

# 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

Systems that think like humans	Systems that think rationally
<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>
Systems that act like humans	Systems that act rationally
<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>

**Figure 1.1** Some definitions of artificial intelligence, organized into four categories.

# Systems that think like humans

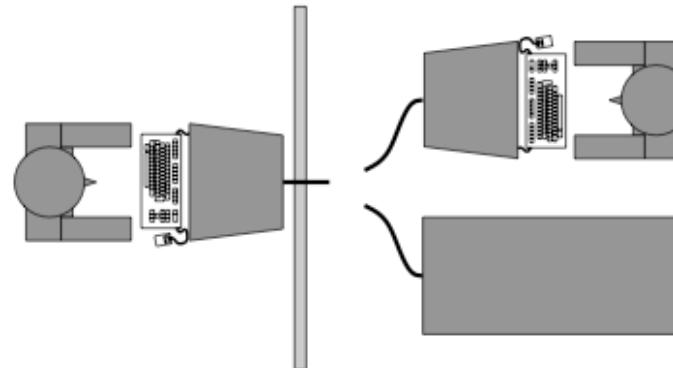
- How do humans think?
  - Requires scientific theories of internal brain activities (cognitive model):
    - Level of abstraction? (knowledge or circuitry?)
    - Validation?
      - Predicting and testing human behavior
      - Identification from neurological data
- Cognitive Science
  - brings together 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.

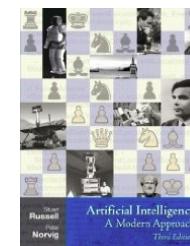
# Systems that act rationally

- 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

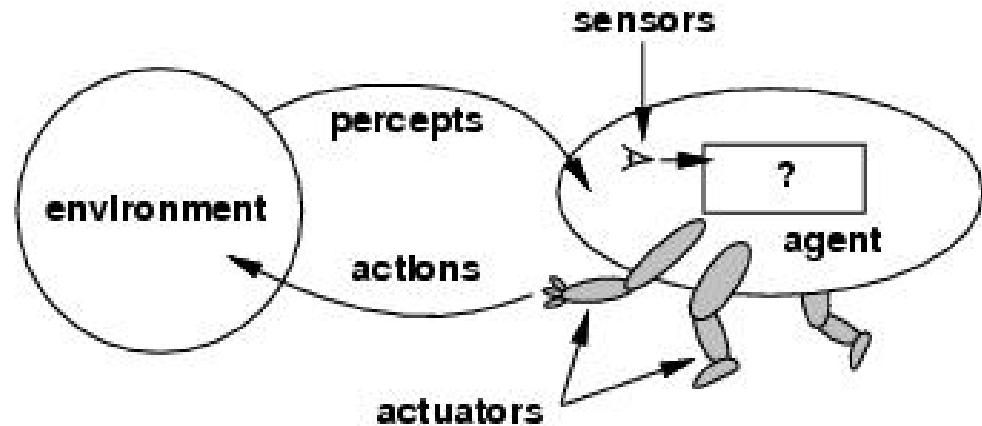
- Agents and environments
  - The vacuum-cleaner world
- Rationality
  - The concept of rational behavior.
- Environment types
- Agent types



Many slides based on  
Russell & Norvig's slides  
**Artificial Intelligence:  
A Modern Approach**

