based on Gianni A. Di Caro lecture on

ROBOT CONTROL RCHITECTURES SINGLE AND MULTI-ROBOT SYSTEMS: A CASE STUDY IN SWARM ROBOTICS

POLITECNICO MILANO 1863

Unmanned autonomous vehicles in air land and sea

Robots and Unmanned Vehicles Control Architectures

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Dealing with the real world is hard!

Providing autonomy to robots and vehicles can be a cumbersome matter:

- Complex tasks (e.g., autonomous driving from Kolkata to New Delhi)
- Multiple issues to take care of (e.g., batteries, avoid obstacles, don’t fall to stairs)
- Sensor/effector noise and uncertainty
- Dynamic environment and unexpected events
- Lack of precise information / models
- Mechanical constraints (e.g., non-holonomic constraints)

To face such a complexity we need to define and organize a set of building blocks / tools to perform system control ➔ *Robot Control Architecture*

Control architecture

- A principled way of organizing a control system. In addition to providing structure, it also imposes constraints on the way the control problem can be solved (M. Mataric)
- The description of a set of architectural components and how they interact (Dean and Wellman)

Different architectural approaches (based on the same building blocks) produces different designs/results of the same general concept …




Robot architectural paradigms

Classical architectural approaches are based on different "mental models" (*paradigms)*

Paradigm:
A philosophy or set of assumptions and/or techniques which characterize an approach to a class of problems (R. Murphy).

In the case of robots, it defines the general model of operations.

In classic robot control architectures three main paradigms exists

- *Deliberative / Model-based / Hierarchical / Orizontal*
- *Reactive / Behavioral / Vertical*
- *Hybrid / Multi layered (Deliberative + Reactive)*

Deliberative paradigm: “think hard, act later”

Deliberation:
Thoughtfulness in decision and action ➔ Thinking hard

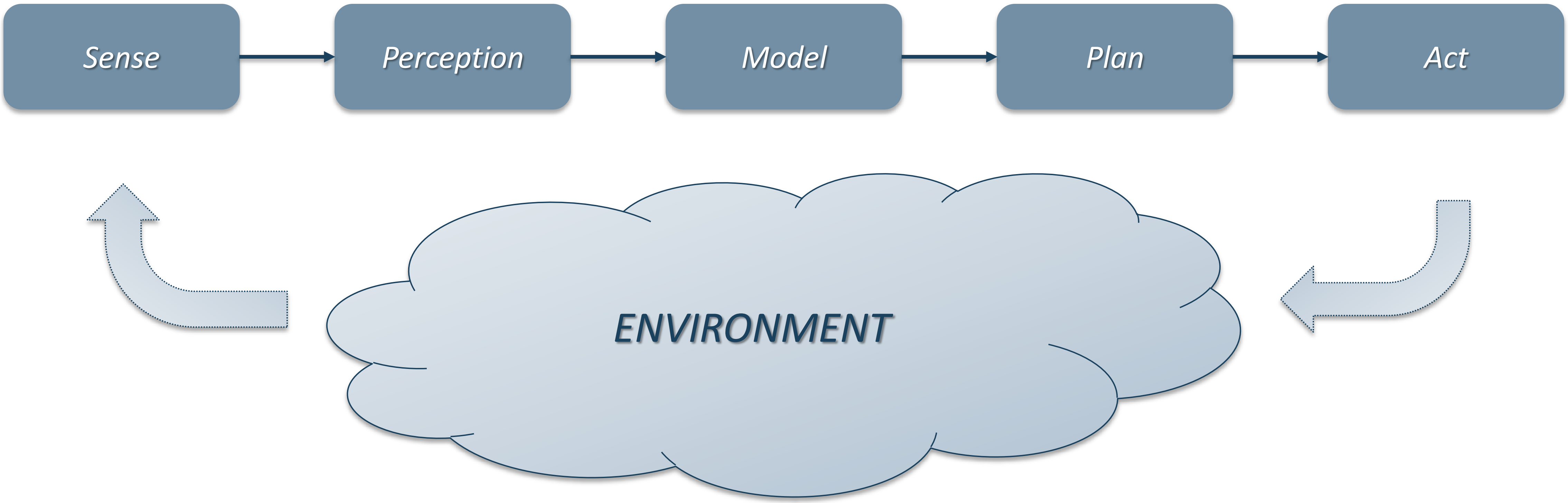
Deliberative control grew out of ***Classical AI*** (60’s - 80’s) and its vision of human intelligence. To be intelligent, machines/robots have to be able to perform some intensive forms of “thinking”, that in turn would require:

- *Internal models of the world*
- *Search through possible solutions*
- *Planning and reasoning to solve problems*
- *Hierarchical system organization*

Top-Down Approach to Problem Solving

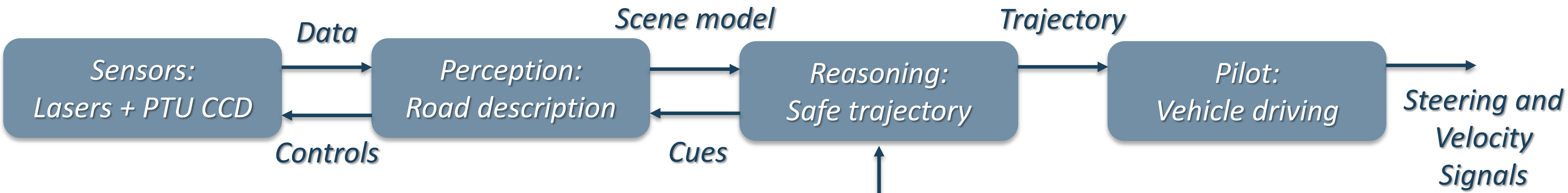
Deliberative paradigm: "think hard, act later"

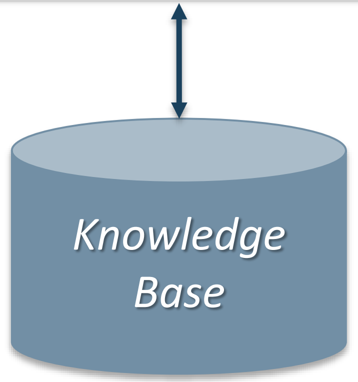
The deliberative paradigm adopt a well defined pipeline of functional modules

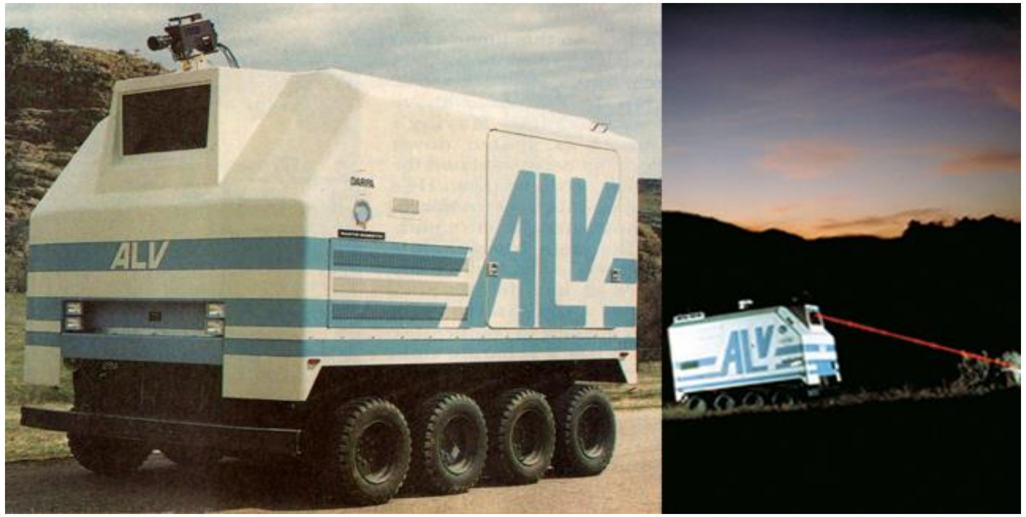


Example of deliberative architecture: *ALVIN*

The *Autonomous Land Vehicle* (ALV) Alvin (CMU mid to end 80’s) was the first on-road and off-road vehicle performing autonomous navigation.



