Reinforcement Learning

11-785, Fall 2019
Defining MDPs, Planning
The story of Flider and Spy

- Flider the spider is at the far corner of the room, and Spy the fly is sleeping happily at the near corner.
The story of Flider and Spy

- Flider only walks along edges
- She begins walking along one of the three edges at random
- She takes one minute to cover the distance from one corner to the other along any edge
- When she arrives at the new corner, she randomly chooses one of the three edges and continues walking (she may even turn back)
The story of Flider and Spy

- What is the life expectancy of Spy?
Let $T_i$ be the life expectancy if Flider is at the $i^{th}$ corner
• $1 + T_i$ is the life expectancy if Flider the Spider begins walking towards the $i$th corner
  – 1 minute to get to the corner plus the time taken to get from that corner to Spy the fly
• 8 Equations, 8 unknowns, trivial to solve

\[
\begin{align*}
T_1 &= \frac{1}{3} (1 + T_2) + \frac{1}{3} (1 + T_3) + \frac{1}{3} (1 + T_4) \\
T_2 &= \frac{1}{3} (1 + T_1) + \frac{1}{3} (1 + T_6) + \frac{1}{3} (1 + T_8) \\
&\vdots \\
T_7 &= \frac{1}{3} (1 + T_8) + \frac{1}{3} (1 + T_6) + \frac{1}{3} (1 + T_5) \\
T_8 &= 0
\end{align*}
\]
• What if the room has many corners?
  – A Fuller’s dome?
SWITCHING GEARS A BIT...
Alpha Go

Deep Blue: 1997

Alpha Go: 2016

• “Learning” to play
  – How?
Problems?

• How do we write a program to beat Magnus Carlsson?

• Can’t just make a table of rules
  – Too many positions, too many combinations

• How about some general principles?
  – Who will enumerate them?
  – How many are there in the first place?

• How do humans do it?
Learning from experience

• Learn by playing (or observing)
  – Problem: The tree of possible moves is exponentially large

• Learn to generalize
  – What do we mean by “generalize”? 
  – If a particular board position always leads to loss, avoid any moves that move you into that position
Lets draw a diagram..

- Circles are game states
  - Exponentially large number of them
  - In the beginning we don’t know if they are good or bad
- Each state can move into one of $N$ states depending on the opponent’s move
  - Figure does not show arrows
Let's draw a diagram..

- Play a very large number of games
  - Each time a board position leads to victory, give it a little green color
  - Each time it leads to a loss give it a little red color
A game we won

• Sequence of game states we moved into until the winning state
  – Alternates with states arrived at by moves by the opponent

• All of these are “winning” states: color them green
A game we won

- Sequence of game states we moved into until the winning state
  - Alternates with states arrived at by moves by the opponent
- All of these are “winning” states: color them green
- But things from the distant past are less certain
  - Too many possibilities; can’t be certain of their “winningness”
  - Fade the green with distance
A game we lost

• Sequence of game states we moved into until the losing state
  – Alternates with states arrived at by moves by the opponent
• All of these are “losing” states: color them red
• But things from the distant past are less certain
  – Too many possibilities; can’t be certain of their “losingness”
  – Fade the red with distance

Loss: final move is by opponent
Continue playing games

• Play many many games
• Some of which you will lose..
Continue playing games

• Play many many games
• Some of which you will lose..
• And some you’ll win..
Continue playing games

- When multiple games visit a state, simply average the colors derived from all visits
  - Some states will get greener
  - Some will get redder
  - Some, that can lead to both victory and loss will become different shades of yellow.
- More in the early stages of the game than during the endgame
Collecting more games...

- You can also learn colors from your opponent’s moves
  - When you win he/she loses and vice versa
- You can learn from others’ games
  - Collections of games by amateurs and experts, of which you can find millions in the books
- To really speed up matters, play with yourself
  - A schizophrenic computer can play thousands of games with itself in the time that it plays with another person
• Eventually, we’ll get many board positions with different shades of green (more winning than losing), red (more losing than winning) or various shades of yellow/green/orange (can go either way)
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• We will also get many “blank” positions that were never visited in all our practice games
  – In fact the *vast majority* of positions will be unvisited!
• Generalization: From the coloured nodes, learn some way of colouring the blank nodes too
  – Which will have some colour between red and green
    • Different nodes will have different colours
• The magic: some function that assigns color to different board positions
  – How do you describe a board position numerically
  – What type of function maps a board position to a color between red and green
GAME TIME

- Black circle: Current position
- Where do we move?
GAME TIME

- Evaluate all our possible moves
  - And all of opponents responses
  - Can evaluate the graph to any depth (compute and memory bound)

- Identify the move that gives the opponent the least chance to win
  - The opponent’s best path leads to a least red state
A little terminology

• Markov Process: Does not matter how you got here, only matters where you are
An interesting class of problems

• Is a move good?
  – You will not know until the end of the game
An interesting class of problems

• Is an investment plan good?
  – You will not know for a while
An interesting class of problems

- Do I
  - Change lane left?
  - Change lane right?
  - Accelerate?
  - Decelerate?
Reward-based problems

• And many others

• Common theme: These are control problems where
  – Your actions beget rewards
    • Win the game
    • Make money
    • Get home sooner
  – But not deterministically
    • A world out there that is not predictable

• From experience of belated rewards, you must learn to act rationally
General cartoon of the world

• Agent operates in an environment
  – Agent may be you..
  – Environment is the game, the market, the road..
General cartoon of the world

- Agent takes actions which affect the environment
General cartoon of the world

- Agent takes actions which affect the environment
- Which changes in a somewhat unpredictable way
Agent takes actions which affect the environment
Which changes in a somewhat unpredictable way
Which affects the agent’s situation
General cartoon of the world

• The agent also receives rewards..
  – Which may be apparent immediately
  – Or not apparent for a very long time
Challenge

• How must the agent behave to maximize its rewards
What the environment “experiences”

- Responds to some action by the agent
  - Changes in response
- Returns some reward (or punishment) to agent
What the Agent sees

• The agent may *observe* something about its environment
  – Sensor readings, images of a game board, stock indices..
• The agent takes actions
• The agent receives rewards

• This is the agent’s world; it must make sense of it
• Again: Agent’s objective → to take the actions that maximize rewards
Let's formalize the problem

• These can be cast as problems of *reinforcement* learning

• **There is no supervisor, only a reward signal**
  – Did you get home sooner
  – Did you win the game
  – Did you make money?

• i.e. nobody telling the agent “you did well”

• **Reward is a scalar** – a single number, may be negative
  – Game was won/lost (binary)
  – Time taken to arrive
  – Amount of money made

• Reward may be delayed
  – Wait till the end of the game!

• Agents actions affect its current and future rewards
  – Must optimize actions for maximum reward
To Maximize Reward

• We can represent the environment as a *process*  
  – A mathematical characterization with a *true* value for its  
    parameters representing the *actual* environment

• The agent must *model* this environment process  
  – Formulate its own model for the environment, which must  
    ideally match the true values as closely as possible  
    • Based only on what it observes

• Agent must formulate winning strategy based on model of  
  environment
Let's formalize the system

• At each time $t$ the agent:
  – Makes an observation $O_t$ of the environment
  – Receives a reward $R_t$
  – Performs an action $A_t$

• At each time $t$ the environment:
  – Receives an action $A_t$
  – Emits a reward $R_{t+1}$
  – Changes and produces an observation $O_{t+1}$
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From the perspective of the Agent

• What the agent perceives..

