Robotic Agent Architectures

Intelligent Robotics

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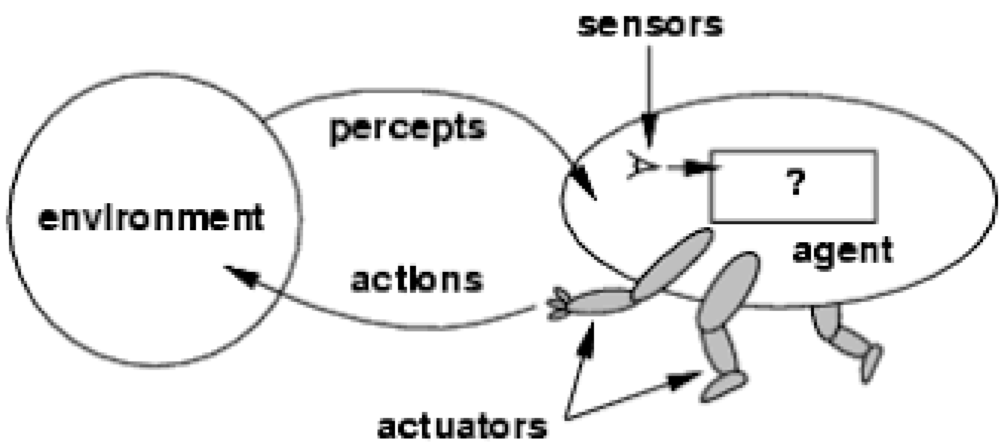
Outline

- Introduction to Robotic Agents
- Deliberative Architectures
- Reactive Architectures
- Behavior-Based Architectures
  - Subsumption Architecture
- Hybrid Architectures

Autonomous Agents

- **Traditional Definition:**

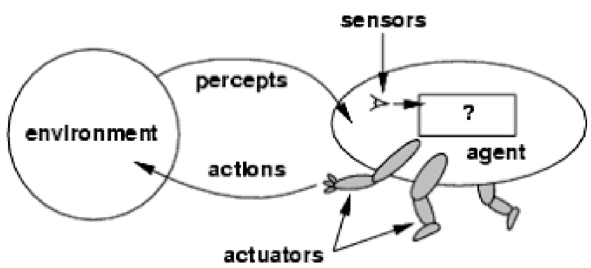
  "Computational System, situated in a given **environment**, that has the ability to **perceive** that environment using **sensors** and **act**, in an **autonomous way**, in that environment using its **actuators** to fulfill a given **function**."



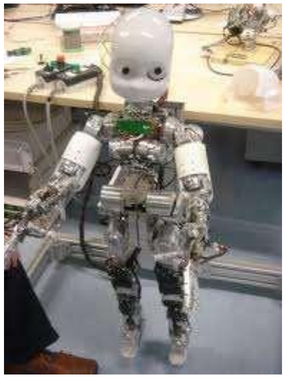
Russel and Norvig, AI: Modern Approach

Robotic and Human Agents

- **Agent:**
  - Perceive its environment using sensors and executes actions using its actuators
  - Sensors:
    - Eyes, ears, nose, touch, …
  - Actuators:
    - Legs, Arms, hands, vocal cords, …



- **Robotic Agent:**
  - Sensors:
    - Cameras, sonar, infra-red, microphone
  - Actuators:
    - Motors, wheels, manipulators, speakers



Intelligent Robotics

- **Robotics**
  - Science and technology for **projecting, building, programming and using Robots**
  - Study of **Robotic Agents (with body)**
  - Increased Complexity:
    - **Environments**: Dynamic, Inaccessible, Continuous and Non Deterministic!
    - **Perception**: Vision, Sensor Fusion
    - **Action**: Robot Control
    - **Robot Architecture** (Physical / Control)
    - **Navigation** in unknown environments
    - **Interaction** with other robots/humans
    - **Multi-Robot Systems**

Definition of Robot

- Notion derives from 2 strands of thought:
  - Humanoids: human-like
  - Automata: self-moving things
- "Robot" - derives from Czech word *robota*
  - "*Robota*": forced work or compulsory service
  - Term coined by Czech playwright Karel Capek (1920)
- Current notion of robot:
  - Programmable
  - Mechanically capable
  - Flexible

Some Definitions of Robot

- "I can't define a robot, but **I know one when I see one**."
  Joseph Engelberger
- "Any automatically operated machine that **replaces human effort**, though it **may not resemble human beings** in appearance or perform functions in a humanlike manner"
  Encyclopedia Britannica
- "Machine that **looks like a human being** and performs various **complex acts** (as walking or talking) of a human being"

  "Device that automatically **performs complicated often repetitive tasks**"

  "Mechanism guided by **automatic controls**"
  Merriam-Webster

Best Definitions of Robot

- **Electromechanical device which can perform tasks on its own, or with guidance**
- **Physical agent (with body) that generates intelligent/ autonomous connection between perception and action**
- **Autonomous system in the physical world which may sense its environment and act on it to achieve a set of goals**

Some Robotic Issues

- Agent/Robot control architectures
- Behavior-based systems
- Sensors and Perception
- Representation Issues
- Adaptation and Learning
- Path planning and Navigation
- Localization and Mapping
- Intelligent Planning
- Multi-robot systems

Some Robotic Issues

- How do I interpret my sensor feedback to determine my current state and surroundings? [sensor processing/perception]
- Where am I? [localization]
- How do I make sense of noisy sensor readings? [uncertainty management]
- How do I fuse information from multiple sensors to improve my estimate of the current situation? [sensor fusion]
- What assumptions should I make about my surroundings? [structured/unstructured environments]
- How do I know what to pay attention to? [focus-of-attention]

Robotic Architecture - Definition(s)

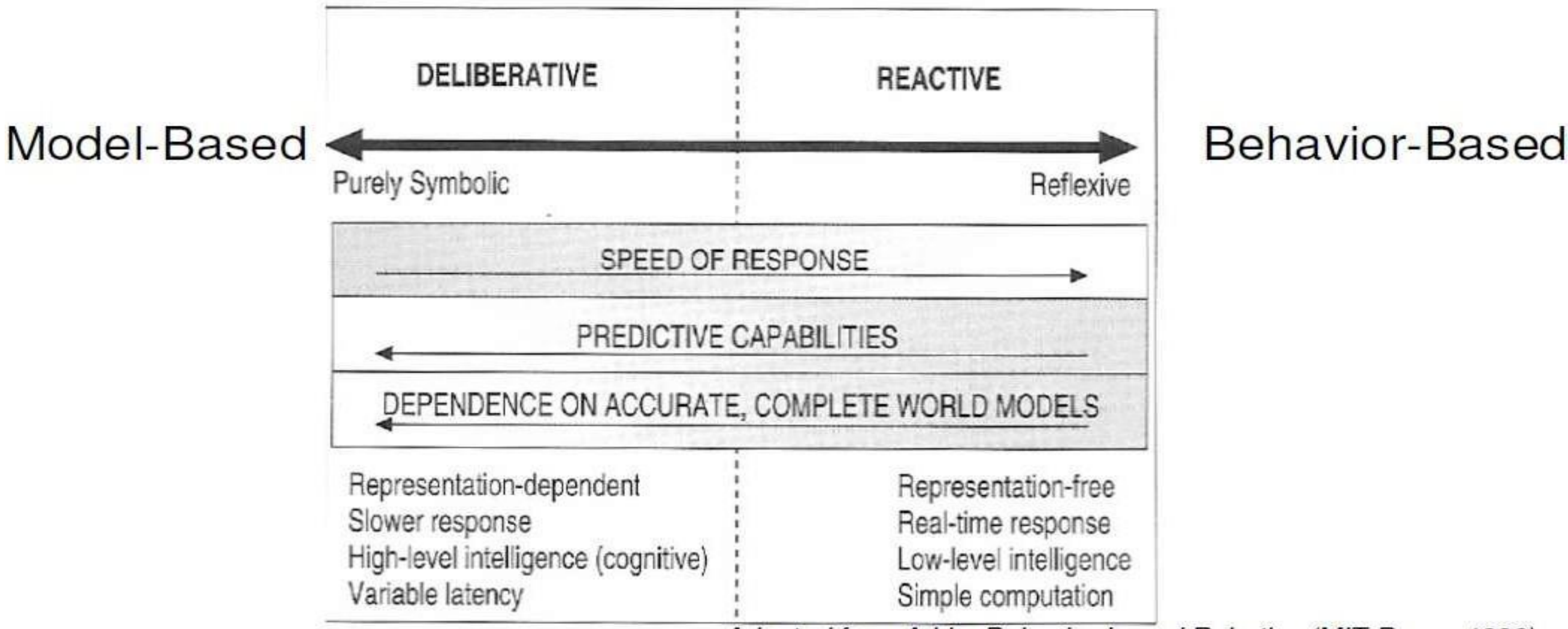
- An **architecture** provides a **principled way of organizing a control system.** However, in addition to **providing structure**, it **imposes constraints** on the way the control problem can be solved
  [Mataric, 1992]
- An architecture is a description of how a **system is constructed from basic components** and how those **components fit together** to form the whole
  [Albus, 1995]
- Robotic architecture usually refers to **software**, rather than hardware
  [Arkin, 1998]
- How **the job** of generating actions from percepts **is organized**
  [Russel and Norvig, 2002]