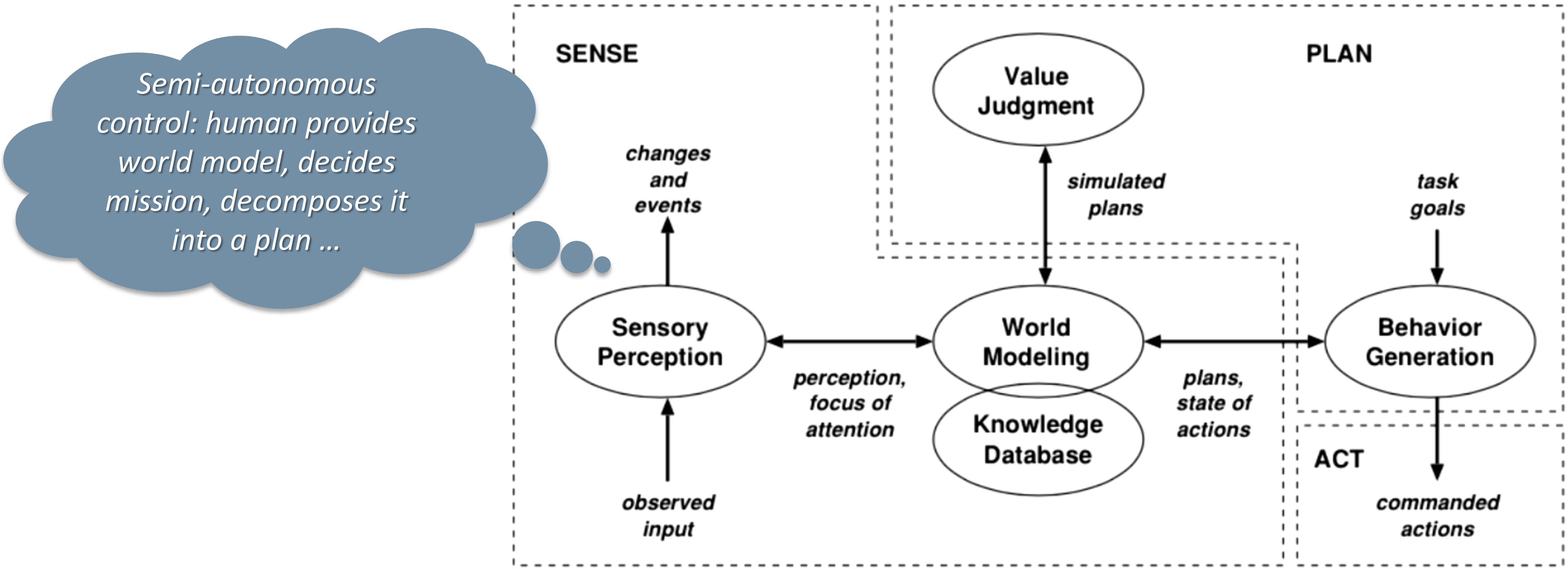




Check SRI Shakey and Flakey and their STRIPS planner!

A more general example: *RCS*

Real-time Control System (RCS) Architecture was proposed by J. Albus (NIST 1986--) as a flexible architecture for manufacturing robots



Source: R. Murphy, *AI Robotics*, MIT Press, 2000

Drawbacks of deliberative architectures (time scale)

Time scale issues

- Inability to react rapidly (e.g., in case of emergency the robot must still sense + model + plan before acting) and to meet multiple goals

- The planning step can potentially be very expensive/long in large state spaces (sensor + model states)
  - This might require the robot to stop and wait for the next plan
  - A large planning time compared to robot speeds “encourages” open loop control, to avoid keep doing (expensive) re-planning. However, this might be a very bad idea in dynamic or uncertain environments

Drawbacks of deliberative architectures (information)

Information issues

- The representation of the state space needs to be accurate, comprehensive, and up to date. This is not always the case in the real-world, and requires continual updating of the world model (which takes time … see previous issues).

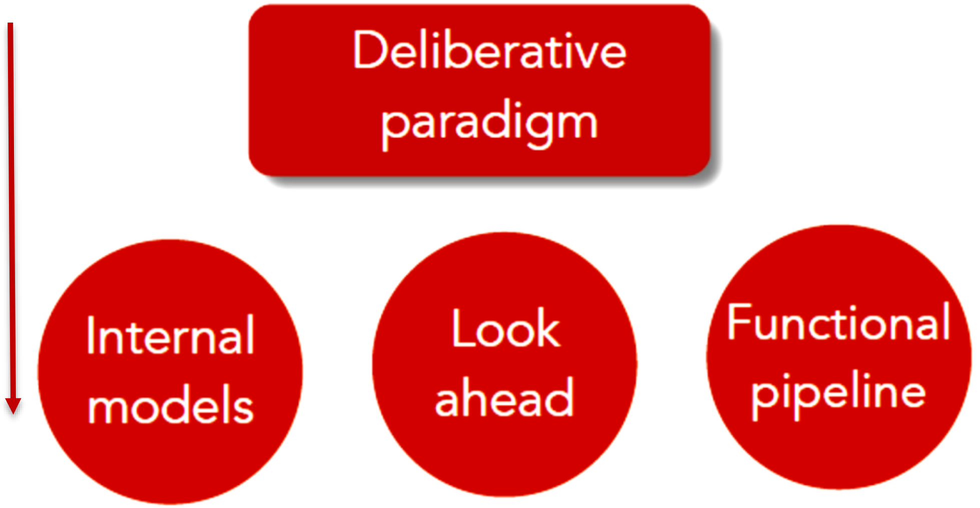
- The robot needs to know with precision the state of the world and of the plan execution at all times. What about dynamic environments? Effector errors? …

Closed-world assumption

Reactive paradigm: “don’t think, react!”

Top Down
Problem Solving

Requires a
closed world



Starting from the mid 1980s, a number of different views (mostly *bio-inspired*) and approaches were developed and employed in robotics, and in AI, moving from symbolic to sub-symbolic / neural models

Works in
an open world

Bottom Up
Problem Solving

Reactive paradigm: “don’t think, react!”

Ethological view (Behavior):
Direct mapping of sensory inputs to a pattern of motor actions that are then used to achieve a task.

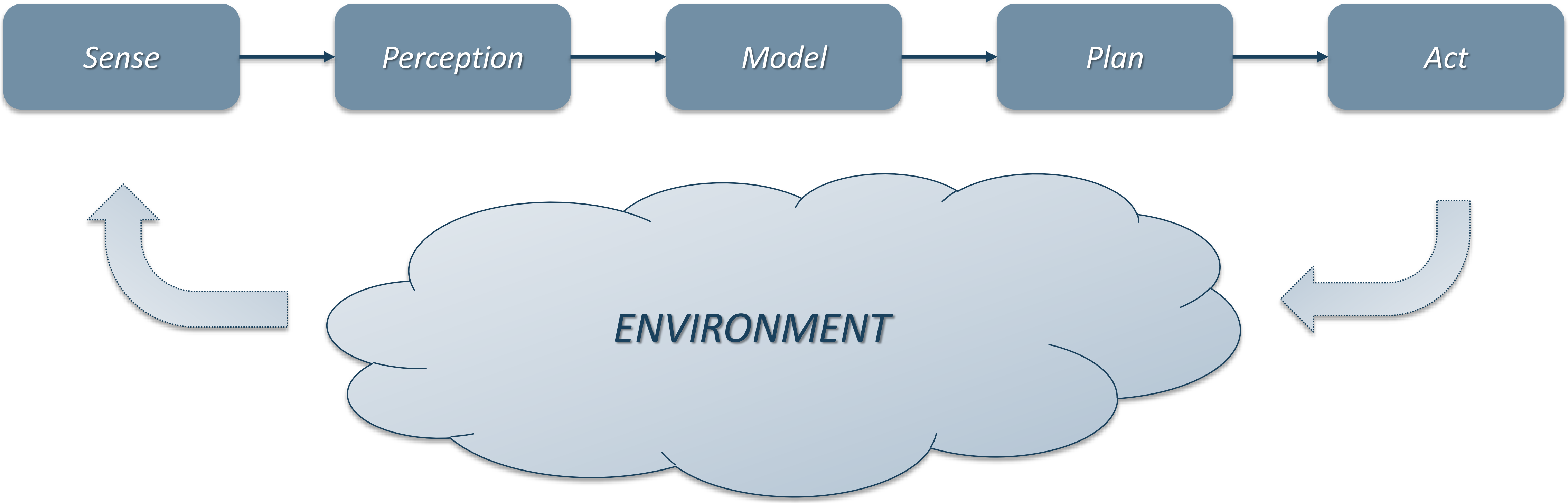
Mathematical view (Function):
A transfer function, transforming sensory inputs into actuator commands

Main difference with respect to the deliberative approach

- Concurrent mode vs. Sequential mode
- Vertical decomposition vs. Horizontal decomposition (alternative view)