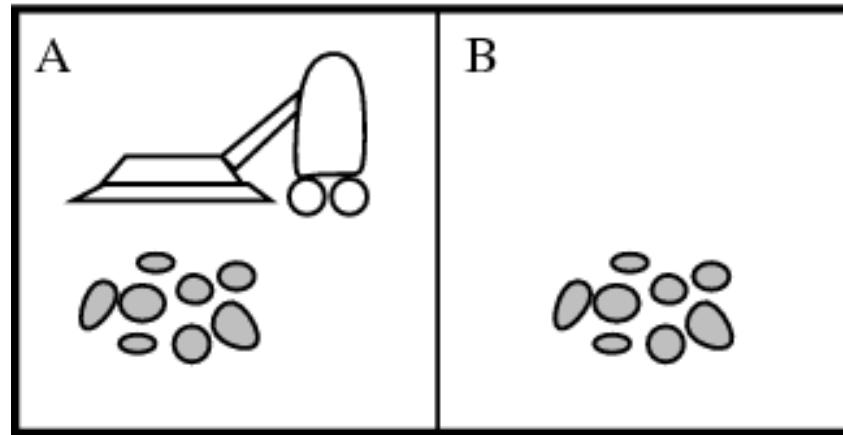
# Agents

- 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 ≠ omniscient
  - An omniscient agent knows the actual outcome of its actions.
- Rational ≠ successful
  - Rationality maximizes expected performance
  - This may not be the optimal outcome
  - Example:
    - the expected monetary outcome of playing 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*



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- *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, ...



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- *Example: Internet Shopping Agent*



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- *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>	
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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

<b>Task Environment</b>	<b>Observable</b>	<b>Deterministic</b>	<b>Episodic</b>	<b>Static</b>	<b>Discrete</b>
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>	
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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>	

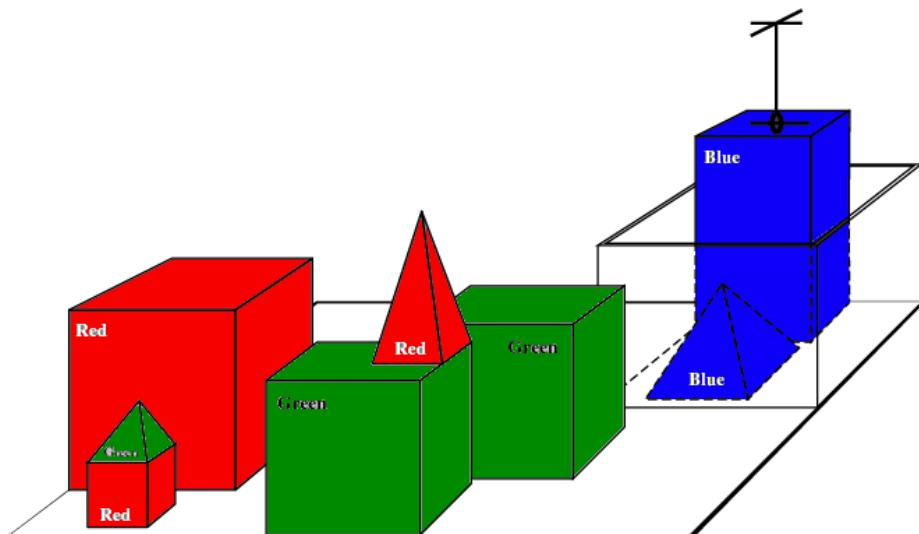
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<b>Task Environment</b>	<b>Observable</b>	<b>Deterministic</b>	<b>Episodic</b>	<b>Static</b>	<b>Discrete</b>	<b>Agents</b>
Sudoku	<i>Fully</i>	<i>Deterministic</i>	<i>Sequential</i>	<i>Static</i>	<i>Discrete</i>	<i>Single</i>
Chess With a Clock	<i>Fully</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>
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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>

