

Reinforcement Learning

- Control learning
- Control policies that choose optimal actions
- Q learning
- Convergence

Control Learning

Consider learning to choose actions, e.g.,

- Robot learning to dock on battery charger
- Learning to choose actions to optimize factory output
- Learning to play Backgammon

Note several problem characteristics

- Delayed reward
- Opportunity for active exploration
- Possibility that state only partially observable
- Possible need to learn multiple tasks with same sensors/effectors

One Example: TD-Gammon

Tesauro, 1995

Learn to play Backgammon

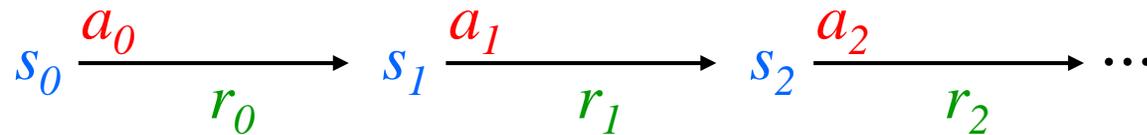
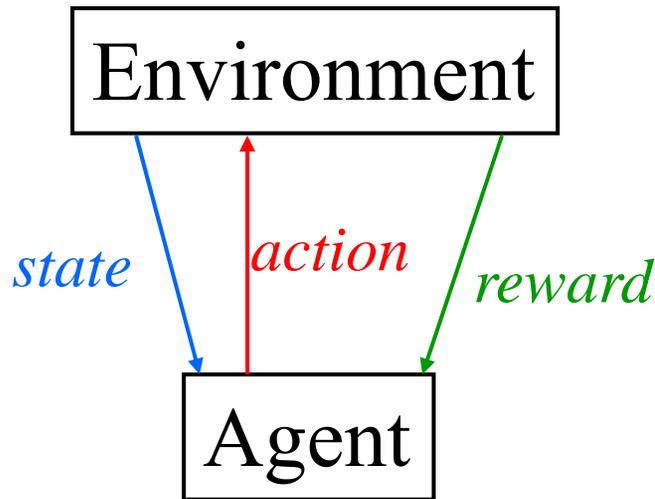
Immediate reward

- +100 if win
- -100 if lose
- 0 for all other states

Trained by playing 1.5 million games against itself

Now approximately equal to best human player

Reinforcement Learning Problem



Goal: learn to choose actions that maximize
 $r_0 + \gamma r_1 + \gamma^2 r_2 + \dots$, where $0 \leq \gamma < 1$

Markov Decision Process

Assume

- finite set of states S
- set of actions A
- at each discrete time, agent observes state $s_t \in S$ and choose action $a_t \in A$
- then receives immediate reward r_t
- and state changes to s_{t+1}
- Markov assumption: $s_{t+1} = \delta(s_t, a_t)$ and $r_t = r(s_t, a_t)$
 - i.e., r_t and s_{t+1} depend only on current state and action
 - functions δ and r may be nondeterministic
 - functions δ and r no necessarily known to agent

Agent's Learning Task

Execute action in environment, observe results, and

- learn action policy $\pi : S \rightarrow A$ that maximizes

$$E[r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \dots]$$

from any starting state in S

- here $0 \leq \gamma < 1$ is the *discount factor* for future rewards

Note something new:

- target function is $\pi : S \rightarrow A$
- but we have no training examples of form $\langle s, a \rangle$
- training examples are of form $\langle \langle s, a \rangle, r \rangle$

Value Function

To begin, consider deterministic worlds ...

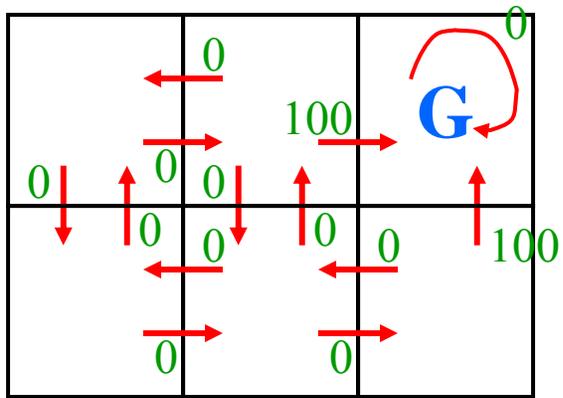
For each possible policy π the agent might adopt, we can define an evaluation function over states

$$\begin{aligned} V^\pi(s) &\equiv r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \dots \\ &\equiv \sum_{i=0}^{\infty} \gamma^i r_{t+i} \end{aligned}$$

