Markov Decision Processes CS60077: Reinforcement Learning

Abir Das

IIT Kharagpur

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- § Understand definitions and notation to be used in the course.
- § Understand definition and setup of sequential decision problems.



Resources

§ Reinforcement Learning by David Silver [Link]

- § Deep Reinforcement Learning by Sergey Levine [Link]
- § SB: Chapter 3

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Markov Decision Process

Terminology and Notation



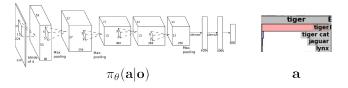


Figure credit: S. Levine - CS 294-112 Course, UC Berkeley

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Markov Decision Process

Terminology and Notation



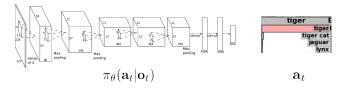


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Markov Decision Process

Terminology and Notation

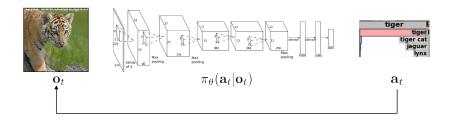


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Markov Decision Process

Terminology and Notation

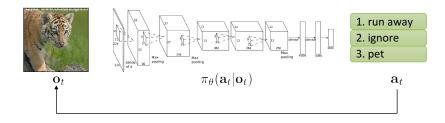


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Markov Decision Process

Terminology and Notation

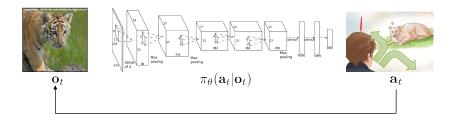


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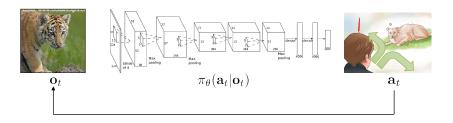
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Markov Decision Process

Terminology and Notation



 \mathbf{o}_t – observation \mathbf{a}_t – action

 $\pi_{\theta}(\mathbf{a}_t | \mathbf{o}_t) - \text{policy}$

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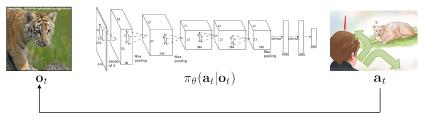
Figure credit: S. Levine - CS 294-112 Course, UC Berkeley

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Markov Decision Process

Terminology and Notation



 $\mathbf{s}_t - \text{state}$ $\mathbf{o}_t - \text{observation}$ $\mathbf{a}_t - \text{action}$

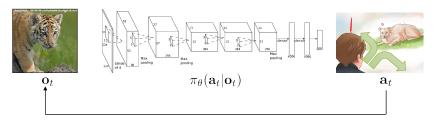
 $\pi_{\theta}(\mathbf{a}_t | \mathbf{o}_t) - \text{policy} \\ \pi_{\theta}(\mathbf{a}_t | \mathbf{s}_t) - \text{policy (fully observed)}$

Figure credit: S. Levine - CS 294-112 Course, UC Berkeley

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Markov Decision Process

Terminology and Notation



- \mathbf{s}_t state
- \mathbf{o}_t observation
- \mathbf{a}_t action

 $\pi_{\theta}(\mathbf{a}_t | \mathbf{o}_t) - \text{policy}$ $\pi_{\theta}(\mathbf{a}_t | \mathbf{s}_t) - \text{policy (fully observed)}$

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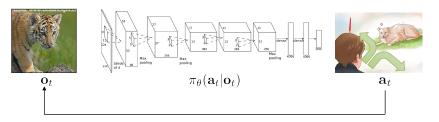
 \mathbf{o}_{t} – observation Figure credit: S. Levine - CS 294-112 Course, UC Berkelev

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Markov Decision Process

Terminology and Notation



- $\mathbf{s}_t \text{state}$ $\mathbf{o}_t - \text{observation}$
- \mathbf{a}_t action

 $\pi_{\theta}(\mathbf{a}_t | \mathbf{o}_t) - \text{policy} \\ \pi_{\theta}(\mathbf{a}_t | \mathbf{s}_t) - \text{policy (fully observed)}$

Image: A matrix





 \mathbf{s}_t – state

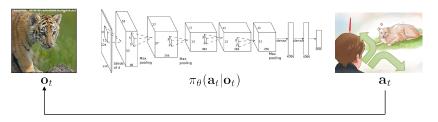
 $\mathbf{o}_t = \mathrm{observation}$ Figure credit: S. Levine - CS 294-112 Course, UC Berkeley

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Markov Decision Process

Terminology and Notation



- \mathbf{s}_t state \mathbf{o}_t – observation
- \mathbf{a}_t action

 $\pi_{\theta}(\mathbf{a}_t | \mathbf{o}_t) - \text{policy}$ $\pi_{\theta}(\mathbf{a}_t | \mathbf{s}_t) - \text{policy (fully observed)}$

Image: A matrix



 \mathbf{o}_{t} – observation Figure credit: S. Levine - CS 294-112 Course, UC Berkelev

 \mathbf{s}_t – state

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Terminology

Markov Property

Markov Decision Process

The future is independent of the past given the present.

Definition

A state S_t is Markov if and only if

$$P(S_{t+1}|S_t) = P(S_{t+1}|S_t, S_{t-1}, S_{t-2}, \cdots, S_1)$$



Andrey Markov

- \S Once the present state is known, the history may be thrown away
- § The current state is a sufficient statistic of the future

Markov Chain

A Markov Chain or Markov Process is temporal process *i.e.*, a sequence of random states S_1, S_2, \cdots where the states obey the Markov property.

