

Fundamentals of Artificial Intelligence

Chapter 02: Intelligent Agents

Roberto Sebastiani

DISI, Università di Trento, Italy – roberto.sebastiani@unitn.it

https://disi.unitn.it/rseba/DIDATTICA/fai_2023/

Teaching assistants:

Mauro Dragoni, dragoni@fbk.eu, <https://www.maurodragoni.com/teaching/fai/>

Paolo Morettin, paolo.morettin@unitn.it, <https://paolomorettin.github.io/>

M.S. Course “Artificial Intelligence Systems”, academic year 2023-2024

Last update: Tuesday 12th September, 2023, 17:38

Copyright notice: Most examples and images displayed in the slides of this course are taken from [Russell & Norvig, “Artificial Intelligence, a Modern Approach”, 3rd ed., Pearson], including explicitly figures from the above-mentioned book, so that their copyright is detained by the authors. A few other material (text, figures, examples) is authored by (in alphabetical order): Pieter Abbeel, Bonnie J. Dorr, Anca Dragan, Dan Klein, Nikita Kitaev, Tom Lenaerts, Michela Milano, Dana Nau, Maria Simi, who detain its copyright.

These slides cannot be displayed in public without the permission of the author.

Outline

- 1 Agents and Environments
- 2 Rational Agents
- 3 Task Environments
- 4 Task-Environment Types
- 5 Agent Types
- 6 Environment States

Outline

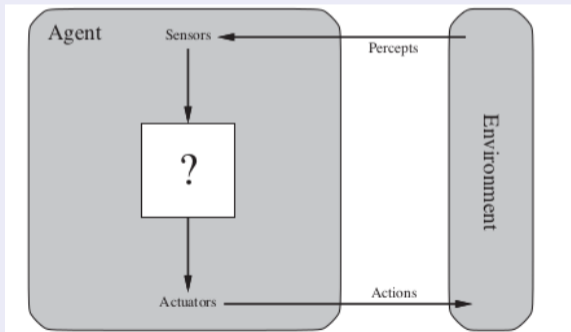
- 1 Agents and Environments
- 2 Rational Agents
- 3 Task Environments
- 4 Task-Environment Types
- 5 Agent Types
- 6 Environment States

Agents and Environments

Agents

An **agent** is any entity that can be viewed as:

- **perceiving** its environment through **sensors**, and
- **acting** upon that environment through **actuators**.



(© S. Russell & P. Norwig, AIMA)

Agents and Environments [cont.]

Agents

Agents include humans, robots, softbots, thermostats, etc.

- **human:**

perceives: with eyes, ears, nose, hands, ...

acts: with voice, hands, arms, legs, ...

- **robot:**

perceives: with video-cameras, infra-red sensors, radar, ...

acts: with wheels, motors, ...

- **softbot:**

perceives: receiving keystrokes, files, network packets, ...

acts: displaying on the screen, writing files, sending network packets

- **thermostat:**

perceives: with heat sensor

acts: electric impulses to valves, devices, ...

Key concepts

Percept and Percept sequences

- **percept**: the collection of agent's perceptual inputs at any given instant
- **percept sequence**: the complete history of everything the agent has ever perceived

An agent's choice of action at any given instant

- can depend on **the entire percept sequence** observed to date
- does not depend on anything it hasn't perceived

Remark

An agent can perceive its own actions, but not always its effects.

Key concepts [cont.]

Agent function

An agent's behavior is described by the **agent function** $f : P^* \mapsto A$ which **maps any given percept sequence into an action**.

- ideally, can be seen as a table [*percept sequence, action*]

Agent program

Internally, the agent function for an artificial agent is implemented by an **agent program**.

