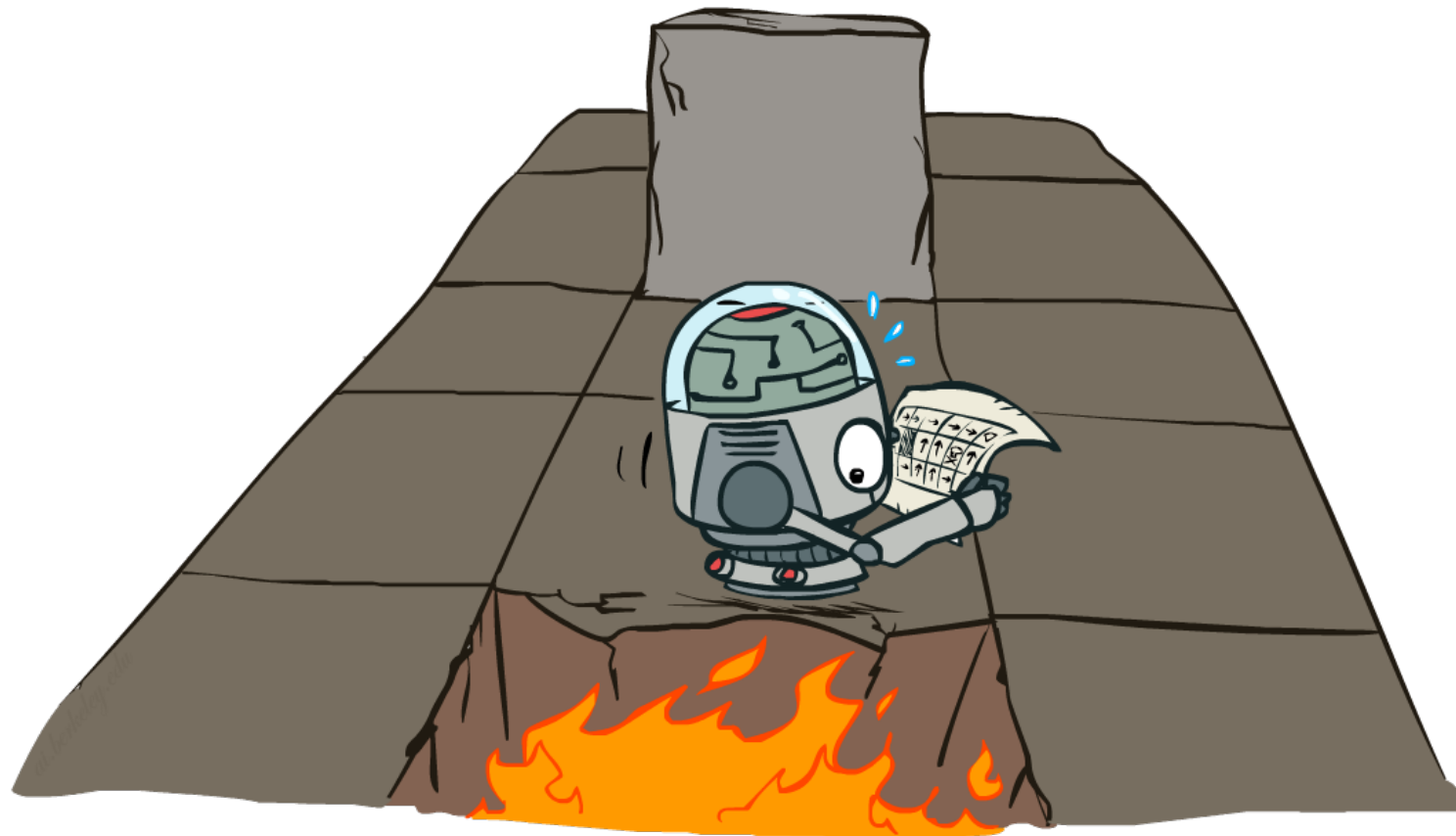

Ve492: Introduction to Artificial Intelligence

Markov Decision Processes II



Paul Weng

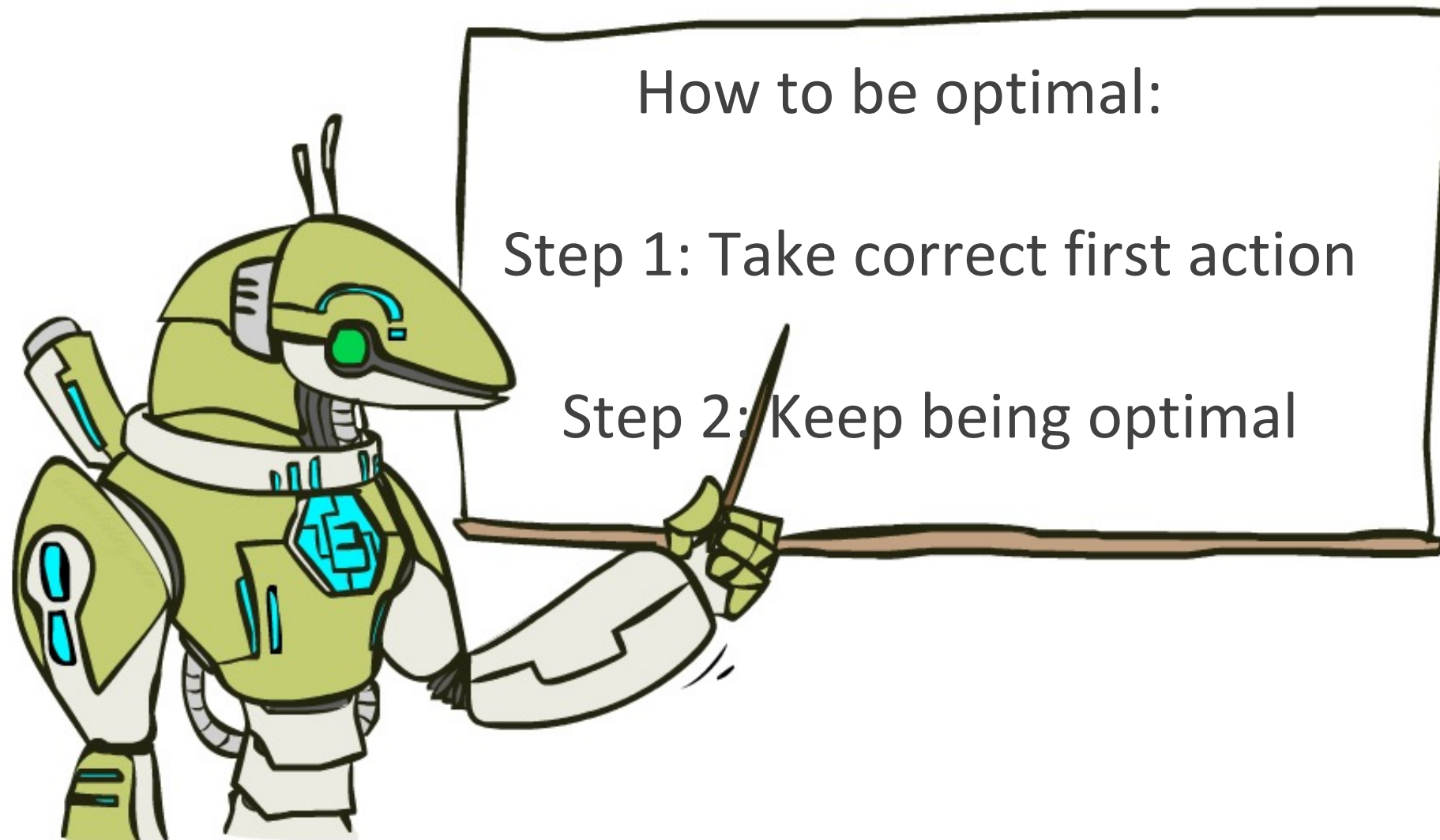
UM-SJTU Joint Institute

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

Announcements

- ❖ Project 2: Search
 - ❖ Released on last Saturday
 - ❖ Due June 20 at 11:59pm
- ❖ Homework 3: Games + MDP
 - ❖ Released on Wednesday
 - ❖ Due June 14 at 11:59pm
- ❖ Anonymous participation on Piazza

The Bellman Equations



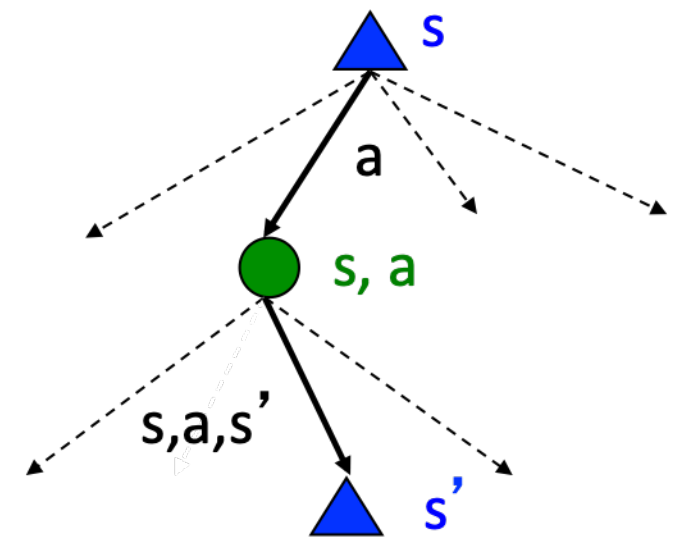