Definition

A Markov Process is a tuple $\langle \mathcal{S}, \mathcal{P} \rangle$, where

- $\S \ S$ is the state space (can be continuous or discrete)
- $\S \ \mathcal{P}$ is the state transition probability matrix. \mathcal{P} also called an operator

$$\mathcal{P} = \begin{bmatrix} \mathcal{P}_{11} & \mathcal{P}_{12} & \cdots & \mathcal{P}_{1n} \\ \mathcal{P}_{21} & \mathcal{P}_{22} & \cdots & \mathcal{P}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathcal{P}_{n1} & \mathcal{P}_{n2} & \cdots & \mathcal{P}_{nn} \end{bmatrix}$$

where $\mathcal{P}_{ss'} = P(S_{t+1} = s' | S_t = s)$

Terminology

Markov Chain

$$\mathcal{P} = \begin{bmatrix} \mathcal{P}_{11} & \mathcal{P}_{12} & \cdots & \mathcal{P}_{1n} \\ \mathcal{P}_{21} & \mathcal{P}_{22} & \cdots & \mathcal{P}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathcal{P}_{n1} & \mathcal{P}_{n2} & \cdots & \mathcal{P}_{nn} \end{bmatrix}$$

Let $\mu_{t,i} = P(S_t = s_i)$ and $\mu_t = [\mu_{t,1}, \mu_{t,2}, \cdots, \mu_{t,n}]^T$, *i.e.*, μ_t is a vector of probabilities, then $\mu_{t+1} = \mathcal{P}^T \mu_t$

$$\begin{bmatrix} \mu_{t+1,1} \\ \mu_{t+1,2} \\ \vdots \\ \mu_{t+1,n} \end{bmatrix} = \begin{bmatrix} \mathcal{P}_{11} & \mathcal{P}_{12} & \cdots & \mathcal{P}_{1n} \\ \mathcal{P}_{21} & \mathcal{P}_{22} & \cdots & \mathcal{P}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \mathcal{P}_{n1} & \mathcal{P}_{n2} & \cdots & \mathcal{P}_{nn} \end{bmatrix}^T \begin{bmatrix} \mu_{t,1} \\ \mu_{t,2} \\ \vdots \\ \mu_{t,n} \end{bmatrix}$$

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Markov Chain

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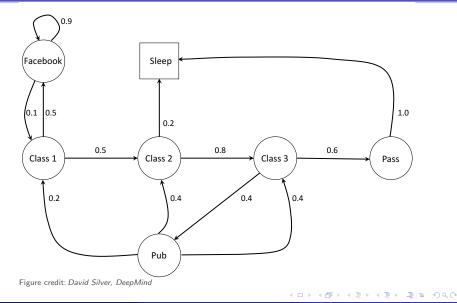
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 $(\mathbf{s}_1) \xrightarrow{p(\mathbf{s}_t | \mathbf{s}_{t-1})} (\mathbf{s}_2) \xrightarrow{p(\mathbf{s}_{t+1} | \mathbf{s}_t)} (\mathbf{s}_3) \xrightarrow{\text{Markov property}} (\mathbf{s}_1)$

Terminology

Markov Decision Process

Student Markov Process



Markov Decision Process

Student Markov Process - Episodes

Terminology

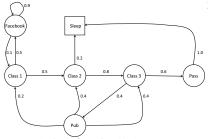


Figure credit: David Silver, DeepMind

Agenda

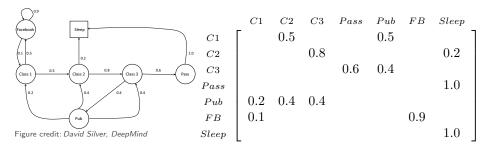
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Sample episodes for Student Markov process starting from $S_1 = C1$

- § C1 C2 C3 Pass Sleep
- § C1 FB FB C1 C2 Sleep
- § C1 C2 C3 Pub C2 C3 Pass Sleep
- § C1 FB FB C1 C2 C3 Pub C1 FB FB FB C1 C2 C3 Pub C2 Sleep

Terminology

Student Markov Process - Transition Matrix



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Markov Reward Process

A Markov reward process is a Markov process with rewards.

Definition

A Markov Reward Process is a tuple $\langle S, \mathcal{P}, \mathcal{R}, \gamma \rangle$, where

- $\S \ \mathcal{S}$ is the state space (can be continuous or discrete)
- § \mathcal{P} is the state transition probability matrix. \mathcal{P} also called an operator. $\mathcal{P}_{ss'} = P(S_{t+1} = s' | S_t = s)$
- § \mathcal{R} is a reward function, $\mathcal{R} = \mathbb{E}[R_{t+1}|S_t = s] = R(s)$
- $\S~\gamma$ is a discount factor, $\gamma \in \big[0,1\big]$

Terminology

Markov Reward Process

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Definition

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 - $\S~\gamma$ is a discount factor, $\gamma \in \begin{bmatrix} 0,1 \end{bmatrix}$

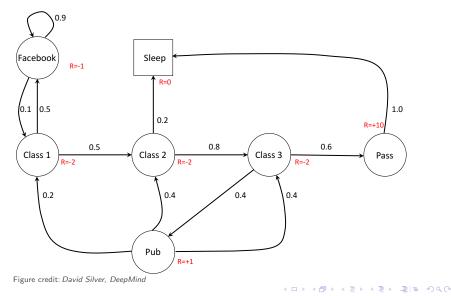
If we want it to do something for us, we must provide rewards to it in such a way that in maximizing them the agent will also achieve our goals.

reward signal is your way of communicating to the robot *what* you want it to achieve, not *how* you want it achieved.⁶ From Sutton and Barto

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Student Markov Reward Process



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Return

Definition

The return G_t is the total discounted reward from timestep t.

$$G_t = R_{t+1} + \gamma R_{t+2} + \dots = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}$$
(1)

§ $\gamma \in [0, 1]$ is the discounted present value of the future rewards. § Immediate rewards are valued above delayed rewards.

- > γ close to 0 leads to "myopic" evaluation.
- \triangleright γ close to 1 leads to "far-sighted" evaluation.



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§ Uncertainty about the future may not be fully represented



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- § Immediate rewards are valued above delayed rewards.



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- § Avoids infinite returns in cyclic Markov processes or infinite horizon problems.

- Uncertainty about the future may not be fully represented ξ
- Immediate rewards are valued above delayed rewards. 8
- 8 Avoids infinite returns in cyclic Markov processes or infinite horizon problems.
- Mathematically convenient. We can use stationarity property to ξ better effect.

Agenda

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Why Discount?