• The following History:

\[ H_t = O_0, R_0, A_0, O_1, R_1, A_1, \ldots, O_t, R_t \]

• The total history at any time is the sequence of observations, rewards and actions

• We need to model this sequence such that at any time \( t \), the best \( A_t | H_t \) can be chosen
  
  – The Strategy that maximizes total reward \( R_0 + R_1 + \ldots + R_T \)
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Can define a “state”

• Fully captures the “status” of the system
  – E.g., in an automobile: [position, velocity, acceleration]
  – In traffic: the position, velocity, acceleration of every vehicle on the road
  – In Chess: the state of the board + whose turn it is next
The state of the environment

- The environment’s state!
  - This is what will finally decide the rewards
- May be a complex combination of many things
- Generally assumed to be dynamic – keeps changing
- The agent’s actions can affect the way in which it responds
  - But agent may not be able to observe all of it
Markov property

- Markov Property: A well-defined state fully captures all information needed to predict the future
  - No additional information from the past required

\[ P(S_{t+1}|S_0, S_1, ..., S_t) = P(S_{t+1}|S_t) \]

- The environment’s future only depends on its present
A brief trip to Nostalgia..

• Glider, Flider’s brother, never turns around during his wanderings
  – On arriving at any corner, he chooses one of the two “forward” paths randomly.
    • The future possibilities depend on the edge he arrived from
  – Is he Markovian?
Any causal system can be viewed as Markov, with appropriately defined state

- The *Information state* $S_t$ may differ from the *apparent* state $s_t$
- Defining $S_t = s_1, s_2, ..., s_t$
- $P(S_{t+1}|S_0, S_1, ..., S_t) = P(S_{t+1}|S_t)$
Markov property

- **Assumption:** The *true* environment state is Markov

\[
P(S_{t+1}|S_0, S_1, ..., S_t) = P(S_{t+1}|S_t)
\]

- The environment’s future only depends on its present
Markov property

- To be able to maximize his reward, the agent must ideally know all about the environment state and its dynamics.
To Maximize Reward

• We can represent the environment as a *process*
  – A mathematical characterization with a *true* value for its parameters representing the *actual* environment

• The agent must *model* this environment process
  – Formulate its own model for the environment, which must ideally match the true values as closely as possible
    • Based only on what it observes

• Agent must formulate winning strategy based on model of environment
The Agent’s Side of the Story

- Agent has an internal representation of the environment state
  - May not match the true one at all

- May be defined in any manner
  - Formally the agent state $S_t = f(H_t)$ is some function of the history
  - The closer the agent’s model is to the true environment state, the better the agent will be able to strategize
Defining Agent State

• What is the outcome?
Defining Agent State

• Different definitions of state result in different predictions
• *True* environment state not really known
  – Would greatly improve prediction if known
Markov property and observability

• **Environment state is Markov**
  – An assumption that is generally valid for a properly defined *true* environment (information) state
    \[ P(S_{t+1}|S_0, S_1, ..., S_t) = P(S_{t+1}|S_t) \]

• In theory, if the agent *doesn’t* observe the environment’s internals, he *cannot* model what he observes of the environment as Markov!
  – Amazing, but trivial result
  – E.g. the observations generated by an HMM are not Markov

• In practice, the agent may assume anything
  – The agent may only have a local model of the true state of the system
    • But can still assume that the states in its model behave in the same Markovian way that the environment’s actual states do
Markov property and observability

- **Observability**
  - The agent’s observations inform it about the environment state
  - The agent may observe the *entire* environment state
    - Now the agent's state is isomorphic to the environment state
    - Note – observing the state is not the same as knowing the state’s true dynamics $P(S_{t+1} = s_j | S_t = s_i)$
      - Markov Decision Process
  - Or only *part* of it
    - E.g. only seeing some stock prices, or only the traffic immediately in front of you
    - Partially Observable Markov Decision Process
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      - Markov Decision Process
  - Or only *part* of it
    - E.g. only seeing some stock prices, or only the traffic immediately in front of you
    - **Partially Observable Markov Decision Process**
The World as we model It

• Definition of Markov property:
  – The state of the system has a Markov property if the future only depends on the present
  \[ P(S_{t+1}|S_0, S_1, \ldots, S_t) = P(S_{t+1}|S_t) \]

• States can be defined to have this property
A Markov Process

- A Markov process is a random process where the future is only determined by the present
  - Memoryless

- Is fully defined by the set of states $\mathcal{S}$, and the state transition probabilities $P(s_i \mid s_j)$
  - Formally, the tuple $M = \langle \mathcal{S}, \mathcal{P} \rangle$.
  - $\mathcal{S}$ is the (possibly finite) set of states
  - $\mathcal{P}$ is the complete set of transition probabilities $P(s \mid s')$
  - Note $P(s \mid s')$ stands for $P(S_{t+1} = s \mid S_t = s')$ at any time $t$
  - Will use the shorthand $P_{s,s'}$
The transition probability

• For processes with a discrete, finite set of states, is generally arranged as transition probability matrix

\[ \mathcal{P} = \begin{bmatrix}
  P_{s_1,s_1} & P_{s_2,s_1} & \cdots & P_{s_N,s_1} \\
  P_{s_1,s_2} & P_{s_2,s_2} & \cdots & P_{s_N,s_2} \\
  \vdots & \vdots & \ddots & \vdots \\
  P_{s_1,s_N} & P_{s_2,s_N} & \cdots & P_{s_N,s_N}
\end{bmatrix} \]

• More generally (for continuous-state processes, e.g. the state of an automobile), it is modelled as a parametric distribution

\[ P_{s,s_t} = f(s; \theta_{s_t}) \]
State Transition Probabilities

Where the spider can go next only depends on where she is.

From any corner, she is equally likely to wander off in any direction.

• What is the transition probability matrix?
The World as we model It

This spider does not like to turn back

Is this a Markov process?
The World as we model It

This spider does not like to turn back

Is this a Markov process?

How many states?
What is the transition matrix?
A Markov Reward Process

- A Markov Reward Process (MRP) is a Markov Process where states give you rewards.

- At each state $s$, upon arriving at that state, you obtain a reward $r$, drawn from a distribution $P(r|s)$. 
Markov Reward Process

Reward: Upon arriving at any corner, the spider may catch a fly from the swarm hovering there.

Rewards are corner specific and probabilistic: Different corners have different sized swarms with flies of different sizes. The spider only has a probability of catching a fly, but may not always catch one.

• Flider and the Markov reward process!
Is This an MRP?

- Is this a Markov Reward Process?
Markov Reward Process

• Formally, a Markov Reward Process is the tuple \( M = \langle S, \mathcal{P}, \mathcal{R}, \gamma \rangle \)
  
  – \( S \) is the (possibly finite) set of states
  
  – \( \mathcal{P} \) is the complete set of transition probabilities \( P_{s,s'} \)
  
  – \( \mathcal{R} \) is a \textit{reward} function, consisting of the distributions \( P(r|s) \)
    
    • Or alternately, the expected value \( R_s = E[r|s] \)
  
  – \( \gamma \in [0,1] \) is a \textit{discount} factor
Markov Reward Process

• Formally, a Markov Reward Process is the tuple $M = \langle S, P, R, \gamma \rangle$
  
  – $S$ is the (possibly finite) set of states
  
  – $P$ is the complete set of transition probabilities $P_{s,s'}$
  
  – $R$ is a reward function, consisting of the distributions $P(r|s)$
    
    • Or alternately, the expected value $R_s = E[r|s]$
  
    – $\gamma \in [0,1]$ is a discount factor

*What on earth is this?*
Rewards and Expected rewards

- One step expected reward: $R_1$
  - Will this be greater if the spider heads to corner 2 or to corner 3?
Rewards and Expected Rewards

Note: Distinction between *expected* reward and *sample* reward

Sample reward is what we actually get. Will represent by \( r \)

Expected reward is what we may *expect* to get. Will represent by \( R \)

• One step *expected* reward: \( R_1 \)
  – Will this greater if the spider heads to corner 2 or to corner 3?

No route to corner 4 except from corner 3
Where should the spider be?