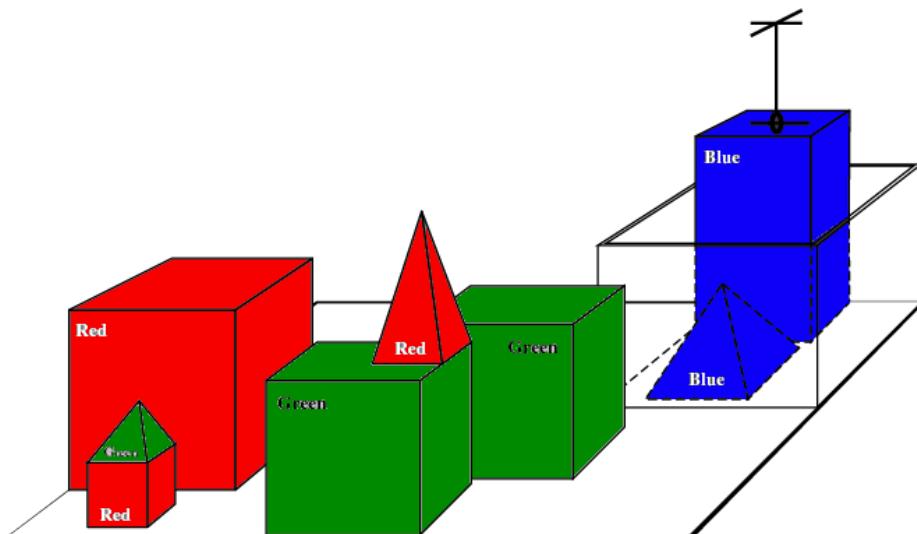
# Environment Types

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



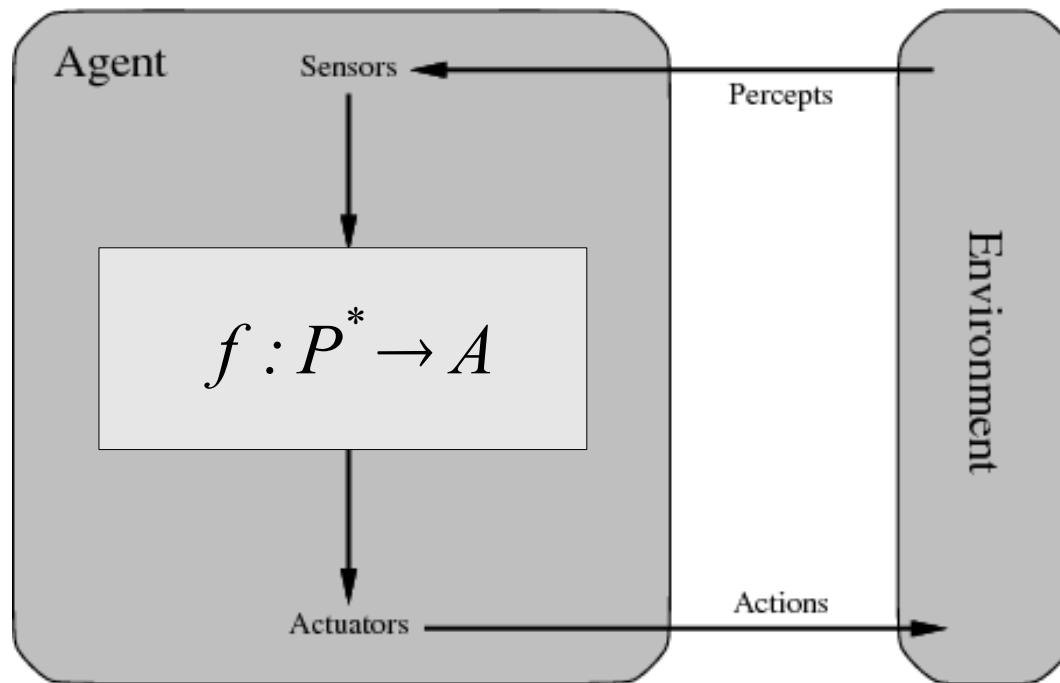
# Environment Types

- 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
$[A, Clean]$	$Right$
$[A, Dirty]$	$Suck$
$[B, Clean]$	$Left$
$[B, Dirty]$	$Suck$
$[A, Clean], [A, Clean]$	$Right$
$[A, Clean], [A, Dirty]$	$Suck$
:	:

# 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  $\leftarrow$  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  $\sum_{t=1}^T |P'|$
- For example: chess:
  - about 36 moves per position, average game-length 40 moves  
 $\rightarrow 5105426007029058700898070779698222806522450657188621232590965$

