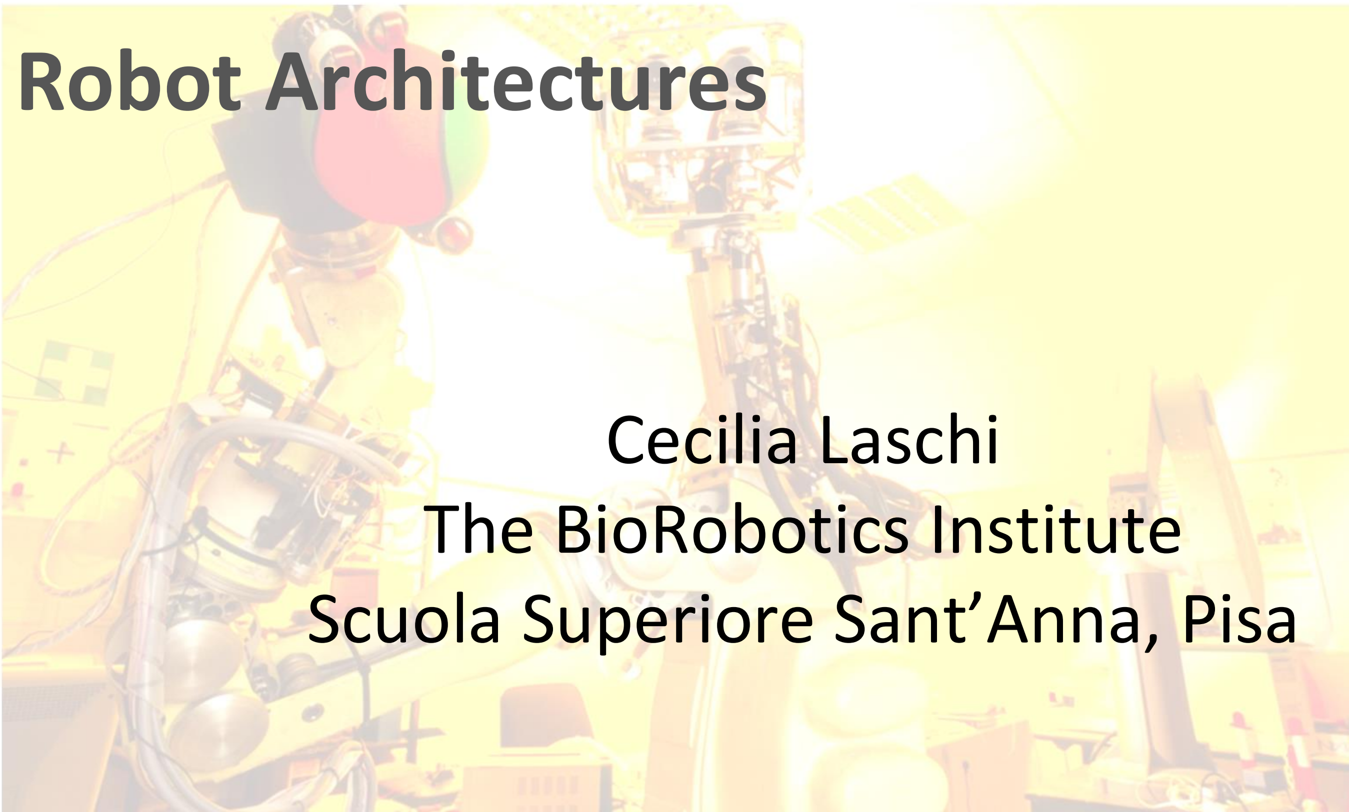
University of Pisa

Master of Science in Computer Science

Course of Robotics (ROB)

A.Y. 2016/17



Robot Architectures

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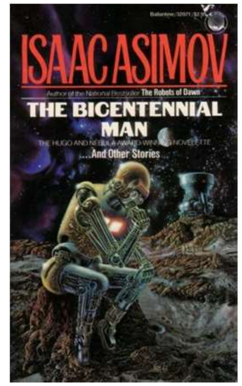

Industrial robotics:
birth and growth of theories and techniques for robot control

→

Service robotics:
birth and growth of theories and techniques for robot **behaviour** (perception & action) control

Structured environment

Unstructured environment

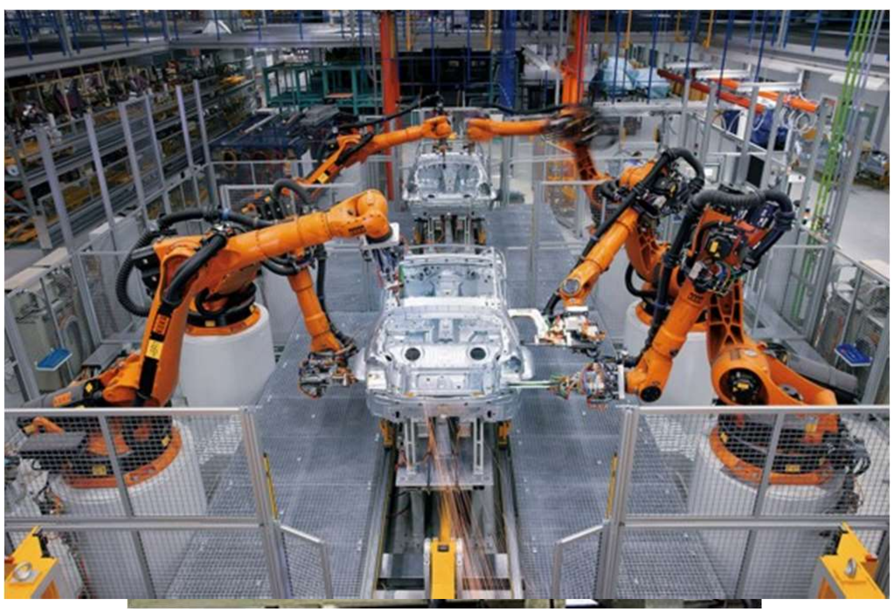

Photo: Center for Robot-Assisted Search and Rescue

Definition of *intelligent robot*

- *"A mechanical creature which can function autonomously"*
- 'Function autonomously' means that the robot can operate, self-contained, under all reasonable conditions without requiring recourse to a human operator.
- Autonomy means that a robot can adapt to changes in its environment (the lights get turned off) oritself (a part breaks) and continue to reach its goal.
- *Unstructured environments*
- Technological challenges:
  dynamically planning the robot behaviour in an unknown and variabale environment, in order to achieve a given task

↓

Control of robot behaviour

R. Murphy, *Introduction to AI Robotics*, MIT Press, 2000

The robotic paradigms

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- *"A paradigm is a philosophy or set of assumptions and/or techniques which characterize an approach to a class of problems"*
- No one paradigm is right; rather, some problems seem better suited for different approaches.
- Applying the right paradigm makes problem solving easier.

The robotic paradigms

- Traditionally, there are 3 main paradigms for facing the problem of controlling robot behaviour:
  - Hierarchial paradigm
  - Reactive paradigm
  - Hybrid paradigm

The robotic paradigms

The 3 paradigms can be described in 2 ways:

- By the relationships between the 3 commonly accepted primitives of robotics
- By the way sensory data is processed and distributed thorugh the system

The robotic paradigms

- The 3 paradigms differ in the way the commonly accepted primitives of robotics are organized
- the commonly accepted primitives of robotics are:
  - **SENSE**: takes information from the robot sensors and produces an output for other functions
  - **PLAN**: takes information from the SENSE or from a world model and produces tasks for the robot
  - **ACT**: takes the tasks for PLAN and produces output commands for the robot actuators

The robotic paradigms

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Primitive functions

The robotic paradigms

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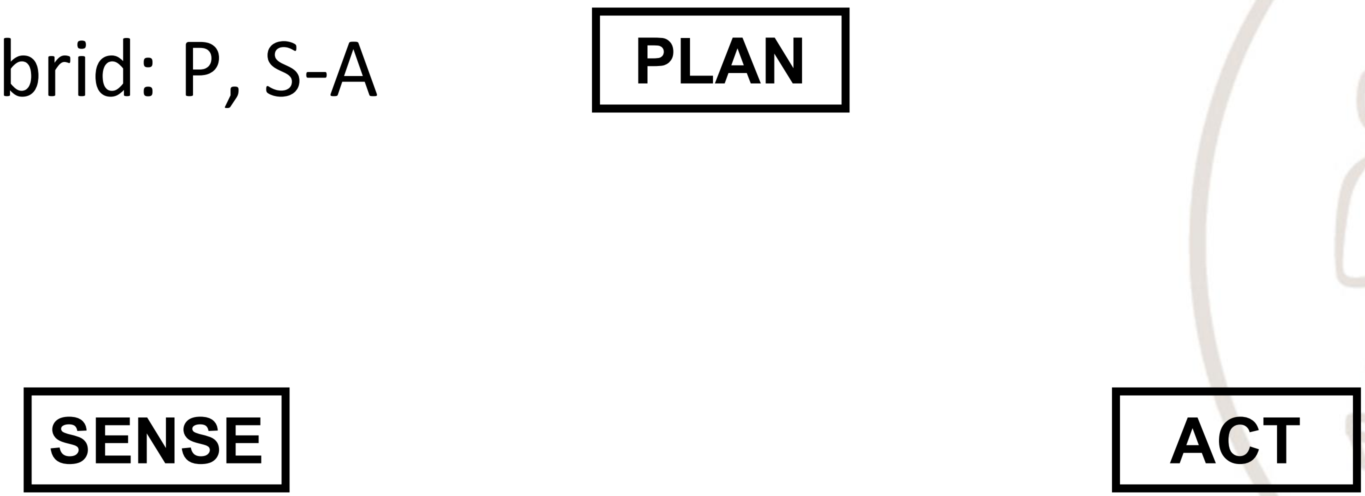
Information flow

ROBOT PRIMITIVES	INPUT	OUTPUT
SENSE	Sensor data	Sensed information
PLAN	Information (sensed and/or cognitive)	Directives
ACT	Sensed information or directives	Actuator commands

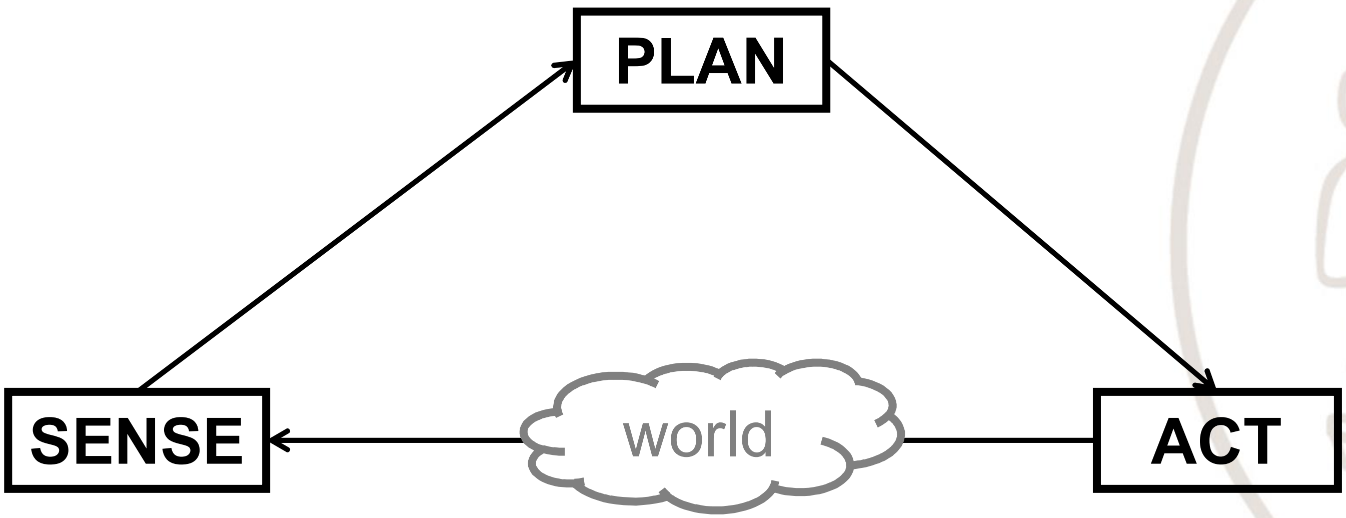
The robotic paradigms

- Hierarchical: S-P-A
- Reactive: S-A
- Hybrid: P, S-A



Hierarchical paradigm

S-P-A



Hierarchical paradigm

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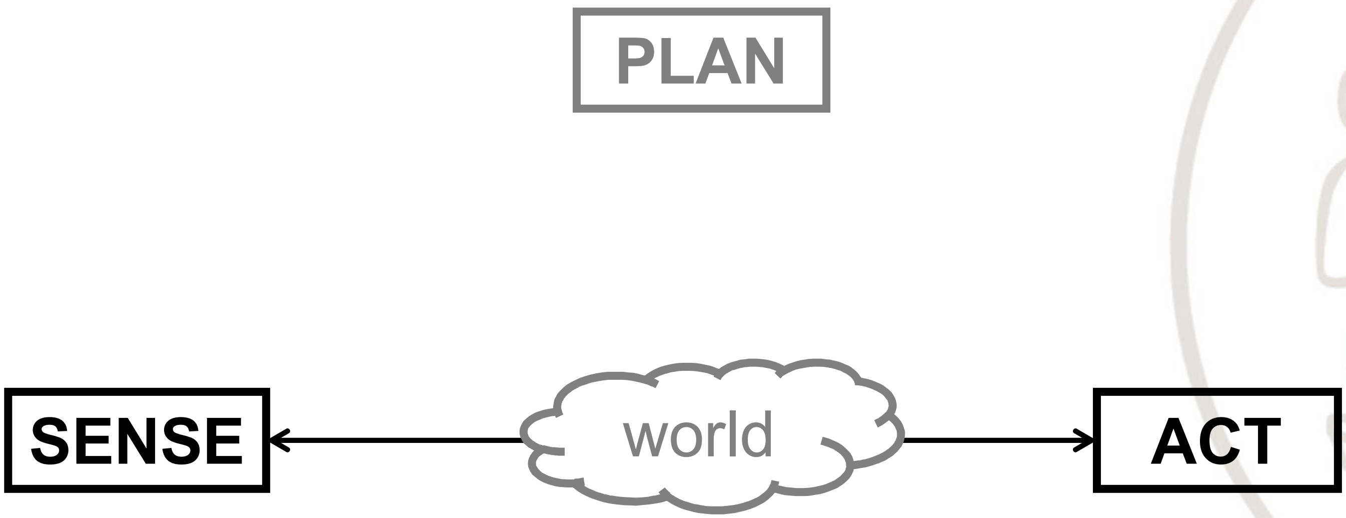
ROBOT PRIMITIVES	INPUT	OUTPUT
SENSE	Sensor data	Sensed information
PLAN	Information (sensed and/or cognitive)	Directives
ACT	Sensed information or directives	Actuator commands

Reactive paradigm

S-A

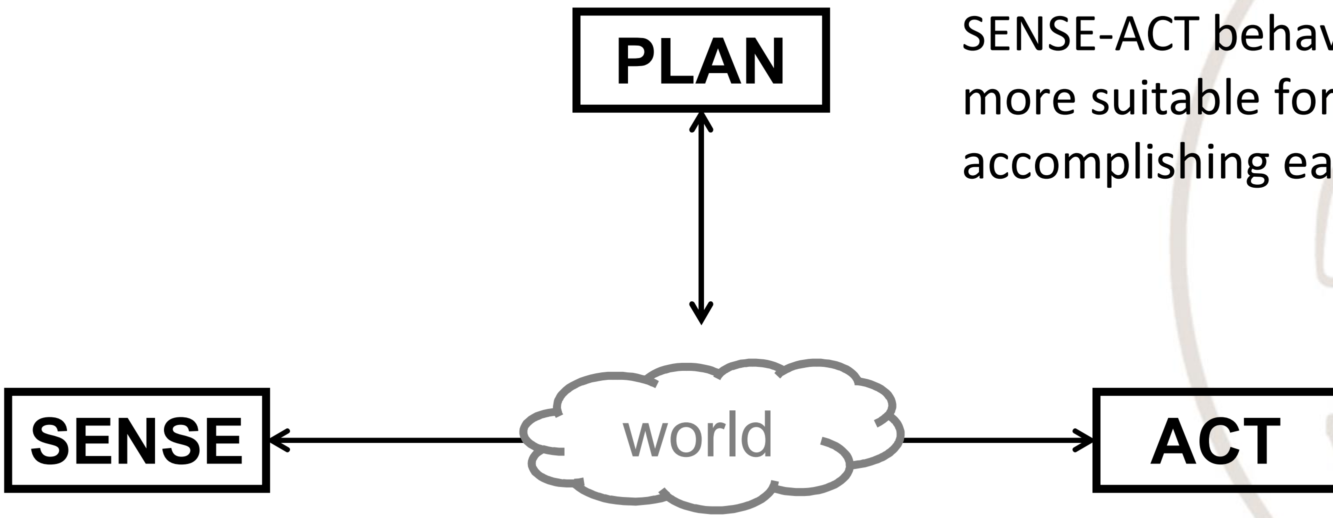


Reactive paradigm

ROBOT PRIMITIVES	INPUT	OUTPUT
SENSE	Sensor data	Sensed information
PLAN	Information (sensed and/or cognitive)	Directives
ACT	Sensed information or directives	Actuator commands

Hybrid paradigm

S, P-A



The robot decides how to decompose the task in sub-tasks and then which SENSE-ACT behaviour is more suitable for accomplishing each sub-task

Hybrid paradigm

ROBOT PRIMITIVES	INPUT	OUTPUT
PLAN	Information (sensed and/or cognitive)	Directives
SENSE-ACT (behaviors)	Sensor data →	Actuator commands

Robotic architectures

- Provide a principled way of organizing a control system
- Impose constraints on the way the control problem can be solved
- Describe a set of architectural components and how they interact

  -> building blocks of programming a robot
- Criteria for evaluating an architecture:
  - Modularity
  - Niche targettability
  - Portability
  - Robustness

Hierarchical architectures

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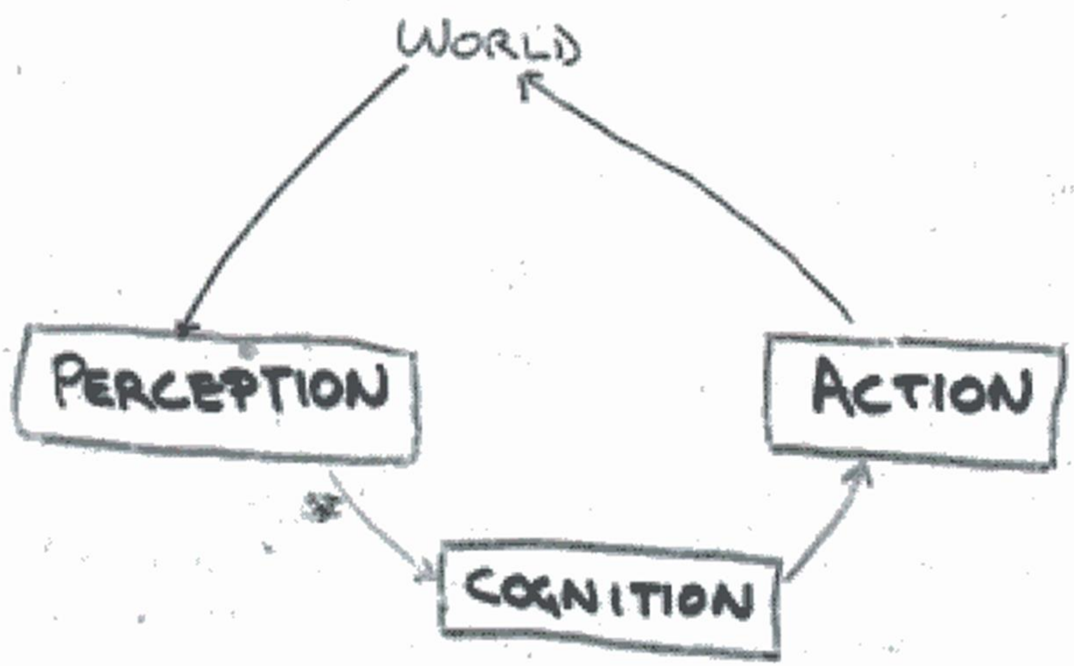


Figure 1: The traditional model where cognition mediates between perceptions and plans of actions.

