Announcements

- OH on Wednesdays 1:30pm-2:30pm

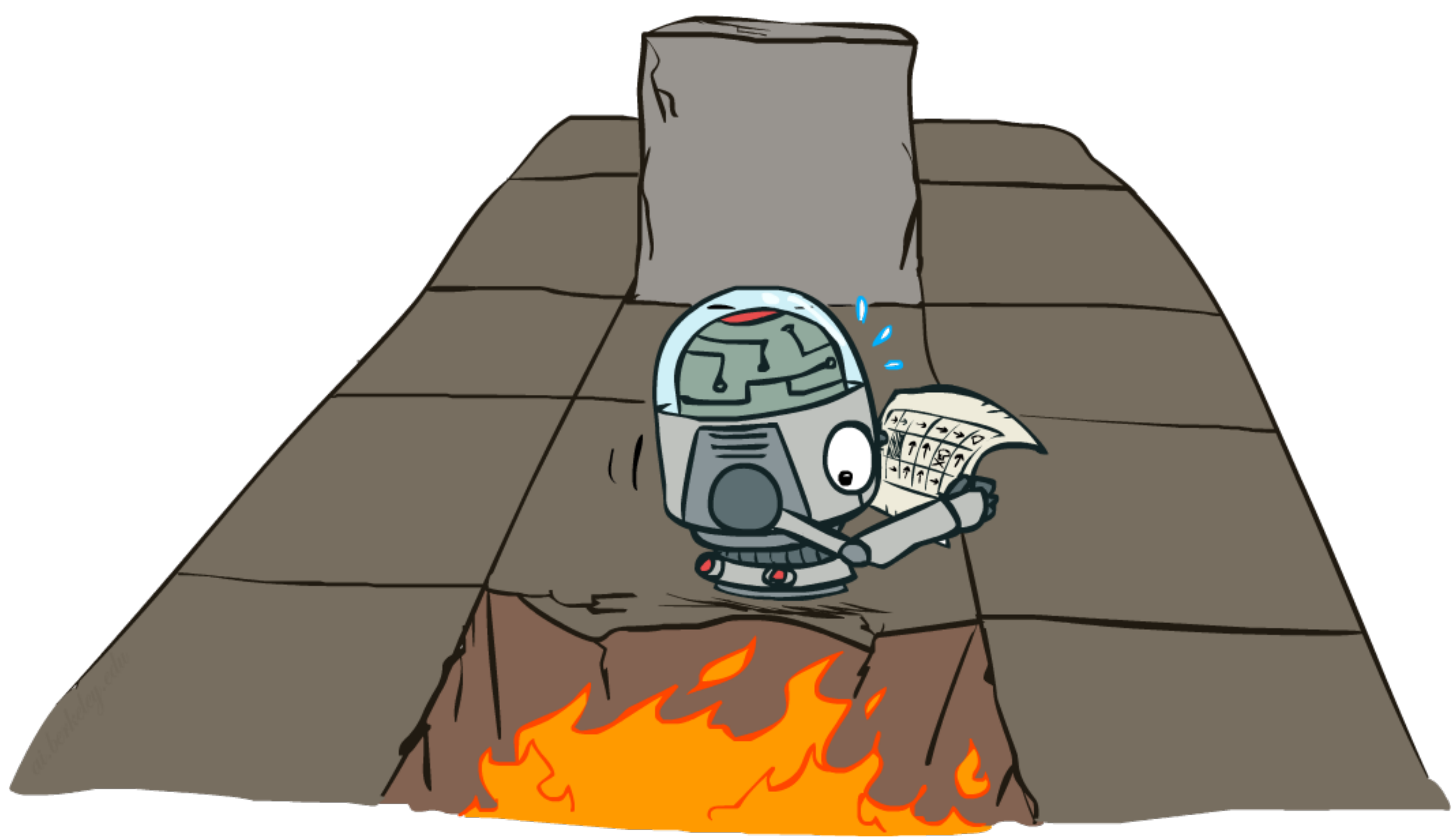
- Project 1: Search
  - Due today at 11:59pm
- Homework 3: Games
  - Due Oct. 14 at 11:59pm

- Ask questions via Piazza preferably
- Send email to the whole teaching team
- Avoid private messaging via Canvas

- Project slip days: total 5, max 2 per project
- Homework Drop policy: 2 electronic, 2 written

Ve492: Introduction to Artificial Intelligence

Markov Decision Processes II

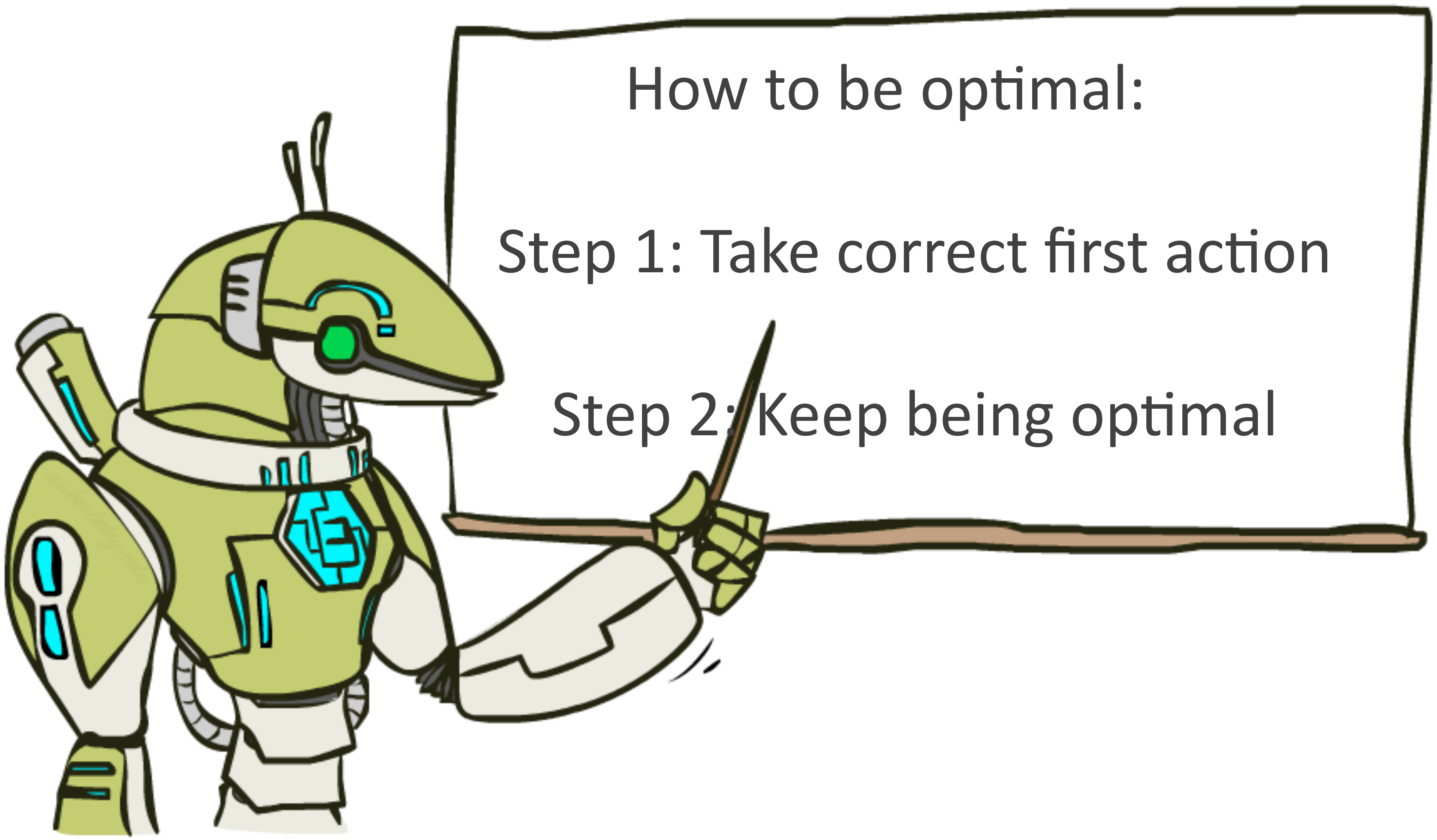


Paul Weng

UM-SJTU Joint Institute

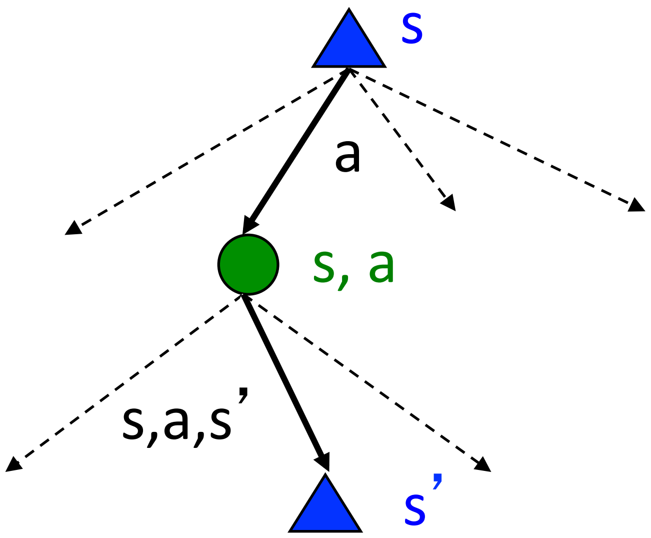
Slides adapted from http://ai.berkeley.edu, AIMA, UM, CMU

The Bellman Equations



The Bellman Equations

- Definition of "optimal utility" via expectimax recurrence gives a simple one-step lookahead relationship amongst optimal utility values



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

$$Q^*(s,a) = \sum_{s'} T(s,a,s') \left[R(s,a,s') + \gamma V^*(s') \right]$$

$$V^*(s) = \max_a \sum_{s'} T(s,a,s') \left[R(s,a,s') + \gamma V^*(s') \right]$$

- These are the Bellman equations, and they characterize optimal values in a way we'll use over and over

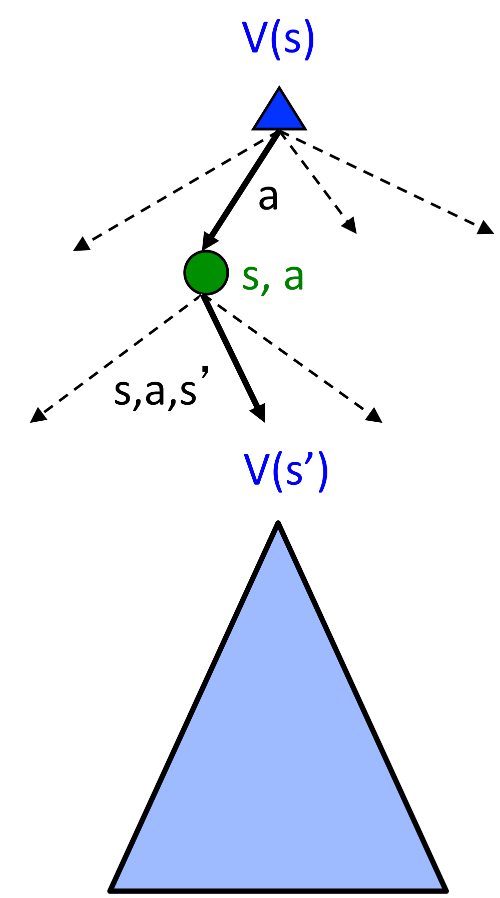
Value Iteration

- Bellman equations characterize the optimal values:

$$V^*(s) = \max_a \sum_{s'} T(s,a,s') \left[R(s,a,s') + \gamma V^*(s') \right]$$

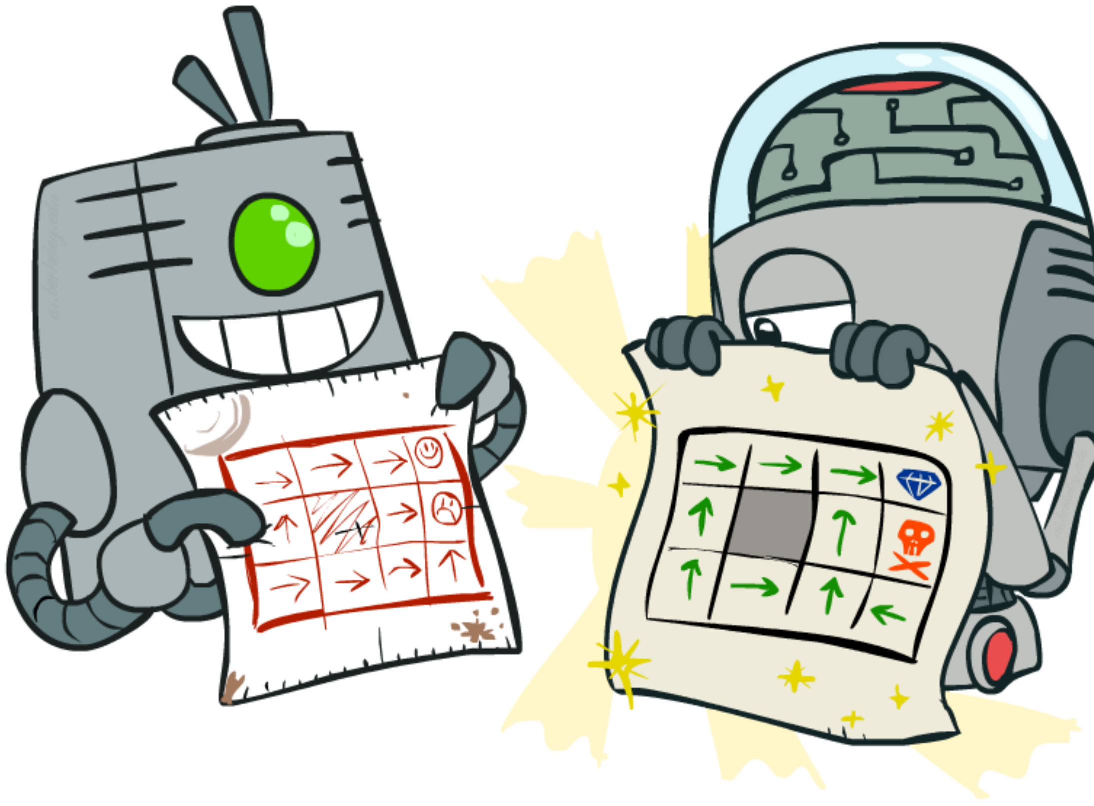
- Value iteration computes them:

