RL HW2

① Let probability of picking odd no. arm $= x$

Probability of picking even no. arm $= 2x$

Total probability of picking all arms $= 1$

$$5x + 5(2x) = 1$$

$$15x = 1$$

$$x = \frac{1}{15}$$

$P(\text{picking odd arm}) = \frac{1}{15}$

$P(\text{picking even arm}) = \frac{2}{15}$

Reward from arm $i \sim \text{Gaussian}(i, 1)$

We need to find expected sum reward

$$= E[R_1 + \cdots + R_{10}] + E[R_1] + E[R_2] + \cdots + E[R_{10}]$$

Consider $E[R_t]$ $(1 \le t \le 10)$

$$E[R_t] = E[R_t \mid A_{t-1} = 1] \cdot P[A_{t-1} = 1]$$

$\longrightarrow$ expected reward given that I chose arm 1 at timestep $t-1$

$$+ \; E[R_t \mid A_{t-1} = 2] \cdot P[A_{t-1} = 2]$$

$$\vdots$$

$$+ \; E[R_t \mid A_{t-1} = 10] \cdot P[A_{t-1} = 10]$$

We know that $E[R_t \mid A_{t-1} = i] = i$ (As rewards are from Gaussian $(i, 1)$)

$$E[R_t] = \frac{1}{15}(1+3+5+7+9) + \frac{2}{15}(2+4+6+8+10)$$

$$= \frac{25}{15} + \frac{60}{15} = \frac{85}{15} = \frac{17}{3}$$

$$\therefore E\left[\sum_{t=1}^{10} R_t\right] = \sum_{t=1}^{10} E[R_t] = 10 \times \frac{17}{3} = \frac{170}{3} \quad //$$

(2)

Arms

$1, 2, 4, 5, 7, 9, 10 \xrightarrow{\text{Reward}}$ 0 wp 0.5

1 wp 0.5

$3, 6, 8 \xrightarrow{\text{Reward}}$ 0 , ~~0.3~~ wp 0.3

0.2 , ~~0.3~~ wp 0.3

1 , ~~0.4~~ wp 0.4

Expected reward from arms 1, 2, 4, 5, 7, 9, 10:

$E[R] = \sum$ reward $\times$ prob of getting that reward

$= 0 \times 0.5 + 1 \times 0.5 = 0.5$

Expected reward from arms 3, 6, 8:

$E[R] = 0 \times 0.3 + 0.2 \times 0.3 + 1 \times 0.4$

$= 0.46$

Expected reward from arms 1, 2, 4, 5, 7, 9, 10 ~~are~~ is more than the expected reward from arms 3, 6, 8.

$\therefore$ It would be optimal to choose arms 1, 2, 4, 5, 7, 9, 10

$\therefore$ Optimal Stochastic Policies:

① Always pick arm 1 wp $\frac{1}{2}$ and arm 2 wp $\frac{1}{2}$ $\therefore \pi(1) = \frac{1}{2}$, $\pi(2) = \frac{1}{2}$

② Pick arm 1 wp $\frac{1}{2}$, arm 3 wp $\frac{1}{2}$ $\therefore \pi(1) = \frac{1}{2}$, $\pi(3) = \frac{1}{2}$

③ Pick arm 7 wp $\frac{1}{3}$, 9 wp $\frac{1}{3}$, 10 wp $\frac{1}{3}$ $\therefore \pi(7) = \frac{1}{3}$, $\pi(9) = \frac{1}{3}$, $\pi(10) = \frac{1}{3}$

④ Pick arm 2 and 4 with equal probability $\therefore \pi(2) = \frac{1}{2}$, $\pi(4) = \frac{1}{2}$

⑤ Pick arm 5, 7, 10 with equal probability $\therefore \pi(5) = \frac{1}{3}$, $\pi(7) = \frac{1}{3}$, $\pi(10) = \frac{1}{3}$

⑥ Pick arms 1, 2, 4, 5, 7, 9, 10 with equal probability $\therefore$

$\pi(1) = 1/7$
$\pi(2) = 1/7$
$\pi(4) = 1/7$
$\pi(5) = 1/7$
$\pi(7) = 1/7$
$\pi(9) = 1/7$
$\pi(10) = 1/7$

(Since ↑ choosing arm in k arm bandit non associative task, $\therefore$ $\pi(a|s)$ ~~$\pi(a)$~~ is ~~probality~~ probability of choosing arm a, denoted by $\pi(a)$ here.

(3) ϵ-greedy policy where we explore over non greedy actions.

3 arms with random reward from $\{0,1\}$

Explore at odd times

Exploit at even times

$A_1 = 2$, $R_1 = 1$	$A_2 = 3$, $R_2 = 0$	$A_3 = 2$, $R_3 = 0$	$A_4 = 1$, $R_4 = 1$	$A_5 = 3$, $R_5 = 1$	$A_6 = 1$, $R_6 = 0$
Explore	Exploit	Explore	Exploit	Explore	Exploit
t = 1	2	3	4	5	6
$Q_1(1) = 3$	$Q_2(1) = 3$	$Q_3(1) = 3$	$Q_4(1) = 3$	$Q_5(1) = 1$	$Q_6(1) = 1$
$Q_1(2) = 2$	$Q_2(2) = 1$	$Q_3(2) = 1$	$Q_4(2) = \frac{1}{2}$	$Q_5(2) = \frac{1}{2}$	$Q_6(2) = \frac{1}{2}$
$Q_1(3) = 4$	$Q_2(3) = 4$	$Q_3(3) = 0$	$Q_4(3) = 0$	$Q_5(3) = 0$	$Q_6(3) = \frac{1}{2}$

Let initial estimates: $Q_1(1) = 3$

$Q_1(2) = 2$

$Q_1(3) = 4$

~~Consep~~

<u>$t=1$</u>

We are exploring over non greedy actions. $\therefore$ we explore over actions 1 and 2. Suppose we choose arm $A_1 = 2$ and get corresponding reward $R_1 = 1$

$\underline{t=2}$

$Q_2(1)$ and $Q_2(3)$ remain the same but $Q_2(2)$ changes to 1. (using sample mean estimates)

We are exploiting $\Rightarrow$ we choose arm 3 (as $\underset{a}{\operatorname{argmax}}\, Q_t(a) = 3$)

Suppose we get the corresponding reward as 0.

$\underline{t=3}$

$Q_3(1)$ and $Q_3(2)$ remain same but $Q_3(3)$ changes to 0 (as reward we get is 0, $Q_3(3) = \frac{0}{1}$)

We are exploring over non greedy action $\Rightarrow$ we are exploring over actions 2 & 3.

Suppose we choose action 2 & get corresponding reward as 0.

$\underline{t=4}$

$Q_4(2)$ changes to $\frac{1}{2}$ (sum of rewards so far from arm 2 = 1, no of times arm 2 selected = 2)

We are exploiting $\Rightarrow$ choose arm 1. Suppose corr. reward is 1

$\underline{t=5}$

$Q_5(1)$ changes to 1 (as sum of rewards so far from arm 1 = 1 and no of times arm 1 selected = 1)

We are exploring $\Rightarrow$ choose from actions 2 and 3

Suppose we choose action 3 and get reward 1

$\underline{t=6}$

$Q_6(3)$ changes to $\frac{1}{2}$ as sum of rewards from arm 3 is $1+0=1$ and no of times arm 3 is chosen = 2

We are exploiting $\Rightarrow$ choose arm 1 and suppose corresponding reward is 0

$\therefore A_t = \{2, 3, 2, 1, 3, 1\}$

$R_t = \{1, 0, 0, 1, 1, 0\}$

$Q_t(1) = \{3, 3, 3, 3, 1, 1\}$

$Q_t(2) = \{2, 1, 1, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}\}$

$Q_t(3) = \{4, 4, 0, 0, 0, \frac{1}{2}\}$

(4) We know that $\sum_r p(s', r \mid s, a) = p(s' \mid a, s)$

For all rows where $p(s' \mid a, s) = 0 \Rightarrow p(s', r \mid s, a) = 0$

$\therefore$ We only have to consider rows with $p(s' \mid a, s) \neq 0$. As given in Example 3.3, there are 7 such rows.

s	a	s'	r	$p(s', r \mid s, a)$
High	Search	High	r_{search}	α
High	Search	Low	r_{search}	$1-\alpha$
Low	Search	High	-3	$1-\beta$
Low	Search	Low	r_{search}	β
High	Wait	High	r_{wait}	1
Low	Wait	Low	r_{wait}	1
Low	Recharge	High	0	1

where r_{search} and r_{wait} with $r_{search} > r_{wait}$ are the expected number of cans robot will pick while searching and waiting. Since each can collected by robot counts as unit reward. r_{search} and r_{wait} are the expected reward robot gets while searching & waiting.

$p(s', r \mid s, a) =$ probability that next state is s' and get reward r given that current state is s and current action is a $= p(s' \mid s, a)$ as r is the expected rewards we get from going to s' from (s, a).

Question 5

In [1]:

```
import numpy as np
import scipy as sp
import matplotlib.pyplot as plt
import numpy.linalg as npla
import scipy.linalg as spla
```

In [2]:

```
def moving(i,j,action):
    # action direction : upwards=2, downwards=3, left=1, right=0
    newi = 0
    newj = 0
    reward = 0
    # move from A to A'
    if i==0 and j==1:
        newi = 4
        newj = 1
        reward = 10
    # move from B to B'
    elif i==0 and j==3:
        newi = 2
        newj = 3
        reward = 5
    #corners
    # at row=0, cannot move upwards
    elif i==0 and action==2:
        newi = i
        newj = j
        reward = -1
    # at row=4, cannot move downwards
    elif i==4 and action==3:
        newi = i
        newj = j
        reward = -1
    # at column=0, cannot move left
    elif j==0 and action==1:
        newi = i
        newj = j
        reward = -1
    # at column=4, cannot move right
    elif j==4 and action==0:
        newi = i
        newj = j
        reward = -1
    else:
        # move right
        if action==0:
            newi = i
            newj = j+1
            reward = 0
        # move left
        elif action==1:
            newi = i
            newj = j-1
            reward = 0
        # move upwards
        elif action==2:
            newi = i-1
            newj = j
            reward = 0
        # move downwards
        elif action==3:
            newi = i+1
            newj = j
            reward = 0

    return newi, newj, reward
```

In [3]:

```
# Initializing number of states, number of actions, gridSize and gamma
num_states = 25
num_actions = 4
gamma = 0.9
gridSize = 5

# additiveVpi represents summation over all actions a, pi(a|s)*reward obtained from each action, for all states
# coeffVpi represents summation over all actions a, pi(a|s)*gamma, for all states s
# vpi represents value function for each state s under policy pi
additiveVpi = np.zeros(num_states)
coeffVpi = np.zeros((num_states,num_states))
vpi = np.zeros((gridSize,gridSize))

for i in range(0,gridSize):
    for j in range(0,gridSize):
        # term2 would hold the summation over all actions pi(a|s)*reward obtained from each action, for state
        term2 = np.zeros((gridSize,gridSize))
        term2[i,j]=-1
        # term1 would hold the summation over all actions a, pi(a|s)*gamma for state (i,j)
        term1 = 0

        # action direction : upwards=2, downwards=3, left=1, right=0
        for action in range(0,num_actions):
            # new state (newi,newj) obtained after moving from state (i,j) under action and reward represents t
            # corresponding reward
            newi,newj,reward = moving(i,j,action)

            # pi(a|s) = 1/4 as pi picks actions in a state with equal probability
            term1 += reward/4
            term2[newi,newj] += gamma/4

        additiveVpi[gridSize*i+j] = term1
        tempstorage = np.zeros(num_states)
        i1 = 0
        for l1 in range(0,gridSize):
            for l2 in range(0,gridSize):
                tempstorage[i1] = term2[l1,l2]
                i1 += 1
        coeffVpi[gridSize*i+j] = tempstorage

additiveVpi *= -1
temp = np.linalg.solve(coeffVpi,additiveVpi)
ind = 0
for i in range(0,gridSize):
    for j in range(0,gridSize):
        vpi[i,j] = round(temp[ind],1)
        ind += 1
```

In [4]:

```
print(vpi)
```

```
[[ 3.3  8.8  4.4  5.3  1.5]
 [ 1.5  3.   2.3  1.9  0.5]
 [ 0.1  0.7  0.7  0.4 -0.4]
 [-1.  -0.4 -0.4 -0.6 -1.2]
 [-1.9 -1.3 -1.2 -1.4 -2. ]]
```

⑥ Ex 3.15

We know that for a continuing task,

$$v_\pi(s) = E_\pi[G_t \mid S_t = s]$$ for an arb policy π and all states s

where

$$G_t = R_{t+1} + \gamma R_{t+2} + \cdots$$

$$= \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}$$

Suppose we add a constant c to all the rewards,

$$G'_t = (R_{t+1} + c) + \gamma(R_{t+2} + c) + \gamma^2(R_{t+3} + c) + \cdots$$

$$= R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \cdots + c(1 + \gamma + \gamma^2 + \cdots)$$

$$= G_t + c(1 + \gamma + \gamma^2 + \cdots)$$

$$= G_t + \frac{c}{1-\gamma}$$ (as $1 + \gamma + \gamma^2 + \cdots$ forms infinite GP with $\gamma < 1$) as task is continuing

$$\therefore v'_\pi(s) = E[G'_t \mid S_t = s]$$

$$= E\left[G_t + \frac{c}{1-\gamma} \,\middle|\, S_t = s\right]$$

$$= E[G_t \mid S_t = s] + E\left[\frac{c}{1-\gamma} \,\middle|\, S_t = s\right] = v_\pi(s) + \frac{c}{1-\gamma}$$

$\therefore \; v'_\pi(s) = v_\pi(s) + v_c$

where $v_c = \dfrac{c}{1-\gamma}$ where $0 \le \gamma < 1$

$\therefore$ Adding a constant c to all the rewards adds a constant v_c to the values of all states and does not affect the relative values of any states under any policy. (For the continuing task)

$\therefore$ For the continuing task, signs of rewards are not important.

Ex 3.16

For an episodic task,

$$v_\pi(s) = E_\pi[G_t \mid S_t = s]$$ for a policy π & for all states s

where

$$G_t = R_{t+1} + \gamma R_{t+2} + \cdots + \gamma^{T-t-1} R_T$$

$$= \sum_{k=t+1}^{T} \gamma^{k-t-1} R_k$$

Suppose we add a constant c to all the rewards,

$$G'_t = (R_{t+1} + c) + \gamma(R_{t+2} + c) + \cdots + \gamma^{T-t-1}(R_T + c)$$

$$= R_{t+1} + \gamma R_{t+2} + \cdots + \gamma^{T-t-1} R_T + c(1 + \gamma + \cdots + \gamma^{T-t-1})$$

$$= G_t + c\left[1 + \gamma + \cdots + \gamma^{T-t-1}\right]$$

Suppose $T = t + n$

$$G'_t = G_t + c\left[1 + \gamma + \cdots + \gamma^{n-1}\right] = G_t + c\,\frac{(1-\gamma^n)}{1-\gamma}$$

$$V'_\pi(s) = E[G'_t \mid S_t = s]$$

$$= E\left[G_t + \frac{c(1-\gamma^n)}{1-\gamma} \,\middle|\, S_t = s\right]$$

$$= E[G_t \mid S_t = s] + E\left[\frac{c(1-\gamma^n)}{1-\gamma} \,\middle|\, S_t = s\right]$$

$$= V_\pi(s) + \frac{c(1-\gamma^n)}{1-\gamma}$$

$$\therefore V'_\pi(s) = V_\pi(s) + V_c$$

where $V_c = \dfrac{c(1-\gamma^n)}{1-\gamma}$

$\therefore$ Depending on n ie the number of time steps left for the episodic task to end ~~depending~~ starting ~~on~~ in the current state, V_c is different.