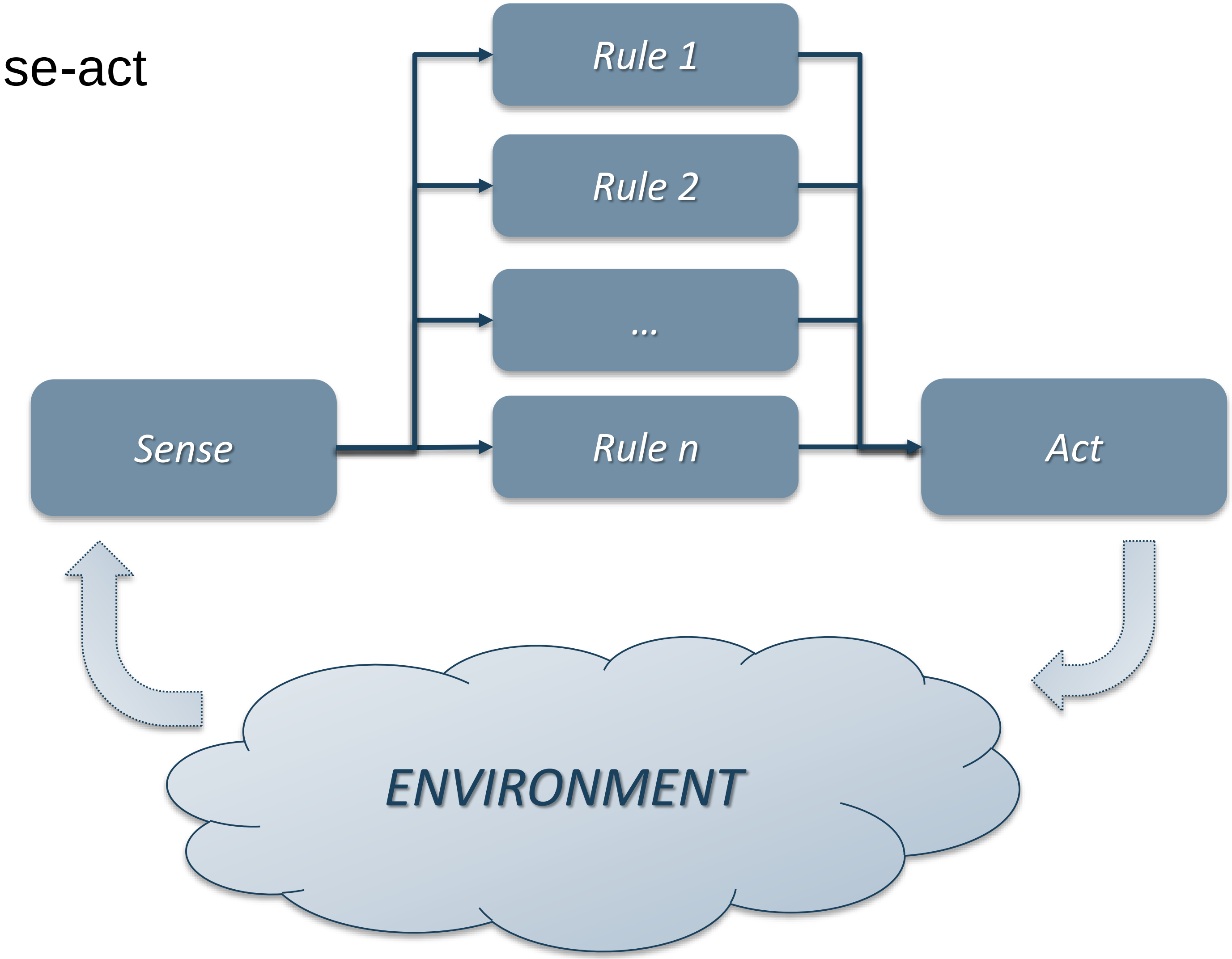
Deliberative paradigm: “think hard, act later”

The deliberative paradigm adopt a well defined pipeline of functional modules



Reactive paradigm: “don’t think, react!”

The Reactive paradigm executes sense-act transfer rules behaviors



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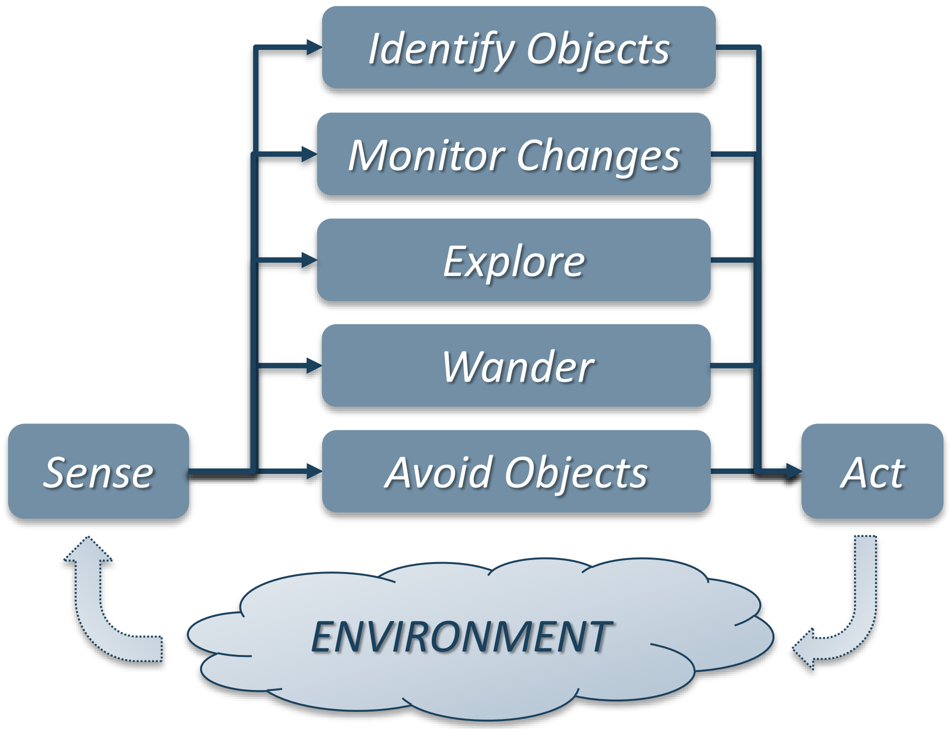

