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## LAB13 tutorial for Machine Learning Markov Decision Process

The document description are designed by Jia Yanhong in 2022. Nov. 22th

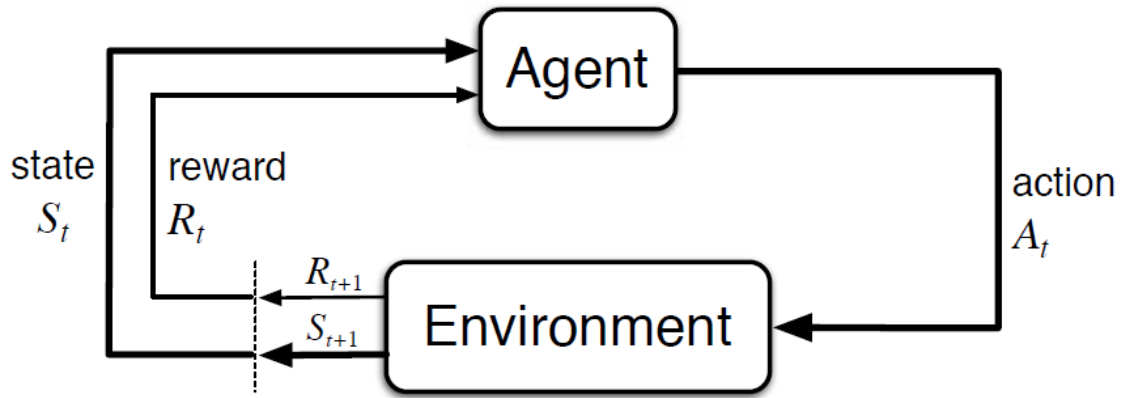
### 1 Objective

- Understand the theory of Markov Decision Process
- Implement the Value Iteration or Policy Iteration in python
- Complete the LAB assignment and submit it to BB or sakai.

### 2 Introduction

The basic elements of a reinforcement learning problem are:

- **Environment:** The outside world with which the agent interacts
- **State:** Current situation of the agent
- **Reward:** Numerical feedback signal from the environment
- **Policy:** Method to map the agent's state to actions. A policy is used to select an action at a given state
- **Value:** Future reward (delayed reward) that an agent would receive by taking an action in a given state



So, in reinforcement learning, we do not teach an agent how it should do something but presents it with rewards whether positive or negative based on its actions. So our root question for this lab is how we formulate any problem in RL mathematically This is where the Markov Decision Process(MDP) comes in.

Markov Decision Process (MDP) is a mathematical framework to describe an environment in reinforcement learning.

### 3 Markov Decision Process

**Markov Decision Process (MDP)** consists of a tuple of 5 elements  $\langle S, \mathcal{A}, \mathcal{P}, \mathcal{R}, \gamma \rangle$

- $S$ : set of states  $\rightarrow$  At each time step, state of the environment is an element  $s \in S$ .
- $\mathcal{A}$ : set of actions  $\rightarrow$  At each time step, agent takes an action  $a \in \mathcal{A}$ .
- $\mathcal{P}$ : state transition model (matrix)

$$\mathcal{P}_{x \rightarrow x'}^a = P[S_{t+1} | S_t = s, A_t = a]$$

Probability of transition to next state  $x'$  after taking action  $a$  in current state  $x$ .

- $\mathcal{R}$ : reward model (matrix)

$$\mathcal{R}_s^a = E[R_{t+1} | S_t = s, A_t = a]$$

Reward obtained after taking action  $a$  in current state  $x$ . (to be more general,