# 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*

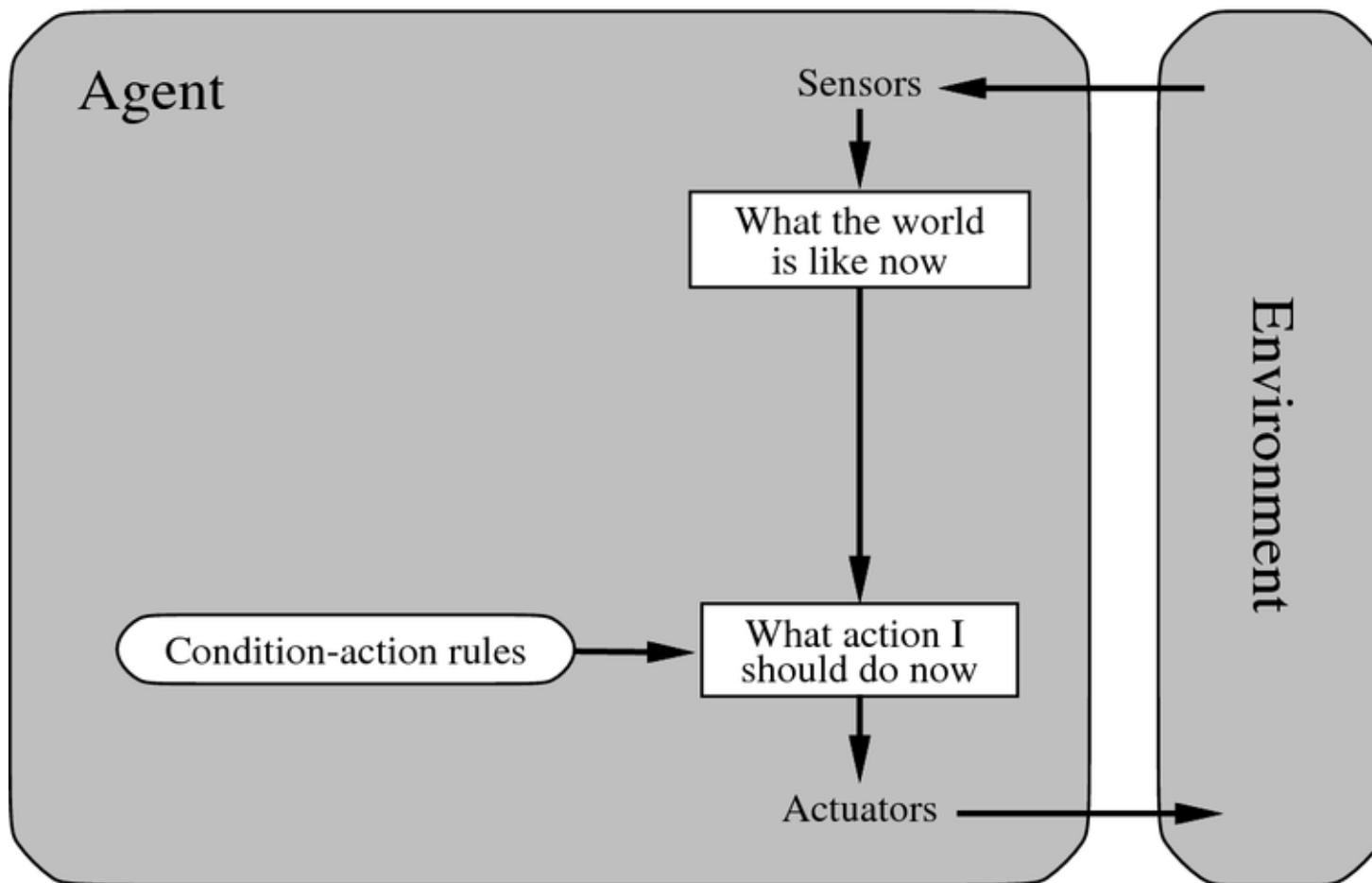
- Writing down the agent functions is not practical for real applications
- But feasibility is also important
  - you can write a perfect chess playing agent with a few lines of code
  - it will run forever, though...
- Agent = architecture + program