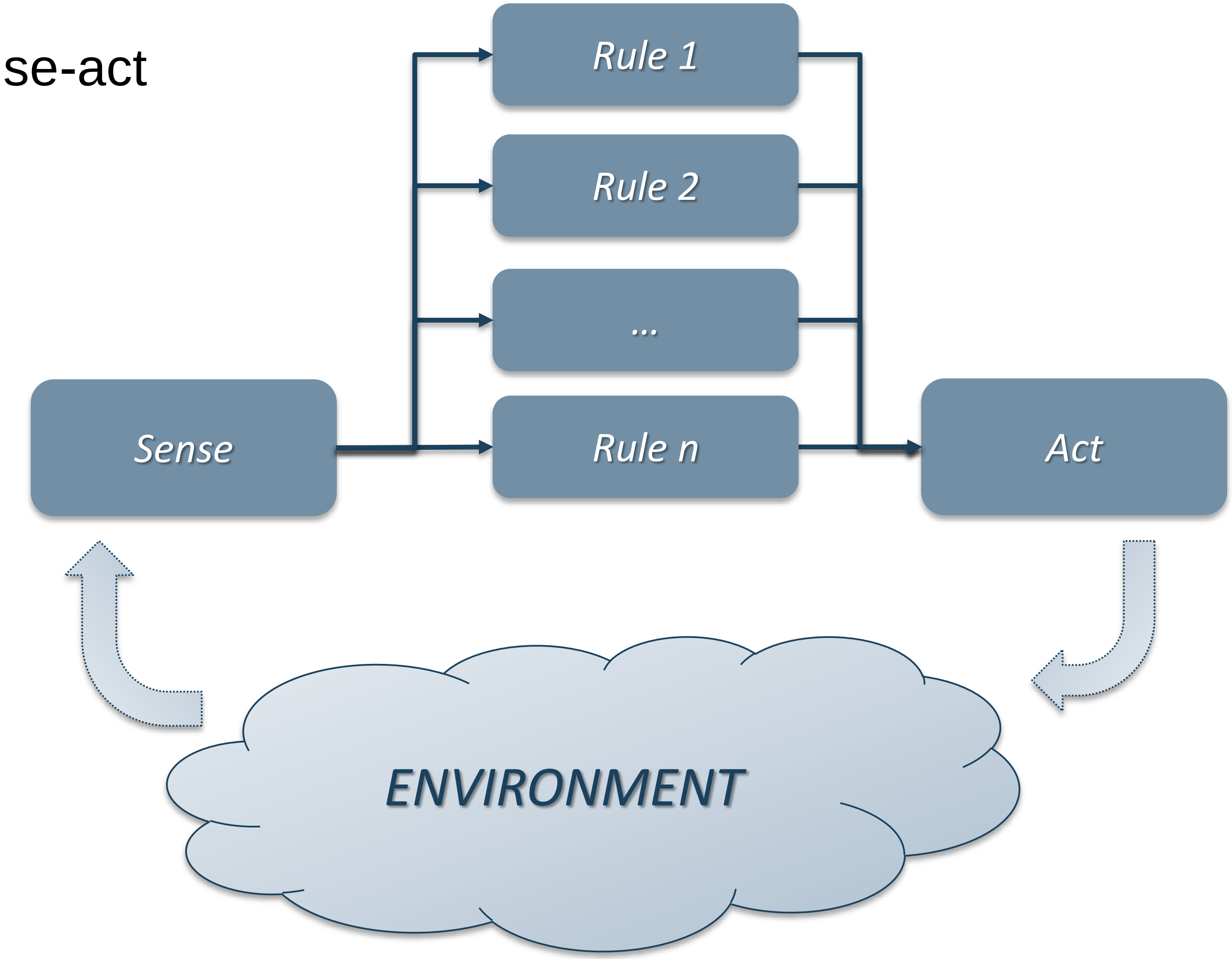

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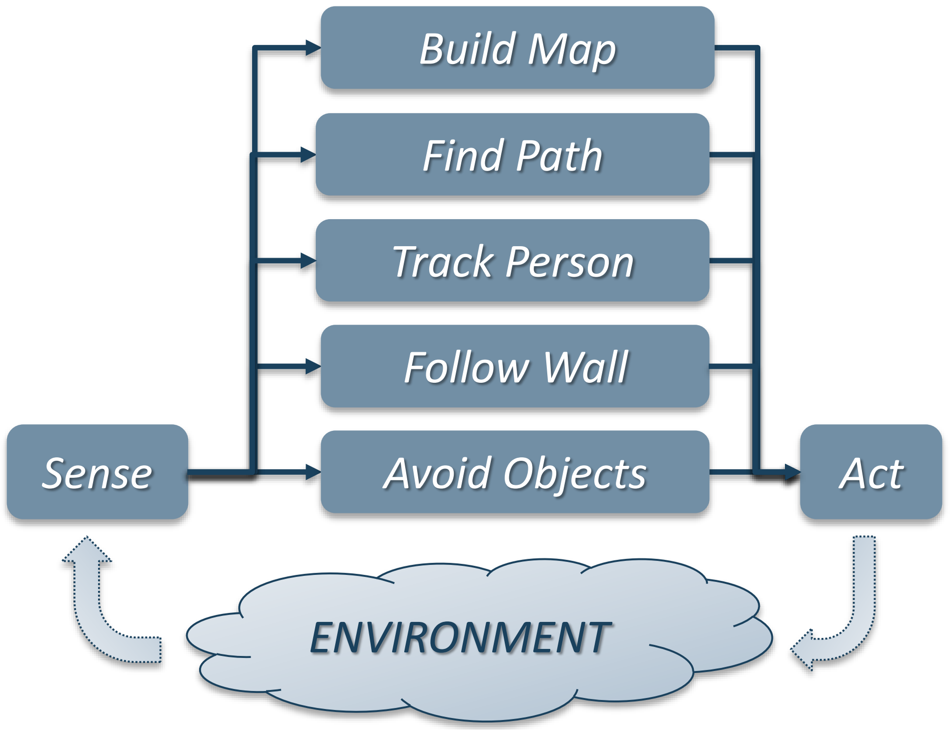
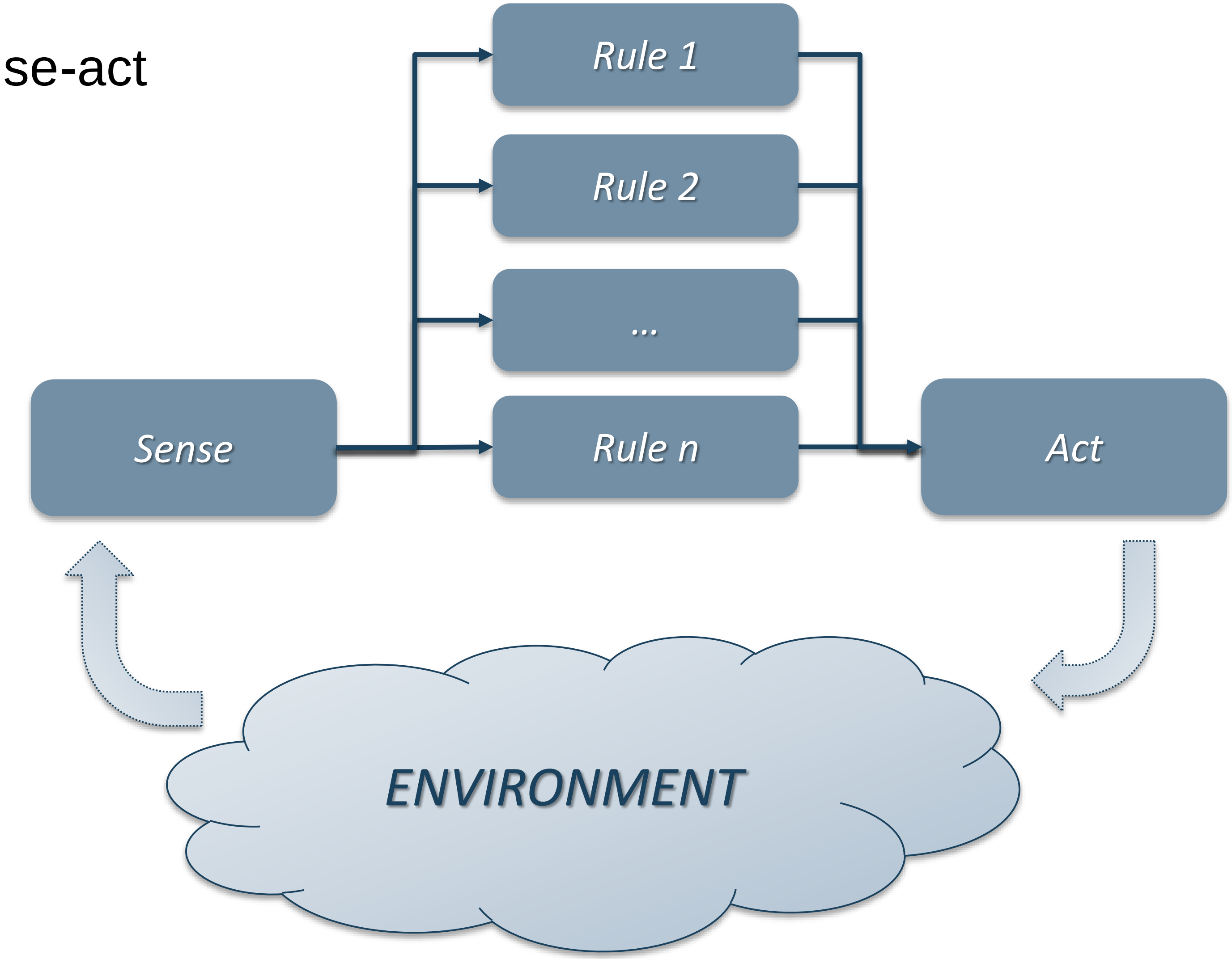
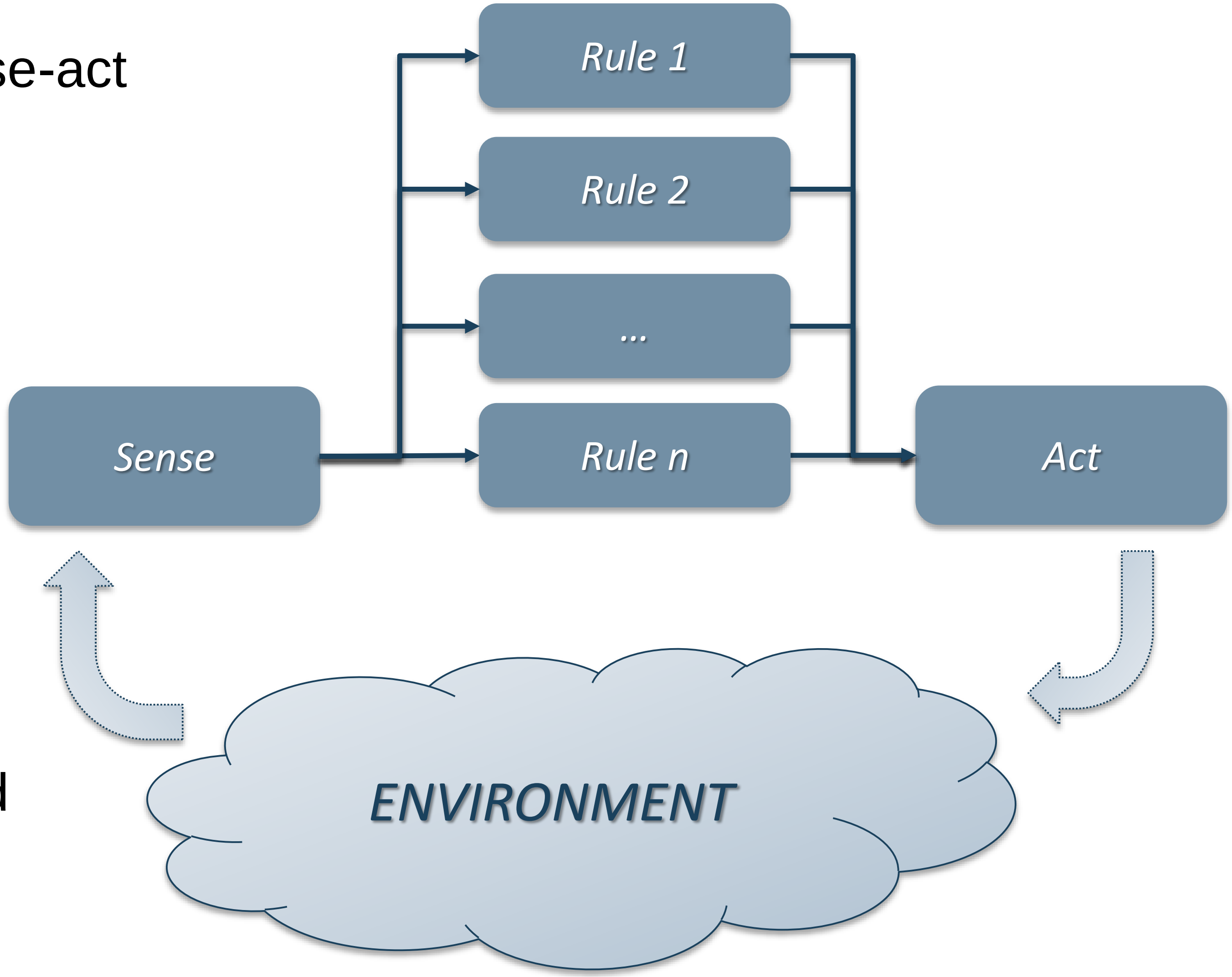




Reactive paradigm: “don’t think, react!”

The Reactive paradigm executes sense-act transfer rules behaviors

- Where the Reactive paradigm finds its roots?
- What is the exact nature/characteristic of the Sense-Act rules?
- How the Act output from the different rules is arbitrated as a single, coherent command to the effectors?



