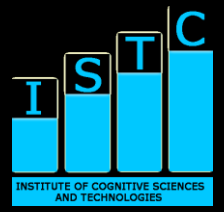

Evolutionary Robotics:
Behaviour and Cognition as Complex Adaptive Systems

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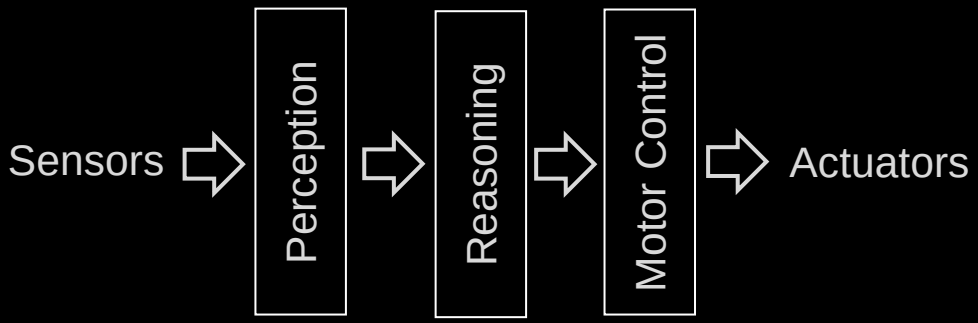
Engineering versus bio-inspired approaches

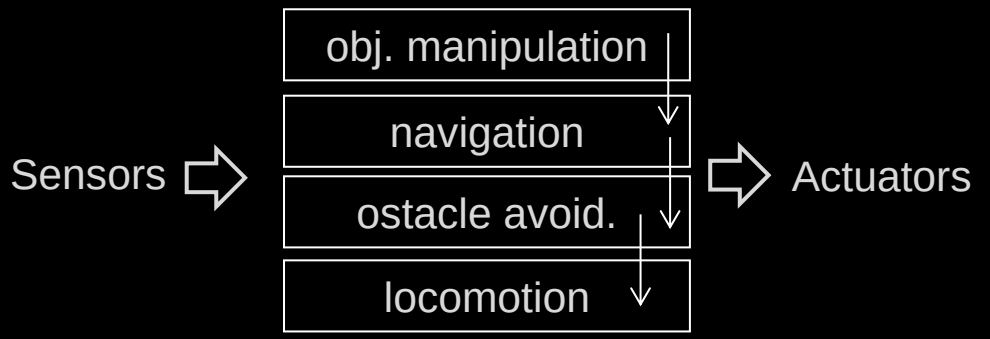
- Engineering/designing the characteristics of the agent and the rules that determine how it operates

- Imitating the solutions discovered by natural system or the evolutionary/developmental process through which such solutions are synthesized in nature

Design Methods



deliberative architecture



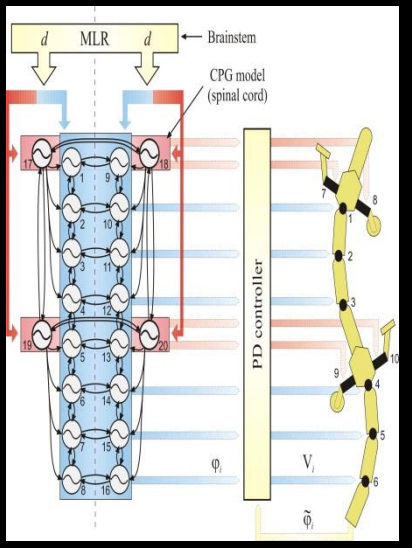
behavior-based architecture

Problem 1: These design methods based on a set of relatively independent layers/modules playing different functionalities tend to minimize the effect of the interactions

Problem 2: The effect of the interaction can be minimized but not eliminated. The human designer therefore needs to face the problem caused by unexpected emerging properties that can hardly be predicted or deduced by the characteristics of the interacting elements

Bio-Inspired Methods

Franceschini et al. 1992



Ijspeert el al. 2007

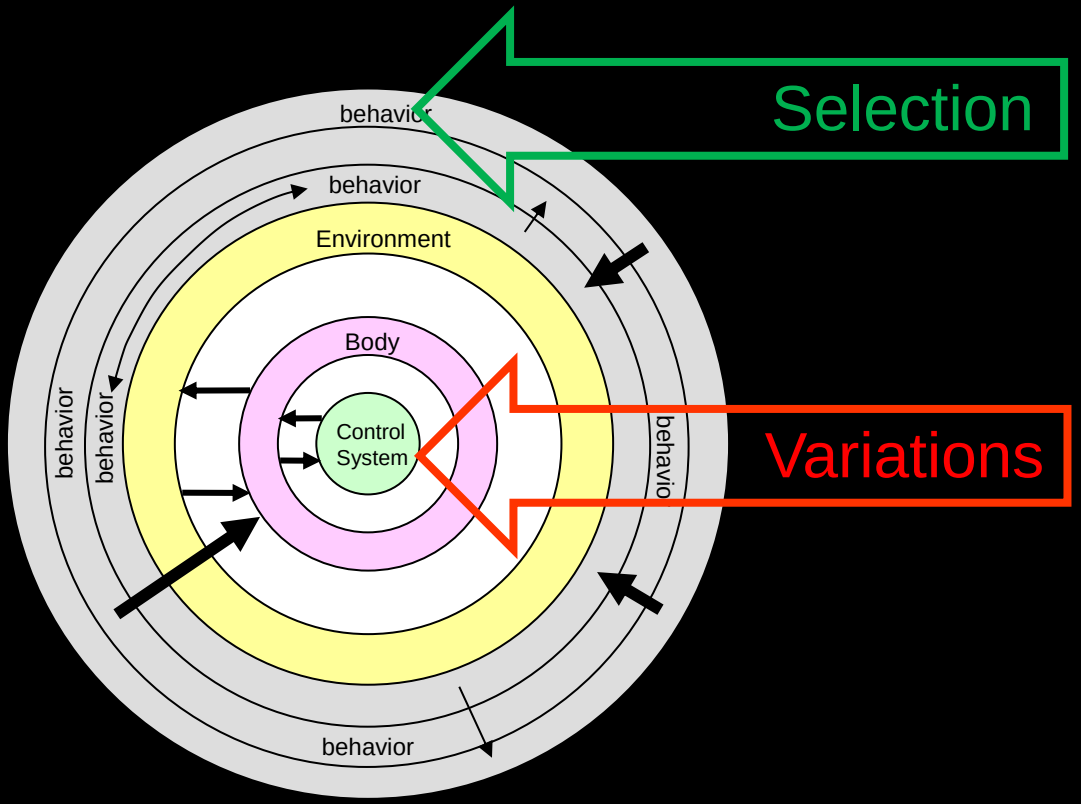
This method allows to capitalize on embodied and situated solutions discovered by natural evolution but can be applied only to domains/solutions for which we have a detailed understanding

Adaptive Methods

Allowing the robots themselves to develop their skills autonomously while they are situated in their environment through a phylogenetic and/or ontogenetic adaptive processes homologous to natural evolution and/or learning

Evolutionary methods, inspired by the way in which natural organisms adapt phylogenetically, developmental methods, inspired by the way in which natural organism change ontogenetically, and combination of the two.

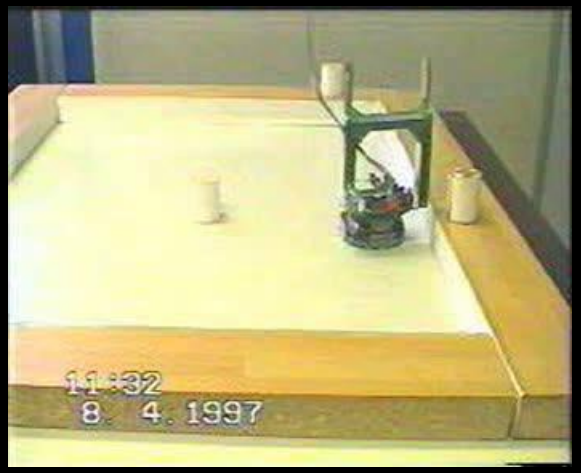
Fundamental property 1: Variation and selection operate at the lowest and highest levels of organization

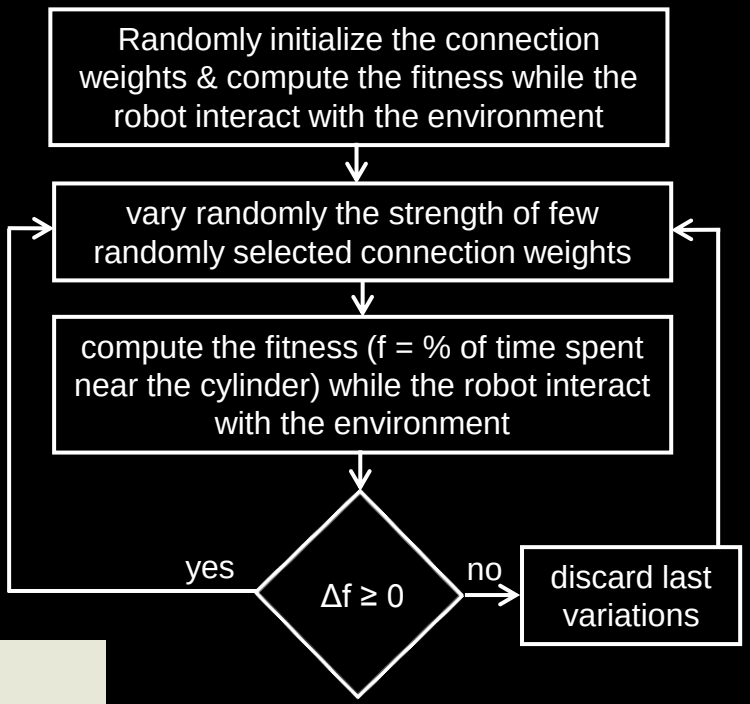


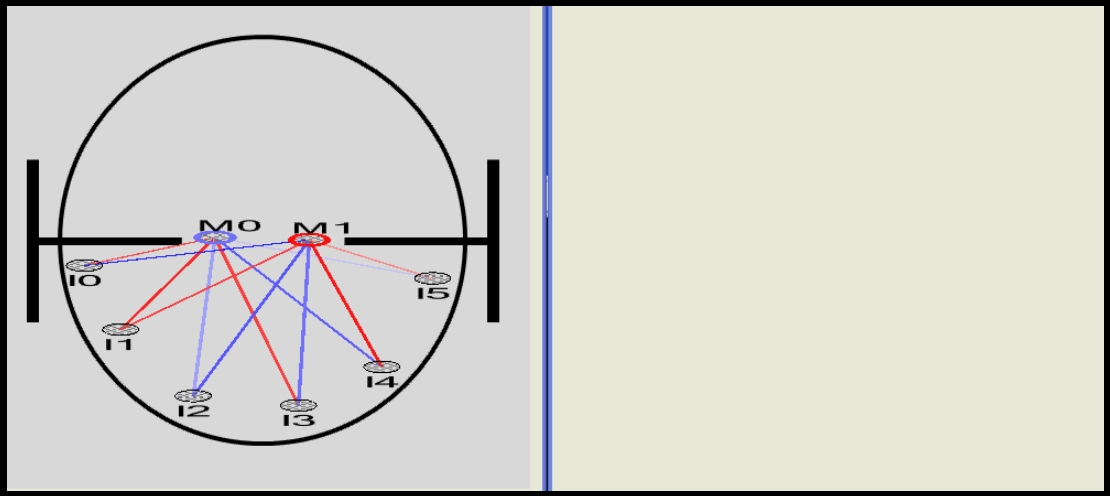
The variation process operates on the characteristic of the agent

Selection operates on a process that result from the agent/environmental interaction