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



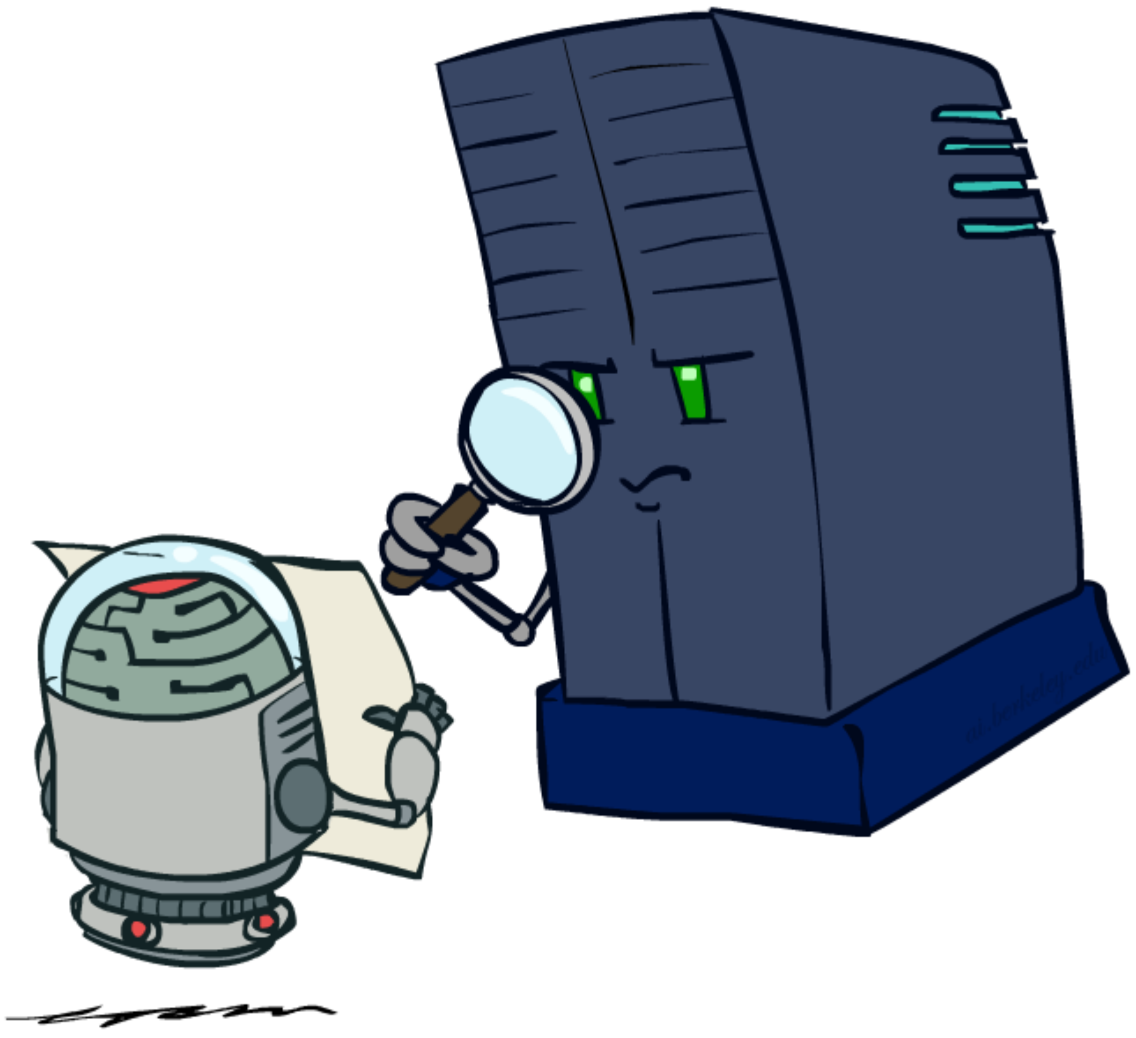
- Value iteration is just a fixed point solution method
  - … though the V_k vectors are also interpretable as time-limited values

Policy Methods



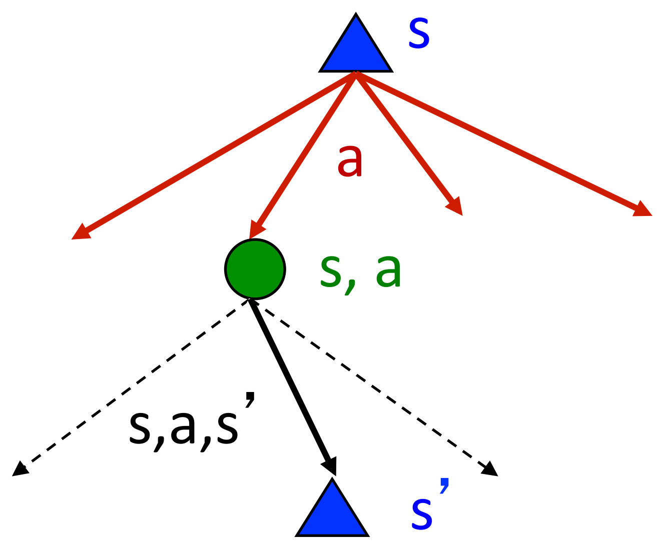
Policy Methods

Policy Evaluation



Fixed Policies

Do the optimal action



Do what π says to do

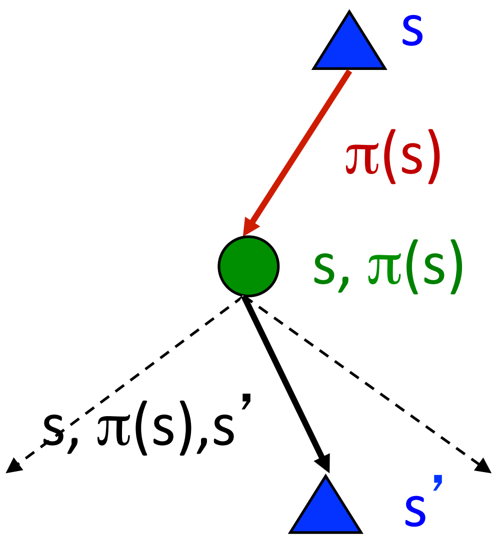
- Expectimax trees max over all actions to compute the optimal values
- If we fixed some policy π(s), then the tree would be simpler – only one action per state
  - … though the tree's value would depend on which policy we fixed

Utilities for a Fixed Policy

- Another basic operation: compute the utility of a state s under a fixed (generally non-optimal) policy
- Define the utility of a state s, under a fixed policy π:

  $V^{\pi}(s)$ = expected total discounted rewards starting in s and following π

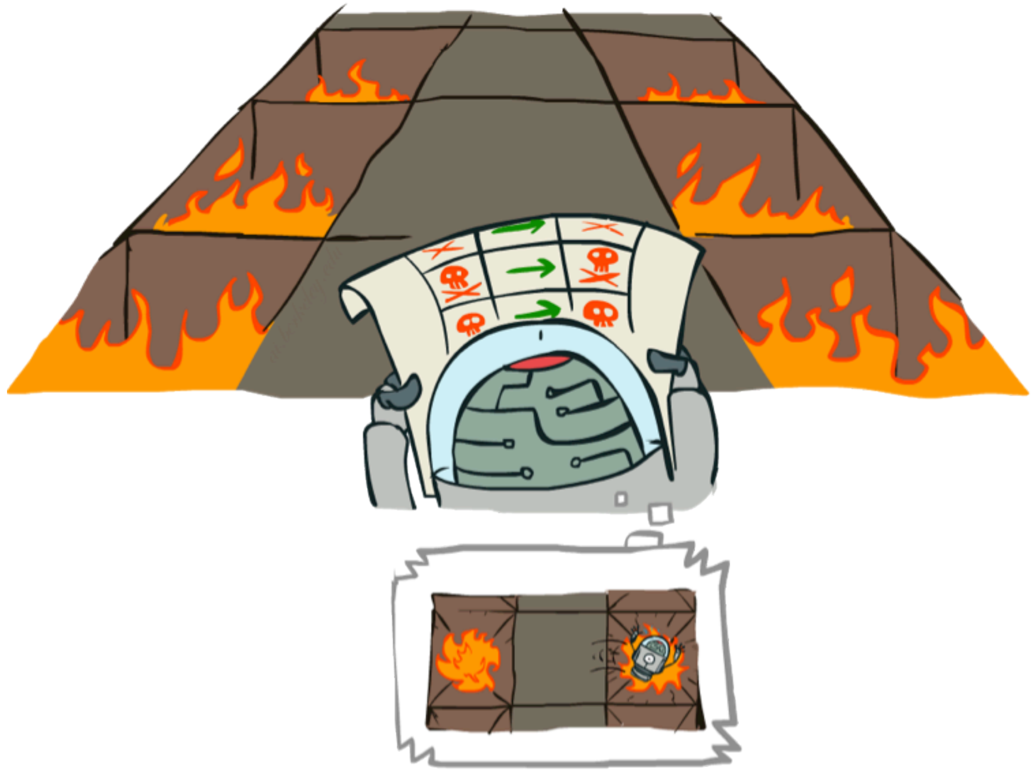
- Recursive relation (one-step look-ahead / Bellman equation):



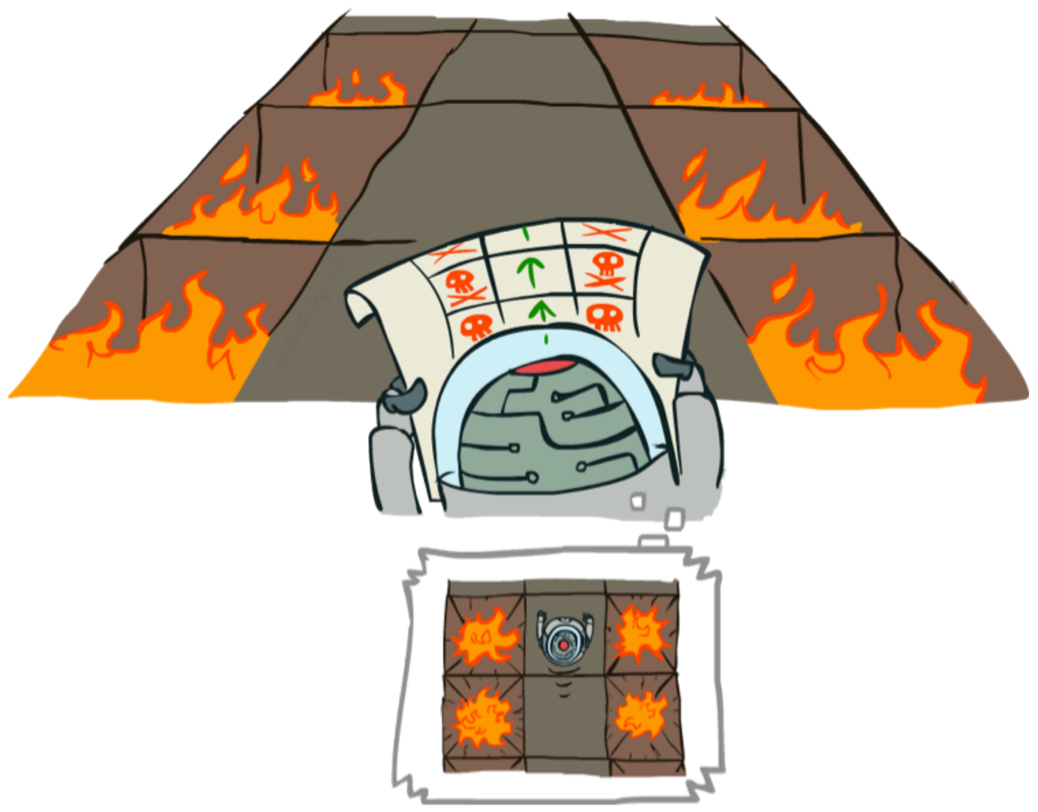
$$V^{\pi}(s) = \sum_{s'} T(s, \pi(s), s')[R(s, \pi(s), s') + \gamma V^{\pi}(s')]$$

