236609 - AI and Robotics

Lesson 1: Components of Autonomy

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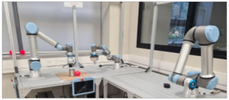
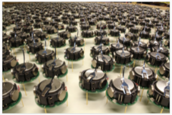
What is a robot

Many Types of Robots

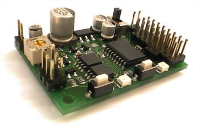




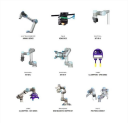
Components of a Robotic Agents

Sensors

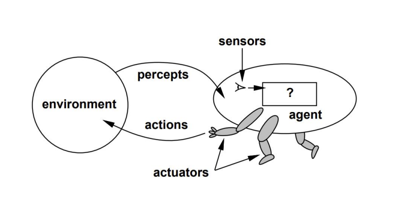
Controllers



Actuators

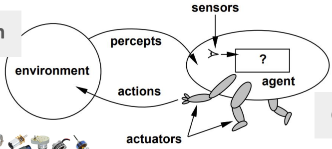


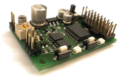
Autonomy



Autonomy

state estimation





decision making

motion control

Autonomy

State Estimation

$$\beta : \mathcal{S} \mapsto [0, 1]$$

Process incoming observations to maintain a *belief* as a probability distribution over states

Decision Making

$$\pi : \beta \mapsto \mathcal{A}$$
$$\pi : \beta \times \mathcal{A} \mapsto [0, 1]$$

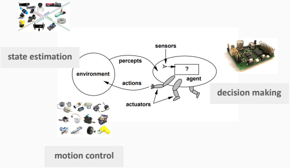
Find a policy - a mapping belief and objective into actions (probabilities)

Motion Control

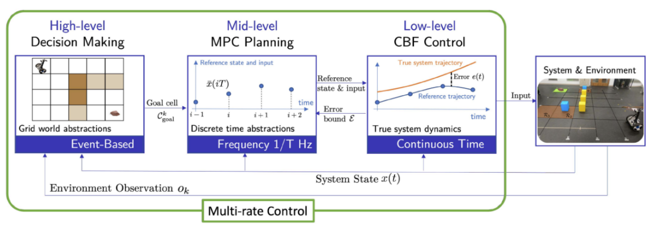
$$\dot{x}(t) = f(x(t), u(t), t) + w(t)$$

Translate actions into low-level commands (and monitor their execution)

- $x(t) \in \mathbb{R}^n$ - state vector
- $u(t) \in \mathbb{R}^m$ - control input
- $f : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R} \to \mathbb{R}^n$ - system dynamics
- $w(t)$ - noise or disturbance



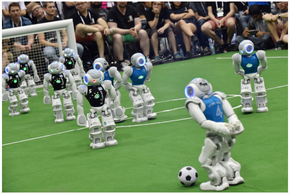
Layered Control Architecture (LCA)



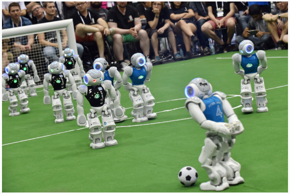
Matni, Nikolai, Aaron D. Ames, and John C. Doyle. "A Quantitative Framework for Layered Multirate Control: Toward a Theory of Control Architecture." IEEE Control Systems Magazine (2024)

AI Approaches to Decision Making

Reactive vs. Rational Agent

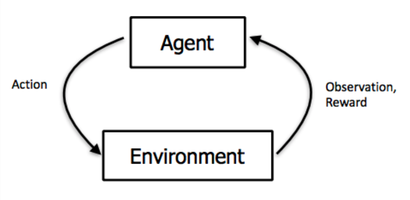


Reactive vs. Rational Agent

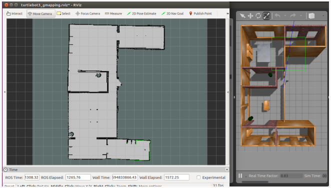


- **Reactive** or **Reflex** agent:
  - simple reactions to stimulus
  - mostly used when fast response times are needed or when computational resources are limited (e.g., a Vacuum cleaning robot).
- **Rational agent:**
  - extended reasoning capabilities and can use its resources and skills to autonomously achieve complex objectives
  - selects actions that maximize its (expected) utility.
  - can learn and gain knowledge from their environment
  - can react to changes in the environment
  - Social ability: can negotiate, cooperate or compete by

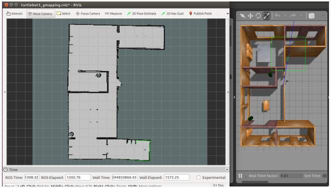
What does it mean to be autonomous ?