Tratto da R. Brooks, Cambrian Intelligence, MIT Press, 1999

Hierarchical architectures

- Cognition is used to interpret perception and for planning robot tasks

- The SENSE primitive generates a world description, used by the PLAN, which produces a sequence of tasks for the ACT

Hierarchical architectures

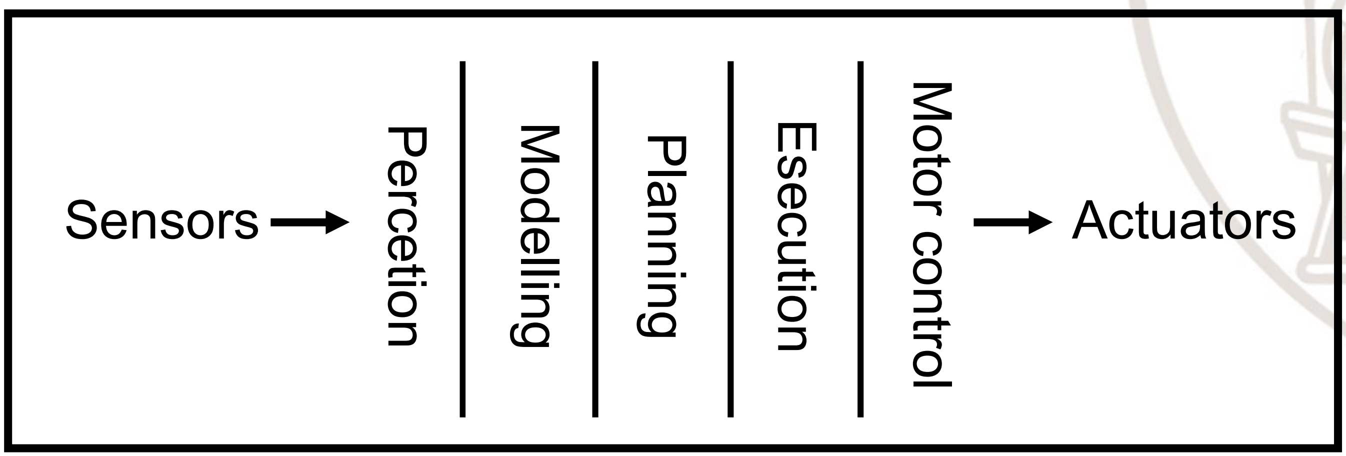
- Perception is used for establishing and maintaining a correspondence between the **internal world model** and the external world.

- Typically, the world model contains:
  - a priori representation of the environment where the robot operates
  - perceived sensory information
  - more information needed for task execution

- The world representation is modified each time the robot perceives the environment and the action plan is established on the basis of such representation

Hierarchical architectures

- Logical and functional division and distribution of tasks
- Horizontal and sequential decomposition of the chain of the information processed by the central system



Hierarchical architectures

- Generally, the PLAN primitive is structured in 3 levels:
  - Strategic
  - Tactical
  - Executive
- The highest, or **strategic**, level generates a strategy on the basis of the task to accomplish
- The intermediate, or **tactical**, level generates the commands by interpreting instructions coming from the higher level, or strategic level
- The lowest level, or **executive** level, receives macro-commands generated by the intermediate level and takes care of real-time control of actuators

Hierarchical architectures

3-level PLAN structure

What the robot has to do

How to accomplish tasks

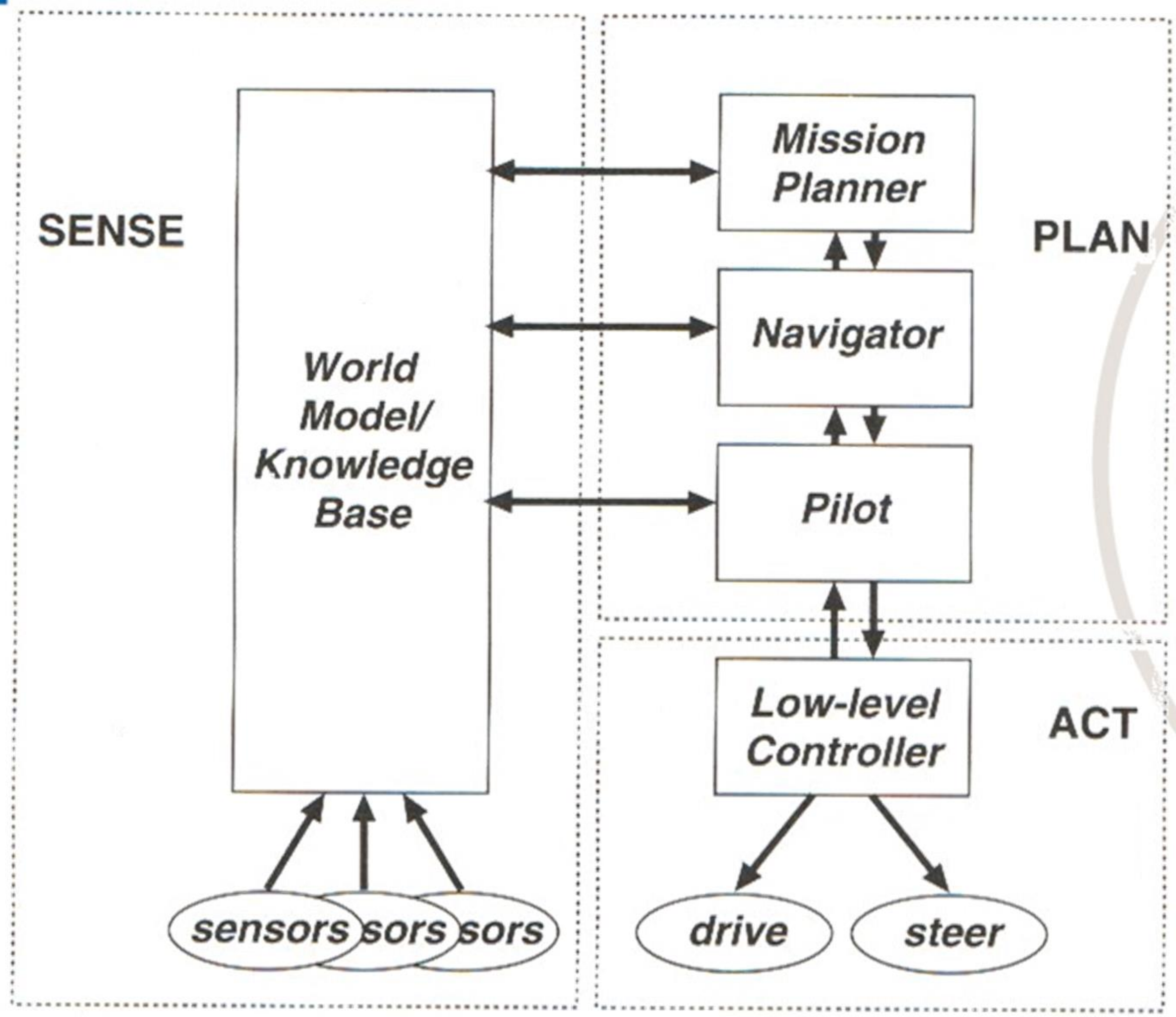
Command execution

Architetture gerarchiche

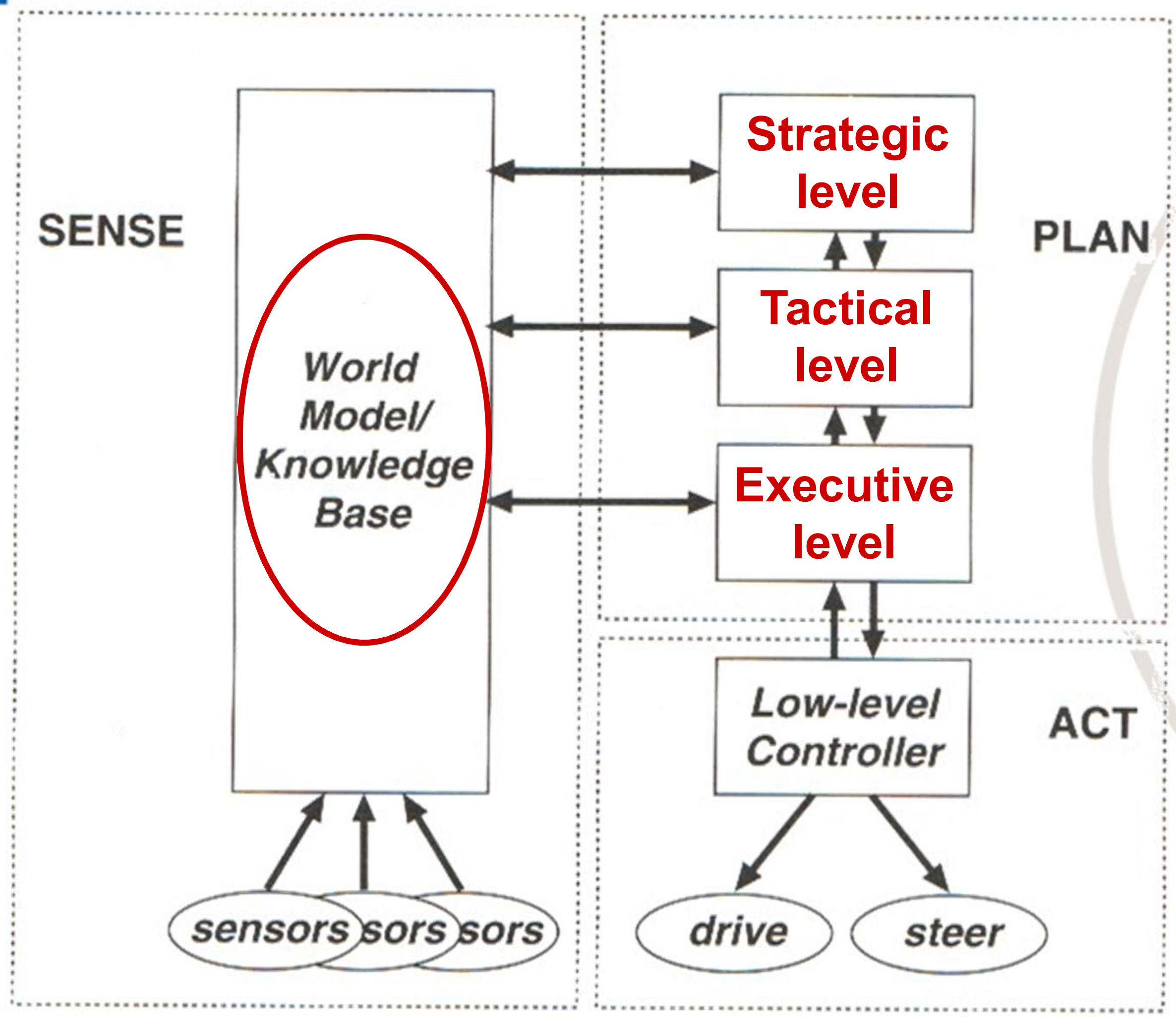
Example for the task: *"take the bottle out of the fridge"*

- **Strategic level**: go to the kitchen, go in front of the fridge, open the fridge, take the bottle…
- **Tactical level**:
  - Go to the kitchen: move_base(X1,Y1); move_base(X2,Y2)…
  - Open the fridge: move_arm(P1), open_hand()….
- **Executive level**:
  - Move_base(X1,Y1); move_base(X2,Y2); move_braccio(P1)…

Nested Hierarchical Controller



Nested Hierarchical Controller



Nested Hierarchical Controller - PLAN

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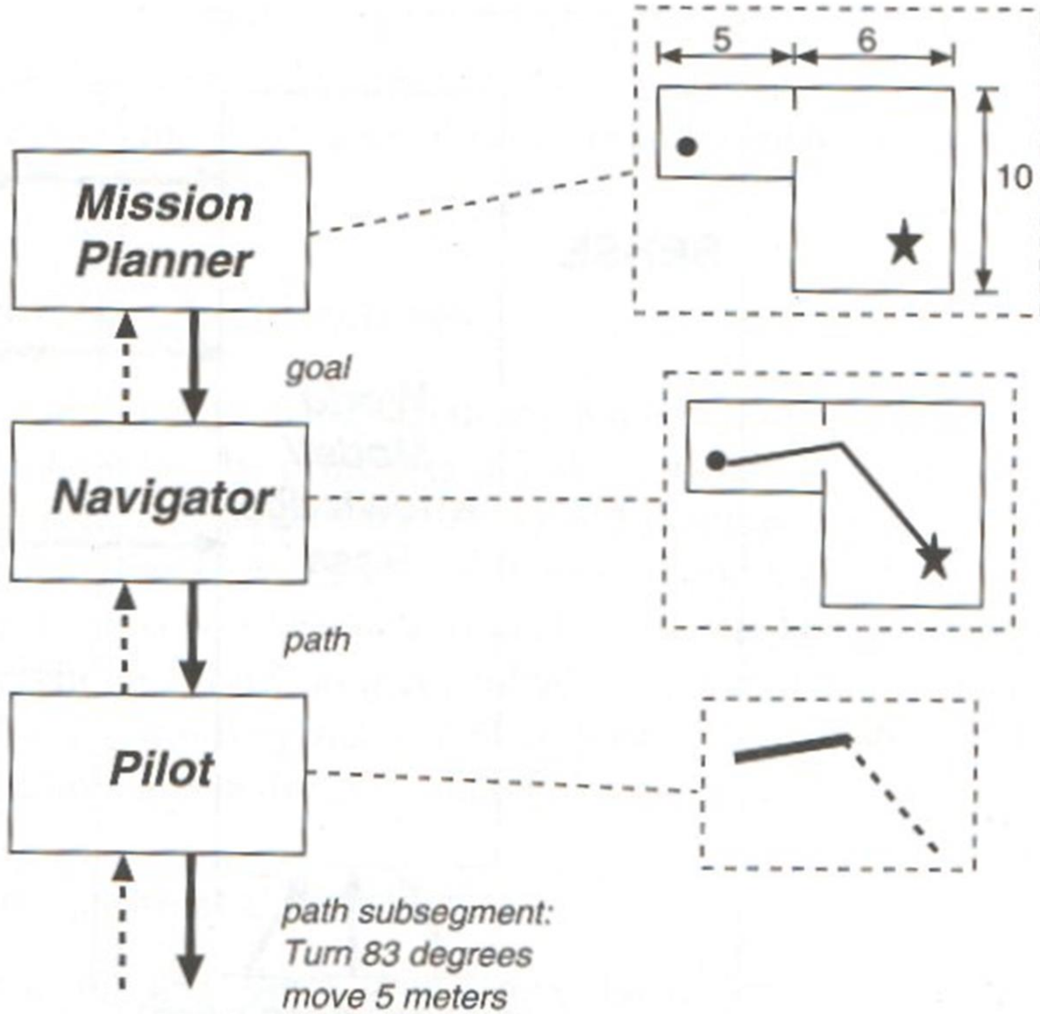


Figure 2.6 Examination of planning components in the NHC architecture.

- The Mission Planner module receives a mission from a human operator (ex. take the boxe in the next room) and encodes it in terms usable by the other modules. It also derives the position and goal of the robot from a map
- The Navigator module receives such information and generates the trajectory from the current position to the goal
- The Pilot modules generates the actions that the actuators have to perform for following the trajectory

Hierarchical architectures

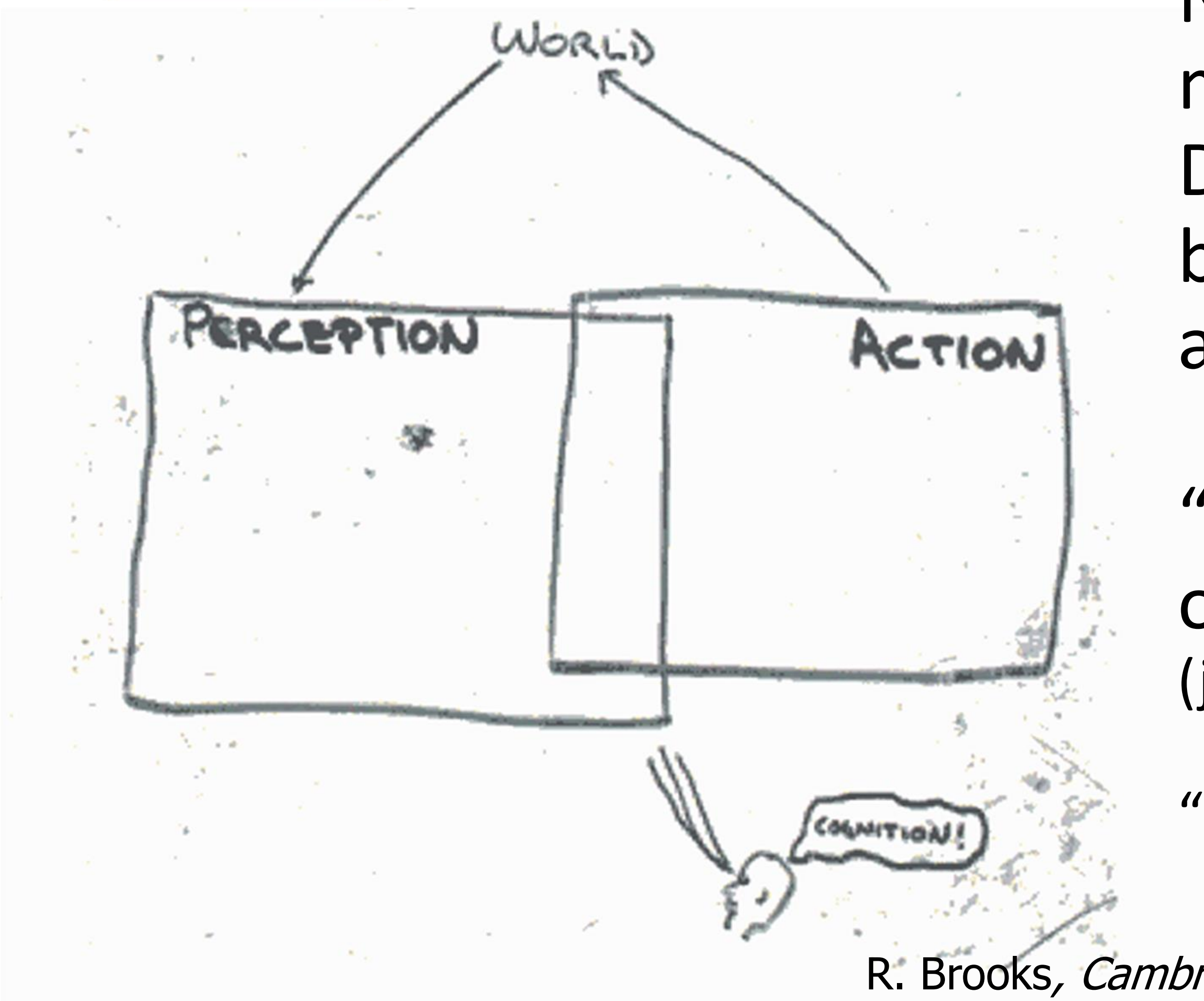
Advantages

- Clear order between perception, planning and action
- Predictable behaviour, e.g. a priori behaviour planning
- System stability

Disadvantages

- High computation cost, especially due to the world model update and to planning
- Separation between perception, planning and action and consequent low reactivty, e.g. limited adaptability to real-time environment modifications
- Poor uncertainty management and effectiveness
- Low parallelism

Reactive architectures or *behavior-based architectures*



No 'cognition' module
Direct interaction between perception and action modules

"The world is its own best model"
(just need sensors)

"Cognition is in the eyes of the observer"

R. Brooks, *Cambrian Intelligence,* MIT Press, 2000

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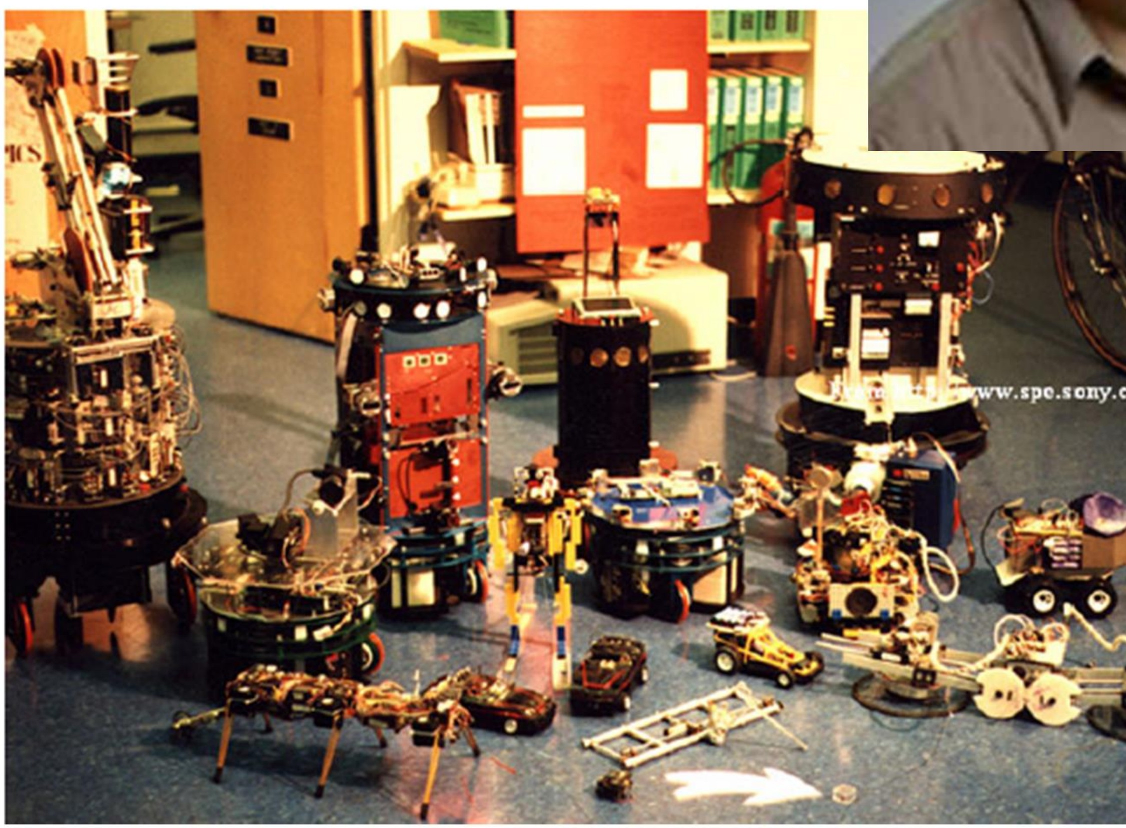
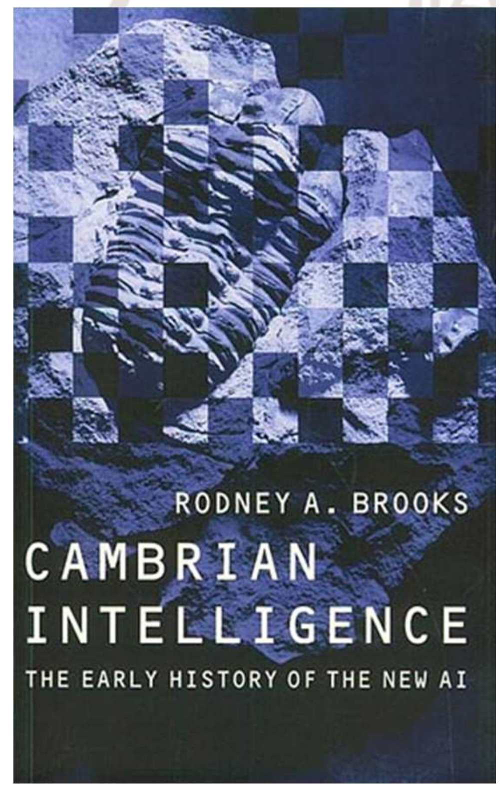
Rodney Brooks