Example: Policy Evaluation

Always Go Right



Always Go Forward



Example: Policy Evaluation

Always Go Right

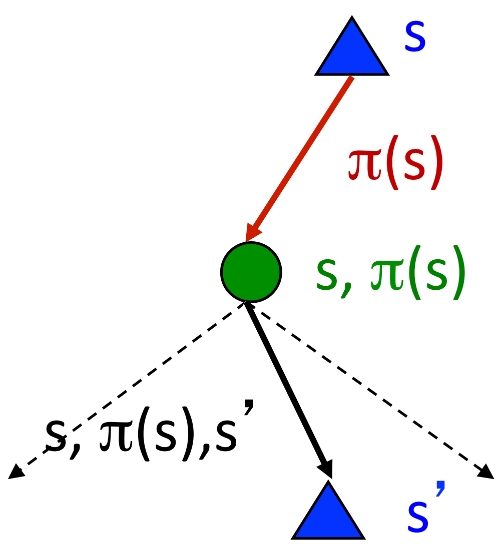
Always Go Forward

Policy Evaluation

- How do we calculate the V's for a fixed policy π?
- Idea 1: Turn recursive Bellman equations into updates (like value iteration)

$$V_0^{\pi}(s) = 0$$

$$V_{k+1}^{\pi}(s) \leftarrow \sum_{s'} T(s,\pi(s),s')[R(s,\pi(s),s') + \gamma V_k^{\pi}(s')]$$

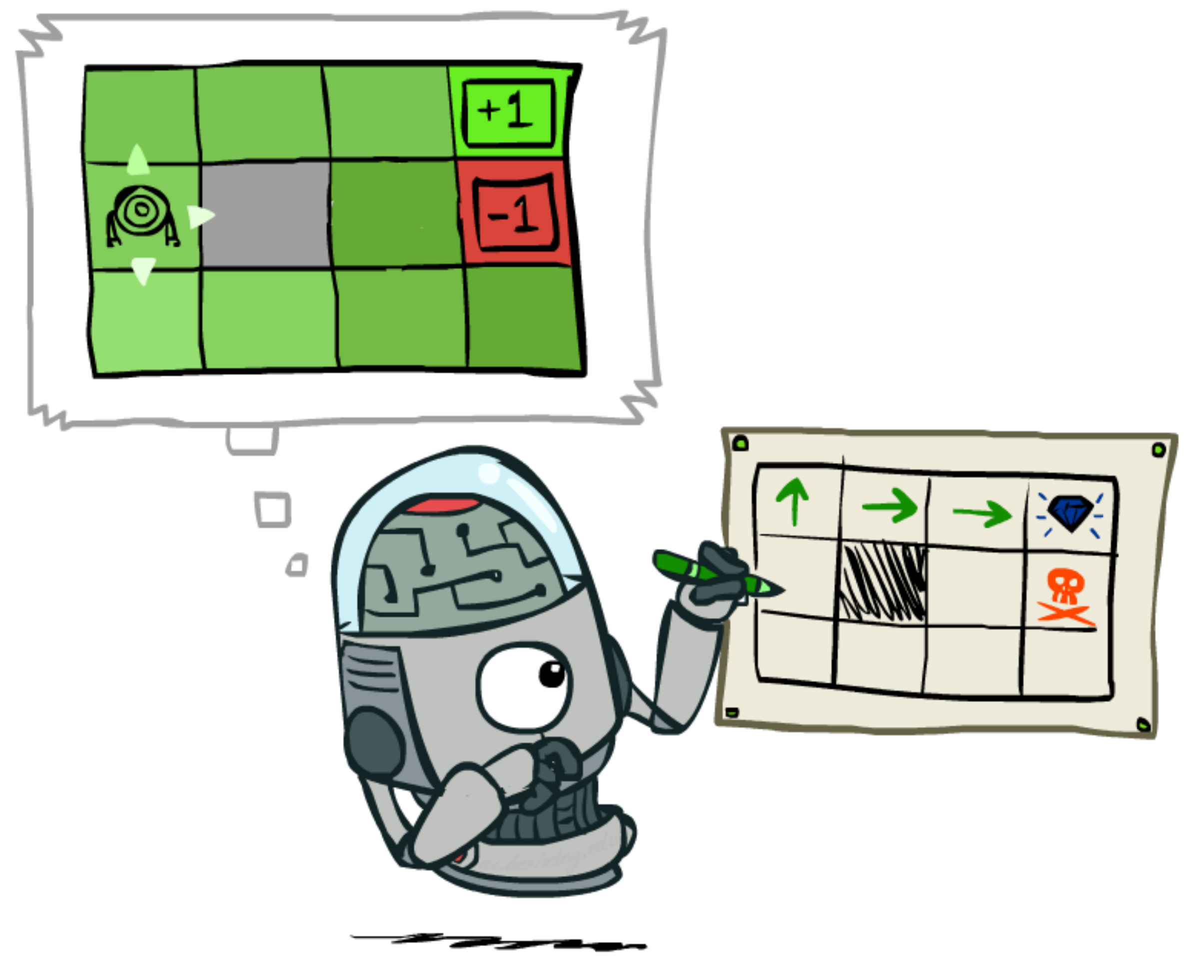


- Efficiency: O(S²) per iteration

- Idea 2: Without the maxes, the Bellman equations are just a linear system
  - Solve with Matlab (or your favorite linear system solver)

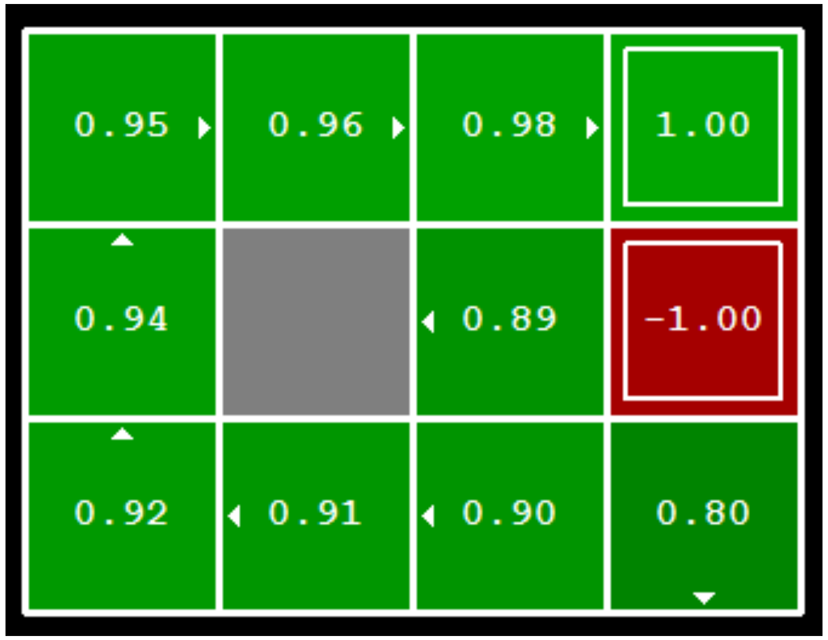
Policy Methods

Policy Extraction



Computing Actions from Values

- Let's imagine we have the optimal values V*(s)



- How should we act?
    - It's not obvious!

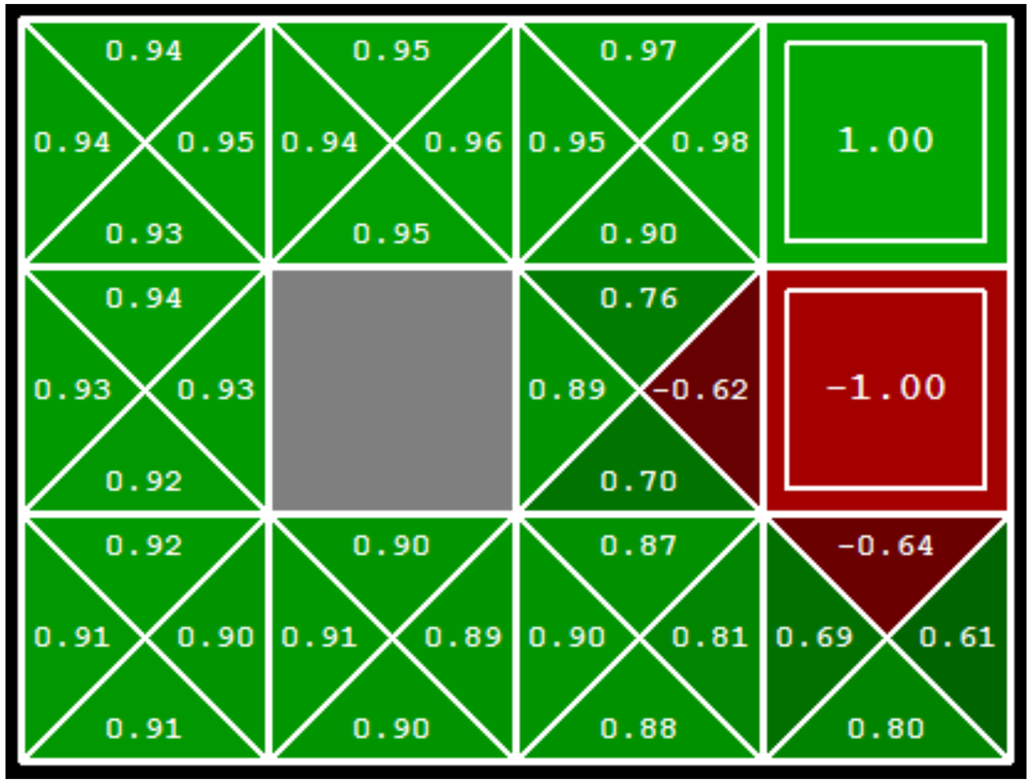
- We need to do a one-step expectimax

$$\pi^*(s) = \arg\max_a \sum_{s'} T(s,a,s')[R(s,a,s') + \gamma V^*(s')]$$

- This is called policy extraction, since it gets the policy implied by the values

Computing Actions from Q-Values

- Let's imagine we have the optimal q-values:



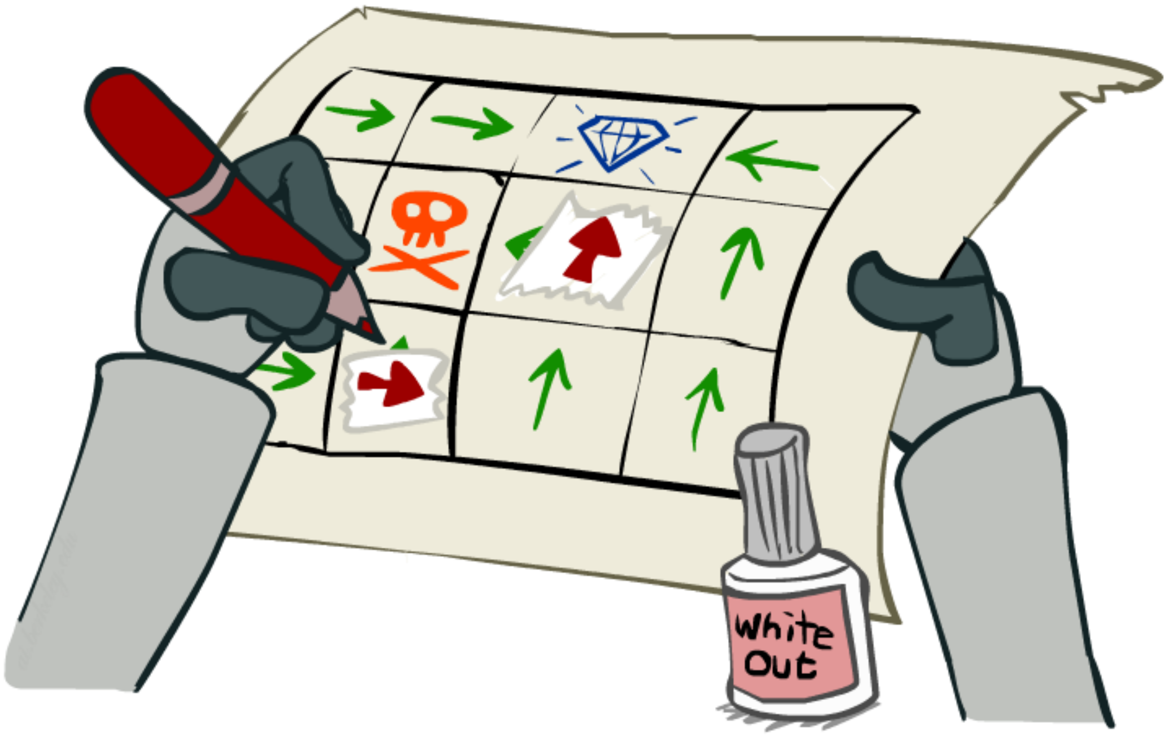
- How should we act?
  - Completely trivial to decide!

