Bio-Inspired Artificial Intelligence

Lecture 11: Communication-based Cooperation

Knowledge Technology

http://www.informatik.uni-hamburg.de/WTM/

Motivation

- What we learned so far:
  - Language foundations from the biological perspective
  - Models for grounding of words and embodiment
- Today we follow up with
  - Communication foundation
  - Models for emergence of communication beyond grounding
  - Communication for cooperation

- Slides based on:
  - *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies* by Floreano & Mattiussi, MIT 2008.
  - With additional material from A. Cangelosi, M. Mirolli, S. Nolfi

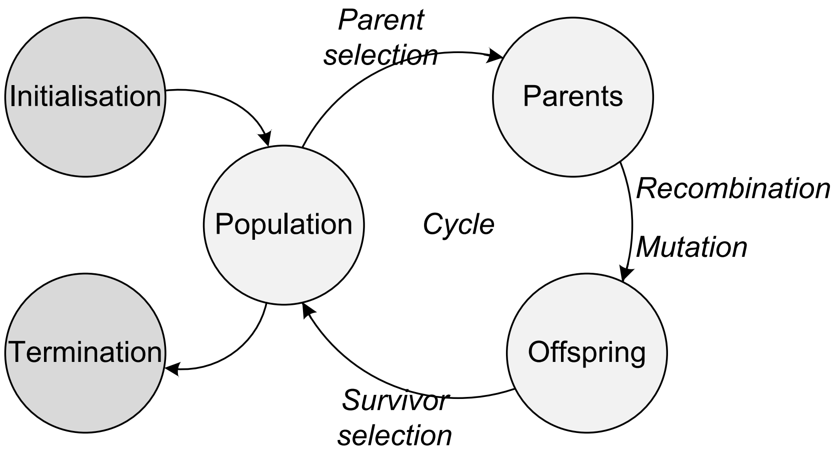
Motivating Example: Cooperate, Communicate, and Rescue?

Scope and Assumptions

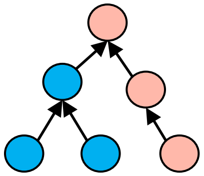
- Investigate communication based cooperation through synthetic methodology based on ***Embodiment***, ***Situatedness*** and ***Adaptivity***
- Assumptions:
  - Communication systems are not pre-defined nor fixed
  - Agents are embodied: physical entities that interact between themselves and with the environment
  - Agents are situated: social environment that includes other agents and require cooperation to perform a task
  - Adaptive processes affect communication and underlying knowledge
    ⇨ Agent has to ***adapt*** to and ***learn*** the demands

Evolutionary Robotics Recap

- Classic evolution happens over generations, not within an agent's lifetime (≠ Learning)
- Genotype ≠ Phenotype
- Several evolutionary operators
  - Fitness based selection
  - Mutation, recombination



- Evolution can create controllers of neural networks that…
  - Show interesting embodied behaviour
  - Create robots that are situated in the environment
- Most important AND difficult: ***fitness function***!



Outline for Today

- Basic considerations on communication
- Theoretical aspects of cooperation
- Evolution of communication and cooperation
- Evolution of language
- Software and hardware tools

What is the Basis of Communication?

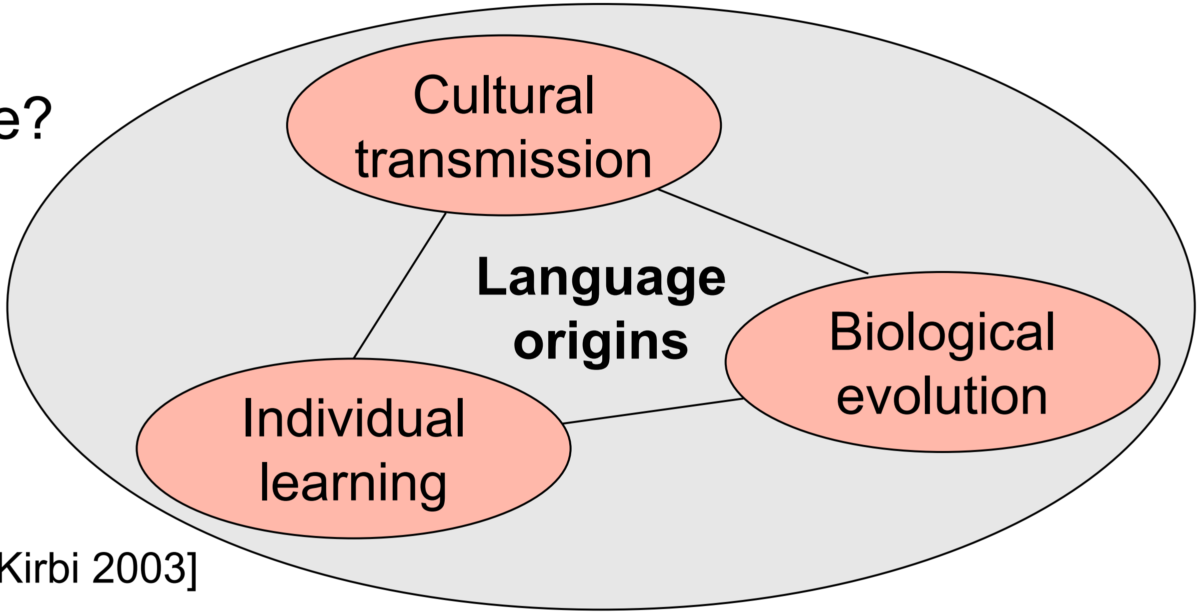
- ***Communication***: The execution of a behaviour that alters the behaviour of another individual (or individuals) that has evolved because it is beneficial to one or both individuals
- Most powerful communication system: ***Natural Language***
- ….but how does

  language emerge?

  in animals?

  in humans?

  in robots?



[Kirbi 2003]

Some Characteristics of Human Language

1. Is made up of signals which are arbitrarily connected to their meanings.
2. Has syntax and, more generally, its signals are made up of smaller signals.
3. Is culturally transmitted and culturally evolved.
4. Is also used to communicate with oneself (e.g. for reasoning) and not only with others.
5. Is particularly sophisticated for communicating information about the external environment.
6. Uses displaced signals.
7. Is intentional and requires recognition of intentions in others.
8. Is the product of a complex nervous system.
9. Influences human cognition.

[Parisi 2010, based on: Hockett 1960]

Communication with Human Language

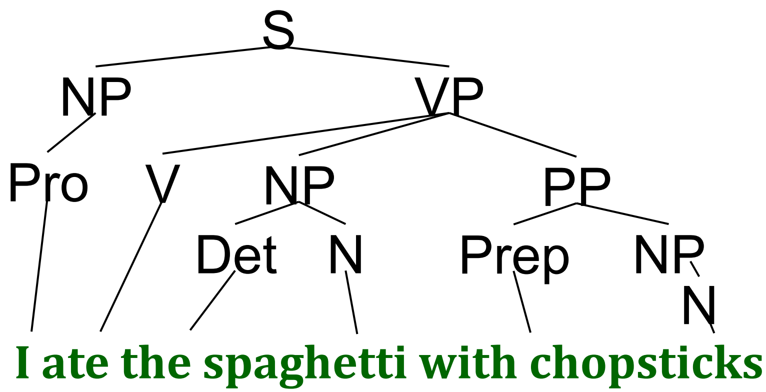
- ***Communication*** in humans is ***complex***
- Computer systems can be created to use and understand communication
- Linguistics and Computerlinguistics aim to ***model*** and understand human language capabilities
- Different ***Parts Of Speech***
  - Annotate each word in a sentence with a part-of-speech.

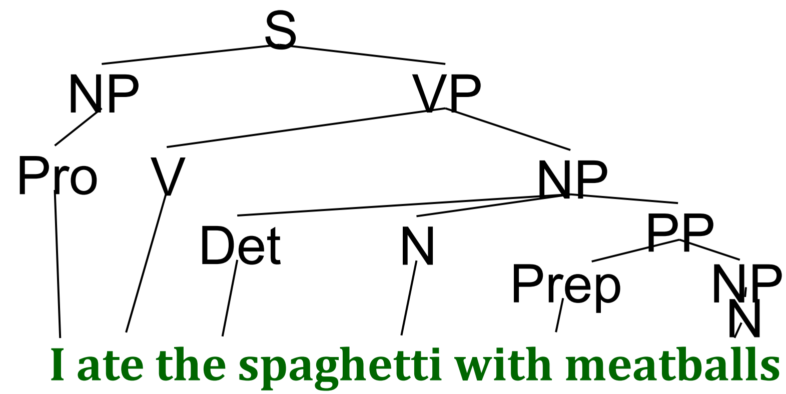
    I ate the spaghetti with meatballs.
    Pro V Det N Prep N

    John saw the saw and decided to take it to the table.
    PN V Det N Con V Part V Pro Prep Det N
  - Useful for subsequent syntactic parsing and word sense disambiguation. Note the ambiguities above.

Linguistics: Syntax and Semantics

- Produce the correct ***syntactic*** parse tree for a sentence.





- For each clause, determine the ***semantic*** role played by each noun phrase that is an argument to the verb.

John drove Mary from Austin to Dallas in his Toyota Prius.

The hammer broke the window.

---

agent *patient* *source* *destination* *instrument*

Position does not determine semantic roles

- Also referred to a “case role analysis,” “thematic analysis,” and “shallow semantic parsing”

Theoretical Aspects of Cooperation

- Cooperation: Several agents work together for a common or mutual benefit
  - Solve problems much ***more efficient***
  - Solve problems that cannot be solved alone
- Cooperation needs communication
  - Inform about ***states***
  - Coordinate ***goals*** and tasks
- Cooperation can be unilateral
  - Agents can ***defect*** or “betray”
  - Agents can act ***altruistic*** on purpose
  - Different behaviours are differently evolutionary stable
    - Axelrod (1995): “Reciprocity is a sufficient basis for cooperation”

Reciprocal Altruism

- Individual makes sacrifices for another individual in expectation of similar treatment [Trivers 1971]
- Different paradigms:
  - Connected with ***kinship relations***: altruistic cooperation still serves genes, if a close relatative survives
  - ***Egoism***: altruistic behaviour serves the individual directly

    Example: Birds alarm each other if they spot a predator
    - Apparent benefit: help each other
    - Real benefit: Make other birds to stick to the alarming one => the alarming bird is covered by other potential victims
  - Connected with ***higher-level non-altruistic*** behaviour: Help other individuals to make them helpful at more important aspects (social contracts)

Evolutionary Emergence of Communication

- Basic research of emergence of communication investigates
  - How communication can ***emerge*** and evolve from situated embodied interaction?
  - How **communication and behaviour** evolve and co-adapt?