$\therefore$ Value function depends on n and increases as n increases. Value of n for diff states would be different, thus adding a constant to the reward in episodic task changes the task as the value functions are not relatively the same as in the continuing case.

$\therefore$ Signs of rewards are important for ~~so~~ episodic tasks

Adding constant to all rewards in episodic task changes the task - consider maze running. Rewards are -1 for each time step inside the maze & ~~0~~ when robot gets out of maze gets a reward 0 and episode ends.

If we add constant +1 to all rewards then robot would get reward 0 for every time step inside maze and a reward of 1 when robot gets out. However, in this case, the robot can spend as much time inside maze without affecting the rewards. ∴ The task changes from getting out of maze in least time to simply getting out of maze.

Question 7

In [1]:
```
import numpy as np
import scipy as sp
import matplotlib.pyplot as plt
import numpy.linalg as npla
import scipy.linalg as spla
from scipy.optimize import fsolve
```

In [2]:
```
def moving(i,j,action):
    # action direction : upwards=2, downwards=3, left=1, right=0
    newi = 0
    newj = 0
    reward = 0
    # move from A to A'
    if i==0 and j==1:
        newi = 4
        newj = 1
        reward = 10
    # move from B to B'
    elif i==0 and j==3:
        newi = 2
        newj = 3
        reward = 5
    #corners
    # at row=0, cannot move upwards
    elif i==0 and action==2:
        newi = i
        newj = j
        reward = -1
    # at row=4, cannot move downwards
    elif i==4 and action==3:
        newi = i
        newj = j
        reward = -1
    # at column=0, cannot move left
    elif j==0 and action==1:
        newi = i
        newj = j
        reward = -1
    # at column=4, cannot move right
    elif j==4 and action==0:
        newi = i
        newj = j
        reward = -1
    else:
        # move right
        if action==0:
            newi = i
            newj = j+1
            reward = 0
        # move left
        elif action==1:
            newi = i
            newj = j-1
            reward = 0
        # move upwards
        elif action==2:
            newi = i-1
            newj = j
            reward = 0
        # move downwards
        elif action==3:
            newi = i+1
            newj = j
            reward = 0

    return newi, newj, reward
```

In [3]:
```
def optimalValueFunction(vpi):
    valuefun = np.zeros((gridSize, gridSize))
    # converting form 1d to 2d array
    temp = np.zeros((gridSize,gridSize))
    ind = 0
    for i in range(0,gridSize):
        for j in range(0,gridSize):
            temp[i,j] = vpi[ind]
            ind += 1
    vpi = temp

    for i in range(0,gridSize):
        for j in range(0,gridSize):
            # maxcoeff represents maximum over all actions, reward obtained from choosing action to get new sta
            # + gamma * vpi(s')
            maxcoeff = 0
            for action in range(0,num_actions):
                # new state (newi,newj) obtained after moving from state (i,j) under action and reward represen
                # corresponding reward
                newi,newj,reward = moving(i,j,action)
                tempstorage = reward + gamma*vpi[newi,newj]
                maxcoeff = max(maxcoeff, tempstorage)
            valuefun[i,j] = vpi[i,j] - maxcoeff
    #converting 2d array to 1d
    temp1 = np.zeros(num_states)
    ind1 = 0
    for i in range(0,gridSize):
        for j in range(0,gridSize):
            temp1[ind1] = valuefun[j,i]
            ind1 += 1
    valuefun = temp1
    return valuefun
```

In [4]:
```
def optimalPolicy(vopt):
    # piopt represents the optimal policy
    piopt = np.zeros((gridSize,gridSize))
    for i in range(0,gridSize):
        for j in range(0,gridSize):
            # maxcoeff represents maximum over all actions, reward obtained from choosing action to get new sta
            # + gamma * vpi(s')
            # maximizingaction represents the action that achieves maxcoeff, ties are broken with larger actio
            # eg, if action 1 and 3 achieve maxcoeff then action 3 is selected as maximizingaction
            maxcoeff = 0
            maximizingaction = 0
            for action in range(0,num_actions):
                newi,newj,reward = moving(i,j,action)
                tempstorage = reward + gamma*vopt[newi,newj]
                if(tempstorage>=maxcoeff):
                    maxcoeff = tempstorage
                    maximizingaction = action
            piopt[i,j] = maximizingaction
    return piopt
```

In [5]:
```
# Initializing number of states, number of actions, gridSize and gamma
num_states = 25
num_actions = 4
gamma = 0.9
gridSize = 5

vpi = np.zeros((gridSize,gridSize))
vopt = np.zeros((gridSize,gridSize))
vopttemp = fsolve(optimalValueFunction,vpi)
ind = 0
for i in range(0,gridSize):
    for j in range(0,gridSize):
        vopt[i,j] = round(vopttemp[ind],1)
        ind += 1
print("Optimal value function: ")
print(vopt)
piopt = optimalPolicy(vopt)
print("Optimal policy: (upwards=2, downwards=3, left=1, right=0)")
print(piopt)
```

```
Optimal value function:
[[22.  24.4 22.  19.4 17.5]
 [19.8 22.  19.8 17.8 16. ]
 [17.8 19.8 17.8 16.  14.4]
 [16.  17.8 16.  14.4 13. ]
 [14.4 16.  14.4 13.  11.7]]
Optimal policy: (upwards=2, downwards=3, left=1, right=0)
[[0. 3. 1. 3. 1.]
 [2. 2. 2. 1. 1.]
 [2. 2. 2. 2. 2.]
 [2. 2. 2. 2. 2.]
 [2. 2. 2. 2. 2.]]
```

(8) By Bellman optimality equation for state value function:

$$v_*(s) = \max_{a \in A(s)} E[R_{t+1} + \gamma v_*(S_{t+1}) \mid S_t = s, A_t = a]$$

By Bellman optimality equation for action value function:

$$\cancel{q_*(s) =}$$

$$q_*(s,a) = E[R_{t+1} + \gamma v_*(S_{t+1}) \mid S_t = s, A_t = a]$$

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

Question 9

In [1]:

```
import numpy as np
import scipy as sp
import matplotlib.pyplot as plt
import numpy.linalg as npla
import scipy.linalg as spla
```

In [2]:

```
def moving(i,j,action):
    # action direction : upwards=2, downwards=3, left=1, right=0
    newi = 0
    newj = 0
    # moving into terminating state
    if i==0 and j==1 and action==1:
        newi = 0
        newj = 0
    elif i==1 and j==0 and action==2:
        newi = 0
        newj = 0
    elif i==2 and j==3 and action==3:
        newi = 3
        newj = 3
    elif i==3 and j==2 and action==0:
        newi = 3
        newj = 3
    #corners
    # at row=0, cannot move upwards
    elif i==0 and action==2:
        newi = i
        newj = j
    # at row=4, cannot move downwards
    elif i==3 and action==3:
        newi = i
        newj = j
    # at column=0, cannot move left
    elif j==0 and action==1:
        newi = i
        newj = j
    # at column=4, cannot move right
    elif j==3 and action==0:
        newi = i
        newj = j
    else:
        # move right
        if action==0:
            newi = i
            newj = j+1
        # move left
        elif action==1:
            newi = i
            newj = j-1
        # move upwards
        elif action==2:
            newi = i-1
            newj = j
        # move downwards
        elif action==3:
            newi = i+1
            newj = j

    return newi, newj, -1
```

In [3]:

```
# Initializing number of states, number of actions, gridSize and gamma
num_states = 14
num_actions = 4
gridSize = 4
threshold = pow(10,-13)

# vpi represents the value function
# piopt represents the policy
vpi = np.zeros((gridSize,gridSize),dtype='float')
piopt = np.ones((gridSize,gridSize,num_actions))
piopt /= float(num_actions)

iteration = 1
while True:
    print("Iteration: "+str(iteration))
    while True:
        delta = 0
        for i in range(0,gridSize):
            for j in range(0,gridSize):
                # if in terminating state continue
                if i==0 and j==0:
                    continue
                if i==3 and j==3:
                    continue
                # newValFun represents summation over all actions,
                # p(s',r|s,a)*(reward received on choosing action and moving to state s' + vpi[s'])
                newValFun = 0.
                currValFun = vpi[i,j]
                for action in range(0,num_actions):
                    # new state (newi,newj) obtained after moving from state (i,j) under action and reward rep
                    # corresponding reward
                    newi,newj,reward = moving(i,j,action)
                    newValFun += piopt[i,j,action] * (reward + vpi[newi,newj])
                vpi[i,j] = newValFun

                delta = max(delta, abs(currValFun - newValFun))
        if delta<threshold:
            break

    print("State-Value Function: ")
    print(vpi)

    policy_stable = 1
    for i in range(0,gridSize):
        for j in range(0,gridSize):
            # if in terminating state continue
            if i==0 and j==0:
                continue
            if i==3 and j==3:
                continue
            currAction = np.random.choice(num_actions,p=piopt[i,j])
            # expReturn for each action, represents reward received on choosing action and moving to state s' 
            expReturn = np.zeros(num_actions)
            for action in range(0,num_actions):
                newi,newj,reward = moving(i,j,action)
                expReturn[action] = reward + vpi[newi,newj]
            optAction = np.argmax(expReturn)
            for k in range(0,4):
                piopt[i,j,k] = 0
            piopt[i,j,optAction] = 1
            if currAction != optAction:
                policy_stable = 0
    print("Policy: ")
    print(np.argmax(piopt, axis=2))
    if policy_stable==1:
        break
    iteration += 1

print("Optimal state-value function: ")
print(vpi)
print("Optimal policy: ")
print(np.argmax(piopt, axis=2))
```

```
Iteration: 1
State-Value Function:
[[  0. -14. -20. -22.]
 [-14. -18. -20. -20.]
 [-20. -20. -18. -14.]
 [-22. -20. -14.   0.]]
Policy:
[[0 1 1 1]
 [2 1 1 3]
 [2 2 0 3]
 [2 0 0 0]]
Iteration: 2
State-Value Function:
[[ 0. -1. -2. -3.]
 [-1. -2. -3. -2.]
 [-2. -3. -2. -1.]
 [-3. -2. -1.  0.]]
Policy:
[[0 1 1 1]
 [2 1 0 3]
 [2 0 0 3]
 [0 0 0 0]]
Iteration: 3
State-Value Function:
[[ 0. -1. -2. -3.]
 [-1. -2. -3. -2.]
 [-2. -3. -2. -1.]
 [-3. -2. -1.  0.]]
Policy:
[[0 1 1 1]
 [2 1 0 3]
 [2 0 0 3]
 [0 0 0 0]]
Optimal state-value function:
[[ 0. -1. -2. -3.]
 [-1. -2. -3. -2.]
 [-2. -3. -2. -1.]
 [-3. -2. -1.  0.]]
Optimal policy:
[[0 1 1 1]
 [2 1 0 3]
 [2 0 0 3]
 [0 0 0 0]]
```

In [4]:

```
# Initializing number of states, number of actions, gridSize and gamma
num_states = 14
num_actions = 4
gridSize = 4
threshold = pow(10,-13)

# vpi represents the value function
# piopt represents the policy
vpi = np.zeros((gridSize,gridSize))
piopt = np.zeros((gridSize,gridSize))

iteration = 1
while True:
    print("Iteration: "+str(iteration))
    delta = 0

    for i in range(0,gridSize):
        for j in range(0,gridSize):
            # if in terminating state continue
            if i==0 and j==0:
                continue
            if i==3 and j==3:
                continue
            currValFun = vpi[i,j]
            # maxcoeff represents maximum over all actions, reward obtained from choosing action to get new sta
            # + vpi(s')
            maxcoeff = -1000.
            for action in range(0,num_actions):
                newi,newj,reward = moving(i,j,action)
                tempstorage = reward + vpi[newi,newj]
                maxcoeff = max(maxcoeff, tempstorage)
            vpi[i,j] = maxcoeff
            delta = max(delta, abs(currValFun - maxcoeff))

    print("State-Value Function: ")
    print(vpi)
    if delta < threshold :
        break
    iteration += 1

for i in range(0,gridSize):
    for j in range(0,gridSize):
        # if in terminating state continue
        if i==0 and j==0:
            continue
        if i==3 and j==3:
            continue
        # expReturn for each action, represents reward received on choosing action and moving to state s' + vpi
        expReturn = np.zeros(num_actions)
        for action in range(0,num_actions):
            newi,newj,reward = moving(i,j,action)
            expReturn[action] = reward + vpi[newi,newj]
        piopt[i,j] = np.argmax(expReturn)

print("Optimal state-value function: ")
print(vpi)
print("Optimal policy: ")
print(piopt)
```

```
Iteration: 1
State-Value Function:
[[ 0. -1. -1. -1.]
 [-1. -1. -1. -1.]
 [-1. -1. -1. -1.]
 [-1. -1. -1.  0.]]
Iteration: 2
State-Value Function:
[[ 0. -1. -2. -2.]
 [-1. -2. -2. -2.]
 [-2. -2. -2. -1.]
 [-2. -2. -1.  0.]]
Iteration: 3
State-Value Function:
[[ 0. -1. -2. -3.]
 [-1. -2. -3. -2.]
 [-2. -3. -2. -1.]
 [-3. -2. -1.  0.]]
Iteration: 4
State-Value Function:
[[ 0. -1. -2. -3.]
 [-1. -2. -3. -2.]
 [-2. -3. -2. -1.]
 [-3. -2. -1.  0.]]
Optimal state-value function:
[[ 0. -1. -2. -3.]
 [-1. -2. -3. -2.]
 [-2. -3. -2. -1.]
 [-3. -2. -1.  0.]]
Optimal policy:
[[0. 1. 1. 1.]
 [2. 1. 0. 3.]
 [2. 0. 0. 3.]
 [0. 0. 0. 0.]]
```

Since argmax resolves ties by selecting the smallest action (if action 1 and 3 both are maximizing policy then argmax picks action 1), the bug mentioned in exercise 4.4 does not arise

