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Deep Reinforcement Learning

2022-23 Second Semester, M.Tech (AIML)

Session #4:
Markov Decision Processes

Instructors :

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Agenda for the class

- Agent-Environment Interface (Sequential Decision Problem)
- MDP

  Defining MDP,
  Rewards,
  Returns, Policy & Value Function,
  Optimal Policy and Value Functions
- Approaches to solve MDP

Announcement !!!

We have our Teaching Assistants now !!!

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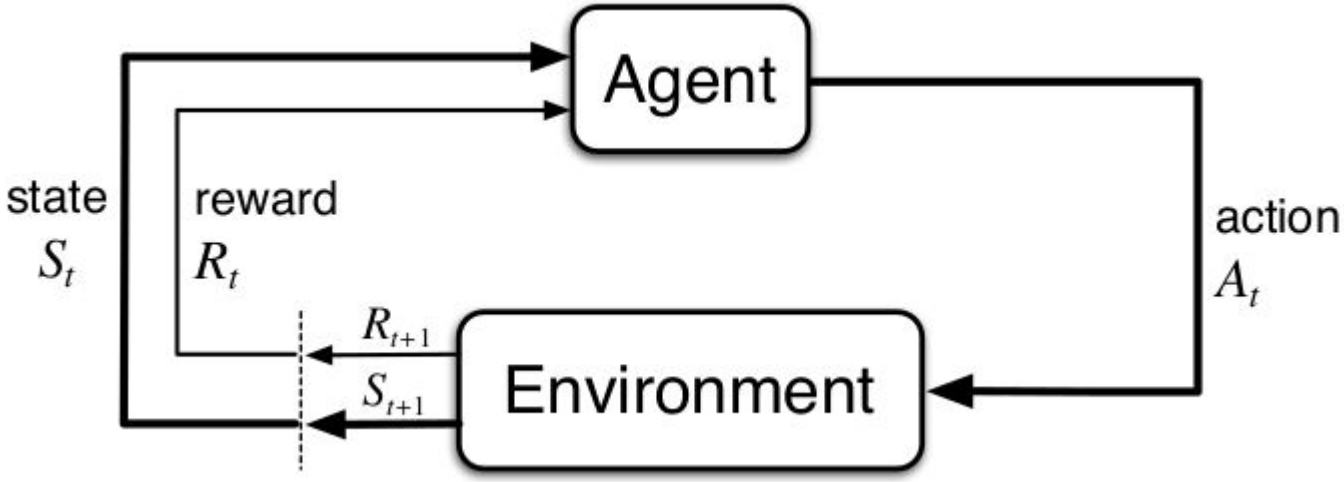
Acknowledgements: Some of the slides were adopted *with permission* from the course CSCE-689 (Texas A&M University) by Prof. Guni Sharon

Agent-Environment Interface

- Agent - Learner & the decision maker
- Environment - Everything outside the agent
- Interaction:
  - Agent performs an action
  - Environment responds by
    - presenting a new situation (change in state)
    - presents numerical reward
- Objective (of the interaction):
  - Maximize the return (cumulative rewards) over time



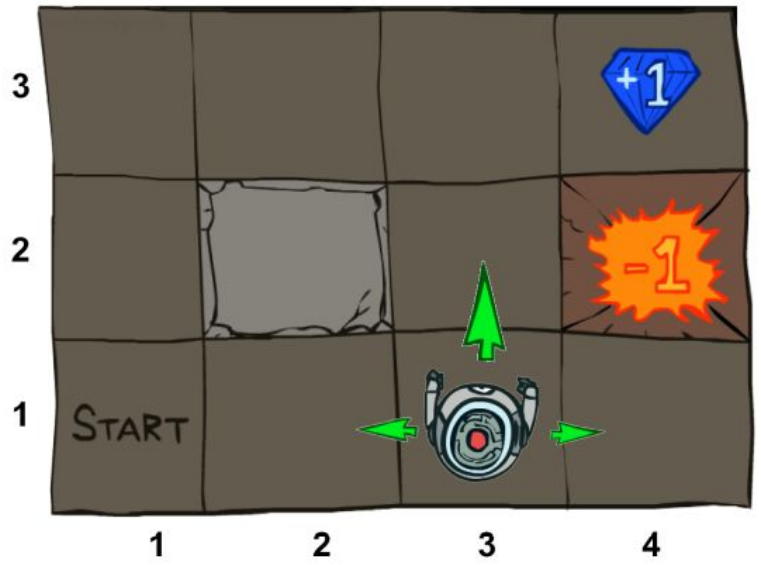
Note:

- Interaction occurs in discrete time steps

$$S_0, A_0, R_1, S_1, A_1, R_2, S_2, A_2, R_3, \ldots$$

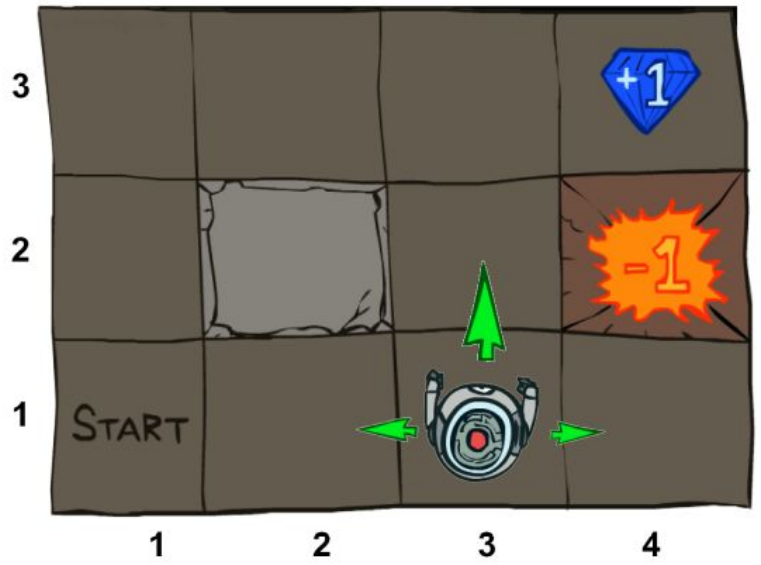
Grid World Example

- A maze-like problem
  - The agent lives in a grid
  - Walls block the agent's path
- Noisy movement: actions do not always go as planned
  - 80% of the time, the action North takes the agent North (if there is no wall there)
  - 10% of the time, North takes the agent West; 10% East
  - If there is a wall in the direction the agent would have been taken, the agent stays put
- The agent receives rewards each time step
  - -0.1 per step (battery loss)
  - +1 if arriving at (4,3) ; -1 for arriving at (4,2) ;1 for arriving at (2,2)
- Goal: maximize accumulated rewards



Markov Decision Processes

- An MDP is defined by
  - A set of states
  - A set of actions
  - State-transition probabilities
    - Probability of arriving to after performing at
    - Also called the model dynamics
  - A reward function
    - The utility gained from arriving to after performing at
    - Sometimes just or even
  - A start state
  - Maybe a terminal state



Markov Decision Processes

Model Dynamics

$$p(s', r \mid s, a) \doteq \Pr\{S_t = s', R_t = r \mid S_{t-1} = s, A_{t-1} = a\}$$

State-transition probabilities

$$p(s' \mid s, a) \doteq \Pr\{S_t = s' \mid S_{t-1} = s, A_{t-1} = a\} = \sum_{r \in \mathcal{R}} p(s', r \mid s, a)$$

Expected rewards for state–action–next-state triples

$$r(s, a, s') \doteq \mathbb{E}[R_t \mid S_{t-1} = s, A_{t-1} = a, S_t = s'] = \sum_{r \in \mathcal{R}} r \frac{p(s', r \mid s, a)}{p(s' \mid s, a)}$$

Markov Decision Processes - Discussion

- *MDP framework is abstract and flexible*
  - Time steps need not refer to fixed intervals of real time
  - The actions can be
    - at low-level controls or high-level decisions
    - totally mental or computational
  - States can take a wide variety of forms
    - Determined by *low-level sensations* or *high-level and abstract* (ex. symbolic descriptions of objects in a room)
- *The agent–environment boundary represents the limit of the agent's absolute control*, not of its knowledge.
  - *The boundary can be located at different places for different purposes*

Markov Decision Processes - Discussion

- *MDP framework is a considerable abstraction of the problem of goal-directed learning from interaction.*
- It proposes that *whatever the details of the sensory, memory, and control apparatus, and whatever objective one is trying to achieve, any problem of learning goal-directed behavior can be reduced to three signals passing back and forth between an agent and its environment:*
  - *one signal to represent the choices made by the agent (the actions)*
  - *one signal to represent the basis on which the choices are made (the states),*
  - *and one signal to define the agent's goal (the rewards).*

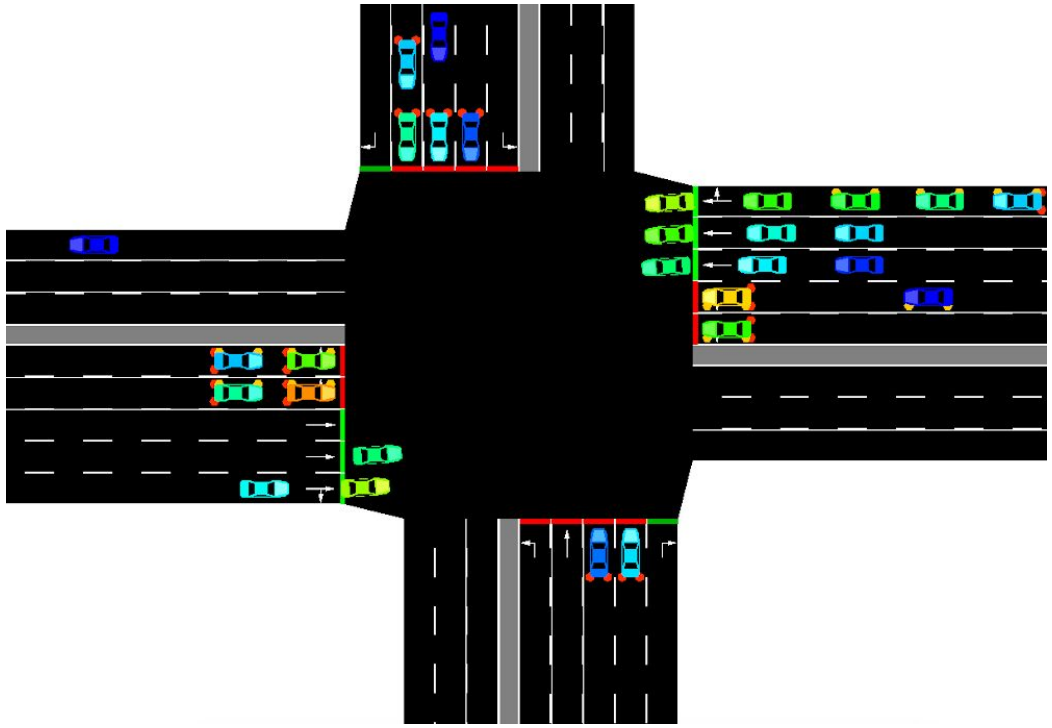
MDP Formalization : Video Games

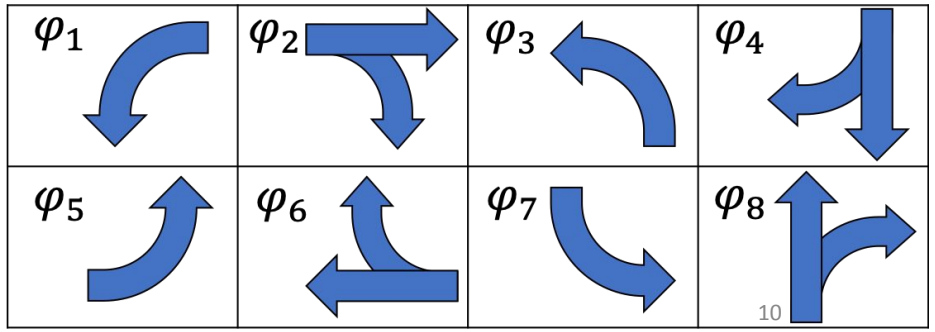
- *State:*
  - *raw pixels*
- *Actions:*
  - *game controls*
- *Reward:*
  - *change in score*
- *State-transition probabilities:*
  - *defined by stochasticity in game evolution*

Ref: Playing Atari with deep reinforcement learning", Mnih et al., 2013

MDP Formalization : Traffic Signal Control

- *State:*
  - *Current signal assignment (green, yellow, and red assignment for each phase)*
  - *For each lane: number of approaching vehicles, accumulated waiting time, number of stopped vehicles, and average speed of approaching vehicles*
- *Actions:*
  - *signal assignment*
- *Reward:*
  - *Reduction in traffic delay*
- *State-transition probabilities:*
  - *defined by stochasticity in approaching demand*





Ref: "Learning an Interpretable Traffic Signal Control Policy", Ault et al., 2020

MDP Formalization : Recycling Robot (Detailed Ex.)

- *Robot has*
  - *sensors for detecting cans*
  - *arm and gripper that can pick the cans and place in an onboard bin;*
- *Runs on a rechargeable battery*
- *Its control system has components for interpreting sensory information, for navigating, and for controlling the arm and gripper*
- *Task for the RL Agent: Make high-level decisions about how to search for cans based on the current charge level of the battery*

MDP Formalization : Recycling Robot (Detailed Ex.)

- *State:*
  - *Assume that only two charge levels can be distinguished*
  - *S = {high, low}*
- *Actions:*
  - *A(high) = {search, wait}*
  - *A(low) = {search, wait, recharge}*
- *Reward:*
  - *Zero most of the time, except when securing a can*
  - *Cans are secured by searching and waiting, but* $r_{search} > r_{wait}$
- *State-transition probabilities:*
  - *[Next Slide]*

MDP Formalization : Recycling Robot (Detailed Ex.)

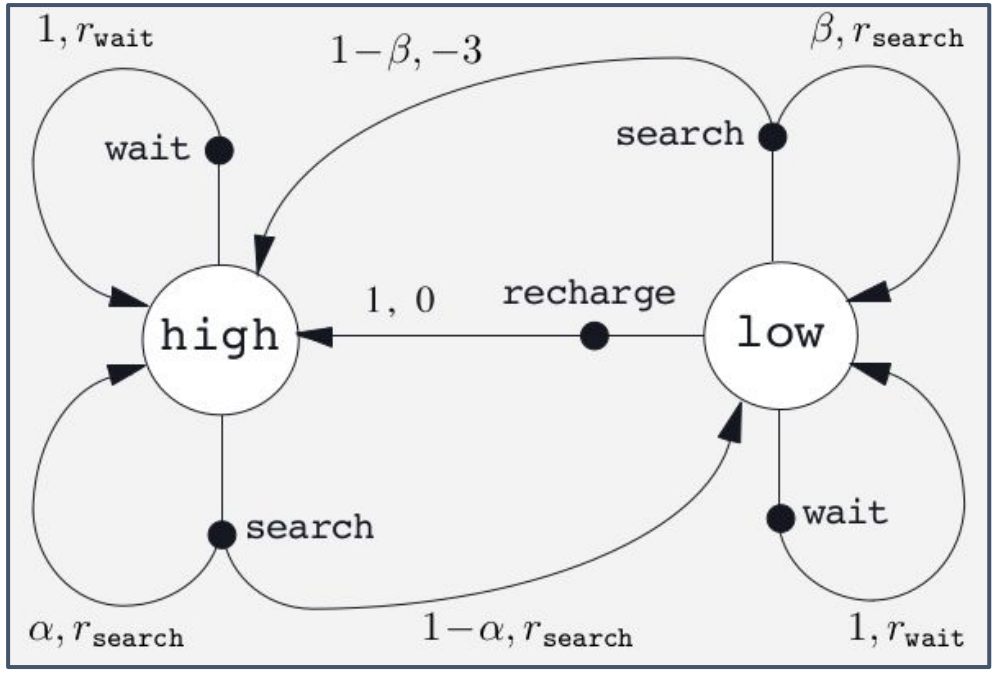
- *State-transition probabilities (contd…):*

s	a	s'	$p(s'\|s,a)$	$r(s,a,s')$
high	search	high	α	r_{search}
high	search	low	$1-\alpha$	r_{search}
low	search	high	$1-\beta$	-3
low	search	low	β	r_{search}
high	wait	high	1	r_{wait}
high	wait	low	0	-
low	wait	high	0	-
low	wait	low	1	r_{wait}
low	recharge	high	1	0
low	recharge	low	0	-

MDP Formalization : Recycling Robot (Detailed Ex.)

- *State-transition probabilities (contd…):*

s	a	s'	$p(s' \mid s, a)$	$r(s, a, s')$
high	search	high	α	r_{search}
high	search	low	$1-\alpha$	r_{search}
low	search	high	$1-\beta$	-3
low	search	low	β	r_{search}
high	wait	high	1	r_{wait}
high	wait	low	0	-
low	wait	high	0	-
low	wait	low	1	r_{wait}
low	recharge	high	1	0
low	recharge	low	0	-



Note on Goals & Rewards

- *Reward Hypothesis:*

  All of what we mean by goals and purposes can be well thought of as the maximization of the expected value of the cumulative sum of a received scalar signal (called reward).

