Department of Applied Mathematics
Faculty of Transportation Sciences
Czech Technical University in Prague

Multi-agent Systems and Smart Cities

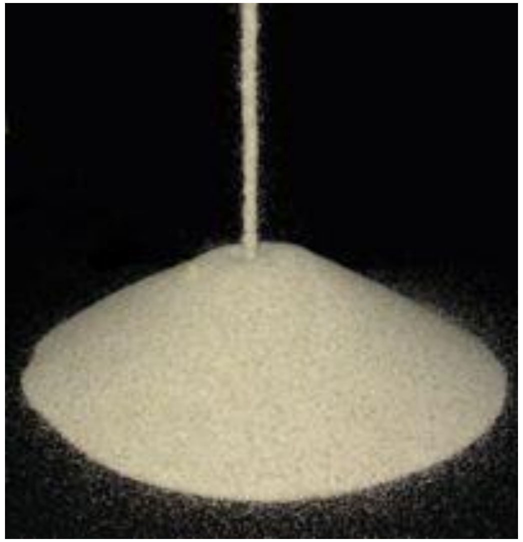
Ondřej Přibyl

Prague, 2019

Our world is full of complex systems

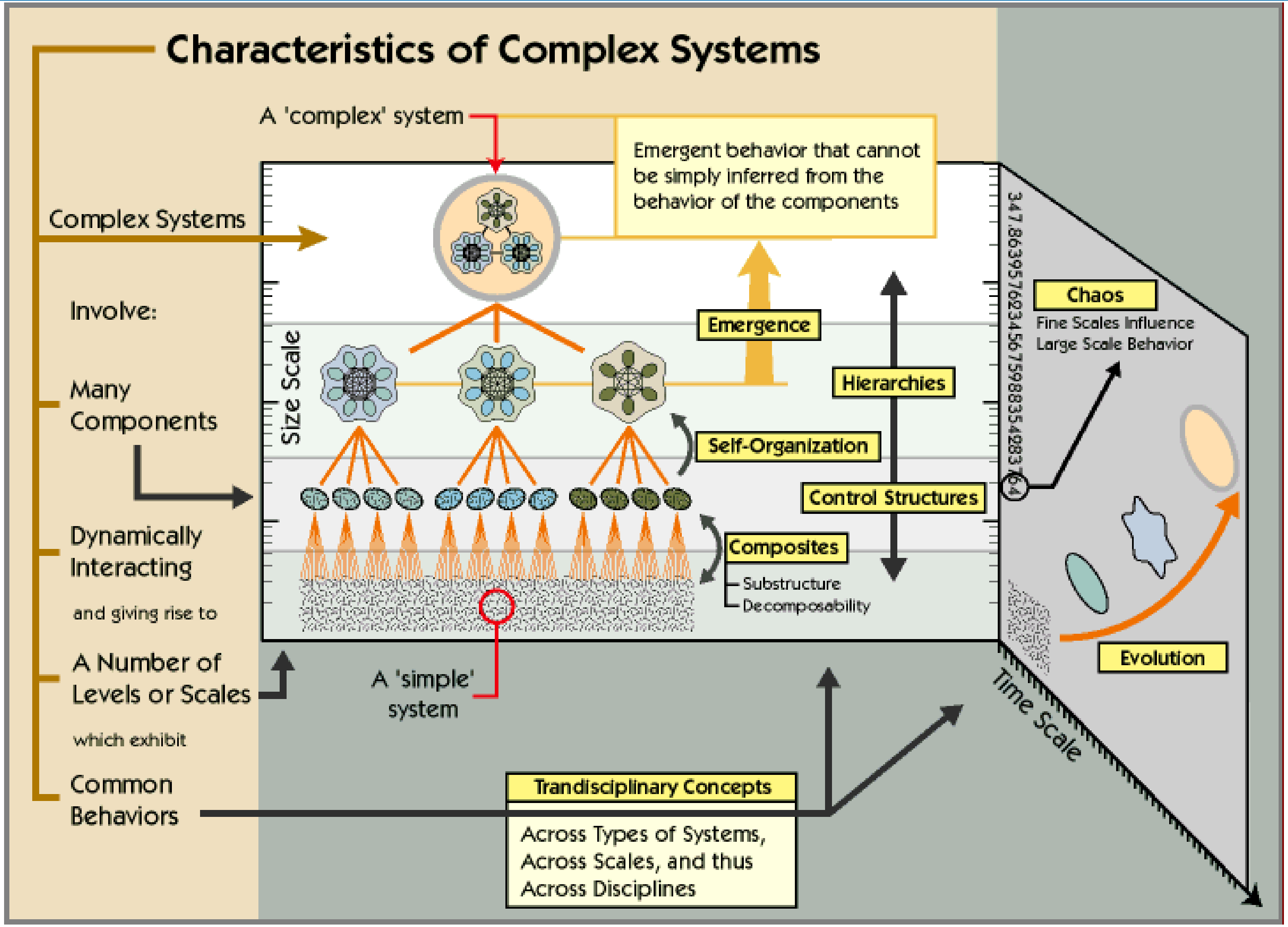
- In a **complex system** numerous independent elements continuously interact and spontaneously organize and reorganize themselves into more and more elaborate structures over time

- Within complex systems, relationships between elements are frequently *non-linear*
  - that is, they are unpredictable



Sand pile

Characteristics of complex systems



Ferreira

Complex versus Complicated

A **complicated system** is folded and thus conceals its internal structure.
Nevertheless, given enough time we can discover how it works.
We can partition a complicated system into a number of subsystems