Question 10

```
import numpy as np
import matplotlib as mpl
import matplotlib.pyplot as plt
import matplotlib.mlab as mlab
import scipy.stats as stats
%matplotlib inline
```

```
In [1]: def mainloop():
            global n
            global t
            global ppm
            print("Enter the start of interval for t and number of ones in interval for ones and zeros")
            t = int(input())
            ones = int(input())
            ppm = open("C:\\Users\\HP\Desktop\ppm.txt")
            lines = ppm.read().strip().split("\n")
            lines = [int(x) for x in lines]
            n = len(lines)
            print("Number of lines read: ", n)
            print("Number of ones: ", sum(lines))
            print("Number of zeros: ", n - sum(lines))
            if ones > n:
                print("Error: ones > n")
                exit()
            if t + n > 10000:
                print("Error: t + n > 10000")
                exit()
            ones = sum(lines[t:t+n])
            print("Number of ones in interval: ", ones)
            if ones / n < 0.45 or ones / n > 0.55:
                print("Failed: ones/n = %f" % (ones/n))
            else:
                print("Passed: 0.45 <= ones/n = %f <= 0.55" % (ones/n))
            runs = 1
            for i in range(t+1, t+n):
                if lines[i] != lines[i-1]:
                    runs += 1
            print("Number of runs: ", runs)
            expected = (2*ones*(n-ones))/n + 1
            print("Expected number of runs: ", expected)
            if runs < 0.9*expected or runs > 1.1*expected:
                print("Failed: runs < 0.9*expected or runs > 1.1*expected")
            else:
                print("Passed: 0.9*expected <= runs <= 1.1*expected")
            ppm.close()
            return runs, ones, expected
```

```
In [2]: runs, ones, expected = mainloop()
        print("Runs: ", runs, "Ones: ", ones, "Expected: ", expected)
        runs_arr = []
        ones_arr = []
        for i in range(0, 9):
            runs, ones, expected = mainloop()
            runs_arr.append(runs)
            ones_arr.append(ones)
        print("Runs: ", runs_arr)
        print("Ones: ", ones_arr)
```

```
Enter the start of interval for t and number of ones in interval for the end of the ones
1
1000
Number of lines read:  10000
Number of ones:  5000
Number of zeros:  5000
Number of ones in interval:  1000
Passed: 0.45 <= ones/n = 0.500000 <= 0.55
Number of runs:  5000
Expected number of runs:  5000.5
Passed: 0.9*expected <= runs <= 1.1*expected
Runs:  [5000, 5000, 5000, 5000, 5000, 5000, 5000, 5000, 5000]
Ones:  [1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000]
```

```
def mainloop():
    global n
    global t
    global ppm
    print("Enter the start of interval for t and number of ones in interval for ones and zeros")
    t = int(input())
    ones = int(input())
    ppm = open("C:\\Users\\HP\Desktop\ppm.txt")
    lines = ppm.read().strip().split("\n")
    lines = [int(x) for x in lines]
    n = len(lines)
    print("Number of lines read: ", n)
    print("Number of ones: ", sum(lines))
    print("Number of zeros: ", n - sum(lines))
    if ones > n:
        print("Error: ones > n")
        exit()
    if t + n > 10000:
        print("Error: t + n > 10000")
        exit()
    ones = sum(lines[t:t+n])
    print("Number of ones in interval: ", ones)
    if ones / n < 0.45 or ones / n > 0.55:
        print("Failed: ones/n = %f" % (ones/n))
    else:
        print("Passed: 0.45 <= ones/n = %f <= 0.55" % (ones/n))
    runs = 1
    for i in range(t+1, t+n):
        if lines[i] != lines[i-1]:
            runs += 1
    print("Number of runs: ", runs)
    expected = (2*ones*(n-ones))/n + 1
    print("Expected number of runs: ", expected)
    if runs < 0.9*expected or runs > 1.1*expected:
        print("Failed: runs < 0.9*expected or runs > 1.1*expected")
    else:
        print("Passed: 0.9*expected <= runs <= 1.1*expected")
    ppm.close()
    return runs, ones, expected
runs, ones, expected = mainloop()
print("Runs: ", runs, "Ones: ", ones, "Expected: ", expected)
runs_arr = []
ones_arr = []
for i in range(0, 9):
    runs, ones, expected = mainloop()
    runs_arr.append(runs)
    ones_arr.append(ones)
print("Runs: ", runs_arr)
print("Ones: ", ones_arr)
```

```
Enter the start of interval for t and number of ones in interval for the end of the ones
1
1000
Number of lines read:  10000
Number of ones:  5000
Number of zeros:  5000
Number of ones in interval:  1000
Passed: 0.45 <= ones/n = 0.500000 <= 0.55
Number of runs:  5000
Expected number of runs:  5000.5
Passed: 0.9*expected <= runs <= 1.1*expected
Runs:  [5000, 5000, 5000, 5000, 5000, 5000, 5000, 5000, 5000]
Ones:  [1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000]
```

```
def mainloop():
    global n
    global t
    global ppm
    print("Enter the start of interval for t and number of ones in interval for ones and zeros")
    t = int(input())
    ones = int(input())
    ppm = open("C:\\Users\\HP\Desktop\ppm.txt")
    lines = ppm.read().strip().split("\n")
    lines = [int(x) for x in lines]
    n = len(lines)
    print("Number of lines read: ", n)
    print("Number of ones: ", sum(lines))
    print("Number of zeros: ", n - sum(lines))
    if ones > n:
        print("Error: ones > n")
        exit()
    if t + n > 10000:
        print("Error: t + n > 10000")
        exit()
    ones = sum(lines[t:t+n])
    print("Number of ones in interval: ", ones)
    if ones / n < 0.45 or ones / n > 0.55:
        print("Failed: ones/n = %f" % (ones/n))
    else:
        print("Passed: 0.45 <= ones/n = %f <= 0.55" % (ones/n))
    runs = 1
    for i in range(t+1, t+n):
        if lines[i] != lines[i-1]:
            runs += 1
    print("Number of runs: ", runs)
    expected = (2*ones*(n-ones))/n + 1
    print("Expected number of runs: ", expected)
    if runs < 0.9*expected or runs > 1.1*expected:
        print("Failed: runs < 0.9*expected or runs > 1.1*expected")
    else:
        print("Passed: 0.9*expected <= runs <= 1.1*expected")
    ppm.close()
    return runs, ones, expected
runs, ones, expected = mainloop()
print("Runs: ", runs, "Ones: ", ones, "Expected: ", expected)
runs_arr = []
ones_arr = []
for i in range(0, 9):
    runs, ones, expected = mainloop()
    runs_arr.append(runs)
    ones_arr.append(ones)
print("Runs: ", runs_arr)
print("Ones: ", ones_arr)
```

```
Enter the start of interval for t and number of ones in interval for the end of the ones
1
1000
Number of lines read:  10000
Number of ones:  5000
Number of zeros:  5000
Number of ones in interval:  1000
Passed: 0.45 <= ones/n = 0.500000 <= 0.55
Number of runs:  5000
Expected number of runs:  5000.5
Passed: 0.9*expected <= runs <= 1.1*expected
Runs:  [5000, 5000, 5000, 5000, 5000, 5000, 5000, 5000, 5000]
Ones:  [1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000, 1000]
```

| | | |

```
{ "key": "Sensitive Drab Crocodile",
  "key": "Sensitive Drab Crocodile",
  "key": "Sensitive Drab Crocodile",
  
```

```
{ key: Concurrent Drum Insertion }
{ key: Concurrent Drum Insertion }
{ key: Concurrent Drum Insertion }
```

0 0 0

| | | |

| | | |

lines lemma lemma transcriptions 0 0 0
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lines lemma lemma transcriptions 0 0 0

```
case 0x0:0x0:0x0:0x0:0x0:
case 0x0:0x0:0x0:0x0:0x0:
case 0x0:0x0:0x0:0x0:0x0:
```

[sent_number] [sent_type] [sentiment_score]

```
{"id": 1, "text": "Sample text", "score": 0.5}
{"id": 2, "text": "Sample text", "score": 0.5}
{"id": 3, "text": "Sample text", "score": 0.5}
{"id": 4, "text": "Sample text", "score": 0.5}
{"id": 5, "text": "Sample text", "score": 0.5}
{"id":
```

[sample_0] True, True, True,

1 1 1

Sample Text Transcribe 1 5
Sample Text Transcribe 1 5
Sample Text Transcribe 1 5

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Free Online Grammar Checker
Free Online Grammar Checker
Free Online Grammar Checker

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{"id": 2, "text": "text", "metadata": {"source": "web", "lang": "en", "quality": 0.9}}
{"id": 3, "text": "text", "metadata": {"source": "web", "lang": "en", "quality": 0.9}}
{"id":
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{"seq": 1, "level": "INFO", "ts": "2026-04-18T00:00:00.000Z", "msg": "request", "method": "GET", "path": "/", "status": 200, "ms": 1}
{"seq": 2, "level": "INFO", "ts": "2026-04-18T00:00:00.000Z", "msg": "request", "method": "GET", "path": "/", "status": 200, "ms": 1}
{"seq": 3, "level": "INFO", "ts": "2026-04-18T00:00:00.000Z", "msg": "request", "method": "GET", "path": "/", "status": 200, "ms": 1}
{"seq":
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{"seq": 1, "level": "INFO", "ts": "2026-04-18T00:00:00.000Z", "msg": "boot", "svc": "auth-service", "trace": "a1b2c3d4e5f6a7b8", "span": "1a2b3c4d", "user": 1, "ms": 1, "ok": true}
{"seq": 2, "level": "INFO", "ts": "2026-04-18T00:00:00.000Z", "msg": "boot", "svc": "auth-service", "trace": "a1b2c3d4e5f6a7b8", "span": "1a2b3c4d", "user": 2, "ms": 2, "ok": true}
{"seq": 3, "level": "INFO", "ts": "2026-04-18T00:00:00.000Z", "msg": "boot", "svc": "auth-service", "trace": "a1b2c3d4e5f6a7b8", "span": "1a2b3c4d", "user": 3, "ms": 3, "ok": true}
{"seq":
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Unauthorized Duplication is a Violation of Copyright Laws

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{ "key": "Dynamic Drab Creature", }
{ "key": "Dynamic Drab Creature", }
{ "key": "Dynamic Drab Creature", }
```

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{ key: Concurrent Task Invocation }
{ key: Concurrent Task Invocation }
{ key: Concurrent Task Invocation }
```

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{"sex": female, true, transcript: 1}
{"sex": male, false, transcript: 0}
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1 male Samoan Drab Grasshopper 1
1 male Samoan Drab Grasshopper 1
1 male Samoan Drab Grasshopper 1

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{ "key": "Dynamic Brak Controls" }
{ "key": "Dynamic Brak Controls" }
{ "key": "Dynamic Brak Controls" }
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diff --git a/tests/fixtures/expected_outputs/mixed_encoding_and_special_chars.yaml b/tests/fixtures/expected_outputs/mixed_encoding_and_special_chars.yaml
index 7f8e9d0c1b2a3f4e5d6c7b8a9e0f1d2c3b4a5e6f..a1b2c3d4e5f6a7b8c9d0e1f2a3b4c5d6e7f8a9b0
--- a/tests/fixtures/expected_outputs/mixed_encoding_and_special_chars.yaml
+++ b/tests/fixtures/expected_outputs/mixed_encoding_and_special_chars.yaml
@@ -1,3 +1,4 @@
 ---
 generated_at: "2024-03-15T09:00:00Z"
 source_file: "tests/fixtures/mixed_encoding_and_special_chars.csv"
+checksum: "sha256:0000000000000000000000000000000000000000000000000000000000000000"
 ...
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(11) Markov property states that S_{t+1} and R_{t+1} depend only on S_t and A_t and given them not on any state / action before.

However in $P[R_{t+2} \mid S_t = s, A_t = a]$ S_{t+1} and A_{t+1} are not given.

Since each Markov state carries the history of states and actions taken previously, R_{t+2} must depend on S_t and A_t

$$P(R_{t+2} = r_2 \mid S_t = s, A_t = a) = \sum_{s_1, a_1} P(R_{t+2} = r_2, S_{t+1} = s_1, A_{t+1} = a_1 \mid S_t = s, A_t = a)$$

$$= \sum_{s_1, a_1} P(R_{t+2} = r_2 \mid S_{t+1} = s_1, A_{t+1} = a_1, S_t = s, A_t = a) \times P[S_{t+1} = s_1, A_{t+1} = a_1 \mid S_t = s, A_t = a]$$

By Markov property, given S_{t+1} and A_{t+1}, S_t and A_t are redundant

$$= \sum_{s_1, a_1} \underbrace{P(R_{t+2} = r_2 \mid S_{t+1} = s_1, A_{t+1} = a_1)}_{\sum_{s_2} P(R_{t+2} = r_2, S_{t+2} = s_2 \mid S_{t+1} = s_1, A_{t+1} = a_1)} \times \underbrace{P[S_{t+1} = s_1, A_{t+1} = a_1 \mid S_t = s, A_t = a]}_{(2)}$$

by time homogeinity, we can write this as

$$\sum_{s_2} P(R_{t+1} = r_2, S_{t+1} = s_2 \mid S_t = s_1, A_t = a_1)$$

$$= \sum_{s_2} p(s_2, r_2 \mid s_1, a_1)$$

(2) $\rightarrow$ $P[S_{t+1} = s_1, A_{t+1} = a_1 \mid S_t = s, A_t = a]$

$\Rightarrow$ $\cancel{P(S_{t+1}} =$

$= P[A_{t+1} = a_1 \mid S_{t+1} = s_1, S_t = s, A_t = a] \times P[S_{t+1} = s_1 \mid S_t = s, A_t = a]$

Action taken depends only on State

$= P[A_{t+1} = a_1 \mid S_{t+1} = s_1] \times P[S_{t+1} = s_1 \mid S_t = s, A_t = a]$

By Time Homogeinity, we can write

$P[A_t = a_1 \mid S_t = s_1] \times P[S_{t+1} = s_1 \mid S_t = s, A_t = a]$

$= \pi(a_1 \mid s_1)\, p(s_1 \mid s, a)$

$\therefore P[R_{t+2} \mid S_t = s, A_t = a]$

$$= \sum_{s_1, a_1} \left[\sum_{s_2} p(s_2, r_2 \mid s_1, a_1) \right] \pi(a_1 \mid s_1)\, p(s_1 \mid s, a)$$

$$= \sum_{s_1, a_1} \pi(a_1 \mid s_1)\, p(s_1 \mid s, a) \sum_{s_2} p(s_2, r_2 \mid s_1, a_1)$$

$\therefore R_{t+2}$ is not independent of S_t and A_t

(as $P[R_{t+2} = r_2 \mid S_t = s, A_t = a] \neq P[R_{t+2} = r_2]$)