- *The rewards we set up truly indicate what we want accomplished,*
  - *not the place to impart prior knowledge on how we want it to do*
- *Ex: Chess Playing Agent*
  - *If the agent is rewarded for taking opponents pieces, the agent might fall for the opponent's trap.*
- *Ex: Vacuum Cleaner Agent*
  - *If the agent is rewarded for each unit of dirt it sucks, it can repeatedly deposit and suck the dirt for larger reward*

Returns & Episodes

- *Goal is to maximize the expected return*
- *Return (Gt) is defined as some specific function of the reward sequence*
- *Episodic tasks vs. Continuing tasks*
- *When there is a notion of final time step, say T, return can be*

$$G_t \doteq R_{t+1} + R_{t+2} + R_{t+3} + \cdots + R_T$$

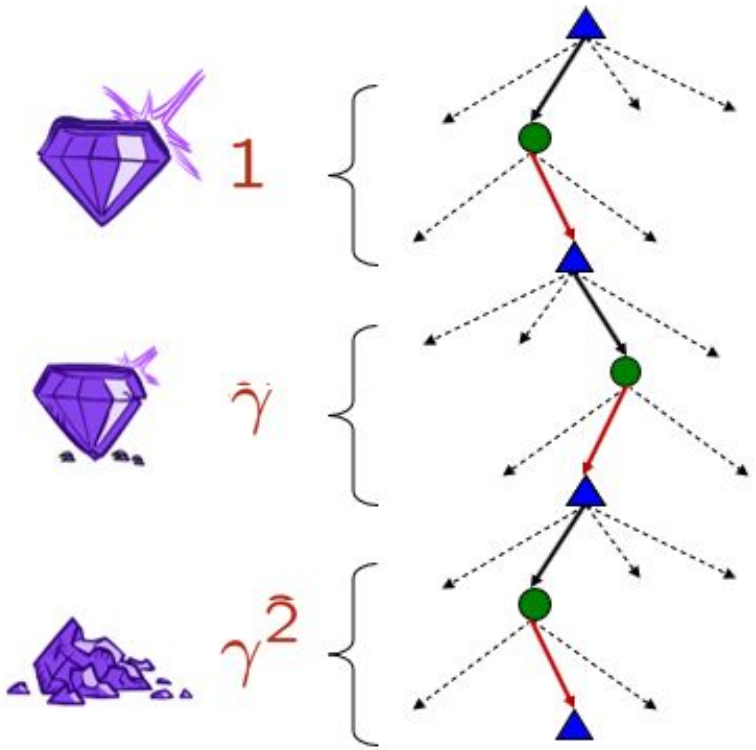
  - *Applicable when agent-environment interaction breaks into episodes*
  - *Ex: Playing Game, Trips through maze etc. [called episodic tasks]*

Returns & Episodes

- *Generally T = ∞*
  - *What if the agent receive a reward of +1 for each timestep?*
  - *Discounted Return:*

$$G_t \doteq R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \cdots = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}$$

Note: γ is a parameter, $0 \leq \gamma \leq 1$, called the *discount rate*.



  - *Discount rate determines the present value of future rewards*

Returns & Episodes

- *What if γ is 0?*
- *What if γ is 1?*
- *Computing discounted rewards incrementally*

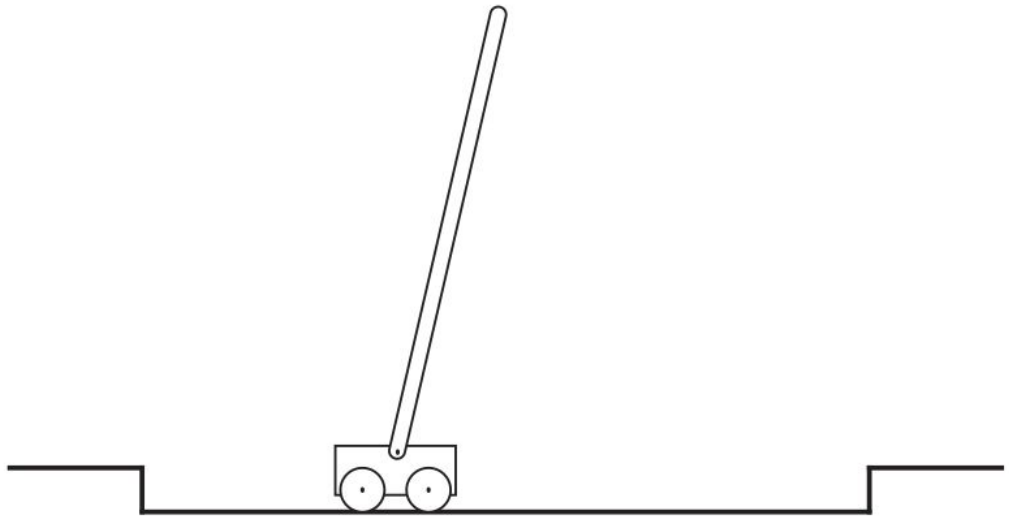
$$\begin{aligned} G_t &\doteq R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \gamma^3 R_{t+4} + \cdots \\ &= R_{t+1} + \gamma \left(R_{t+2} + \gamma R_{t+3} + \gamma^2 R_{t+4} + \cdots \right) \\ &= R_{t+1} + \gamma G_{t+1} \end{aligned}$$

- *Sum of an infinite number of terms, it is still finite if the reward is nonzero and constant and if $\gamma < 1$.*
- *Ex: reward is +1 constant*

$$G_t = \sum_{k=0}^{\infty} \gamma^k = \frac{1}{1-\gamma}.$$

Returns & Episodes

- *Objective: To apply forces to a cart moving along a track so as to keep a pole hinged to the cart from falling over*
- *Discuss:*
  - *Consider the task as episodic, that is try/maintain balance until failure. What could be the reward function?*
  - *Repeat prev. assuming task is continuous.*



Policy

- A mapping from states to probabilities of selecting each possible action.
  - $\pi(a|s)$ is the probability that $A_t = a$ if $S_t = s$
- The purpose of learning is to improve the agent's policy with its experience

Defining Value Functions

State-value function for policy π

$$v_\pi(s) \doteq \mathbb{E}_\pi[G_t \mid S_t = s] = \mathbb{E}_\pi\left[\sum_{k=0}^{\infty} \gamma^k R_{t+k+1} \,\middle|\, S_t = s\right], \text{ for all } s \in \mathcal{S},$$

Action-value function for policy π

$$q_\pi(s,a) \doteq \mathbb{E}_\pi[G_t \mid S_t = s, A_t = a] = \mathbb{E}_\pi\left[\sum_{k=0}^{\infty} \gamma^k R_{t+k+1} \,\middle|\, S_t = s, A_t = a\right]$$

Defining Value Functions

State Value function in terms of Action-value function for policy π

$$v_\pi(s) = \sum_{a \in \mathcal{A}(s)} \pi(a|s) q_\pi(s,a)$$

Action Value function in terms of State value function for policy π

$$q_\pi(s,a) = \sum_{s \in \mathcal{S}} \sum_{r \in \mathcal{R}} p(s', r \,|\, s, a) \left[r + \gamma v_\pi(s') \right]$$

Bellman Equation for V_π

May skip to the next slide !

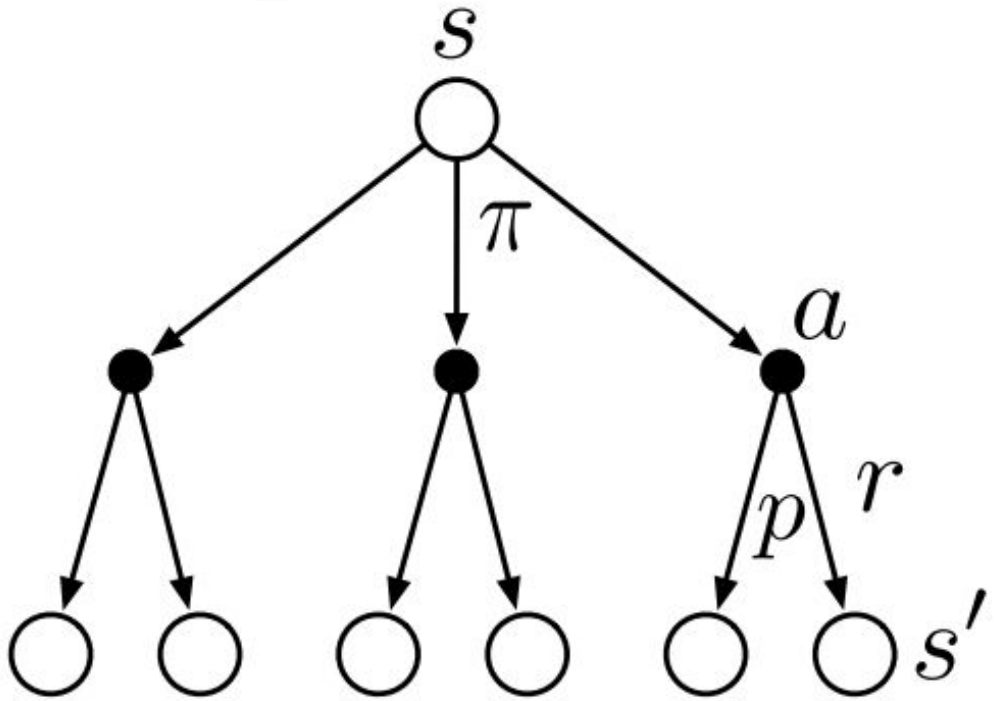
- Dynamic programming equation associated with discrete-time optimization problems
  - Expressing V_π recursively i.e. relating $V_\pi(s)$ to $V_\pi(s')$ for all $s' \in succ(s)$

$$
\begin{aligned}
v_\pi(s) &\doteq \mathbb{E}_\pi[G_t \mid S_t = s] \\
&= \mathbb{E}_\pi[R_{t+1} + \gamma G_{t+1} \mid S_t = s] \\
&= \sum_a \pi(a|s) \sum_{s'} \sum_r p(s', r \mid s, a) \Big[r + \gamma \mathbb{E}_\pi[G_{t+1} | S_{t+1} = s'] \Big] \\
&= \sum_a \pi(a|s) \sum_{s', r} p(s', r \mid s, a) \Big[r + \gamma v_\pi(s') \Big], \quad \text{for all } s \in \mathcal{S}
\end{aligned}
$$

Bellman Equation for V_π

$$v_\pi(s) \doteq \sum_a \pi(a|s) \sum_{s',r} p(s',r|s,a)\left[r + \gamma v_\pi(s')\right]$$

Value of the start state must equal
(1) the (discounted) value of the expected next state,
plus
(1) the reward expected along the way

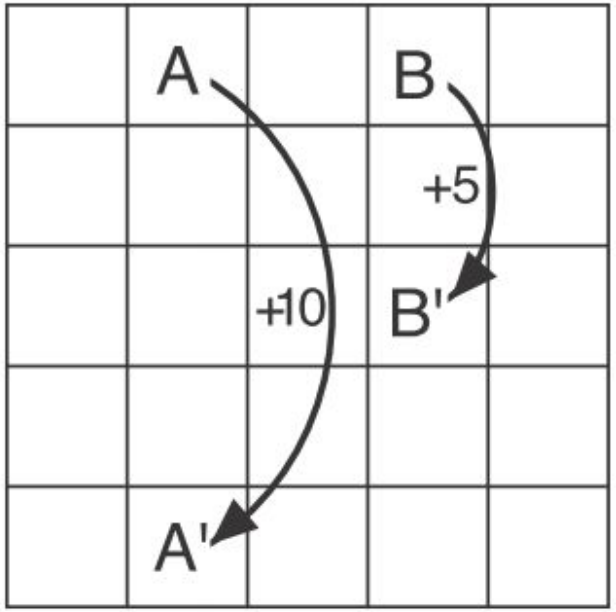


Backup Diagram

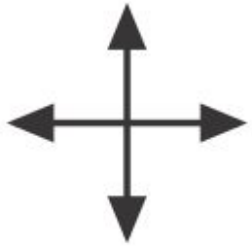
Understanding $V_\pi(s)$ with Gridworld

Reward:

- -1 if an action takes agent off the grid
- Exceptional reward from A and B for all actions taking agent to A' and B' resp.
- 0, everywhere else



Exceptional reward dynamics



Actions

3.3	8.8	4.4	5.3	1.5
1.5	3.0	2.3	1.9	0.5
0.1	0.7	0.7	0.4	-0.4
-1.0	-0.4	-0.4	-0.6	-1.2
-1.9	-1.3	-1.2	-1.4	-2.0

State-value function for the equiprobable random policy with $\gamma = 0.9$

Understanding $V_\pi(s)$ with Gridworld

$$v_\pi(s) \doteq \sum_a \pi(a|s) \sum_{s',r} p(s',r|s,a)\left[r + \gamma v_\pi(s')\right]$$

Verify $V_\pi(s)$ using Bellman equation for this state with γ = 0.9, and equiprobable random policy

3.3	8.8	4.4	5.3	1.5
1.5	3.0	2.3	1.9	0.5
0.1	0.7	0.7	0.4	-0.4
-1.0	-0.4	-0.4	-0.6	-1.2
-1.9	-1.3	-1.2	-1.4	-2.0

Understanding $V_\pi(s)$ with Gridworld

$$v_\pi(s) \doteq \sum_a \pi(a|s) \sum_{s',r} p(s',r|s,a)\left[r + \gamma v_\pi(s')\right]$$

$$\begin{aligned} v_\pi(s) &= \sum_a \pi(a|s) \sum_{s',r} p(s',r|s,a)\left[r + \gamma v_\pi(s')\right] \\ &= \sum_a 0.25 \cdot \left[0 + 0.9 \cdot (2.3 + 0.4 - 0.4 + 0.7)\right] \\ &= 0.25 \cdot [0.9 \cdot 3.0] = 0.675 \approx 0.7 \end{aligned}$$

3.3	8.8	4.4	5.3	1.5
1.5	3.0	2.3	1.9	0.5
0.1	0.7	0.7	0.4	-0.4
-1.0	-0.4	-0.4	-0.6	-1.2
-1.9	-1.3	-1.2	-1.4	-2.0

Ex-1

Recollect the reward function used for Gridworld as below:

- -1 if an action takes agent off the grid
- Exceptional reward from A and B for all actions taking agent to A’ and B’ resp.
- 0, everywhere else

Let us add a constant c (say 10) to the rewards of all the actions. Will it change anything?

Optimal Policies and Optimal Value Functions

- $\pi \geq \pi'$ if and only if $v_\pi(s) \geq v_\pi(s)$ for all $s \in S$
- There is always at least one policy that is better than or equal to all other policies $\rightarrow$ optimal policy (denoted as π_*)
  - There could be more than one optimal policy !!!