*It is important to understand that the opposite of **complicated** is **simple** and opposite of **complex** is **independent**.*

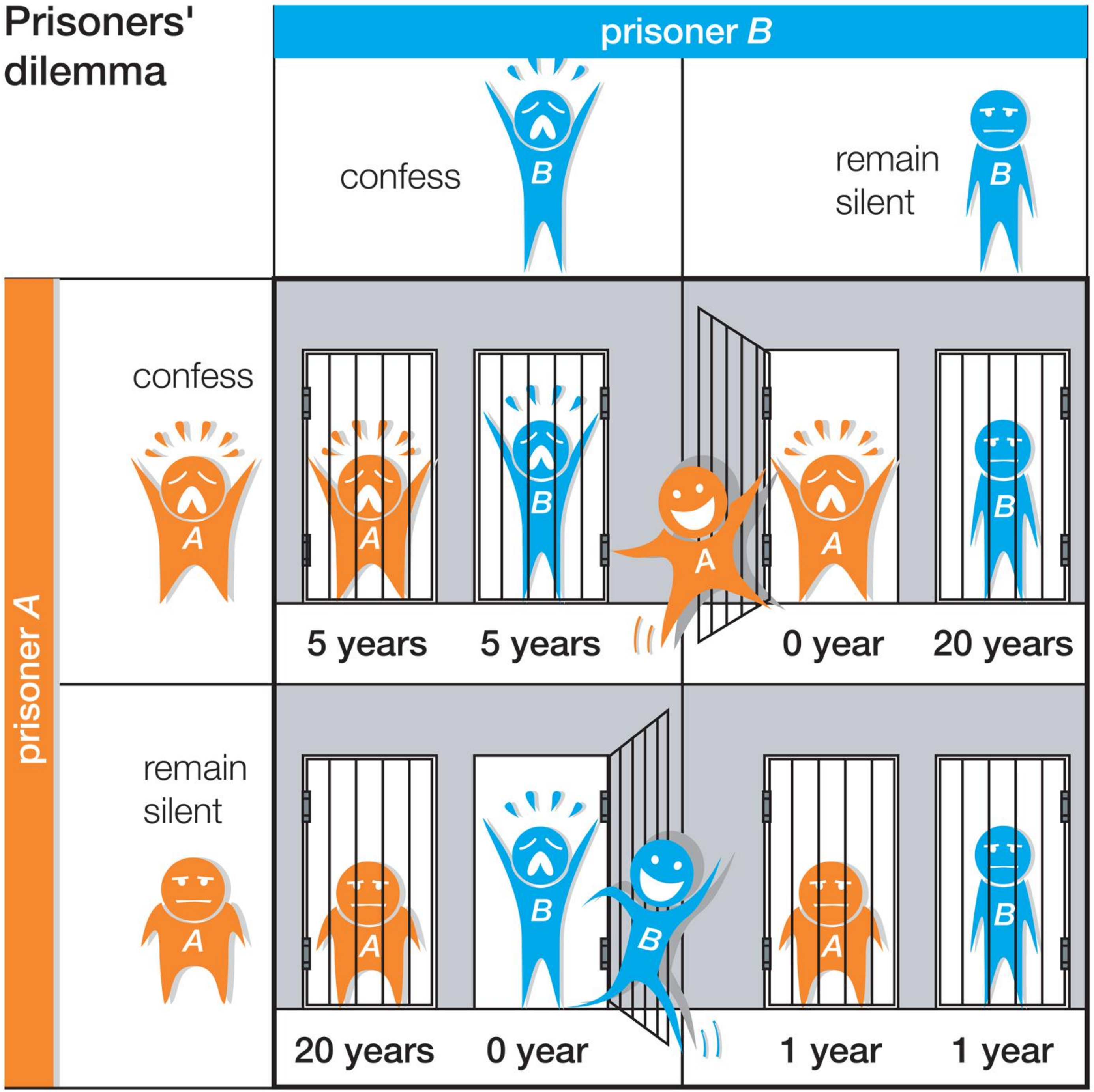
COMPLEX SYSTEMS	COMPLICATED SYSTEMS
The Internet-based global market	Centrally planned economy
Flexible manufacturing system	Mass production line
Management team	Command and Control Management
Adaptive scheduling system	Batch scheduling system
Multi-agent system	Large monolithic computer program
Agent negotiations	An algorithm
Aircraft life cycle	Aircraft

The Seven Criteria of Complex systems

1. ***Connectivity* -** consists of a large number of diverse components - Agents
2. ***Autonomy* -** Agents are not centrally controlled
3. ***Emergence* -** Global behaviour *emerges* from the interaction of agents
4. ***Nonequilibrium* –** *Complex systems* generate unpredictable disruptive events
5. ***Nonlinearity* -** Relations between agents are *nonlinear*
6. ***Self-Organisation* -** Complex systems *self-organise*, i.e., autonomously change their behaviour or modify their structure, to eliminate or reduce impact of disruptive events
7. ***Co-Evolution*** – *Complex systems* are open, they adapt to their environments, and in turn, change their environments.

The History of Multi-agent Systems

- 1940s – **John Von Neumann** proposed a theoretical kinematic self-reproducing automaton model as a thought experiment (Agent-Based Model).
- 1971 – **Thomas Schelling's segregation model** - embodied the basic concept of agent-based models as autonomous agents interacting in a shared environment with an observed aggregate, emergent outcome.
- 1980s – Robert Axelrod hosted a tournament of **Prisoner's Dilemma strategies** and had them interact in an agent-based manner to determine a winner.
- 1990s – the largest application has come with development of computers because the fact that MAS are **computer systems**.



