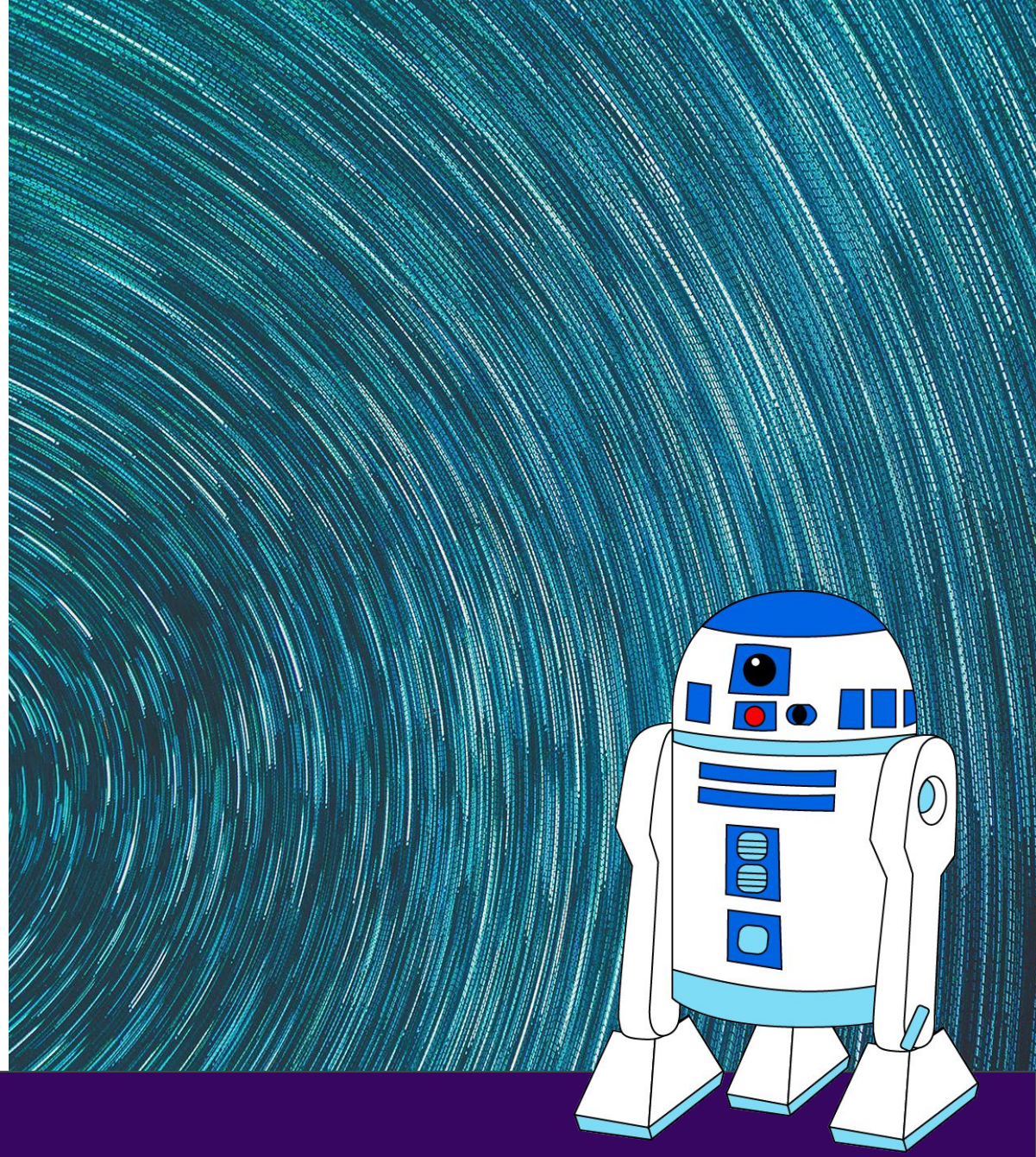
CIS 421/521:
ARTIFICIAL INTELLIGENCE

Markov Decision Processes



Navigating an Asteroid Field

Suppose we have a **fully-observable** 4x3 environment with goal states.

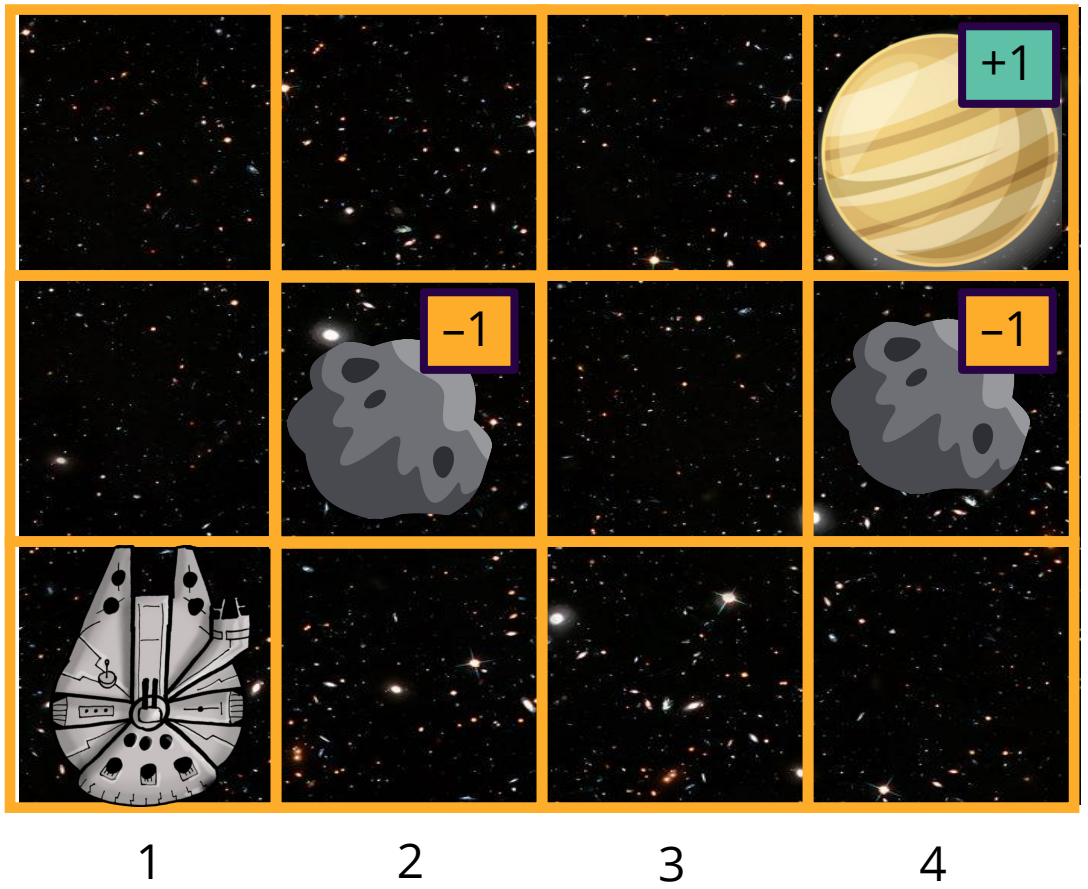
The millennium falcon begins in the start state and **picks an action at each time step**.

Actions: *Up, Down, Left, Right*

The game **terminates when it reaches a goal state** (+1 or -1).

If the environment were **deterministic**, the solution would be easy:

[*Up, Up, Right, Right, Right*]



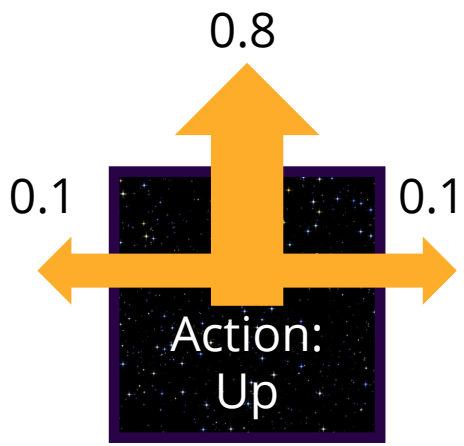
Navigating an Asteroid Field

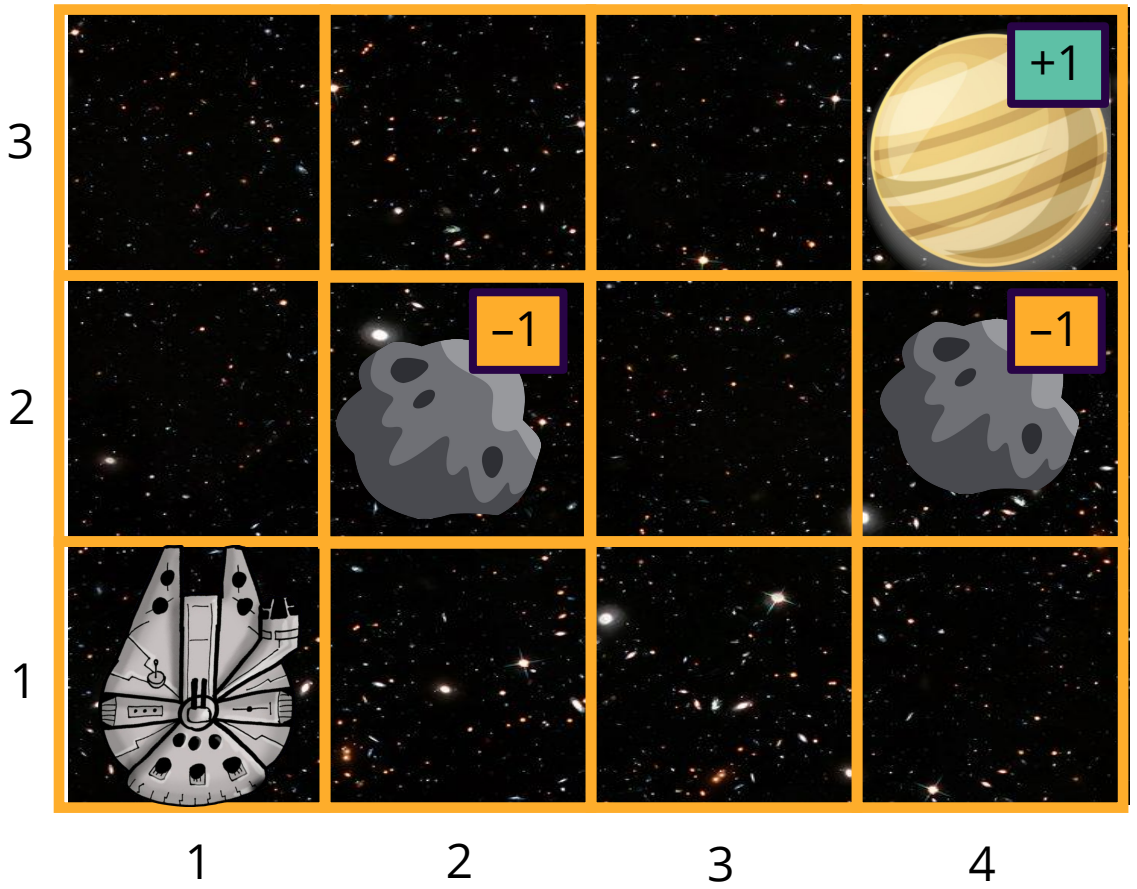
Instead of making the environment deterministic, we will make it **stochastic**.

If the Falcon selects the action *Up* then it only moves up 80% of the time.

10% of the time the weird gravity fields cause it to veer off to the left or right.

Transition Model:





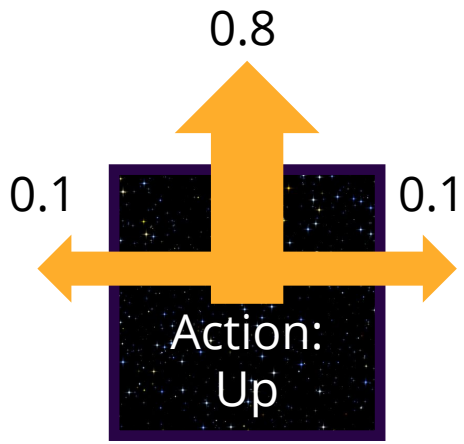
Navigating an Asteroid Field

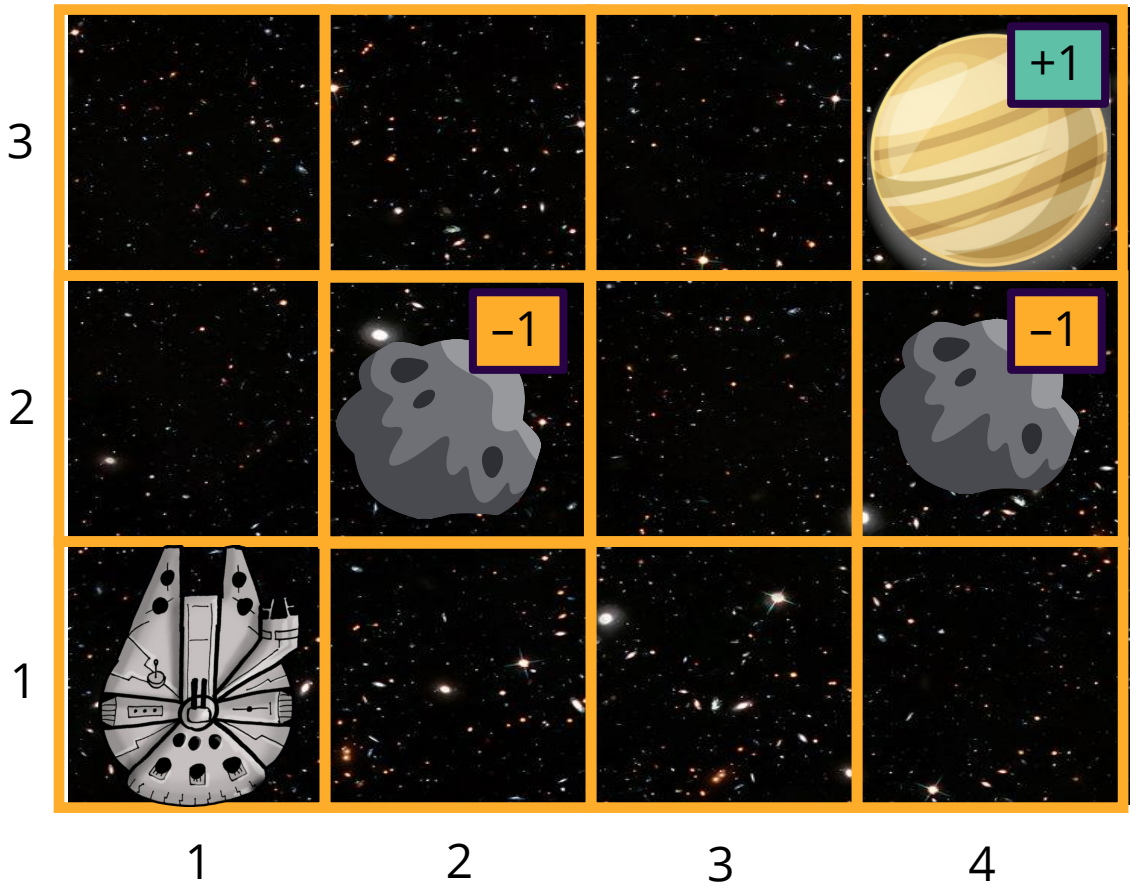
For action sequence

[*Up, Up, Right, Right, Right*],

what's the probability that the millennium falcon reaches the intended goal?

Transition Model:





Navigating an Asteroid Field

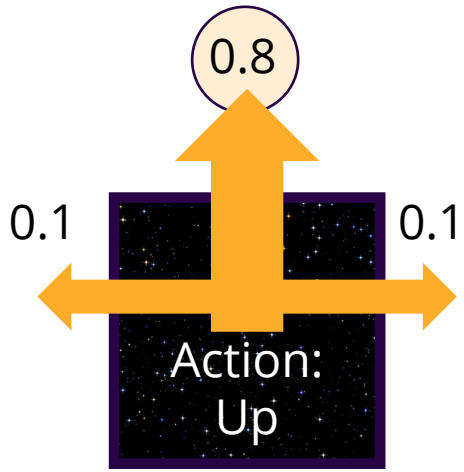
For action sequence

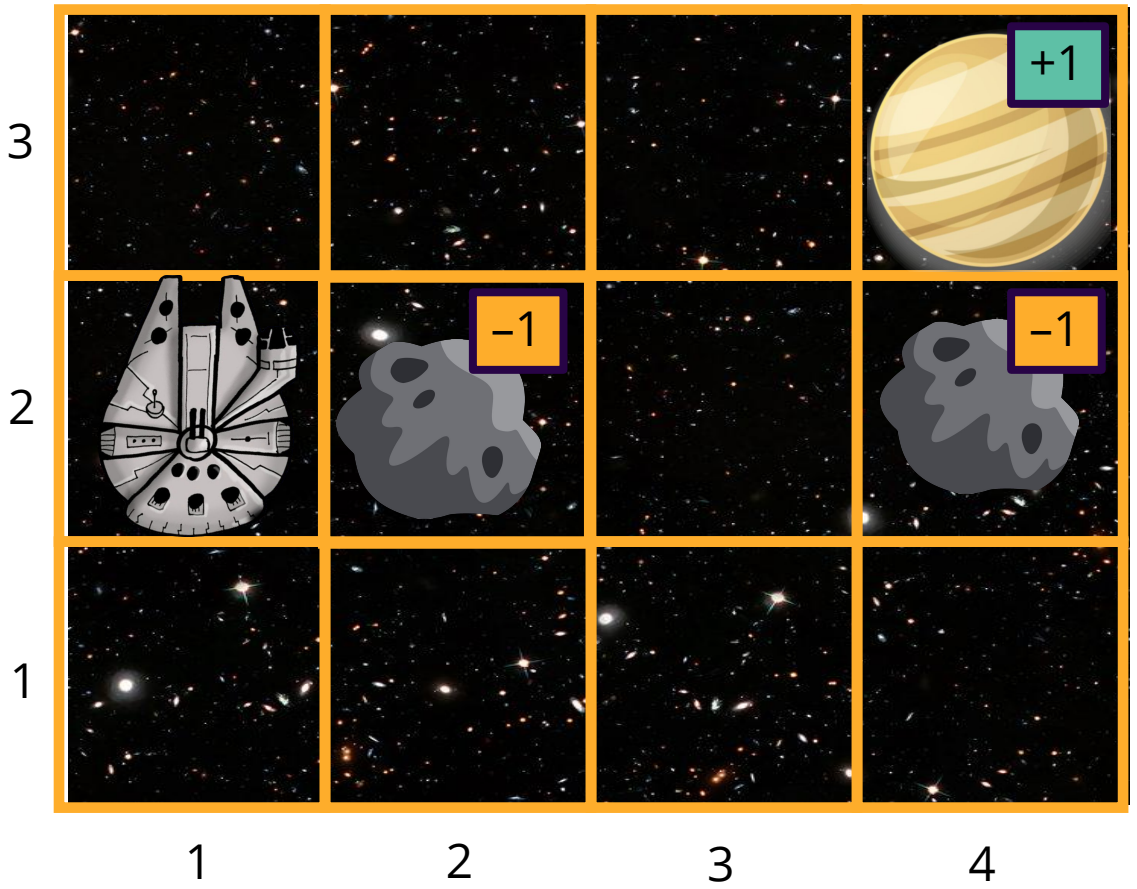
[*Up, Up, Right, Right, Right*],

what's the probability that the millennium falcon reaches the intended goal?

0.8

Transition Model:





Navigating an Asteroid Field

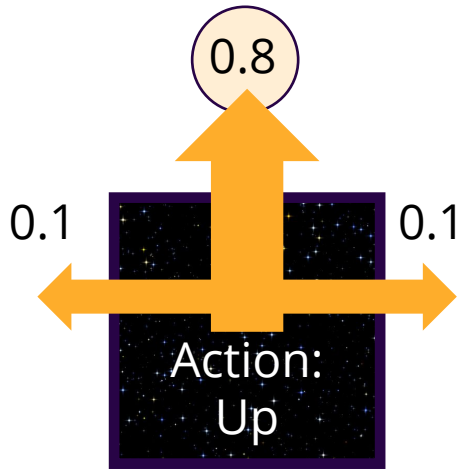
For action sequence

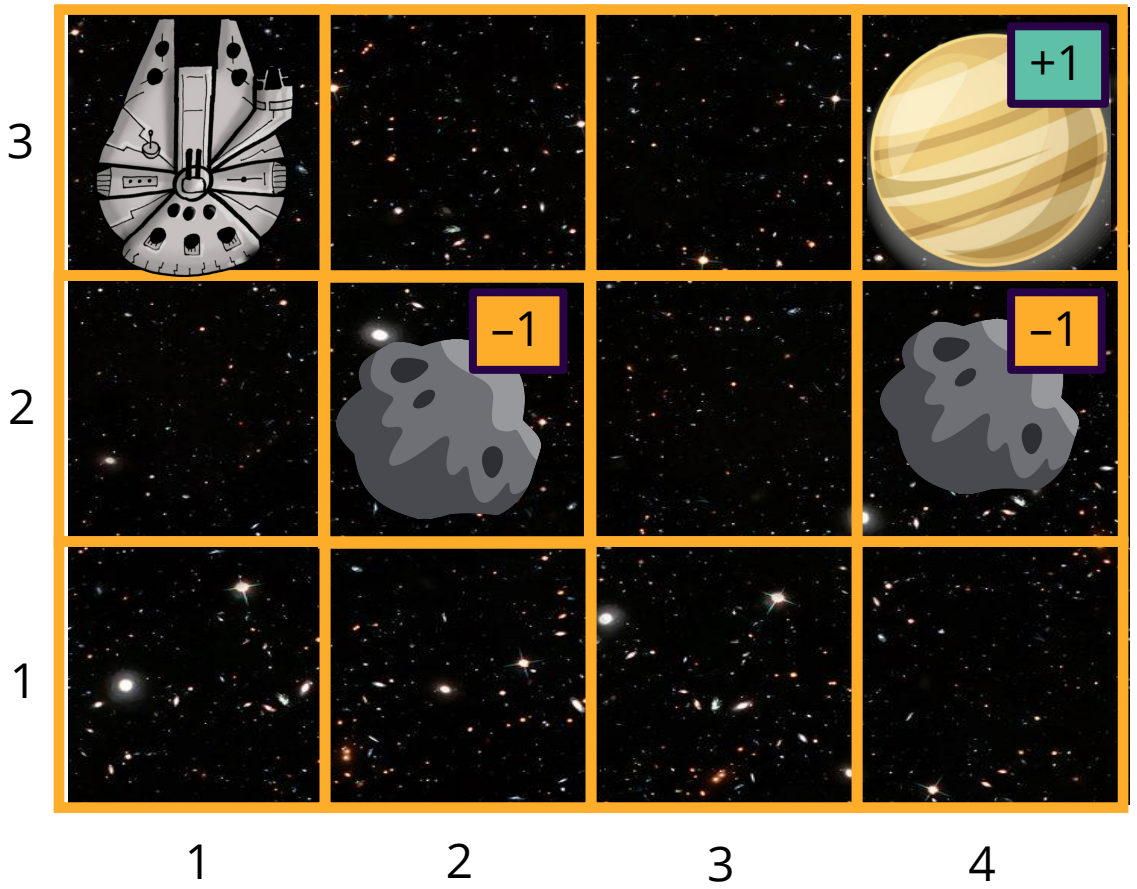
[*Up, Up, Right, Right, Right*],

what's the probability that the millennium falcon reaches the intended goal?

0.8 * 0.8

Transition Model:





Navigating an Asteroid Field

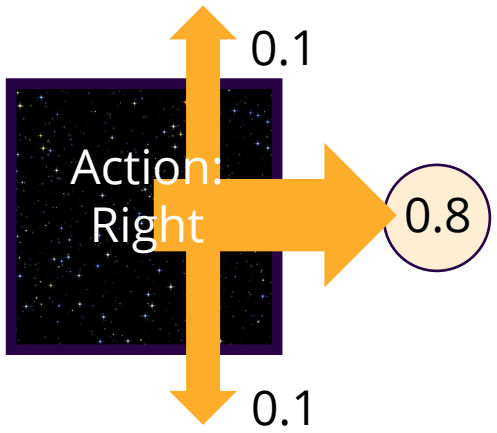
For action sequence

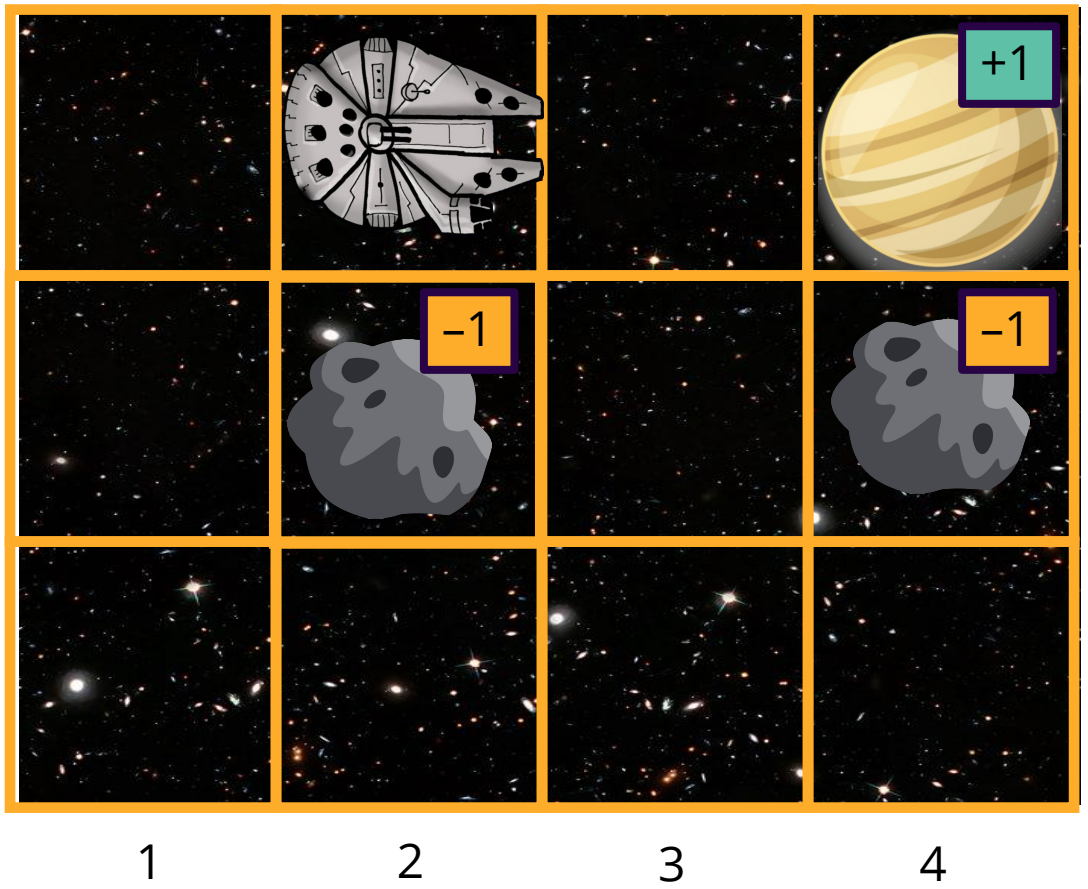
[*Up, Up, Right, Right, Right*],

what's the probability that the millennium falcon reaches the intended goal?

0.8 * 0.8 * 0.8

Transition Model:





Navigating an Asteroid Field

For action sequence

[*Up, Up, Right, Right, Right*],

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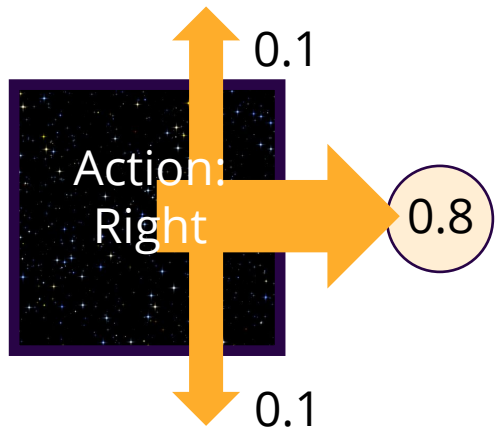
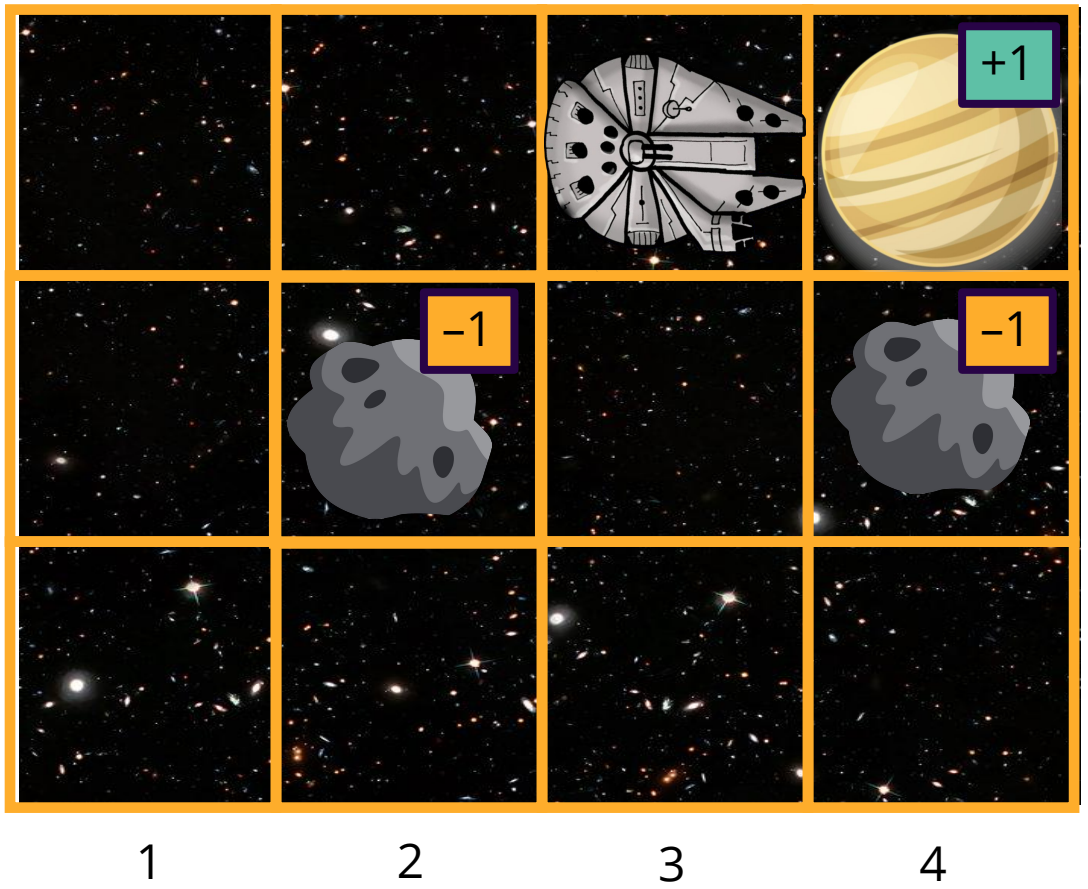
0.8 * 0.8 * 0.8 * 0.8

Transition Model:





Navigating an Asteroid Field

For action sequence

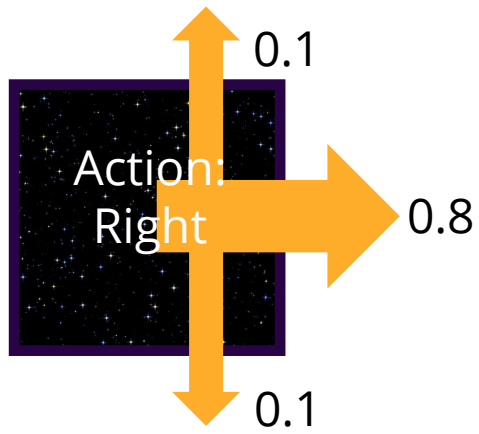
[*Up, Up, Right, Right, Right*],

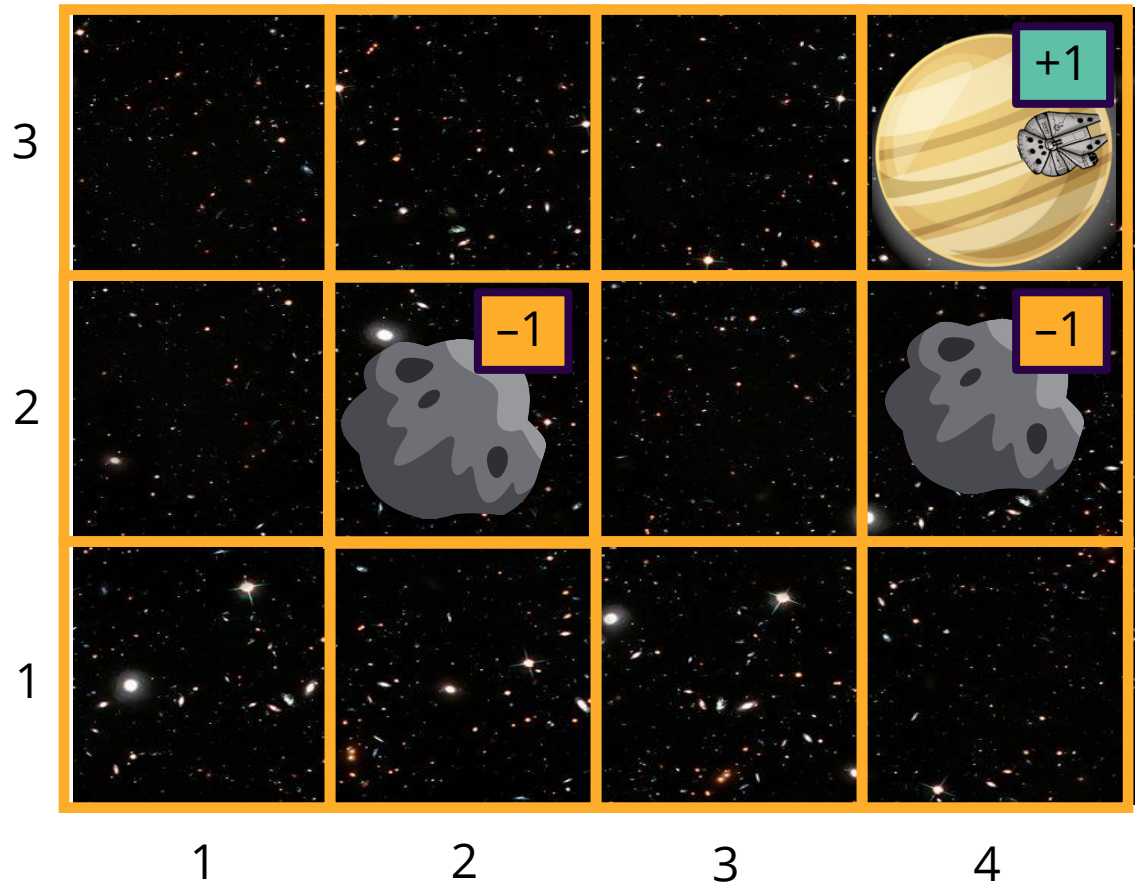
what's the probability that the millennium falcon reaches the intended goal?