- Flider has the option of landing on corner 1, 2 or 3 before she begins wandering the room
  - Which is the better corner to land on?
Where should the spider be?

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- Which is the better corner to land on?

Need to know the long-term consequences of landing in the two corners.

Where can she expect to get more food in the long term?
Where should the spider be?

- Assume she is allowed to “practice” once from each corner
  - To plan her future strategy
Where should the spider be?

- Must use her “practice” turn to assign a “value” to each of the corners
  - Guess how much food she would get in the long term from that corner
• Starting from 3, she gets $r_1, r_2, r_3, ...$.

• Is $r_1 + r_2 + r_3, ...$ a realistic representation of what she’d get if she did it again?
Flider practices

\[ r_1 \text{ is somewhat realistic – it is obtained from corner 3} \]

\[ r_2: \text{ she had a choice of 3 corners for her next stop and chose one randomly during practice. Unlikely she’ll go to the same corner in the next run (less representative)} \]

\[ r_3: \text{ she had 9 possible corners to choose from in 2 steps. } r_3 \text{ is even less representative of future runs} \]

And so on...

- Starting from 3, she gets \( r_1, r_2, r_3 \ldots \)
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And so on...

A better guess for how good it is to land at “3”:

\[ r_1 + a_1 r_2 + a_2 r_3 + a_3 r_4 + \ldots \]

Where $0 \leq a_i \leq 1$

(you “trust” the readings from farther in the future less)

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Where $0 \leq a_i \leq 1$

(you “trust” the readings from farther in the future less)

• A “mathematically good” choice: $a_i = \gamma^i$ where $0 \leq \gamma \leq 1$
The discounted return

\[ G_t = r_{t+1} + \gamma r_{t+2} + \gamma^2 r_{t+3} + \cdots = \sum_{k=0}^{\infty} \gamma^k r_{t+k+1} \]

- The *return* is the total *future* reward all the way to the end
- But each future step is slightly less “believable” and is hence discounted
  - We trust our own observations of the future less and less
    - The future is a fuzzy place

- The discount factor \( \gamma \) is our belief in the predictability of the future
  - \( \gamma = 0 \): The future is totally unpredictable, only trust what you see immediately ahead of you (myopic)
  - \( \gamma = 1 \): The future is clear; consider all of it (far sighted)

- Part of the Markov Reward Process model
The discounted return

Caveat: Weird notation. $r_{t+1}$ is actually associated with the state at time $t$

$$G_t = r_{t+1} + \gamma r_{t+2} + \gamma^2 r_{t+3} + \cdots = \sum_{k=0}^{\infty} \gamma^k r_{t+k+1}$$

- The return is the total future reward all the way to the end
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- Part of the Markov Reward Process model
Rewards

• Our spider goes wandering..
  \[ r_1 = 1, r_2 = 2, r_3 = 0.7, r_4 = 1.2, r_5 = 0.5, \ldots \]

• Are these sample rewards or expected rewards?
Rewards

- Our spider goes wandering..
  \[ r_1 = 1, r_2 = 2, r_3 = 0.7, r_4 = 1.2, r_5 = 0.5, \ldots \]
- Are these sample rewards or expected rewards?
- What are the expected rewards at t=1,2,\ldots
Rewards

- Our spider goes wandering..
  \[ r_1 = 1, r_2 = 2, r_3 = 0.7, r_4 = 1.2, r_5 = 0.5, \ldots \]

- Are these *sample rewards* or *expected rewards*?
- What are the *expected* rewards at \( t=1,2,\ldots \)?
- Under what condition would both be the same?
• Our spider goes wandering..
  \[ r_1 = 1, r_2 = 2, r_3 = 0.7, r_4 = 1.2, r_5 = 0.5, \ldots \]

• We decide the discounting factor \( \gamma = 1 \)
  – Really trusting the future

• What is the return \( G_t \) at \( t = 1 \)?
Returns

- Our spider goes wandering..
  \[ r_1 = 1, r_2 = 2, r_3 = 0.7, r_4 = 1.2, r_5 = 0.5, \ldots \]

- We decide the discounting factor \( \gamma = 1 \)
  - Really trusting the future

- What is the return \( G_t \) at \( t = 1 \)?
- What is the return \( G_t \) at \( t = 7 \)?
Our spider goes wandering..

\[ r_1 = 1, r_2 = 2, r_3 = 0.7, r_4 = 1.2, r_5 = 0.5, \ldots \]

We decide the discounting factor \( \gamma = 1 \)

- Really trusting the future

What is the return \( G_t \) at \( t = 1 \)?

What is the return \( G_t \) at \( t = 7 \)?

Are these sample returns or expected returns?
Our spider goes wandering..

\[ r_1 = 1, r_2 = 2, r_3 = 0.7, r_4 = 1.2, r_5 = 0.5, \ldots \]

What is the return at \( t = 2 \) with \( \gamma = 0.5 \)
Returns

• Discounted sample returns $G_t$ by themselves carry a fuzzy meaning
  – Why should we discount something we already observed?

• However, they make sense as samples of the possible future when you are at any state
  – If you are at any state, what is the expected return $E[G_t]$
Introducing the “Value” function

• The “Value” of a state is the expected total discounted return, when the process begins in that state

\[ V_s = E[G_0|S_0 = s] \]

• Or, since the process is Markov and the future only depends on the present and not the past

\[ V_s = E[G_t|S_t = s] \]

• Or more generally

\[ V_s = E[G|S = s] \]
The spider again

- The spider gains a reward of value 1 if she consumes the fly
- The spider has infinite patience
- What is the value of starting at each corner?
The spider again

- Regardless of which corner the spider starts at, she will eventually, randomly, nab the fly
- The expected return from any corner is 1!
• The value of being at any corner is 1 for all corners
  – She can expect to get a fly from anywhere
The hungry spider

- The spider is hungry
- She gets a negative reward of -1 for every minute spent finding food
- What is the expected return if she starts at $c_1$
The *hungry* spider

- Posing the problem: There is a total reward/penalty associated with each corner
  - $-1$ if the corner has no fly
    - Will definitely spend at least one more minute hunting
  - $1$ at the corner that has the fly (satisfied!)
- Thus $r_{c_x} = -1$ for $c_1 \ldots c_7$
- $r_{c_8} = 1$
- Note: We could also assign costs/rewards to edges in addition to nodes, if we want more detail, but won't do so for our lectures
The *hungry* spider

\[ V_{c_1} = -1 + \frac{1}{3} V_{c_2} + \frac{1}{3} V_{c_3} + \frac{1}{3} V_{c_4} \]
\[ V_{c_2} = -1 + \frac{1}{3} V_{c_1} + \frac{1}{3} V_{c_7} + \frac{1}{3} V_{c_8} \]
\[ \vdots \]
\[ V_{c_8} = 1 \]

- A familiar solution
- Assuming \( \gamma = 1 \)
  - A natural fit in this problem
The *gluttonous* spider

- There are flies at every corner
- The expected reward *after* arriving at any corner is $R_{c,x}$
  - The average size of the fly there minus the travel penalty

- Immediate rewards matter
  - Ideally $\gamma < 1$
  - Give more importance to immediate rewards than future ones
The *gluttonous* spider

\[
V_{c_1} = R_{c_1} + \gamma \left( \frac{1}{3} V_{c_2} + \frac{1}{3} V_{c_3} + \frac{1}{3} V_{c_4} \right)
\]

\[
V_{c_2} = R_{c_2} + \gamma \left( \frac{1}{3} V_{c_1} + \frac{1}{3} V_{c_7} + \frac{1}{3} V_{c_8} \right)
\]

\[
\vdots
\]

\[
V_{c_8} = R_{c_8} + \gamma \left( \frac{1}{3} V_{c_2} + \frac{1}{3} V_{c_3} + \frac{1}{3} V_{c_6} \right)
\]

- A familiar solution
- What happens if $\gamma = 1$?
The Bellman Expectation Equation

• The value function of a state is the *expected discounted return*, when the process begins at that state

\[
G_t = \sum_{k=0}^{\infty} \gamma^k r_{t+k+1}
\]

\[
V_s = E[G|S = s]
\]

• The Bellman Expectation Equation:

\[
V_s = R_s + \gamma \sum_{s'} P_{s',s} V_{s'}
\]
Why discounted return?