The Bellman Equations

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

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

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

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



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

Value Iteration

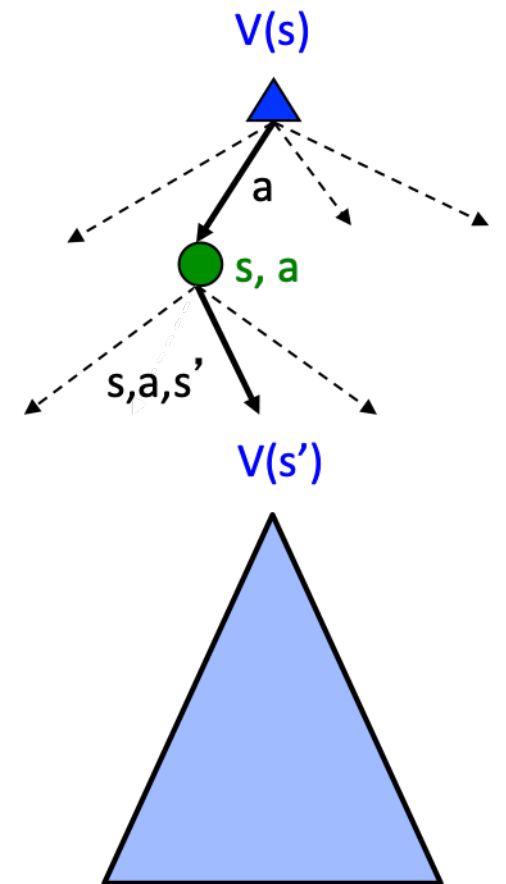
- ❖ Bellman equations **characterize** the optimal values:

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

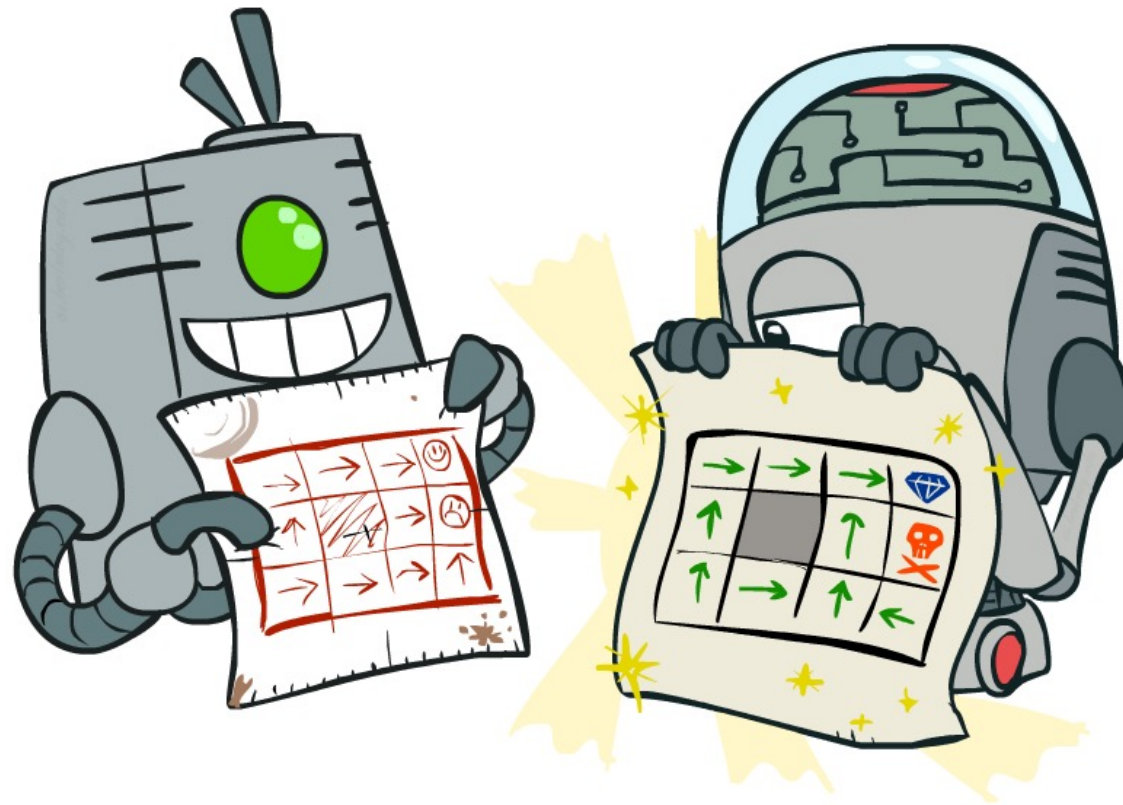
- ❖ Value iteration **computes** them:

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

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

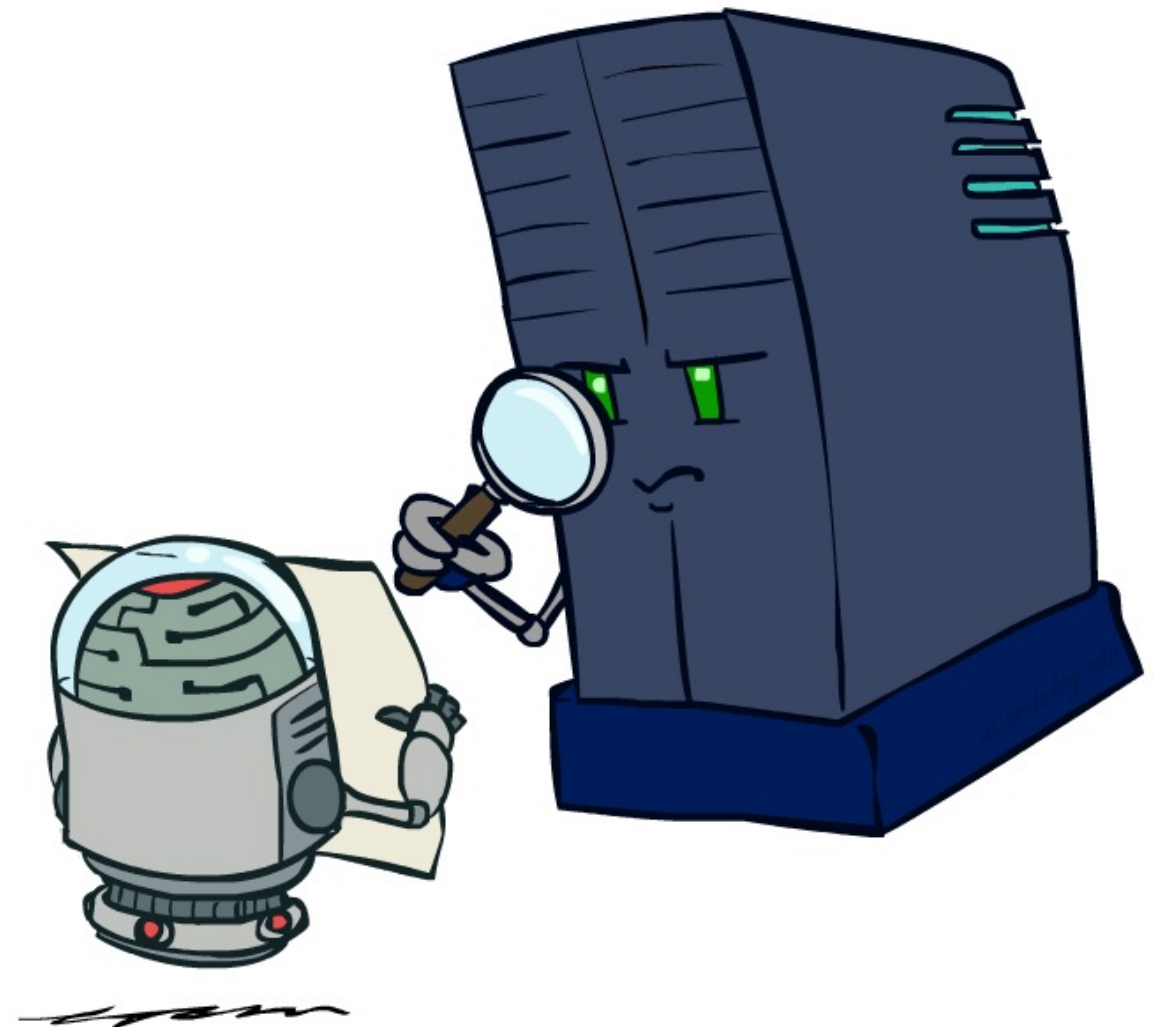


Policy Methods



Policy Methods

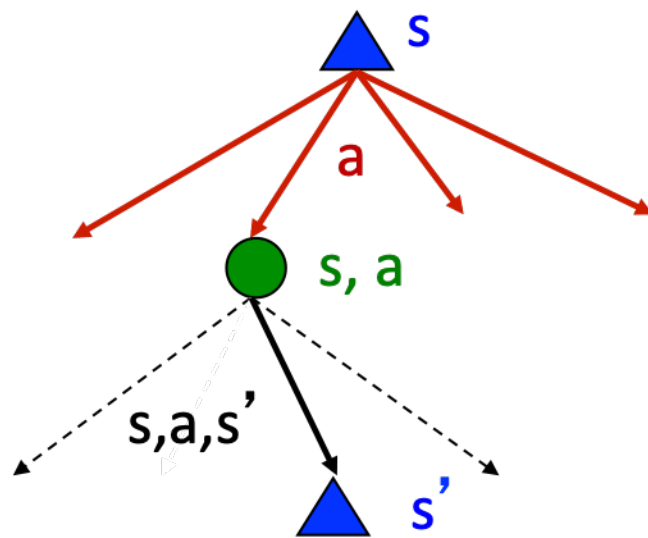
Policy Evaluation



Fixed Policies

Do the optimal action

Do what π says to do

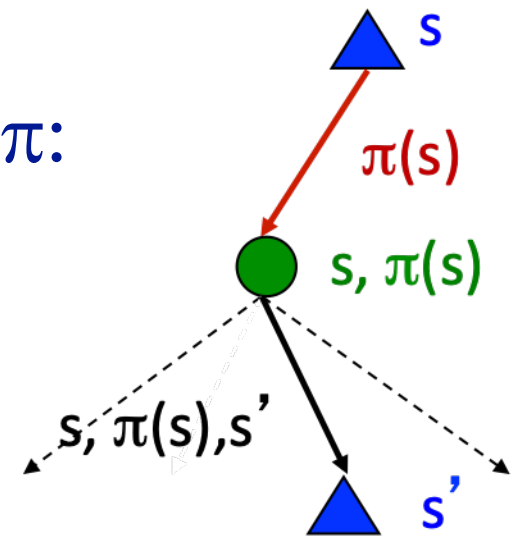


- ❖ Expectimax trees max over all actions to compute the optimal values
- ❖ If we fixed some policy $\pi(s)$, then the tree would be simpler – only one action per state
 - ❖ ... though the tree's value would depend on which policy we fixed

Utilities for a Fixed Policy

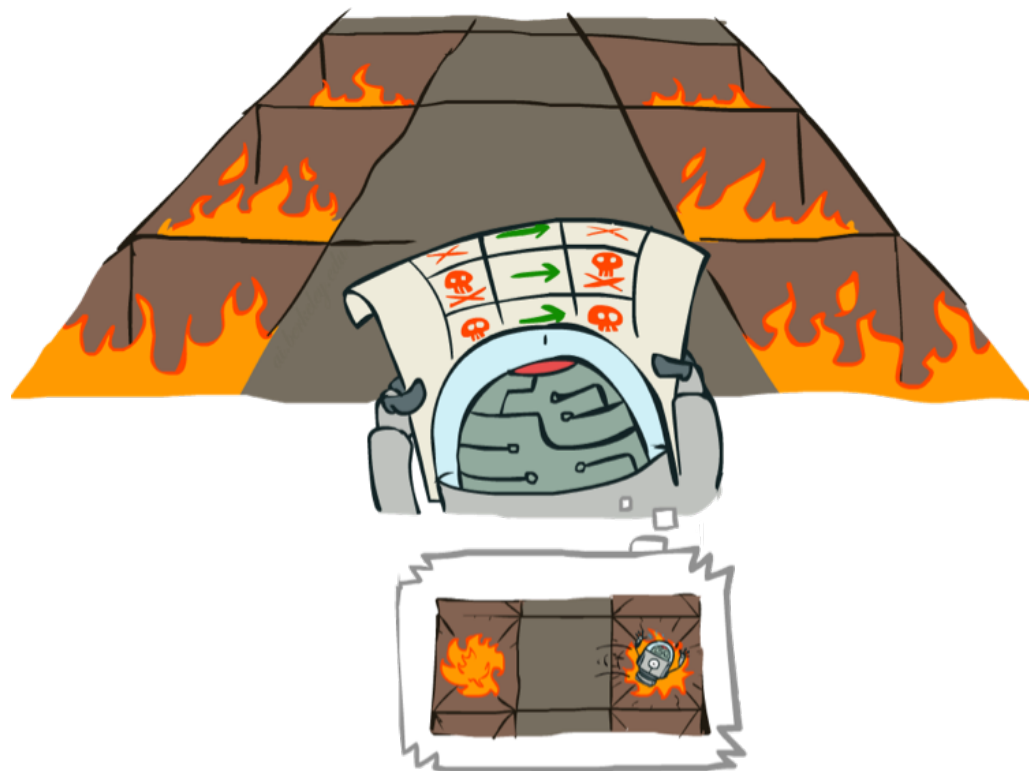
- ❖ **Basic operation:** compute the utility of a state s under a fixed (generally non-optimal) policy
- ❖ **Define the utility of a state s , under a fixed policy π :**
 $V^\pi(s)$ = expected total discounted rewards starting in s and following π
- ❖ **Recursive relation (one-step look-ahead / Bellman equation):**