0.8 * 0.8 * 0.8 * 0.8 * 0.8

= 0.32768

Transition Model:





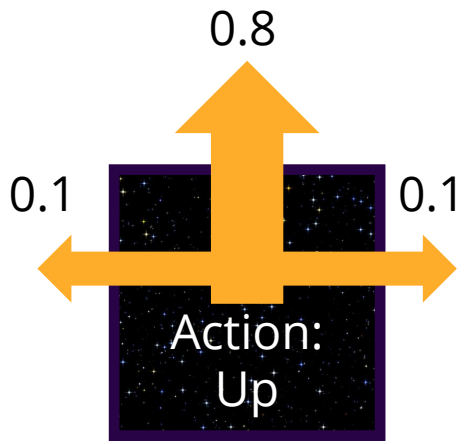
Navigating an Asteroid Field

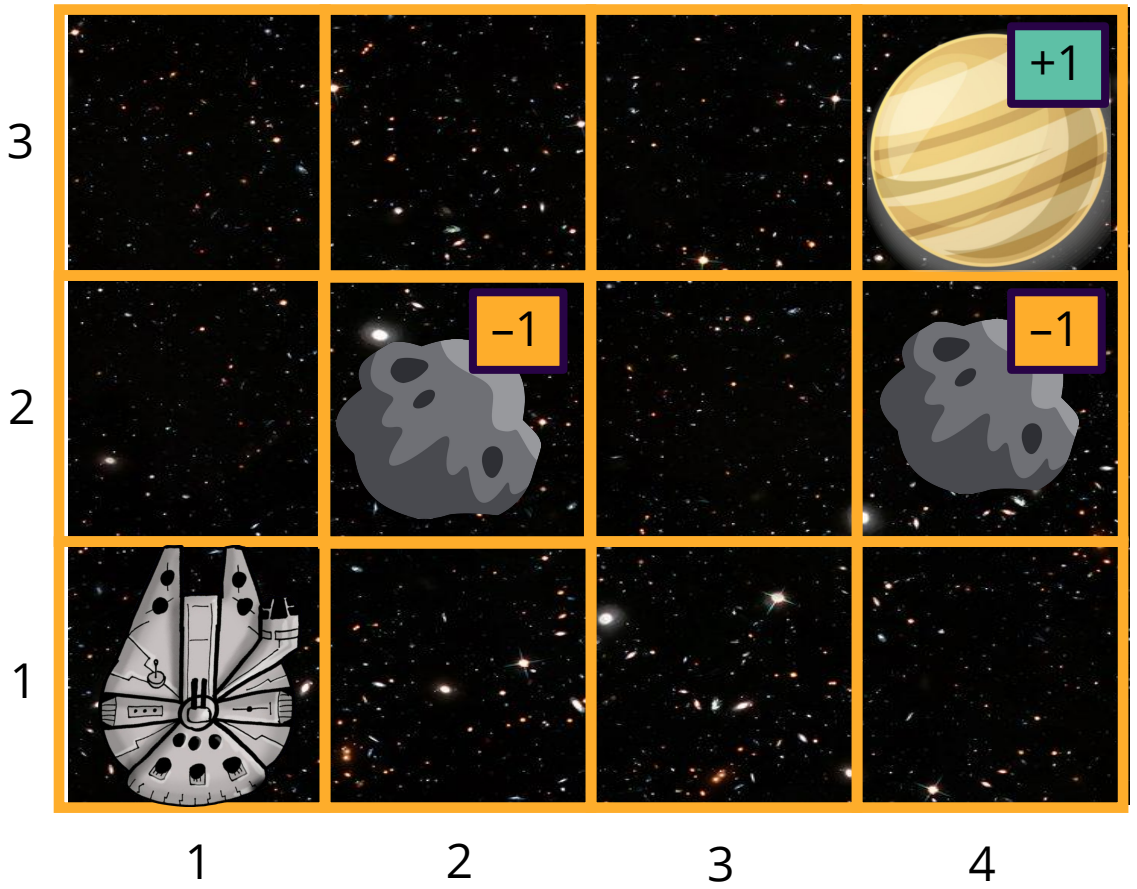
For action sequence

[*Up, Up, Right, Right, Right*],

what's the probability that the millennium falcon reaches the intended goal?

Transition Model:





Navigating an Asteroid Field

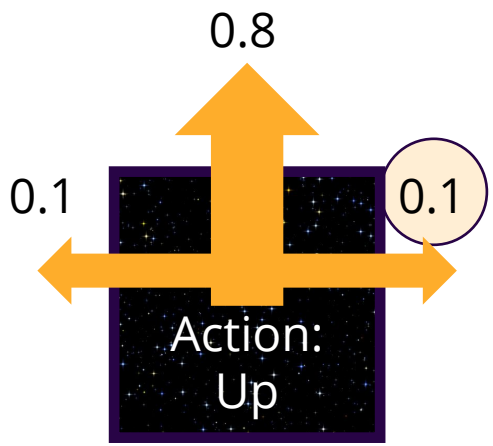
For action sequence

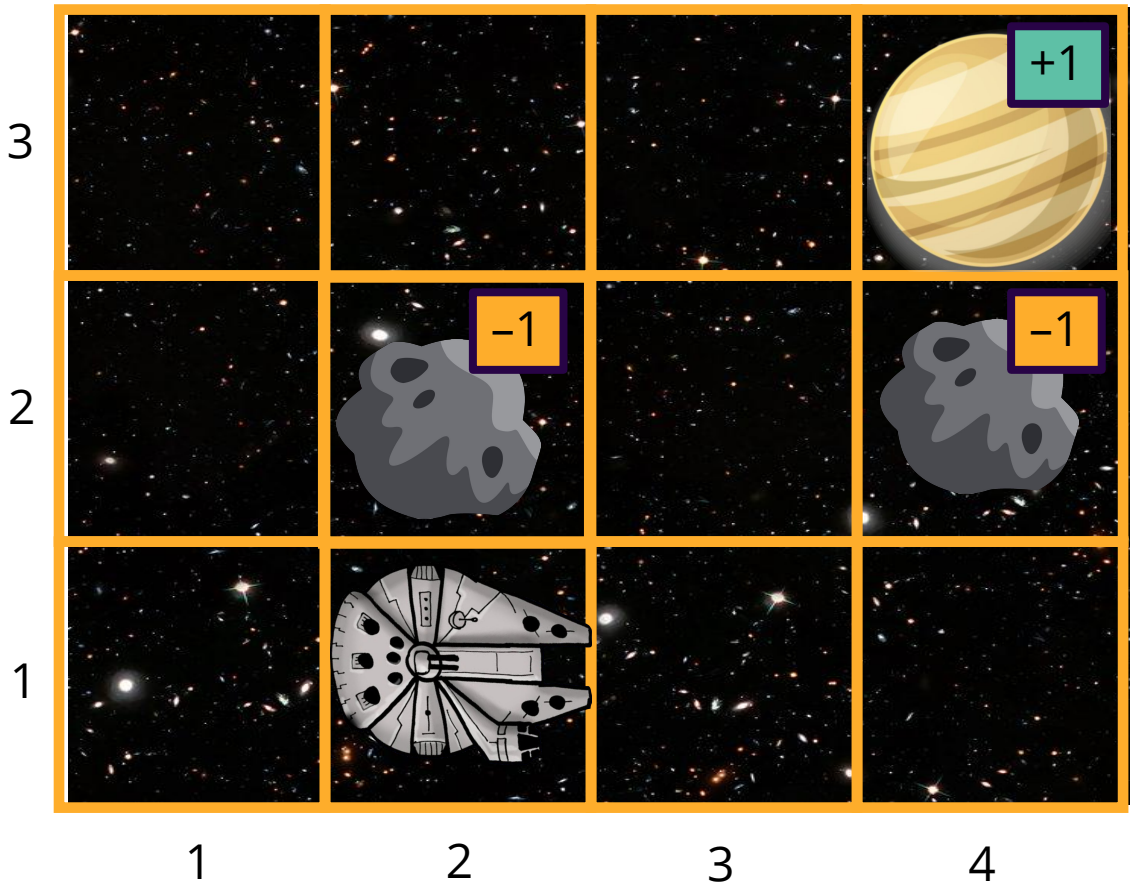
[*Up, Up, Right, Right, Right*],

what's the probability that the millennium falcon reaches the intended goal?

0.1

Transition Model:





Navigating an Asteroid Field

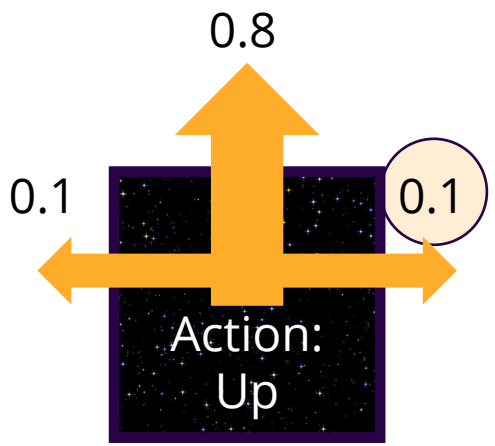
For action sequence

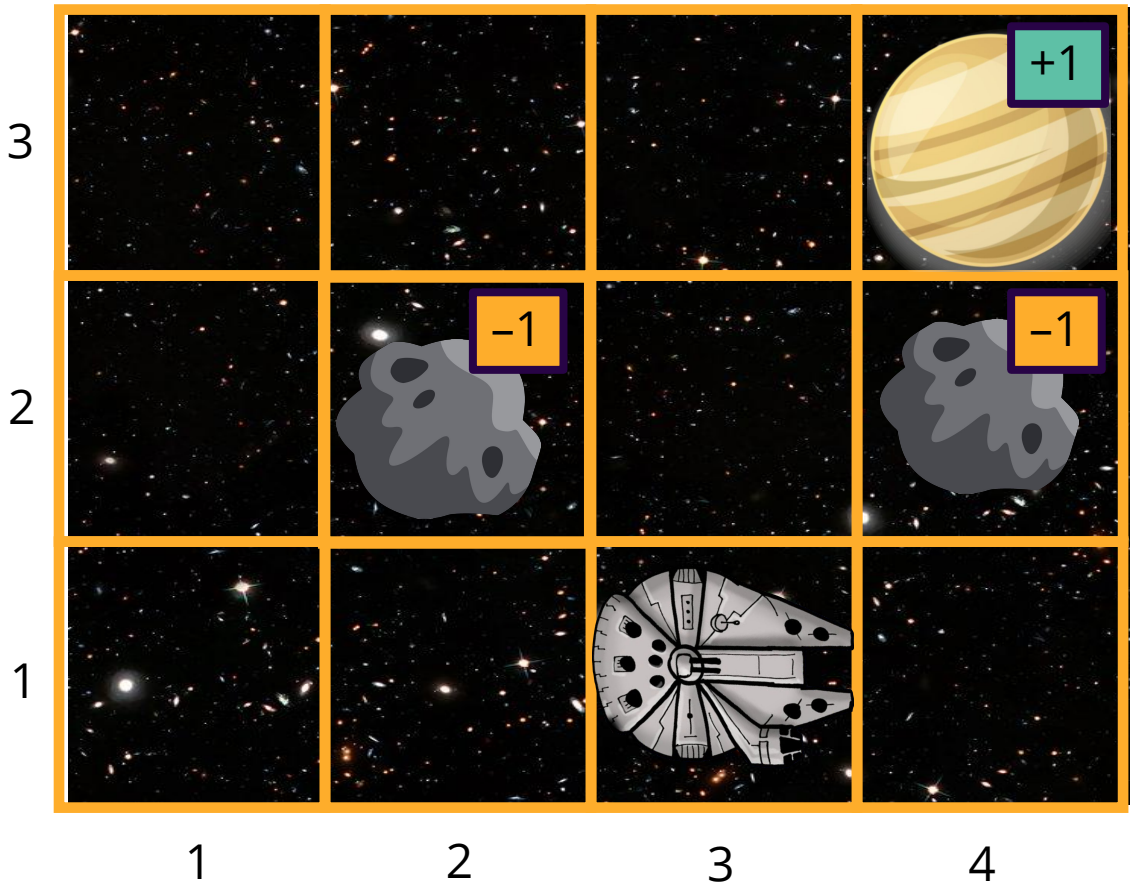
[*Up, Up, Right, Right, Right*],

what's the probability that the millennium falcon reaches the intended goal?

0.1 * 0.1

Transition Model:





Navigating an Asteroid Field

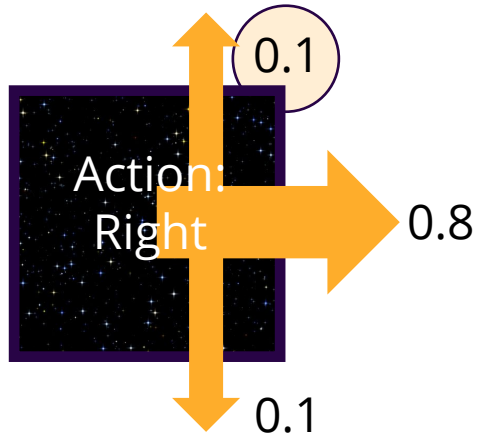
For action sequence

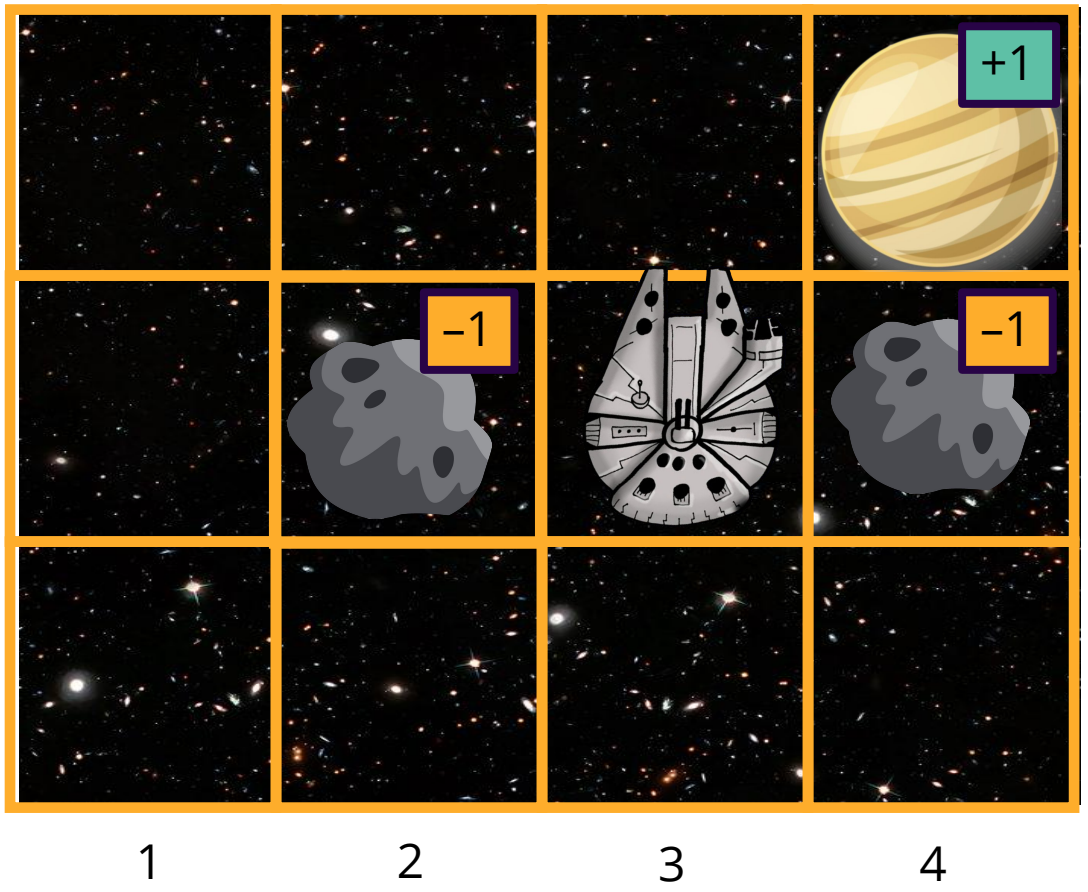
[*Up, Up, Right, Right, Right*],

what's the probability that the millennium falcon reaches the intended goal?

0.1 * 0.1 * 0.1

Transition Model:





Navigating an Asteroid Field

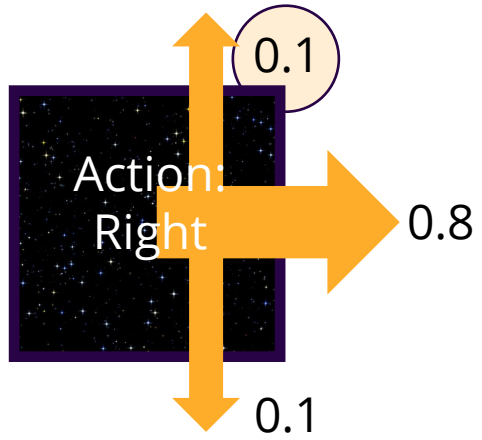
For action sequence

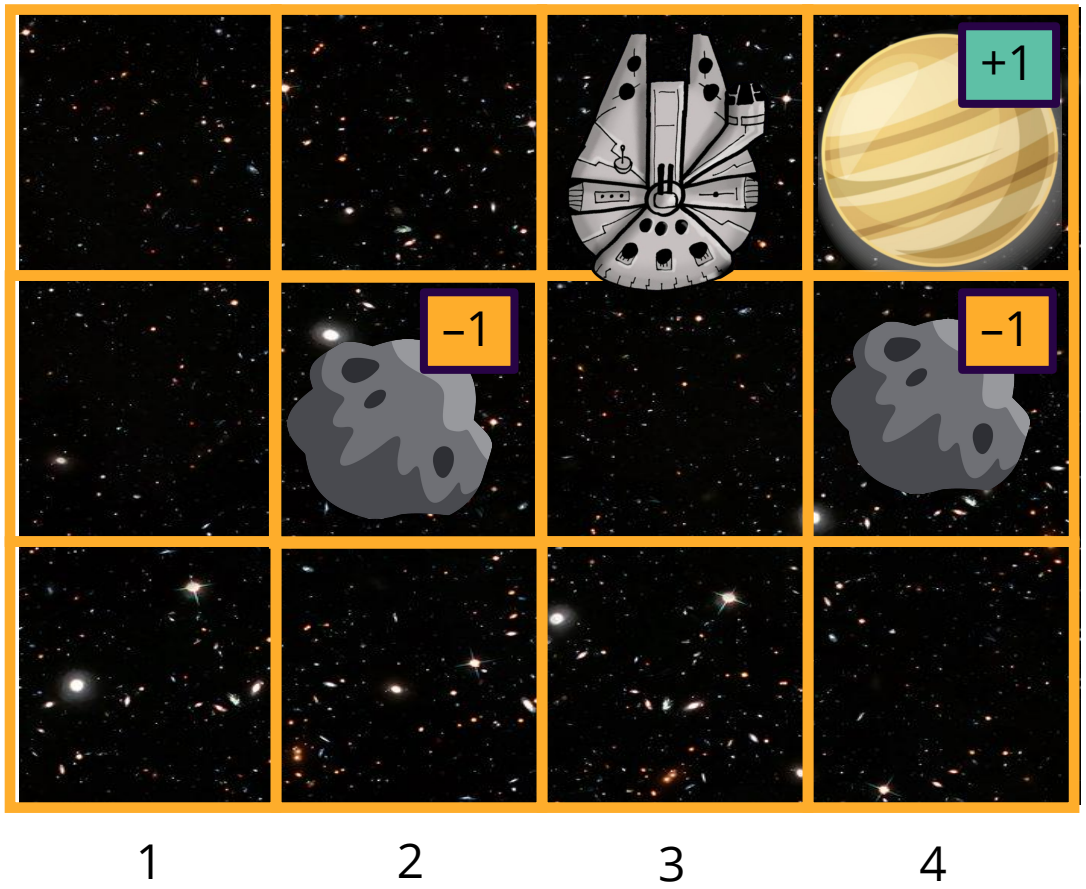
[*Up, Up, Right, Right, Right*],

what's the probability that the millennium falcon reaches the intended goal?

0.1 * 0.1 * 0.1 * 0.1

Transition Model:





Navigating an Asteroid Field

For action sequence

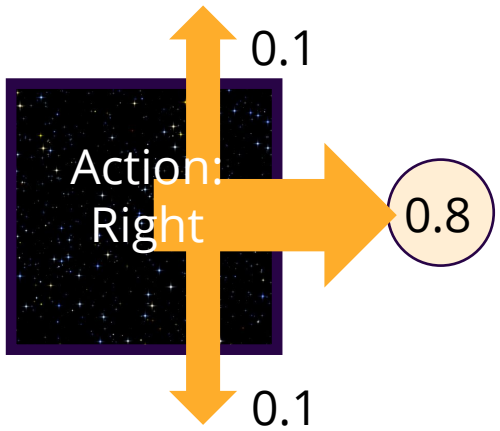
[*Up, Up, Right, Right, Right*],

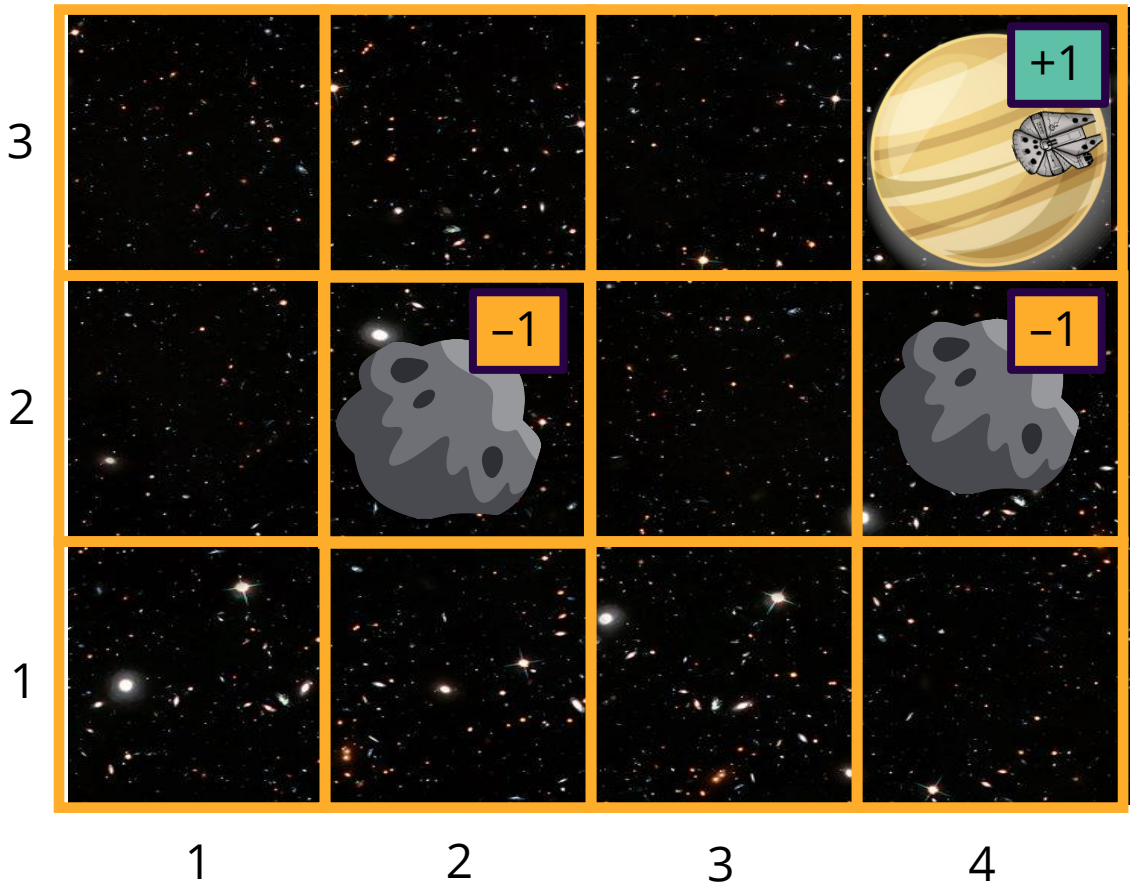
what's the probability that the millennium falcon reaches the intended goal?

0.1 * 0.1 * 0.1 * 0.1 * 0.8

= 0.00008

Transition Model:





Navigating an Asteroid Field

For action sequence

[*Up, Up, Right, Right, Right*],

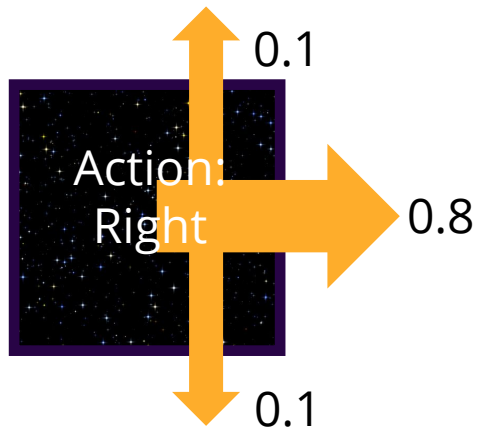
what's the probability that the millennium falcon reaches the intended goal?

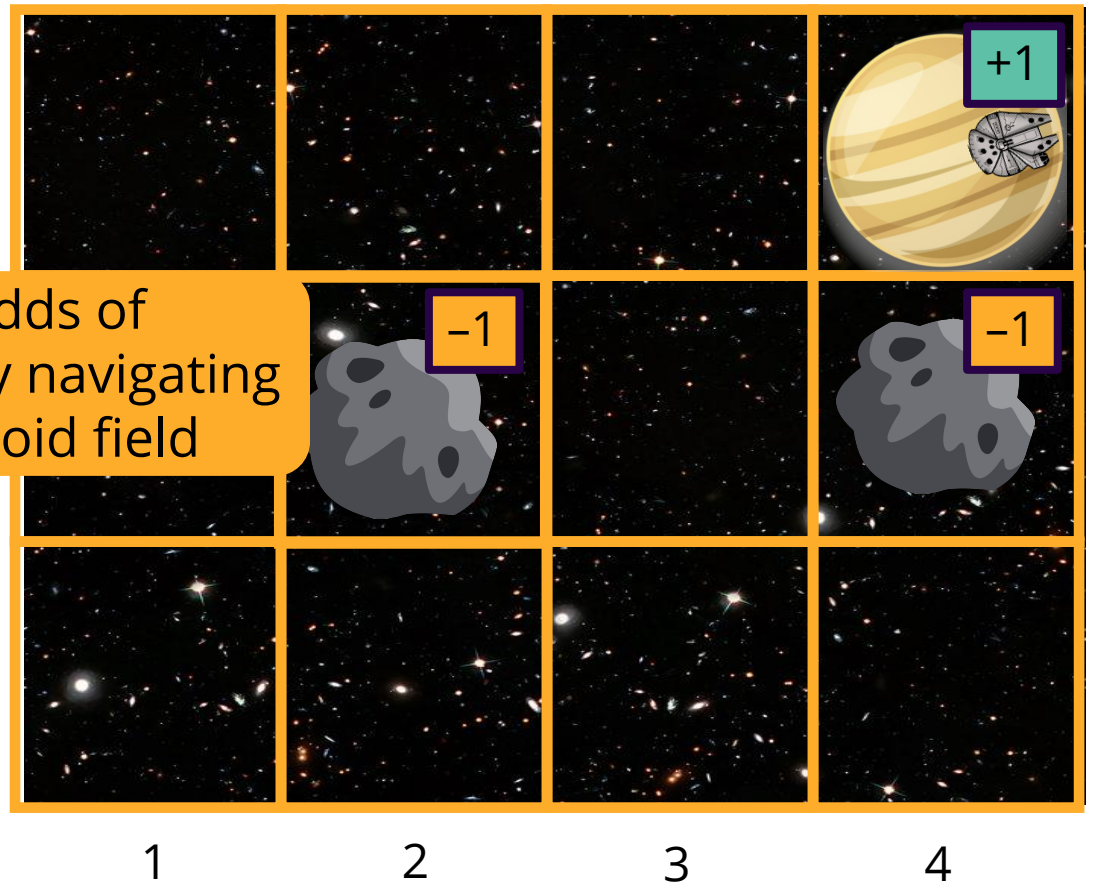
0.32768 + 0.00008

= 0.32776

The odds of successfully navigating an asteroid field

Transition Model:





Stochastic Transition Model

In our search algorithms so far, the transition model was deterministic and described the outcome of each action in each state.

