Markov Decision Processes

CS60077: Reinforcement Learning

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IIT Kharagpur

July 26, Aug 01, 02, 08, 2019

Agenda

- 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

Terminology and Notation

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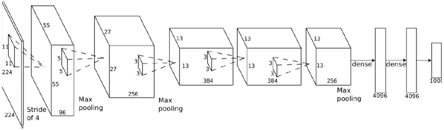

$\pi_\theta(\mathbf{a}|\mathbf{o})$

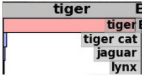

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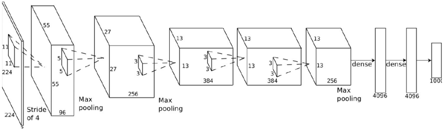
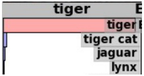
Figure credit: *S. Levine - CS 294-112 Course, UC Berkeley*

Terminology and Notation

$\mathbf{o}_t$



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



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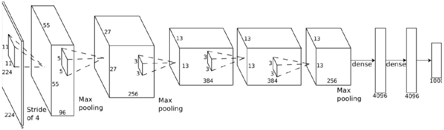

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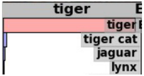

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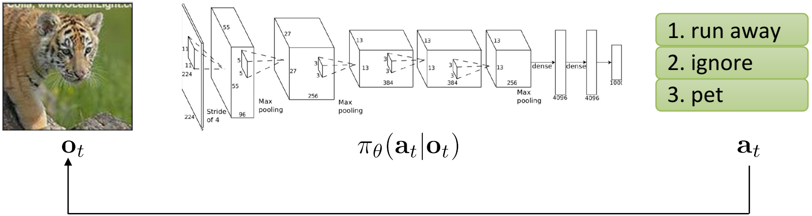

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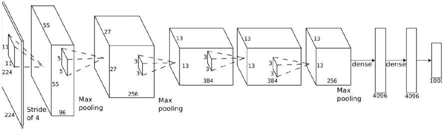

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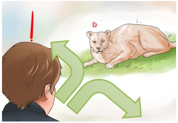

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Terminology and Notation

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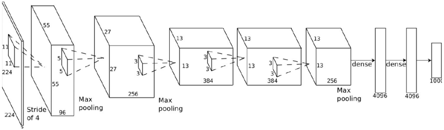

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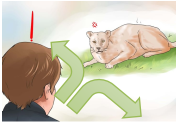

$\mathbf{a}_t$

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

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

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Terminology and Notation

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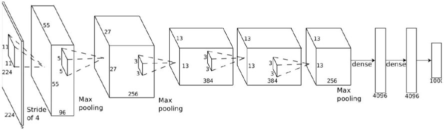

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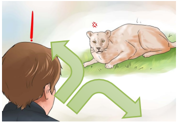

$\mathbf{a}_t$

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

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

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

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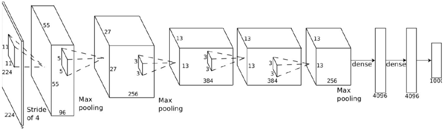

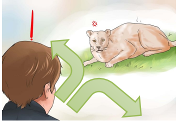

$\mathbf{o}_t$ $\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$ $\mathbf{a}_t$

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$\mathbf{o}_t$ – observation

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Terminology and Notation

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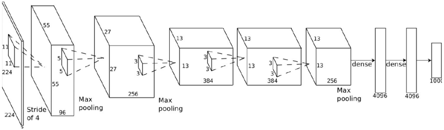
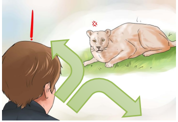


$\pi_\theta(\mathbf{a}_t|\mathbf{o}_t)$



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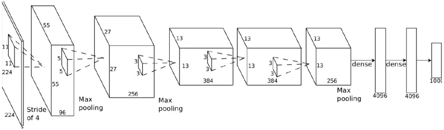

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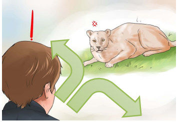

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$\mathbf{s}_t$ – state

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Markov Property

The future is independent of the past given the present.