Issues in Robotic Architectures

- **Representation**
  - unified, heterogeneous, multiple or no representation
- **Control and coordination**
  - centralized or distributed control
- **Learning**
  - architecture should organize structures to facilitate learning
- **Timely performance**
  - deal with real-time constraints
- **Biological and psychological inspiration**
  - parallelism, distributed control, reflex loops, etc
- **Evaluation**

Spectrum of Robot Control Architectures

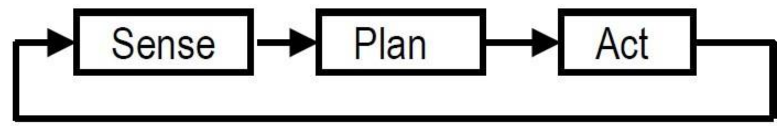
- Deliberative control: “think hard, then act”
- Reactive control: “don't think, (re)act”
- Hybrid control: “think and act in parallel”



Adapted from Arkin, Behavior-based Robotics (MIT Press, 1998)

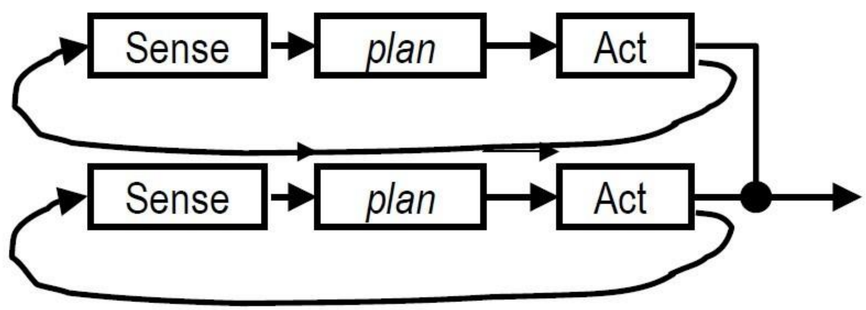
Typical Organizations

- Typical organizations:
  - Hierarchical / Deliberative

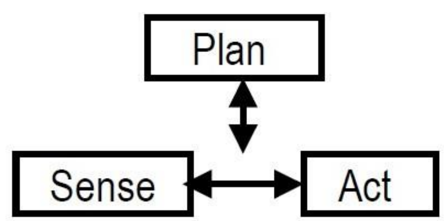


  - Reactive

  - Behavior-based



  - Hybrid

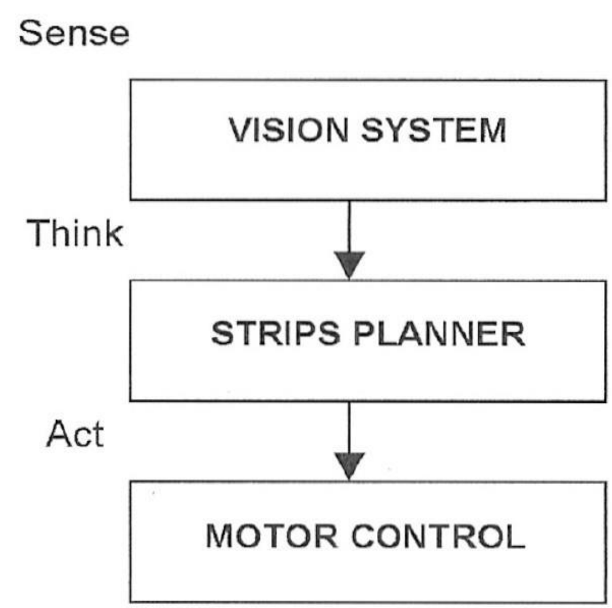


Typical Organizations

- Deliberative
  - Making maps
  - Selecting behaviors
  - Monitor performance
  - Planning
  - Hybrid deliberative/reactive paradigm
- Reactive
  - Cheap low memory processing
  - No world model
- Behavior-Based
  - Combination of simple behaviors
  - No centralized world model
  - Each behavior may store own representation
- Hybrid
  - Combine Reactive and Deliberative approaches

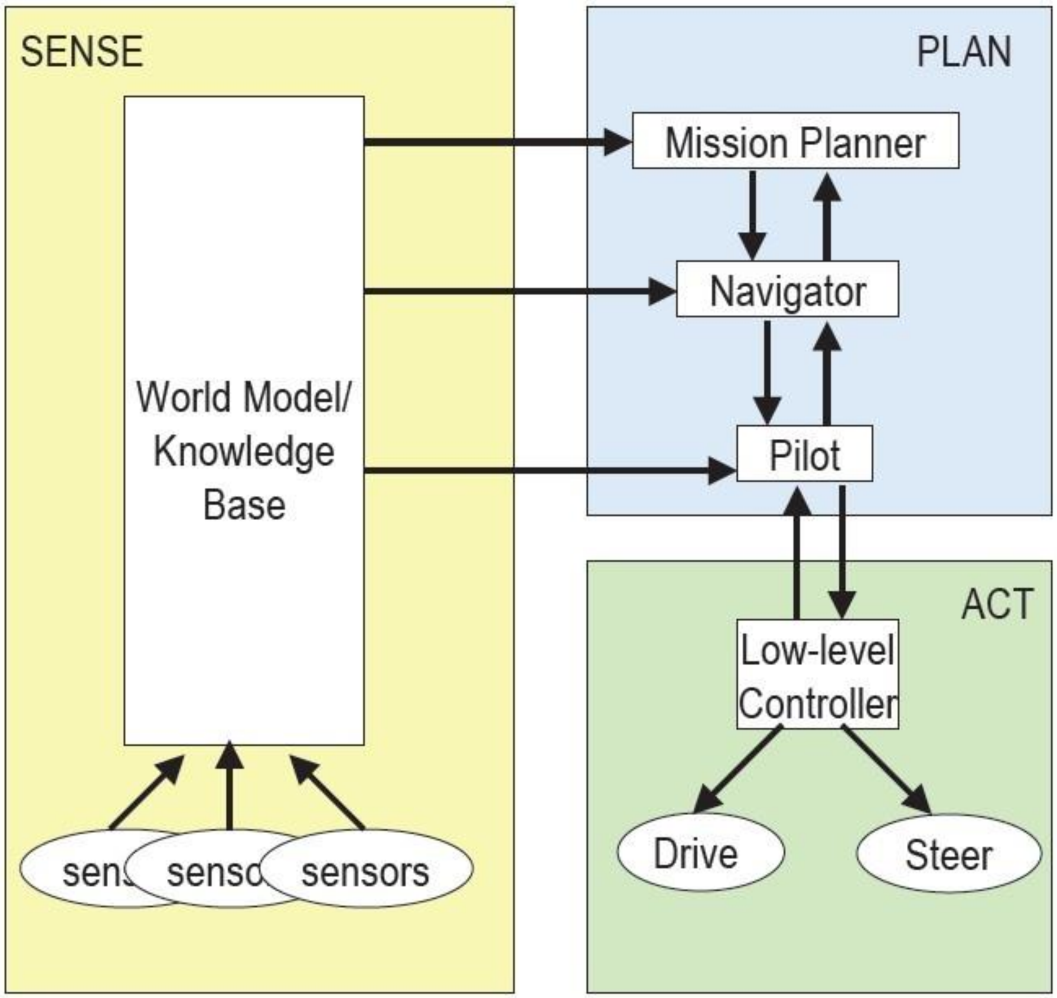
Model-based - Deliberative

- Sense-plan-act paradigm: dominant view in the AI community was that a control system for an autonomous mobile robot should be decomposed into three functional elements [Nilsson, 1980]:
  - a sensing system (translate raw sensor input into a world model)
  - a planning system (take the world model and a goal and generate a plan to achieve the goal)
  - and an execution system (take the plan and generate the actions it prescribes)
- Perception is the establishment and maintenance of correspondence between the internal world model and the external real world [Albus 1991].
- Action results from reasoning over the world model.
- Perception is not tied directly to action.