The transition function is sometimes written as T(s, a, s'), or explicitly as a probability:

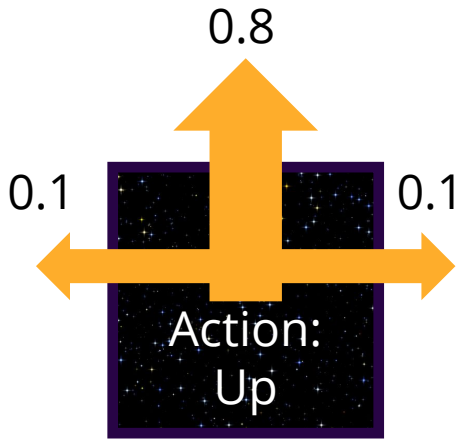
The probability of

arriving in state **s'**

$$p(s' \mid s, a)$$

given that

we are in state **s** and we selected action **a**



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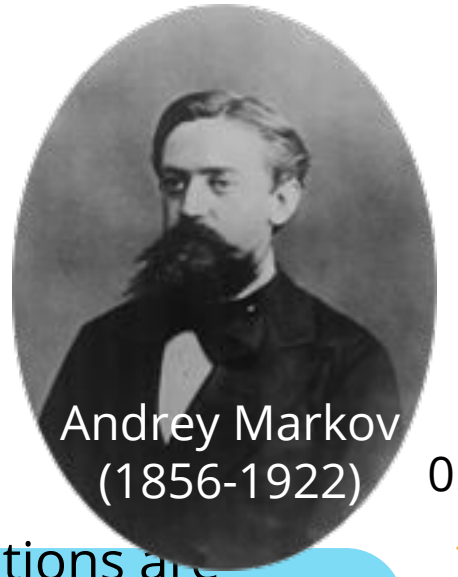
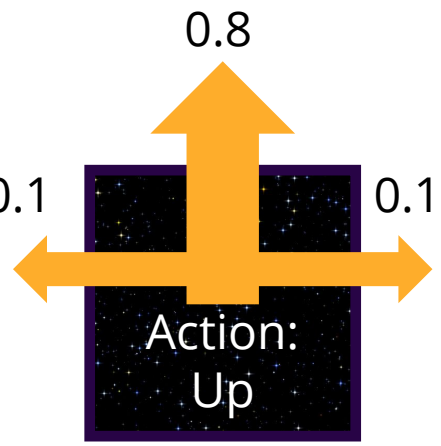




$p(s' \mid s, a)$

Transitions are **Markovian**: the probability of arriving in s' only depends on s and not the history of earlier states.

Reward function

We will specify a **utility or reward function** for the agent.

The “rewards“ can be **positive** or **negative** but are bounded by some maximum value.

Because the decision process is **sequential,** we must specify the utility function on a sequence of states and actions.

Instead of only giving a reward at the goal states, the agent can **receive a reward at each time step**, based on its transition from **s** to **s’** via action **a**.

This is defined by a reward function

R(s, a, s’)

For example, we could give the Millennium Falcon a small negative reward of -0.04 for every transition except for entering the terminal states (+1 for entering the planet’s orbit or -1 for smashing into an asteroid).

The **rewards are additive**, so if the Millennium Falcon takes 4 steps before entering the planet's orbit, it gets *-0.04 + -0.04 + -0.04 + -0.04 + 1 = 0.84* for that solution.

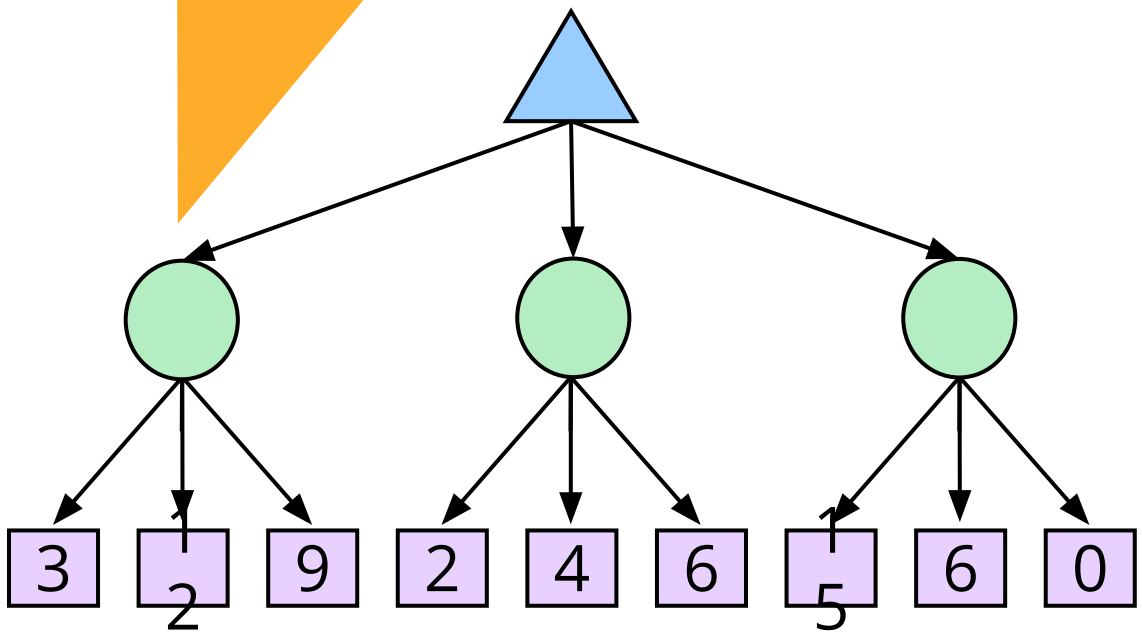
Markov Decision Process

A **Markov decision process** or **MDP** is

- a **sequential** decision problem
- for a **fully observable** environment
- with a **stochastic** transition model
- that has **additive rewards**

MDPs are non-deterministic search problems. One way of solving them is via **expectimax** search.

Expectimax node: outcome is uncertain. In expectimax search we calculate their expected utilities.



Markov Decision Process

To find a solution to an MDP, you need to define the following things:

- **A set of states** $s \in S$
- **A set of actions** $a \in A$
- A transition function **T(s, a, s')**
  - Probability that executing action **a** in **s** will lead to **s' P(s' | s, a)**
  - The probability is called **the model**
- A reward function **R(s, a, s')**
  - Sometimes just R(s) or R(s')
- An **initial state** s_0
- Optionally, one or more **terminal states**

Solution == Policy

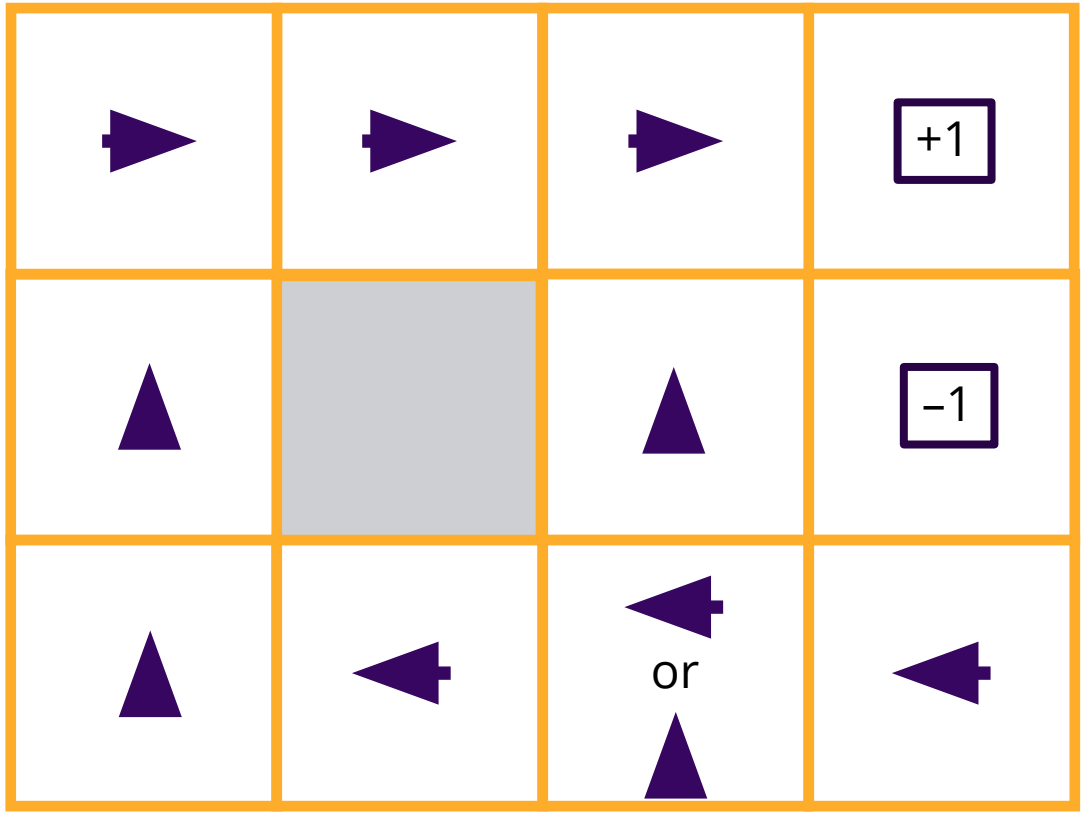
In search problems a solution was a sequence of action that corresponded to the shortest path.

Because of the non-determinism in MDPs we cannot simply give a sequence of actions.

Instead, the solution to an MDP is a **policy.** A policy maps from a state onto the action to take if the agent is in that state.

$$\pi(s) = a$$

Policy **π** tells the agent what action to take at state s.



This is an example policy for a grid world

Solution == Policy

In search problems a solution was **a plan**: a sequence of action that corresponded to the shortest path from the start to a goal.

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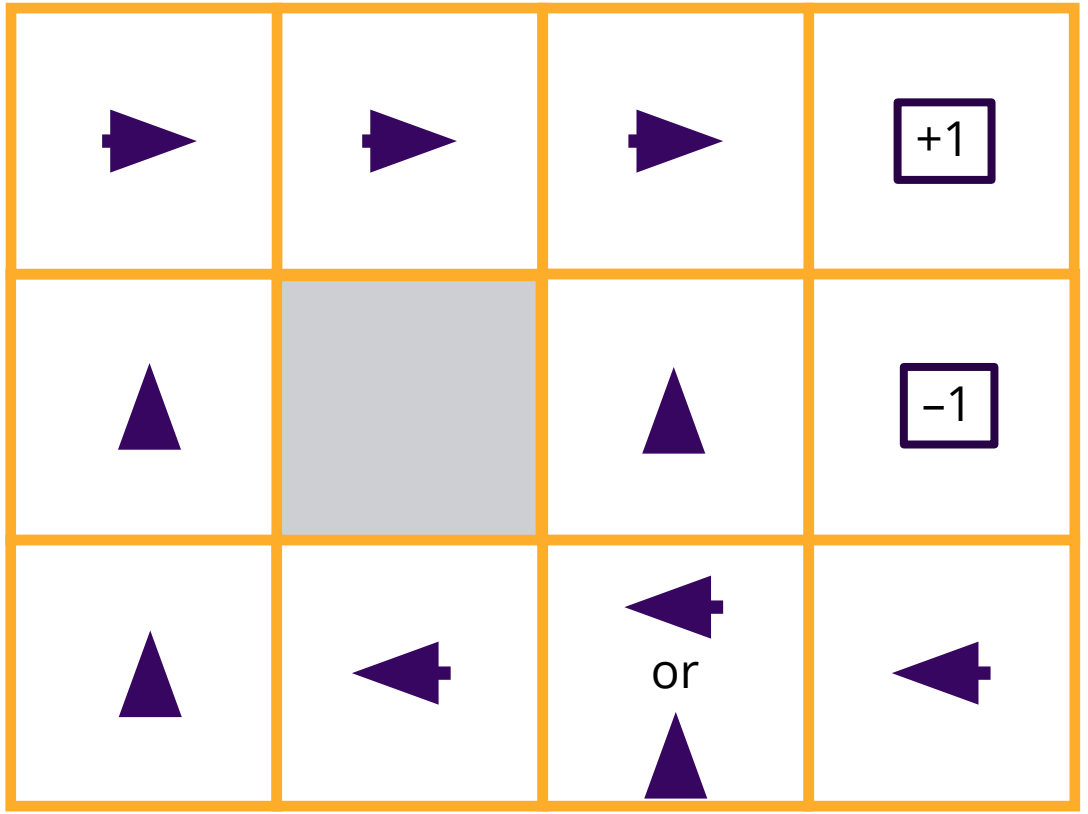

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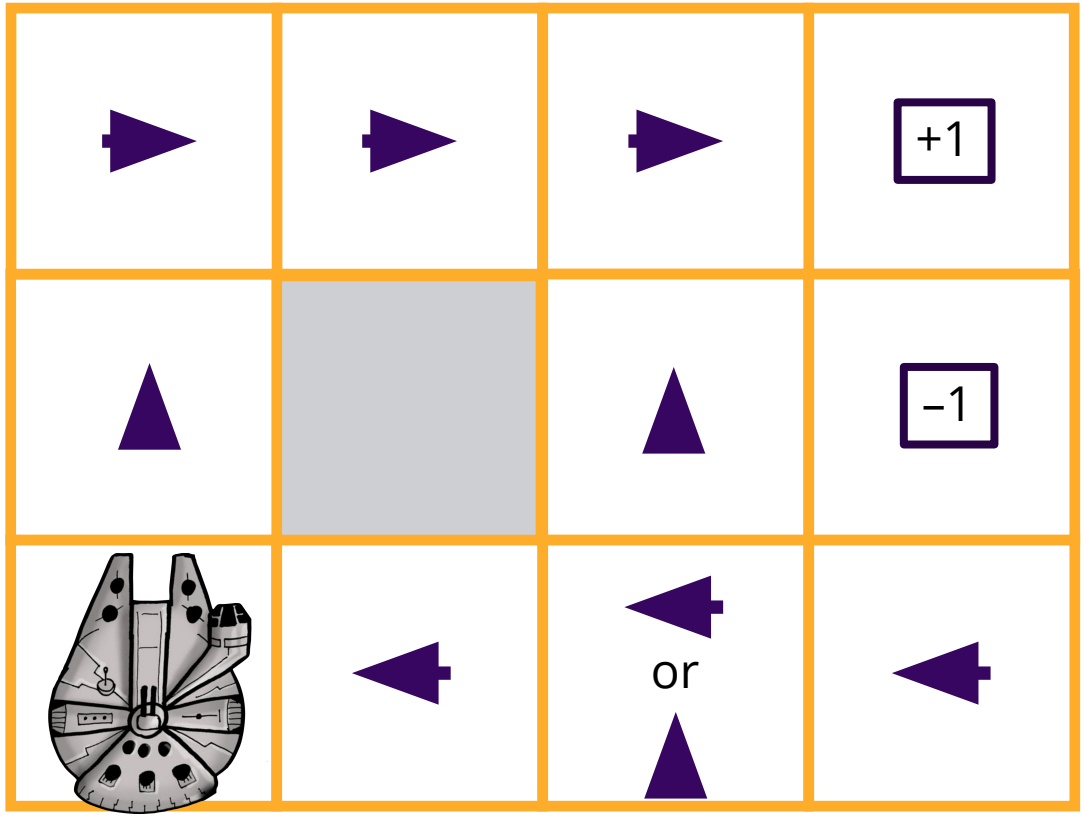

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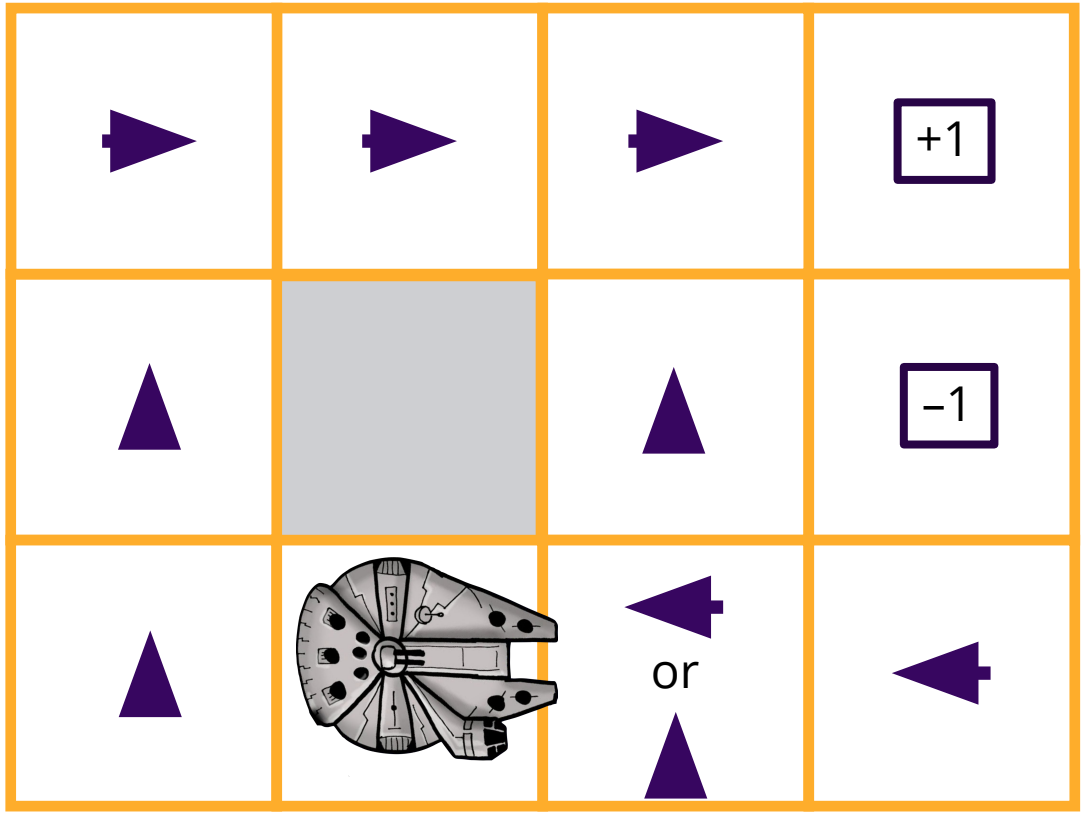

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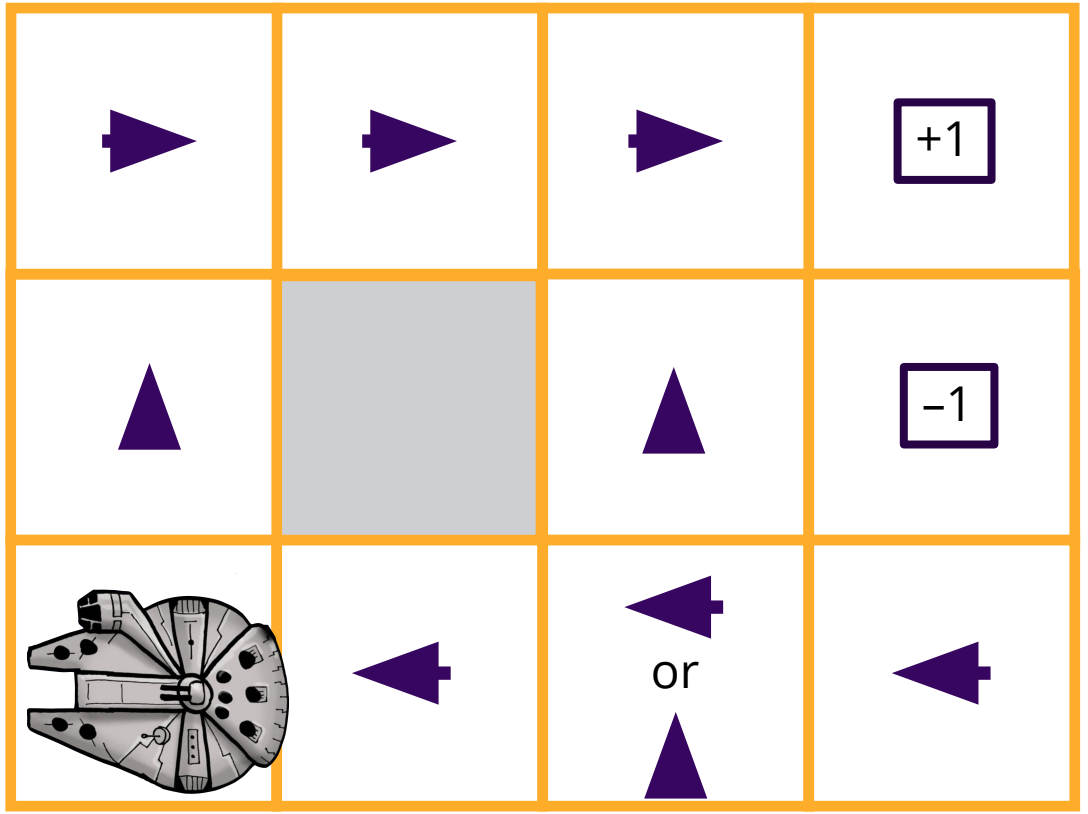

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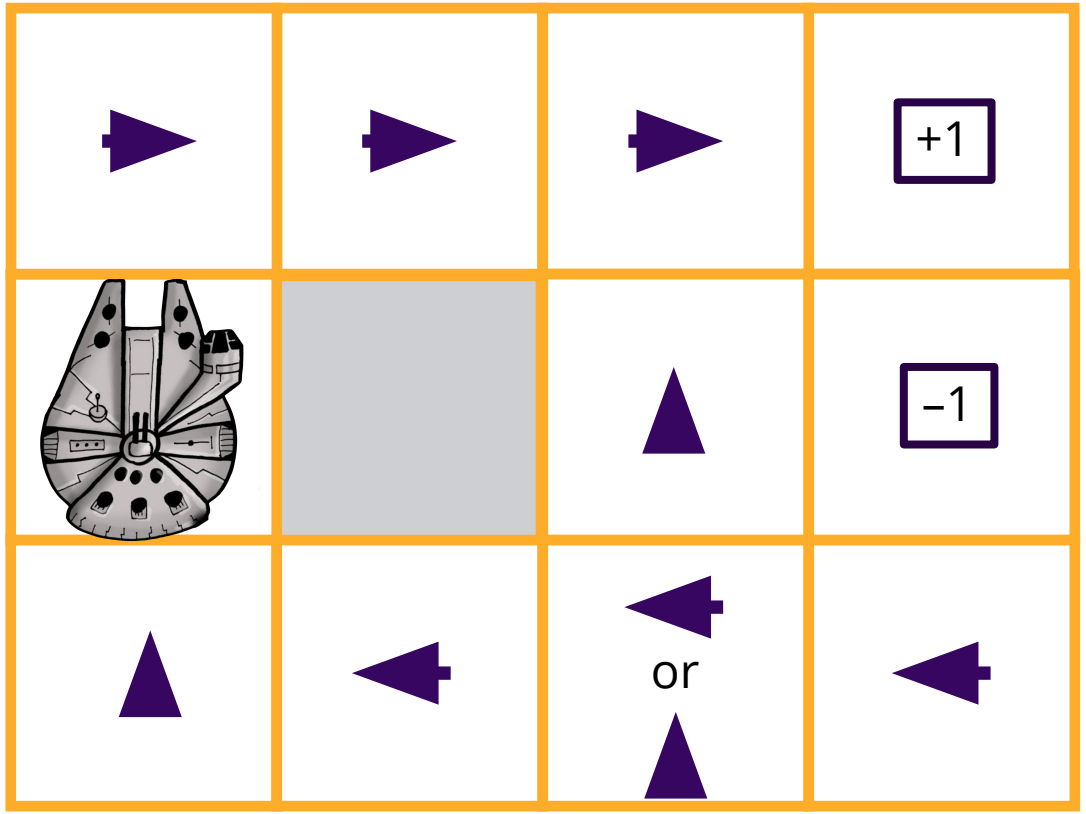

Solution == Policy

In search problems a solution was **a plan**: a sequence of action that corresponded to the shortest path from the start to a goal.

Because of the non-determinism in MDPs we cannot simply give a sequence of actions.

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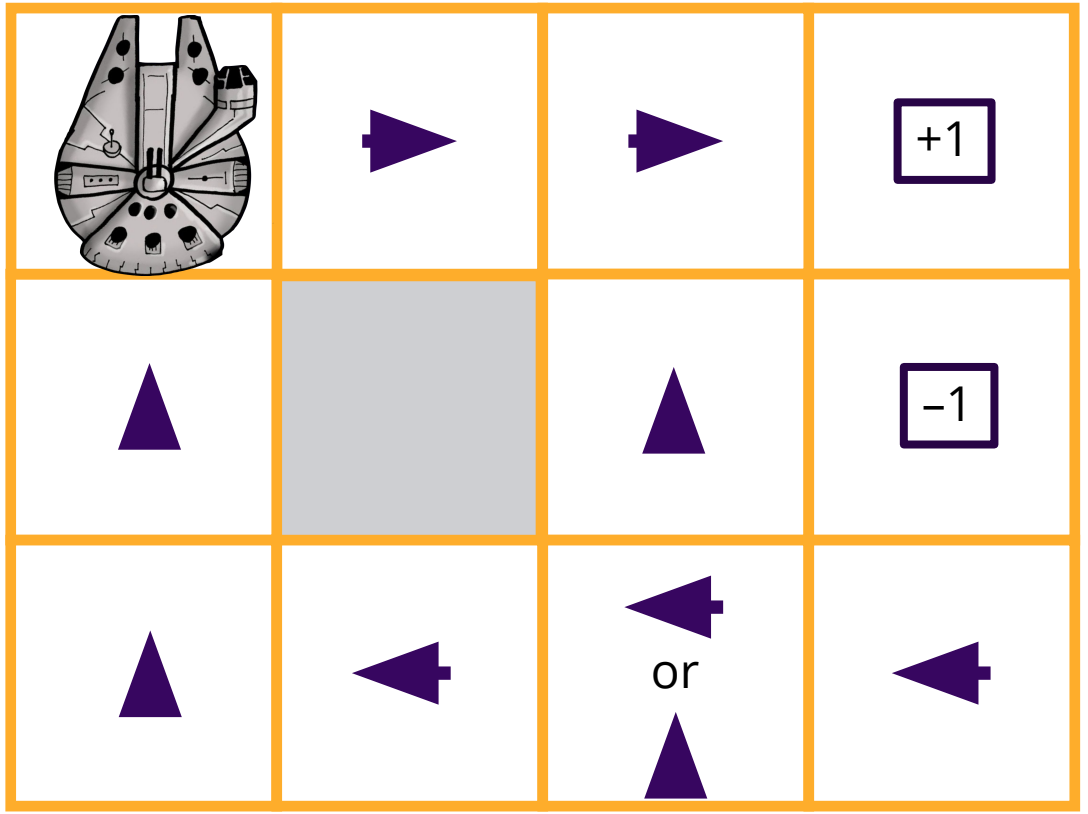

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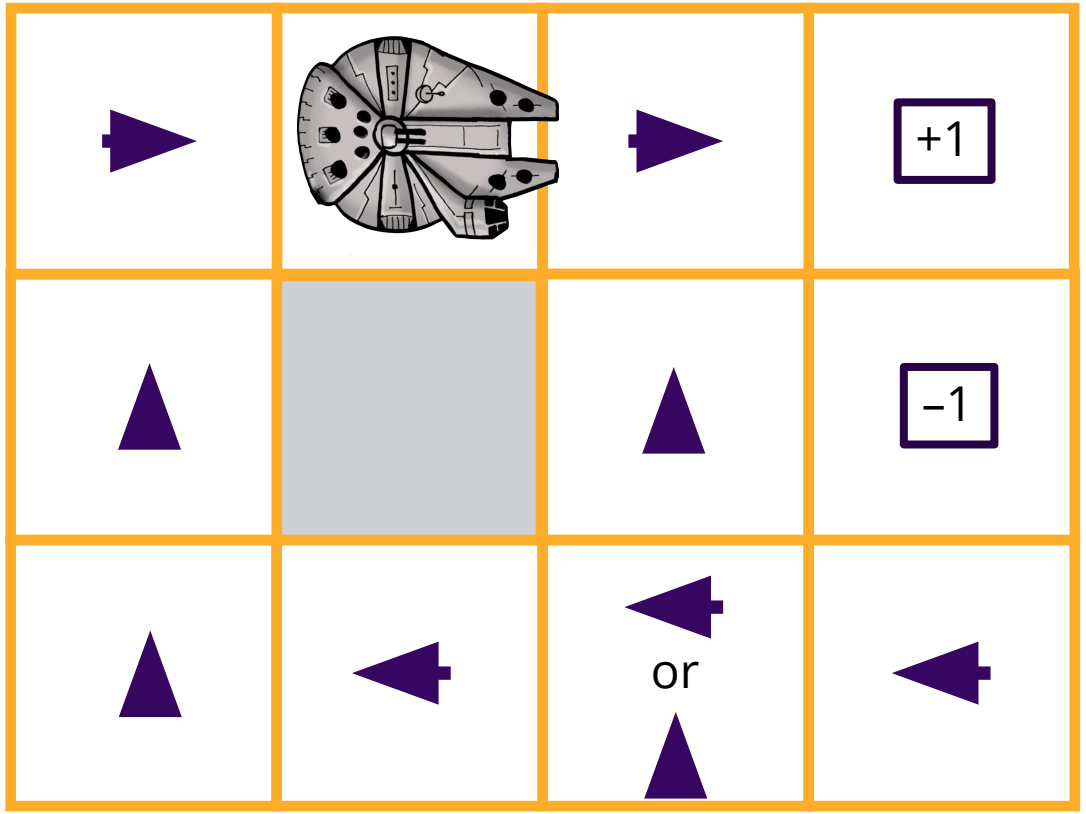

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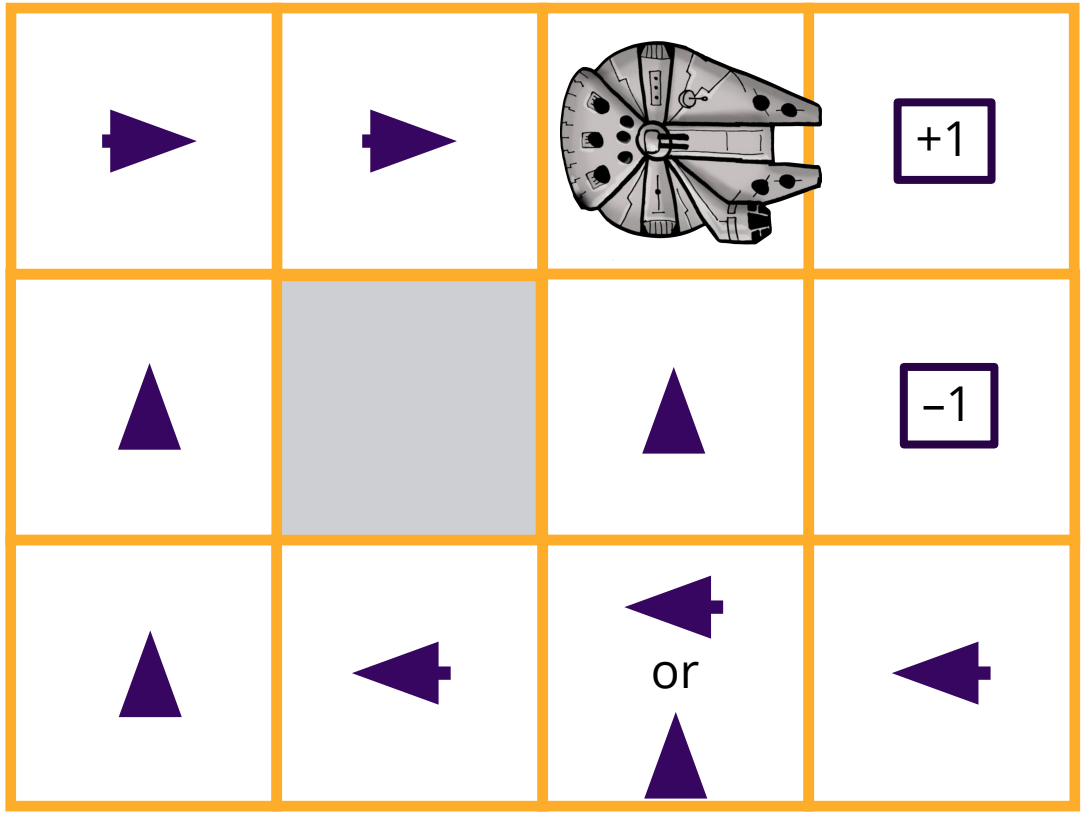

Solution == Policy

Even though the policy told me to go right here, there's no guarantee that me picking the action Right will result in me moving right. It's stochastic!

