Topics:

- Reinforcement Learning Part 1
  - **Markov Decision Processes**
  - **Value Iteration**

CS 4803-DL / 7643-A

ZSOLT KIRA

Admin

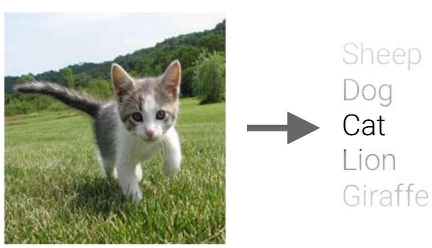
- HW4 due **April 10th**
  - See OH on Attention/Seq2seq and HW4

Reinforcement Learning Introduction

Types of Machine Learning

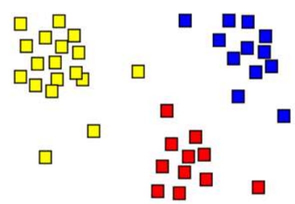
Supervised Learning

- Train Input: $\{X, Y\}$
- Learning output: $f : X \rightarrow Y$, $P(y|x)$
- e.g. classification



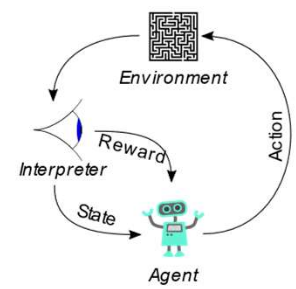
Unsupervised Learning

- Input: $\{X\}$
- Learning output: $P(x)$
- Example: Clustering, density estimation, etc.



Reinforcement Learning

- Evaluative feedback in the form of **reward**
- No supervision on the right action



RL: Sequential decision making in an environment with evaluative feedback.

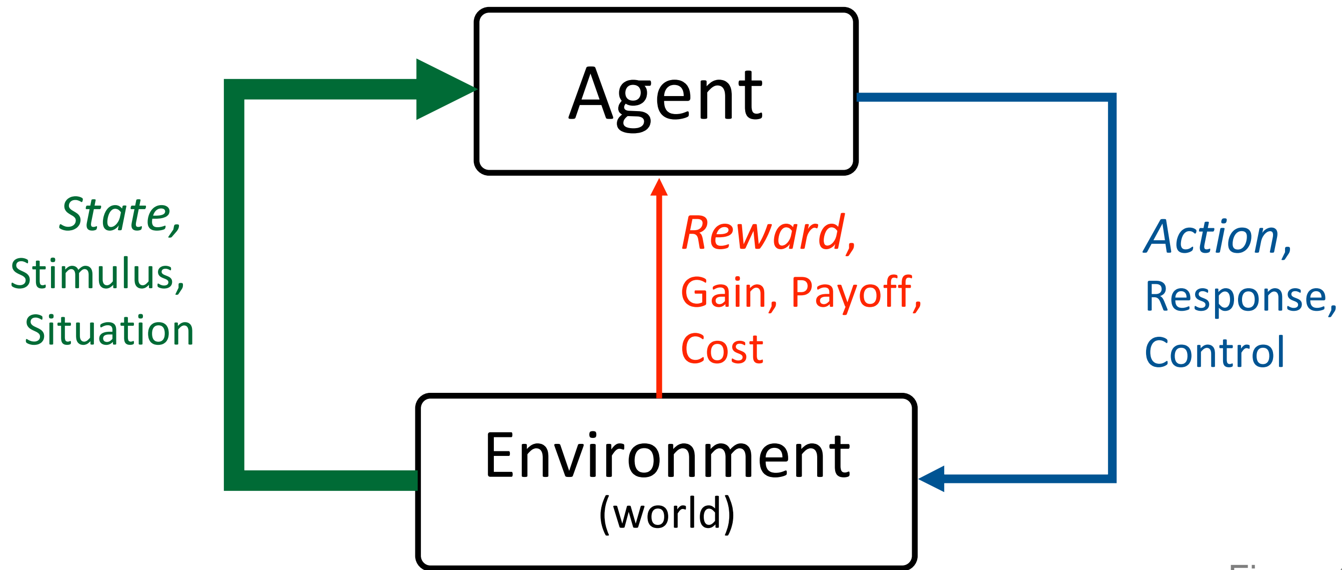


Figure Credit: Rich Sutton

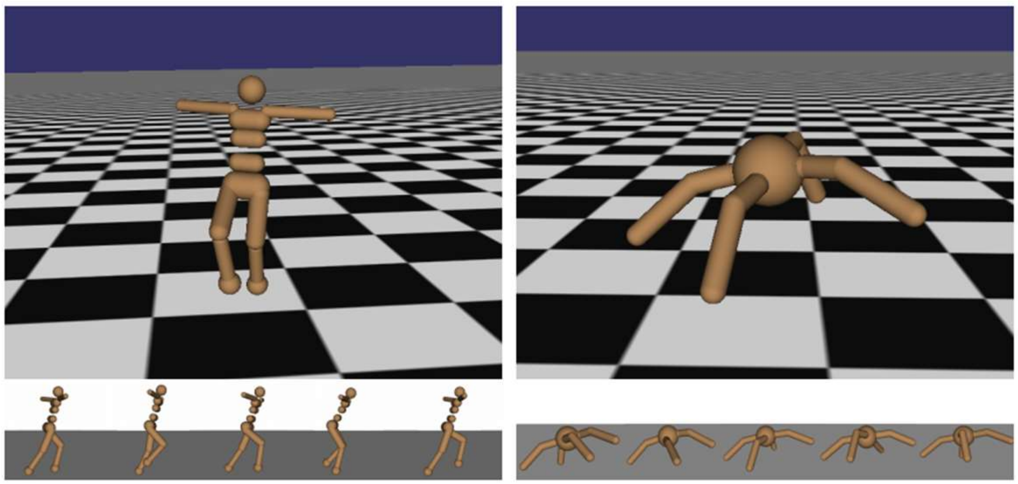
- **Environment** may be unknown, non-linear, stochastic and complex.
- **Agent** learns a **policy** to map states of the environments to actions.
  - Seeking to maximize cumulative reward in the long run.