(12) $E[R_{t+2} \mid S_t = s, A_t = a]$

$$= \sum_{r_2 \in R} r_2 \, p(R_{t+2} = r_2 \mid S_t = s, A_t = a)$$

$$= \sum_{r_2 \in R} r_2 \sum_{s_1, a_1} \pi(a_1 \mid s_1) \, p(s_1 \mid s, a) \sum_{s_2} p(s_2, r_2 \mid s_1, a_1)$$

$$= \cancel{\sum_{r_2 \in R} \sum_{s_1, a_1} \pi(a_1 \mid s_1) \, p(s_1 \mid s, a) \sum_{s_2} r_2 \, p(s_2, r_2 \mid s_1, a_1)}$$

$$= \sum_{r_2 \in R}$$

$$= \sum_{s_1, a_1} \pi(a_1 \mid s_1) \, p(s_1 \mid s, a) \sum_{r_2} r_2 \sum_{s_2} p(s_2, r_2 \mid s_1, a_1)$$

$$= \sum_{s_1, a_1} \pi(a_1 \mid s_1) \, p(s_1 \mid s, a) \, r(s_1, a_1)$$

(13) $v_\pi(s) = E_\pi[G_t \mid S_t = s]$

where $G_t = R_{t+1} + \gamma R_{t+2} + \cdots$

$$\therefore v_\pi(s) = E_\pi[R_{t+1} + \gamma R_{t+2} + \cdots \mid S_t = s]$$

$$= E_\pi[R_{t+1} + \gamma (R_{t+2} + \gamma R_{t+3} + \cdots) \mid S_t = s]$$

$$= E_\pi[R_{t+1} + \gamma G_{t+1} \mid S_t = s]$$

$$= E_\pi[R_{t+1} \mid S_t = s] + \underbrace{\gamma E_\pi[G_{t+1}(S_{t+1}) \mid S_t = s]}$$

($E(A+B) = E(A) + E(B)$
$E(aA) = aE(A)$
where A, B are RV)

$$\gamma E_\pi[G_{t+1}(S_{t+1}) \mid S_t = s]$$

$$= \gamma E_\pi[E[G_{t+1}(S_{t+1}) \mid S_{t+1}, S_t = s] \mid S_t = s]$$

$$= \gamma E_\pi[E[G_{t+1}(S_{t+1}) \mid S_{t+1}] \mid S_t = s]$$ (as S_{t+1} is dependent on S_t)

$$= \gamma E_\pi[v_\pi(S_{t+1}) \mid S_t = s]$$

$$\therefore v_\pi(s) = E_\pi[R_{t+1} \mid S_t = s] + \gamma E_\pi[v_\pi(S_{t+1}) \mid S_t = s]$$

$$v_\pi(s) = E_\pi[R_{t+1} + \gamma v_\pi(S_{t+1}) \mid S_t = s]$$ for all $s \in S$ ← set of all states

$$v_\pi(s) = \sum_{\substack{r \in R \\ s' \in S}} [r + \gamma v_\pi(s')]\, p(r, s' \mid s)$$

$$= \sum_{r, s', a} [r + \gamma v_\pi(s')]\, p(s', r \mid s, a)\, \pi(a \mid s) \quad (*)$$

$$\therefore v_\pi(s) = \sum_a \pi(a|s) \sum_{s',r} p(s', r \mid s, a) \left[r + \gamma v_\pi(s') \right]$$

for all $s \in S$

$\circledast \rightarrow$ Used : $p(r, s' \mid s) = \sum_a p(r, s', a \mid s)$

$$= \sum_a p(r, s' \mid s, a) \cdot p(a|s)$$

$$= \sum_a p(r, s' \mid s, a)\, \pi(a|s)$$

(14) Discounted return $G_t = R_{t+1} + R_{t+2}\gamma + \cdots + \gamma^{T-t-1} R_T$

Suppose

~~$G_T = 0 \Rightarrow$~~ $G_4 = 0$

In general, $G_t = R_{t+1} + \gamma(R_{t+2} + \cdots + \gamma^{T-t-2} R_T)$

$$G_t = R_{t+1} + \gamma G_{t+1}$$

$$G_3 = R_4 + \gamma \cdot G_4$$
$$= -3$$

$$G_2 = R_3 + \gamma \cdot G_3$$
$$= 10 + \frac{1}{2} \times (-3) = 10 - \frac{3}{2} = \frac{17}{2} = 8.5$$

$$G_1 = R_2 + \gamma G_2$$
$$= (-1) + \left(\frac{1}{2}\right)\left(\frac{17}{2}\right) = -1 + \frac{17}{4} = \frac{13}{4} = 3.25$$

$$G_0 = R_1 + \gamma G_1$$
$$= 2 + \frac{1}{2} \times \frac{13}{4} = 2 + \frac{13}{8} = \frac{29}{8} = 3.625$$

For continuing task,

$$G_t = R_{t+1} + \gamma R_{t+2} + \cdots$$

Agent receives constant reward c at every time step. Also $\gamma < 1$

$$G_t = c + \gamma c + \gamma^2 c + \cdots$$
$$= c(1 + \gamma + \gamma^2 + \cdots)$$

$$G_t = \frac{c}{1-\gamma} \quad //$$ (since $\gamma < 1$ and $1 + \gamma + \gamma^2 + \cdots$ forms infinite GP)

(15) We know that,

optimal policy $\pi_*(s) = \underset{a \in A(s)}{\operatorname{argmax}}\ q_*(s,a)$

$$\pi_*(s) = \underset{a \in A(s)}{\operatorname{argmax}} \left[\underbrace{E\left[R_{t+1} + \gamma v_*(S_{t+1}) \mid S_t = s, A_t = a\right]}_{\sum_{\substack{r \in R \\ s' \in S}} \left[r + \gamma v_*(s')\right] p(r, s' \mid s, a)} \right]$$

$$\therefore\ \pi_*(s) = \underset{a \in A(s)}{\operatorname{argmax}} \sum_{r} \sum_{s'} \left(r + \gamma v_*(s')\right) p(s', r \mid s, a)$$

for all $s \in S$

(16)

I)

s	a	s'	$r(s,a)$	$p(s' \mid s,a)$
F	Q	F	-4	0.9
F	Q	S	-4	0.1
S	Q	F	-8	0.8
S	Q	S	-8	0.2
F	S	F	4	0.5
F	S	S	4	0.5
S	S	F	4	0
S	S	S	4	1

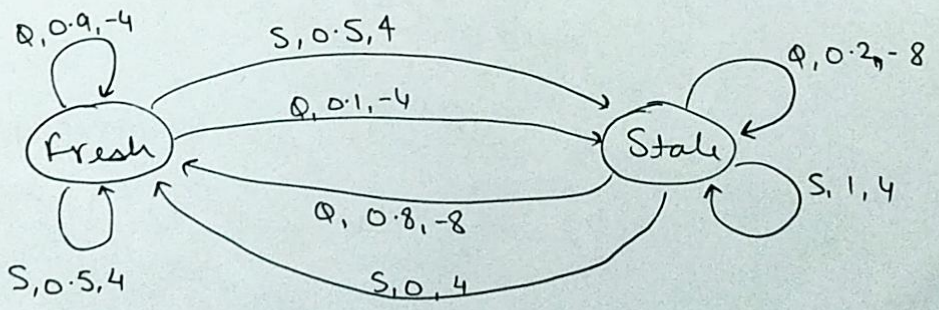
(The remaining entries of $p(s' \mid s,a)$ were calculated using $\sum_{s'} p(s' \mid s,a) = 1$)

States = {Fresh, Stale} = {F, S}

Actions = {Query, Silent} = {Q, S}

Rewards = {-8, -4, 4}

Transition graph:



arrows represent Action, probability $p(s' \mid s,a)$, $r(s,a)$

By Value Iteration:

$$v^*_k(s) = \max_a \sum_{s',r} p(s',r|s,a)\,[r + \gamma v^*_{k-1}(s')]$$

$$= \max_a \left[\sum_{s',r} r\, p(s',r|s,a) + \gamma \sum_{s',r} v_{k-1}(s')\, p(s',r|s,a) \right]$$

$$= \max_a \left[\sum_r r \sum_{s'} p(s',r|s,a) + \gamma \sum_{s'} v_{k-1}(s') \sum_r p(s',r|s,a) \right]$$

$$= \max_a \left[\sum_r r\, p(r|s,a) + \gamma \sum_{s'} v_{k-1}(s')\, p(s'|s,a) \right]$$

$$= \max_a \left[r(s,a) + \gamma \sum_{s'} v_{k-1}(s')\, p(s'|s,a) \right]$$

II) $\gamma = \frac{1}{2}$

For finite horizon problem, over k time steps

$$V_k^*(s) = \max_a \left\{ E[R_t \mid \underset{S_t = s,\, A_t = a}{S_t}] + \gamma \sum_{s'} P(s' \mid a, s)\, V_{k-1}^*(s') \right\}$$

<u>K = 1</u>

$$V_1^*(s) = \max_a E[R_t \mid \underset{A_t = a}{S_t = s}] \qquad (V_0^*(s) = 0 \ \forall s \in S)$$

$\therefore$ we are maximizing immediate rewards

a) $V_1^*(\text{Fresh}) = \max_a E[R_t \mid \underset{A_t = a}{S_t = \text{Fresh}}]$

<u>If a = Q</u>

$$E[R_t \mid \underset{A_t = Q}{S_t = \text{Fresh}}] = 0.9 \times (-4) + 0.1 \times (-4) = -4$$

<u>If a = S</u>

$$E[R_t \mid \underset{A_t = S}{S_t = \text{Fresh}}] = 0.5 \times 4 + 0.5 \times 4 = 4$$

If server is State then reward = -10
" " " fresh " " = 10

If a = Q $\rightarrow$ E[reward given at the end of timestep K]

$$= E[\text{reward} \mid \text{State} = F]\, P[F] + E[\text{reward} \mid \text{State} = S] \times P[S]$$

$$= (10 \times 0.9) + (-10 \times 0.1)$$

$$= 9 - 1 = 8$$

$\therefore$ <u>If a = Q</u> expected reward = $-4 + 8 = 4$ //

If $a = S \rightarrow E[\text{reward at end of timestep } K]$

$$= (10 \times 0.5) + (-10 \times 0.5) = 0$$

$\therefore$ <u>If $a = S$</u> expected reward $= 4 + 0 = 4$ //

$v_1^*(\text{Fresh}) = 4$

b) $v_1^*(\text{Stale}) = \max_a E[R_t \mid S_t = \text{Stale}, A_t = a]$

<u>If $a = Q$</u>

$$E[R_t \mid S_t = \text{Stale}, A_t = Q] = 0.2 \times -8 + 0.8 \times -8 = -8$$

expected reward given at end of timestep K :

$$10 \times 0.8 + (-10) \times 0.2 = 8 - 2 = 6$$

$\therefore$ total expected reward $= -8 + 6 = -2$ //

<u>If $a = S$</u>

$$E[R_t \mid S_t = \text{Stale}, A_t = S] = 1 \times 4 = 4$$

Expected reward given at end of timestep K :

$$1 \times (-10) = -10$$

$\therefore$ total expected reward $= -6$ //

$\therefore v_1^*(\text{Stale}) = -2$

$\underline{K=2}$

$$V_2^*(s) = \max_a \left\{ E[R_t \mid S_t = s, A_t = a] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, V_1^*(s') \right\}$$

a) $$V_2^*(\text{Fresh}) = \max_a \left\{ E[R_t \mid S_t = F, A_t = a] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, V_1^*(s') \right\}$$

<u>If $a = Q$</u>

$$E[R_t \mid S_t = F, A_t = Q] = -4$$

$$\sum_{s'} P(s' \mid a, s)\, V_1^*(s') = 0.9 \times V_1^*(F) + 0.1 \times V_1^*(S)$$

$$= 0.9 \times 4 + 0.1 \times (-2)$$

$$= 3.6 - 0.2 = 3.4$$

$$E[R_t \mid S_t = F, A_t = Q] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, V_1^*(s') = -4 + \frac{3.4}{2}$$

$$= -4 + 1.7 = -2.3$$

Expected reward given $= 0.9 \times 10 - 0.1 \times 10$
$= 8$

$\therefore$ Total expected reward $= 8 - 2.3 = 5.7$

<u>If $a = S$</u>

$$E[R_t \mid S_t = S, A_t = S] = 0.5 \times 4 + 0.5 \times 4 = 4$$

$$\sum_{s'} P(s' \mid a, s)\, V_1^*(s') = 0.5 \times V_1^*(F) + 0.5 \times V_1^*(S)$$

$$= 0.5(4 - 2) = 1$$

$$E[R_t \mid S_t = S, A_t = S] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, V_1^*(s') = 4 + \frac{1}{2} = \frac{9}{2}$$

$$= 4.5$$

Expected reward given $= 10 \times 0.5 - 10 \times 0.5 = 0$

$\therefore$ Total expected reward $= 4.5$

$\therefore V_2^*(\text{Fresh}) = 5.7$ //

b) $v_2^*(\text{Stale}) = \max_a \left\{ E[R_t \mid S_t = S, A_t = a] + \frac{1}{2} \sum_{s'} p(s' \mid a, s)\, v_1^*(s') \right\}$

<u>If $a = Q$</u>

$E[R_t \mid S_t = S, A_t = Q] = -8$

$\sum_{s'} p(s' \mid a, s)\, v_1^*(s') = 0.2 \times v_1^*(S) + 0.8 \times v_1^*(F)$

$= 0.2 \times (-2) + 0.8 \times (4)$

$= \cancel{0.8 - 1.6 = -0.8}$

$= -0.4 + 3.2 = 2.8$

$E[R_t \mid S_t = S, A_t = Q] + \frac{1}{2} \sum_{s'} p(s' \mid a, s)\, v_1^*(s') = -8 + 1.4 = -6.6$

Expected reward given $= 10 \times 0.8 + (-10) \times 0.2$
$= 6$

$\therefore$ Total expected reward $= -6.6 + 6 = -0.6$

<u>If $a = S$</u>

$E[R_t \mid S_t = S, A_t = S] = 4$

$\sum_{s'} p(s' \mid a, s)\, v_1^*(s') = 1 \times v_1^*(S) = -2$

$E[R_t \mid S_t = S, A_t = S] + \frac{1}{2} \sum_{s'} p(s' \mid a, s)\, v_1^*(s') = 4 - 1 = 3$

Expected reward given $= 1 \times (-10) = -10$

$\therefore$ Total exp. reward $= -10 + 3 = -7$

$\therefore v_2^*(\text{Stable}) = -0.6$

$\underline{k=3}$

$$V_3^*(s) = \max_a \left\{ E[R_t \mid S_t = s, A_t = a] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, V_2^*(s') \right\}$$

a) $$V_3^*(\text{fresh}) = \max_a \left\{ E[R_t \mid S_t = F, A_t = a] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, V_2^*(s') \right\}$$

<u>If $a = Q$</u>

$$E[R_t \mid S_t = F, A_t = Q] = -4$$

$$\sum_{s'} P(s' \mid a, s)\, V_2^*(s') = 0.9 \times V_2^*(F) + 0.1 \times V_2^*(S)$$
$$= 0.9 \times 5.7 + 0.1 \times (-0.6)$$
$$= 5.13 - 0.06 = 5.07$$

$$E[R_t \mid S_t = 0, A_t = Q] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, V_2^*(s') = -4 + 2.535$$
$$= -1.465$$