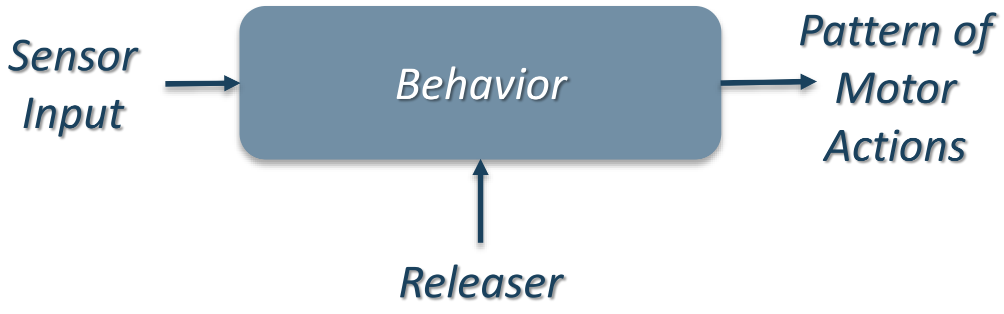
The biological roots of the reactive approach

Dissatisfaction with the limitations of the Deliberative approach led to observing that:

- Animals live in an open world, and roboticists would like to overcome the closed world assumption
- Many “simple” animals exhibit individual and collective intelligent behavior yet have virtually no brain. Therefore, they must be doing something to manage world’s representation complexity!

Reactive rules as *Behaviors*

A fundamental building block of natural intelligence is a behavior: a mapping of sensory inputs to a pattern of motor actions, which then are used to achieve a task



Reactive rules as *Behaviors*

A fundamental building block of natural intelligence is a behavior: a mapping of sensory inputs to a pattern of motor actions, which then are used to achieve a task

Sensor input: Water source detected
Releaser: Giraffe is thirsty
No predators

Action pattern:

```
Move head checking for predators
Put legs in right position,
Lower the neck
Adjust legs position
Drink rapidly
Neck up and check surroundings
```

Ethology studies animal behavior

What kind of (animal) behaviors?

Increasing level of complexity

Reflexive behaviors

- Stimulus-response, “hardwired” behaviors.
- Stimulus is directly connected to the motor action to produce the fastest response time.
- No cognition: if you sense it, you do it!

Reactive behaviors:

- Learned, and then consolidated so they can be executed without conscious thought, but can be changed by conscious thought.

Conscious behaviors:

- Deliberative, requiring conscious thought, possibly combining previously developed behaviors

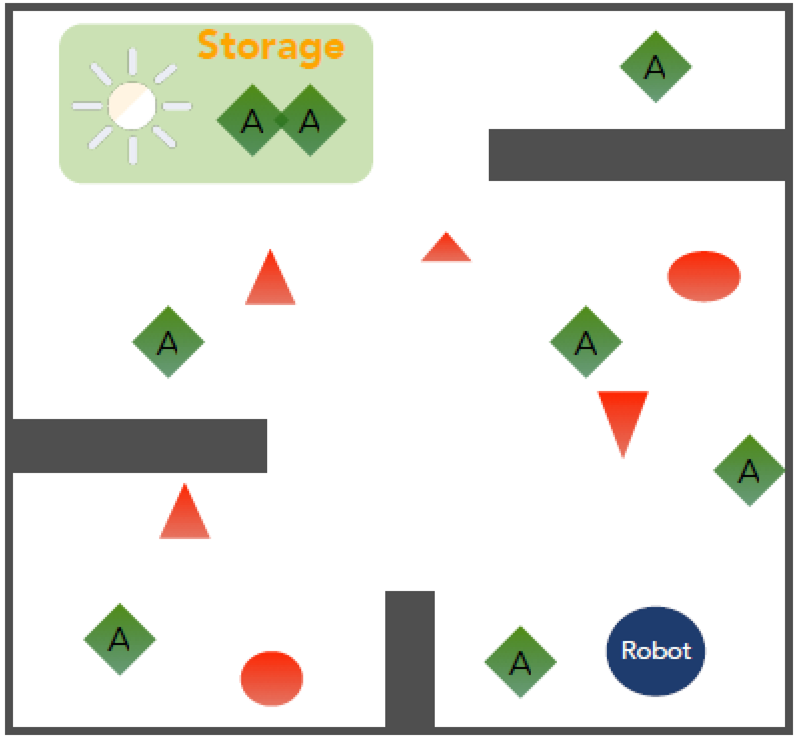
A practical example: object collection

Task specification

- Search for type A objects
- When an A object is found, brought it (pushing) at a storing location identified by a bright light
- Collect as many A objects as possible
- Other objects cannot be pushed
- The environment can feature walls

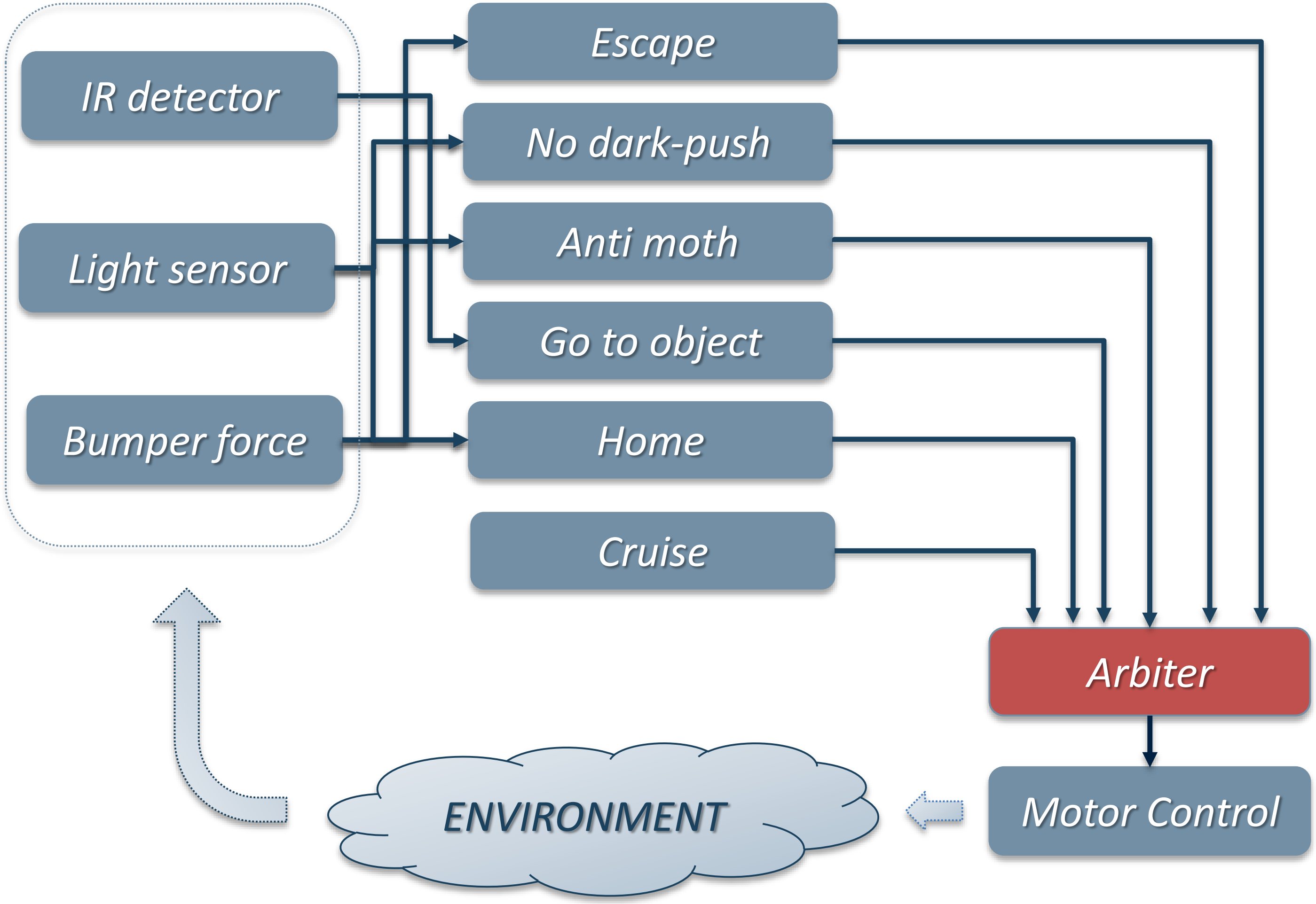
The robot:

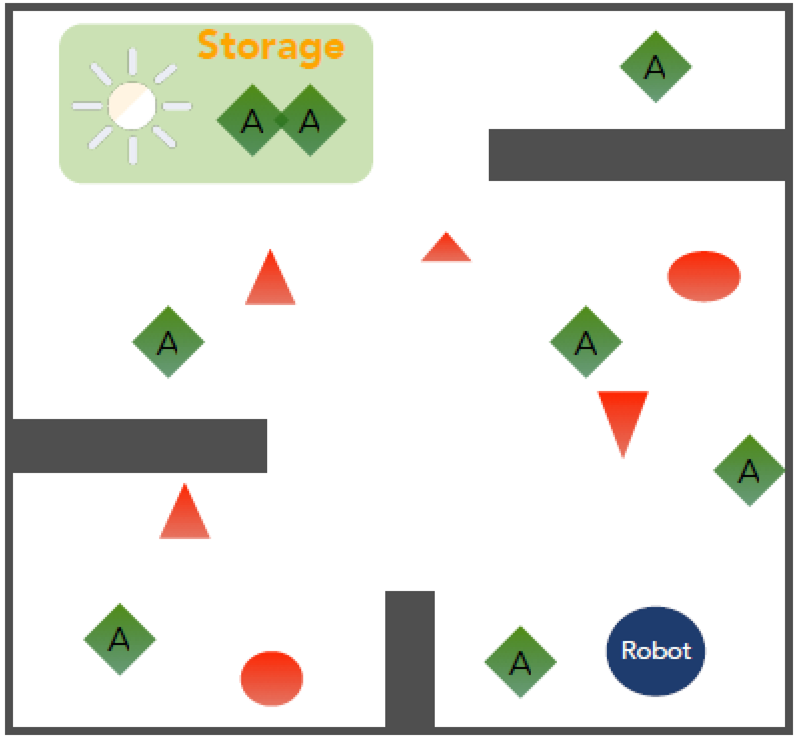
- Frontal IR emitters / detectors
- Light sensors
- Frontal bumper
- Two standard wheels



