Behaviour as a Complex Adaptive System: Evolving coordinated cooperative behaviours and communication in autonomous robots

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Outline

1. Behavior as a complex adaptive system (by Stefano Nolfi)

2. Evolution of communication in teams of cooperating robots (by Davide Marocco)

3. Evolutionary Robotics: a brief practical introduction (by Stefano Nolfi)

4. Using Evorobot* to run experiments on the evolution of communication (by Davide Marocco)

Behaviour as a Complex Adaptive System

1. **Emergence**: behaviors are phenomena occurring at a given time scale resulting from several non-linear interactions occurring at smaller time scales. Moreover, behavior originates from the combination of different dynamical processes occurring within the agent, within the environment, and as a result of the agent/environmental interactions.

2. **Multi-level and multi-scale organization**: behavior displays a multi-level organization in which the interaction between properties at a given level of organization lead to higher level behavioral properties and in which higher level properties later affect lower level behaviors

3. **Adaptivity**: behavioral systems can be effectively synthesized through adaptation processes in which the free parameters regulate the interaction at lower levels of organization, and in which variations of the free parameters are retained or discarded on the basis of their effects at higher levels of organization.

Outline Part I:
Behaviour as a Complex Adaptive Systems

1. Behavior as a phenomenon emerging from fine-grained agent/environmental interactions

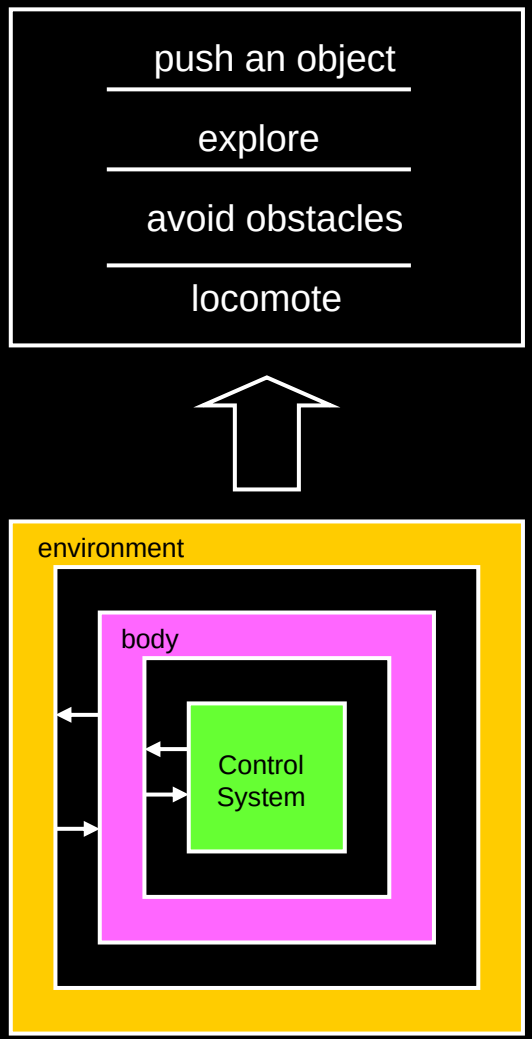
2. Behavior as a phenomenon originating from the interaction between coupled dynamical processes

3. Behavior as a phenomenon with a multi-level and multi-scale organization

4. Behavior as a phenomenon affected by higher levels of organization

5. Behavior as an adaptive process

1a. Behaviour as a dynamical process resulting from fine-grained interactions between the control system the body and the environment

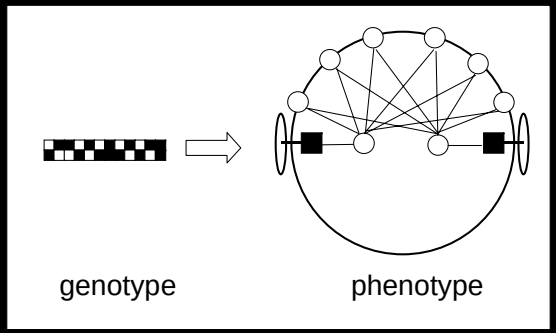


The environment and the agent/environmental relation co-determine the body and the motor reaction of the agent that, in turn, co-determines how the environment and/or the agent/environmental relation changes

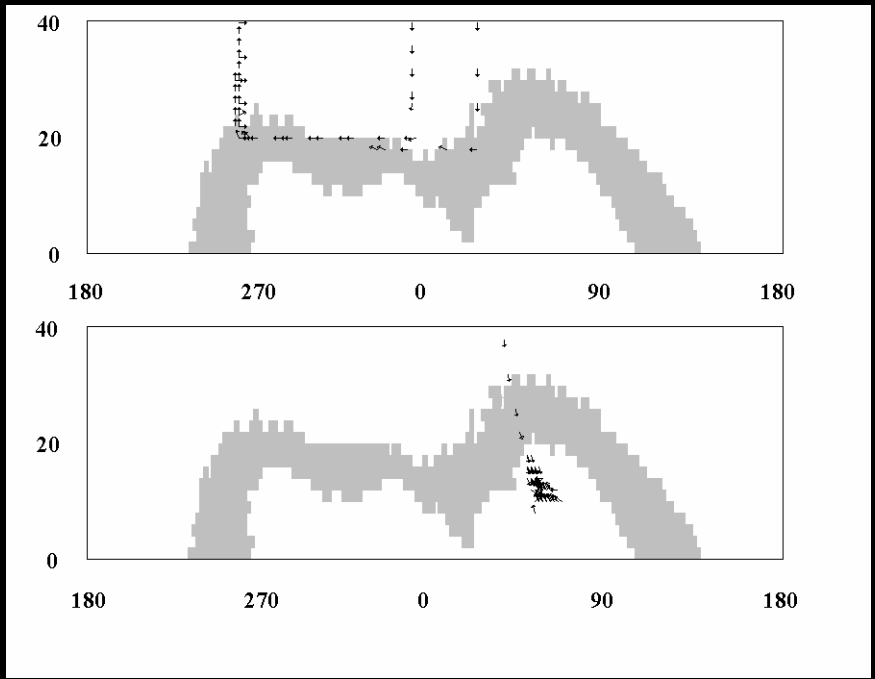
Sequences of interactions (occurring at a fast time rate) lead to dynamical processes – behaviors – that extend over significant longer time spans