Deliberative Architectures

- Nested Hierarchical Controller



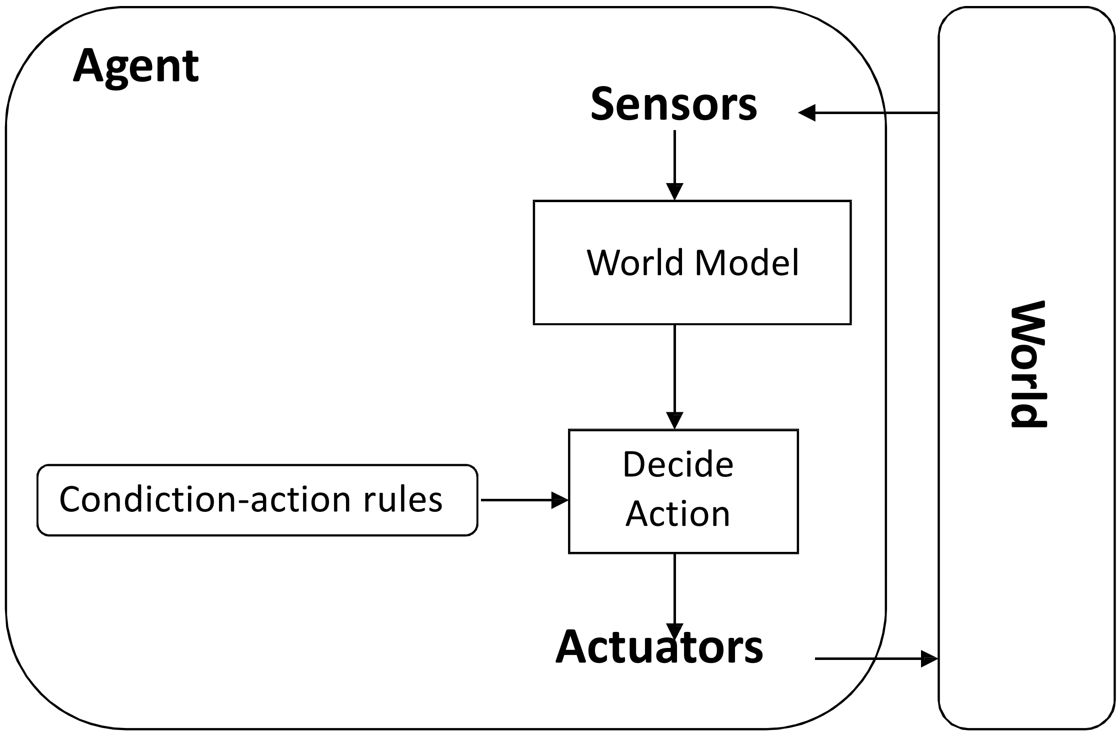
Meystel, A., "*Knowledge Based Nested Hierarchical Control*", 1990

Reactive Agents

- General assumptions:
  - The environment lacks temporal consistency and stability
  - The robot’s immediate sensing is adequate for the task at hand
  - It is difficult to localize a robot relative to a world model
  - Symbolic representational world knowledge is of little or no value