Agenda

Most Markov reward and decision processes are discounted. Why?

- § Uncertainty about the future may not be fully represented
- § Immediate rewards are valued above delayed rewards.
- § Avoids infinite returns in cyclic Markov processes or infinite horizon problems.
- § Mathematically convenient. We can use stationarity property to better effect.

It is sometimes possible to use average rewards also to bound the return to finite values.



Terminology

Value Function

Markov Decision Process

The value function $\boldsymbol{v}(\boldsymbol{s})$ gives the long-term value of state \boldsymbol{s}

Definition

The state value function $\boldsymbol{v}(s)$ of an MRP is the expected return starting from state s

$$v(s) = \mathbb{E}[G_t | S_t = s]$$
⁽²⁾

Terminology

Markov Decision Process

Example Student MRP Returns

Sample returns for Student MRP: Starting from $S_1 = C1$ with $\gamma = \frac{1}{2}$

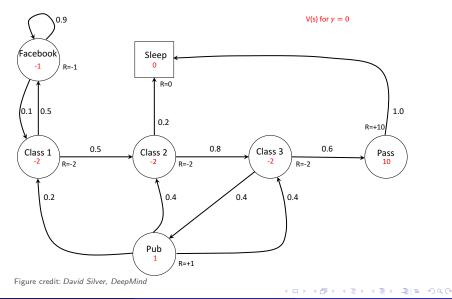
$$G_1 = R_2 + \gamma R_3 + \dots + \gamma^{T-1} R_{T+1}$$

- § C1 C2 C3 Pass Sleep
- § C1 FB FB C1 C2 Sleep
- § C1 C2 C3 Pub C2 C3 Pass Sleep
- § C1 FB FB C1 C2 C3 Pub C1 FB FB FB C1 C2 C3 Pub C2 Sleep

$$\begin{cases} -2 - \frac{1}{2} * 2 - \frac{1}{4} * 2 + \frac{1}{8} * 10 = -2.25 \\ 8 -2 - \frac{1}{2} * 1 - \frac{1}{4} * 1 - \frac{1}{8} * 2 - \frac{1}{16} * 2 = -3.125 \\ 8 -2 - \frac{1}{2} * 2 - \frac{1}{4} * 2 + \frac{1}{8} * 1 - -\frac{1}{16} * 2 - \frac{1}{32} * 2 + \frac{1}{64} * 10 = -3.41 \\ 8 -2 - \frac{1}{2} * 1 - \frac{1}{4} * 1 - \frac{1}{8} * 2 - \frac{1}{16} * 2 + \cdots = -3.20 \end{cases}$$

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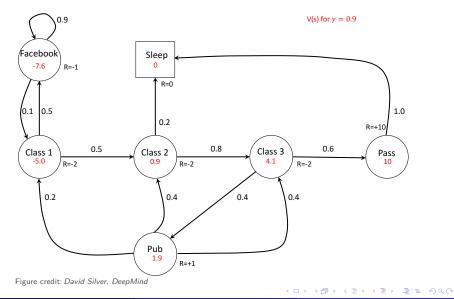
State-Value Function for Student MRP (1)



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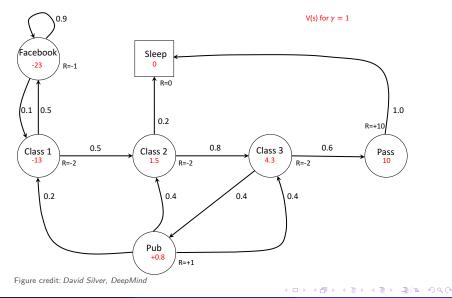
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State-Value Function for Student MRP (2)



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State-Value Function for Student MRP (3)



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Terminology

Bellman Equation for MRPs

The value function can be decomposed into two parts:

- \S immediate reward R(s)
- \S discounted value of successor state $\gamma v(s')$

$$v(s) = R(s) + \gamma \mathbb{E}_{s' \in \mathcal{S}} [v(s')]$$

= $R(s) + \gamma \sum_{s' \in \mathcal{S}} \mathcal{P}_{ss'} v(s')$



Richard Bellman

(3)

Terminology

Bellman Equation for MRPs

The value function can be decomposed into two parts:

- \S immediate reward R(s)
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$$v(s) = R(s) + \gamma \mathbb{E}_{s' \in S} [v(s')]$$

= $R(s) + \gamma \sum_{s' \in S} \mathcal{P}_{ss'} v(s')$ (3)
$$V(s) \bigcirc s$$

$$V(s') \bigcirc s$$

$$V(s'') \bigcirc s' \lor V(s'')$$



Richard Bellman

Bellman Equation for MRPs - Proof

$$v(s) = \mathbb{E}[G_t|S_t = s] = \mathbb{E}[R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \gamma^3 R_{t+4} + \dots |S_t = s]$$

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Bellman Equation for MRPs - Proof

$$v(s) = \mathbb{E}[G_t|S_t = s] = \mathbb{E}[R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \gamma^3 R_{t+4} + \dots | S_t = s]$$

= $\mathbb{E}[R_{t+1}(S_t) + \gamma R_{t+2}(S_{t+1}) + \gamma^2 R_{t+3}(S_{t+2}) + \gamma^3 R_{t+4}(S_{t+3}) + \dots | S_t = s]$

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Bellman Equation for MRPs - Proof

$$v(s) = \mathbb{E}[G_t|S_t = s] = \mathbb{E}[R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \gamma^3 R_{t+4} + \dots | S_t = s]$$

= $\mathbb{E}[R_{t+1}(S_t) + \gamma R_{t+2}(S_{t+1}) + \gamma^2 R_{t+3}(S_{t+2}) + \gamma^3 R_{t+4}(S_{t+3}) + \dots | S_t = s]$
= $\sum_{S_{t+1}, S_{t+2}, \dots} \left(P(S_{t+1}, S_{t+2}, \dots | S_t = s) [R_{t+1}(S_t) + \gamma R_{t+2}(S_{t+1}) + \gamma$

$$\gamma^2 R_{t+3}(S_{t+2}) + \gamma^3 R_{t+4}(S_{t+3}) + \cdots] \Big)$$

Image: Image:

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Markov Decision Process

Bellman Equation for MRPs - Proof

$$\begin{split} v(s) &= \mathbb{E} \left[G_t | S_t = s \right] = \mathbb{E} \left[R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \gamma^3 R_{t+4} + \dots | S_t = s \right] \\ &= \mathbb{E} \left[R_{t+1}(S_t) + \gamma R_{t+2}(S_{t+1}) + \gamma^2 R_{t+3}(S_{t+2}) + \gamma^3 R_{t+4}(S_{t+3}) + \dots | S_t = s \right] \\ &= \sum_{S_{t+1}, S_{t+2}, \dots} \left(P(S_{t+1}, S_{t+2}, \dots | S_t = s) \left[R_{t+1}(S_t) + \gamma R_{t+2}(S_{t+1}) + \gamma^2 R_{t+3}(S_{t+2}) + \gamma^3 R_{t+4}(S_{t+3}) + \dots \right] \right) \\ &= \sum_{S_{t+1}, S_{t+2}, \dots} P(S_{t+1}, S_{t+2}, \dots | S_t = s) R_{t+1}(S_t) + \\ &\qquad \gamma \sum_{S_{t+1}, S_{t+2}, \dots} \left(P(S_{t+1}, S_{t+2}, \dots | S_t = s) \left[R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \gamma^2 R_{t+4}(S_{t+3}) + \dots \right] \right) \end{split}$$

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Bellman Equation for MRPs - Proof

$$= R_{t+1}(S_t) \sum_{\substack{S_{t+1}, S_{t+2}, \cdots \\ S_{t+1}, S_{t+2}, \cdots }} P(S_{t+1}, S_{t+2}, \cdots | S_t = s) + \frac{\gamma \sum_{\substack{S_{t+1}, S_{t+2}, \cdots \\ S_{t+1}, S_{t+2}, \cdots }} \left(P(S_{t+1}, S_{t+2}, \cdots | S_t = s) \left[R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \frac{\gamma^2 R_{t+4}(S_{t+3}) + \cdots }{\gamma^2 R_{t+4}(S_{t+3}) + \cdots } \right] \right)}$$

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Bellman Equation for MRPs - Proof

$$= R_{t+1}(S_t) \sum_{\substack{S_{t+1}, S_{t+2}, \cdots \\ S_{t+1}, S_{t+2}, \cdots \\ S_{t+1}, S_{t+2}, \cdots \\ S_{t+1}, S_{t+2}, \cdots \\ \gamma \sum_{i=1}^{t} \left(P(S_{t+1}, S_{t+2}, \cdots | S_t = s) \left[R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \right. \right. \right) \\ \left. + \gamma \sum_{\substack{S_{t+1}, S_{t+2}, \cdots \\ S_{t+1}, S_{t+2}, \cdots \\ S_{t+1}, S_{t+2}, \cdots \\ \gamma^2 R_{t+4}(S_{t+3}) + \cdots \\ \left. \right] \right)$$

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Bellman Equation for MRPs - Proof

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Markov Decision Process

Bellman Equation for MRPs - Proof

$$= R_{t+1}(S_t) + \gamma \sum_{S_{t+1}, S_{t+2}, \cdots} \left(P(S_{t+2}, \cdots | S_{t+1}) P(S_{t+1} | S_t = s) \left[R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \frac{2}{S_{t+1}(S_{t+2}, \cdots | S_{t+1})} \right] \left[P(S_{t+1} | S_t = s) \left[R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \frac{2}{S_{t+1}(S_{t+2}, \cdots | S_{t+1})} \right] \right]$$

 $\gamma^2 R_{t+4}(S_{t+3}) + \cdots]$ [Conditional independence (Ref eq. (7))]

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Bellman Equation for MRPs - Proof

$$= R_{t+1}(S_t) + \gamma \sum_{S_{t+1}, S_{t+2}, \cdots} (P(S_{t+2}, \cdots | S_{t+1}) P(S_{t+1} | S_t = s) [R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \gamma^2 R_{t+4}(S_{t+3}) + \cdots]) [\text{Conditional independence (Ref eq. (7))}]$$

$$= R_{t+1}(S_t) + \gamma \sum_{S_{t+1}} \sum_{S_{t+2}, S_{t+3}, \cdots} (P(S_{t+2}, \cdots | S_{t+1}) P(S_{t+1} | S_t = s) [R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \gamma^2 R_{t+4}(S_{t+3}) + \cdots])$$

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Bellman Equation for MRPs - Proof

$$= R_{t+1}(S_t) + \gamma \sum_{S_{t+1}, S_{t+2}, \cdots} (P(S_{t+2}, \cdots | S_{t+1}) P(S_{t+1} | S_t = s) [R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \gamma^2 R_{t+4}(S_{t+3}) + \cdots]) [\text{Conditional independence (Ref eq. (7))}]$$

$$= R_{t+1}(S_t) + \gamma \sum_{S_{t+1}} \sum_{S_{t+2}, S_{t+3}, \cdots} (P(S_{t+2}, \cdots | S_{t+1}) P(S_{t+1} | S_t = s) [R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \gamma^2 R_{t+4}(S_{t+3}) + \cdots])$$

$$= R_{t+1}(S_t) + \gamma \sum_{S_{t+1}} P(S_{t+1} | S_t = s) \sum_{S_{t+2}, S_{t+3}, \cdots} (P(S_{t+2}, \cdots | S_{t+1}) [R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \gamma^2 R_{t+4}(S_{t+3}) + \cdots])$$

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Markov Decision Process

Bellman Equation for MRPs - Proof

$$= R_{t+1}(S_t) + \gamma \sum_{S_{t+1}, S_{t+2}, \cdots} (P(S_{t+2}, \cdots | S_{t+1}) P(S_{t+1} | S_t = s) [R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \gamma^2 R_{t+4}(S_{t+3}) + \cdots]) [\text{Conditional independence (Ref eq. (7))]}$$

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$$= R_{t+1}(S_t) + \gamma \sum_{S_{t+1}} P(S_{t+1} | S_t = s) v(S_{t+1})$$

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Markov Decision Process

Bellman Equation for MRPs - Proof

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Terminology

Markov Decision Process

Bellman Equation for MRPs - Proof

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Bellman Equation in Matrix Form

So, we have seen,

$$v(s) = R(s) + \gamma \sum_{s' \in \mathcal{S}} \mathcal{P}_{ss'} v(s')$$

Where are the time subscripts? **Hint:** Think about (1). Definition of value function, (2). Expectation operation.