Signature Challenges in Reinforcement Learning

- Evaluative feedback: Need trial and error to find the right action
- Delayed feedback: Actions may not lead to immediate reward
- Non-stationarity: Data distribution of visited states changes when the policy changes
- Fleeting nature of time and online data

Slide adapted from: Richard Sutton

Robot Locomotion



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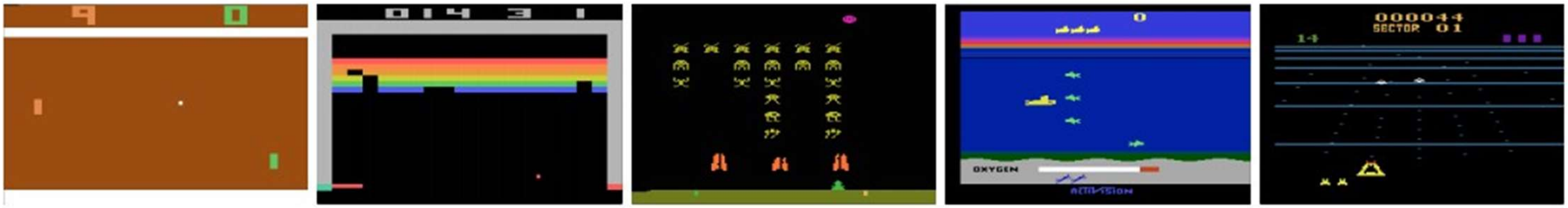
- **Objective**: Make the robot move forward
- **State**: Angle and position of the joints
- **Action**: Torques applied on joints
- **Reward**: +1 at each time step upright and moving forward

Slide Credit: Fei-Fei Li, Justin Johnson, Serena Yeung, CS 231n

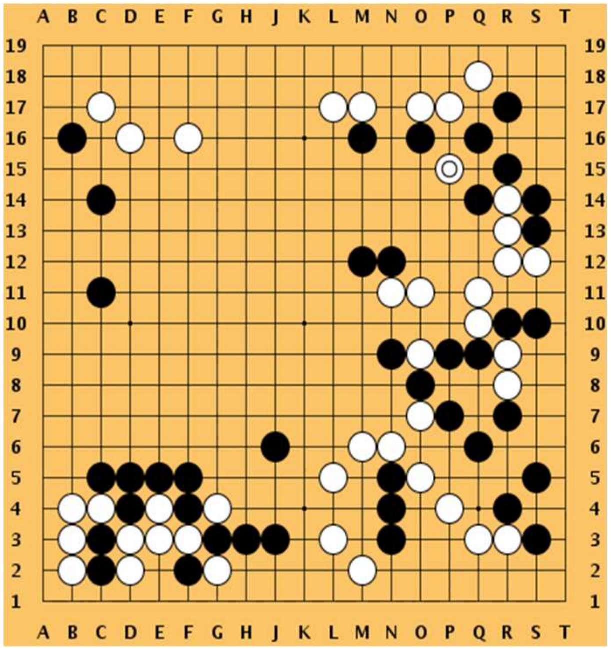
Atari Games



- **Objective**: Complete the game with the highest score
- **State**: Raw pixel inputs of the game state
- **Action**: Game controls e.g. Left, Right, Up, Down
- **Reward**: Score increase/decrease at each time step

Slide Credit: Fei-Fei Li, Justin Johnson, Serena Yeung, CS 231n

Go



- **Objective**: Defeat opponent
- **State**: Board pieces
- **Action**: Where to put next piece down
- **Reward**: +1 if win at the end of game, 0 otherwise

Slide Credit: Fei-Fei Li, Justin Johnson, Serena Yeung, CS 231n

Markov Decision Processes

- **MDPs**: Theoretical framework underlying RL

Markov Decision Processes (MDPs)

- **MDPs**: Theoretical framework underlying RL
- An MDP is defined as a tuple $(\mathcal{S}, \mathcal{A}, \mathcal{R}, \mathbb{T}, \gamma)$
  - $\mathcal{S}$: Set of possible states
  - $\mathcal{A}$: Set of possible actions
  - $\mathcal{R}(s, a, s')$: Distribution of reward
  - $\mathbb{T}(s, a, s')$: Transition probability distribution, also written as p(s'|s,a)
  - γ : Discount factor

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- **Interaction trajectory**: $\ldots s_t, a_t, r_{t+1}, s_{t+1}, a_{t+1}, r_{t+2}, s_{t+2}, \ldots$