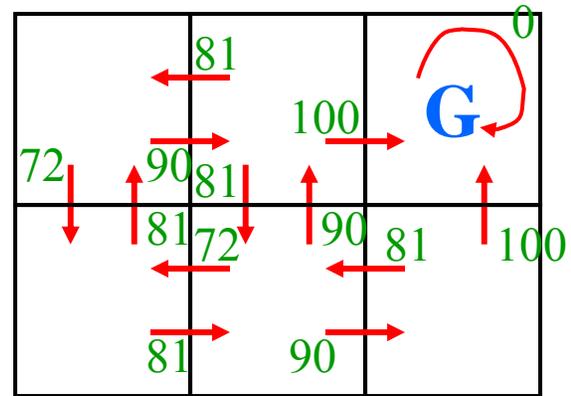
where r_t, r_{t+1}, \dots are generated by following policy π starting at state s

Restated, the task is to learn the optimal policy π^*

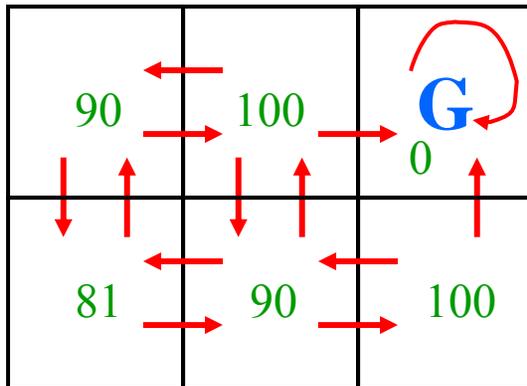
$$\pi^* \equiv \operatorname{argmax}_{\pi} V^\pi(s), (\forall s)$$



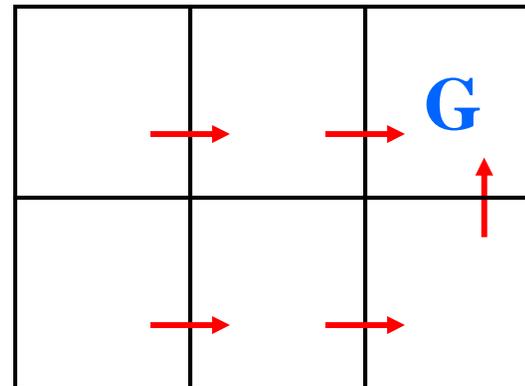
$r(s,a)$ (immediate reward) values



$Q(s,a)$ values



$V^*(s)$ values



One optimal policy

What to Learn

We might try to have agent learn the evaluation function V^{π^*} (which we write as V^*)

We could then do a lookahead search to choose best action from any state s because

$$\pi^*(s) \equiv \underset{a}{\operatorname{argmax}} [r(s,a) + \gamma V^*(\delta(s,a))]$$

A problem:

- This works well if agent knows a $\delta : S \times A \rightarrow S$, and $r : S \times A \rightarrow \mathcal{R}$
- But when it doesn't, we can't choose actions this way

Q Function

Define new function very similar to V^*

$$Q(s, a) \equiv r(s, a) + \gamma V^*(\delta(s, a))$$

If agent learns Q, it can choose optimal action even without knowing d !

$$\pi^*(s) \equiv \underset{a}{\operatorname{argmax}} [r(s, a) + \gamma V^*(\delta(s, a))]$$

$$\pi^*(s) \equiv \underset{a}{\operatorname{argmax}} Q(s, a)$$

Q is the evaluation function the agent will learn

Training Rule to Learn Q

Note Q and V^* closely related:

$$V^*(s) = \max_{a'} Q(s, a')$$

Which allows us to write Q recursively as

$$\begin{aligned} Q(s_t, a_t) &= r(s_t, a_t) + \gamma V^*(\delta(s_t, a_t)) \\ &= r(s_t, a_t) + \gamma \max_{a'} Q(s_{t+1}, a') \end{aligned}$$

Let \hat{Q} denote learner's current approximation to Q .