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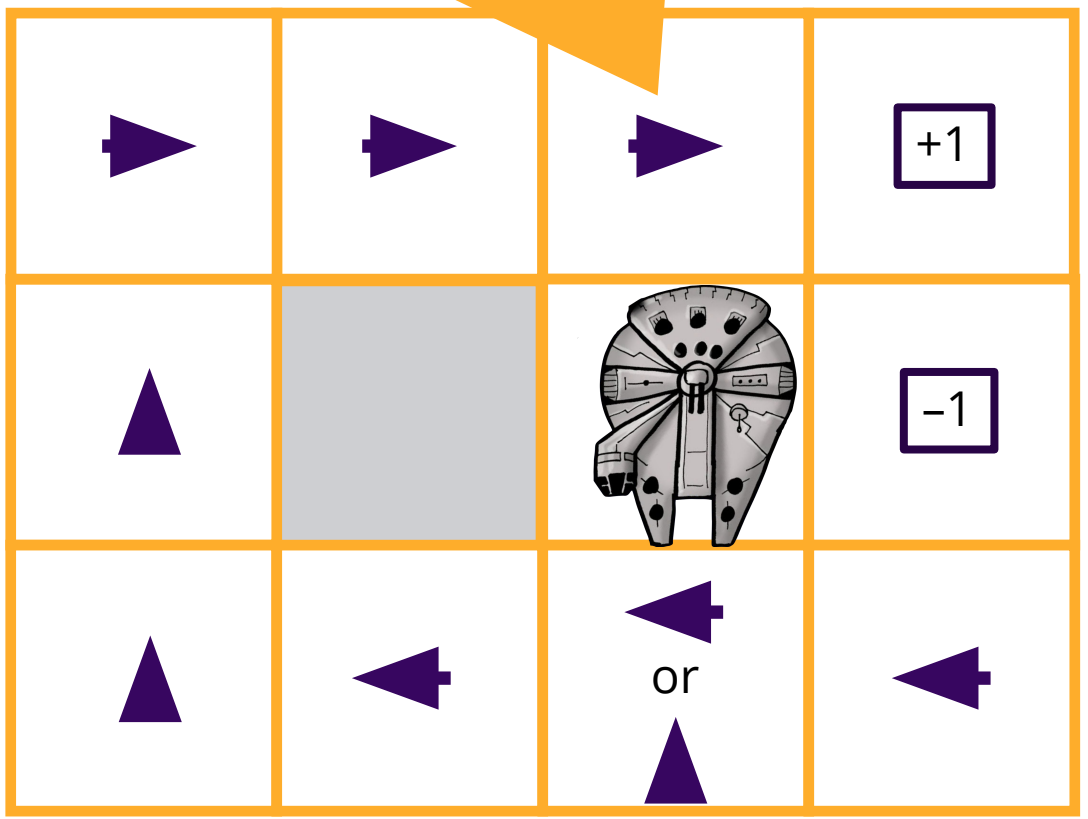

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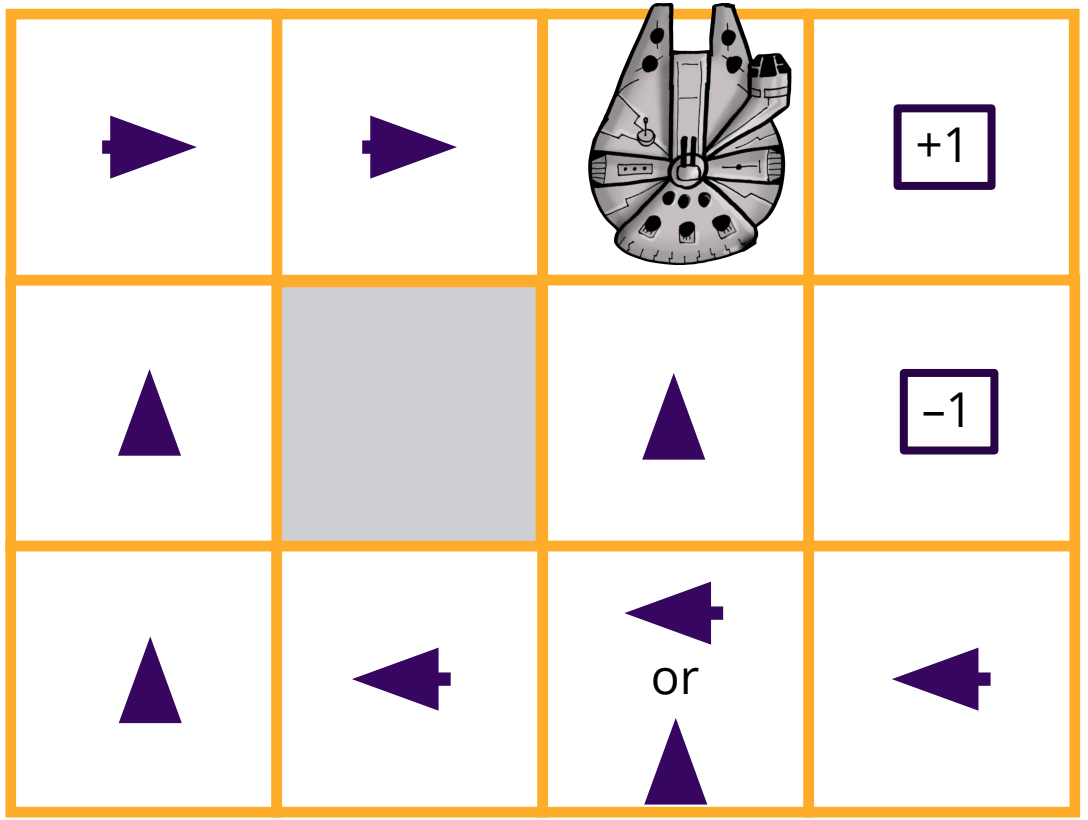

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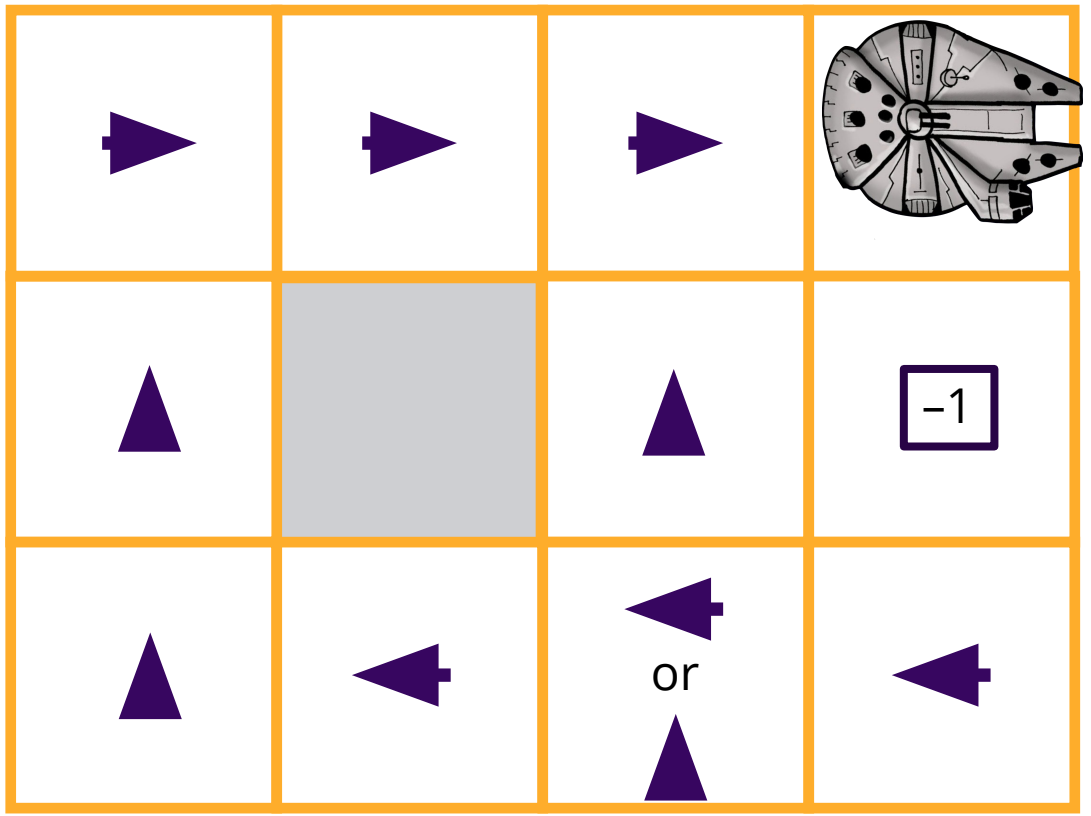
$$\pi(s) = a$$

We will use π^* to denote the **optimal policy**.

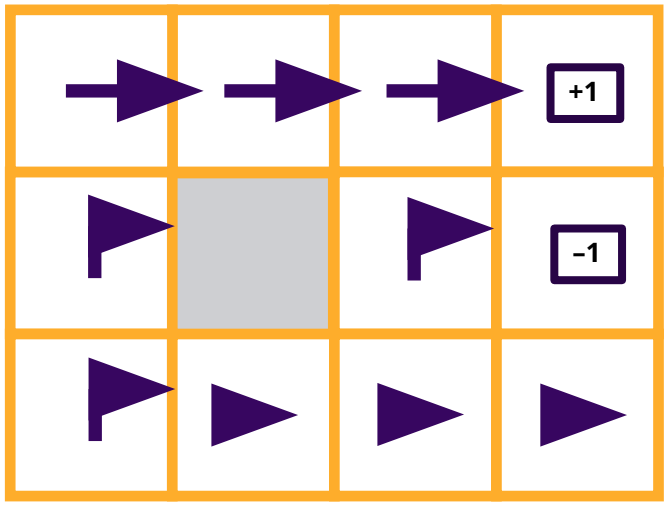


Policies and Rewards

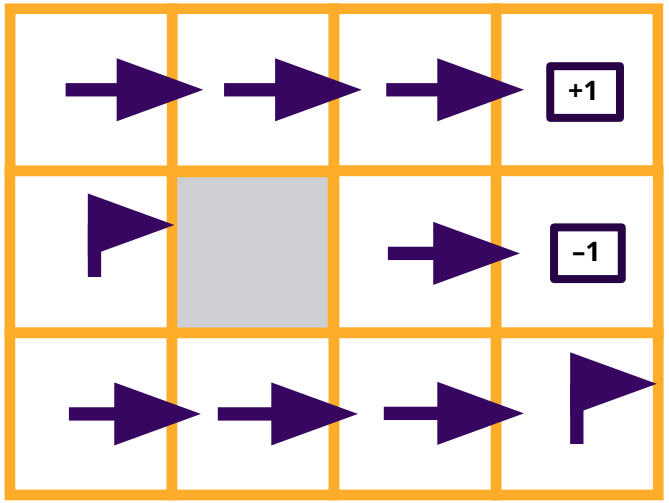
Even if the **same policy** is executed multiple times by the agent, this may lead to different sequence of states and actions (**environment history**), and thus a **different score** under the reward function.

Therefore we need to compute the **expected utility** of all the possible paths generated by a policy.

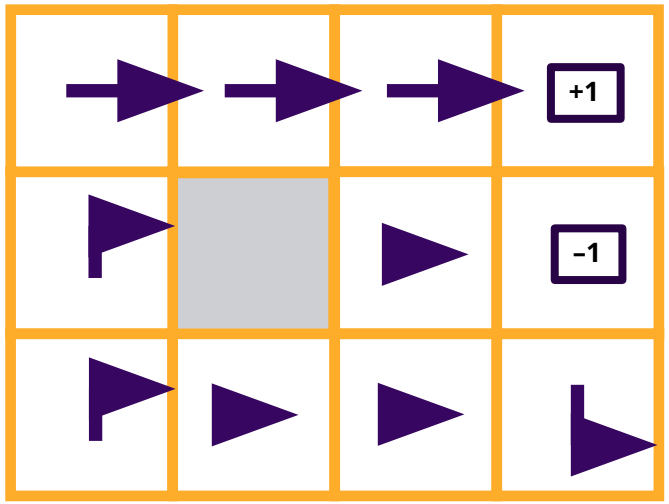
r = -0.04



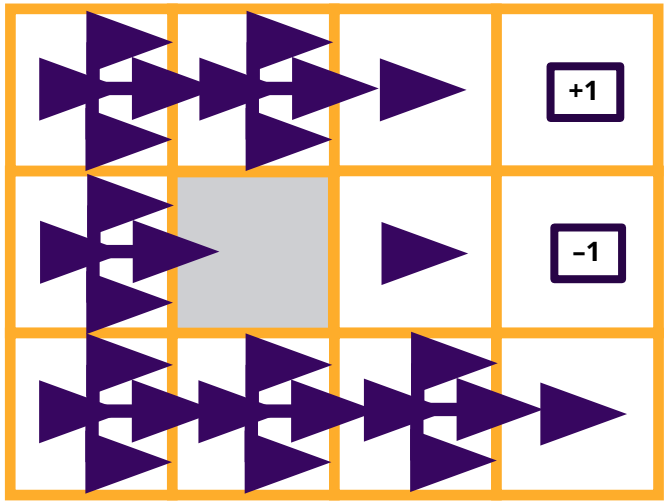
r < -1.65



-0.03 < r < 0



r > 0



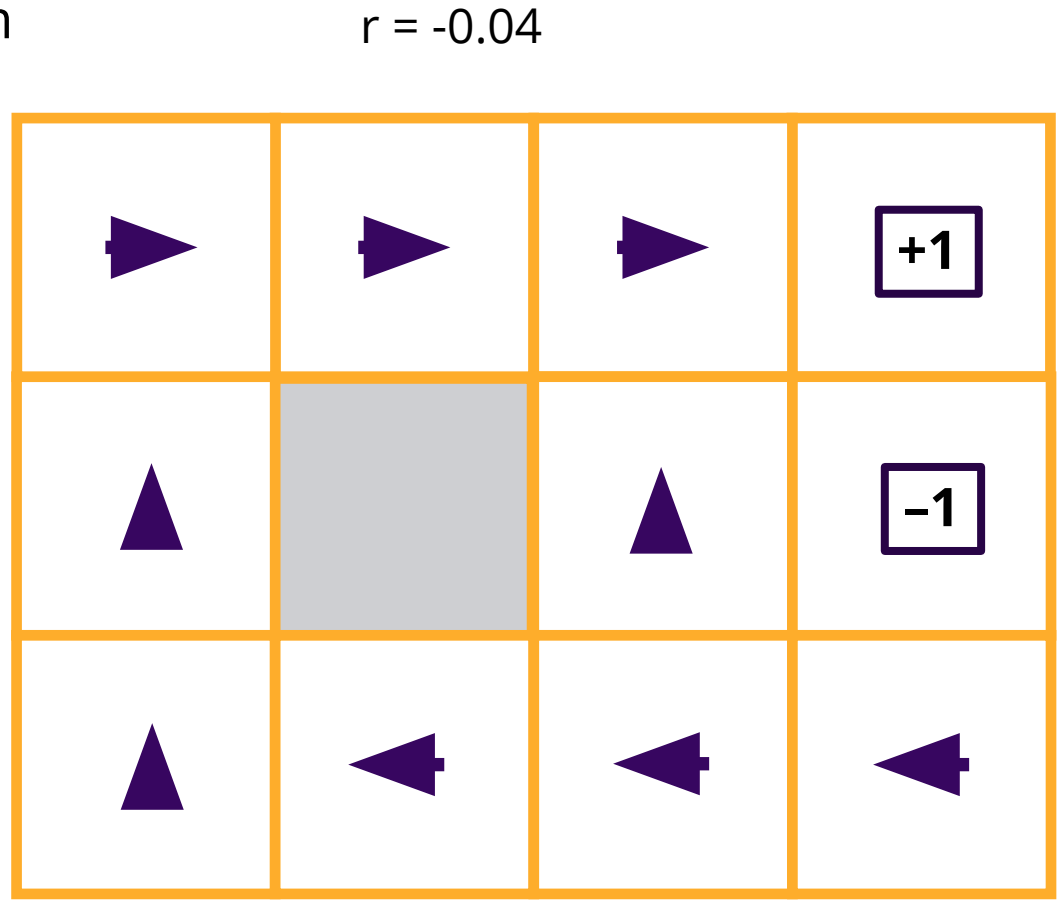
Sequences of Rewards

The performance of an agent in an MDP is the sum of the rewards for the transitions it takes.

$$U_h([s_0, a_0, s_1, a_1 \ldots, s_n])$$

Utility function on an environment history.

Sequence of states and actions



Sequences of Rewards

The performance of an agent in an MDP is the sum of the rewards for the transitions it takes.

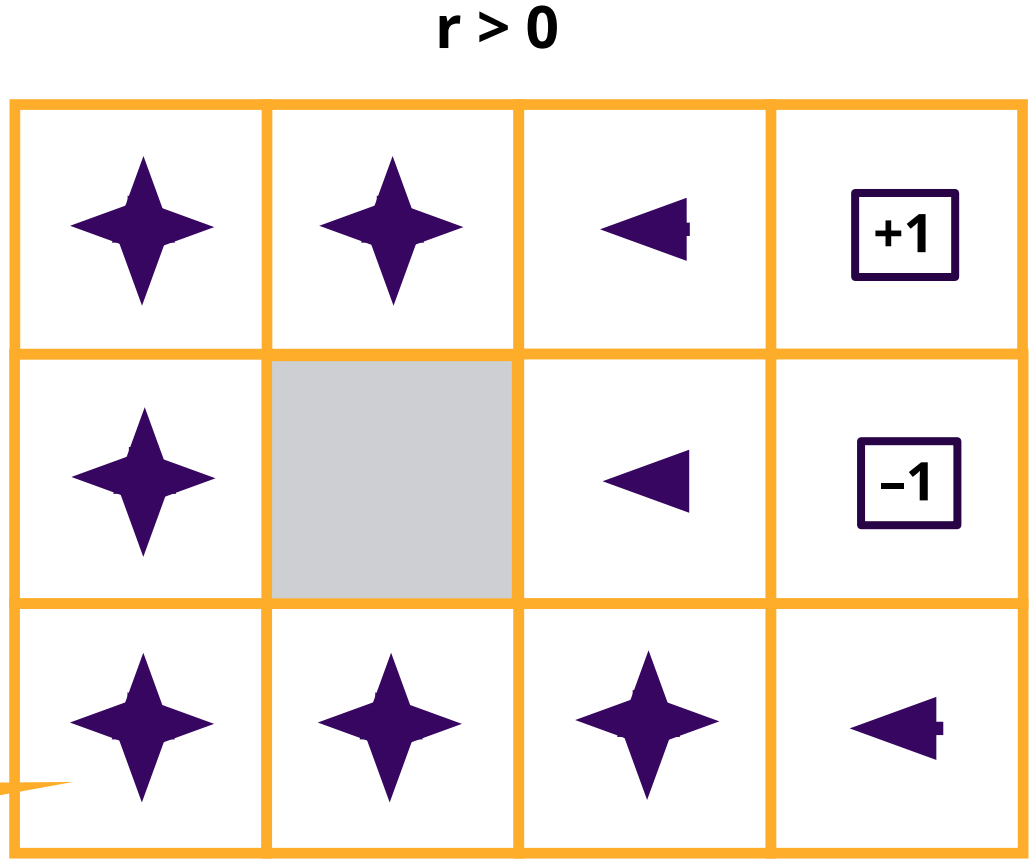
$$U_h([s_0, a_0, s_1, a_1 \ldots, s_n])$$

$$= R(s_0, a_0, s_1) + R(s_1, a_1, s_2) + \ldots + R(s_{n-1}, a_{n-1}, s_n)$$

Utility function on an environment history.

Sequence of states and actions

Bounce around forever, and avoid the exits … **infinite rewards!!**



Sequences of Rewards

Finite Horizons

Fixed time (**N** actions) after which the game ends and the agent gets no additional score.

An optimal action can depend on how much time is left.

Policies that depend on time are called **nonstationary.**

Infinite Horizons

With no fixed time limit, there is no reason to behave differently in the same state at different times.

The optimal policy is **stationary**.

Infinite horizons are therefore easier.

Utilities Over Time

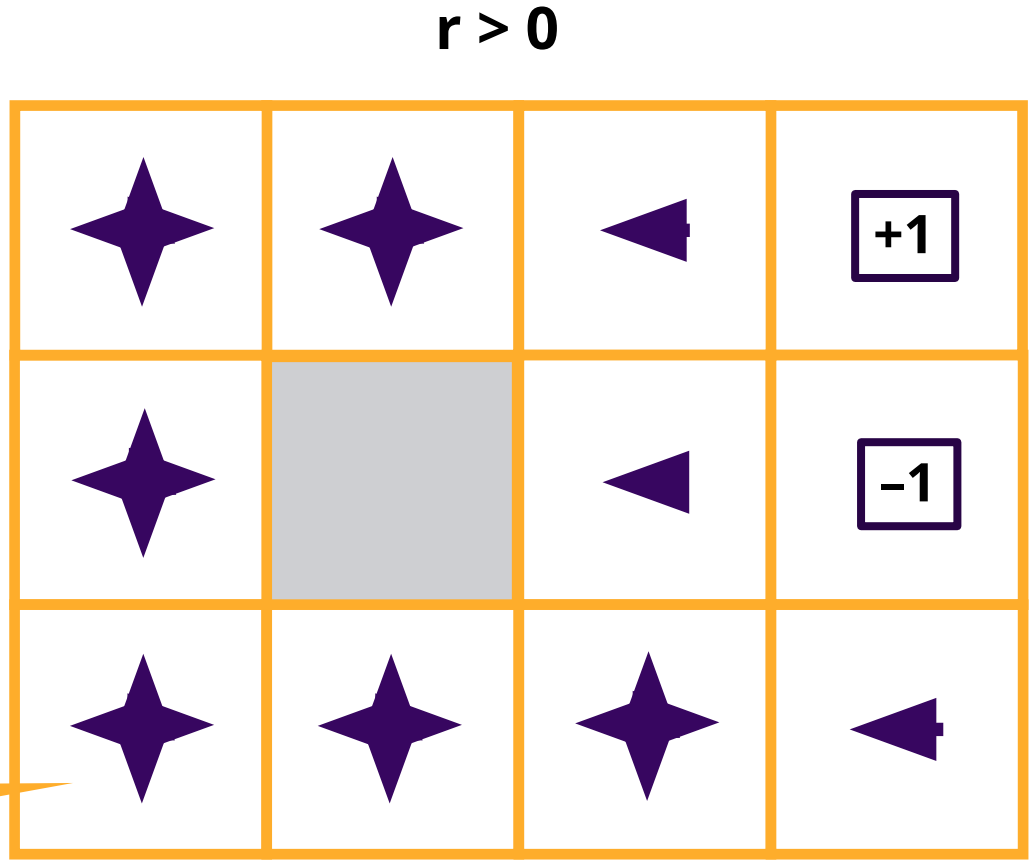
The performance of an agent in an MDP is the sum of the rewards for the transitions it takes.

$U_h([s_0, a_0, s_1, a_1 \ldots, s_n])$

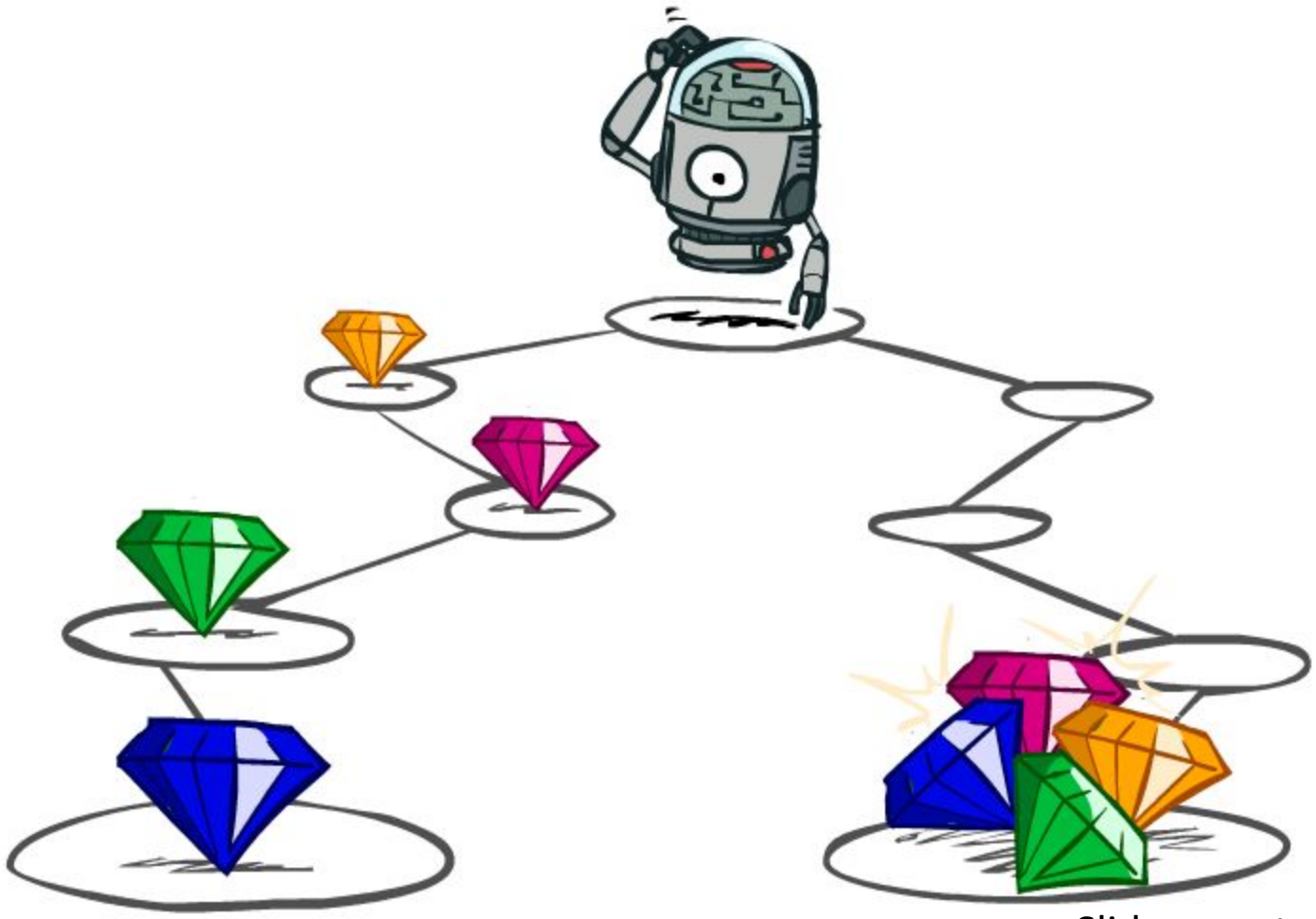
Utility function on an environment history.

Sequence of states and actions

Bounce around forever, and avoid the exits … **infinite rewards!!**



Utilities of Sequences



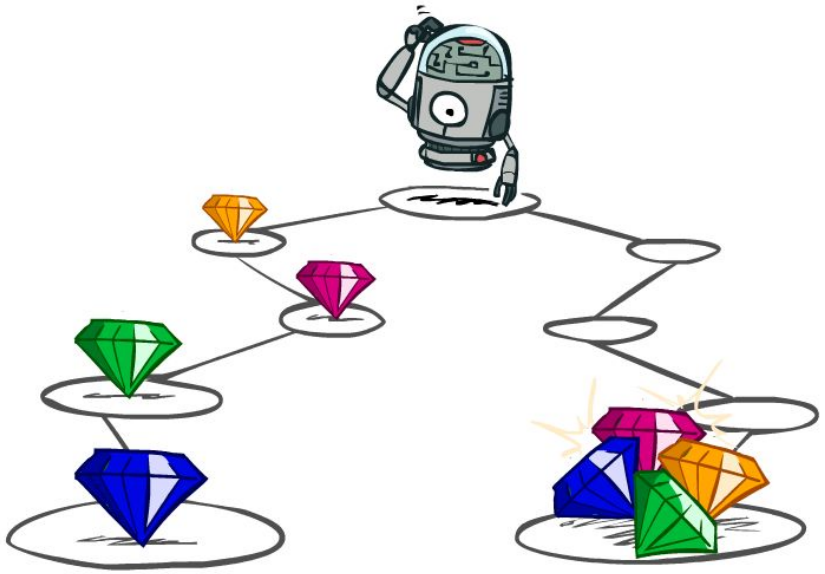
Slides courtesy of Dan Klein and Pieter Abbee
University of California, Berkeley

Utilities of Sequences

What preferences should an agent have over reward sequences?

More or less? [1, 2, 2] or [2, 3, 4]

Now or later? [0, 0, 1] or [1, 0, 0]



Discounting

It’s reasonable to maximize the sum of rewards

It’s also reasonable to prefer rewards now to rewards later

One solution: values of rewards decay exponentially

1

Worth Now

γ

Worth Next Step

γ^2

Worth In Two Steps

Discounting

How to discount?

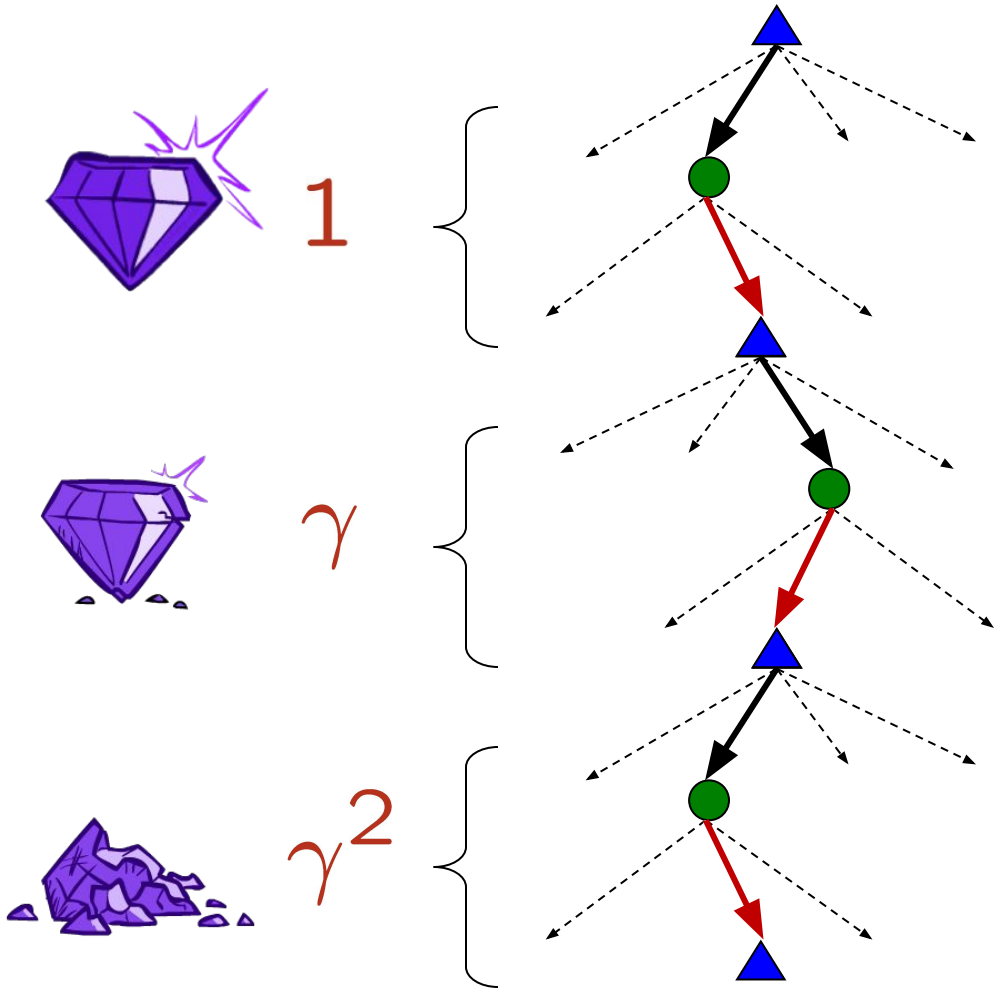
- Each time we descend a level, we multiply in the discount once

Why discount?