Optimal state-value function $v_*(s) \doteq \max_\pi v_\pi(s)$

Optimal action-value function $q_*(s,a) \doteq \max q_\pi(s,a)$

$$q_*(s,a) = \mathbb{E}[R_{t+1} + \gamma v_*(S_{t+1}) \mid S_t = s, A_t = a]$$

Optimal Policies and Optimal Value Functions

Bellman optimality equation - expresses that *the value of a state under an optimal policy must equal the expected return for the best action from that state*

Bellman optimality equation for V_*

$$
\begin{aligned}
v_*(s) &= \max_{a \in \mathcal{A}(s)} q_{\pi_*}(s,a) \\
&= \max_a \mathbb{E}_{\pi_*}[G_t \mid S_t = s, A_t = a] \\
&= \max_a \mathbb{E}_{\pi_*}[R_{t+1} + \gamma G_{t+1} \mid S_t = s, A_t = a] \\
&= \max_a \mathbb{E}[R_{t+1} + \gamma v_*(S_{t+1}) \mid S_t = s, A_t = a] \\
&= \max_a \sum_{s',r} p(s', r \mid s, a)\big[r + \gamma v_*(s')\big].
\end{aligned}
$$

Optimal Policies and Optimal Value Functions

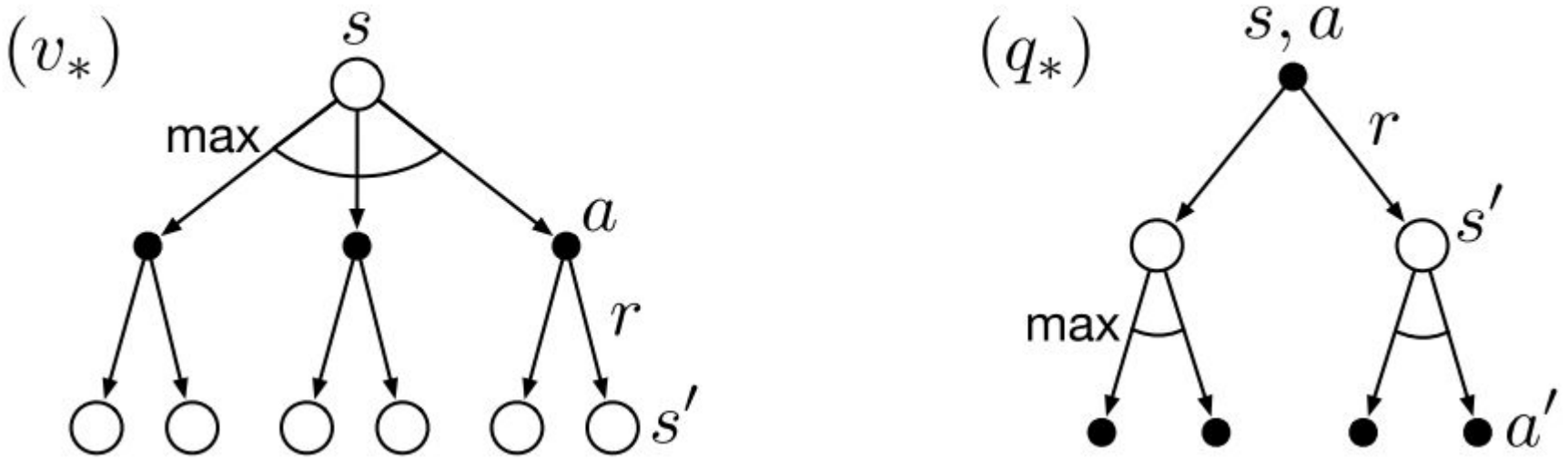
Bellman optimality equation - expresses that *the value of a state under an optimal policy must equal the expected return for the best action from that state*

Bellman optimality equation for q_*

$$
\begin{aligned}
q_*(s,a) &= \mathbb{E}\left[R_{t+1} + \gamma \max_{a'} q_*(S_{t+1}, a') \;\middle|\; S_t = s, A_t = a\right] \\
&= \sum_{s',r} p(s', r \mid s, a)\left[r + \gamma \max_{a'} q_*(s', a')\right].
\end{aligned}
$$

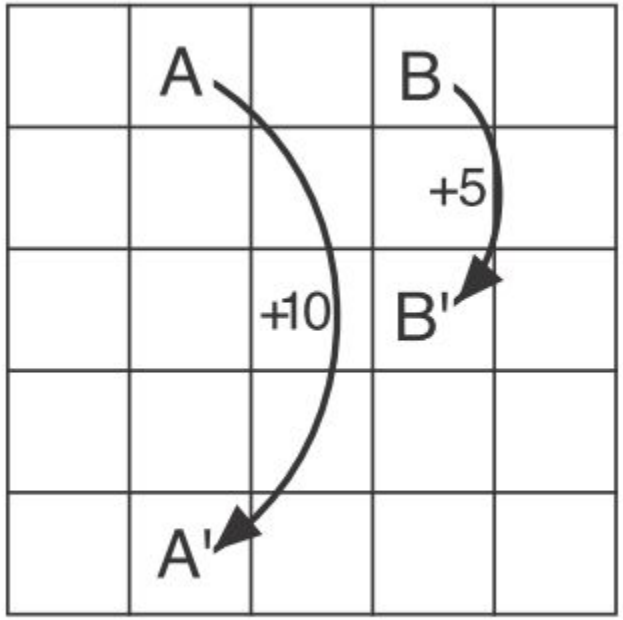
Optimal Policies and Optimal Value Functions

Bellman optimality equation - expresses that *the value of a state under an optimal policy must equal the expected return for the best action from that state*



Backup diagrams for v* and q*

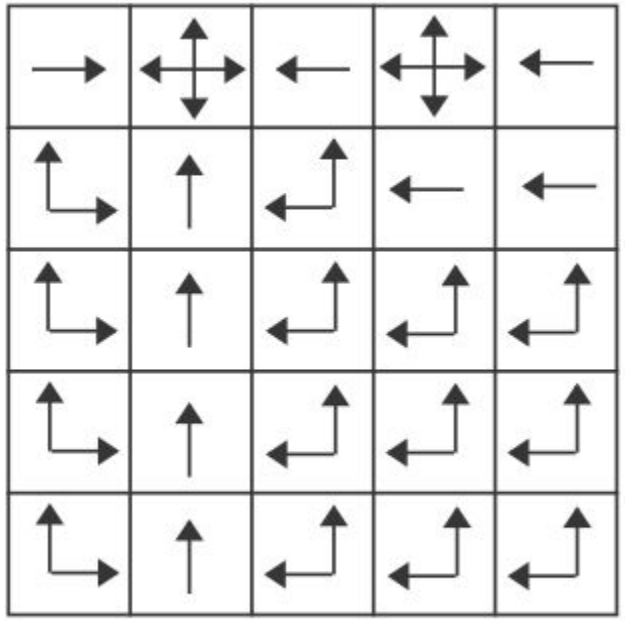
Optimal solutions to the gridworld example



Gridworld

22.0	24.4	22.0	19.4	17.5
19.8	22.0	19.8	17.8	16.0
17.8	19.8	17.8	16.0	14.4
16.0	17.8	16.0	14.4	13.0
14.4	16.0	14.4	13.0	11.7

v_*



π_*

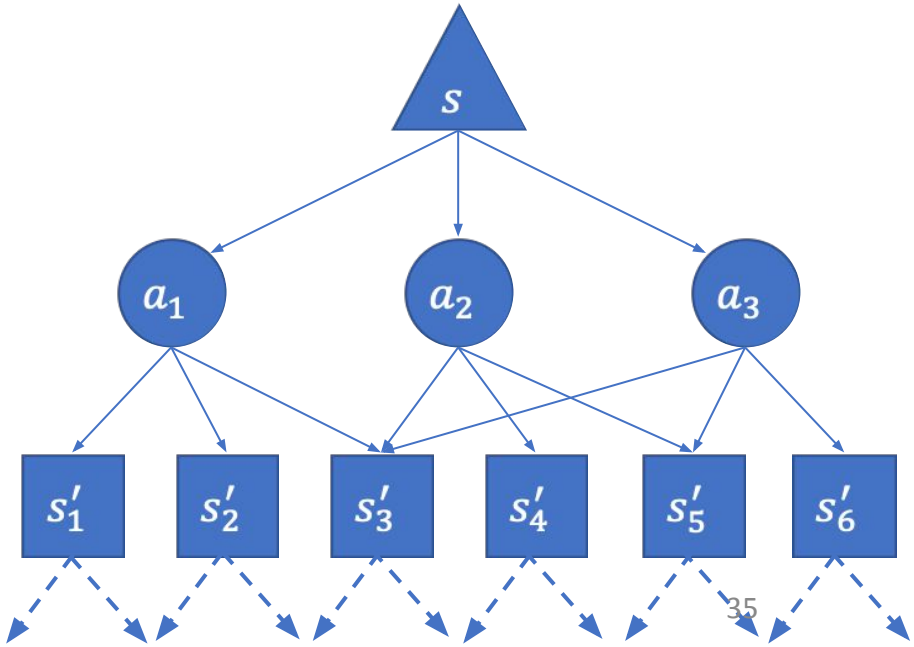
Backup diagrams for v* and q*

Break for 5 mins

MDP - Objective

A set of states $s \in \mathcal{S}$
A set of actions $a \in \mathcal{A}$
State-transition probabilities $P(s'|s,a)$
A reward function $R(s,a,s')$

- Compute a policy: what action to take at each state
  - $\pi: S \rightarrow A$
- Compute the **optimal** policy: maximum expected reward, π^*
- $\pi^*(s) = ?$
- $= \underset{a}{\text{argmax}}[\sum_{s'} P(s'|s,a)R(s,a,s')]$
  - Must also optimize over the future (next steps)
- $= \underset{a}{\text{argmax}}[\sum_{s'} P(s'|s,a)\,(R(s,a,s') + \underbrace{\mathbb{E}_{\pi^*}[G|s']}_{v^*(s')})]$



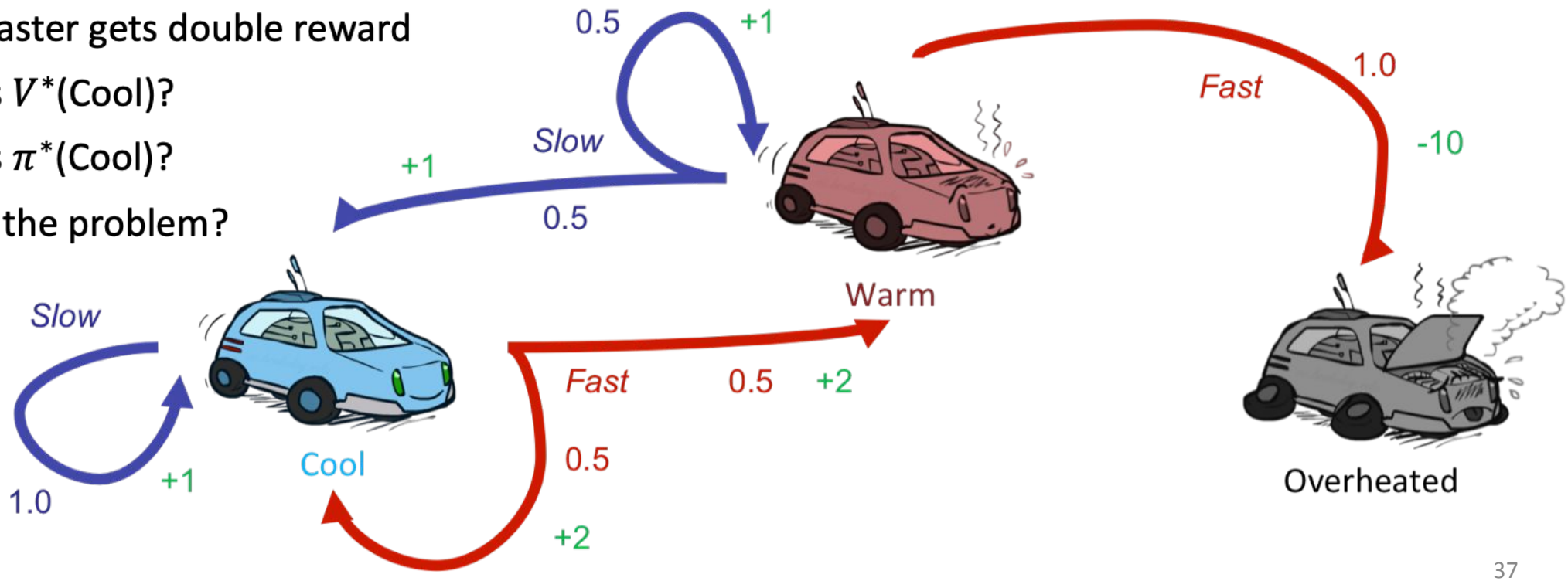
Notation

- π^* - a policy that yields the maximal expected sum of rewards
- G- observed sum of rewards, i.e., $\sum r_t$
- $v^*(s)$ - the expected sum of rewards from being at s then following π^*
  - $= \mathbb{E}_{\pi^*}[G|s]$

Race car example

$$\max_a \left[\sum_{s'} P(s'|s,a) \left(R(s,a,s') + v^*(s') \right) \right]$$

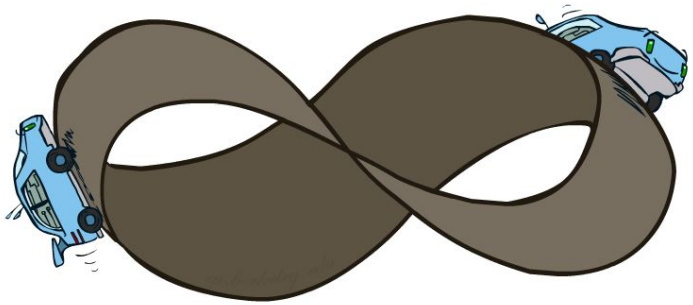
- A robot car wants to travel far, quickly
- Three states: Cool, Warm, Overheated
- Two actions: *Slow*, *Fast*
- Going faster gets double reward
- What is V^*(Cool)?
- What is π^*(Cool)?
- What's the problem?



Infinite Utilities?!

- Problem: What if the game lasts forever? Do we get infinite rewards?

- Solutions:
  - Finite horizon: (similar to depth-limited search)
    - Terminate episodes after a fixed T steps (e.g. life)
    - Gives nonstationary policies (π depends on time left)



  - Discounting: use $0 < \gamma < 1$

$$U([r_0, \ldots r_\infty]) = \sum_{t=0}^{\infty} \gamma^t r_t \leq R_{\max}/(1-\gamma)$$

    - Smaller γ means smaller "horizon" – shorter term focus

Discount factor

- As the agent traverse the world it receives a sequence of rewards
- Which sequence has higher utility?
  - $\tau_1 = +1, +1, +1, +1, +1, +1 \ldots$
  - $\tau_2 = +2, +2, +2, +2, +2, +2 \ldots$

$$\sum_{t=0}^{\infty} 1 = \sum_{t=0}^{\infty} 2 = \infty$$

- Let's decay future rewards exponentially by a factor, $0 \leq \gamma < 1$

$$\sum_{t=0}^{\infty} \gamma^t r = \frac{r}{1-\gamma}$$

Geometric series

- Now τ_1 yields higher utility than τ_2

Discounting

- It's reasonable to maximize the sum of rewards
- It's also reasonable to prefer rewards now to rewards later
- Discount factor: values of rewards decay exponentially

1

Worth Now

γ

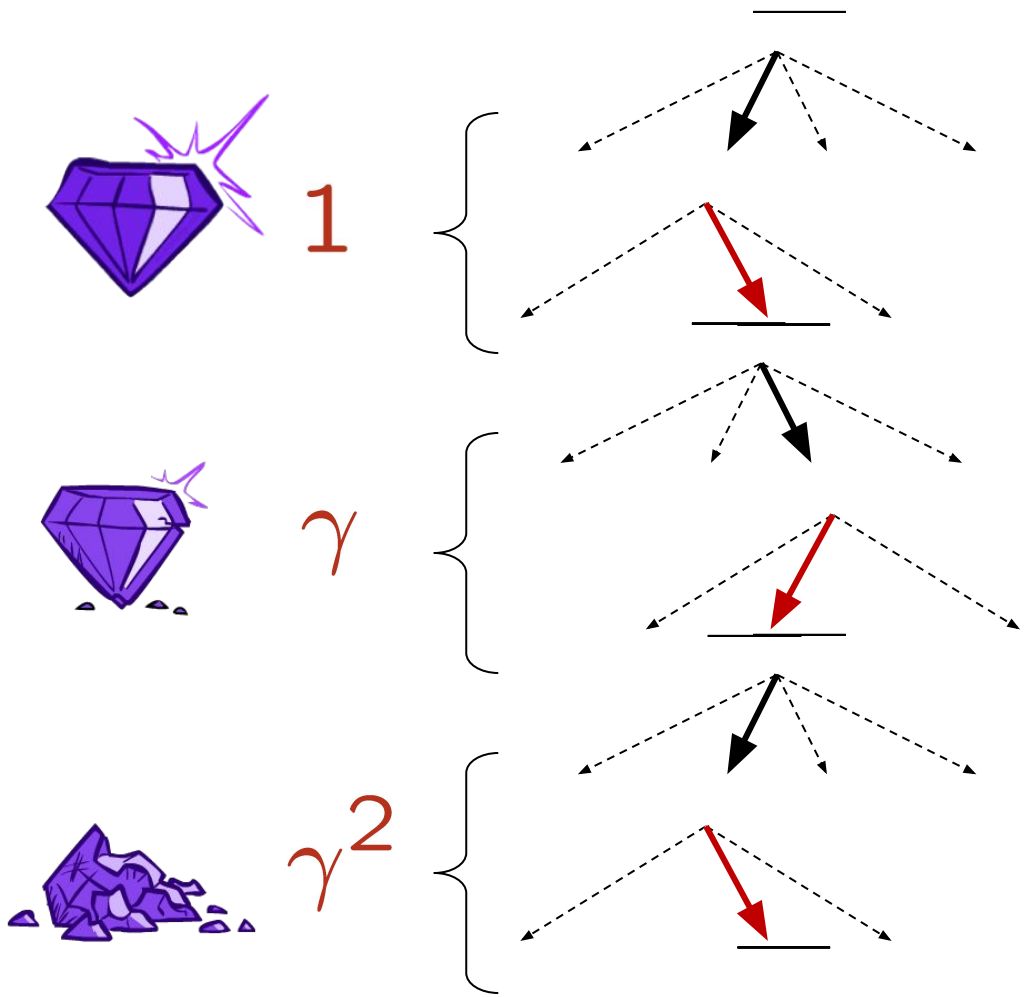
Worth Next Step

γ^2

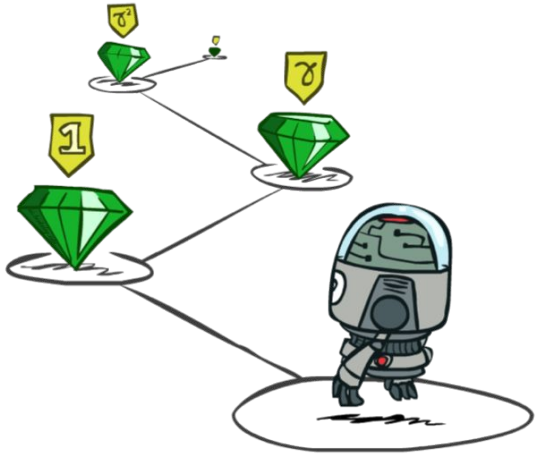
Worth In Two Steps

Discounting

- How to discount?
  - Each time we descend a level, we multiply in the discount once
- Why discount?
  - Sooner rewards probably do have higher utility than later rewards
  - Also helps our algorithms converge
- Example: discount of 0.5
  - G(r=[1,2,3]) = 1*1 + 0.5*2 + 0.25*3
  - G([1,2,3]) < G([3,2,1])



Quiz: Discounting



- Given grid world:

10				1
a	b	c	d	e

  - Actions: East, West, and Exit ('Exit' only available in terminal states: a, e)
  - Rewards are given only after an exit action
  - Transitions: deterministic

- Quiz 1: For γ = 1, what is the optimal policy?