Consider training rule

$$\hat{Q}(s, a) \leftarrow r + \gamma \max_{a'} \hat{Q}(s', a')$$

where s' is the state resulting from applying action a in state s

Q Learning for Deterministic Worlds

For each s, a initialize table entry $\hat{Q}(s, a) \leftarrow 0$

Observe current state s

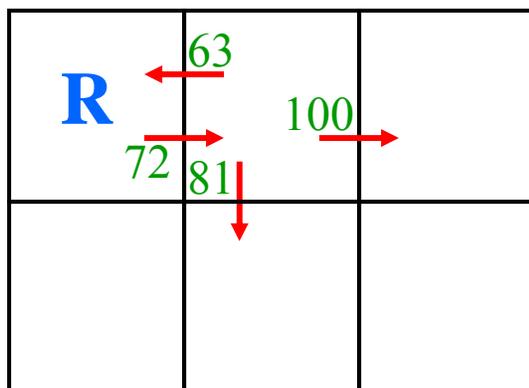
Do forever:

- Select an action a and execute it
- Receive immediate reward r
- Observe the new state s'
- Update the table entry for $\hat{Q}(s, a)$ as follows:

$$\hat{Q}(s, a) \leftarrow r + \gamma \max_{a'} \hat{Q}(s', a')$$

- $s \leftarrow s'$

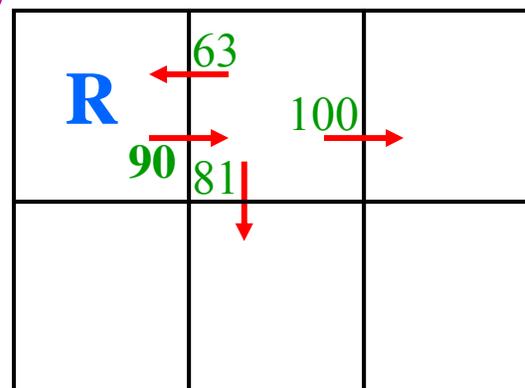
Updating



initial state: s_1



a_{right}



next state: s_2

$$\hat{Q}(s_1, a_{right}) \leftarrow r + \gamma \max_{a'} \hat{Q}(s_2, a')$$

$$\leftarrow 0 + 0.9 \max \{63, 81, 100\} = 90$$

notice if rewards non - negative, then

$$(\forall s, a, n) \hat{Q}_{n+1}(s, a) \geq \hat{Q}_n(s, a)$$

and

$$(\forall s, a, n) 0 \leq \hat{Q}_n(s, a) \leq Q(s, a)$$

Convergence

\hat{Q} converges to Q . Consider case of deterministic world where each $\langle s, a \rangle$ visited infinitely often.

Proof: define a full interval to be an interval during which each $\langle s, a \rangle$ is visited. During each full interval the largest error in \hat{Q} table is reduced by factor of γ

Let \hat{Q}_n be table after n updates, and Δ_n be the maximum error in \hat{Q}_n ; that is

$$\Delta_n = \max_{s,a} \left| \hat{Q}_n(s, a) - Q(s, a) \right|$$

Convergence (cont)

For any table entry $\hat{Q}_n(s, a)$ updated on iteration $n+1$, the error in the revised estimate $\hat{Q}_n(s, a)$ is

$$\begin{aligned} \left| \hat{Q}_{n+1}(s, a) - Q(s, a) \right| &= \left| (r + \gamma \max_{a'} \hat{Q}_n(s', a')) - (r + \gamma \max_{a'} Q(s', a')) \right| \\ &= \gamma \left| \max_{a'} \hat{Q}_n(s', a') - \max_{a'} Q(s', a') \right| \\ &\leq \gamma \max_{a'} \left| \hat{Q}_n(s', a') - Q(s', a') \right| \\ &\leq \gamma \max_{s'', a'} \left| \hat{Q}_n(s'', a') - Q(s'', a') \right| \end{aligned}$$

$$\left| \hat{Q}_{n+1}(s, a) - Q(s, a) \right| \leq \gamma \Delta_n$$

Note we used general fact that

$$\left| \max_a f_1(a) - \max_a f_2(a) \right| \leq \max_a \left| f_1(a) - f_2(a) \right|$$

Nondeterministic Case

What if reward and next state are non-deterministic?