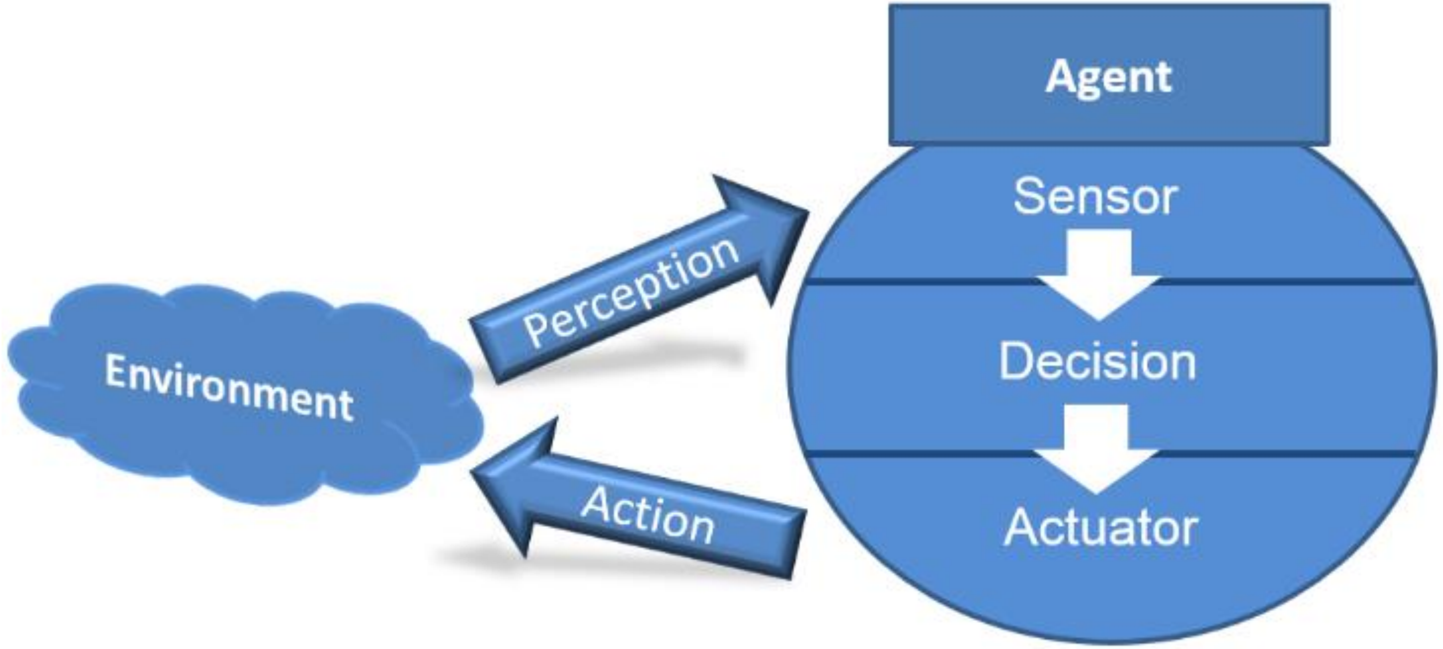
Prisoners' dilemma
prisoner B
confess
remain silent
prisoner A
confess
remain silent
5 years
5 years
0 year
20 years
20 years
0 year
1 year
1 year

The Definition of an Agent

- *„An agent is a computer system that is situated in some* ***environment,*** *and that is capable of* ***autonomous*** *action in this environment in order to achieve its delegated* ***objectives****." (Wooldridge, 1995)*
- *„Most often, when people use the term 'agent' they refer to an entity that functions* ***continuously*** *and* ***autonomously*** *in an environment in which other processes take place and other agents exist." (Shoham, 1993)*
- *„An agent is an entity that* ***senses*** *its environment and* ***acts*** *upon it." (Russell, 1997)*

The Definition of an Agent

- These definitions embrace three key concepts:
  - **Situatedness**
    - The agent receives sensory input from its environment and it can perform actions which change the environment in some way.
  - **Autonomy**
  - **Flexibility**



Autonomy

- Dictionary definitions:
  - **Autonomy**: self determined freedom, especially moral independence.
  - **Autonomous**: self-governing, independent.
- Agent definition:
  - The system should be able to act without the direct intervention of humans (or other agents). The system should have control over its own actions and internal state.
- Sometimes used in a stronger sense to mean systems that are capable of learning from experience.
- Examples:
  - any process control system: monitor real-world environment and perform actions to modify it as conditions change (in real-time)
    - Simple thermostats
    - Very complex nuclear reactor control systems.

Flexibility

- Intelligent agent exhibits the following types of behavior in order to meet its delegated objectives:
  - **Reactivity**
    - Agents are able to perceive its environment, and respond in a timely fashion to changes that occur in it in order to satisfy its delegated objectives.
  - **Proactiveness**
    - Agents should not simply act in response to their environment, they should be able to exhibit opportunistic, goal directed behavior and take the initiative where appropriate.
  - **Social ability**
    - Agents should be able to interact, when appropriate, with other artificial agents and humans in order to complete their own problem solving and to help others with their activities.

