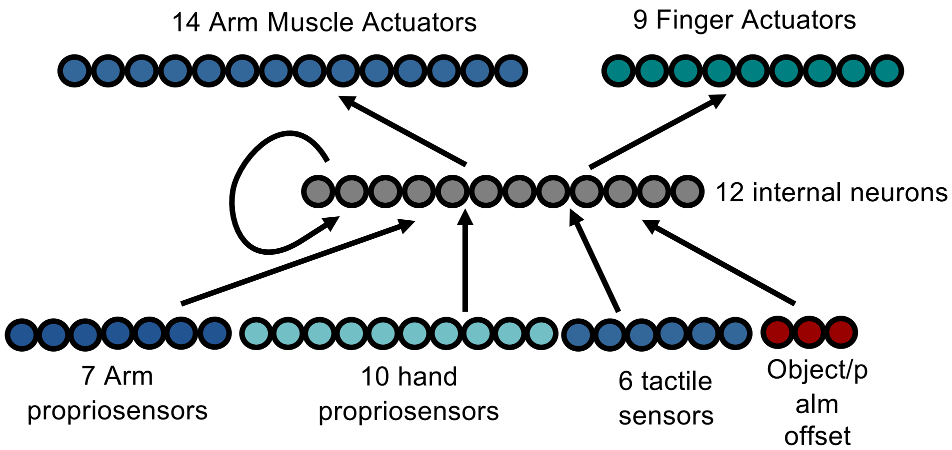
An iCub robot trained to display a reaching and grasping behaviour through a combination of kinestetic teaching, in which the robot tries to imitate the actions demonstrated by the caretaker who appropriately drives the robot arm-hand in a series of demonstration trials, and trial and error learning, in which the robot refine in skills on the basis of its ability to realized the goal of the action.

http://laral.istc.cnr.it/farsa/index.php

iCub Language Evolution







Tuci et al. (2012). [IEEE Trans AMD]

Co-Evolution and Arm Race

"An adaptation in one lineage (e.g. predators) may change the selection pressure on another lineage (e.g. prey), giving rise to a counter-adaptation. If this occurs reciprocally, an unstable runaway escalation of 'arm races' may result."
(Dawkins and Krebs, 1979, pp. 55)

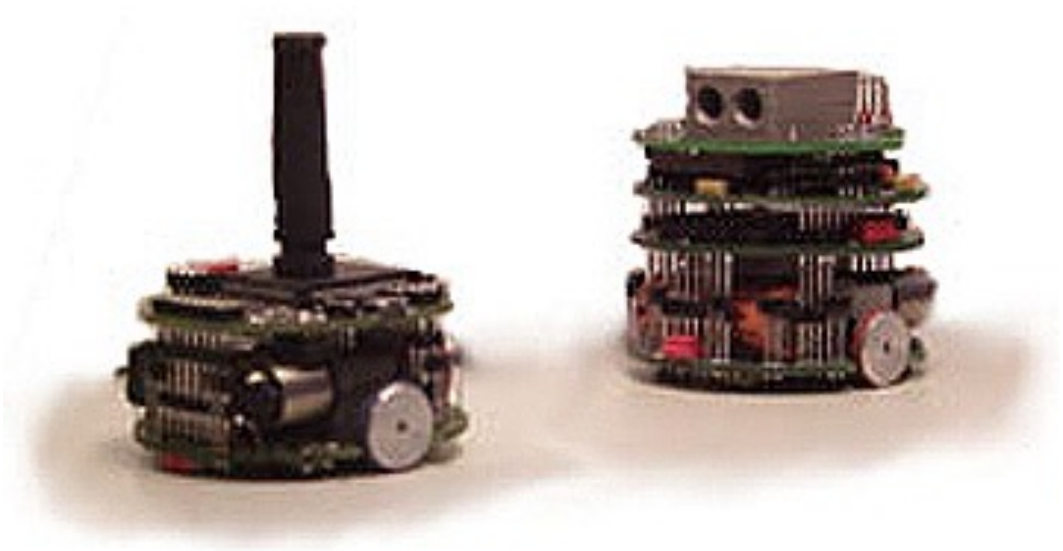
Co-Evolution and Arm Race

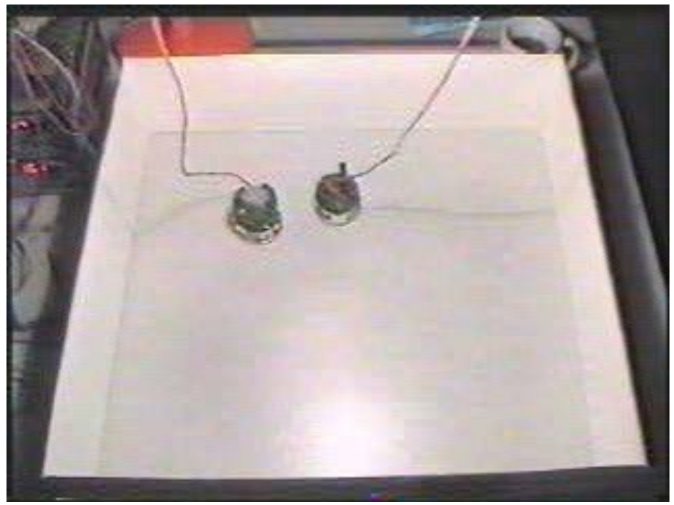
"An adaptation in one lineage (e.g. predators) may change the selection pressure on another lineage (e.g. prey), giving rise to a counter-adaptation. If this occurs reciprocally, an unstable runaway escalation of 'arm races' may result."
(Dawkins and Krebs, 1979, pp. 55)

In EvoRobots, it can produce a training process in which progress in one population is accompanied by gradual complexification of the adaptive task caused by parallel progress in the competing population (Rosin and Belew, 1997).