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

1b. Discriminating objects with different shapes



F = time spent close to cylinders

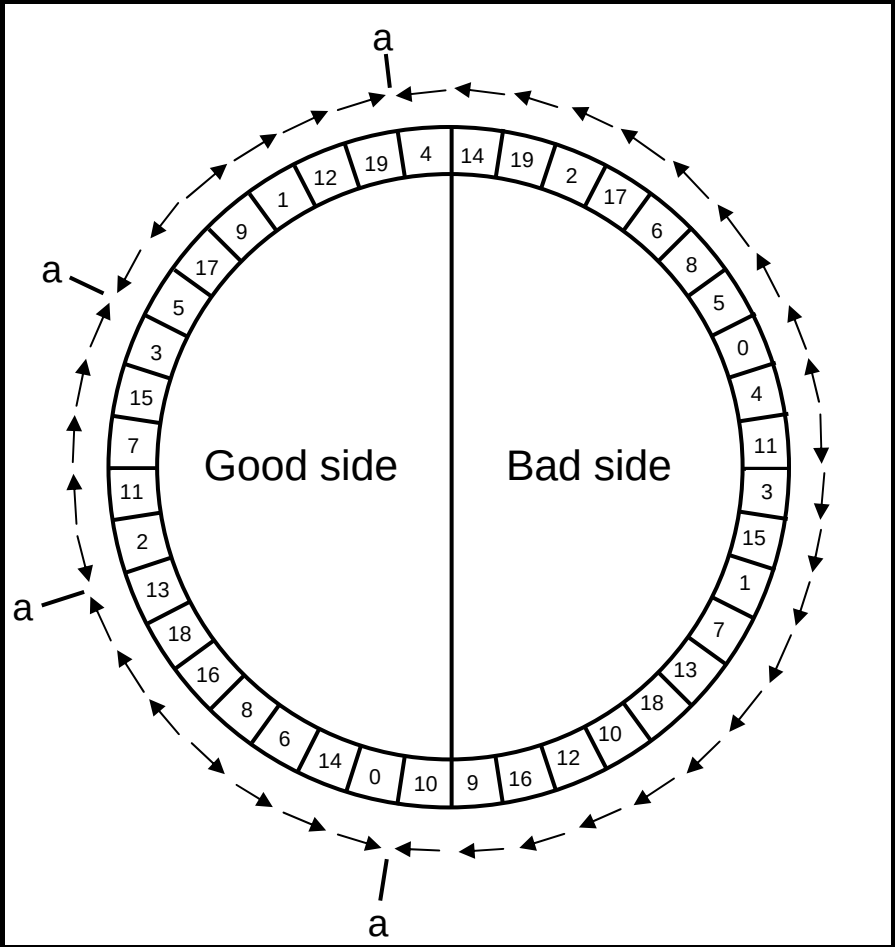


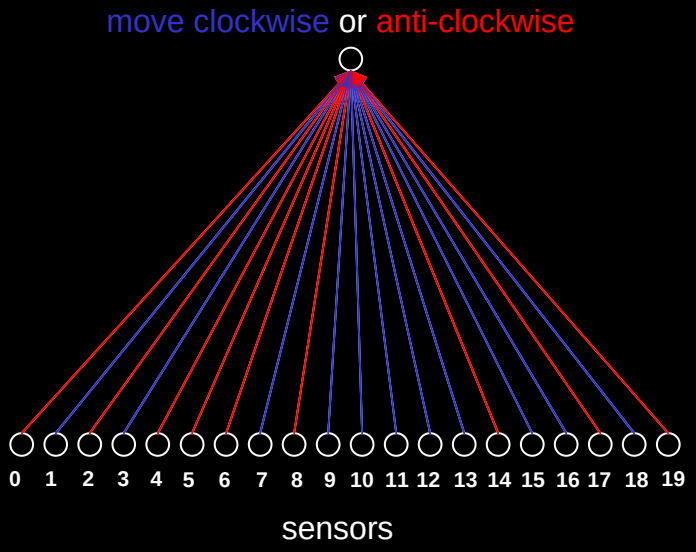
The observed behavior arise from the interaction between the robot and the environment

Discrimination is the emergent result of several agent/environmental interactions

[Nolfi, 1996]

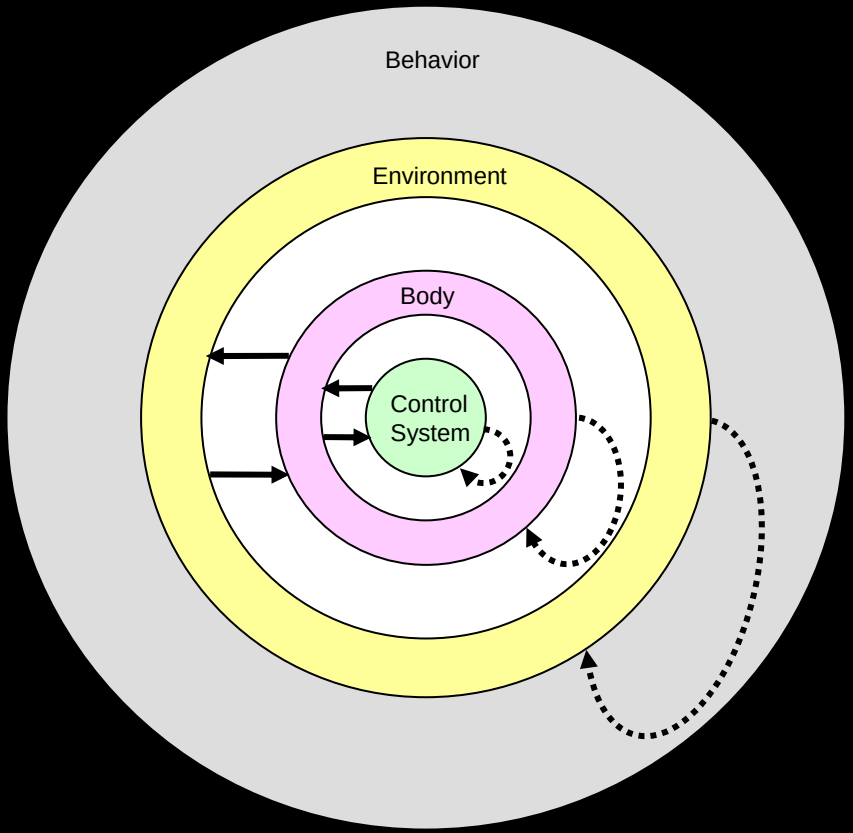
1c. Reaching and remaining in the good side of the environment