Computer Science and Artificial Intelligence Lab, MIT

Founder of iRobot

Re-Think Robotics





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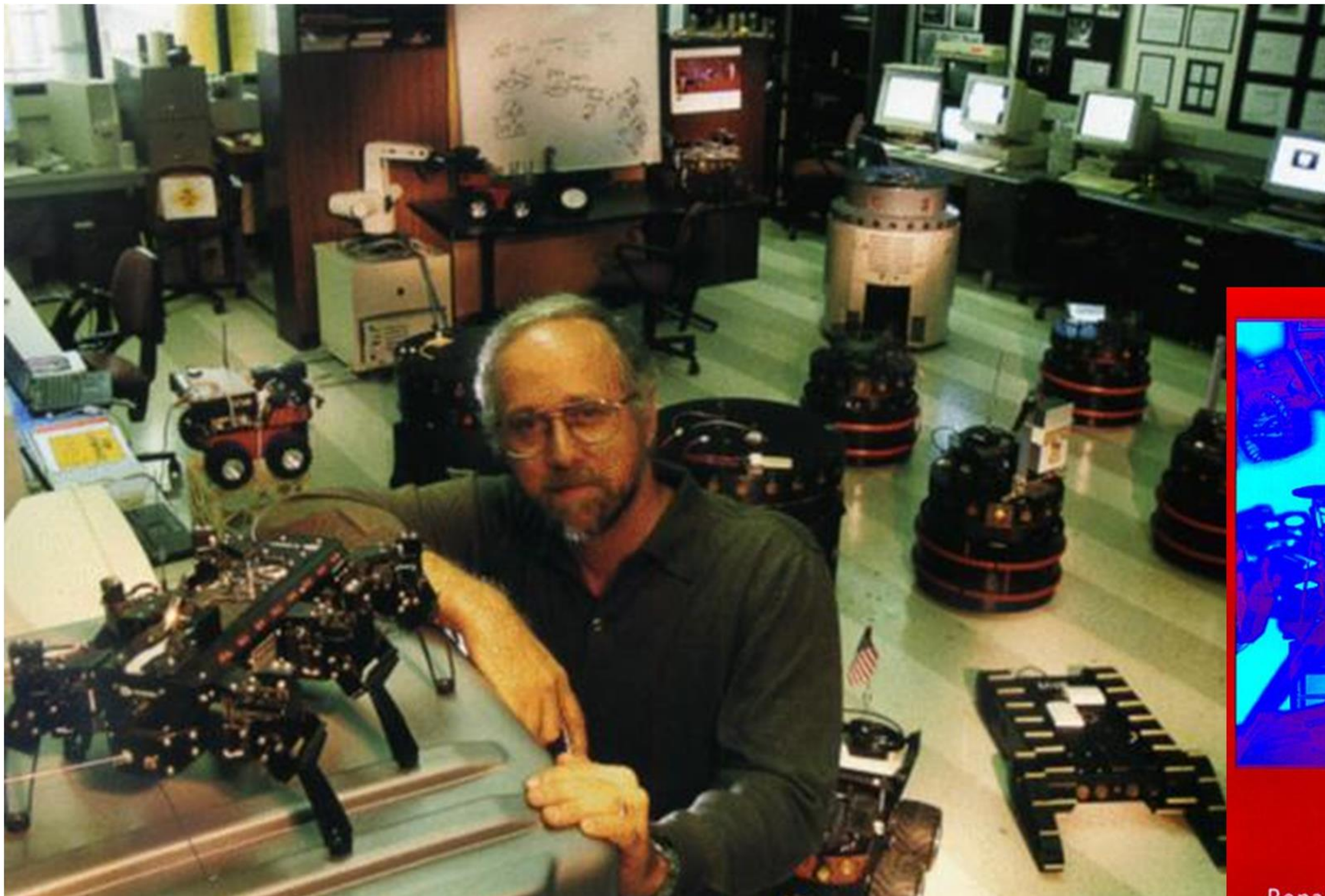
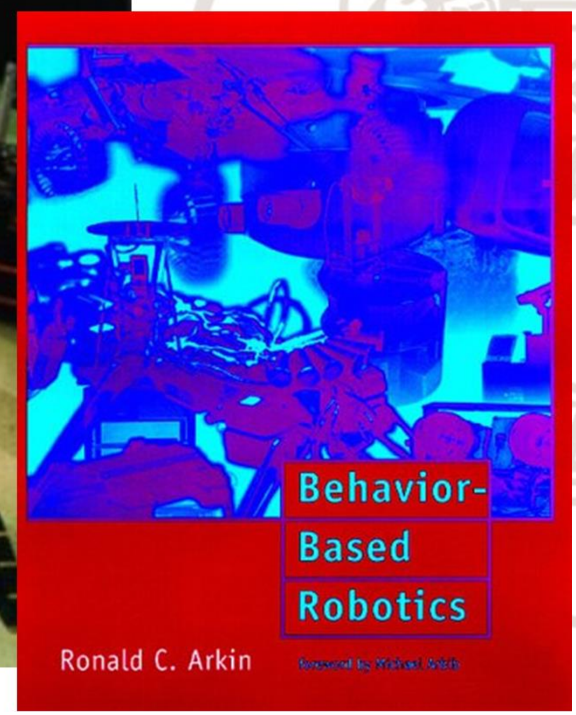
Ronald Arkin
Georgia Institute of Technology





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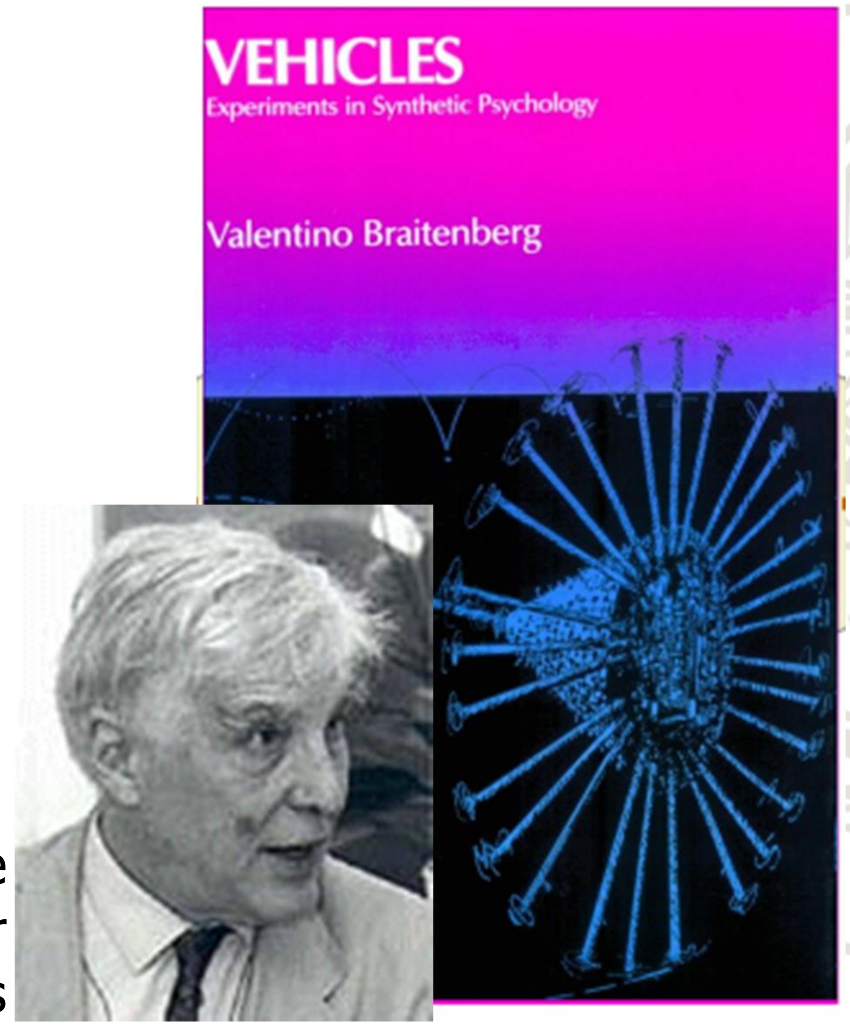
Before Brooks…

Vehicles
Experiment in Synthetic Psychology

By Valentino Braitenberg
The MIT Press

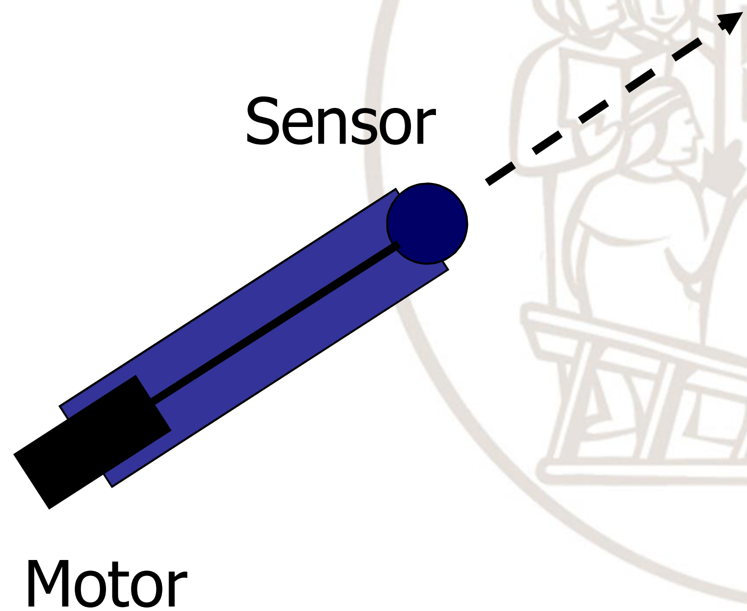


Director of the
Max Planck Institute For
Biological Cybernetics

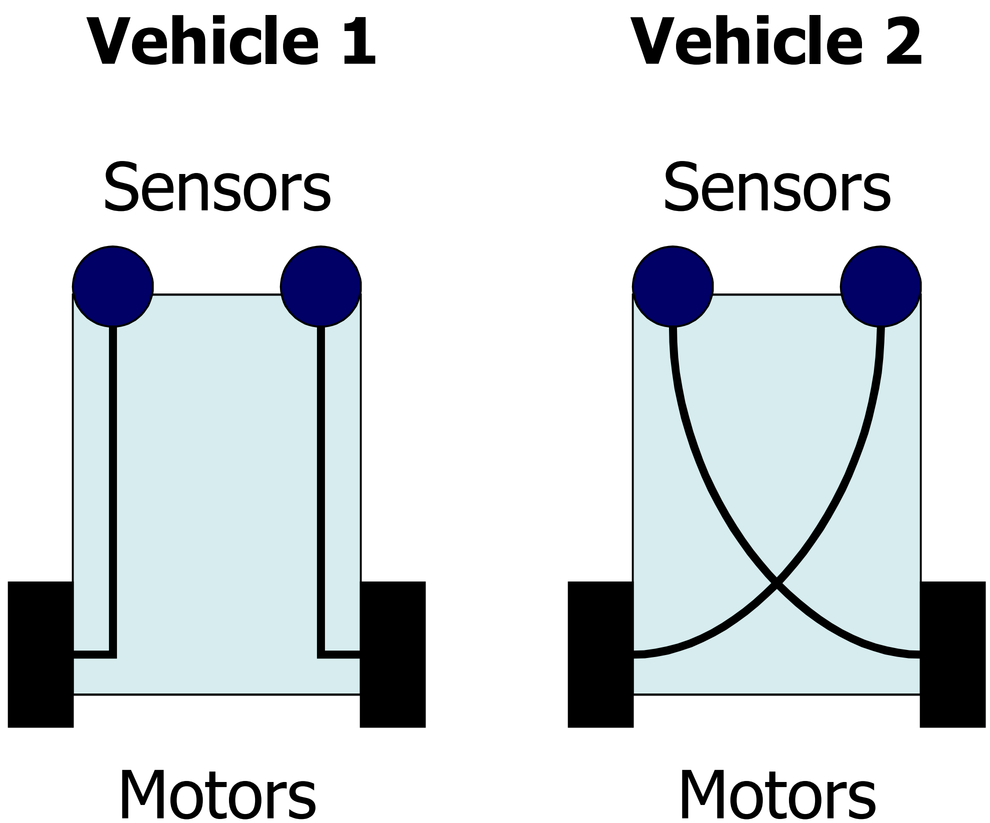
Experiment 1

- Direct connection between sensor and motor
- The motor speed is proportional to the temperature returned by the sensor

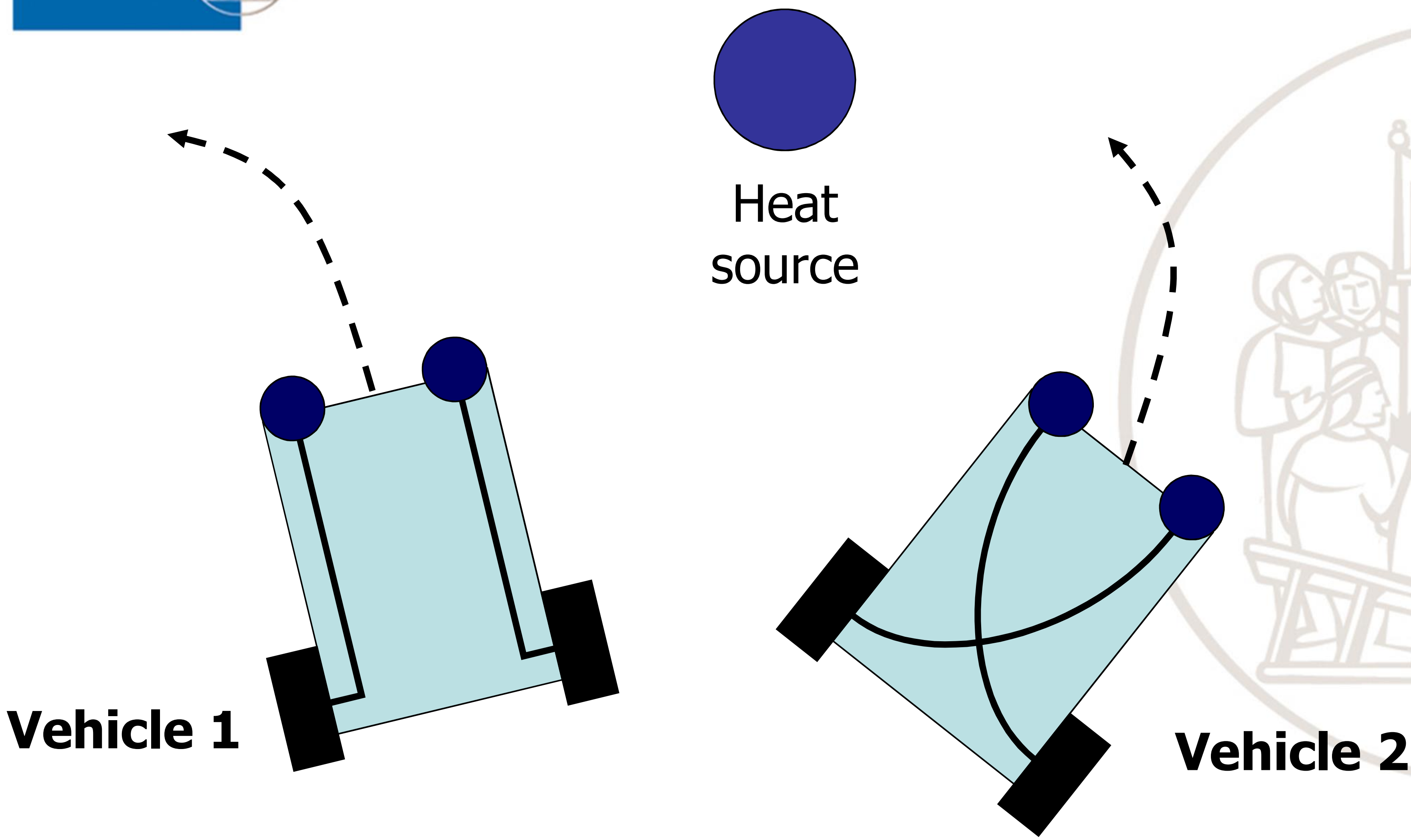
- Resulting behaviour?
- The vehicle moves along a same direction, faster in warmer areas, slowlier in coler areas



Experiment 2: fear and aggression

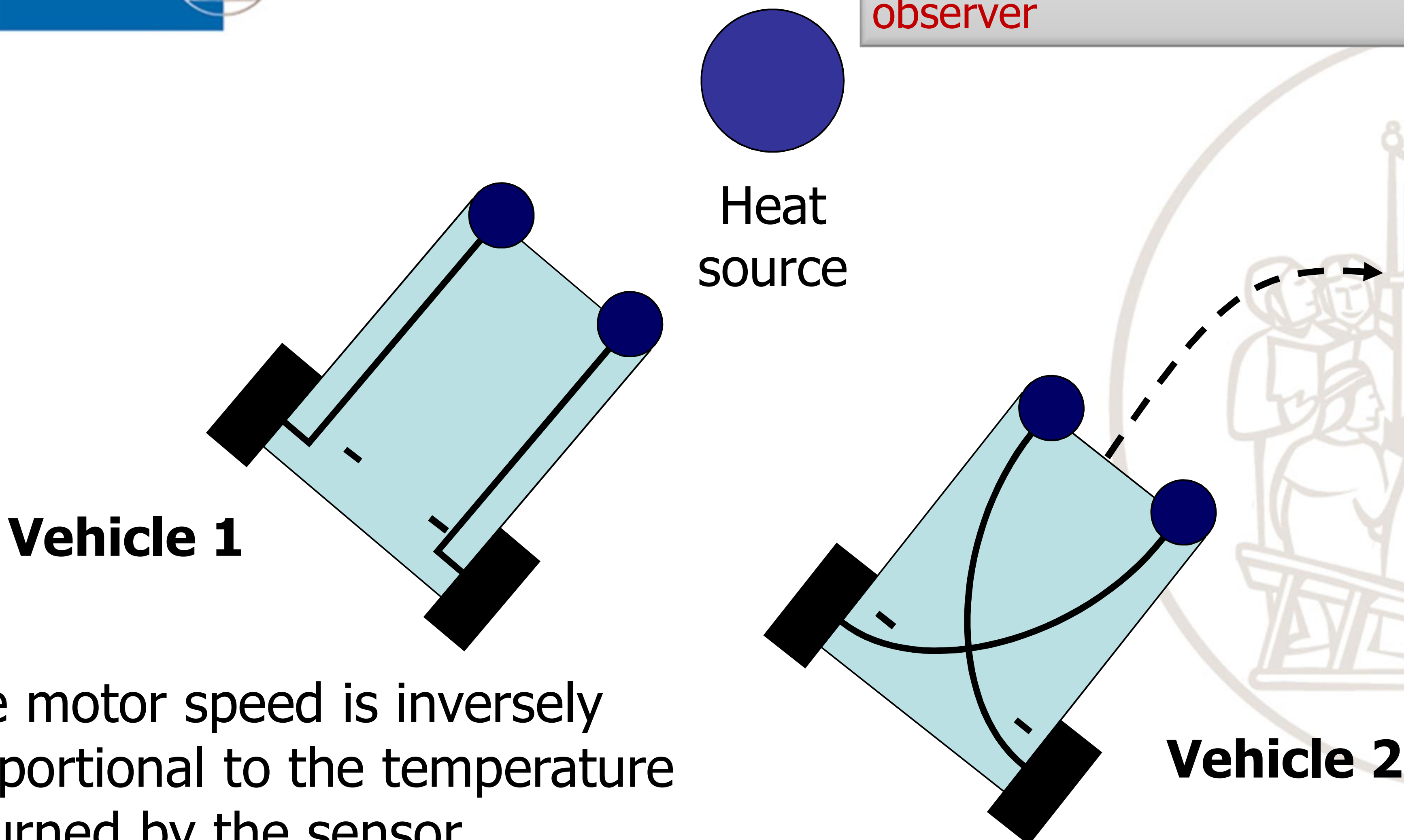


Experiment 2: fear and aggression



Experiment 3: love

Message: with very simple connections between sensors and actuators, behaviours are obtained that seem ‘cognitive’ in the eyes of the observer