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- **Interaction trajectory**: $\ldots s_t, a_t, r_{t+1}, s_{t+1}, a_{t+1}, r_{t+2}, s_{t+2}, \ldots$
- **Markov property**: Current state completely characterizes state of the environment
- **Assumption**: Most recent observation is a sufficient statistic of history

$$p\left(S_{t+1} = s' | S_t = s_t, A_t = a_t, S_{t-1} = s_{t-1}, \ldots S_0 = s_0\right) = p\left(S_{t+1} = s' | S_t = s_t, A_t = a_t\right)$$

Markov Decision Processes (MDPs)

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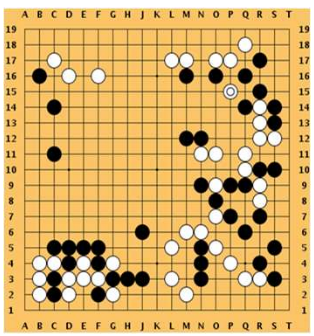
Fully observed MDP

- Agent receives the true state s_t at time t
- Example: Chess, Go



Partially observed MDP

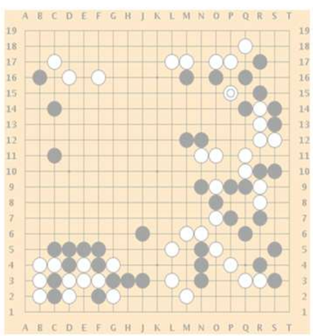
- Agent perceives its own partial observation o_t of the state s_t at time t, using past states e.g. with an RNN
- Example: Poker, First-person games (e.g. Doom)

Source: https://github.com/mwydmuch/ViZDoom

MDP Variations

Fully observed MDP

- Agent receives the true state s_t at time t
- Example: Chess, Go



Partially observed MDP

- Agent perceives its own partial observation o_t of the state s_t at time t, using past

Source: https://github.com/mwydmuch/ViZDoom

We will assume **fully observed MDPs** for this lecture

MDP Variations

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- In **Reinforcement Learning**, we assume an underlying **MDP** with unknown:
  - Transition probability distribution $\mathbb{T}$
  - Reward distribution $\mathcal{R}$

MDP
$(\mathcal{S}, \mathcal{A}, \mathcal{R}, \mathbb{T}, \gamma)$

MDPs in the context of RL

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MDP
$(\mathcal{S}, \mathcal{A}, \mathcal{R}, \mathbb{T}, \gamma)$

- Evaluative feedback comes into play, trial and error necessary

- For this lecture, assume that we know the true reward and transition distribution and look at algorithms for **solving MDPs** i.e. finding the best policy
  - Rewards known everywhere, no evaluative feedback
  - Know how the world works i.e. all transitions