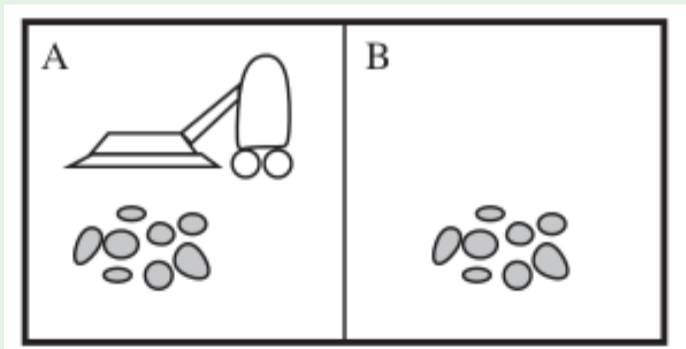
Note: Agent function vs. agent program

- The **agent function** is an **abstract mathematical description**
 - possibly-infinite description
- The **agent program** is a **concrete implementation** of the agent function
 - finite description
 - runs on the physical architecture to produce the agent function f

Example

A very-simple vacuum cleaner

- Environment: squares A and B
- Percepts: location ($\{A, B\}$) and content ($\{Dirty, Clean\}$)
 - e.g. [A, Dirty]
- Actions: $\{left, right, suck, no_op\}$



Example [cont.]

A simple agent function

If the current square is dirty, then suck; otherwise, move to the other square.

Percept sequence	Action
<i>[A, Clean]</i>	<i>Right</i>
<i>[A, Dirty]</i>	<i>Suck</i>
<i>[B, Clean]</i>	<i>Left</i>
<i>[B, Dirty]</i>	<i>Suck</i>
<i>[A, Clean], [A, Clean]</i>	<i>Right</i>
<i>[A, Clean], [A, Dirty]</i>	<i>Suck</i>
<i>⋮</i>	<i>⋮</i>
<i>[A, Clean], [A, Clean], [A, Clean]</i>	<i>Right</i>
<i>[A, Clean], [A, Clean], [A, Dirty]</i>	<i>Suck</i>
<i>⋮</i>	<i>⋮</i>

(© S. Russell & P. Norwig, AIMA)

Note: this agent function depends only on the last percept, not on the whole percept sequence.

Example [cont.]

Corresponding agent program

```
function REFLEX-VACUUM-AGENT([location,status]) returns an action  
if status = Dirty then return Suck  
else if location = A then return Right  
else if location = B then return Left
```

(© S. Russell & P. Norwig, AIMA)

Outline

- 1 Agents and Environments
- 2 Rational Agents**
- 3 Task Environments
- 4 Task-Environment Types
- 5 Agent Types
- 6 Environment States

Rational Agents

Main question

What is a **rational** agent?

- Intuition: a rational agent is one that “does the right thing”
 - i.e., every entry in the agent function-table is filled out correctly
- Problem: What is the right thing?
- Approximated answer: the most “**successful**” thing:
 - In a given environment, according to the **percept sequence** it receives, an agent generates a **sequence of actions**, ...
 - ... causing the environment to go through a **sequence of states**.
 - If such sequence is **desirable**, then the agent has performed well.

⇒ We need a **performance measure** to evaluate any sequence of environment states

Rational Agents [cont.]

What is rational at any given time depends on four ingredients:

- The **performance measure** that defines the criterion of success
- The agent's **prior knowledge** of the environment
- The **actions** that the agent can perform
- The agent's **percept sequence** to date (from sensors)

Definition of a rational agent

For each possible **percept sequence**, a rational agent should **select an action that is expected to maximize its performance measure**, given the **evidence provided by the percept sequence** and whatever **built-in knowledge the agent has**.

