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ELEC-E8125 Reinforcement Learning
Solving discrete MDPs

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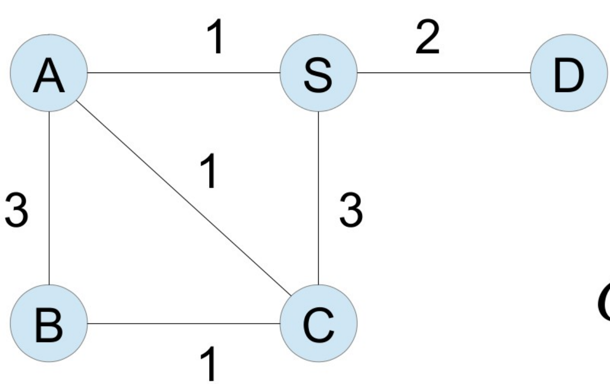
Previous lecture: find shortest path exercise

- Use backward value iteration for

Initial start state → $s_I = S$

Goal set → $S_G = \{B\}$

Final cost → $l_F(s) = \begin{cases} 0, & s \in S_G \\ \infty, & s \notin S_G \end{cases}$



Reminder:

$$G^*(s) = min_a \{ l(s,a) + G^*(f(s,a)) \}$$

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Hints: Moving from A to B costs $l(A, A \rightarrow B) = 3$. Arriving at final state B costs $l_F(B) = 0$. Arriving at final state C costs $l_F(C) = \infty$. When moving from C to B we arrive at B: $B = f(C, C \rightarrow B)$

Today

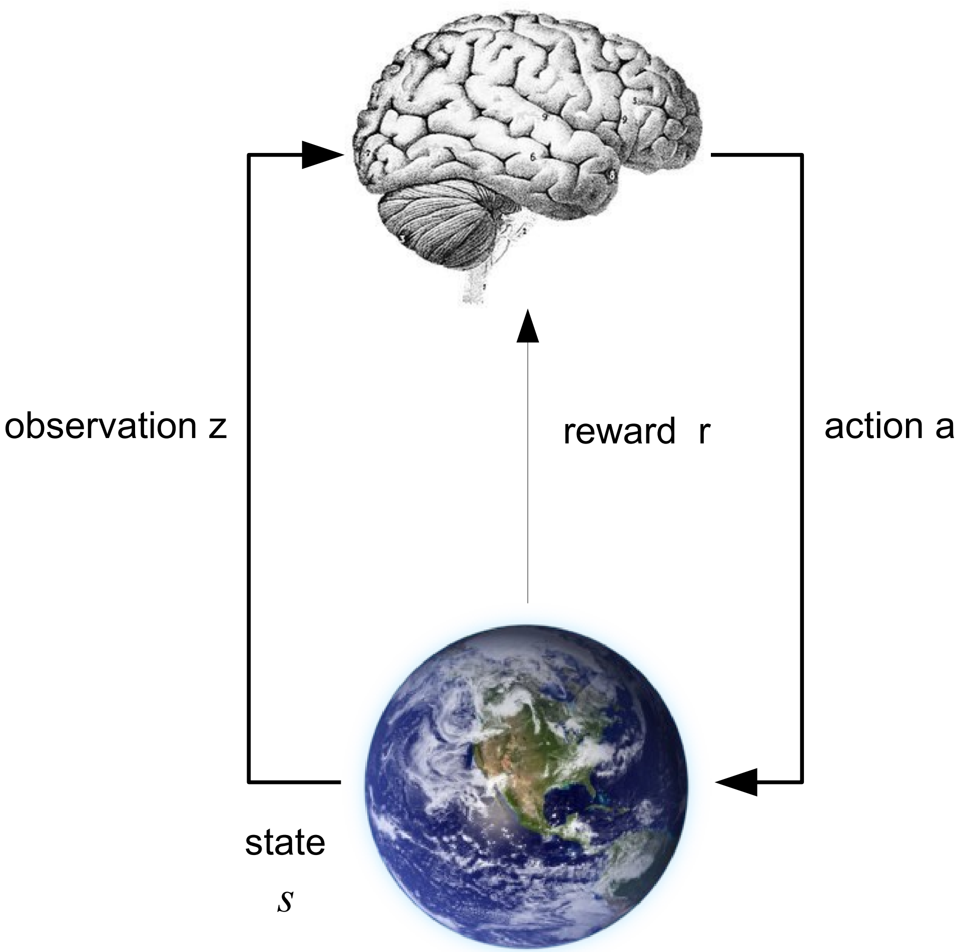
- Markov decision processes (MDPs)