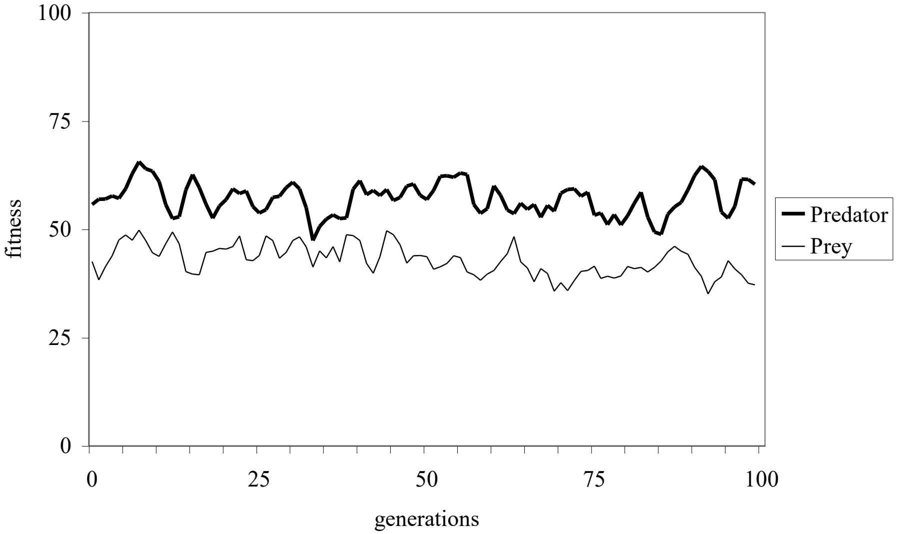
Co-Evolution with Kheperas

- Co-evolution of two khepera species
  (Nolfi & Floreano 1998; Simione and Nolfi 2017)

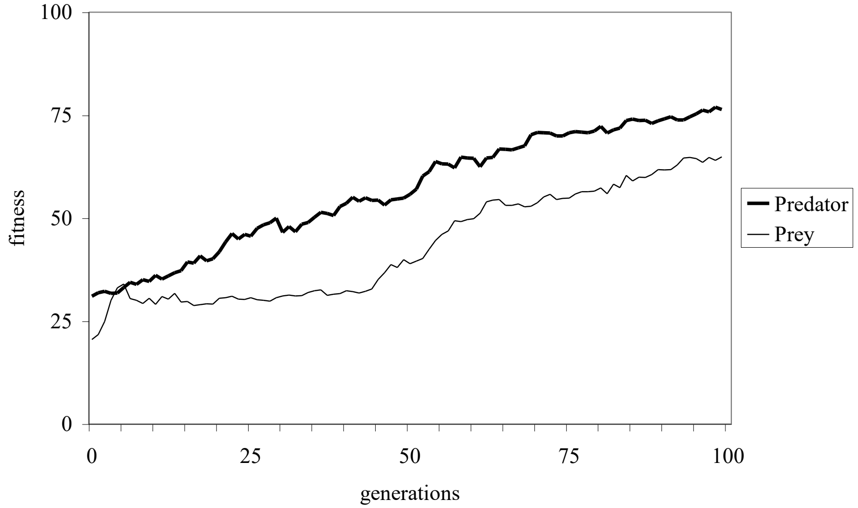




Co-Evolution Results



Independent evolution



Co-evolution

Co-evolution

– Selects the most effective solutions

– Selects solutions to match counter-strategies

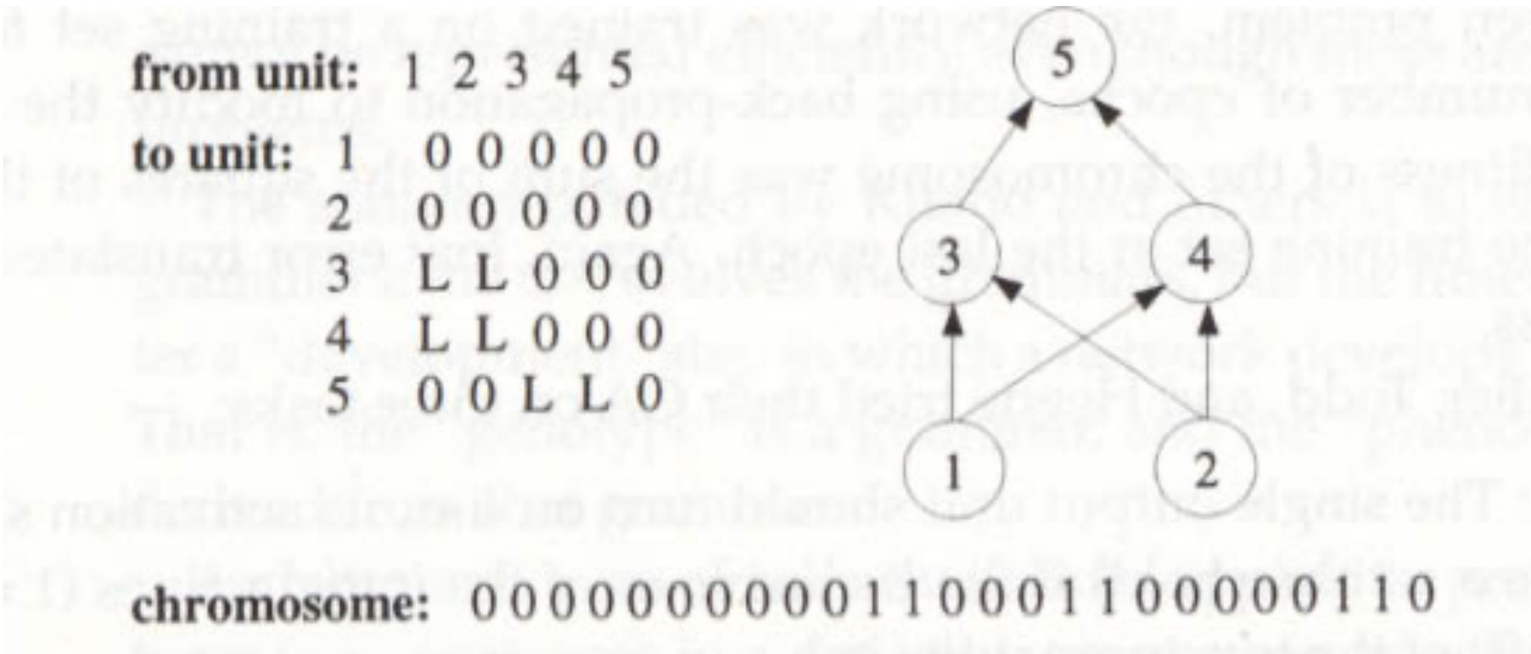
– Complexity without increased supervision