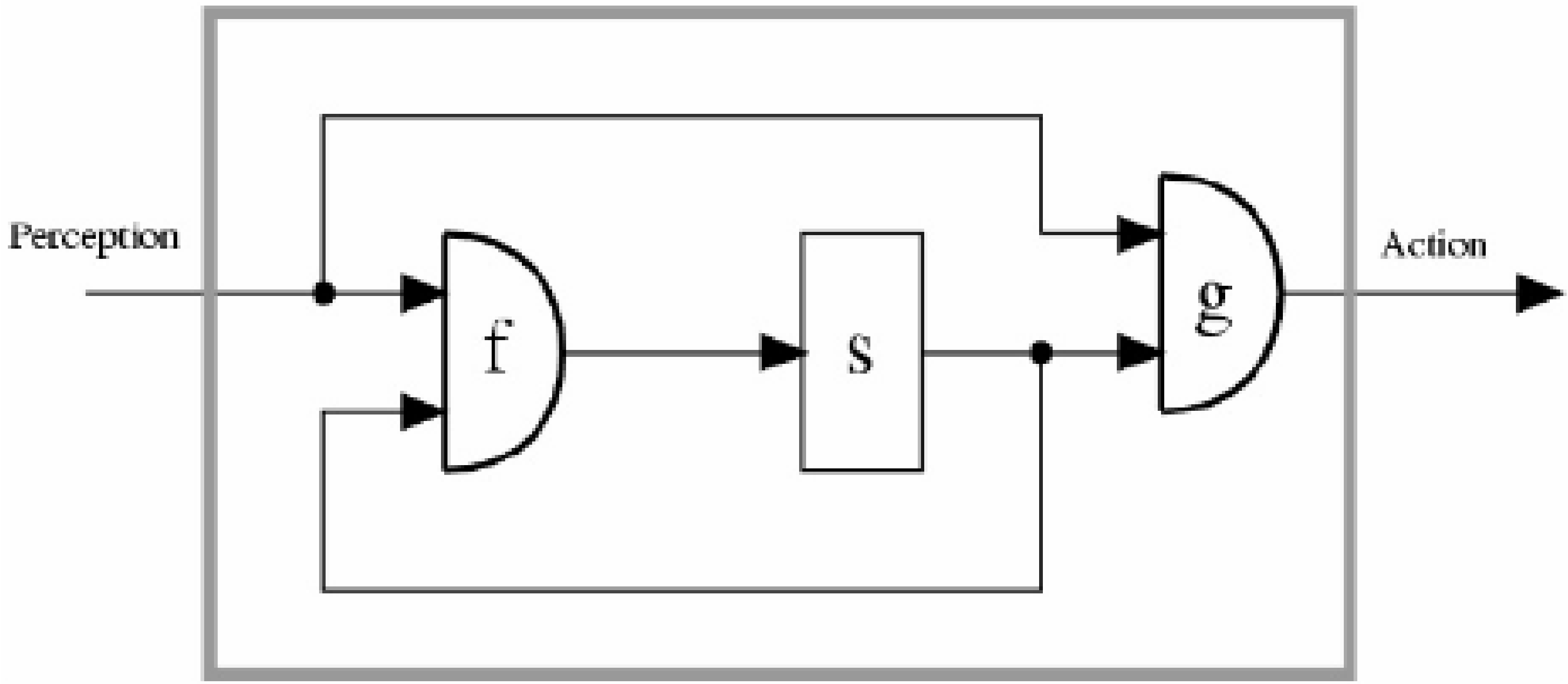
The Definition of an Agent

- An agent has three basic properties:
  - **Perception**
    - Collecting runtime information from the environment in order to get complex picture of its environment.
  - **Decision Making**
    - „Brain“ of the agent that is responsible for making decision based on inputs received in perception phase. A decision means a selection of particular action, which influences its environment in order to achieve the best result performed by the agent task.
  - **Action**
    - Based on the desicion makes during decision making phase described above, the specific action is selected and invoked in order to influence the environment and adapt the environment according to task of the agent.

Our Environment Is the Most Complex

- The environment we are living in is:
  - **Nondeterministic**
  - **Dynamic**
  - **Inaccesible**
  - **Nonepisodic**
  - **Continuous**

From Perception To Action



f = state update function
s = internal state
g = output function

MAS Problem Formulation

- Determine global objectives and goals
  - Fluent traffic flow, safety increase, etc.
- Determine the agents and their roles in the global system
  - Detectors, meteo-stations
- Determine the set of states of the world (environment) $S = \{s_j\}$
  - Possible states of traffic flow on highways
- Define agents' utility function $u_i : S \rightarrow \Re$
  - Represents the agents' behavior
- Define a set of actions, $A = \{a_i\}$, arising from the agent observations, θ_t
  - Traffic control (VMS)
- The agent selects an action at time t, based on the history of observations θ_t and its previous actions:

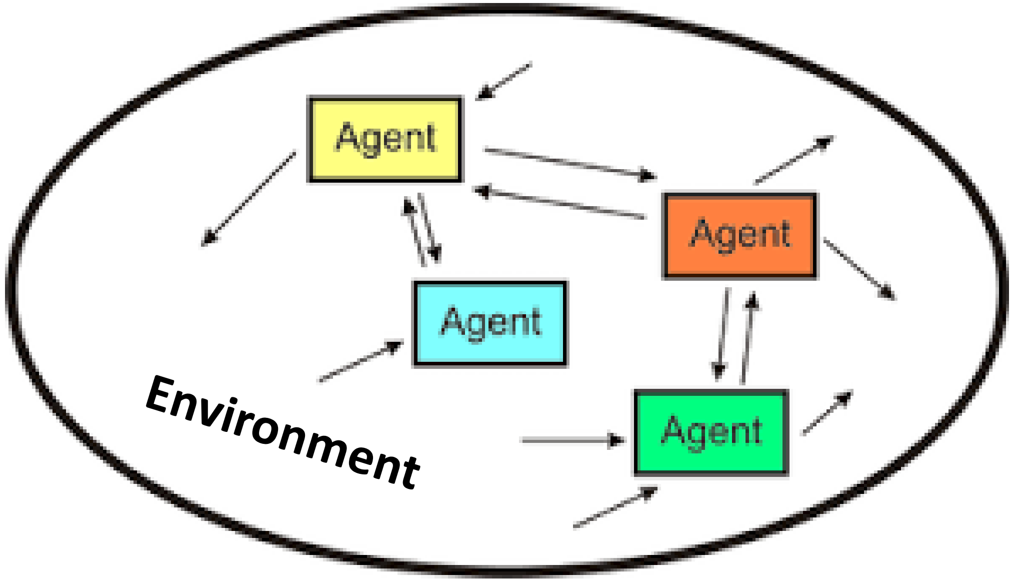
$$a_t = \pi(\theta_0, a_0, \theta_1, a_1, \dots \theta_t)$$

- Optimal action ${a_t}^*$ of the agent at state s_t should maximize expected utility:

$${a_t}^* = \arg\max_{a_t \in A} \sum_{s_{t+1}} p(s_{t+1}|s_t, a_t)\, U(s_{t+1})$$

Types of Agent Architectures

- **Logic-based Architecture**
- **Reactive Architecture**
- **Belief-Desire-Intention Architecture**
- **Hybrid Architecture**



Logic-based Architecture

- These agents have internal states
- See and next functions and model decision making bz a set of deduction rules for inference

see: S → P

next: D x P → D

action: D → A

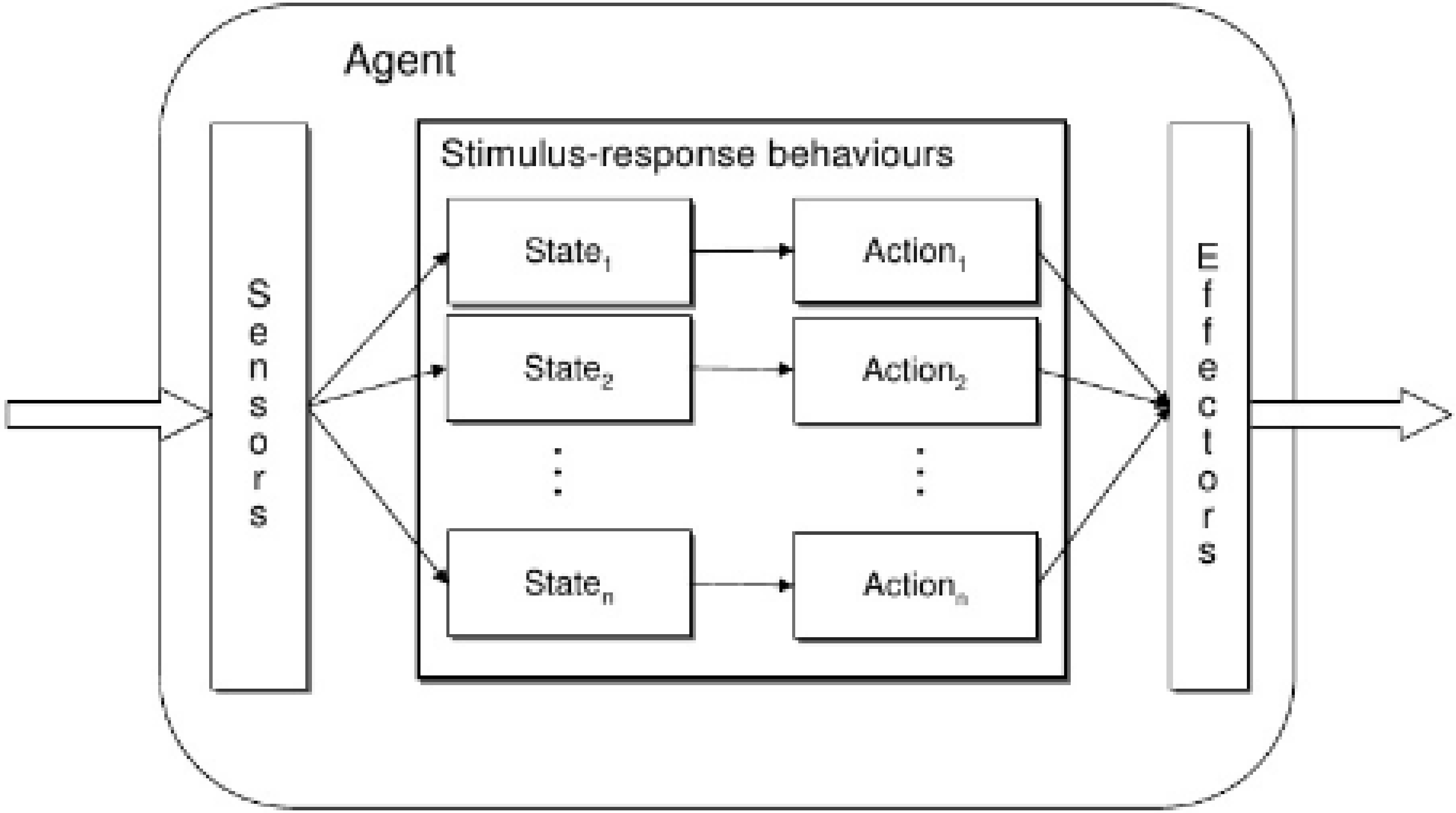
- Use logical deduction to try to prove the next action to take
- **Advantages**
  - Simple, elegant, logical semantics
- **Disadvantages**
  - Computational complexity, representing the real world