Learning goals

- Understand MDPs and related concepts
- Understand value functions

- Be able to implement value iteration for determining an optimal policy (in exercise #2, you will get to do this for real)

Markov decision process (MDP)



MDP
Environment observable
$z = s$

Defined by dynamics
$P(s_{t+1} | s_t, a_t)$

And reward function
$r_t = r(s_t, a_t)$

Solution, for example
$a^*_{1,\ldots,T} = \arg\max_{a_1,\ldots,a_T} \sum_{t=1}^{T} r_t$

Represented as policy
$a = \pi(s)$

Let's discuss MDPs in more detail

Markov property

Andrey Markov

- "Future is independent of past given the present"
- State sequence *S* is Markov iff ← "if and only if"

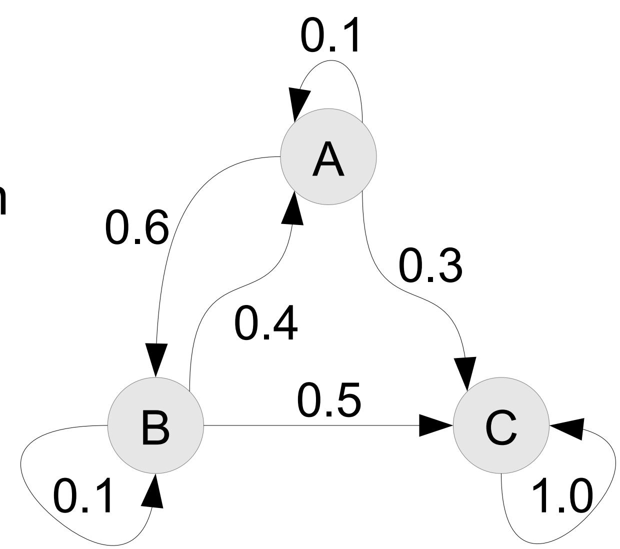
$$P\left(S_{t+1} \middle| S_t\right) = P\left(S_{t+1} \middle| S_1, \ldots, S_t\right)$$

- State captures all history
- Once state is known, history may be thrown away

Markov process

No “decision” here!

- Markov process is a memoryless random process that generates a state sequence *S* with the Markov property
- Defined as *(S,T)*
  - *S:* set of states
  - *T*: S x *S* → *[0,1]* state transition function
    - $T_t(s,s')=P(s_{t+1}=s'|s_t=s)$
    - *P* can be represented as a transition probability matrix
- State sequences called *episodes*



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How to calculate probability of a particular episode?
Starting from A, what is the probability of A,B,C?

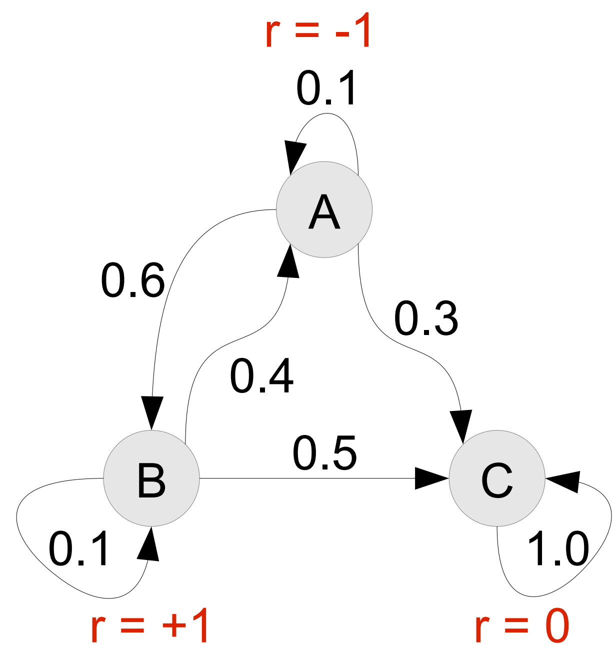
Markov reward process

Still no "decision"!