- Sooner rewards probably do have higher utility than later rewards
- Also helps our algorithms converge

Example: discount of 0.5

- $U([1,2,3]) = 0.5^0*1 + 0.5^1*2 + 0.5^2*3$
  $= 1*1 + 0.5*2 + 0.25*3$
- $U([1,2,3]) < U([3,2,1])$



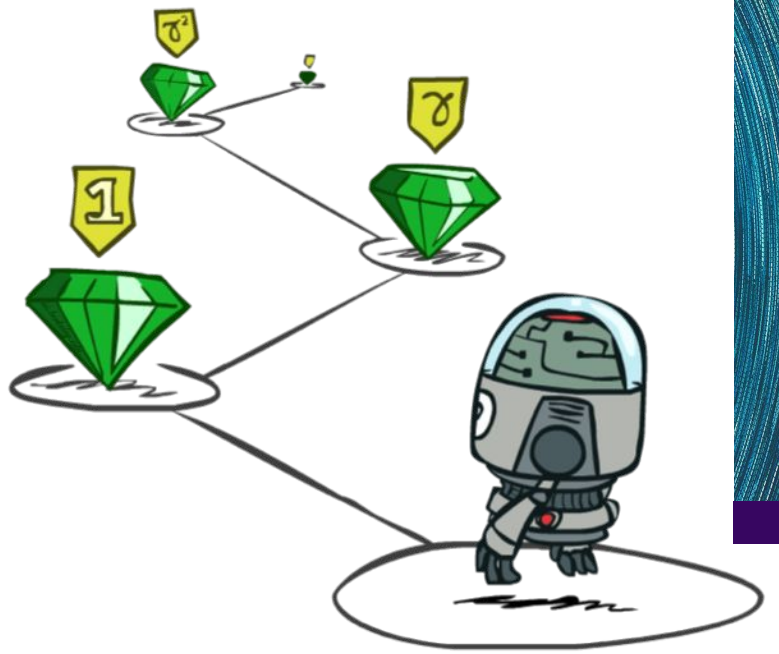
Stationary Preferences

Theorem: if we assume stationary preferences:

$$[a_1, a_2, \ldots] \succ [b_1, b_2, \ldots]$$

$$\Updownarrow$$

$$[r, a_1, a_2, \ldots] \succ [r, b_1, b_2, \ldots]$$



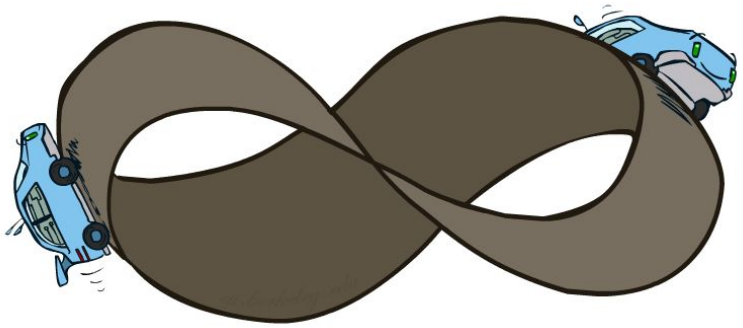
Then: there are only two ways to define utilities

- Additive utility: $U([r_0, r_1, r_2, \ldots]) = r_0 + r_1 + r_2 + \cdots$
- Discounted utility: $U([r_0, r_1, r_2, \ldots]) = r_0 + \gamma r_1 + \gamma^2 r_2 \cdots$

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 $0 < \gamma < 1$



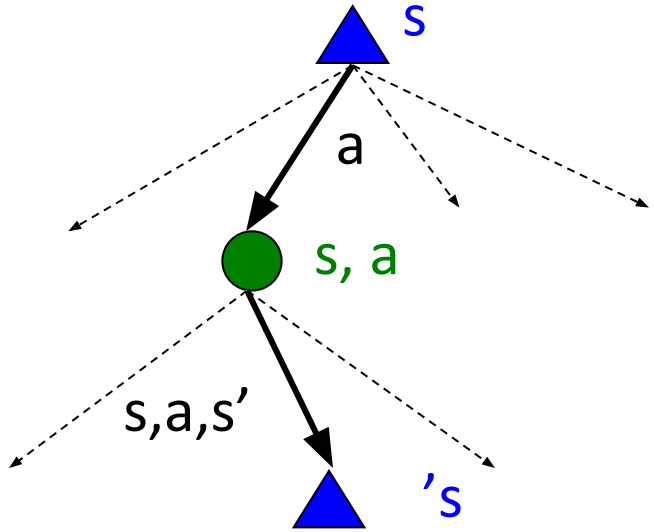
$$U([r_0, \ldots r_\infty]) = \sum_{t=0}^{\infty} \gamma^t r_t \leq R_{\max}/(1-\gamma)$$

    - Smaller γ means smaller "horizon" – shorter term focus
  - Absorbing state: guarantee that for every policy, a terminal state will eventually be reached (like "overheated" for racing)

Recap: Defining MDPs

Markov decision processes:

- Set of states S
- Start state s_0
- Set of actions A
- Transitions P(s'|s,a) (or T(s,a,s'))
- Rewards R(s,a,s') (and discount γ)

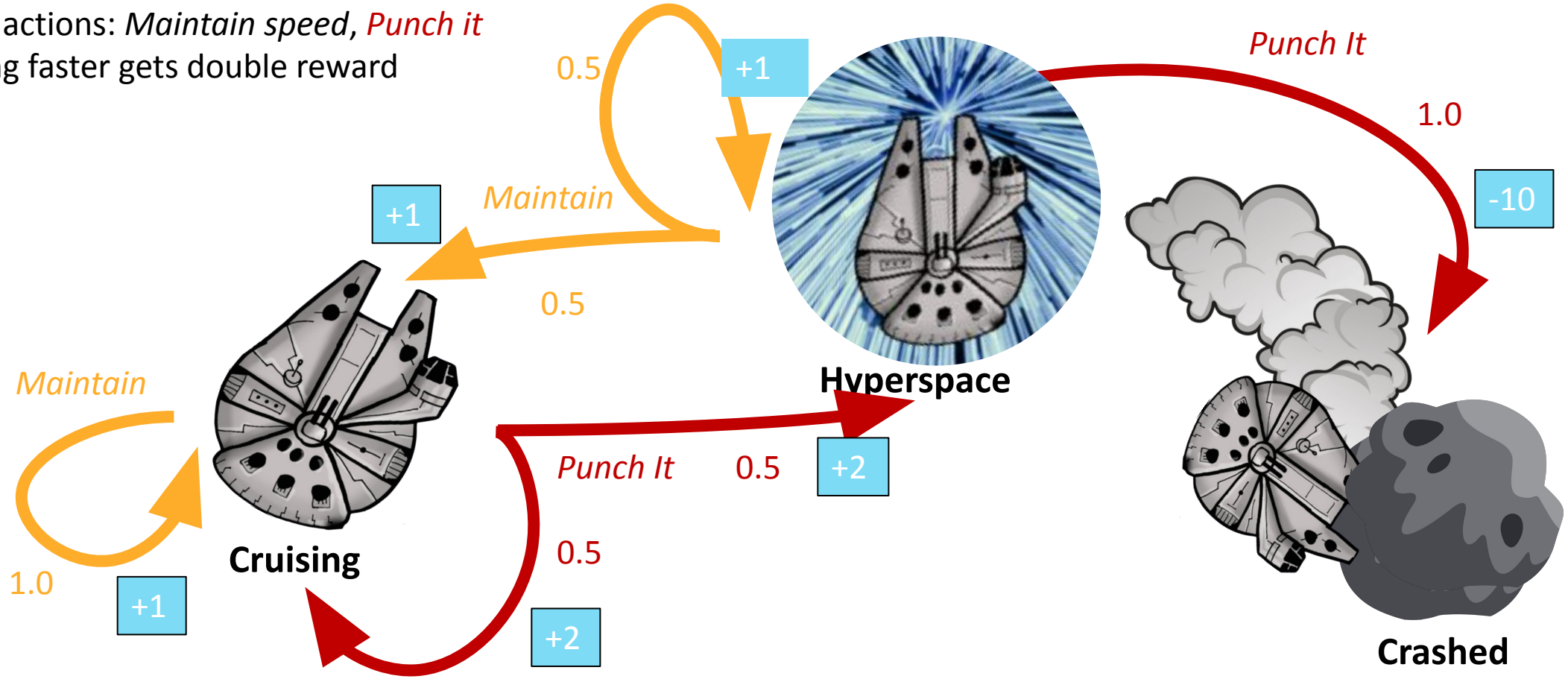


MDP quantities so far:

- Policy = Choice of action for each state
- Utility = sum of (discounted) rewards

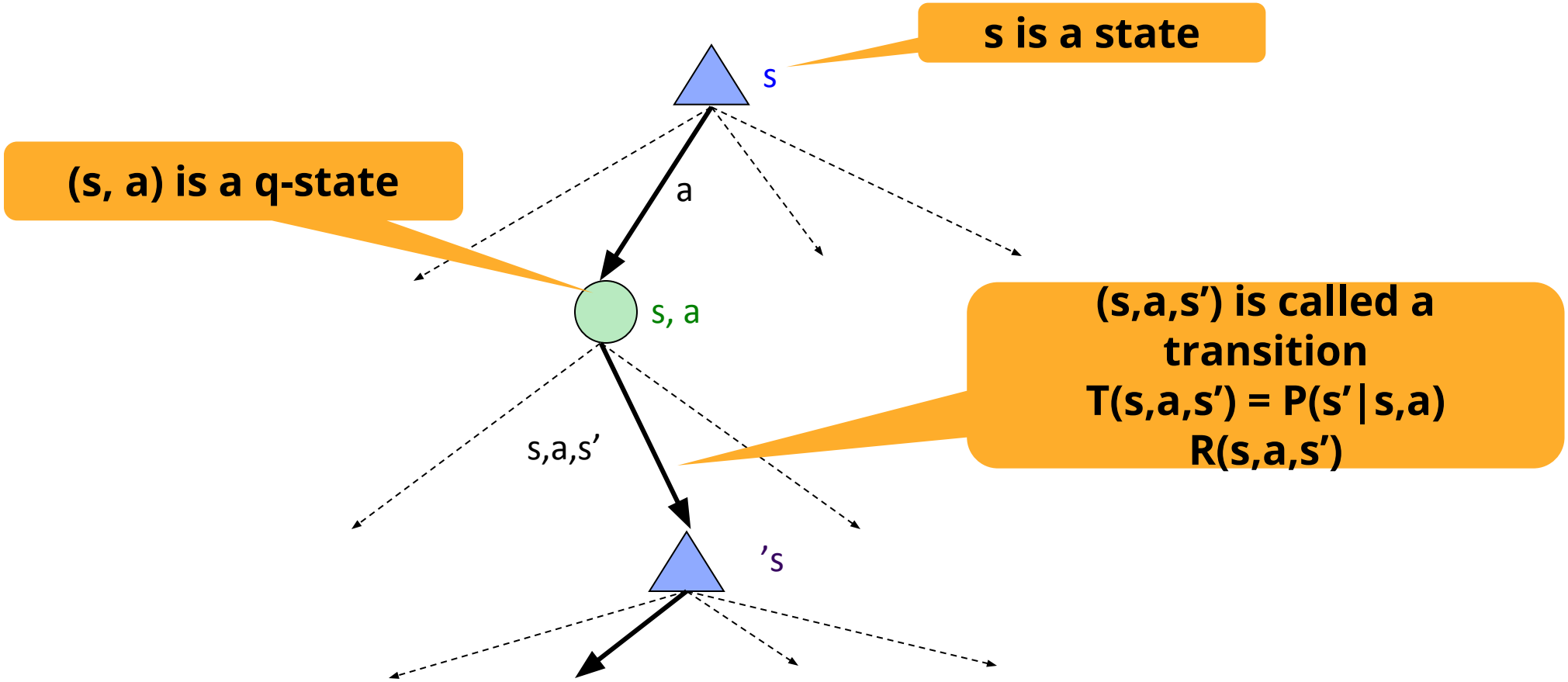
Example Hyperdrive MDP

The Millennium Falcon needs to travel far far away, quickly
Three states: Cruising, Hyperspace, Crashed
Two actions: *Maintain speed*, *Punch it*
Going faster gets double reward

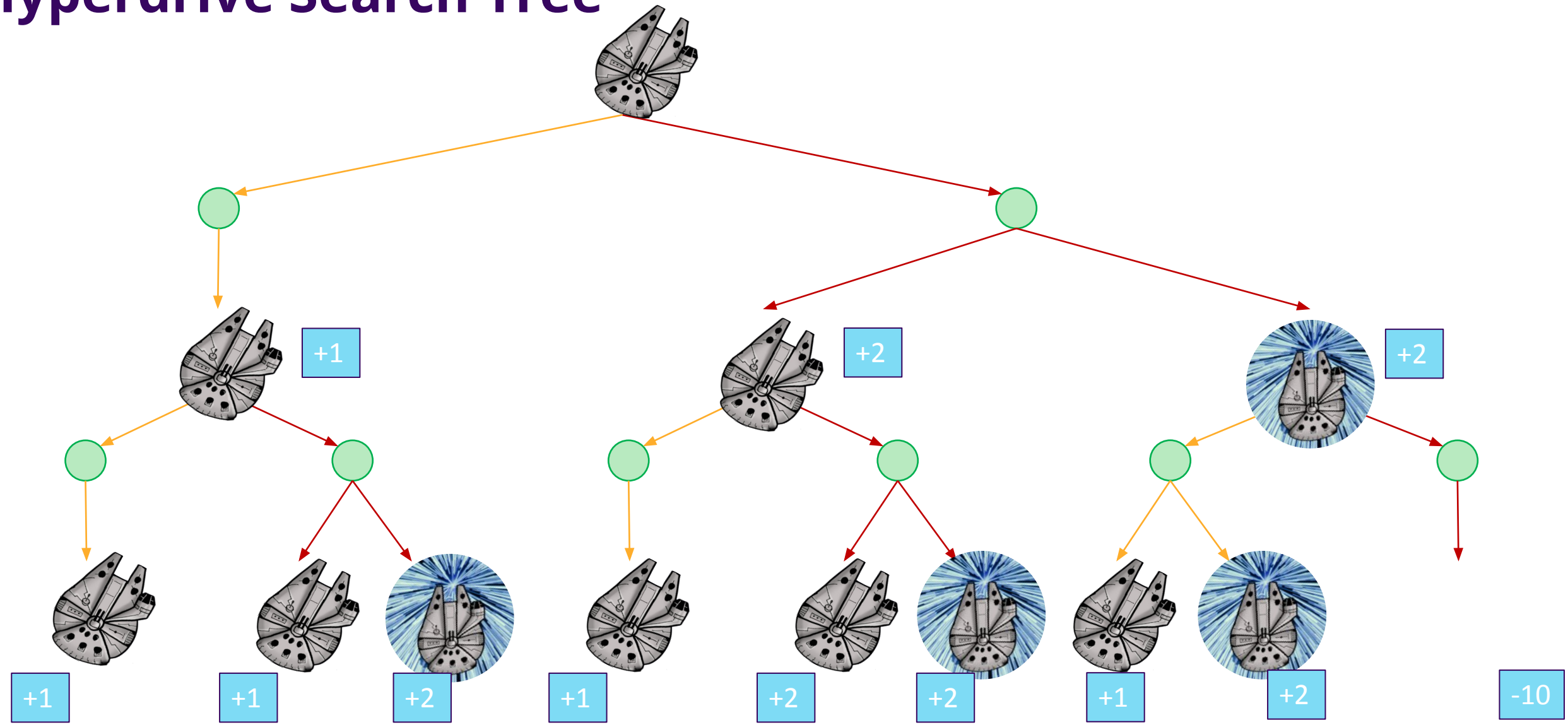


MDP Search Trees

Each MDP state projects an expectimax-like search tree



Hyperdrive Search Tree



Optimal Quantities

- The value (utility) of a state s:

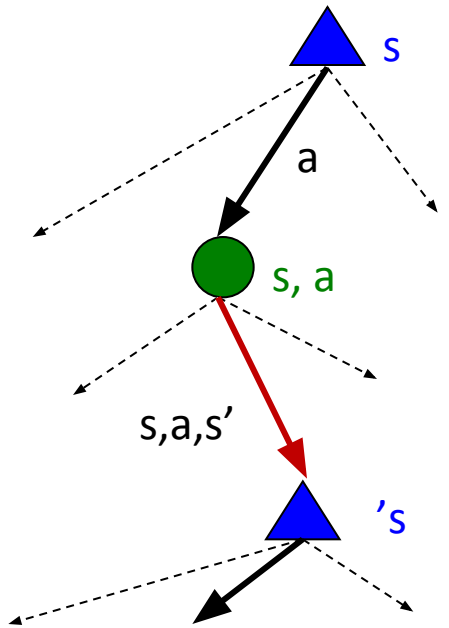
  $V^*(s)$ = expected utility starting in s and acting optimally

- The value (utility) of a q-state (s,a):

  $Q^*(s,a)$ = expected utility starting out having taken action a from state s and (thereafter) acting optimally

- The optimal policy:

  $\pi^*(s)$ = optimal action from state s



s is a *state*

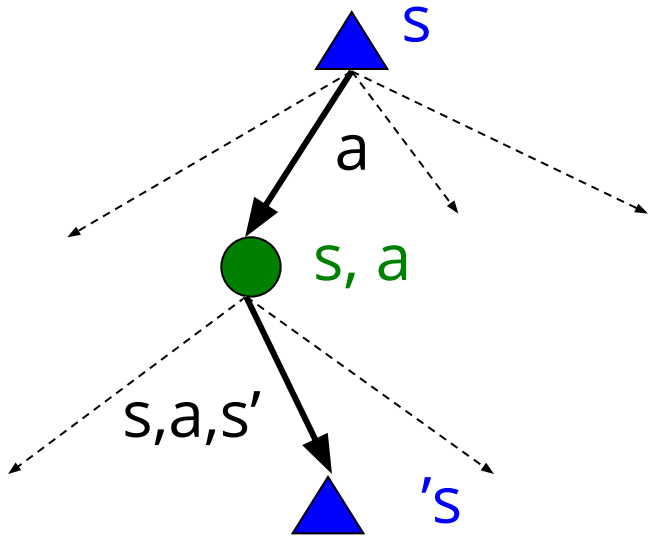
(s, a) is a *q-state*

(s,a,s') is a *transition*

Values of States

Fundamental operation: compute the (expectimax) value of a state

- Expected utility under optimal action
- Average sum of (discounted) rewards
- This is just what expectimax computed!



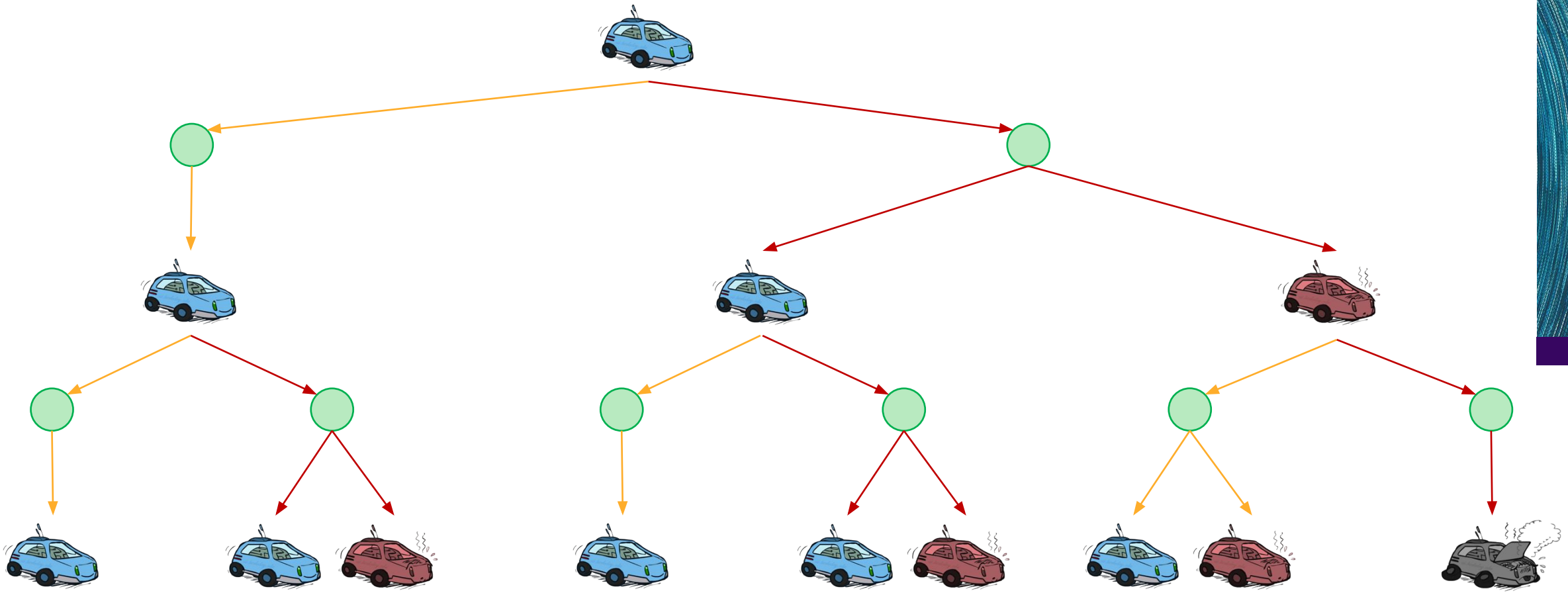
Recursive definition of value:

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

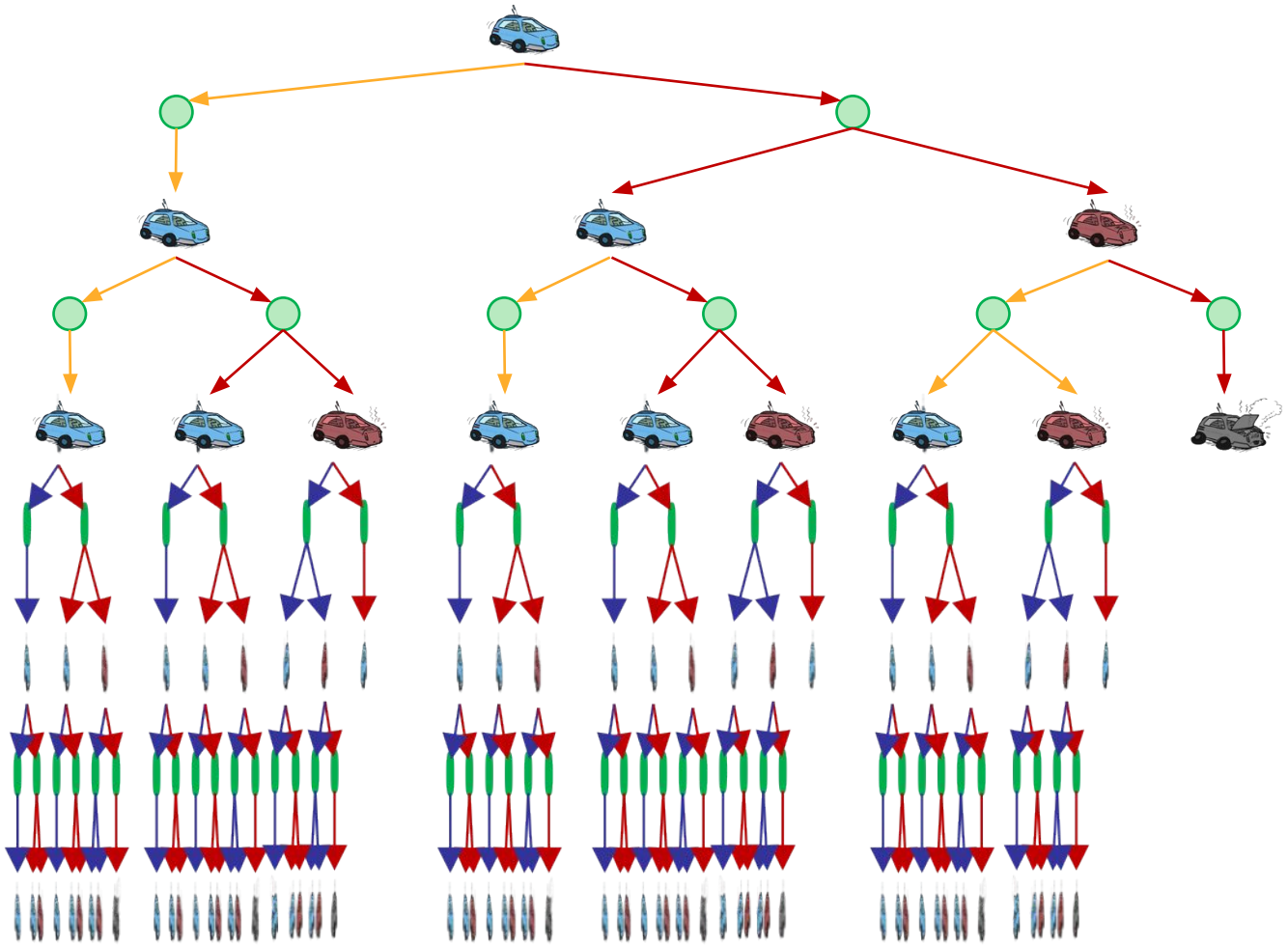
$$Q^*(s,a) = \sum_{s'} T(s,a,s') \left[R(s,a,s') + \gamma V^*(s') \right]$$

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

Racing Search Tree



Racing Search Tree



Racing Search Tree

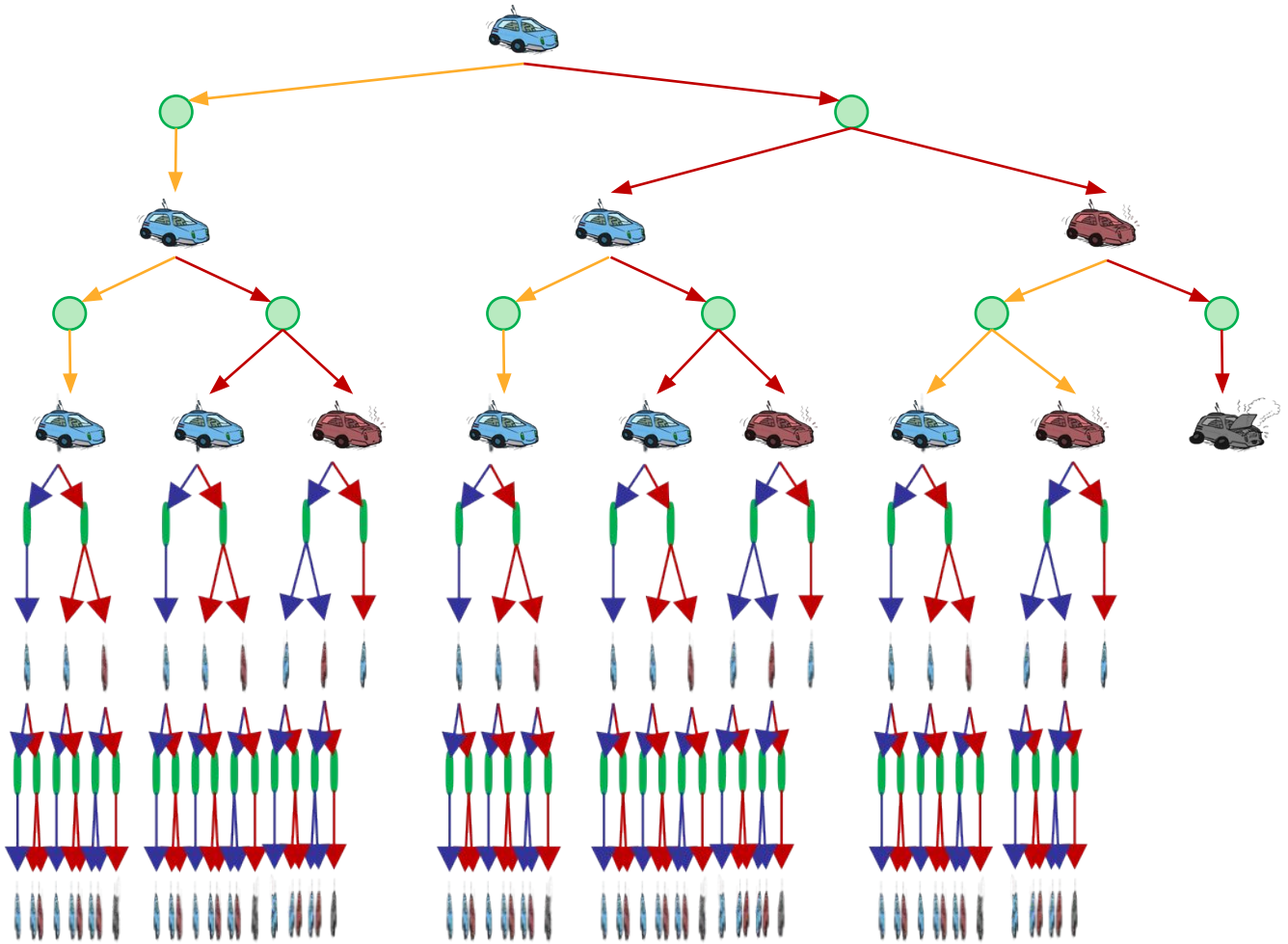
We're doing way too much work with expectimax!

Problem: States are repeated

- Idea: Only compute needed quantities once

Problem: Tree goes on forever

- Idea: Do a depth-limited computation, but with increasing depths until change is small
- Note: deep parts of the tree eventually don't matter if $\gamma < 1$

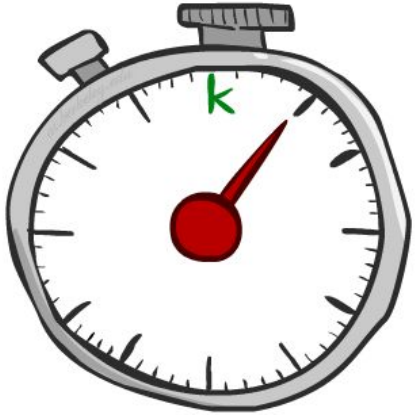


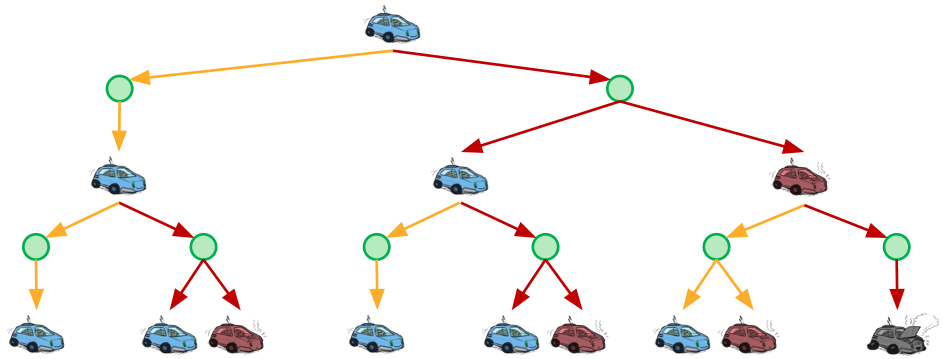
Time-Limited Values

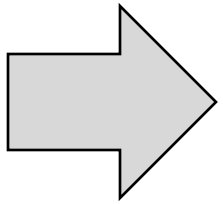
Key idea: time-limited values

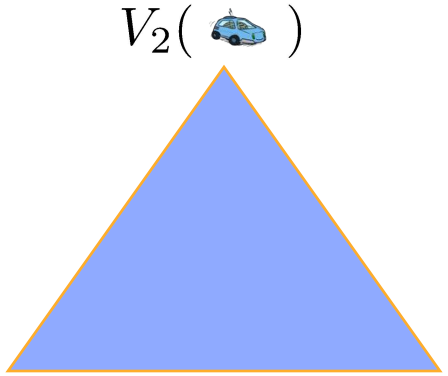
Define $V_k(s)$ to be the optimal value of s if the game ends in k more time steps

- Equivalently, it's what a depth-k expectimax would give from s









Reminders

21 days until the American election. I voted. Did you?

Deadline to register to vote in PA is **Monday, Oct 19.**

HW4 due tonight at 11:59pm Eastern.

Quiz 5 on Adversarial Search is due tomorrow.