MDPs in the context of RL

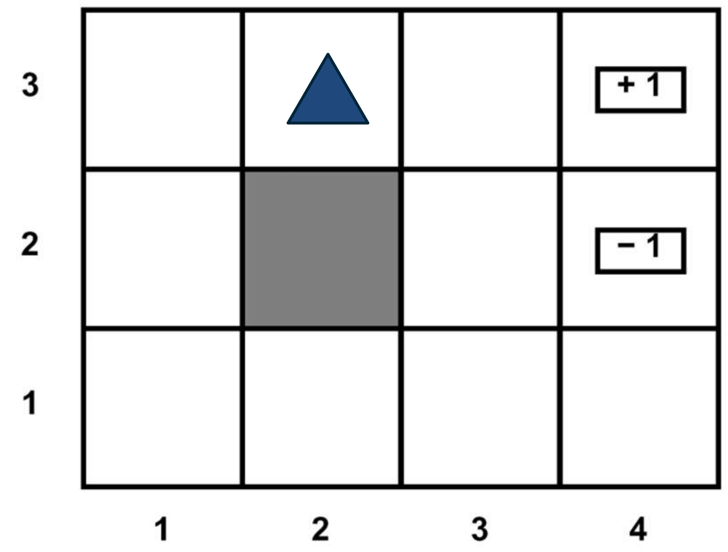


Figure credits: Pieter Abbeel

A Grid World MDP

- Agent lives in a 2D grid environment

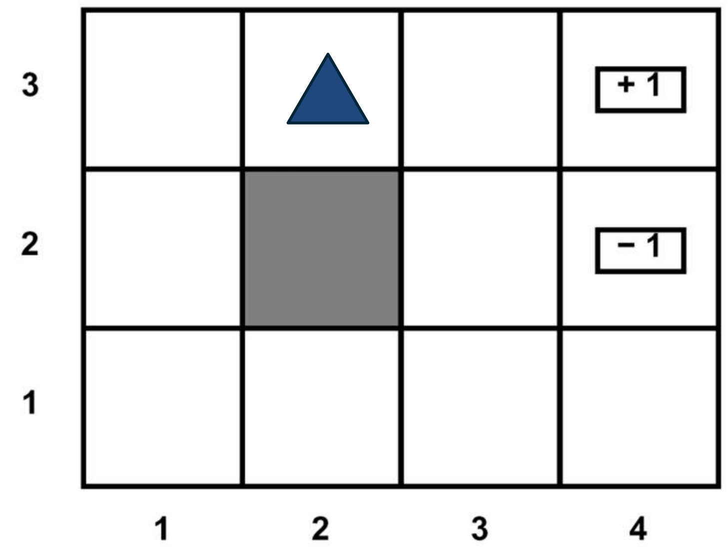
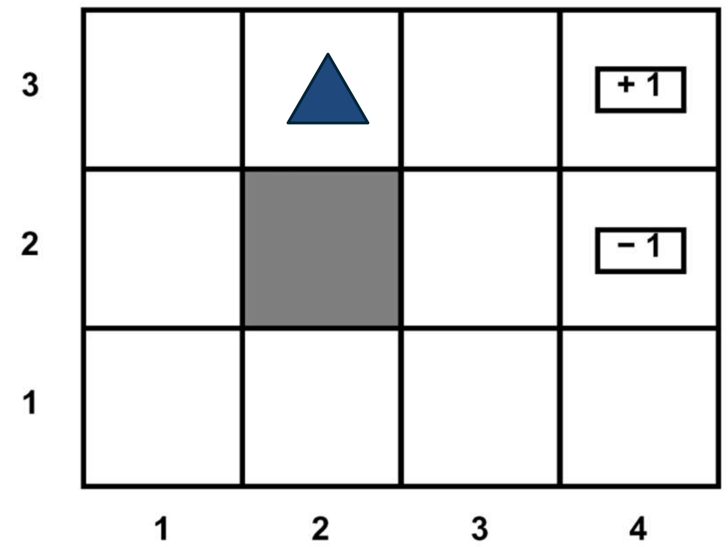


Figure credits: Pieter Abbeel

A Grid World MDP

- Agent lives in a 2D grid environment

- State: Agent's 2D coordinates
- Actions: N, E, S, W
- Rewards: +1/-1 at absorbing states



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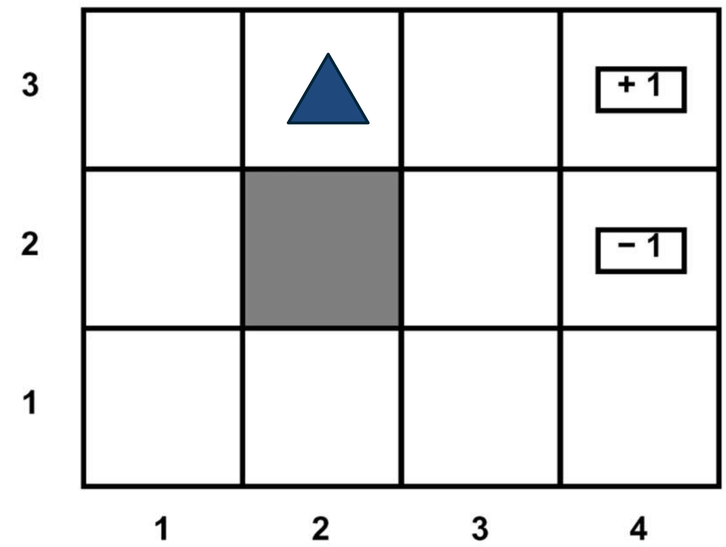
A Grid World MDP

A Grid World MDP

- Agent lives in a 2D grid environment
- State: Agent's 2D coordinates
- Actions: N, E, S, W
- Rewards: +1/-1 at absorbing states
- Walls block agent's path
- Actions to not always go as planned
  - 20% chance that agent drifts one cell left or right of direction of motion (except when blocked by wall).



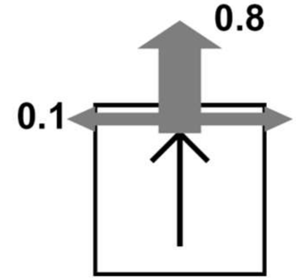


Figure credits: Pieter Abbeel

- Solving MDPs by finding the **best/optimal policy**

Solving MDPs: Optimal policy

- Solving MDPs by finding the **best/optimal policy**
- Formally, a **policy** is a mapping from states to actions

e.g.

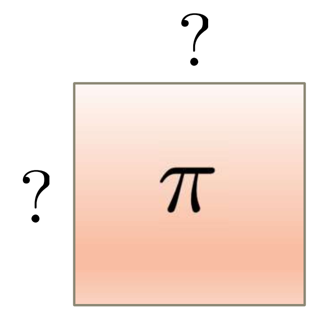
State	Action
A →	2
B →	1

Solving MDPs: Optimal policy

- Solving MDPs by finding the **best/optimal policy**

- Formally, a **policy** is a mapping from states to actions
  - Deterministic $\pi(s) = a$

$$n = |\mathcal{S}|$$
$$m = |\mathcal{A}|$$



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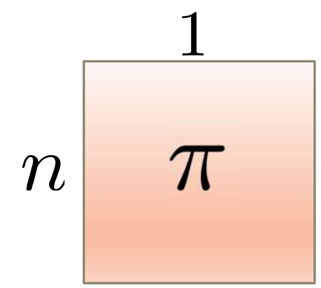