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

- Important lesson: actions are easier to select from q-values than values!

Policy Methods

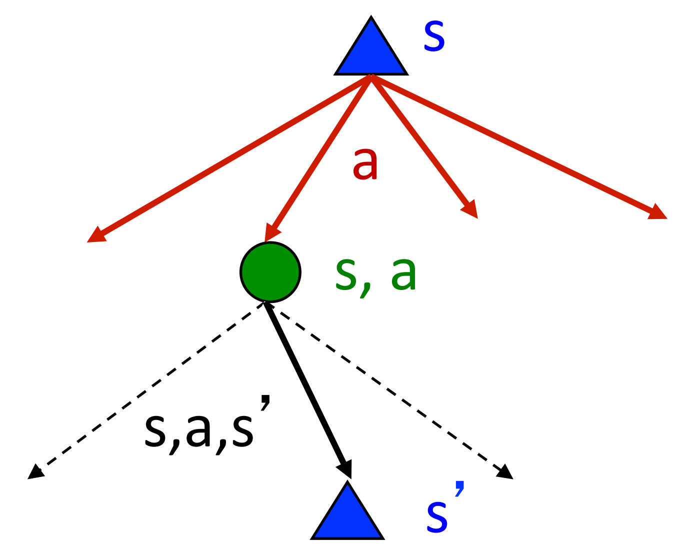
Policy Iteration



Problems with Value Iteration

- Value iteration repeats the Bellman updates:

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

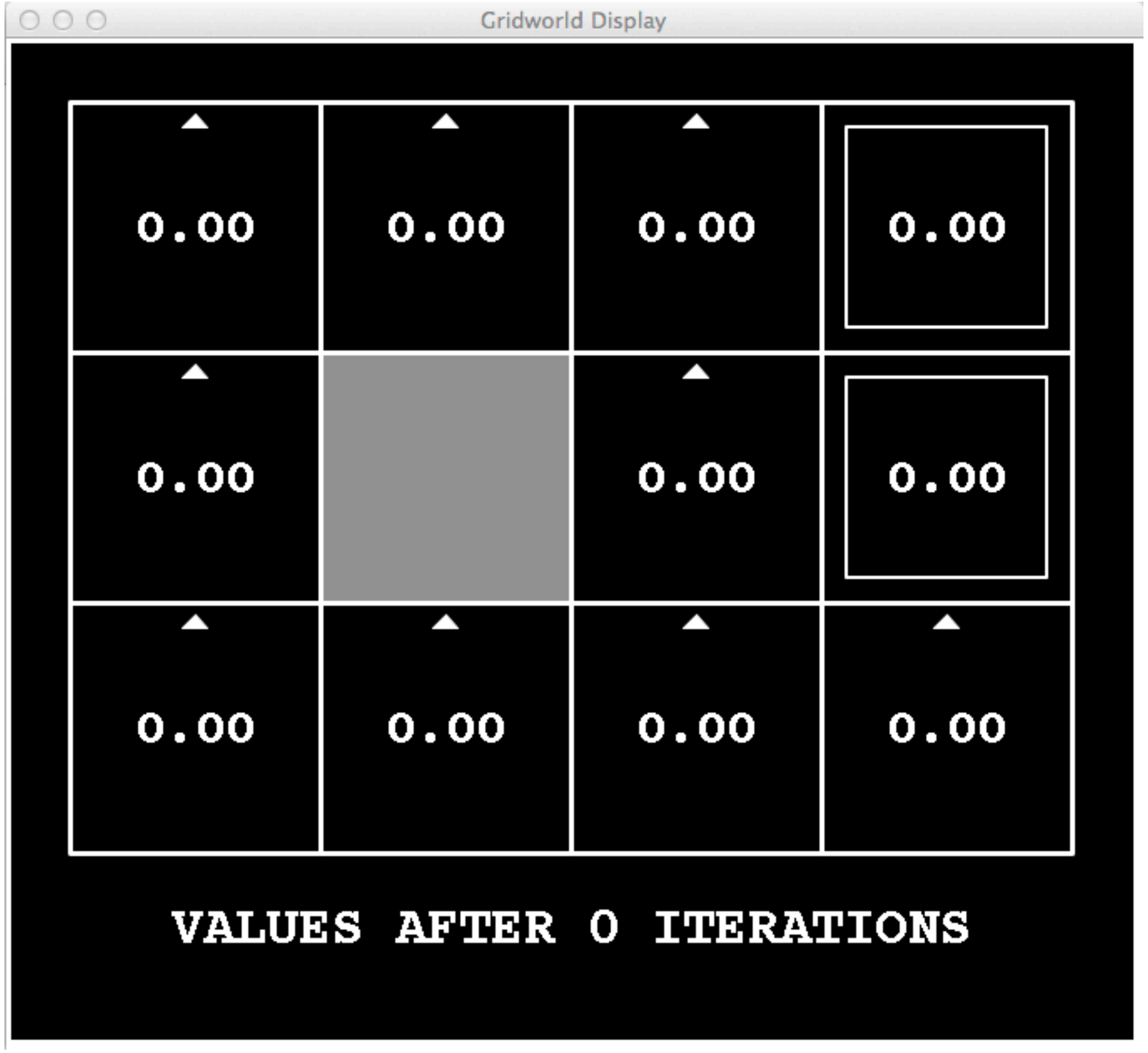


- Problem 1: It's slow – O(S²A) per iteration

- Problem 2: The "max" at each state rarely changes

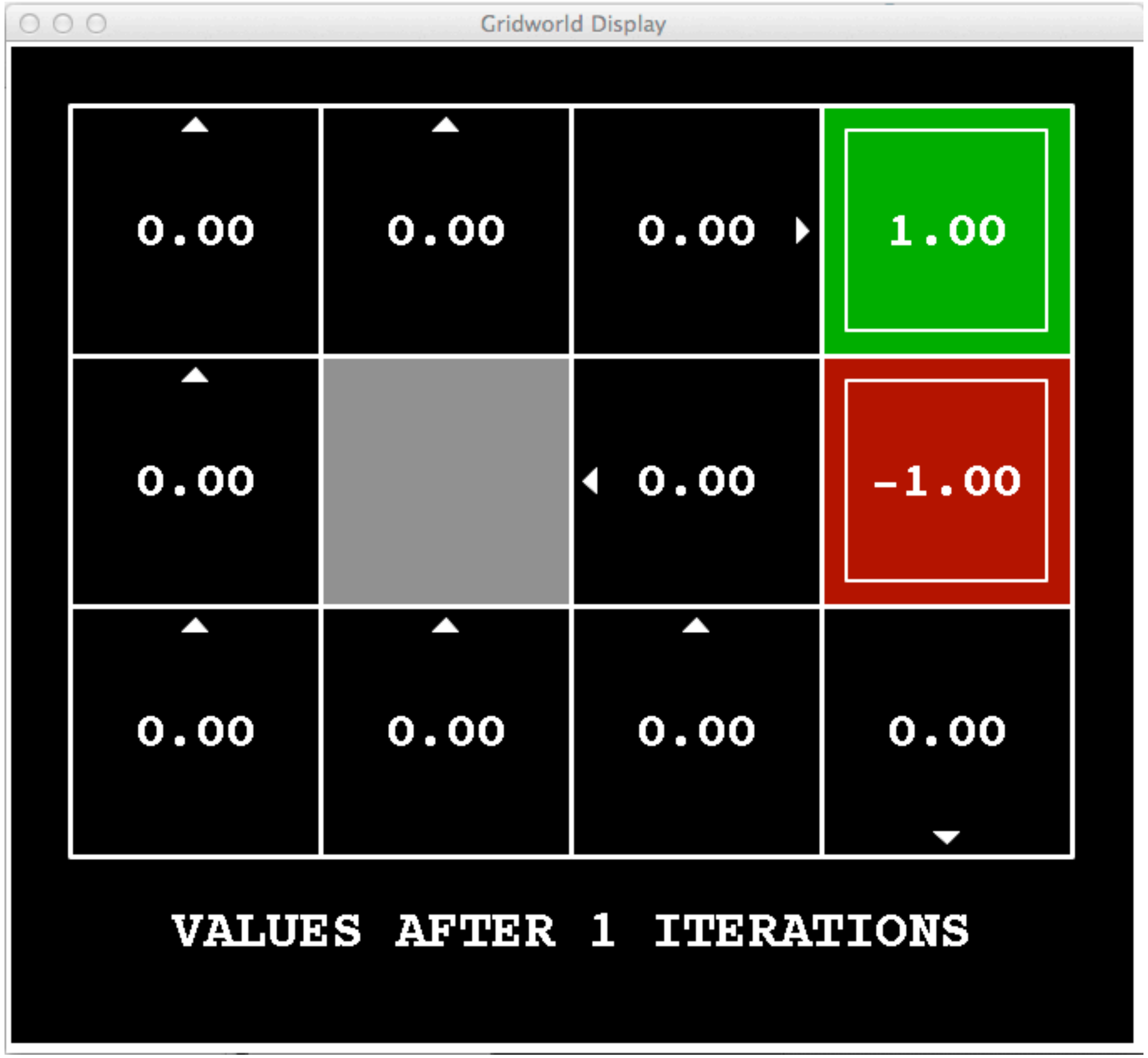
- Problem 3: The policy often converges long before the values