Rational Agents: Example

The simple vacuum-cleaner agent

Under the following assumptions:

- **Performance measure:**
one point for each clean square at each time step, over 1000 time steps
- **Environment knowledge:**
 - “geography” known a priori,
 - dirt distribution and agent initial location unknown
 - [clean squares cannot become dirty again]
- **Perception:** self location, presence of dirt
- **Actions:** Left, Right, Suck

```
function REFLEX-VACUUM-AGENT([location,status]) returns an action
if status = Dirty then return Suck
else if location = A then return Right
else if location = B then return Left
```

(© S. Russell & P. Norwig, AIMA)

Is the above-described agent rational? \implies **Yes!** (provided the given performance measure)

Beware: if a penalty for each move is given, the agent behaves poorly
 \implies better agent: do nothing once it is sure all the squares are clean

Rationality vs. Omniscience vs. Perfection

Remark

- **Rationality \neq Omniscience!**
 - An omniscient agent **knows for sure** the outcome of its actions
 \implies omniscience impossible in reality
 - A rational agent may only know “up to a reasonable confidence”
(e.g., when crossing a road, what if something falling from a plane flattens you?
if so, would you be considered irrational?)
- **Rational behaviour is not perfect behaviour!**
 - perfection maximizes **actual** performance
 - (given uncertainty) rationality maximizes **expected** performance

Information Gathering, Learning, Autonomy

Rationality requires other important features

- **Information gathering/exploration:**
 - the rational choice depends only on the percept sequence to date
⇒ actions needed in order to modify future percepts
 - Ex: look both ways before crossing a busy road
- **Learning:**
 - agent's prior knowledge of the environment incomplete
⇒ learning from percept sequences improves & augments it
 - Ex: a baby learns from trial&errors the right movements to walk
- **Being Autonomous:**
 - prior knowledge may be partial/incorrect or evolving
⇒ learn to compensate for partial or incorrect prior knowledge
 - Ex: a child learns how to climb a tree

Information gathering, learning, autonomy play an essential role in AI.

Outline

- 1 Agents and Environments
- 2 Rational Agents
- 3 Task Environments**
- 4 Task-Environment Types
- 5 Agent Types
- 6 Environment States

Task Environments

PEAS Description of Task Environments

- To design a rational agent we must specify its **task environment**
 - i.e. the “problems” to which rational agents are the “solutions”
- Task environment described in terms of four elements (“PEAS”):
 - **P**erformance measure
 - **E**nvironment
 - **A**ctuators
 - **S**ensors

Simple Example: Simple Vacuum Cleaner

- **Performance measure**: 1 point per clean square per time step
- **Environment**: squares A and B, possibly dirty
- **Actuators**: move left/right, suck
- **Sensors**: self location, presence of dirt

Task Environments [cont.]

Complex Example: Autonomous Taxi

- **Performance measure**: safety, destination, profits, comfort, ...
- **Environment**: streets/freeways, other traffic, pedestrians, ...
- **Actuators**: steering, accelerator, brake, horn, speaker/display, ...
- **Sensors**: video, sonar, speedometer, engine sensors, GPS, ...

Remark

Some goals to be measured may conflict!

- e.g. **profits** vs. **safety**, **profits** vs. **comfort**, ...
⇒ tradeoffs are required

Task Environments: Examples

Agent Type	Performance Measure	Environment	Actuators	Sensors
Medical diagnosis system	Healthy patient, reduced costs	Patient, hospital, staff	Display of questions, tests, diagnoses, treatments, referrals	Keyboard entry of symptoms, findings, patient's answers
Satellite image analysis system	Correct image categorization	Downlink from orbiting satellite	Display of scene categorization	Color pixel arrays
Part-picking robot	Percentage of parts in correct bins	Conveyor belt with parts; bins	Jointed arm and hand	Camera, joint angle sensors
Refinery controller	Purity, yield, safety	Refinery, operators	Valves, pumps, heaters, displays	Temperature, pressure, chemical sensors
Interactive English tutor	Student's score on test	Set of students, testing agency	Display of exercises, suggestions, corrections	Keyboard entry

Outline

- 1 Agents and Environments
- 2 Rational Agents
- 3 Task Environments
- 4 Task-Environment Types**
- 5 Agent Types
- 6 Environment States

Properties of Task Environments

Task environments can be categorized along six dimensions:

- Single-agent vs. multi-agent
- Fully observable vs. partially observable
- Deterministic vs. stochastic
- Episodic vs. sequential
- Static vs. dynamic
- Discrete vs. continuous

Properties of Task Environments [cont.]