Evolving Morphologies

- From direct genotype-phenotype encoding to **grammar encoding** (aka morphogenetic encoding)
  - Evolving network's connections (Kitano)
  - Evolving virtual creatures (Sims, Bongard)
  - Evolving robots (Bongard & Lipson)

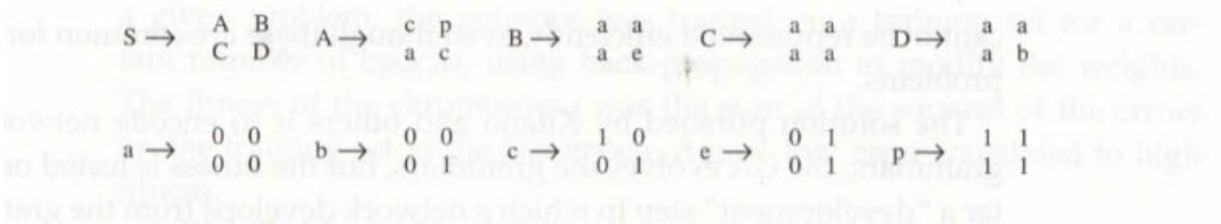
Direct Encoding

- Direct encoding (Miller, Todd, & Hedge, 1989)
  - N x N matrix, binary genotype 0/L (learning connection)



Grammar Encoding (Kitano)

- For encoding a nnet weight matrix
  - non terminal *a*-*p* for all 16 2x2 binary matrices
  - non terminal *A*-*Z* rewrite as a-p quadruplets



(a)

S	A	B	C	D	A	c	p	a	c	B	a	a	a	e	...

Evolving Virtual Creatures
(K. Sims)

http://www.karlsims.com/

GRN: Genetic Regulator Network

- Model DNA and protein-gene interaction
  - Bentley & Kumar 1999; Cangelosi 1999; Bongard & Pfeifer 2003

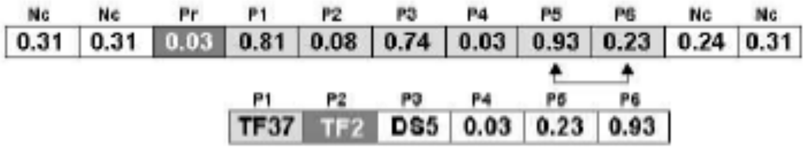
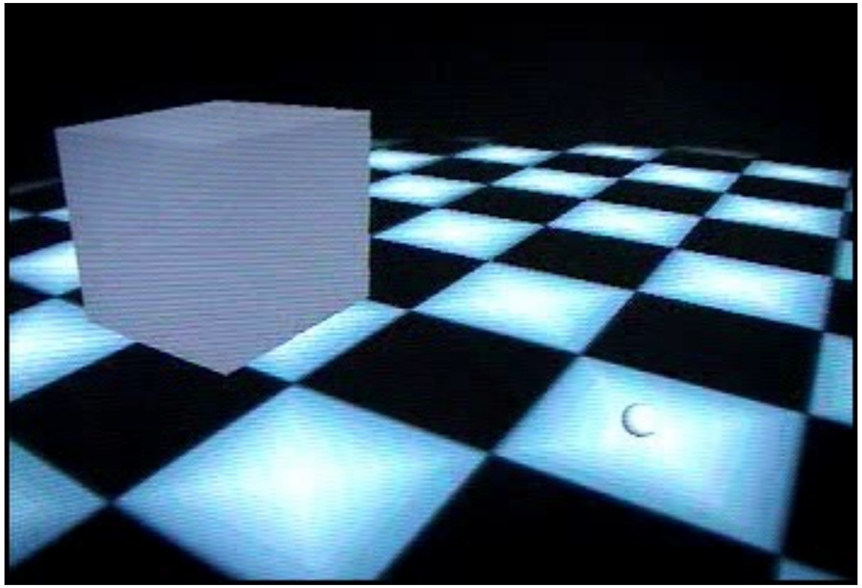


Figure 3: **A sample gene.** This gene (*G3* in Fig. 2) emits TF 2 from diffusion site 5 (*DS5*) if it is expressed (the concentration of TF 2 is increased by 0.03 at *DS5* during each time step of the growth phase that *G3* is expressed). If the average concentration of TF 37 in the current unit is between 0.23 and 0.93 the gene is expressed; otherwise, it is repressed. The gene is flanked by non-coding values (*Nc*).

