Robot Planning
Robot Decision Making and Planning

"His path-planning may be sub-optimal, but it's got flair."
Robot Decision Making and Planning

Robots need to make various decisions and construct different plans, for example:

- Reactive decision making
- Task planning
- Motion planning (e.g., for robotic arms)
- Path planning (e.g., for mobile robotics)
Robot Decision Making and Planning

Robots need to make decisions and construct plans:

- Reactive decision making
- Task planning
- Motion planning (e.g., for robotic arms)
- Path planning (e.g., for mobile robotics)

Perspectives to consider robot planning methods

- Reactive (single-time) decision making versus sequential planning
- Certain and uncertain scenarios
- Observable versus partially observable space

We will focus on sequential decision making
Decision Making/Planning Types

• Deterministic, fully observable
  • Agent knows exactly which state it will be in
  • Agent action is executed as expected

• Dynamic, partially observable
  • Observations provide new information about current state with uncertainty
  • Robot actions may not be successfully executed

• Non-observable
  • Agent may have no idea where it is
Example: Vacuum World

- Observable, start in #5.
  - [Right; Suck]
- Non-observable, start in: \{1; 2; 3; 4; 5; 6; 7; 8\}
  - e.g., Right goes to \{2; 4; 6; 8\}
  - [Right; Suck; Left; Suck]
- Partially observable, start in #5, suck can dirty a clean carpet, local sensing only
  - [Right; if dirt then Suck]

- Possible actions: left, right, suck
Example: Vacuum World (observable)

- **States**: cross product of dirtiness and robot locations
- **Successor function**: Left/Right changes location, Suck changes dirtiness
- **Actions**: Left, Right, Suck, NoOp
- **Goal test**: no dirt
- **Path cost**: 1 per action (0 for NoOp)
  (Also called reward, penalty, or utility)
Example: Vacuum World (non-observable)
Planning with Uncertainty

• How about in an uncertain scenario?
  • Uncertainty in action outcomes
  • Uncertainty in state of knowledge
  • Any combination of the two
Planning with Uncertainty

• Solutions based on decision tree
Planning with Uncertainty

• Utility (i.e., reward or cost) function associates a real-valued utility (reward or cost) with each outcome (state or state-action pair)
• With utilities, we can compute and optimize expected utilities for planning under uncertainty
  • For example, the expected utility of decision $d$ in the state $s$ is defined as
    $$EU(d) = \sum_{s \in S} \Pr_d(s)U(s)$$
  • The principle of maximum expected utility states that the optimal decision under uncertainty is the one that has greatest expected utility
Reinforcement Learning for Planning

Two fundamental problems in sequential decision making

• Reinforcement Learning:
  • The environment is initially unknown
  • The agent interacts with the environment
  • The agent improves its policy

• Planning:
  • A model of the environment is known
  • The agent performs computations with its model (without any external interaction)
Reinforcement Learning

• Branches of Machine Learning
Characteristics of Reinforcement Learning

• 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 data it receives
Applications of Reinforcement Learning
Applications of Reinforcement Learning

Robot Motor Skill Coordination with EM-based Reinforcement Learning

Petar Kormushev, Sylvain Calinon, and Darwin G. Caldwell

Italian Institute of Technology
Applications of Reinforcement Learning
Reinforcement Learning

• Reinforcement learning is based on the reward hypothesis

• Definition (Reward Hypothesis): All goals can be described by the *maximization of expected cumulative reward*
  
  • A reward $R_t$ is a scalar feedback signal
  • Indicates how well agent is doing at step $t$
  • The agent's job is to maximize cumulative reward

• Actions may have long term consequences, thus reward may be delayed
  
  • It may be better to sacrifice immediate reward to gain more long-term reward
Agent and Environment

At each step $t$ the agent:
- Executes action $A_t$
- Receives observation $O_t$
- Receives scalar reward $R_t$

The environment:
- Receives action $A_t$
- Emits observation $O_{t+1}$
- Emits scalar reward $R_{t+1}$

$t$ increments at env. step

The slides of RL are from Dr. David Silver: http://www0.cs.ucl.ac.uk/staff/d.silver/web/Teaching.html
History and State

- The **history** is the sequence of observations, actions, rewards
  \[ H_t = O_1, R_1, A_1, ..., A_{t-1}, O_t, R_t \]

- i.e. all observable variables up to time \( t \)
- i.e. the sensorimotor stream of a robot or embodied agent
- What happens next depends on the history:
  - The agent selects actions
  - The environment selects observations/rewards
- **State** is the information used to determine what happens next
- Formally, state is a function of the history:
  \[ S_t = f(H_t) \]
Environment State

- The environment state $S_t^e$ is the environment’s private representation.
- i.e. whatever data the environment uses to pick the next observation/reward.
- The environment state is not usually visible to the agent.
- Even if $S_t^e$ is visible, it may contain irrelevant information.
Agent State

- The agent state $S_t^a$ is the agent’s internal representation
- i.e. whatever information the agent uses to pick the next action
- i.e. it is the information used by reinforcement learning algorithms
- It can be any function of history:

$$S_t^a = f(H_t)$$
Information State

An information state (a.k.a. Markov state) contains all useful information from the history.