Solving MDPs: Optimal policy

- Solving MDPs by finding the **best/optimal policy**
- Formally, a **policy** is a mapping from states to actions
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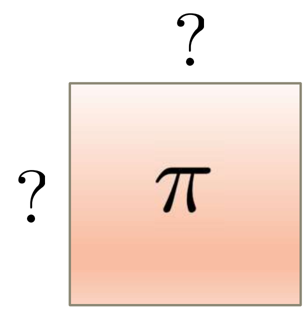

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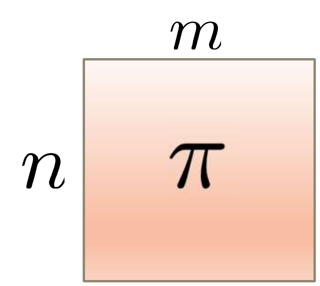

Solving MDPs: Optimal policy

- Solving MDPs by finding the **best/optimal policy**
- Formally, a **policy** is a mapping from states to actions
  - Deterministic $\pi(s) = a$
  - Stochastic $\pi(a|s) = \mathbb{P}(A_t = a | S_t = s)$
- What is a good policy?
  - Maximize **current reward**? Sum of all **future rewards**?
  - **Discounted sum of future rewards**!
    - Discount factor: γ

- Formally, the **optimal policy** is defined as:

$$\pi^* = \arg\max_{\pi} \mathbb{E}\left[\sum_{t \geq 0} \gamma^t r_t | \pi\right]$$

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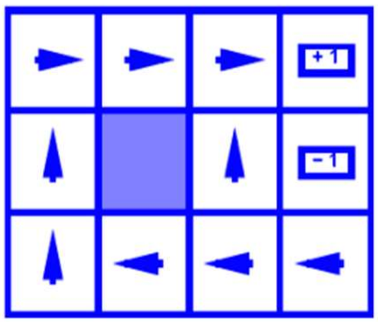
$$\boldsymbol{s}_0 \sim p\left(\boldsymbol{s}_0\right), a_t \sim \pi\left(\cdot\middle|\boldsymbol{s}_t\right), \boldsymbol{s}_{t+1} \sim p\left(\cdot\middle|\boldsymbol{s}_t, a_t\right)$$

Expectation over initial state, actions from policy,
next states from transition distribution

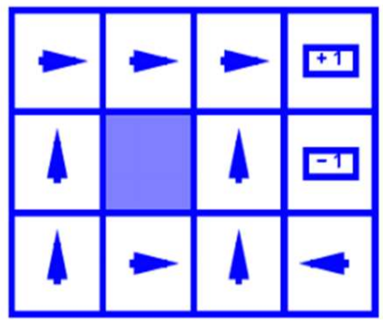
Solving MDPs: Optimal policy

Optimal policy examples

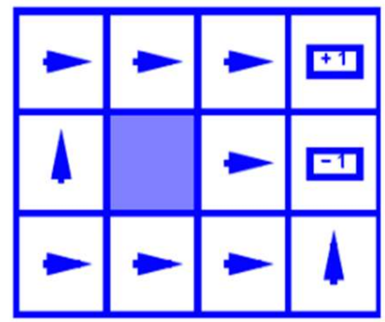
- Some optimal policies for three different grid world MDPs (gamma=0.99)
  - Varying reward for non-absorbing states (states other than +1/-1)



R(s) = -0.03



R(s) = -0.4



R(s) = -2.0

Image Credit: Byron Boots, CS 7641

- A **value function** is a prediction of discounted sum of future reward

Value Function

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- **State** value function / **V**-function / $V : \mathcal{S} \rightarrow \mathbb{R}$

Value Function

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- A **value function** is a prediction of discounted sum of future reward

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  - How good is this state?
  - Am I likely to win/lose the game from this state?

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- **State-Action** value function / **Q**-function / $Q : \mathcal{S} \times \mathcal{A} \rightarrow \mathbb{R}$

Value Function

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- **State-Action** value function / **Q**-function / $Q : \mathcal{S} \times \mathcal{A} \rightarrow \mathbb{R}$
  - How good is this state-action pair?
  - In this state, what is the impact of this action on my future?

Value Function

- For a policy that produces a trajectory sample $(s_0, a_0, s_1, a_1, s_2 \cdots)$

Value Function

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- For a policy that produces a trajectory sample $(s_0, a_0, s_1, a_1, s_2 \cdots)$

- The **V-function** of the policy at state s, is the expected cumulative reward from state s:

$$V^{\pi}(s) = \mathbb{E}\left[\sum_{t \geq 0} \gamma^t r_t | s_0 = s, \pi\right]$$

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Value Function

- For a policy that produces a trajectory sample $(s_0, a_0, s_1, a_1, s_2 \cdots)$

- The **Q-function** of the policy at state **s** and action **a**, is the expected cumulative reward upon taking action **a** in state **s** (and following policy thereafter):

Action-Value Function

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Action-Value Function

Optimal V & Q functions

- The V and Q functions corresponding to the optimal policy $\pi^\star$

$$V^*(s) = \mathbb{E}\left[\sum_{t\geq 0} \gamma^t r_t | s_0 = s, \pi^*\right]$$

$$Q^*(s,a) = \mathbb{E}\left[\sum_{t\geq 0} \gamma^t r_t | s_0 = s, a_0 = a, \pi^*\right]$$

Recursive Bellman expansion (from definition of Q)