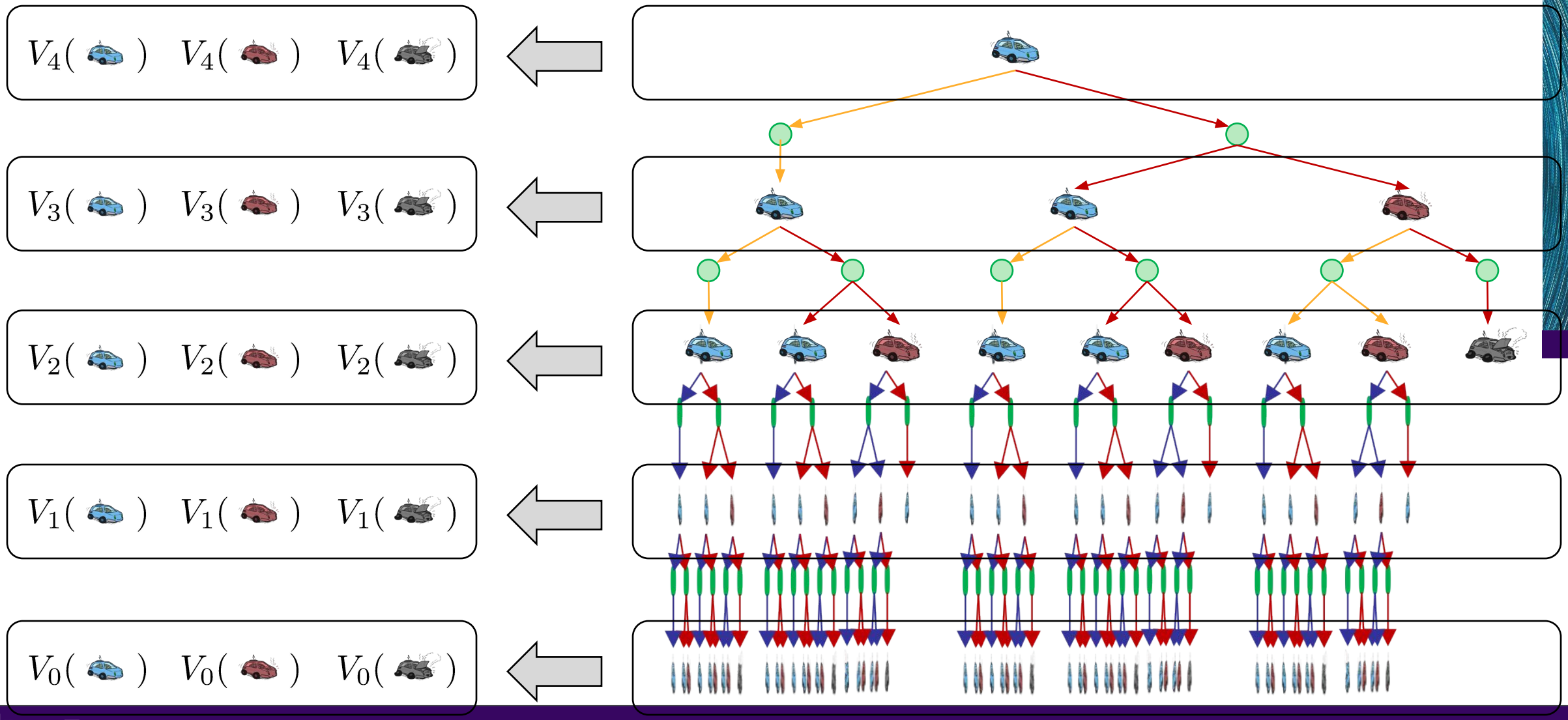
HW5 has been released. It will be due on Tuesday Oct 20.

No lecture on Thursday.

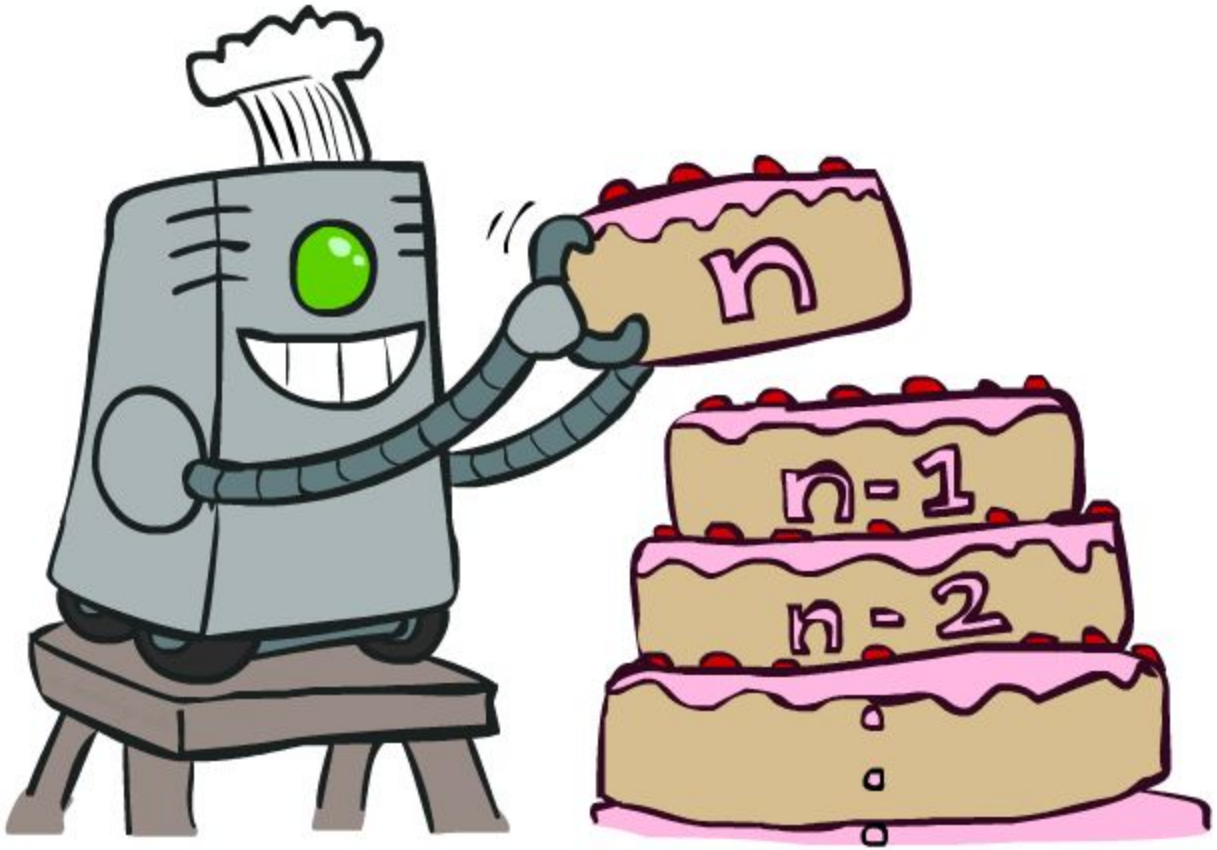
Midterm details:

* No HW from Oct 20-27.
* Tues Oct 20: Practice midterm released (for credit)
* Saturday Oct 24: Practice midterm is due.
* Midterm available Monday Oct 26 and Tuesday Oct 27.
* 3 hour block. Open book, open notes, no collaboration.

Computing Time-Limited Values



Value Iteration

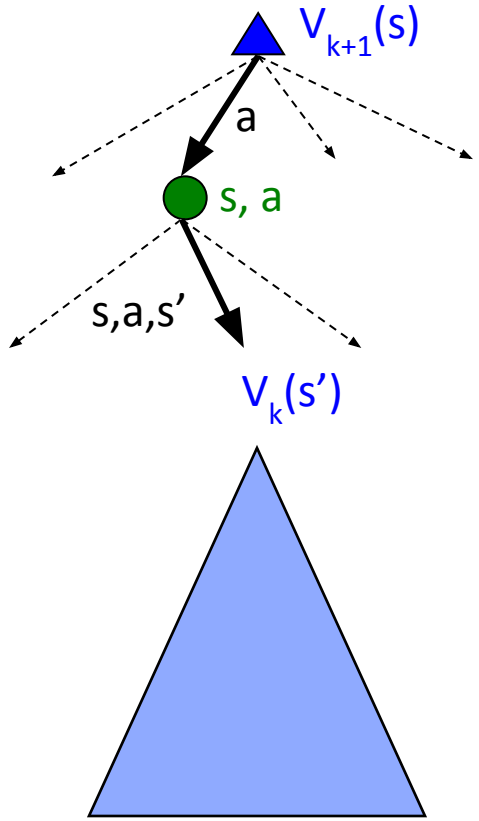


Value Iteration

Start with $V_0(s) = 0$: no time steps left means an expected reward sum of zero

Given vector of $V_k(s)$ values, do one ply of expectimax from each state:

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



Repeat until convergence

Complexity of each iteration: $O(S^2A)$

Theorem: will converge to unique optimal values

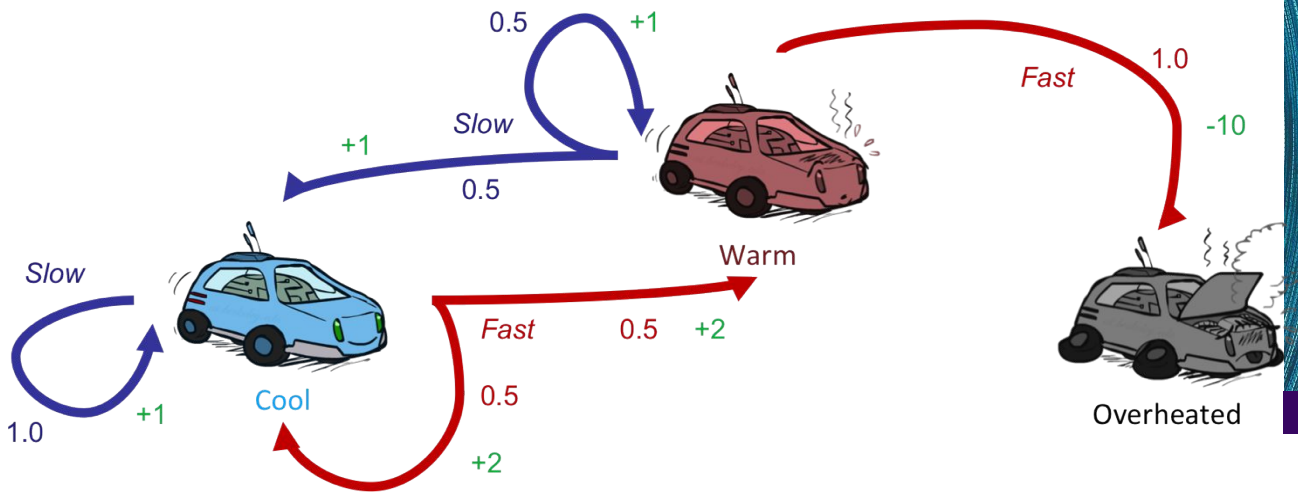
- Basic idea: approximations get refined towards optimal values
- Policy may converge long before values do

Example: Value Iteration

V_2

V_1

V_0

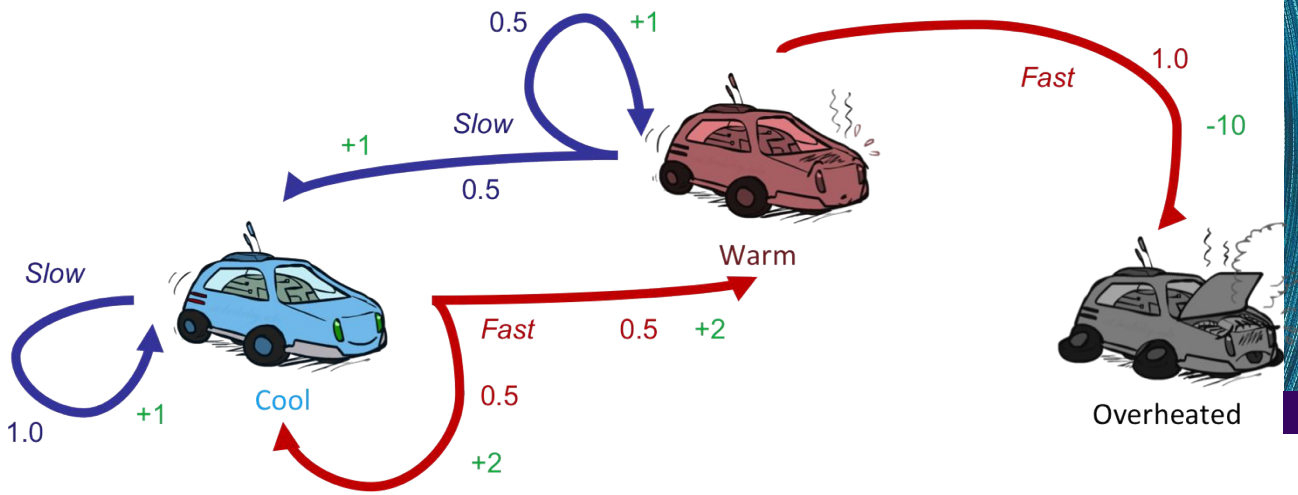


Assume no discount!

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

Example: Value Iteration

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



Assume no discount!

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

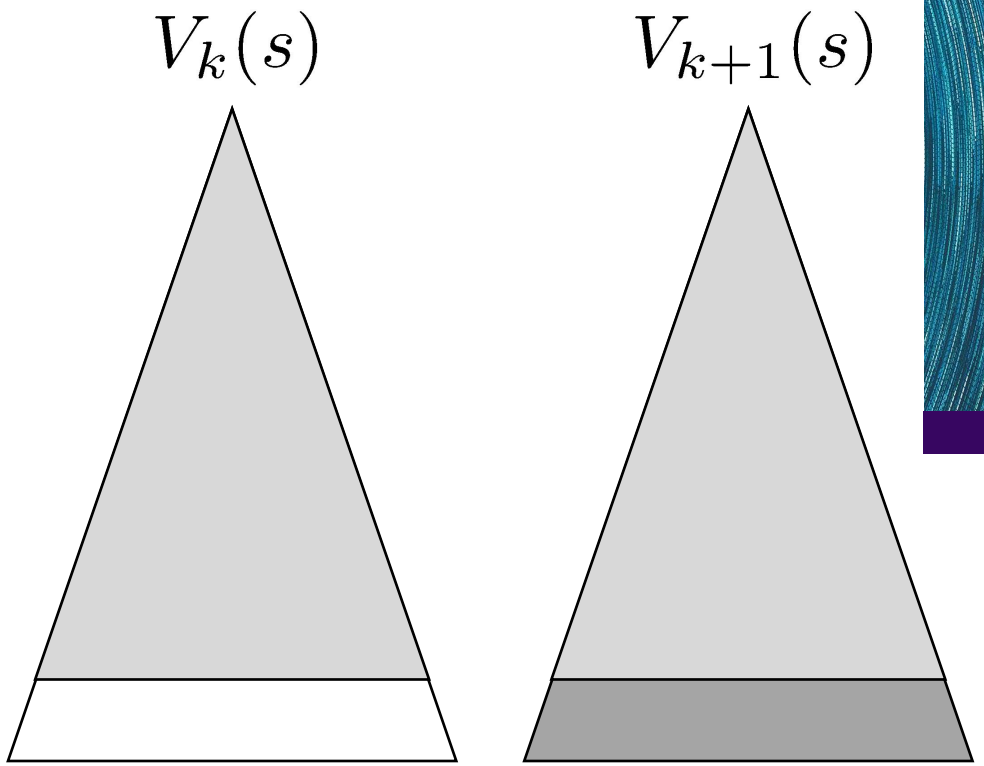
Convergence*

How do we know the V_k vectors are going to converge?

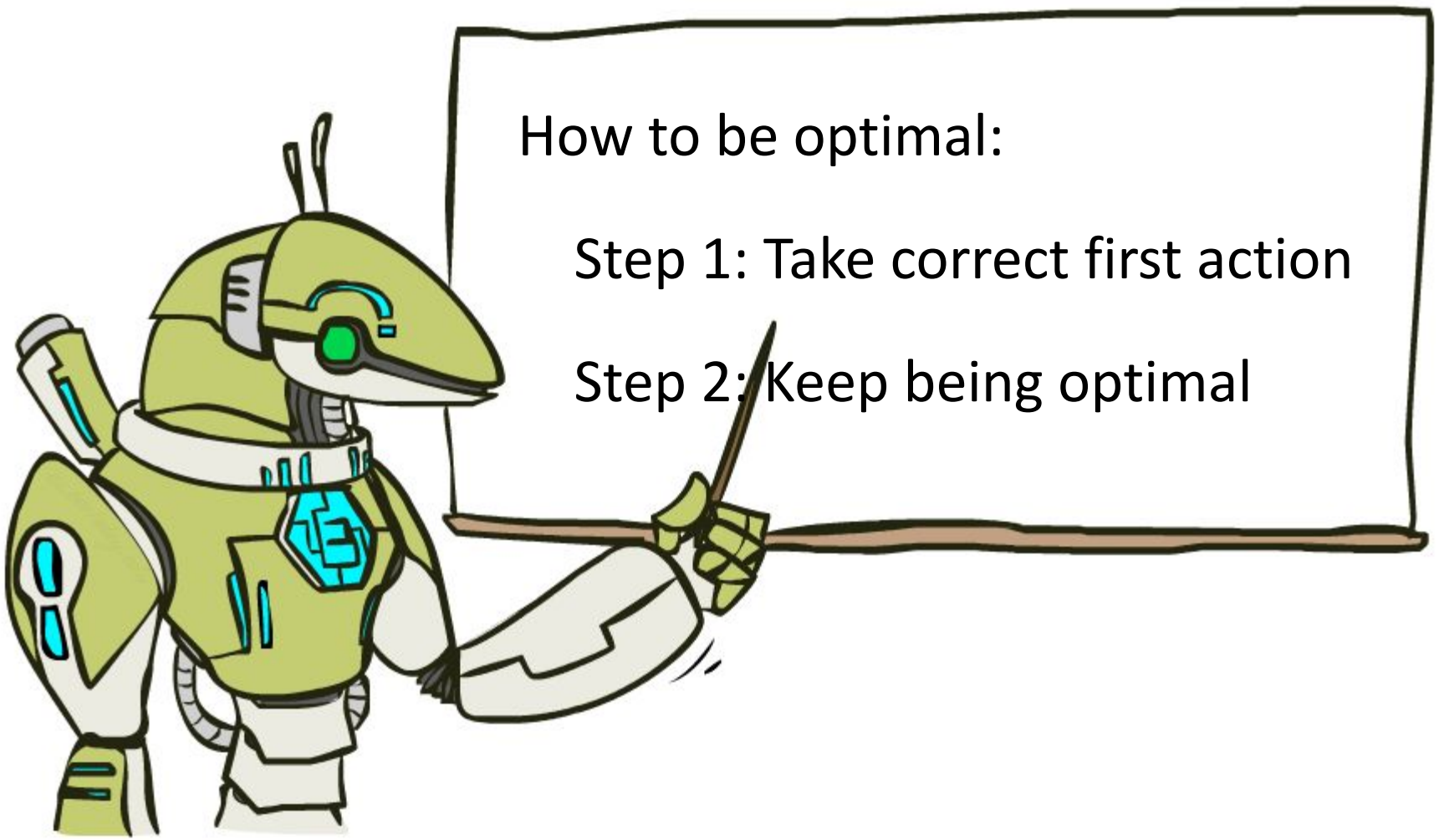
Case 1: If the tree has maximum depth M, then V_M holds the actual untruncated values

Case 2: If the discount is less than 1

- Sketch: For any state V_k and V_{k+1} can be viewed as depth k+1 expectimax results in nearly identical search trees
- The difference is that on the bottom layer, V_{k+1} has actual rewards while V_k has zeros
- That last layer is at best all R_{MAX}
- It is at worst R_{MIN}
- But everything is discounted by γ^k that far out
- So V_k and V_{k+1} are at most γ^k max|R| different
- So as k increases, the values converge

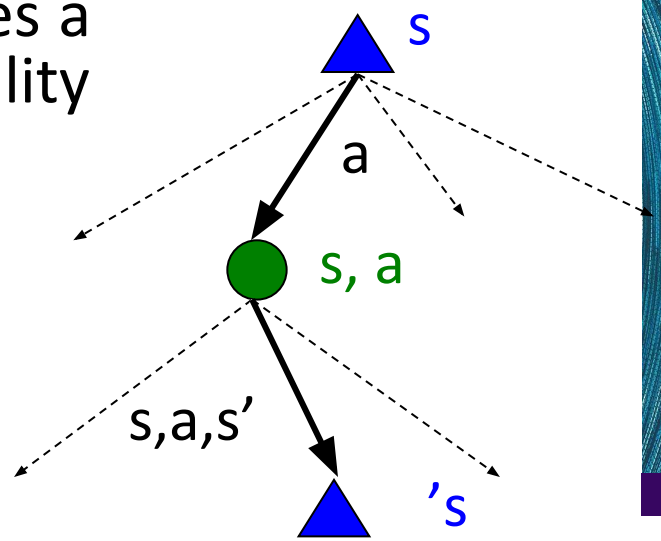


The Bellman Equations



The Bellman Equations

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



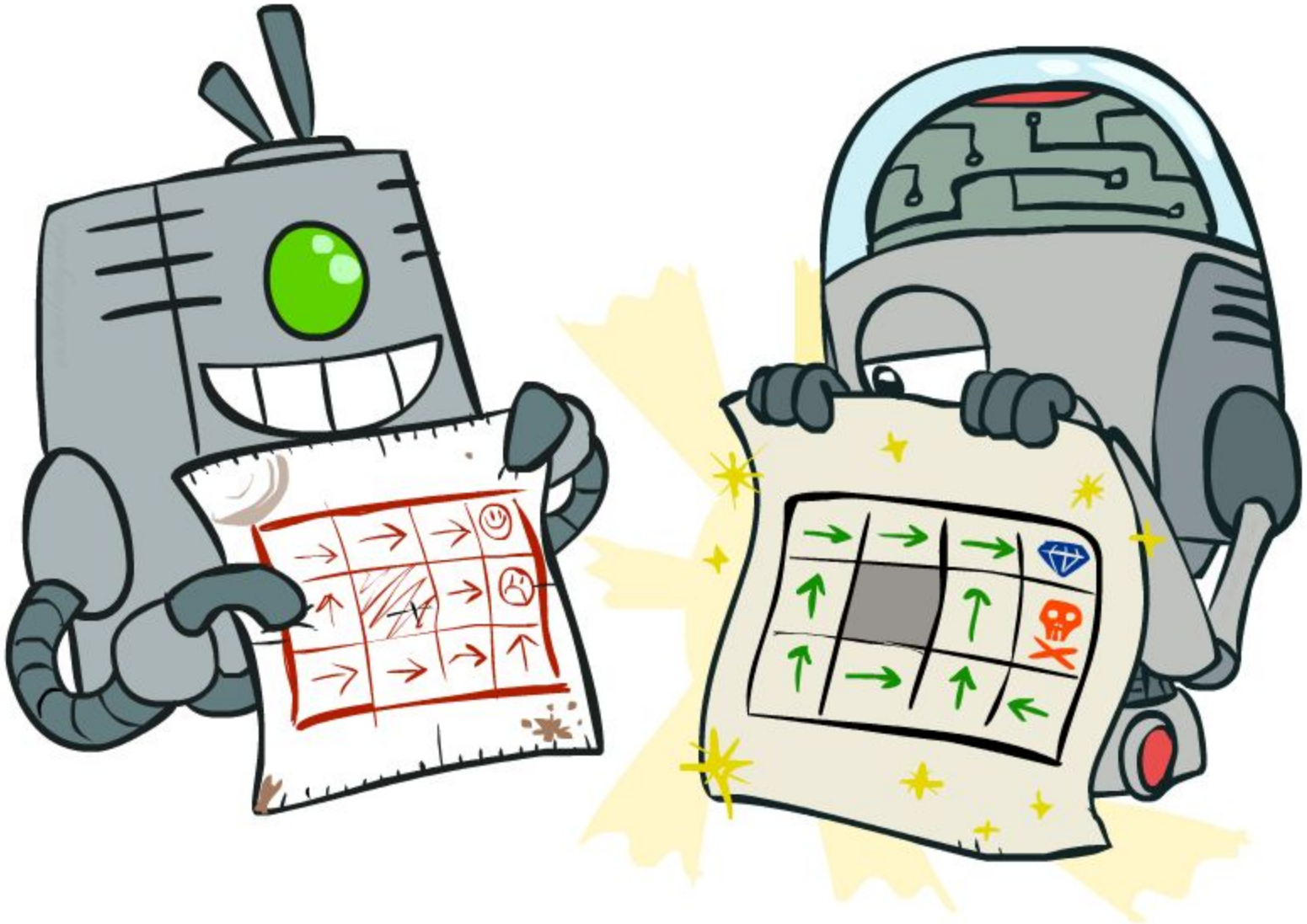
$$V^*(s) = \max_a Q^*(s,a)$$

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

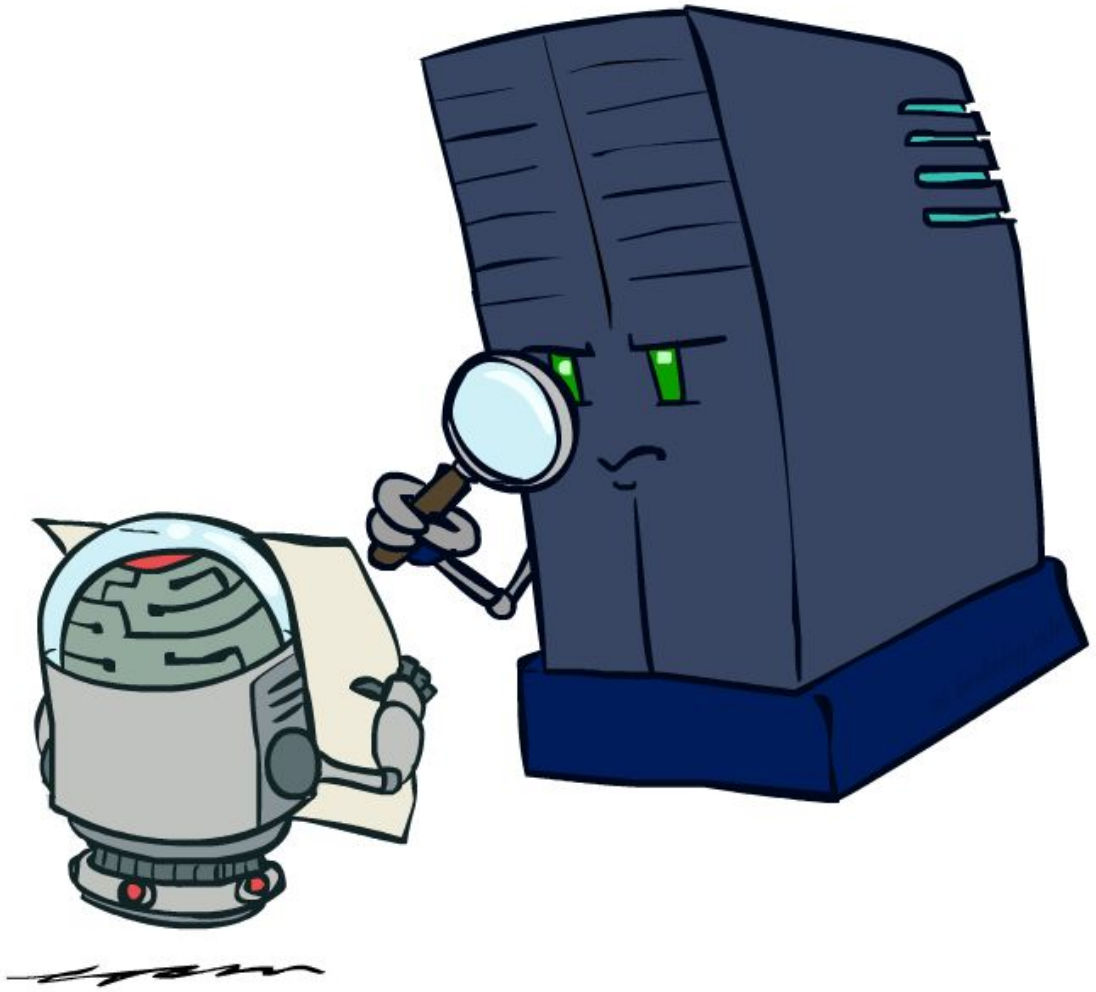
$$V^*(s) = \max_a \sum_{s'} T(s,a,s') \left[R(s,a,s') + \gamma V^*(s') \right]$$

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

Policy Methods

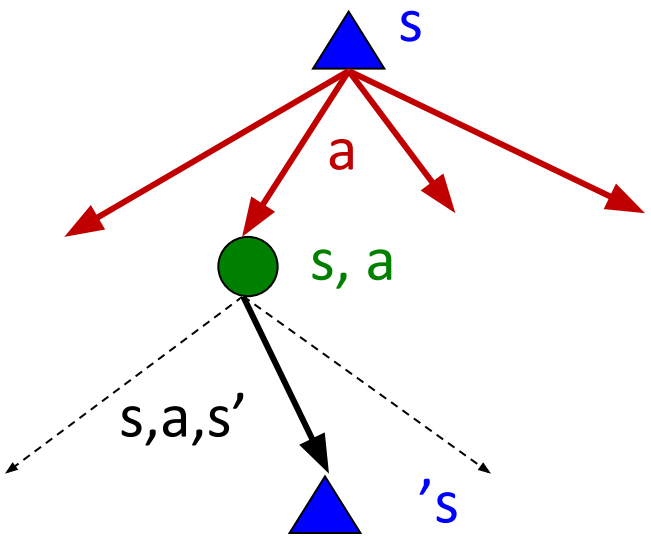


Policy Evaluation

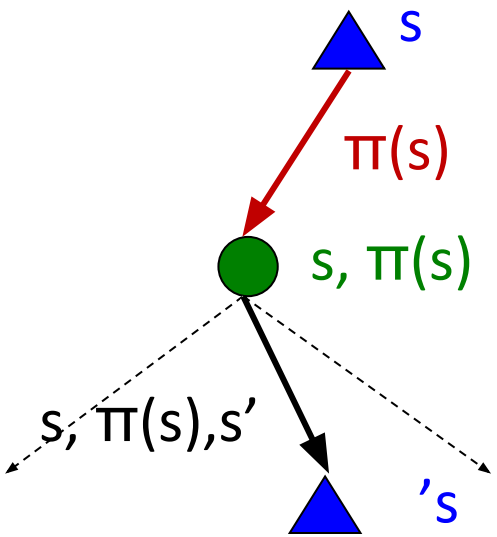


Fixed Policies

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

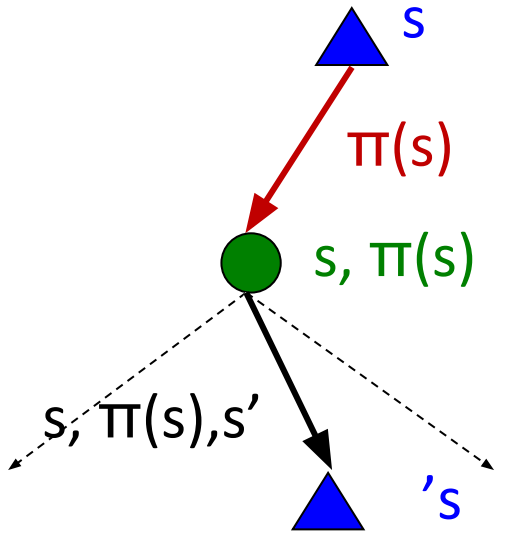
Another basic operation: compute the utility of a state s under a fixed (generally non-optimal) policy

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

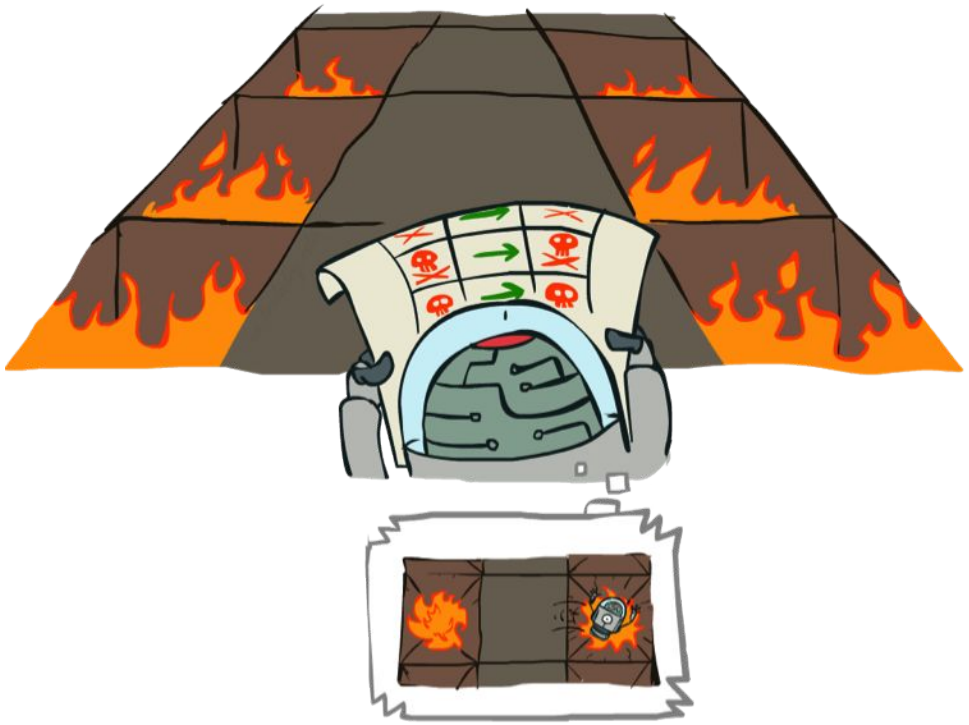
Recursive relation (one-step look-ahead / Bellman equation):

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

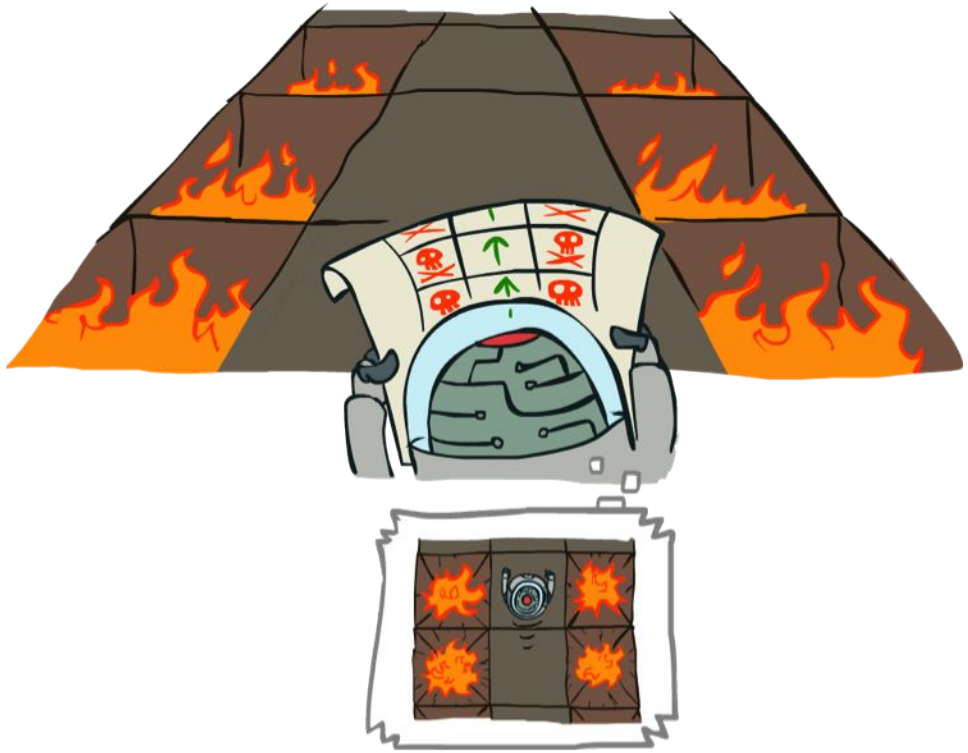


Example: Policy Evaluation

Always Go Right



Always Go Forward



Example: Policy Evaluation

Always Go Right

Always Go Forward

Policy Evaluation

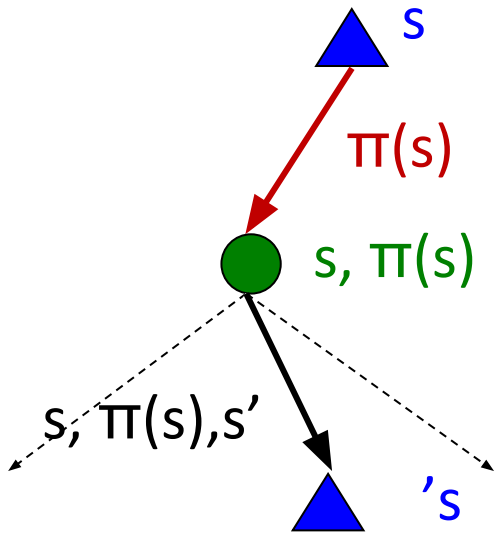
How do we calculate the V's for a fixed policy π?