**Definition**

A state $S_t$ is Markov if and only if

$$P[S_{t+1} \mid S_t] = P[S_{t+1} \mid S_1, \ldots, S_t]$$

- “The future is independent of the past given the present”
  $$H_{1:t} \rightarrow S_t \rightarrow H_{t+1:\infty}$$

- Once the state is known, the history may be thrown away
- i.e. The state is a sufficient statistic of the future
- The environment state $S^e_t$ is Markov
- The history $H_t$ is Markov
Fully Observable Environments

Full observability: agent directly observes environment state

\[ O_t = S^a_t = S^e_t \]

- Agent state = environment state = information state
- Formally, this is a Markov decision process (MDP)
Markov Property

“The future is independent of the past given the present”

**Definition**

A state $S_t$ is *Markov* if and only if

$$\mathbb{P}[S_{t+1} \mid S_t] = \mathbb{P}[S_{t+1} \mid S_1, \ldots, S_t]$$

- The state captures all relevant information from the history
- Once the state is known, the history may be thrown away
- i.e. The state is a sufficient statistic of the future
State Transition Matrix

For a Markov state $s$ and successor state $s'$, the state transition probability is defined by

$$P_{ss'} = \mathbb{P}[S_{t+1} = s' \mid S_t = s]$$

State transition matrix $P$ defines transition probabilities from all states $s$ to all successor states $s'$,

$$P = \begin{bmatrix}
P_{11} & \cdots & P_{1n} \\
\vdots & \ddots & \vdots \\
P_{n1} & \cdots & P_{nn}
\end{bmatrix}$$

where each row of the matrix sums to 1.
A Markov process is a memoryless random process, i.e., a sequence of random states $S_1, S_2, \ldots$ with the Markov property.

**Definition**

A *Markov Process* (or *Markov Chain*) is a tuple $\langle \mathcal{S}, \mathcal{P} \rangle$

- $\mathcal{S}$ is a (finite) set of states
- $\mathcal{P}$ is a state transition probability matrix,
  
  $\mathcal{P}_{ss'} = \mathbb{P} [S_{t+1} = s' \mid S_t = s]$
Markov Process: Example
Markov Process: Example

Sample episodes for Student Markov Chain starting from $S_1 = C1$

$S_1, S_2, ..., S_T$

- C1 C2 C3 Pass Sleep
- C1 FB FB C1 C2 Sleep
- C1 C2 C3 Pub C2 C3 Pass Sleep
- C1 FB FB C1 C2 C3 Pub C1 FB FB FB C1 C2 C3 Pub C2 Sleep

$\mathcal{P} =$

\[
\begin{bmatrix}
C1 & C2 & C3 & Pass & Pub & FB & Sleep \\
C1 & 0.5 & 0.8 & 0.6 & 0.4 & 0.5 & 0.2 \\
C2 & 0.2 & 0.4 & 0.4 & 0.9 & & \\
C3 & 0.1 & 0.4 & 0.4 & & & \\
Pass & & & & & & \\
Pub & & & & & & \\
FB & & & & & & \\
Sleep & & & & & 1 & \\
\end{bmatrix}
\]
A Markov reward process is a Markov chain with values.

**Definition**

A *Markov Reward Process* is a tuple \( \langle S, \mathcal{P}, \mathcal{R}, \gamma \rangle \)

- \( S \) is a finite set of states
- \( \mathcal{P} \) is a state transition probability matrix,
  \[
  \mathcal{P}_{ss'} = \mathbb{P} [ S_{t+1} = s' \mid S_t = s ]
  \]
- \( \mathcal{R} \) is a reward function,
  \[
  \mathcal{R}_s = \mathbb{E} [ R_{t+1} \mid S_t = s ]
  \]
- \( \gamma \) is a discount factor, \( \gamma \in [0, 1] \)
Markov Reward Process: Example
A Markov decision process (MDP) is a Markov reward process with decisions. It is an environment in which all states are Markov.