Andrey Markov

Definition

A state S_t is Markov if and only if

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

- 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

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

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

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

Markov Chain

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

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

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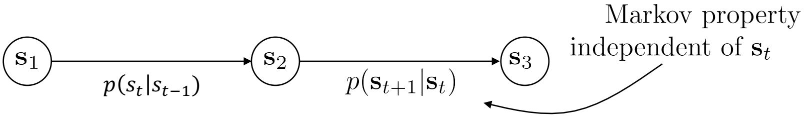

Student Markov Process

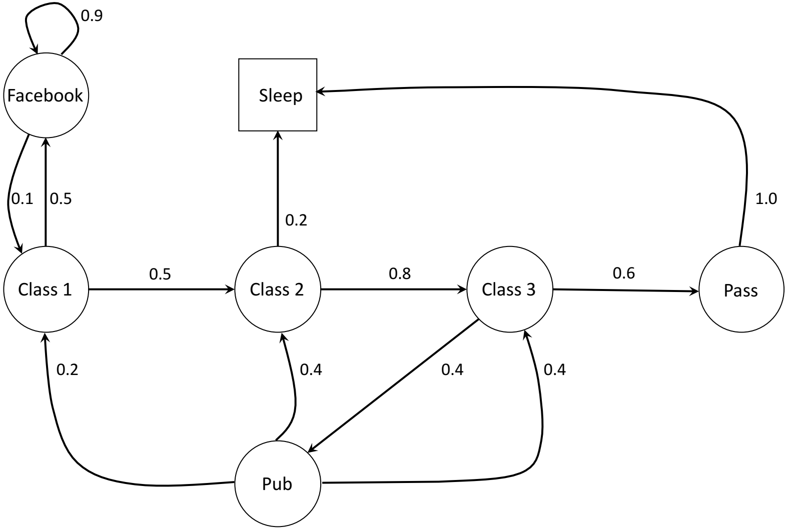

Figure credit: *David Silver, DeepMind*

Student Markov Process - Episodes

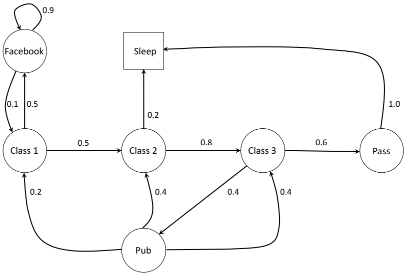

Figure credit: *David Silver, DeepMind*

Sample episodes for Student Markov process starting from $S_1 = \text{C1}$

- 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

Student Markov Process - Transition Matrix

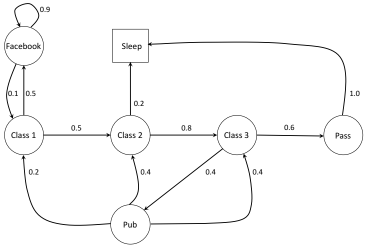

Figure credit: *David Silver, DeepMind*

$$
\begin{array}{cc}
 & \begin{array}{ccccccc} C1 & C2 & C3 & Pass & Pub & FB & Sleep \end{array} \\
\begin{array}{c} C1 \\ C2 \\ C3 \\ Pass \\ Pub \\ FB \\ Sleep \end{array} &
\begin{bmatrix}
 & 0.5 & & & 0.5 & & \\
 & & 0.8 & & & & 0.2 \\
 & & & 0.6 & 0.4 & & \\
 & & & & & & 1.0 \\
0.2 & 0.4 & 0.4 & & & & \\
0.1 & & & & & 0.9 & \\
 & & & & & & 1.0
\end{bmatrix}
\end{array}
$$

Markov Reward Process

A Markov reward process is a Markov process with rewards.