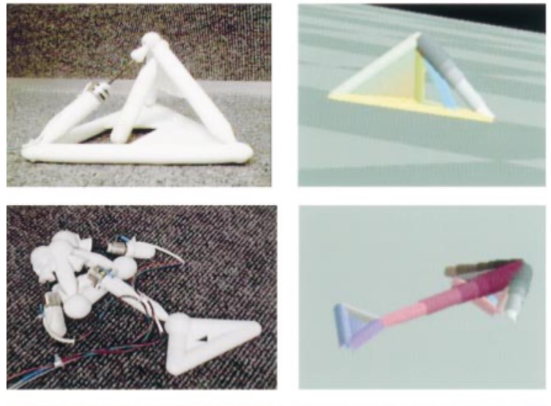


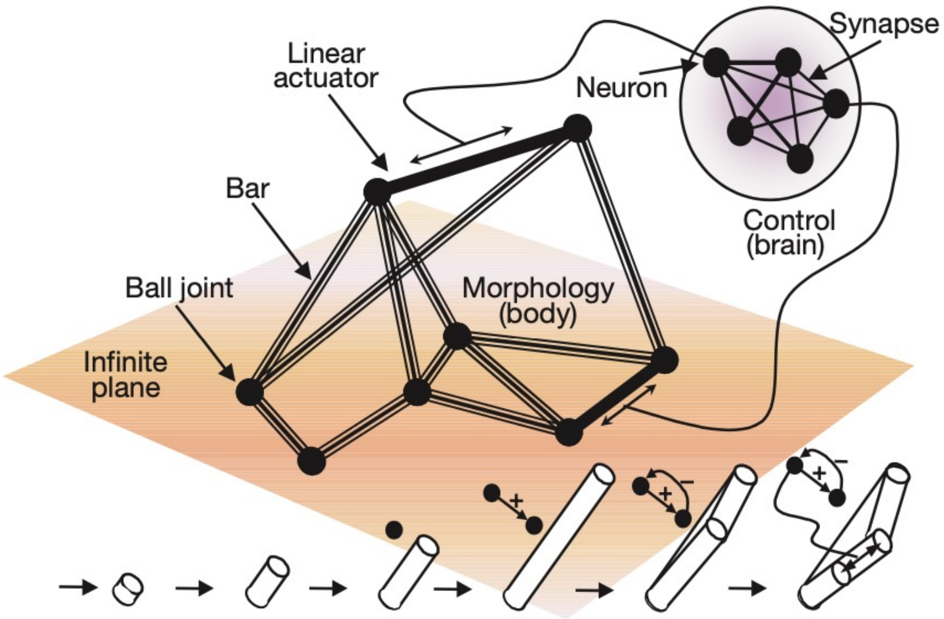
Genotype
(Chromosomes)

Phenotype
(Body + Behaviour)

Evolving Robots

- Automatic robot body design (Lipson & Pollack 2000)
  - Simulation to hardware
  - GA simulation, 3D printing best robot





Genotype

robot:= ⟨vertices⟩⟨bars⟩⟨neurons⟩⟨actuators⟩

vertex:= ⟨x, y, z⟩

bar:= ⟨vertex 1 index, vertex 2 index, relaxed length, stiffness⟩

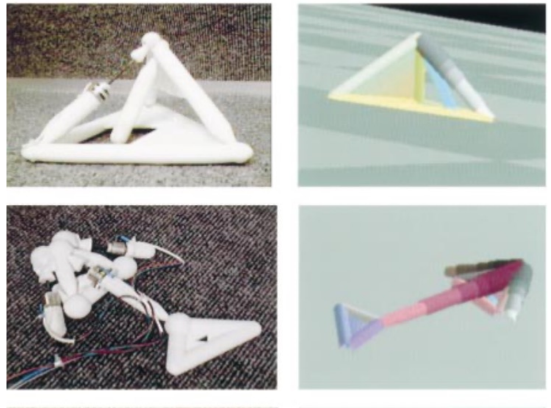
neuron:= ⟨threshold, synapse coefficients of connections to all neurons⟩

actuator:= ⟨bar index, neuron index, bar range⟩

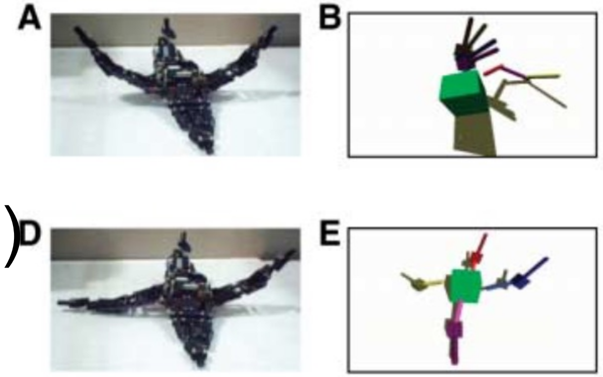
Lipson & Pollack (2000). Automatic design and manufacture of robotic lifeforms. *Nature*, *406*(6799), 974-978.

Evolving Robots

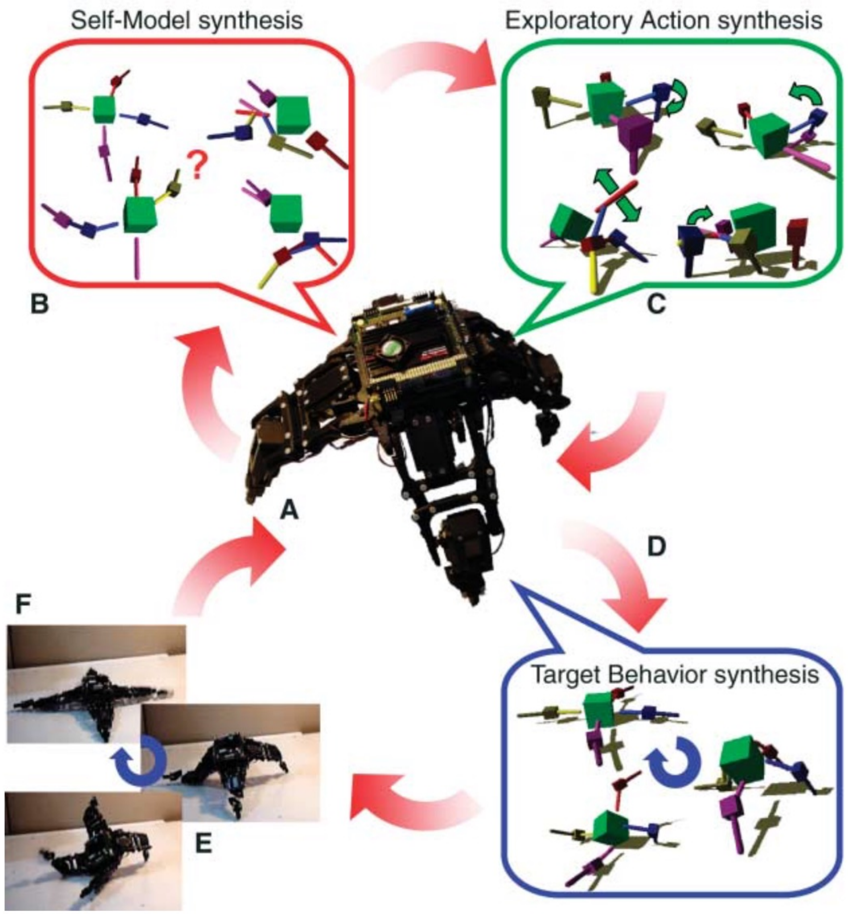
- Automatic robot body design
  (Lipson & Pollack 2000)
  - Simulation to hardware
  - GA simulation, 3D printing best robot

