Smart and Adaptive Cyber-Physical Systems

Chapters 1, 2
Cyber-Physical Systems

- Smart mobility
- Smart factory
- Smart grid
- Smart health care
- Smart city

But what does it mean to be smart?
Being Smart

We call ourselves Home Sapiens = Wise Man

Understanding human intelligence

- How do we perceive, understand, predict and manipulate
- A world far larger and more complicated than ourselves?

Building intelligent systems

- Originally: the aim of artificial intelligence
- Nowadays: control and decision theory, CPS theory, etc
Being Smart (Artificial Intelligence)

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<thead>
<tr>
<th>Thinking Humanly</th>
<th>Thinking Rationally</th>
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<tbody>
<tr>
<td>Make computers think, make machines with mind</td>
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Acting Humanly

Turing Test (Proposed in 1950)
- After posing some written questions a human interrogator
- Cannot tell if the written responses came from a computer

A Computer Needs the Following Capabilities
- Natural language processing: To communicate
- Knowledge representation: To store what it knows
- Automated reasoning: To draw new conclusions
- Machine learning: To adapt to new circumstances
Acting Humanly

Total Turing Test Contains in Addition

- A video signal: To test subject’s perceptual abilities
- A hatch: To pass physical objects to the subject

A Computer Needs Additional Capabilities

- Computer vision: To perceive objects
- Robotics: To manipulate objects and move about
Thinking Humanly

Need to get inside the actual working of human minds

- **Introspection**: Try to catch our own thoughts
- **Psychological experiments**: Observing a person in action
- **Brain imaging**: Observing the brain in action

Cognitive science brings together

- **Computer models**: From artificial intelligence
- **Experimental techniques**: From psychology
- **In order to**: Construct precise and testable theories
What About the Brain?

- Brains (human minds) are very good at making rational decisions (but not perfect)
- "Brains are to intelligence as wings are to flight"
- Brains aren’t as modular as software
- Lessons learned: prediction and simulation are key to decision making
Thinking Rationally

The syllogism of Greek philosopher Aristotle

- Pattern for right thinking: Always yield correct conclusions
- Main pattern: $A \land (A \rightarrow B) = A \land B = B \land (B \rightarrow A)$
- Problem: World is not black and white (qualitative)

The extension of syllogisms to a logic of science

- Main pattern: $P(A) P(B | A) = P(A \land B) = P(B) P(A | B)$
- Advantage: Shades of gray (quantitative)
Acting Rationally

Computer Agent  Latin *agere* = doing

- Operates autonomously and persists *over long time*
- Perceives, acts upon and adapts *to its environment*
- Creates and pursues *its own goals*
Pacman as an Agent

SCORE: 18

Agent

Sensors

Actuators

Environment

? | Percepts |

Actions
Acting Rationally

Rational Agent Extension of Computer Agent

- Acts so as to **achieve the best outcome**, and when
- There is **uncertainty**, the **best expected outcome**
Advantages of Rational Agents

The rational-agent approach has two advantages

- It is more general than the laws-of-thought approach
  - Correct inference is just one way of achieving rationality
- It is more amenable to scientific development
  - Rationality is mathematically well defined and very general

In this class: Smart = Rational!
Rational Agent (RA)

What is rational at any given time depends on

- The performance measure that defines success
- The agent’s prior knowledge of the environment
- The actions that the agent can perform
- The agent’s percept sequence to date

For each percept sequence a RA 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
# Task Environment (TE)

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PEAS=(Performance, Environment, Actuators, Sensors)
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<td>Student’s Score on a Test</td>
<td>Set of Students, Testing Agency</td>
<td>Display Exercises Suggestions</td>
<td>Keyboard Entry</td>
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PEAS=(Performance, Environment, Actuators, Sensors)
TE: Observable-Unobservable

Fully observable task environments (crossword)
- Sensors always capture complete environment’s state
- Effective if all aspects relevant to action choices detected
- Relevance depends on the performance measure
- Agent does not need to maintain the world’s state

Partially observable task environments (taxi driving)
- Noisy and inaccurate sensors
- Parts of the state are simply missing from sensor data
- E.g. a taxi driver cannot see what other drivers think

Unobservable task environments
- The agent has no sensors
TE: Single-Multi Agent

Single agent task environment
- E.g. an agent solving a crossword puzzle by itself

Multi agent task environment
- E.g. a game of chess is a two agent environment
- Agent’s B performance depends on agent’s A performance
- Cooperative or competitive multi agents (taxi, chess)

Multi-agent design is quite different
- Communication is rational as it receives hidden state
- Randomization is rational as it avoids predictability
TE: Certain-Uncertain

Deterministic task environments (certain)
- Environment’s next state completely determined by
  - Current state of the environment
  - The action executed by the agent (e.g. crossword)
- Uncertainty ignored in fully observable deterministic TE