Definition

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

- § $\mathcal{S}$ 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, $\mathcal{R} = \mathbb{E}\big[R_{t+1} | S_t = s\big] = R(s)$
- § γ is a discount factor, $\gamma \in \big[0, 1\big]$

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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. The 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

Student Markov Reward Process

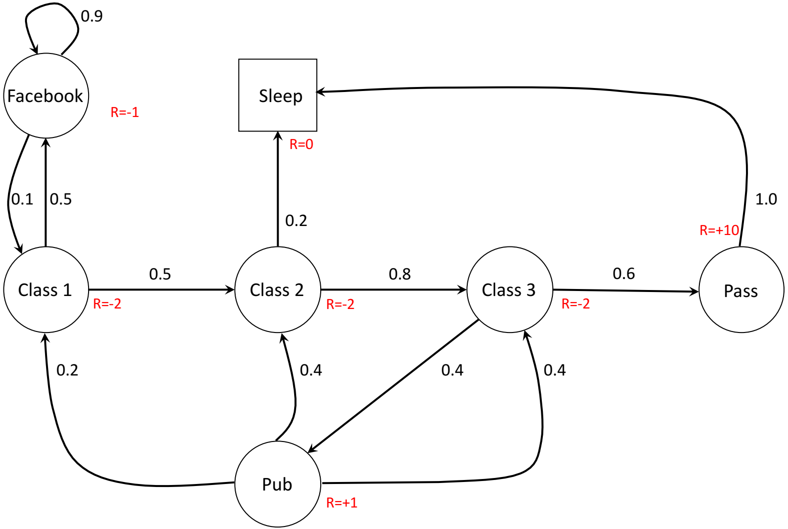

Figure credit: *David Silver, DeepMind*

Return

Definition

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

$$G_t = R_{t+1} + \gamma R_{t+2} + \cdots = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1} \tag{1}$$

- $\gamma \in [0, 1]$ is the discounted present value of the future rewards.
- Immediate rewards are valued above delayed rewards.
  - γ close to 0 leads to "myopic" evaluation.
  - γ close to 1 leads to "far-sighted" evaluation.

Why Discount?

Most Markov reward and decision processes are discounted. Why?

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- § 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. More of it to follow when we discuss Markov Decision Process

Value Function

The value function $v(s)$ gives the long-term value of state s

Definition

The *state value function* $v(s)$ of an MRP is the expected return starting from state s

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

Example Student MRP Returns

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

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

- 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

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

State-Value Function for Student MRP (1)

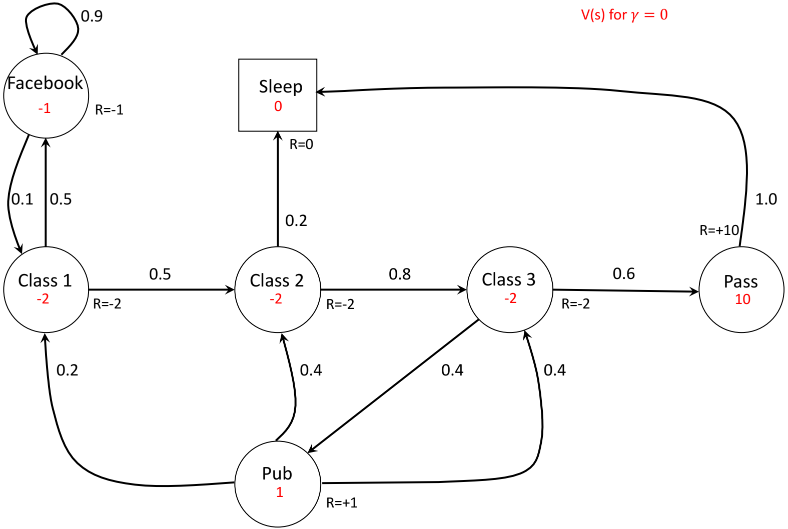
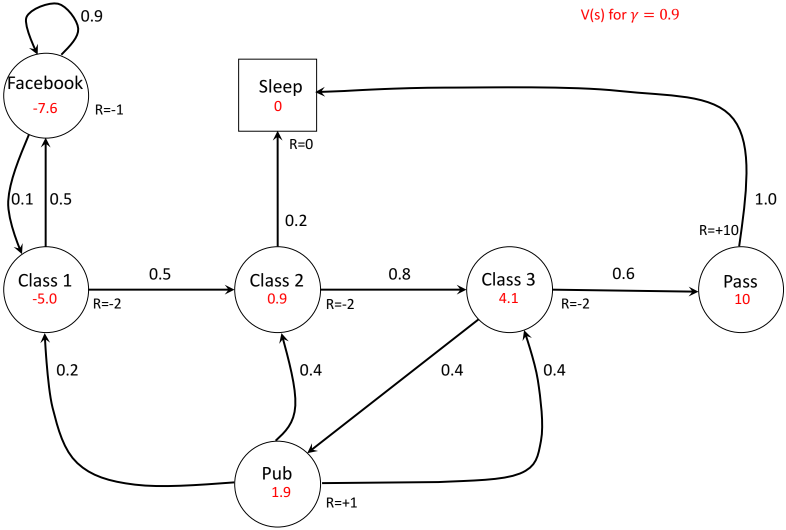