Reactive Architecture

- Each behavior continually maps perceptual input to action output
- Reactive behavior: **action rules: S→A**
- Example:

$$\text{action}(s) = \begin{cases} \textit{Heater off}, & \text{if temperature is OK in state s} \\ \textit{Heater on}, & \text{otherwise} \end{cases}$$

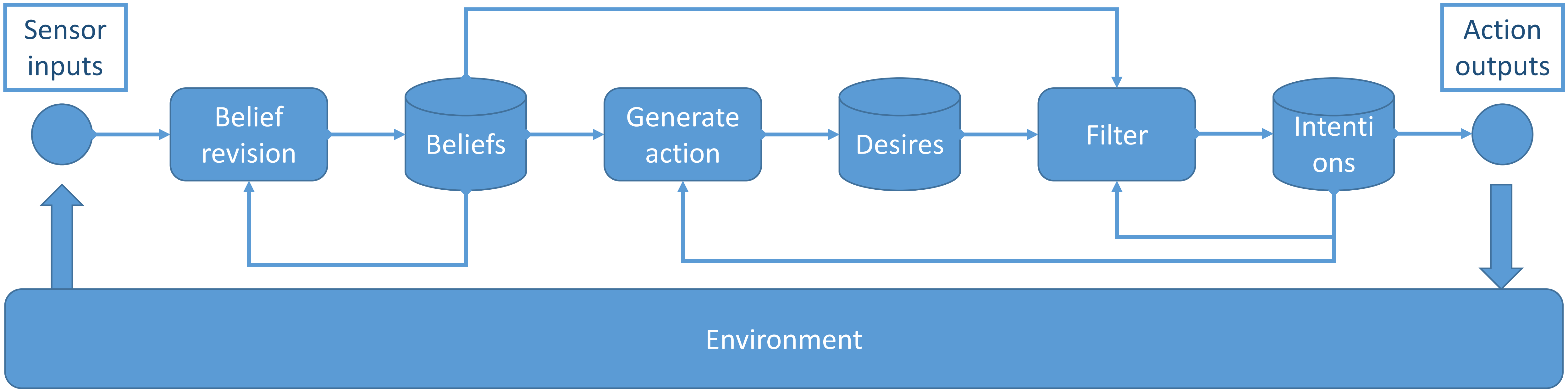
Basic Schema of Reactive Architecture



BDI Architecture

- **Practical reasoning** - deciding what goals we want to achieve (deliberation), and how we are going to achieve these goals (means-ends).
- **Human Practical reasoning**
  - **Deliberation**
    - Deciding what state of affairs we want to achieve
    - The outputs of deliberation are intentions
  - **Means-ends reasoning**
    - Deciding how to achieve these states of affairs
    - The outputs of means-ends reasoning are plans

BDI process



Sensor inputs
Belief revision
Beliefs
Generate action
Desires
Filter
Intenti ons
Action outputs
Environment

BDI Architecture

- Beliefs:
  - Agent's view of the environment/world.

- Desires:
  - Follow from the beliefs. Desires can be unrealistic and inconsistent.
- Goals:
  - A subset of the desires. Realistic and consistent.

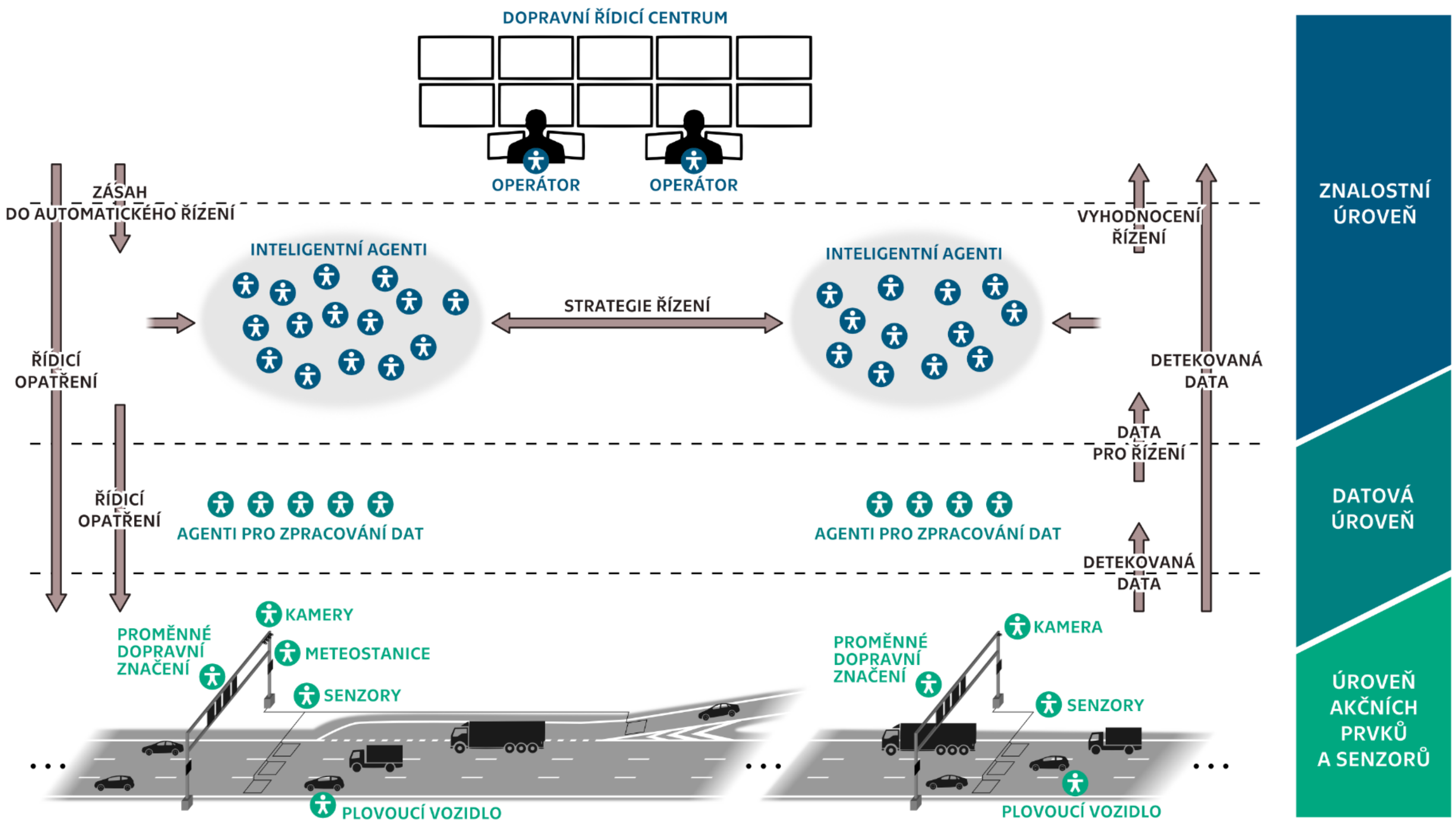
    Determine potential processing.
- Intentions:
  - A subset of the goals. A goal becomes an intention when an agent decides to commit to it (e.g. by assigning priorities to goals)