(Expected) return from t = 0

$$Q^*(s,a) = \mathop{\mathbb{E}}_{\substack{a_t \sim \pi^*(\cdot|s_t) \\ s_{t+1} \sim p(\cdot|s_t,a_t)}} \left[\sum_{t \geq 0} \gamma^t r(s_t, a_t) \mid s_0 = s, a_0 = a \right]$$

(Reward at t = 0) + gamma * (Return from expected state at t=1)

$$= \gamma^0 r(s,a) + \mathop{\mathbb{E}}_{s' \sim p(\cdot|s,a)} \left[\gamma \mathop{\mathbb{E}}_{\substack{a_t \sim \pi^*(\cdot|s_t) \\ s_{t+1} \sim p(\cdot|s_t,a_t)}} \left[\sum_{t \geq 1} \gamma^{t-1} r(s_t, a_t) \mid s_1 = s' \right] \right]$$

$$= r(s,a) + \gamma \mathop{\mathbb{E}}_{s' \sim p(s'|s,a)} [V^*(s')]$$

$$= \mathop{\mathbb{E}}_{s' \sim p(s'|s,a)} [r(s,a) + \gamma V^*(s')]$$

- Equations relating optimal quantities

$$V^*(s) = \max_a Q^*(s,a)$$

$$\pi^*(s) = \arg\max_a Q^*(s,a)$$

- Recursive Bellman optimality equation

$$\begin{aligned} Q^*(s,a) &= \mathop{\mathbb{E}}_{s' \sim p(s'|s,a)} \left[r(s,a) + \gamma V^*(s) \right] \\ &= \sum_{s'} p(s'|s,a) \left[r(s,a) + \gamma V^*(s) \right] \\ &= \sum_{s'} p(s'|s,a) \left[r(s,a) + \gamma \max_a Q^*(s',a') \right] \end{aligned}$$

Bellman Optimality Equations

- Equations relating optimal quantities

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$$V^*(s) = \max_a \sum_{s'} p(s'|s,a) \left[r(s,a) + \gamma V^*(s') \right]$$

Bellman Optimality Equations

Based on the **bellman optimality equation**

$$V^*(s) = \max_a \sum_{s'} p(s'|s,a)\left[r(s,a) + \gamma V^*(s')\right]$$

Algorithm

- Initialize values of all states
- While not converged:
  - For each state: $V^{i+1}(s) \leftarrow \max_a \sum_{s'} p(s'|s,a)\left[r(s,a) + \gamma V^i(s')\right]$
- Repeat until convergence (no change in values)

$$V^0 \rightarrow V^1 \rightarrow V^2 \rightarrow \quad \cdots \rightarrow V^i \rightarrow \ldots \quad \rightarrow V^*$$