- Core question:
  - Whether and how honest communication can emerge despite the problems caused by the **conflict of interests between individuals**?
  - Whether and how communication can emerge and evolve despite the need to concurrently **develop behavior**?

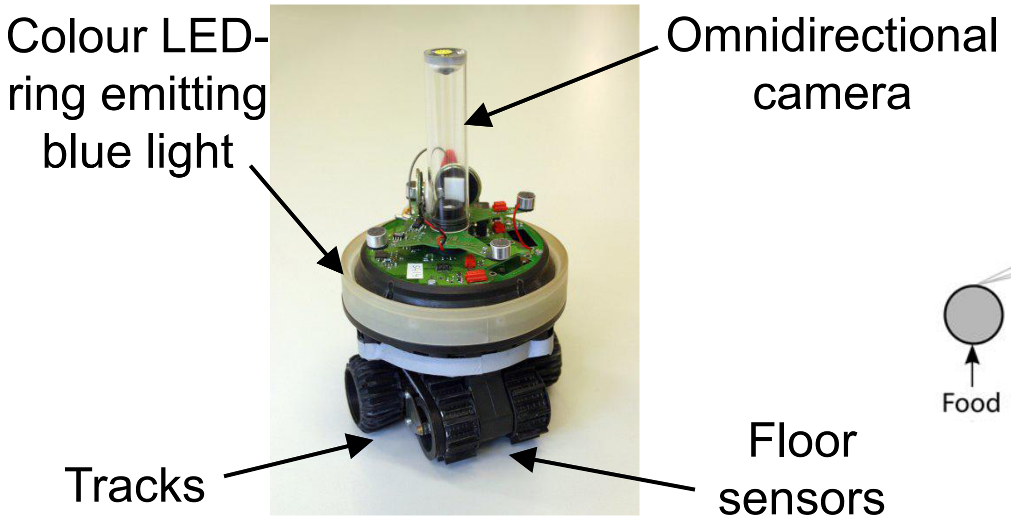
Adaptive Methods

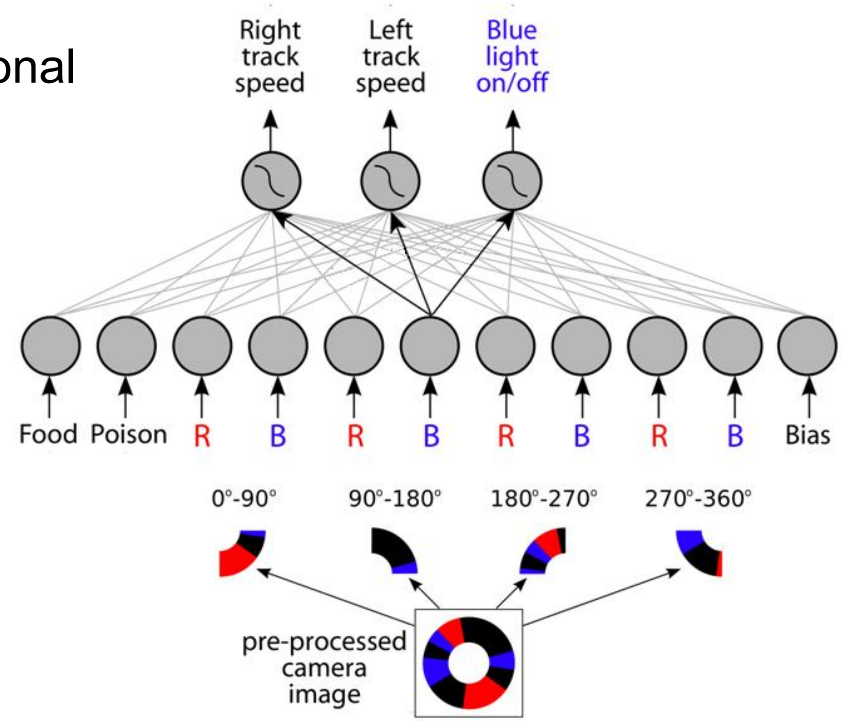
- General Framework: ***Embodied Cognition***
- Use design methods, which are based on a self-organising process:
  - Agents develop the skills ***autonomously***
  - Interactions characteristics varied in the ***adaptation process***
  - Variations are ***retained*** based on effects at the level of the global behaviour of the agents
- Methods which meet these characteristics:
  - Evolutionary Algorithms
  - Simulated annealing
  - Reinforcement learning

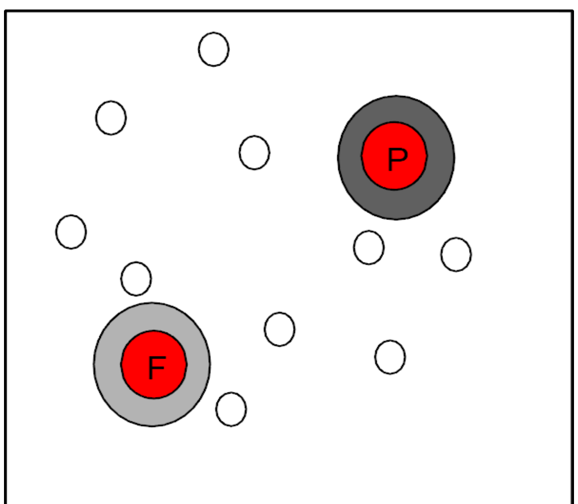
Evaluation Criteria

- Adaptive Role:
  - Emergence of a communication system?
  - Has communication enhanced the agents' adaptive capabilities?
- Expressive Power and Organisational Complexity
  - Shape and intensity of the signalling
  - Developed protocol/set of rules for signal exchange
- Stability, Robustness and Evolvability
  - Successful development in terms of evolutionary stability

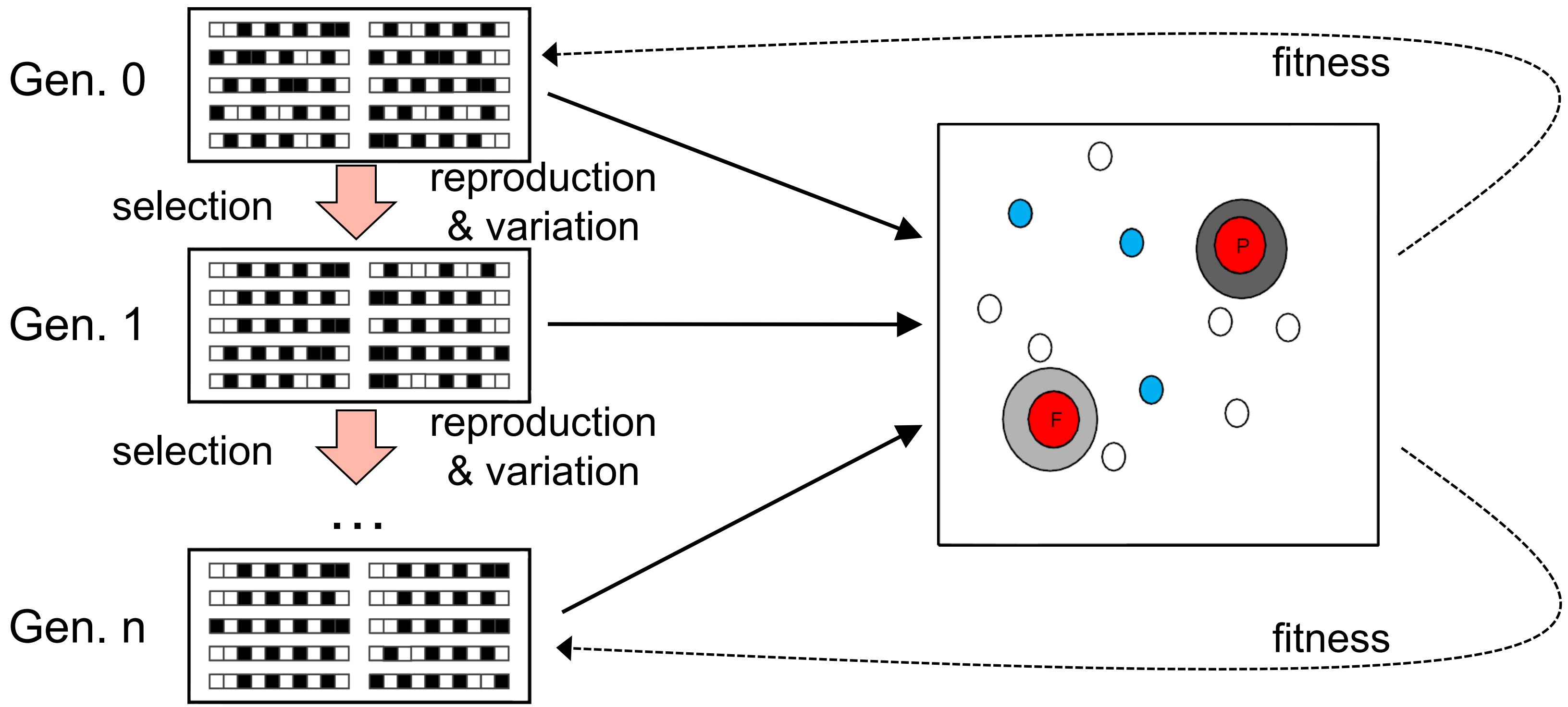
Food/Poison Foraging Experiment [Floreano et al. 2007]







Neural Controller Weights as Genomes: weight as 8 bits x 10 inputs x 3 output neurons

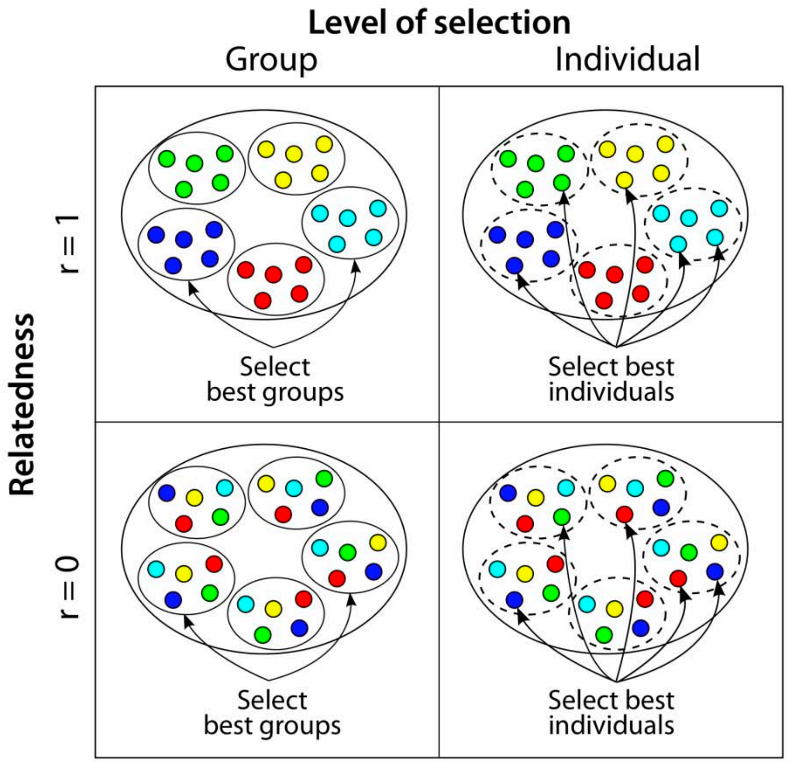


- ***Fitness***: robots are scored with 1 point for each time step passed near the food source
- ***Conflict of interests***: competitive selection & limitation in the number of foraging individuals; agents also can defect