Seems an easy task …

A practical example: object collection



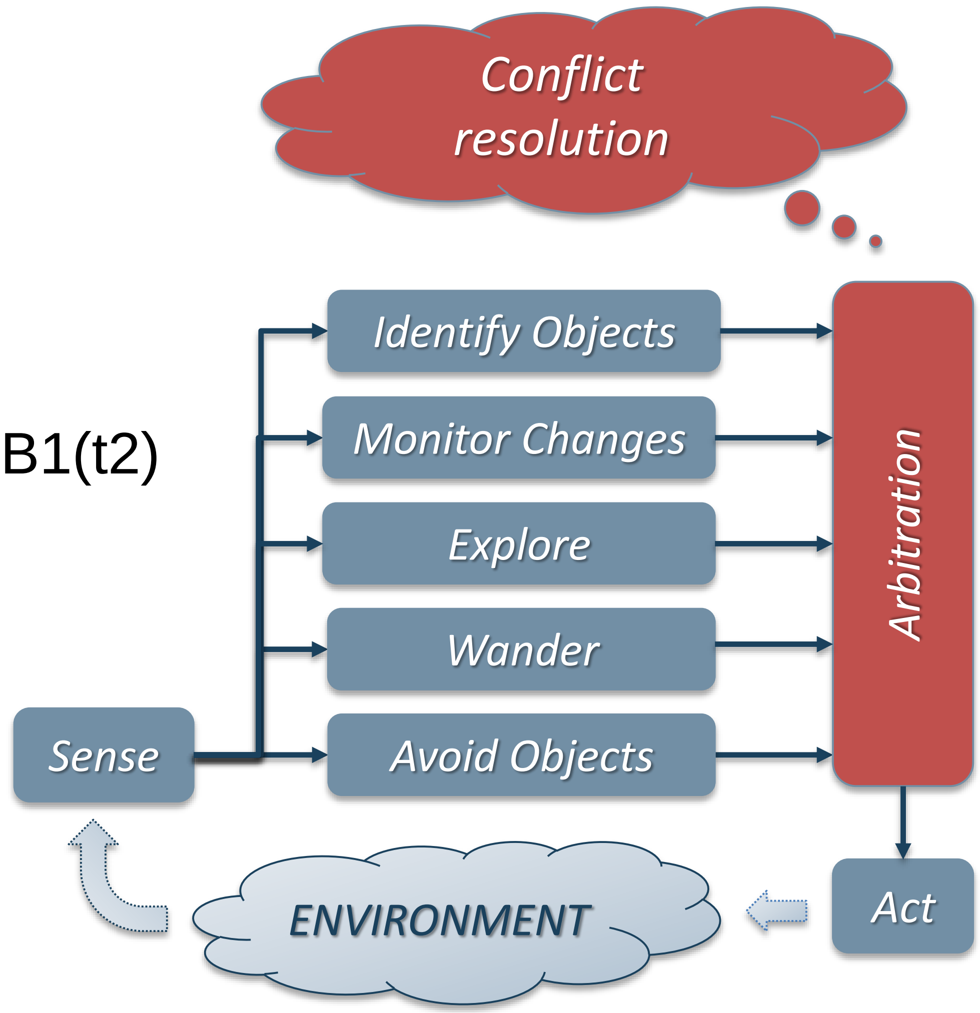


Emergent behavior: a set of simple behaviors that, when acting together, produce the overall desired activity

Behavior arbitration

Several aproaches have been proposed

- Fixed priority: B1(t) $\succ$ B2(t), $\forall t$
- Alternate: B2([t1,t2]), B1([t2,t3])
- Variable priority B1(t1) $\succ$ B2(t1), B2(t2) $\succ$ B1(t2)
- Subsumption
  - Suppression: $B^{New} \succ B^{old}$
  - Inhibition: $B^{New} \wedge B^{Old}$ then $\emptyset$
- Voting: {R1, R2, R3}: X, {R4}: Y, then X
- Averaging / Composition: B1 $\oplus$ B2

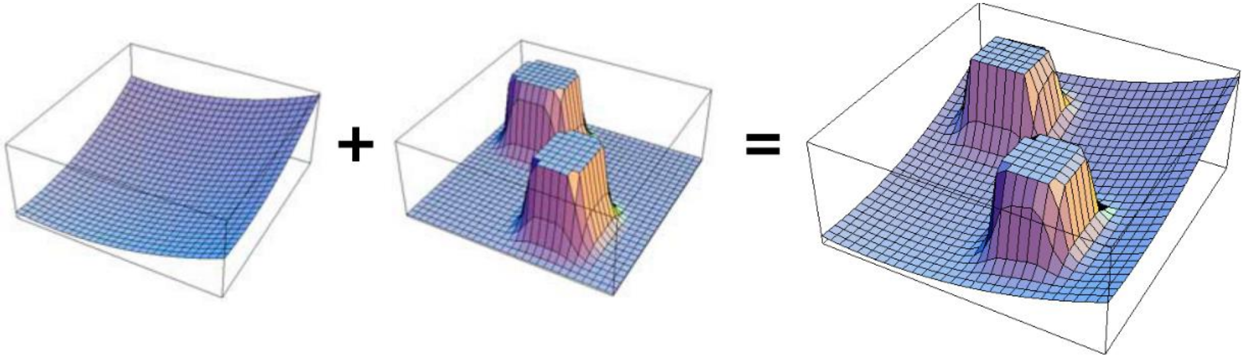


Composition approach by Potential Fields

A navigation method commonly adopted uses *Motor schemas / Potential fields.*

The robot can be represented as a particle under the influence of an *artificial potential field U(q)* which superimposes:

- Repulsive forces from obstacles
- Attractive force from goal(s)



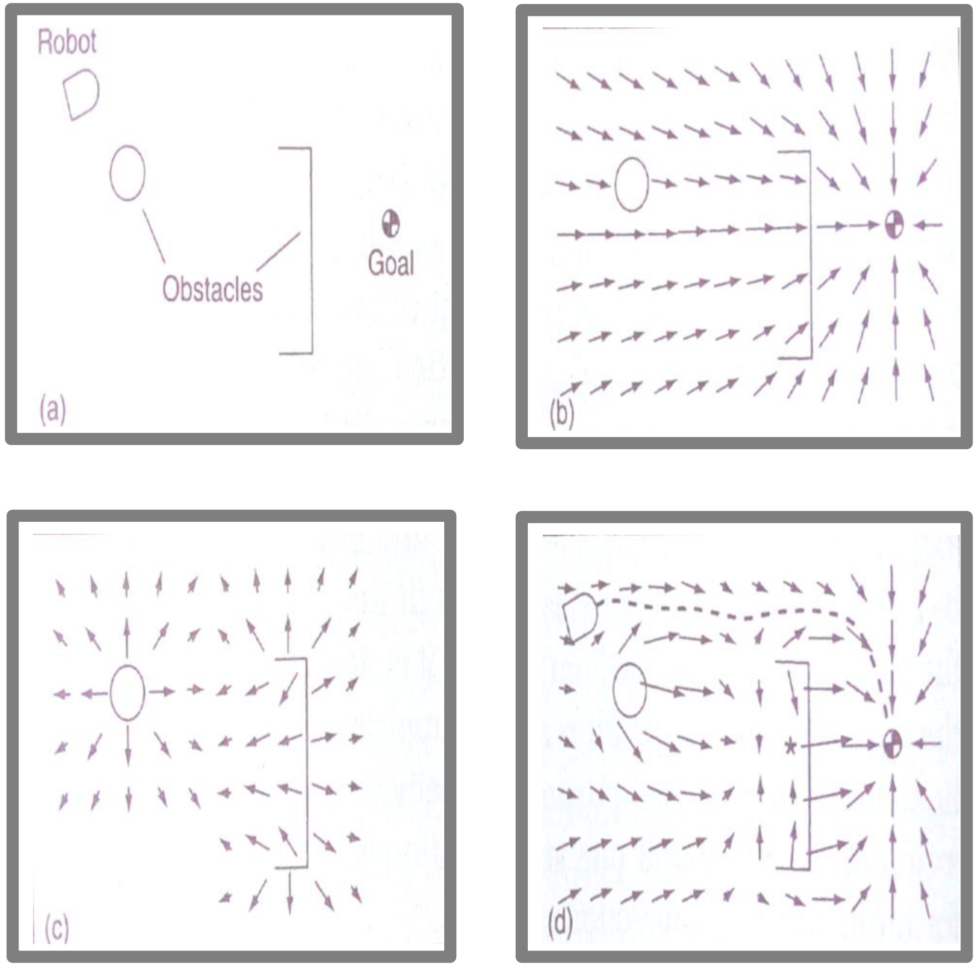
Different behaviors *feels* different fields, and the arbiter combines their proposed motion vectors