**Definition**

A Markov Decision Process is a tuple $\langle S, A, P, R, \gamma \rangle$

- $S$ is a finite set of states
- $A$ is a finite set of actions
- $P$ is a state transition probability matrix,
  
  $P_{ss'} = P[S_{t+1} = s' \mid S_t = s, A_t = a]$

- $R$ is a reward function,
  
  $R_s^a = E[R_{t+1} \mid S_t = s, A_t = a]$

- $\gamma$ is a discount factor $\gamma \in [0, 1]$. 
Markov Decision Process: Example
MDP and Reinforcement Learning

- *Markov decision processes* formally describe an environment for reinforcement learning
- Where the environment is *fully observable*
- i.e. The current *state* completely characterises the process
- Almost all RL problems can be formalised as MDPs, e.g.
  - Optimal control primarily deals with continuous MDPs
  - Partially observable problems can be converted into MDPs

- An RL agent may include one or more of these components:
  - Policy: agent’s behaviour function
  - Value function: how good is each state and/or action
  - Model: agent’s representation of the environment
Final Project Presentation Schedule

• 04/26: Graduate Teams 2, 3, 4, 5, 6
• 05/01: Graduate Teams 7, 8, 9, 10, 11
• 05/03: Undergraduate Teams 1, 2, 3, 4
  Individual Projects 1, 2

• Instructions:
  • Each team has a total of 15 minutes:
    10-12 mins for presentation + 3-5 mins for Q/A
  • The projector supports VGA and HDMI interfaces
Components of an RL Agent

Policy

Definition

A \textit{policy} $\pi$ is a distribution over actions given states,

$$\pi(a|s) = \mathbb{P}[A_t = a \mid S_t = s]$$

- A policy fully defines the behaviour of an agent
- MDP policies depend on the current state (not the history)
- i.e. Policies are \textit{stationary} (time-independent), $A_t \sim \pi(\cdot | S_t), \forall t > 0$
- Deterministic policy: $a = \pi(s)$ (and greedy)
- Stochastic policy: $\pi(a|s) = \mathbb{P}[A_t = a|S_t = s]$
Components of an RL Agent

Value Function

- Value function is a prediction of future reward
- Used to evaluate the goodness/badness of states
- And therefore to select between actions, e.g.

\[ v_\pi(s) = \mathbb{E}_\pi \left[ R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \ldots \mid S_t = s \right] \]

Model

- A model predicts what the environment will do next
- \( \mathcal{P} \) predicts the next state
- \( \mathcal{R} \) predicts the next (immediate) reward, e.g.

\[ \mathcal{P}_{ss'}^a = \mathbb{P}[S_{t+1} = s' \mid S_t = s, A_t = a] \]
\[ \mathcal{R}_s^a = \mathbb{E}[R_{t+1} \mid S_t = s, A_t = a] \]
Maze Example

- Rewards: -1 per time-step
- Actions: N, E, S, W
- States: Agent’s location
Maze Example: Policy

Arrows represent policy \( \pi(s) \) for each state \( s \)
Maze Example: Value Function

Numbers represent value $v_\pi(s)$ of each state $s$
Maze Example: Model

- Grid layout represents transition model $P^a_{ss'}$.
- Numbers represent immediate reward $R_s^a$ from each state $s$ (same for all $a$).
- Agent may have an internal model of the environment.
- Dynamics: how actions change the state.
- Rewards: how much reward from each state.
- The model may be imperfect.
Model-Based and Model-Free RL

- Model-Free RL
  - No model
  - Learn value function (and/or policy) from experience

- Model-Based RL
  - Learn a model from experience
  - Plan value function (and/or policy) from model
Model-Based and Model-Free RL

- **Model-Free RL**
  - No model
  - Learn value function (and/or policy) from experience
- **Model-Based RL**
  - Learn a model from experience
  - Plan value function (and/or policy) from model

---

Model-based RL

Model-free RL
Q-Learning: Integrating Learning and Planning

• We’re going to learn model-free RL (though knowing a model also works)
• We will focus on finding a way to estimate the value function directly
  • The value function is not necessary to directly associate with the world and represent the world
• The value function is the Q-function
  • A recursive way to approximate a value function
• The process of estimation the Q-function is called Q-learning
  • Q-Learning integrates learning and planning
Q-Learning Basics

• Given a sequence of states, actions, and rewards defined by a MDP:

\[ s_0a_0r_0 \quad s_1a_1r_1 \quad s_2a_2r_2 \quad s_3a_3r_3 \ldots \quad s_ka_kr_k \ldots \]

we define a unit of experience \( \langle s_k \quad a_k \quad r_k \quad s_{k+1} \rangle \)

