

What is Artificial Intelligence

- Different definitions due to different criteria
- Two dimensions:
 - Thought processes/reasoning vs. behavior/action
 - Success according to human standards vs. success according to an ideal concept of intelligence: rationality.

| | |
|--------------------------------|-------------------------------|
| Systems that think like humans | Systems that think rationally |
| Systems that act like humans | Systems that act rationally |

Definitions of Artificial Intelligence

| | |
|--|---|
| <p>Systems that think like humans</p> | <p>Systems that think rationally</p> |
| <p>“The exciting new effort to make computers think . . . <i>machines with minds</i>, in the full and literal sense.” (Haugeland, 1985)</p> <p>“[The automation of] activities that we associate with human thinking, activities such as decision-making, problem solving, learning . . .” (Bellman, 1978)</p> | <p>“The study of mental faculties through the use of computational models.” (Charniak and McDermott, 1985)</p> <p>“The study of the computations that make it possible to perceive, reason, and act.” (Winston, 1992)</p> |
| <p>Systems that act like humans</p> | <p>Systems that act rationally</p> |
| <p>“The art of creating machines that perform functions that require intelligence when performed by people.” (Kurzweil, 1990)</p> <p>“The study of how to make computers do things at which, at the moment, people are better.” (Rich and Knight, 1991)</p> | <p>“Computational Intelligence is the study of the design of intelligent agents.” (Poole <i>et al.</i>, 1998)</p> <p>“AI . . . is concerned with intelligent behavior in artifacts.” (Nilsson, 1998)</p> |
| <p>Figure 1.1 Some definitions of artificial intelligence, organized into four categories.</p> | |

Systems that think like humans

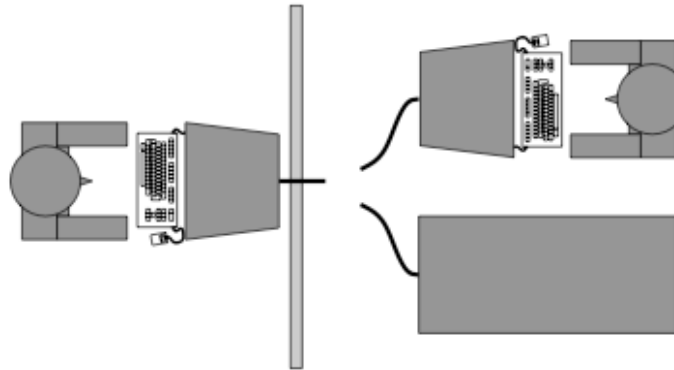
- How do humans think?
 - Requires scientific theories of internal brain activities (cognitive model):
 - Level of abstraction? (knowledge or circuitry?)
 - Validation?
 - Predicting and testing human behavior
 - Identification from neurological data
- Cognitive Science
 - brings together computational models from AI
 - and experimental techniques from psychology
 - to construct precise and testable theories of the mind
 - Cognitive Science is now distinct from AI
- Cognitive Neuroscience
 - How does the brain work at the neuronal level?

Systems that think rationally

- Capturing the laws of thought
 - Aristotle: What are ‘correct’ argument and thought processes?
 - Correctness depends on irrefutability of reasoning processes.
 - Syllogisms:
 - first patterns of correct formal reasoning
 - “Socrates is a man, all man are mortal → Socrates is mortal”
 - This study initiated the field of logic.
 - The logicist tradition in AI hopes to create intelligent systems using logic programming.
- Problems:
 - It is hard to formalize knowledge exactly
 - Feigenbaum Bottleneck in expert systems
 - Practical constraints
 - it is easy to write a logically optimal chess player...
 - Not all intelligence is mediated by logic behavior

Systems that act like humans

- When does a system behave intelligently?
 - Turing (1950) Computing Machinery and Intelligence
Operational test of intelligence: imitation game



- Test still relevant now, yet might be the wrong question.
 - Requires the collaboration of major components of AI: knowledge, reasoning, language understanding, learning, ...
- Problem with Turing test:
 - not reproducible, constructive or amenable to mathematical analysis.

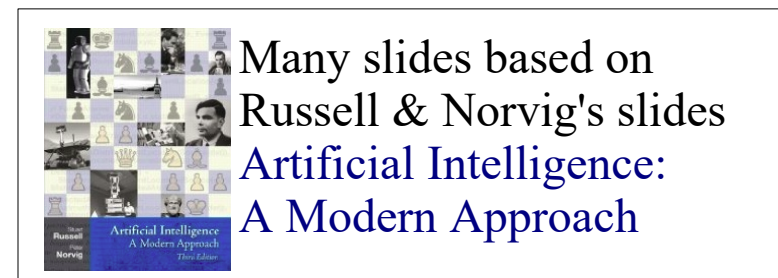
Systems that act rationally

- Rational behavior: “doing the right thing”
 - The “Right thing” is that what is expected to maximize goal achievement given the available information.
- Can include thinking, yet in service of rational action
 - Action without thinking: e.g. reflexes.
- Two advantages over previous approaches
 - More general than law of thoughts approach
 - in many situations, a provably correct action does not exist
 - More amenable to scientific development
 - rationality can be defined and optimized
- On the other hand
 - perfect rationality is only feasible in ideal environments.
 - rationality is often not a very good model of reality.
 - humans are, e.g., very bad in estimating probabilities...

Agents

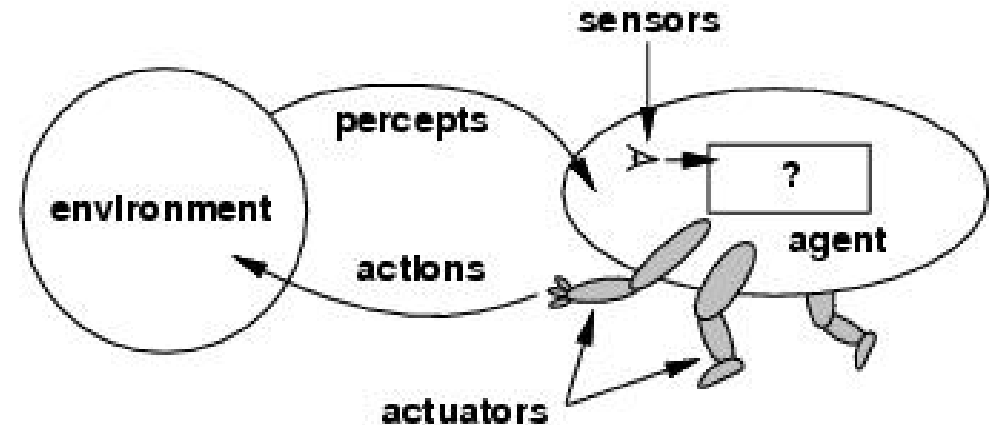
This course is about designing intelligent agents