Figure credit: *David Silver, DeepMind*

State-Value Function for Student MRP (2)



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State-Value Function for Student MRP (3)

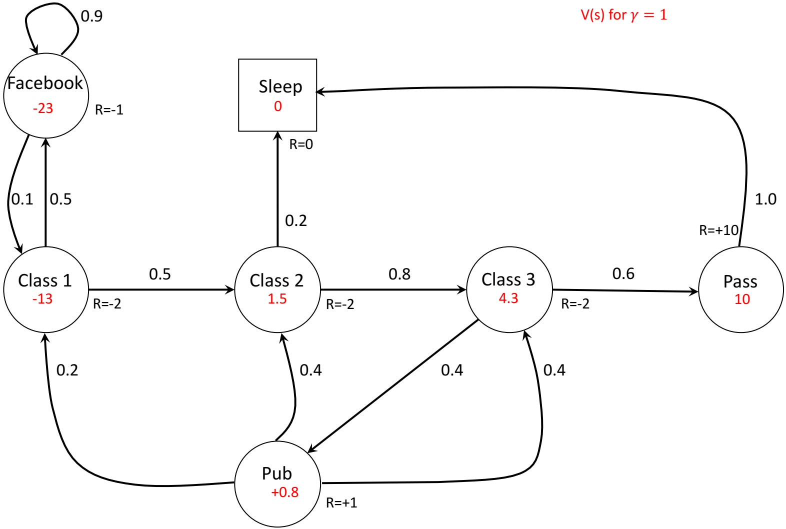

Figure credit: *David Silver, DeepMind*

Bellman Equation for MRPs

The value function can be decomposed into two parts:

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

$$
\begin{aligned}
v(s) &= R(s) + \gamma \mathbb{E}_{s' \in \mathcal{S}} \big[v(s') \big] \\
&= R(s) + \gamma \sum_{s' \in \mathcal{S}} \mathcal{P}_{ss'} v(s')
\end{aligned} \tag{3}
$$

Richard Bellman

Bellman Equation for MRPs

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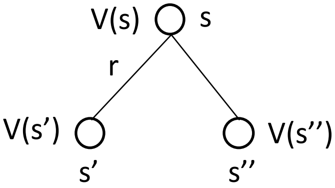
Richard Bellman



Bellman Equation for MRPs - Proof

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

Bellman Equation for MRPs - Proof

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&= \mathbb{E}\big[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}) + \cdots |S_t = s\big]
\end{aligned}
$$

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&= \mathbb{E}\big[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}) + \cdots |S_t = s\big] \\
&= \sum_{S_{t+1}, S_{t+2}, \cdots} \Big(P(S_{t+1}, S_{t+2}, \cdots |S_t = s)\big[R_{t+1}(S_t) + \gamma R_{t+2}(S_{t+1}) + \\
&\qquad\qquad \gamma^2 R_{t+3}(S_{t+2}) + \gamma^3 R_{t+4}(S_{t+3}) + \cdots\big]\Big)
\end{aligned}
$$