Finding and Remaining Close to a Target Object







Fundamental property 2: Evolution operates on a population of individuals

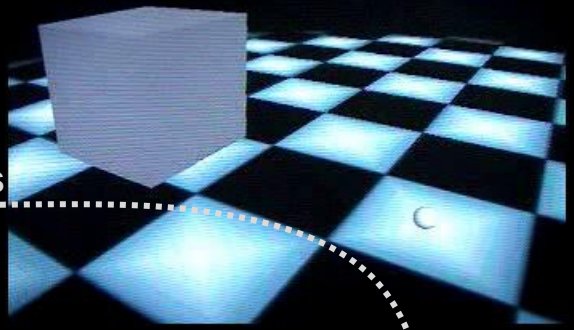
To speed-up the adaptive process (parallel search, recombination)

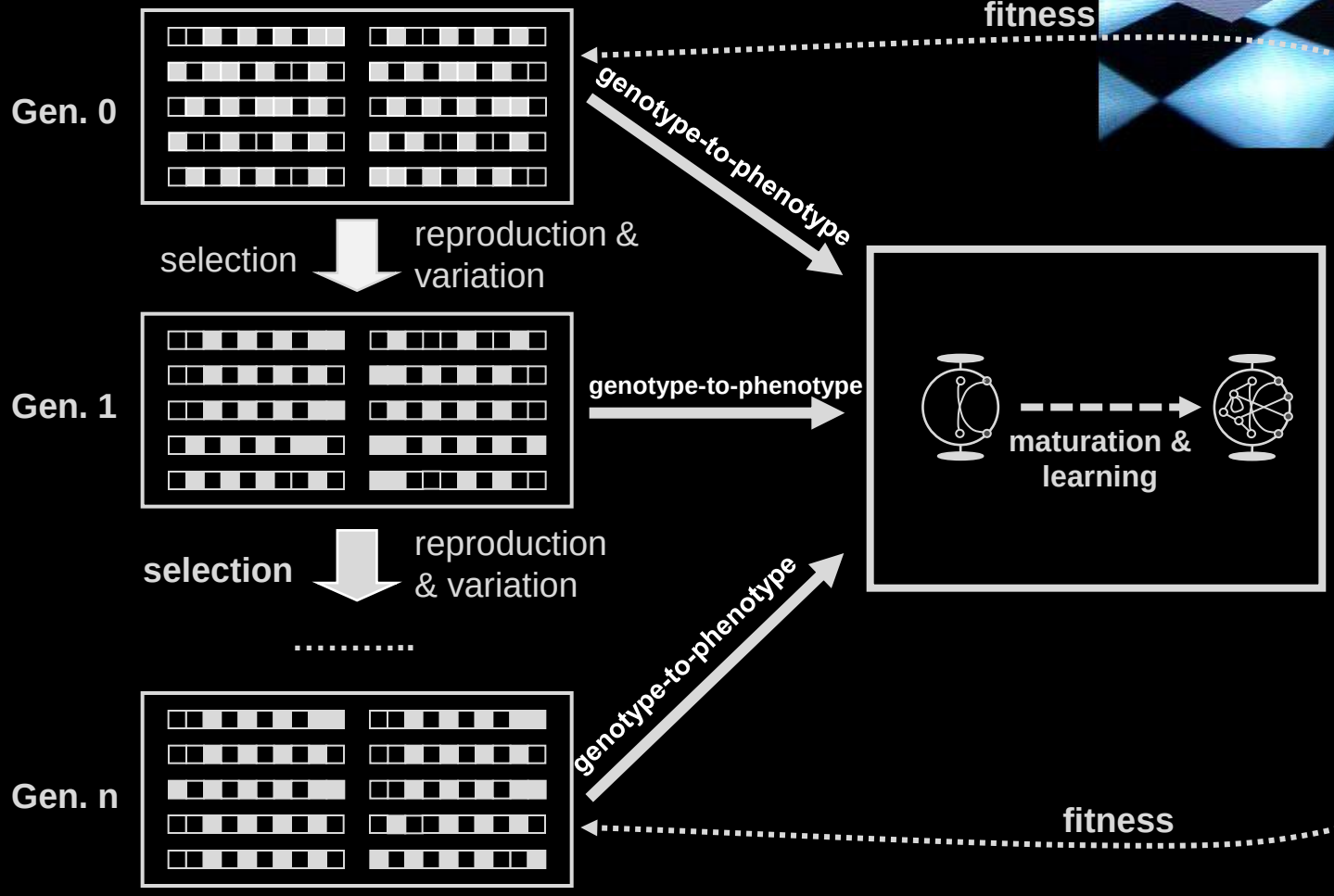
To increase the robustness of the adaptive process

Enable the synthesis of social behavior

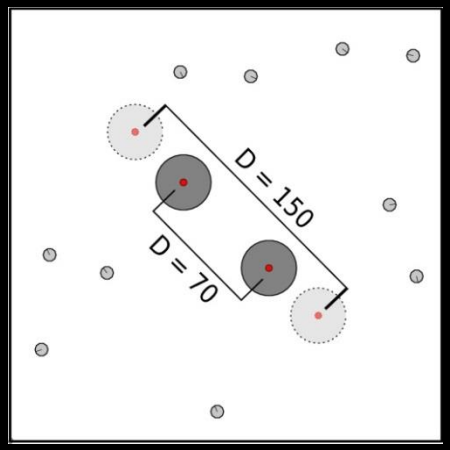
Evolutionary Robotics

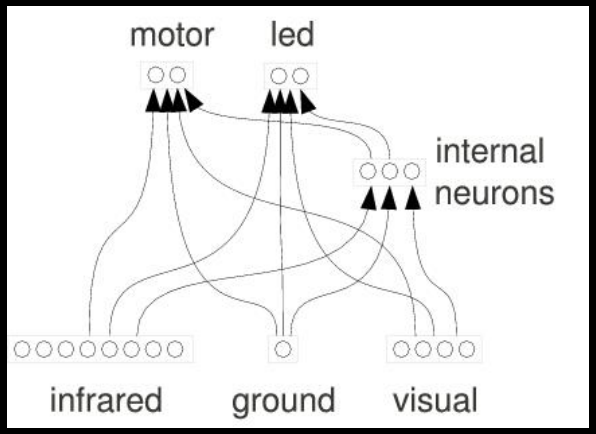
[Bongard & Pfeifer, 2001']

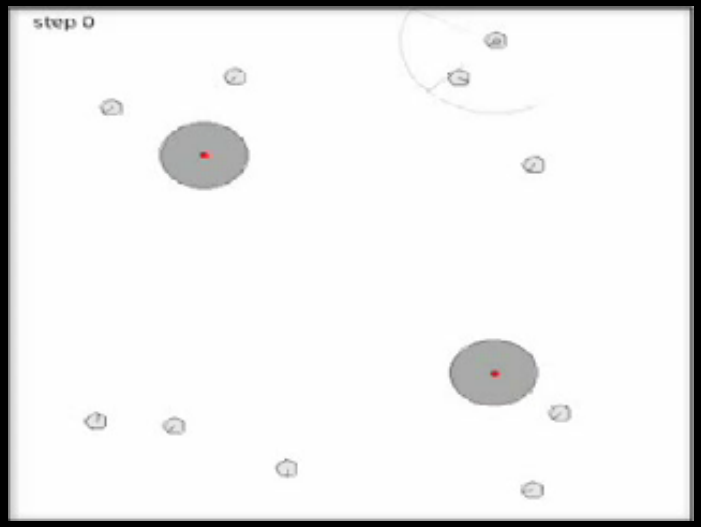


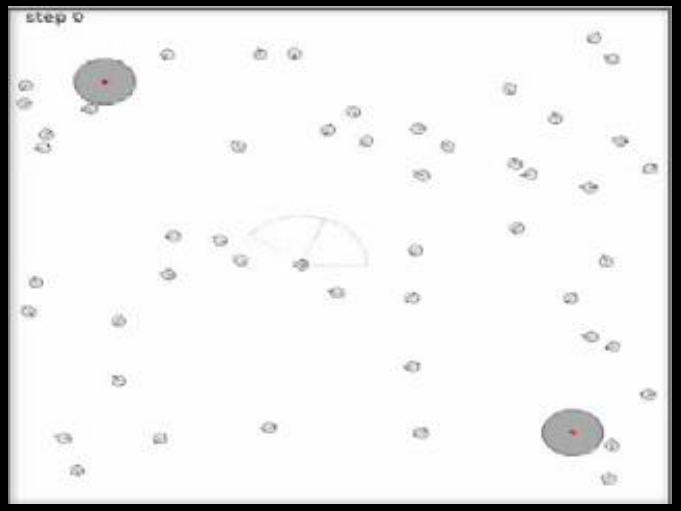


Fundamental property 3: Individuals evolve in dynamical physical and social environment









Sperati, Trianni & Nolfi, 2011

On the Emergent Nature of Behaviour and Cognition

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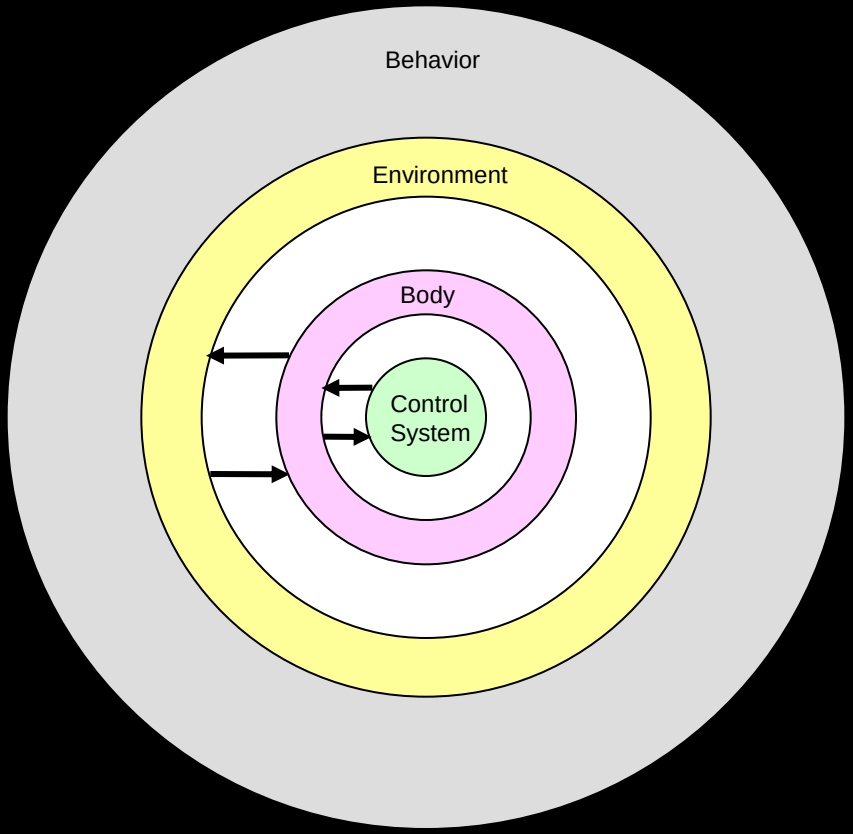
Behavior and cognition as emergent dynamical properties

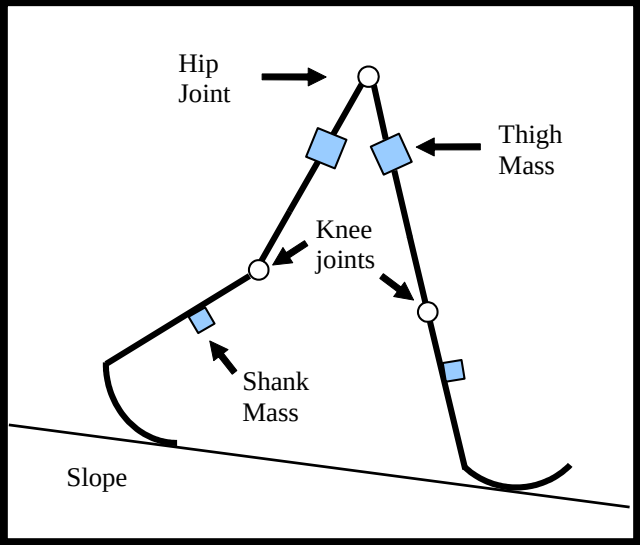


The environment and the robot/environmental relation co-determine the body and the motor reaction of the robot that, in turn, co-determines how the environment and/or the agent/environmental relation changes