# 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
```

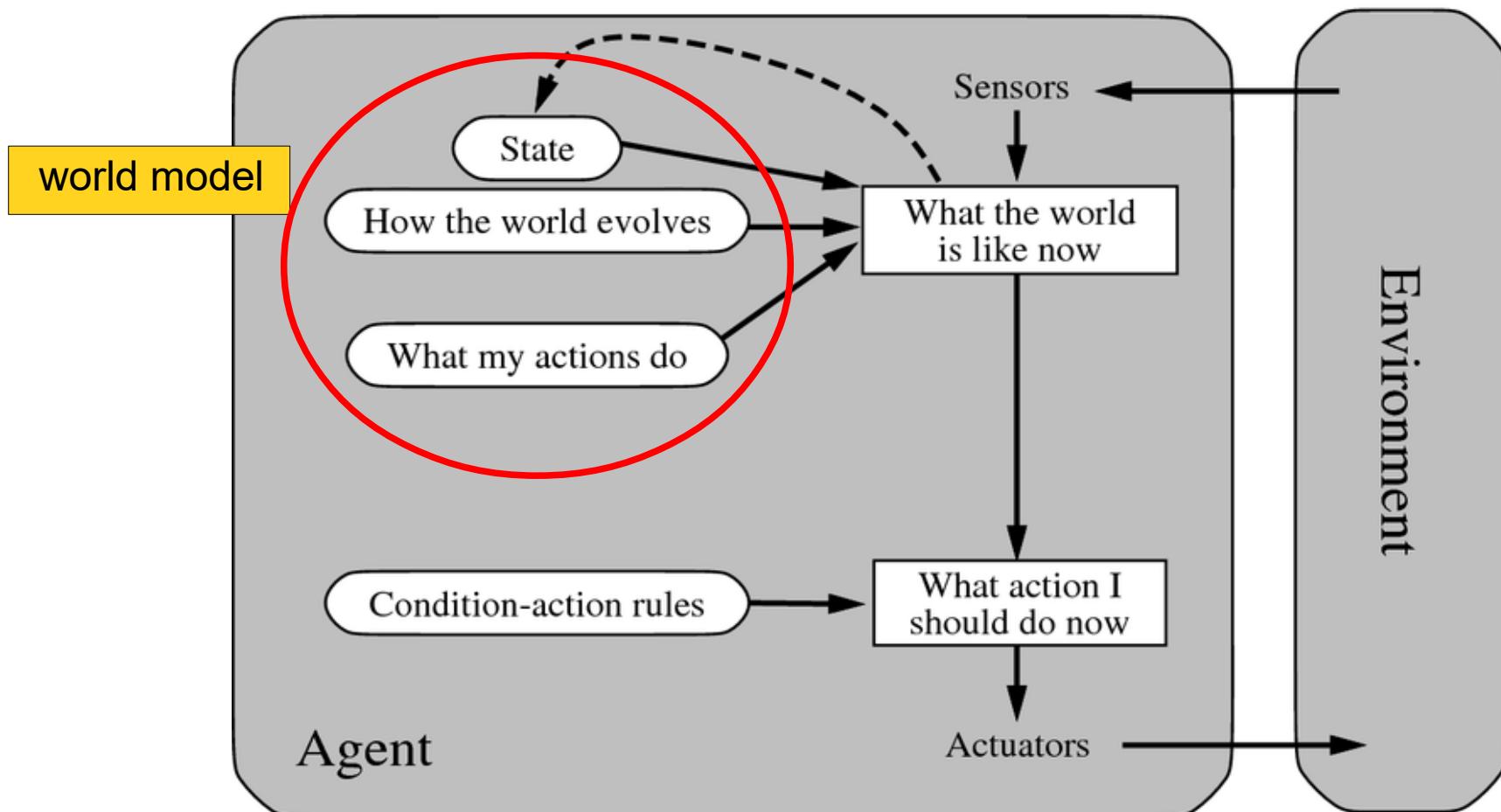
# General Simple Reflex Agent

```
function SIMPLE-REFLEX-AGENT(percept) returns an action
  static: rules, a set of condition-action rules
    state  $\leftarrow$  INTERPRET-INPUT(percept)
    rule  $\leftarrow$  RULE-MATCH(state, rule)
    action  $\leftarrow$  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