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v(s) &= \mathbb{E}\big[G_t|S_t = s\big] = \mathbb{E}\big[R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \gamma^3 R_{t+4} + \cdots |S_t = s\big] \\
&= \mathbb{E}\big[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}) + \cdots |S_t = s\big] \\
&= \sum_{S_{t+1}, S_{t+2}, \cdots} \Big(P(S_{t+1}, S_{t+2}, \cdots |S_t = s)\big[R_{t+1}(S_t) + \gamma R_{t+2}(S_{t+1}) + \\
&\qquad\qquad \gamma^2 R_{t+3}(S_{t+2}) + \gamma^3 R_{t+4}(S_{t+3}) + \cdots\big]\Big) \\
&= \sum_{S_{t+1}, S_{t+2}, \cdots} P(S_{t+1}, S_{t+2}, \cdots |S_t = s) R_{t+1}(S_t) + \\
&\qquad \gamma \sum_{S_{t+1}, S_{t+2}, \cdots} \Big(P(S_{t+1}, S_{t+2}, \cdots |S_t = s)\big[R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \\
&\qquad\qquad \gamma^2 R_{t+4}(S_{t+3}) + \cdots\big]\Big)
\end{aligned}
$$

Bellman Equation for MRPs - Proof

$$= R_{t+1}(S_t) \sum_{S_{t+1}, S_{t+2}, \cdots} P(S_{t+1}, S_{t+2}, \cdots | S_t = s) +$$

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

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

Bellman Equation for MRPs - Proof

$$
\begin{aligned}
&= R_{t+1}(S_t) \underbrace{\sum_{S_{t+1},S_{t+2},\cdots} P(S_{t+1}, S_{t+2}, \cdots | S_t = s)}_{1} + \\
&\quad \gamma \sum_{S_{t+1},S_{t+2},\cdots} \Big(P(S_{t+1}, S_{t+2}, \cdots | S_t = s) \big[R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \\
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&= R_{t+1}(S_t) + \gamma \sum_{S_{t+1},S_{t+2},\cdots} \Big(P(S_{t+1}, S_{t+2}, \cdots | S_t = s) \big[R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \\
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\end{aligned}
$$

Bellman Equation for MRPs - Proof

$$
\begin{aligned}
&= R_{t+1}(S_t) \cancelto{1}{\sum_{S_{t+1}, S_{t+2}, \cdots} P(S_{t+1}, S_{t+2}, \cdots | S_t = s)} + \\
&\quad \gamma \sum_{S_{t+1}, S_{t+2}, \cdots} \Big(P(S_{t+1}, S_{t+2}, \cdots | S_t = s) \big[R_{t+2}(S_{t+1}) + \gamma R_{t+3}(S_{t+2}) + \\
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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.

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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.

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

Solving Bellman Equation

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

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

- 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.

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

Proof

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 contradiction and so $\lambda > 1$ is not possible.

Existence of Solution to Bellman Equation

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

Existence of Solution to Bellman Equation

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Theorem and its proof

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

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

Proof:

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

Existence of Solution to Bellman Equation

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

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

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

Markov Decision Process

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

Definition

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

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

Example: Student MDP

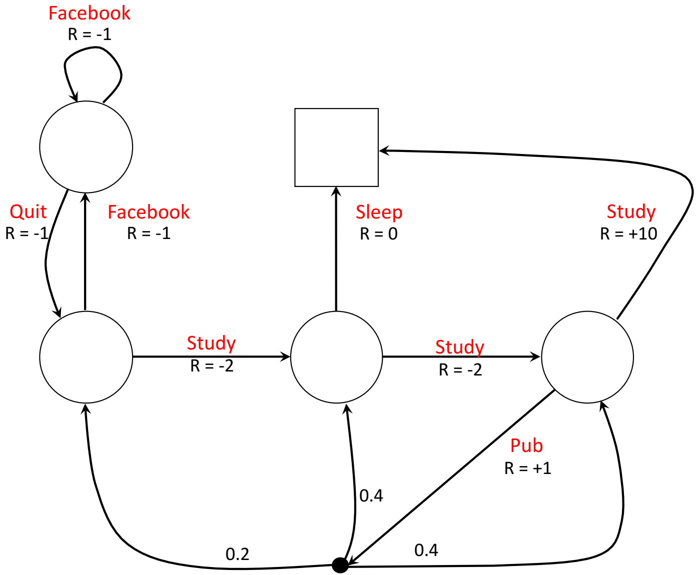


Figure credit: *David Silver, DeepMind*

Policy

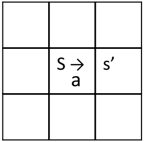
Definition

A *policy* π is a distribution over actions given states,

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

- 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

Policy



- For a deterministic environment $p(s'/s,a) = 1$, else for stochastic environment $0 \leq p(s'/s,a) \leq 1$
- 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 $p_\pi(s'|s) = \sum\limits_a \pi(a|s)p(s'|s,a)$
- Similarly, the one-step expected reward for following policy π is given by $r_\pi(s) = \sum\limits_a \pi(a|s)r(s,a)$
- Side note: The above is given by $r_\pi(s) = \sum\limits_a \pi(a|s) \sum\limits_{s'} p(s'|s,a)r(s,a,s')$ when reward is a function of the transiting state s' also.

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

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

Example: State-Value function for Student MDP

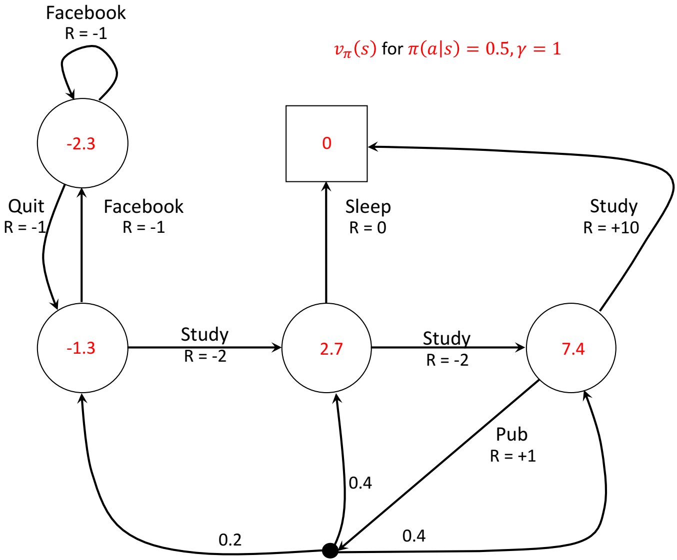
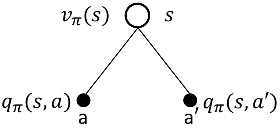


Figure credit: *David Silver, DeepMind*

Relation between v_π and q_π



$$v_\pi(s) = \sum_{a \in \mathcal{A}} \pi(a|s) q_\pi(s,a)$$

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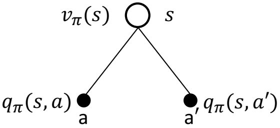

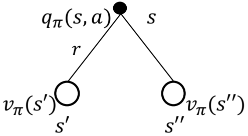

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$$q_\pi(s,a) = r(s,a) + \gamma \sum_{s' \in \mathcal{S}} p(s'|s,a) v_\pi(s')$$

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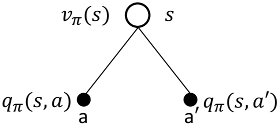

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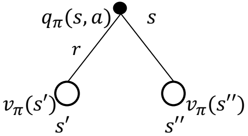

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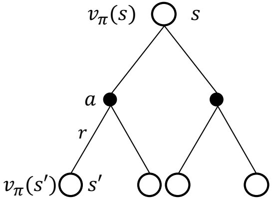

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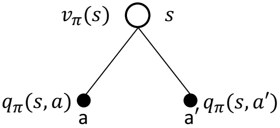

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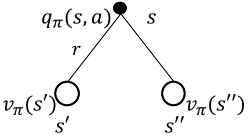