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

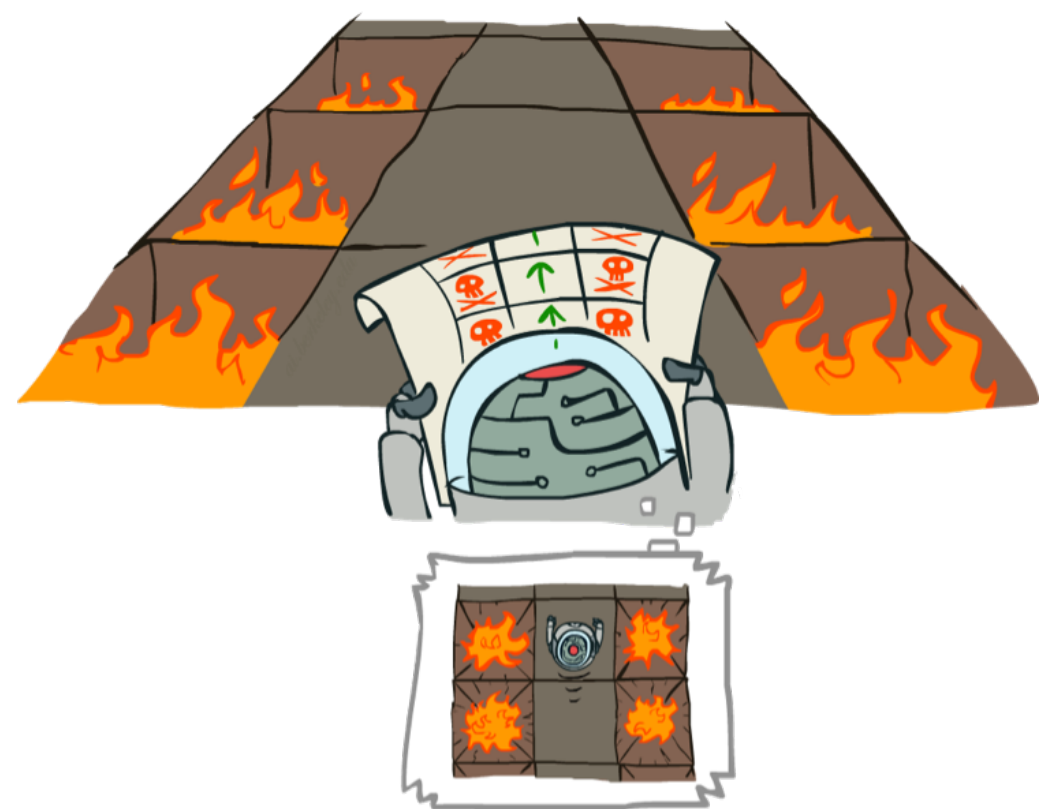


Example: Policy Evaluation

Always Go Right



Always Go Forward

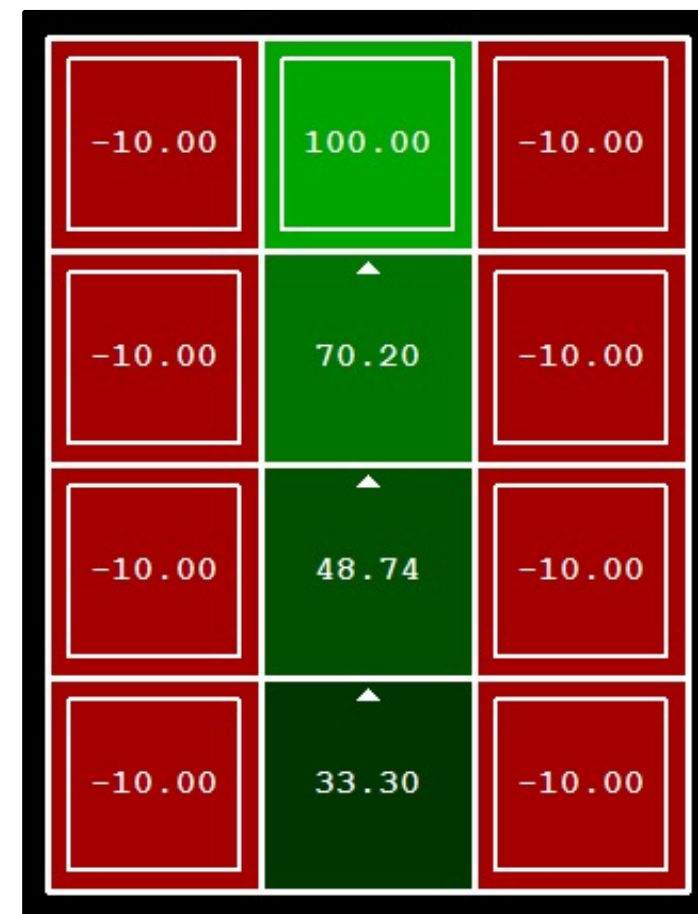


Example: Policy Evaluation

Always Go Right



Always Go Forward



Policy Evaluation

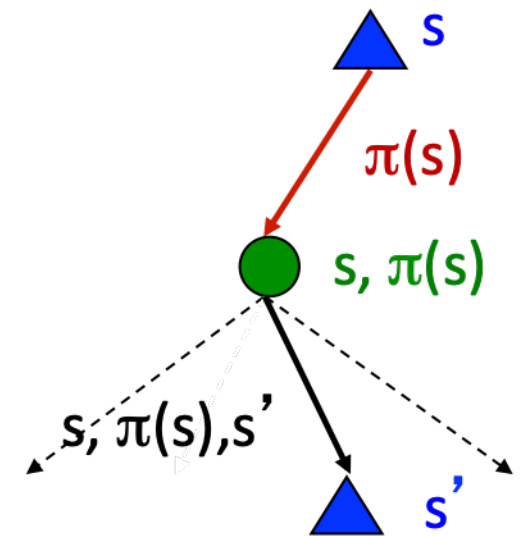