Sequences of interactions (occurring at a fast time rate) lead to dynamical processes – behaviors – that extend over a significant longer time scale

Behaviors and behavioral properties cannot be traced back to any of the three elements taken in isolation

How bipedal walking can emerge from the interaction between a passive body and an inclined terrain

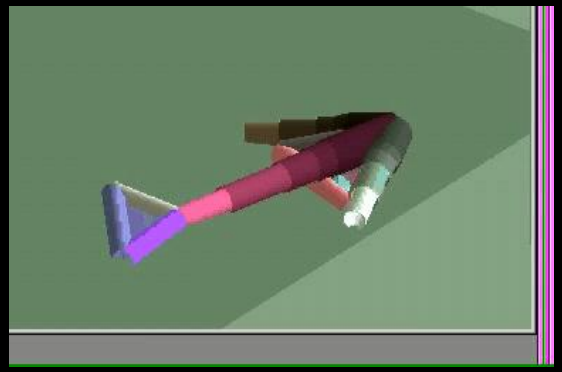


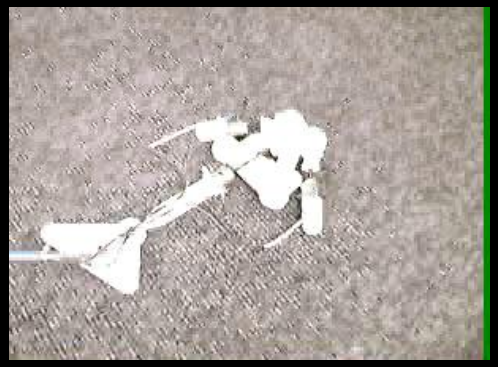
[McGeer, 1996]

[Collins, 2000']

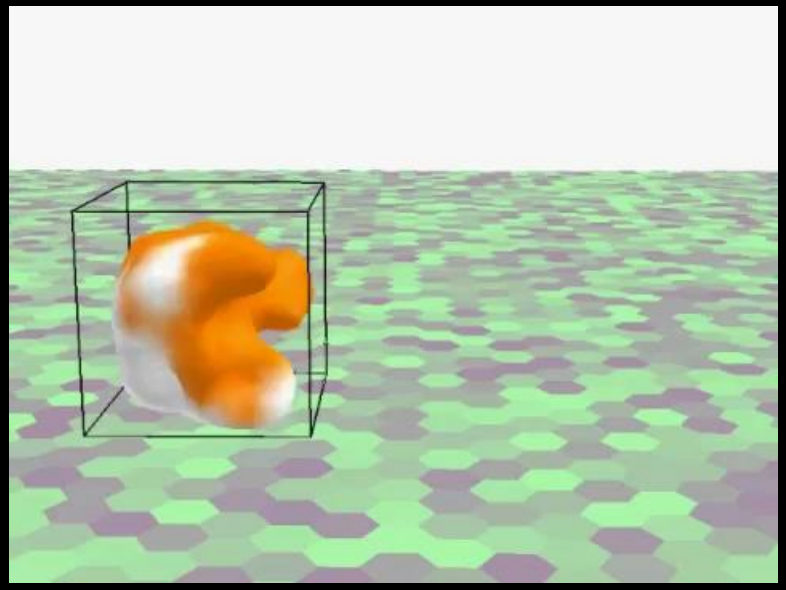
The designer has carefully selected the length, the mass, and the size of the leg segments and of the foot in order to obtain the desired behavior.

Co-evolving body and brains



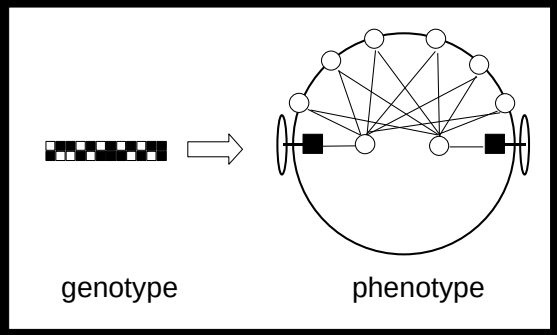


[Funes and Pollak, 1998; Lipson and Pollack 2000]



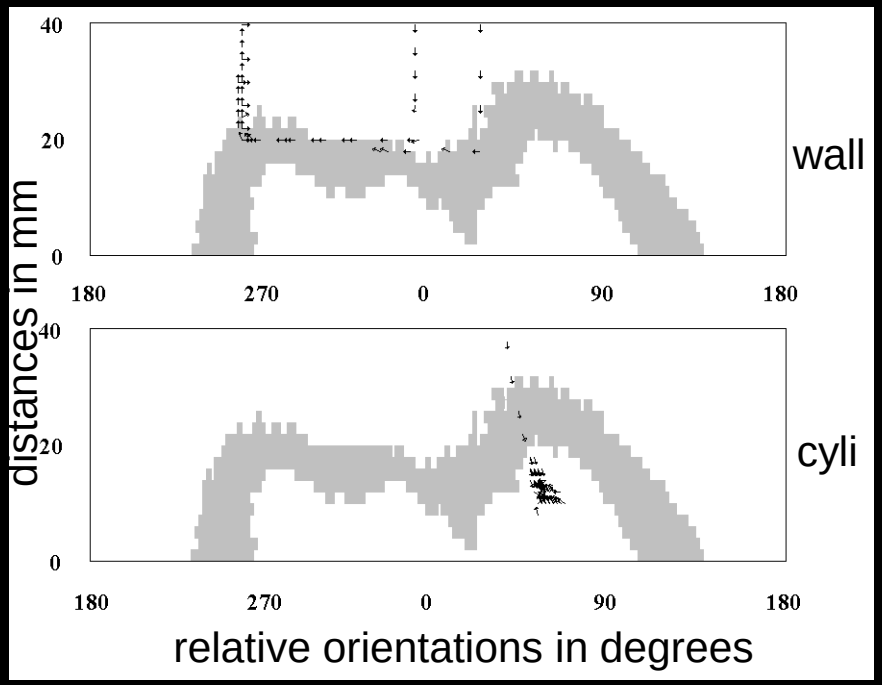
[Hiller & Lipson, 2012]

As object categorization emerges from robot/environmental interaction mediated by simple rules



Fitness = time spent close to cylinders

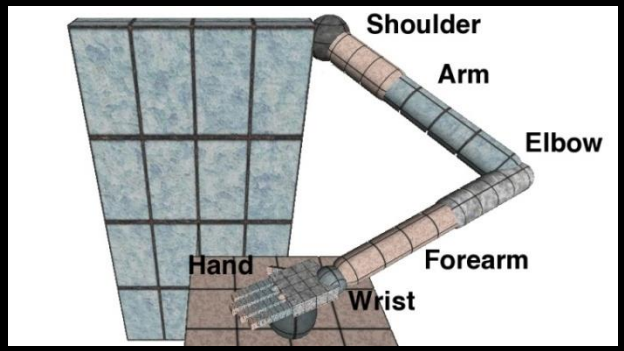
6 infrared sensors, 2 motorized wheels

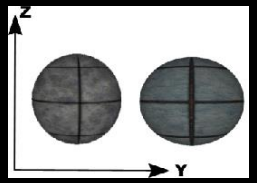


By tuning how much the robot turns left/right and forward/backward depending on how the infrared sensors are activated lead to a behavioral attractor close to cylindrical but not close to wall objects.

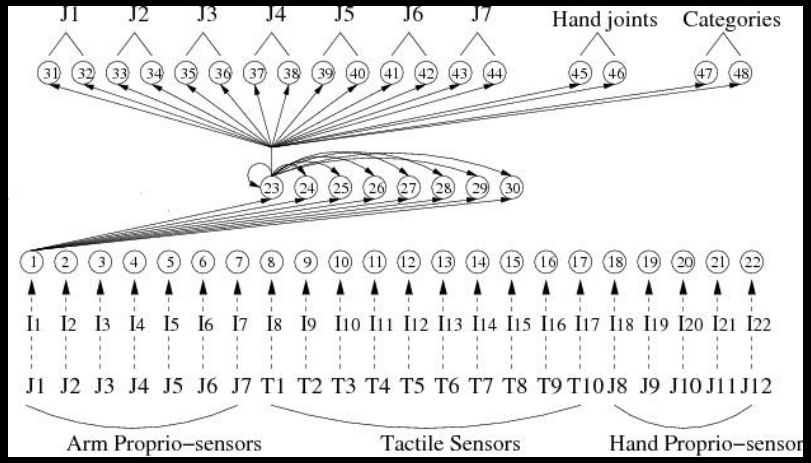
[Nolfi, 1996]

Active Categorical Perception





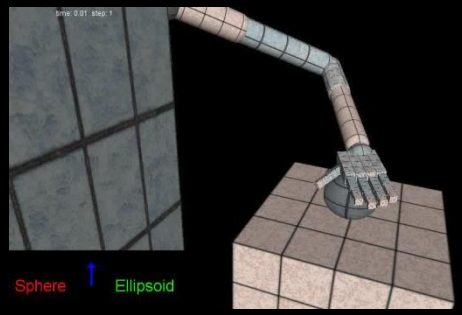
sphere ellipsoid

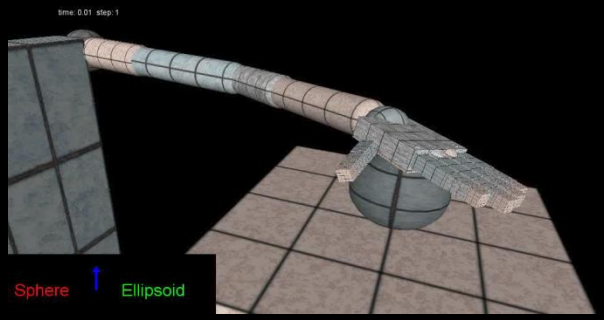


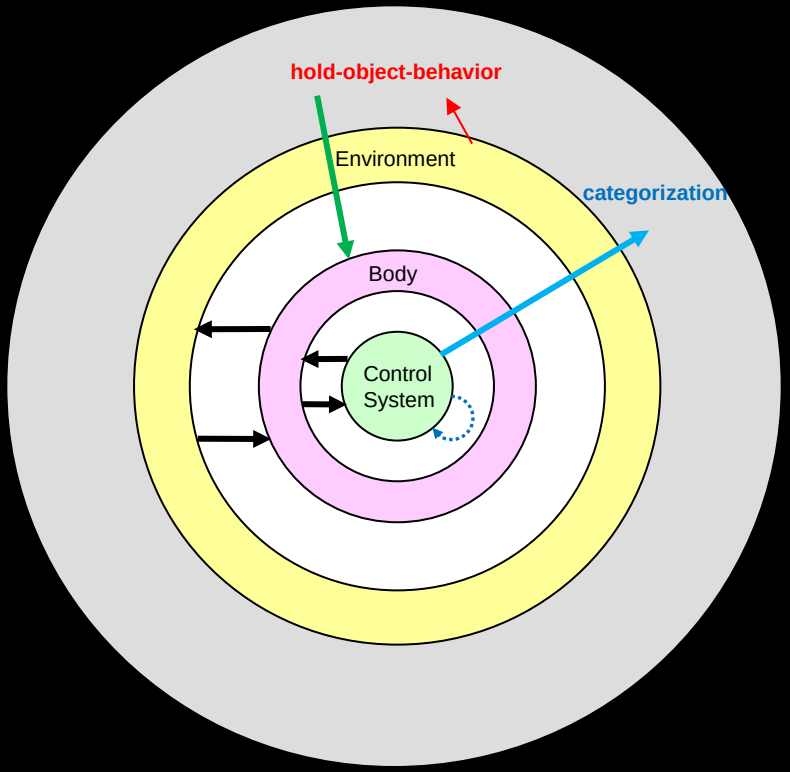
Evaluation criterion: (1) producing non-overlapping categorization outputs for object with different shapes, and (2) touching the object.