What do we need ?



What do we need ?

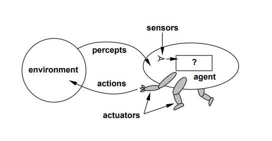


- Sequential decision making
- Dealing with uncertainty
- Recovering from failure
- Accounting for other agents

Single Agent Autonomy

What does it mean to be autonomous?

- Action (Actuation)
  - Locomotion
  - Manipulation
  - Interaction
- Perception (Sensors)
  - Internal
  - External
- Cognition (Control)
  - From reactive to proactive
  - From finite state machines to cognitive robotics



Approaches to Decision Making

We are seeking a policy a (potentially probabilistic) mapping from state space to actions.

Basic approaches:

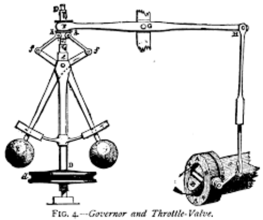
- Programming/reactive
- Planning (using a domain-independent descriptive language)
- Machine Learning (from data and experience)
- Reinforcement Learning

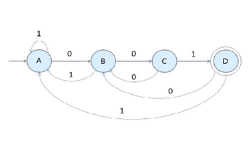
Example

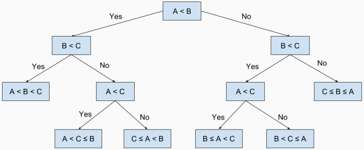
You are in Kibutz Ein Dor and you want to get to Austin Texas.

How do you decide how to get to Austin?

Programming/reactive



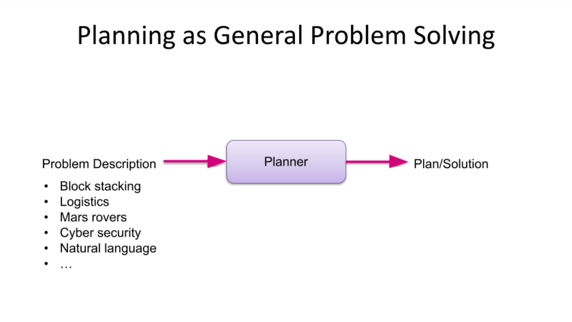




Very practical in many applications, but lacks flexibility.

Is this approach relevant to robotics ?

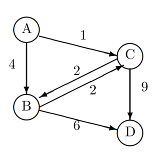
Planning

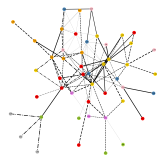


Planning is the **model-based** approach to autonomous behavior.

Planning as State Space Search

- A system can be in one of many **states**
- States assign values to a set of **variable**.
- **Actions** change the values of certain variables.
- **Reward** is a numeric signal passed from the environment to the agent which is used to signal the objective. A **goal state** is a particular state an agent should achieve.
- Basic task: find a **policy** (or action sequence in deterministic domains) to drive initial state into goal state or to maximize the expected accumulated reward.
- Language is **generic** and not domain specific.
- Complexity: NP-hard; i.e., exponential in number of variables in worst case.





Planning as State Space Search

- **Classical planning** - fully observable deterministic
- **Probabilistic planning** - fully observable stochastic action outcomes
- **Planning with partial information** - partially observable stochastic action outcomes

Which planning algorithms do you know ?

Planning as State Space Search

- **Classical planning** - fully observable deterministic
- **Probabilistic planning** - fully observable stochastic action outcomes
- **Planning with partial information** - partially observable stochastic action outcomes

Which planning algorithms do you know ?