Idea 1: Turn recursive Bellman equations into updates
(like value iteration)

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

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

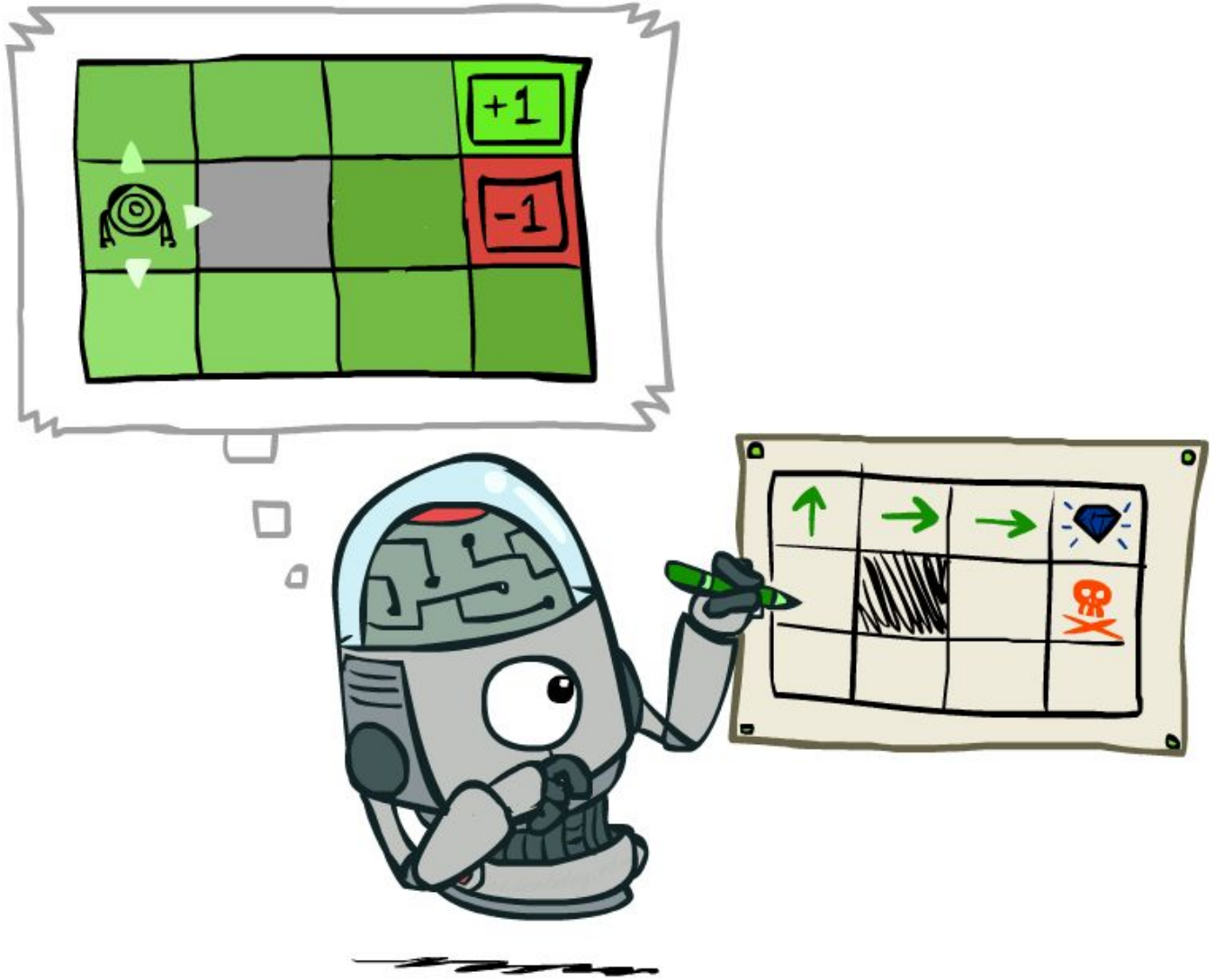
Efficiency: $O(S^2)$ per iteration



Idea 2: Without the maxes, the Bellman equations are just a linear system

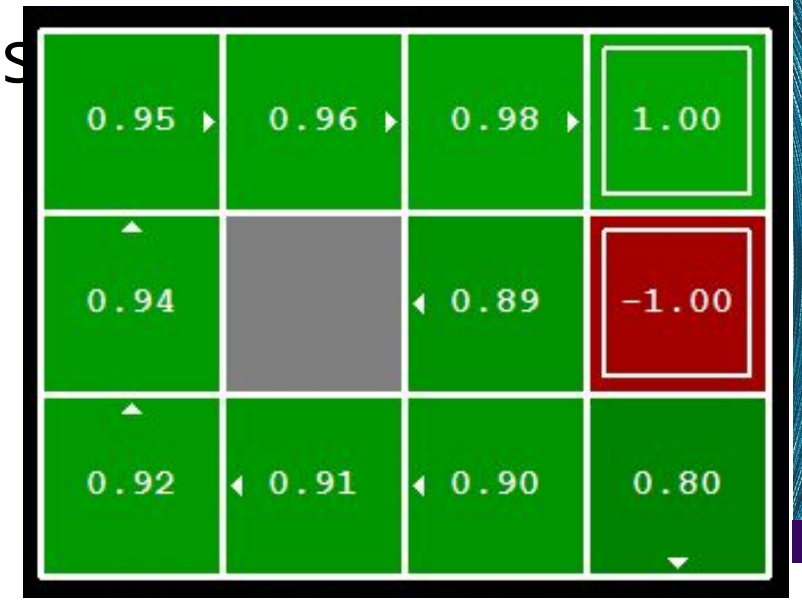
- Solve with Matlab (or your favorite linear system solver)

Policy Extraction



Computing Actions from Values

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



How should we act?

- It's not obvious!

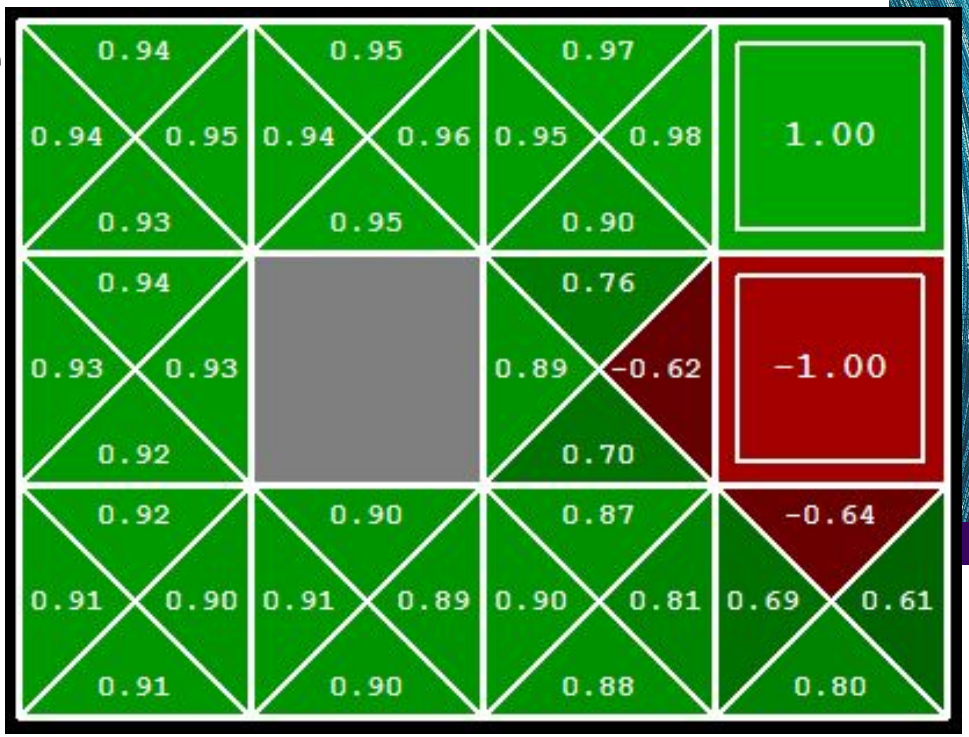
We need to do a mini-expectimax (one step)

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

This is called p implied by the values

Computing Actions from Q-Values

Let's imagine we have the optimal q-value



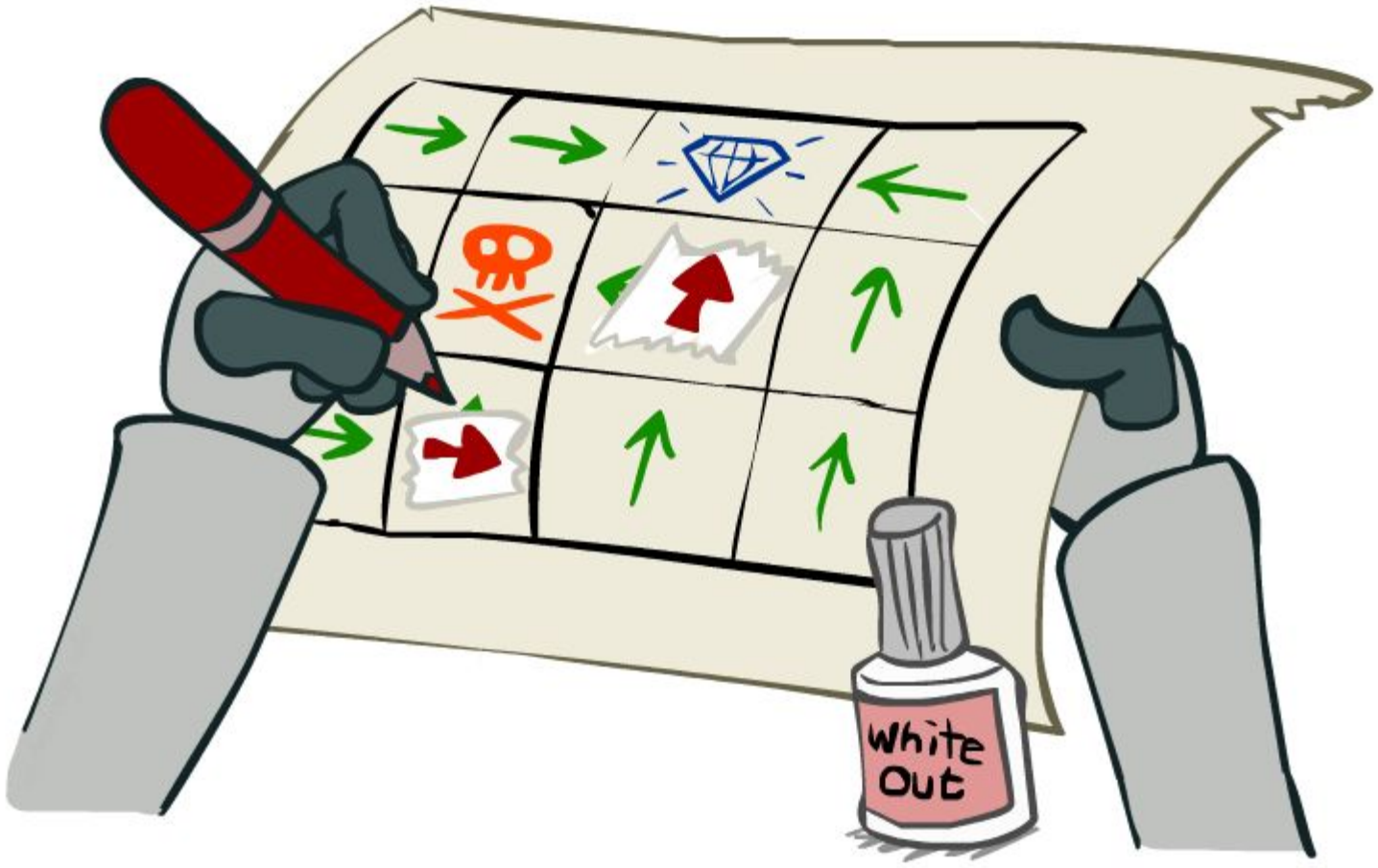
How should we act?

- Completely trivial to decide!

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

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

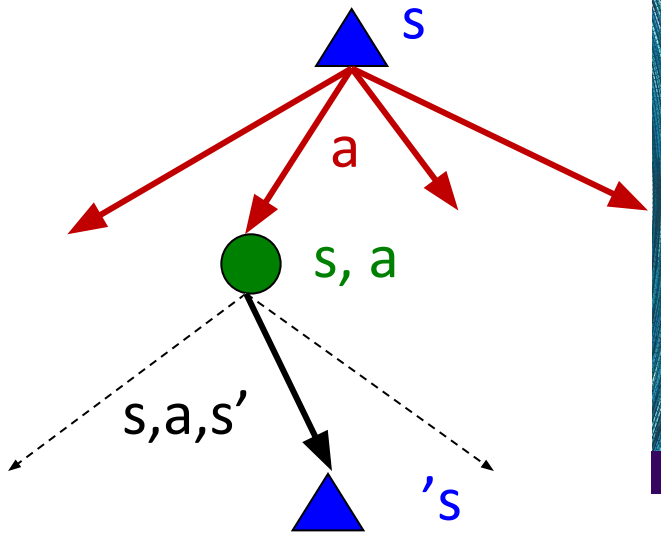
Policy Iteration



Problems with Value Iteration

Value iteration repeats the Bellman updates:

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



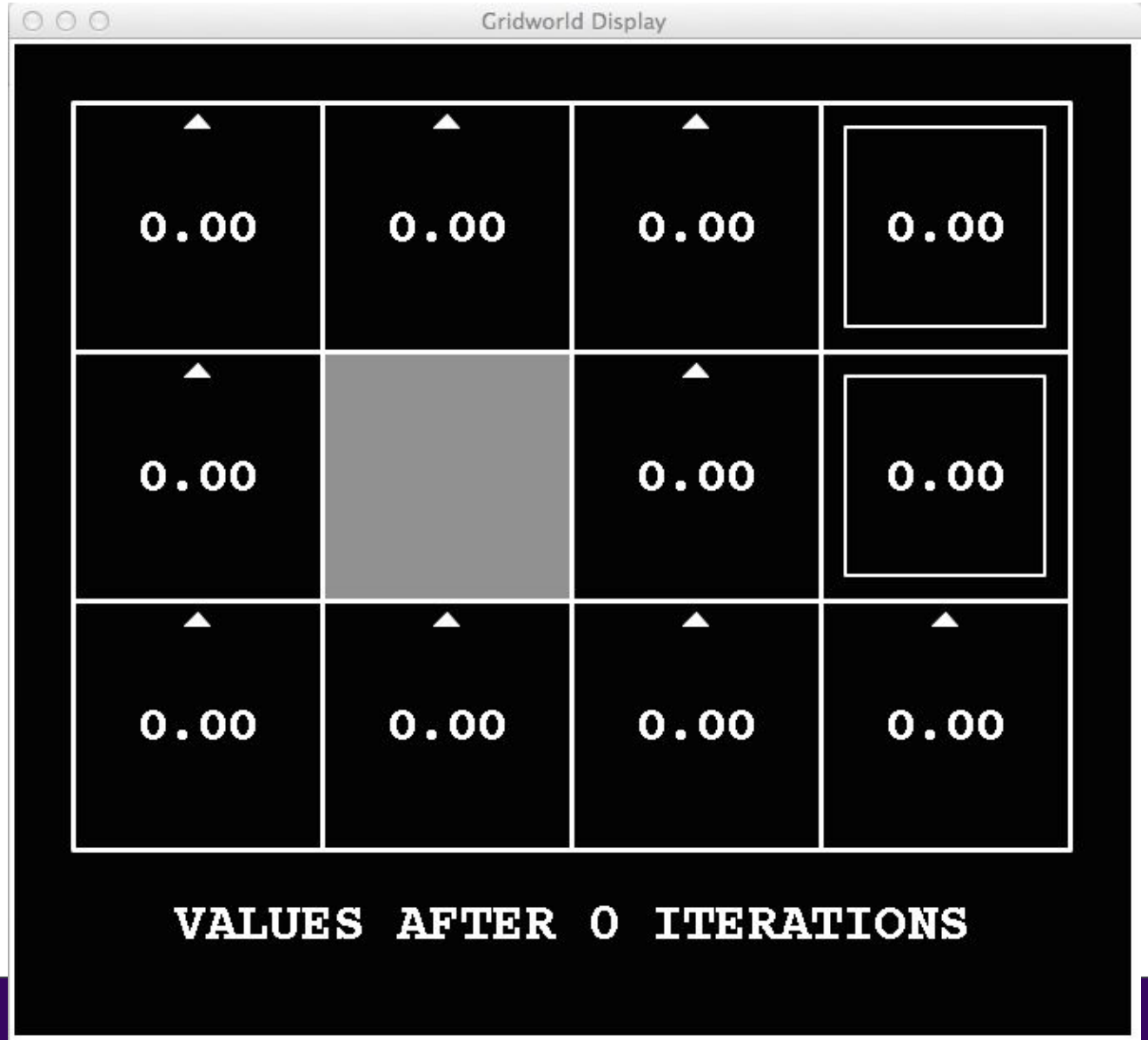
Problem 1: It's slow – $O(S^2A)$ per iteration

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

Problem 3: The policy often converges long before the values

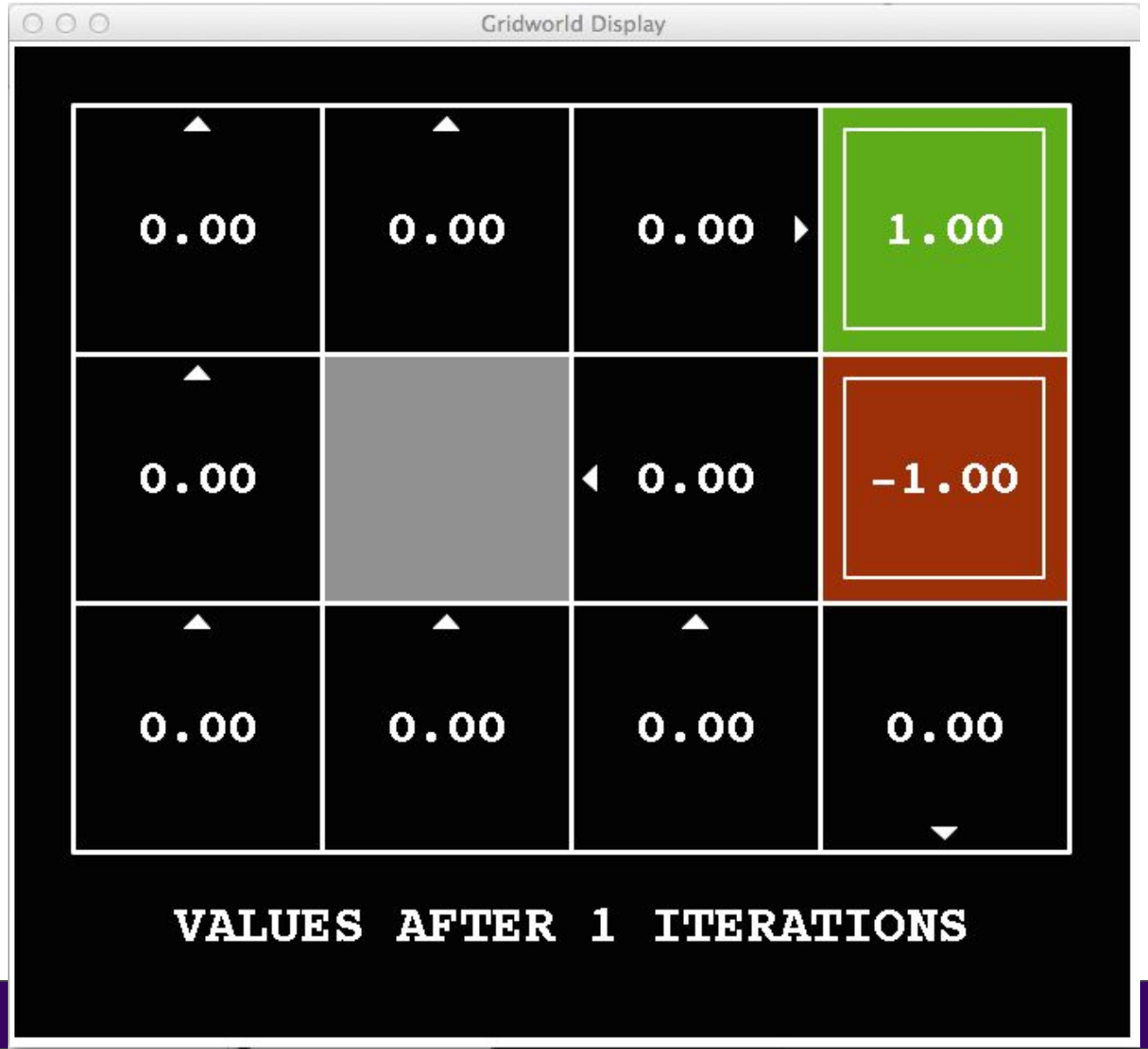
[Demo: value iteration (L9D2)]

k=0



Noise = 0.2
Discount = 0.9
Living reward = 0

k=1



Noise = 0.2
Discount = 0.9
Living reward = 0

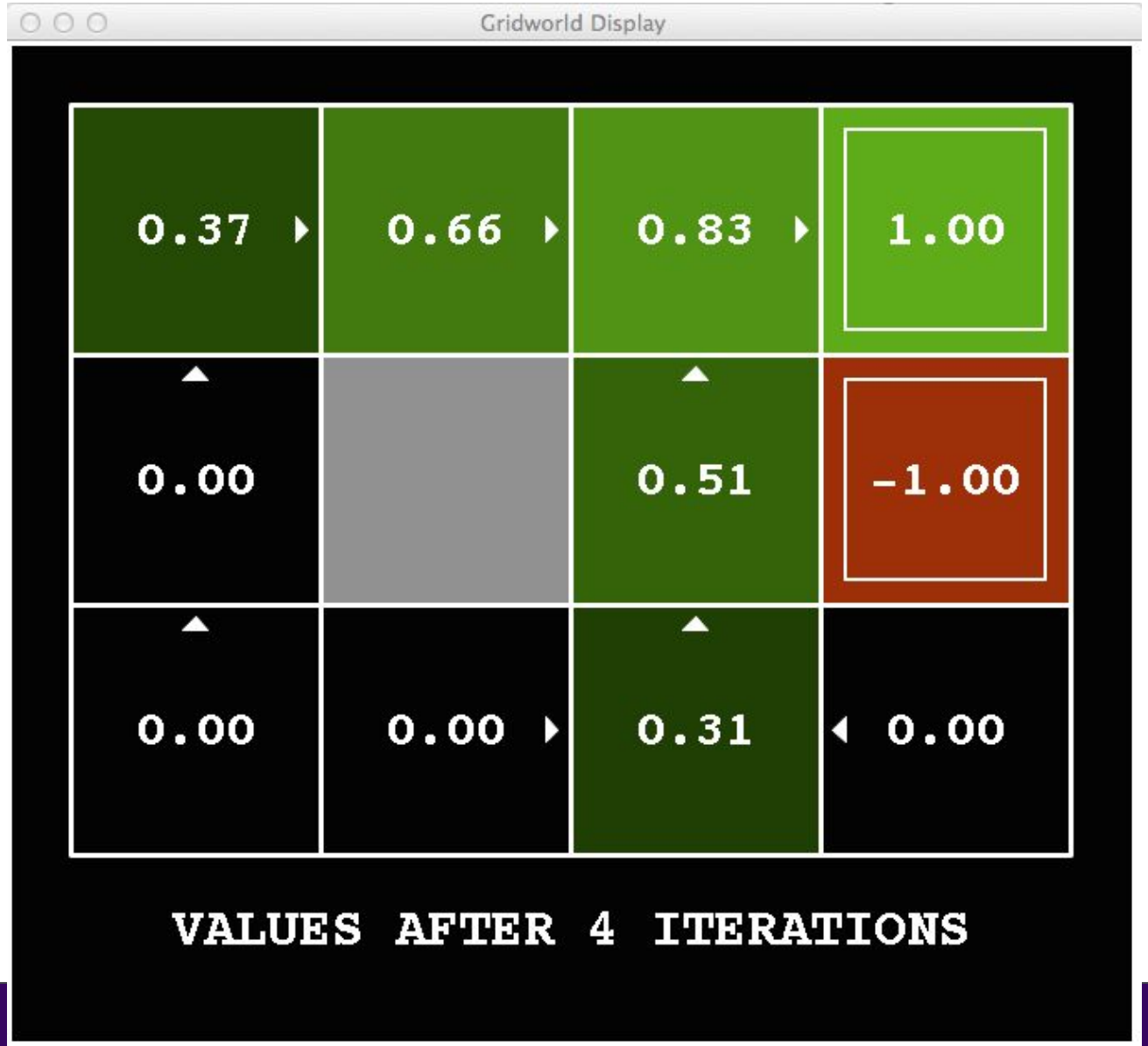
k=2

Noise = 0.2
Discount = 0.9
Living reward = 0

k=3

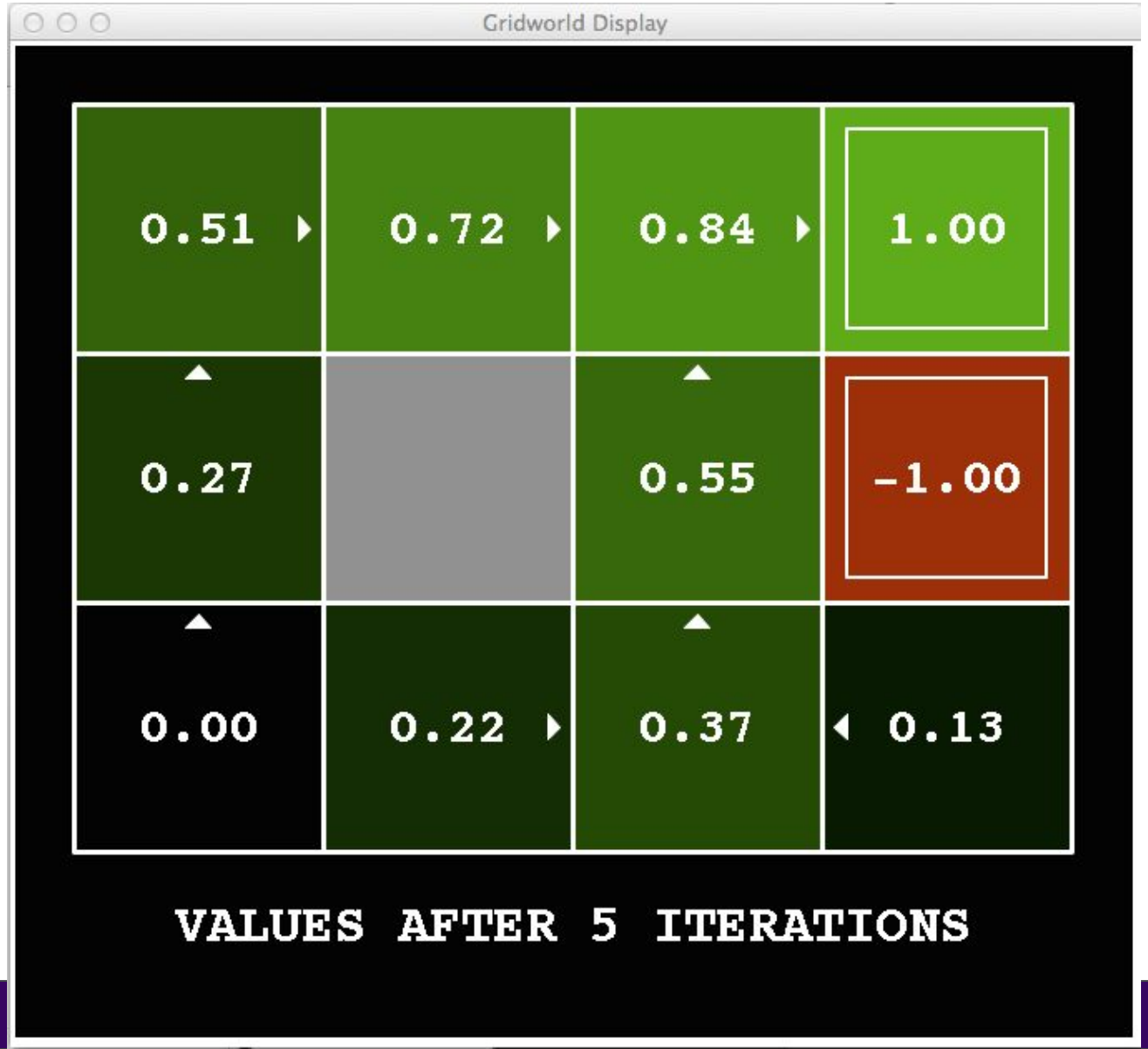
Noise = 0.2
Discount = 0.9
Living reward = 0