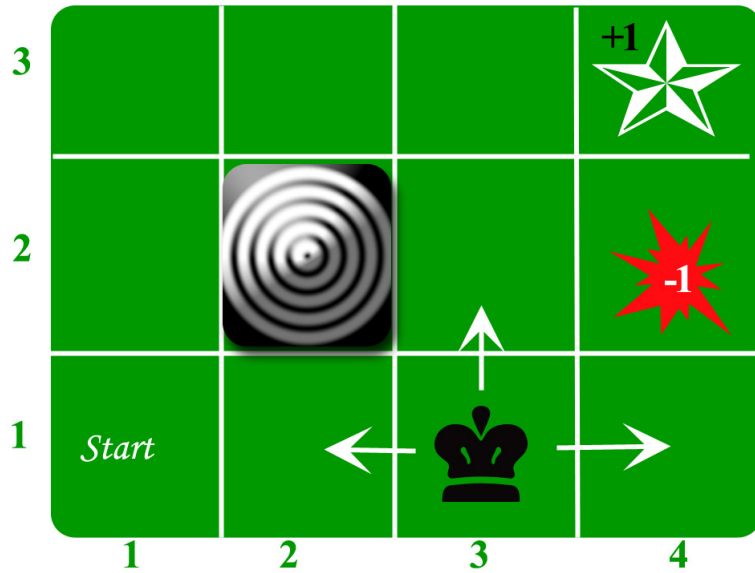
$$\mathcal{R}_{x \rightarrow x'}^a = E[R_{t+1} | S_t = s, A_t = a, S_{t+1} = s'] )$$

- $\gamma$ : discount factor  $\rightarrow$  Control the importance of future rewards.

The goal is to find an optimal policy  $\pi$  maximizing a cumulative function of the random rewards.

#### 3.1 What is a policy ?

Policy is the agent's behavior, it is a mapping from states to actions.



A policy is defined as follows :

- Deterministic policy:

$$a = \pi(s)$$

- Stochastic policy:

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

## 3.2 The Discounted Returns

The total discounted reward for a state from time-step  $t$ :

$$G_t(s) = R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \dots = \sum_{k=0}^{\infty} \gamma^k R_{t+k+1}$$

Rewards are temporary. Even after picking an action that gives a decent reward, we might be missing on a greater total reward in the long-run. This long-term total reward is the Return. However, in practice, we consider discounted Returns.

## 3.3 Value Function

A value function is the long-term value of a state or an action. In other words, it's the expected Return over a state or an action. This is something that we are actually interested in optimizing.

### 3.3.1 The state value function:

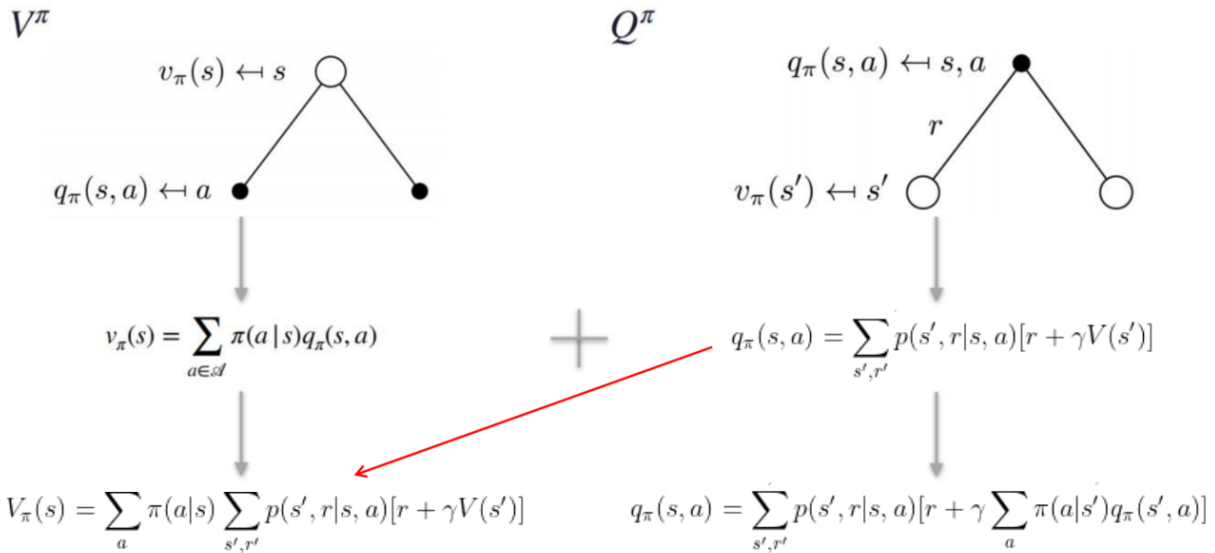
$$V_{\pi}(s) = E_{\pi}(G_t(s) | S_t = s) = E_{\pi}(R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \dots | S_t = s) = E_{\pi}(R_{t+1} + \gamma V_{\pi}(s_{t+1}) | S_t = s)$$