10				1

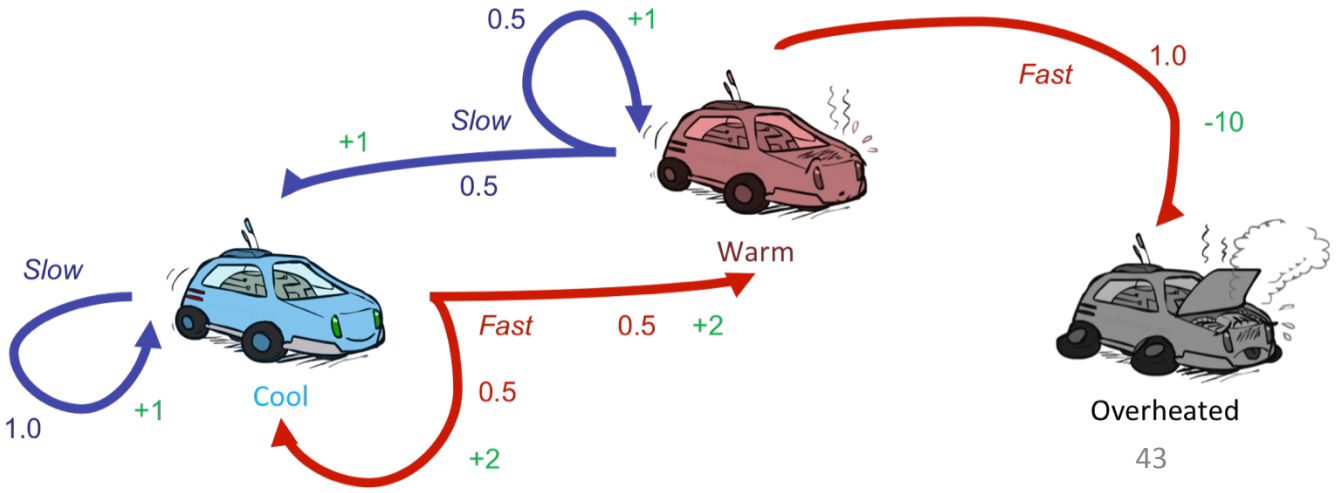
- Quiz 2: For γ = 0.1, what is the optimal policy?

10				1

- Quiz 3: For which γ are West and East equally good when in state d?

Race car example

- Consider a discount factor, $\gamma = 0.9$
- What is $v^*(Cool)$
- $= \max_a \left[r(s,a) + \sum_{s'} p(s'|s,a)\ \gamma\ v^*(s') \right]$
- $= \max[1 + 0.9 \cdot 1 v^*(Cool), 2 + 0.9 \cdot 0.5 v^*(Cool) + 0.9 \cdot 0.5 v^*(Warm)]$
  - Computing…
  - …Stack overflow
- Work in iterations



Value iteration

Value iteration

Initialize array V arbitrarily (e.g., $V(s) = 0$ for all $s \in \mathcal{S}^+$)

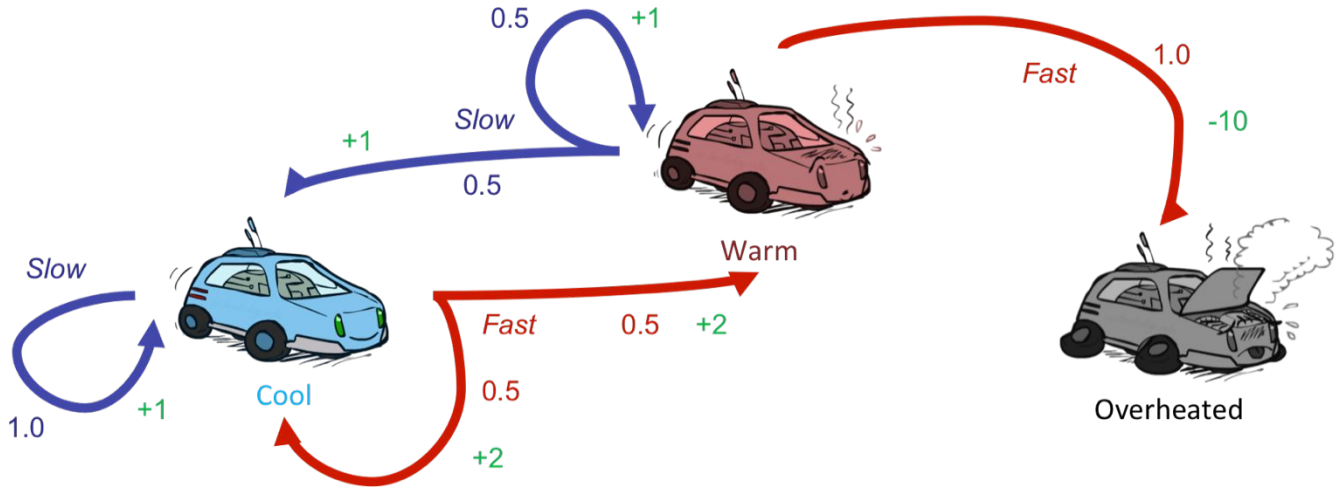
Repeat
$\Delta \leftarrow 0$
For each $s \in \mathcal{S}$:
$v \leftarrow V(s)$
$V(s) \leftarrow \max_a \sum_{s',r} p(s', r \mid s, a)\left[r + \gamma V(s')\right]$
$\Delta \leftarrow \max(\Delta, |v - V(s)|)$
until $\Delta < \theta$ (a small positive number)

Output a deterministic policy, $\pi \approx \pi_*$, such that
$\pi(s) = \arg\max_a \sum_{s',r} p(s', r \mid s, a)\left[r + \gamma V(s')\right]$

Value Iteration

V_0	0	0	0
V_1	2	1	0
V_2	3.35	2.35	0

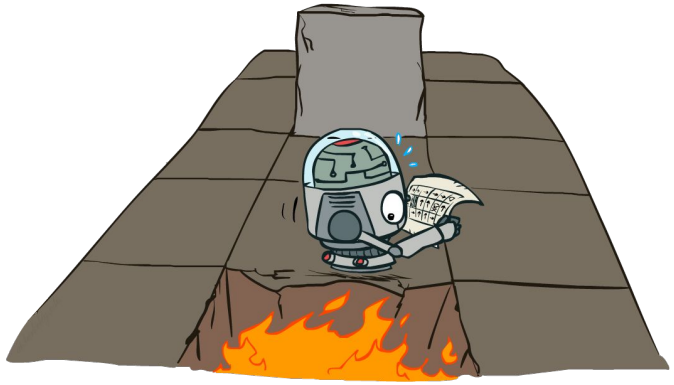
Check this computation on paper.



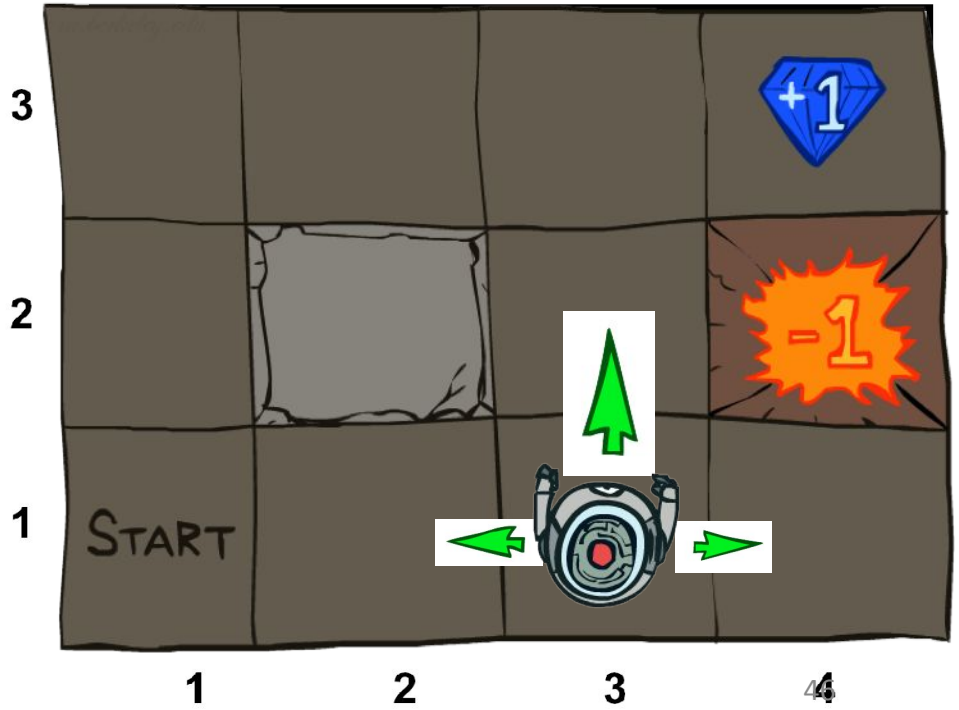
$\gamma = 0.9$

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s', r \mid s, a)\left[r + \gamma v_k(s')\right]$$

Example: Grid World

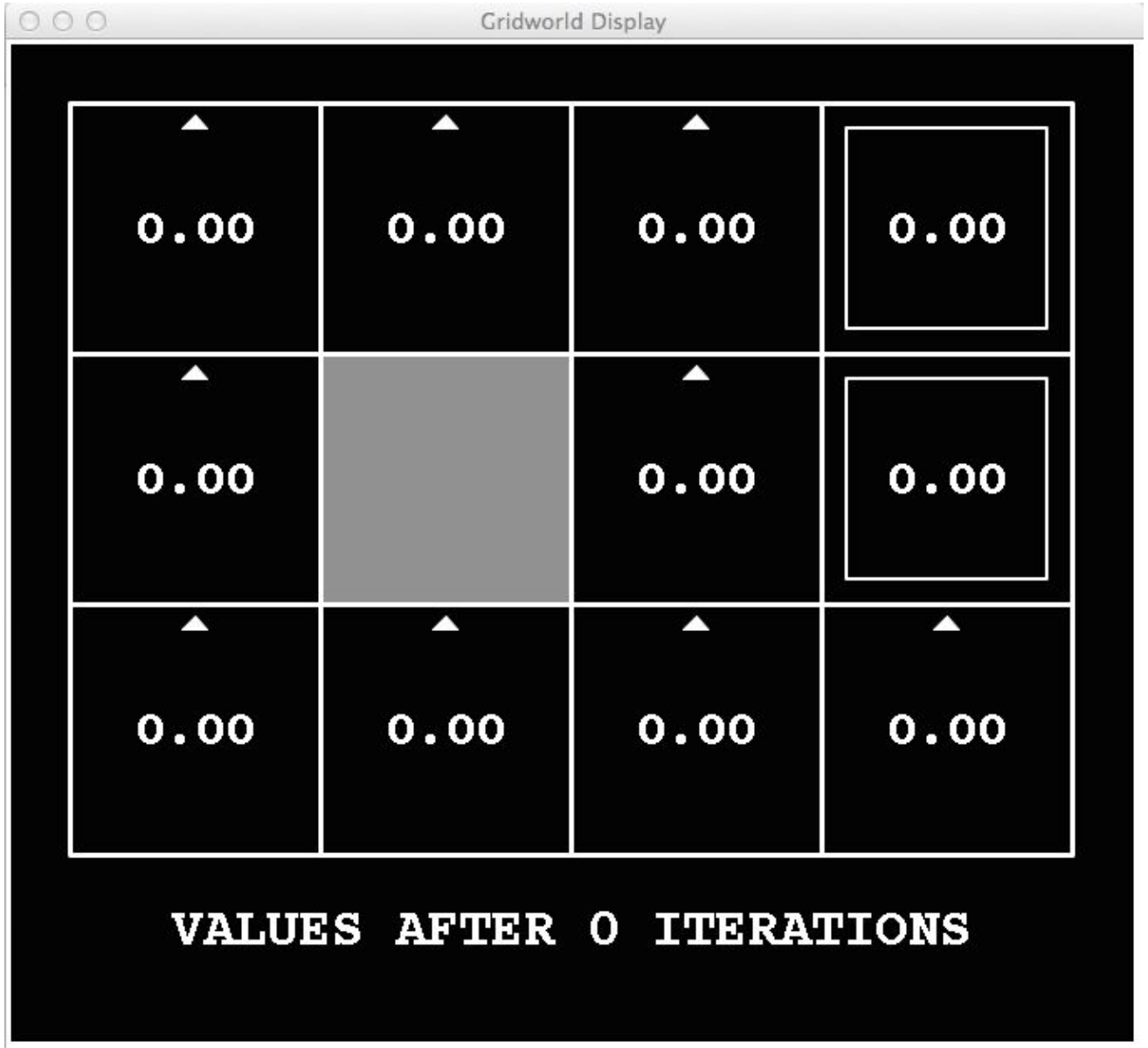


- A maze-like problem
  - The agent lives in a grid
  - Walls block the agent's path
- Noisy movement: actions do not always go as planned
  - 80% of the time, the action North takes the agent North
  - 10% of the time, North takes the agent West; 10% East
  - If there is a wall in the direction the agent would have been taken, the agent stays put
- The agent receives rewards each time step
  - Small negative reward each step (battery drain)
  - Big rewards come at the end (good or bad)
- Goal: maximize sum of (discounted) rewards