k=0



Noise = 0.2
Discount = 0.9
Living reward = 0

k=1



Noise = 0.2
Discount = 0.9
Living reward = 0

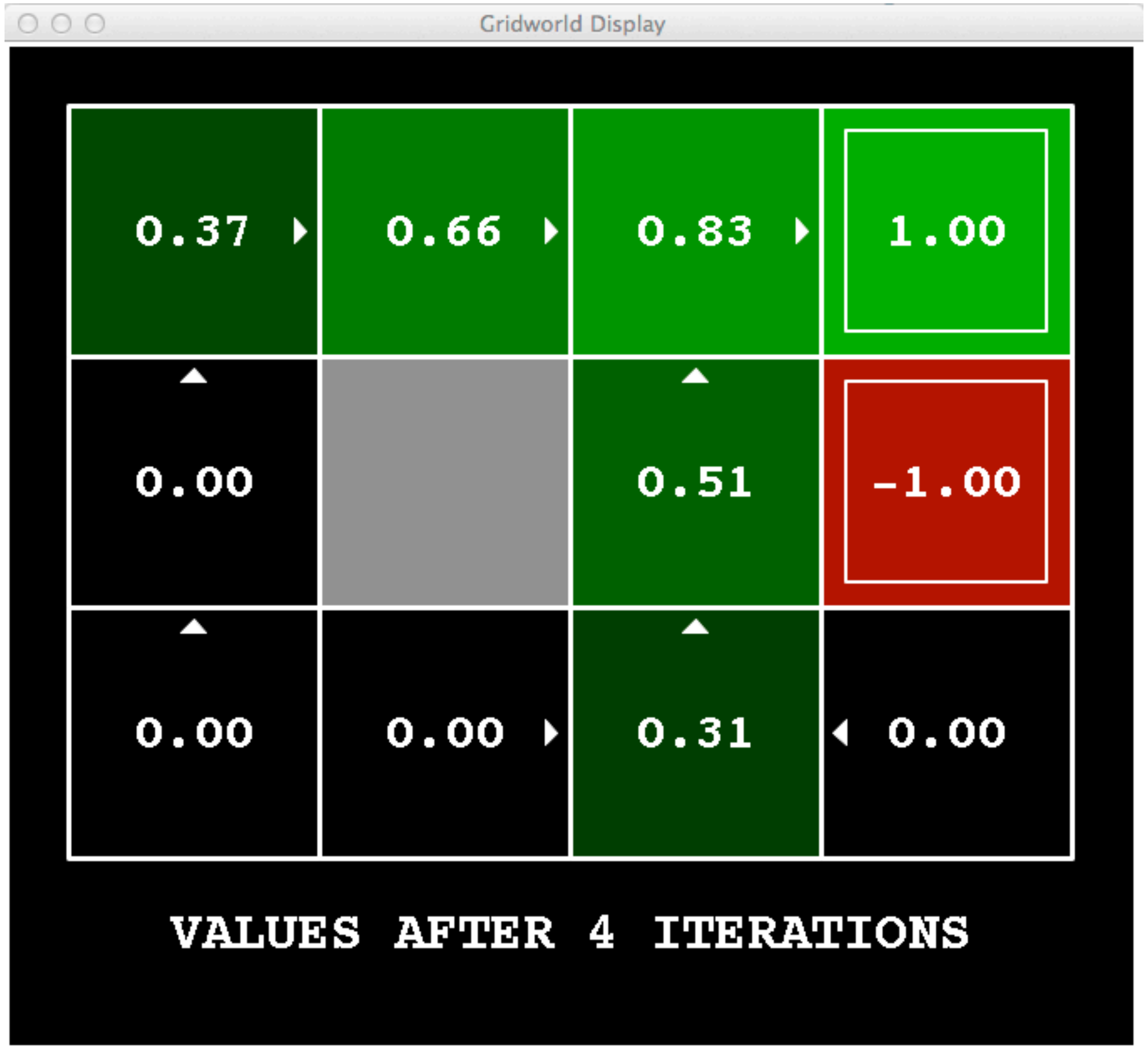
k=2

Noise = 0.2
Discount = 0.9
Living reward = 0

k=3

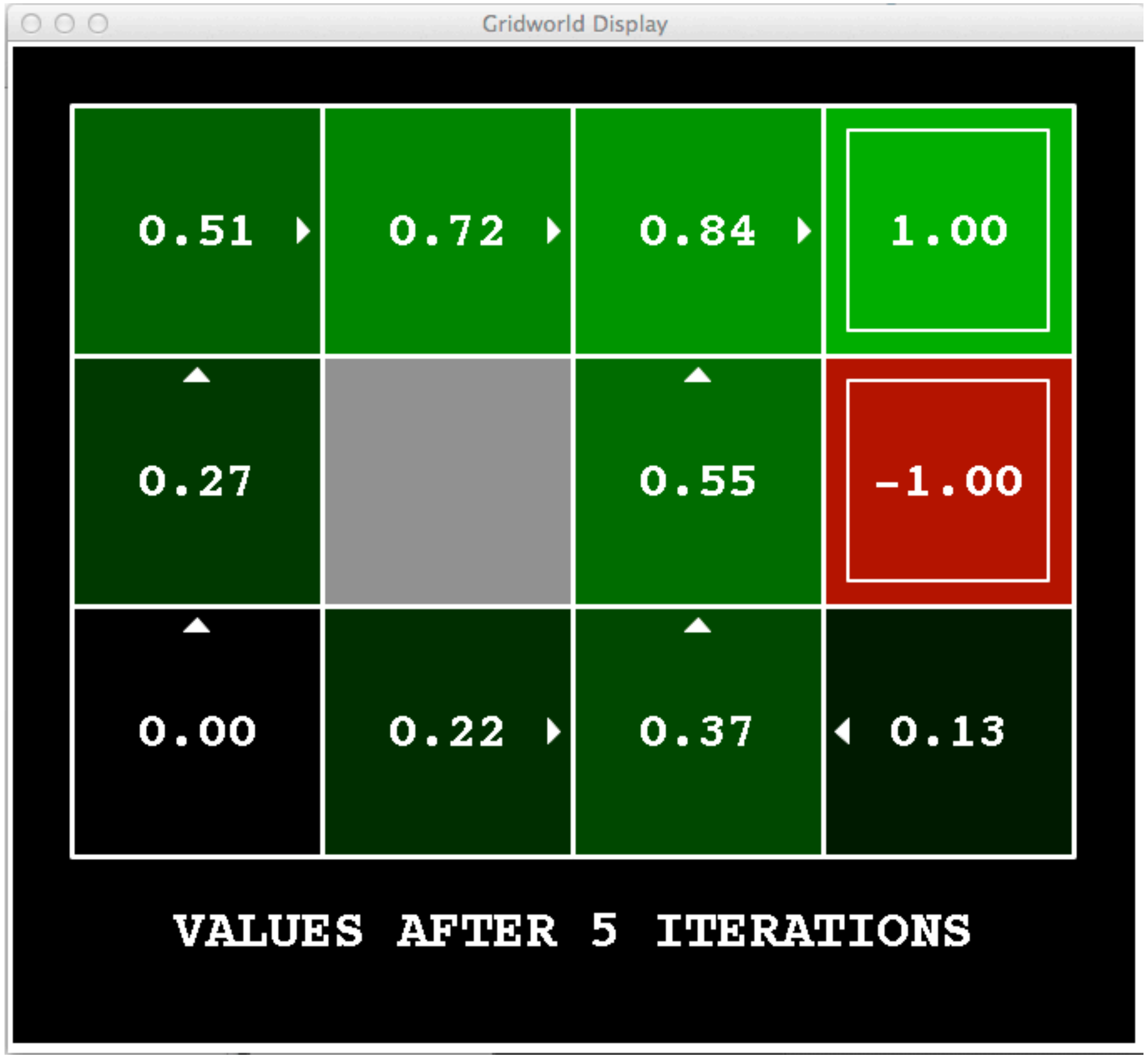
Noise = 0.2
Discount = 0.9
Living reward = 0

k=4



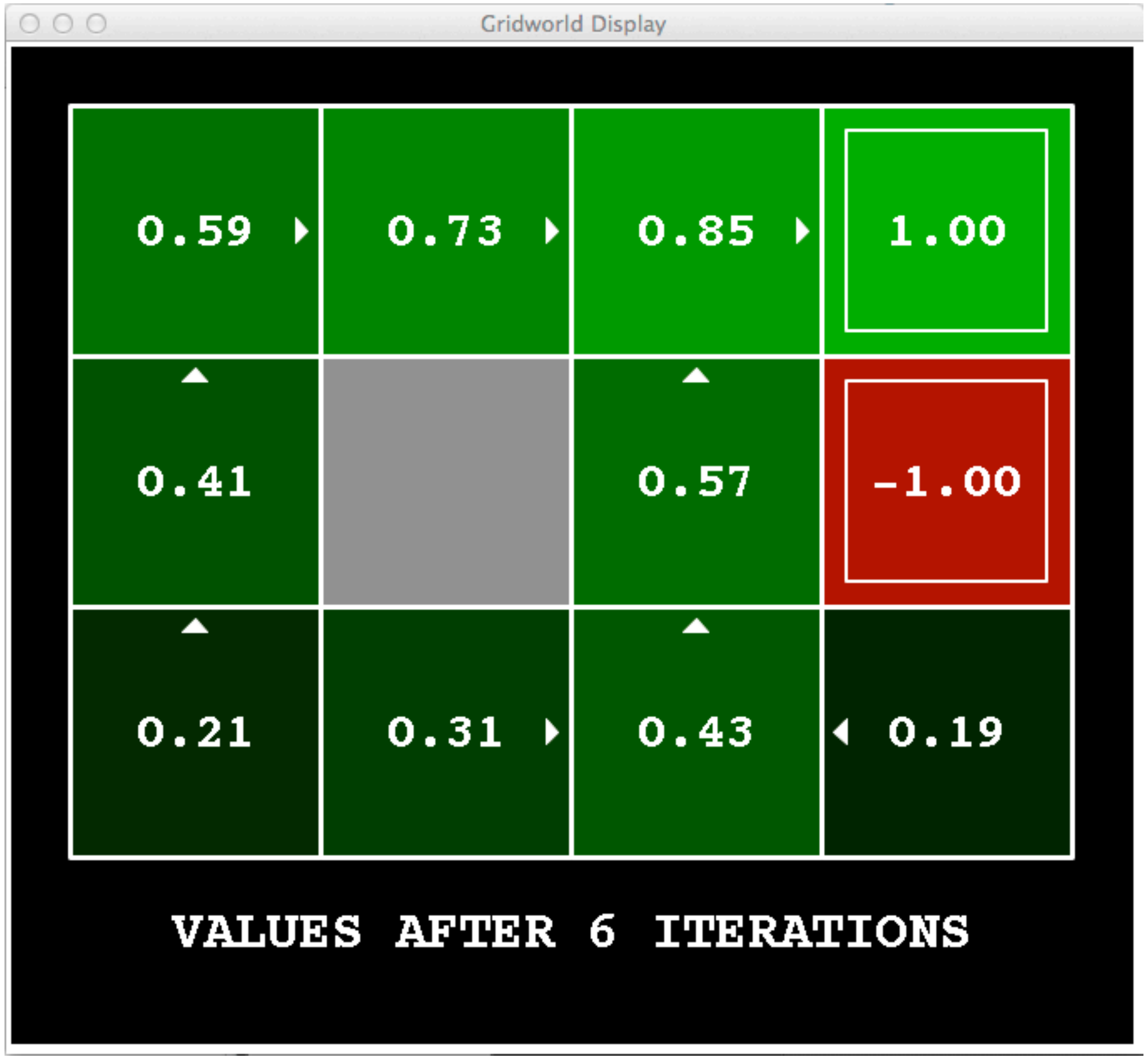
Noise = 0.2
Discount = 0.9
Living reward = 0

k=5



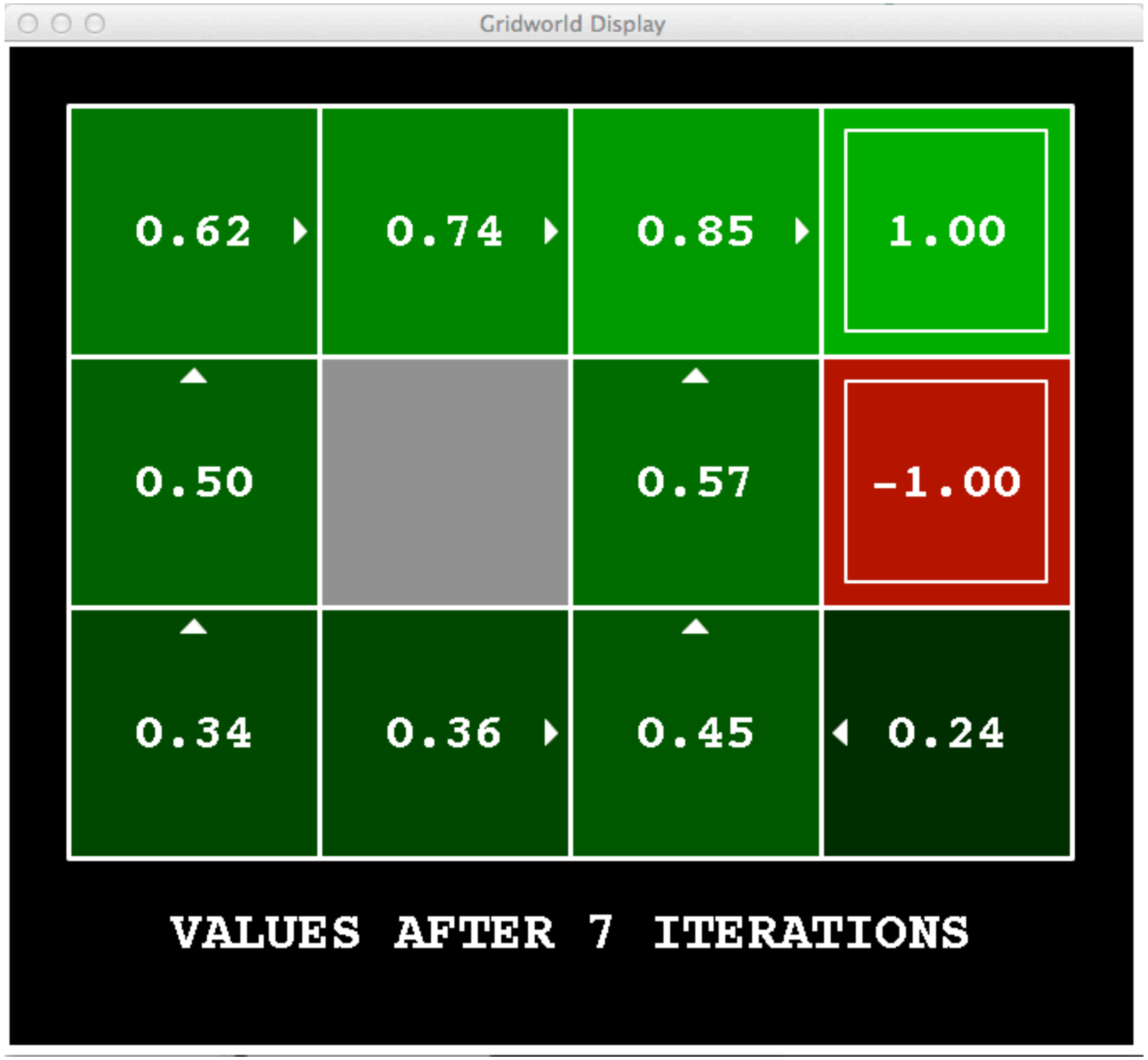
Noise = 0.2
Discount = 0.9
Living reward = 0