Time complexity per iteration $O(|\mathcal{S}|^2|\mathcal{A}|)$

Value Iteration

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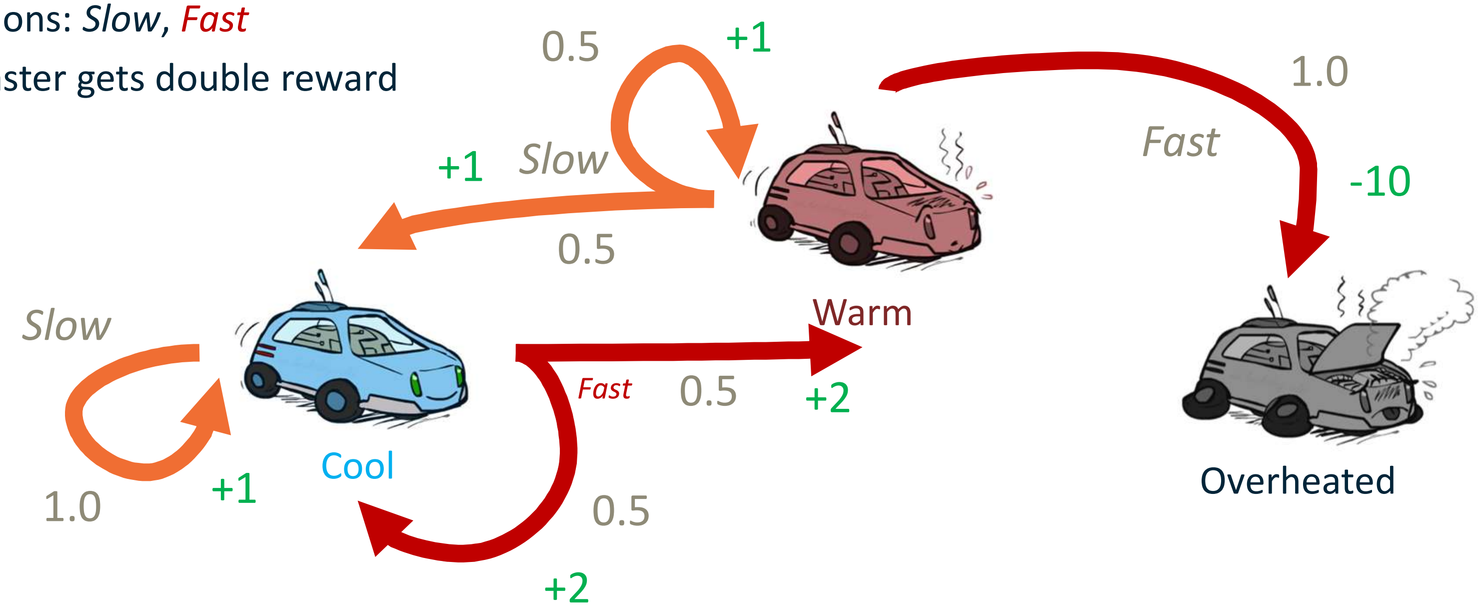
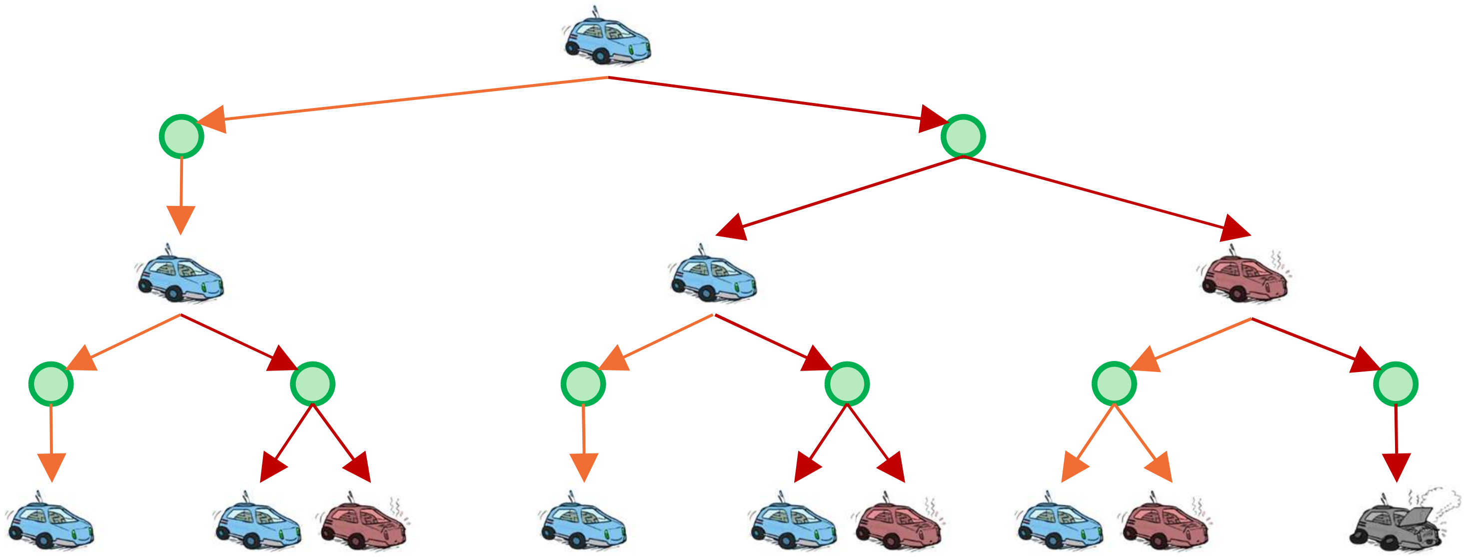
Example: Racing

- A robot car wants to travel far, quickly
- Three states: Cool, Warm, Overheated
- Two actions: *Slow*, *Fast*
- Going faster gets double reward



Slide Credit: http://ai.berkeley.ed



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Racing Search Tree

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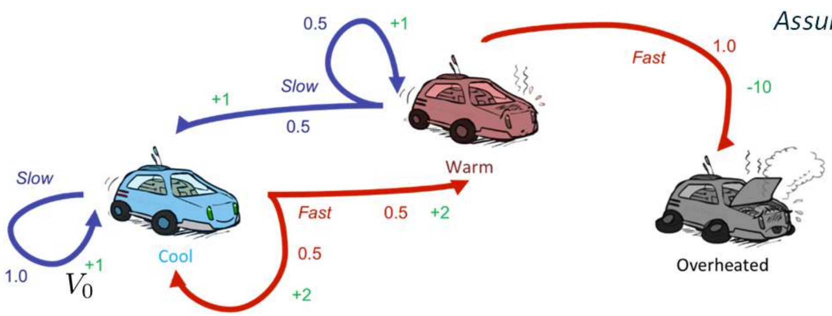
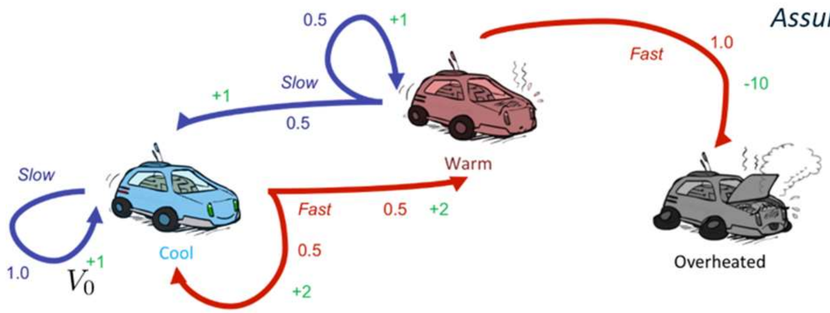


Assume no discount!

$$V_{k+1}(s) \leftarrow \max_a \sum_{s'} T(s,a,s') \left[R(s,a,s') + \gamma V_k(s')\right]$$

	Cool	Warm	Overheated
V_2	3.5	2.5	0
V_1	2	1	0
	0	0	0



V_0

Assume no discount!