Single-agent vs. multi-agent

- A task environment is **multi-agent** iff contains **other agents** who are also maximizing some **performance measure that depends on the current agent's actions**
 - latest condition essential
 - distinction between single- and multi-agent sometimes subtle
- Two important cases
 - **competitive** multi-agent environment:
other agents' goals conflict with, or even oppose to, the agent's goals
 - Ex: **chess**, **war scenarios**, **taxi driving** (compete for parking lot), ...
 - **cooperative** multi-agent environment:
other agents' goals coincide in full, or in part, with the agent's goals
 - Ex: **ants' nest**, **factory**, **taxi driving** (avoid collisions), ...
- **Different design problems** for multi-agent wrt. single-agent
 - competitive: **randomized** behaviour often rational (unpredictable)
 - collaborative: **communication** with other agents often rational

Properties of Task Environments [cont.]

Fully observable vs. partially observable

- A task environment is **fully observable** iff the sensors detect **the complete state of the environment**
 - ⇒ no need to maintain internal state to keep track of the environment
- A task environment is **effectively fully observable** iff the sensors detect **all aspects of the state of the environments that are relevant to the choice of action**
 - "relevant" depends on the performance measure
- A t.e. may be **partially observable** (Ex: **Taxi driving**):
 - noisy and inaccurate sensors
 - parts of the state are not accessible for sensors
- A t.e. might be even **unobservable** (no sensors)
 - e.g. fully-deterministic actions

Properties of Task Environments [cont.]

Deterministic vs. stochastic

- A task environment is **deterministic** iff its next state is completely determined by its current state and by the action of the agent. (Ex: **a crossword puzzle**).
- If not so:
 - A t.e. is **stochastic** if uncertainty about outcomes **is quantified in terms of probabilities** (Ex: **dice, poker game, component failure**,...)
 - A t.e. is **nondeterministic** iff actions are characterized by their possible outcomes, but no probabilities are attached to them

In a multi-agent environment we ignore uncertainty that arises from the actions of other agents (Ex: **chess** is deterministic even though each agent is unable to predict the actions of the others).

A **partially observable** environment could **appear to be stochastic**.

⇒ for practical purposes, when it is impossible to keep track of all the unobserved aspects, they must be treated as stochastic.

(Ex: **Taxi driving**)

Properties of Task Environments [cont.]

Episodic vs. sequential

- In an **episodic** task environment
 - the agent's experience is divided into **atomic episodes**
 - in each episode the agent receives a percept and then performs a single action
 - ⇒ **episodes do not depend on the actions taken in previous episodes, and they do not influence future episodes**
 - Ex: **an agent that has to spot defective parts on an assembly line,**
- In **sequential** environments the current decision could affect future decisions
 - ⇒ actions can have long-term consequences
 - Ex: **chess, taxi driving, ...**
- Episodic environments **are much simpler** than sequential ones
 - No need to think ahead!

Properties of Task Environments [cont.]

Static vs. dynamic

- The task environment is **dynamic** iff **it can change while the agent is choosing an action**, **static** otherwise
 - ⇒ **agent needs keep looking at the world while deciding an action**
 - Ex: **crossword puzzles** are static, **taxi driving** is dynamic
- The t.e. is **semidynamic** if the environment itself does not change with time, but **the agent's performance score does**
 - Ex: **chess with a clock**
- Static environments are easier to deal wrt. [semi]dynamic ones

Properties of Task Environments [cont.]

Discrete vs. continuous

- The **state of the environment**, the way **time** is handled, and agents **percepts** & **actions** can be **discrete** or **continuous**
 - Ex: **Crossword puzzles**: discrete state, time, percepts & actions
 - Ex: **Taxi driving**: continuous state, time, percepts & actions
 - ...

Properties of Task Environments [cont.]