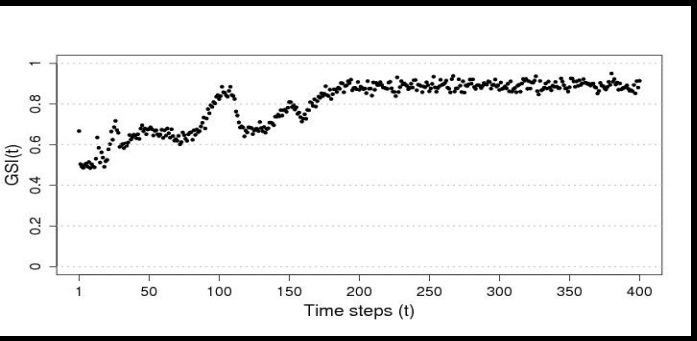
Tuci, Massera, Nolfi (2008, 2010)

On the dynamics of the categorization process









separation of stimuli in sensory space

1) Robot/environmental interactions mediated by simple control rules give rise an hold-object behavior

2) Such behavior ensure that the robot later experience mostly discriminative stimuli (but also conflicting evidences)

3) The integration over time of the partially conflicting cue provide by these stimuli produce the categorization process

Tuci, Massera, Nolfi (2008, 2010)

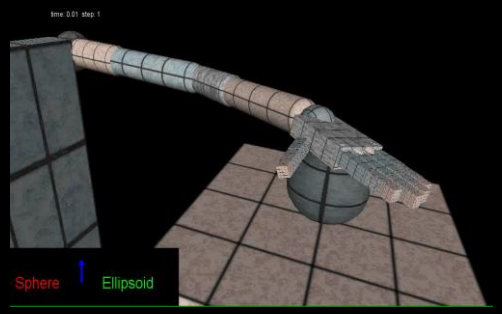
Embodiment and Situatedness

Embodiment: Suitability of the body to exploit the interaction with the environment

[Collins, 2000']

Situatedness: Suitability of the control system to exploit the interaction with the environment

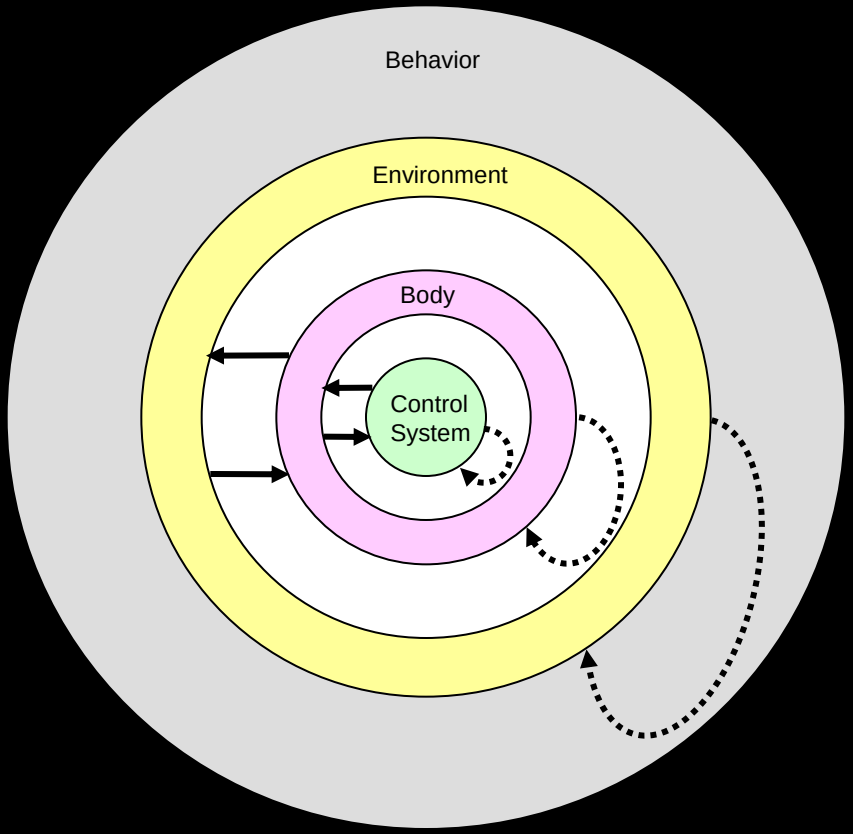
[Baldassarre, Trianni, Nolfi 2006']



[Tuci, Ferrauto, Nolfi 2010']

In embodied and situated systems, the characteristics of the agents are tightly integrated with the characteristics of the environment and of the task

Behavior and cognition as phenomena originating from the interaction between coupled dynamical processes

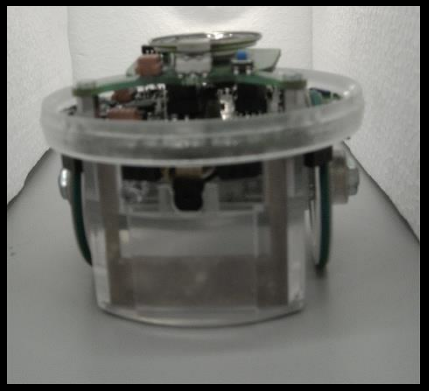


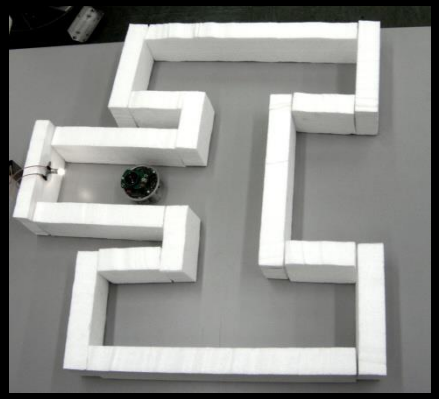
The external dynamic originates from the interaction between the control system, the body, and the environment

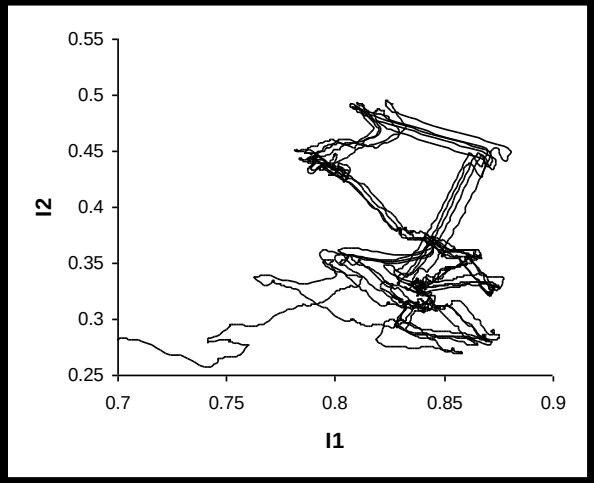
The internal dynamics originates from the interaction occurring within the control system, the body, and the environment

The interaction between dynamical processes which have been co-adapted might lead to coupled dynamics (i.e. to dynamical properties that are co-shaped so to produce adaptive properties as a result of their interaction)

A robot capable of self-localizing in a maze-like environment







8 Infrared, 8 light sensors, 2 motors

Fitness = recognize previously visited locations

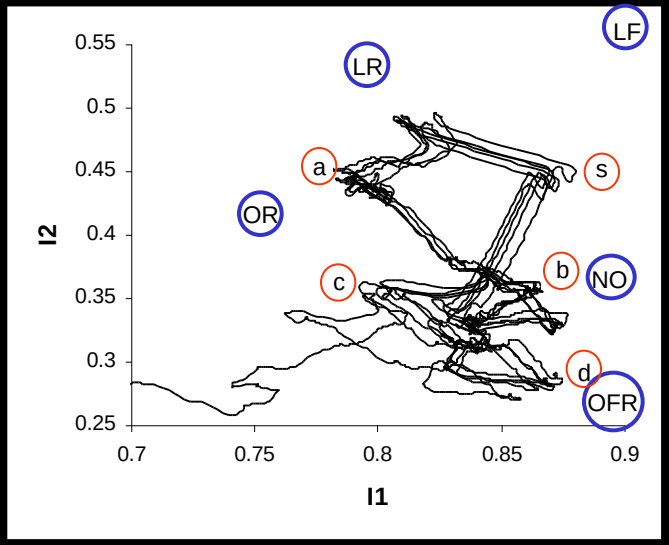
The internal dynamics consists of the inertial dynamic of robots' internal neurons

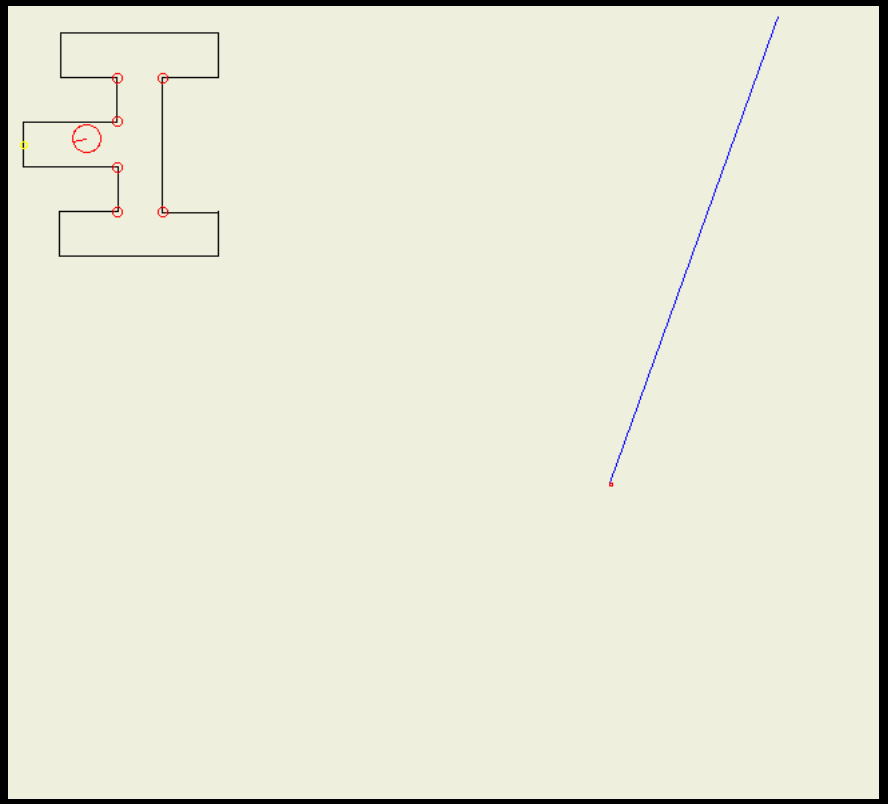
The agent/environmental dynamics consists in the alternation of few relatively stable sensory states lasting for different time duration

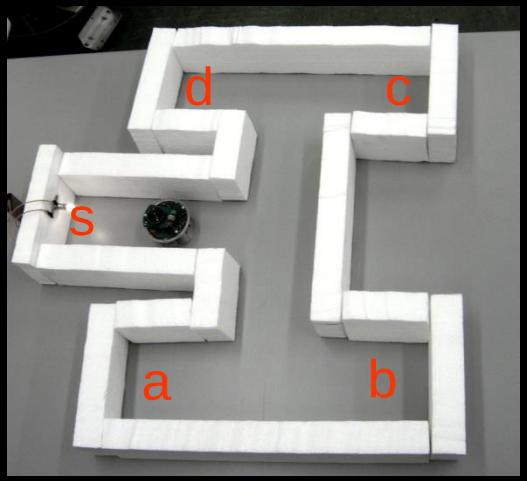
The coupling between the two dynamical processes originates from the fact that the free parameters that regulate the two dynamics and their interaction are co-adapted and co-shaped during the evolutionary process

[Gigliotta & Nolfi, 2007]

How a representation skill can emerge from the interaction between robot's internal and external dynamics

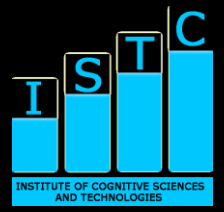






The limit cycle originates from the slow movement of the internal state toward the transient attractors that alternates while the robot move in the env.