$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

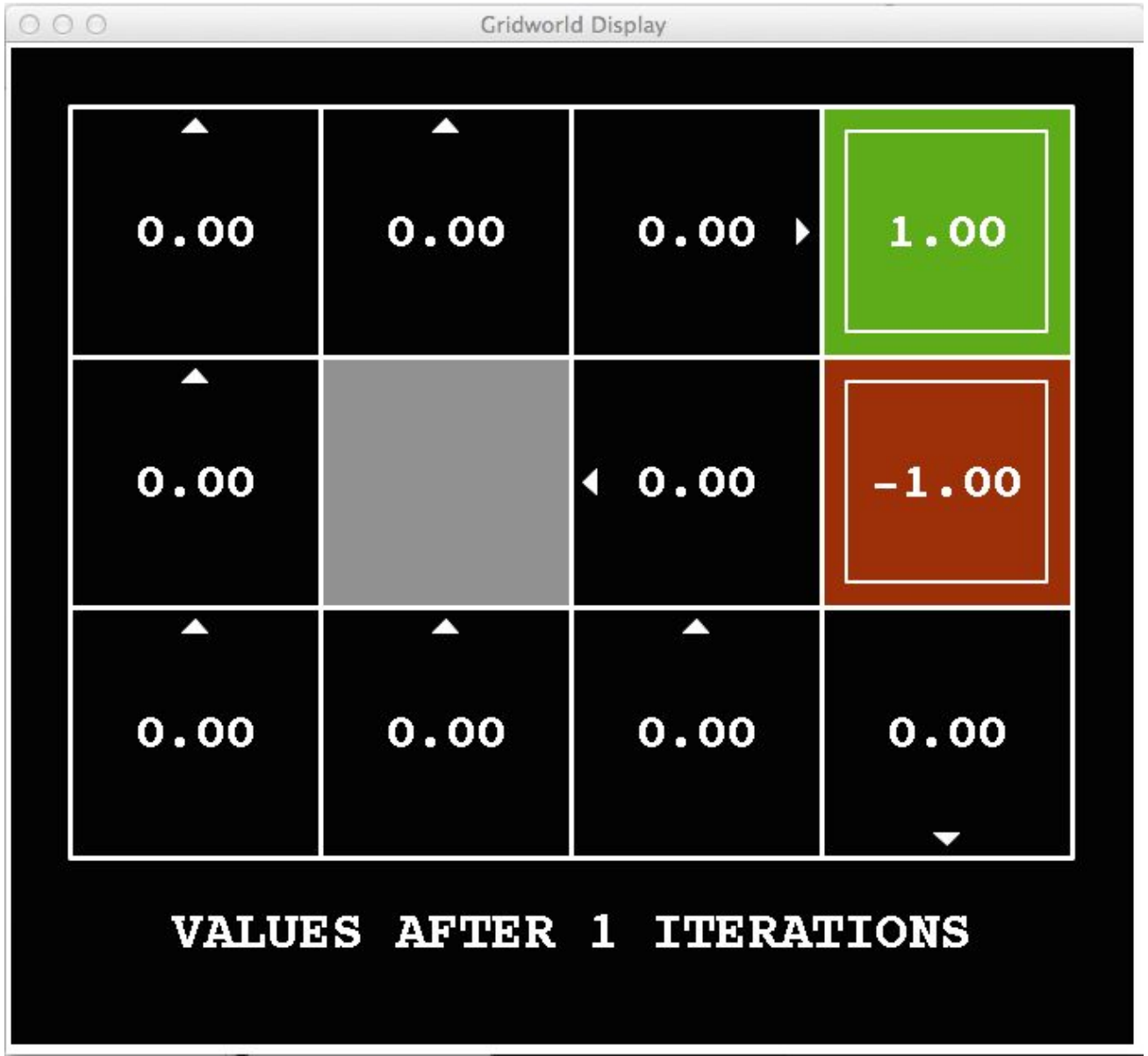
k=0



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

k=1



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

k=2

Noise = 0.2
Discount = 0.9
Living reward = 0

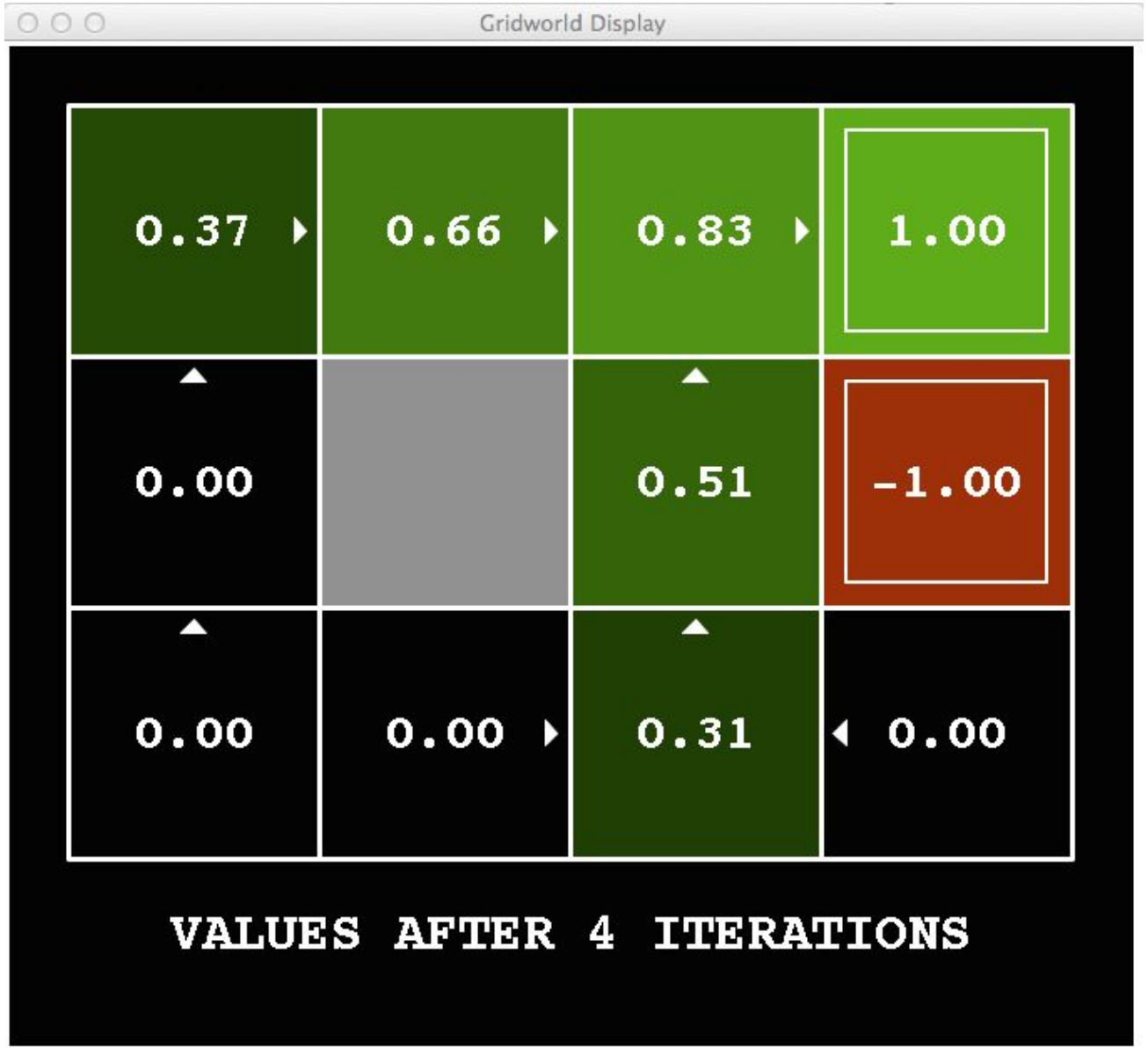
$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