- In processes with infinite horizon, which can go on for ever, the total undiscounted return will be infinite for every path \( \sum_{k=0}^{\infty} r_{t+k+1} \) will be infinite for every path
  - For finite horizon processes, a discount factor \( \gamma = 1 \) is good. It lets us talk in terms of actual total return.
  - For infinite horizon processes, discounting \( \gamma < 1 \) is required for meaningful mathematical analysis: \( \sum_{k=0}^{\infty} \gamma^k r_{t+k+1} \)
The Bellman Expectation Equation

\[ V_s = R_s + \gamma \sum_{s'} P_{s,s'} V_{s'} \]

\[
\begin{bmatrix}
V_{s_1} \\
V_{s_2} \\
\vdots \\
V_{s_N}
\end{bmatrix} =
\begin{bmatrix}
R_{s_1} \\
R_{s_2} \\
\vdots \\
R_{s_N}
\end{bmatrix} + \gamma
\begin{bmatrix}
P_{s_1,s_1} & P_{s_2,s_1} & \cdots & P_{s_N,s_1} \\
P_{s_1,s_2} & P_{s_2,s_2} & \cdots & P_{s_N,s_2} \\
\vdots & \vdots & \ddots & \vdots \\
P_{s_1,s_N} & P_{s_2,s_N} & \cdots & P_{s_N,s_N}
\end{bmatrix}
\begin{bmatrix}
V_{s_1} \\
V_{s_2} \\
\vdots \\
V_{s_N}
\end{bmatrix}
\]

\[ \mathcal{V} = \mathcal{R} + \gamma \mathcal{P} \mathcal{V} \]

- Bellman expectation equation in matrix form
The Bellman Expectation Equation

\[ \mathcal{V} = \mathcal{R} + \gamma P \mathcal{V} \]

• Given the MRP \( M = \langle S, P, R, \gamma \rangle \)
  • I.e. the expected rewards at every state, and the transition probability matrix,
  – the value functions for all states can be easily computed through matrix inversion
  \[ \mathcal{V} = (I - \gamma P)^{-1} \mathcal{R} \]

• Finding the values of states is a key problem in planning and reinforcement learning

• Unfortunately, for very large state spaces, the above matrix inversion is not tractable
  – Also not invertible for small state spaces if \( \gamma = 1 \)
    • Inversion cannot be used to find \( \mathcal{V} \) even when it is finite (e.g. our fly problem), if \( \gamma = 1 \)

• Much of what we will deal with is how to tackle this problem
Moving on..

• Up next ... Markov *Decision* Processes
We have assumed so far that the agent behaves randomly.

- The agent has no *agency*
- Lets make the agent more intelligent..
A more realistic problem

• The spider actively chooses which way to move
  – The agent *takes action*
  – Ideally, it would move in the general direction of the fly

• However, each time the spider moves, the fly jumps up and settles at another corner
  – The agent’s action changes the environment!

Full set of possible actions
A more realistic problem

• The spider actively chooses which way to move
  – The agent *takes action*
  – Ideally, it would move in the general direction of the fly

• However, each time the spider moves, the fly jumps up and settles at another corner
  – The agent’s action changes the environment!

How do we model this system?
Redefining the problem

• Each time the spider moves in any direction, the fly randomly jumps
• The fly arrives at a new state but ..
  – The state it arrives in depends on where the fly jumped
  – Which depends on which direction the Spider moved
• The spider’s action *modifies the state transition probabilities!!*
What is $p_{s,s'}^a$?

- Each time the spider moves in any direction, the fly randomly jumps.
- The fly arrives at a new state but ..
  - The state it arrives in depends on where the fly jumped
  - Which depends on which direction the Spider moved.
- The spider’s action modifies the state transition probabilities!!
What is $P^a_{S,S'}$?

- Each time the spider moves in any direction, the fly randomly jumps
- The fly arrives at a new state but...
  - The state it arrives in depends on where the fly jumped
  - Which depends on which direction the Spider moved
- The spider’s action modifies the state transition probabilities!!

Trick question. Must modify our notion of states and actions, and define the behavior of the fly, to characterize.
Trick Question: Redefining the States

• There are, in fact, only four states, not eight
  – Manhattan distance between fly and spider = 0 ($s_0$)
  – Distance between fly and spider = 1 ($s_1$)
  – Distance between fly and spider = 2 ($s_2$)
  – Distance between fly and spider = 3 ($s_3$)
• Can, in fact, redefine the MRP entirely in terms of these 4 states
• There are two actions $a+$ and $a-$
• Need an idea of the behavior of the fly
The Fly Markov Reward Process

- There are, in fact, only four states, not eight
  - Manhattan distance between fly and spider = 0 ($s_0$)
  - Distance between fly and spider = 1 ($s_1$)
  - Distance between fly and spider = 2 ($s_2$)
  - Distance between fly and spider = 3 ($s_3$)
- Can, in fact, redefine the MRP entirely in terms of these 4 states
The Markov *Decision* Process: Defining Actions

- Two types of actions:
  - $a_+$: Increases distance to fly by 1
  - $a_-:$ Decreases distance to fly by 1
The Fly Markov Decision Process

• The behavior of the fly:
  – If the spider is moving *away from it*, it does nothing
  – If the spider is moving *towards* it, it randomly hops to a different adjacent corner
    • 2/3 of the time, it increases the distance to the fly by 1
    • 1/3 of the time, it *decreases* the distance to the fly by 1
The Fly Markov Decision Process

Process ends

\[ s_0 \]

\[ s_2 \rightarrow s_1 \]

\[ a_+ \]

\[ a_- \]

\[ 1 \]

\[ s_1 \rightarrow 1.0 \]

\[ s_1 \]

\[ s_3 \rightarrow s_2 \]

\[ a_+ \]

\[ a_- \]

\[ 2/3 \]

\[ s_2 \rightarrow s_0 \]

\[ 1 \]

\[ s_0 \rightarrow 1/3 \]

\[ s_0 \]

\[ s_0 \rightarrow s_2 \]

\[ 2/3 \]

\[ s_2 \rightarrow s_3 \]

\[ 1/3 \]

\[ s_3 \rightarrow 2/3 \]
Redefining the problem

• Each time the spider moves in any direction, the fly randomly jumps

**Note:** This is a simile for many problems in life, e.g. driving, stock market, advertising, etc.

The agents actions modifies how the environment behaves
  – Which depends on which direction the spider moved

• The spider’s action *modifies the state transition probabilities*!!
The Markov Decision Process

- A *Markov Decision Process* is a Markov Reward Process, where the agent has the ability to decide its actions!
  - We will represent individual actions as \( a \)
  - We will represent the action at time \( t \) as \( A_t \)

- The agent’s actions affect the environment’s behavior
  - The transitions made by the environment are functions of the action
  - The rewards returned are functions of the action
The Markov Decision Process

- Formally, a Markov Decision Process is the tuple $M = \langle S, P, A, R, \gamma \rangle$
  - $S$ is a (possibly finite) set of states: $S = \{s\}$
  - $A$ is a (possibly finite) set of actions: $A = \{a\}$
  - $P$ is the set of action conditioned transition probabilities: $P_{s,s'}^a = P(S_{t+1} = s | S_t = s', A_t = a)$
  - $R$ is an action conditioned reward function: $R_s^a = E[r | S = s, A = a]$
  - $\gamma \in [0,1]$ is a discount factor
Introducing: Policy

• The *policy* is the probability distribution over actions that the agent may take at any state

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

– What are the preferred actions of the spider at any state

• The policy may be deterministic, i.e.

\[ \pi(a|s) = 1 \text{ for } a = a_s; \quad 0 \text{ for } a \neq a_s \]

– where \( a_s \) is the preferred action in state \( s \)
An example of a policy

- Assuming the fly does not move
  - This example is not a particularly good policy for the spider
An example of a policy

• What are the (action dependent) transition probabilities of the states here?
An example of a policy

• What are the (action dependent) transition probabilities of the states here?