Expected reward given $= 0.9 \times 10 - 0.1 \times 10$
$= 8$

$\therefore$ Total exp. reward $= 8 - 1.465 = 6.535$

<u>If $a = S$</u>

$$E[R_t \mid S_t = F, A_t = S] = 4$$

$$\sum_{s'} P(s' \mid a, s)\, V_2^*(s') = 0.5\left[V_2^*(F) + V_2^*(S) \right]$$
$$= 0.5 \times [5.7 - 0.6]$$
$$= \frac{5.1}{2} = 2.55$$

$$E[R_t \mid S_t = F, A_t = S] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, V_2^*(s') = 4 + \frac{2.55}{2}$$
$$= 4 + 1.275$$
$$= 5.275$$

Total expected reward $= 5.275 + (0.5 \times 10 - 0.5 \times 10)$
$= 5.275$

$\therefore V_3^*(\text{Fresh}) = 6.535$

b) $v_3^*(\text{Stale}) = \max_a \left\{ E[R_t \mid S_t = S, A_t = a] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, v_2^*(s') \right\}$

<u>If $a = Q$</u>

$E[R_t \mid S_t = S, A_t = Q] = -8$

$\sum_{s'} P(s' \mid a, s)\, v_2^*(s') = 0.2 \times v_2^*(S) + 0.8 \times v_2^*(F)$

$= 0.2 \times (-0.6) + 0.8 \times 5.7$

$= 4.56 - 0.12 = 4.44$

~~Exp~~

$E[R_t \mid S_t = S, A_t = Q] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, v_2^*(s')$

$= -8 + \frac{4.44}{2} = \cancel{-3.56}\ -5.8$

Total exp. reward $= \cancel{-3.56}\ -5.8 + [10 \times 0.8 - 10 \times 0.2]$

$= \cancel{-3.56}\ -5.8 + 6 = \cancel{2.44}\ 0.2$

<u>If $a = S$</u>

$E[R_t \mid S_t = S, A_t = S] = 4$

$\sum_{s'} P(s' \mid a, s)\, v_2^*(s') = 1 \times v_2^*(S) = -0.6$

$E[R_t \mid S_t = S, A_t = S] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, v_2^*(s')$

$= 4 - 0.3 = 3.7$

Total exp. reward $= 3.7 + (1 \times -10)$

$= 3.7 - 10 = -6.3$

$\therefore v_3^*(\text{Stale}) = 0.2$ //

Optimal Costs

$V_3^*(F) = 6.535$

$V_3^*(S) = 0.2$

Optimal Policy:

$$\pi(s) = \underset{a}{\operatorname{argmax}} \sum_{s',r} p(s', r \mid s, a)\left[r + \gamma V(s')\right]$$

$$= \underset{a}{\operatorname{argmax}} \left[\sum_{s',r} p(s', r \mid s, a)\, r + \sum_{s',r} \gamma V(s')\, p(s', r \mid s, a) \right]$$

$$= \underset{a}{\operatorname{argmax}} \left[r(s,a) + \frac{1}{2} \sum_{s'} p(s' \mid s, a)\, v(s') \right]$$

$$\pi(F) = \underset{a}{\operatorname{argmax}} \left[r(F, a) + \frac{1}{2} \sum_{s'} p(s' \mid F, a)\, v(s') \right]$$

If $a = Q$

$$RHS = -4 + \frac{1}{2}\left(0.9 \times V(F) + 0.1 \times V(S)\right)$$

$$= -4 + \frac{1}{2}\left[0.9 \times 6.535 + 0.1 \times 0.2\right]$$

$$= -1.05$$

Expected reward given $= 0.9 \times 10 - 0.1 \times 10 = 8$

$\therefore$ Total exp. reward $= -1.05 + 8 = 6.95$

If $a = S$

$$RHS = 4 + \frac{1}{2}\left(0.5 \times (6.735)\right)$$

$$= 5.68$$

Expected reward given $= 0.5 \times 10 - 0.5 \times 10 = 0$

$\therefore$ Total exp. reward $= 5.68$

$\therefore \pi(F) = Q$ //

$$\pi(s) = \underset{a}{\operatorname{argmax}} \left[r(s,a) + \frac{1}{2} \sum_{s'} p(s' \mid s,a)\, v(s') \right]$$

<u>If $a = \varphi$</u>

$$RHS = -8 + \frac{1}{2}\left(0.8\, v(f) + 0.2\, v(s) \right)$$

$$= -8 + \frac{1}{2}\left(0.8 \times 6.535 + 0.2 \times 0.2 \right)$$

$$= -5.366$$

Expected reward given $= 0.8 \times 10 - 0.2 \times 10 = 6$

$\therefore$ Total expected reward $= 6 - 5.366 = 0.634$

<u>If $a = S$</u>

$$RHS = 4 + \frac{1}{2}(-0.2) = 3.9$$

Expected reward given $= -10$

$\therefore$ Total expected reward $= -6.1$

$\therefore \pi(s) = \varphi$ //

Value Iteration

III) From the previous part,

$V_0(\text{Fresh}) = 0$ $\quad$ $V_0(\text{Stale}) = 0$

$V_1(\text{Fresh}) = 4$ $\quad$ $V_1(\text{Stale}) = -2$

$V_2(\text{Fresh}) = 5.7$ $\quad$ $V_2(\text{Stale}) = -0.6$

$V_3(\text{Fresh}) = 6.535$ $\quad$ $V_2(\text{Stale}) = 0.2$

For 4th iteration: $(k=4)$

$$V_4(s) = \max_a \left\{ E[R_t \mid S_t = s, A_t = a] + \frac{1}{2} \sum_{s'} P(s' \mid s, a)\, V_3(s') \right]$$

a) $s = \text{Fresh}$

If $a = Q$

$$E[R_t \mid S_t = F, A_t = Q] = (-4 \times 0.9) + (-4 \times 0.1) = -4$$

$$\sum_{s'} P(s' \mid F, Q)\, V_3(s')$$

$$= P(F \mid F, Q)\, V_3(F) + P(S \mid F, Q)\, V_3(S)$$

$$= 0.9 \times 6.535 + 0.1 \times 0.2$$

$$= 5.8815 + 0.02 = 5.9015$$

$$E[R_t \mid S_t = F, A_t = Q] + \frac{1}{2} \sum_{s'} P(s' \mid F, Q)\, V_3(s')$$

$$= -4 + \frac{5.9015}{2} = -1.04925$$

Expected reward given $= 8(0.9 \times 10 - 0.1 \times 10)$

$\therefore$ Total exp. reward $= 8 - 1.04925$
$= 6.95075$

If $a = S$

$$E[R_t \mid S_t = F, A_t = S] = 4$$

$$\sum_{s'} P(s' \mid F, S)\, V_3(s')$$

$$= 0.5 \times V_3(F) + 0.5\, V_3(S) = \frac{1}{2}(6.735) = 3.3675$$

$$\therefore E[R_t \mid S_t = F, A_t = S] + \frac{1}{2} \sum_{s'} P(s' \mid F, S)\, V_3(s') = 4 + \frac{3.3675}{2} = 5.68$$

Expected rewards given $= 10 \times 0.5 - 10 \times 0.5$

$= 0$

$\therefore$ Total expected reward $=$ ~~6.95075~~ ~~3.3675~~ 5.68

$\therefore v_4(\text{Fresh}) = 6.95075$

b) $v_4(\text{Stale}) = \max_a \left\{ E[R_t \mid S_t = s, A_t = a] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, v_3(s') \right\}$

<u>If $a = Q$</u>

$E[R_t \mid S_t = s, A_t = Q] = -8(0.8 + 0.2) = -8$

$\sum_{s'} P(s' \mid a, s)\, v_3(s') = 0.8 \times v_3(F) + 0.2 \times v_3(S)$

$= 0.8 \times 6.535 + 0.2 \times 0.2$

$= 5.228 + 0.04$

$= 5.268$

$E[R_t \mid S_t = s, A_t = Q] + \frac{1}{2} \sum_{s'} P(s' \mid a, s)\, v_3(s') = -8 + \frac{5.268}{2} = -5.366$

Expected reward given $= 0.8 \times 10 - 0.2 \times 10 = 6$

Total expected reward $= 6 - 5.366 = 0.634$

<u>If $a = S$</u>

$E[R_t \mid S_t = s, A_t = S] = 4$

$\sum_{s'} P(s' \mid a, s)\, v_3(s') = 1 \times v_3(S) = +0.2$

$E[R_t \mid S_t = s, A_t = S] + \frac{1}{2} \sum_{s'} P(s' \mid a, s) = 4 + 0.1 = 4.1$

Expected reward $= -10$

$\therefore$ Total exp. reward $= -10 + 4.1 = -5.9$

$\therefore v_4(\text{Stale}) = 0.634$

∴ For value iteration:

	Fresh	Stale
V_0	0	0
V_1	4	-2
V_2	5.7	-0.6
V_3	6.535	0.2
V_4	6.95075	0.634

Optimal Policy:

$$\pi(f) = \arg\max_a \left[r(f,a) + \frac{1}{2} \sum_{s'} p(s'|f,a)\, v(s') \right]$$

<u>If $a = \phi$</u>

$$RHS = -4 + \frac{1}{2}\left[0.9 \times 6.95 + 0.1 \times 0.634\right]$$

$$= -0.8$$

Expected reward $= -0.8 + 10 \times 0.9 - 10 \times 0.1$

$= -0.8 + 8 = 7.2$

<u>If $a = S$</u>

$$RHS = +4 + \frac{1}{2}\left(0.5(6.95 + 0.634)\right)$$

$$= 5.89$$

Expected reward $= 5.89 + 10 \times 0.5 - 10 \times 0.5$

$= 5.89$

$\therefore \pi(f) = \phi$ //

$$\pi(s) = \arg\max_a \left[r(s,a) + \frac{1}{2} \sum_{s'} p(s'|s,a)\, v(s') \right]$$

<u>If $a = \phi$</u>

$$RHS = -8 + \frac{1}{2}\left(0.8\, v(f) + 0.2\,(v(s))\right)$$

$$= -8 + \frac{1}{2}\left(0.8 \times 6.95 + 0.2 \times 0.634\right)$$

$$= -5.156$$

Expected reward $= -5.156 + 10 \times 0.8 - 10 \times 0.2$

$= -5.156 + 6 = 0.8$

<u>If $a = S$</u>

$$RHS = 4 + \frac{1}{2}(v(s)) = 4 + \frac{1}{2} \times 0.634$$

$$= 4.317$$

Expected reward $= 4.317 - 10 = -5.68$

$\therefore \pi(s) = \phi$ //

Policy Iteration:

① Initial Policy π_0 : $\pi_0(\Phi|s) = \frac{1}{2}$

$\pi_0(S|s) = \frac{1}{2}$ $\forall s \in$ State Set

$V_{\pi_0,0}(s) = 0 \ \forall s$

ⓐ Policy Evaluation:

$$V_{\pi_0,K}(s) = \sum_a \pi(a|s) \sum_{s',r} [r + \gamma V_{\pi_0,K-1}(s')] \, p(s',r|s,a)$$

$$= \sum_a \pi(a|s) \left[\sum_{s',r} r \, p(s',r|s,a) + \sum_{s',r} \gamma V_{\pi_0,K-1}(s') \, p(s',r|s,a) \right]$$

$$= \sum_a \pi(a|s) \left[\sum_r r \, p(r|s,a) + \sum_{s'} \gamma V_{\pi_0,K-1}(s') \, p(s'|s,a) \right]$$

$$= \sum_a \pi(a|s) \left[r(a,s) + \frac{1}{2} \sum_{s'} V_{\pi_0,K-1}(s') \, p(s'|s,a) \right]$$

$\underline{K=1}$

$$\rightarrow V_{\pi_0,1}(F) = \sum_a \pi(a|F) \left[r(a,F) + \frac{1}{2} \sum_{s'} V_{\pi_0,0}(s') \, p(s'|F,a) \right]$$

$\underline{\text{If } a = \Phi}$

$$RHS = \left(\frac{1}{2}\right)\left[-4 + \frac{1}{2} \times 0\right] = -2$$

$\underline{\text{If } a = S}$

$$RHS = \left(\frac{1}{2}\right)\left[4 + \frac{1}{2} \times 0\right] = 2$$

$\therefore V_{\pi_0,1}(F) = 0$

$\rightarrow v_{\pi_0,1}(s) = \sum_a \pi(a|s) \left[r(a,s) + \frac{1}{2} \sum_{s'} v_{\pi_0,0}(s') \cancel{p(s'|s,} \right.$

$p(s'|s,a)$

<u>If $a = Q$</u>

$$RHS = \left(\frac{1}{2}\right)\left[-8 + \frac{1}{2} \times 0\right] = -4$$

<u>If $a = S$</u>

$$RHS = \frac{1}{2}\left[+4\right] = 2$$

$$\therefore v_{\pi_0,1}(s) = -2$$

(b) Policy Improvement:

$$\pi_1(F) = \underset{a}{\operatorname{argmax}} \sum_{s',r} \left(r + \frac{1}{2} v_{\pi_0}(s')\right) p(s',r|F,a)$$

$$= \underset{a}{\operatorname{argmax}} \left[\sum_r r\, p(r|F,a) + \frac{1}{2} \sum_{s'} v_{\pi_0}(s')\, p(s'|F,a) \right]$$

$$= \underset{a}{\operatorname{argmax}} \left[r(F,a) + \frac{1}{2} \sum_{s'} v_{\pi_0}(s')\, p(s'|F,a) \right]$$

<u>If $a = Q$</u>

$$RHS = -4 + \frac{1}{2}\left(0.9 \times 0 + 0.1 \times (-2)\right)$$

$$= -4 + \frac{1}{2} \times -2 \times 0.1 = -4.1$$

Total exp. return $= -4.1 + (0.9 \times 10 - 0.1 \times 10)$
$= -4.1 + 8 = 3.9$

<u>If $a = S$</u>

$$RHS = 4 + \frac{1}{2}\left(0.5 \times \left(v_{\pi_0}(F) + v_{\pi_0}(S)\right)\right)$$

$$= 4 + \frac{1}{2} \times \frac{1}{2} \times -2$$

$$= 4 - 0.5 = 3.5$$

Total expected return
$= 3.5 + [0.5 \times 10 - 0.5 \times 0]$
$= 3.5$

$\therefore \pi_1(F) = Q$

$$\pi_7(S) = \underset{a}{\operatorname{argmax}} \left[r(S,a) + \frac{1}{2} \sum_{s'} v_{\pi_0}(s') \, p(s' \mid S, a) \right]$$