We redefine V, Q by taking expected values

$$\begin{aligned} V^\pi(s) &\equiv \mathbb{E}[r_t + \gamma r_{t+1} + \gamma^2 r_{t+2} + \dots] \\ &\equiv \mathbb{E}\left[\sum_{i=0}^{\infty} \gamma^i r_{t+i}\right] \end{aligned}$$

$$Q(s, a) \equiv \mathbb{E}[r(s, a) + \gamma V^*(\delta(s, a))]$$

Nondeterministic Case

Q learning generalizes to nondeterministic worlds

Alter training rule to

$$\hat{Q}_n(s, a) \leftarrow (1 - \alpha_n) \hat{Q}_{n-1}(s, a) + \alpha_n [r + \max_{a'} \hat{Q}_{n-1}(s', a')]$$

where

$$\alpha_n = \frac{1}{1 + \text{visits}_n(s, a)}$$

Can still prove converge of \hat{Q} to Q [Watkins and Dayan, 1992]

Temporal Difference Learning

Q learning: reduce discrepancy between successive Q estimates

One step time difference:

$$Q^{(1)}(s_t, a_t) \equiv r_t + \gamma \max_a \hat{Q}(s_{t+1}, a)$$

Why not two steps?

$$Q^{(2)}(s_t, a_t) \equiv r_t + \gamma r_{t+1} + \gamma^2 \max_a \hat{Q}(s_{t+2}, a)$$

Or n ?

$$Q^{(n)}(s_t, a_t) \equiv r_t + \gamma r_{t+1} + \dots + \gamma^{n-1} r_{t+n-1} + \gamma^n \max_a \hat{Q}(s_{t+n}, a)$$

Blend all of these:

$$Q^\lambda(s_t, a_t) \equiv (1-\lambda) \left[Q^{(1)}(s_t, a_t) + \lambda Q^{(2)}(s_t, a_t) + \lambda^2 Q^{(3)}(s_t, a_t) + \dots \right]$$

Temporal Difference Learning

$$Q^\lambda(s_t, a_t) \equiv (1-\lambda) \left[Q^{(1)}(s_t, a_t) + \lambda Q^{(2)}(s_t, a_t) + \lambda^2 Q^{(3)}(s_t, a_t) + \dots \right]$$

Equivalent expression:

$$Q^\lambda(s_t, a_t) \equiv r_t + \gamma \left[(1-\lambda) \max_a \hat{Q}(s_t, a_t) + \lambda Q^\lambda(s_{t+1}, a_{t+1}) \right]$$

TD(λ) algorithm uses above training rule

- Sometimes converges faster than Q learning
- converges for learning V^* for any $0 \leq \lambda \leq 1$ (Dayan, 1992)
- Tesauro's TD-Gammon uses this algorithm

Subtleties and Ongoing Research

- Replace \hat{Q} table with neural network or other generalizer
- Handle case where state only partially observable
- Design optimal exploration strategies
- Extend to continuous action, state
- Learn and use $d : S \times A \rightarrow S$, d approximation to δ
- Relationship to dynamic programming

RL Summary

- Reinforcement learning (RL)
 - control learning
 - delayed reward
 - possible that the state is only partially observable
 - possible that the relationship between states/actions unknown
- Temporal Difference Learning
 - learn discrepancies between successive estimates
 - used in TD-Gammon
- $V(s)$ - state value function
 - needs known reward/state transition functions

RL Summary

- $Q(s,a)$ - state/action value function
 - related to V
 - does not need reward/state trans functions
 - training rule
 - related to dynamic programming
 - measure actual reward received for action and future value using current Q function
 - deterministic - replace existing estimate
 - nondeterministic - move table estimate towards measure estimate
 - convergence - can be shown in both cases