Note

- The simplest environment is **fully observable**, **single-agent**, **deterministic**, **episodic**, **static** and **discrete**.
 - Ex: **simple vacuum cleaner**
- Most real-world situations are **partially observable**, **multi-agent**, **stochastic**, **sequential**, **dynamic**, and **continuous**.
 - Ex: **taxi driving**

Properties of Task Environments [cont.]

Example properties of task Environments

Task Environment	Observable	Agents	Deterministic	Episodic	Static	Discrete
Crossword puzzle	Fully	Single	Deterministic	Sequential	Static	Discrete
Chess with a clock	Fully	Multi	Deterministic	Sequential	Semi	Discrete
Poker	Partially	Multi	Stochastic	Sequential	Static	Discrete
Backgammon	Fully	Multi	Stochastic	Sequential	Static	Discrete
Taxi driving	Partially	Multi	Stochastic	Sequential	Dynamic	Continuous
Medical diagnosis	Partially	Single	Stochastic	Sequential	Dynamic	Continuous
Image analysis	Fully	Single	Deterministic	Episodic	Semi	Continuous
Part-picking robot	Partially	Single	Stochastic	Episodic	Dynamic	Continuous
Refinery controller	Partially	Single	Stochastic	Sequential	Dynamic	Continuous
Interactive English tutor	Partially	Multi	Stochastic	Sequential	Dynamic	Discrete

Properties of the Agent's State of Knowledge

Known vs. unknown

- Describes the agent's (or designer's) **state of knowledge** about the “laws of physics” of the environment
 - if the environment is **known**, then **the outcomes (or outcome probabilities if stochastic) for all actions are given**.
 - if the environment is **unknown**, then **the agent will have to learn how it works** in order to make good decisions
- Orthogonal wrt. task-environment properties

Known \neq Fully observable

- a known environment can be partially observable
(Ex: **a solitaire card games**)
- an unknown environment can be fully observable
(Ex: **a game I don't know the rules of**)

Outline

- 1 Agents and Environments
- 2 Rational Agents
- 3 Task Environments
- 4 Task-Environment Types
- 5 Agent Types**
- 6 Environment States

Agents

Agent = Architecture + Program

- AI Job: **design an agent program implementing the agent function**
- The agent program runs on some computing device with physical sensors and actuators: **the agent architecture**
- All agents have the same skeleton:
 - Input: current percepts
 - Output: action
 - Program: manipulates input to produce output

Remark

- the **agent function** takes the **entire percept history** as input
 - the **agent program** takes **only the current percept** as input
- ⇒ if the actions need to depend on the entire percept sequence, **then the agent will have to remember the percepts**

A trivial Agent Program

The Table-Driven Agent

- The table represents explicitly the agent function
 - Ex: the simple vacuum cleaner

function TABLE-DRIVEN-AGENT(*percept*) **returns** an action

persistent: *percepts*, a sequence, initially empty

table, a table of actions, indexed by percept sequences, initially fully specified

append *percept* to the end of *percepts*

action ← LOOKUP(*percepts*, *table*)

return *action*

(© S. Russell & P. Norwig, AIMA)

Blow-up in table size \implies doomed to failure

Agent Types

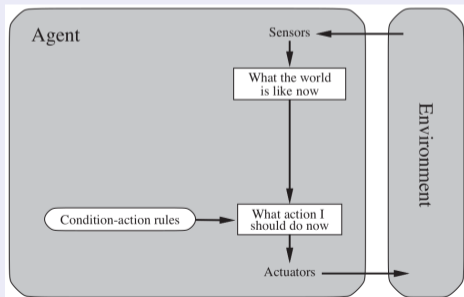
Four basic kinds of agent programs

- Simple-reflex agents
- Model-based reflex agents
- Goal-based agents
- Utility-based agents

All these can be turned into **learning** agents.