The transition probabilities depend on actions, but not on policy

Full set of possible actions
An example of a policy

• Assuming the fly does not move
  – This is a different *optimal* policy
An example of a policy

- Assuming the fly does not move
  - This is a different *optimal* policy
  - What are the transition probabilities here?
The value function of an MDP

- The *expected return* from any state depends on the policy you follow.
The Fly MDP: Policy 1

\[ V_{s_1} = R_{s_1} + \gamma V_{s_1} \]

\[ V_{s_2} = R_{s_2} + \gamma \left( \frac{1}{3} V_{s_0} + \frac{2}{3} V_{s_2} \right) \]

\[ V_{s_3} = R_{s_3} + \gamma \left( \frac{2}{3} V_{s_1} + \frac{1}{3} V_{s_3} \right) \]
The Fly MDP: Policy 2 (optimal)

\[ V_{s_1} = R_{s_1} + \gamma V_{s_2} \]

\[ V_{s_2} = R_{s_2} + \gamma \left( \frac{1}{3} V_{s_0} + \frac{2}{3} V_{s_2} \right) \]

\[ V_{s_3} = R_{s_3} + \gamma \left( \frac{2}{3} V_{s_1} + \frac{1}{3} V_{s_3} \right) \]
The Fly MDP: Stochastic Policy
The Fly MDP: Stochastic Policy

\[ V_{s_1} = \frac{2}{3} (R_{s_1} + \gamma V_{s_2}) + \frac{1}{3} (R_{s_1} + \gamma V_{s_1}) \]

\[ V_{s_2} = \frac{1}{3} (R_{s_2} + \gamma V_{s_3}) + \frac{2}{3} \left( R_{s_2} + \gamma \left( \frac{1}{3} V_{s_0} + \frac{2}{3} V_{s_2} \right) \right) \]

\[ V_{s_3} = R_{s_3} + \gamma \left( \frac{2}{3} V_{s_1} + \frac{1}{3} V_{s_3} \right) \]
The \textit{state value} function of an MDP

- The \textit{expected return} from any state depends on the policy you follow.
- We will index the value of any state by the policy to indicate this.

$$v_\pi(s) = \sum_{a \in A} \pi(a|s) \left( R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_\pi(s') \right)$$

\textbf{Bellman Expectation Equation for State Value Functions of an MDP}

\textit{Note:} Although reward was not dependent on action for the fly example, more generally it will be.
The action value function of an MDP

There are different value equations associated with different actions.

So we can actually associate value to state action pairs.

**Note:** The LHS in the equation is the action-specific value at the source state, but the RHS is the overall value of the target states.
The *action value* function of an MDP

- The *expected return* from any state under a given policy, when you follow a specific action

\[ q_\pi(s, a) = R_s^a + \gamma \sum_{s'} P_{s,s'}^a \nu_\pi(s') \]

Bellman Expectation Equation for Action Value Functions of an MDP
All together now

• The Bellman expectation equation for state value function

\[ v_\pi(s) = \sum_{a \in \mathcal{A}} \pi(a|s) \left( R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_\pi(s') \right) \]

• For action value function

\[ q_\pi(s, a) = R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_\pi(s') \]

• Giving you (obviously)

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

• And

\[ q_\pi(s, a) = R_s^a + \gamma \sum_{s'} P_{s,s'}^a \sum_{a' \in \mathcal{A}} \pi(a|s') q_\pi(s', a') \]
The Bellman Expectation Equations

• The Bellman expectation equation for state value function

\[ \nu_\pi(s) = \sum_{a \in A} \pi(a|s) \left( R_s^a + \gamma \sum_{s'} p_{s,s'}^a \nu_\pi(s') \right) \]

• The Bellman expectation equation for action value function

\[ q_\pi(s, a) = R_s^a + \gamma \sum_{s'} p_{s,s'}^a \sum_{a' \in A} \pi(a'|s') q_\pi(s', a') \]
“Computing” the MDP

• Finding the state and/or action value functions for the MDP:
  – Given complete MDP (all transition probabilities \( P_{s,s'}^a \), expected
    rewards \( R_s^a \), and discount \( \gamma \))
  – and a policy \( \pi \)
  – find all value terms \( v_\pi(s) \) and/or \( q_\pi(s,a) \)

• The Bellman expectation equations are simultaneous
  equations that can be solved for the value functions
  – Although this will be computationally intractable for very large
    state spaces
Computing the MDP

\[ \mathcal{V}_\pi = \mathcal{R}_\pi + \gamma \mathcal{P}_\pi \mathcal{V}_\pi \]

- Given the expected rewards at every state, the transition probability matrix, the discount factor and the policy:
  \[ \mathcal{V}_\pi = (I - \gamma \mathcal{P}_\pi)^{-1} \mathcal{R}_\pi \]

- Matrix inversion \(O(N^3)\); intractable for large state spaces
Optimal Policies

• Different policies can result in different value functions
• What is the *optimal* policy?

• The optimal policy is the policy that will maximize the expected total discounted reward at every state:

\[
E[G_t \mid S_t = s] = \mathbb{E} \left[ \sum_{k=0}^{\infty} \gamma^k r_{t+k+1} \mid S_t = s \right]
\]
Optimal Policies

• Different policies can result in different value functions
• What is the optimal policy?

• The optimal policy is the policy that will maximize the expected total discounted reward at every state:
\[ E[G_t|S_t = s] \]

\[ = E \left[ \sum_{k=0}^{\infty} \gamma^k r_{t+k+1} | S_t = s \right] \]

– Recall: why do we consider the discounted return, rather than the actual return \( \sum_{k=0}^{\infty} r_{t+k+1} \)?
Policy Ordering Definition

• A policy $\pi$ is “better” than a policy $\pi'$ if the value function under $\pi$ is greater than or equal to the value function under $\pi'$ at all states

\[ \pi \geq \pi' \Rightarrow v_\pi(s) \geq v_{\pi'}(s) \ \forall s \]

• Under the better policy, you will expect better overall outcome no matter what the current state
The optimal policy theorem

• **Theorem**: For any MDP there exists an optimal policy $\pi_*$ that is better than or equal to every other policy:
  $$\pi_* \geq \pi \quad \forall \pi$$

• **Corollary**: If there are *multiple* optimal policies $\pi_{opt_1}, \pi_{opt_2}, \ldots$ all of them achieve the same value function
  $$v_{\pi_{opti}}(s) = v_*(s) \quad \forall s$$

• All optimal policies achieve the same action value function
  $$q_{\pi_{opti}}(s, a) = q_*(s, a) \quad \forall s, a$$
How to find the optimal policy

• For the optimal policy:
  \[ \pi_*(a|s) = \begin{cases} 
    1 & \text{for } \underset{a'}{\arg\max} q_*(s,a') \\
   0 & \text{otherwise} 
  \end{cases} \]

• Easy to prove
  – For any other policy \(\pi\), \(q_\pi(s,a) \leq q_*(s,a)\)