Bellman Equation in Matrix Form

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The Bellman equation can be expressed concisely using matrices.

$$\mathbf{v} = \mathcal{R} + \gamma \mathcal{P} \mathbf{v}$$

where \mathbf{v} and \mathcal{R} are column vectors with one entry per state.

$$\begin{bmatrix} v(s_1)\\v(s_2)\\\vdots\\v(s_n) \end{bmatrix} = \begin{bmatrix} R(s_1)\\R(s_2)\\\vdots\\R(s_n) \end{bmatrix} + \gamma \begin{bmatrix} \mathcal{P}_{11} & \mathcal{P}_{12} & \cdots & \mathcal{P}_{1n}\\\mathcal{P}_{21} & \mathcal{P}_{22} & \cdots & \mathcal{P}_{2n}\\\vdots & \vdots & \ddots & \vdots\\\mathcal{P}_{n1} & \mathcal{P}_{n2} & \cdots & \mathcal{P}_{nn} \end{bmatrix} \begin{bmatrix} v(s_1)\\v(s_2)\\\vdots\\v(s_n) \end{bmatrix}$$

Markov Decision Process

Solving Bellman Equation

Terminology

Agenda

§ The Bellman equation being a linear equation, it can be solved directly.

$$\mathbf{v} = \mathcal{R} + \gamma \mathcal{P} \mathbf{v}$$
$$(\mathbf{I} - \gamma \mathcal{P}) \mathbf{v} = \mathcal{R}$$
$$\mathbf{v} = (\mathbf{I} - \gamma \mathcal{P})^{-1} \mathcal{R}$$

- § As computational complexity is $O(n^3)$ for n states, direct solution is only feasible for small MRPs.
- § There are many iterative methods for large MRPs, *e.g.*, Dynamic programing, Monte-Carlo, Temporal difference learning



Existence of Solution to Bellman Equation

§ We need to show that $(\mathbf{I} - \gamma \mathcal{P})$ is invertible and for that we will use the following result from linear algebra - The inverse of a matrix exists if and only if all its eigenvalues are non-zero.

Existence of Solution to Bellman Equation

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- § For a stochastic matrix (row sum equal to 1 and all entries are ≥ 0), the largest eigenvalue is 1.

Existence of Solution to Bellman Equation

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- § For a stochastic matrix (row sum equal to 1 and all entries are ≥ 0), the largest eigenvalue is 1.

Proof

Agenda

As \mathcal{P} is a stchoastic matrix, $\mathcal{P}\mathbb{1} = \mathbb{1}$ where $\mathbb{1} = [1, 1, \cdots 1]^T$. This means 1 is an eigenvalue of \mathcal{P} .

Now, lets suppose $\exists \lambda > 1$ and non-zero \mathbf{x} such that $\mathcal{P}\mathbf{x} = \lambda \mathbf{x}$.

Since the rows of \mathcal{P} are non-negative and sum to 1, each element of vector $\mathcal{P}\mathbf{x}$ is a convex combination of the components of the vector \mathbf{x} .

A convex combination can't be greater than x_{\max} , the largest component of \mathbf{x} . However, as $\lambda > 1$, at least one element (λx_{\max}) in the R.H.S. (*i.e.*, in $\lambda \mathbf{x}$) is greater than x_{\max} . This is a <u>contradiction</u> and so $\lambda > 1$ is not possible.

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Existence of Solution to Bellman Equation

 \S So the largest eigenvalue of \mathcal{P} is 1.

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Existence of Solution to Bellman Equation

 \S So the largest eigenvalue of \mathcal{P} is 1.

Theorem and its proof

For all eigenvalues λ_i of a square matrix A and corresponding eigenvectors v_i such that $Av_i = \lambda_i v_i$,

$$\operatorname{eig}(\mathbf{I}+\gamma\mathbf{A})=1+\gamma\lambda_i \;\; [\gamma \; ext{is any scalar}]$$

Proof:

$$\begin{aligned} \mathbf{A}\mathbf{v}_i &= \lambda_i \mathbf{v}_i \\ \gamma \mathbf{A}\mathbf{v}_i &= \gamma \lambda_i \mathbf{v}_i \\ \mathbf{v}_i &+ \gamma \mathbf{A}\mathbf{v}_i &= \mathbf{v}_i + \gamma \lambda_i \mathbf{v}_i \\ (\mathbf{I} + \gamma \mathbf{A})\mathbf{v}_i &= (1 + \gamma \lambda_i)\mathbf{v}_i \end{aligned}$$

Terminology

Existence of Solution to Bellman Equation

 \S So the largest eigenvalue of \mathcal{P} is 1.

Theorem and its proof

For all eigenvalues λ_i of a square matrix \mathbf{A} and corresponding eigenvectors \mathbf{v}_i such that $\mathbf{A}\mathbf{v}_i = \lambda_i \mathbf{v}_i$,

$$eig(\mathbf{I} + \gamma \mathbf{A}) = 1 + \gamma \lambda_i \ [\gamma \text{ is any scalar}]$$

Proof:

$$\begin{aligned} \mathbf{A}\mathbf{v}_i &= \lambda_i \mathbf{v}_i \\ \gamma \mathbf{A}\mathbf{v}_i &= \gamma \lambda_i \mathbf{v}_i \\ \mathbf{v}_i &+ \gamma \mathbf{A}\mathbf{v}_i &= \mathbf{v}_i + \gamma \lambda_i \mathbf{v}_i \\ (\mathbf{I} + \gamma \mathbf{A})\mathbf{v}_i &= (1 + \gamma \lambda_i) \mathbf{v}_i \end{aligned}$$

§ So the smallest eigenvalue of $(\mathbf{I} - \gamma \mathcal{P})$ is $1 - \gamma$. For $\gamma < 1$ which is > 0. And hence, $(\mathbf{I} - \gamma \mathcal{P})$ is invertible.