k=6



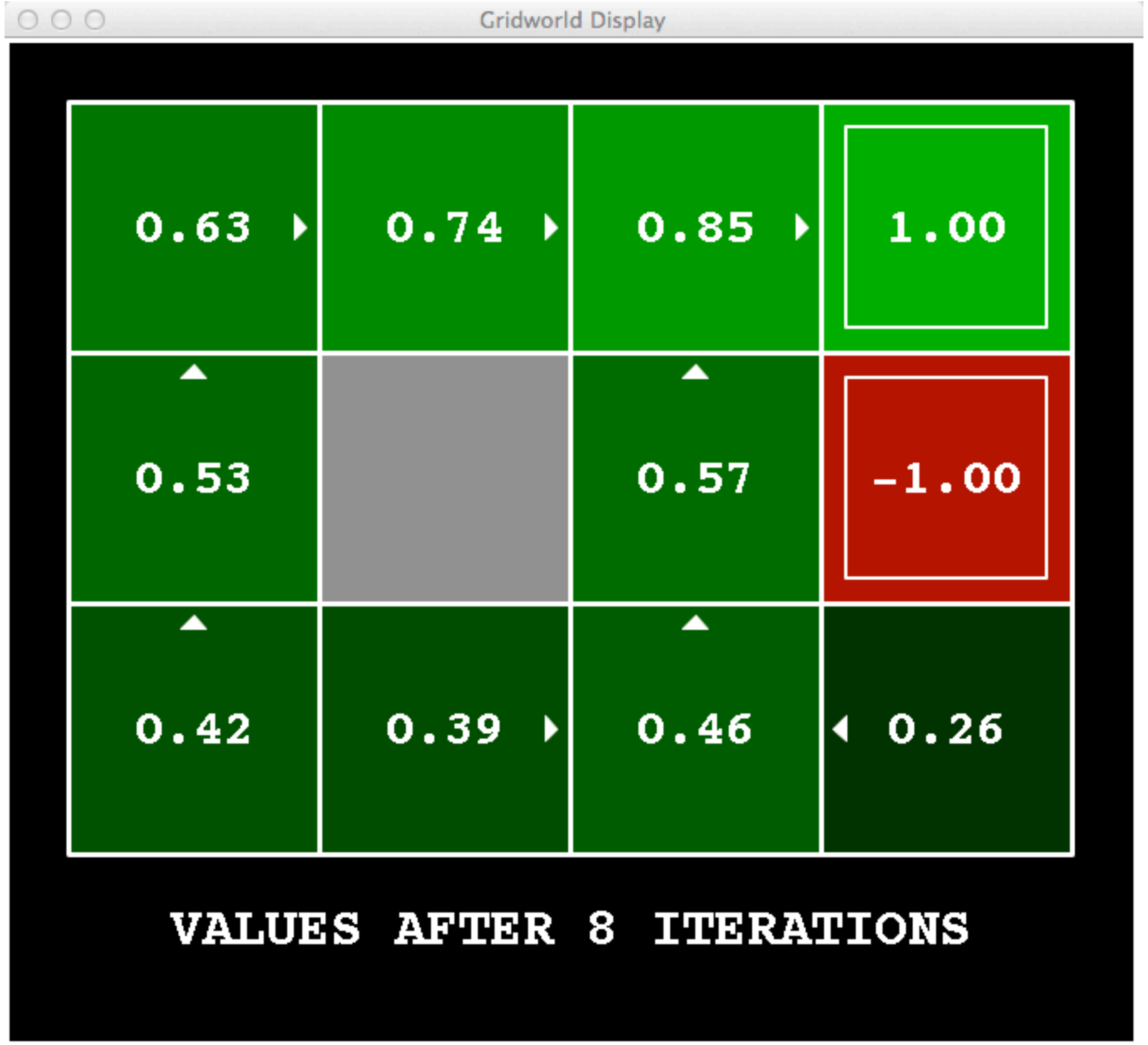
Noise = 0.2
Discount = 0.9
Living reward = 0

k=7



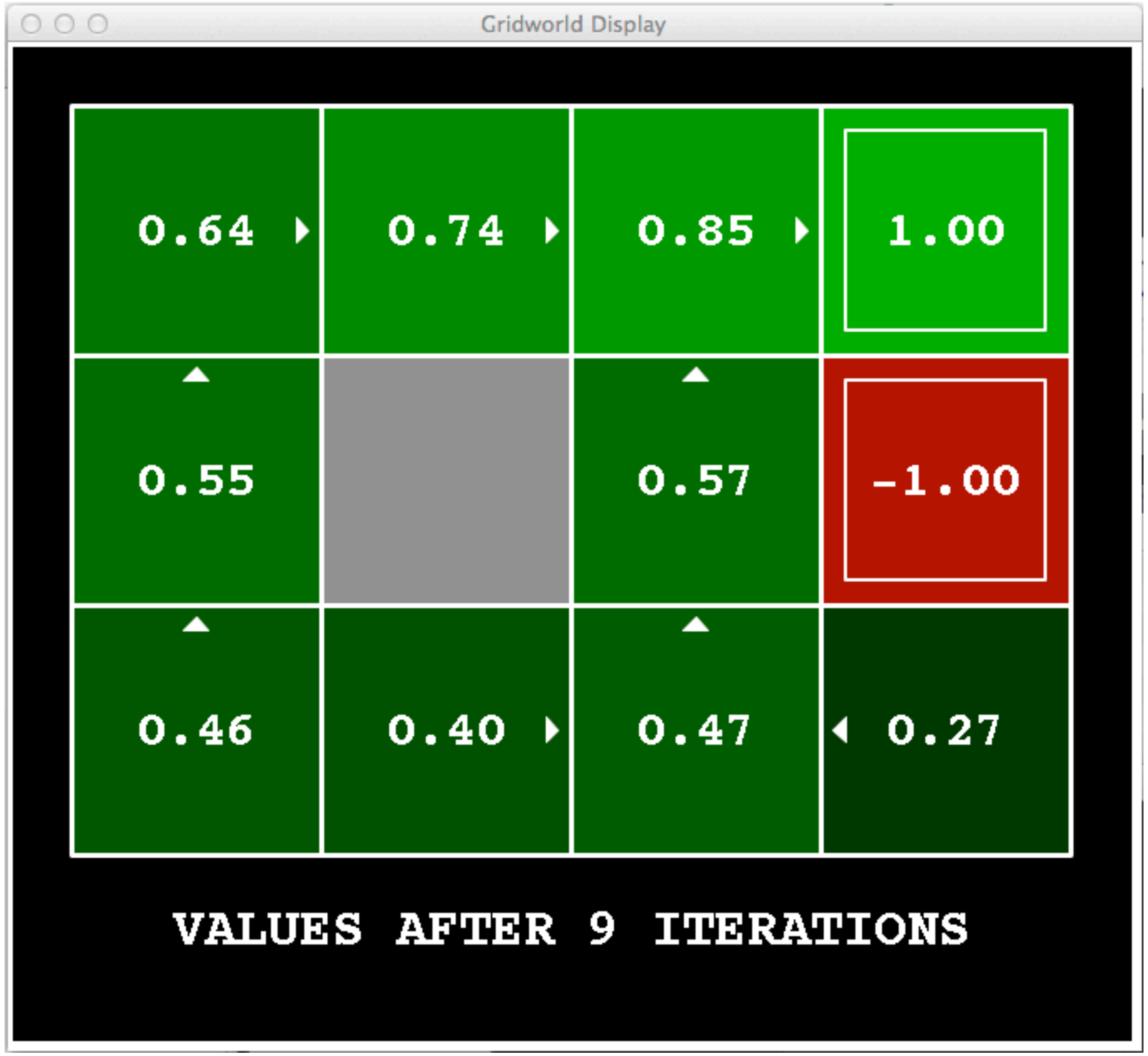
Noise = 0.2
Discount = 0.9
Living reward = 0

k=8



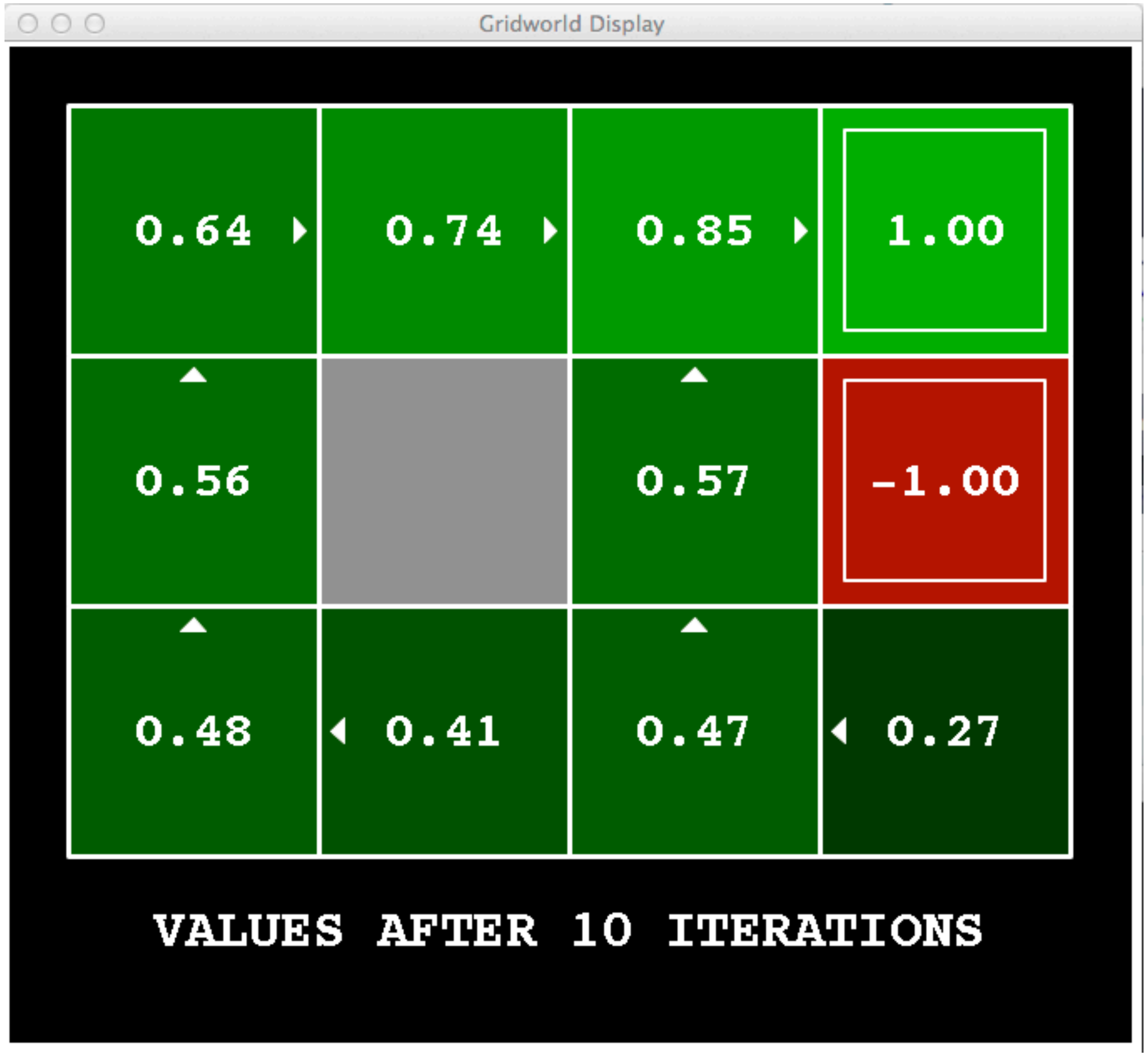
Noise = 0.2
Discount = 0.9
Living reward = 0