- Agents and environments
 - The vacuum-cleaner world
- Rationality
 - The concept of rational behavior.
- Environment types
- Agent types



Agents

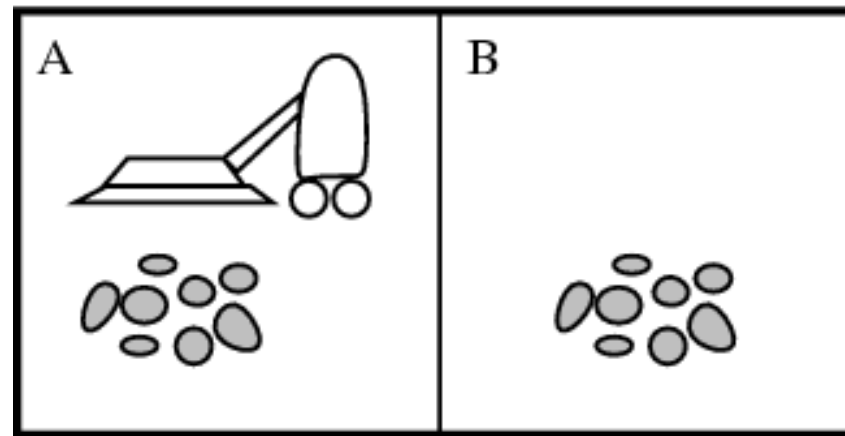
- An **agent** is an entity that perceives and acts in an environment
 - environment can be real or virtual



- An agent can always perceive its actions, but not necessarily their effects on the environment
- **Rational agent:** optimizes some performance criterion
 - For any given task and class of environments we seek the agent (or class of agents) with the best performance.
- Problem:
 - computational limitations make perfect rationality unachievable

The Vacuum-Cleaner world

- A robot-vacuum-cleaner that operates in a simple world



- **Environment:**
 - Virtual house with room A and room B
- **Percepts:**
 - The robot can sense pairs [*location*], [*status*]
 - *Location*: whether it is in room A or B
 - *Status*: whether the room is *Clean* or *Dirty*
- **Actions:**
 - *Left*, *Right*, *Suck*, *NoOp*

Rational Agent – Performance Measure

- A **rational agent** is an agent that “does the right thing”
 - intuitively clear, but needs to be measurable in order to be useful for computer implementation
- **Performance Measure:**
 - a function that evaluates sequence of actions/environment states
 - obviously not fixed but task-dependent
- **Vacuum-World performance measures:**
 - reward for the amount of dust cleaned
 - one point per square cleaned up in time T
 - can be maximized by dumping dust on the floor again...
 - reward for clean floors
 - one point per clean square per time step
 - possibly with penalty for consumed energy
 - minus one per move?
- **General rule:**
 - design performance measure based on desired environment state
 - not on desired agent behavior

Rational Agent

*A **rational agent** chooses whichever action maximizes the expected value of the performance measure given the percept sequence to date and prior environment knowledge.*

- Rational \neq omniscient
 - An omniscient agent knows the actual outcome of its actions.
- Rational \neq successful
 - Rationality maximizes expected performance
 - This may not be the optimal outcome
 - Example:
 - the expected monetary outcome of playing in the in the lottery/casino, etc. is negative (hence it is rational not to play)
 - but if you're lucky, you may win...

PEAS

What is rational at a given time depends on four things:

- **P**: the **performance measure** that defines the success
 - **E**: the agent's prior knowledge of the **environment**
 - **A**: the **actions** that the agent can perform
 - **S**: the agent's **percept sequence** to date
-
- *Example: Fully automated Taxi*



PEAS

What is rational at a given time depends on four things:

- **P**: the **performance measure** that defines the success
- **E**: the agent's prior knowledge of the **environment**
- **A**: the **actions** that the agent can perform
- **S**: the agent's **percept sequence** to date

- Example: Fully automated Taxi

- **Performance**
 - Safety, destination, profits, legality, comfort
- **Environment**
 - Streets/freeways, other traffic, pedestrians, weather, ...
- **Actuators**
 - Steering, accelerating, brake, horn, speaker/display, ...
- **Sensors**
 - Video, sonar, speedometer, engine sensors, keyboard, GPS, ...



PEAS

What is rational at a given time depends on four things:

- **P**: the **performance measure** that defines the success
- **E**: the agent's prior knowledge of the **environment**
- **A**: the **actions** that the agent can perform
- **S**: the agent's **percept sequence** to date

- *Example: Internet Shopping Agent*



PEAS

What is rational at a given time depends on four things:

- **P**: the **performance measure** that defines the success
- **E**: the agent's prior knowledge of the **environment**
- **A**: the **actions** that the agent can perform
- **S**: the agent's **percept sequence** to date

- *Example: Internet Shopping Agent*

- **Performance**
 - price, quality, appropriateness, efficiency
- **Environment**
 - the Web: current and future WWW sites, vendors, shippers
- **Actuators**
 - display to user, follow URL, fill in form
- **Sensors**
 - parsing of HTML pages (text, graphics, scripts)...



PEAS

What is rational at a given time depends on four things:

- **P**: the **performance measure** that defines the success
- **E**: the agent's prior knowledge of the **environment**
- **A**: the **actions** that the agent can perform
- **S**: the agent's **percept sequence** to date

- *Example: Chess Program*



PEAS

What is rational at a given time depends on four things:

- **P**: the **performance measure** that defines the success
- **E**: the agent's prior knowledge of the **environment**
- **A**: the **actions** that the agent can perform
- **S**: the agent's **percept sequence** to date

- Example: Chess Program

- **Performance**
 - number of games won, ELO rating,...
- **Environment**
 - the chess board
- **Actuators**
 - moves that can be performed
- **Sensors**
 - placement of pieces in current position, whose turn is it?, ...