The motor speed is inversely proportional to the temperature returned by the sensor

From hierarchical to reactive architectures

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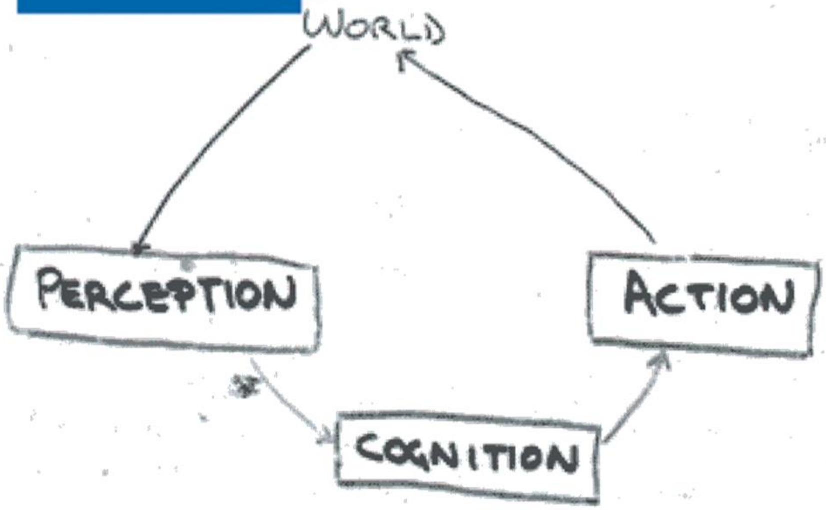


Figure 1: The traditional model where cognition mediates between perceptions and plans of actions.

deliberative, model-based

reactive, behavior-based

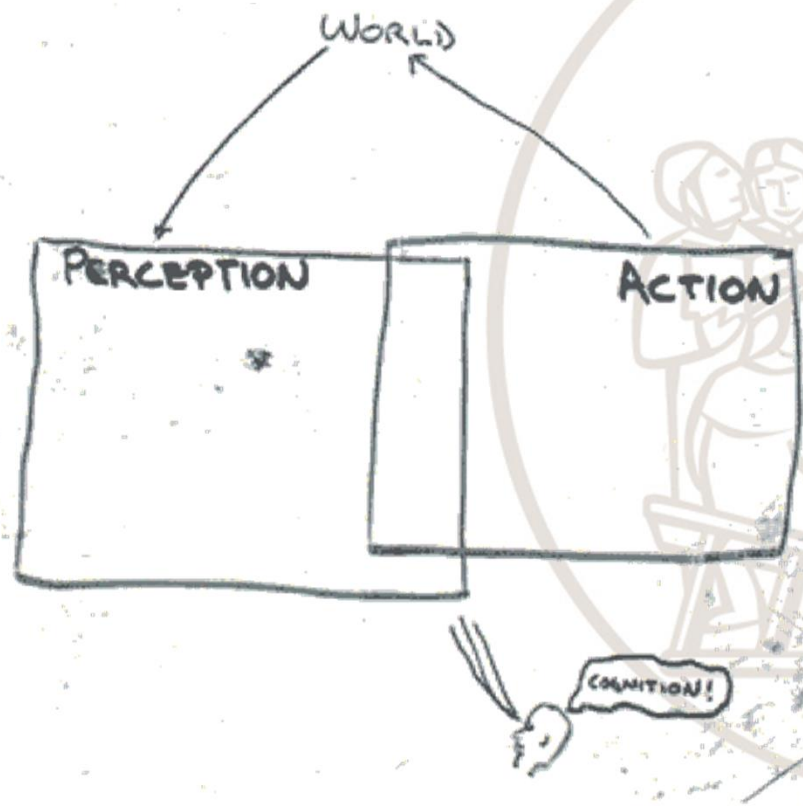
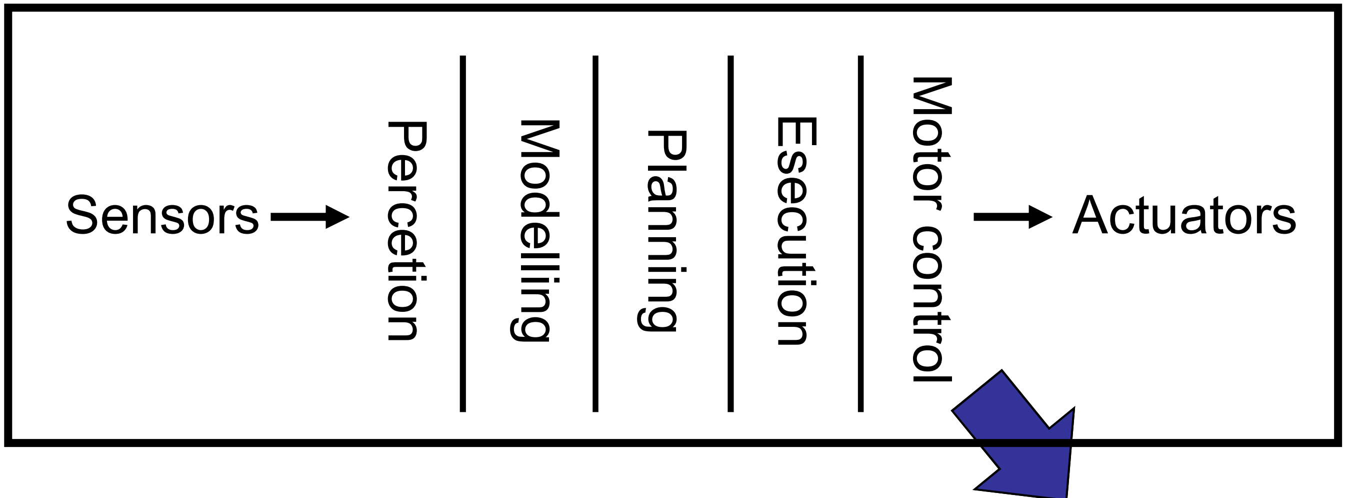


Figure 2: The new model, where the perceptual and action subsystems are all there really is. Cognition is only in the eye of an observer.

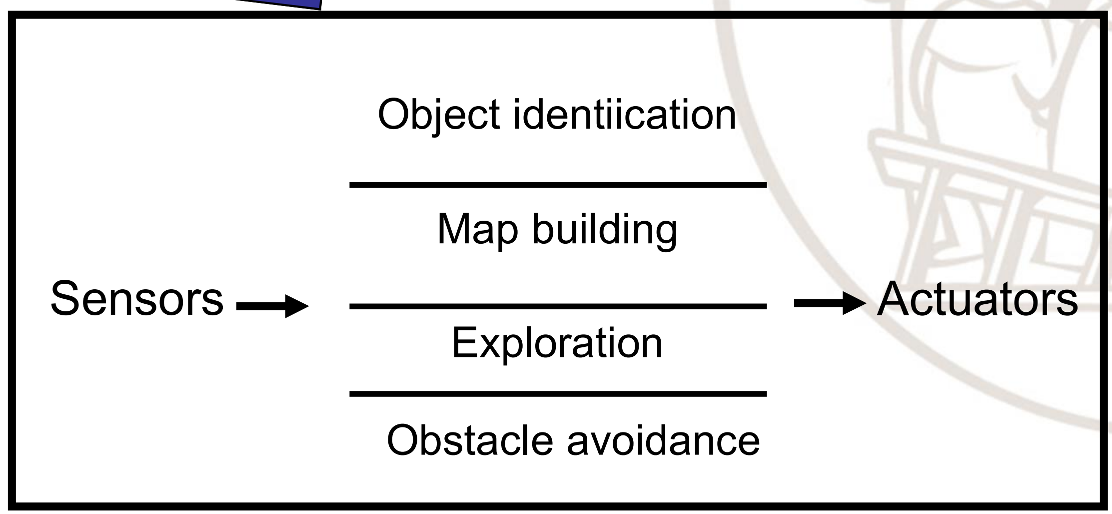
R. Brooks, "Cambrian Intelligence", MIT Press, 1999

From hierarchical to reactive architectures



From *horizontal and sequential* division of the information processing chain to *vertical and parallel* division

Competence levels



Decomposition based on desired internal manifestation, not based on internal robot working

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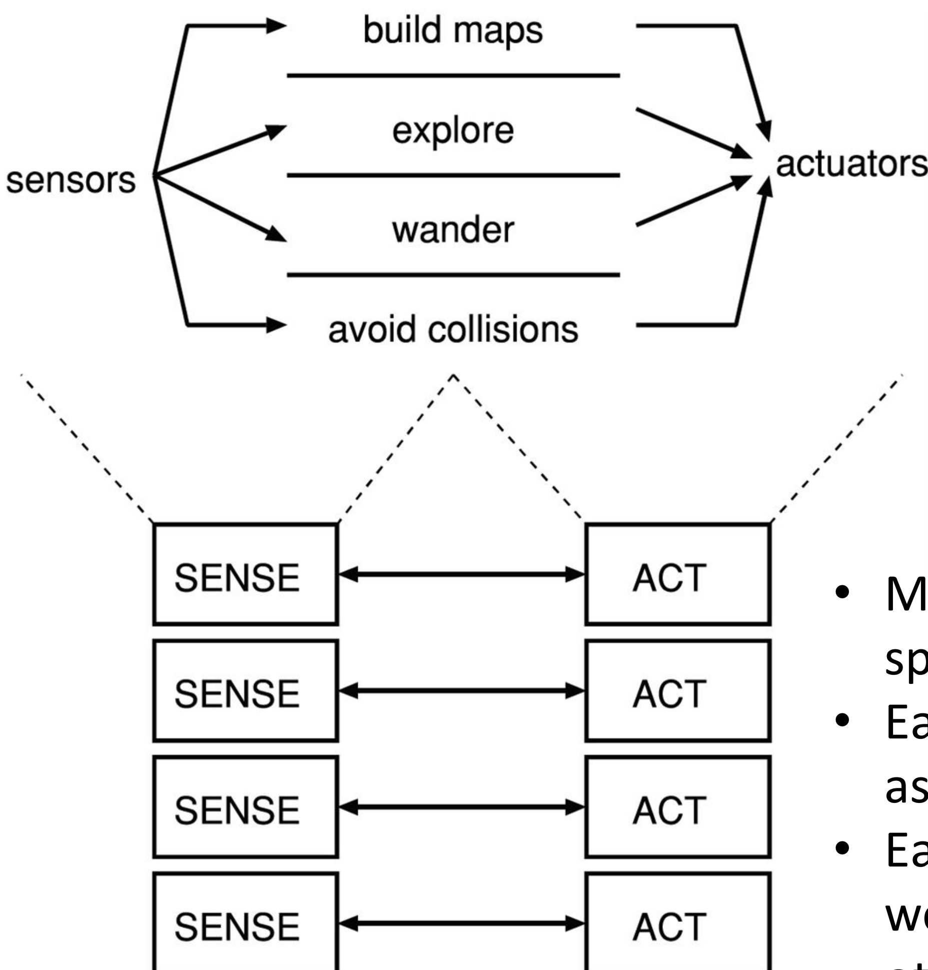
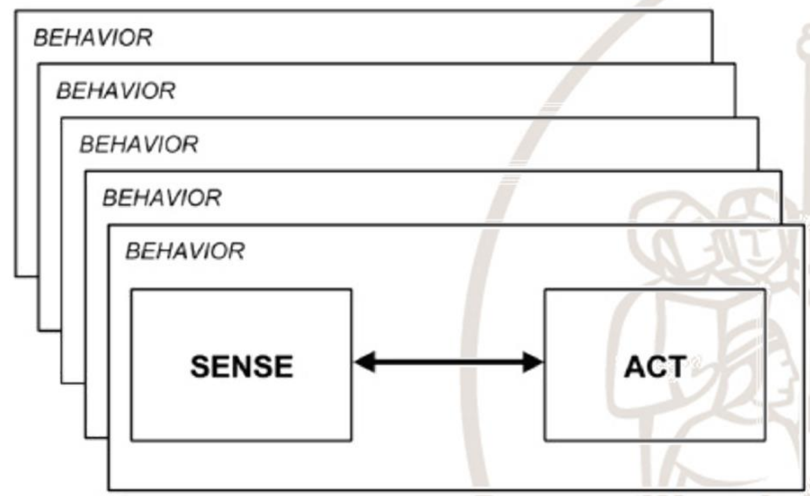
From hierarchical to reactive architectures



The SENSE-ACT couple is named BEHAVIOUR



- Multiple information flows, each related to a specific robot function
- Each behaviour is concerned with one specific aspect of the overall behaviour
- Each behaviour is a finite-state machine ad it works asynchronously and in parallel with the others

Reactive architectures or *behavior-based architectures*

- The robot behaviours are reactions to the information perceived from the environment
- The basic module is a so-called **behaviour**, obtained from a direct interaction between sensors and actions
- The robots based on reactive architectures are called **reactive robots**, i.e. robots responding to environmental stimuli in real-time, and the term ***behaviour-based robotics*** is also used.

Reactive architectures or *behavior-based architectures*

- The robot interacts with the environment with sensors and actuators
- **There is no world representation** ("The world is its best model", R. A. Brooks, 1986): the knowledge on the world is not modelled nor stored in a memory, but it is extracted in real time from the world itself, through sensors
- Since a world model does not exist, a priori planning of the robot actions cannot exist

Reactive architectures
or *behavior-based architectures*

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1. **Situated agent**: the robot is a situated agent operating in an ecological niche. It is an integral part of the world and when it acts it changes the world and receives new sensory inputs.
2. **Behaviour-based**: behaviours serve as the basic building blocks for robotic actions, and the overall behaviour of the robot is emergent. Behaviours are independent, computational entities and operate concurrently.
3. **Locality**: only local, behaviour-specific sensing is permitted. The use of explicit abstract representational knowledge in perceptual processing, even though it is behaviour-specific, is avoided.
4. **Independence**: the various behaviours must be independent to each other. As a consequence, a shared world model is not possible.

Reactive architectures
or *behavior-based architectures*

Advantages

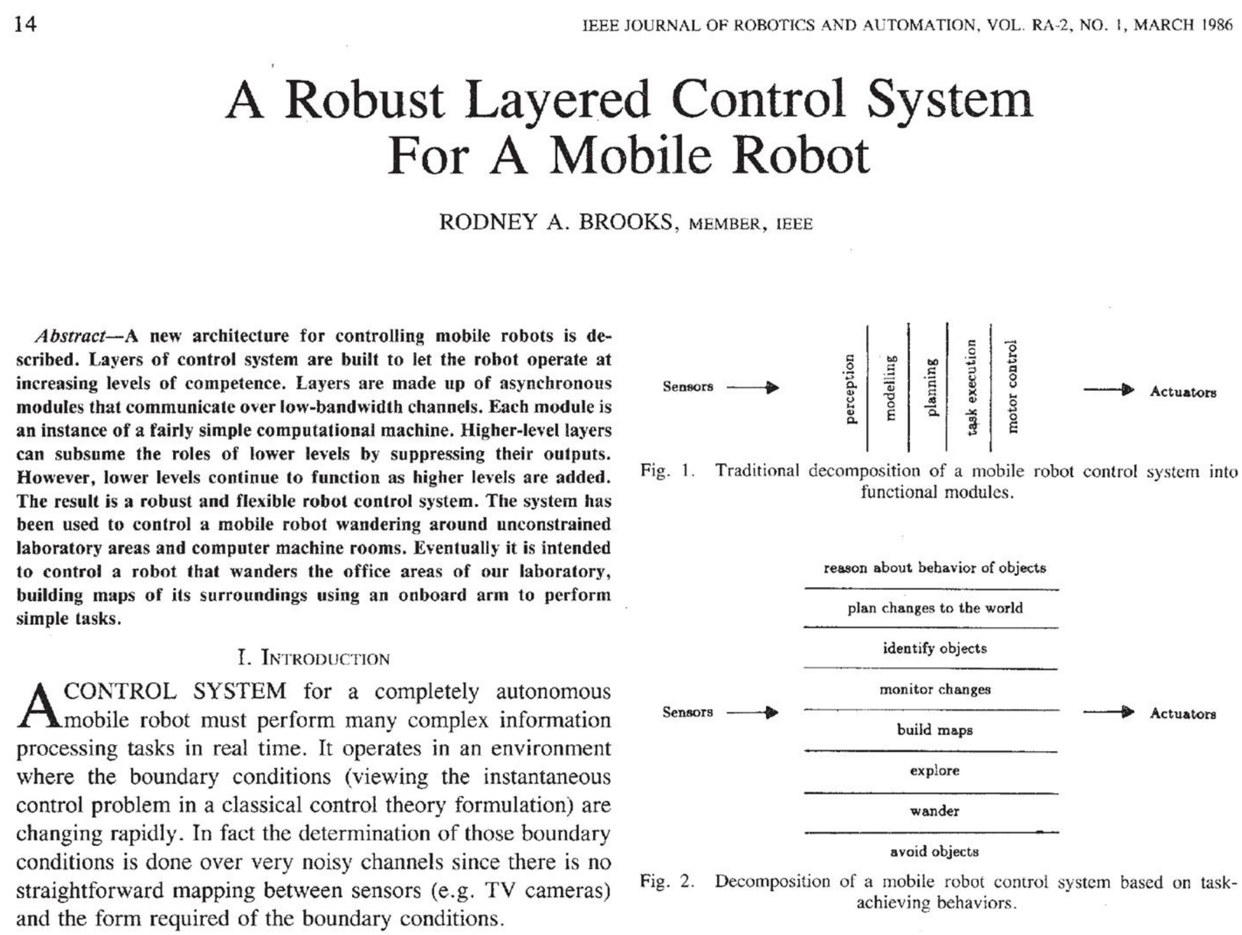
- High adaptability to envorinment changes (real-time response)
- Low computational complexity in each behaviour and the overall computational cost is low
- Parallelism
- Extension of behaviours is very easy thanks to modularity
- No world model

Disadvantages

- The overall robot behaviour is difficult to predict
- Management of concurrency between behaviours
- When increasing the number of behaviours, the complexity of concurrency management also increases, with a consequence difficulty in conflict resolution

An example of reactive architecture: subsumption architecture

Collision-free navigation of a mobile robot equipped with ultrasound sensors



14 IEEE JOURNAL OF ROBOTICS AND AUTOMATION, VOL. RA-2, NO. 1, MARCH 1986

A Robust Layered Control System For A Mobile Robot

RODNEY A. BROOKS, MEMBER, IEEE

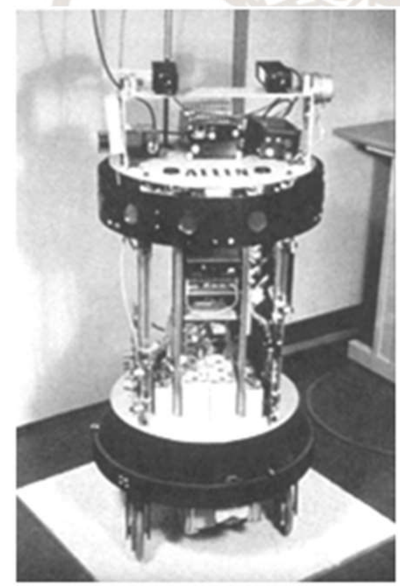
Abstract—**A new architecture for controlling mobile robots is described. Layers of control system are built to let the robot operate at increasing levels of competence. Layers are made up of asynchronous modules that communicate over low-bandwidth channels. Each module is an instance of a fairly simple computational machine. Higher-level layers can subsume the roles of lower levels by suppressing their outputs. However, lower levels continue to function as higher levels are added. The result is a robust and flexible robot control system. The system has been used to control a mobile robot wandering around unconstrained laboratory areas and computer machine rooms. Eventually it is intended to control a robot that wanders the office areas of our laboratory, building maps of its surroundings using an onboard arm to perform simple tasks.**

I. Introduction

A CONTROL SYSTEM for a completely autonomous mobile robot must perform many complex information processing tasks in real time. It operates in an environment where the boundary conditions (viewing the instantaneous control problem in a classical control theory formulation) are changing rapidly. In fact the determination of those boundary conditions is done over very noisy channels since there is no straightforward mapping between sensors (e.g. TV cameras) and the form required of the boundary conditions.

Fig. 1. Traditional decomposition of a mobile robot control system into functional modules.