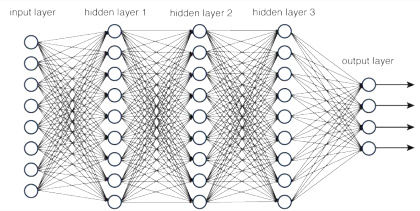
We will re-visit some planning algorithms you already know (A*, policy iteration, value iteration, MCTS) and explore new approaches (LAO*, planning in belief space).

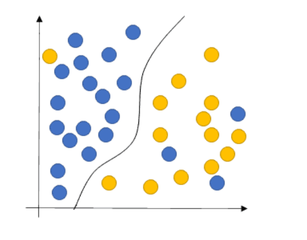
Are these relevant to robotics ?

Machine Learning

Use statistics to find patterns in massive amounts of data.

The input vector x (e.g., an image) is mapped to an output $f(x)$, which represents a classification label, a probability distribution over the possible labels, or object labels with suitable bounding boxes.





Machine Learning

Template algorithm (for supervised learning)*:

- **Input:**
  - Sample set: $S = \{(x_i, y_i)_{i=1}^{m}\}$
  - Model calls H (candidate classifiers)
- **Output:**
  - Classifier with lowest **expected error** (e.g. loss).

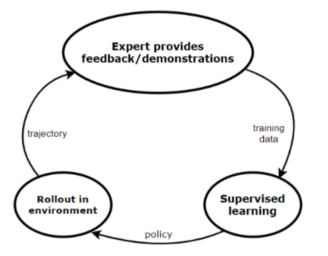
* from Intro to ML course

Various approaches and methods for learning: linear regression, decision trees, DNN etc.

Relevance to robotics ?

Machine Learning: Imitation Learning

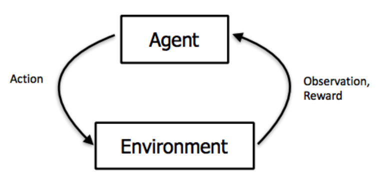
- Learning from demonstrations
- Useful when it is easier for an expert to demonstrate the desired behaviour rather than to specify a reward function.
- The simplest form of imitation learning is behaviour cloning (BC), which focuses on learning the expert's policy using supervised learning.



Taken from *https://smartlabai.medium.com/a-brief-overview-of-imitation-learning-8a8a75c44a9c*

Reinforcement Learning (RL)

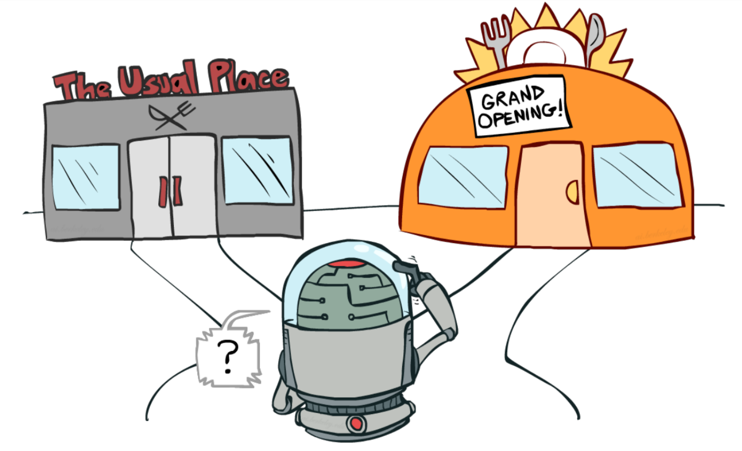
- Reinforcement learning is about learning from interaction how to behave in order to achieve a goal.
- Learning what to do - how to map situations to actions - so as to maximize a numerical reward signal.
- The learner is not told which actions to take, but instead must discover which actions yield the highest total **reward** by trying them.



Reinforcement Learning in Robotics
https://slideslive.com/38955294/how-robots-can-learn-endtoend-from-data?ref=recommended
Is reward enough ?
https://deepmind.com/research/publications/2021/Reward-is-Enough

Reinforcement Learning

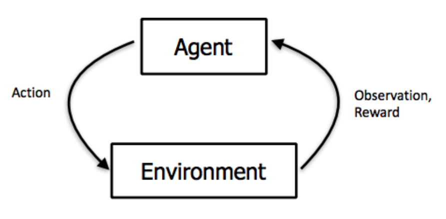
In RL there's a tradeoff between **exploration** (choosing an action for which the outcome is unknown or choosing a random action) and **exploitation** (choosing an action based on learned values).