Environment Types

- *Fully observable*
 - the complete state of the environment can be sensed
 - at least the relevant parts
 - no need to keep track of internal states
- *Partially observable*
 - parts of the environment cannot be sensed

| Task Environment | Observable |
|-------------------------|-------------------|
| Sudoku | |
| Chess With a Clock | |
| Poker | |
| Backgammon | |
| Taxi driving | |
| Medical diagnosis | |
| Image Analysis | |
| Part-Picking Robot | |
| Refinery Controller | |
| Interactive Tutor | |

Environment Types

- *Deterministic*
 - the next environment state is completely determined by the current state and the executed action
- *Strategic*
 - only the opponents' actions cannot be foreseen
- *Stochastic*

| Task Environment | Observable | Deterministic |
|-------------------------|-------------------|----------------------|
| Sudoku | <i>Fully</i> | |
| Chess With a Clock | <i>Fully</i> | |
| Poker | <i>Partially</i> | |
| Backgammon | <i>Fully</i> | |
| Taxi driving | <i>Partially</i> | |
| Medical diagnosis | <i>Partially</i> | |
| Image Analysis | <i>Fully</i> | |
| Part-Picking Robot | <i>Partially</i> | |
| Refinery Controller | <i>Partially</i> | |
| Interactive Tutor | <i>Partially</i> | |

Environment Types

- *Episodic*
 - the agent's experience can be divided into atomic steps
 - the agent perceives and then performs a single action
 - the choice of action depends only on the episode itself
- *Sequential*
 - the current decision could influence all future decision

| Task Environment | Observable | Deterministic | Episodic |
|-------------------------|-------------------|----------------------|-----------------|
| Sudoku | <i>Fully</i> | <i>Deterministic</i> | |
| Chess With a Clock | <i>Fully</i> | <i>Strategic</i> | |
| Poker | <i>Partially</i> | <i>Strategic</i> | |
| Backgammon | <i>Fully</i> | <i>Stochastic</i> | |
| Taxi driving | <i>Partially</i> | <i>Stochastic</i> | |
| Medical diagnosis | <i>Partially</i> | <i>Stochastic</i> | |
| Image Analysis | <i>Fully</i> | <i>Deterministic</i> | |
| Part-Picking Robot | <i>Partially</i> | <i>Stochastic</i> | |
| Refinery Controller | <i>Partially</i> | <i>Stochastic</i> | |
| Interactive Tutor | <i>Partially</i> | <i>Stochastic</i> | |

Environment Types

- *Dynamic*
 - the environment may change while the agent deliberates
- *Static*
 - the environment does not change
- *Semidynamic*
 - the environment does not change, but the performance score may

| Task Environment | Observable | Deterministic | Episodic | Static |
|-------------------------|-------------------|----------------------|-------------------|---------------|
| Sudoku | <i>Fully</i> | <i>Deterministic</i> | <i>Sequential</i> | |
| Chess With a Clock | <i>Fully</i> | <i>Strategic</i> | <i>Sequential</i> | |
| Poker | <i>Partially</i> | <i>Strategic</i> | <i>Sequential</i> | |
| Backgammon | <i>Fully</i> | <i>Stochastic</i> | <i>Sequential</i> | |
| Taxi driving | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | |
| Medical diagnosis | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | |
| Image Analysis | <i>Fully</i> | <i>Deterministic</i> | <i>Episodic</i> | |
| Part-Picking Robot | <i>Partially</i> | <i>Stochastic</i> | <i>Episodic</i> | |
| Refinery Controller | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | |
| Interactive Tutor | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | |

Environment Types

- *Discrete*
 - finite number of actions / environment states / percepts
- *Continuous*
 - actions, states, percepts are on a continuous scale
- this distinction applies separately to actions, states, and percepts
 - can be mixed in individual tasks

| Task Environment | Observable | Deterministic | Episodic | Static | Discrete |
|-------------------------|-------------------|----------------------|-------------------|----------------|-----------------|
| Sudoku | <i>Fully</i> | <i>Deterministic</i> | <i>Sequential</i> | <i>Static</i> | |
| Chess With a Clock | <i>Fully</i> | <i>Strategic</i> | <i>Sequential</i> | <i>Semi</i> | |
| Poker | <i>Partially</i> | <i>Strategic</i> | <i>Sequential</i> | <i>Static</i> | |
| Backgammon | <i>Fully</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Static</i> | |
| Taxi driving | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | |
| Medical diagnosis | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | |
| Image Analysis | <i>Fully</i> | <i>Deterministic</i> | <i>Episodic</i> | <i>Semi</i> | |
| Part-Picking Robot | <i>Partially</i> | <i>Stochastic</i> | <i>Episodic</i> | <i>Dynamic</i> | |
| Refinery Controller | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | |
| Interactive Tutor | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | |

Environment Types

- *Single-Agent*
 - No other agents (other agents may be part of the environment)
- *Multi-Agent*
 - Does the environment contain other agents whose performance measure depends on my *actions*?
 - other agents may be *co-operative* or *competitive*

| Task Environment | Observable | Deterministic | Episodic | Static | Discrete | Agents |
|---------------------|------------------|----------------------|-------------------|----------------|-------------------|--------|
| Sudoku | <i>Fully</i> | <i>Deterministic</i> | <i>Sequential</i> | <i>Static</i> | <i>Discrete</i> | |
| Chess With a Clock | <i>Fully</i> | <i>Strategic</i> | <i>Sequential</i> | <i>Semi</i> | <i>Discrete</i> | |
| Poker | <i>Partially</i> | <i>Strategic</i> | <i>Sequential</i> | <i>Static</i> | <i>Discrete</i> | |
| Backgammon | <i>Fully</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Static</i> | <i>Discrete</i> | |
| Taxi driving | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | <i>Continuous</i> | |
| Medical diagnosis | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | <i>Continuous</i> | |
| Image Analysis | <i>Fully</i> | <i>Deterministic</i> | <i>Episodic</i> | <i>Semi</i> | <i>Continuous</i> | |
| Part-Picking Robot | <i>Partially</i> | <i>Stochastic</i> | <i>Episodic</i> | <i>Dynamic</i> | <i>Continuous</i> | |
| Refinery Controller | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | <i>Continuous</i> | |
| Interactive Tutor | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | <i>Discrete</i> | |