V_2:

V_1: 2

0 0 0

$$V_{k+1}(s) \leftarrow \max_a \sum_{s'} T(s,a,s') \left[R(s,a,s') + \gamma V_k(s') \right]$$

$V_1(S_0) = \max\big($ slow: $[1.0 \cdot (+1 + V(S_0))] = 1$,

Fast: $0.5\,[+2 + V(S_1)] + 0.5\,(+2 \cdot V(S_0))]\big) = 2$

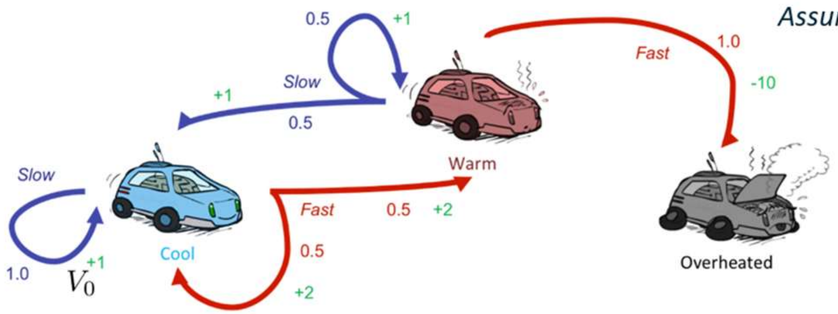
$= 2$

Slide Credit: http://ai.berkeley.edu

Racing Search Tree

Georgia Tech

Racing Search Tree



Assume no discount!

V_2	3.5	2.5	0
V_1	2	1	0
V_0	0	0	0

$$V_{k+1}(s) \leftarrow \max_a \sum_{s'} T(s,a,s') \left[R(s,a,s') + \gamma V_k(s') \right]$$

$$V_2(s_0) = \max \Big[\underbrace{1 \cdot (+1 + V_1(s_0))}_{\text{slow}} = 3, \quad \underbrace{0.5(+2 + V_1(s_0)) + 0.5(+2 + V_1(s_1))}_{\text{fast}} = 3.5 \Big] = 3.5$$

($V_1(s_0) = 2$, $V_1(s_1) = 1$)

Slide Credit: http://ai.berkeley.edu

Value Iteration Update:

$$V^{i+1}(s) \leftarrow \max_a \sum_{s'} p(s'|s,a)\left[r(s,a) + \gamma V^i(s')\right]$$

Q-Iteration Update:

$$Q^{i+1}(s,a) \leftarrow \sum_{s'} p\left(s'|s,a\right)\left[r\left(s,a\right) + \gamma \max_{a'} Q^i(s',a')\right]$$

The algorithm is same as value iteration, but it loops over actions as well as states

Q-Iteration

For **Value Iteration**:

Theorem: will converge to unique optimal values

Basic idea: approximations get refined towards optimal values

Policy may converge long before values do

Time complexity per iteration $O(|\mathcal{S}|^2|\mathcal{A}|)$

Feasible for:

- 3x4 Grid world?
- Chess/Go?
- Atari Games with integer image pixel values [0, 255] of size 16x16 as state?

Summary: MDP Algorithms

Value Iteration

- Bellman update to state value estimates

Q-Value Iteration

- Bellman update to (state, action) value estimates

Reinforcement Learning, Deep RL

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- Recall RL assumptions:
  - $\mathbb{T}(s, a, s')$ unknown, how actions affect the environment.
  - $\mathcal{R}(s, a, s')$ unknown, what/when are the good actions?
- But, we can learn by trial and error.
  - Gather experience (data) by performing actions.
  - Approximate unknown quantities from data.

Reinforcement Learning

- Old Dynamic Programming Demo
  - https://cs.stanford.edu/people/karpathy/reinforcejs/gridworld_dp.html
- RL Demo
  - https://cs.stanford.edu/people/karpathy/reinforcejs/gridworld_td.html

Slide credit: Dhruv Batra

Q-Learning

- We'd like to do Q-value updates to each Q-state:

$$Q_{k+1}(s,a) \leftarrow \sum_{s'} T(s,a,s') \left[R(s,a,s') + \gamma \max_{a'} Q_k(s',a') \right]$$

  - But can't compute this update without knowing T, R

- Instead, compute average as we go
  - Receive a sample transition (s,a,r,s')
  - This sample suggests

$$Q(s,a) \approx r + \gamma \max_{a'} Q(s',a')$$

  - But we want to average over results from (s,a)
  - So keep a running average

$$Q(s,a) \leftarrow (1-\alpha)Q(s,a) + (\alpha) \left[r + \gamma \max_{a'} Q(s',a') \right]$$

Q-Learning Properties

- Amazing result: Q-learning converges to optimal policy -- even if you're acting suboptimally!
- This is called off-policy learning
- Caveats:
  - You have to explore enough
  - You have to eventually make the learning rate small enough
  - … but not decrease it too quickly
  - Basically, in the limit, it doesn't matter how you select action