Reinforcement Learning (contd.)

The process of Reinforcement Learning involves these steps:

- Observing of the environment
- Deciding how to act using some strategy
- Acting accordingly
- Receiving a reward or penalty
- Learning from the experiences and refining our strategy
- Iterating until an optimal strategy is found



RL vs. Planning

Both are fundamental problems in sequential decision making

- **Planning:** A model of the environment is known. The agent performs computations with its model (without any external interaction). The agent improves its policy a.k.a. deliberation, reasoning, introspection, pondering, thought, and search.
- **Reinforcement Learning:** The environment is initially unknown. The agent improves its policy by interacting with the environment.

The distinction is very fuzzy...

RL vs. ML

What makes reinforcement learning different from other machine learning paradigms?

- There is no supervisor, only a reward signal
- Feedback is delayed, not instantaneous
- Time really matters (sequential, non i.i.d data): agent's actions affect the subsequent reward it receives

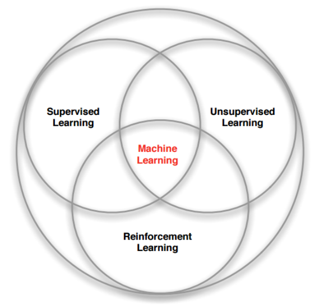


Image by David Silver.

RL vs. IL

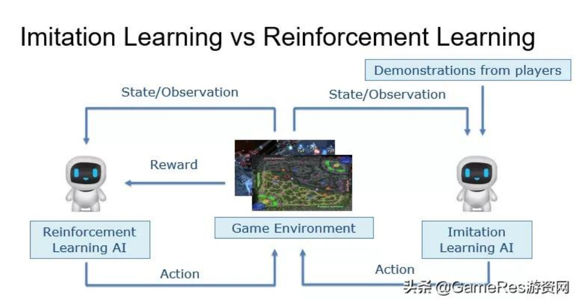
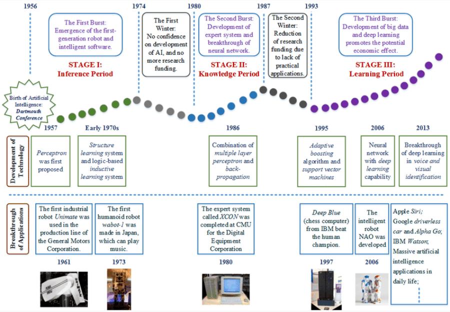
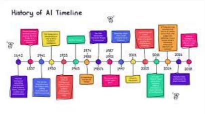
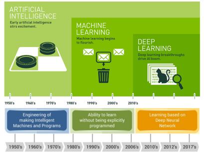


Image from *https://inf.news/en/game/3e21da98acd998d2774deac09944e5b0.html*

Historical Overview





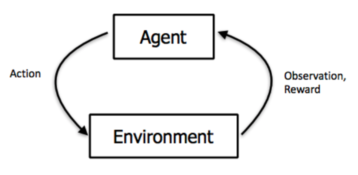


Watch Henry Kautz's talk at AAAI 2020 to learn more

https://vimeo.com/389560858

Decision Making in AI : Summary

- Different approaches for decision: from data-driven to model-based approaches.
- Different settings require different solutions.

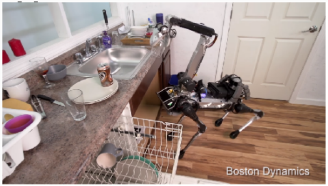


Open Questions:

- How to choose the right paradigm for your problem ?
- What is a good model for the decision making process ?
- How does the presence of other agents affect these decision ?