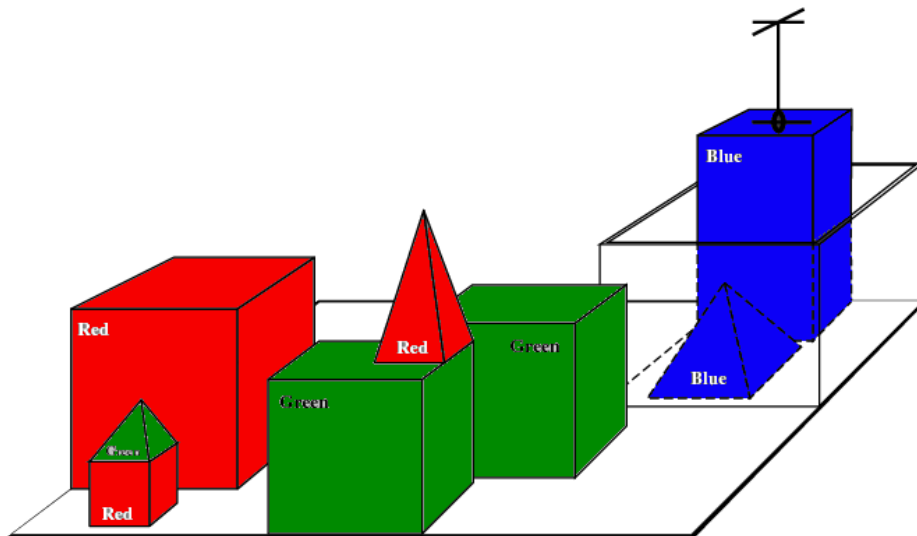
Environment Types

- *Single-Agent*
 - No other agents (other agents may be part of the environment)
- *Multi-Agent*
 - Does the environment contain other agents whose performance measure depends on my *actions*?
 - other agents may be *co-operative* or *competitive*

| Task Environment | Observable | Deterministic | Episodic | Static | Discrete | Agents |
|-------------------------|-------------------|----------------------|-------------------|----------------|-------------------|---------------|
| Sudoku | <i>Fully</i> | <i>Deterministic</i> | <i>Sequential</i> | <i>Static</i> | <i>Discrete</i> | <i>Single</i> |
| Chess With a Clock | <i>Fully</i> | <i>Strategic</i> | <i>Sequential</i> | <i>Semi</i> | <i>Discrete</i> | <i>Multi</i> |
| Poker | <i>Partially</i> | <i>Strategic</i> | <i>Sequential</i> | <i>Static</i> | <i>Discrete</i> | <i>Multi</i> |
| Backgammon | <i>Fully</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Static</i> | <i>Discrete</i> | <i>Multi</i> |
| Taxi driving | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | <i>Continuous</i> | <i>Multi</i> |
| Medical diagnosis | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | <i>Continuous</i> | <i>Single</i> |
| Image Analysis | <i>Fully</i> | <i>Deterministic</i> | <i>Episodic</i> | <i>Semi</i> | <i>Continuous</i> | <i>Single</i> |
| Part-Picking Robot | <i>Partially</i> | <i>Stochastic</i> | <i>Episodic</i> | <i>Dynamic</i> | <i>Continuous</i> | <i>Single</i> |
| Refinery Controller | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | <i>Continuous</i> | <i>Single</i> |
| Interactive Tutor | <i>Partially</i> | <i>Stochastic</i> | <i>Sequential</i> | <i>Dynamic</i> | <i>Discrete</i> | <i>Multi</i> |

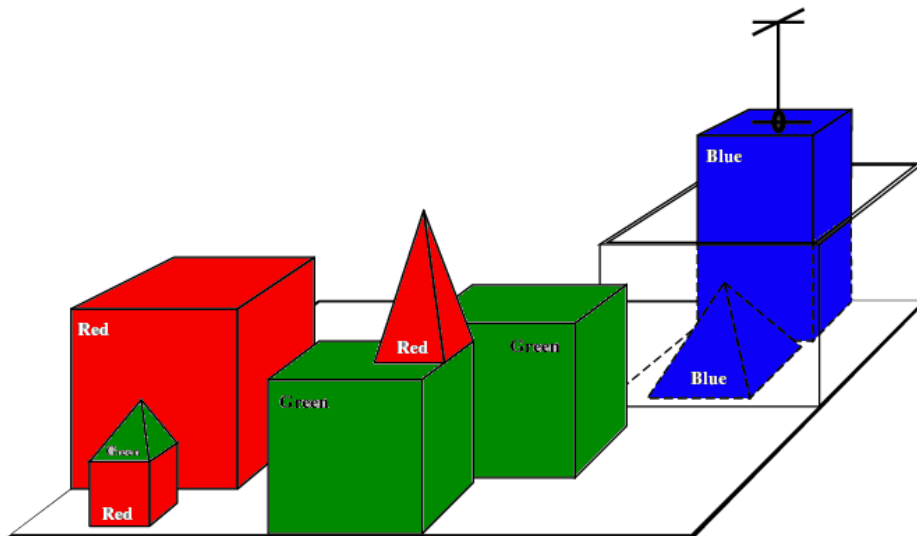
Environment Types

- The simplest environment is
 - fully observable
 - deterministic
 - episodic
 - static
 - discrete
 - single-agent