Level of Selection and Kin-Relation

No Light:
Robots are not allowed to produce blue light

Light:
Robots are allowed to produce blue light



Relateness = 1:
Group are formed by highly related (identical) individuals

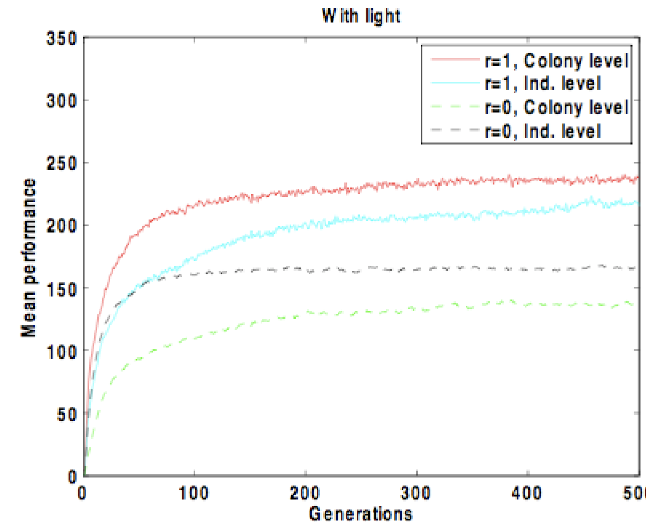
Relateness = 0:
Group are formed by non-related individuals

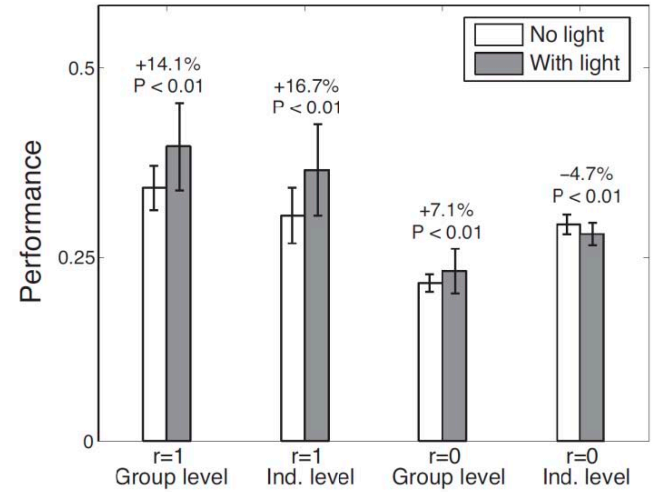
Group Selection:
Group are formed by related individuals

Individuals Selection:
The best individuals are selected independently from the group they belong to

Results

- For all conditions: robots evolved ability to forage
- Communicating (light- emitting) outperform non-communicating robots *(in 75% of cases)*
- Best performance:
  - Related individuals
  - Selection at group level
- No advantage with communication:
  - Low-related individuals
  - Individual-level selection

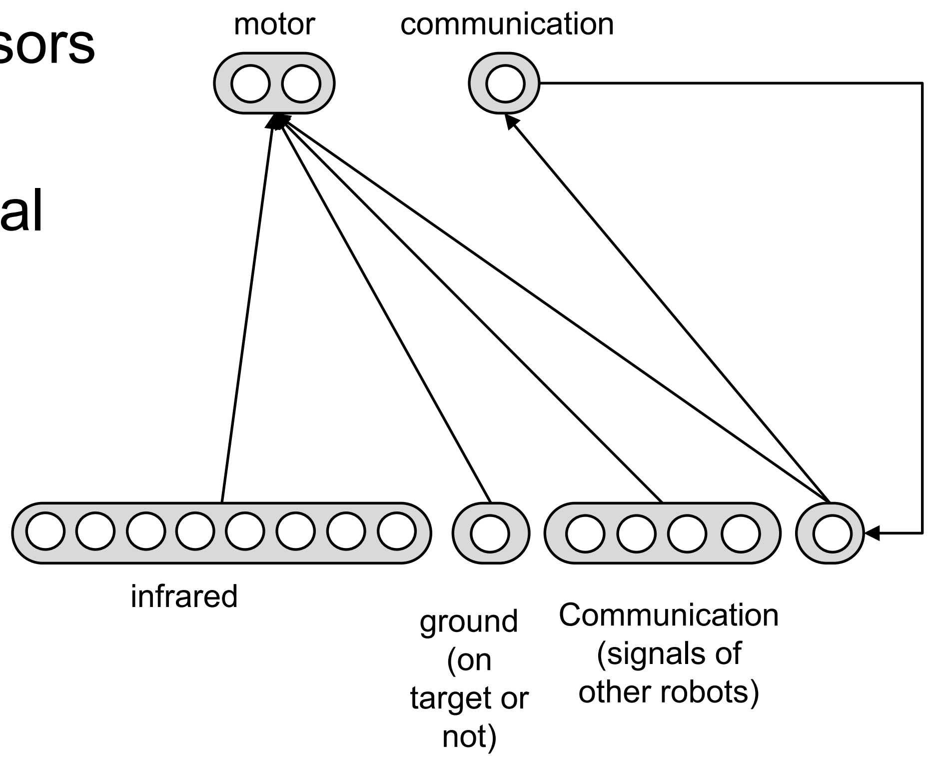




Cooperative Signalling Strategy

Collective Navigation Experiment [Marocco 2007]

- Simulated robot:
  - 11 cm circular body
  - 8 infrared, 1 ground sensor
  - 4 communication sensors
  - 2 wheels
  - 1 communication signal



Output of the motor neurons:

$$O_j = \frac{1}{1+e^{-A_j}}$$

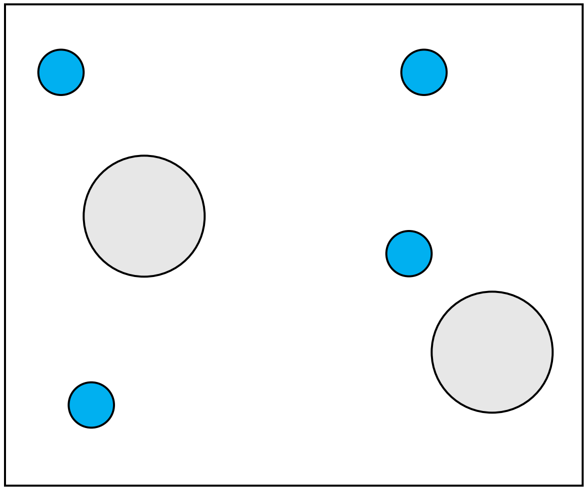
$$A_j = t_j + \sum_i w_{ij} O_i$$

Bias of *j*th neuron

Activity of the neurons

Scenario and Emergence of Communication

- Four simulated ***reactive robots*** situated in a square arena with two circular target areas
- 100 randomly generated genotypes for neural controllers over 100 generations



- Motor actions can be determined only on the basis of
  - The current sensory state
  - The copy of the communication neuron at the time $t - 1$
- Communication is represented as value between 0.0 and 1.0

- ***Fitness****:* robots score points if in target area but score costs if maximum number of two exceeded

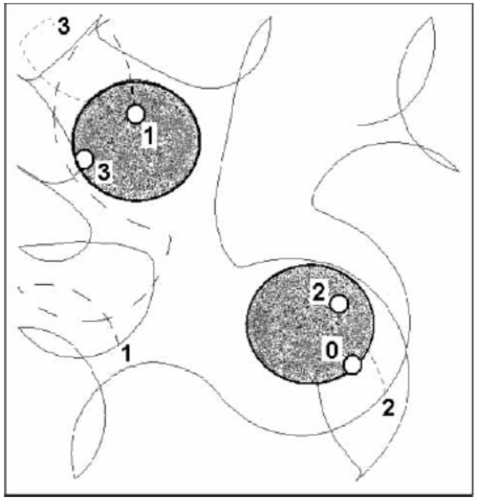
The Evolved Communication System

- Robots evolved to move onto target sites in pairs and ***developed different signals***:
  a) one robot outside target
  b) single robot in target area
  c) robot in target with another robot
  d) robot approaching target, interacting with robot inside.

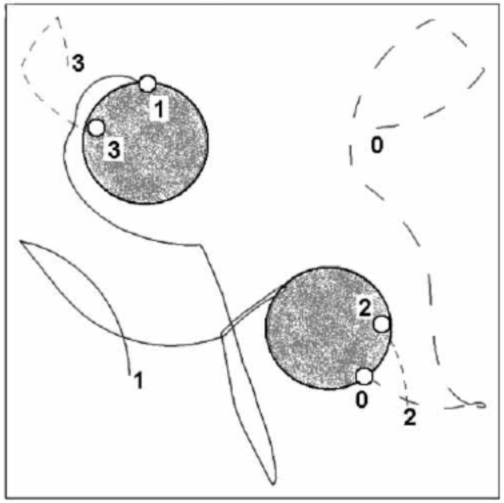
Controller gets additional recurrent state neurons

e.g. robot in target area hearing signal c would exit

e.g. robot outside target hearing signal b, would approach target + signal d.