$$V_{\pi}(s) = \sum_a \pi(a|s) q_{\pi}(s, a) = \sum_a \pi(a|s) \sum_{s', r} p(s', r | s, a) [r + \gamma V(s')]$$

### 3.3.2 The Action Value Function

$$q_{\pi}(s, a) = E_{\pi}(G_t(s) | S_t = s, A_t = a) = E_{\pi}(R_{t+1} + \gamma R_{t+2} + \gamma^2 R_{t+3} + \dots | S_t = s, A_t = a) = E_{\pi}(R_{t+1} + \gamma V(s_{t+1}) | S_t = s, A_t = a)$$

$$q_{\pi}(s, a) = \sum_{s', r} p(s', r | s, a) [r + \gamma V(s')]$$



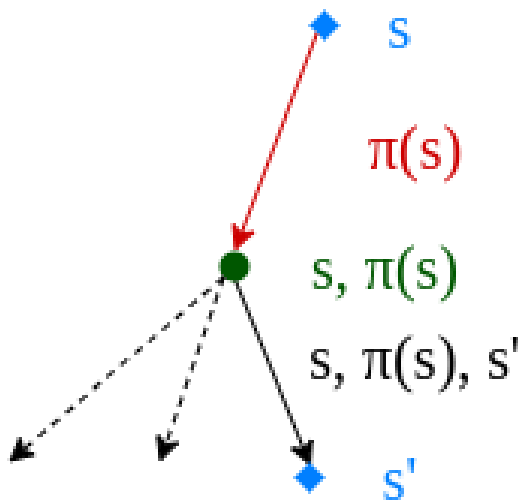
Given an MDP environment, we can use **dynamic programming algorithms** to compute optimal policies, which lead to the highest possible sum of future rewards at each state.

Dynamic programming algorithms work on the assumption that we have a perfect model of the environment's MDP. So, we're able to use a one-step look-ahead approach and compute rewards for all possible actions.

In this tutorial, we'll discuss how to find an optimal policy  $\pi$  for a given MDP. More specifically, **we'll learn about two dynamic programming algorithms: policy iteration and value iteration**.

## 4 Policy Iteration

In policy iteration, we start by choosing an arbitrary policy  $\pi$ . Then, we iteratively evaluate and improve the policy until convergence:



We evaluate a policy  $\pi(s)$  by calculating the state value function  $V(s)$ :

$$V^\pi(s) = \sum_a \pi(a|s) \sum_{s', r} p(s', r|s, a) [r + \gamma V(s')]$$

Then, we calculate the improved policy by using one-step look-ahead to replace the initial policy  $\pi(s)$  (E:\2022FALL\Machine-Learning-LAB\Lab13.Markov Decision Process\images\quicklatex.com-94a6c8fce241848251dbd30ea24f9706\_l3.svg):

$$\pi(s) = \arg \max_a \sum_{s', r} p(s', r | s, a) [r + \gamma V(s')]$$

Here,  $r$  is the reward generated by taking the action  $a$ ,  $\gamma$  is a discount factor for future rewards and  $p(s', r | s, a)$  is the transition probability.