• At each step \( s \), choose the action \( a \) which maximizes the Q-function \( Q(s, a) \)
  • \( Q \) is the estimated value function
  • \( Q \) tells us how good an action is given a certain state
  • \( Q(s, a) = \) immediate reward for making an action + best value (Q) for the resulting (future) state
Q-Learning Formal Definition

• Q-function learning has a recursive definition:

\[ Q(s, a) = r(s, a) + \gamma \max_{a'}(Q(s', a')) \]

\[ r(s, a) = \text{Immediate reward} \]
\[ \gamma = \text{relative value of delayed vs. immediate rewards (0 to 1)} \]
\[ s' = \text{the new state after action } a \]
\[ a, a': \text{actions in states } s \text{ and } s', \text{respectively} \]

Selected action:

\[ \pi(s) = \text{argmax}_a Q(s, a) \]

• Q-learning is about maintaining and updating the table of Q-values
  • Only updates Q-values related to the state-action pairs that are visited
Q-Learning Algorithm

• The Q-learning algorithm is also recursive:
  • Consider the unit experience $< s_k, a_k, r_k, s_{k+1} >$

For each state-action pair $(s, a)$, initialize the table entry $\hat{Q}(s, a)$ to zero
Observe the current state $s$
Do forever:
--- Select an action $a$ and execute it
--- Receive immediate reward $r$
--- Observe the new state $s'$
--- Update the table entry for $\hat{Q}(s, a)$ as follows:
  \[ \hat{Q}(s, a) = r + \gamma \max_a \hat{Q}(s', a') \]
--- $s = s'$
Q-Learning Example

Example Problem

\[ \gamma = 0.5, \quad r = 100 \text{ if moving into state } s6, \quad 0 \text{ otherwise} \]
Q-Learning Example

Initial State

<table>
<thead>
<tr>
<th>State, Action</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1, a12</td>
<td>0</td>
</tr>
<tr>
<td>s1, a14</td>
<td>0</td>
</tr>
<tr>
<td>s2, a21</td>
<td>0</td>
</tr>
<tr>
<td>s2, a23</td>
<td>0</td>
</tr>
<tr>
<td>s2, a25</td>
<td>0</td>
</tr>
<tr>
<td>s3, a32</td>
<td>0</td>
</tr>
<tr>
<td>s3, a36</td>
<td>0</td>
</tr>
<tr>
<td>s4, a41</td>
<td>0</td>
</tr>
<tr>
<td>s4, a45</td>
<td>0</td>
</tr>
<tr>
<td>s5, a54</td>
<td>0</td>
</tr>
<tr>
<td>s5, a52</td>
<td>0</td>
</tr>
<tr>
<td>s5, a56</td>
<td>0</td>
</tr>
</tbody>
</table>
Q-Learning Example

The Algorithm

<table>
<thead>
<tr>
<th>State, Action</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0</td>
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<tr>
<td>s3, a36</td>
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<tr>
<td>s4, a41</td>
<td>0</td>
</tr>
<tr>
<td>s4, a45</td>
<td>0</td>
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<tr>
<td>s5, a54</td>
<td>0</td>
</tr>
<tr>
<td>s5, a52</td>
<td>0</td>
</tr>
</tbody>
</table>

Current Position: Red
Available actions: a12, a14
Chose a12

Diagram of the algorithm with states and transition arrows.
Q-Learning Example

\[ \hat{Q}(s, a) = r + \gamma \max_{a'} \hat{Q}(s', a') \]

**Update \( Q(s_1, a_{12}) \)**

<table>
<thead>
<tr>
<th>State</th>
<th>Action</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1, a12</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>s1, a14</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>s2, a21</td>
<td>0</td>
<td></td>
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<tr>
<td>s2, a23</td>
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</tr>
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<td></td>
</tr>
<tr>
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<td>0</td>
<td></td>
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<tr>
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<td>0</td>
<td></td>
</tr>
<tr>
<td>s4, a41</td>
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<td></td>
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<td>s4, a45</td>
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</tr>
<tr>
<td>s5, a54</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>s5, a52</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Current Position:** Red

Available actions: a21, a25, a23

Update \( Q(s_1, a_{12}) \):

\[
Q(s_1, a_{12}) = r + .5 * \max(Q(s_2,a_{21}), \ Q(s_2,a_{25}), \ Q(s_2,a_{23}))
\]

\[= 0\]

**Diagram:**

- States: s1, s2, s3, s4, s5, s6
- Actions: a12, a21, a23, a32, a36
- Transition arrows between states
Q-Learning Example