- Markov reward process = Markov process with rewards
- Defined by (S, *T*, *r*, γ)
  - *S*, *T* : as above
  - $r : S \to \Re$ reward function
  - $\gamma \in [0, 1]$ discount factor
- Accumulated rewards in finite (*H* steps) or infinite horizon

$$\sum_{t=0}^{H} \gamma^t r_t \qquad \sum_{t=0}^{\infty} \gamma^t r_t$$

- *Return G*: accumulated rewards from time t



$$G_t = \sum_{k=0}^{H} \gamma^k r_{t+k}$$

Why discount?

Return of (A,B,C), γ = 0.9?

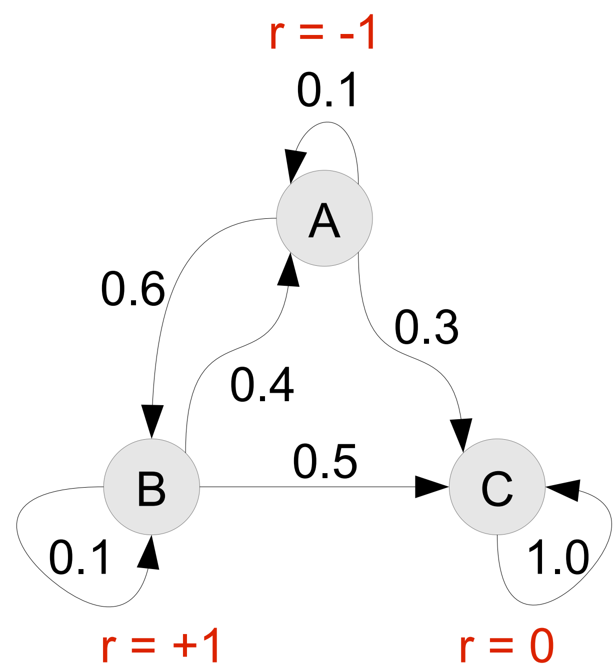
State value function for Markov reward processes

- State value function *V(s)* is expected cumulative reward starting from state *s*

$$V(s) = E[G_t | s_t = s]$$

- Value function can be defined by the Bellman equation

$$V(s) = E[G_t | s_t = s]$$
$$V(s) = E[r_t + \gamma V(s_{t+1}) | s_t = s]$$



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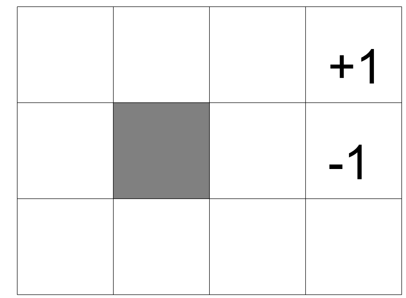
What is the value function for γ = 0?

What is the value function for γ = 0.5 after a single Bellman update when starting with zero values?

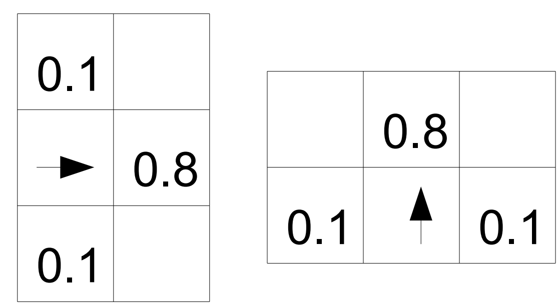
Markov decision process (MDP)

- Markov decision process defined by (*S, A, T, R,* γ)
  - *S,* γ : as above
  - *A:* set of actions (inputs)
  - *T: S x A x S* $\rightarrow$ *[0,1]*
    $T_t(s,a,s')=P(s_{t+1}=s'|s_t=s,\, a_t=a)$
  - *R: S x A* $\rightarrow \Re$ reward function
    $r_t(s,a)=r(s_t=s,\, a_t=a)$
- Goal: Find policy π*(s)* that maximizes expected cumulative reward

Grid world



Agent tries to move forward:
P(success) = 0.8
P(left) = 0.1
P(right) = 0.1



Grid world example!