“Planning is Just a Way of Avoiding Figuring Out What To Do Next”, Brooks 1987

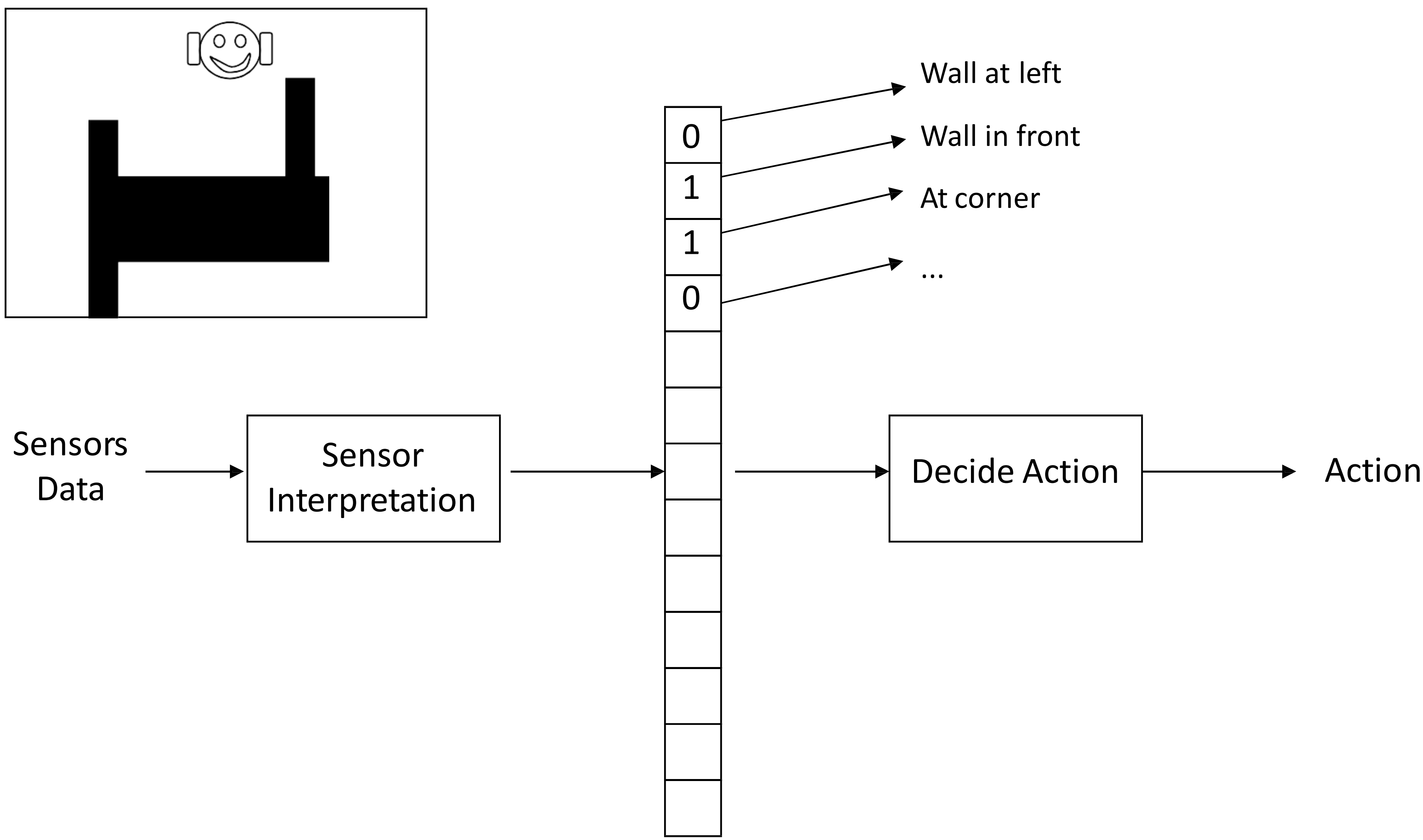
Simple Reactive Agent



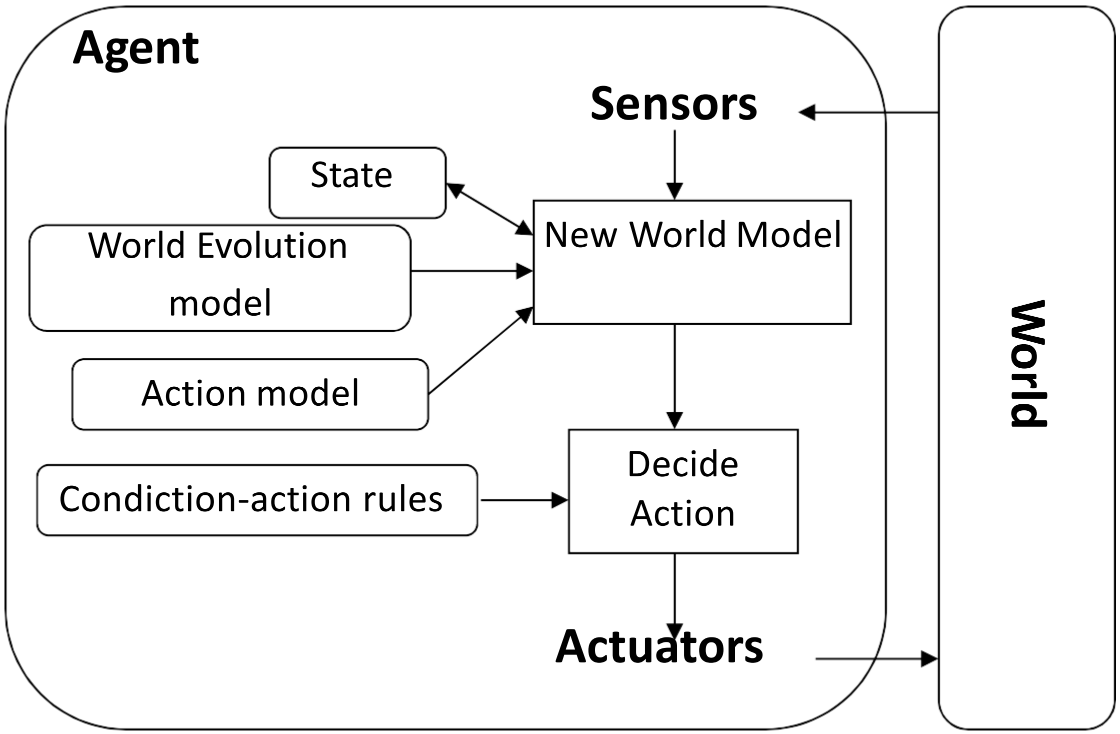
Russel and Norvig, AI: Modern Approach

Simple Reactive Agent

- Perception represented by a feature vector



Reactive Agent with Internal State



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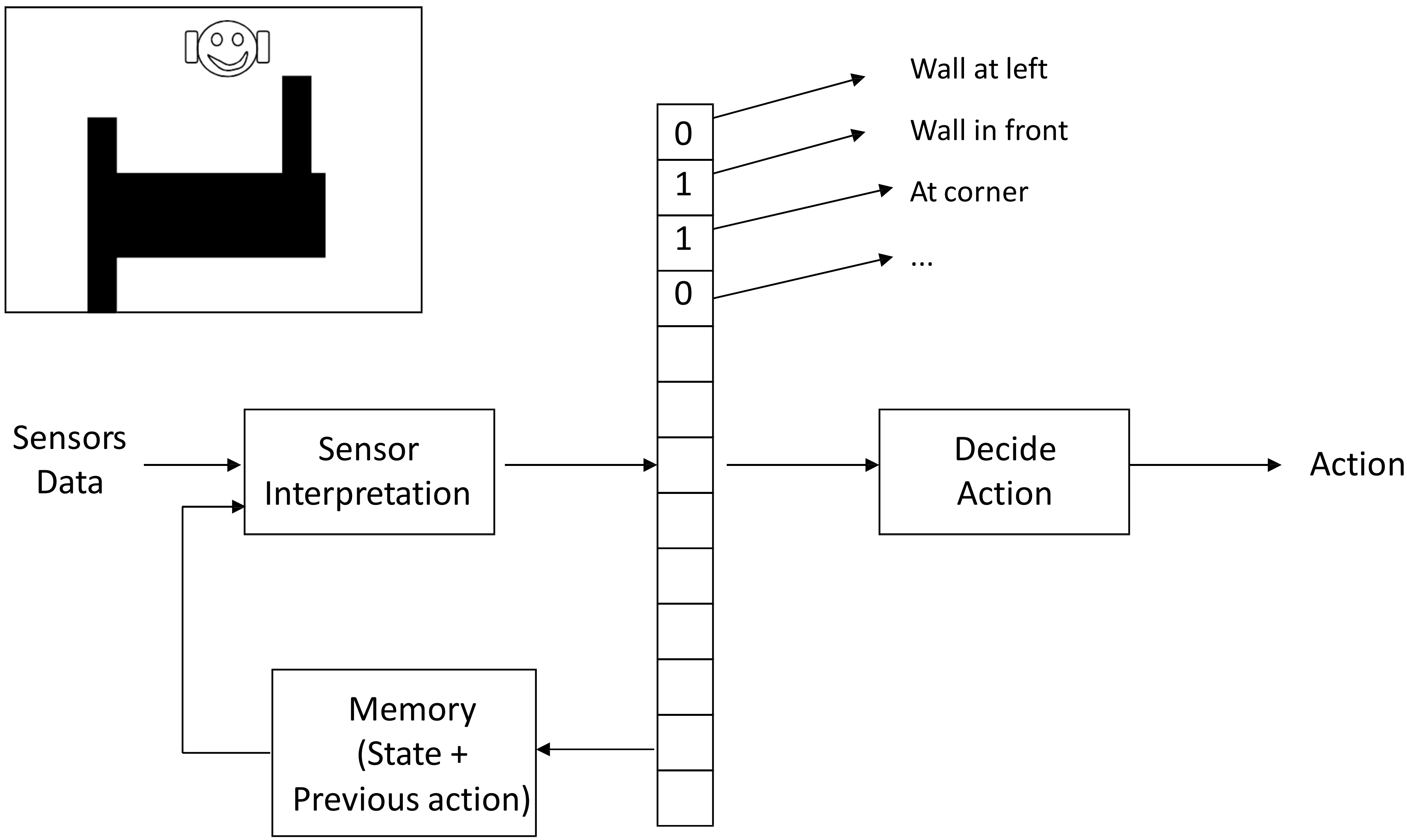


Reactive Biological Foundations

- Possible pigeon flight algorithm

```
if (sunny)
    followSun();
else
    followMagneticCues();

sometimes
   { useUltrvioletLight();
     usePolarizationOfLight();
     useSmell();
     useThunderstormDetector();
     useDetectionOfLowFrequencySound();
    }
```

Deliberative vs Reactive

- No single approach is "the best" for all robots; each has its strengths and weaknesses
- Control requires some unavoidable trade-offs because:
  - Thinking is slow
  - Reaction must be fast
  - Thinking allows looking ahead (planning) to avoid bad actions
  - Thinking too long can be dangerous (e.g., falling off a cliff)
  - To think, the robot needs (a lot of) accurate information
  - The world keeps changing as the robot is thinking, so the slower it thinks, the more inaccurate its solutions
- As a result of these trade-offs, some robots don't think at all, while others mostly think and act very little.
  - **It all depends on the robot's task and its environment!**

Behavior-Based Architectures

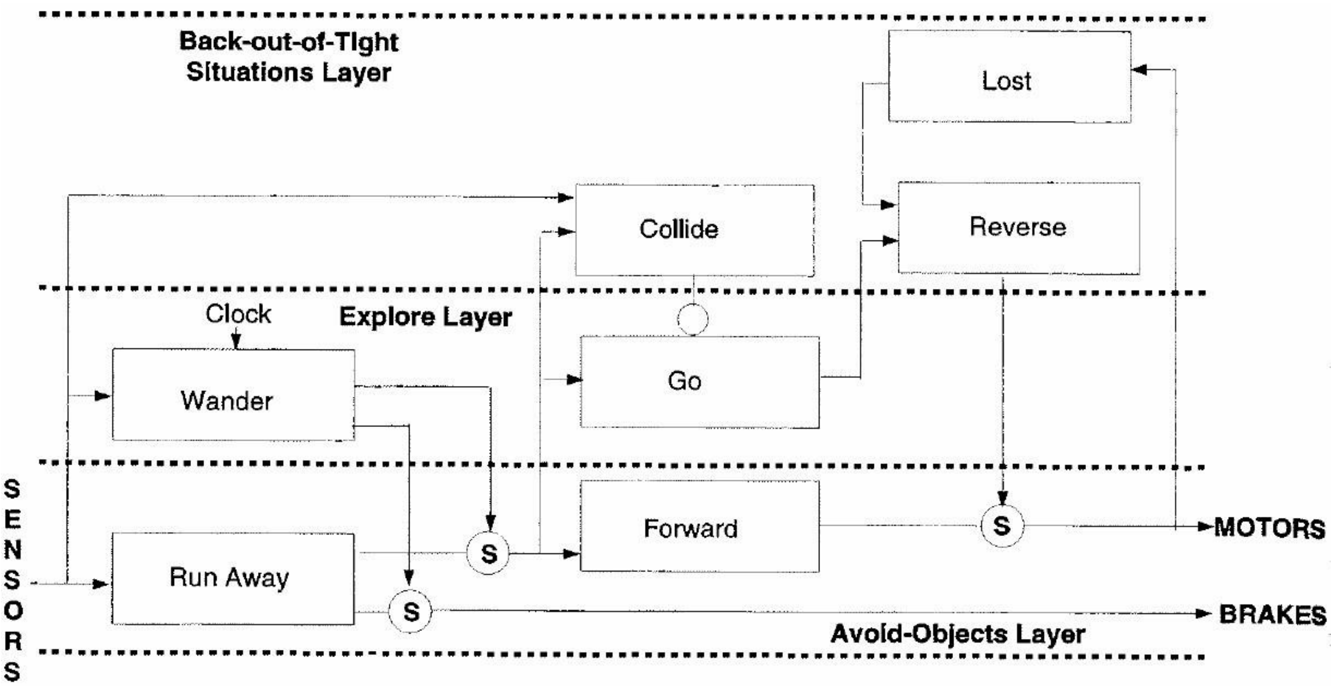
- Behaviors implemented as control laws (in software or hardware)
- Each behavior receives inputs from the robot's sensors and/or from other modules, and sends outputs to the robot's effectors and/or to other modules.
- Many different behaviors may receive input from the same sensors and output commands to the same actuators.
- Behaviors are encoded to be relatively simple, and are added to the system incrementally.
- Behaviors (or subsets) are executed concurrently

Behavior-Based - Reactive

- Common features:
  - Emphasis on the importance of coupling sensing and action tightly.
  - Avoidance of representational symbolic knowledge (because the world can change over time and uncertainty is hard to model).
  - Decomposition into contextually meaningful units (behaviors or situation-action pairs).
- Distinctions:
  - Granularity of behavioral decomposition
  - Basis for behavior specification (ethological, situated activity, or experimental)
  - Response encoding (e.g., discrete or continuous)
  - Coordination methods (e.g., competitive vs cooperative)
  - Programming methods, language, reusability

Subsumption Architecture [Brooks 1986]

- Behaviors are Augmented Finite State Machines (AFSM)
- Stimulus or response signals can be suppressed or inhibited by other active behaviors; a reset input returns the behavior to its start conditions
- Each behavior is responsible for its own perception of the world
- Arrangement in layers: lower layers have no awareness of higher layers

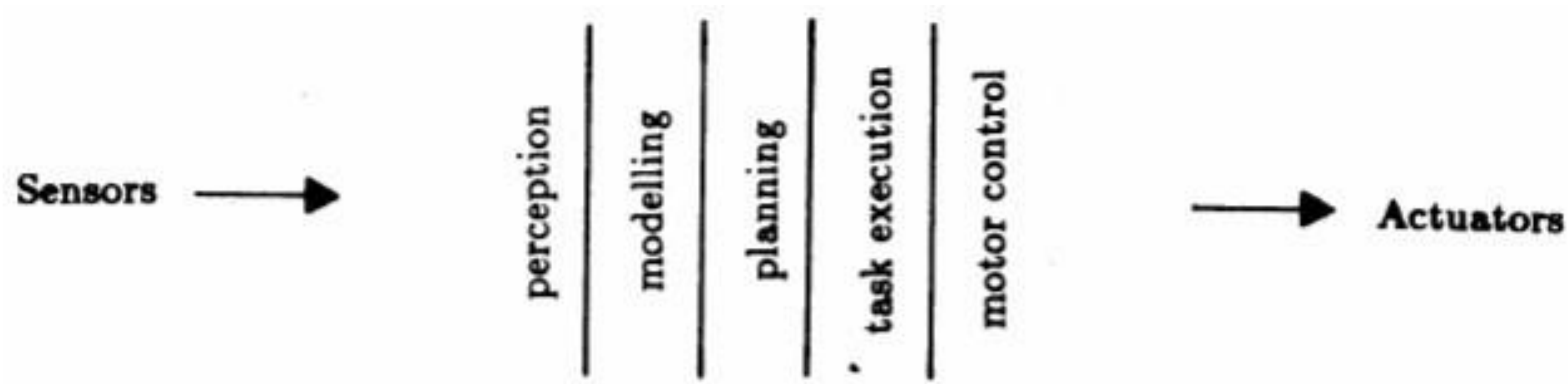


Brooks – Behavior languages

Brooks has put forward three theses:

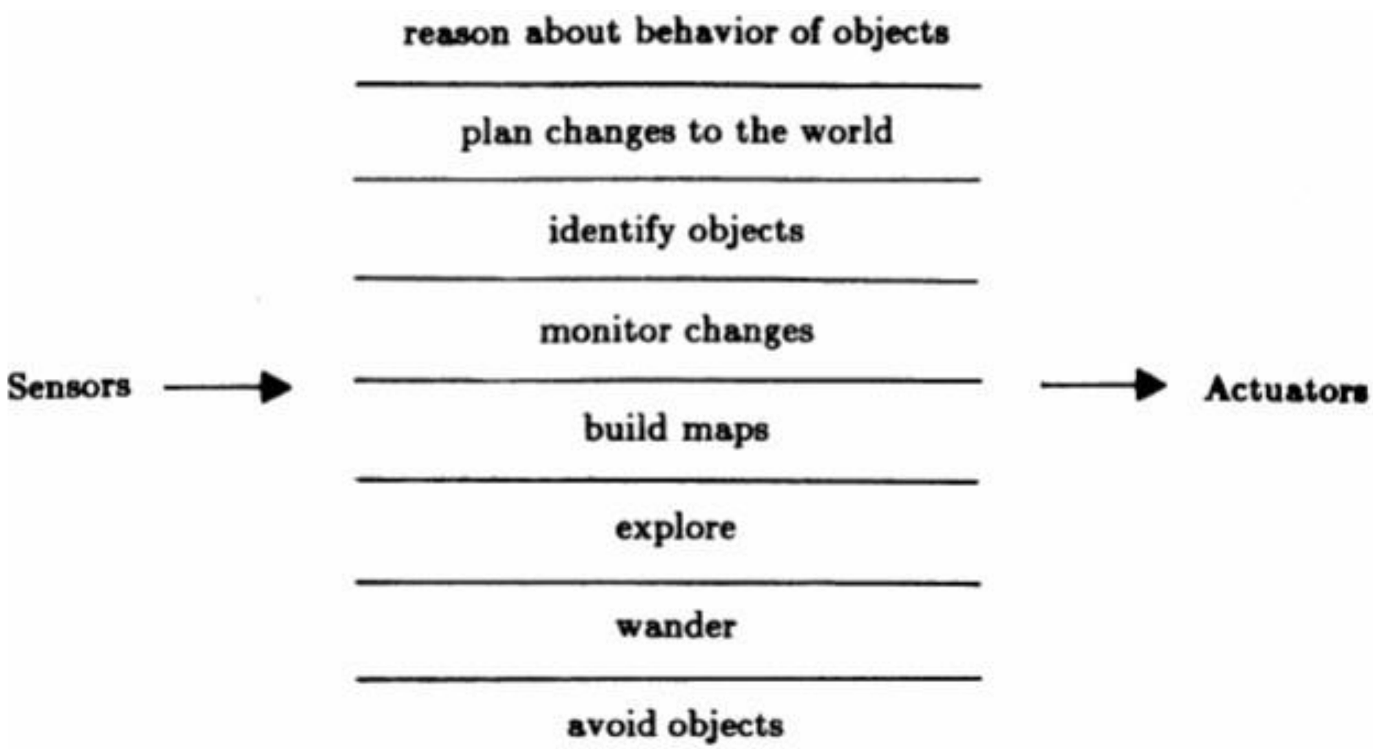
1. **Intelligent behavior** can be generated ***without*** **explicit representations** of the kind that symbolic AI proposes
2. **Intelligent behavior** can be generated ***without*** **explicit abstract reasoning** of the kind that symbolic AI proposes
3. **Intelligence is an *emergent property*** *of* certain complex systems

A Traditional Decomposition of a Mobile Robot Control System into Functional Modules



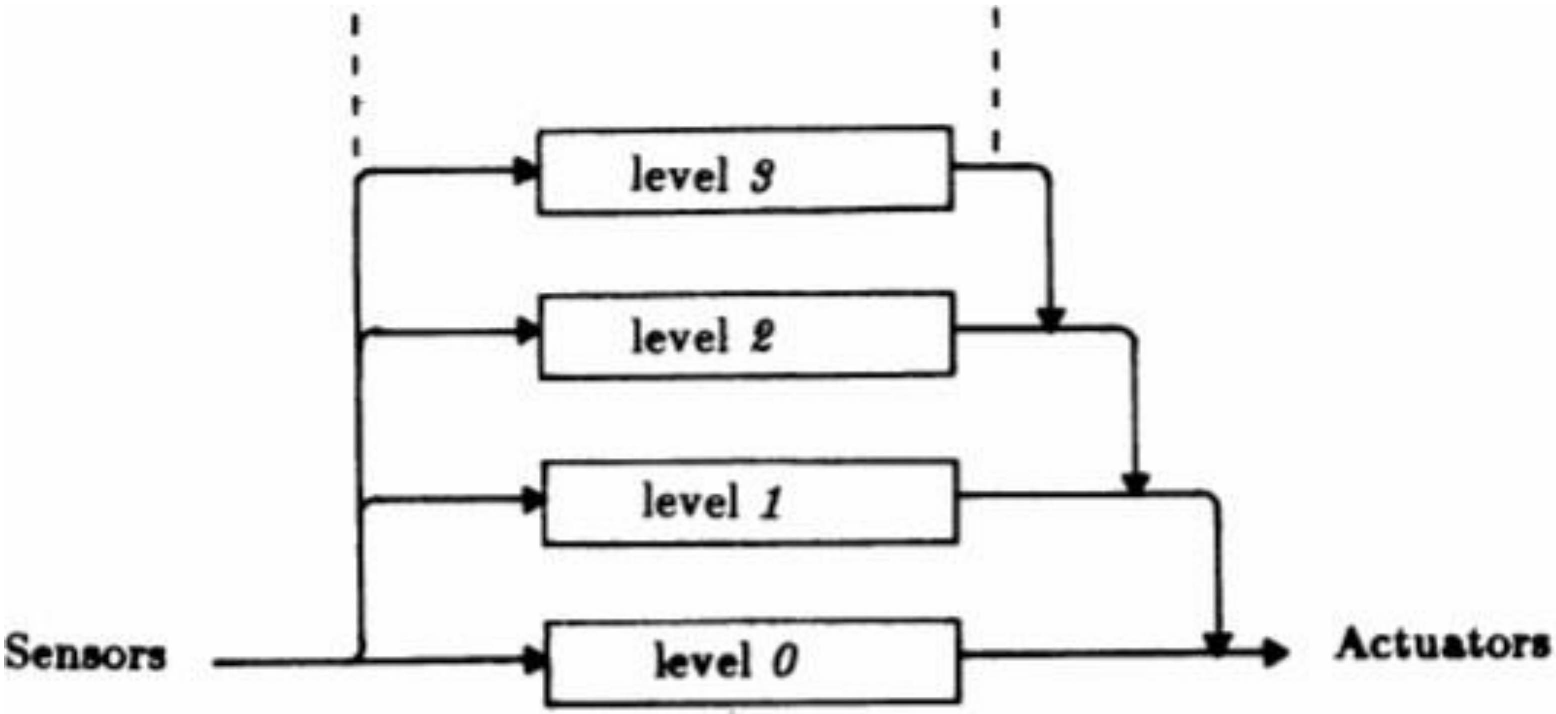
From Brooks, “A Robust Layered Control System for a Mobile Robot”, 1985

A Decomposition of a Mobile Robot Control System Based on Task Achieving Behaviors