Reactive robots

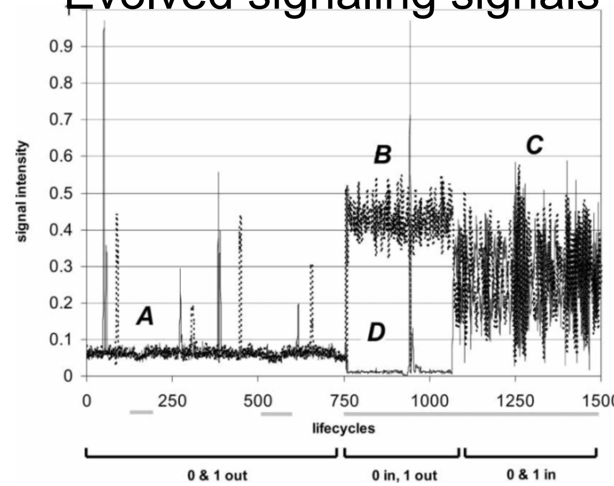


Non-reactive robots

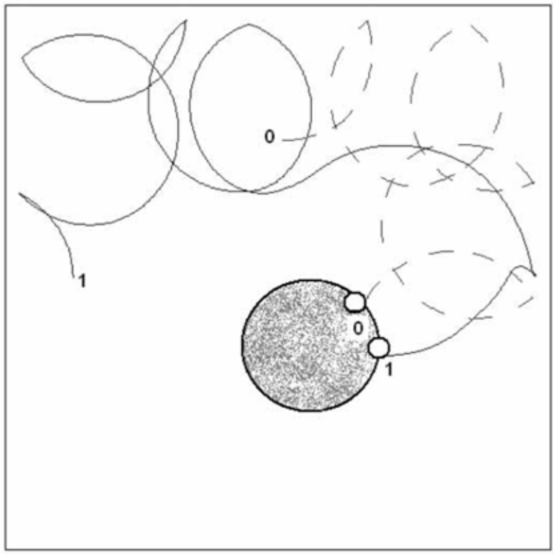
Evolved Communication Modalities

- Mono-directional communication:
  - ***Information exchange***: ‘hearer’ access information of the ‘speaker’
  - ***Manipulation***: ‘speaker’ alters the behaviour of the ‘hearer’

Evolved signaling signals

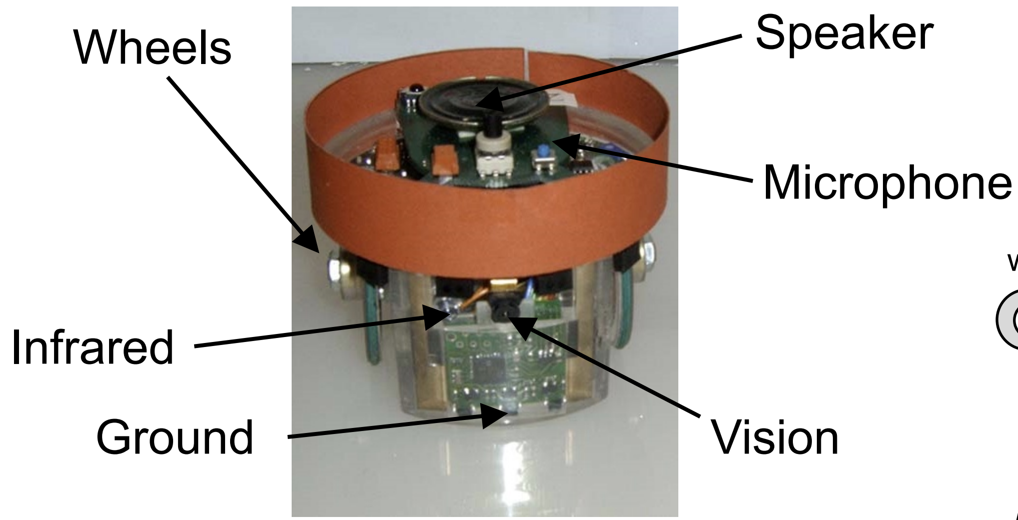


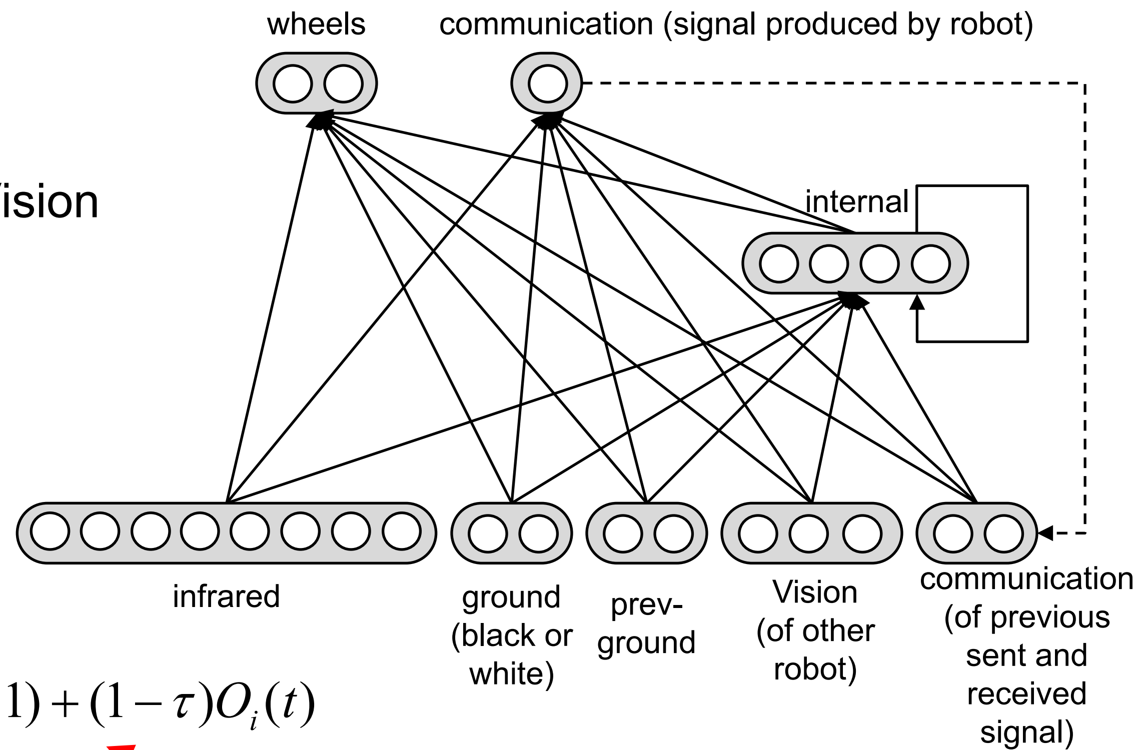
- Bi-directional communication:
  - Motor or signalling behaviour of one individual affects the second individual and vice versa



Typical motor behaviour of two robots.

The Target Switching Experiment [De Greef 2010]





Output of the motor neurons:

$$O_j(t) = \sigma\left(\sum_i w_{ij} I_i(t) + \beta_j\right)$$

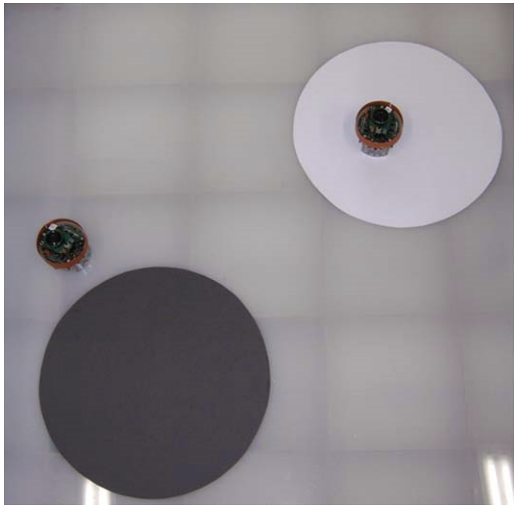
$$\sigma(z) = \frac{1}{1+e^{-z}} \qquad O_i(t) = \tau O_i(t-1) + (1-\tau) O_i(t)$$

Sigmoid function

Output of internal neurons

Scenario and Evolution

- Two robots situated in an arena with two target areas
- Population of 100 pairs of two robots for 1000 generations
- Perception allows the development of different modalities:
  - Radio
  - Vision
  - Infrared

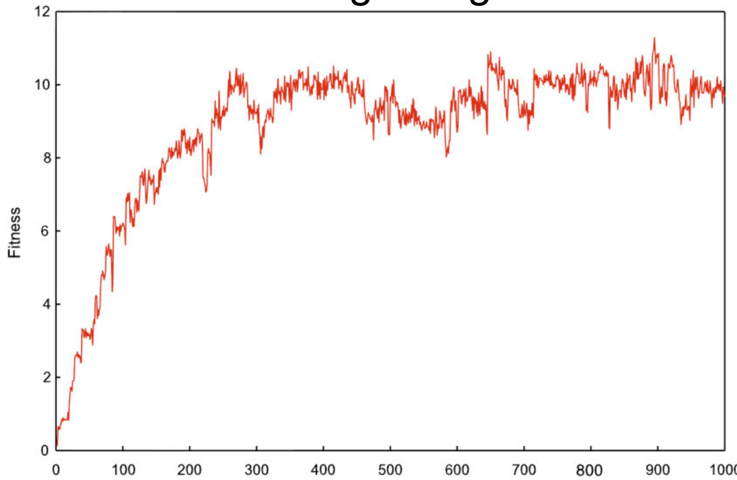


- ***Fitness**:* the two robots score points <u>every time </u>they occupy the two different areas; and die immediately at collisions

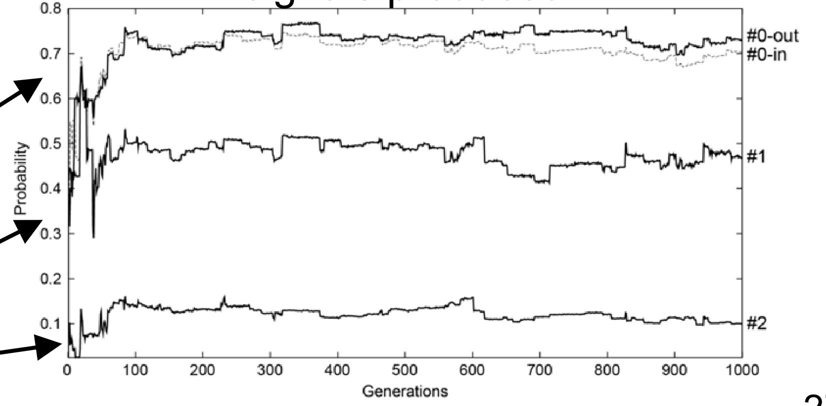
Results

- Robot exploit ***explicit*** communication to coordinate and cooperate
- Robots rely on ***implicit*** communication in most cases
- Evolved different strategies:
  - Symmetrical / Simultaneous
  - Asymmetrical