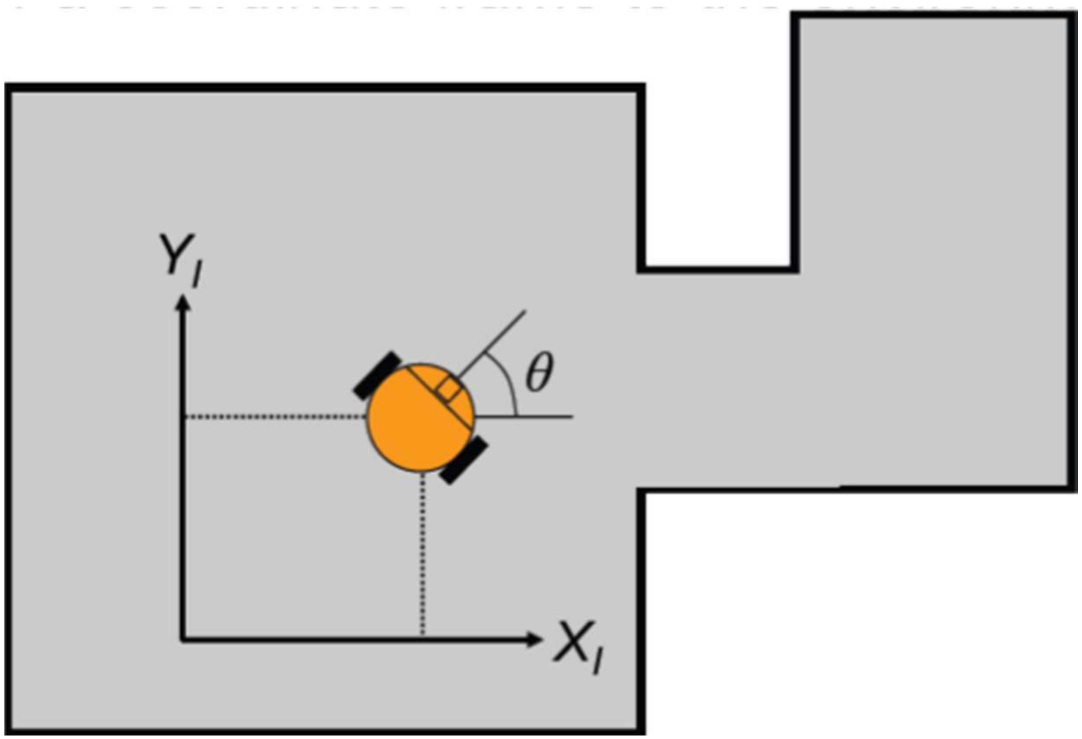
Fig. 2. Decomposition of a mobile robot control system based on task-achieving behaviors.



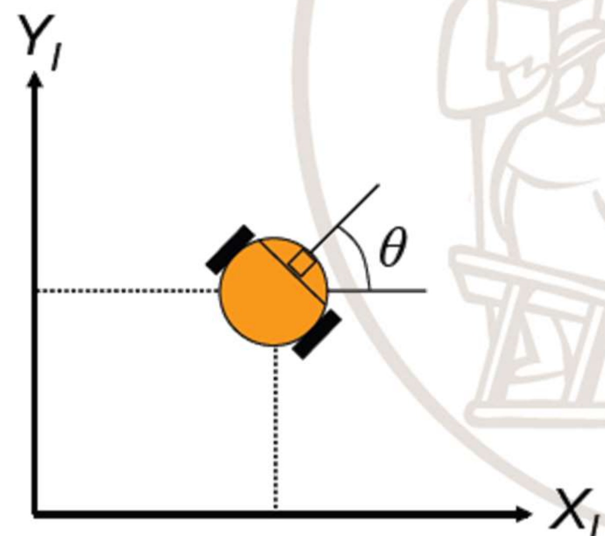
R.A. Brooks, "A Robust Layered Control System for a Mobile Robot", in *Cambrian Intelligence*, The MIT Press, 1999
R.A. Brooks, "A Robust Layered Control System for a Mobile Robot", *IEEE Journal of Robotics and Automation*, Vol. Ra-2, No. I, March 1986

Position of a mobile robot

Reference coordinate system fixed in the world



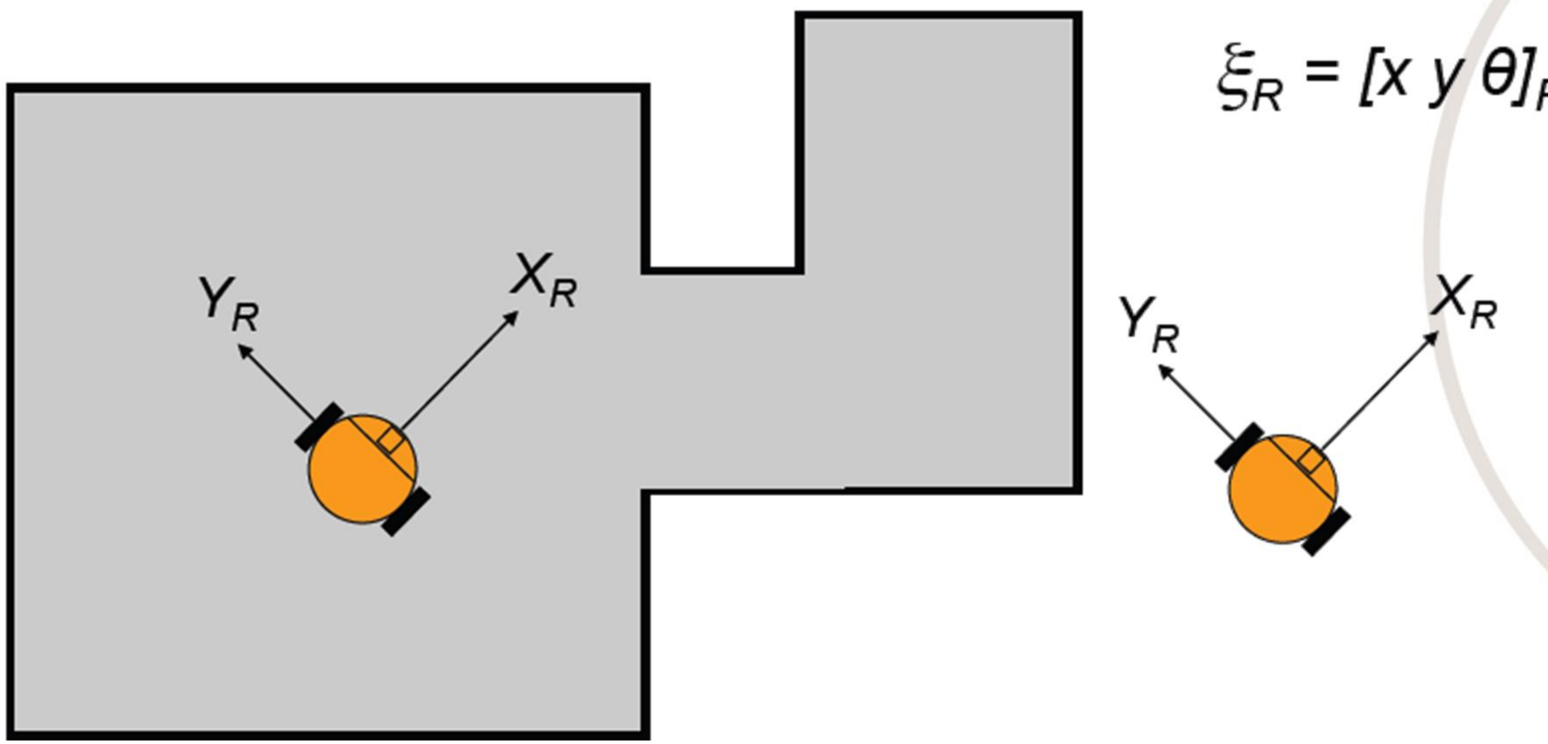
$$\xi_I = [x\ y\ \theta]_I$$



Position of a mobile robot

Reference coordinate system fixed on the robot

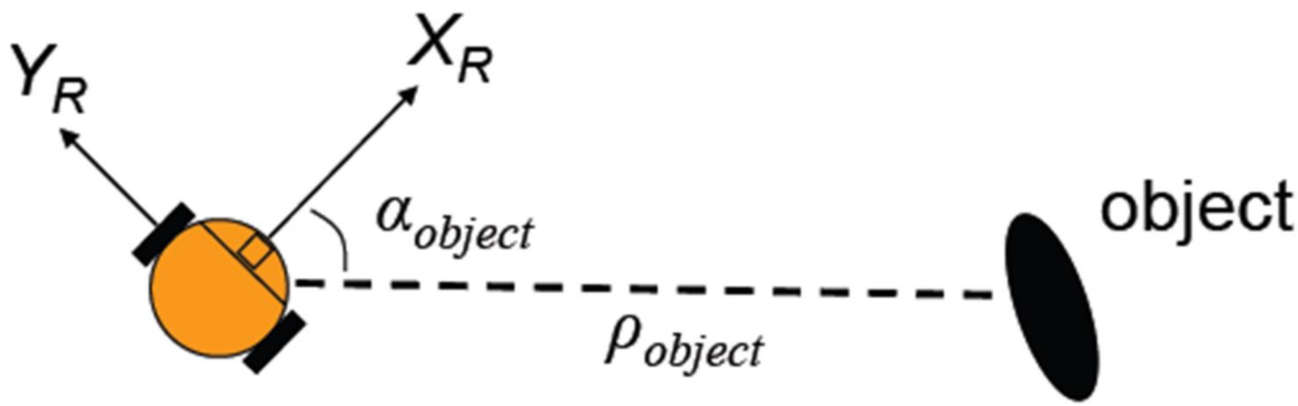
$$\xi_R = [x\ y\ \theta]_R = [0\ 0\ 0]$$



Position of an obstacle

$$x_{object,\,R} = \rho_{object} \cos(\alpha_{object})$$

$$y_{object,\,R} = \rho_{object} \sin(\alpha_{object})$$



Distance measurement: time of flight

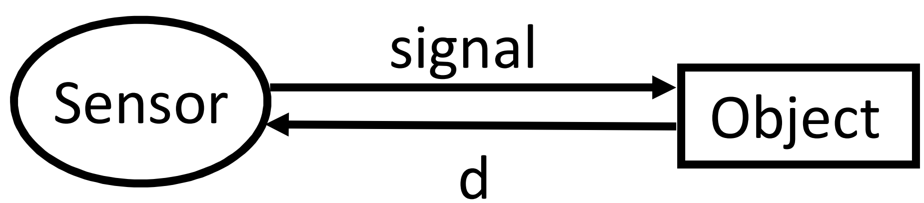
The measurement of the distance of an object is given by the measurement of the time needed by a signal to reach the object and to come back

$$d = (v \times t)/2$$

d = object distance

v = signal velocity

t = time needed by the signal to reach the object and to come back

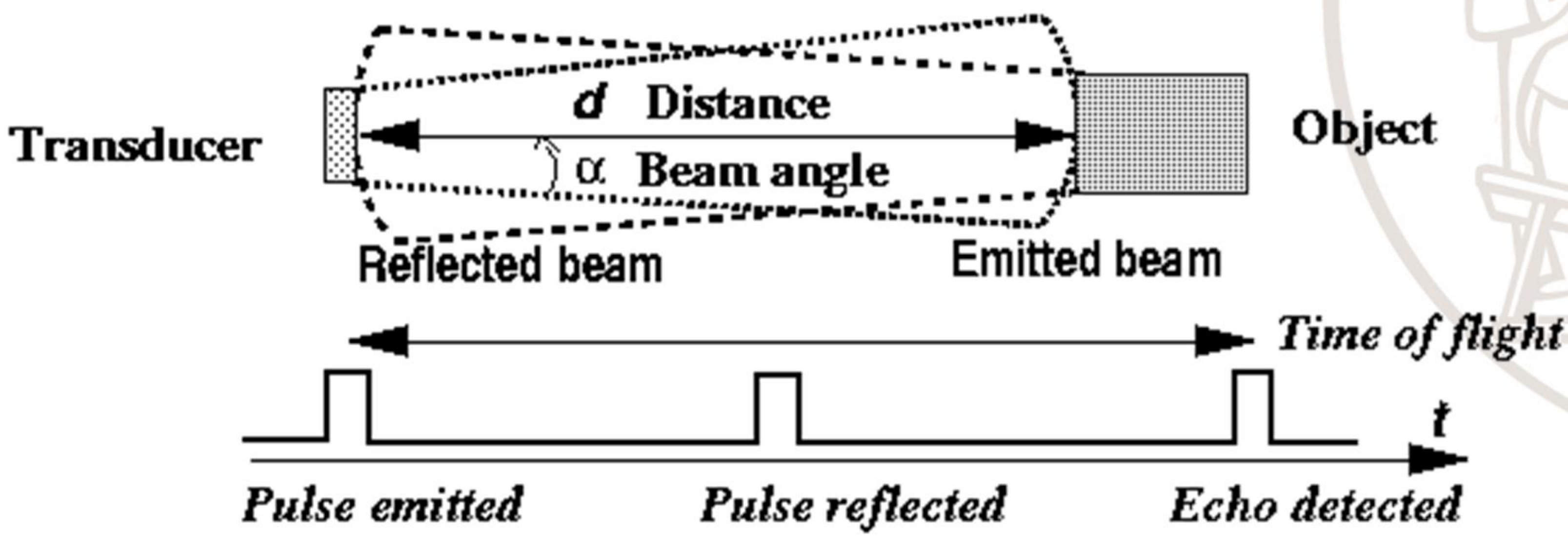


Ultrasound sensors

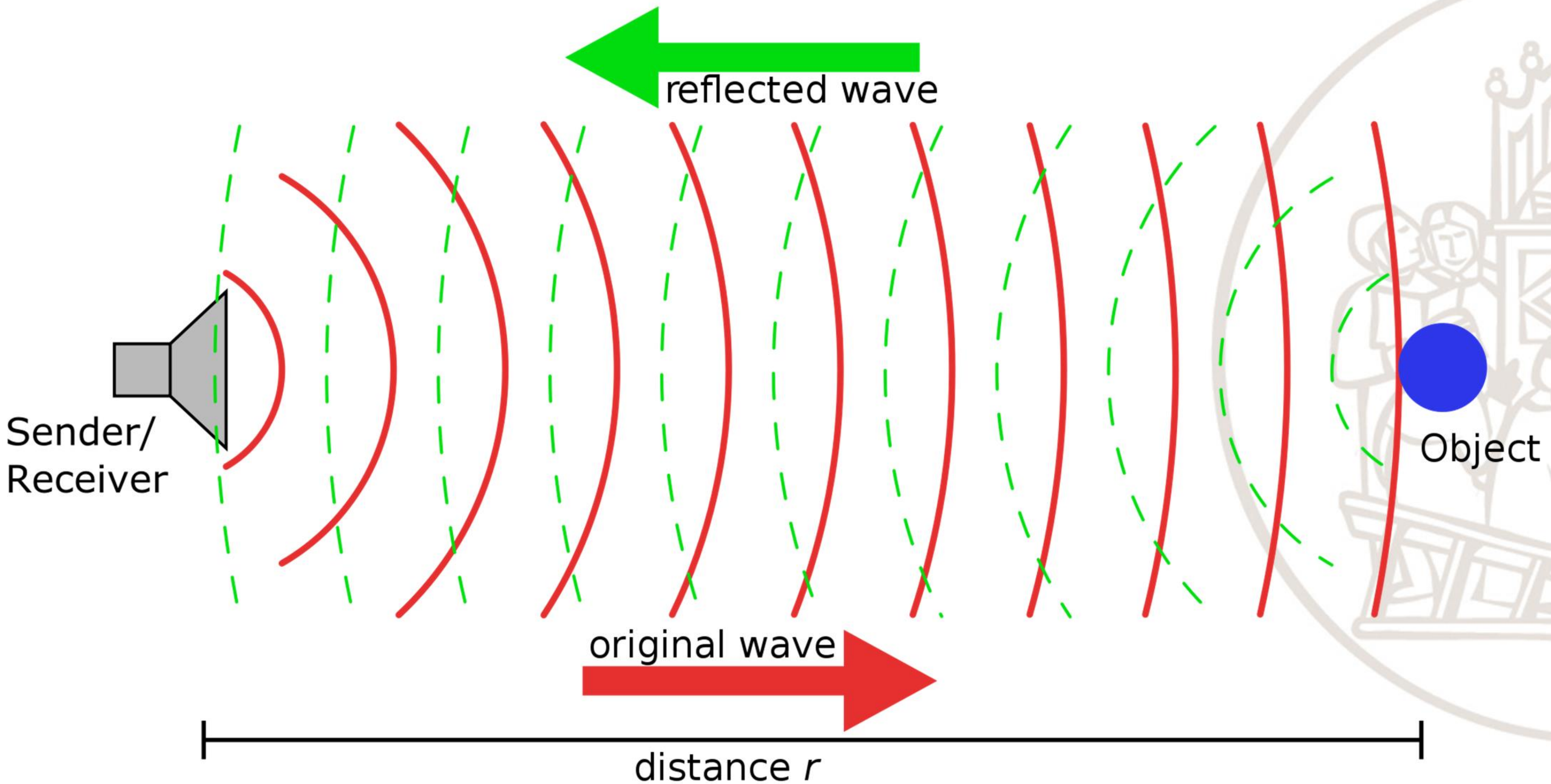
Distance measurement based on the time of flight

$$d = 0.5\, t_e\, v$$

where v is the average speed of the signals emitted and t_e is the time between the signal emitted and the signal echo received.



Ultrasound sensors



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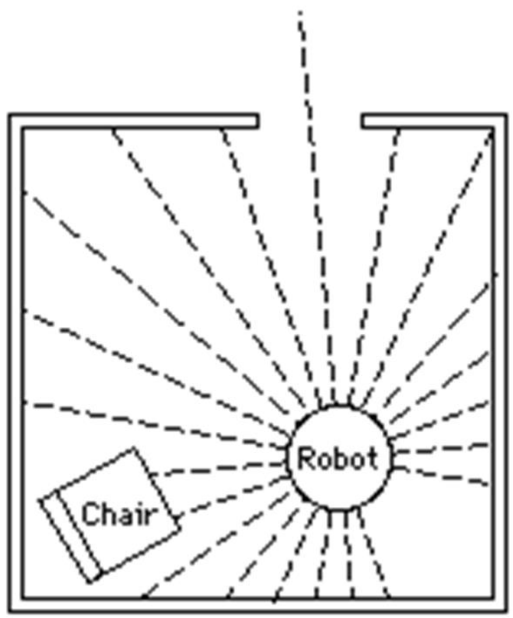
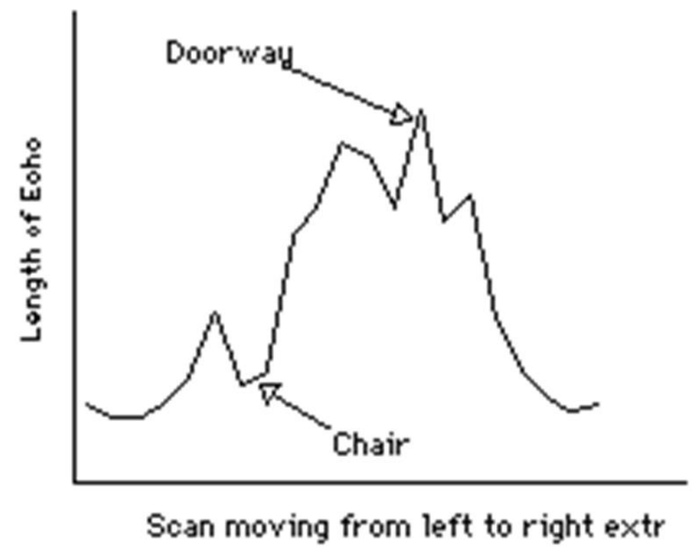
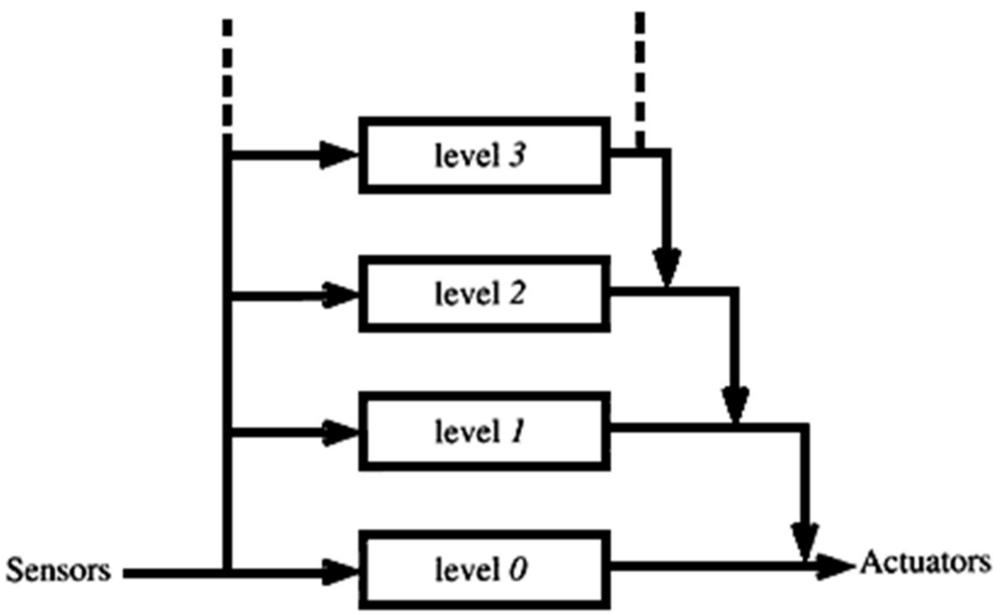
Example of ultrasound sensors and their response