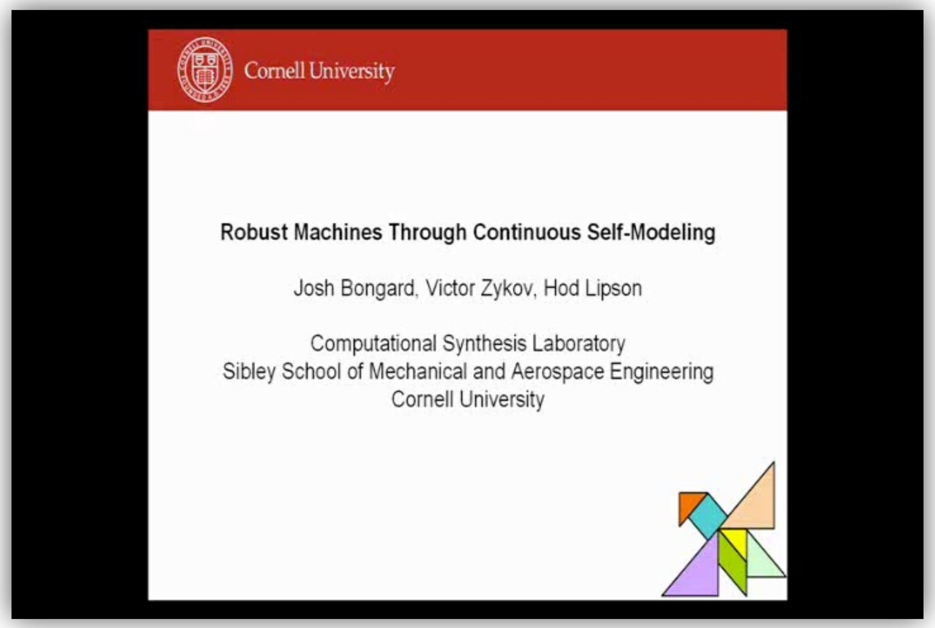


- Resilient machines
  (Bongard et al. 2006)
  - Self-modelling mechanism
  - Repair when body changes (lost leg)



Resilient Machines





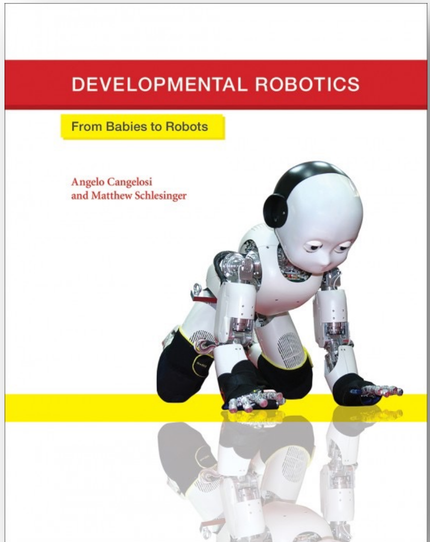
https://www.youtube.com/watch?v=x579QKA6fkY

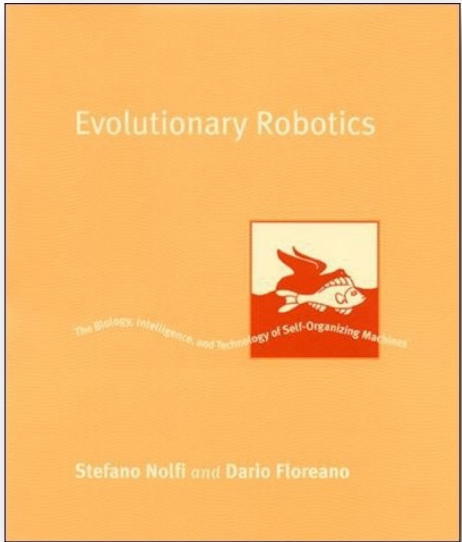
Bongard, Zykov & Lipson (2006). Resilient machines through continuous self modelling. *Science*, *314*(5802), 1118-1121.

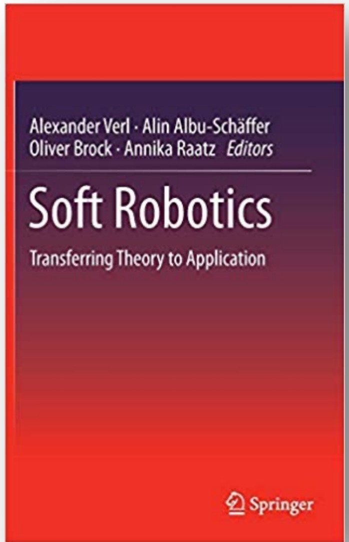
Swarm Robotics

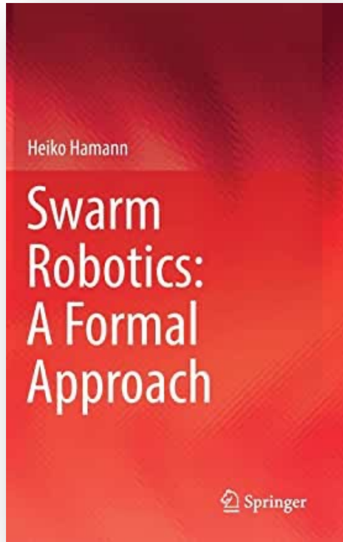
Terminology II

- Cognitive Robotics Approaches
  - Developmental Robotics (Cangelosi & Schlesinger 2015)
  - Evolutionary Robotics (Nolfi & Floreano 2002)
  - **Swarm Robotics** (Dorigo et al. 2014; Hamann 2018)
  - Soft Robotics (Laschi et al. 2016; Veri et al. 2015)









Swarm Robotics

Kilobot (Rubenstein et al., 2012).