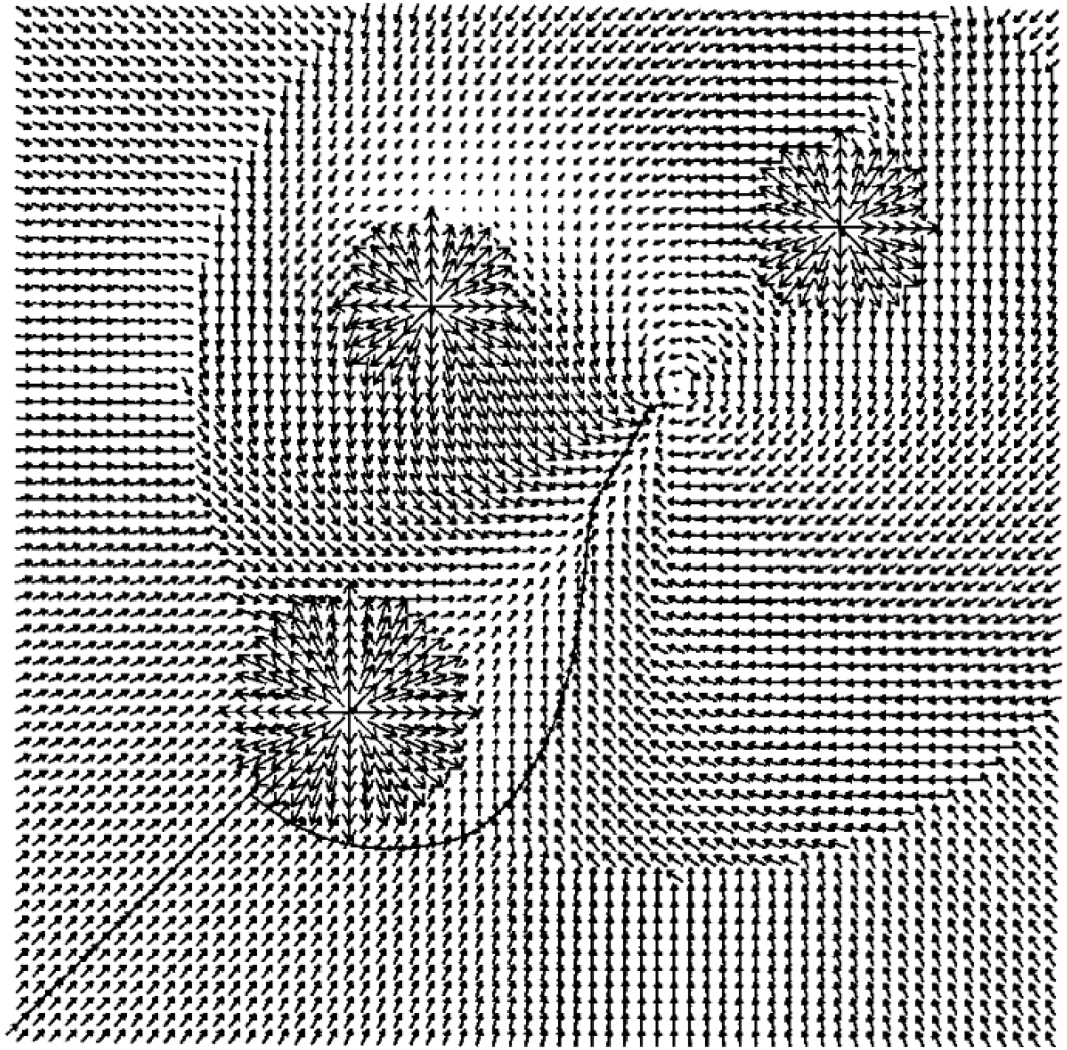
Following a gradient descent moves the robot towards the minima (goal = global minimum)

$$U(q) = U_{att}(q) + U_{rep}(q)$$

$$\vec{F}(q) = -\vec{\nabla} U(q)$$

Potential fields at work





Reactive paradigm and beyond

- Real-time capabilities, works in open worlds, doesn’t need models
- Task-oriented decomposition of the controller in parallel modules,
- Can deal with multiple sensors operating at different time-scales
- Easily extensible / modifiable by adding / removing modules/behaviors
- A network of behaviors can be created to build up more complex behaviors
- Rely only on minimal state, have no memory, no learning, no internal models

Bottom-up design, emergent behavior:

- Looks easier compared to top-down specification, but it’s also a sort of art
- Issues with predictability and formal analysis

High-level reasoning and planning:

- Planning, and more general, cognition and deliberation are useful, if not needed in complex scenarios

They complete each other

Hybrid architectures: Deliberative + Reactive

The most used approach today, but still an art!

Combine the best of two world in a single architecture

- Deliberative:
  - Representations
  - Models
  - Planning

Strategic planning / reasoning

- Reactive
  - Real-time
  - Multiple goals
  - Robustness
  - Flexibility
  - Modularity

Low(er)-level controls and behaviors

Hybrid architectures: Deliberative + Reactive

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- Deliberative:
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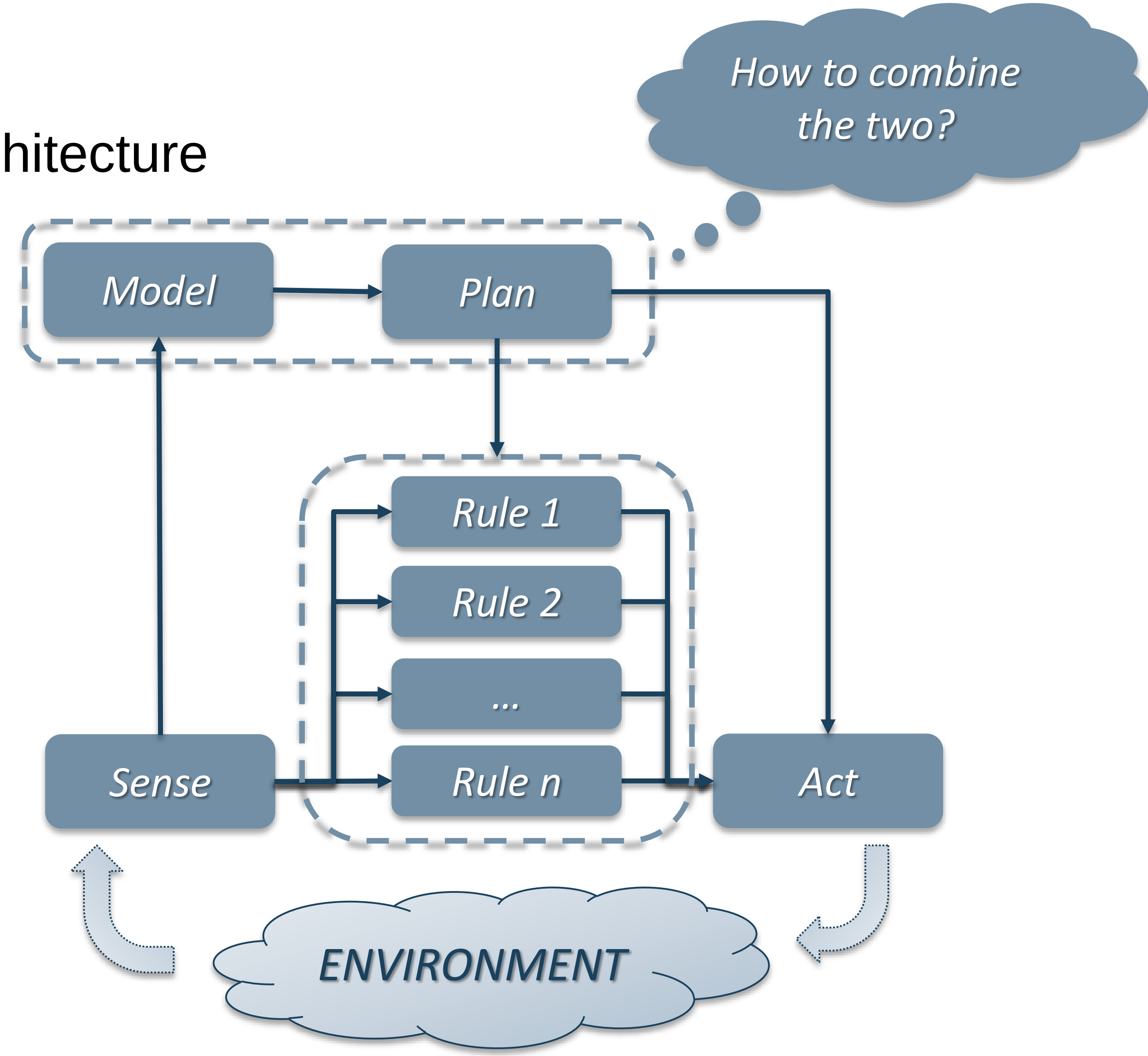
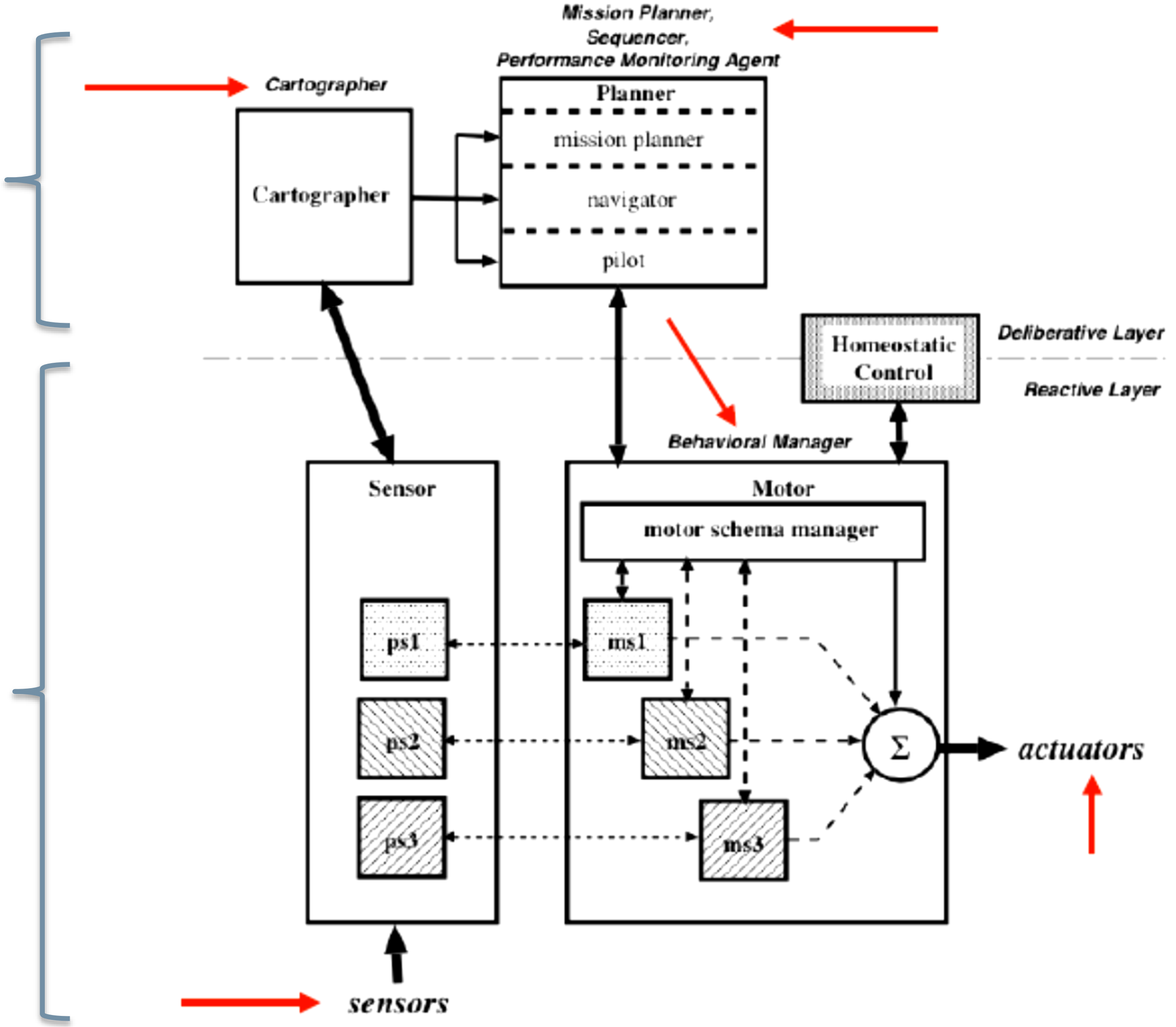