Fitness throughout generations



Average value of the explicit signals produced

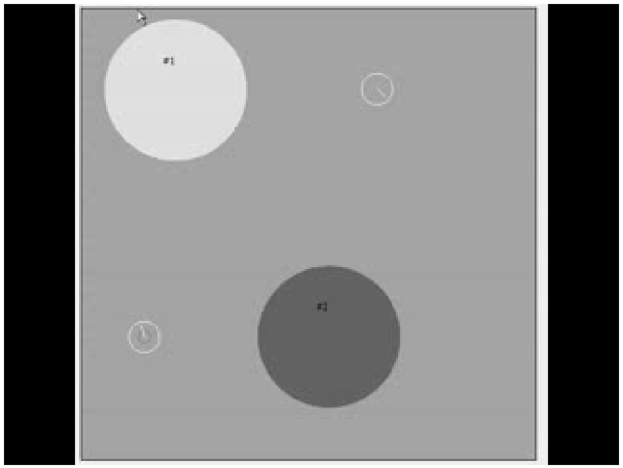


Robots outside target areas

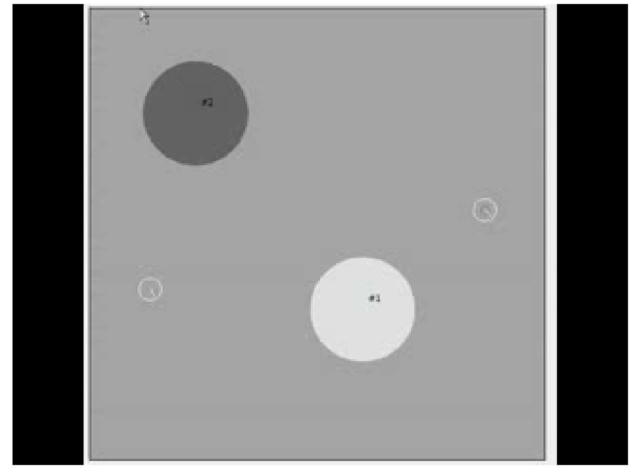
Robots in target area #1

Robots in target area #2

Illustration of the Evolved Solutions



Simulation, symmetrical strategy

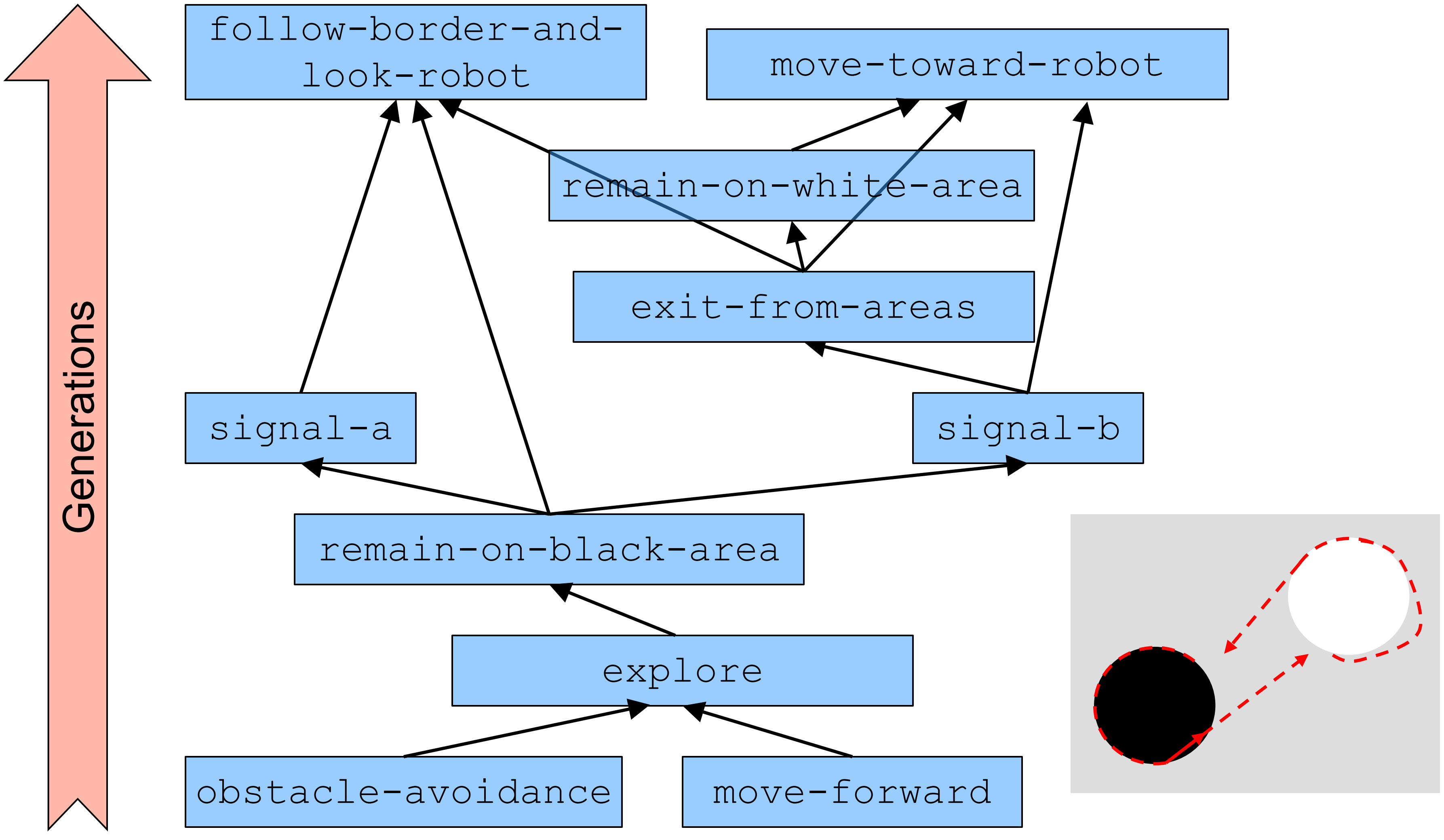


Simulation, asymmetrical strategy

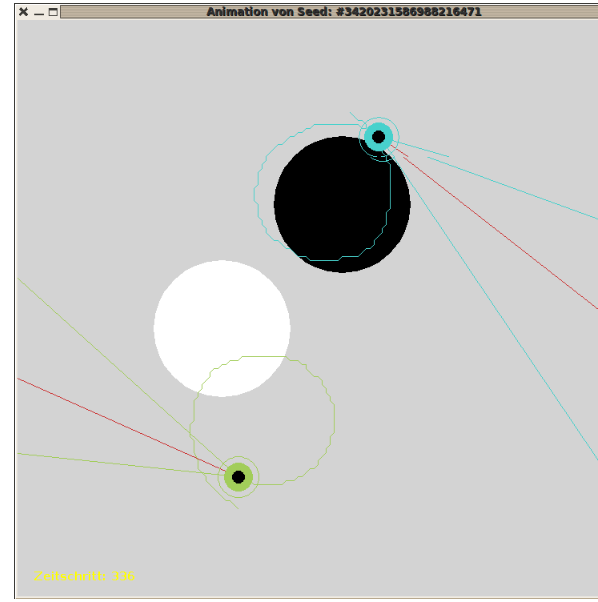
Real environment, symmetrical strategy

Real environment, asymmetrical strategy

Analysis of the Evolutionary Process



WTM BSc Project Re-Implementation



- Close to original experiments
- Few changes:
  - ***Improved fitness function***
    - Collision not fatal, only punished
    - Added cumulative distance
  - ***Increased vision*** capabilities
    - Distance sensor array (5 forward rays)
    - Agents can produce and sense visible signal (“blinking”)
- Question: Is visual or audio communication preferred?
- Results: Almost no communication, simple circling motion through environment which included both areas
- Reason? ⇨ Evolution favors simple solutions

From Communication to Evolution of Language

- Efficient communication requires tight **co-evolution** between
  - the signal emitted
  - the response elicited

- Main Goals for Embodied Language Agents
  - To get language robots beyond simple single word commands and more sophisticated language processing
  - To get speech language interfaces embodied
  - Grounding actors in real world may provide the context
  - Context matters a lot when learning language and concepts

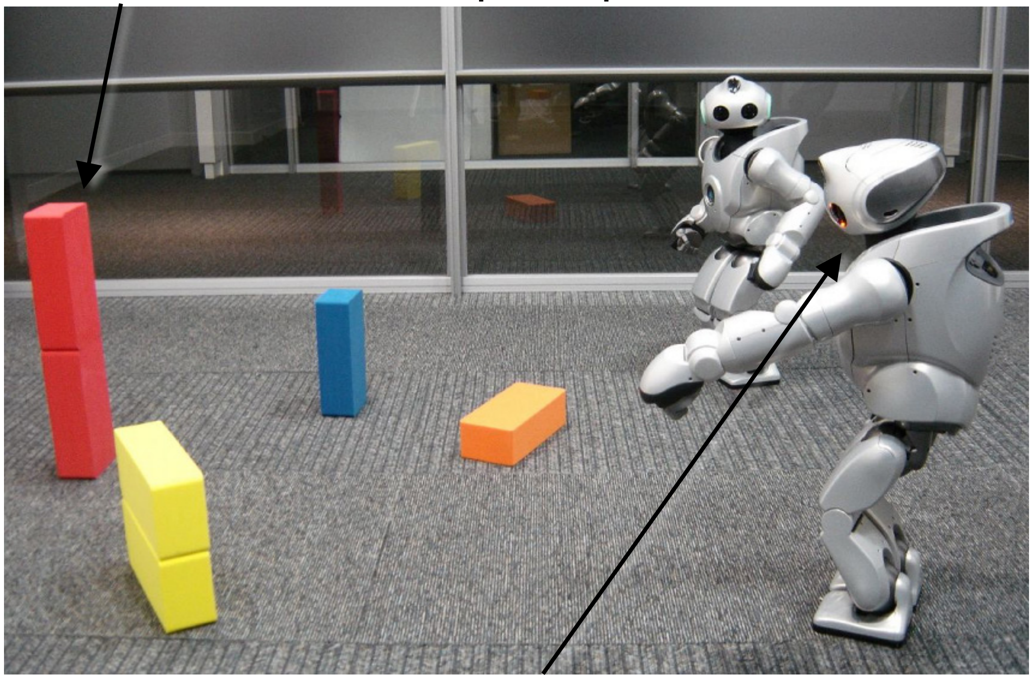
Evolution and Formation of Language

The Grounded Naming Game Experiment [Steels]

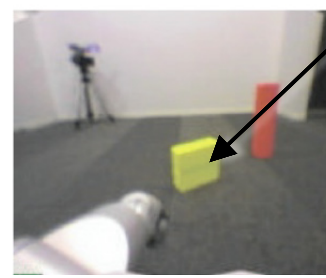
[2002]

World is a collection of objects with
features: colours, shape, & position

[2010]