Swarm Robotics

Swarm robotics is the study of how independent robots can interact as a ***group****, giving rise to* ***collective behavior*** *that a single such robot could not achieve on its own*

(Dorigo et al. 2014; Heinrich et al. (2020)

Self-Organisation & Micro-Macro Link

- From **microscale** interaction (local, peer-to-peer) to **macroscale** structures (global, systemwide)
  - link micro/macroscale via self-organization

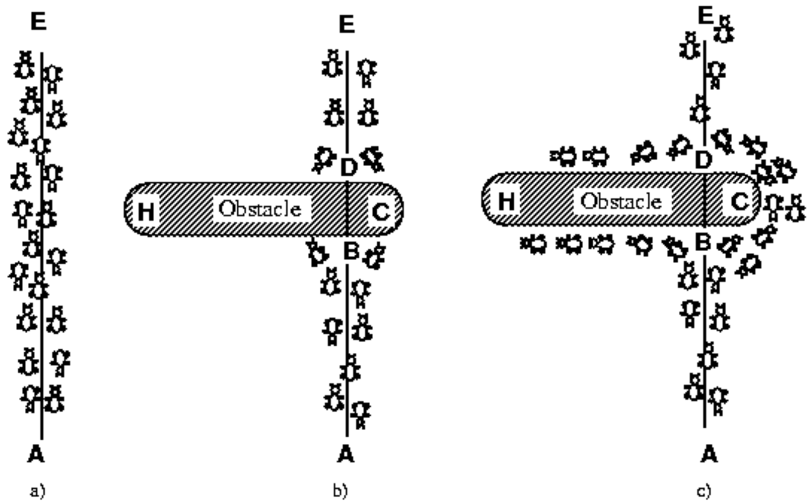
- Principles of self-organisation (Bonabeau et al. 1999)
  - Positive and negative feedback
  - Fluctuations (i.e., random events)
  - Multiple microscale interactions.

Scalability and Fault-Tolerance

- Swarm robotics targets maximal **scalability,** i.e. the possibility to scale to virtually any system size
  - strictly decentralized approach
  - limited communication
- Fault-Tolerance
  - Multi-robot systems have higher degree of fault tolerance than a single robot, due merely to the system’s inherent **redundancy**

Ant Colony Optimisation (ACO) and Swarm

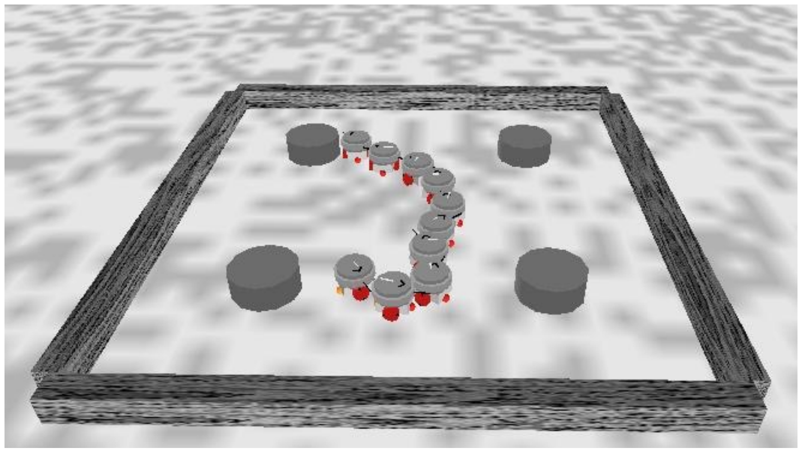
- Social insect behaviour (Ants) → ACO
  (Dorigo et al., IEEE Transactions on Systems, Man, and Cybernetics, 1996)