k=9



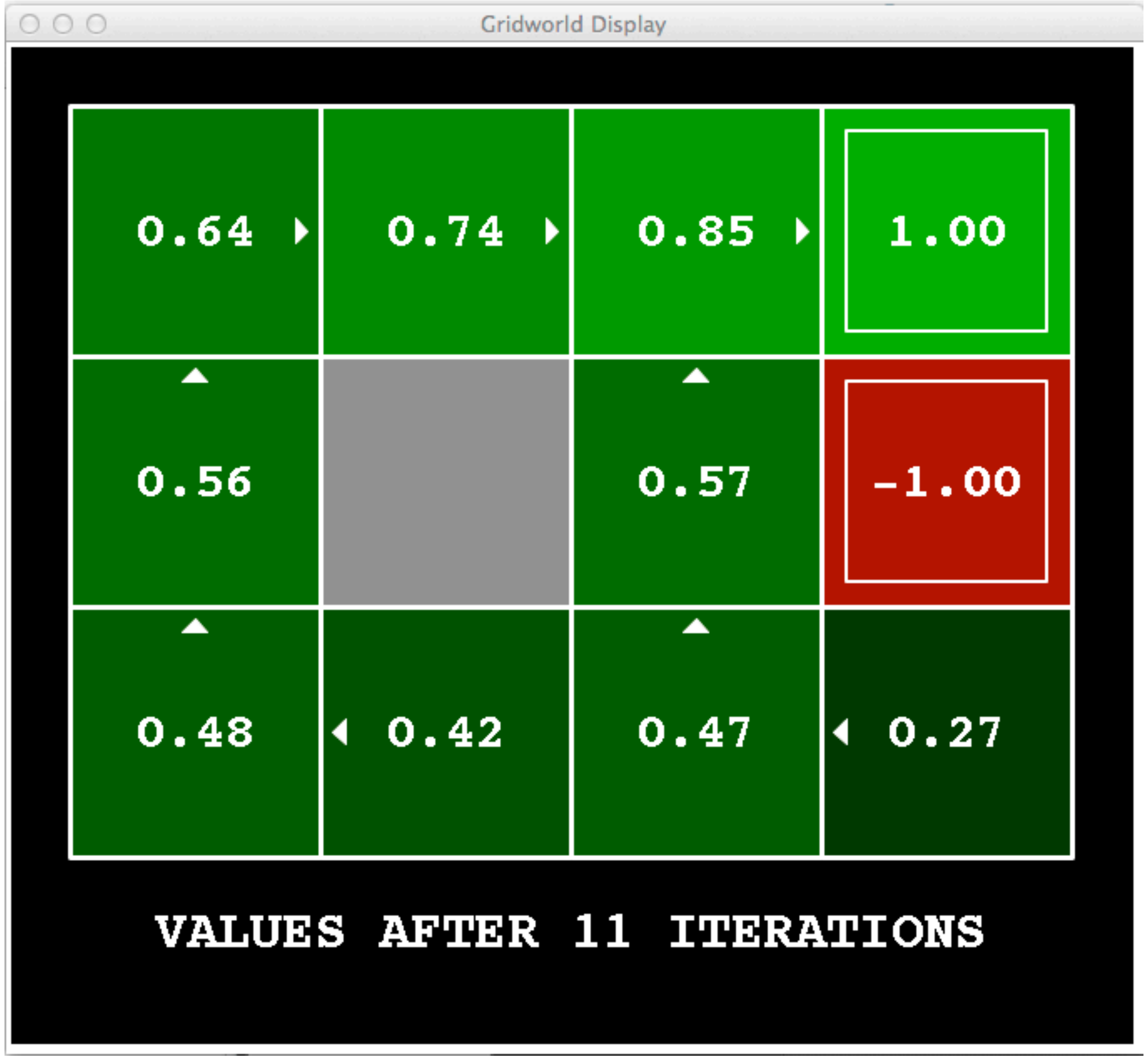
Noise = 0.2
Discount = 0.9
Living reward = 0

k=10



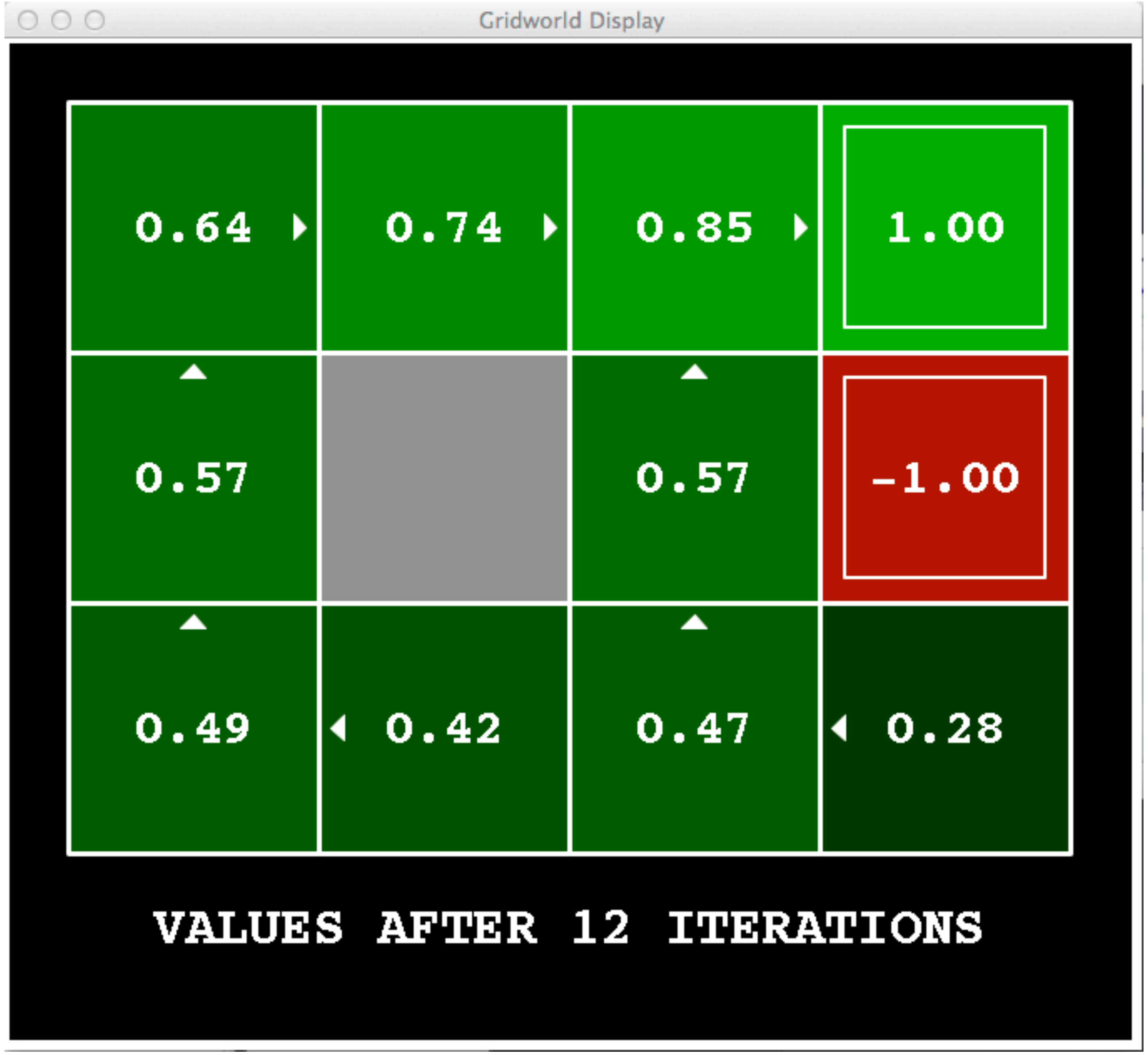
Noise = 0.2
Discount = 0.9
Living reward = 0

k=11



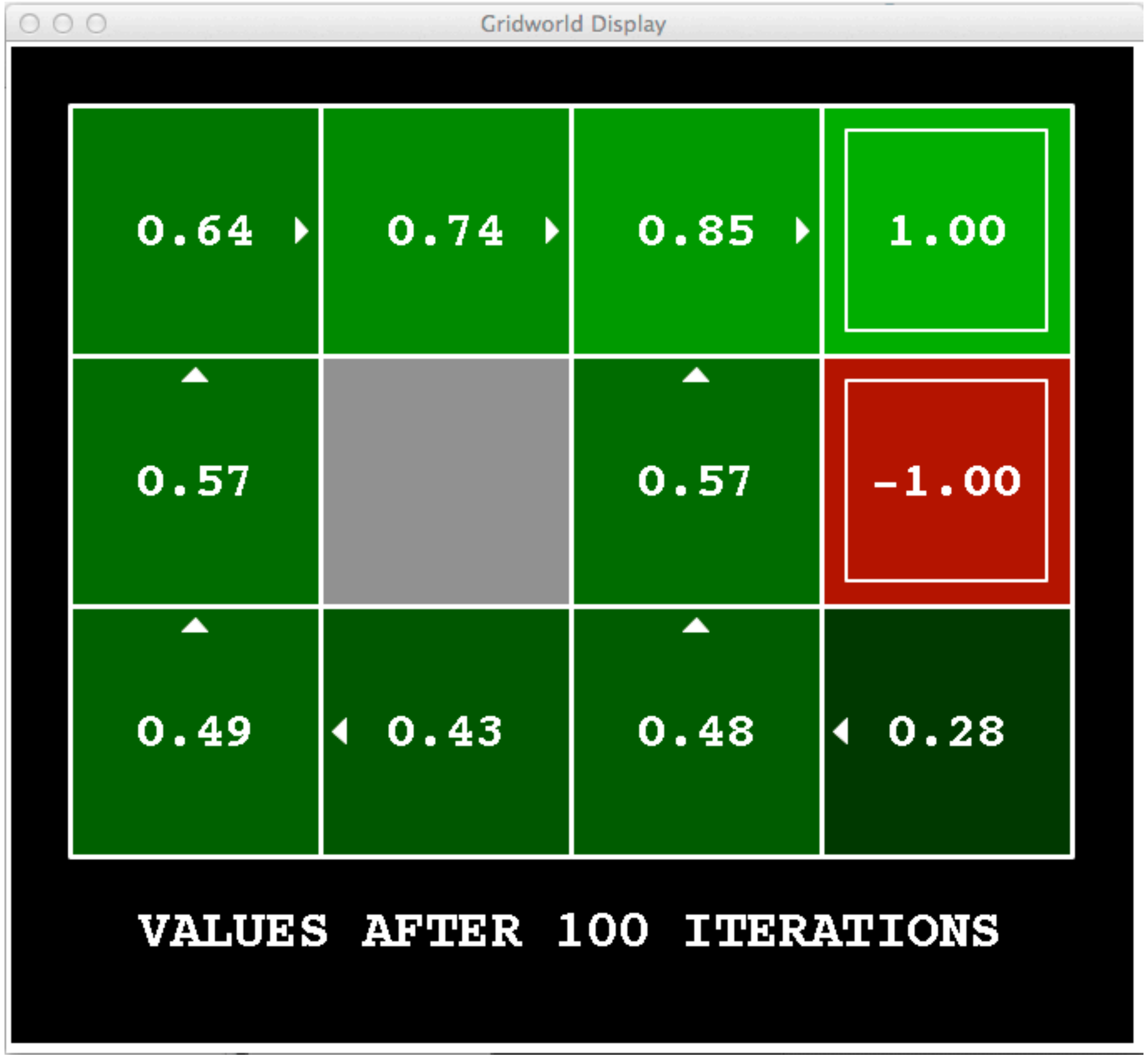
Noise = 0.2
Discount = 0.9
Living reward = 0

k=12



Noise = 0.2
Discount = 0.9
Living reward = 0

k=100



Noise = 0.2
Discount = 0.9
Living reward = 0

Policy Iteration

- Alternative approach for optimal values:
  - Step 1: Policy evaluation: calculate utilities for some fixed policy (not optimal utilities!) until convergence
  - Step 2: Policy improvement: update policy using one-step look-ahead with resulting converged (but not optimal!) utilities as future values
  - Repeat steps until policy converges

- This is policy iteration
  - It's still optimal!
  - Can converge (much) faster under some conditions

Policy Iteration

- Evaluation: For fixed current policy π, find values with policy evaluation:
  - Iterate until values converge:

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

- Improvement: For fixed values, get a better policy using policy extraction
  - One-step look-ahead:

$$\pi_{i+1}(s) = \arg\max_a \sum_{s'} T(s, a, s') \left[R(s, a, s') + \gamma V^{\pi_i}(s')\right]$$

Comparison

- Both value iteration and policy iteration compute the same thing (all optimal 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 recomputes it

- In policy iteration:
  - We do several passes that update utilities with fixed policy (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)

- Both are dynamic programming methods for solving MDPs

Summary: MDP Algorithms

- So you want to….
  - Compute optimal values: use value iteration or policy iteration
  - Compute values for a particular policy: use policy evaluation
  - Turn your values into a policy: use policy extraction (one-step lookahead)
- These all look the same!
  - They basically are – they are all variations of Bellman updates
  - They all use one-step lookahead expectimax fragments
  - They differ only in whether we plug in a fixed policy or max over actions

MDP Notation

Standard expectimax: $V(s) = \max_a \sum_{s'} P(s' | s, a) V(s')$

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

Value iteration: $V_{k+1}(s) = \max_a \sum_{s'} P(s' | s, a) \left[R(s, a, s') + \gamma V_k(s')\right], \quad \forall\ s$

Q-iteration: $Q_{k+1}(s, a) = \sum_{s'} P(s' | s, a)[R(s, a, s') + \gamma \max_{a'} Q_k(s', a')], \quad \forall\ s, a$

Policy extraction: $\pi_V(s) = \operatorname{argmax}_a \sum_{s'} P(s' | s, a)[R(s, a, s') + \gamma V(s')], \quad \forall\ s$

Policy evaluation: $V^{\pi}_{k+1}(s) = \sum_{s'} P\left(s' | s, \pi(s)\right)\left[R\left(s, \pi(s), s'\right) + \gamma V^{\pi}_k(s')\right], \quad \forall\ s$

Policy improvement: $\pi_{new}(s) = \operatorname{argmax}_a \sum_{s'} P(s' | s, a)\left[R(s, a, s') + \gamma V^{\pi_{old}}(s')\right], \quad \forall\ s$

MDP Notation

Standard expectimax: $V(s) = \max_a \sum_{s'} P(s' | s, a) V(s')$

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Q-iteration: $Q_{k+1}(s, a) = \sum_{s'} P(s' | s, a) [R(s, a, s') + \gamma \max_{a'} Q_k(s', a')], \quad \forall\ s, a$

Policy extraction: $\pi_V(s) = \operatorname{argmax}_a \sum_{s'} P(s' | s, a) [R(s, a, s') + \gamma V(s')], \quad \forall\ s$