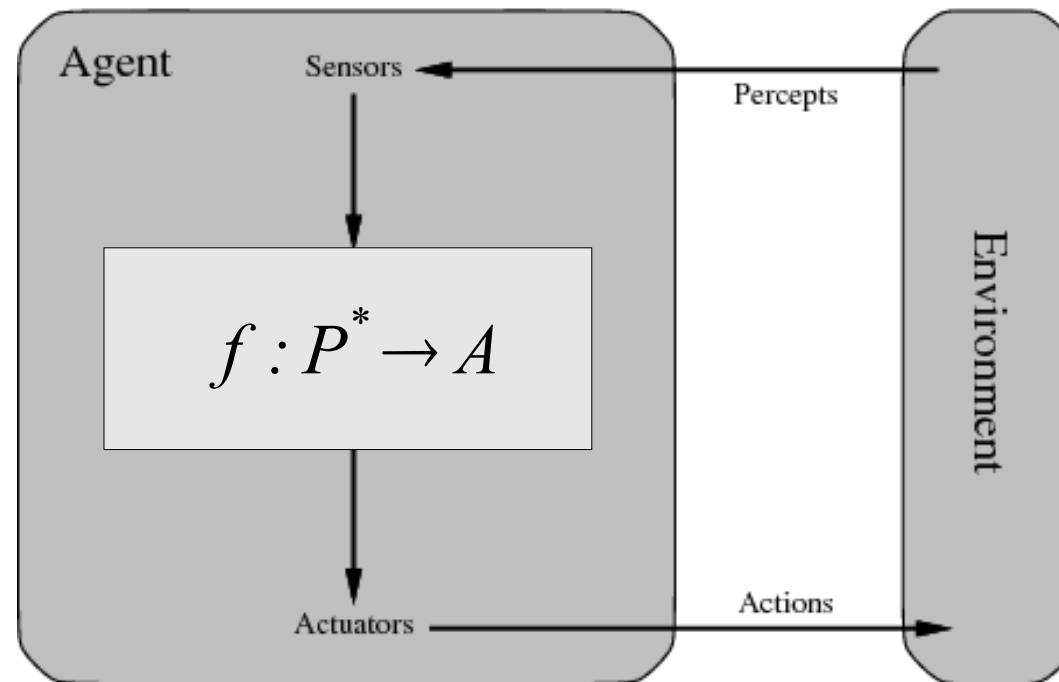
Environment Types

- The simplest environment is
 - fully observable
 - deterministic
 - episodic
 - static
 - discrete
 - single-agent
- Most real situations are
 - partially observable
 - stochastic
 - sequential
 - dynamic
 - continuous
 - multi-agent



Agent Function

- The **agent function** maps percept histories to actions



- The agent function will internally be represented by the **agent program**.
- The agent program runs on the physical architecture to produce f .

A Simple Vacuum Cleaner Agent

- Table of mappings from Percept sequences to actions:

| 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> |

A Simple General Agent

```

function TABLE-DRIVEN-AGENT(percept) returns an action
  static: percepts, a sequence initially empty
           table, a table of actions, indexed by percept sequence

  append percept to the end of percepts
  action ← LOOKUP(percepts, table)
  return action

```

- has a table of all possible percept histories
- looks up the right response in the table
- Clearly infeasible:
 - if there are $|P|$ percepts and a life-time of T time steps, we need a look-up table of size $\sum_{t=1}^T |P|^t$
- For example: chess:
 - about 36 moves per position, average game-length 40 moves
 → 5105426007029058700898070779698222806522450657188621232590965

A Simple Vacuum Cleaner Agent

- Strategy

“If current room is dirty then suck, otherwise move to the other room.”

- As an 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
```

- Obvious Questions:

- Is this the right agent?
- Is this a good agent?
- Is there a right agent?

Agent Programs

The key challenge for AI is to write programs that produce rational behavior from a small amount of code rather than a large number of table entries

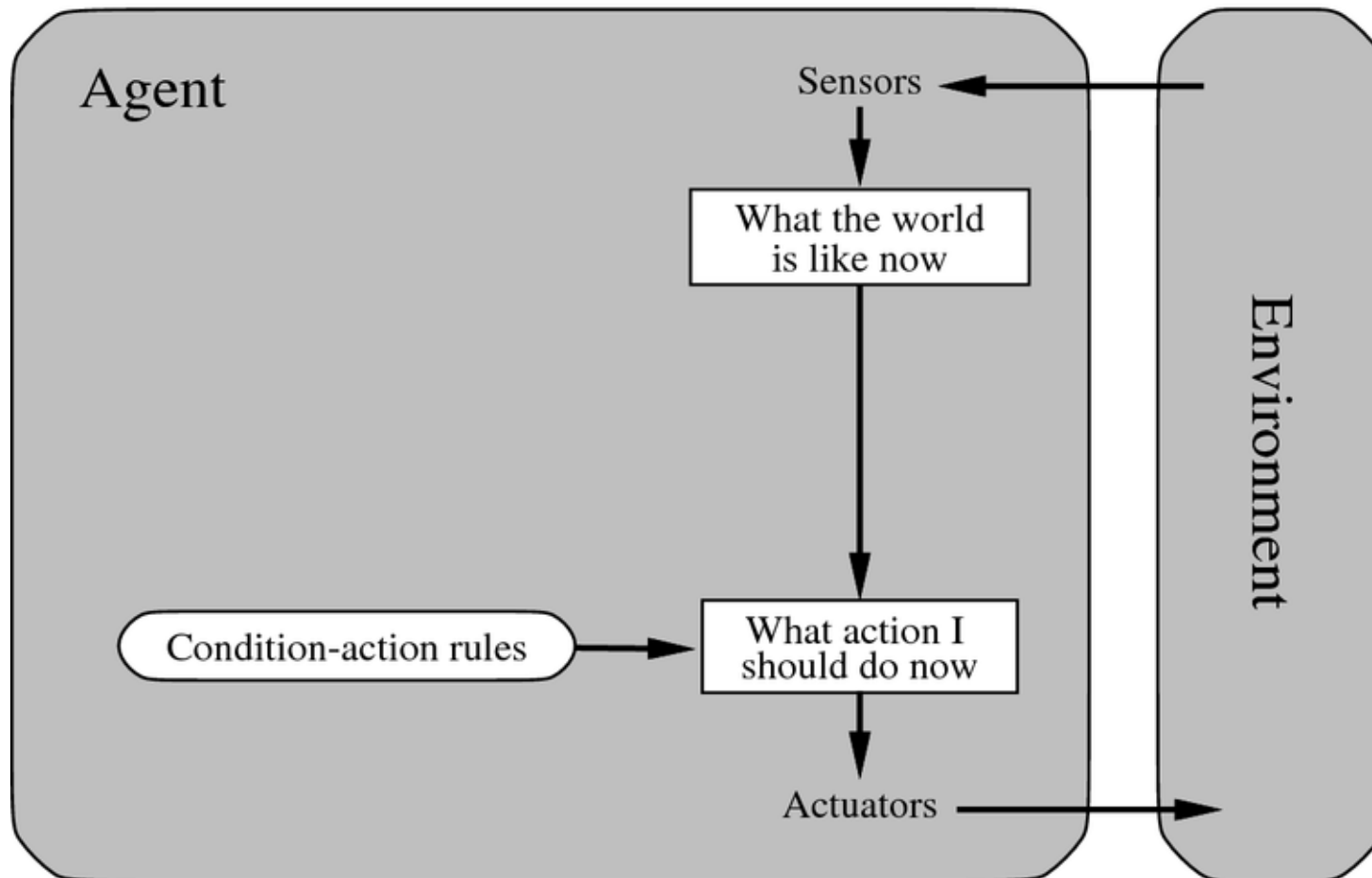
- Writing down the agent functions is not practical for real applications
- But feasibility is also important
 - you can write a perfect chess playing agent with a few lines of code
 - it will run forever, though...
- Agent = architecture + program

Agent Types

- Four basic kinds of agent programs will be discussed:
 - Simple reflex agents
 - Model-based reflex agents
 - Goal-based agents
 - Utility-based agents
- All these can be turned into learning agents.

Simple Reflex Agent

- Select action on the basis of only the current percept
 - ignores the percept history



Simple Reflex Agent

- Select action on the basis of only the current percept
 - ignores the percept history
- Implemented through condition-action rules
- Large reduction in possible percept/action situations
 - from $\sum_{t=1}^T |P^t|$ to $|P|$
- But will make a very bad chess player
 - does not look at the board, only at the opponent's last move (assuming that the sensory input is only the last move, no visual)

Example:

```
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
```

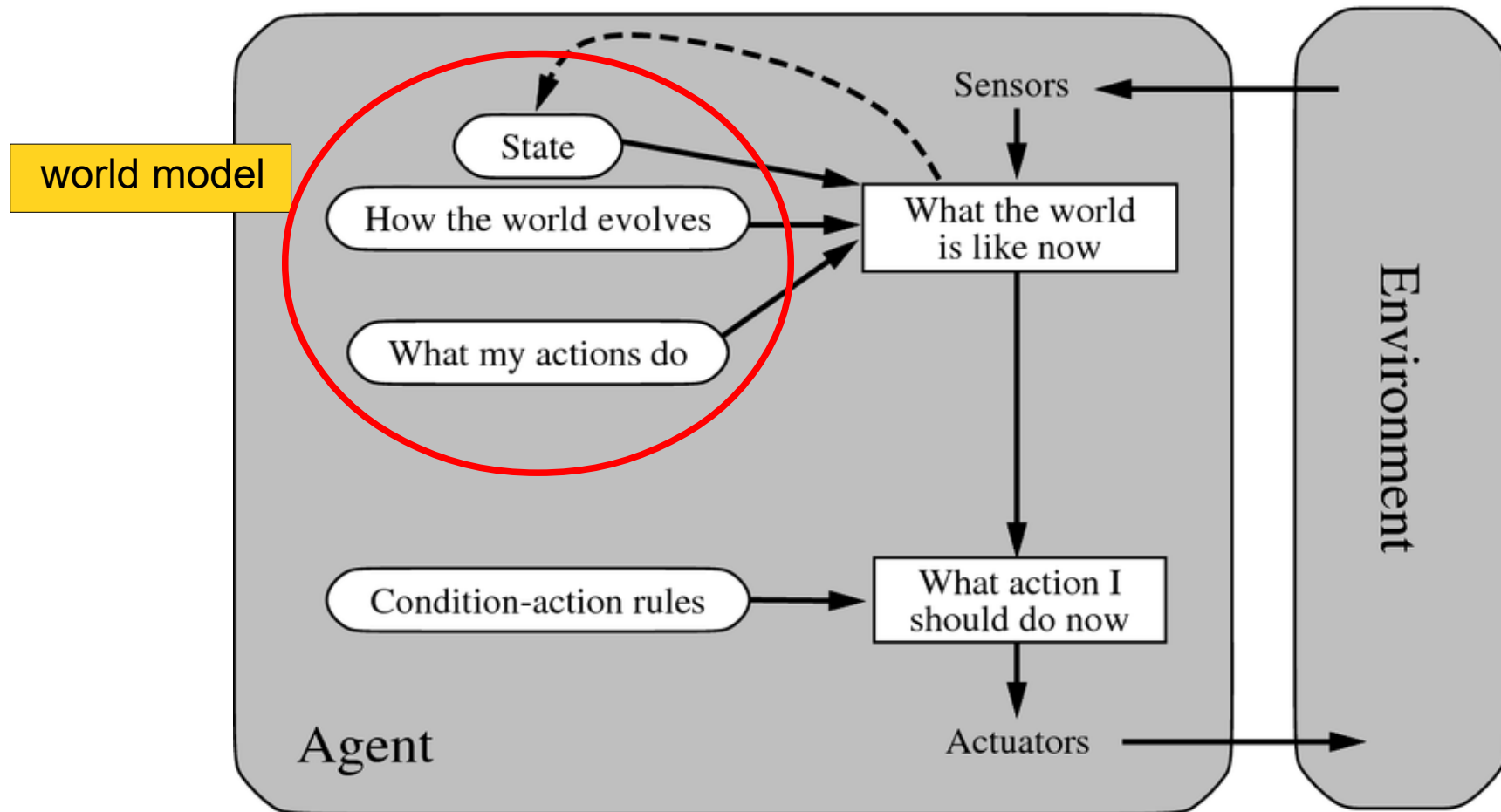
General Simple Reflex Agent

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

- Note that rules are just used as a concept
 - actual implementation could, e.g., be logical circuitry
- Will only work if the environment is *fully observable*
 - everything important needs to be determinable from the current sensory input
 - otherwise infinite loops may occur
 - e.g. in the vacuum world without a sensor for the room, the agent does not know whether to move right or left
 - possible solution: randomization

Model-Based Reflex Agent

- Keep track of the state of the world
 - better way to fight partial observability



General Model-Based Reflex Agent

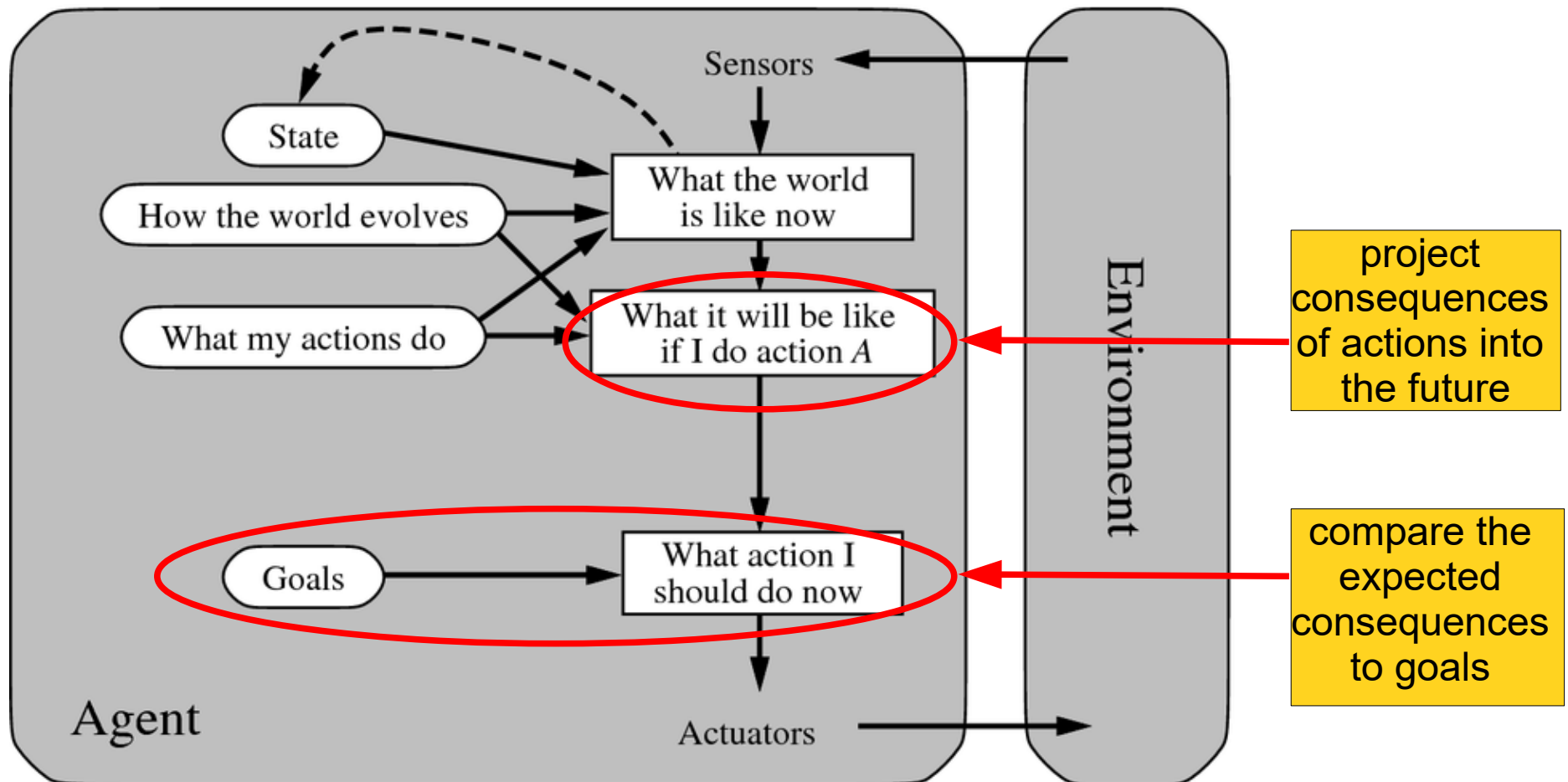
```
function REFLEX-AGENT-WITH-STATE(percept) returns an action
  static: state, a description of the current world state
           rules, a set of condition-action rules
           action, the most recent action, initially none