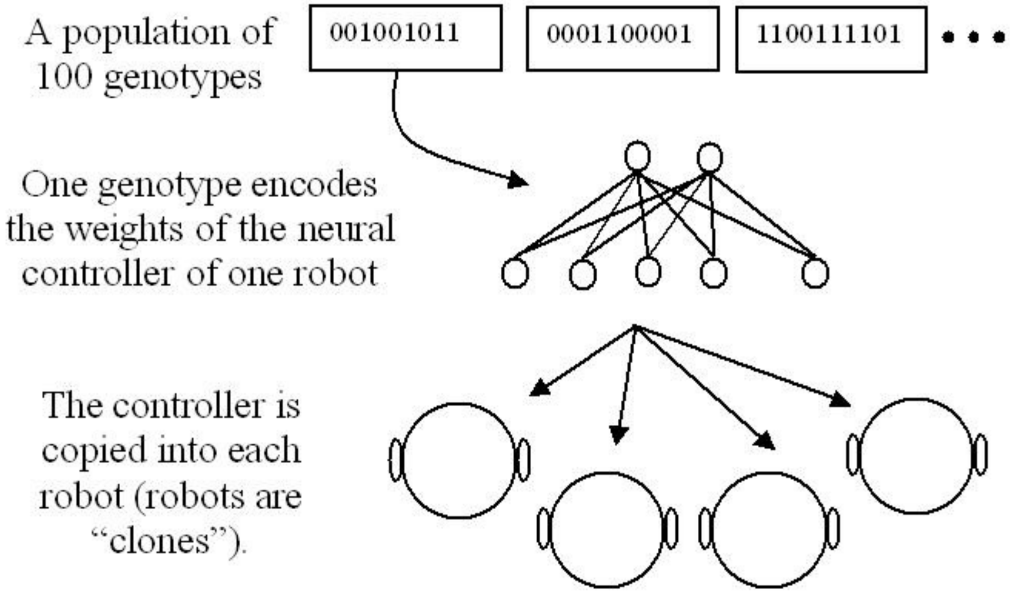


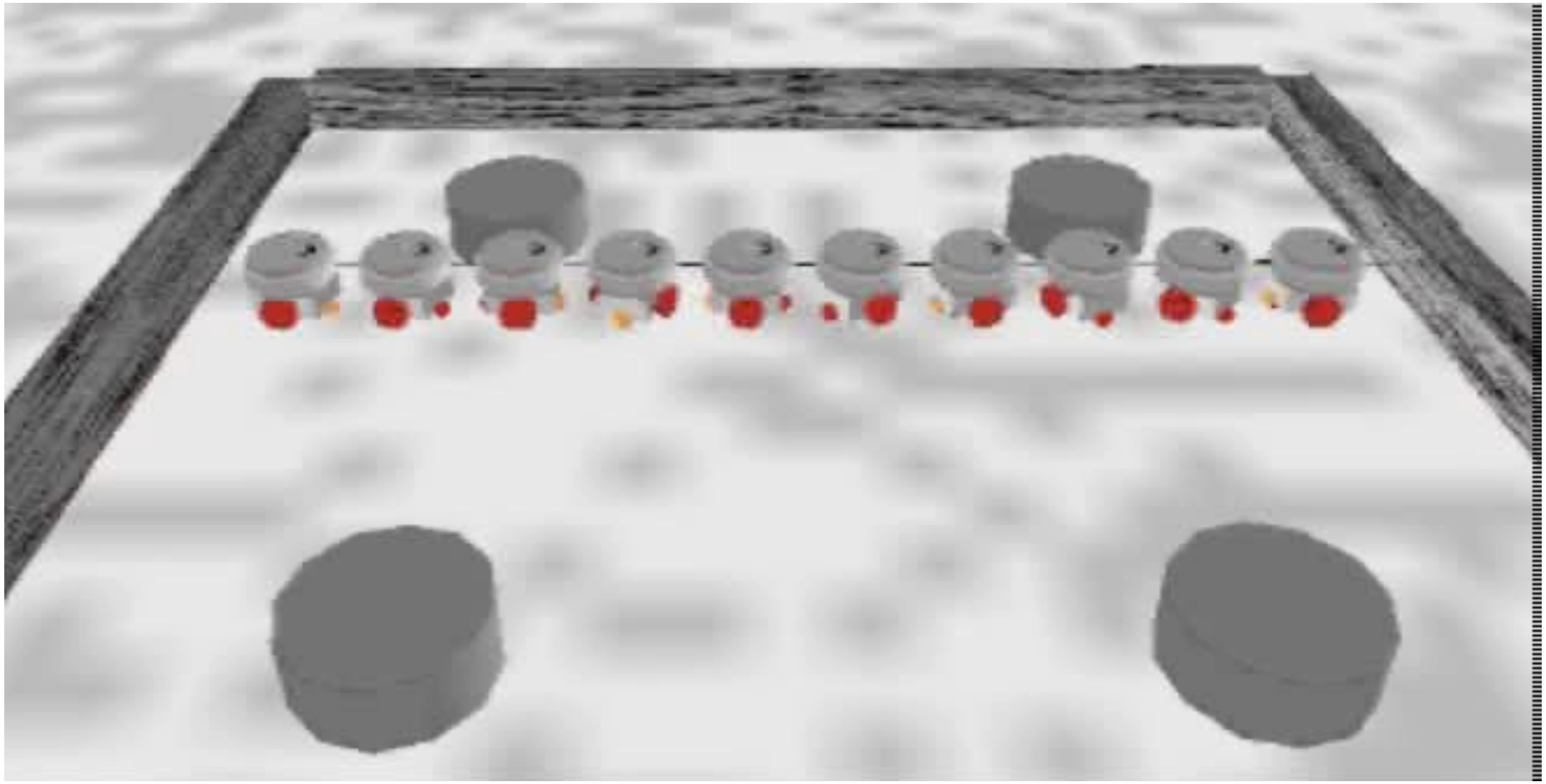
http://iridia.ulb.ac.be/~mdorigo/ACO/ACO.html

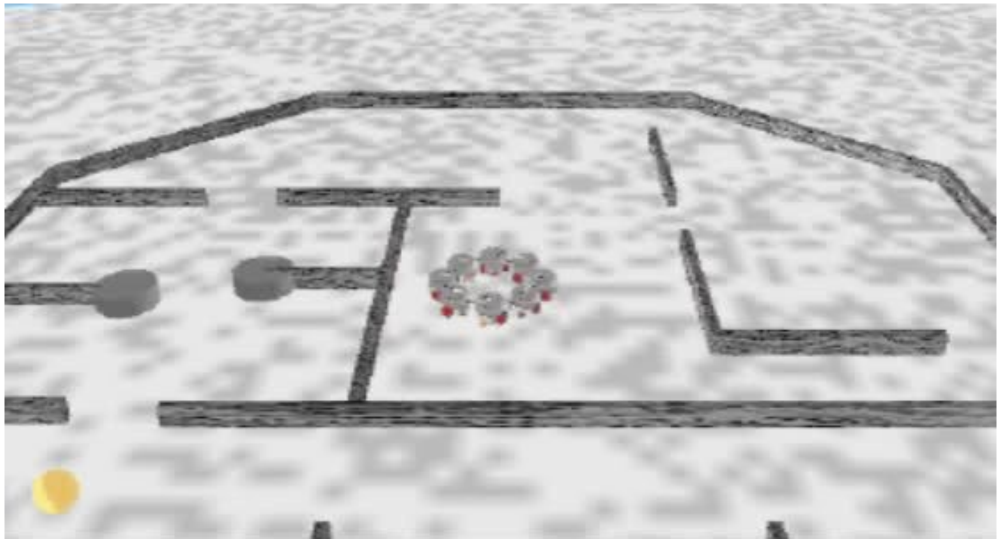
EvoRobot and Swarm

- Swarm (e.g. ants) behaviour
- Collaborative robots (colony of clones)