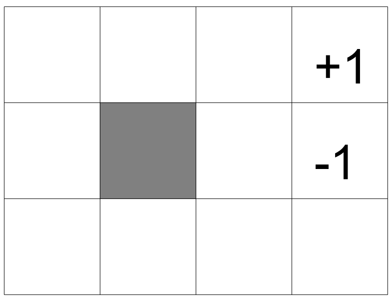
Policy

- Deterministic policy $\pi(S)$: $S \rightarrow A$ is a mapping from states to actions

- Stochastic policy $\pi(a|s)$: $S,A \rightarrow [0,1]$ is a distribution over actions given states

- Optimal policy $\pi^*(s)$ is a policy that is better or equal than any other policy (in terms of cumulative rewards)
  - There always exists a deterministic optimal policy for an MDP

Grid world



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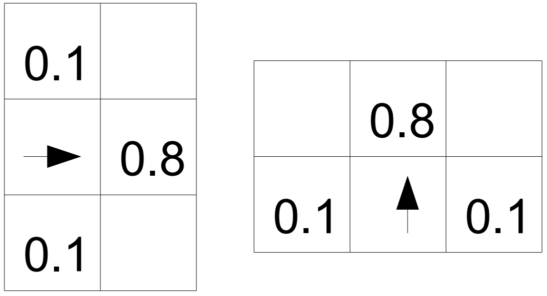
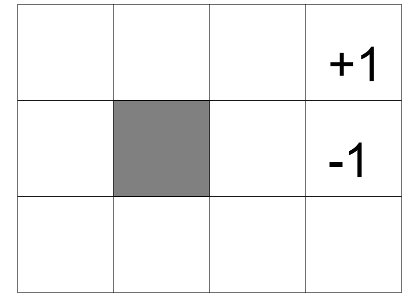


What is the optimal policy in the grid world?

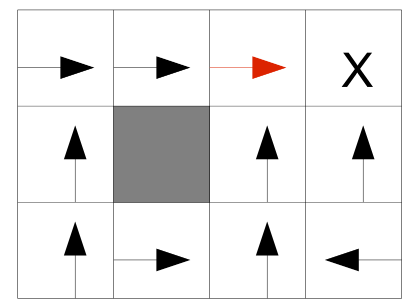
MDP value function



- *State-value function* of an MDP is the expected return starting from state *s* and following policy π

$$V_\pi(s) = E_\pi[G_t | s_t = s]$$

- Can be decomposed into immediate and future components using Bellman expectation equation

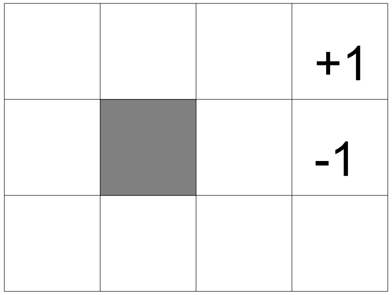


$$V_\pi(s) = E_\pi[r_t + \gamma V_\pi(s_{t+1}) | s_t = s]$$

$$V_\pi(s) = r(s, \pi(s)) + \gamma \sum_{s'} T(s, \pi(s), s') V_\pi(s')$$

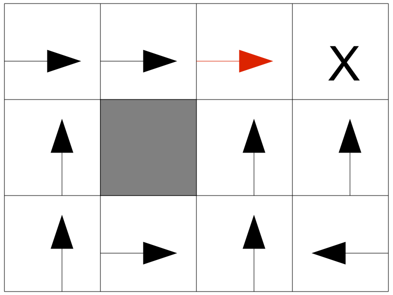
What is value function here?

Action-value function



- *Action-value function Q* is expected return starting from state *s*, taking action *a*, and then following policy π

$$Q_\pi(s,a)=E_\pi[G_t|s_t=s,a_t=a]$$



- Using Bellman expectation equation

$$Q_\pi(s,a)=E_\pi[r_t+\gamma Q_\pi(s_{t+1},a_{t+1}|s_t=s,a_t=a)]$$

$$Q_\pi(s,a)=r(s,a)+\gamma\sum_{s'}T(s,a,s')Q_\pi(s',\pi(s'))$$

Optimal value function

- Optimal state-value function is maximum value function over all policies

$$V^*(s) = max_\pi V_\pi(s)$$

- Optimal action-value function is maximum action-value function over all policies

$$Q^*(s,a) = max_\pi Q_\pi(s,a)$$

- All optimal policies achieve optimal state- and action-value functions

What is the optimal action if we know Q^*?
What about V^*?