k=4



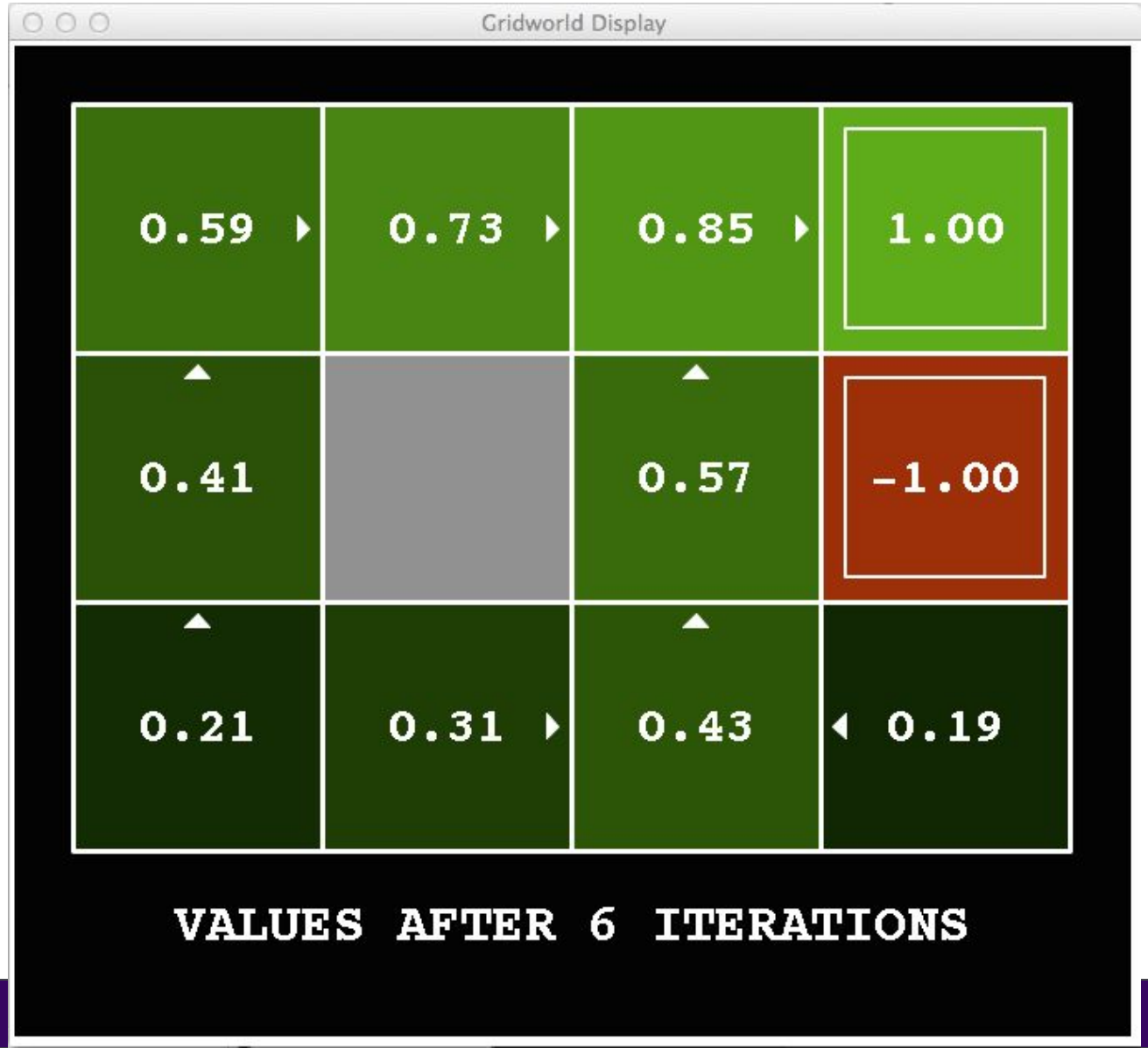
Noise = 0.2
Discount = 0.9
Living reward = 0

k=5



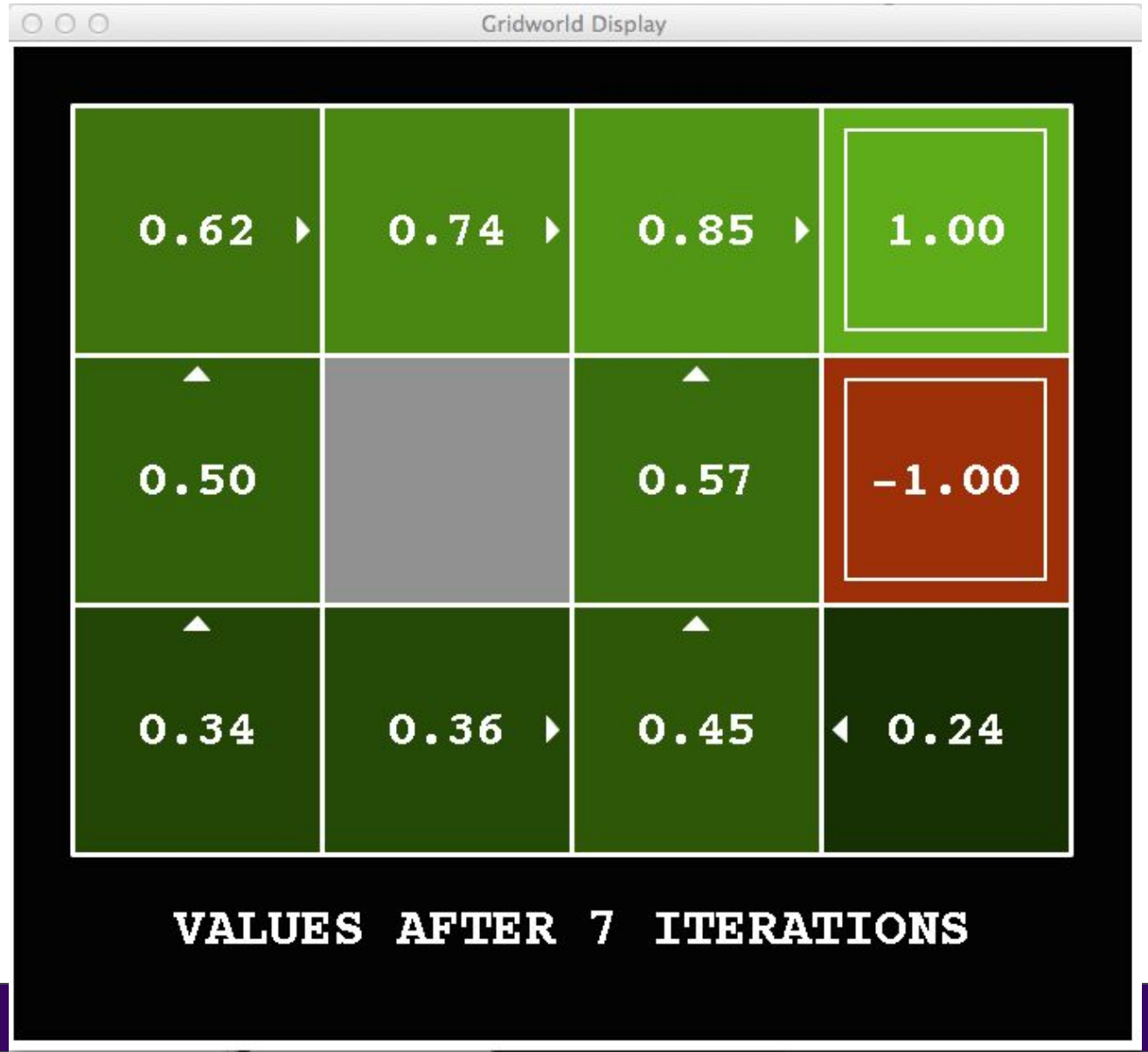
Noise = 0.2
Discount = 0.9
Living reward = 0

k=6



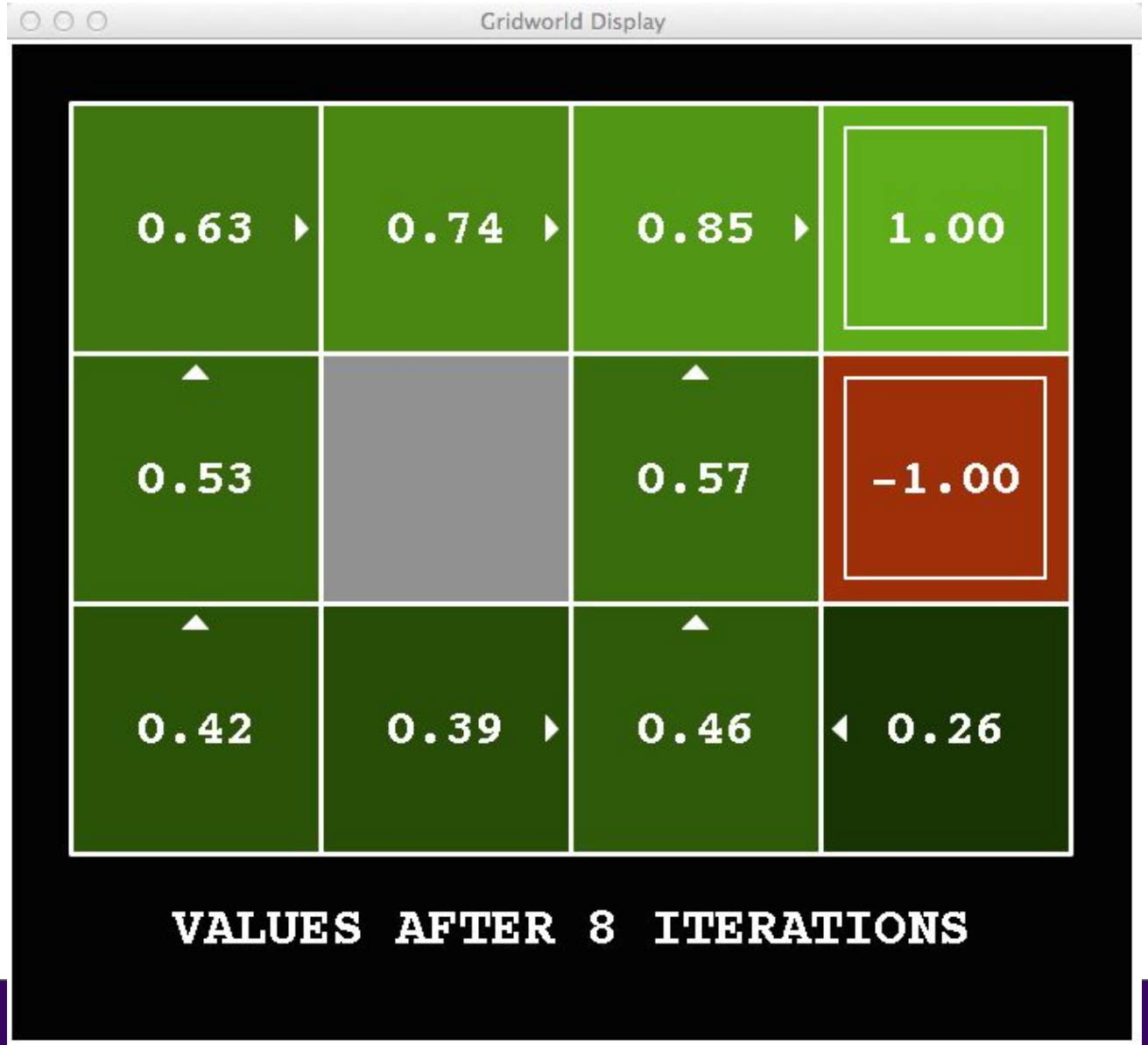
Noise = 0.2
Discount = 0.9
Living reward = 0

k=7



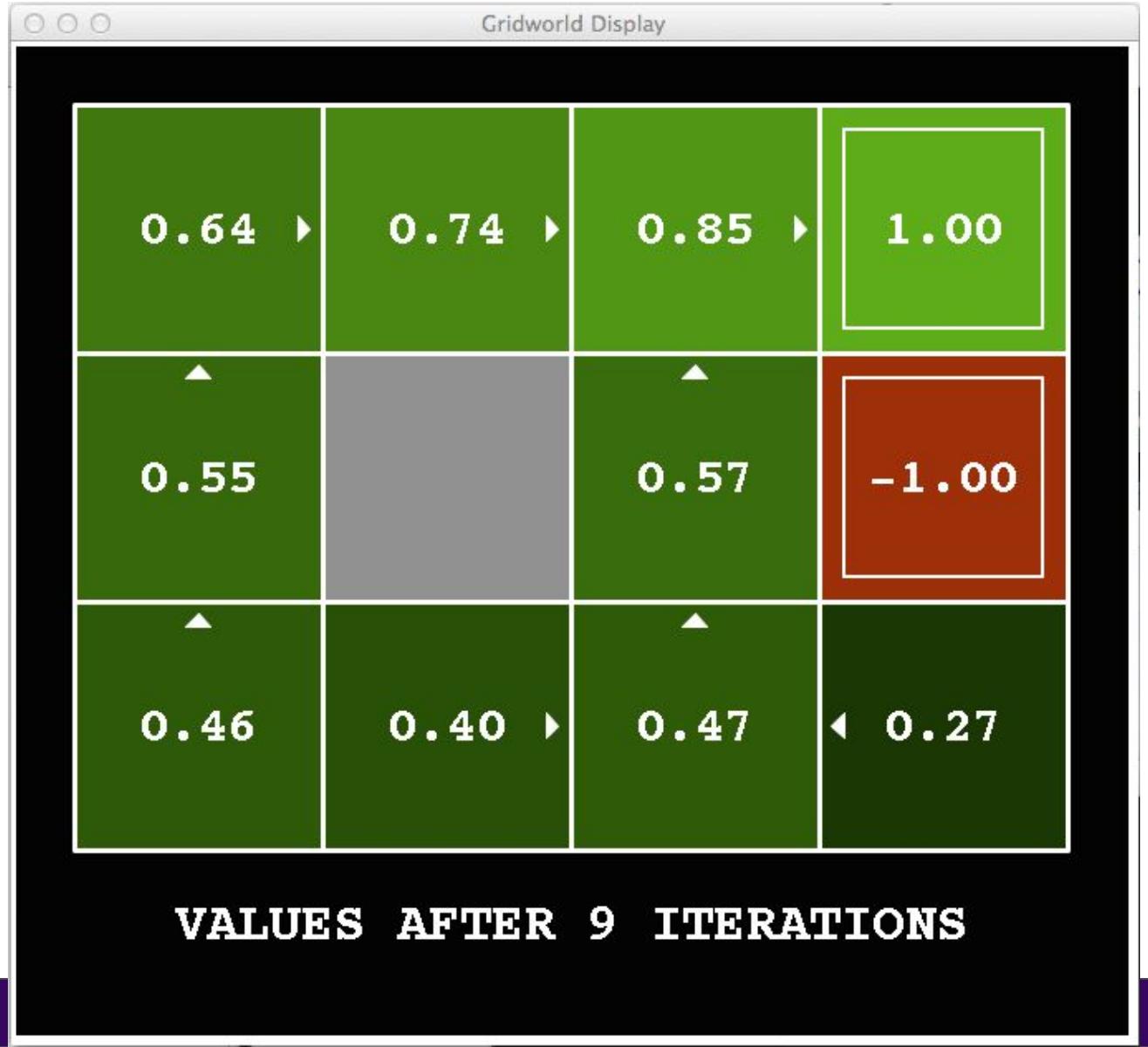
Noise = 0.2
Discount = 0.9
Living reward = 0

k=8



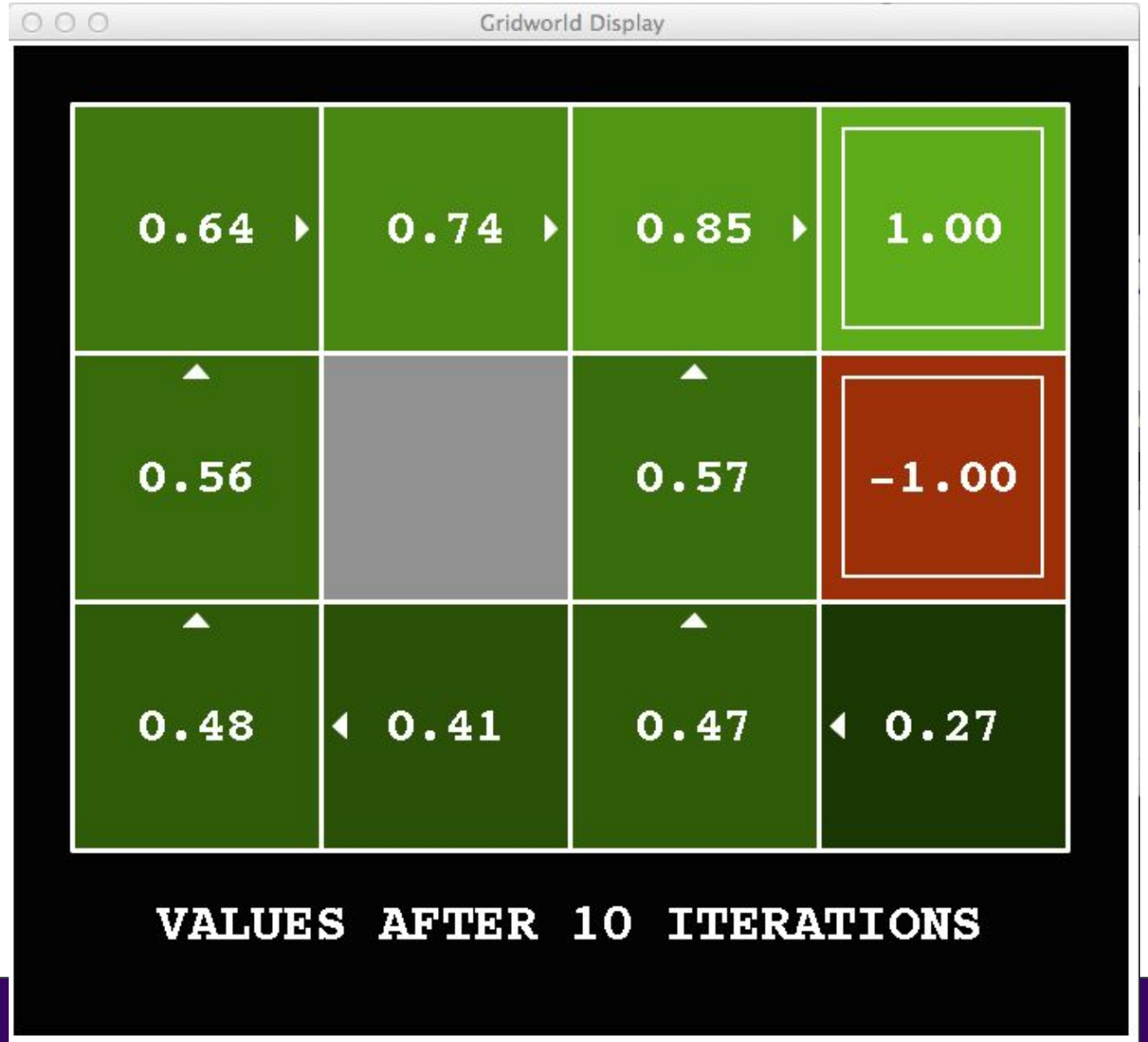
Noise = 0.2
Discount = 0.9
Living reward = 0

k=9



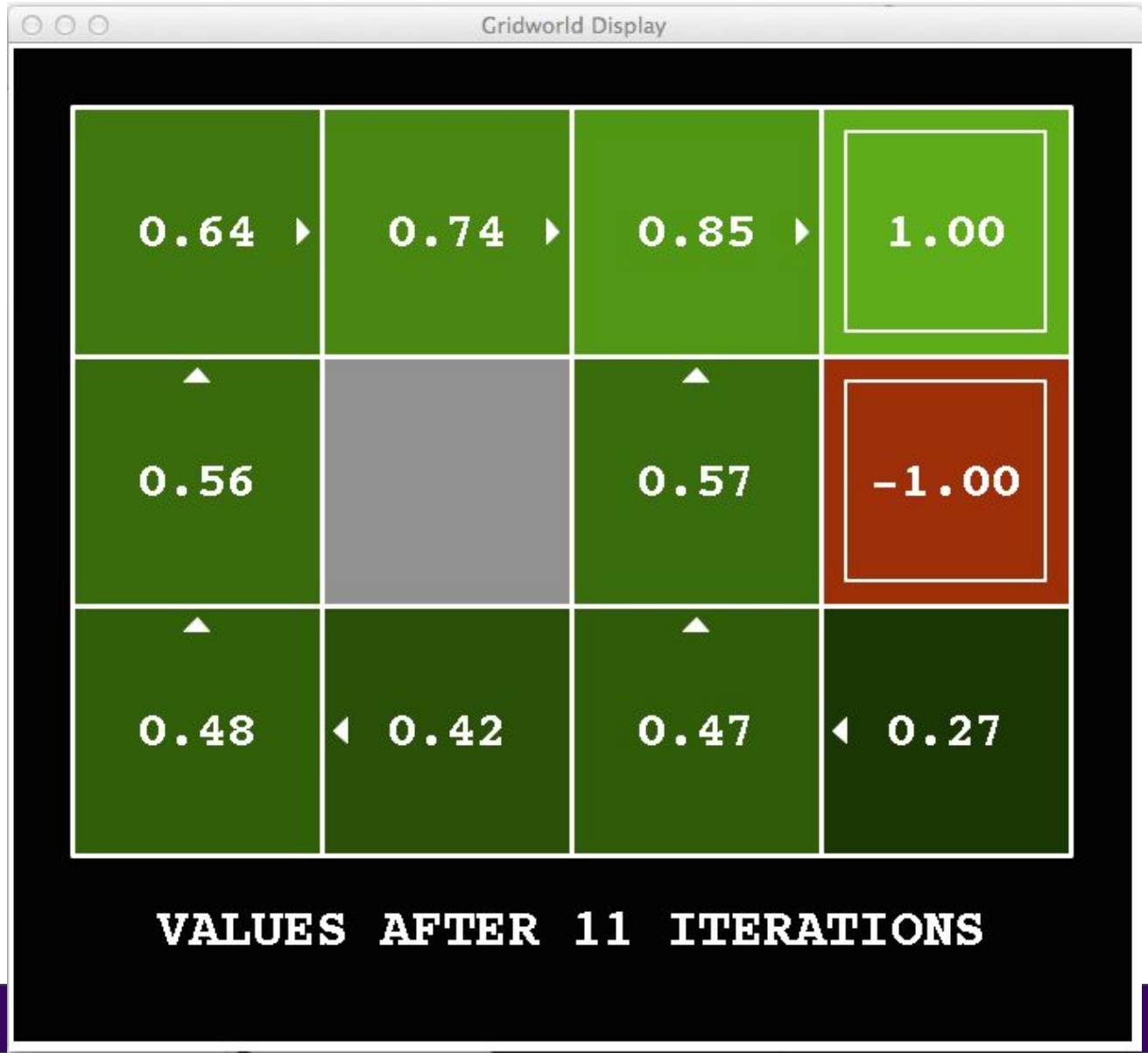
Noise = 0.2
Discount = 0.9
Living reward = 0

k=10



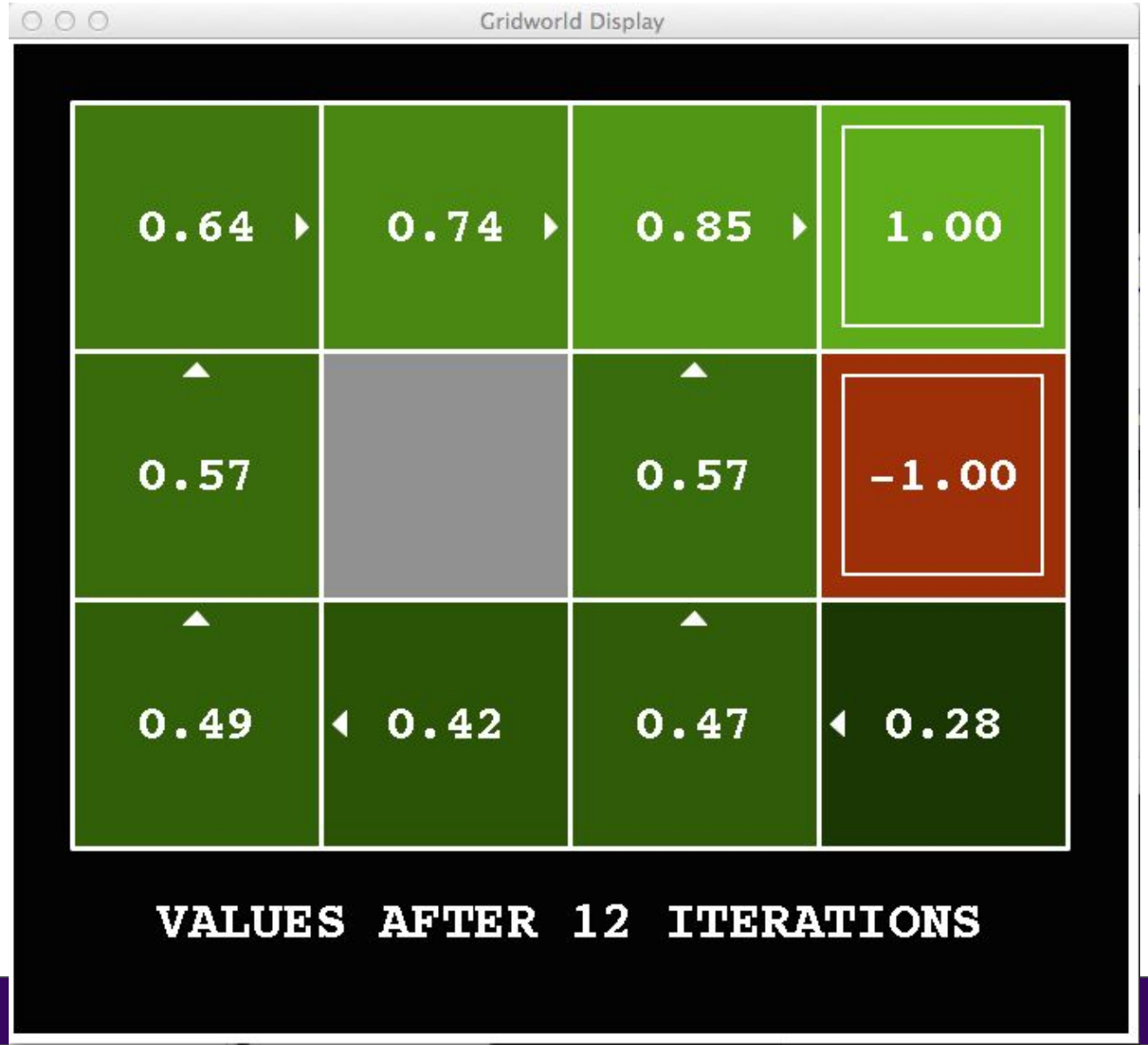
Noise = 0.2
Discount = 0.9
Living reward = 0

k=11



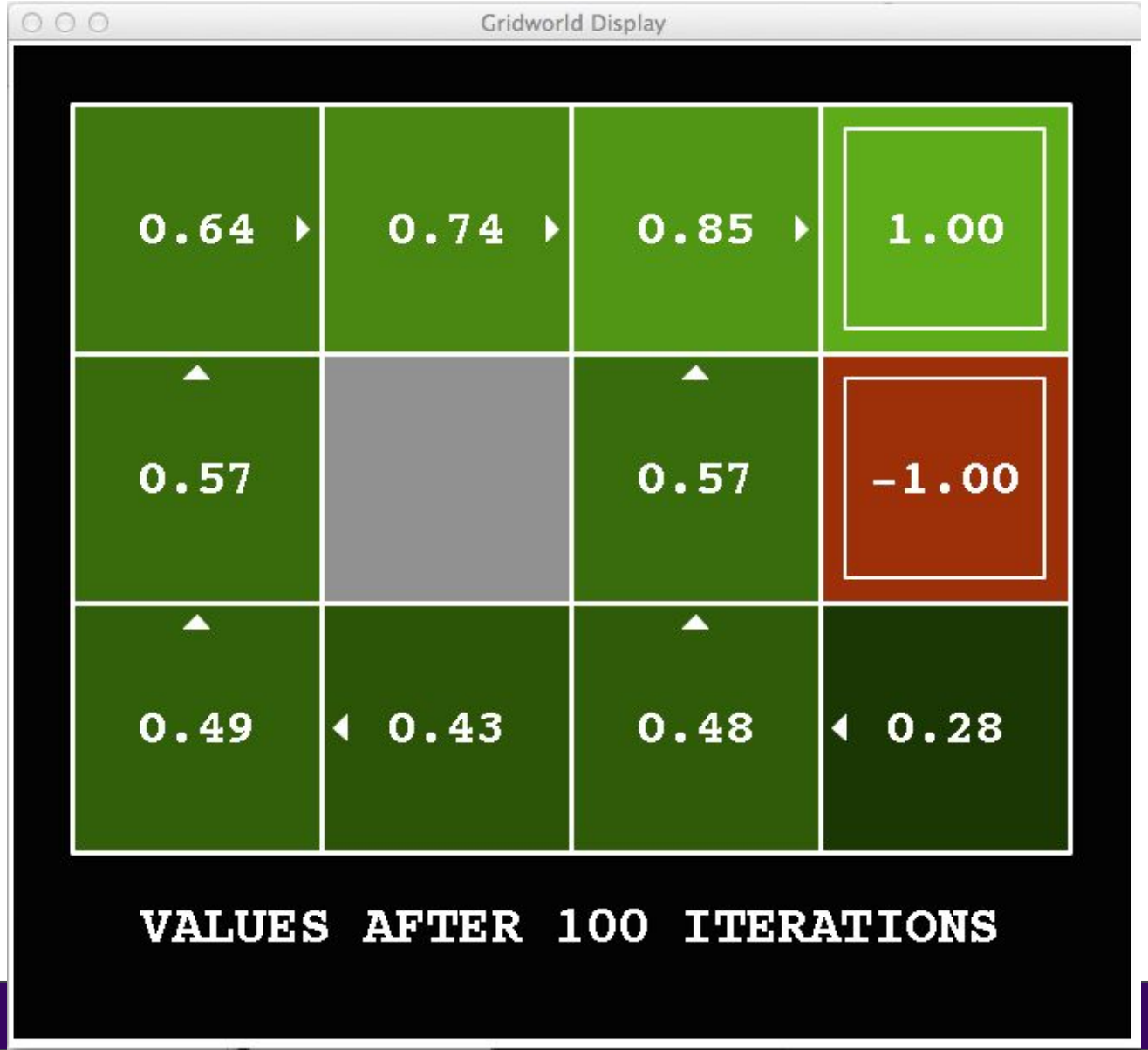
Noise = 0.2
Discount = 0.9
Living reward = 0

k=12



Noise = 0.2
Discount = 0.9
Living reward = 0

k=100

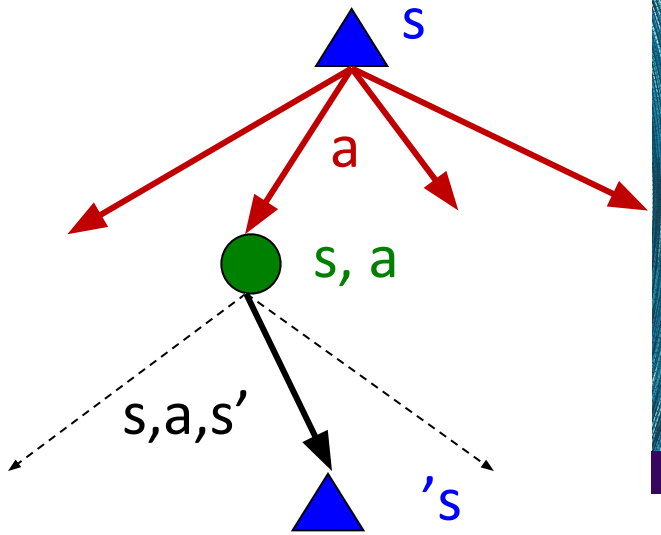


Noise = 0.2
Discount = 0.9
Living reward = 0

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 – $O(S^2A)$ per iteration

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

Problem 3: The policy often converges long before the values

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 programs 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


ALL RIGHT CHEWIE... PUNCH IT!
WGGGRRR!