Terminology

Markov Decision Process

A Markov decision process is a Markov reward process with actions.

Definition

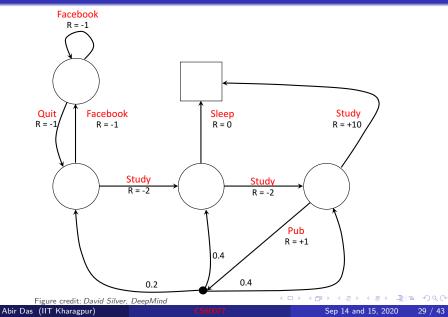
A Markov Decision Process is a tuple $\langle S, \mathcal{A}, \mathcal{P}, \mathcal{R}, \gamma \rangle$, where

- $\S \ \mathcal{S}$ is the state space (can be continuous or discrete)
- $\S~\mathcal{A}$ is the action space (can be continuous or discrete)
- § \mathcal{P} is the state transition probability matrix. $\mathcal{P}_{ss'}^{a} = P(S_{t+1} = s' | S_t = s, A_t = a) = p(s'/s, a)$ § \mathcal{R} is a reward function, $\mathcal{R} = \mathbb{E}[R_{t+1}|S_t = s, A_t = a] = R(s, a)$
- $\S~\gamma$ is a discount factor, $\gamma\inig[0,1ig]$

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Terminology

Example: Student MDP



Policy

Definition

A policy π is a distribution over actions given states,

$$\pi(a/s) = P[A_t = a | S_t = s]$$

- § The Markov property means the policy depends on the current state (not the history)
- § The policy can be either deterministic or stochastic
- § The policy can be either stationary or non-stationary

Terminology

Markov Decision Process

Policy

- § For a deterministic environment p(s'/s, a) = 1, else for stochastic environment $0 \le p(s'/s, a) \le 1$
- \S In a stochastic environment, there is always some chance to end up in s' starting from state s and taking any action.



- § So, probability of ending up in state s' from s irrespective of the action (*i.e.*, taking any action according to the policy), = probability of taking action 1 from state $s \times$ probability of ending up in state s' taking action 1 + probability of taking action 2 from state $s \times$ probability of ending up in state s' taking action 2 + \cdots
- § This means $p_{\pi}(s'|s) = \sum_{a} \pi(a|s)p(s'|s,a)$
- § Similarly, the one-step expected reward for following policy π is given by $r_{\pi}(s) = \sum_{a} \pi(a|s)r(s,a)$

§ Side note: The above is given by $r_{\pi}(s) = \sum_{a} \pi(a|s) \sum_{s'} p(s'|s, a) r(s, a, s')$ when reward is a function of the transiting state s'_{π} also, we have $s \in \mathbb{R}$

Markov Decision Process

Value Functions

Definition

The state-value function $v_{\pi}(s)$ of an MDP is the expected return starting from state s, and then following policy π

$$v_{\pi}(s) = \mathbb{E}_{\pi} \big[G_t | S_t = s \big] \tag{4}$$

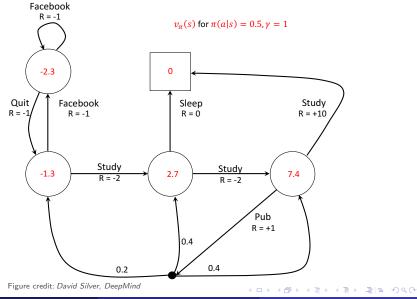
Definition

The *action-value* function $q_{\pi}(s, a)$ of an MDP is the expected return starting from state s, taking action a, and then following policy π

$$q_{\pi}(s,a) = \mathbb{E}_{\pi} \big[G_t | S_t = s, A_t = a \big]$$
(5)

Terminology

Example: State-Value function for Student MDP

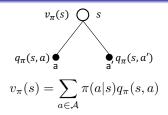


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Markov Decision Process

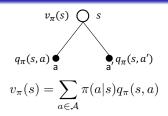
Relation between v_{π} and q_{π}

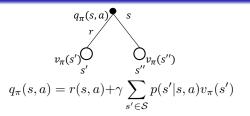


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Relation between v_{π} and q_{π}

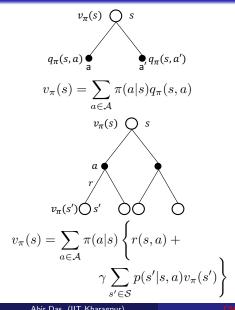


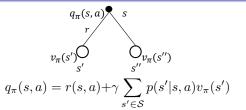


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Relation between v_{π} and q_{π}

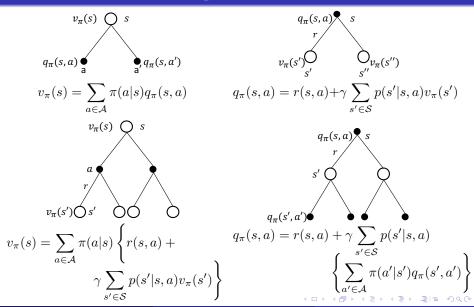




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Markov Decision Process

Relation between v_{π} and q_{π}



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Bellman Expectation Equations

Like MRPs, the value function can be decomposed into two parts - immediate reward r(s) and the discounted value of successor state $\gamma v(s')$. But, as action is involved in MDP, the form is a little different.

$$\begin{aligned} v_{\pi}(s) &= \sum_{a \in \mathcal{A}} \pi(a|s) \sum_{s' \in \mathcal{S}} p(s'|s, a) \left\{ r(s, a, s') + \gamma v_{\pi}(s') \right\} \\ \text{[when } r \text{ is a function of } s, a, s'] \\ &= \sum_{a \in \mathcal{A}} \pi(a|s) \left\{ r(s, a) + \gamma \sum_{s' \in \mathcal{S}} p(s'|s, a) v_{\pi}(s') \right\} \\ \text{[when } r \text{ is a function of } s, a] \\ &= r(s) + \gamma \sum_{a \in \mathcal{A}} \pi(a|s) \sum_{s' \in \mathcal{S}} p(s'|s, a) v_{\pi}(s') \\ \text{[when } r \text{ is a function of } s] \end{aligned}$$