Agent Types: Simple-reflex agent

- Select action on the basis of **the current percept only**
 - Ex: **the simple vacuum-agent**
- Implemented through **condition-action rules**
 - Ex: “**if car-in-front-is-braking then initiate-braking**”
 - can be implemented, e.g., in a Boolean circuit
- **Large reduction in possible percept/action situations due to ignoring the percept history**



(© S. Russell & P. Norwig, AIMA)

Agent Types: Simple-reflex agent [cont.]

Simple-reflex agent program

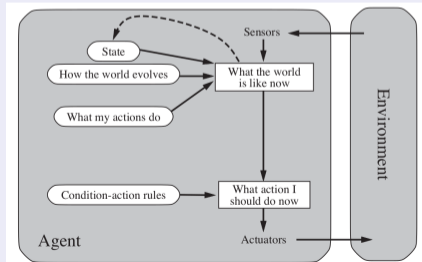
```
function SIMPLE-REFLEX-AGENT(percept) returns an action  
persistent: rules, a set of condition–action rules  
  
state ← INTERPRET-INPUT(percept)  
rule ← RULE-MATCH(state, rules)  
action ← rule.ACTION  
return action
```

© S. Russell & P. Norwig, AIMA

- very simple
 - may work **only if the environment is fully observable**
 - errors, deadlocks or infinite loops may occur otherwise
- ⇒ limited applicability

Agent Types: Model-based Reflex Agent

- Idea: To tackle partially-observable environments,
keeps track of the part of the world it can't see now
 - maintain **internal state** depending on the percept history
 - reflects at least some of the unobserved aspects of current state
- To update internal state the agent needs **a model of the world**:
 - how the world evolves independently of the agent
 - Ex: an overtaking car will soon be closer behind than it was before
 - how the agent's own actions affect the world
 - Ex: turn the steering wheel clockwise \implies the car turns to the right



Agent Types: Model-based Reflex Agent [cont.]

Model-based Agent program

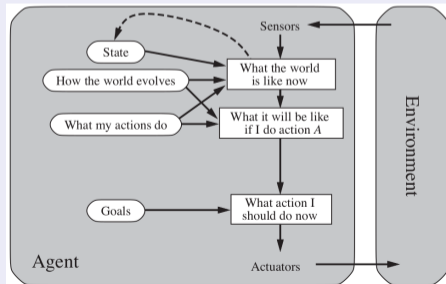
function MODEL-BASED-REFLEX-AGENT(*percept*) **returns** an action

persistent: *state*, the agent's current conception of the world state
model, a description of how the next state depends on current state and action
rules, a set of condition–action rules
action, the most recent action, initially none

state ← UPDATE-STATE(*state*, *action*, *percept*, *model*)
rule ← RULE-MATCH(*state*, *rules*)
action ← *rule*.ACTION
return *action*

Agent Types: Model-based Goal-based agent

- The agent needs **goal information** describing **desirable situation**
 - Ex: **destination** for a **Taxi driver**
- Idea: **combine goal with the model to choose actions**
- Difficult if long action sequences are required to reach the goal
⇒ Typically investigated in **search** and **planning** research.
- Major difference: **future is taken into account**
 - rules are simple condition-action pairs, do not target a goal



Agent Types: Model-based Goal-based Agent [cont.]

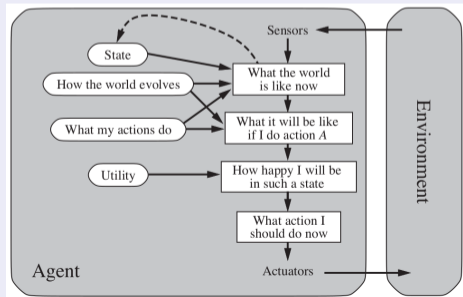
Goal-based Agents

- **more flexible:**
 - the knowledge that supports its decisions **is represented explicitly**
 - **such knowledge can be modified**
 - ⇒ all of the relevant behaviors to be altered to suit the new conditions
 - Ex: **If it rains, the agent can update its knowledge of how effectively its brakes operate**
 - **the goal can be modified/updated** ⇒ modify its behaviour
 - no need to rewrite all rules from scratch
- more complicate to implement
- **may require expensive computation** (search, planning)