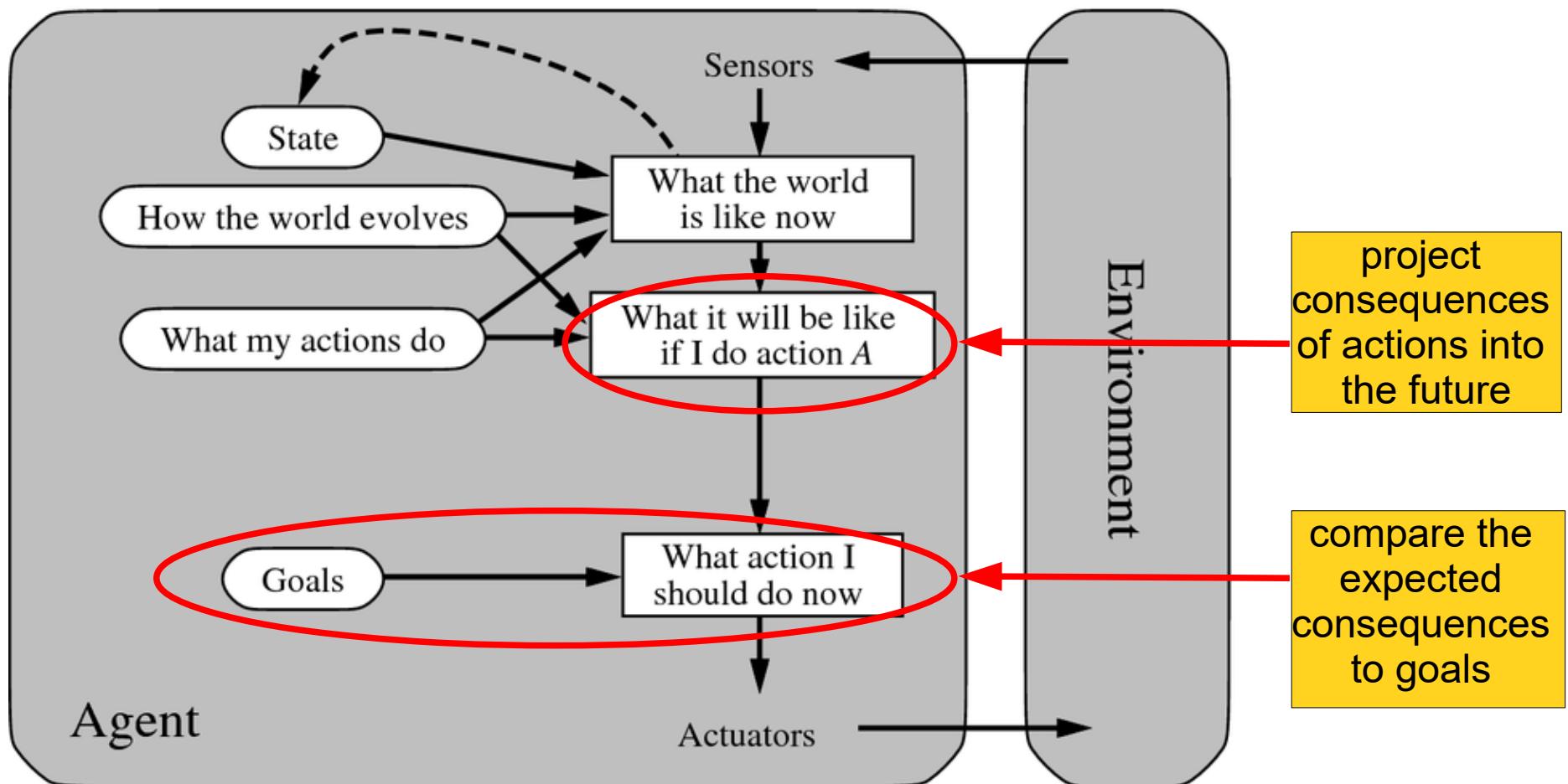
# General Model-Based Reflex Agent

```
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  $\leftarrow$  UPDATE-STATE(state, action, percept)
    rule  $\leftarrow$  RULE-MATCH(state, rule)
    action  $\leftarrow$  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