[Nolfi & Parisi 1996]

2a.Behavior as a phenomenon originating from the interaction between coupled dynamical processes

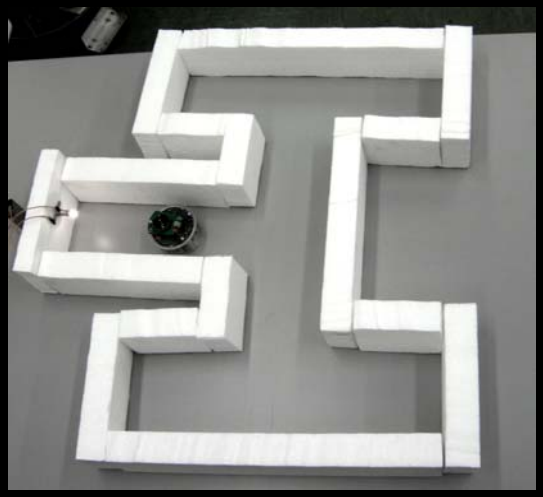


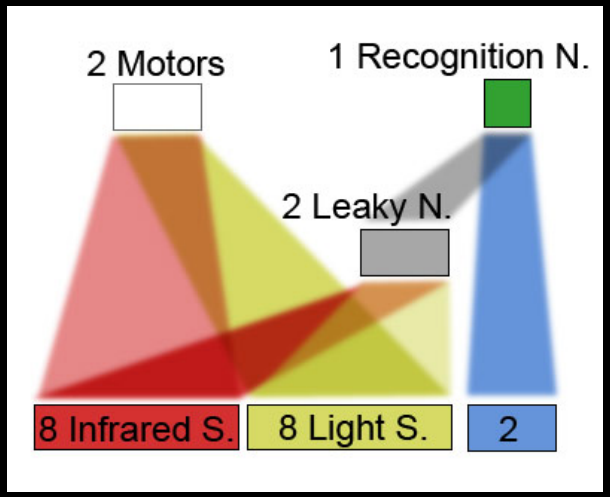
The external dynamic originates from the interaction between the control system, the body, and the environment.

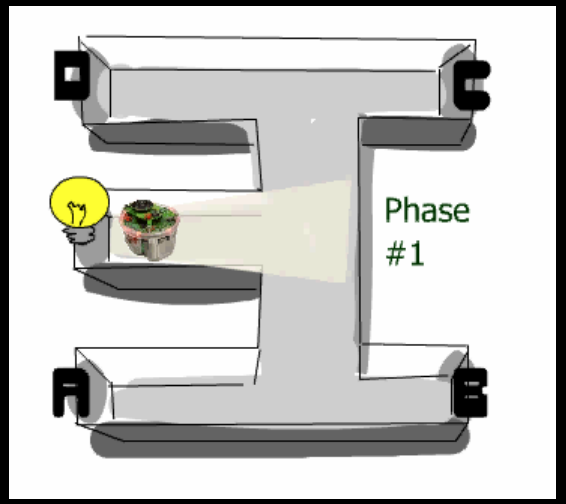
The internal dynamics originate from the interaction occurring within the control system, the body, and the environment.

The interaction between dynamical processes which have been co-adapted might lead to coupled dynamics (to the synthesis of adaptive properties that emerge from the interaction between different dynamical processes).

2b. Development of spatial representation in evolving autonomous robots



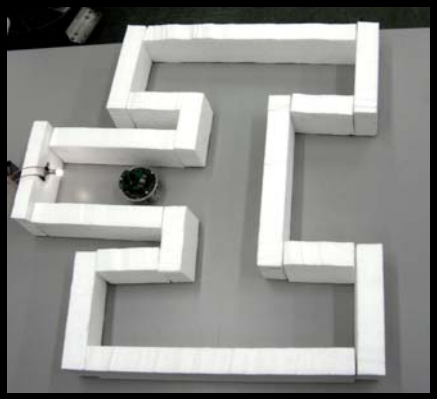


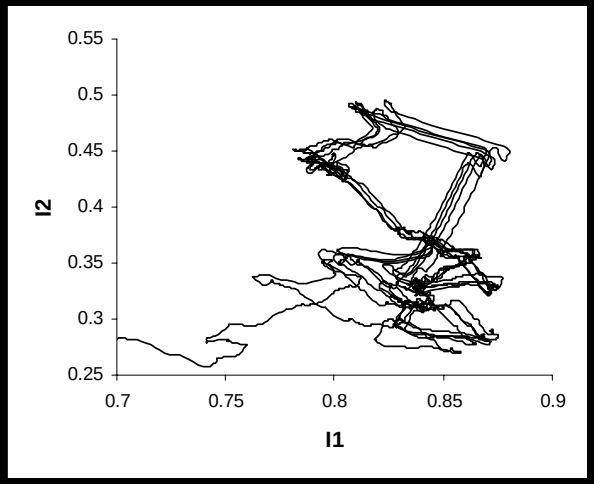


Selection criterion: The robot is rewarded for exploring the environment by visiting all locations and for recognizing the location in which it previously found the black disk

[Gigliotta & Nolfi, 2007]

2c. Development of spatial representation in evolving autonomous robots





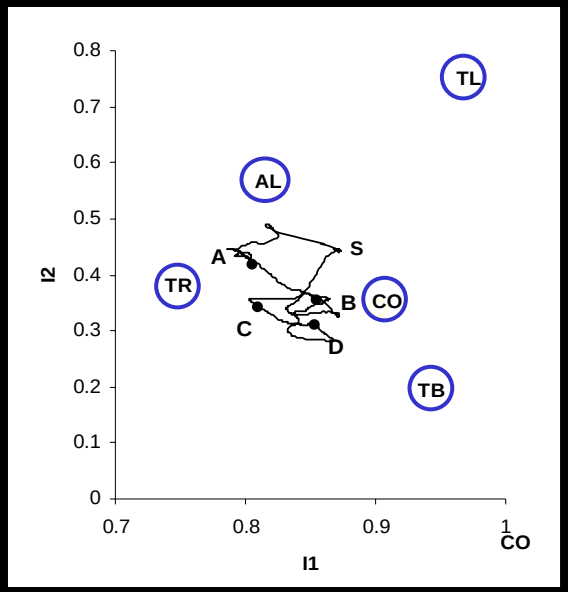
The internal dynamics consists of dynamical internal neurons working at tunable time scales