(6)

Terminology

Bellman Expectation Equations

$$\begin{split} q_{\pi}(s,a) &= \mathbb{E}_{\pi} \left[G_t | S_t = s, a_t = a \right] \text{ [eqn. 3.13 in SB]} \\ &= \mathbb{E}_{\pi} \left[r_{t+1} + \gamma r_{t+2} + \gamma^2 r_{t+3} ... | S_t = s, a_t = a \right] \\ &= \mathbb{E}_{\pi} \left[r_{t+1} + \gamma (r_{t+2} + \gamma r_{t+3} ...) | S_t = s, a_t = a \right] \\ &= \mathbb{E}_{\pi} \left[r_{t+1} + \gamma G_{t+1} | S_t = s, a_t = a \right] \text{ [By definition, eqn. 3.11 in SB]} \\ &= \mathbb{E}_{\pi} \left[r_{t+1} | S_t = s, a_t = a \right] + \gamma \mathbb{E}_{\pi} \left[G_{t+1} | S_t = s, a_t = a \right] \end{split}$$

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Bellman Expectation Equations

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Bellman Expectation Equations

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Terminology

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Terminology

Bellman Expectation Equations

$$\begin{split} q_{\pi}(s,a) &= \mathbb{E}_{\pi} \left[G_{t} | S_{t} = s, a_{t} = a \right] \quad [\text{eqn. 3.13 in SB}] \\ &= \mathbb{E}_{\pi} \left[r_{t+1} + \gamma r_{t+2} + \gamma^{2} r_{t+3} \dots | S_{t} = s, a_{t} = a \right] \\ &= \mathbb{E}_{\pi} \left[r_{t+1} + \gamma (r_{t+2} + \gamma r_{t+3} \dots) | S_{t} = s, a_{t} = a \right] \\ &= \mathbb{E}_{\pi} \left[r_{t+1} + \gamma G_{t+1} | S_{t} = s, a_{t} = a \right] \quad [\text{By definition, eqn. 3.11 in SB}] \\ &= \mathbb{E}_{\pi} \left[r_{t+1} | S_{t} = s, a_{t} = a \right] + \gamma \mathbb{E}_{\pi} \left[G_{t+1} | S_{t} = s, a_{t} = a \right] \\ &= \mathbb{E}_{\pi} \left[r_{t+1} | S_{t} = s, a_{t} = a \right] + \gamma \mathbb{E}_{\pi} \left[\mathbb{E}_{\pi} \left[G_{t+1} | S_{t} = s, a_{t} = a \right] + \gamma \mathbb{E}_{\pi} \left[\mathbb{E}_{\pi} \left[G_{t+1} | S_{t} = s, a_{t} = a \right] + \mathbb{E} \left[\mathbb{E} \left[Y | X, Z \right] | X \right] \right) \\ & \text{[Get the intuition behind the formula in this youtube link]} \\ &= \mathbb{E}_{\pi} \left[r_{t+1} | S_{t} = s, a_{t} = a \right] + \gamma \mathbb{E}_{\pi} \left[\mathbb{E}_{\pi} \left[G_{t+1} | S_{t+1} = s', a_{t+1} = a' \right] | S_{t} = s, a_{t} = a \right] \\ & \left[G_{t+1} \text{depends only on } s_{t+1} \text{ and } a_{t+1} \right] \\ &= \mathbb{E}_{\pi} \left[r_{t+1} | S_{t} = s, a_{t} = a \right] + \gamma \mathbb{E}_{\pi} \left[q_{\pi}(s', a') | S_{t} = s, a_{t} = a \right] \end{aligned} \right] \\ \end{aligned}$$

Terminology

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Terminology

Bellman Expectation Equations

$$= r(s,a) + \sum_{s' \in \mathcal{S}} \sum_{a' \in \mathcal{A}} q_{\pi}(s',a') p(a',s'|s,a)$$

$$= r(s,a) + \sum_{s' \in \mathcal{S}} \sum_{a' \in \mathcal{A}} q_{\pi}(s',a') p(a'|s',s,a) p(s'|s,a)$$

$$= r(s,a) + \sum_{s' \in \mathcal{S}} \sum_{a' \in \mathcal{A}} q_{\pi}(s',a') p(a'|s') p(s'|s,a) \text{ [Markov property]}$$

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Terminology

Bellman Expectation Equations

$$= r(s, a) + \sum_{s' \in S} \sum_{a' \in A} q_{\pi}(s', a') p(a', s'|s, a)$$

= $r(s, a) + \sum_{s' \in S} \sum_{a' \in A} q_{\pi}(s', a') p(a'|s', s, a) p(s'|s, a)$
= $r(s, a) + \sum_{s' \in S} \sum_{a' \in A} q_{\pi}(s', a') p(a'|s') p(s'|s, a)$ [Markov property]
= $r(s, a) + \sum_{s' \in S} p(s'|s, a) \sum_{a' \in A} q_{\pi}(s', a') p(a'|s')$

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Terminology

Bellman Expectation Equations

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Terminology

Bellman Expectation Equations

$$\begin{split} &= r(s,a) + \sum_{s' \in \mathcal{S}} \sum_{a' \in \mathcal{A}} q_{\pi}(s',a') p(a',s'|s,a) \\ &= r(s,a) + \sum_{s' \in \mathcal{S}} \sum_{a' \in \mathcal{A}} q_{\pi}(s',a') p(a'|s',s,a) p(s'|s,a) \\ &= r(s,a) + \sum_{s' \in \mathcal{S}} \sum_{a' \in \mathcal{A}} q_{\pi}(s',a') p(a'|s') p(s'|s,a) \text{ [Markov property]} \\ &= r(s,a) + \sum_{s' \in \mathcal{S}} p(s'|s,a) \sum_{a' \in \mathcal{A}} q_{\pi}(s',a') p(a'|s') \end{split}$$