[Gigliotta & Nolfi, 2007]



On The Role of the Multi-Level and Multi-Scale Nature of Behaviour and Cognition

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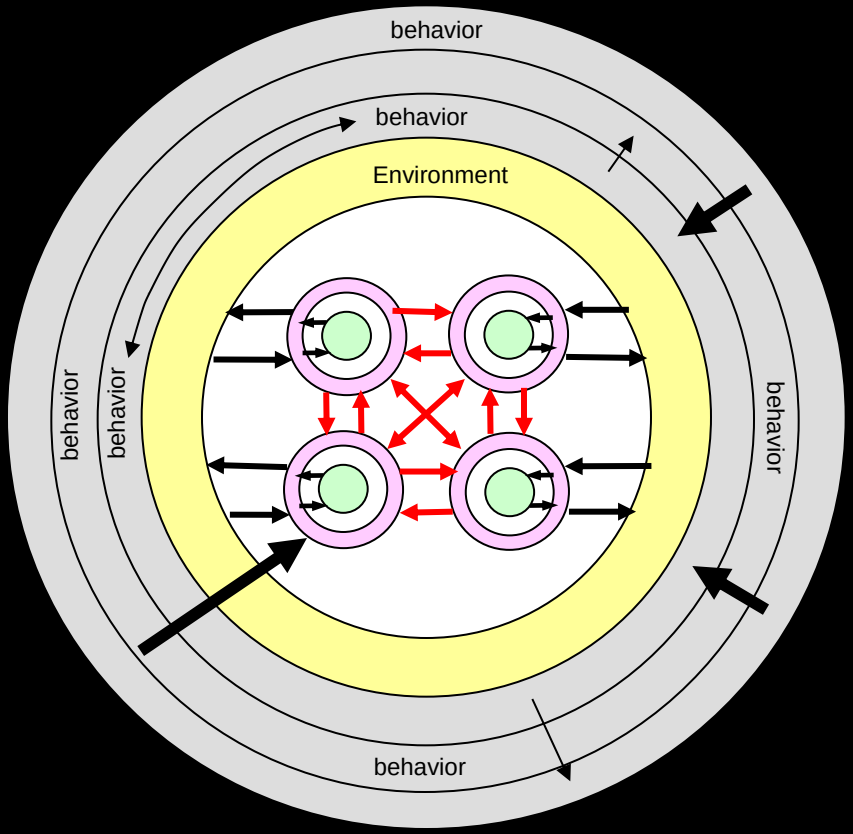
Behavior and cognition are dynamical process with a multi-level and multi-scale organization



Outline

How the behaviour of adaptive robots typically have a multi-level and multi-scale organization

1. How the interaction between lower-level behaviours enable generalizations at the level of behaviour

2. How existing behavioural skills can establish the conditions for the development of new higher-levels skill

3. How the multi-level and multi-scale organization of behaviour enable compositionality and behaviour generalization

1. How the interaction between lower-level behaviours enable behaviour generalizations

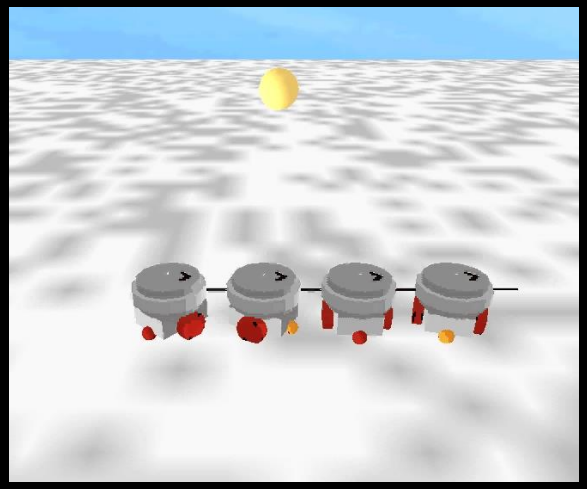
Evolving coordinated locomotion in self-assembled Swarm-Bots

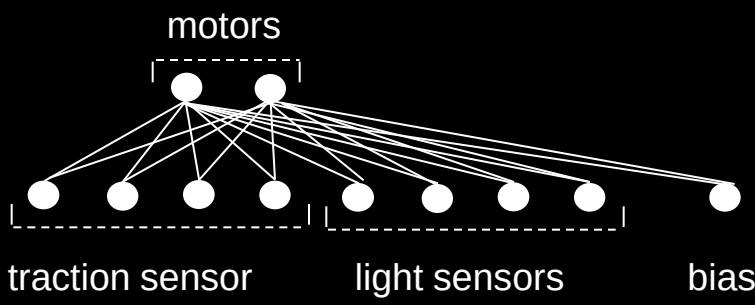
Denebourg, Dorigo, Floreano, Gambardella, Mondada, Nolfi, 2002-2004]

coordinated motion

[Baldassarre, Trianni, Bonani, Mondada, Dorigo, Nolfi, 2006]

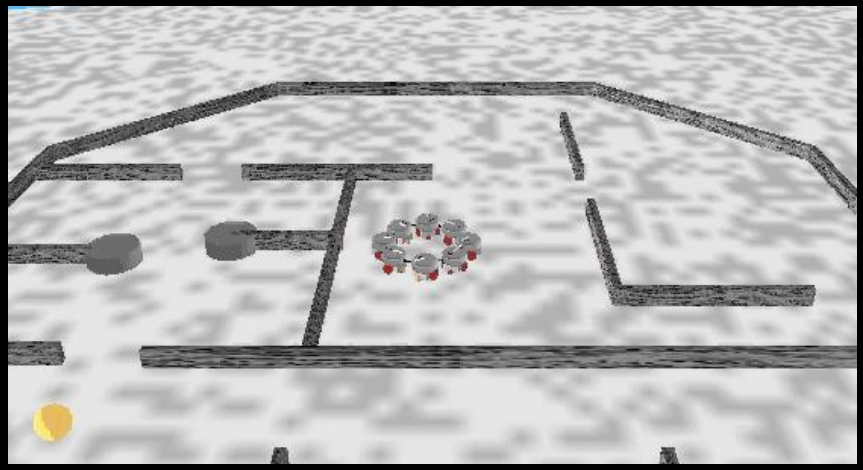
Experimental Scenario & Emergent Behaviours





Robots generalize with respect to:

1) The number of assembled robots
2) The shape of the swarm-bot
3) The type of links

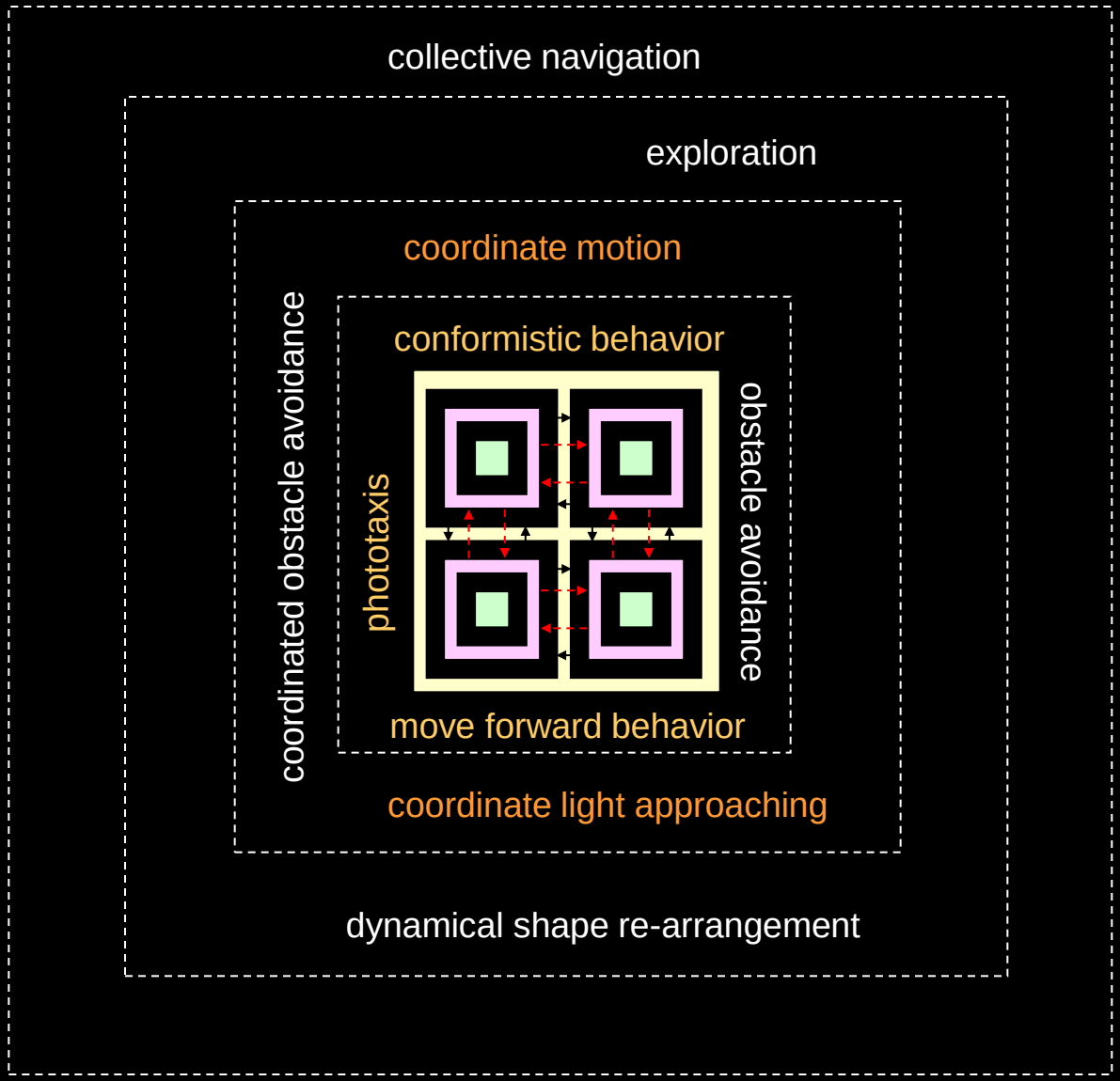


Display additional behavioral capabilities:

1) Collective obstacle avoidance
2) Collective object-pushing pulling
3) Dynamical shape re-arrangement

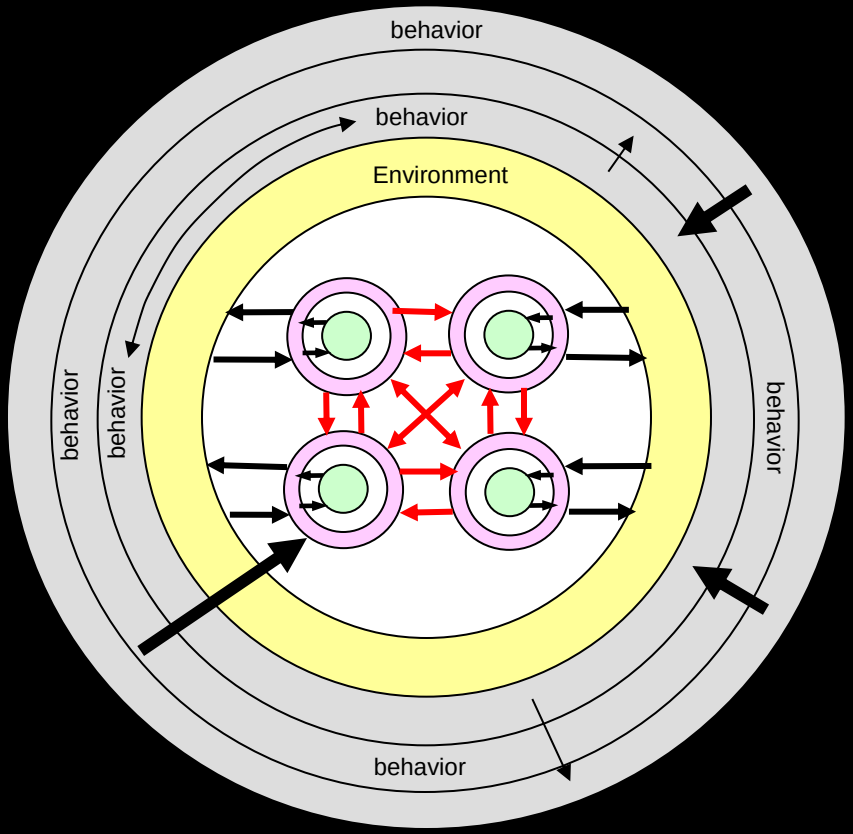
[Baldassarre, Parisi, Nolfi 2004]