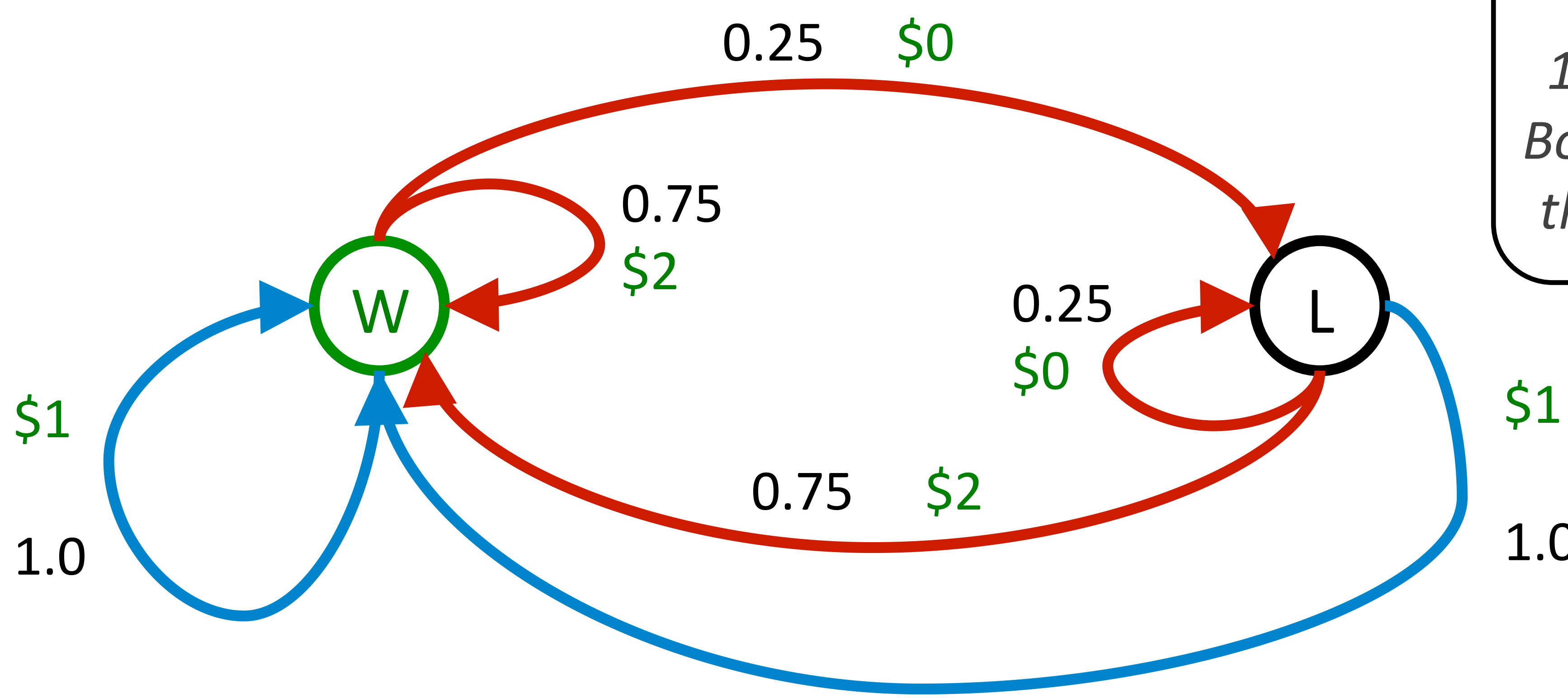
Policy evaluation: $V^{\pi}_{k+1}(s) = \sum_{s'} P\big(s' | s, \pi(s)\big) [R\big(s, \pi(s), s'\big) + \gamma V^{\pi}_k(s')], \quad \forall\ s$

Policy improvement: $\pi_{new}(s) = \operatorname{argmax}_a \sum_{s'} P(s' | s, a) \left[R(s, a, s') + \gamma V^{\pi_{old}}(s') \right], \quad \forall\ s$

Double Bandits

Double-Bandit MDP

- Actions: *Blue*, *Red*
- States: Win, Lose



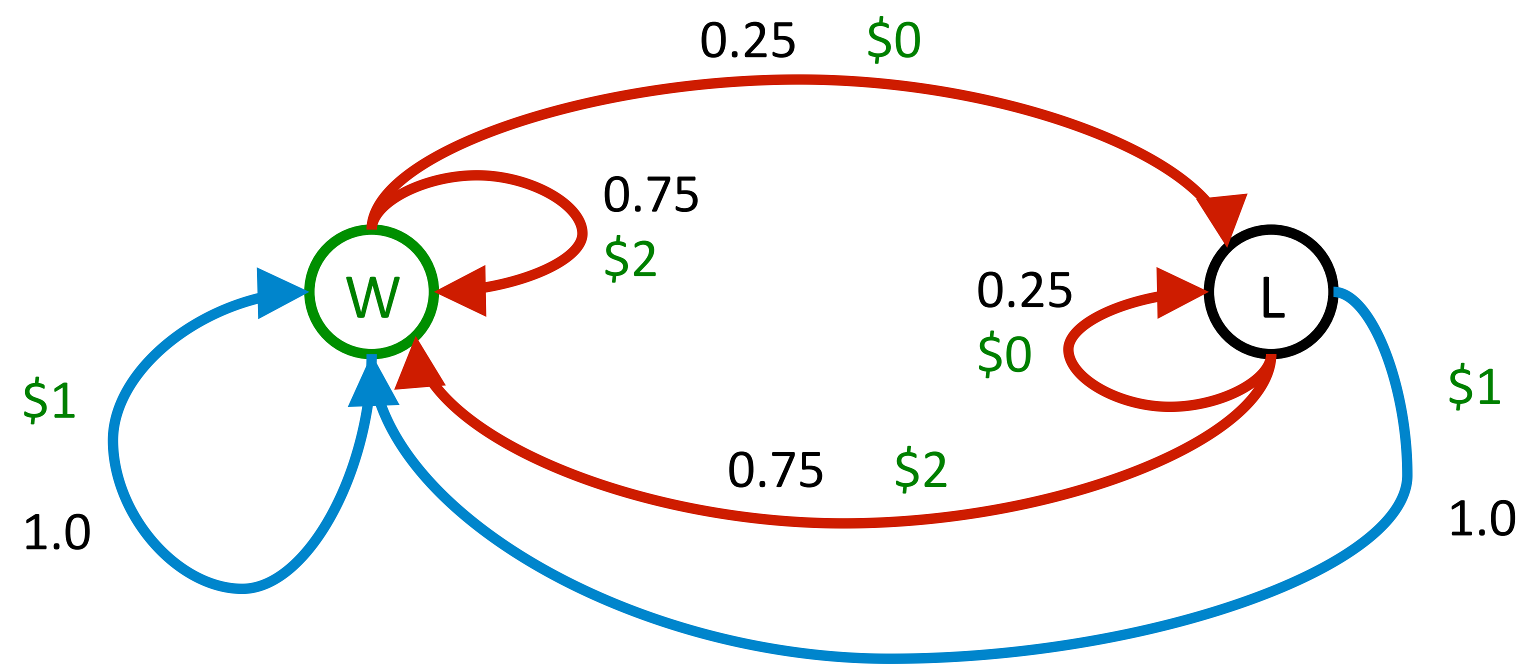
No discount
100 time steps
Both states have
the same value

Offline Planning

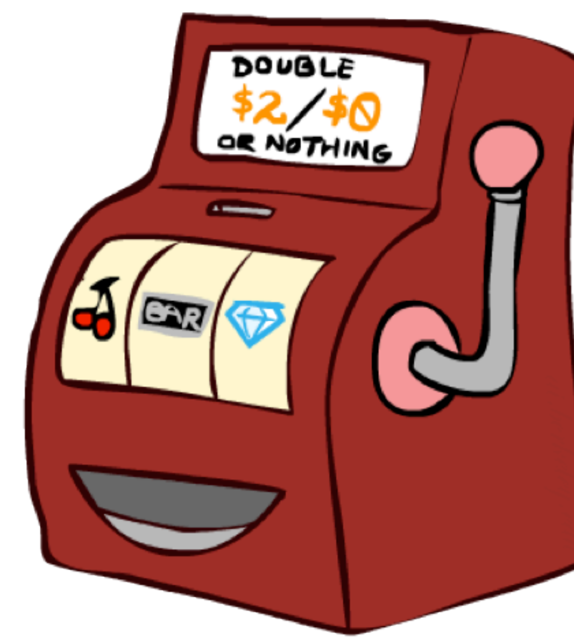
- Solving MDPs is offline planning
  - You determine all quantities through computation
  - You need to know the details of the MDP
  - You do not actually play the game!

No discount
100 time steps
Both states have the same value

	Value
Play Red	150
Play Blue	100



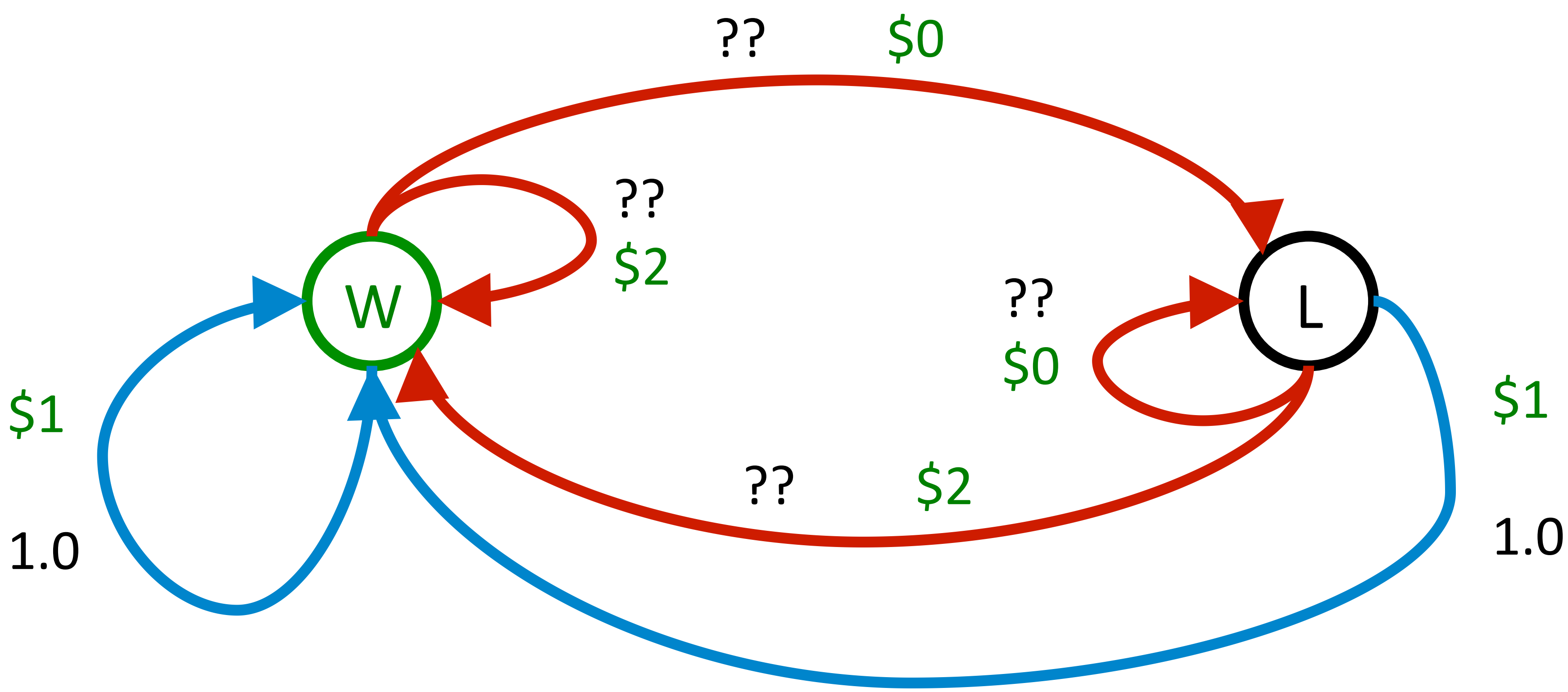
Let's Play!



$2 $2 $0 $2 $2
$2 $2 $0 $0 $0

Online Planning

- Rules changed! Red's win chance is different.



Let's Play!

$0 $0 $0 $2 $0
$2 $0 $0 $0 $0

What Just Happened?

- That wasn't planning, it was learning!
  - Specifically, reinforcement learning
  - There was an MDP, but you couldn't solve it with just computation
  - You needed to actually act to figure it out

- Important ideas in reinforcement learning that came up
  - Exploration: you have to try unknown actions to get information
  - Exploitation: eventually, you have to use what you know
  - Regret: even if you learn intelligently, you make mistakes
  - Sampling: because of chance, you have to try things repeatedly
  - Difficulty: learning can be much harder than solving a known MDP