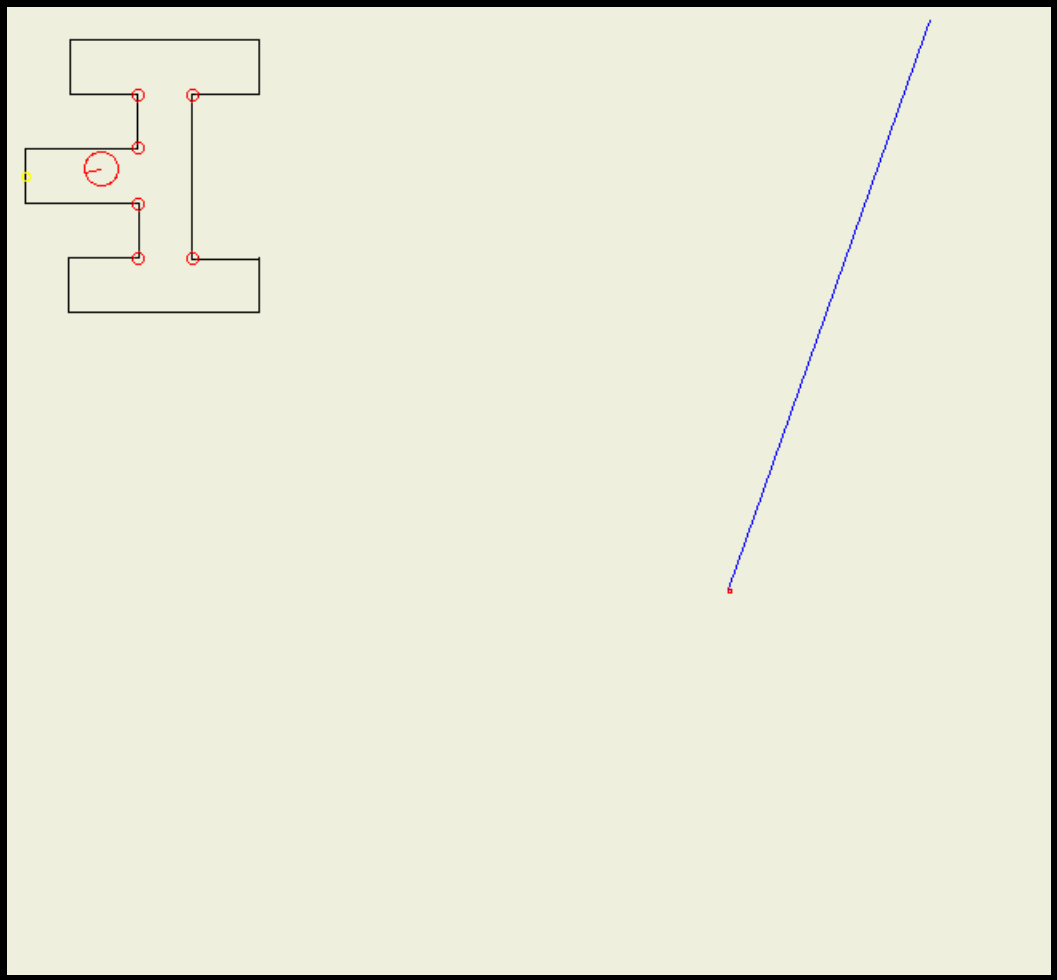
The agent/environmental dynamics consists in the alternation of few relatively stable sensory states lasting for different time duration

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]

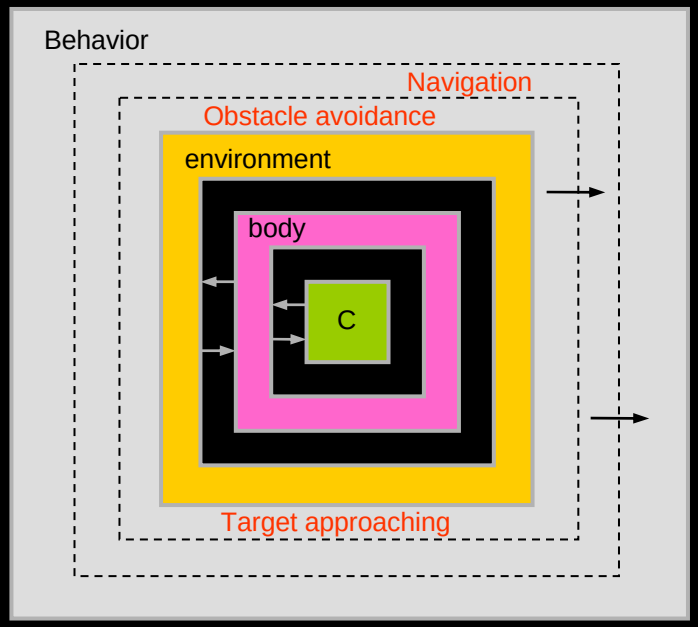
2d. How robot's internal representation is generated while the robot moves in the environment





[Gigliotta & Nolfi, 2007]

3a. Behaviour as a multi-levels and multi-scales phenomenon

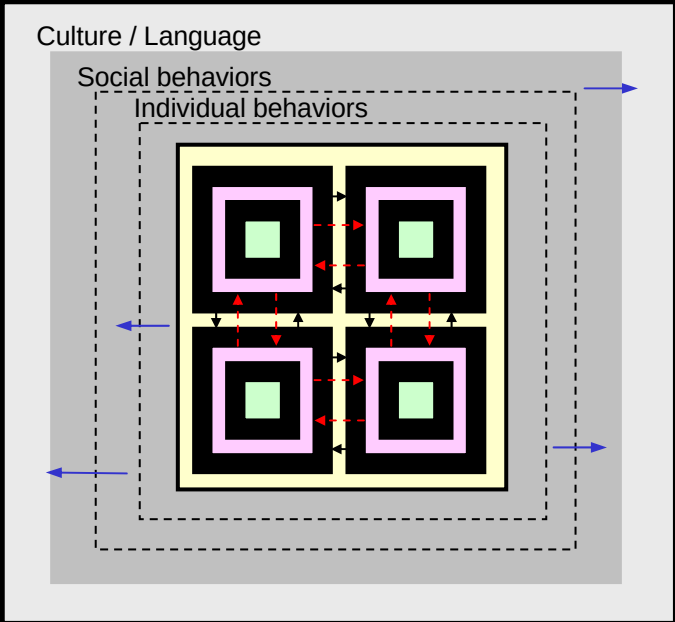


Behavior is a phenomenon with different levels of organization involving properties extending at different time scales