The multi-level structure of the behavior displayed by the robots

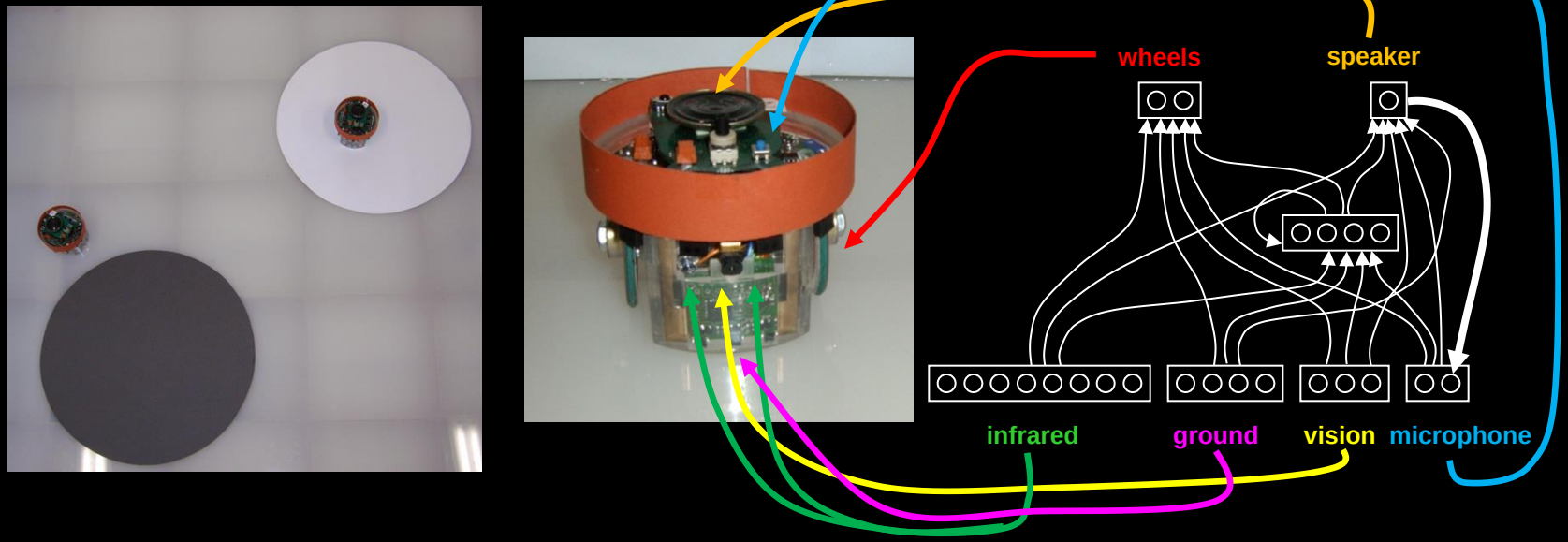


[Nolfi , in press]

2. How the development of behavioral skills establish the conditions for the development of new higher-levels skills

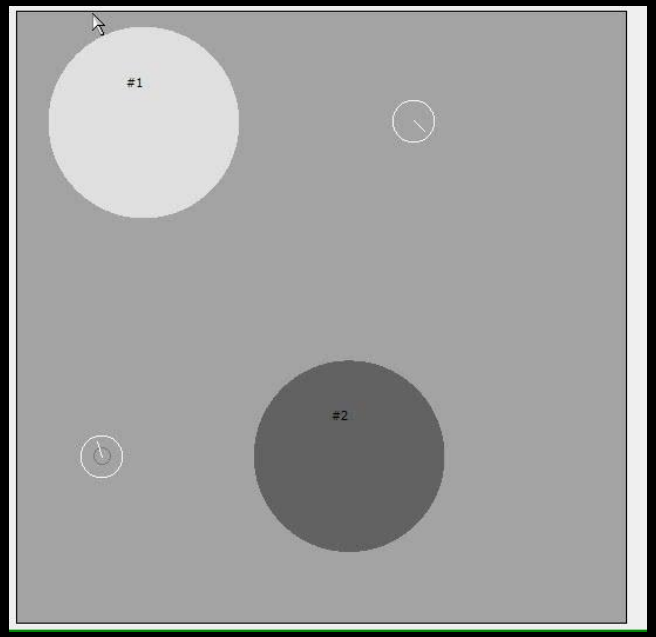


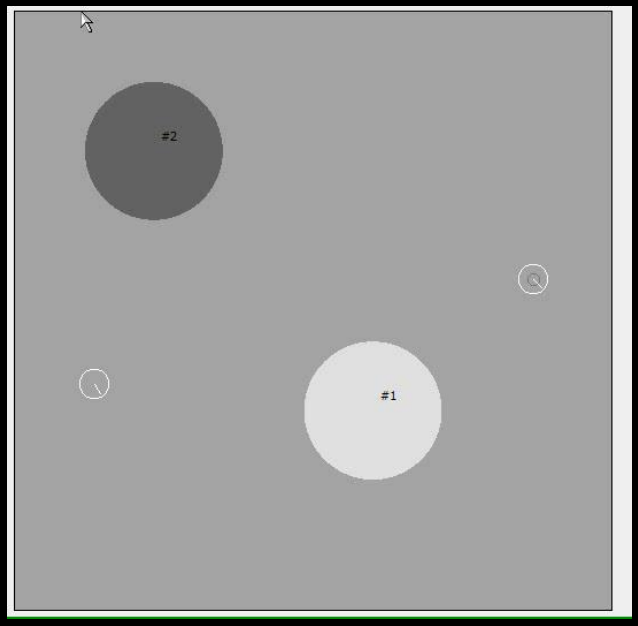
Evolution of behavioral and communication skills in groups of cooperating robots

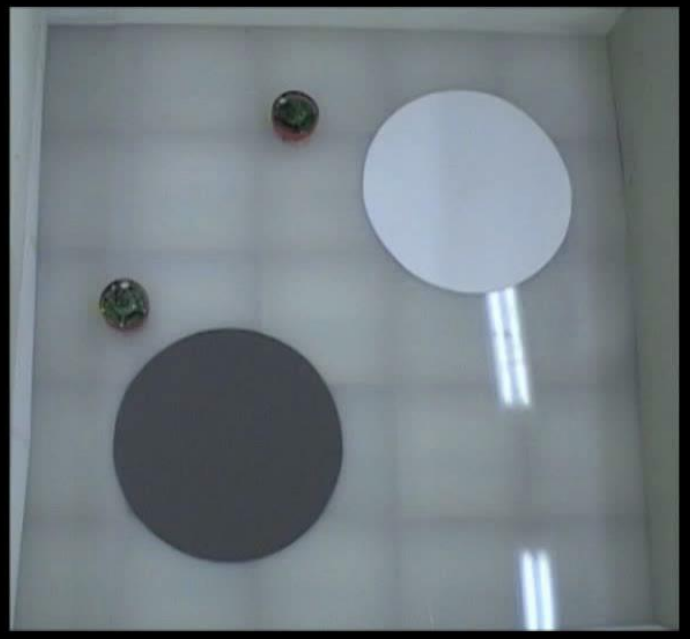


Fitness Function: The group is reward with 1 point every time the robots are concurrently located in the two areas for the first time or after a switch

De Greef & Nolfi, 2010

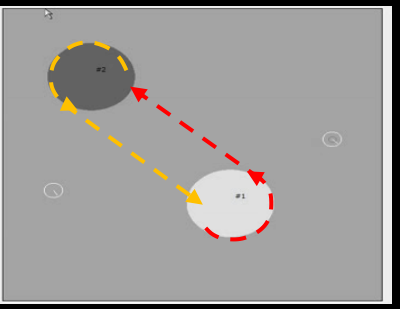






De Greef & Nolfi, 2010

Summary of the main evolutionary progresses



navigate-to-white

look-robot-and-follow-border

navigate-to-black

exit-from-white-area
toward the other robot

exit-from-black-area

remain-on-white-area

signal A/B

remain-on-black-area

find-areas

obstacle-avoidance

move-forward

Infrared-off -> move-forward

Infrared-on -> avoid-obstacles

move-f. & avoid-ob. -> find areas

ground-black -> remain on the black area look-robot-and-follow-border

ground-white/black -> signal A/B

Sound-B & ground-black -> exit from black area

Sound-A & ground-white -> remain on white **area** follow border

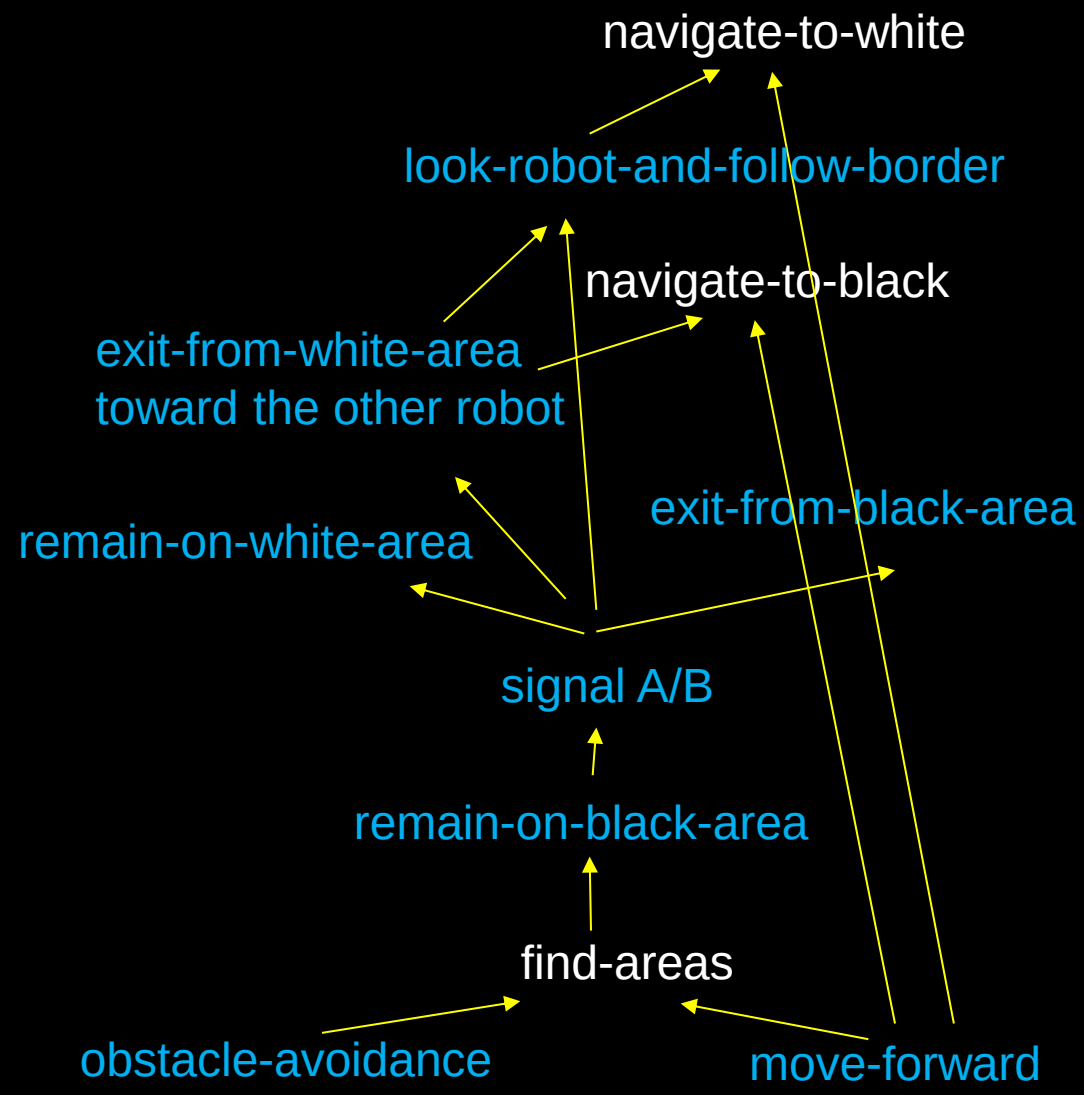
Sound-B & ground-white & see-robot -> exit from white area toward the other robot

exit from white & move-f -> navigate-to-black

look-r.-follow-b. & & move-f -> navigate-to-white

De Greef & Nolfi, 2010.