Agent Types: Utility-based agent

- Goals alone often not enough to generate high-quality behaviors
 - Certain goals can be reached in different ways, of different quality
 - Ex: **some routes are quicker, safer, or cheaper than others**
- Idea: **Add utility function(s) to drive the choice of actions**
 - maps a (sequence of) state(s) onto a real number
 - ⇒ actions are chosen which **maximize the utility function**
 - under uncertainty, maximize the **expected** utility function

⇒ **utility function = internalization of performance measure**



Agent Types: Utility-based Agent [cont.]

Utility-based Agents

- advantages wrt. goal-based:
 - with **conflicting goals**, utility specifies and appropriate tradeoff
 - with **several goals none of which can be achieved with certainty**, utility selects proper tradeoff between importance of goals and likelihood of success
- still complicate to implement
- require sophisticated perception, reasoning, and learning
- **may require expensive computation**

Agent Types: Learning

Problem

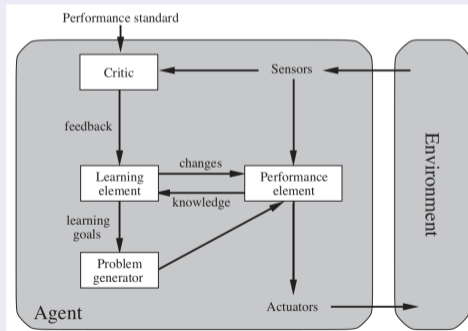
- Previous agent programs describe methods for **selecting actions**
 - **How are these agent programs programmed?**
 - Programming by hand **inefficient** and **ineffective!**
 - Solution: build **learning machines** and then **teach** them (rather than **instruct** them)
 - Advantage: **robustness** of the agent program toward initially-unknown environments

Agent Types: Learning

Learning Agent Types: components

Performance element: **selects actions based on percepts**

- Corresponds to the previous agent programs

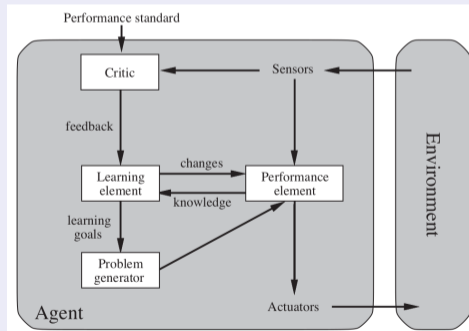


(© S. Russell & P. Norwig, AIMA)

Agent Types: Learning

Learning Agent Types: components

Critic tells how the agent is doing wrt. performance standard



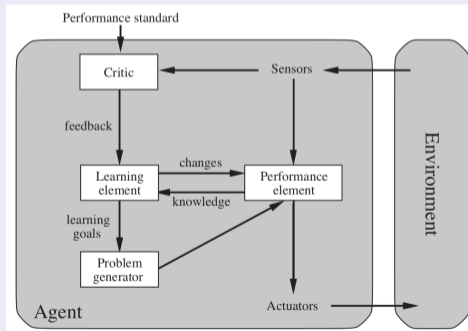
(© S. Russell & P. Norwig, AIMA)

Agent Types: Learning

Learning Agent Types: components

Learning element: introduces improvements

- uses feedback from the **critic** on how the agent is doing
- determines improvements for the performance element



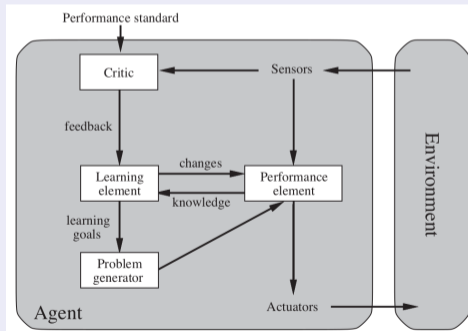
(© S. Russell & P. Norwig, AIMA)