From Brooks, “A Robust Layered Control System for a Mobile Robot”, 1985

Layered Control in the Subsumption Architecture



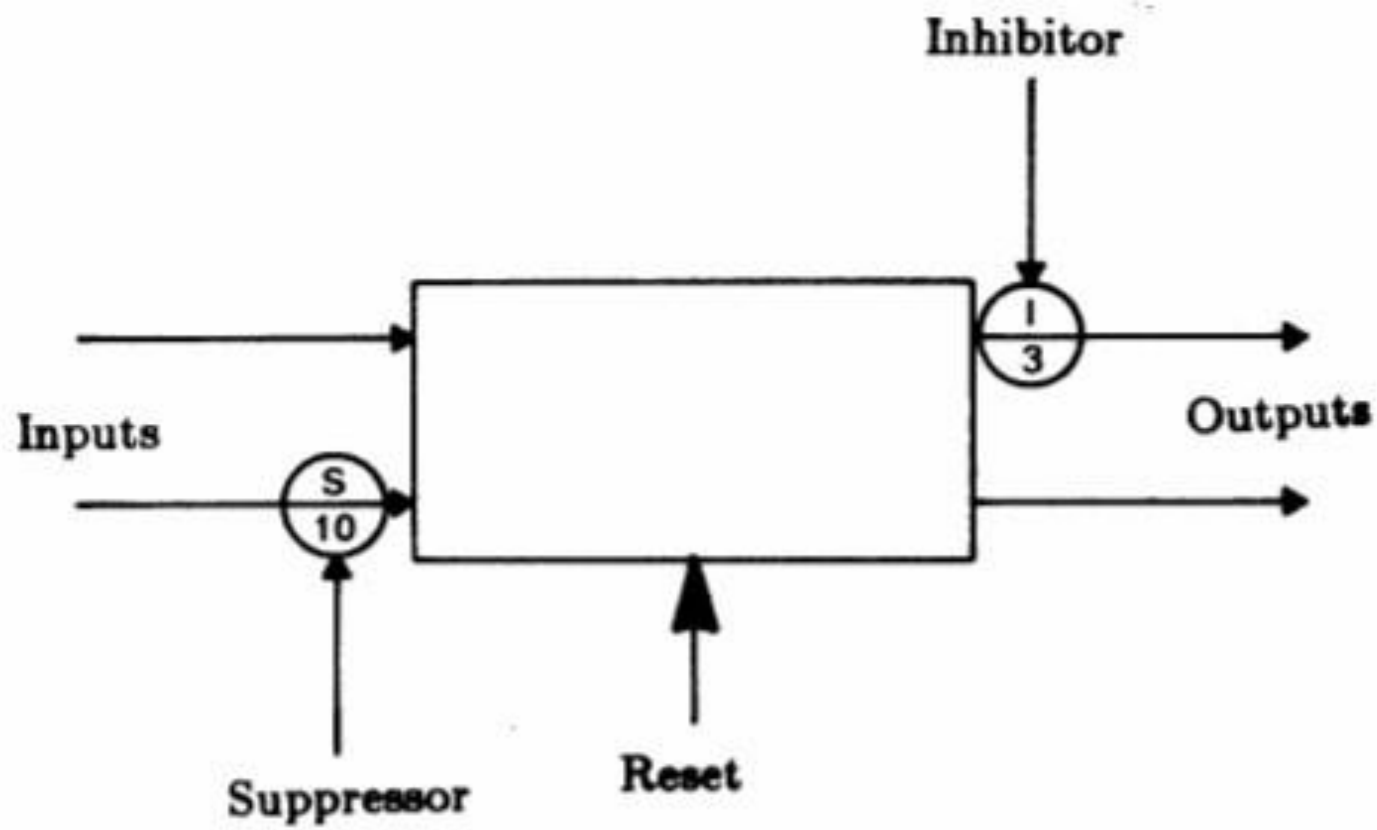
From Brooks, “A Robust Layered Control System for a Mobile Robot”, 1985

Example of a Module – Avoid

```
(defmodule avoid
  :inputs (force heading)
  :outputs (command)
  :instance-vars (resultforce)
  :states
    ((nil (event-dispatch (and force heading) plan))
     (plan (setf resultforce (select-direction force heading))
           go)
     (go (conditional-dispatch (significant-force-p resultforce 1.0)
                               start
                               nil))
     (start (output command (follow-force resultforce))
            nil)))
```

From Brooks, “A Robust Layered Control System for a Mobile Robot”, 1985

Schematic of a Module



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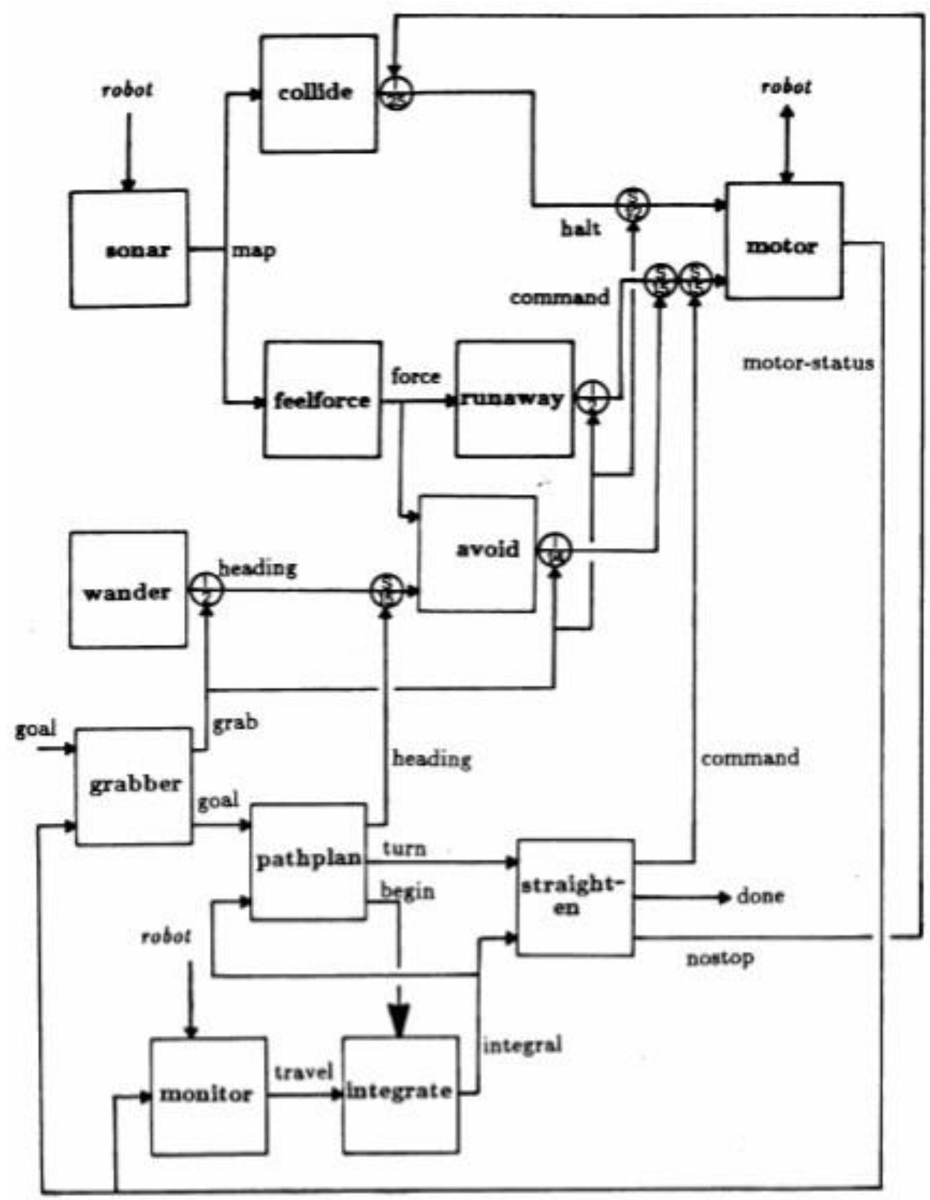
Levels 0, 1, and 2 Control



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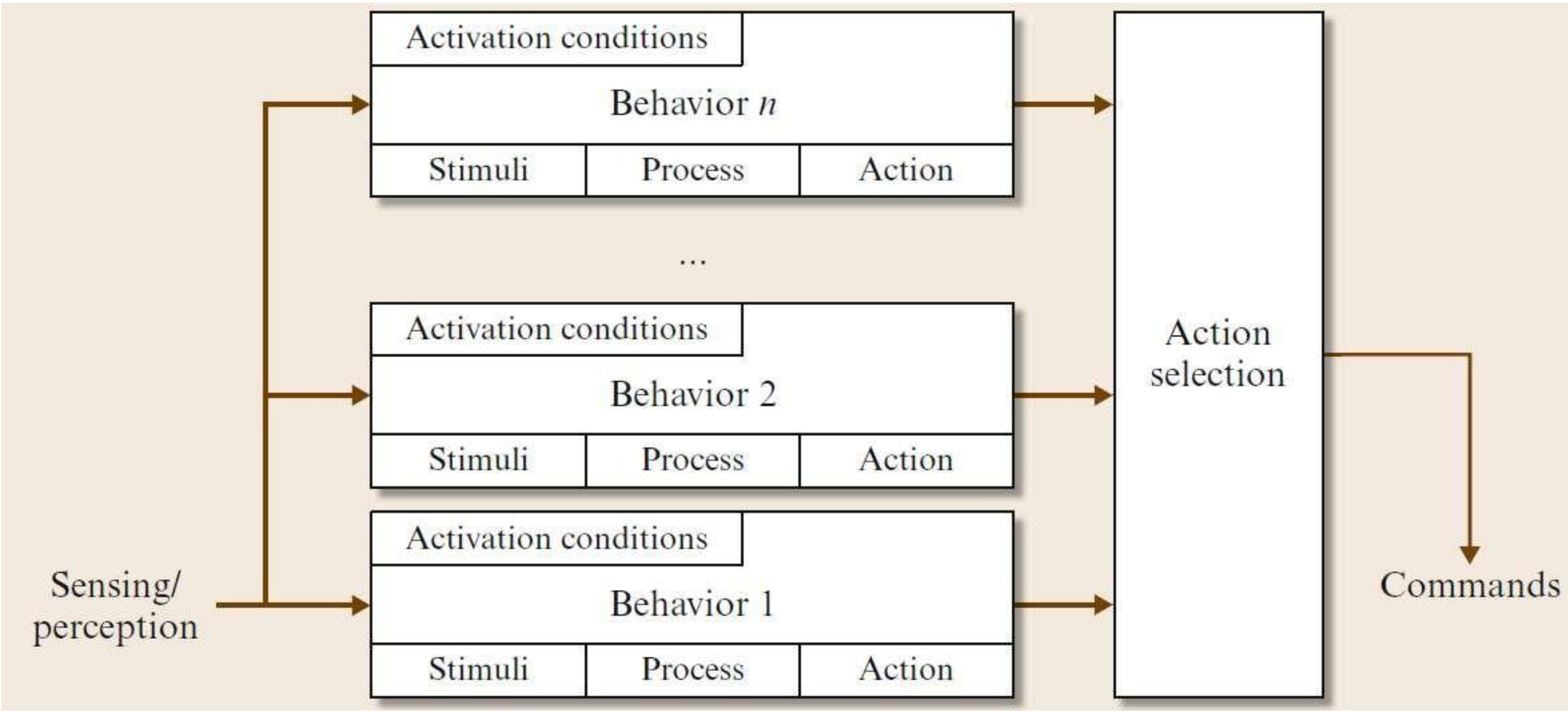
Behavior-Based Architectures