In the beginning, we don't care about the initial policy  $\pi_0$  being optimal or not. During the execution, we concentrate on improving it on every iteration by repeating policy evaluation and policy improvement steps. Using this algorithm we produce a chain of policies, where each policy is an improvement over the previous one:

$$\pi_0 \xrightarrow{E} U_{\pi_0} \xrightarrow{I} \pi_1 \xrightarrow{E} U_{\pi_1} \xrightarrow{I} \pi_2 \xrightarrow{E} \dots \xrightarrow{I} \pi_* \xrightarrow{E} U_*$$

---

**Algorithm 1:** Policy Iteration Algorithm
 

---

**Data:**  $\theta$ : a small number

**Result:**  $V$ : a value function s.t.  $V \approx v_*$ ,  $\pi$ : a deterministic policy  
s.t.  $\pi \approx \pi_*$

**Function** *PolicyIteration* **is**

```

/* Initialization                                     */
Initialize  $V(s)$  arbitrarily;
Randomly initialize policy  $\pi(s)$ ;
/* Policy Evaluation                                   */
 $\Delta \leftarrow 0$ ;
while  $\Delta < \theta$  do
    for each  $s \in S$  do
         $v \leftarrow V(s)$ ;
         $V(s) \leftarrow \sum_{s',r'} p(s',r|s, \pi(s)) [r + \gamma V(s')]$ ;
         $\Delta \leftarrow \max(\Delta, |v - V(s)|)$ ;
    end
end
/* Policy Improvement                                 */
policy-stable  $\leftarrow true$ ;
for each  $s \in S$  do
    old-action  $\leftarrow \pi(s)$ ;
     $\pi(s) \leftarrow \arg \max_a \sum_{s',r'} p(s',r|s, a) [r + \gamma V(s')]$ ;
    if old-action  $\neq \pi(s)$  then
        | policy-stable  $\leftarrow false$ ;
    end
end
if policy-stable then
    | return  $V \approx v_*$  and  $\pi \approx \pi_*$ ;
else
    | go to Policy Evaluation;
end
end

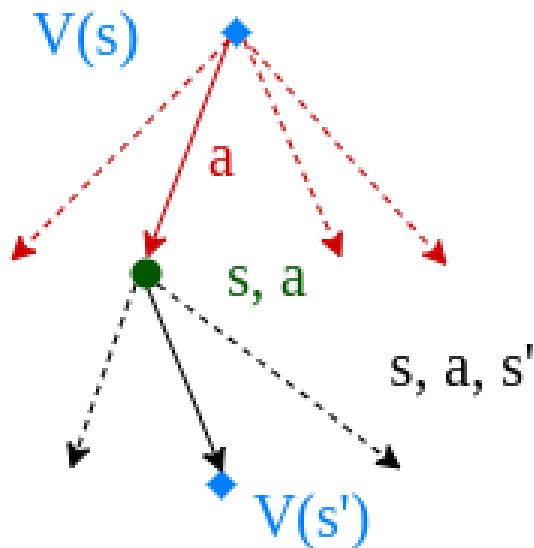
```

---

Since a finite MDP has a finite number of policies, the defined process is finite. In the end, converging an optimal policy  $\pi_*$  and an optimal value function  $v_*$  is guaranteed.

## 5 Value Iteration

In value iteration, we compute the optimal state value function by iteratively updating the estimate  $v(s)$ :



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

$$v_*(s) = \max_{\pi} v_{\pi}(s)$$

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

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

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

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

We start with a random value function  $V(s)$ . At each step, we update it:

$$V(s) = \max_a \sum_{s', r} p(s', r|s, a)[r + \gamma V(s')]$$

Hence, we look-ahead one step and go over all possible actions at each iteration to find the maximum:

**Algorithm 2:** Value Iteration Algorithm**Data:**  $\theta$ : a small number**Result:**  $\pi$ : a deterministic policy s.t.  $\pi \approx \pi_*$ **Function** *ValueIteration* **is**

```

    /* Initialization */
    Initialize  $V(s)$  arbitrarily, except  $V(\text{terminal})$ ;
     $V(\text{terminal}) \leftarrow 0$ ;
    /* Loop until convergence */
     $\Delta \leftarrow 0$ ;
    while  $\Delta < \theta$  do
        for each  $s \in S$  do
             $v \leftarrow V(s)$ ;
             $V(s) \leftarrow \max_a \sum_{s', r} p(s', r|s, a)[r + \gamma V(s')]$ ;
             $\Delta \leftarrow \max(\Delta, |v - V(s)|)$ ;
        end
    end
    /* Return optimal policy */
    return  $\pi$  s.t.  $\pi(s) = \arg \max_a \sum_{s', r} p(s', r|s, a)[r + \gamma V(s')]$ ;
end

```

The update step is very similar to the update step in the policy iteration algorithm. The only difference is that we take the maximum over all possible actions in the value iteration algorithm.

Instead of evaluating and then improving, the value iteration algorithm updates the state value function in a single step. This is possible by calculating all possible rewards by looking ahead.

The value iteration algorithm is guaranteed to converge to the optimal values.

## 6 Policy Iteration vs. Value Iteration

**Policy iteration and value iteration are both dynamic programming algorithms that find an optimal policy  $\pi_*$  in a reinforcement learning environment.** They both employ variations of Bellman updates and exploit one-step look-ahead:

Policy Iteration	Value Iteration
Starts with a random policy	Starts with a random value function
Algorithm is more complex	Algorithm is simpler
Guaranteed to converge	Guaranteed to converge
Cheaper to compute	More expensive to compute
Requires few iterations to converge	Requires more iterations to converge
Faster	Slower

**\*\*In policy iteration, we start with a fixed policy. Conversely, in value iteration, we begin by selecting the value function.\*\*** Then, in both algorithms, we iteratively improve until we reach convergence.

The policy iteration algorithm updates the policy. The value iteration algorithm iterates over the value function instead. Still, both algorithms implicitly update the policy and state value function in each iteration.

In each iteration, the policy iteration function goes through two phases. One phase evaluates the policy, and the other one improves it. The value iteration function covers these two phases by taking a maximum over the utility function for all possible actions.

The value iteration algorithm is straightforward. It combines two phases of the policy iteration into a single update operation. However, the value iteration function runs through all possible actions at once to find the maximum action value. Subsequently, the value iteration algorithm is computationally heavier.



Both algorithms are guaranteed to converge to an optimal policy in the end. Yet, the policy iteration algorithm converges within fewer iterations. As a result, the policy iteration is reported to conclude faster than the value iteration algorithm.

## 7 LAB Assignment

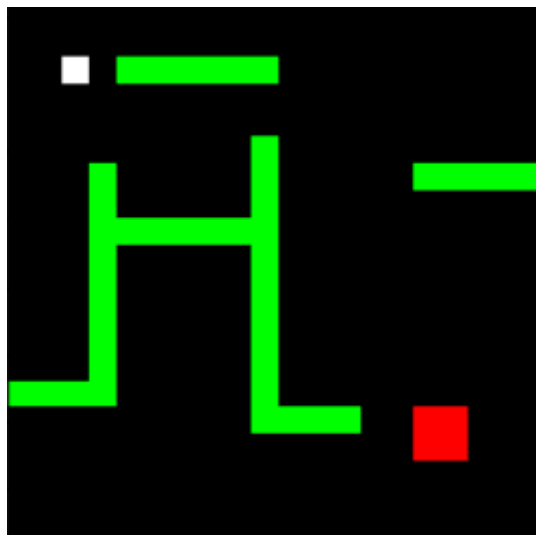
Please finish the **Exercise** and answer **Questions**.

### 7.1 Exercise (100 Points)

In this lab, we are about to find a shortest path with collision avoidance using MDP. We will model the problem as a MDP problem and use **value iteration** or **policy iteration** algorithm to solve it.