The interactions between the agent control system, body, and the environment (and eventually the coupling between the internal and the external dynamics) lead to lower level behaviors extending for short time spans

The Interaction between lower level behaviors lead to higher level behaviors extending over longer time spans

3b. Collective behaviour as a multi-levels and multi-scales phenomenon



The structure of the interactions, in the case of collective behavior, is similar to that of individual behavior but involves a much larger number of concurrent interactions.

Moreover, in the case of collective behavior, the layered structure of the emergent properties might include complex high level properties (e.g. language or culture) that extend over even longer time spans.

3c. Evolving Swarm-Bots displaying coordinated motion and light-approaching

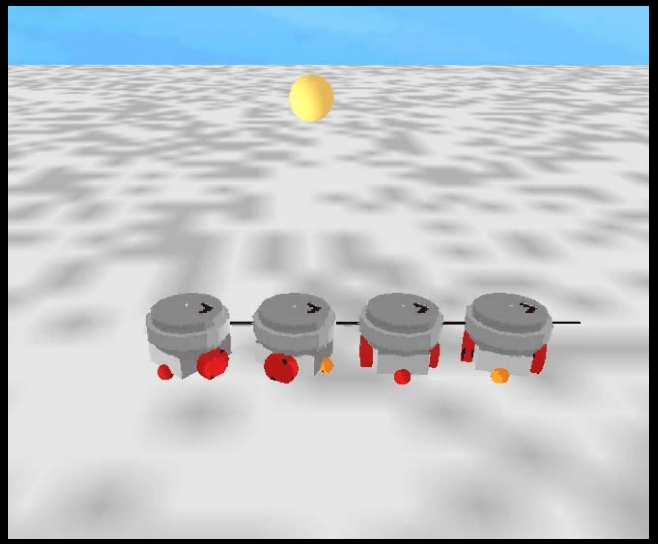
[http://www.swarm-bots.org

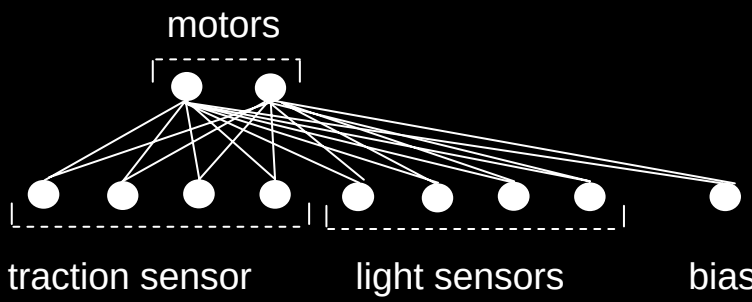
Denebourg, Dorigo, Floreano, Gambardella, Mondada, Nolfi, 2002-2004]

coordinated motion

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

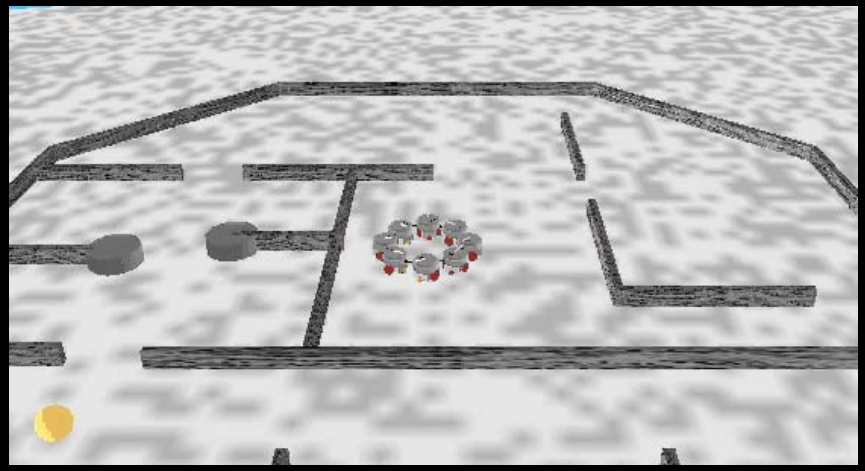
3d. Integration of different behavioral abilities and generalization





Robots generalize with respect to:

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

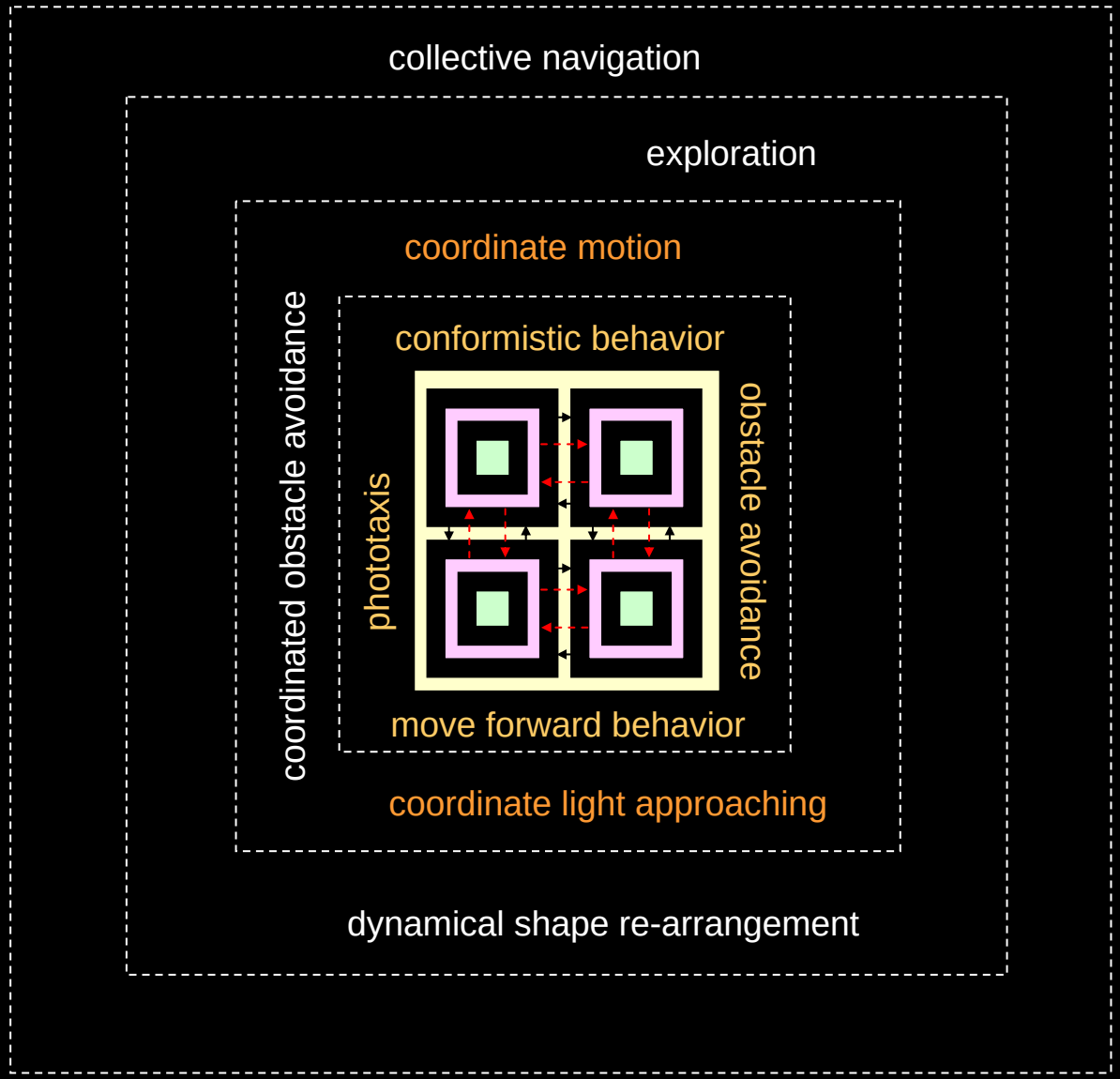


Display additional behavioral capabilities:

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

[Baldassarre, Parisi, Nolfi 2004]

3e. The multi-level structure of the emerging collective behavior



[Baldassarre, Parisi, Nolfi 2004]

3f. Low levels behaviors as a pre-requisite for the development of higher levels skills

Even simple robots evolved for solving relatively simple problems display behaviors with a multi-level and multi-scale organization

The multi-level organization of behavior is important for explaining robots' generalization abilities

The development of lower-level behavioral skills might pose the basis for the development of further skills at higher levels of organization potentially leading to an open-ended process in which innovations create the basis for further innovations

3g.The emergence of communication in population of initially non communicating agents

In this experiment we evolved a population of robots for the ability to perform a collective foraging problem in which group of robots has to equally distribute between foraging areas to maximize the energy extracted by the group

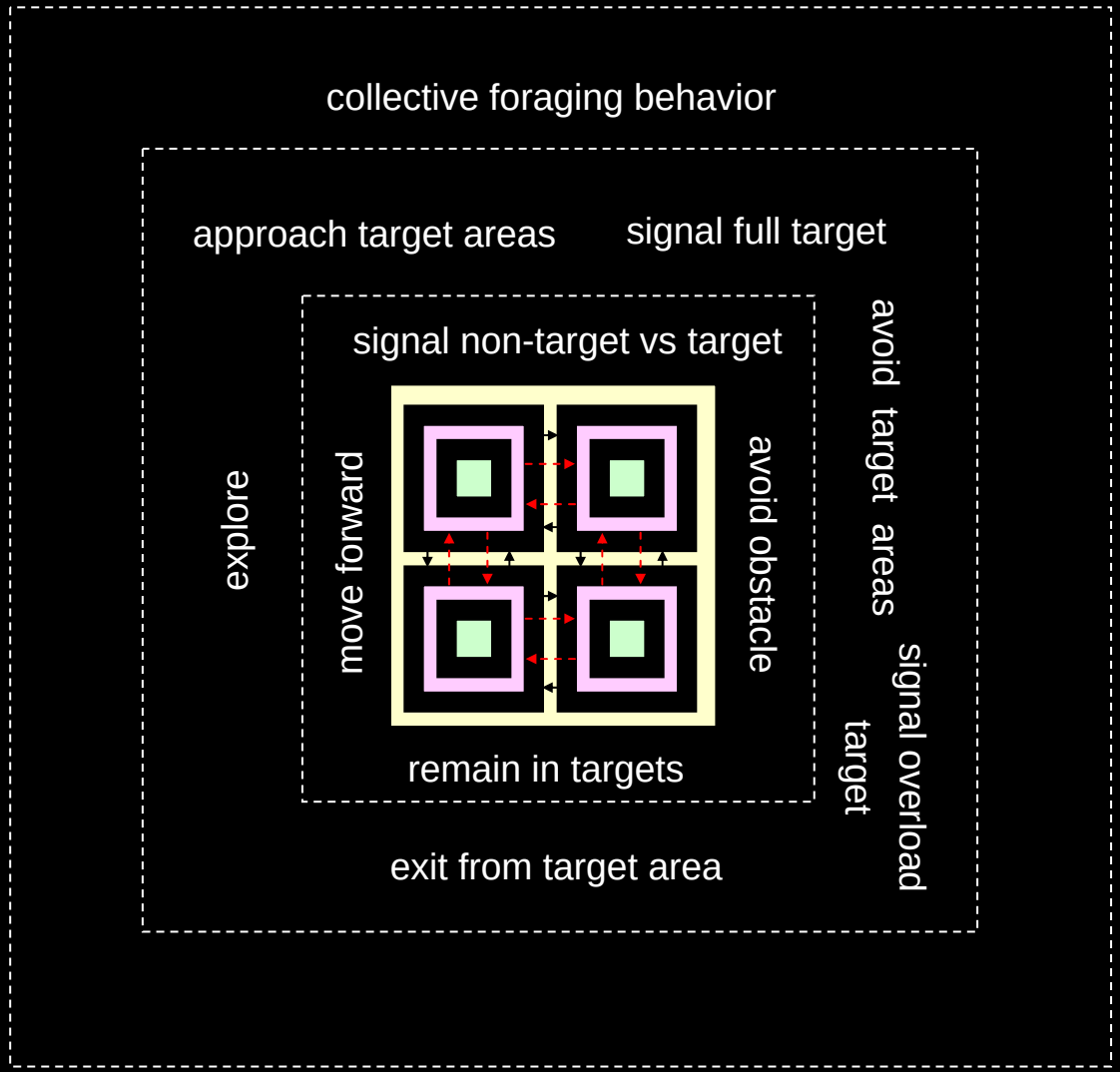
The analysis of the results obtained indicates that robots develop:

Several individual and social behavioral skills with a multi-level and a multi-scale organization

A shared communication system including 4-6 different signals each playing different functions and/or carrying different meanings depending on the context

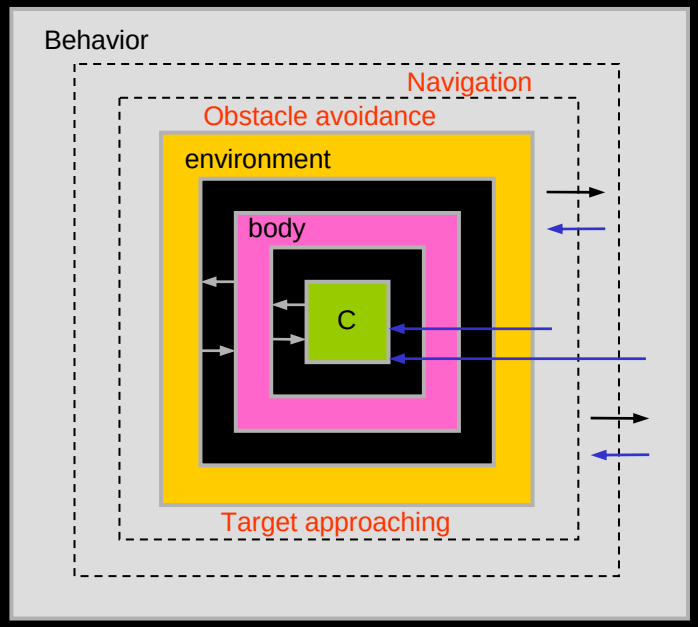
[Marocco & Nolfi 2006, 2007]

3h. The multi-level organization of robots' behaviour



[Marocco & Nolfi 2006, 2007]

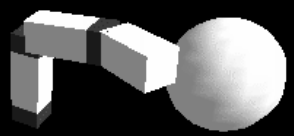
4a. Behavior as a phenomenon affected by higher levels of organization

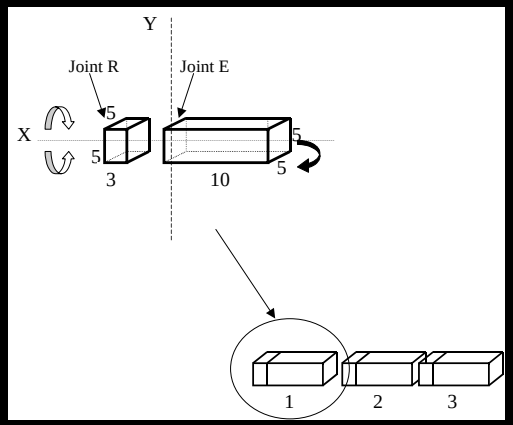


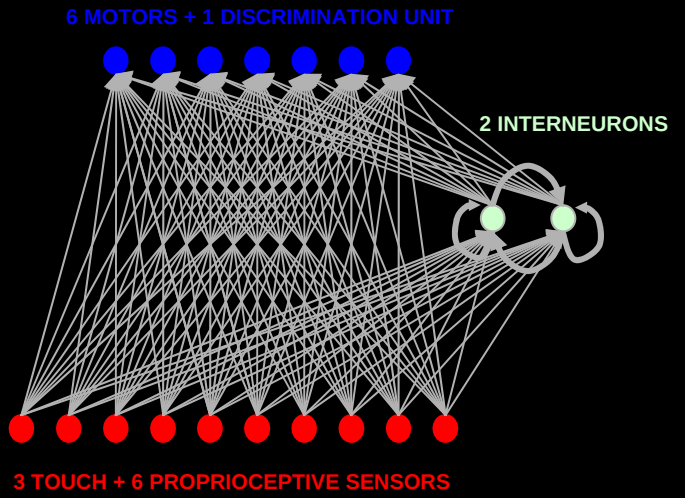
High-level behaviors extending over long time spans later affect lower-level behaviors extending at shorter time spans

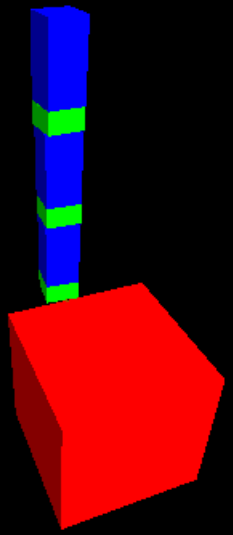
This means that the behaviors, which originate from the interaction between the agent and the environment and from the interaction between lower levels behaviors, later affect the lower levels behaviors and the interaction from which they originate.