• Knowing the optimal action value function \(q_*(s,a)\) \(\forall s,a\) is sufficient to find the optimal policy
The optimal value function

\[ \pi_*(a|s) = \begin{cases} 
1 & \text{for } \arg\max_{a'} q_*(s, a') \\
0 & \text{otherwise}
\end{cases} \]

• Which gives us

\[ \nu_*(s) = \max_{a} q_*(s, a) \]
Pictorially

Figures from Sutton

\[ \nu_*(s) = \max_a q_*(s, a) \]

- Blank circles are states, filled dots are state-action pairs
The optimal value function

$$\pi_*(a|s) = \begin{cases} 
1 & \text{for } \underset{a'}{\arg\max} q_*(s, a') \\
0 & \text{otherwise}
\end{cases}$$

• Which gives us

$$\nu_*(s) = \max_a q_*(s, a)$$

• But, for the optimal policy we also have

$$q_*(s, a) = R_s^a + \gamma \sum_{s'} p_{s,s'}^a \nu_*(s')$$
Backup Diagram

Figures from Sutton

\[ v_*(s) = \max_a q_*(s, a) \]

\[ q_*(s, a) = R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_*(s') \]
Backup Diagram

Figures from Sutton

\[ v_*(s) = \max_a R_s^a + \gamma \sum_{s'} p_{s,s'}^a v_*(s') \]
Backup Diagram

Figures from Sutton

\[ q_*(s, a) = R_s^a + \gamma \sum_{s'} p_{s,s',v_*(s')} \]

\[ v_*(s') \]
Backup Diagram

Figures from Sutton

\[ q_*(s, a) = R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_*(s') \]

\[ v_*(s') = \max_{a'} q_*(s', a') \]
Backup Diagram

Figures from Sutton

\[ q_*(s, a) = R_s^a + \gamma \sum_{s'} P_{s,s'}^a \max_{a'} q_*(s', a') \]
Bellman Optimality Equations

- Optimal value function equation

\[ v_*(s) = \max_a R_s^a + \gamma \sum_{s'} P_{s,s'} v_*(s') \]

- Optimal action value equation

\[ q_*(s, a) = R_s^a + \gamma \sum_{s'} P_{s,s'} \max_{a'} q_*(s', a') \]
Optimality Relationships

• Given the MDP: \( \langle S, P, A, R, \gamma \rangle \)
• Given the optimal action value functions, the optimal value function can be found

\[
v_*(s) = \max_a q_*(s, a)
\]

• Given the optimal value function, the optimal action value function can be found

\[
q_*(s, a) = R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_*(s')
\]

• Given the optimal action value function, the optimal policy can be found

\[
\pi_*(a|s) = \begin{cases} 
1 & \text{for } \arg\max_{a'} q_*(s, a') \\
0 & \text{otherwise}
\end{cases}
\]
“Solving” the MDP

• Solving the MDP equates to finding the optimal policy \( \pi_*(a|s) \)

• Which is equivalent to finding the optimal value function \( v_*(s) \)

• Or finding the optimal action value function \( q_*(s,a) \)

• Various solutions will estimate one or the other
  - Value based solutions solve for \( v_*(s) \) and \( q_*(s,a) \) and derive the optimal policy from them
  - Policy based solutions directly estimate \( \pi_*(a|s) \)
Solving the Bellman Optimality Equation

• No closed form solutions

• Solutions are iterative

• Given the MDP (Planning):
  – Value iterations
  – Policy iterations

• Not given the MDP (Reinforcement Learning):
  – Q-learning
  – SARSA..
QUESTIONS before we dive?
Planning with an MDP

• Problem:
  – **Given:** an MDP \(<S, P, A, R, \gamma>\)
  – **Find:** Optimal policy \(\pi_\star\)

• Can either
  – **Value-based Solution:** Find optimal value (or action value) function, and derive policy from it  OR
  – **Policy-based Solution:** Find optimal policy directly
Value-based Planning

• “Value”-based solution

• Breakdown:
  – **Prediction**: Given *any* policy $\pi$ find value function $v_\pi(s)$
  – **Control**: Find the optimal policy
Value-based Planning

• “Value”-based solution

• Breakdown:
  – **Prediction:** Given *any* policy $\pi$ find value function $v_\pi(s)$
  – **Control:** Find the optimal policy
Preliminaries

• How do we represent the value function?

• Table:
  – Value function
    • \( s \rightarrow v_\pi(s) \)
    • For a process with \( N \) discrete states, must store/compute \( N \) unique values
  – Action value functions
    • \( s, a \rightarrow q_\pi(s, a) \)
    • For a process with \( N \) discrete states and \( M \) discrete actions, must store/compute \( NM \) unique values

• Later we will see how to represent these when the number of states/actions is too large or continuous
The Bellman Expectation Equation for the value function

\[ v_\pi(s) = \sum_{a \in \mathcal{A}} \pi(a|s) \left( R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_\pi(s') \right) \]

- In vector form

\[
\begin{bmatrix}
  v_\pi(s_1) \\
  v_\pi(s_2) \\
  \vdots \\
  v_\pi(s_N)
\end{bmatrix}
= \begin{bmatrix}
  R_{s_1} \\
  R_{s_2} \\
  \vdots \\
  R_{s_N}
\end{bmatrix}
+ \gamma
\begin{bmatrix}
  P_{s_1,s_1} & P_{s_1,s_2} & \cdots & P_{s_1,s_N} \\
  P_{s_2,s_1} & P_{s_2,s_2} & \cdots & P_{s_2,s_N} \\
  \vdots & \vdots & \ddots & \vdots \\
  P_{s_N,s_1} & P_{s_N,s_2} & \cdots & P_{s_N,s_N}
\end{bmatrix}
\begin{bmatrix}
  v_\pi(s_1) \\
  v_\pi(s_2) \\
  \vdots \\
  v_\pi(s_N)
\end{bmatrix}
\]

- Where

\[ R_s = \sum_{a \in \mathcal{A}} \pi(a|s) R_s^a \]
\[ P_{s_1,s} = \sum_{a \in \mathcal{A}} \pi(a|s) P_{s_1,s}^a \]
The Bellman Expectation Equation for the value function

$$v_\pi(s) = \sum_{a \in A} \pi(a|s) \left( R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_\pi(s') \right)$$

- In vector form

$$\mathbf{v}_\pi = \mathbf{R}_\pi + \gamma \mathbf{P}_\pi \mathbf{v}_\pi$$

- Where
  
  - $R_s = \sum_{a \in A} \pi(a|s) R_s^a$
  
  - $P_{s,s'} = \sum_{a \in A} \pi(a|s) \sum_{s'} P_{s,s'}^a$
Solving the MDP

\[ V_\pi = R_\pi + \gamma P_\pi V_\pi \]

- Given the expected rewards at every state, the transition probability matrix, the discount factor and the policy:

\[ V_\pi = (I - \gamma P_\pi)^{-1} R_\pi \]

- Easy for processes with a small number of states
- Matrix inversion \( O(N^3) \); intractable for large state spaces
What about the action value function?

- The Bellman expectation equation for action value function

\[ q_\pi(s, a) = R_s^a + \gamma \sum_{s'} P_{s,s'}^{a} \sum_{a' \in A} \pi(a|s') q_\pi(s', a') \]

\[ Q_\pi = R_{\pi,Q} + \gamma P_{\pi,Q} Q_\pi \]

Even worse!!
So how do we solve these

• The equations are too large, how do we solve them?