Multi-level formation, innovations, incrementality & complexification



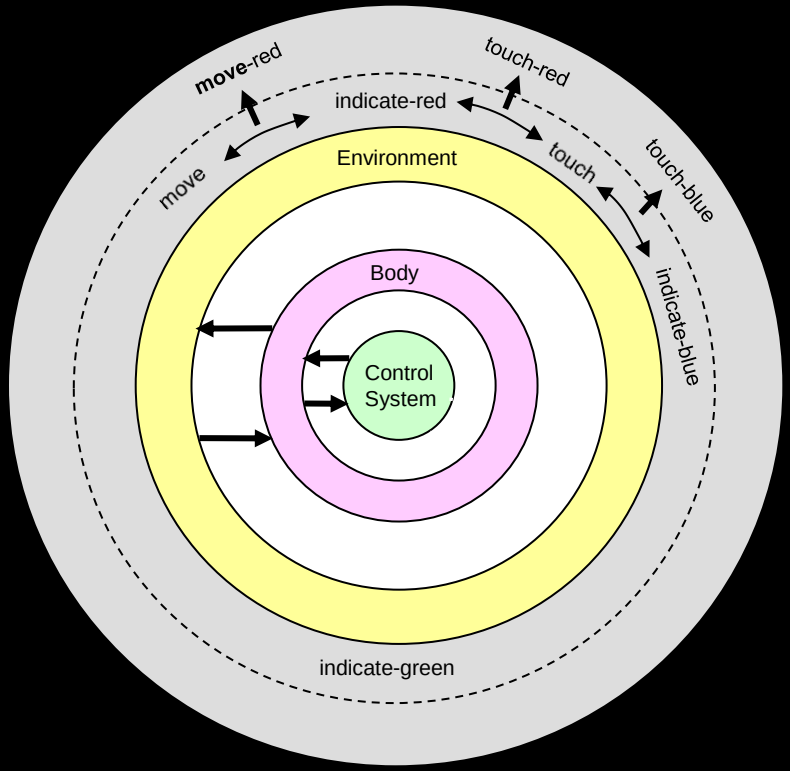
New higher-level capacities emerge through the interactions between pre-existing skills or through new traits combined with skill re-use

Innovations are enabled by the new adaptive opportunities created by the effects of agents' behaviors and by the possibility to re-use existing capacity

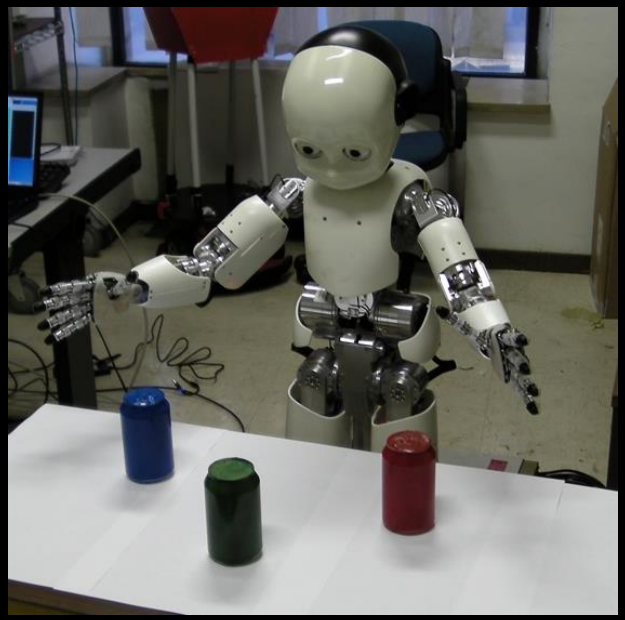
Established skills (assuming new functions) tend to be preserved thus leading to an incremental process and to a complexification of agents skills

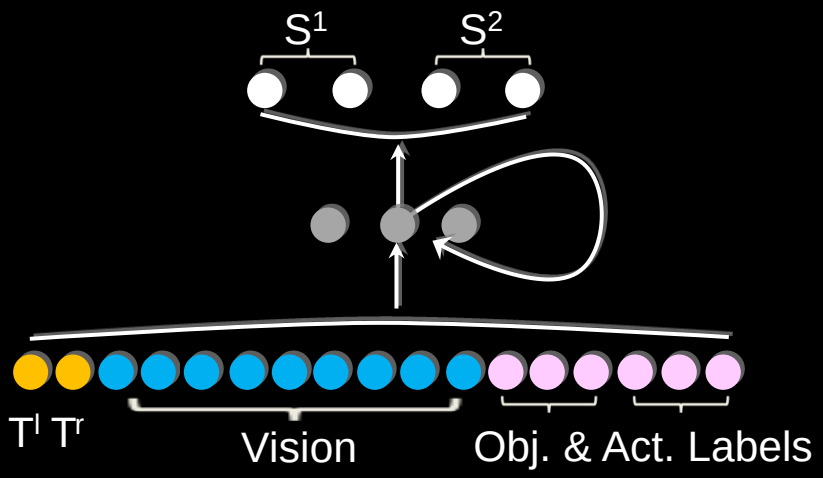
De Greef & Nolfi, 2010.

3. How the multi-level and multi-scale organization of behavior enable compositionality and behavior generalization



Development of early language comprehension capabilities



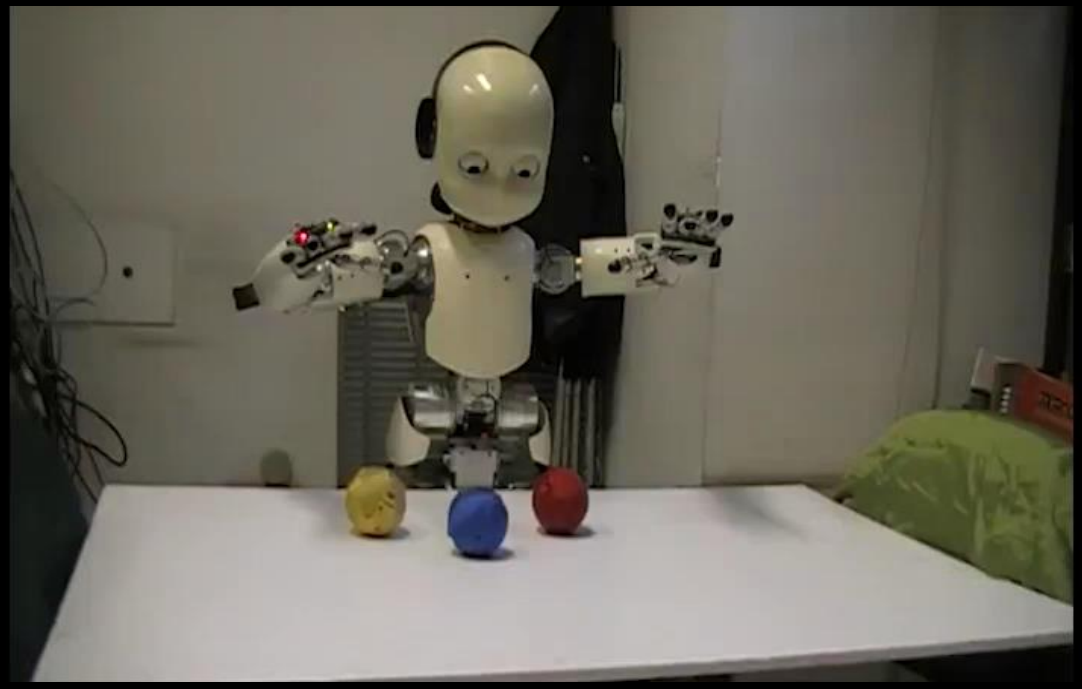


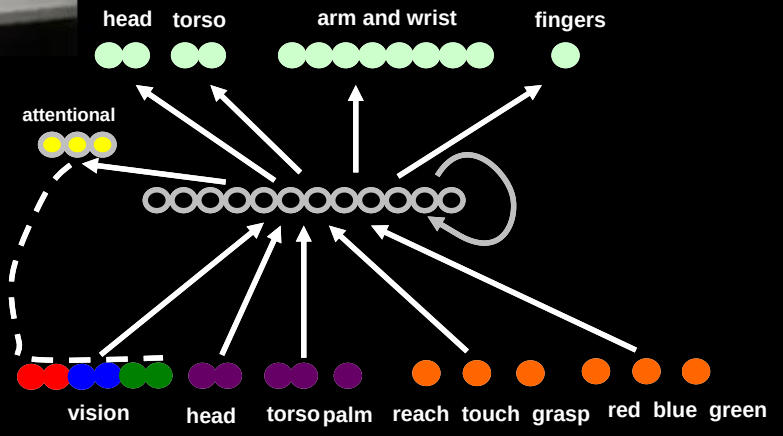
Fitness: The robot is rewarded for the ability to realize the goals of the experienced utterances.

	BLUE	RED	GREEN
IGNORE	YES	YES	YES
TOUCH	YES	YES	NO
MOVE	NO	YES	YES

Tuci, Ferrauto, Zeschel, Massera, Nolfi (2009, 2011)

Development of early language comprehension capabilities

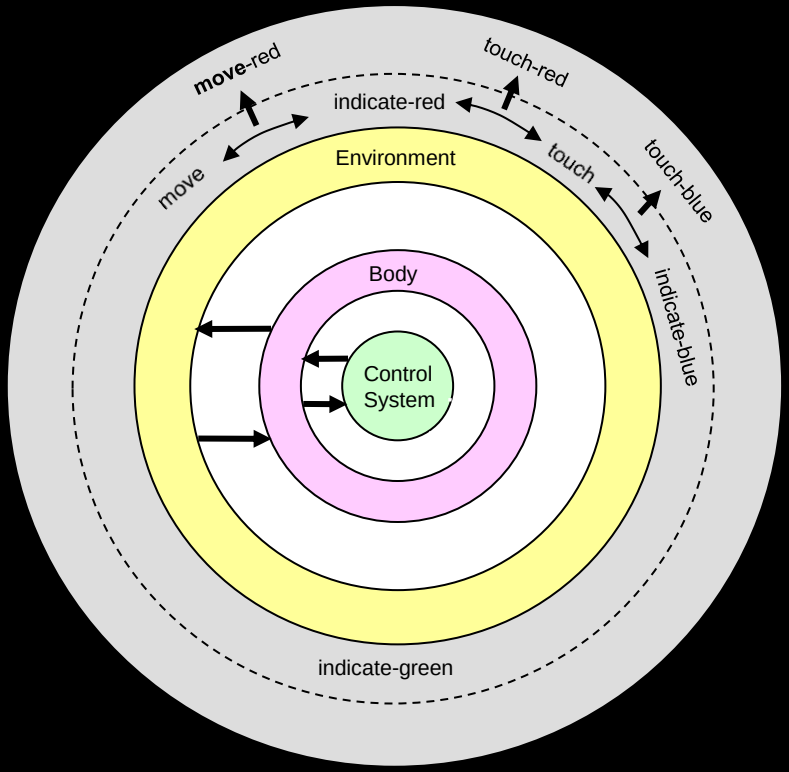




Ferrauto and Nolfi (2013)

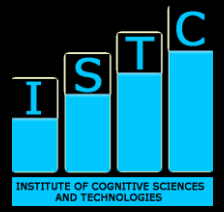
Generalization in Comprehension and Action Production

By post-evaluating the robots at the end of the training process with observed that some of them display an ability to comprehend the two new utterances by displaying the corresponding appropriate behaviors.