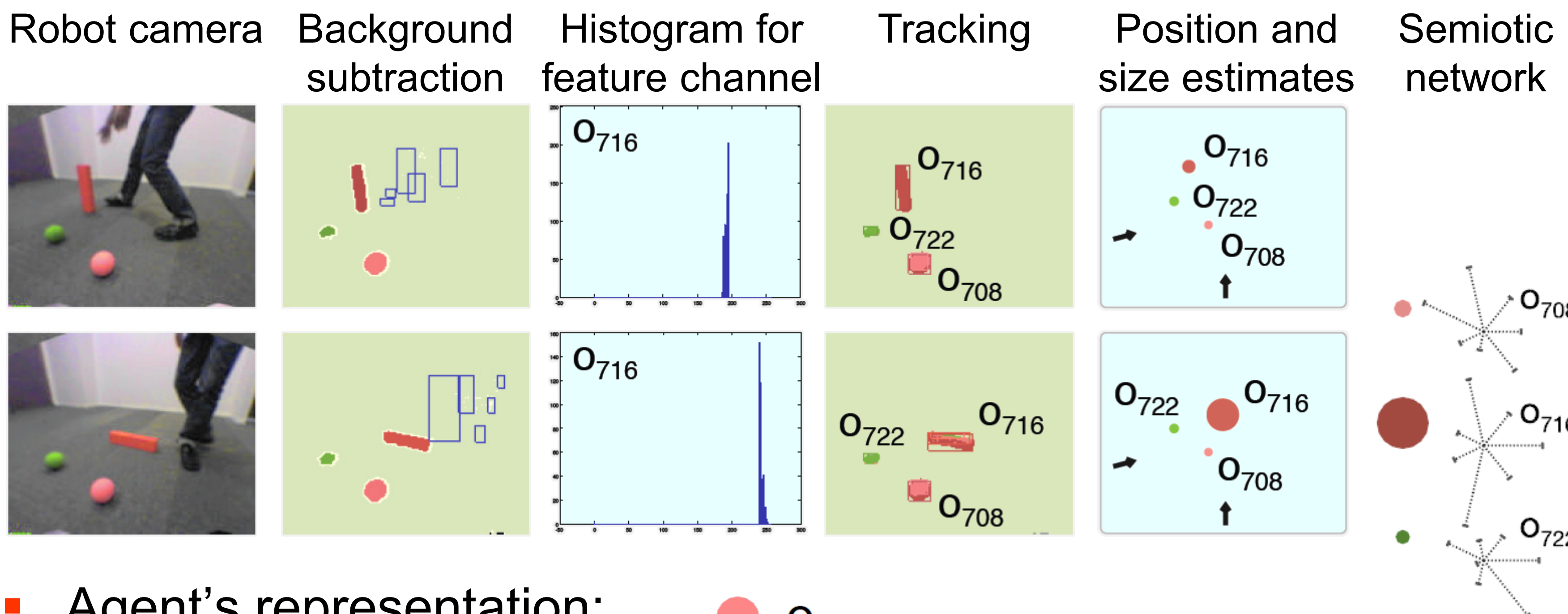
Agents perceive world from own perspective
& want to create a ***set of meanings***



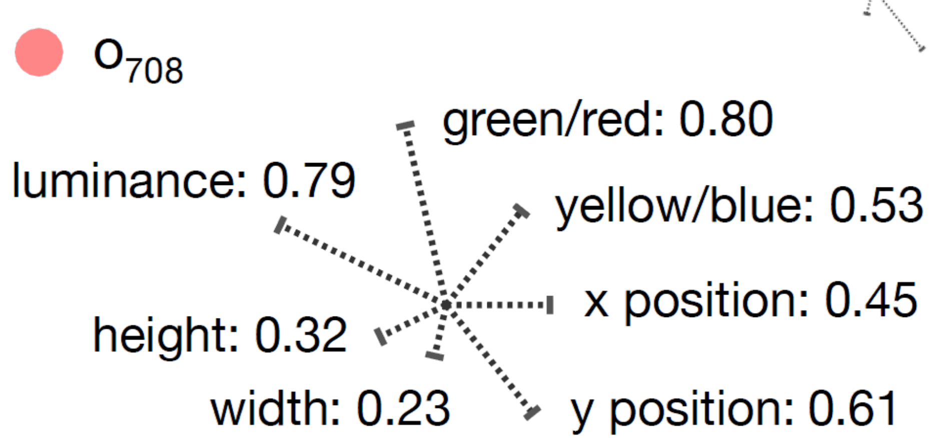
The ***category*** of every object is the region represented by its nearest prototype

An object is ***discriminated*** if its category is different from all others in the context

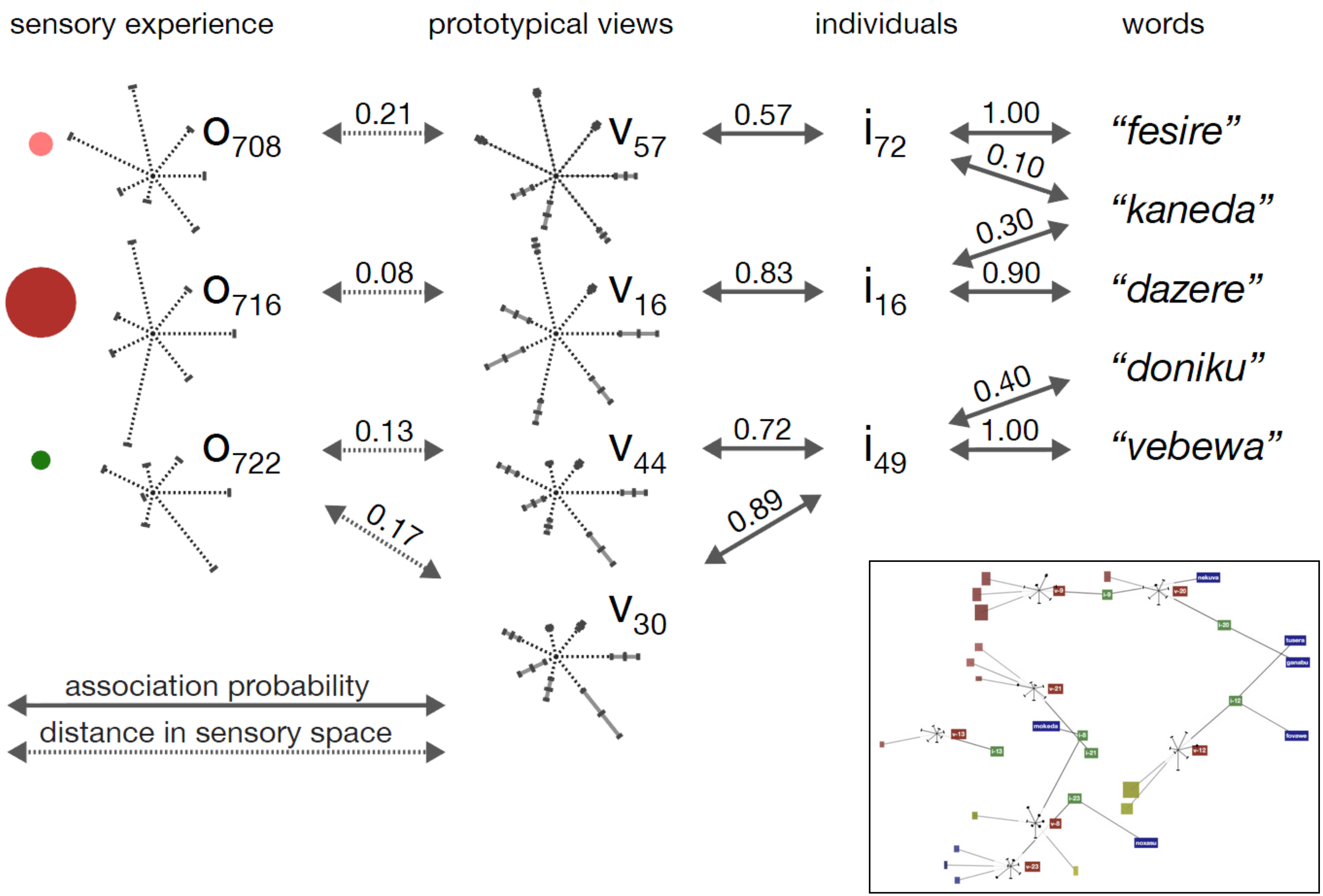
From Sensori-Motor Experience to Concepts



- Agent's representation: ***Semiotic networks*** of concepts
  - Weighted features f
  - Dynamic
  - Initially empty



Semiotic Networks

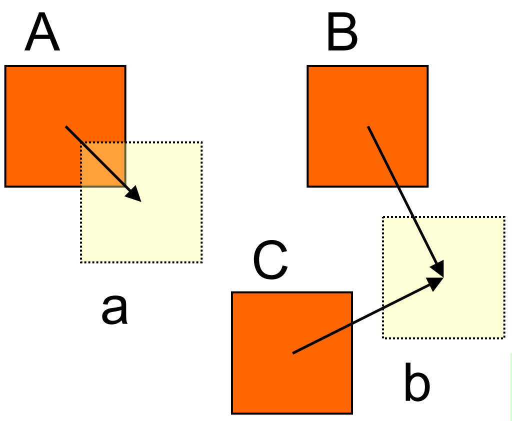


Game Step 1: Discrimination

- If discrimination of the topic fails:
  - Add new prototype that corresponds to exactly that topic
- If discrimination of the topic succeeds:
  - Shift prototype slightly so that it moves closer to the topic
- Simplified **Example**:

Context:
A=(0.1, 0.3)
B=(0.3, 0.3)
C=(0.25, 0.15)

Agent's Prototypes:
a=(0.15, 0.25)
b=(0.35, 0.3)



A is discriminated
B and **C** are not

A is categorised as **a**
B is categorised as **b**
C is categorised as **b**

Discrimination: The Evolutionary Process

- Agents are kept, but adapt over time
  - No children, no decease
  - ***Fitness function*** is replayed by ***adaptation function***
  - ⇨ Often called ***cultural evolution***, sometimes *learning*

Prototype feature values: $$f_i(v_t) = \alpha \cdot f_i(v_{t-1}) + \left(1-\alpha\right) \cdot f_i(e)$$