- ❖ How do we calculate the V 's for a fixed policy π ?
- ❖ **Idea 1:** Turn recursive Bellman equations into updates (like value iteration)

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

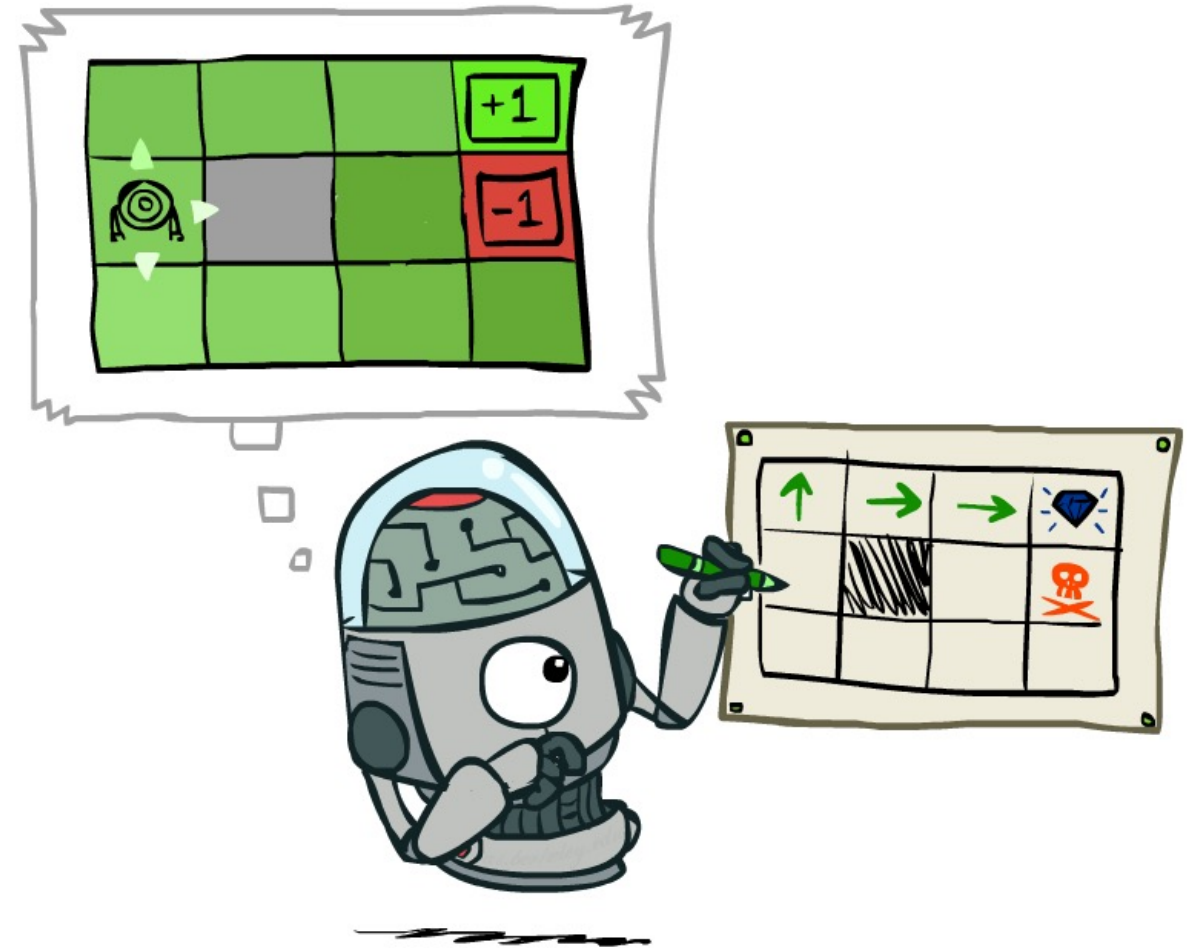
$$V_{k+1}^\pi(s) \leftarrow \sum_{s'} T(s, \pi(s), s') [R(s, \pi(s), s') + \gamma V_k^\pi(s')]$$