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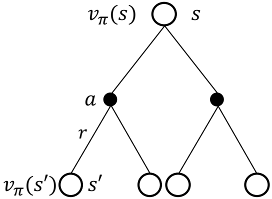

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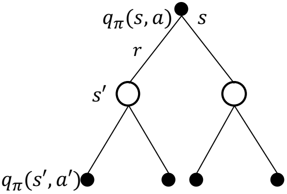

$$q_\pi(s,a) = r(s,a) + \gamma \sum_{s' \in \mathcal{S}} p(s'|s,a) \left\{ \sum_{a' \in \mathcal{A}} \pi(a'|s') q_\pi(s',a') \right\}$$

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.

$$\begin{aligned} v_\pi(s) &= \sum_{a\in\mathcal{A}} \pi(a|s) \sum_{s'\in\mathcal{S}} p(s'|s,a) \left\{ r(s,a,s') + \gamma v_\pi(s') \right\} \\ &\quad \text{[when } r \text{ is a function of } s,a,s'\text{]} \\ &= \sum_{a\in\mathcal{A}} \pi(a|s) \left\{ r(s,a) + \gamma \sum_{s'\in\mathcal{S}} p(s'|s,a) v_\pi(s') \right\} \\ &\quad \text{[when } r \text{ is a function of } s,a\text{]} \\ &= r(s) + \gamma \sum_{a\in\mathcal{A}} \pi(a|s) \sum_{s'\in\mathcal{S}} p(s'|s,a) v_\pi(s') \\ &\quad \text{[when } r \text{ is a function of } s\text{]} \end{aligned} \tag{6}$$

Bellman Expectation Equations

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(Above applies the formula $\mathbb{E}[Y|X] = \mathbb{E}[\mathbb{E}[Y|X,Z]|X]$)

[Get the intuition behind the formula in this youtube link]

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\end{aligned}
$$

Bellman Expectation Equation for Student MDP

$v_\pi(s)$ for $\pi(a|s) = 0.5, \gamma = 1$

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

7.4 = 0.5*{10+0} + 0.5*{1+1*(-0.2*1.3+0.4*2.7+0.4*7.4)}

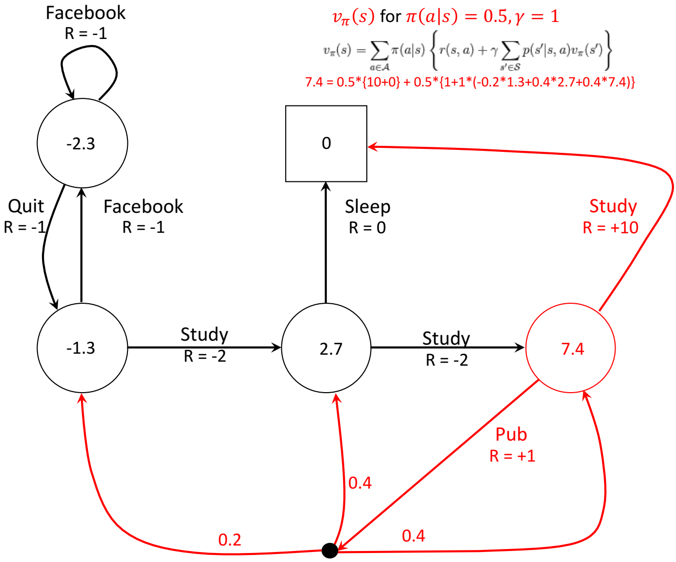

Figure credit: *David Silver, DeepMind*

Optimal Policies and Optimal Value Functions

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- 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