Prototypical view

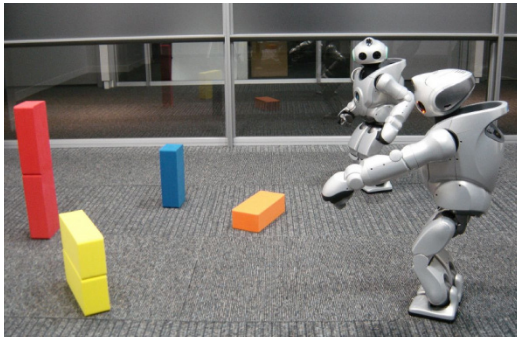
stability factor

Sensory experience

Variance: $$\sigma(f_i(v_t)) = \alpha \cdot \left(\sigma(f_i(v_{t-1})) + \left(f_i(v_t) - f_i(v_{t-1})\right)^2\right) + \left(1-\alpha\right) \cdot \left(f_i(e) - f_i(v_t)\right)^2$$

Game Step 2: The Language Game

- If discrimination succeeds, the ***distinctive category*** is used to play a ***language game***
- In some sense, the distinctive category is *the meaning that will be communicated*



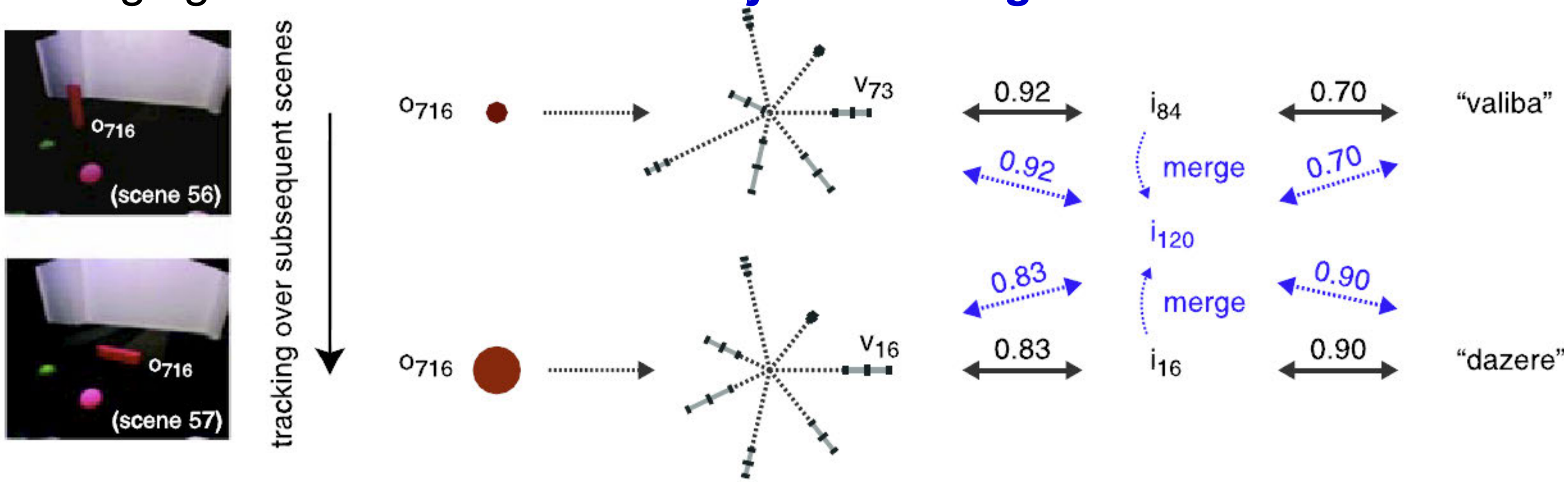
- The lexicon is a set of meaning-word pairs with an association score (between 0 and 1)
- Language game: speakers use a word to refer to the topic (possibly by invention) and hearers try to interpret that word
- Different game types possible
  - ***Guessing game***,
  - Observational game, …

Language Guessing Game

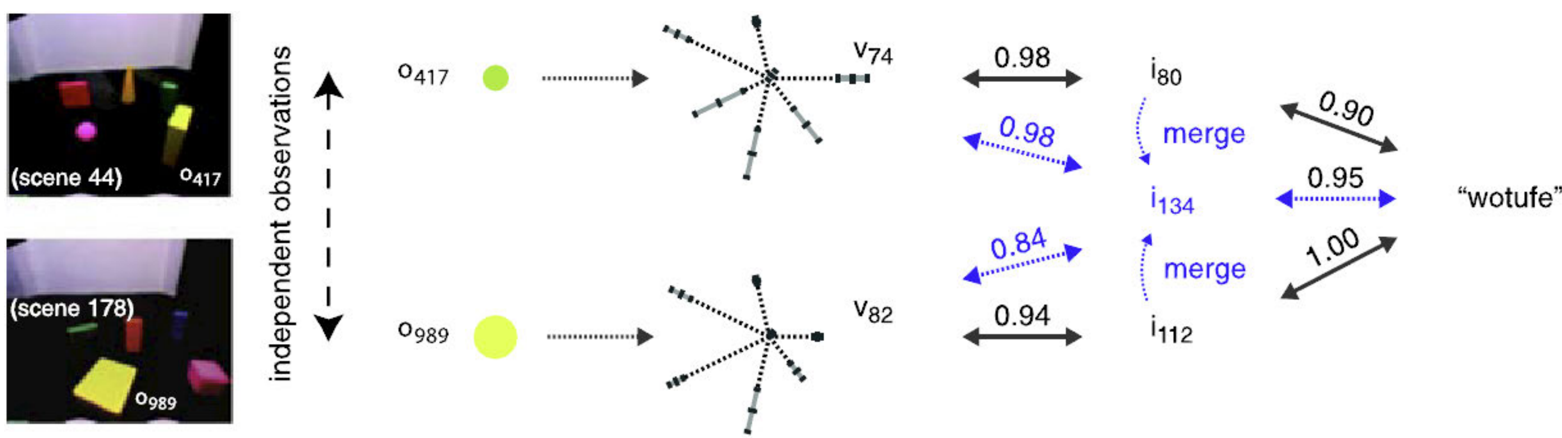
1. Hearers try and guess the topic
   - Looks at all discriminated objects as possible topics
   - Looks for association between each possible topic and speakers word
   - Select one with highest score
2. Speakers provide corrective feedback
   - Yes, that's the topic
   - No, that's not the topic: and indicate the correct one
3. Both speaker and hearer adjust lexicon
   - Speaker:
     - Success: increase association, and laterally inhibit other associations
     - Failure: decrease association
   - Hearer:
     - Success : increase association, and laterally inhibit other associations
     - Failure to guess correct topic: decrease association, and increase association with correct topic
     - Failure to understand word: add word

Adjusting Lexicon: Establishing Object Identity

Changing environment: Use the ***object tracking*** heuristic

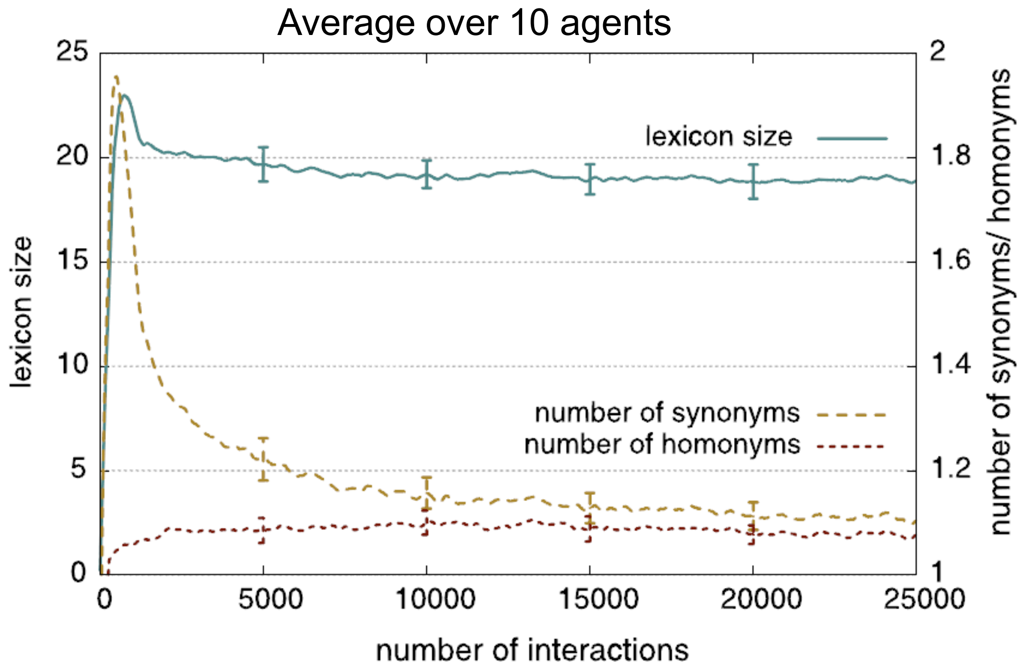


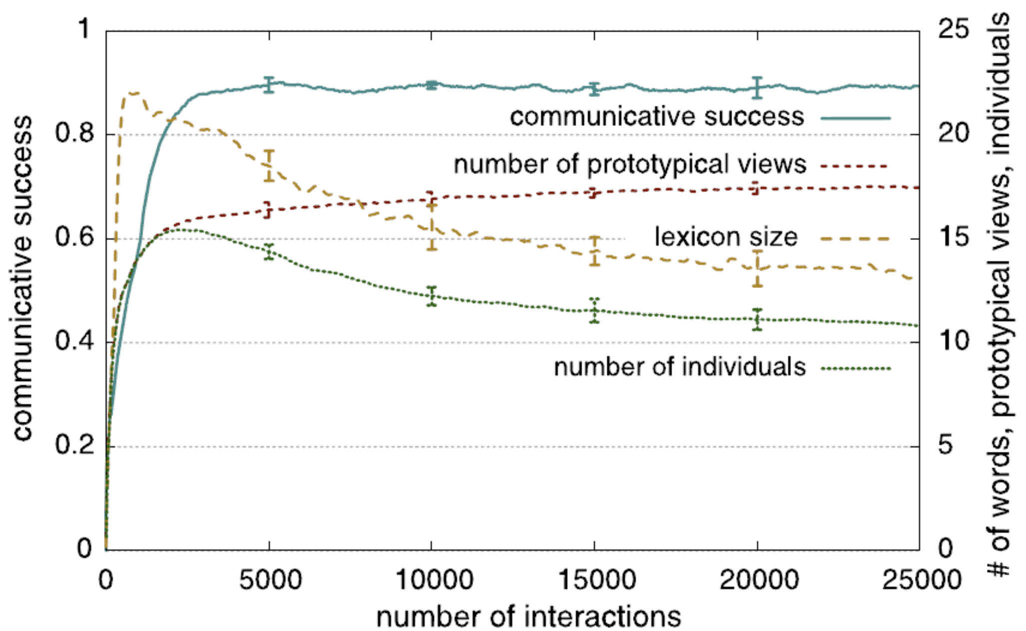
Differing opinion among two agents: Use the ***same name*** heuristic