• First, a little lesson – from middle school...
What they never taught you in school

• Consider the following equation:

\[ ax = b \]

• Where \( 0 < a < 2 \)

• Trivial solution: \( x = a^{-1} b = \frac{b}{a} \)

• But my CPU does not permit division..
  – How do I solve this?
What they never taught you in school

- Must solve the following without division
  \[ ax = b \]
  - where \( 0 < a < 2 \)
- Rewrite as follows
  \[ x = (1 - a)x + b \]
- The following iteration solves the problem:
  \[ x^{(k+1)} = (1 - a)x^{(k)} + b \]
- Can start with any \( x^{(0)} \)
- Proof??
What they never taught you in school

• Must solve the following without division
  \[ ax = b \]
  – where \( 0 < a < 2 \)
• Rewrite as follows
  \[ x = (1 - a)x + b \]
• The following iteration solves the problem:
  \[ x^{(k+1)} = (1 - a)x^{(k)} + b \]
• Can start with any \( x^{(0)} \)
• Proof?? \textbf{Hint:} \( 0 < a < 2 \ \Rightarrow \ |1 - a| < 1 \)
What they never taught you in school

• Consider any vector equation

\[ x = Ax + b \]

– Where all Eigen values \(|\lambda(A)| \leq 1\)

• And some extra criteria...
  – The square submatrix of \((I - A)\) corresponding to non-zero entries of \(b\) is full rank
  – The square submatrix of \((I - A)\) corresponding to zero entries of \(b\) is an identity matrix

• The following iteration solves the problem:

\[ x^{(k+1)} = Ax^{(k)} + b \]
Eigen values of a probability matrix

• For any Markov transition probability matrix $\mathcal{P}$, all Eigenvalues have magnitude less than or equal to 1

$$|\lambda(\mathcal{P})| \leq 1$$
Solving for the value function

\[ V_\pi = R_\pi + \gamma P_\pi V_\pi \]

- This can be solved by following iteration starting from any initial vector

\[ V^{(k+1)}_\pi = R_\pi + \gamma P_\pi V^{(k)}_\pi \]
Solving for the value function

\[ \mathcal{V}_\pi = R_\pi + \gamma P_\pi \mathcal{V}_\pi \]

• This can be solved by following iteration starting from any initial vector
  \[ \mathcal{V}^{(k+1)}_\pi = R_\pi + \gamma P_\pi \mathcal{V}^{(k)}_\pi \]

• But how did that help if we need infinite iterations to converge?
Solving for the value function

\[ \mathcal{V}_\pi = R_\pi + \gamma P_\pi \mathcal{V}_\pi \]

• This can be solved by following iteration starting from any initial vector

\[ \mathcal{V}^{(k+1)}_\pi = R_\pi + \gamma P_\pi \mathcal{V}^{(k)}_\pi \]

• But how did that help if we need infinite iterations to converge?
  – Solution: Stop when the changes becomes small

\[ |\mathcal{V}^{(k+1)}_\pi - \mathcal{V}^{(k+1)}_\pi| < \varepsilon \]
Actual Implementation

- Initialize $v^{(0)}_\pi(s)$ for all states

- Update

\[ v^{(k+1)}_\pi(s) = \sum_{a \in \mathcal{A}} \pi(a|s) \left( R_s^a + \gamma \sum_{s'} P_{s,s'}^a v^{(k)}_\pi(s') \right) \]

- Update may be in batch mode
  - Keep sweep through all states to compute $v^{(k+1)}_\pi(s)$
  - Update $k = k + 1$

- Or incremental
  - Sweep through all the states performing

\[ v_\pi(s) = \sum_{a \in \mathcal{A}} \pi(a|s) \left( R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_\pi(s') \right) \]
Actual Implementation

- Initialize $\nu_{\pi}^{(0)}(s)$ for all states

- Update

$$
\nu_{\pi}^{(k+1)}(s) = \sum_{a \in A} \pi(a|s) \left( R_s^a + \gamma \sum_{s'} P_{s,s'}^a \nu_{\pi}^{(k)}(s') \right)
$$

- This is an instance of *dynamic programming*:

*dynamic programming* (also known as *dynamic optimization*) is a method for solving a complex problem by breaking it down into a collection of simpler subproblems, solving each of those subproblems just once, and storing their solutions. The next time the same subproblem occurs, instead of recomputing its solution, one simply looks up the previously computed solution, thereby saving computation time at the expense of a (hopefully) modest expenditure in storage space. (Each of the subproblem solutions is indexed in some way, typically based on the values of its input parameters, so as to facilitate its lookup.) (from wikipedia)
An Example

Example from Sutton

- All squares, except shaded square have reward -1, shaded square has reward 0
- **Policy:** Random – can step in any of the four directions with equal probability
  - If you run into a wall, you just return to the square
- Find the value of being in each square
The Gridworld Example

- Actual iterations use random policy
- Right column shows greedy policy according to current value function
The Gridworld Example

- Iterations use random policy
- Greedy policy converges to optimal long before value function of random policy converges!
Value-based Planning

• “Value”-based solution

• Breakdown:
  – Prediction: Given any policy $\pi$ find value function $v_\pi(s)$
  – Control: Find the optimal policy
Revisit the grid world

Example from Sutton

\[ R = -1 \]
on all transitions
Revisit the gridworld

- Actual iterations use random policy
- Right column shows greedy policy according to current value function
Revisit the gridworld

- Iterations use random policy
- Greedy policy converges to optimal long before value function of random policy converges!
Finding an optimal policy

- Start with any policy, e.g. random policy $\pi^{(0)}$
- Iterate ($k = 0 \ldots$ convergence):
  - Use prediction DP to find the value function $v_{\pi^{(k)}}(s)$
  - Compute action value function $\forall s, a$:
    \[
    q_{\pi^{(k)}}(s, a) = R_s + \gamma \sum_{s'} P_{s,s'} v_{\pi^{(k)}}(s')
    \]
  - Find the greedy policy
    \[
    \pi^{(k+1)}(a|s) = \begin{cases} 
      1 & \text{for } a = \arg\max_{a'} q_{\pi^{(k)}}(s, a') \\ 
      0 & \text{otherwise}
    \end{cases}
    \]
Finding an optimal policy: Compact

• Start with any policy $\pi^{(0)}$
• Iterate ($k = 0$ ... convergence):
  – Use prediction DP to find the value function $v_{\pi^{(k)}}(s)$
  – Find the greedy policy

$$
\pi^{(k+1)}(a|s) = \begin{cases} 
1 & \text{for } a = \arg\max_{a'} R^a_{s} + \gamma \sum_{s'} P^a_{s,s'} v_{\pi^{(k)}}(s') \\
0 & \text{otherwise}
\end{cases}
$$
Finding an optimal policy: Shorthand

- Start with any policy \( \pi^{(0)} \)
- Iterate \( (k = 0 \ldots \text{convergence}) \):
  - Use prediction DP to find the value function \( v_{\pi^{(k)}}(s) \)
  - Find the greedy policy
    \[
    \pi^{(k+1)}(s) = \text{greedy} \left( v_{\pi^{(k)}}(s) \right)
    \]

This is known as **Policy Iteration**

In each iteration, we find a policy, and then find its value.
Policy Iteration

- Start with any policy $\pi^{(0)}$

- Iterate ($k = 0$ ... convergence):
  - Use prediction DP to find the value function $v_{\pi^{(k)}}(s)$
  - Find the greedy policy
    $$\pi^{(k+1)}(s) = \text{greedy} \left( v_{\pi^{(k)}}(s) \right)$$

- This will provably converge to the optimal policy $\pi_*$
- In the Gridworld example this converged in one iteration
- More generally, it will take several iterations
  - Convergence when policy no longer changes
Generalized Policy Iteration

• Start with any policy $\pi^{(0)}$

• Iterate ($k = 0 \ldots$ convergence):
  – Use *any algorithm* to find the value function $v_{\pi^{(k)}}(s)$
  – Use *any algorithm* to find an update policy

$$\pi^{(k+1)}(s) = \text{algorithm} \left( v_{\pi^{(k)}}(s) \right)$$

Such that $\pi^{(k+1)}(s) \geq \pi^{(k)}(s)$

• Guaranteed to converge to the optimal policy
**Generalized Policy Iteration**

- Start with any policy $\pi^{(0)}$
- Guaranteed to converge to the optimal policy

\[ V \xrightarrow{\text{Evaluation (anyhow)}} \pi \xrightarrow{\text{Improvement (anyhow)}} \]