Complex Tasks for Robotic Agents

Tasks for Autonomous Robots



Household


Warehouse fulfilment

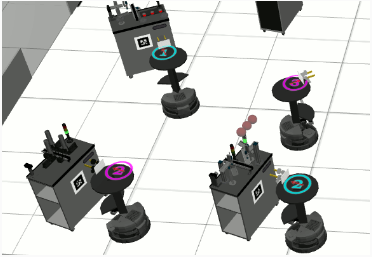
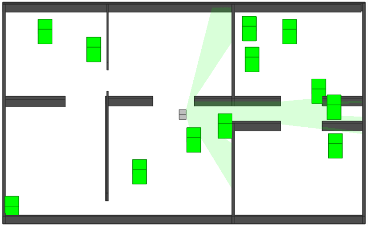
Food service


Construction

Robot must select both high-level actions & low-level controls in semi-structured and human environments.

https://youtu.be/JNOk1rylDpU?t=149

RoboCup Logistics League

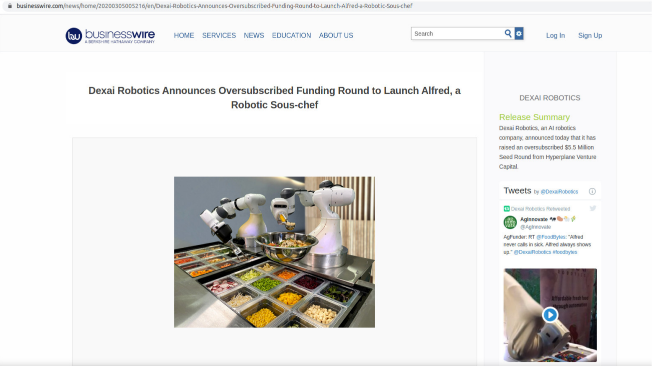
http://www.robocup-logistics.org/

Agile Robotics for Industrial Automation Competition

https://github.com/usnistgov/ARIAC

https://cdnapisec.kaltura.com/index.php/extwidget/preview/partner_id/684682/uiconf_id/31013851/entry_id/0_5oy6lxgu/embed/dynamic

Preparing a meal



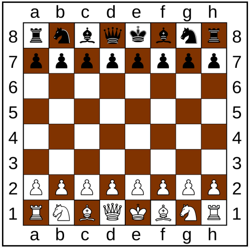
https://vimeo.com/507594076 https://www.businesswire.com/news/home/20200305005216/en/Dexai-Robotics-Announces-Oversubscribed-Funding-Round-t

RoboCupRescue Robot League

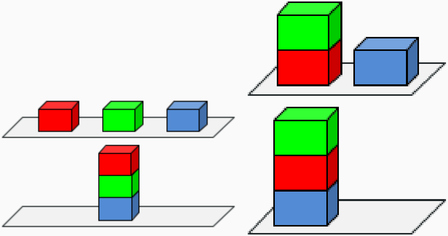
An international league of teams with one objective: develop and demonstrate advanced robotic capabilities for emergency responders.

https://www.youtube.com/watch?v=IIPH8K0KFhE
https://rrl.robocup.org/ Also a track for soccer.

Tasks for Autonomous Robots

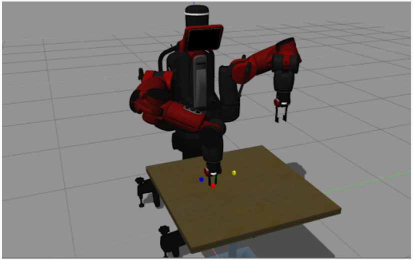


Tasks for Autonomous Robots



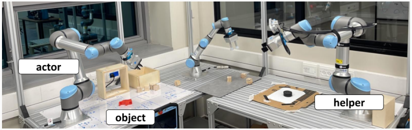
Tasks for Autonomous Robots

http://crml.eelabs.technion.ac.il/projects/
artificial-intelligence-planning-for-solving-blocks-worl



Course Storyline

- Complex decision-making in robotics
- Integrated task planning, motion planning, and motion control
- Task planning revisited
- Low-level control
- Motion planning
- Perception and state estimation
- Task planning under uncertainty
- Putting all together: integrated task and motion planning



Summary

Summary:

- We explored the structure of a robot and the components of autonomy
- We reviewed different approaches for decision making in AI

What next ?

- Discuss the multi-leveled approach to decision making for robotic applications
- Revisit task planning and examine its relationship to robots