k=3

Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

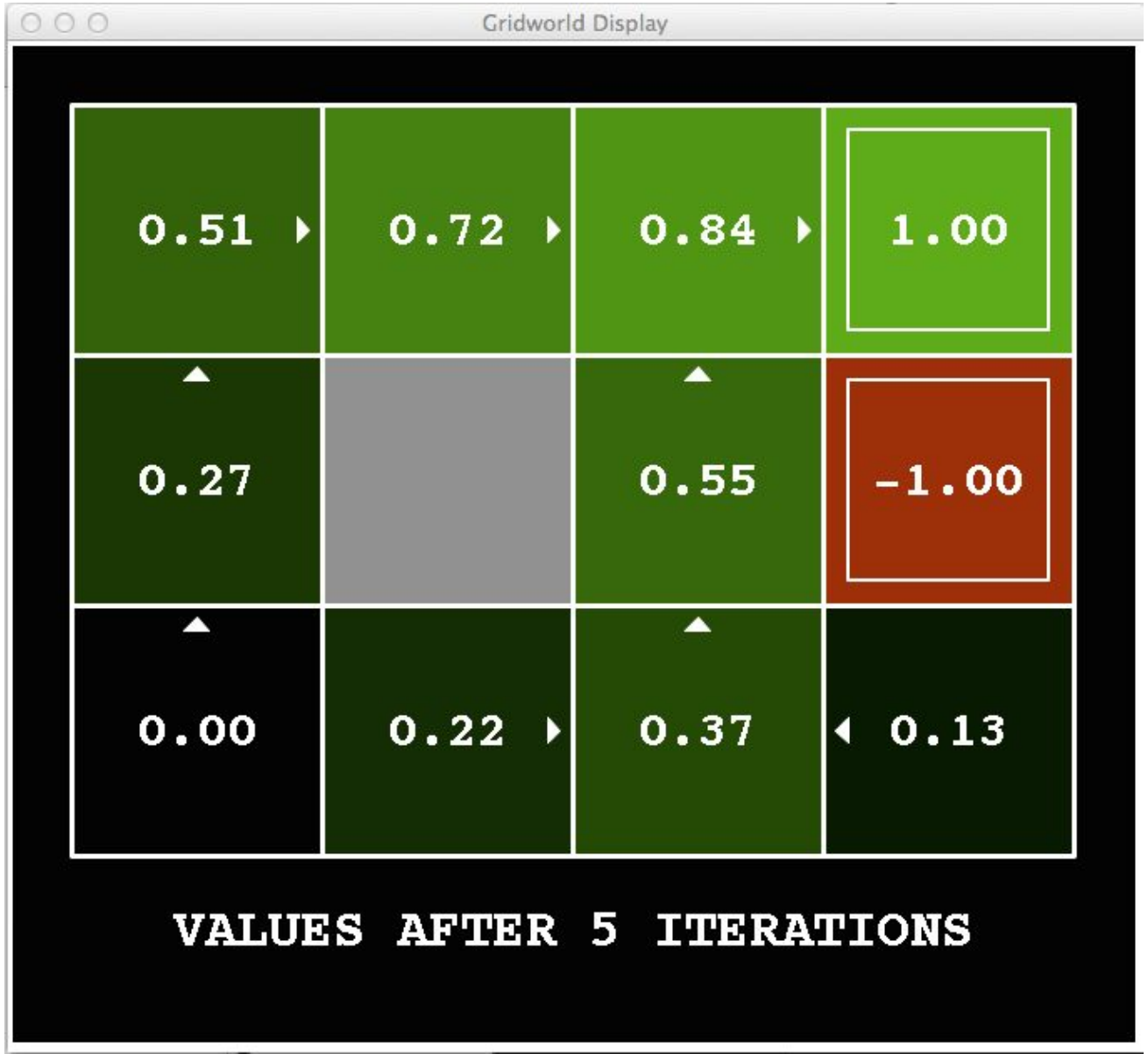
k=4



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

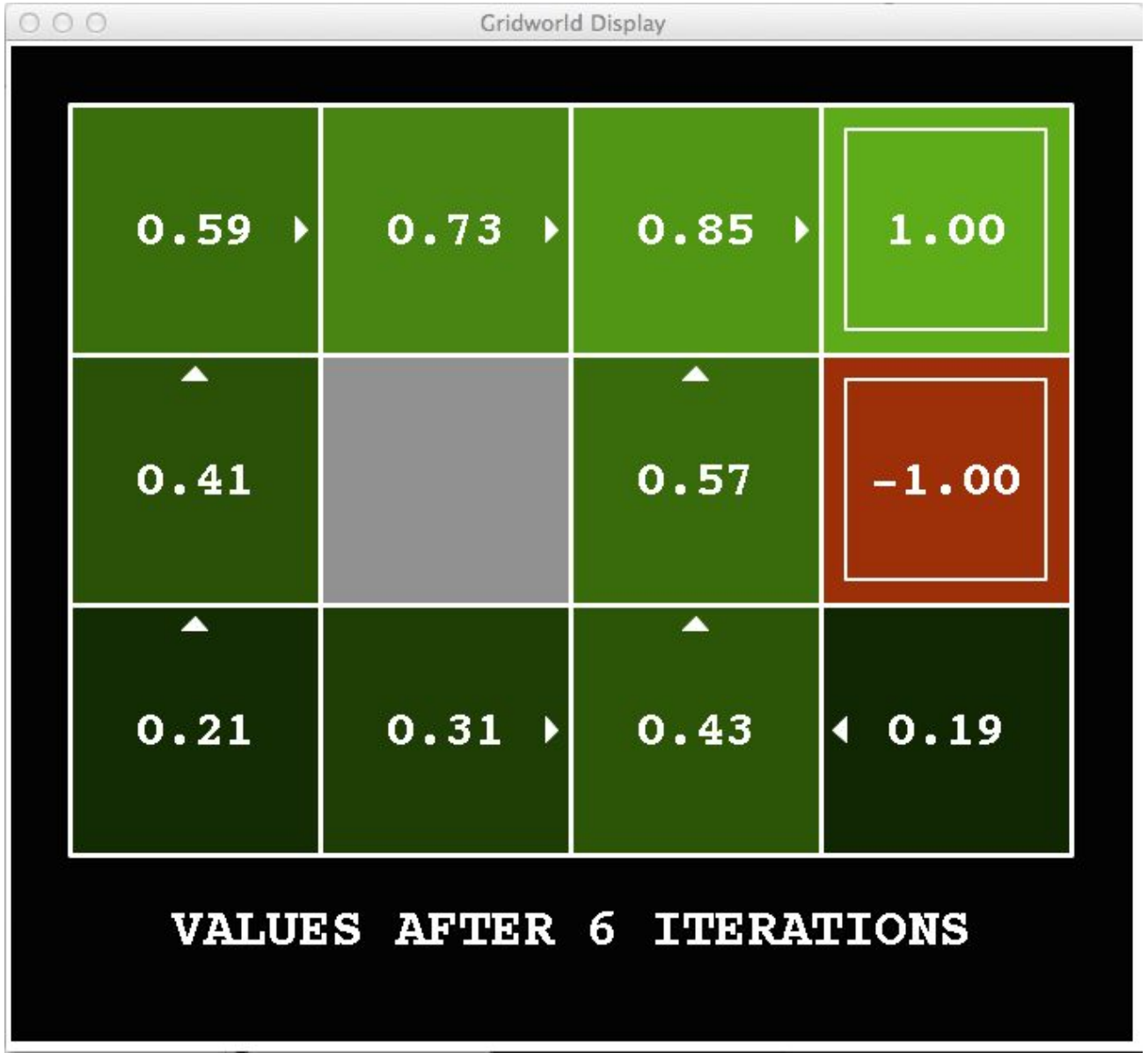
k=5



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

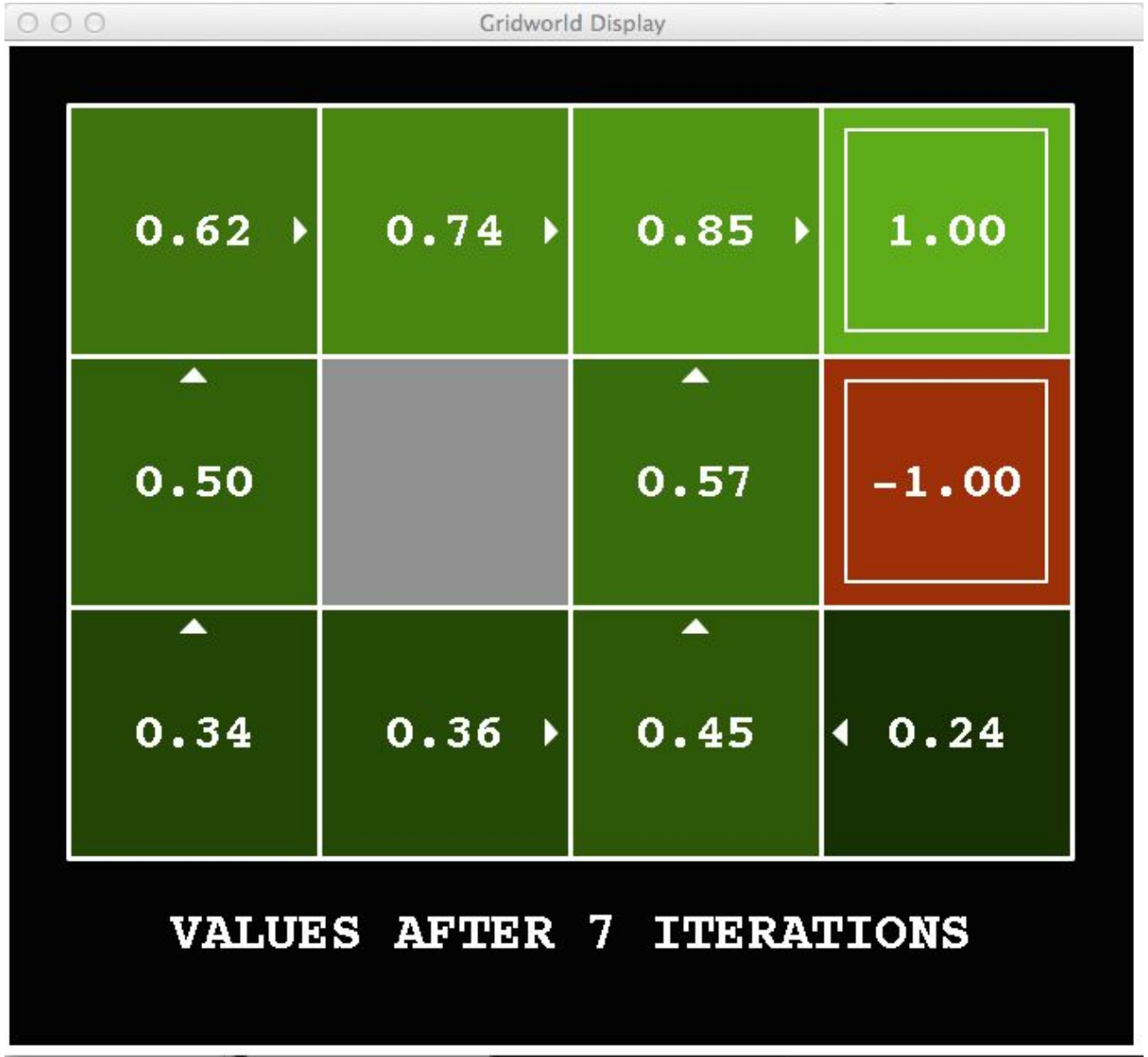
k=6



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

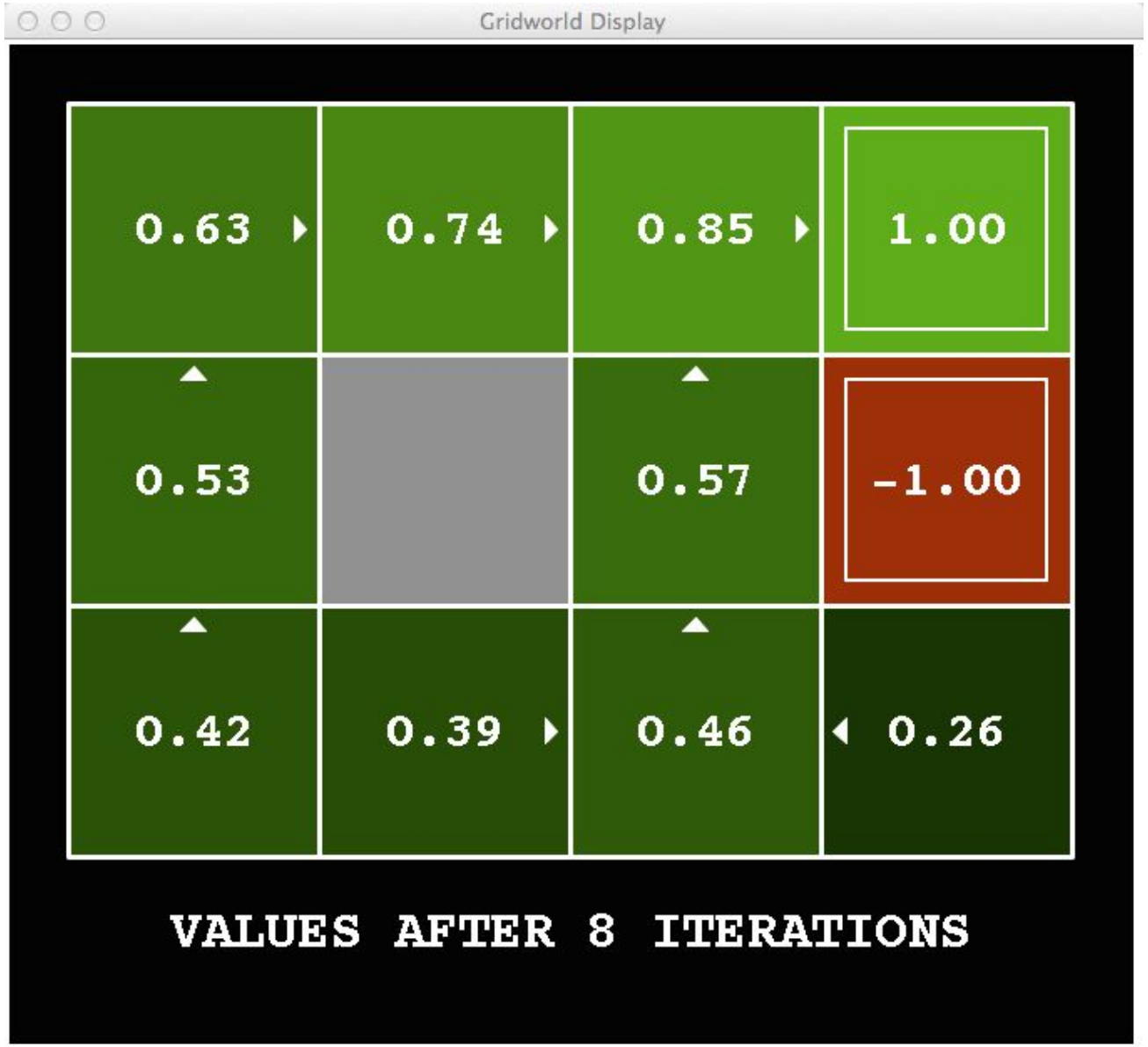
k=7



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

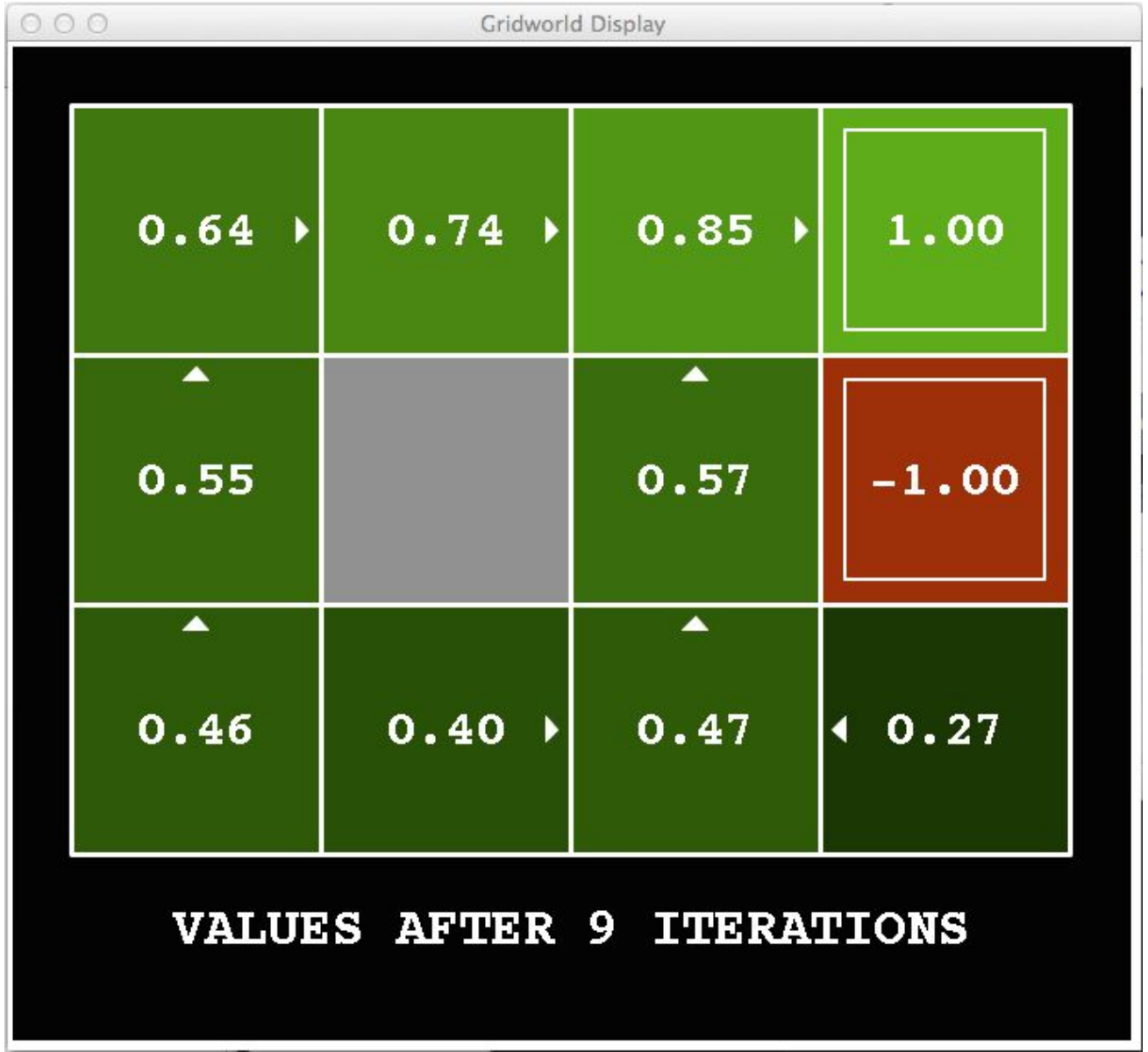
k=8



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

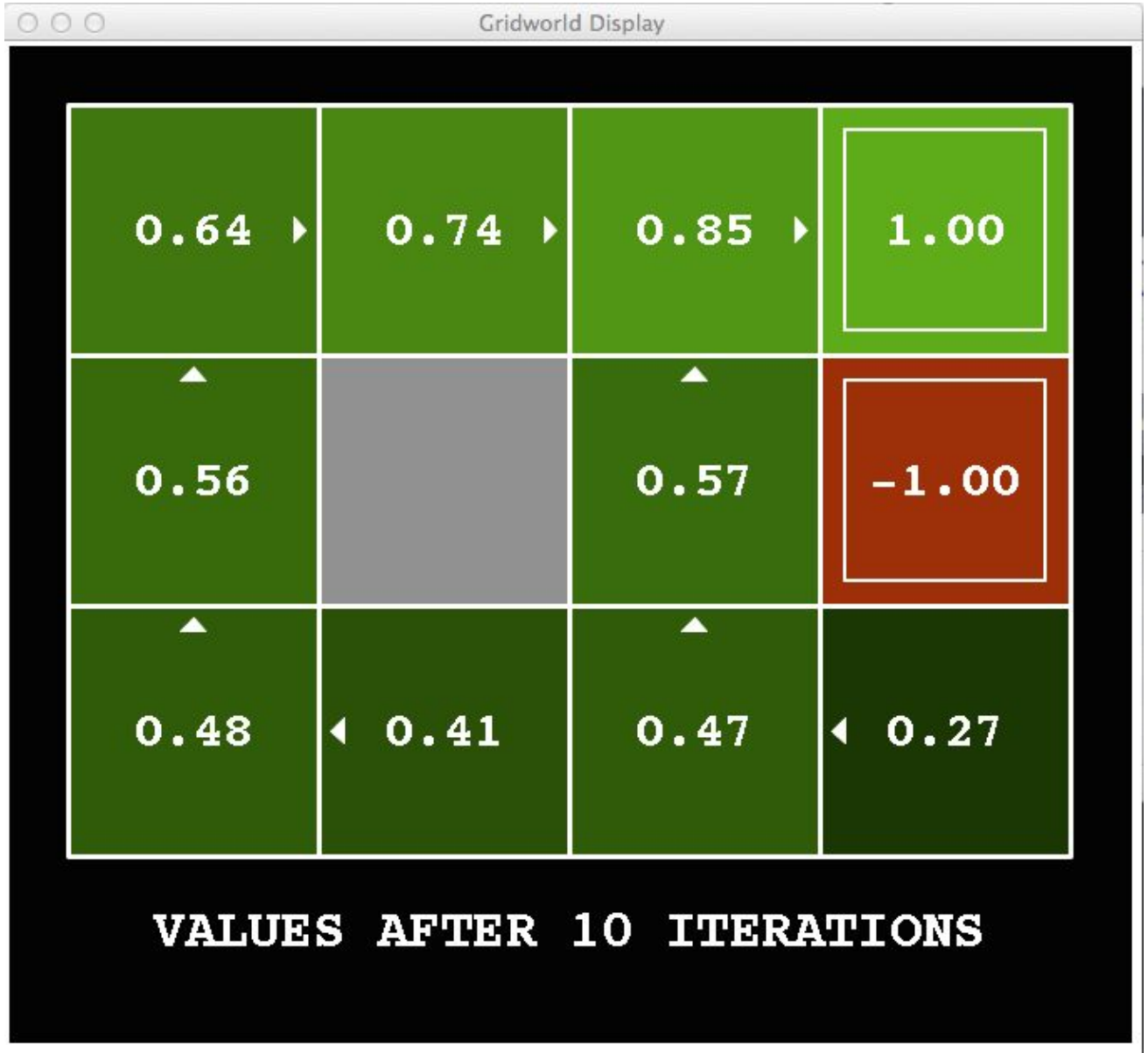
k=9



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

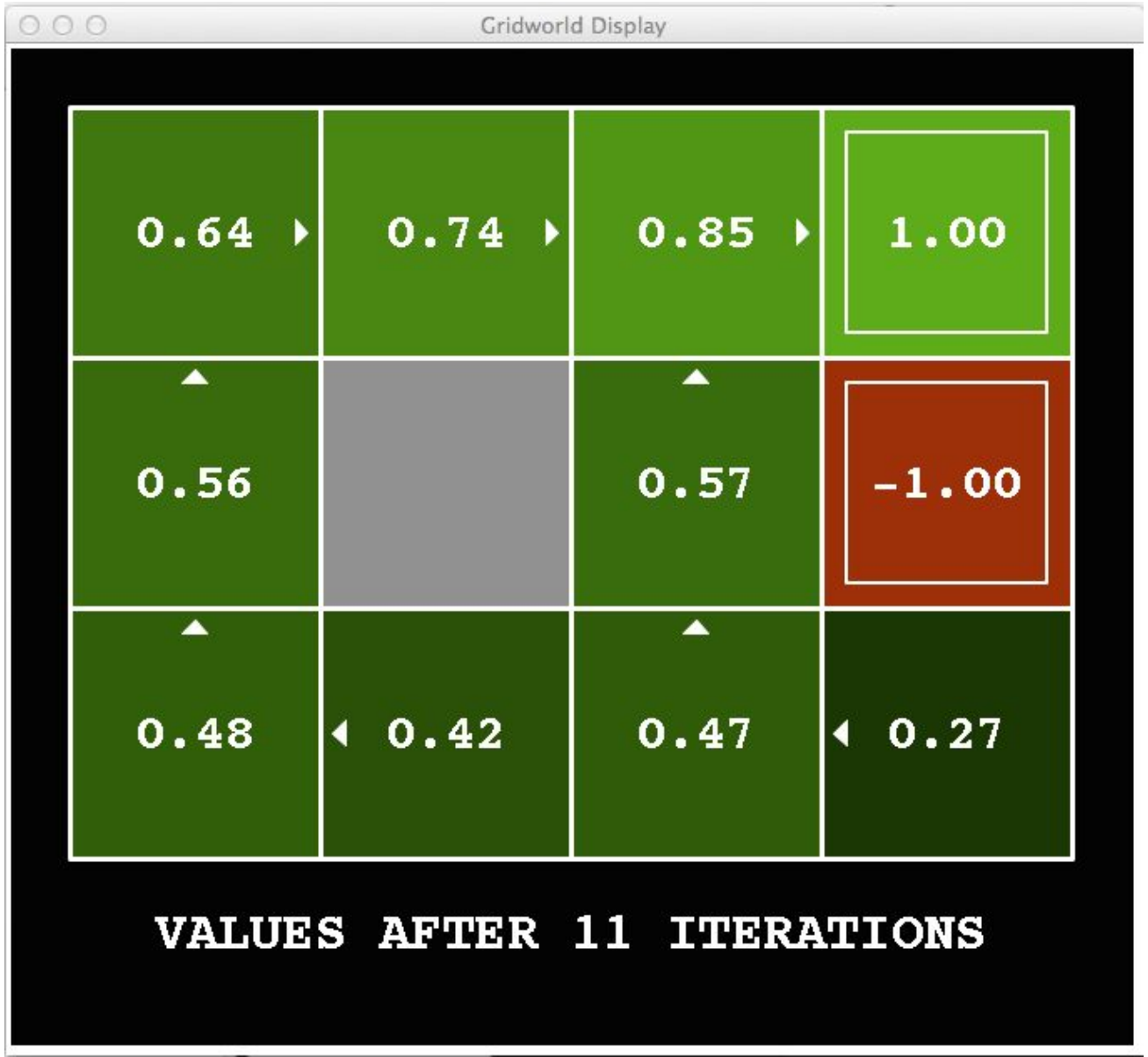
k=10



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

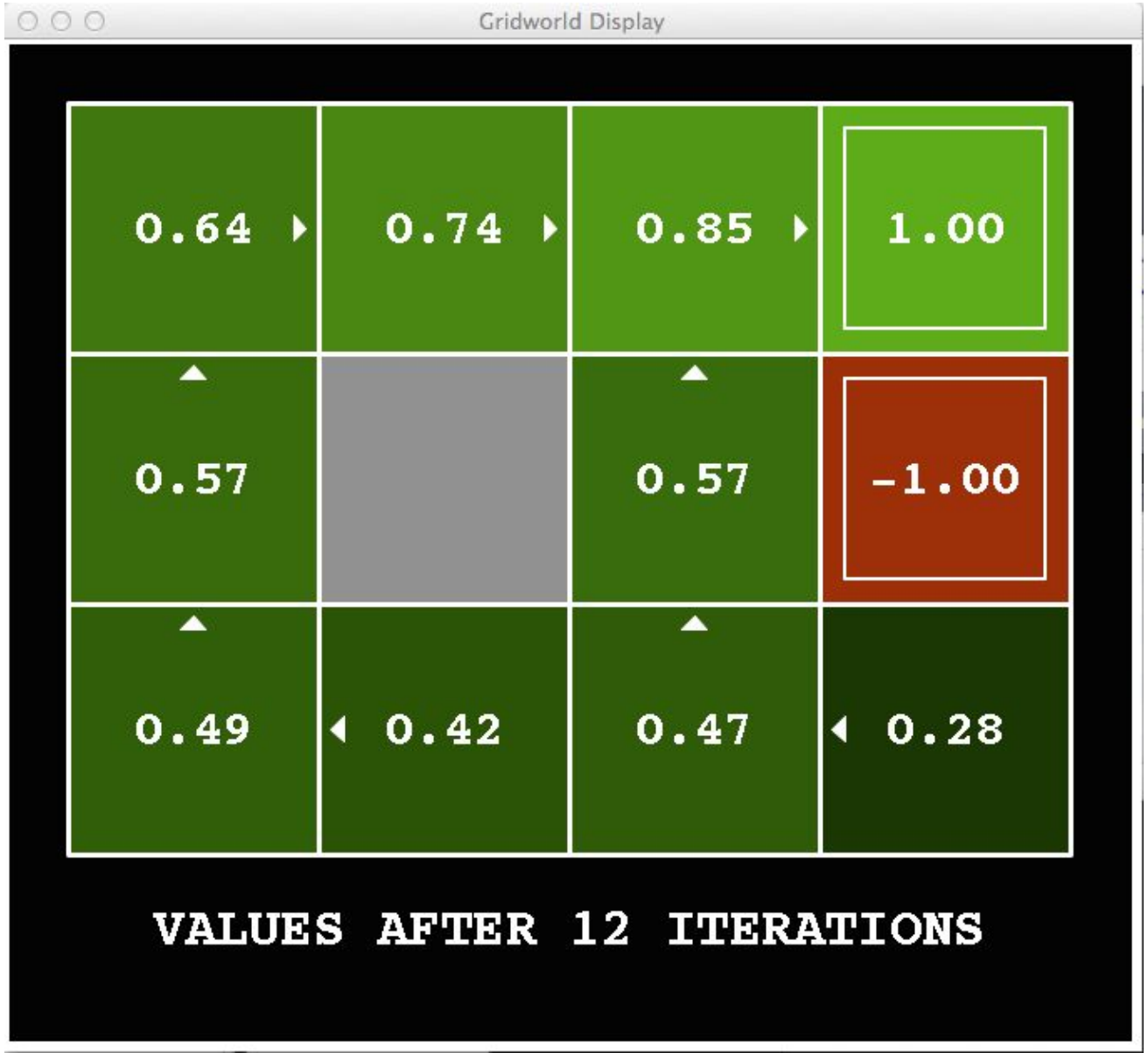
k=11



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

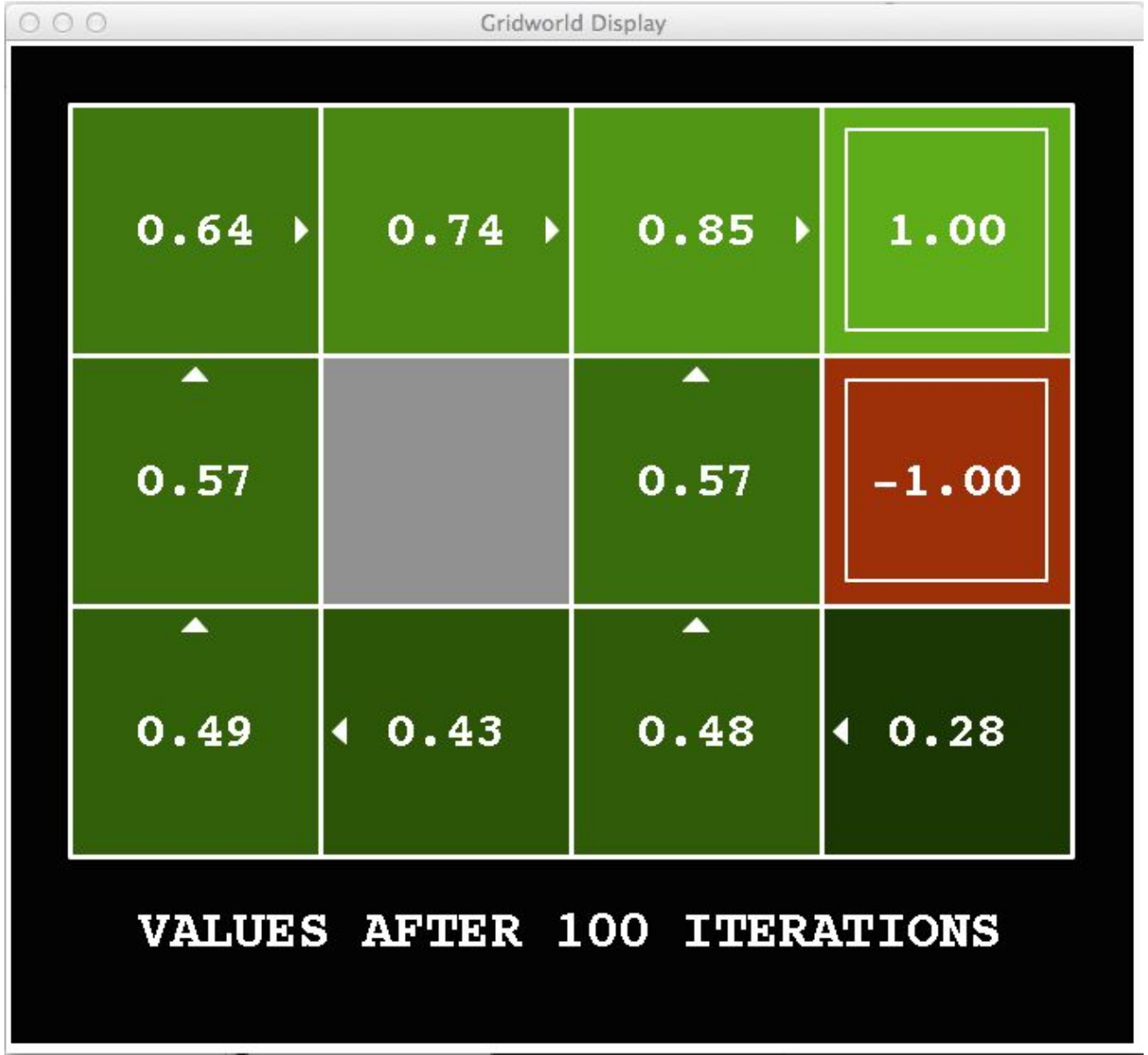
k=12



Noise = 0.2
Discount = 0.9
Living reward = 0

$$v_{k+1}(s) \doteq \max_a \sum_{s',r} p(s',r|s,a)\left[r+\gamma v_k(s')\right]$$

k=100



Noise = 0.2
Discount = 0.9
Living reward = 0

Problems with Value Iteration

- Value iteration repeats the Bellman updates:
- $V_{k+1}(s) \leftarrow \max_a \left[R(s,a) + \sum_{s'} P(s'|s,a)\ \gamma V_k(s')\right]$

$$= \max_a \left[\sum_{s'} P(s'|s,a)\ (R(s,a,s') + \gamma V_k(s'))\right]$$

- Issue 1: It's slow – $O(S^2A)$ per iteration
  - Do we really need to update every state at every iteration?
- Issue 2: A policy cannot be easily extracted
  - Policy extraction requires another $O(S^2A)$
- Issue 3: The policy often converges long before the values
  - Can we identify when the policy converged?
- Issue 4: requires knowing the model, $P(s'|s,a)$, and the reward function, $R(s,a)$
- Issue 5: requires discrete (finite) set of actions
- Issue 6: infeasible in large state spaces

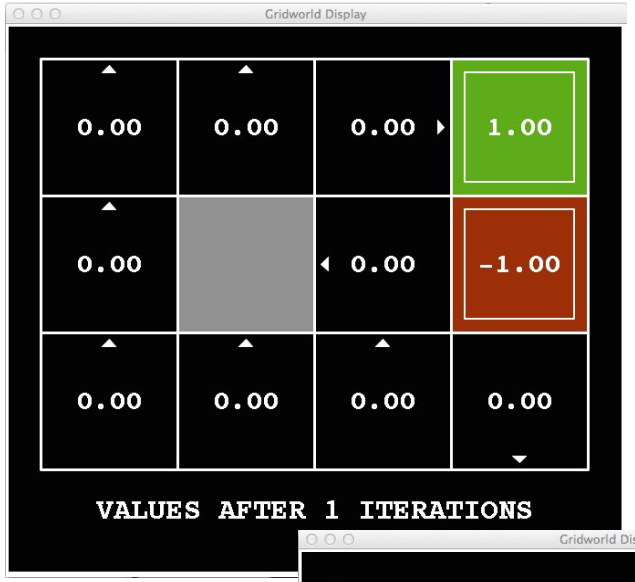
Solutions (briefly, more later…)

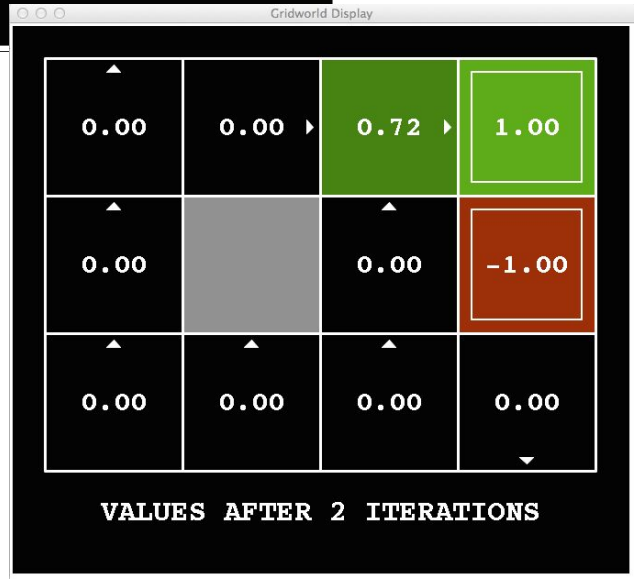
- Issue 1: It's slow – $O(S^2A)$ per iteration
  - Asynchronous value iteration
- Issue 2: A policy cannot be easily extracted
  - Learn q (action) values
- Issue 3: The policy often converges long before the values
  - Policy-based methods
- Issue 4: requires knowing the model and the reward function
  - Reinforcement learning
- Issue 5: requires discrete (finite) set of actions
  - Policy gradient methods