<u>If $a = \Phi$</u>

$$RHS = -8 + \frac{1}{2}\left[0.8 \times 0 + 0.2 \times -2\right]$$

$$= -8 - 0.2 = -8.2$$

Total expected reward $= -8.2 + (0.8 \times 10 - 0.2 \times 10)$

$$= -8.2 + 6 = -2.2$$

<u>If $a = S$</u>

$$RHS = 4 + \frac{1}{2}\left[0.2 \times -2\right] = 4 - 0.2 = 3.8$$

Total expected reward $= 3.8 + (-10 \times 1)$

$$= -10 + 3.8 = -6.2$$

$\therefore \pi_1(S) = \Phi$

(2) Policy π_1 : $\pi_1(F) = \Phi$

$\pi_1(S) = \Phi$

(a) Policy Evaluation

$\rightarrow$ $$v_{\pi_{1,1}}(F) = \sum_{a} \pi_1(a \mid F) \left[r(a, F) + \frac{1}{2} \sum_{s'} v_{\pi_{1,0}}(s') \, p(s' \mid F, a) \right]$$

<u>If $a = \Phi$</u>

$$RHS = -4 + \frac{1}{2} \times 0 = -4$$

<u>If $a = S$</u>

then $RHS = 0$ as $\pi_1(F) = \Phi$ ie $\pi_1(\Phi \mid F) = 1$ ie $\pi_1(S \mid F) = 0$

$\therefore v_{\pi_{1,1}}(F) = -4$

$\rightarrow v_{\pi_{1,0}}(S) = \sum_a \pi_1(a|S)\left[r(a,S) + \frac{1}{2}\sum_{s'} v_{\pi_{1,0}}(s') p(s'|S,a)\right]$

$= -8 \quad (\text{as } \pi_1(S) = \phi)$

(b) Policy Improvement:

$$\pi_2(F) = \underset{a}{\operatorname{argmax}}\left[r(F,a) + \frac{1}{2}\sum_{s'} v_{\pi_1}(s') p(s'|F,a)\right]$$

If $a = \phi$

$RHS = -4 + \frac{1}{2}[0.9 \times -4 + 0.1 \times -8]$

$= -4 + \frac{1}{2}[-4.4] = -6.2$

Total expected reward $= -6.2 + (10 \times 0.9 - 10 \times 0.7)$

$= -6.2 + 8 = 1.8$

If $a = S$

$RHS = 4 + \frac{1}{2}\left[\frac{1}{2}(-4-8)\right]$

$= 4 + \frac{1}{4} \times -12 = 4 - 3 = 1$

Total expected reward $= 1 + (10 \times 0.5 - 10 \times 0.5)$

$= 1$

$\therefore \pi_2(F) = \phi$

$$\pi_2(S) = \underset{a}{\operatorname{argmax}}\left[r(S,a) + \frac{1}{2}\sum_{s'} v_{\pi_1}(s') p(s'|S,a)\right]$$

If $a = \phi$

$RHS = -8 + \frac{1}{2}[0.8 \times -4 + 0.2 \times -8]$

$= -8 + \frac{1}{2}[-4.8] = -8 - 2.4 = -10.4$

Total expected reward $= -10 \cdot 4 + (10 \times 0.8 - 10 \times 0.2)$

$= -10 \cdot 4 + 6 = -4.4$

<u>If $a = S$</u>

$RHS = 4 + \frac{1}{2}(-8) = 0$

Total expected reward $= 0 + (-10) = -10$

$\therefore \pi_2(S) = \phi$

$\therefore \pi_2(F) = \phi = \pi_1(F)$

$\pi_2(S) = \phi = \pi_1(S)$

Optimal Policy is $\pi_*(F) = \phi$

$\pi_*(S) = \phi$

The rest 2 iterations would be same as iteration 2.

(17)

In infinite horizon discounted costs problem, using policy iteration, we do policy improvement via greedy action selection, given $V_{\pi_K}(s)$ for all $s \in S$

Policy improvement:

$$\pi_{K+1}(s) = \underset{a \in A(s)}{\operatorname{argmax}} \; E[R_{t+1} + \gamma V_{\pi_K}(S_{t+1}) \mid S_t = s, A_t = a]$$

We are choosing the greedy action in policy π_{K+1}
The resulting value function is $V_{\pi_{K+1}}(s) \; \forall s$

$$V_{\pi_{K+1}}(s) = \max_{a \in A(s)} E[R_{t+1} + \gamma V_{\pi_K}(S_{t+1}) \mid S_t = s, A_t = a] \quad \text{— (1)}$$

Since we are picking the greedy action with probability 1 in (1):

$$(1) \geq E_{\pi_K}[R_{t+1} + \gamma V_{\pi_K}(S_{t+1}) \mid S_t = s] \quad \text{— (2)}$$

where in RHS we choose actions with probability given by π_K

We assign policy π_{K+1} st

$$T_{\pi_{K+1}} V_{\pi_K}(s) = T V_{\pi_K}(s) \quad \text{— (4)}$$

$\downarrow$ greedy action selection (max operation)

$\therefore$ (2) becomes

$$T V_{\pi_K}(s) \geq T_{\pi_K} V_{\pi_K}(s)$$

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We need to show that policy improvement step either improves the policy or leaves it unchanged. If it is left unchanged then the policy is optimal

$$T v_{\pi_k}(s) \geq T_{\pi_k} v_{\pi_k}(s)$$

$$T_{\pi_{k+1}} v_{\pi_k}(s) \geq T_{\pi_k} v_{\pi_k}(s) \quad [\text{as } T v_{\pi_k}(s) = T_{\pi_{k+1}} v_{\pi_k}(s)]$$

$$T_{\pi_{k+1}} v_{\pi_k}(s) \geq v_{\pi_k}(s) \quad [\text{since } T_{\pi_k} v_{\pi_k}(s) = v_{\pi_k}(s)]$$

$$E_{\pi_{k+1}}[R_{t+1} + \gamma v_{\pi_k}(S_{t+1}) \mid S_t = s] \geq v_{\pi_k}(s)$$

Suppose $g(s) = E_{\pi_{k+1}}[R_{t+1} + \gamma v_{\pi_k}(S_{t+1}) \mid S_t = s]$

$$\therefore g(s) \geq v_{\pi_k}(s)$$

Now, $T_{\pi_{k+1}} g(s) = E_{\pi_{k+1}}[R_{t+1} + \gamma g(S_{t+1}) \mid S_t = s]$

~~$= E_{\pi_{k+1}}[R_{t+1} + \gamma$~~

Since $g(s) \geq v_{\pi_k}(s)$

$$E_{\pi_{k+1}}[R_{t+1} + \gamma g(S_{t+1}) \mid S_t = s] \geq v_{\pi_k}(s)$$

$$\therefore T_{\pi_{k+1}} g(s) \geq v_{\pi_k}(s)$$

$$\therefore T_{\pi_{k+1}} T_{\pi_{k+1}} v_{\pi_k}(s) \geq v_{\pi_k}(s)$$

(*) as $\lim_{N\to\infty} T_{\pi_{k+1}} v_{\pi_k}(s)$ is policy evaluation step.

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Continuing in this manner, we get

$$T_{\pi_{k+1}} T_{\pi_{k+1}} \cdots T_{\pi_{k+1}} v_{\pi_k}(s) \geq v_{\pi_k}(s)$$

$$\lim_{N\to\infty} T^N_{\pi_{k+1}} v_{\pi_k}(s) \geq v_{\pi_k}(s)$$

$\lim_{N\to\infty} T^N_{\pi_{k+1}} v_{\pi_k}(s) = v_{\pi_{k+1}}(s)$ ~~as~~ due to policy evaluation (*)

$$\therefore \quad v_{\pi_{k+1}}(s) \geq v_{\pi_k}(s) \text{ for all } s$$

$\therefore$ This shows that policy improvement step either improves the policy or leaves it unchanged.

Now we need to show that if policy left unchanged then policy is optimal ie if

$v_{\pi_{k+1}}(s) = v_{\pi_k}(s) \ \forall s$ then $\pi_k = \pi_{k+1}$ is optimal policy

$$v_{\pi_{k+1}}(s) = v_{\pi_k}(s) \quad \forall s \quad \text{— (3)}$$

$v_{\pi_{k+1}}(s) = T_{\pi_{k+1}} v_{\pi_{k+1}}(s)$ and $v_{\pi_k}(s) = T_{\pi_k} v_{\pi_k}(s)$

$\therefore$ (3) implies

$$v_{\pi_{k+1}}(s) = T_{\pi_{k+1}} v_{\pi_{k+1}}(s) = v_{\pi_k}(s) = T_{\pi_k} v_{\pi_k}(s)$$

Since $T_{\pi_{k+1}} v_{\pi_{k+1}}(s) = T_{\pi_{k+1}} v_{\pi_k}(s) = T v_{\pi_k}(s)$ (from (4))

$$T v_{\pi_k}(s) = v_{\pi_k}(s) \quad \forall s$$

This means that $v_{\pi_k}(s)$ is a fixed point of T

$$\therefore v_{\pi_k}(s) = \max_{a\in A(s)} E\left[R_{t+1} + \gamma v_{\pi_k}(S_{t+1}) \mid S_t = s, A_t = a\right]$$

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$\therefore$ $v_{\pi_k}(s)$ is a fixed point of bellman optimality equations and we know that bellman optimality equations have a unique fixed point which is the optimal value function $v_*(s)$

$$\therefore v_{\pi_k}(s) = v_{\pi_{k+1}}(s) = v_*(s)$$

$\therefore$ $\pi_k(s) = \pi_{k+1}(s)$ is the optimal policy

(18) $n=2, \quad r=1$

s	a	s'	r	$p(s', r \mid s, a)$
1	D	0	1	1
1	U	2	-1	1
2	D	1	2	0.5
2	D	1	0	0.5
2	U	3	4	1

States = $\{0, 1, 2, 3\}$ where states 0 and 3 are terminal states (state 0 represents G, State 3 represents F)

Actions = {Up, Down} = $\{U, D\}$

<u>Policy Iteration</u>

① Initial policy π_0 : $\pi_0(U \mid s) = \frac{1}{2} \quad \forall s \in S$

$\pi_0(D \mid s) = \frac{1}{2}$

$V_{\pi_0, 0}(s) = 0 \quad \forall s \in S$

ⓐ Policy Evaluation:

$$V_{\pi_0, K}(s) = \sum_a \pi(a \mid s) \sum_{s', r} \left[r + V_{\pi_0, K-1}(s') \right] p(s', r \mid s, a)$$

<u>$K = 1$</u>

$\rightarrow V_{\pi_0, K}(0) = 0$] as States 0 & 3 are terminal states $\forall K$

$\rightarrow V_{\pi_0, K}(3) = 0$

$$\rightarrow V_{\pi_0, 1}(1) = \sum_a \pi(a \mid 1) \sum_{s', r} \left[r + V_{\pi_0, 0}(s') \right] p(s', r \mid 1, a)$$

<u>If $a = U$</u>

$$RHS = \left(\frac{1}{2}\right)\left[(-1+0)(1)\right] = -\frac{1}{2}$$

If $a = D$

$$RHS = \left(\frac{1}{2}\right)\left[(1+0)\,1\right] = \frac{1}{2}$$

$$\therefore v_{\pi_{0,1}}(1) = 0$$

$$\rightarrow v_{\pi_{0,1}}(2) = \sum_{a} \pi(a|s) \sum_{s',r} \left[r + v_{\pi_{0,0}}(s')\right] p(s',r|s,a)$$

If $a = U$

$$RHS = \left(\frac{1}{2}\right)\left[(4+0)\,1\right] = 2$$

If $a = D$

$$RHS = \left(\frac{1}{2}\right)\left[(2+0)\frac{1}{2} + (0+0)\frac{1}{2}\right] = \frac{1}{2}$$

$$\therefore v_{\pi_{0,1}}(2) = \frac{5}{2}$$

$K = 2$

$$v_{\pi_{0,2}}(s) = \sum_{a} \pi(a|s) \sum_{s',r} \left[r + v_{\pi_{0,1}}(s')\right] p(s',r|s,a)$$

$$\rightarrow v_{\pi_{0,2}}(1) = \sum_{a} \pi(a|1) \sum_{s',r} \left[r + v_{\pi_{0,1}}(s')\right] p(s',r|1,a)$$

If $a = U$

$$RHS = \left(\frac{1}{2}\right)\left[-1 + v_{\pi_{0,1}}(2)\right]1 = \left(\frac{1}{2}\right)\left[-1 + \frac{5}{2}\right] = \frac{3}{4}$$

If $a = D$

$$RHS = \left(\frac{1}{2}\right)\left[+1 + v_{\pi_{0,1}}(0)\right]1 = \frac{1}{2}(1+0) = \frac{1}{2}$$

$$\therefore v_{\pi_{0,2}}(1) = \frac{5}{4}$$

$$\rightarrow v_{\pi_0,2}(2) = \sum_a \pi(a|2) \sum_{s',r} \left[r + v_{\pi_0,1}(s') \right] p(s',r|2,a)$$

<u>If $a = U$</u>

$$RHS = \left(\frac{1}{2}\right)\left[(4+0)\ 1\right] = 2$$

<u>If $a = D$</u>

$$RHS = \left(\frac{1}{2}\right)\left[(2+0)\ \frac{1}{2}\right] = \frac{1}{2}$$

$$\therefore v_{\pi_0,2}(2) = \frac{5}{2}$$

<u>$K = 3$</u>

$$\rightarrow v_{\pi_0,3}(1) = \sum_a \pi(a|1) \sum_{s',r} \left[r + v_{\pi_0,2}(s') \right] p(s',r|1,a)$$

<u>If $a = U$</u>

$$RHS = \left(\frac{1}{2}\right)\left[-1 + \frac{5}{2}\right] = \frac{3}{4}$$

<u>If $a = D$</u>

$$RHS = \left(\frac{1}{2}\right)\left[1\right] = \frac{1}{2}$$

$$\therefore v_{\pi_0,3}(1) = \frac{5}{4}$$

$$\rightarrow v_{\pi_0,3}(2) = \sum_a \pi(a|2) \sum_{s',r} \left[r + v_{\pi_0,3}(s') \right] p(s',r|2,a)$$

<u>If $a = U$</u>

$$RHS = \left(\frac{1}{2}\right)\left[4\right] = 2$$

<u>If $a = D$</u>

$$RHS = \left(\frac{1}{2}\right)\left[\left[2 + \frac{5}{4}\right]\frac{1}{2} + \left[0 + \frac{5}{4}\right]\frac{1}{2}\right]$$

$$= \left(\frac{1}{2}\right)\left[\frac{13}{8} + \frac{5}{8}\right] = \frac{9}{8}$$

$$\therefore v_{\pi_0,3}(2) = 2 + \frac{9}{8} = \frac{25}{8}$$

$\underline{K=4}$

$$\rightarrow V_{\pi_0,4}(1) = \sum_a \pi(a|1) \sum_{s',r} \left[r + V_{\pi_0,3}(s')\right] p(s',r|1,a)$$

$\underline{\text{If } a = U}$

$$RHS = \left(\frac{1}{2}\right)\left[-1 + \frac{25}{8}\right] = \frac{1}{2} \times \frac{17}{8} = \frac{17}{16}$$

$\underline{\text{If } a = D}$

$$RHS = \left(\frac{1}{2}\right)[1] = \frac{1}{2}$$

$$\therefore V_{\pi_0,4}(1) = \frac{17+8}{16} = \frac{25}{16}$$

$$\rightarrow V_{\pi_0,4}(2) = \sum_a \pi(a|2) \sum_{s',r} \left[r + V_{\pi_0,3}(s')\right] p(s',r|2,a)$$

$\underline{\text{If } a = U}$

$$RHS = \left(\frac{1}{2}\right)[4] = 2$$

$\underline{\text{If } a = D}$

$$RHS = \left(\frac{1}{2}\right)\left[\left(2 + \frac{5}{4}\right)\frac{1}{2} + \frac{5}{4} \times \frac{1}{2}\right]$$

$$= \left(\frac{1}{2}\right)\left[\frac{13}{8} + \frac{5}{8}\right] = \frac{9}{8}$$

$$\therefore V_{\pi_0,4}(2) = \frac{25}{8}$$

Since the difference b/w last 2 successive iterations of policy iteration ≈ 0.3, we'll move to policy improvement phase.