Subsumption architecture



- Behaviours are organized in an architecture based on levels: control levels corresponding to the competence levels of vertical decomposition
  - Lower levels concern more basic functions, like obstacle avoidance
  - Higher levels concern more goal-directed actions.
- Higher levels 'subsume' lower levels
- The levels work in an independent and concurrent way

Subsumption architecture: suppression and inhibition

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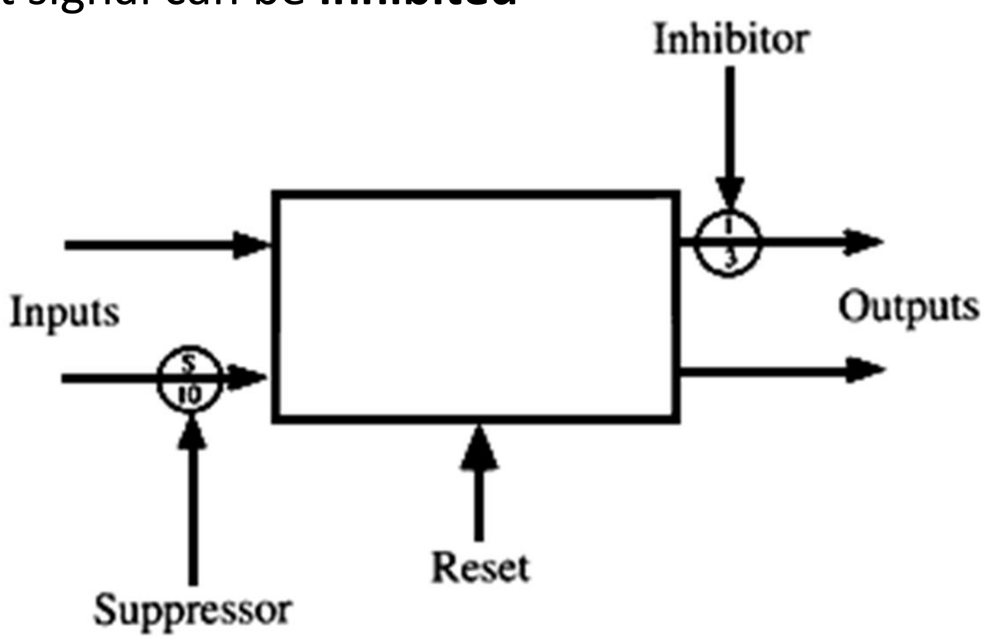
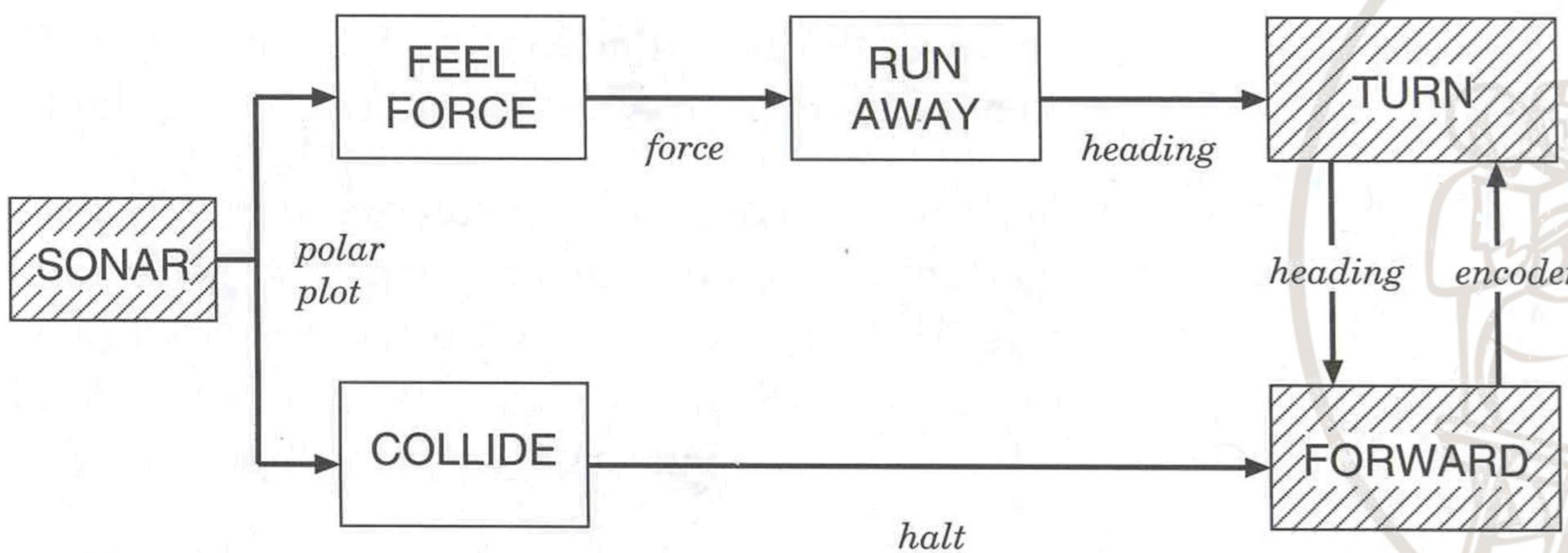
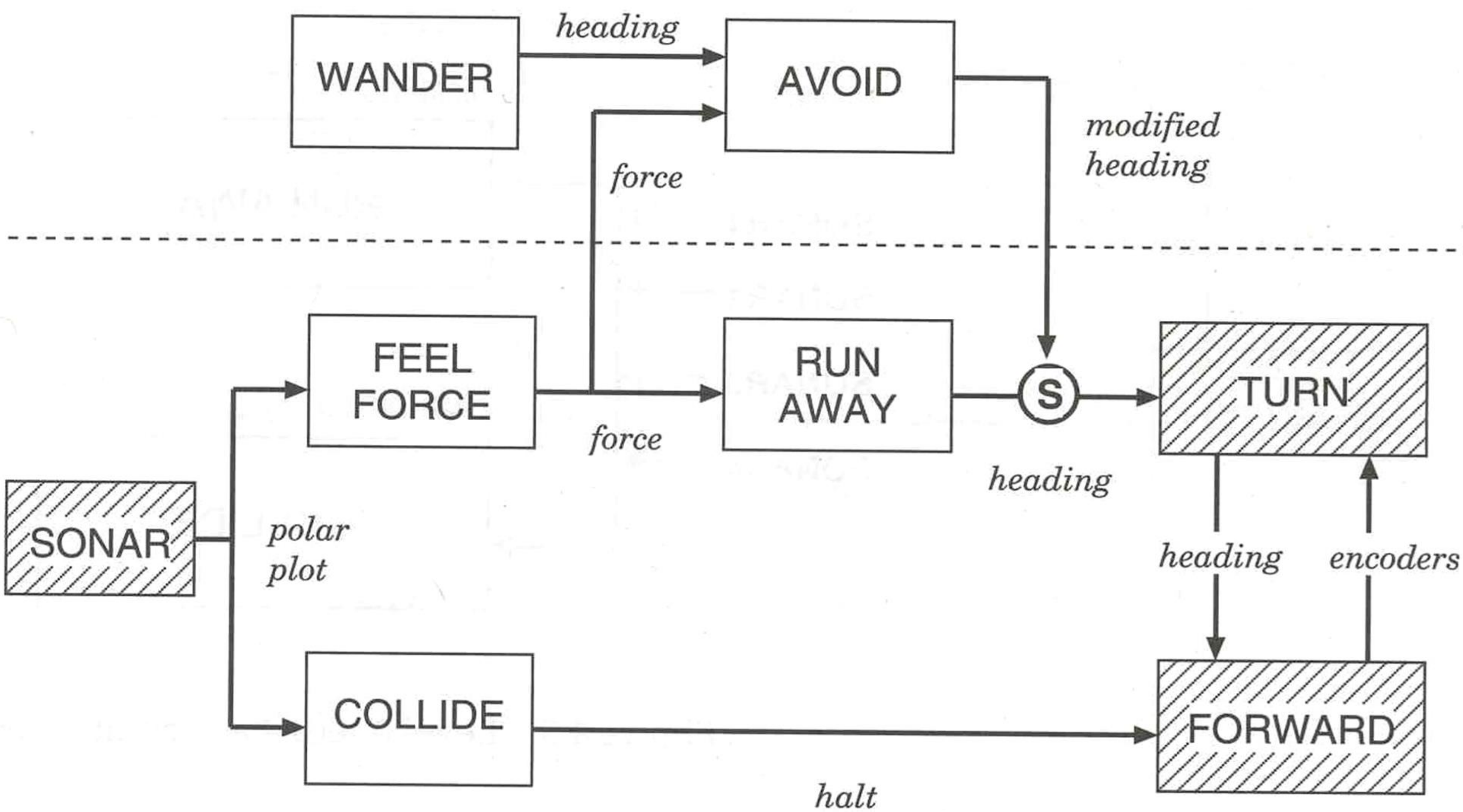
- Each behaviour has input and output lines.
- Outpur lines of a behaviour can be connected to input or output lines of other behaviours:
  - An input signal can be **suppressed** and replaced with the signal that suppressed it
  - An output signal can be **inhibited**



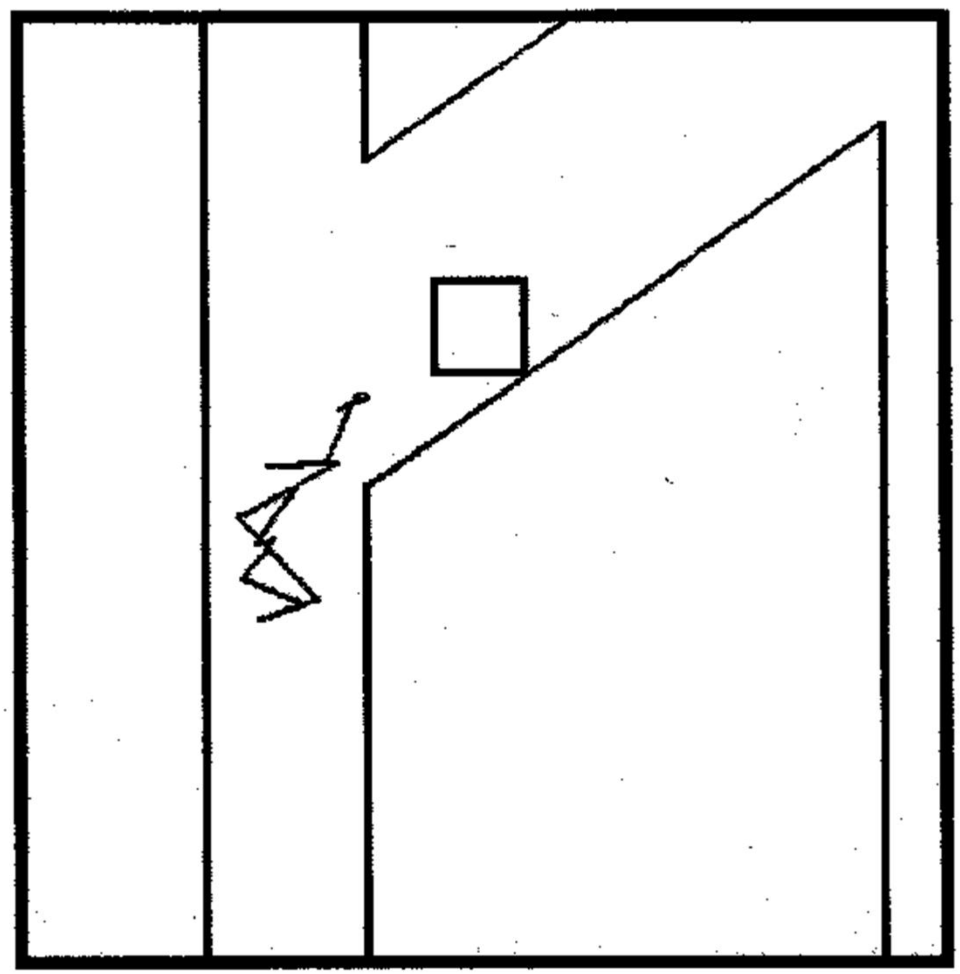
Level 0 - Avoid



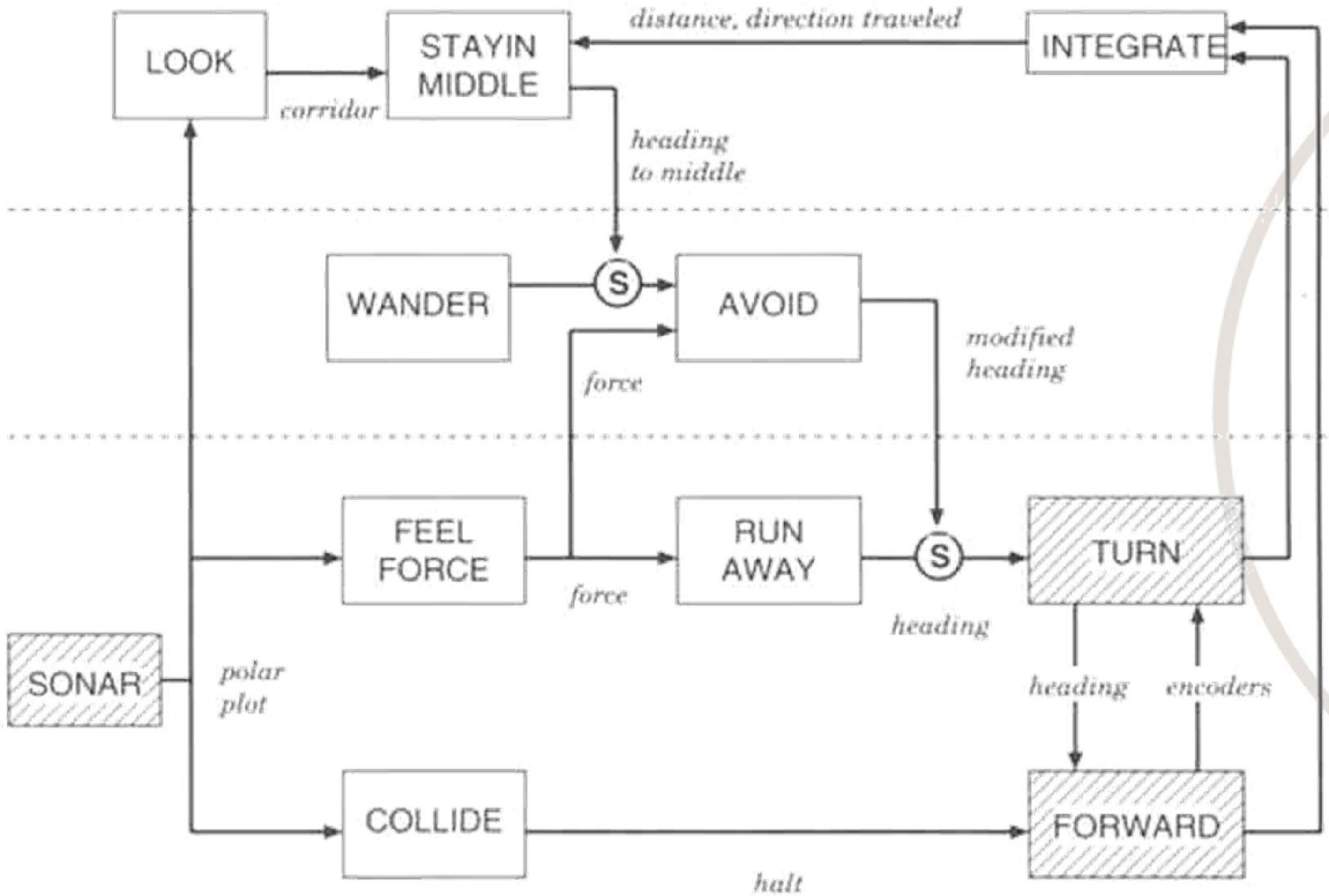
Level 1 - Wander



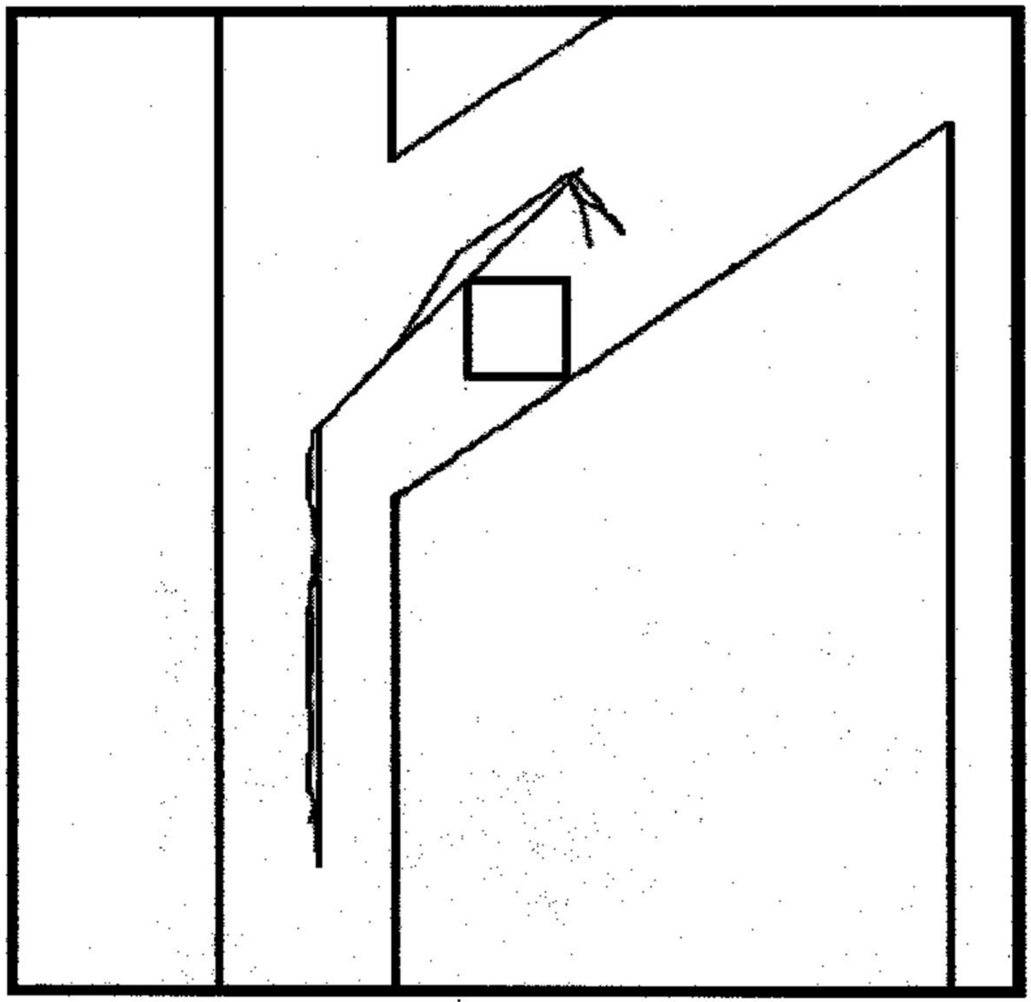
Results from simulations of levels 0 e 1



Level 2 - Explore



Results from simulation of levels 0, 1 e 2



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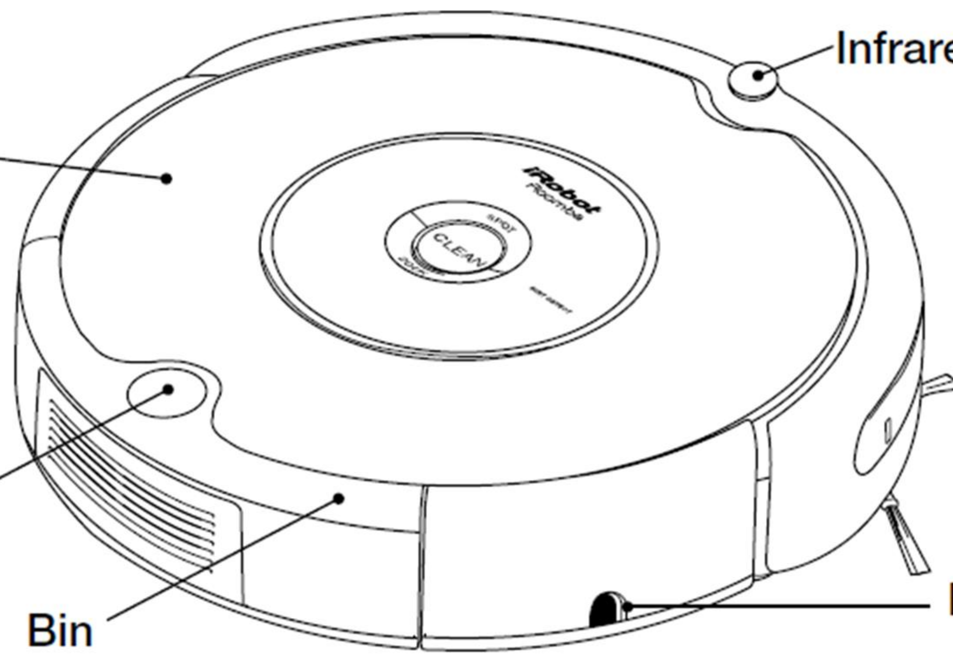