- Issue 6: infeasible for large (or continues) state spaces
  - Function approximators

Issue 1: It's slow – $O(S^2A)$ per iteration

- Asynchronous value iteration
- In value iteration, we update every state in each iteration
- Actually, *any* sequences of Bellman updates will converge if every state is visited infinitely often regardless of the visitation order
- Idea: prioritize states whose value we expect to change significantly

Asynchronous Value Iteration





- Which states should be prioritized for an update?

A single update per iteration

Algorithm 3 Prioritized Value Iteration

1: **repeat**
2: $s \leftarrow \arg\max_{\xi \in S} H(\xi)$
3: $V(s) \leftarrow \max_{a \in A} \{R(s,a) + \gamma \sum_{s' \in S} Pr(s'|s,a) V(s')\}$
4: **for all** $s' \in SDS(s)$ **do**
5: // recompute $H(s')$
6: **end for**
7: **until** convergence

$$SDS(s) = \{s' : \exists a, p(s|s',a) > 0\}$$

For the home assignment set:

$$H(s') = \left| V(s') - \max_{a} \left\{ R(s',a) + \gamma \sum_{s''} \Pr(s''|s',a) V(s'') \right\} \right|$$

Double the work?

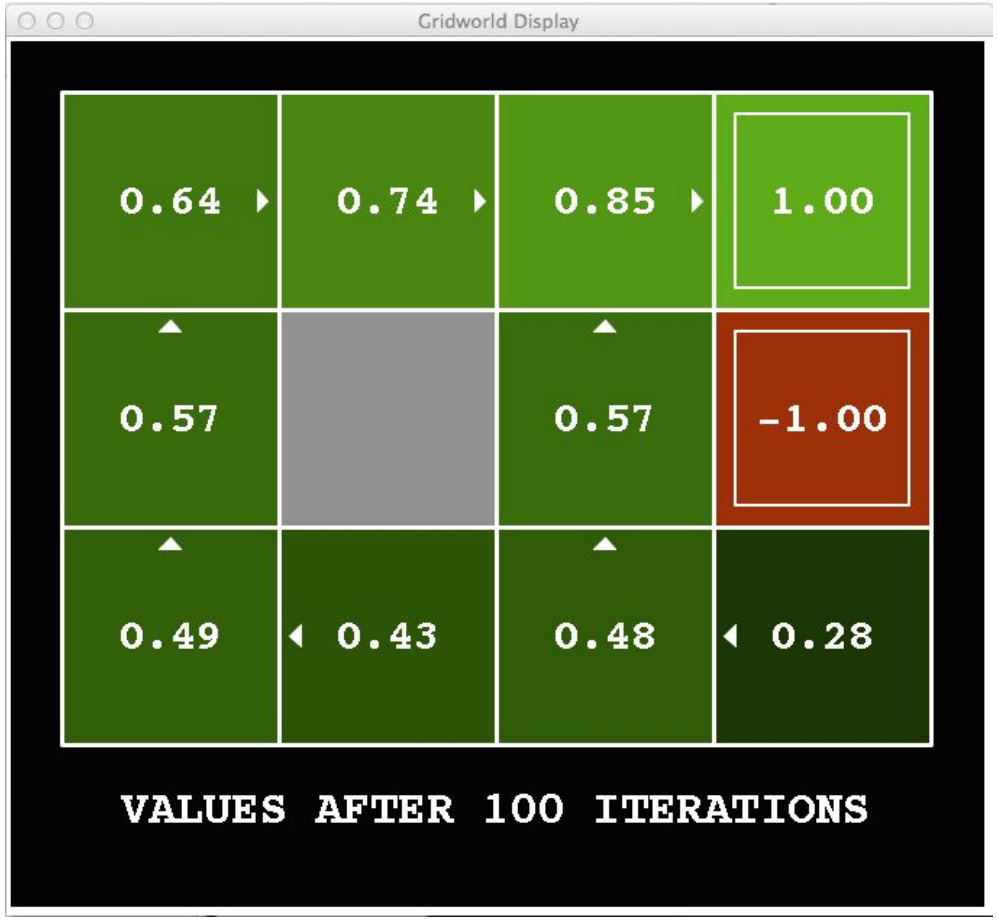
For the home assignment set:

$$H(s') = \left| V(s') - \max_{a} \left\{ R(s', a) + \gamma \sum_{s''} \Pr(s''|s', a) V(s'') \right\} \right|$$

- Computing priority is similar to updating the state value (W.R.T computational effort)
- Why do double work?
  - If we computed the priority, we can go ahead and update the value for free
- Notice that we don't need to update the priorities for the entire state space
- For many of the states the priority doesn't change following an updated value for a single state s
- Only states s' with $\sum_a p(s'|s,a) > 0$ require update

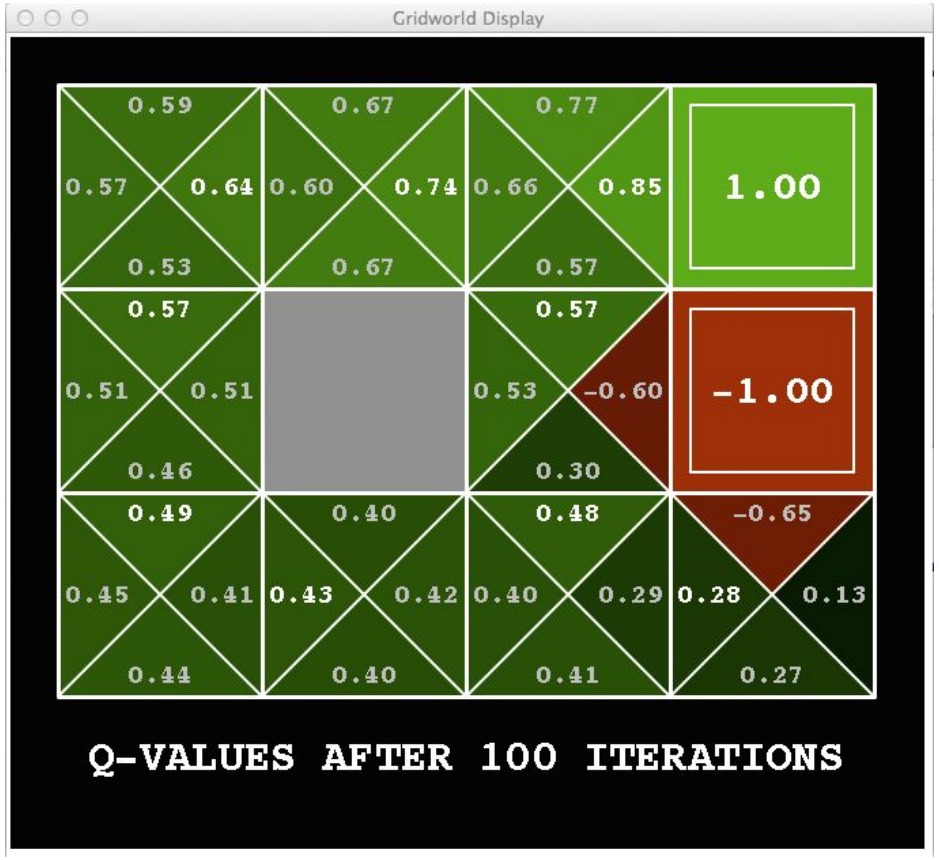
Issue 2: A policy cannot be easily extracted

- Given state values, what is the appropriate policy?
  - $\pi(s) \leftarrow \underset{a}{\text{argmax}}\left[R(s,a) + \sum_{s'} P(s'|s,a)\ \gamma V_k(s')\right]$
  - Requires another full value sweep: $O(S^2A)$
- Learn q (action) values instead
- $Q^*(s,a)$ - the expected sum of rewards from being at s, taking action a and then following π^*



Q-learning

- $Q^*(s, a)$ - the expected sum of rewards from being at s, taking action a and then following π^*
- $\pi^*(s) \leftarrow \underset{a}{\text{argmax}}[Q^*(s, a)]$
- Can we learn Q values with dynamic programming?
  - Yes, similar to value iteration