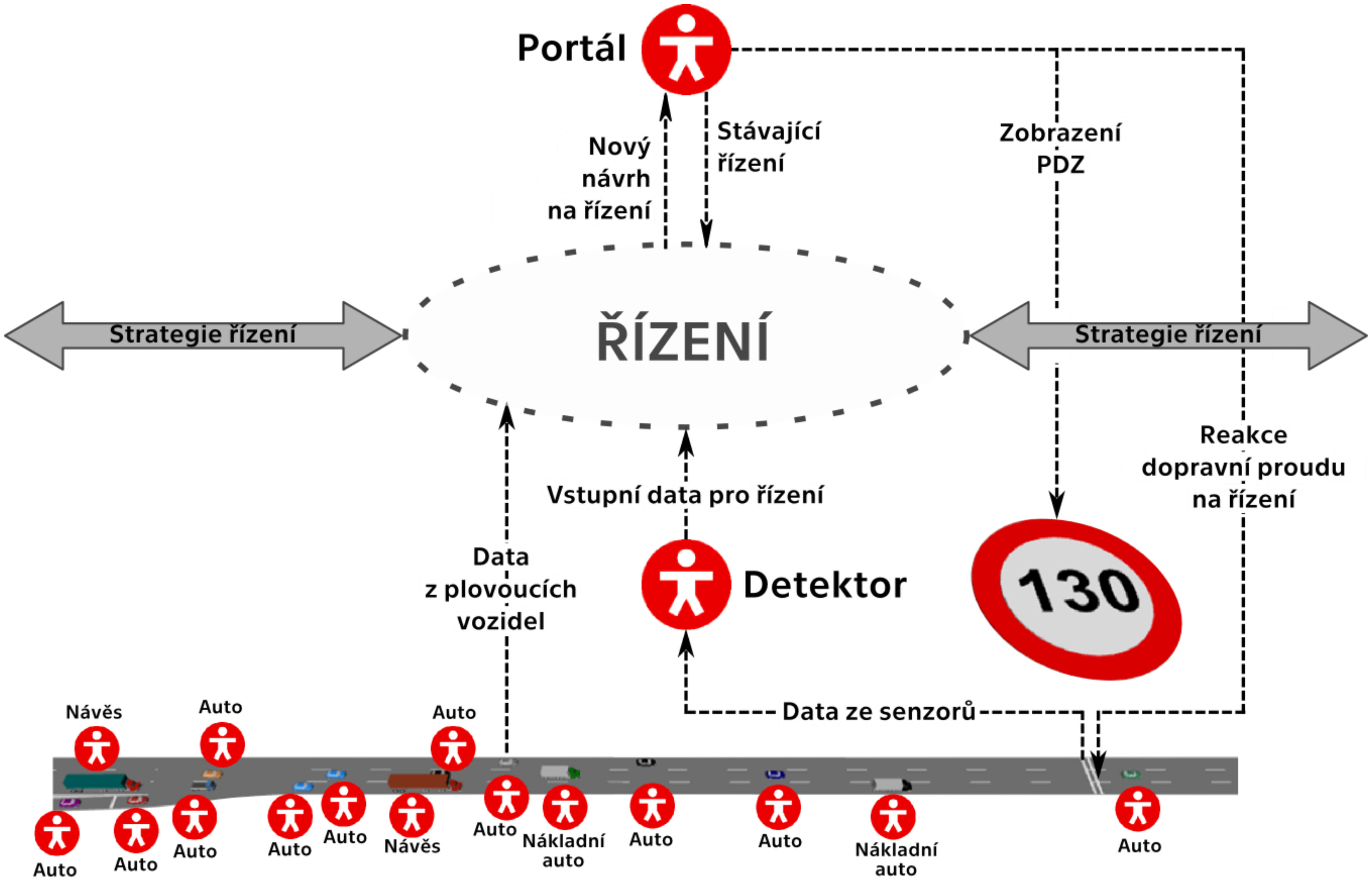
- Plans:
  - Sequences of actions that are needed to achieve the intentions, given the agent's beliefs

Multi-agent Systems

- In Multi-agent systems, we address questions such as:
  - How can **cooperation** emerge in societies of self-interested agents?
  - What kinds of languages can agents use to communicate?
  - How can **self-interested** agents recognize conflict, and how can they (nevertheless) reach agreement?
  - How can autonomous agents coordinate their activities so as to cooperatively achieve goals?
- While these questions are all addressed in part by other disciplines (notably economics and social sciences), what makes the multi-agent systems field unique is that it emphasizes that the agents in question are **computational**, **information processing** entities.