- ❖ **Efficiency:** $O(S^2)$ 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 Extraction



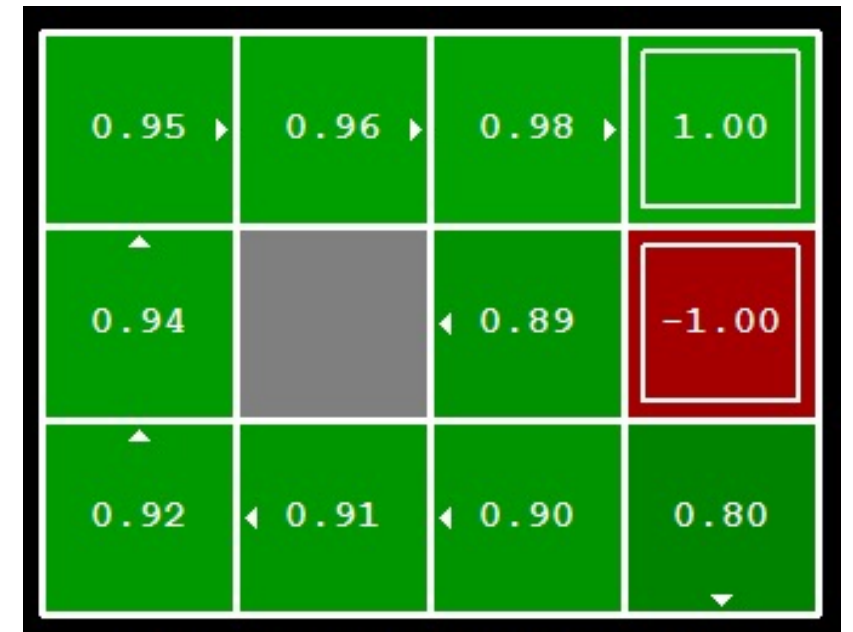
Computing Actions from Values

❖ 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

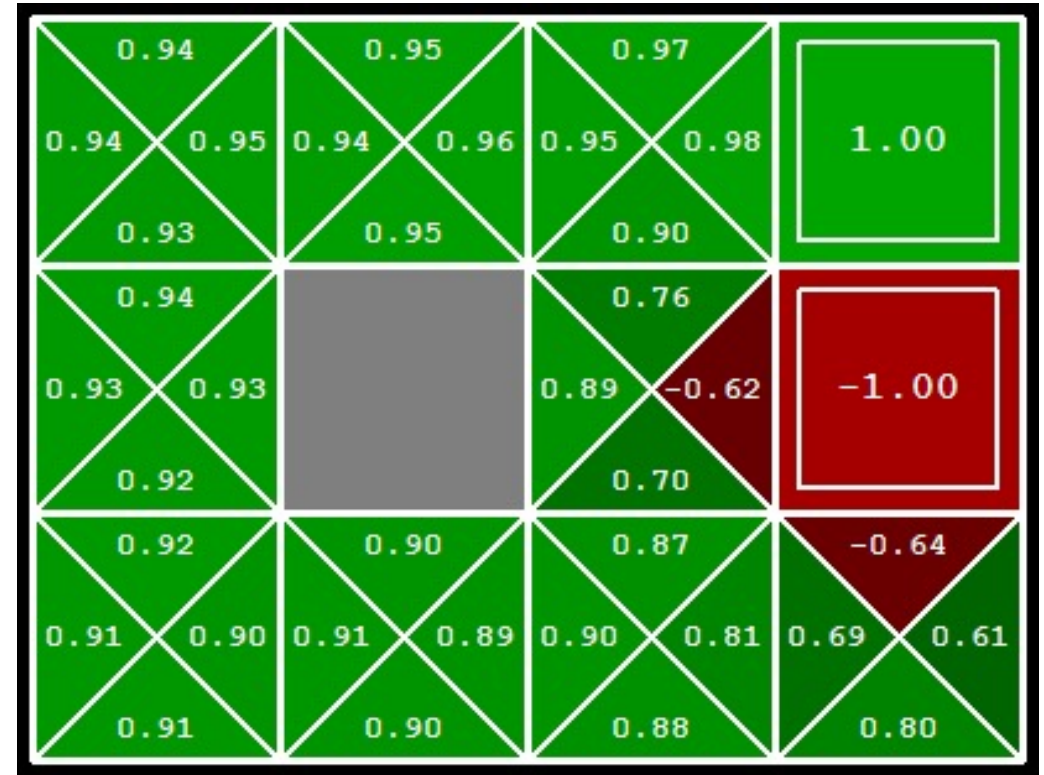
Computing Actions from Q-Values

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

❖ How should we act?