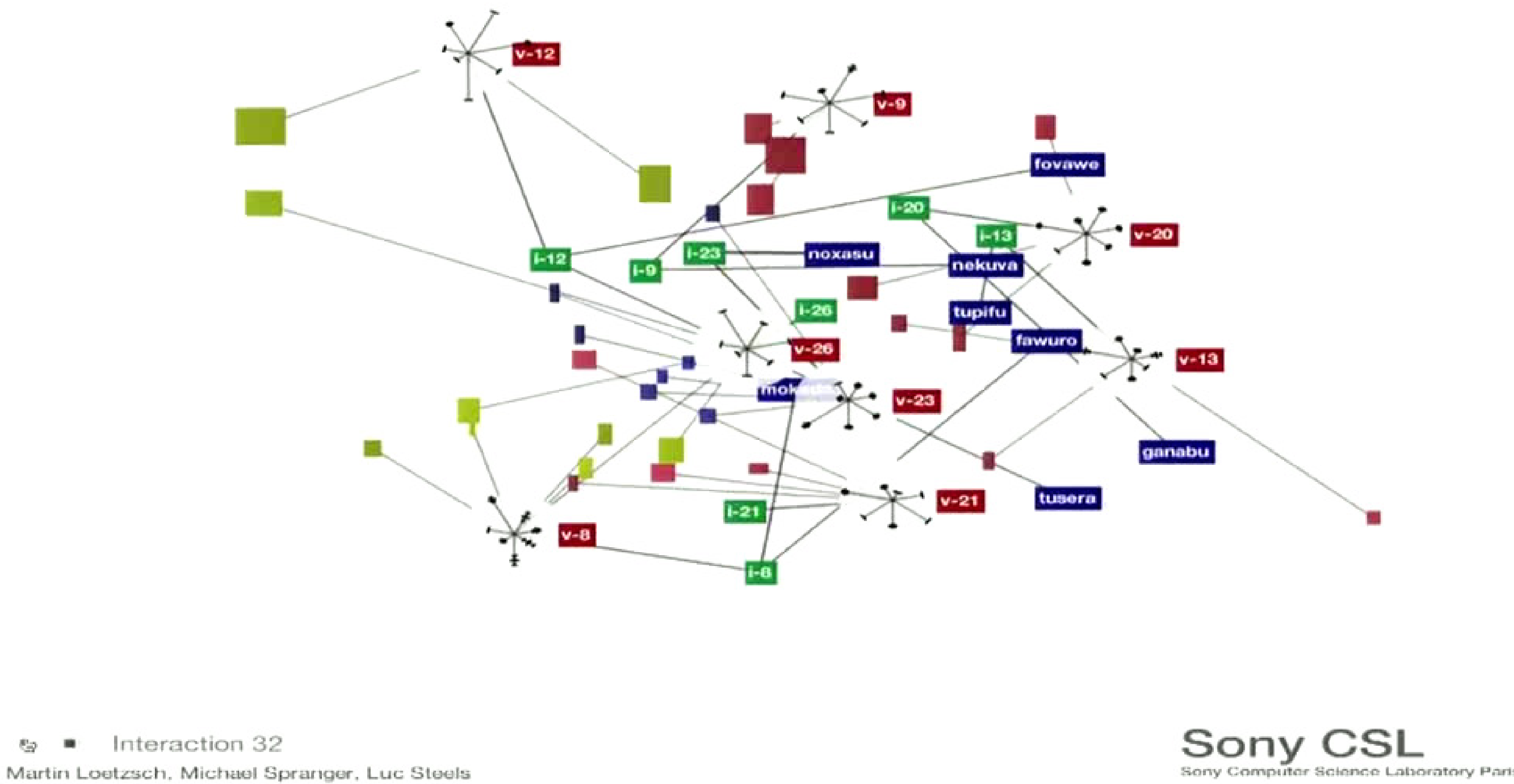
Results

- Lexicon:
  - Agents create words independently
  - Interaction between random agents decreases number of synonyms
- Communication success:
  - Agents quickly find common words
  - Heuristics help to drastically reduce the lexicon size
  - Prototypical views are constantly optimised





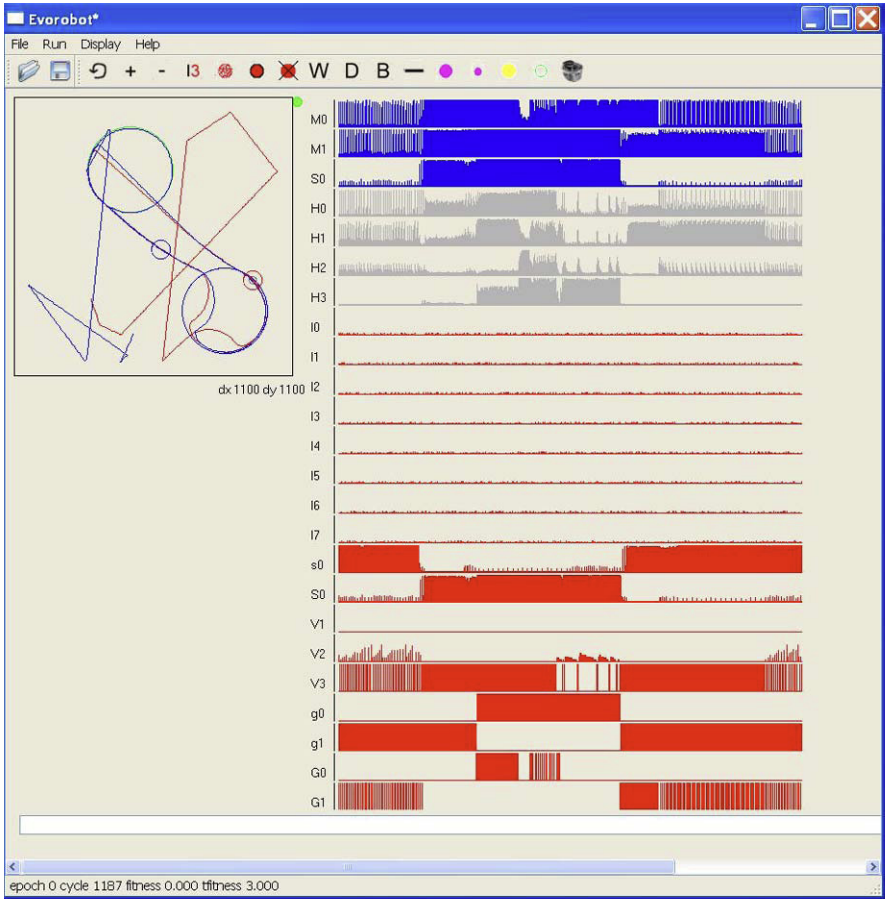
Semiotic Networks Evolution



Evolution of the internal semiotic networks of a single agent

Software tool: Evorobot

- Software for experiments on
  - Collective behaviour
  - Communication
- Features:
  - Robot models based on e-puck platform
  - Evolutionary algorithm module
  - Neural Network simulator



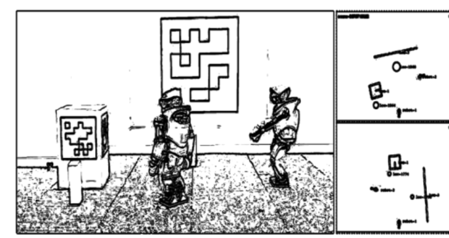
[Stefano Nolfi & Onofrio Gigliotta]

http://laral.istc.cnr.it

Software tool: BABEL2

- Framework for
  - Language formation experiments
  - Language dynamics

- Features
  - Computational framework for exploring fluid construction grammar
  - Allows for representing and processing semantic structures that underlie compositional grammatical utterances
  - Provides embodied multi-robot interaction mechanisms
    and their monitoring



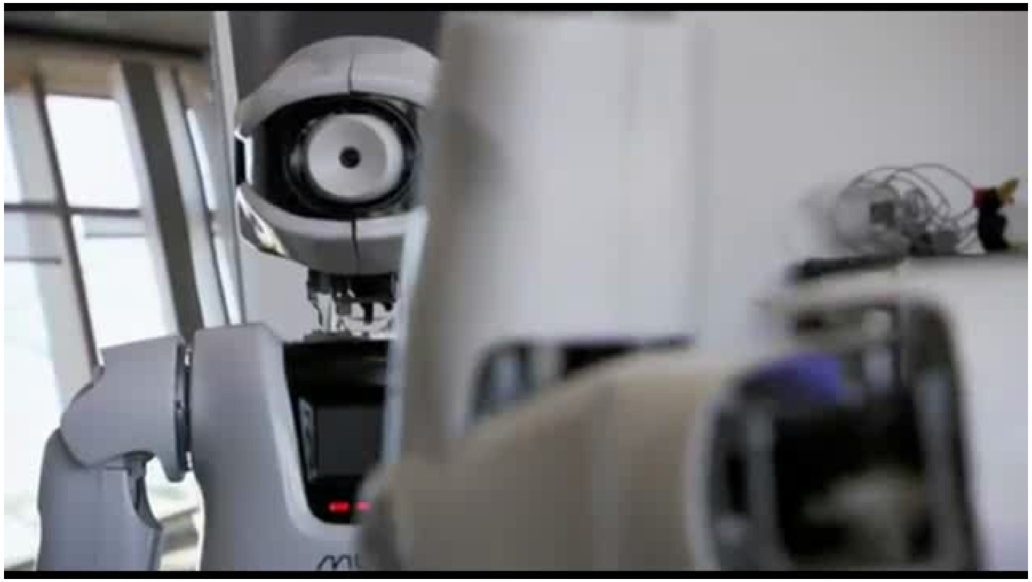
http://emergent-languages.org/Babel2/

Summary

- Research in emergence of communication and language can
  - Advance our knowledge about how communication and language can develop and evolve in active organism
  - Advance our ability to develop useful artefacts that can cooperate in the physical environment
- Methods like ***Evolutionary Algorithms***, ***Simulated Annealing*** and ***Reinforcement Learning*** allow for
  - exploiting properties emerging from the interactions between lower-level properties.
- Models using ***Cultural Evolution*** can demonstrate
  - how a symbolic communication system can emerge in situated embodied interactions between autonomous agents

Closing Outlook

Interaction of humanoid robots:
The grounded naming game in actions.



- Further readings:
  - Lyon, C., Nehaniv, C.L., Cangelosi, A., editors. Emergence of Communication and Language. Springer London, 2007. online available
  - Nolfi, S., Mirolli, M., editors. Evolution of Communication and Language in Embodied Agents. Springer Berlin, 2010. online available