(b) Policy Improvement:

$$\rightarrow \pi_1(1) = \underset{a}{\operatorname{argmax}} \sum_{s',r} \left(r + v_{\pi_0}(s')\right) p(s', r \mid 1, a)$$

<u>If $a = U$</u>

$$RHS = \left[-1 + v_{\pi_0}(2)\right] = -1 + \frac{25}{8} = \frac{17}{8}$$

<u>If $a = D$</u>

$$RHS = \left[1 + v_{\pi_0}(0)\right] = 1$$

$\therefore$ ~~$\pi_1(1) = D$~~

$\therefore \pi_1(1) = U$

$$\rightarrow \pi_1(2) = \underset{a}{\operatorname{argmax}} \sum_{s',r} \left(r + v_{\pi_0}(s')\right) p(s', r \mid 2, a)$$

<u>If $a = U$</u>

$$RHS = [4] = 4$$

<u>If $a = D$</u>

$$RHS = \left[\left(2 + v_{\pi_0}(1)\right)\frac{1}{2} + v_{\pi_0}\left(\frac{1}{8}\right)\frac{1}{2}\right]$$

$$= \left(2 + \frac{25}{16}\right)\frac{1}{2} + \frac{25}{16} \times \frac{1}{2}$$

$$= 1 + \frac{25}{16} = \frac{41}{16}$$

$\therefore \pi_1(2) = U$

$\therefore \pi_1(1) = U$ ~~$\forall s \in S$, non terminal state~~.

$\pi_1(2) = U$

$\therefore \pi_1(U \mid 1) = 1, \quad \pi_1(D \mid 1) = 0$

$\pi_1(U \mid 2) = 1, \quad \pi_1(D \mid 2) = 0$

② Policy : π_1

ⓐ Policy Evaluation :

$$v_{\pi_1,k}(s) = \sum_a \pi(a|s) \sum_{s',r} \left[r + v_{\pi_1,k-1}(s')\right] p(s',r|s,a)$$

<u>K = 0</u>

$v_{\pi_1,0}(s) = 0 \quad \forall s \in S$

<u>K = 1</u>

$$\rightarrow v_{\pi_1,1}(1) = \sum_a \pi(a|1) \sum_{s',r} \left[r + v_{\pi_1,0}(s')\right] p(s',r|s,a)$$

~~If a ≠ U~~ ~~RHS =~~

$$= \pi(U|1) \sum_{s',r} \left[r + v_{\pi,0}(s')\right] p(s',r|s,a)$$

$$v_{\pi_1,1}(1) = \sum_{s',r} \left[r + v_{\pi,0}(s')\right] p(s',r|1,a)$$

$$= -1$$

$$\rightarrow v_{\pi_1,1}(2) = \pi(U|2) \sum_{s',r} \left[r + v_{\pi,0}(s')\right] p(s',r|2,a)$$

$$= 4$$

<u>K = 2</u>

$$\rightarrow v_{\pi_1,2}(1) = \sum_{s',r} \left[r + v_{\pi,1}(s')\right] p(s',r|1,U)$$

$$= \cancel{(-1-1) = 2}$$

$$= -1 + v_{\pi,1}(2) = -1 + 4 = 3$$

$$\rightarrow v_{\pi_1,2}(2) = \sum_{s',r} \left[r + v_{\pi,1}(s')\right] p(s',r|2,U)$$

$$= 4 + v_{\pi,1}(3) = 4$$

$\underline{k=3}$

$$\rightarrow V_{\pi_1,3}(1) = \sum_{s',r} \left[r + V_{\pi_1,2}(s')\right] p(s',r \mid 1,U)$$

$$= -1 + 4 = 3$$

$$\rightarrow V_{\pi_1,3}(2) = \sum_{s',r} \left[r + V_{\pi_1,2}(s')\right] p(s',r \mid 2,U)$$

$$= 4$$

$\therefore$ Last 2 iterations of policy evaluations are same. We can move to policy improvement

(b) Policy Improvement:

$$\rightarrow \pi_2(1) = \underset{a}{\operatorname{argmax}} \sum_{s',r} \left(r + V_{\pi_1}(s')\right) p(s',r \mid 1,a)$$

<u>If $a = U$</u>

$$RHS = -1 + V_{\pi_1}(2) = -1 + \cancel{4} = \cancel{2}\ 3$$

<u>If $a = D$</u>

$$RHS = 1 + V_{\pi_1}(\cancel{2}) = 1$$

$$\therefore \pi_2(1) = U$$

$$\rightarrow \pi_2(2) = \underset{a}{\operatorname{argmax}} \sum_{s',r} \left(r + V_{\pi_1}(s')\right) p(s',r \mid 2,a)$$

<u>If $a = U$</u>

$$RHS = 4 + V_{\pi_1}(3) = 4$$

<u>If $a = D$</u>

$$RHS = \left[2 + V_{\pi_1}(1)\right]\frac{1}{2} + V_{\pi_1}(1) \times \frac{1}{2}$$

$$= \frac{2+3}{2} + \frac{3}{2} = \frac{5}{2} + \frac{3}{2} = 4$$

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③ Policy π_2

π_2 : $\pi_2(U|1) = 1$

$\pi_2(U|2) = \frac{1}{2}$ $\quad$ $\pi_2(D|2) = \frac{1}{2}$

ⓐ Policy Evaluation:

$\underline{k=1}$

$\rightarrow V_{\pi_{2,1}}(s) = \sum_a \pi(a|s) \sum_{s',r} [r + V_{\pi_{2,0}}(s')] p(s',r|s,a)$

$\underline{\text{If } a=U}$

RHS = -1

$\underline{\text{If } a=D}$

RHS = 0 as $\pi(D|1)=0$

$\therefore V_{\pi_{2,1}}(1) = -1$

$\rightarrow V_{\pi_{2,1}}(2) = \sum_a \pi(a|2) \sum_{s',r} [r + V_{\pi_{2,0}}(s')] p(s',r|2,a)]$

$\underline{\text{If } a=U}$

RHS = $\frac{1}{2} \times 4 = 2$

$\underline{\text{If } a=D}$

RHS = $\frac{1}{2} \times \left[2 \times \frac{1}{2}\right] = \frac{1}{2}$

$V_{\pi_{2,1}}(2) = \frac{5}{2}$

$\boxed{k=2}$

$\rightarrow v_{\pi_{2,2}}(1) = \sum_{a} \pi(a|1) \sum_{s',r} \left[\left[r + v_{\pi_{2,1}}(s') \right] p(s',r|1,a) \right]$

<u>If $a=U$</u>

$RHS = -1 + v_{\pi_{2,1}}(2)$

$= -1 + \frac{5}{2} = \frac{3}{2}$

$v_{\pi_{2,2}}(1) = \frac{3}{2}$

$\rightarrow v_{\pi_{2,2}}(2) = \sum_{a} \pi(a|2) \sum_{s',r} \left[\left(r + v_{\pi_{2,1}}(s') \right) p(s',r|2,a) \right]$

<u>If $a=U$</u>

$RHS = 4 \times \frac{1}{2} = 2$

<u>If $a=D$</u>

$RHS = \frac{1}{2} \left[\frac{2 + (-1)}{2} + \frac{(-1)}{2} \right]$

$= \frac{1}{2} [0] = 0$

$\therefore v_{\pi_{2,2}}(2) = 2$

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$\boxed{k=3}$

$\rightarrow v_{\pi_{2,3}}(1) = \sum_a \pi(a|1) \sum_{s',r} \left[r + v_{\pi_{2,2}}(s')\right] p(s',r|1,a)$

$= -1 + 2 = 1$

$\rightarrow v_{\pi_{2,3}}(2) = \sum_a \pi(a|2) \sum_{s',r} \left[\left[r + v_{\pi_{2,3}}(s')\right] p(s',r|2,a)\right]$

If $a = U$

$RHS = \left(\frac{1}{2}\right)\left[4\right] = 2$

If $a = D$

$RHS = \frac{1}{2}\left[\left(2 + \frac{3}{2}\right)\frac{1}{2} + \frac{3}{2}\left(\frac{1}{2}\right)\right]$

$= \frac{1}{2}\left[1 + \frac{3}{2}\right] = \frac{5}{4}$

$v_{\pi_{2,3}}(2) = \frac{8+5}{4} = \frac{13}{4}$

(b) Policy Improvement

$\rightarrow \pi_3(1) = \underset{a}{\operatorname{argmax}} \sum_{s',r} \left(r + v_{\pi_2}(s')\right) p(s',r|1,a)$

If $a = U$

$RHS = -1 + v_{\pi_2}(2) = -1 + \frac{13}{4} = \frac{9}{4}$

If $a = D$

$RHS = 1 + v_{\pi_2}(0) = 1$

$\therefore \pi_3(1) = U$

$$\rightarrow \pi_3(2) = \underset{a}{\operatorname{argmax}} \sum_{s',r} \left[r + v_{\pi_2}(s')\right] p(s',r|2,a)$$

<u>If $a = U$</u>

$$RHS = \frac{4}{2}$$

<u>If $a = D$</u>

$$RHS = \frac{1}{2}\left[2 + v_{\pi_2}(1)\right] + \frac{1}{2}\left[v_{\pi_2}(1)\right]$$

$$= 1 + v_{\pi_2}(1)$$

$$= 1 + 1 = 2$$

$$\therefore \pi_3(2) = U$$

This is the same as policy π_1

$\therefore$ There are 2 optimal policies :

$\pi_1^*(1) = U$ $\qquad$ $\pi_2^*(1) = U$

$\pi_1^*(2) = U/D$ $\qquad$ $\pi_2^*(2) = U$

~~But~~ In policy π_1^*, the reward would be same if one goes down to step 1 then goes up to step 2 (repeats this any number of times, as reward $= -1 + 1 = 0$) and in the end go up to step 3 and terminate the process.

~~Theoretically~~

As $n \uparrow$, no of optimal policies $\uparrow$ and no of iterations to find those policies ~~would~~ should increase. However if one follows that argmax returns lower index, then U would always be chosen as the action for any state as the reward for transition from step n to step f is 2n which covers all costs of ascending & results in bigger reward than descending.

(19)

s	a	s'	$r(s,a,s')$	$p(s' \mid s,a)$
H	I	H	9.5	0.95
H	I	S	-9	0.05
H	O	H	18	0.7
H	O	S	-9	0.3
S	M	S	-2	0.1
S	M	H	-1	0.9
S	N	S	-1	0.4
S	N	H	0	0.6

States = {Healthy, Sick} = {H, S}

A(Sick) = {Medicine, nomedicine} = {M, N}

A(healthy) = {Inside, Outside} = {I, O}

For State s = Sick $r(s', a, s)$ is deterministic.
for all $a \in A(s)$
$s' \in$ State Set

For State s = Healthy,

$\rightarrow r(H, I, H) = E[R_t \mid S_t = H, A_t = I, S_{t+1} = H]$

$$= \sum_{a \in A(s)} r\, p(r \mid H, I, H)$$

$$= 10 \times 0.95 + 0 \times 0.05 = 9.5$$

$\rightarrow r(H, I, S) = -10 \times 0.9 + 0 \times 0.1 = -9$

$\rightarrow r(H, O, H) = 20 \times 0.9 + 0 \times 0.1 = 18$

$\rightarrow r(H, O, S) = -10 \times 0.9 + 0 \times 0.1 = -9$

(20) policy π: $\pi(I \mid H) = \frac{1}{2}$ $\quad \pi(N \mid S) = \frac{1}{2}$

$\pi(O \mid H) = \frac{1}{2}$ $\quad \pi(M \mid S) = \frac{1}{2}$

Using Iterative Policy Evaluation with initial state value function: $V_{\pi,0}(s) = 0 \quad \forall s \in S$

$$V_{\pi,k}(s) = \sum_a \pi(a \mid s) \sum_{s',r} p(s', r \mid s, a) \left[r + \gamma V_{\pi,k-1}(s') \right]$$

$$= \sum_a \pi(a \mid s) \left[\sum_{s',r} r\, p(s', r \mid s, a) + \sum_{s',r} \gamma V_{\pi,k-1}(s') \, p(s', r \mid s, a) \right]$$

$$= \sum_a \pi(a \mid s) \left[\sum_{s'} p(s' \mid s, a)\, r(s, a, s') + \sum_{s'} \gamma V_{\pi,k-1}(s') \, p(s' \mid s, a) \right]$$

$$= \sum_a \pi(a \mid s) \left[\sum_{s'} p(s' \mid s, a) \left[r(s', a, s) + \gamma V_{\pi,k-1}(s') \right] \right]$$

$\underline{K=1}$

$$v_{\pi,1}(s) = \sum_a \pi(a|s) \left[\sum_{s'} p(s'|s,a) \left[r(s',a,s) + \gamma v_{\pi,0}(s') \right] \right]$$

$$v_{\pi,1}(s) = \sum_a \pi(a|s) \sum_{s'} p(s'|s,a)\, r(s',a,s)$$

$\underline{s = \text{Healthy}}$

$\underline{\text{If } a = I}$

$$\text{RHS} = \left(\tfrac{1}{2}\right)\left[0.95 \times 9.5 + 0.05 \times -9 \right]$$

$$= \left(\tfrac{1}{2}\right)\left[8.575 \right] = 4.2875$$

$\underline{\text{If } a = O}$

$$\text{RHS} = \left(\tfrac{1}{2}\right)\left[18 \times 0.7 + 0.3 \times -9 \right] = \frac{9.9}{2} = 4.95$$

$$v_{\pi,1}(H) = 9.2375$$

$\underline{s = \text{Sick}}$

$\underline{\text{If } a = M}$

$$\text{RHS} = \left(\tfrac{1}{2}\right)\left[-0.2 - 0.9 \right] = -0.55$$

$\underline{\text{If } a = N}$

$$\text{RHS} = \left(\tfrac{1}{2}\right)\left[-0.4 \right] = -0.2$$

$$v_{\pi,1}(S) = -0.75$$

$\underline{K=2}$

$$V_{\pi,2}(s) = \sum_a \pi(a|s) \sum_{s'} p(s'|s,a)\left[r(s',a,s) + \gamma V_{\pi,1}(s')\right]$$