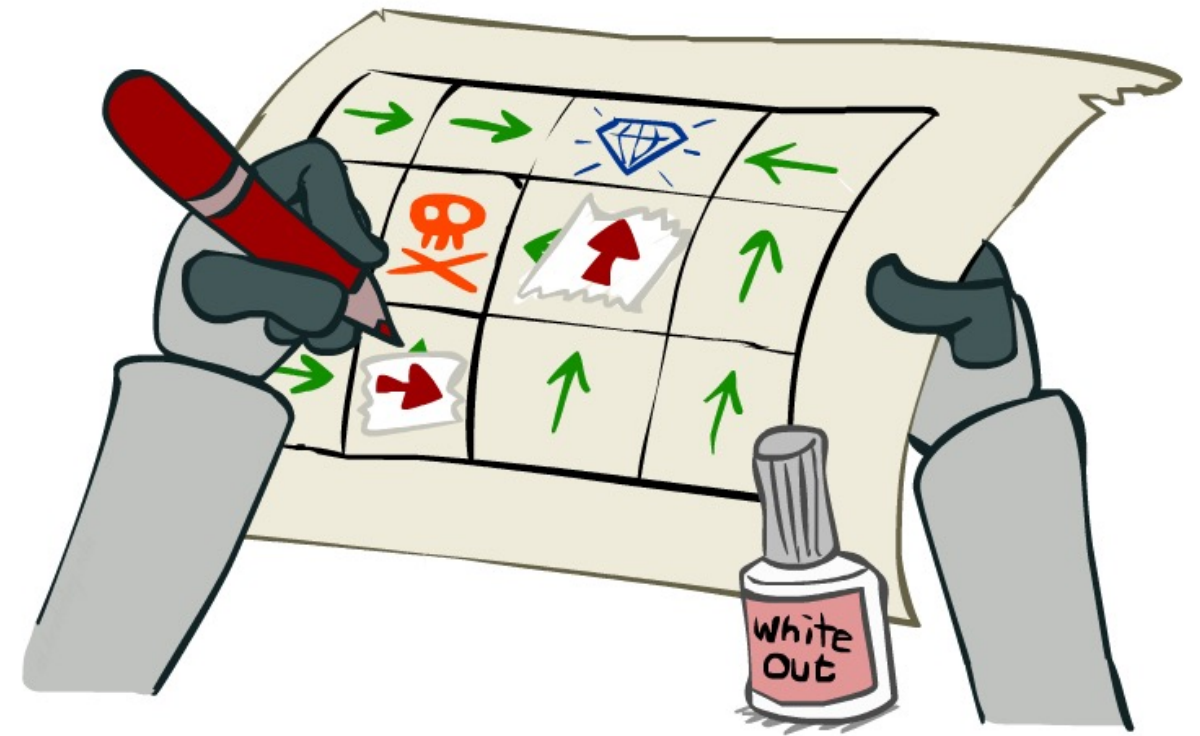
❖ Completely trivial to decide!

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



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

Policy Iteration

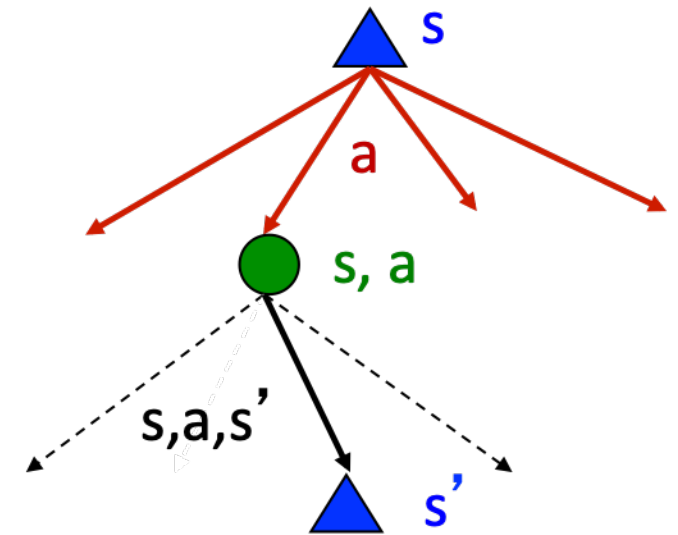


Problems with Value Iteration

- ❖ Value iteration repeats the Bellman updates:

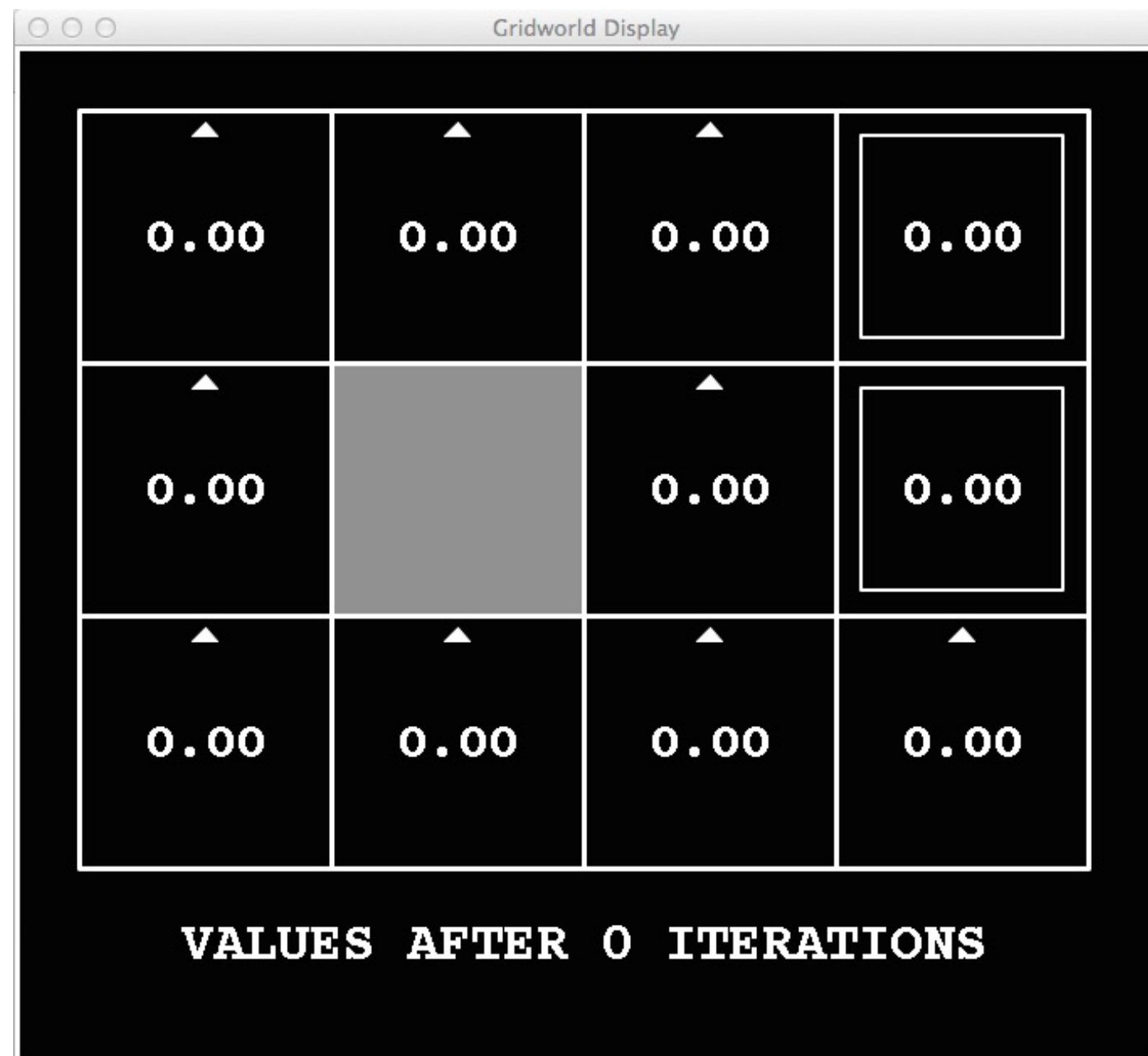
$$V_{k+1}(s) \leftarrow \max_a \sum_{s'} T(s, a, s') [R(s, a, s') + \gamma V_k(s')]$$