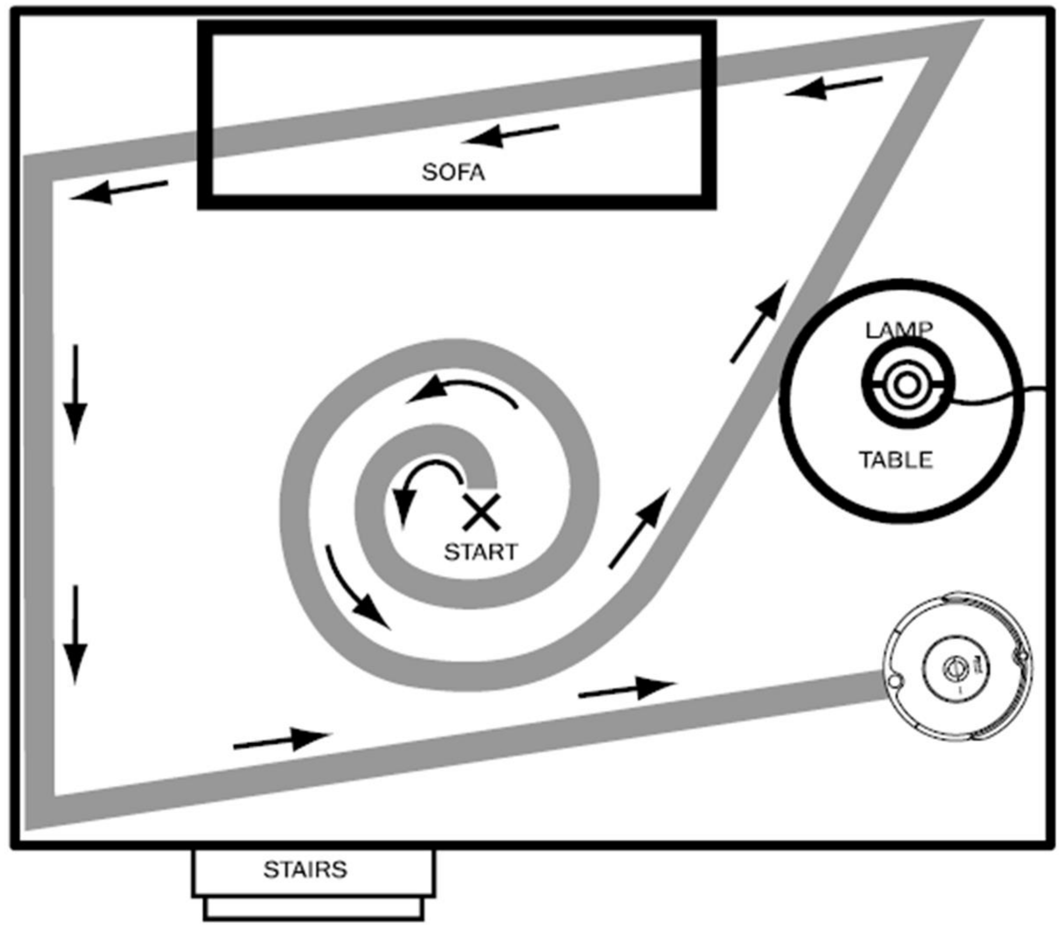
iRobot Roomba – reactive behaviours

Spiraling: Roomba uses a spiral motion to clean a concentrated area.

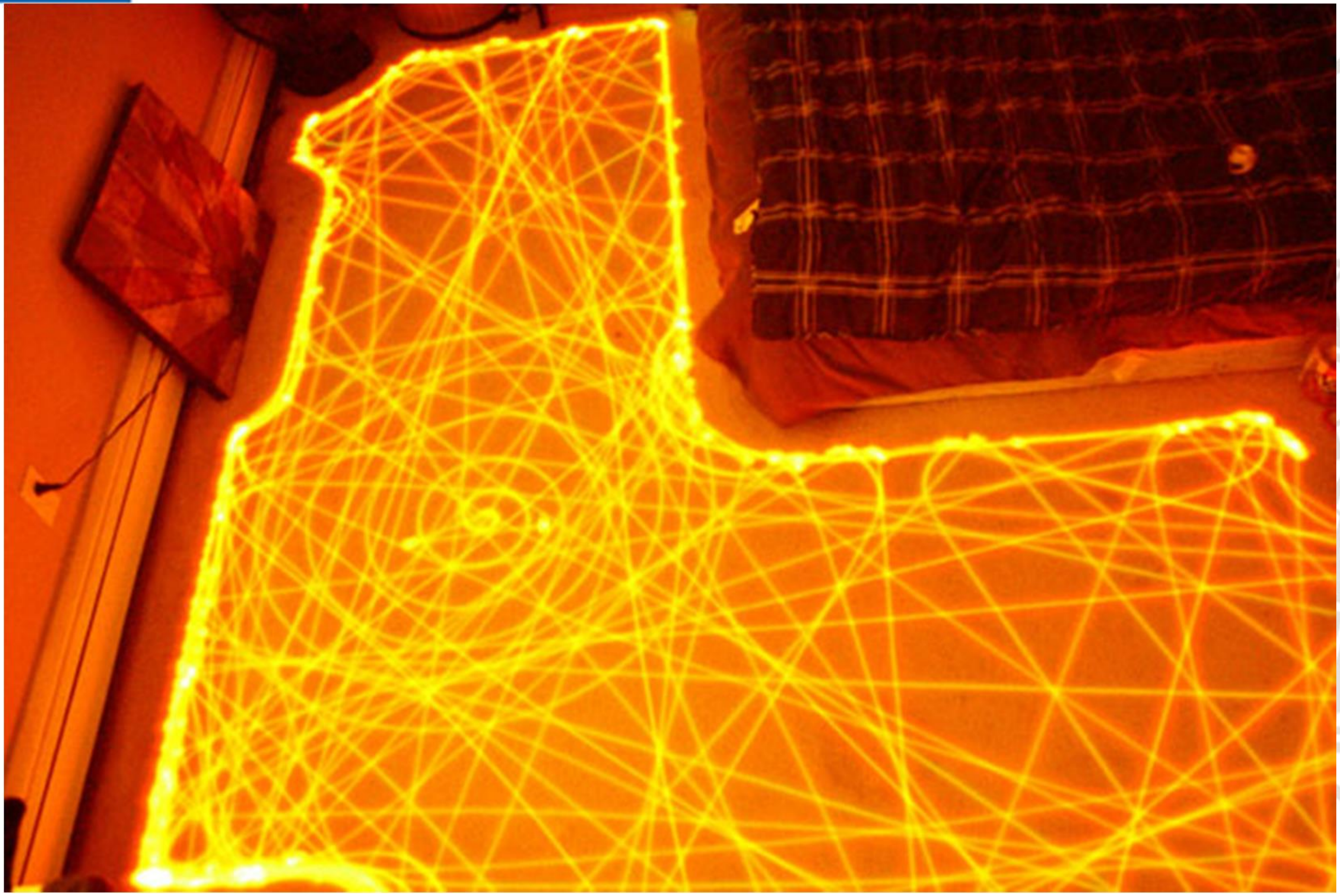
Wall Following: Roomba uses this technique to clean the full perimeter of the room and navigate around furniture and obstacles.

Room Crossing: Roomba crisscrosses the room to ensure full cleaning coverage.

Dirt Detection (selected models)**:** When Roomba senses dirt, the blue Dirt Detect™ light is lit and Roomba cleans more intensely in that area.



iRobot Roomba
Example of working



Hybrid architectures

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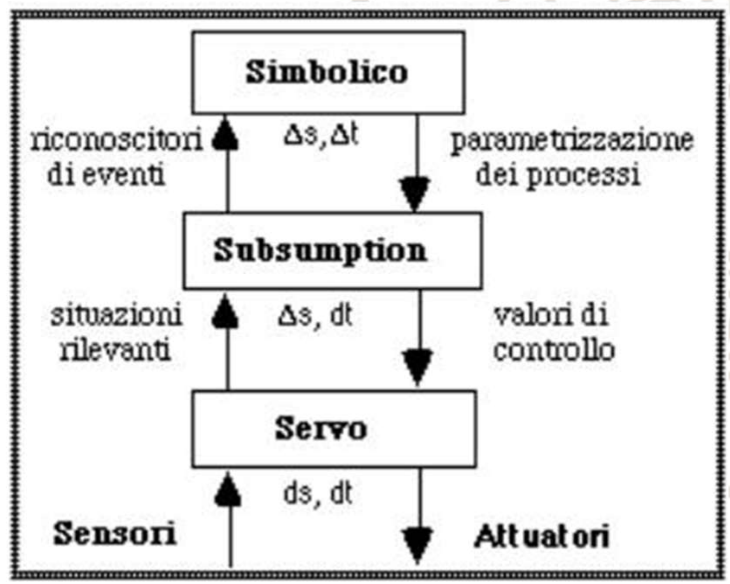
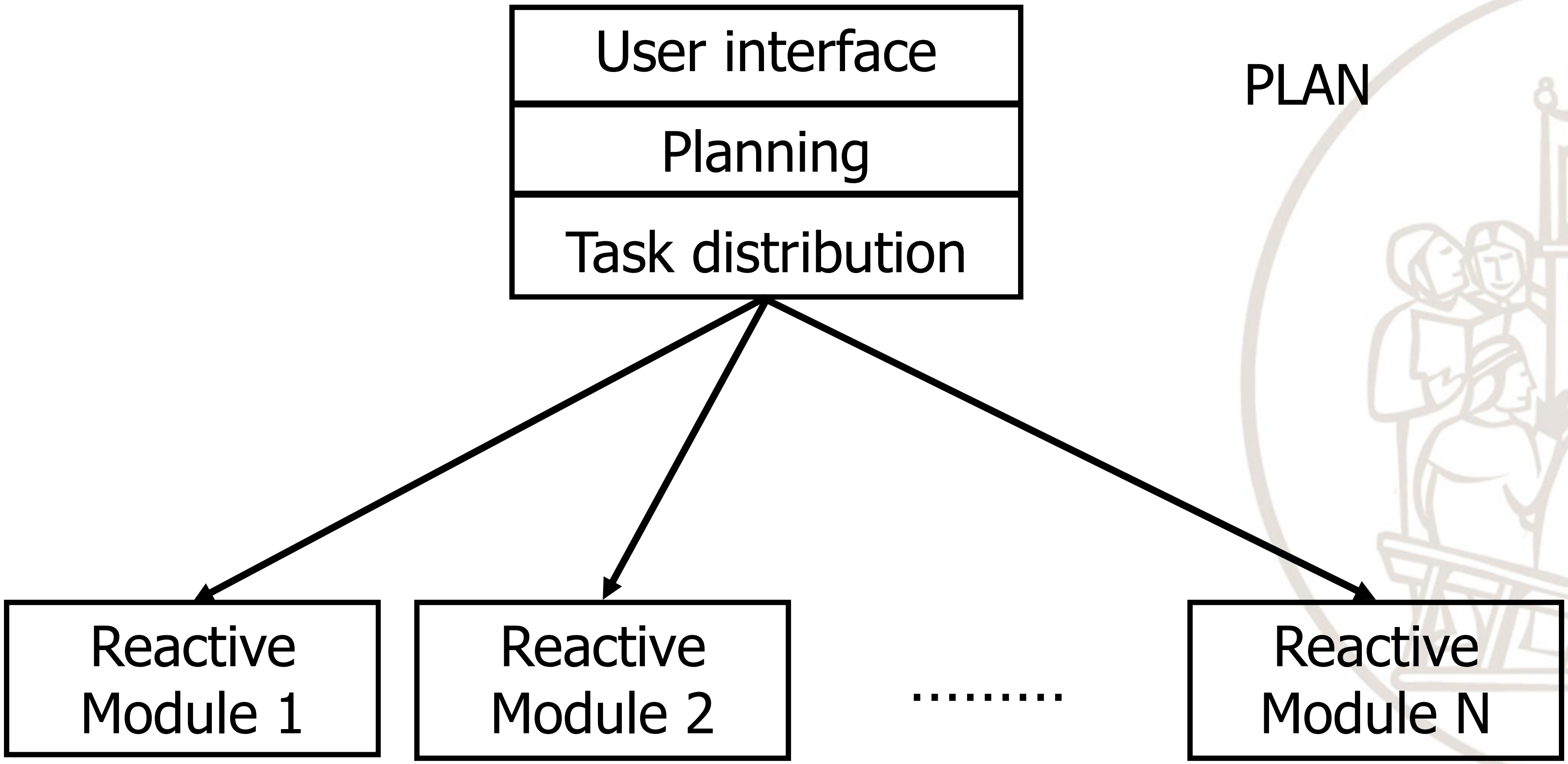
- They have a PLAN primitive, with typically a strategic level and a tactical level.
- The strategic planner makes a long-term plan of the robot actions, by identifying the sequence of sub-tasks needed to reach the goal, and it provides the results to the tactical planner
- The tactical planner initializes and monitors the behaviours, by also coordinating them in time.



General scheme of a hybrid architecture



DustCart hybrid architecture

3 livelli (layer):

AmI – Central station

City maps

maps of the city (40 x 40m) with associated data

High level path planning (waypoints placed about every 40 m)

1st layer

HIERARCHICAL

Robot

Path planning (intermediate waypoints are placed from the current robot position to the next waypoint) - Wavefront

2nd layer

HIERARCHICAL

position data from the Localization Module

data coming from sensors for obstacle avoidance

Path following and obstacle avoidance - **VFH**

3rd layer

REACTIVE

Translational and rotational speed **commands to the Locomotion Module**

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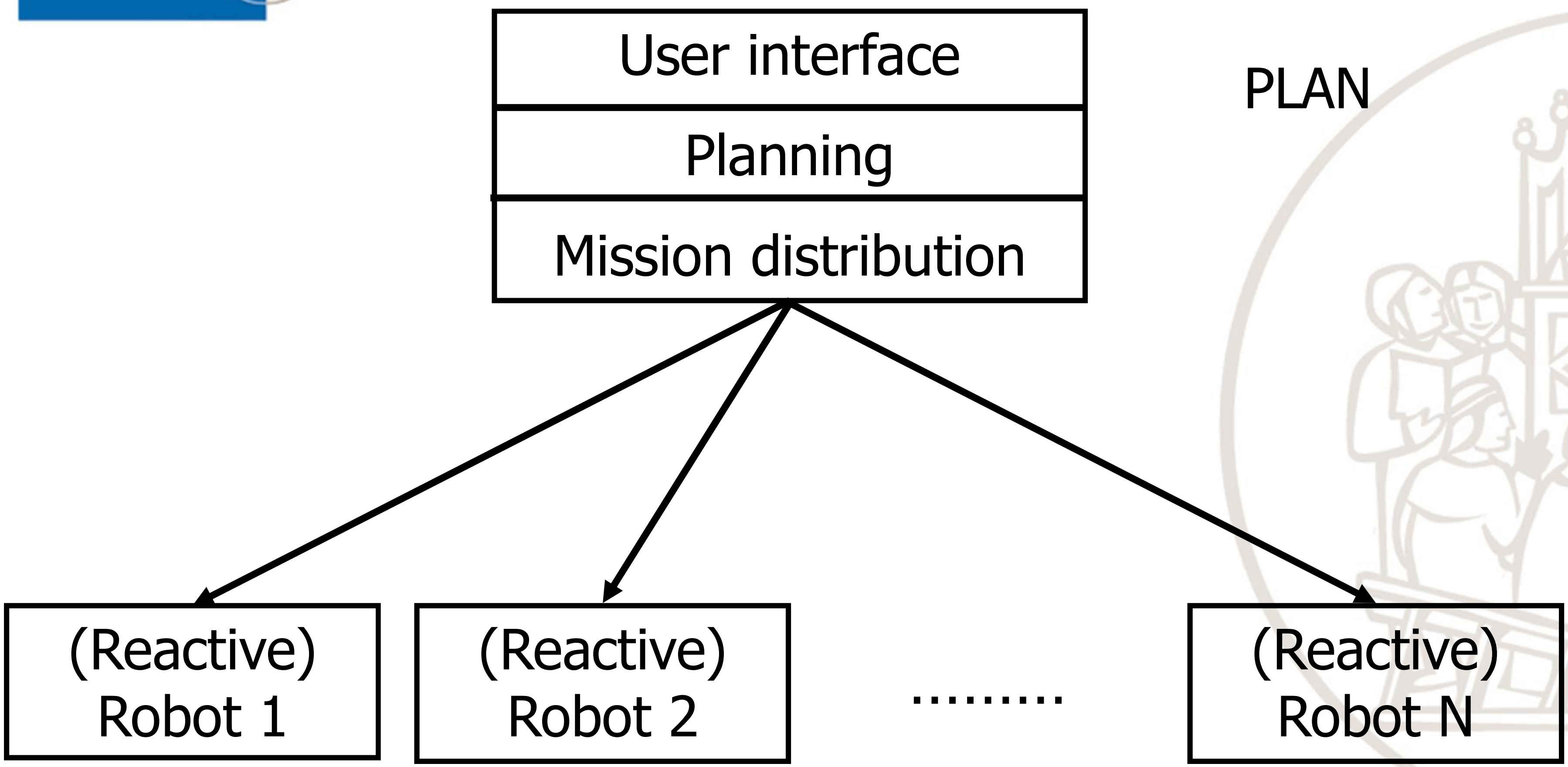
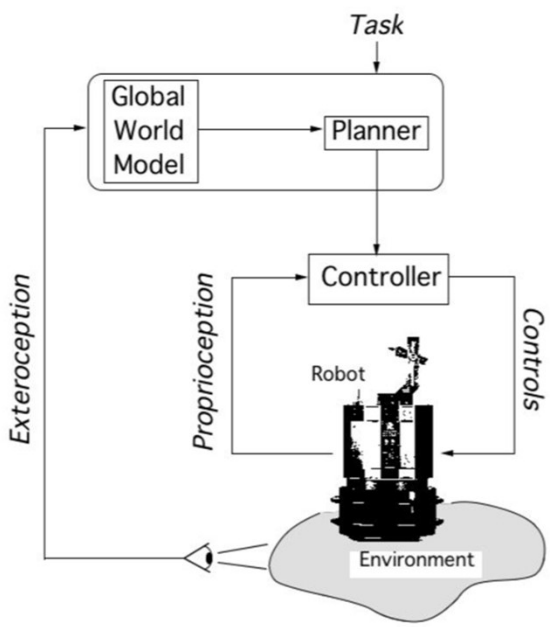
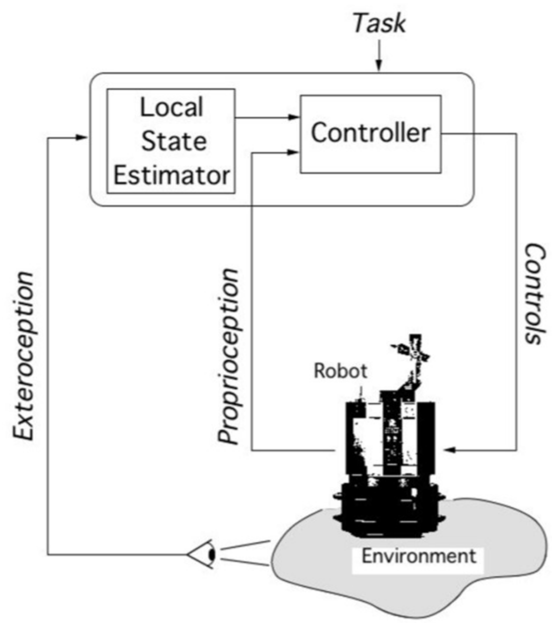
Distributed architectures



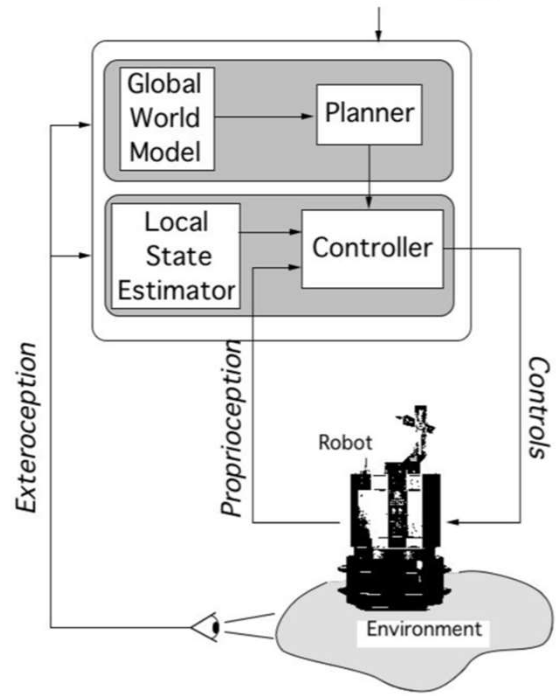
Hierarchical, reactive and hybrid architectures