$\underline{s = \text{Healthy}}$

$$V_{\pi,2}(H) = \sum_a \pi(a|H) \sum_{s'} p(s'|H,a)\left[r(s',a,H) + \frac{9}{10} V_{\pi,1}(s')\right]$$

$\underline{\text{If } a = I}$

$$\text{RHS} = \left(\frac{1}{2}\right)\Big[0.95\left[9.5 + 0.9 \times V_{\pi,1}(H)\right] + 0.05\left[-9 + 0.9 \times V_{\pi,1}(S)\right]\Big]$$

$$= \frac{1}{2}\left[0.95\left(9.5 + 0.9 \times 9.2375\right) + 0.05\left(-9 + 0.9 \times -0.75\right)\right]$$

$$= 8.22$$

$\underline{\text{If } a = O}$

$$\text{RHS} = \left(\frac{1}{2}\right)\Big[0.7\left(18 + 0.9 \times 9.2375\right) + 0.3\left(-9 + 0.9 \times -0.75\right)\Big]$$

$$= \left(\frac{1}{2}\right)\{\quad = 7.75875$$

$$V_{\pi,2}(H) = 15.978$$

$s = S$

If $a = M$

$$RHS = \left(\frac{1}{2}\right)\left[0.1 \times \left[-2 + 0.9 \times v_{\pi,1}(S)\right] + 0.9 \times \left[-1 + 0.9 \times v_{\pi,1}(H)\right]\right]$$

$$= \left(\frac{1}{2}\right)\left[0.1\left(-2 + 0.9 \times (-0.75)\right) + 0.9\left(-1 + 0.9 \times (9.2375)\right)\right]$$

$$= 3.157$$

If $a = N$

$$RHS = \left(\frac{1}{2}\right)\left[0.4\left(-1 + 0.9 \times (-0.75)\right) + 0.6\left(0 + 0.9 \times 9.2375\right)\right]$$

$$= 2.16$$

$$v_{\pi,2}(S) = 5.317$$

$K = 3$

$s = H$

If $a = I$

$$RHS = \left(\frac{1}{2}\right)\left[0.95\left(9.5 + 0.9 \times 15.978\right) + 0.05\left(-9 + 0.9 \times 5.317\right)\right]$$

$$= 11.23$$

If $a = O$

$$RHS = \left(\frac{1}{2}\right)\left[0.7\left(18 + 0.9 \times 15.978\right) + 0.3\left(-9 + 0.9 \times 5.317\right)\right]$$

$$= 10.07$$

$$v_{\pi,3}(H) = 21.93 \approx 22$$

$s = S$

$$v_{\pi,3}(S) = \left(\frac{1}{2}\right)\left[0.1\left(-2 + 0.9 \times 5.317\right) + 0.9 \times \left(-1 + 0.9 \times 15.978\right)\right]$$

$$+ \left(\frac{1}{2}\right)\left[0.4\left(-1 + 0.9 \times 5.317\right) + 0.6\left(0.9 \times 15.978\right)\right]$$

$$= \frac{13.2}{2} + \frac{10.13}{2} = 11.665$$

$$\therefore v_{\pi,3}(S) = 11.665$$

$k = 4$

$$v_{\pi,4}(H) = \left(\frac{1}{2}\right)\left[0.95\left(9.5 + 0.9 \times 22\right) + 0.05\left(-9 + 0.9 \times 11.665\right)\right]$$

$$+$$

$$\left(\frac{1}{2}\right)\left[0.7\left(18 + 0.9 \times 22\right) + 0.3\left(-9 + 0.9 \times \cancel{5.317}\ 11.665\right)\right]$$

$$= 13.94 + \cancel{12.6}\ 13.455 = \cancel{26.54}\ 27.4$$

$$v_{\pi,4}(S) = \left(\frac{1}{2}\right)\left[0.1\left(-2 + 0.9 \times 11.665\right) + 0.9\left(-1 + 0.9 \times 22\right)\right]$$

$$+ \left(\frac{1}{2}\right)\left[0.4\left(-1 + 0.9 \times 11.665\right) + 0.6\left(0.9 \times 22\right)\right]$$

$$= 8.885 + 7.84 = 16.725$$

$\underline{K=5}$

$$v_{\pi,5}(H) = \left(\frac{1}{2}\right)\left[0.95\left(9.5 + 0.9 \times \overset{27.4}{\cancel{26.54}}\right) + 0.05\left(-9 + 0.9 \times 16.725\right)\right]$$

$$+$$

$$\left(\frac{1}{2}\right)\left[0.7\left(18 + 0.9 \times \overset{27.4}{\cancel{26.54}}\right) + 0.3\left(-9 + 0.9 \times 16.725\right)\right]$$

$$= 16.376 + 15.8 \approx 32$$

$$v_{\pi,5}(S) = \left(\frac{1}{2}\right)\left[0.1\left(-2 + 0.9 \times 16.725\right) + 0.9\left(-1 + 0.9 \times 27.4\right)\right]$$

$$+$$

$$\left(\frac{1}{2}\right)\left[0.4\left(-1 + 0.9 \times 16.725\right) + 0.6\left(0.9 \times 27.4\right)\right]$$

$$= 11.3 + 10.2 = 21.5$$

$\therefore v_\pi(H) = 32$ and $v_\pi(S) = 21.5$ at the end of 5th iteration.

(21) $E[G_t \mid S_t = s, S_{t+1} = s'] = E[R_{t+1} + \gamma G_{t+1} \mid S_t = s, S_{t+1} = s']$

$$= \underbrace{E[R_{t+1} \mid S_t = s, S_{t+1} = s']}_{} + \gamma \underbrace{E[G_{t+1} \mid S_t = s, S_{t+1} = s']}_{}$$

$$\sum_{a \in A(s)} E[R_{t+1} \mid S_t = s, S_{t+1} = s', A_t = a] \cdot Pr[A_t = a \mid S_t = s, S_{t+1} = s']$$

$$= \cancel{\sum_{a \in A(s)}} \cancel{r(s', \cdot}$$

$$= \sum_{a \in A(s)} E[R_t \mid S_{t-1} = s, S_t = s', A_{t-1} = a] \cdot Pr[A_t = a \mid S_t = s, S_{t+1} = s']$$

(Time Homogeinity)

$$= \sum_{a \in A(s)} r(s', a, s) \cdot Pr[A_t = a \mid S_t = s]$$

(as A_t does not depend on S_{t+1})

$$= \sum_{a \in A(s)} r(s', a, s) \, \pi(a \mid s)$$

$\gamma E[G_{t+1} \mid S_{t+1} = s']$ as G_{t+1} does not dependent on S_t

$$= \cancel{\gamma v_\pi(s')}$$

$$= \gamma E[G_t \mid S_t = s'] \text{ (Time homogeinity)}$$

$$= \gamma v_\pi(s')$$

$s = H$, $s' = S$

$$\therefore E[G_t \mid S_t = H, S_{t+1} = S] = \sum_{a \in A(H)} r(s', a, s) \, \pi(a \mid s) + \gamma v_\pi(S)$$

$$= \left(\frac{1}{2}\right)\left[-9 \times \frac{1}{2} + -9 \times \frac{1}{2}\right] + 0.9 \times 21.5$$

$$= -4.5 + 19.35 = 14.85$$

$E[R_{t+1} \mid S_t = s, S_{t+1} = s']$ was calculated by first using the formula of conditional Expectation to get $\sum_{a \in A(s)} E[R_{t+1} \mid S_t = s, S_{t+1} = s', A_t = a] \cdot Pr[A_t = a \mid S_t = s, S_{t+1} = s']$

The 1st term can be written as $E[R_t \mid S_{t-1} = s, S_t = s', A_{t-1} = a]$ due to time homogeinity & this is $r(s', a, s)$

The 2nd term can be written as $Pr[A_t = a \mid S_t = s]$ as A_t does not depend on S_{t+1}. $Pr[A_t = a \mid S_t = s] = \pi[a \mid s]$ which we know. Finally we take sum over all $a \in A(s) \Rightarrow a \in \{I, O\}$

(22) <u>Policy Iteration</u>

I) Initial Policy π_0 : $\pi_0(I \mid H) = \frac{1}{2}$ $\pi_0(M \mid S) = \frac{1}{2}$

$\pi_0(O \mid H) = \frac{1}{2}$ $\pi_0(N \mid S) = \frac{1}{2}$

(a) As done in Q20, Policy Evaluation yields

$V_{\pi_0}(H) = 32$

$V_{\pi_0}(S) = 21.5$

(b) Policy Improvement :

$$\pi_1(s) = \arg\max_a \underbrace{\sum_{s', r} (r + \gamma V_{\pi_0}(s'))\, p(s', r \mid s, a)}$$

$$\sum_{s', r} r\, p(s', r \mid s, a) + \gamma \sum_{s', r} V_{\pi_0}(s')\, p(s', r \mid s, a)$$

$$= \sum_{s'} p(s' \mid s, a)\, r(s', a, s) + \gamma \sum_{s'} V_{\pi_0}(s')\, p(s' \mid s, a)$$

$$= \sum_{s'} p(s' \mid s, a) \left[r(s', a, s) + \gamma V_{\pi_0}(s') \right]$$

$$\pi_1(s) = \underset{a}{\operatorname{argmax}} \sum_{s'} p(s'|s,a)\left[r(s',a,s) + \gamma V_{\pi_0}(s')\right]$$

$s = H$

If $a = I$

$$RHS = 0.95(9.5 + 0.9 \times V_{\pi_0}(H)) + 0.05(-9 + 0.9 \times V_{\pi_0}(S))$$

$$= 0.95(9.5 + 0.9 \times 32) + 0.05(-9 + 0.9 \times 21.5)$$

$$= 36.385 + 0.5 = 36.885$$

If $a = O$

$$RHS = 0.7(18 + 0.9 \times 32) + 0.3(-9 + 0.9 \times 21.5)$$

$$= 32.76 + 3.1 = 35.86$$

$\pi_1(H) = I$

$s = S$

If $a = M$

$$RHS = 0.1(-2 + 0.9 \times 21.5) + 0.9(-1 + 0.9 \times 32)$$

$$= 1.735 + 25.02 = 26.7$$

If $a = N$

$$RHS = 0.4(-1 + 0.9 \times 32) + 0.6(0.9 \times 21.5)$$

$$= 11.12 + 11.6 = 22.7$$

$\pi_1(s) = M$

II) Policy π_1: $\pi_1(I|H) = 1$ $\pi_1(M|S) = 1$

$\pi_1(O|H) = 0$ $\pi_1(N|S) = 0$

ⓐ <u>Policy Evaluation</u>

$$V_{\pi_1,k}(s) = \sum_a \pi_1(a|s) \sum_{s',r} p(s',r|s,a)\left[r + \gamma V_{\pi_1,k-1}(s')\right]$$

$$= \sum_a \pi_1(a|s) \sum_{s'} p(s'|s,a)\left[r(s',a,s) + \gamma V_{\pi_1,k-1}(s')\right]$$

$\boxed{k=1}$

<u>$s=H$</u>

$$V_{\pi_1,1}(H) = 0.95(9.5 + 0.9 \times V_{\pi_1,0}(H)) + 0.05(-9 + 0.9 \times V_{\pi_1,0}(S))$$

$$= 0.95 \times 9.5 - 0.05 \times 9 = 8.55$$

<u>$s=S$</u>

$$V_{\pi_1,1}(S) = 0.1(-2) + 0.9(-1) = -1.1$$

$\boxed{k=2}$

$$V_{\pi_1,2}(H) = 0.95(9.5 + 0.9 \times 8.55) + 0.05(-9 + 0.9 \times -1.1)$$

$$= 15.8$$

$$V_{\pi_1,2}(S) = 0.1(-2 + 0.9 \times -1.1) + 0.9(-1 + 0.9 \times 8.55)$$

$$= 5.7$$

$\boxed{k=3}$

$$V_{\pi_1,3}(H) = 0.95(9.5 + 0.9 \times 15.8) + 0.05(-9 + 0.9 \times 5.7)$$

$$= 22.3$$

$$V_{\pi_1,3}(S) = 0.1(-2 + 0.9 \times 5.7) + 0.9(-1 + 0.9 \times 15.8)$$

$$= 12.2$$

$\boxed{k=4}$

$$V_{\pi_1,4}(H) = 0.95(9.5 + 0.9 \times 22.3) + 0.05(-9 + 0.9 \times 12.2)$$

$$= 28$$

$$V_{\pi_1,4}(S) = 0.1(-2 + 0.9 \times 12.2) + 0.9(-1 + 0.9 \times 22.3)$$

$$= 18$$

$\boxed{k=5}$

$$V_{\pi_1,5}(H) = 0.95(9.5 + 0.9 \times 28) + 0.05(-9 + 0.9 \times 18)$$

$$= 33.36$$

$$V_{\pi_1}(S) = 0.1(-2 + 0.9 \times 18) + 0.9(-1 + 0.9 \times 28)$$

$$= 23.18$$

$\therefore V_{\pi_1}(H) = 33.36$

$V_{\pi_1}(S) = 23.18$

(b) Policy Improvement

$$\pi_2(s) = \arg\max_a \sum_{s'} p(s'|s,a)\left[r(s',a,s) + \gamma V_{\pi_1}(s')\right]$$

$s = H$

If $a = I$

$$RHS = 0.95(9.5 + 0.9 \times 33.36) + 0.05(-9 + 0.9 \times 23)$$

$$= 38$$

If $a = O$

$$RHS = 0.7(18 + 0.9 \times 33.36) + 0.3(-9 + 0.9 \times 23)$$

$$= 37$$

$$\pi_2(H) = I$$

$s = S$

If $a = M$

$$RHS = 0.1(-2 + \overset{0.9\times}{23.18}) + 0.9(-1 + 0.9 \times 33.36)$$

$$= 28$$

If $a = N$

$$RHS = 0.4(-1 + 0.9 \times 23.18) + 0.6(0.9 \times 33.36)$$

$$= 26$$

$\pi_1(S) = M$

III) Policy π_2: $\pi_2(I|H) = 1$ $\quad$ $\pi_2(M|S) = 1$

$\pi_2(O|H) = 0$ $\quad$ $\pi_2(N|S) = 0$

(a) Policy evaluation

similar to previous policy evaluation

$\therefore V_{\pi_2,5}(H) = 33.36$

$V_{\pi_2,5}(S) = 23.18$

(b) Policy Improvement

Similar to previous policy improvement

$\pi_3(H) = I$

$\pi_3(S) = M$

$\therefore$ Optimal Policy is : $\cancel{\pi_3(H|I) =}$

$\pi_*(I|H) = 1$ $\quad$ $\pi_*(M|S) = 1$

$\pi_*(O|H) = 0$ $\quad$ $\pi_*(N|S) = 0$

$\therefore$ Optimal value function is: $V_*(H) = 33.36$

$V_*(S) = 23.18$