Robots trained to produce related skills tend to lead to solutions based on multi-level organizations supporting skill re-combination and re-use.

Tuci, Ferrauto, Arne, Massera, Nolfi (2010, 2011)



Farsa: An Open Software Tool for Evolutionary and Adaptive Robotics

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Features

it is open-source, so it can be freely modified, used and extended by the research community, and multi-platform, i.e. it can be compiled and used on Linux, Windows, and Mac OS X

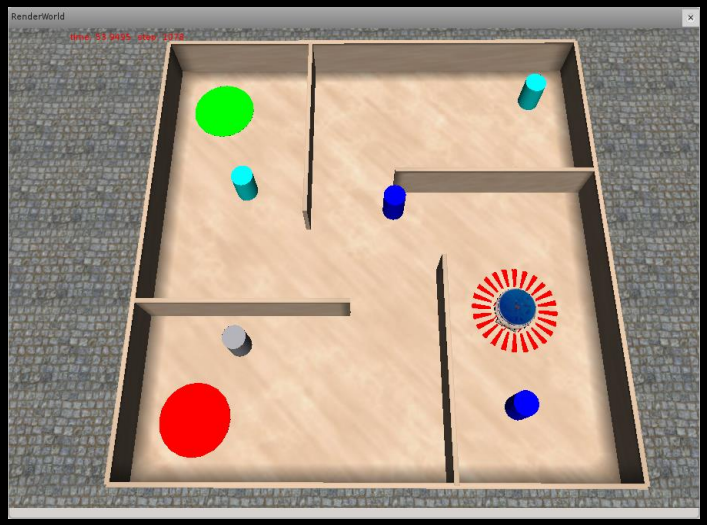
it is constituted by a series of integrated libraries that allow to easily design the different components of an embodied model (i.e. the robots' body and sensory-motor system, the robots' control systems, and the ecological niche in which the agents operate)

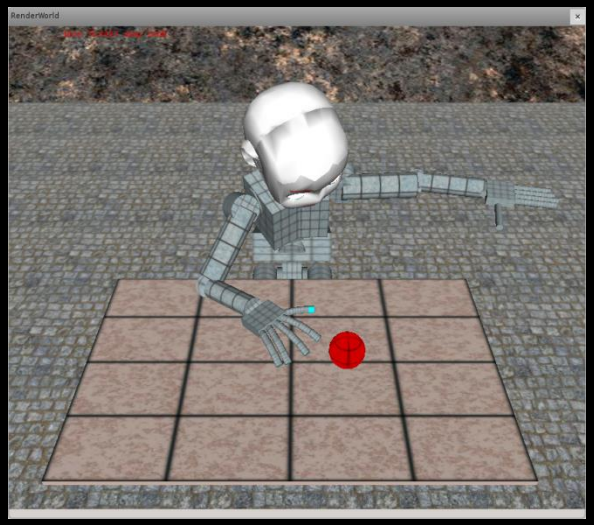
it comes with a rich graphical interface

it is based on a highly modular software architecture that enables a progressive expansion of the tool features and simplifies the implementation of new experiments and of new software components

it comes with a set of exemplificative experiments and with a synthetic but comprehensive documentation that should enable users to quickly master the tool usage

The robot/environmental simulator

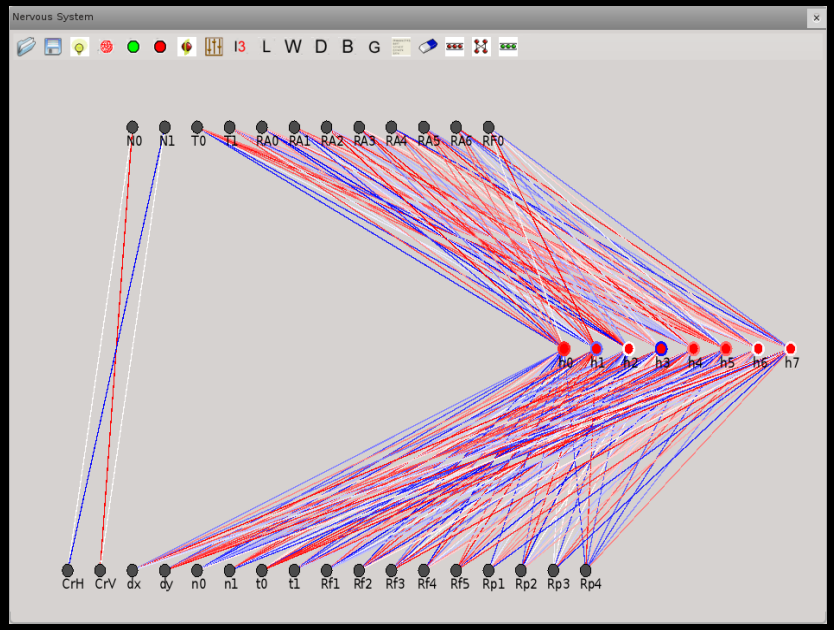


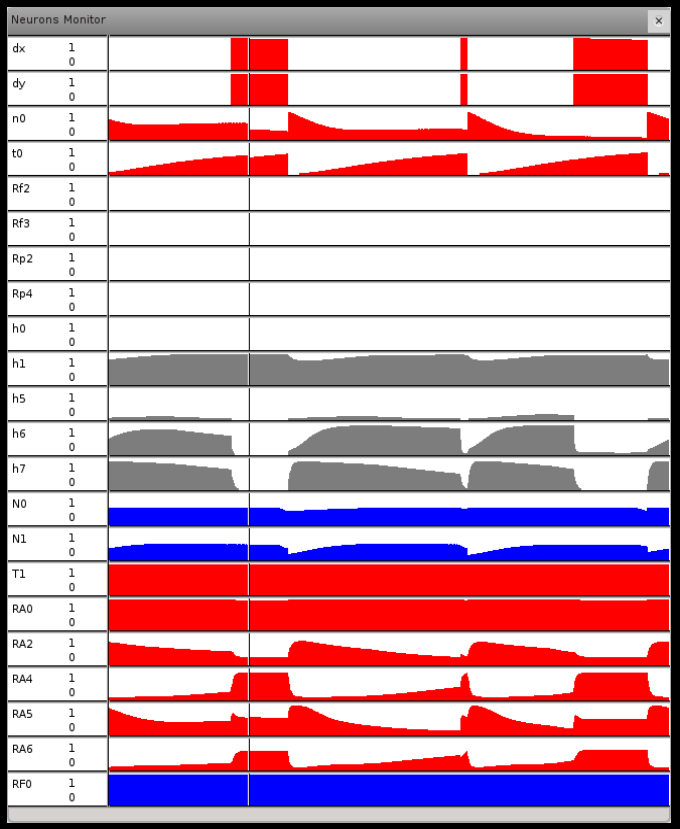


The simulator includes ready to use models of the wheeled robots (Khepera, ePucks, MarxBot) and of the iCub humanoid robot, a library of ready to use sensors and motors, and methods for configuring the environment

The robots/environmental physical interaction are accurately simulated on the basis of the Newton Dynamics library.

The controller library

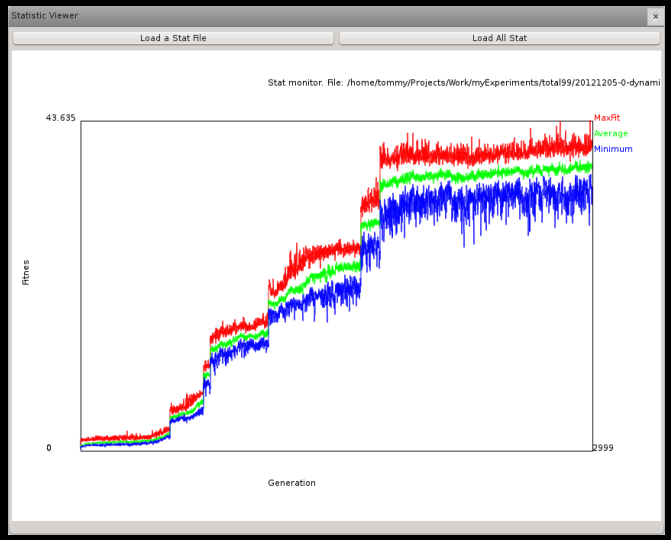




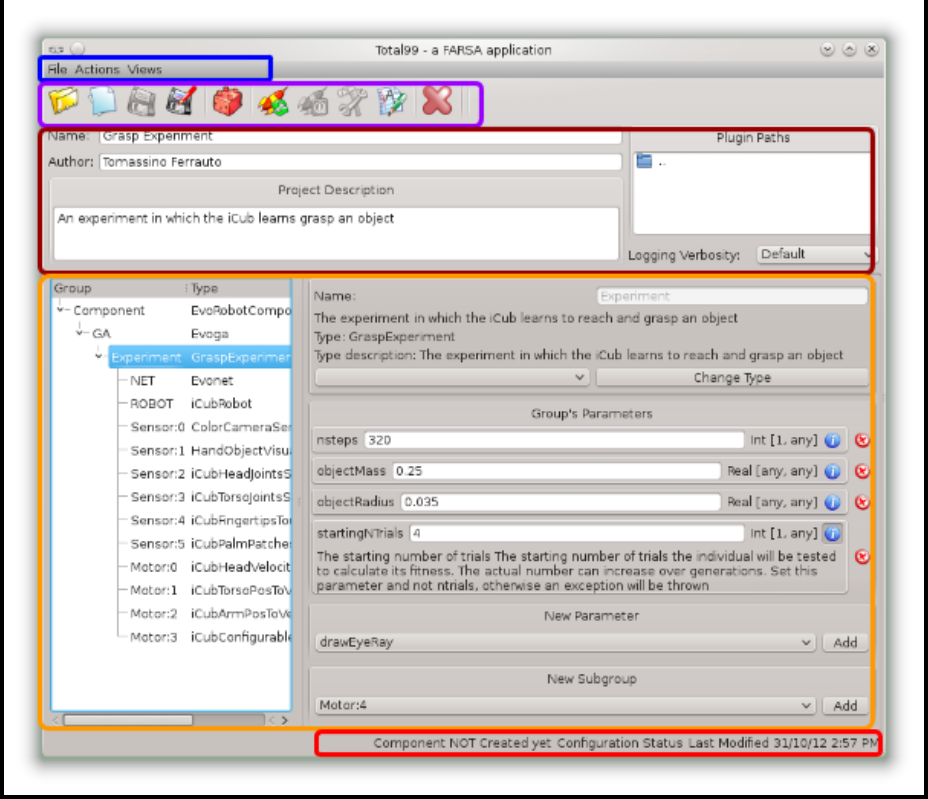
The library allows to graphically edit and visualize characteristics of the neural controllers and to plot the state sensory, internal, and motor neurons while the robots operate in their environment

The adaptive library

The adaptive library allow to evolve the free parameters through customizable evolutionary algorithm and to combine phylogenetic adaptation with ontogenetic adaptation realized through associative or supervised learning algorithms



Usability



The fitness function and the topology of the environment need to be specified in a C++ plugin file that can be then compiled and loaded at runtime.

Setting the number and type of robots

Setting the sensors and motors

Defining the architecture of the robots' controllers

Setting the other parameters

Running the adaptive process

Loading adapted robots and visualizing their characteristics and behaviors through the graphic widgets