Example of hybrid architecture: *AURA*

Strategic planning / reasoning

Low(er)-level controls and behaviors



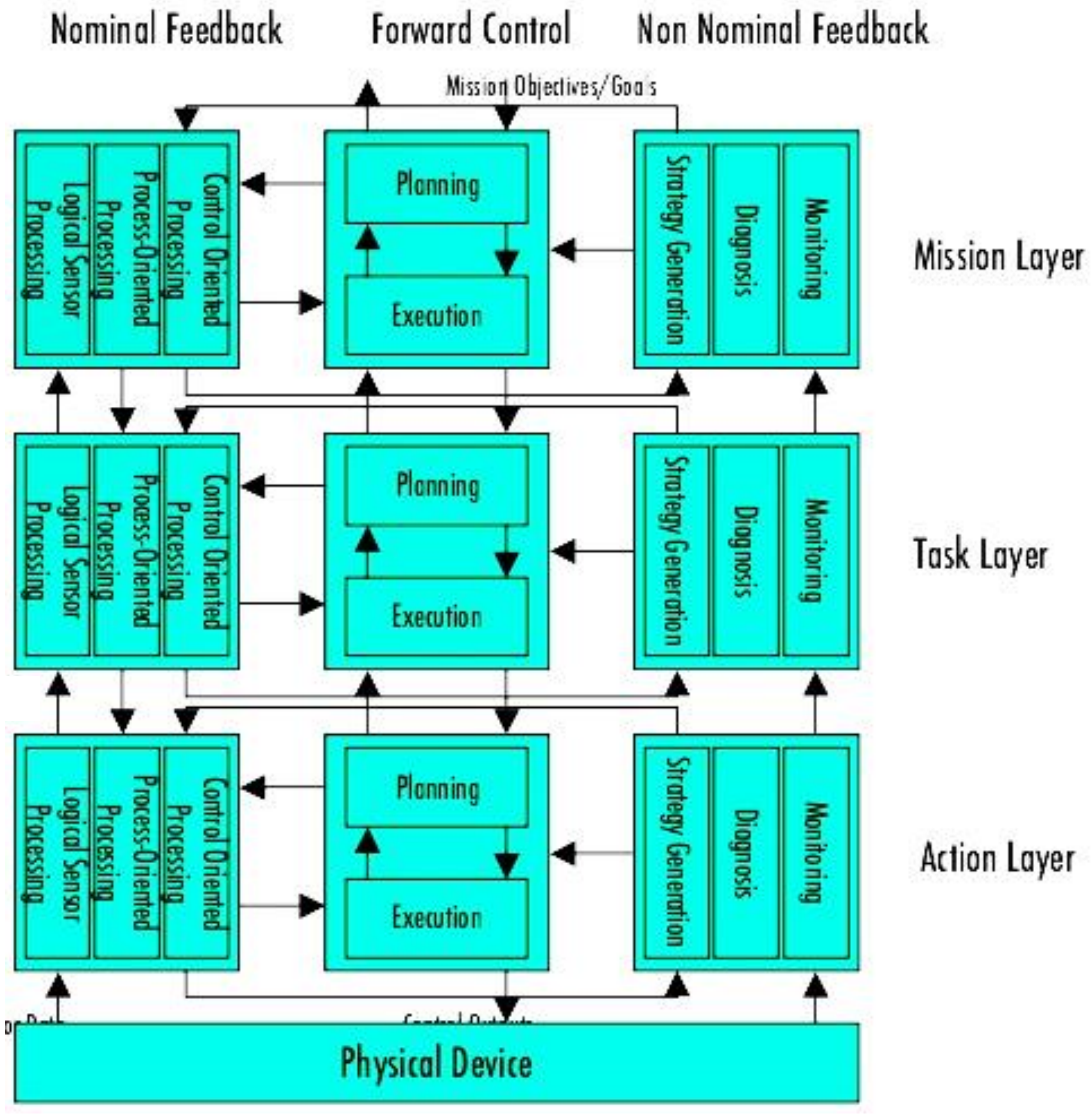
R. Arkin, T. Balch, AuRA: *principles and practice in review*, Journal of Experimental and Theoretical Artificial Intelligence 9 (2–3): 175–189, 1997

An example in space robotics

ESA has developed a hybrid architecture named Functional Reference Model (FRM).

It uses three layers:

- Mission layer to perform decisional planning for high lever objectives
- Task layer handling in reactive way the tasks using pre-defined activities / behaviors
- Action layer implements control schemes to achieve stability and the reflexes to adapt the system



Source: G. Visentin. Autonomy in ESA Planetary Robotics Mission. 2007

Wrap-up slide on “Robots and Unmanned Vehicles Control Architectures”

What should remain from this lecture?

- What a control architecture is for and why it is useful
- Difference between Deliberative / Reactive / Hybrid approaches
- What the «Sense / Plan / Act» paradigm is
- How the Potential Fields navigation approach works

References

- R. Arkin, Behavior-Based Robotics, MIT Press, 1998
- R. Murphy, An Introduction to AI Robotics, MIT Press, 2000
- M. Mataric, The Robotics Primer, MIT Press, 2007
- J. Jones, A Practical Guide to Behavior-based Robotics, McGraw-Hill, 2004

Course teachers and schedule

ACT
(LAND)

Modeling
(Reactive) Control

PLAN /ACT
(LAND)

Architectures
Trajectory Planning
Collision Avoidance

ACT
(LAND)

Modeling
(Reactive) MPC

SENSE/ACT
(AIR)

Modeling
Attitude Estimation
(Reactive) Control

SENSE/PLAN
/ACT (SEA)

Modeling
Perception
(Reactive) Control

SENSE/PLAN
/ACT (SEA)

Sensing
Perception
(Reactive) Control