- ❖ Problem 1: It's slow – $O(S^2A)$ 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



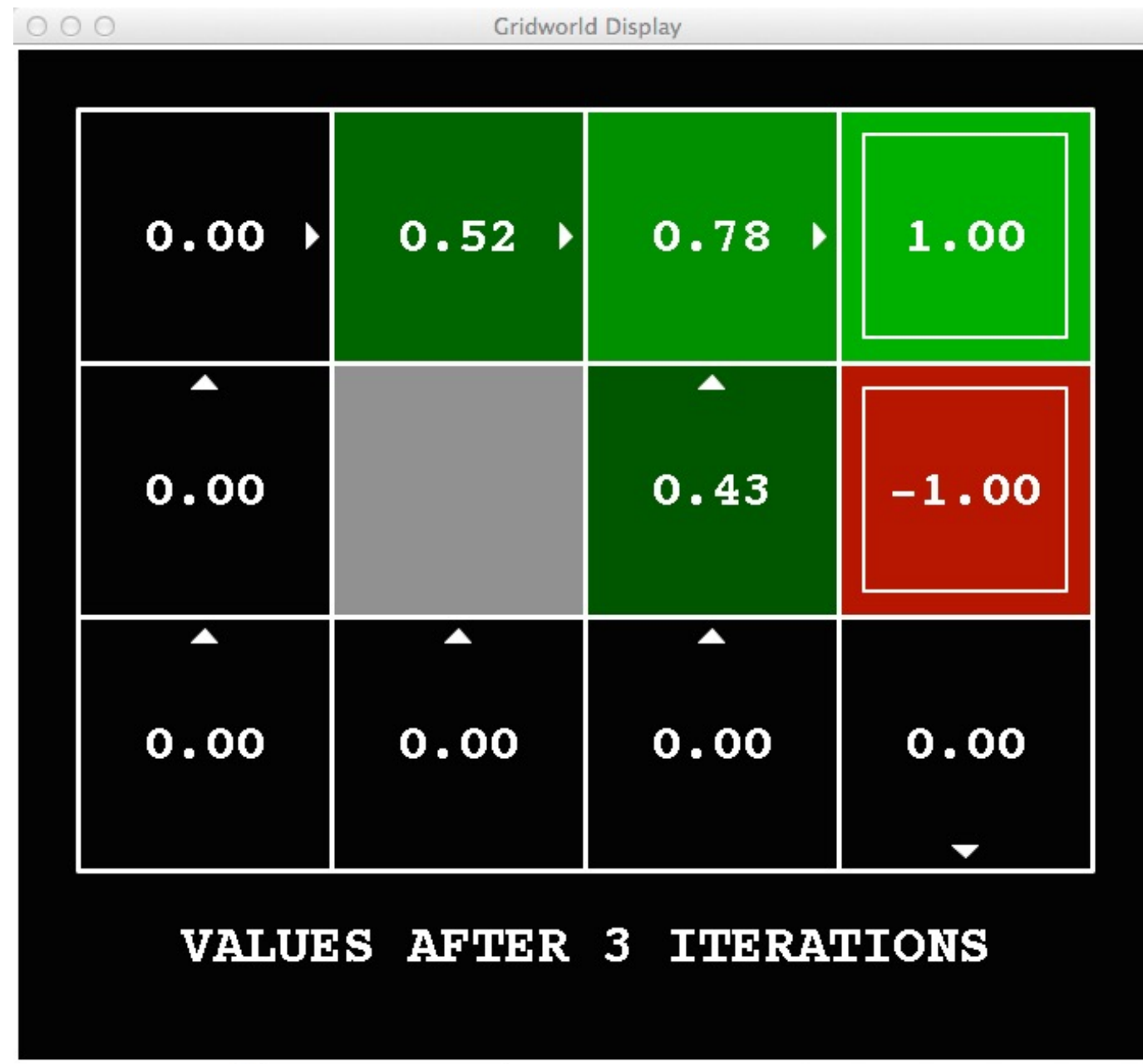
Noise = 0.2
Discount = 0.9
Living reward = 0

$k=2$



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:

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

- ❖ **Improvement:** For fixed values, get a better policy using policy extraction

- ❖ One-step look-ahead:

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

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

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

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: $V_{k+1}^\pi(s) = \sum_{s'} P(s'|s, \pi(s)) [R(s, \pi(s), s') + \gamma V_k^\pi(s')], \quad \forall s$

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