#### 7.1.1 Environment Data

- Environment: `map_matrix.npy` has environment data. You need to use `numpy` to load it.
  - White block: an agent, for example, a robot
  - Red block: destination
  - Green block: obstacle



- $\mathcal{R}$  Reward: reward is implemented in code and it only concerns the next state:
  - wall:  $-1$
  - destination:  $0$
  - else:  $-0.1$
- $\mathcal{P}$  State transformation: next state is deterministic when taking an action under a certain state.
- $\pi$  Initial policy: each direction (up, right, bottom, left) has equal probability.

#### 7.1.2 Display

We have several methods for you to display policy, state value and path on map

```
def display_policy()
def display_v()
def display_path()
```

#### 7.1.3 Implementation code

### 7.1.3.1 Initialize $S, A, R, P$

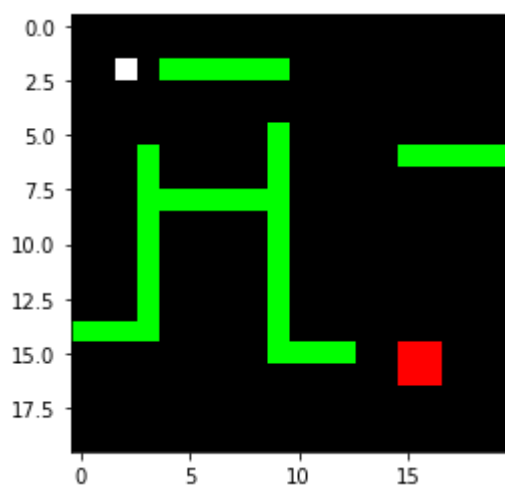
In [1]:

```
1 import numpy as np
2 import pandas as pd
3 import time
4 import matplotlib.pyplot as plt
```

In [2]:

```
1 map_matrix = np.load("map_matrix.npy")
2 plt.imshow(map_matrix)
3 plt.show()
```

Clipping input data to the valid range for imshow with RGB data ([0..1] for floats or [0..255] for integers).



In [3]:

```
1 MAX_Y = map_matrix.shape[0]
2 MAX_X = map_matrix.shape[1]
3 noS = MAX_Y * MAX_X
4 noA = 4
```

In [4]:

```

1  # A, defining action variables
2  UP = 0
3  RIGHT = 1
4  DOWN = 2
5  LEFT = 3
6
7  # S, a sequence of number rather than coordinates
8  S = range(noS)
9
10 # reward
11 reward_blank = -0.1 #for every step -1 in other states
12 reward_wall = -1 # for wall
13 reward_goal = 0 # for destination
14 wall = []
15 goal = []
16 start = None
17 for y in range(MAX_Y):
18     for x in range(MAX_X):
19         if list(map_matrix[y][x]) == [0., 30., 0.]:
20             wall.append(y * MAX_X + x)
21         elif list(map_matrix[y][x]) == [255., 0., 0.]:
22             goal.append(y * MAX_X + x)
23         elif list(map_matrix[y][x]) == [255., 255., 255.]:
24             start = (y, x)
25 print("--> State of walls:", wall)
26 print("--> State of destination:", goal)
27
28 # P[s][a] = (state transition probability, next state, reward, done)
29 P = dict()
30 grid = np.arange(noS).reshape(map_matrix.shape[0:2])
31 it = np.nditer(grid, flags=['multi_index'])
32
33 while not it.finished:
34     s = it.iterindex
35     y, x = it.multi_index
36     P[s] = dict()
37     #if (terminal_state(s)):
38     if (s in goal): #s in terminal_state:
39         P[s][UP] = (1.0, s, reward_goal, True)
40         P[s][RIGHT] = (1.0, s, reward_goal, True)
41         P[s][DOWN] = (1.0, s, reward_goal, True)
42         P[s][LEFT] = (1.0, s, reward_goal, True)
43     else:
44         ns_up = s if y == 0 else s - MAX_X
45         ns_right = s if x == (MAX_X - 1) else s + 1
46         ns_down = s if y == (MAX_Y - 1) else s + MAX_X
47         ns_left = s if x == 0 else s - 1
48
49         if s in goal:
50             rw = reward_goal
51         elif s in wall:
52             rw = reward_wall
53         else:
54             rw = reward_blank
55
56         P[s][UP] = (1.0, ns_up, rw, ns_up in goal)
57         P[s][RIGHT] = (1.0, ns_right, rw, ns_right in goal)
58         P[s][DOWN] = (1.0, ns_down, rw, ns_down in goal)
59         P[s][LEFT] = (1.0, ns_left, rw, ns_left in goal)