MAS PRO ŘÍZENÍ DOPRAVY NA DÁLNICÍCH



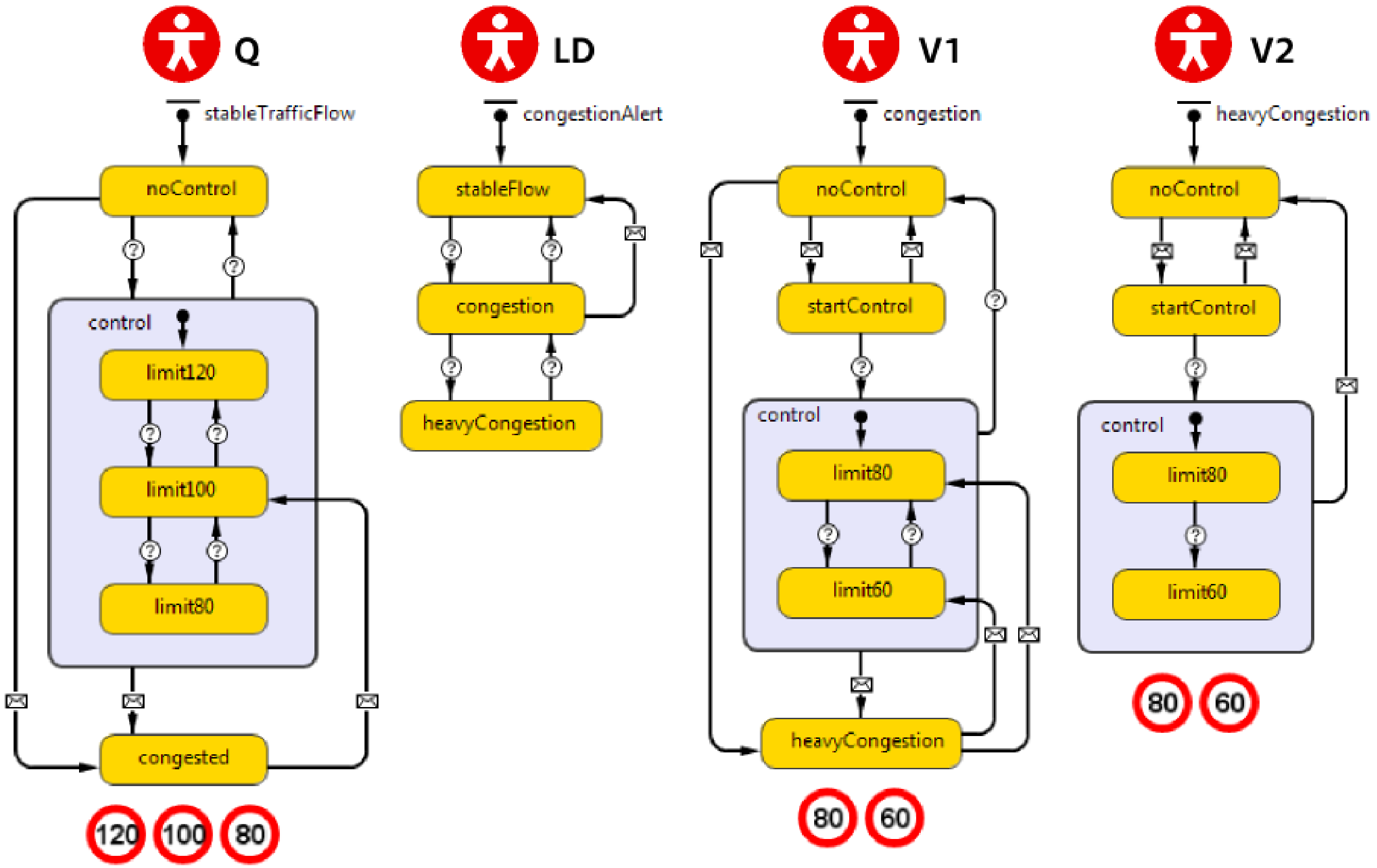


Portál
Nový návrh na řízení
Stávající řízení
Zobrazení PDZ
Strategie řízení
ŘÍZENÍ
Strategie řízení
Vstupní data pro řízení
Reakce dopravní proudu na řízení
Data z plovoucích vozidel
Detektor
130
Data ze senzorů
Návěs
Auto
Auto
Auto
Auto
Auto
Auto
Auto
Auto
Návěs
Auto
Nákladní auto
Auto
Auto
Nákladní auto
Auto

TYPY ŘÍZENÍ

- Manuální řízení operátorem
- Automatické řízení – rozhodovací stromy
- Automatické řízení – agenti

AGENTNÍ ŘÍZENÍ – 1. VRST



SMACEF – Scenarios

Thank you!