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

Optimal Policies and Optimal Value Functions

Definition

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

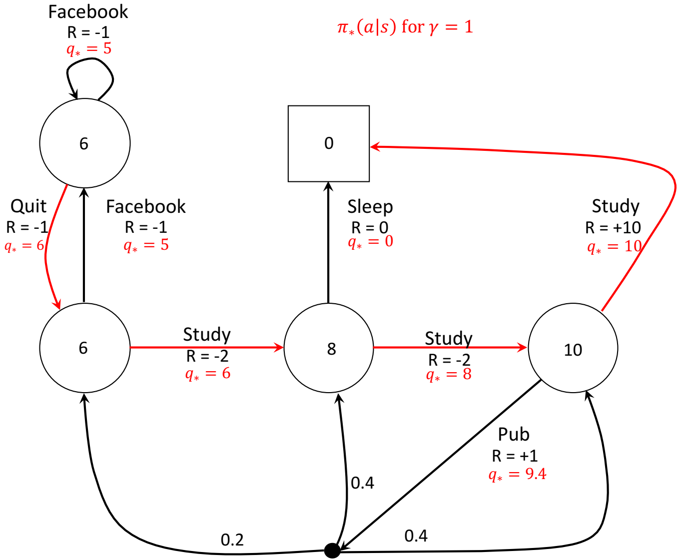
$$v_*(s) = \max_{\pi} v_\pi(s), \, \forall s \in \mathcal{S}$$

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

Optimal Action-Value Function for Student MDP



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Optimal Policy

Theorem

For any Markov Decision Process

- There exists an optimal policy π_* that is better than or equal to all other policies, $\pi_* \geq \pi, \forall\pi$
- All optimal policies achieve the optimal value function $v_{\pi_*}(s) = v_*(s)$
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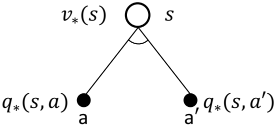
An optimal policy can be found by maximising over $q_*(s, a)$.

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

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

Relation between v_* and q_*



$$v_*(s) = \max_{a \in \mathcal{A}} q_*(s,a)$$

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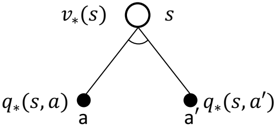

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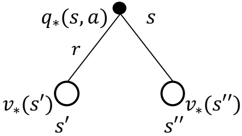

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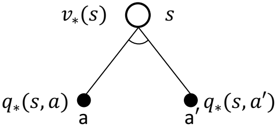

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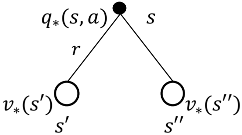

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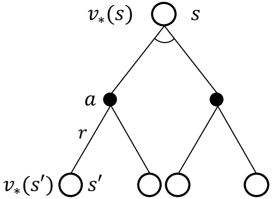

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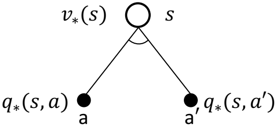

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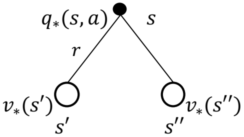

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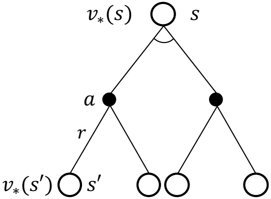

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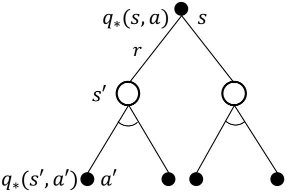

$$q_*(s,a) = r(s,a) + \gamma \sum_{s' \in \mathcal{S}} p(s'|s,a) \max_{a' \in \mathcal{A}} q_*(s',a')$$

Appendices

Appendices

1. Independence

Independence

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

Conditional Independence

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

Proof:

$$\begin{aligned} P(A|B,C) &= \frac{P(A,B,C)}{P(B,C)} = \frac{P(A,B|C)\cancel{P(C)}}{P(B|C)\cancel{P(C)}} \\ &= \frac{P(A|C)P(B|C)}{P(B|C)} [\text{ From definition of conditional independence}] \\ &= P(A|C) \end{aligned} \tag{7}$$

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.

$$\begin{aligned} \det(A^T - \lambda I) &= \det(A^T - \lambda I^T) \\ &= \det(A - \lambda I)^T \\ &= \det(A - \lambda I) \ \ [\text{Since } \det(A) = \det(A^T)] \end{aligned} \tag{8}$$