From Siciliano et al., “Springer Handbook of Robotics”, Springer, 2008

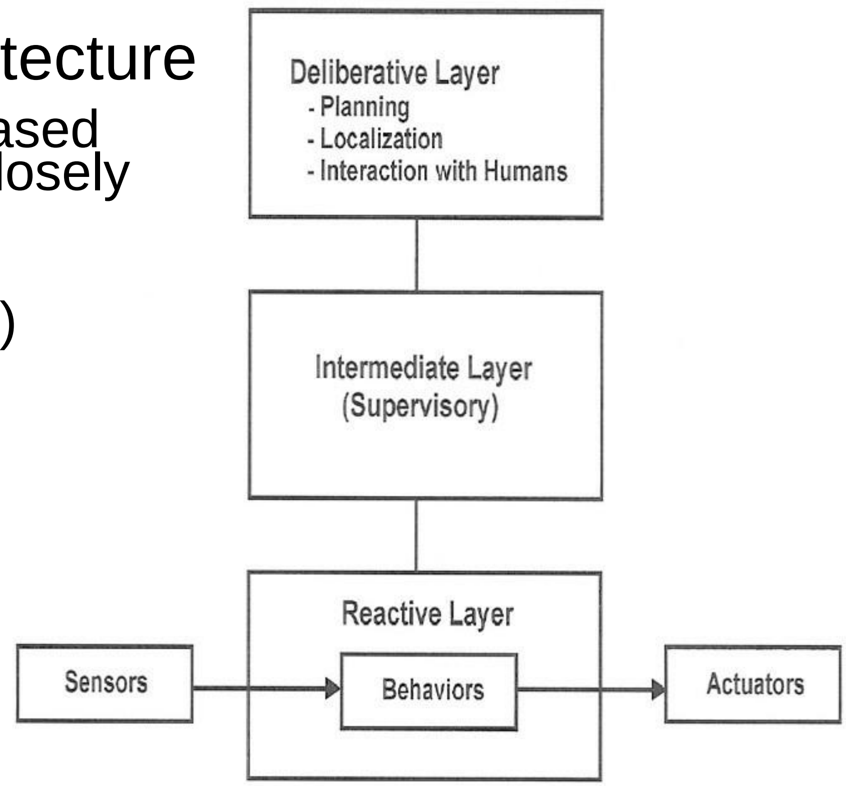
Hybrid Architectures

- In **Hybrid Control**, the goal is to **combine the best of both Reactive and Deliberative** control. In it, one part of the robot's "brain" plans, while another deals with immediate reaction, such as avoiding obstacles and staying on the road.
- The **challenge** of this approach is bringing the **two parts** of the brain **together**, and allowing them to **talk** to each other, and **resolve conflicts** between the two.
- This requires a "third" part of the robot brain, and as a result these systems are often called "three-layer systems“

Adapted from http://www-robotics.usc.edu/~maja/robot-control.html

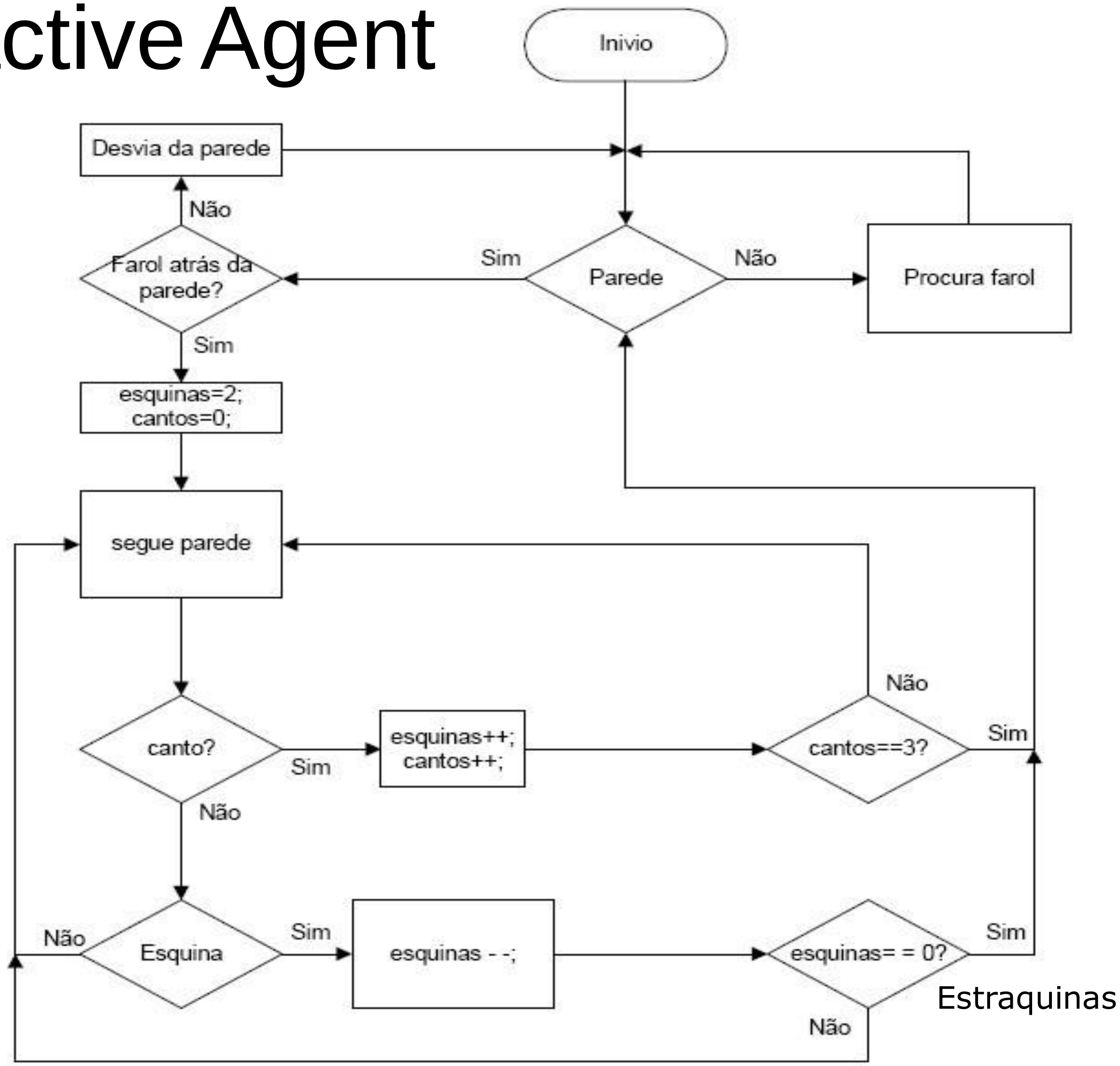
Hybrid Architectures

- Combine the responsiveness, robustness, and flexibility of purely reactive systems with more traditional symbolic/deliberative methods
- Reason: purely reactive systems lack the ability to take into account a priori knowledge (e.g. about the world) and to keep track of the history (memory)
- Typical three-layer (3T) hybrid architecture
  - Bottom layer is the reactive/behavior-based layer, in which sensors/actuators are closely coupled
  - Upper layer provides the deliberative component (e.g., planning, localization)
  - The intermediate between the two is sometimes called supervisory layer
- Examples of coupling between planning and reactive layers:
  - Planning to guide reaction: planning sets reactive system parameters.
  - Coupled: planning and reacting are concurrent activities, each guiding the other