- Guaranteed to converge to the optimal policy
Optimality theorem

• All states will hit their optimal value together

• Theorem:
  A policy \( \pi(a|s) \) has optimal value
  \[ v_\pi(s) = v_*(s) \]
  in any state \( s \) if and only if for every state \( s' \)
  reachable from \( s \),
  \[ v_\pi(s') = v_*(s') \]
Policy Iteration

• Start with any policy $\pi^{(0)}$

• Iterate ($k = 0 \ldots$ convergence):
  – Use prediction DP to find the value function $v_{\pi^{(k)}}(s)$
  – Find the greedy policy

$$\pi^{(k+1)}(s) = \text{greedy} \left( v_{\pi^{(k)}}(s) \right)$$

• This will provably converge to the optimal policy $\pi_*$
• In the Gridworld example this converged in one iteration
• More generally, it will take several iterations
  – Convergence when policy no longer changes
Policy Iteration

- Start with any policy $\pi^{(0)}$

- Iterate ($k = 0 \ldots$ convergence):
  - Use prediction DP to find the value function $v_{\pi^{(k)}}(s)$
  - Find the greedy policy

In the gridworld example we didn’t even need to run this to convergence

The optimal policy was found long before the actual value function converged even in the first upper iteration

- This will provably converge to the optimal policy $\pi_*$
- In the Gridworld example this converged in one iteration
- More generally, it will take several iterations
  - Convergence when policy no longer changes
Revisit the gridworld

- Iterations use random policy
- Greedy policy converges to optimal long before value function of random policy converges!
Policy Iteration

• Start with any policy $\pi^{(0)}$

• Iterate ($k = 0 \ldots$ convergence):
  – Use prediction DP to find the value function $v_{\pi^{(k)}}(s)$
  – Find the greedy policy

$$\pi^{(k+1)}(s) = greedy\left(v_{\pi^{(k)}}(s)\right)$$

In the gridworld example we didn’t even need to run this to convergence

• The optimal policy was found long before the actual value function converged even in the first upper iteration

• Do we even need the prediction DP to converge?
  – More generally, it will take several iterations
    – Convergence when policy no longer changes
Optimal policy estimation

• Start with any policy $\pi^{(0)}$

• Iterate ($k = 0 \ldots$ convergence):
  – Use $L$ iterations of prediction DP to find the value function $v_{\pi^{(k)}}(s)$
  – Find the greedy policy

$$\pi^{(k+1)}(s) = \text{greedy} \left( v_{\pi^{(k)}}(s) \right)$$

• This will provably converge to the optimal policy $\pi_*$
Optimal policy estimation

• Start with any policy $\pi^{(0)}$

• Iterate ($k = 0 \ldots$ convergence):
  – Use 1 iterations of prediction DP to find the value function $v_{\pi^{(k)}}(s)$
  – Find the greedy policy
    \[
    \pi^{(k+1)}(s) = \text{greedy} \left( v_{\pi^{(k)}}(s) \right)
    \]
Optimal policy estimation

• Start with any policy $\pi^{(0)}$

• Iterate ($k = 0 \ldots$ convergence):
  
  – Use 1 iterations of prediction DP to find the value function $\nu_{\pi^{(k)}}(s)$

  $$
  \nu_{\pi^{(k)}}(s) = \sum_{a \in A} \pi^{(k)}(a|s) \left( R_s^a + \gamma \sum_{s'} P_{s,s'}^a \nu_{\pi^{(k)}}(s') \right)
  $$

  – Find the greedy policy

  $$
  \pi^{(k+1)}(s) = \arg\max_a R_s^a + \gamma \sum_{s'} P_{s,s'}^a \nu_{\pi^{(k)}}(s')
  $$
Optimal policy estimation

• Start with any policy $\pi^{(0)}$

• Iterate ($k = 0 \ldots$ convergence):
  – Use 1 iterations of prediction DP to find the value function $v_{\pi^{(k)}}(s)$
  
  \[
  v_{\pi^{(k)}}(s) = \sum_{a \in \mathcal{A}} \mathbb{E}_{\pi^{(k)}}(a | s) \Big( R_s + \sum_{s'} P_{s,s'} v_{\pi^{(k)}}(s') \Big)
  \]

  – Find the greedy policy
  
  \[
  \pi^{(k+1)}(s) = \arg\max_a R_s^a + \sum_{s'} P_{s,s'} v_{\pi^{(k)}}(s')
  \]
Reordering and writing carefully

• Start with any initial value function $v_{\pi(0)}(s)$

• Iterate ($k = 1 \ldots$ convergence):
  
  – Find the greedy policy

  $$
  \pi^{(k)}(a|s) = \begin{cases} 
  1 & \text{for } a = \arg\max_{a'} R_s^{a'} + \gamma \sum_{s'} P_{s,s'}^{a'} v_{\pi^{(k-1)}}(s') \\
  0 & \text{otherwise}
  \end{cases}
  $$

  – Use 1 iterations of prediction DP to find the value function $v_{\pi^{(k)}}(s)$

  $$
  v_{\pi^{(k)}}(s) = \sum_{a \in \mathcal{A}} \pi^{(k)}(a|s) \left( R_s^a + \gamma \sum_{s'} P_{s,s'}^a v_{\pi^{(k-1)}}(s') \right)
  $$
Merging

• Start with any initial value function \( v_{\pi(0)}(s) \)

• Iterate \((k = 1 \ldots \text{convergence})\):
  – Update the value function

\[
v_{\pi(k)}(s) = \max_a R_s^a + \gamma \sum_{s'} P_{s,s'} v_{\pi(k-1)}(s')
\]

• Note: no explicit policy estimation
  – Directly learns value
  – The subscript \( \pi \) is a misnomer
Value Iteration

• Start with any initial value function $v_{\pi}^{(0)}(s)$

• Iterate ($k = 1$ ... convergence):
  – Update the value function

  $v_{\pi}^{(k)}(s) = \max_a R_s^a + \gamma \sum_{s'} P_{s,s'} v_{\pi}^{(k-1)}(s')$

• Note: no explicit policy estimation
• Directly learning optimal value function
• Guaranteed to give you optimal value function at convergence
  – But intermediate value function estimates may not represent any policy
Value iteration

\[ v^{(k)}_*(s) = \max_a R^a_s + \gamma \sum_{s'} P^a_{s,s'} v^{(k-1)}_*(s') \]

- Each state simply inherits the cost of its best neighbour state
  - Cost of neighbor is the value of the neighbour plus cost of getting there
Value Iteration Example

- Target: Find the shortest path
- Every step costs -1
Practical Issues

• Updates can be batch mode
  – Explicitly compute $\nu_*(k+1)(s)$ from $\nu_*(k)(s)$ for all states
  – Set $k = k+1$

• Or asynchronous
  – Compute $\nu_*(s)$ in place while we sweep over states
  – $\nu_*(s) \leftarrow \max_a R^a_s + \gamma \sum_s P^a_{s,s'} \nu_*(s)$
Recap

• Learned about *prediction*
  – Estimating value function given MDP and policy

• Learned *Policy* iteration
  – Iterate prediction and policy estimation

• Learned about *Value* iteration
  – Directly estimate optimal value function
Alternate strategy

• Worked with *Value function*
  – For N states, estimates N terms

• Could alternately work with *action-value function*
  – For M actions, must estimate MN terms
    • Much more expensive
    • But more useful in some scenarios
Next Up

• We’ve worked so far with planning
  – Someone gave us the MDP

• Next: Reinforcement Learning
  – MDP unknown..