Stochastic task environments (uncertain)
- Partially observable environments appear as stochastic
- In most real situations this is the case, e.g. in taxi driving

Nondeterministic task environments (uncertain)
- Uncertain but no probabilities attached (e.g. chess)
- The agent needs to succeed for all possible outcomes
Episodic task environments

- Agent’s experience divided in episodes. In each:
  - It first receives a single percept from its sensors
  - It then performs a single action with its actuators
- Next episode does not depend on actions in previous ones
- Many classification tasks are episodic
  - Spotting defective parts on an assembly line

Sequential task environments

- Current decision could affect all future decisions
  - Crossword, chess game and taxi driving are sequential
- In sequential environments one needs to think ahead
TE: Static-Dynamic

Static task environments
- Environment doesn’t change while agent deliberates
  - Need not look at the world while deciding on an action
  - Need not worry about the passage of time
  - E.g. crossword puzzles

Dynamic task environments
- Environment can change while agent deliberates
  - Are continuously asking the agent what it wants to do
  - If it hasn’t decided yet, that counts as deciding to do nothing
  - E.g. taxi driving

Semi-dynamic task environments
- Environment cannot change in time but agent’s score can
  - E.g. chess playing with a clock
TE: Discrete-Continuous

Discrete task environments
- State of environment is discrete
- Time of environment is discrete
- Percepts and/or actions are discrete
  - E.g. chess has discrete state, percepts and actions

Continuous task environments
- State of environment is continuous
- Time of environment is continuous
- Percepts and/or actions are continuous
  - E.g. taxi driving is continuous state, time, percepts and actions
## Types of Task Environments

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**Simple Reflex Agent (Episodic)**

**function** Simple-Reflex-Agent (percept) **returns** action  
**persistent** set-of-condition-action rules  
state = Interpret-Input(percept)  
rule = Rule-Match(state, rules)  
**return** rule.Action
Simple Reflex Agent (Episodic)

Example: The car in front is braking

- Very simple and very fast as a consequence
- However, one can do better by learning front-car behavior
Model-Based Reflex Agent (Seq)

- Sensors
  - What the world is like now
  - What the world is like now
  - What action I should do now
  - What my actions do
  - How the world evolves
  - state, action

Agent

Condition-action rules

Next state model

Current output model

Environment

- Percepts
- Actions

The most effective way to handle partial observability

- Keep track of the part of the world it can’t see now
- The agent should maintain the previous state and action
- Which depend on the percept history. Braking car: 1-2 frames
Model-Based Reflex Agent (Seq)

function Model-Based-Reflex-Agent (percept) returns action
persistent state, action, model, rules
state = Update-State(state, action, percept, model)
rule = Rule-Match(state, rules)
action = rule.Action
return action
**Model-Based Reflex Agent (Seq)**

**function** Model-Based-Reflex-Agent (percepts) **returns** actions

*Input-output description of an agent (black box)*
This is what is observable and on what the performance is measured!
Knowing internal state not always enough to decide what to do

- At a road junction a car can turn left, right or go straight
Model-Based Goal-Based Agent

What action I should do now

What the world is like now

What are my goals

What my actions do

How the world evolves

state, action

Agent

Environment

Sensors

Percepts

Actuators

Knowing internal state not always enough to decide what to do

- At a road junction a car can turn left, right or go straight
- Correct decision depends on where the car wants to go
Model-Based Goal-Based Agent

Knowing internal state not always enough to decide what to do

- At a road junction a car can turn left, right or go straight
- Correct decision depends on where the car wants to go
- Search and planning involves consideration of the future
Goal-based agent versus model-based reflex agent

- Less efficient but more flexible as knowledge is explicitly represented
- Goals alone are not sufficient as they do not consider performance
- Taxi driving: faster, cheaper, more reliable, safer.
Model-Based Utility-Based Agent

- Goals provide only a crude binary distinction: happy, unhappy
- Utilities provide a more general internalization of performance measure
Is it that simple? Just build agents maximizing expected utility?

- Keep track of environment: perception, modeling, reasoning, learning
Summary: Rational Agent

CPS = Rational Agent

Filter $P(b | e, a)$

Controller $R(b), \pi(b)$

Planner $Map$

Plant (Environment) $P(s' | s, a), P(e | s)$

Percepts $e$

Actions $a$

sensors

actuators

What state if I see $e$?

What utility in $b$?

What action in $b$?

How the world evolves

What my actions do

What overall goal?
Model-Based Utility-Based Agent

Agent

Sensors

Percepts

Environment

Actuators

How happy I will be in this state

What is my utility

What the world is like now

What it will be if I do action A

How happy I will be in this state

What action I should do now

How does one develop such agents?