Next Move

| s1, a12 | 0 |
| s1, a14 | 0 |
| s2, a21 | 0 |
| s2, a23 | 0 |
| s2, a25 | 0 |
| s3, a32 | 0 |
| s3, a36 | 0 |
| s4, a41 | 0 |
| s4, a45 | 0 |
| s5, a54 | 0 |
| s5, a52 | 0 |

Current Position: Red

Available actions: a21, a25, a23
Chose a23

---

[Diagram showing a grid with movements and states labeled s1 to s6, including arrows for a12, a21, a23, a25, a32, a41, a45, a54, and a52.]
Q-Learning Example

Update $Q(s_2, a_{23})$

| s1, a12 | 0 |
| s1, a14 | 0 |
| s2, a21 | 0 |
| s2, a23 | 0 |
| s2, a25 | 0 |
| s3, a32 | 0 |
| s3, a36 | 0 |
| s4, a41 | 0 |
| s4, a45 | 0 |
| s5, a54 | 0 |
| s5, a52 | 0 |

Current Position: Red

Available actions: $a_{32}, a_{36}$

Update $Q(s_1, a_{12})$:

$Q(s_2, a_{23}) = r + .5 \times \max(Q(s_3, a_{32}), Q(s_3, a_{36}))$

$= 0$

Diagram showing the states and actions.
Q-Learning Example

Current Position: Red

Available actions: a32, a36
Chose a36
Q-Learning Example

\[ \hat{Q}(s, a) = r + \gamma \max_{a'} \hat{Q}(s', a') \]

Update Q(s3, a36)

Current Position: Red

FINAL STATE!

Update Q(s3, a36):
\[ Q(s3, a36) = r = 100 \]
Q-Learning Example

New Game

<table>
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<tr>
<th>State, Action</th>
<th>Reward</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1, a12</td>
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<td>s2, a21</td>
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<td>100</td>
</tr>
<tr>
<td>s4, a41</td>
<td>0</td>
</tr>
<tr>
<td>s4, a45</td>
<td>0</td>
</tr>
<tr>
<td>s5, a54</td>
<td>0</td>
</tr>
<tr>
<td>s5, a52</td>
<td>0</td>
</tr>
</tbody>
</table>

Current Position: Red

Available actions: a21, a25, a23
Chose a23
Q-Learning Example

\[ \hat{Q}(s, a) = r + \gamma \max_{a'} \hat{Q}(s', a') \]

Update \( Q(s_2, a_{23}) \)

<table>
<thead>
<tr>
<th>s1, a12</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1, a14</td>
<td>0</td>
</tr>
<tr>
<td>s2, a21</td>
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</tr>
<tr>
<td>s2, a23</td>
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<tr>
<td>s2, a25</td>
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<tr>
<td>s3, a32</td>
<td>0</td>
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<tr>
<td>s3, a36</td>
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<td>s4, a41</td>
<td>0</td>
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<tr>
<td>s4, a45</td>
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<td>0</td>
</tr>
<tr>
<td>s5, a52</td>
<td>0</td>
</tr>
</tbody>
</table>

Current Position: Red

Available actions: a32, a36

Update \( Q(s_1, a_{12}) \):
\[
Q(s_2, a_{23}) = r + .5 \times \max(0.5 \times (Q(s_3, a_{32}) + Q(s_3, a_{36})))
\]
\[
= 0 + .5 \times 100 = 50
\]
Q-Learning Example

Final State (after many iterations)

<table>
<thead>
<tr>
<th>State, Action</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>s1, a12</td>
<td>25</td>
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<tr>
<td>s1, a14</td>
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<tr>
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</tr>
<tr>
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<tr>
<td>s2, a25</td>
<td>25</td>
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Q-Learning Example
Q-Learning Example
Q-Learning Challenges: State/Action Repr.

- Pole-balancing
  - Move car left/right to keep the pole balanced

- State representations
  - Position and velocity of car
  - Angle and angular velocity of pole
  - They are all continuous variables

- Action representations
  - Move the cart left or right with certain speed
  - Speed is also continuous variables

- Straightforward solutions
  - Coarse discretization of 3 state variables: left, center, right
  - Course discretization of speed as well
Q-Learning Challenges: Reward Design

• Rewards
  • Indicate what we want to accomplish
  • NOT how we want to accomplish it

• Robot in a maze
  • Episodic task
  • +1 when out, 0 for each step

• Chess
  • GOOD: +1 for winning, -1 losing
  • BAD: +0.25 for taking opponent’s pieces

• It is hard to design rewards for general tasks
  • An active research topic is reward learning