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Agenda Terminology 00 Bellman Expectation Equation for Student MDP Facebook $v_{\pi}(s)$ for $\pi(a|s) = 0.5, \gamma = 1$ R = -1 $v_{\pi}(s) = \sum \pi(a|s) \left\{ r(s, a) + \gamma \sum_{s \in T} p(s'|s, a)v_{\pi}(s') \right\}$ $7.4 = 0.5^{10+0} + 0.5^{11+1^{-0.2^{1.3+0.4^{2.7+0.4^{7.4}}}$ -2.3 0 Quit Facebook Study Sleep R = -1 R = -1R = 0R = +10

Study

R = -2

7.4

Pub R = +1

Study

R = -2

0.2

-1.3

Figure credit: David Silver, DeepMind

0.4

0.4

2.7

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Optimal Policies and Optimal Value Functions

- § Solving a reinforcement learning task means, roughly, finding a policy that achieves a lot of reward (*maximum*) over the long run.
- § The notion of maximality leads to *optimality* in MDPs.

Optimal Policies and Optimal Value Functions

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Optimal Policies and Optimal Value Functions

- § Solving a reinforcement learning task means, roughly, finding a policy that achieves a lot of reward (*maximum*) over the long run.
- § The notion of maximality leads to *optimality* in MDPs.
- § What is meant by a policy is better than some other policy?
- § A policy π is defined to be better than or equal to a policy π' if its expected return is greater than or equal to that of π' for all states.

Definition

$$\pi \geq \pi' \text{ iff } v_{\pi}(s) \geq v_{\pi'}(s), \, \forall s \in \mathcal{S}$$

Optimal Policies and Optimal Value Functions

Definition

The *optimal* state-value function $v_*(s)$ is the maximum state-value function over all policies

$$v_*(s) = \max_{\pi} v_{\pi}(s), \, \forall s \in \mathcal{S}$$

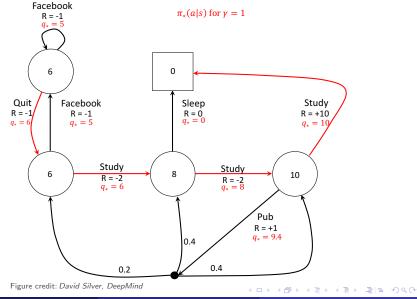
The *optimal* action-value function $q_*(s, a)$ is the maximum action-value function over all policies

$$q_*(s,a) = \max_{\pi} q_{\pi}(s,a), \, \forall s \in \mathcal{S} \text{ and }, \, \forall a \in \mathcal{A}$$

§ An MDP is "solved" when we know the optimal value function

Terminology

Optimal Action-Value Function for Student MDP



Optimal Policy

Theorem

For any Markov Decision Process

- § There exists an optimal policy π_* that is better than or equal to all other policies, $\pi_* \ge \pi$, $\forall \pi$
- § All optimal policies achieve the optimal value function $v_{\pi_*}(s) = v_*(s)$
- § All optimal policies achieve the optimal action-value function

$$q_{\pi_*}(s,a) = q_*(s,a)$$

Optimal Policy

Theorem

For any Markov Decision Process

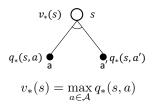
- § There exists an optimal policy π_* that is better than or equal to all other policies, $\pi_* \ge \pi$, $\forall \pi$
- § All optimal policies achieve the optimal value function $v_{\pi_*}(s) = v_*(s)$
- $\$ All optimal policies achieve the optimal action-value function $q_{\pi_*}(s,a)=q_*(s,a)$

An optimal policy can be found by maximising over $q_*(s, a)$.

$$\pi_*(a|s) = \begin{cases} 1 & \text{if } a = \operatorname*{arg\,max}_{a \in \mathcal{A}} q_*(s,a) \\ 0 & \text{otherwise} \end{cases}$$

§ There is always a deterministic optimal policy for any MDP. § If we know $q_*(s, a)$, we immediately have the optimal policy. Agenda Terminology 00

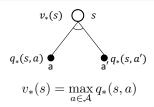
Relation between v_* and q_*

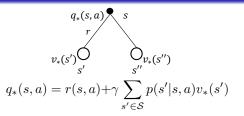


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Relation between v_* and q_*

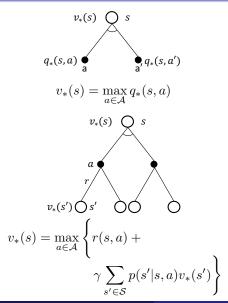




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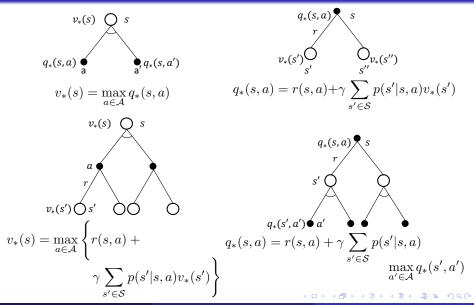
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Relation between v_* and q_*





Relation between v_* and q_*



Abir Das (IIT Kharagpur)

Appendices

Appendices

Abir Das (IIT Kharagpur)

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1. Independence

Independence

$$A \bot\!\!\!\bot B \implies P(A|B) = P(A)$$

Conditional Independence

$$A \bot\!\!\!\bot B | C \implies P(A|B,C) = P(A|C)$$

Proof:

$$P(A|B,C) = \frac{P(A,B,C)}{P(B,C)} = \frac{P(A,B|C)P(C)}{P(B|C)P(C)}$$

$$= \frac{P(A|C)P(B|C)}{P(B|C)} [$$
 From definition of conditional independence]
$$= P(A|C)$$

$$(7)$$

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2. Independence

Theorem

Eigenvalues of the transpose A^T are the same as the eigenvalues of A

Proof

Eigenvalues of a matrix are roots of its characteristic polynomial. Hence if the matrices A and A^T have the same characteristic polynomial, then they have the same eigenvalues.

$$det(A^T - \lambda I) = det(A^T - \lambda I^T)$$

$$= det(A - \lambda I)^T$$

$$= det(A - \lambda I)$$
 [Since $det(A) = det(A^T)$] (8)