• Turing: Manually is too tedious. One should learn them
Turing proposes to build learning machines and teach them:

- 4 components: Learning, performance, and critic elements, problem gen.
General Learning Agent

Agent

- Sensors
- Actuators
- Percepts
- Learning Element
- Performance Element
- Problem Generator

Environment

- Percepts
- Actions

Feedback

- learning
- learning
- feedback

Knowledge

- changes
- goals

Performance

- responsible for making improvements

Standard

- performance
General Learning Agent

- **Agent**
  - **Critic**
    - Feedback
    - Learning Element
    - Problem Generator
  - **Learning Element**
    - Knowledge
    - Goals
  - **Performance Element**
    - Changes
    - Knowledge
  - **Sensors**
  - **Actuators**
  - **Environment**

- **Performance Standard**

- **Responsible for selecting external actions**
General Learning Agent

How performance element should be changed to do better?

Agent

Critic

Learning Element

Problem Generator

Performance Element

Actuators

Perceps

Environment

Sensors

Performsion standard

feedback

learning goals

knowledge

changes

learning
growth

goals

goals
Suggest actions that will lead to new and informative experiences
Preferred method of creating agents in many AI areas

- **Advantage:** Allows the agent to operate in initially unknown environments
A (Short) History of AI

- 1940-1950: Early days
  - 1943: McCulloch & Pitts: Boolean circuit model of brain
  - 1950: Turing's "Computing Machinery and Intelligence"
A (Short) History of AI

- 1940-1950: Early days
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  - 1950: Turing's “Computing Machinery and Intelligence”

- 1950—70: Excitement: Look, Ma, no hands!
  - 1950s: Early AI programs, including
    - Samuel's checkers program,
    - Newell & Simon's Logic Theorist,
    - Gelernter's Geometry Engine
  - 1956: Dartmouth meeting: “Artificial Intelligence” adopted
  - 1965: Robinson's complete algorithm for logical reasoning
    - E.g., generate plan for driving to the airport
  - 1966: Weizenbaum’s Eliza / Turing test
Herb Simon, 1957

It is not my aim to surprise or shock you---but the simplest way I can summarize is to say that there are now in the world machines that think, that learn and that create. Moreover, their ability to do these things is going to increase rapidly until---in a visible future---the range of problems they can handle will be coextensive with the range to which human mind has been applied.

More precisely: within 10 years a computer would be chess champion, and an important new mathematical theorem would be proved by a computer.
Harder than originally thought

- Herb Simon’s prediction came true, but after roughly 40 years instead of after 10
Harder than originally thought

- Herb Simon’s prediction came true, but after roughly 40 years instead of after 10

- Eliza:
  - “… mother …” → “Tell me more about your family”
  - “I wanted to adopt a puppy, but it’s too young to be separated from its mother.” → ???
Harder than originally thought

- Herb Simon’s prediction came true, but after roughly 40 years instead of after 10
- Eliza:
  - “... mother ...” $\rightarrow$ “Tell me more about your family”
  - “I wanted to adopt a puppy, but it’s too young to be separated from its mother.” $\rightarrow$ ???
- 1957: Sputnik
  - Automatic Russian $\rightarrow$ English translation
  - Famous example:
    - “The spirit is willing but the flesh is weak.”
    - E $\rightarrow$ R $\rightarrow$ E: “The vodka is strong but the meat is rotten.”
Observations

- Need some understanding about the world
Observations

- Need some understanding about the world

- Computational tractability, NP-completeness, exponential scaling.
A (Short) History of AI (ctd)

- 1970—88: Knowledge-based approaches
  - 1969—79: Early development of knowledge-based systems
  - 1980—88: Expert systems industry booms
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- 1988—: Statistical approaches
  - Resurgence of probability, focus on uncertainty
  - General increase in technical depth
  - Agents and learning systems… “Al Spring”?
A (Short) History of AI (ctd)

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  - Resurgence of probability, focus on uncertainty
  - General increase in technical depth
  - Agents and learning systems… “AI Spring”? 

- 2000—: Where are we now?
What Can AI Do?

Quiz: Which of the following can be done at present?

Play a decent game of table tennis?
What Can AI Do?

Quiz: Which of the following can be done at present?

✓ Play a decent game of table tennis?
What Can AI Do?

Quiz: Which of the following can be done at present?

- Play a decent game of table tennis?
- Drive safely along a curving mountain road?
What Can AI Do?

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Quiz: Which of the following can be done at present?

✅ Play a decent game of table tennis?
✅ Drive safely along a curving mountain road?
✅ Drive safely along Telegraph Avenue?
What Can AI Do?

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Quiz: Which of the following can be done at present?

- Play a decent game of table tennis?
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- Drive safely along Telegraph Avenue?
- Buy a week's worth of groceries on the web?
What Can AI Do?

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- Buy a week's worth of groceries at Berkeley Bowl?
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Quiz: Which of the following can be done at present?