4b. Behavior as a phenomenon affected by higher levels of organization



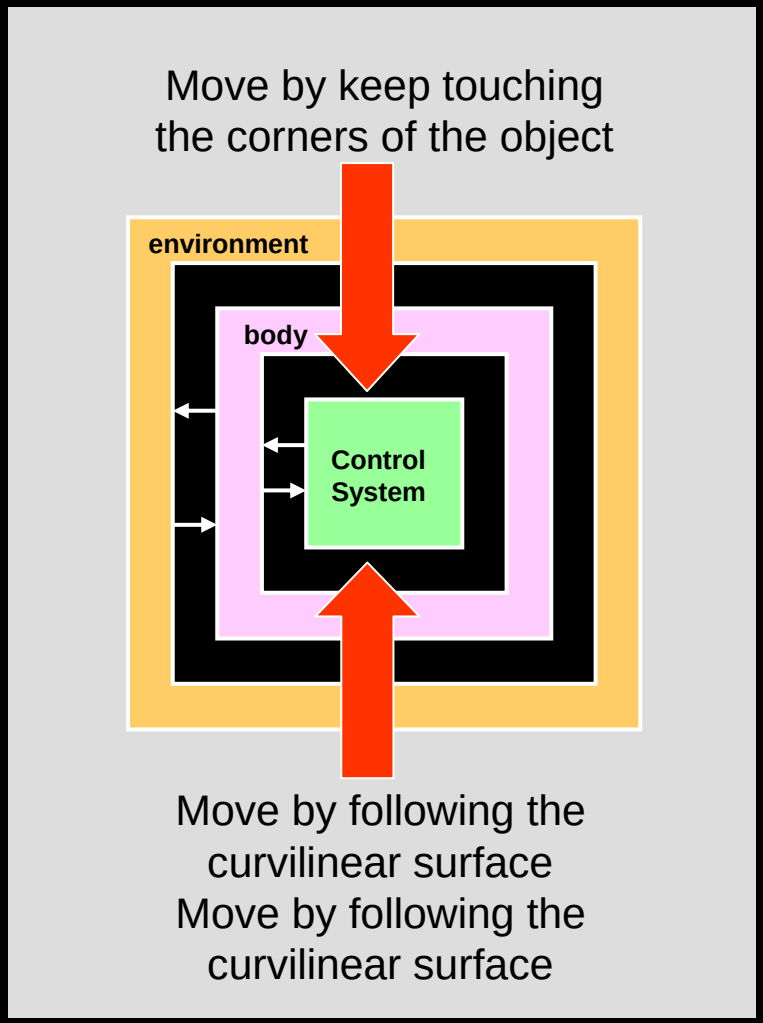






[Nolfi & Marocco, 2002]

4c. Behavior as a phenomenon affected by higher levels of organization

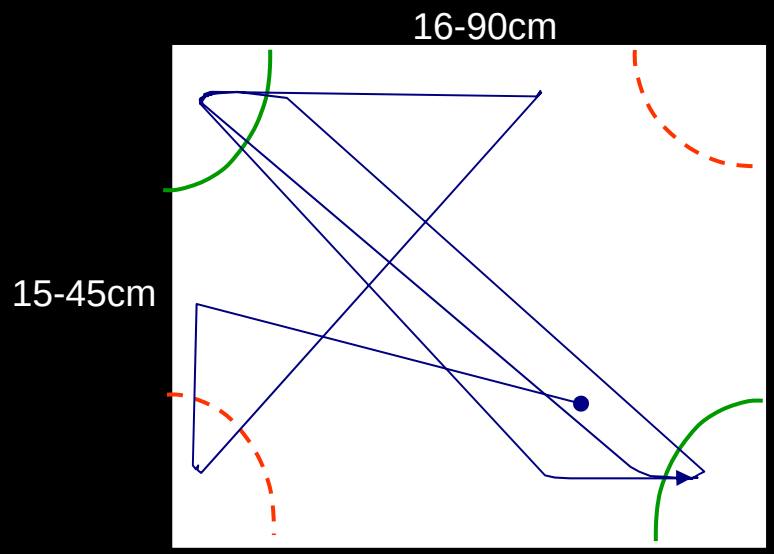


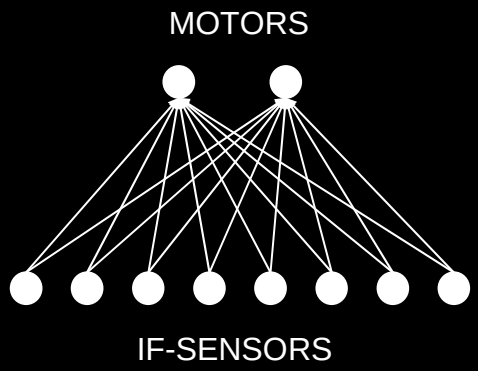
The interaction between the control system of the robot, its body, and the environment lead to the exhibition of different behavior in different environmental conditions

The behaviors exhibited by the robot lead to the perception of two rather different set of stimuli that are used by the robot to discriminate the object shape

The stimuli that are used to categorize the object are not provided directly by the environment but are action-mediated

4d. Navigating toward selected target areas





Leaving a corner with an angle of about 45 degrees ensures that the robots will always encounter long walls which, combined with the behavior of avoiding obstacles by turning on the left, ensures that the robot will always encounter green corners.

The leaving-corner behavior thus eliminates the need to discriminate between long and short walls since obstacles corresponding to short walls are never experienced after the first corner has been left.

5a. Behavior as an Adaptive System

Adaptivity is a foundational characteristic of behavioral systems.

Systems that have been handcrafted by human designers do not fully exploit properties emerging from the interactions. Systems of this sort are embodied and situated only in a limited sense since are provided with a body and are situated in an physical environment, are not shaped so to take full advantage of their embodiment and situatedness

The difficulty designing robots able to exploit emerging properties lies on the complex adaptive system of behavior

5b. Behavior as an Adaptive System

Adaptive techniques, on the other hand, are not affected by the complexity of the relation between the rules that regulate the fine grained interaction and the resulting behavior since they do not need to take this relation into account. They limit themselves to select the variations that lead to useful emergent properties.

Adaptivity is a foundational characteristic of behavioral systems as well as embodiment and situatedness

Conclusions

We have shown how functional behaviors might emerge from the fine-grained interactions between the robot's body, the robot's control system, and the environment without the need of dedicated control structures.

We have seen how complex skills might emerge from the interaction between simple internal and external dynamical processes

We have demonstrated how adaptive systems typically display behaviors with a multi-level and multi-scale organization and how this organization affect agents' generalization skills and agents' evolvability (i.e. agents' chance to further improve their adaptive skills).

We have discussed how higher-level behaviors later affect the lower-levels behaviors and the fine-grained interactions from which they originate and how these effects might be exploited to solve complex problems with simple control mechanisms

Conclusions 2

We have claimed that adaptivity, together with embodiment and situatedness, is a foundational element of behavioral systems