Agent Types: Learning

Learning Agent Types: components

Problem generator: suggests actions that will lead to new and informative experiences

- forces exploration of new stimulating scenarios



(© S. Russell & P. Norwig, AIMA)

Learning Agent Types: Example

Taxi Driving

- After the taxi makes a quick left turn across three lanes, the **critic** observes the shocking language used by other drivers.
- From this experience, the **learning element** formulates a rule saying this was a bad action.
- The **performance element** is modified by adding the new rule.
- The **problem generator** might identify certain areas of behavior in need of improvement, and suggest trying out the brakes on different road surfaces under different conditions.

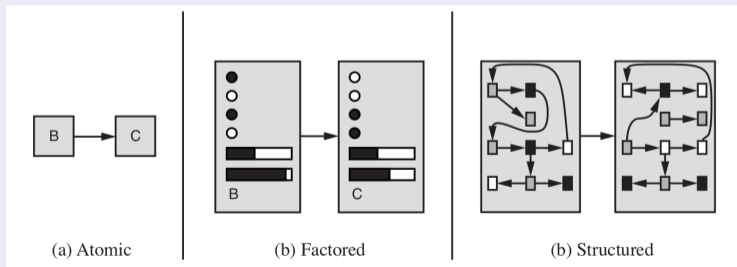
Outline

- 1 Agents and Environments
- 2 Rational Agents
- 3 Task Environments
- 4 Task-Environment Types
- 5 Agent Types
- 6 Environment States**

Representations

Representations of states and transitions

- Three ways to represent states and transitions between them:
 - **atomic**: a state is a **black box with no internal structure**
 - **factored**: a state consists of a **vector of attribute values**
 - **structured**: a state **includes objects**, each of which may have **attributes** of its own as well as **relationships** to other objects
- increasing **expressive power** and **computational complexity**
- reality represented at **different levels of abstraction**



Representations [cont.]

Atomic Representations

- each state of the world is **indivisible**
 - no internal structure
 - state: one among a **collection of discrete state values**
 - Ex: find driving routes: { *Trento*, *Rovereto*, *Verona*, ... }
 - ⇒ only property: be identical to or different from another state
 - **very high level of abstraction**
 - ⇒ lots of details ignored
 - The algorithms underlying
 - **search** and **game-playing**
 - **hidden Markov models**
 - **Markov decision processes**
- all work with atomic representations (or treat it as such)

Representations [cont.]

Factored Representation

- Each state represented in terms of **a vector of attribute values**
 - Ex: $\langle \text{zone}, \{\text{dirty}, \text{clean}\} \rangle$, $\langle \text{town}, \text{speed} \rangle$
- State: **combination of attribute values**
 - Ex: $\langle A, \text{dirty} \rangle$, $\langle \text{Trento}, 40\text{kmh} \rangle$
- Distinct states may share the values of some attribute
 - Ex: $\langle \text{Trento}, 40\text{kmh} \rangle$ and $\langle \text{Trento}, 47\text{kmh} \rangle$
 - identical iff all attribute have the same values
 - ⇒ must differ for at least one value to be different
- **Can represent uncertainty** (e.g., ignorance about the amount of gas in the tank represented by leaving that attribute blank)
- **Lower level of abstraction** ⇒ less details ignored
- Many areas of AI based on factored representations
 - **constraint satisfaction** and **propositional logic**
 - **planning**
 - **Bayesian networks**
 - (most of) **machine learning**

Representations [cont.]

Structured Representation

- States represents in terms of **objects** and **relations** over them
 - Ex $\forall x.(Men(x) \rightarrow Mortal(x))$,
 $Woman(Maria)$, $Mother \equiv Woman \cap \exists hasChild.Person$
- **Lowest level of abstraction** \implies can represent reality in details
- Many areas of Ai based on factored representations
 - relational databases
 - first-order logic
 - first-order probability models
 - knowledge-based learning
 - natural language understanding