- ✔️ Play a decent game of table tennis?
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- Discover and prove a new mathematical theorem?
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- Converse successfully with another person for an hour?
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Unload a dishwasher and put everything away?
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- Unload a dishwasher and put everything away?
- Translate spoken Chinese into spoken English in real time?
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- ✔ Discover and prove a new mathematical theorem?
- ❔ Converse successfully with another person for an hour?
- ❌ Perform a complex surgical operation?
- ❔ Unload a dishwasher and put everything away?
- ✔ Translate spoken Chinese into spoken English in real time?
- ✔ Write an intentionally funny story?
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Natural Language

- **Speech technologies**
  - Automatic speech recognition (ASR)
  - Text-to-speech synthesis (TTS)
  - Dialog systems

the friends family classmates said their final good buys yesterday at her funeral in east falls that these
adams was buried today in on this day a major break in the case
Natural Language

- **Speech technologies**
  - Automatic speech recognition (ASR)
  - Text-to-speech synthesis (TTS)
  - Dialog systems

- **Language processing technologies**
  - Machine translation

**Compétitivité : pourquoi l’écart se creuse entre la France et l’Allemagne**

- La question de la compétitivité de l’économie française mobilise, tout particulièrement par rapport au voisin allemand. Ce sujet est au cœur d’un rapport qui sera remis, jeudi, au ministre de l’industrie, Eric Besson.
  - Le français travaillent moins et sont plus productifs.
  - Christine Lagarde prévoit au moins 1,5 % de croissance en 2010.
  - L’inflation a fait son retour en 2010.
  - La croissance depuis 2007.

**Competitiveness: why the gap between France and Germany**

- The issue of competitiveness of the French economy mobilizes, especially compared to neighboring Germany. This topic is at the heart of a report to be presented Thursday to the Minister of Industry, Eric Besson.
  - The French work less and are more productive.
  - Christine Lagarde provides at least 1.5% growth in 2010.
  - Inflation has made a comeback in 2010.
  - Growth since 2007.
Natural Language

- **Speech technologies**
  - Automatic speech recognition (ASR)
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  - Dialog systems

- **Language processing technologies**
  - Machine translation

Competitiveness: why the gap between France and Germany

- Information extraction
- Information retrieval, question answering
- Text classification, spam filtering, etc…
Vision (Perception)

- Object and character recognition
- Scene segmentation
- 3D reconstruction
- Image classification
Robotics

- Robotics
  - Part mech. eng.
  - Part AI
  - Reality much harder than simulations!

- Technologies
  - Vehicles
  - Rescue
  - Soccer!
  - Lots of automation…

- In this class:
  - We ignore mechanical aspects
  - Methods for planning
  - Methods for control

Images from stanfordracing.org, CMU RoboCup, Honda ASIMO sites
Logic

- Logical systems
  - Theorem provers
  - NASA fault diagnosis
  - Question answering
Logic

- Logical systems
  - Theorem provers
  - NASA fault diagnosis
  - Question answering

- Methods:
  - Deduction systems
  - Constraint satisfaction
  - Satisfiability solvers
    (huge advances here!)
Game Playing

- May, '97: Deep Blue vs. Kasparov
  - First match won against world-champion
  - “Intelligent creative” play
  - 200 million board positions per second!
  - Humans understood 99.9 of Deep Blue’s moves
  - Can do about the same now with a big PC cluster

Text from Bart Selman, image from IBM’s Deep Blue pages
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  - How does human cognition deal with the search space explosion of chess?
  - Or: how can humans compete with computers at all??

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  “I could feel --- I could smell --- a new kind of intelligence across the table.”

- **1997: Deep Blue Beats Kasparov**
  “Deep Blue hasn't proven anything.”

Text from Bart Selman, image from IBM’s Deep Blue pages
Decision Making

- Scheduling, e.g. airline routing, military
Decision Making

- Scheduling, e.g. airline routing, military
- Route planning, e.g. google maps
Decision Making

- Scheduling, e.g. airline routing, military
- Route planning, e.g. google maps
- Medical diagnosis
Decision Making

- Scheduling, e.g. airline routing, military
- Route planning, e.g. google maps
- Medical diagnosis
- Automated help desks
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- Fraud detection
- Spam classifiers
Decision Making

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- Route planning, e.g. google maps
- Medical diagnosis
- Automated help desks
- Fraud detection
- Spam classifiers
- Web search engines
Decision Making

- Scheduling, e.g. airline routing, military
- Route planning, e.g. google maps
- Medical diagnosis
- Automated help desks
- Fraud detection
- Spam classifiers
- Web search engines
- Movie and book recommendations
Decision Making

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- Route planning, e.g. google maps
- Medical diagnosis
- Automated help desks
- Fraud detection
- Spam classifiers
- Web search engines
- Movie and book recommendations

- ... Lots more!