Hierarchical



Reactive



Hybrid

Traditional classification of robotic architectures

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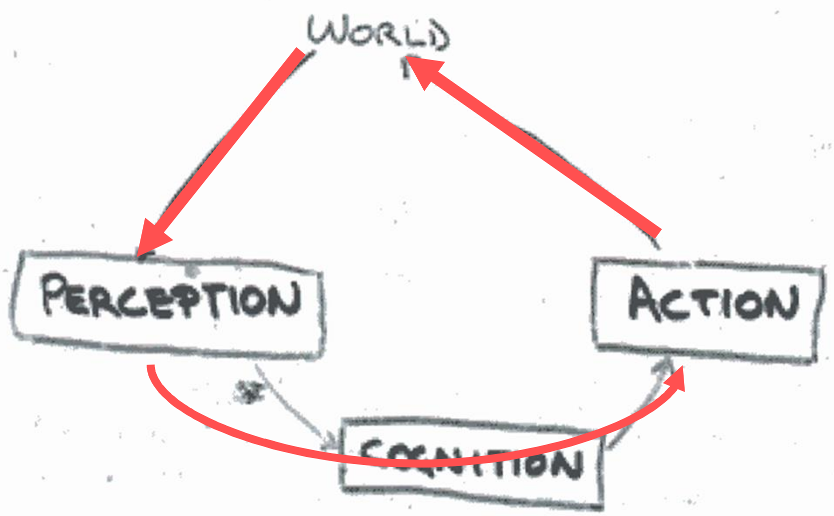

Figure 1: The traditional model where cognition mediates between perceptions and plans of actions.

deliberative, model-based

reactive, behavior-based

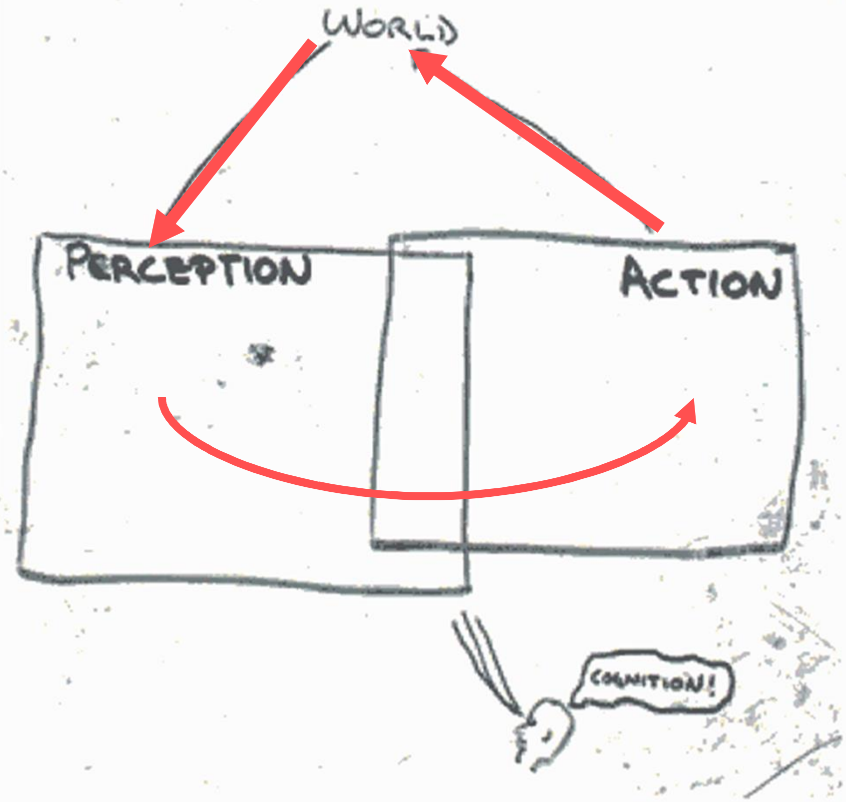

Figure 2: The new model, where the perceptual and action subsystems are all there really is. Cognition is only in the eye of an observer.

R. Brooks, "Cambrian Intelligence", MIT Press, 2000

Delays in the human nervous system

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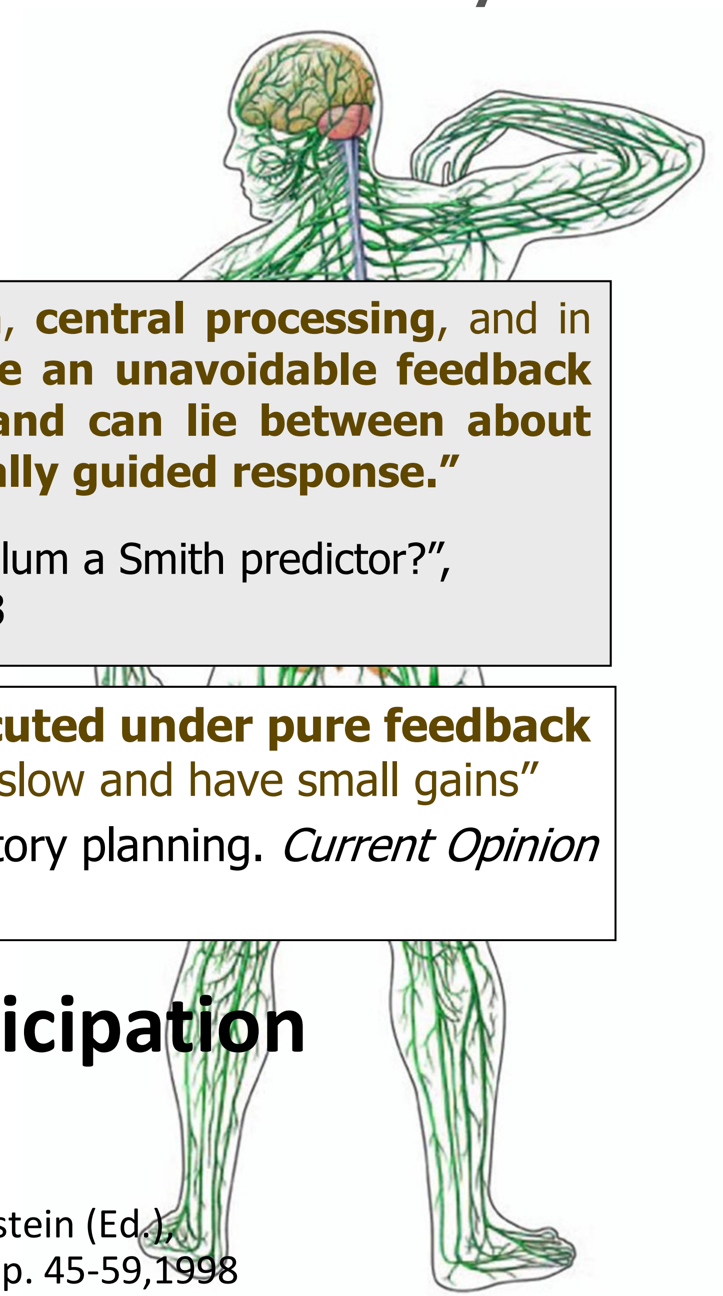


"In motor control **delays** arise in **sensory transduction**, **central processing**, and in the **motor output**. […] **These delays combine to give an unavoidable feedback delay within the negative feedback control loop, and can lie between about 30ms for a spinal reflex up to 200-300 ms for a visually guided response."**

R.C. Miall, D.J. Weir, D.M. Wolpert, J.F. Stein, "Is the cerebellum a Smith predictor?", *Journal of Motor Behavior*, vol. 25, no. 3, pp. 203-216, 1993

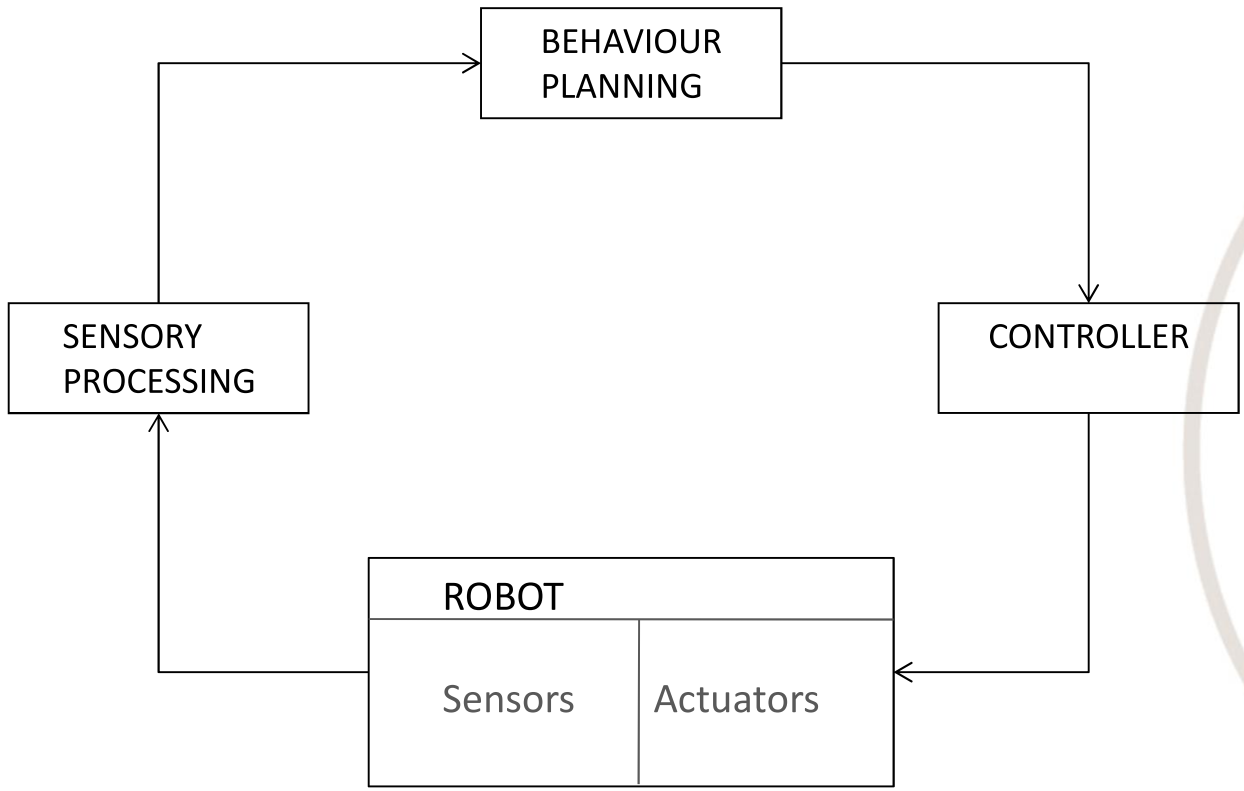
"Fast and coordinated arm movements **cannot be executed under pure feedback control** because biological feedback loops are both too slow and have small gains"

M. Kawato, Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology*, 9, 718-727(1999). Elsevier Science Ltd.

A lesson from neuroscience: anticipation

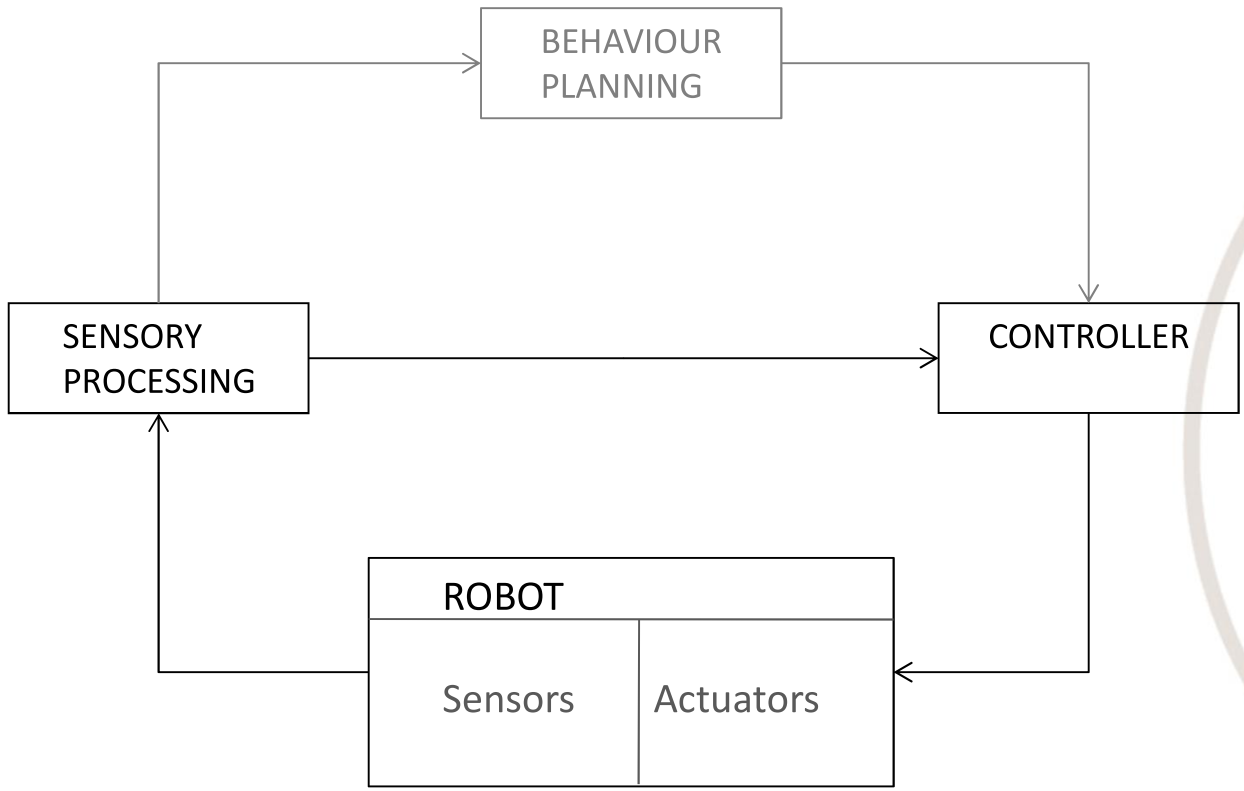
- A. Berthoz, *Le sens du mouvement*. Odile Jacob, Paris, 1997
- R.S. Johansson, "Sensory input and control of grip", in M. Glickstein (Ed.), *Sensory Guidance of Movements*. John Wiley, Chichester, UK, pp. 45-59,1998

Basic scheme for robot behaviour control



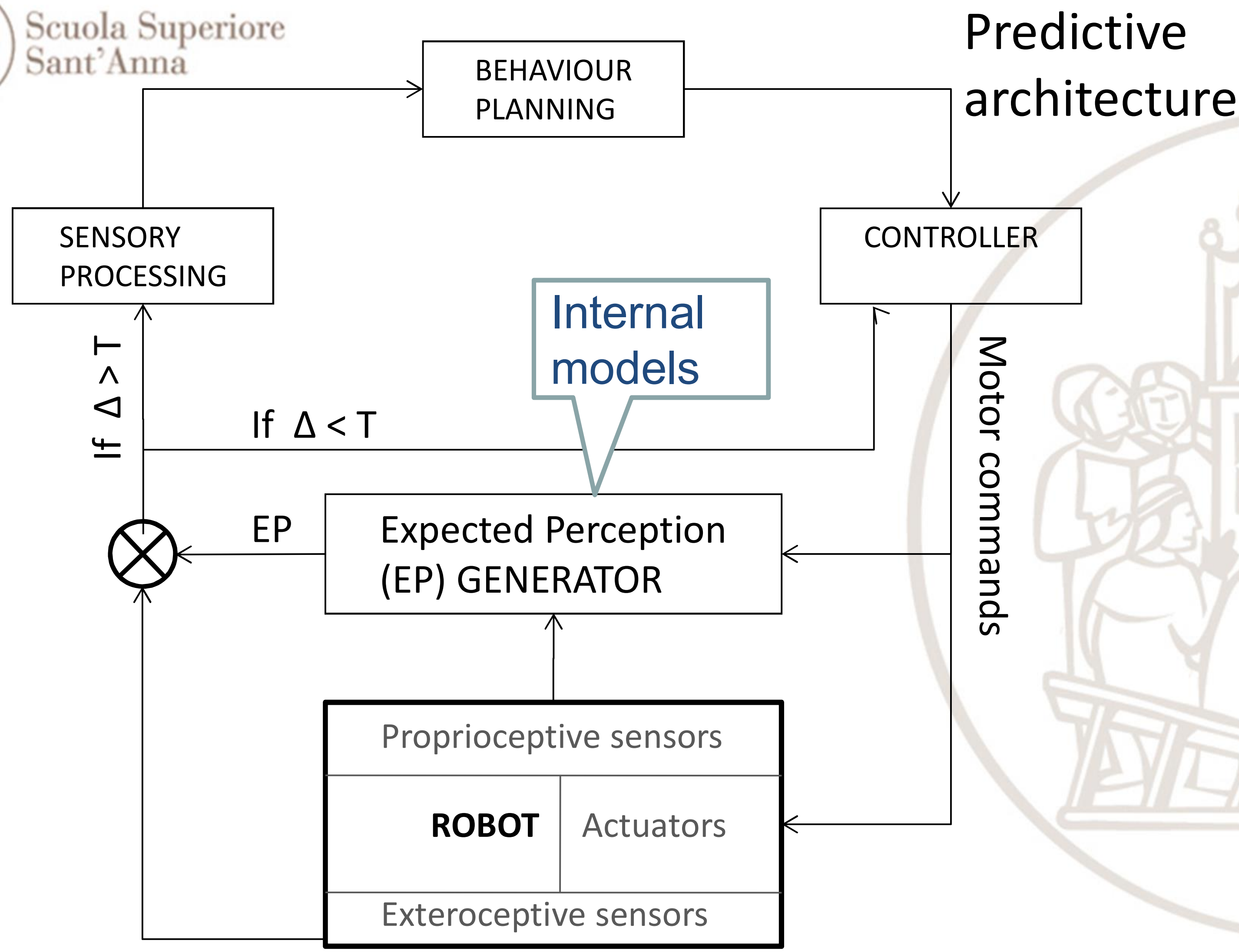
Hierarchical architectures

Basic scheme for robot behaviour control



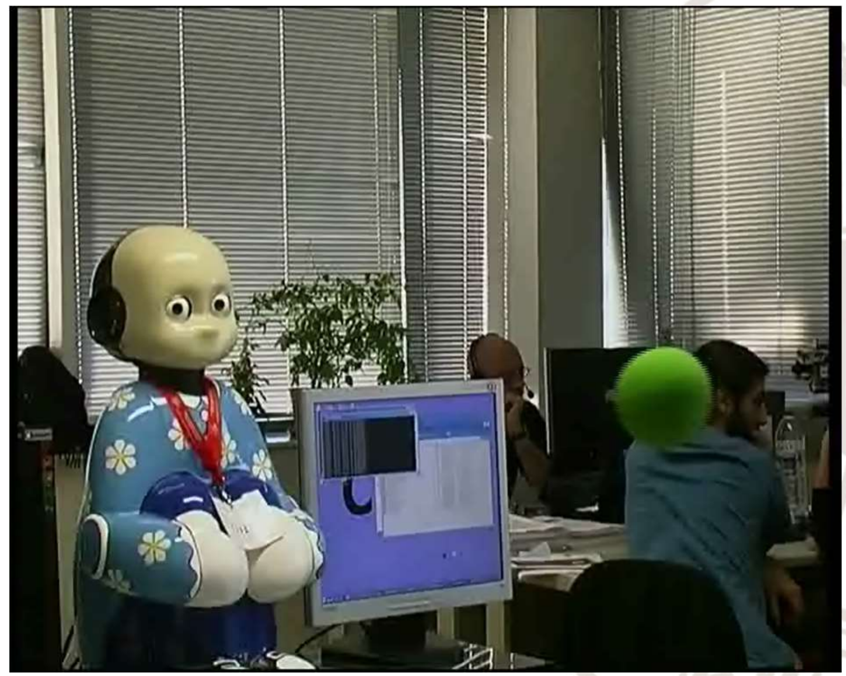
Reactive architectures

Basic scheme for robot behaviour control



C. Laschi, G. Asuni, E. Guglielmelli, G. Teti, R. Johansson, M.C. Carrozza, P. Dario, "A Bio-inspired Neural Sensory-Motor Coordination Scheme for Robot Reaching and Preshaping", *Autonomous Robots*, Vol.5, 2008, pp.85-101.

Predictive smooth pursuit eye movement



The retinal slip (target velocity onto the retina) reaches zero after the algorithm convergence.
When the target is unexpectedly stopped, the system continues to follow the target for a short period.

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Punching a moving target

The prediction is iterated ahead 0.5 seconds
As the predicted target is inside the arm workspace, the robot executes a movement to punch the ball in the ***predicted position***

N. Cauli, E. Falotico, A. Bernardino, J. Santos-Victor, C. Laschi, "Correcting for Changes: Expected Perception-Based Control for Reaching a Moving Target", *IEEE Robotics and Automation Magazine*, 23 (1), pp.63-70, 2016.