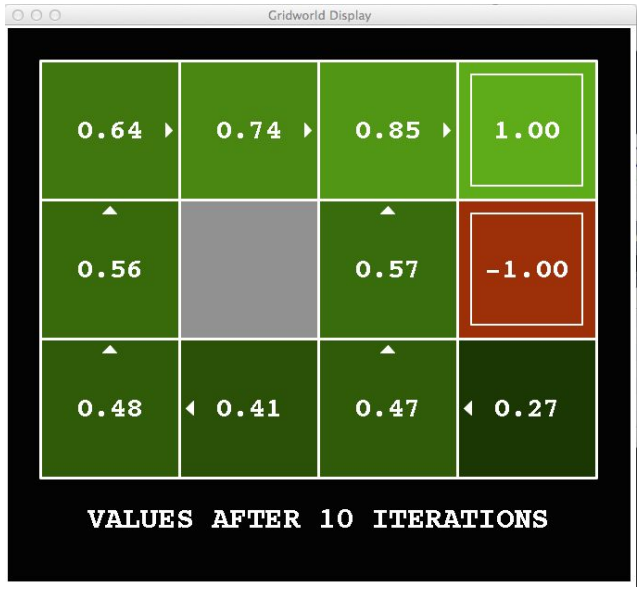


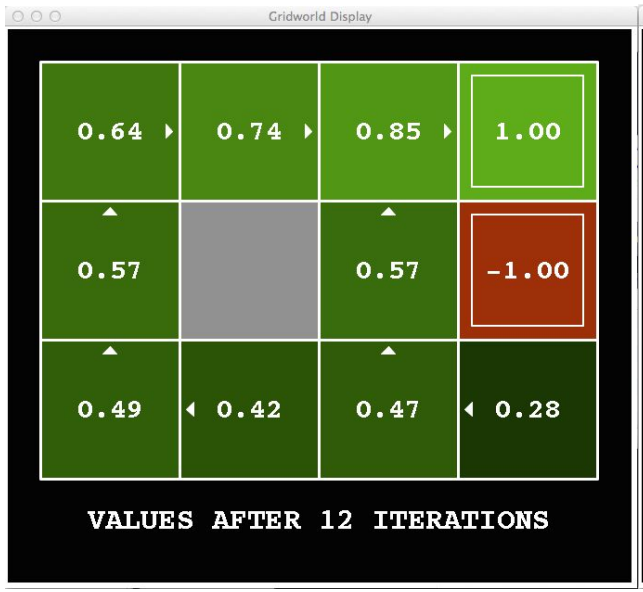
Q-learning as value iteration

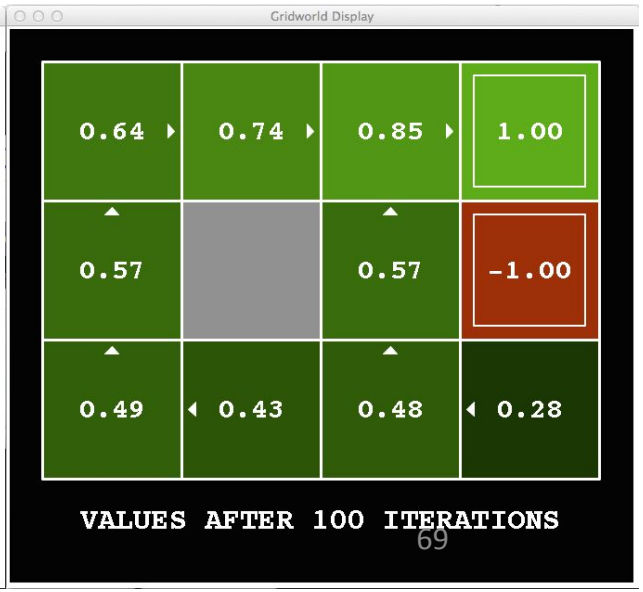
- $V^*(s) \coloneqq \max_a [\sum_{s'} P(s'|s,a)\,(R(s,a,s') + \gamma V^*(s'))]$
- $V^*(s) \coloneqq \max_a [Q^*(s,a)]$
- $Q^*(s,a) \coloneqq \sum_{s'} P(s'|s,a)\,(R(s,a,s') + \gamma V^*(s'))$
- $Q^*(s,a) = \sum_{s'} P(s'|s,a)\,(R(s,a,s') + \gamma \max_a [Q^*(s',a)])$
- Solve iteratively
  - $Q_{k+1}(s,a) = \sum_{s'} P(s'|s,a)\,(R(s,a,s') + \gamma \max_a [Q_k(s',a)])$
  - Can also use Asynchronous learning

Issue 3: The policy often converges long before the values

- Value iteration converges to the true utility value: $V_{k\to\infty} \to V^*$
- V^* implies the optimal policy: π^*
- Can we converge directly on π^*?
  - Improve the policy in iteration until reaching the optimal one

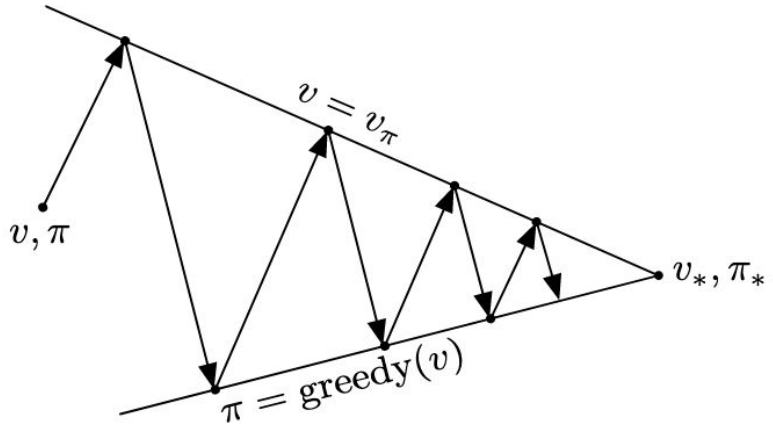






Policy Iteration

1. Compute V_π: calculate state value for some fixed policy (not necessarily the optimal values, $V_\pi \neq V^*$)
2. Update π: update policy using one-step look-ahead with the resulting (non optimal) values
3. Repeat until policy converges
   (optimal values and policy)



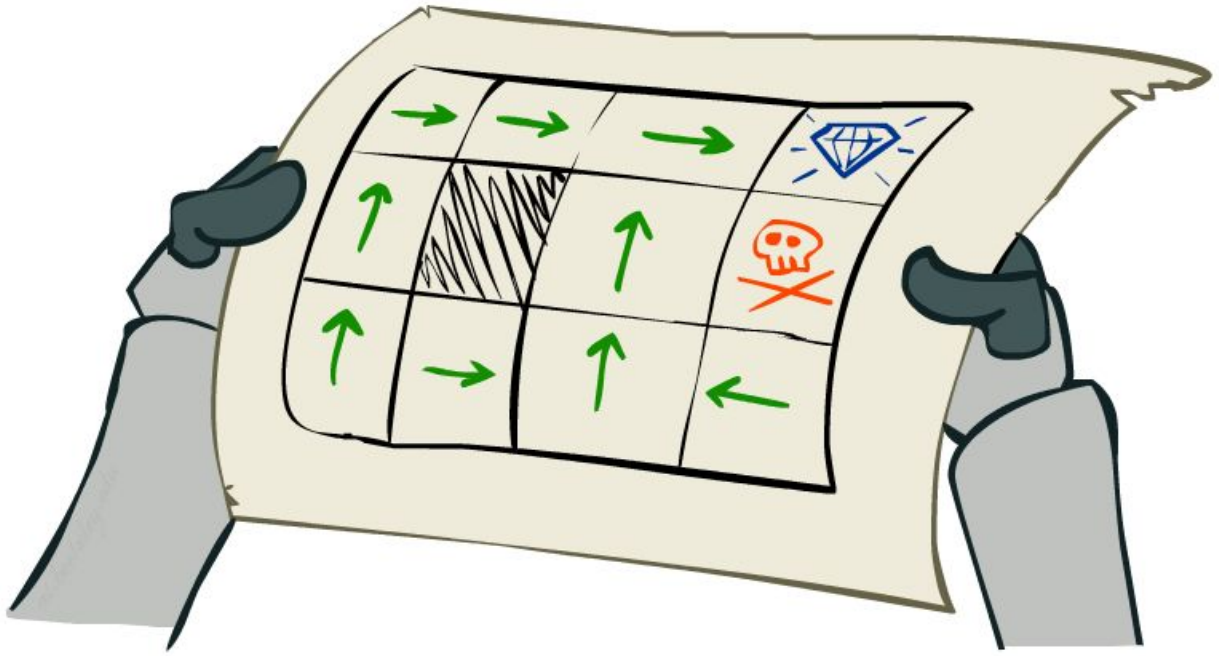
- Guaranteed converges to π^*
  - $\forall s, V_{k>0}(s) \leq V_{k+1}(s)$ i.e., π_i improves monotonically with i
  - A fixed point, $\forall s, V_k(s) = V_{k+1}(s)$, implies π^*

Policy Evaluation

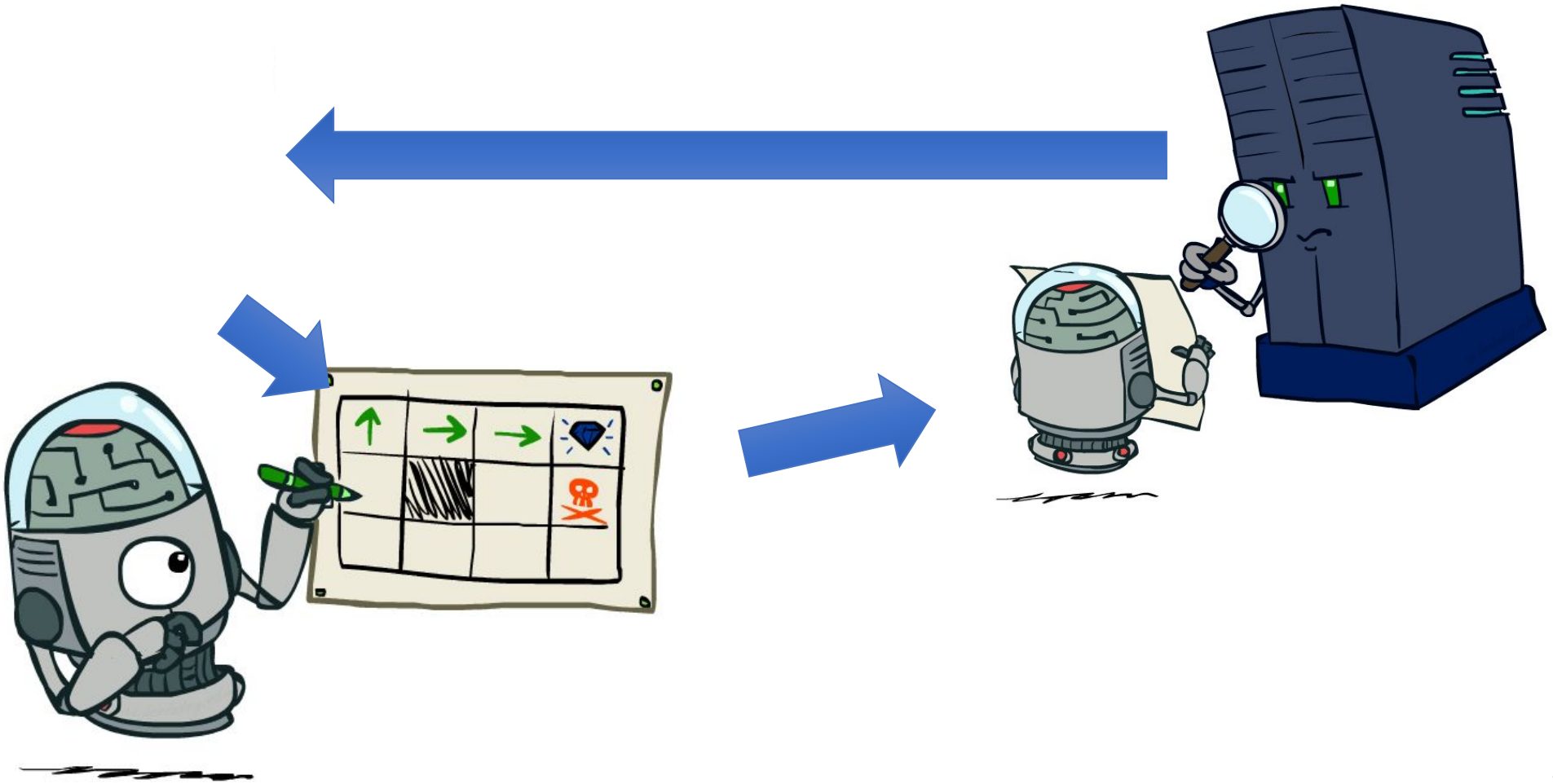
- Why is calculating V_π easier that calculating V^*?
  - Turns non-linear Bellman equations into linear equations
- $v^*(s) = \max_a [\sum_{s'} P(s'|s,a)\,(R(s,a,s') + \gamma v^*(s'))]$
- $v_\pi(s) = \sum_{s'} P(s'|s,\pi(s))\,(R(s,\pi(s),s') + \gamma v^*(s'))$
- Solve a set of linear equations in $O(S^2)$
  - Solve with Numpy (numpy.linalg.solve)
  - Required for your home assignment
  - See: https://numpy.org/doc/stable/reference/generated/numpy.linalg.solve.html#numpy.linalg.solve

Policy value as a Linear program

- $v_{11} = 0.8 \cdot (-0.1 + 0.95 \cdot v_{12}) + 0.1 \cdot (-0.1 + 0.95 \cdot v_{21}) + 0.1 \cdot (-0.1 + 0.95 \cdot v_{11})$
- $v_{12} = 0.8 \cdot (-0.1 + 0.95 \cdot v_{13}) + 0.2 \cdot (-0.1 + 0.95 \cdot v_{12})$
- …
- $v_{42} = -1$
- $v_{43} = 1$



Policy iteration

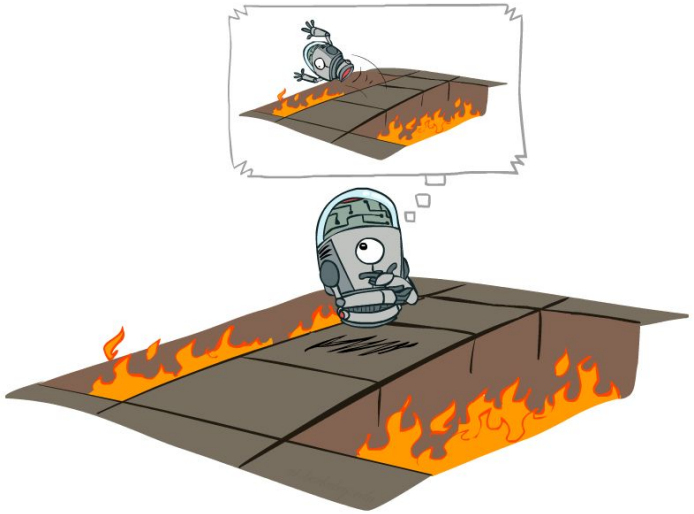


Comparison

- Both value iteration and policy iteration compute the same thing (optimal state values)
- In value iteration:
  - Every iteration updates both the values and (implicitly) the policy
  - We don’t track the policy, but taking the max over actions implicitly define it
- In policy iteration:
  - We do several passes that update utilities with fixed policies (each pass is fast because we consider only one action, not all of them)
  - After the policy is evaluated, a new policy is chosen (slow like a value iteration pass)
  - The new policy will be better (or we’re done)

Issue 4: requires knowing the model and the reward function

- We will explore online learning (reinforcement learning) approaches
- How can we learn the model and reward function from interactions?
- Do we even need to learn them? Can we learn V^*, Q^* without a model?
- Can we do without V^*, Q^* ? Can we run policy iteration without a model?



Offline optimization

Online Learning

Issue 5: requires discrete (finite) set of actions

- We will explore policy gradient approaches that are suitable for continuous actions, e.g., throttle and steering for a vehicle
- Can such approaches be relevant for discrete action spaces?
  - Yes! We can always define a continues action space as a distribution over the discreate actions (e.g., using the softmax function)
- Can we combine value-based approaches and policy gradient approaches and get the best of both?
  - Yes! Actor-critic methods

Issue 6: infeasible in large (or continues) state spaces

- Most real-life problems contain very large state spaces (practically infinite)
- It is infeasible to learn and store a value for every state
- Moreover, doing so is not useful as the chance of encountering a state more than once is very small
- We will learn to generalize our learning to apply to unseen states
- We will use value function approximators that can generalize the acquired knowledge and provide a value to any state (even if it was not previously seen)

Notation

- π^* - a policy that that yields the maximal expected sum of rewards
- $V^*(s)$ - the expected sum of rewards from being at s then following π^*
- $V_\pi(s)$ - the expected sum of rewards from being at s then following π
- $Q^*(s,a)$ - the expected sum of rewards from being at s, taking action a and then following π^*
- $Q_\pi(s,a)$ - the expected sum of rewards from being at s, taking action a and then following π
- G_t - observed sum of rewards following time t, i.e., $\sum_{k=t}^{T} r_k$

Required Readings

1. Chapter-3,4 of Introduction to Reinforcement Learning,2nd Ed., Sutton & Barto

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Thank you