  state ← UPDATE-STATE(state, action, percept)
  rule ← RULE-MATCH(state, rule)
  action ← RULE-ACTION[rule]
  return action
```

- Input is not only interpreted, but mapped into an internal state description (a world model)
 - a chess agent could keep track of the current board situation when its percepts are only the moves
- Internal state is also used for interpreting subsequent percepts
- The world model may include effects of own actions!

Goal-Based Agent

- the agent knows what states are desirable
 - it will try to choose an action that leads to a desirable state

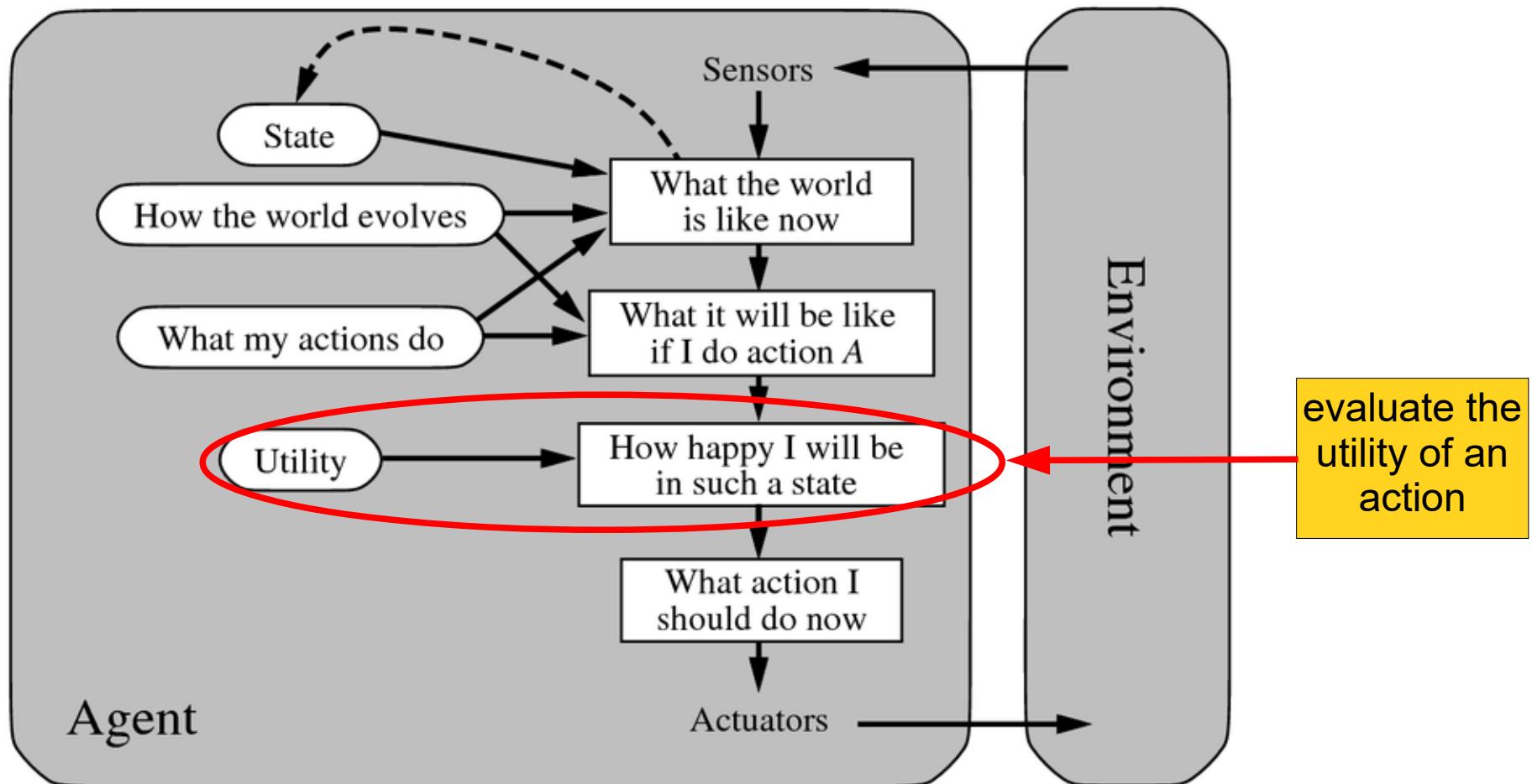


Goal-Based Agent

- the agent knows what states are desirable
 - it will try to choose an action that leads to a desirable state
- things become difficult when long sequences of actions are required to find the goal
 - typically investigated in search and planning research
- main difference to previous approaches
 - decision-making takes future into account
 - “What will happen if I do such-and-such?”
 - “Will this make me happy?”
- is more flexible since knowledge is represented explicitly and can be manipulated
 - changing the goal does not imply changing the entire set of condition-action rules

Utility-Based Agent

- Goals provide just a binary happy/unhappy distinction
 - utility functions provide a continuous scale



Utility-Based Agent

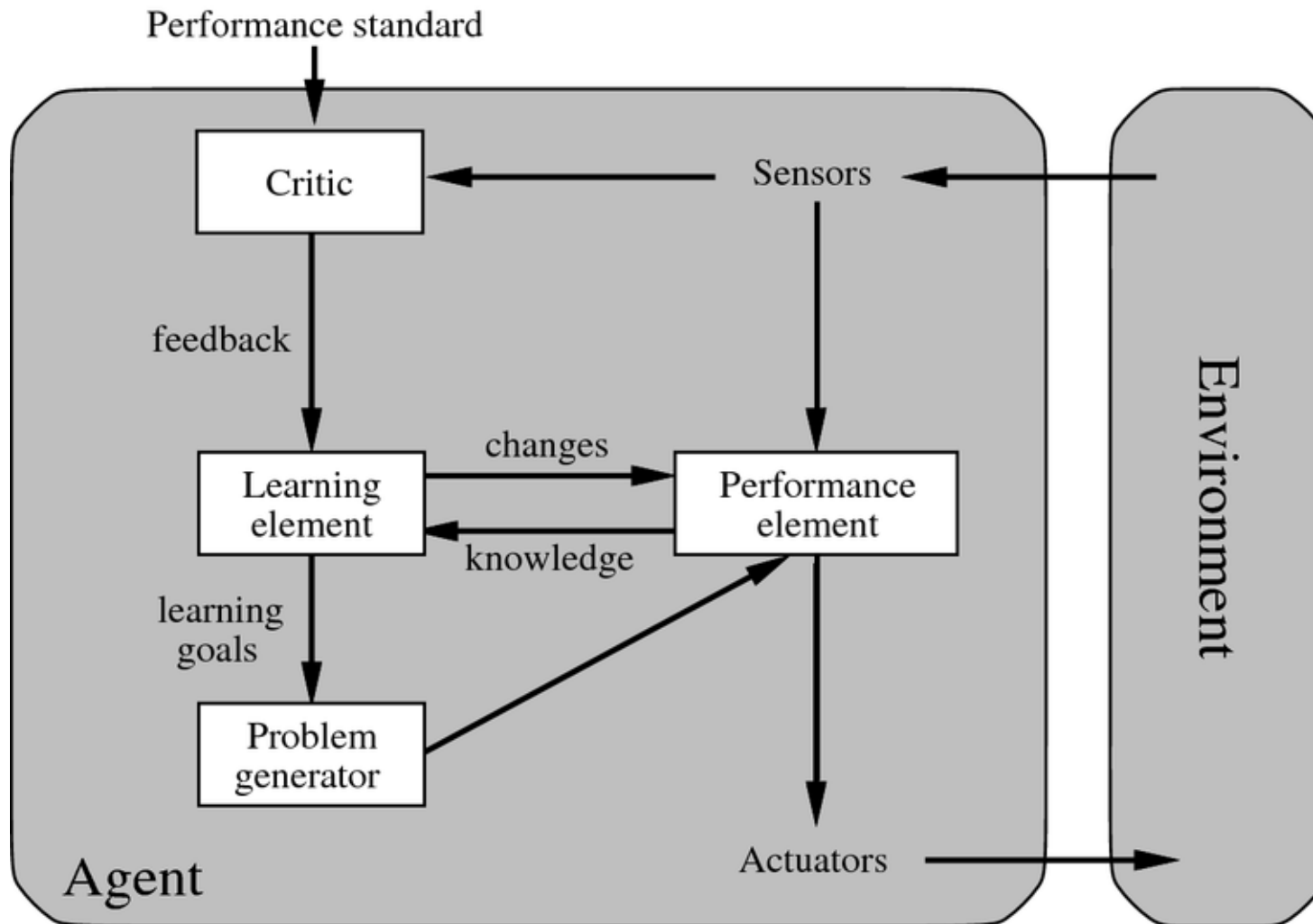
- Goals provide just a binary happy/unhappy distinction
 - utility functions provide a continuous scale
- Certain goals can be reached in different ways.
 - “Alle Wege führen nach Rom”
 - Some ways are quicker, safer, more reliable, cheaper, ...
→ have a higher utility
- **Utility function**
 - maps a state (or a sequence of states) onto a real number
- Improves on goals:
 - selection between conflicting goals (e.g., speed and safety)
 - selection between goals based on trade-off between likelihood of success and importance of goal

Learning

- All previous agent-programs describe methods for selecting actions
 - yet they do not explain the origin of these programs.
- Learning mechanisms can be used for acquiring programs
 - teach them instead of instructing them
- Advantage
 - robustness of the program toward initially unknown environments.
- Every part of the previous agents can be improved with learning

Learning in intelligent agents can be summarized as a process of modification of each component of the agent to bring the components into closer agreement with the available feedback information, thereby improving the overall performance of the agent.

Learning Agent



Learning Agent

- **Performance element**
 - makes the action selection (as usual)
- **Critic**
 - decides how well the learner is doing with respect to a fixed *performance standard*
 - necessary because the percepts do not provide any indication of the agent's success
 - e.g., it needs to know that checkmate is bad
- **Learning element**
 - improves the performance element
 - its design depends very much on the performance element
- **Problem generator**
 - responsible for *exploration* of new knowledge
 - sometimes try new, possibly suboptimal actions to acquire knowledge about their consequences
 - otherwise only *exploitation* of (insufficient) current knowledge