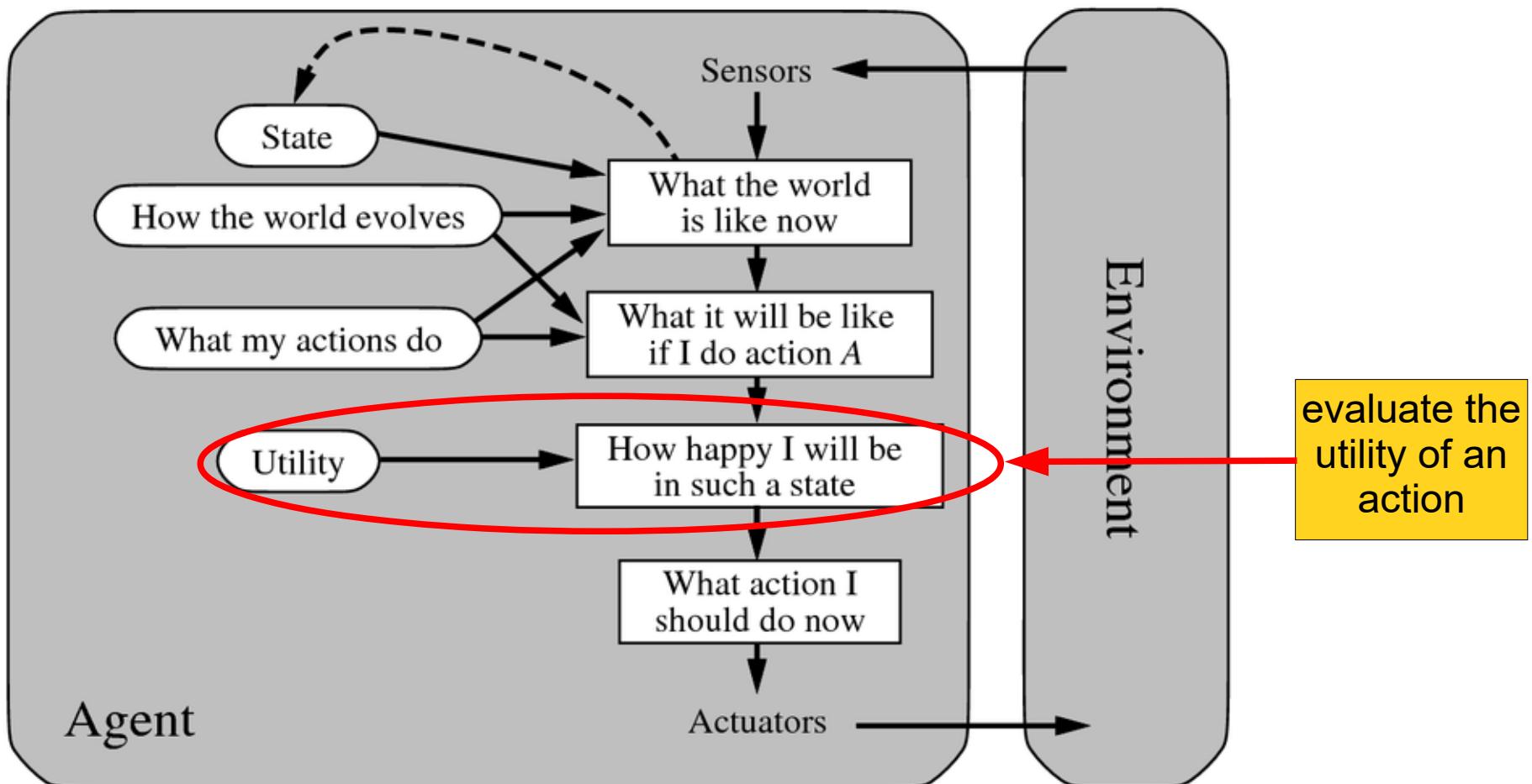


# Goal-Based Agent

- 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

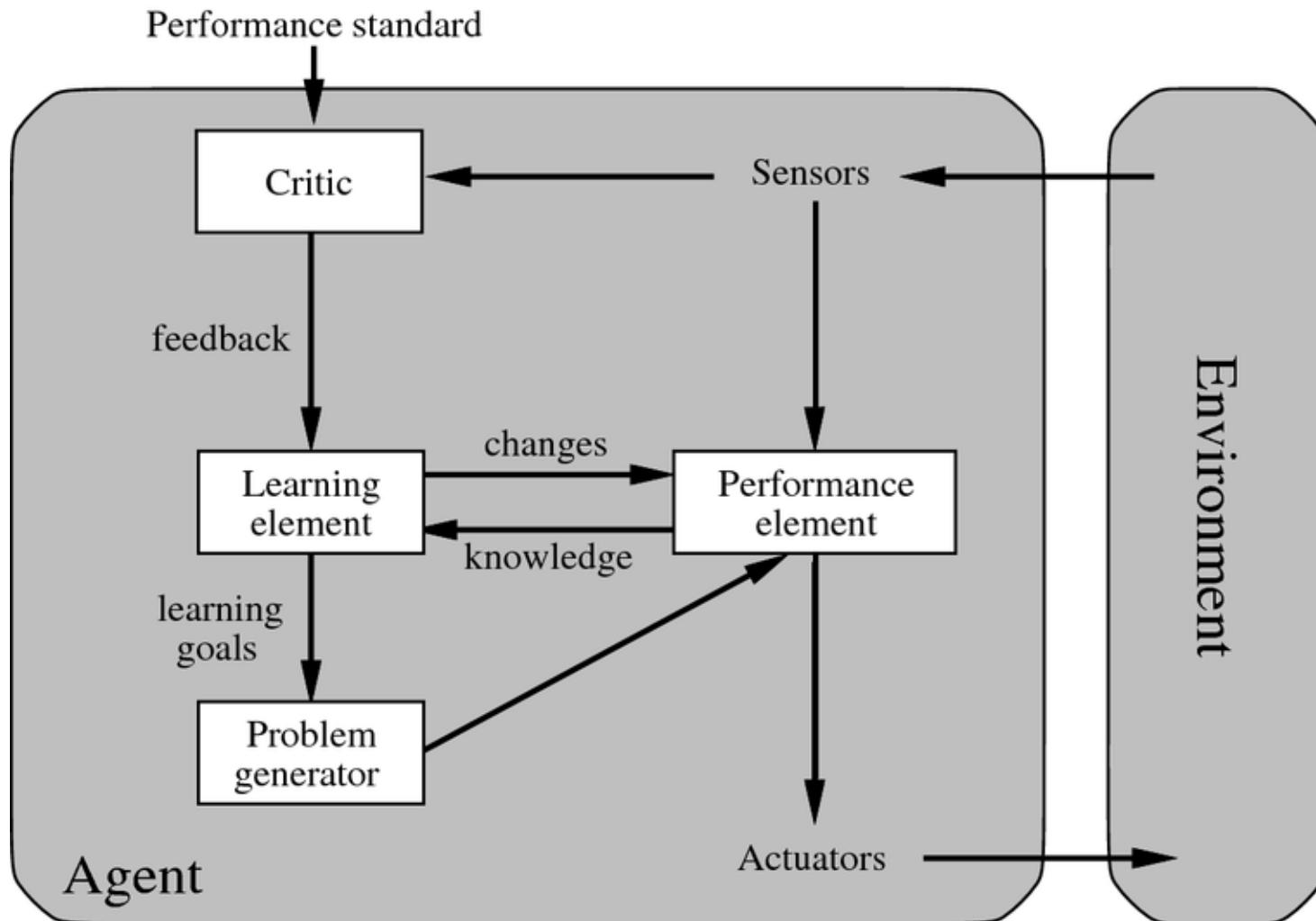
- Goals provide just a binary happy/unhappy distinction
  - utility functions provide a continuous scale
- Certain goals can be reached in different ways.
  - “Alle Wege führen nach Rom”
  - Some ways are quicker, safer, more reliable, cheaper, ...  
→ have a higher utility
- **Utility function**
  - 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