Examples of Robotic Architectures

- Reactive Agent



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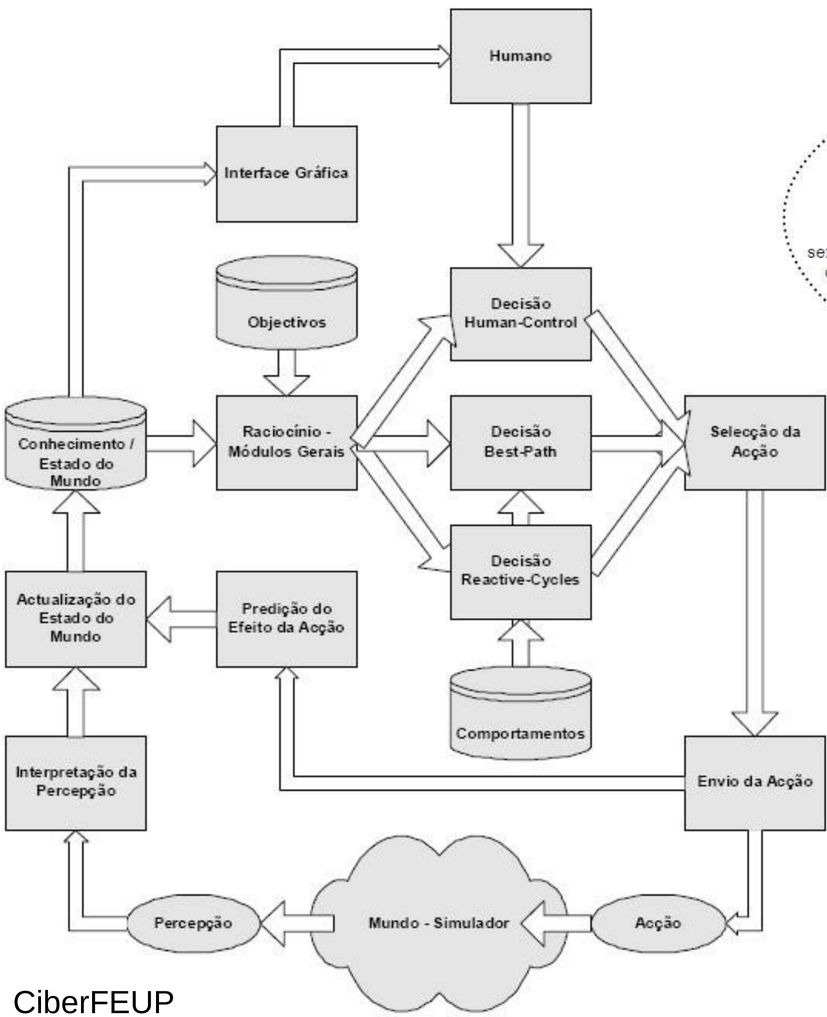

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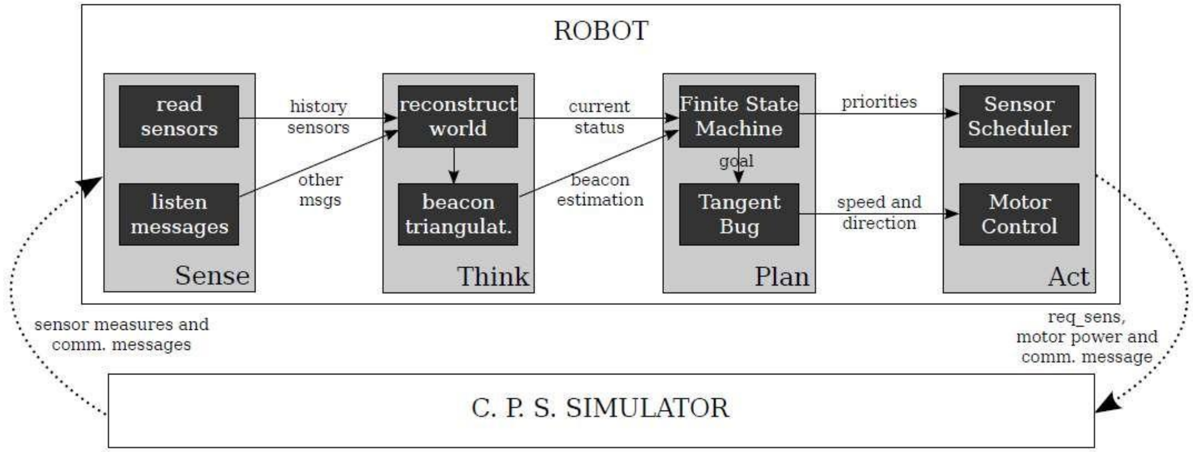
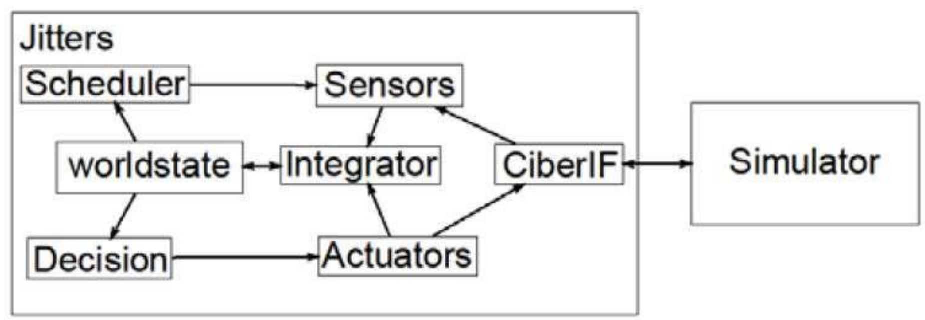
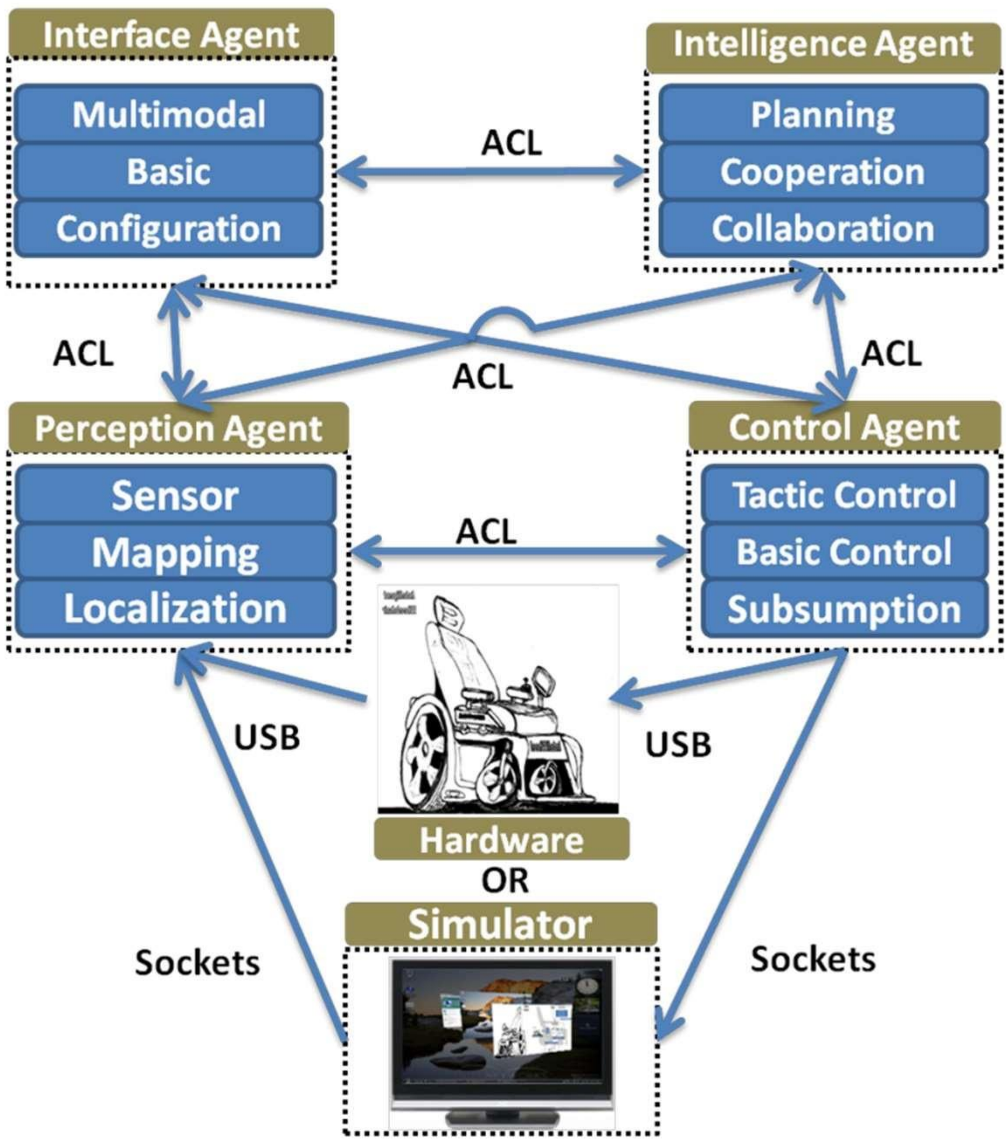


t-bots



Jitters

Macro vs Micro Agents



Conclusions

- Several Types of Architectures
- Deliberative Architectures
- Reactive Architectures
- Behavior-Based Architectures
  - Subsumption Architecture
- Hybrid Architectures

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