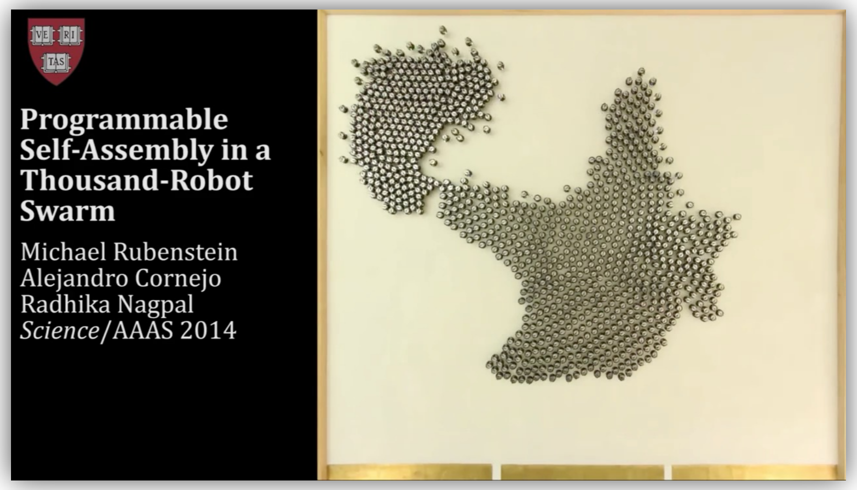


Swarm Robot Applications

- Kilobot
  - Large scale swarm (Roberstein et al. 2014)
- Disaster relief (e.g. impassable step height)
  - construction of ramps (Napp & Nagpal, 2014)
  - stacking of irregular objects (Thangavelu et al., 2018)
- Marine
  - "subCULTron" for lagoon monitoring (Thenius et al., 2016)
- Agriculture
  - "SAGA" project for swarm of quadrotor UAVs (Albani et al., 2017)

Swarm Robot Applications

http://laral.istc.cnr.it/saga/index.php/media-center/



https://www.youtube.com/watch?v=xK54Bu9HFRw&list=PLC7119C2D50BEA077

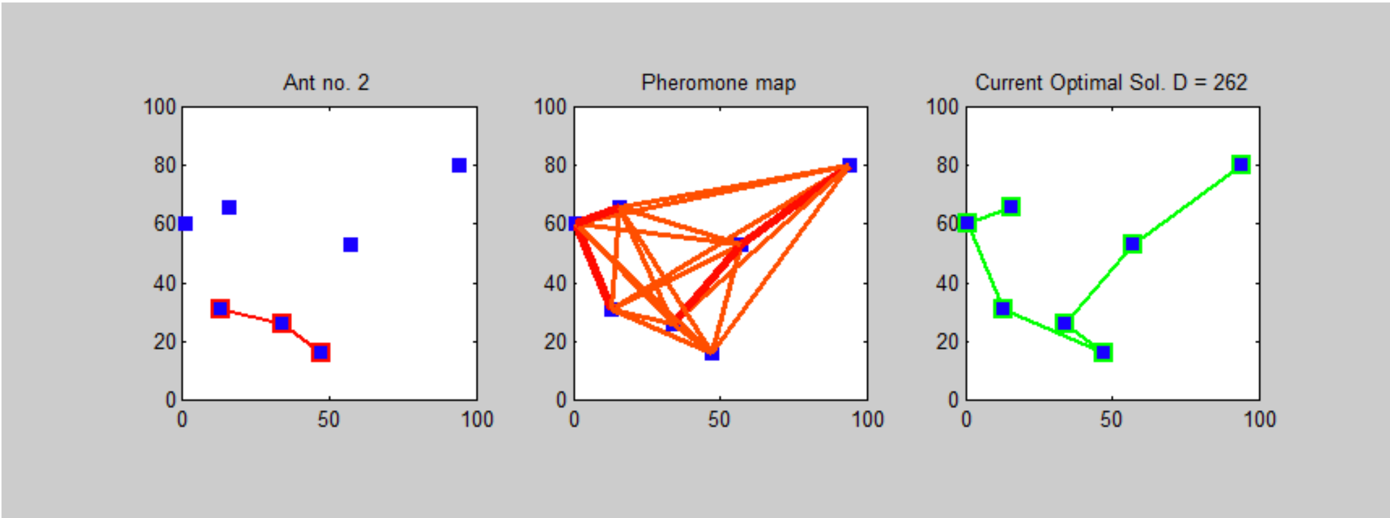
https://www.youtube.com/watch?v=WjDeFzAGJSs

ACO: Ant Colony Optimisation

- Real ants are capable of finding the **shortest path** from a food source to the nest
- No visual clues are used
- Ability to adapt to changes in the environment (obstacles)
- Indirect communication through pheromone (**Stigmergy**)
  - Pheromone: primary means to form and maintaining the line
  - Ants deposit a certain amount of pheromone while walking forming pheromone trails
  - Each ant probabilistically prefers to follow a direction rich in pheromone

ACO and TSP
(Traveling Salesperson Problem)

- Artificial ants:
  - Have some memory (which towns have been visited)
  - Are not completely blind (can choose the closest connected town)
  - Live in an environment where time is discrete
  - https://en.wikipedia.org/wiki/Travelling_salesman_problem



Summary

- Evolutionary Computation and GAs
  - Genetic Algorithms
  - Co-evolution and arms race
- Evolving morphologies
  - Kitano, Sims, Bongard & Lipson
- Swarm

- Reading (optional)
  - Evolutionary robotics: Doncieux et al. 2017
  - Swarm robotics: Sahin et al. 2009