Optimal policy vs optimal value function

- Optimal policy for optimal action-value function

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

- Optimal action for optimal state-value function

$$\pi^*(s) = arg\,max_a E_{s'}[r(s,a) + \gamma V^*(s')]$$

$$\pi^*(s) = arg\,max_a \left(r(s,a) + \gamma \sum_{s'} T(s,a,s') V^*(s') \right)$$

Value iteration

Do you notice that this is an expectation?

- Starting from $V_0^*(s) = 0 \quad \forall s$

  iterate

  $$V_{i+1}^*(s) = max_a \left(r(s,a) + \gamma \sum_{s'} T(s,a,s') V_i^*(s') \right)$$

  until convergence

- Value iteration converges to *V*(s)*

Compare to

$$G^*(s) = min_a \{ l(s,a) + G^*(f(s,a)) \}$$

from last week!

Iterative policy evaluation

- Problem: Evaluate value of policy π
- Solution: Iterate Bellman expectation back-ups
- $V_1 \rightarrow V_2 \rightarrow \ldots \rightarrow V_\pi$
- Using synchronous back-ups:
  - For all states *s*
  - Update $V_{k+1}(s)$ from $V_k(s')$
  - Repeat

From slide 12

$$V_{k+1}(s) = r(s, \pi(s)) + \gamma \sum_{s'} T(s, \pi(s), s') V_k(s')$$

$$V_{k+1}(s) = \sum_a \pi(a|s) \left(r(s,a) + \gamma \sum_{s'} T(s,a,s') V_k(s') \right)$$

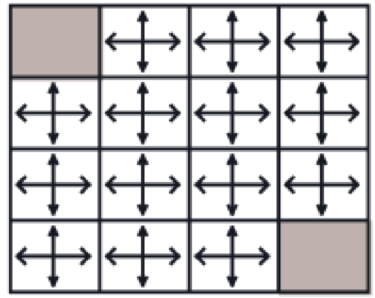
Note: Starting point can be random policy

V

Greedy policy

$k = 0$

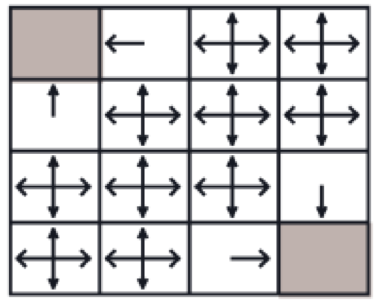
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0



	1	2	3
4	5	6	7
8	9	10	11
12	13	14	

$k = 1$

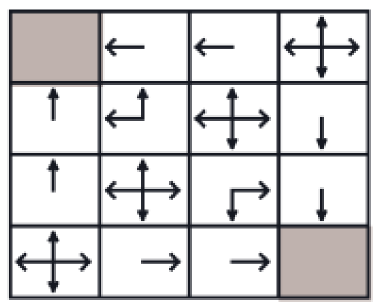
0.0	-1.0	-1.0	-1.0
-1.0	-1.0	-1.0	-1.0
-1.0	-1.0	-1.0	-1.0
-1.0	-1.0	-1.0	0.0



r = -1 for all actions

$k = 2$

0.0	-1.7	-2.0	-2.0
-1.7	-2.0	-2.0	-2.0
-2.0	-2.0	-2.0	-1.7
-2.0	-2.0	-1.7	0.0



Policy improvement and policy iteration

- Given a policy π, it can be improved by
  - Evaluating V_π
  - Forming a new policy by acting greedily with respect to V_π

- This always improves the policy

- Iterating multiple times called *policy* iteration
  - Converges to optimal policy

Computational limits – Value iteration

- Complexity $O(|A||S|^2)$ per iteration
- Effective up to medium size problems (millions of states)

- Complexity when applied to action-value function $O(|A|^2|S|^2)$ per iteration

Summary

- Markov decision processes represent environments with uncertain dynamics
- Deterministic optimal policies can be found using state-value or action-value functions
- Dynamic programming is used in value iteration and policy iteration algorithms

Next week: From MDPs to RL

- Readings
  - Sutton & Barto Ch. 5-5.4, 5.6, 6-6.5