```

```

60     it.itenext()
61
62     print('--> Number of states in grid: ' + str(noS))
63     print('--> Number of action options in each state:' + str(noA))
64     print("--> Transition probabilities matrix(prob, next_state, reward, is_done): ")
65     print(P[0])

```

```

--> State of walls: [44, 45, 46, 47, 48, 49, 109, 123, 129, 135, 136, 137, 138, 139,
143, 149, 163, 164, 165, 166, 167, 168, 169, 183, 189, 203, 209, 223, 229, 243, 249,
263, 269, 280, 281, 282, 283, 289, 309, 310, 311, 312]
--> State of destination: [315, 316, 335, 336]
--> Number of states in grid: 400
--> Number of action options in each state:4
--> Transition probabilities matrix(prob, next_state, reward, is_done):
{0: (1.0, 0, -0.1, False), 1: (1.0, 1, -0.1, False), 2: (1.0, 20, -0.1, False), 3:
(1.0, 0, -0.1, False)}

```

### 7.1.3.2 Optimization Approach

You need to implement one of them

- Value Iteration

In [5]:

```

1  def value_iteration(P, theta=0.0001, discount_factor=1.0):
2      """
3      Value iteration
4
5      :param theta: threshold to stop iteration
6      :param discount_factor: the same as discount factor in formula
7      :return: a policy and a state-value matrix V
8      """
9
10
11     V = np.zeros(noS)
12     step = 0
13     while True:
14         # TODO: finish value iteration
15         break
16
17     # TODO: find the best policy according to V
18     # Create a deterministic policy using the optimal value function
19     # policy[s, a] means the probability of taking action a under state s, in this case, they a
20     policy = np.zeros([noS, noA])
21     pass
22
23     return policy, V

```

- Policy Iteration

In [6]:

```

1 def policy_eval(policy_matrix, P_matrix, discount_factor=1.0, theta=0.00001):
2     # Start with a random (all 0) value function
3     V = np.zeros(noS)
4     while True:
5         delta = 0
6         # TODO: finish evaluation part
7         pass
8
9         if delta < theta:
10             break
11     return np.array(V)
12
13
14 def policy_improvement(P_matrix, policy_eval_fn=policy_eval, discount_factor=1.0):
15     def one_step_lookahead(state, V_matrix):
16         A = np.zeros(noA)
17
18         # TODO: calculate next states' values after taking different actions
19         pass
20
21         return A
22
23     # Start with a random policy
24     policy_now = np.ones([noS, noA]) / noA
25
26     while True:
27         # Evaluate the current policy
28         V = policy_eval_fn(policy_now, P_matrix, discount_factor)
29
30         # Will be set to false if we make any changes to the policy
31         policy_stable = True
32
33         # For each state...
34         for s in range(noS):
35             # TODO: The best action we would take under the current policy
36             pass
37
38             # TODO: Find the best action by one-step lookahead
39             # Ties are resolved arbitrarily
40             pass
41
42             # TODO: Greedily update the policy
43             pass
44
45         # If the policy is stable we've found an optimal policy. Return it
46         if policy_stable:
47             return policy_now, V

```

In [7]:

```

1 iteration = policy_improvement
2 policy, v = iteration(P)

```

### 7.1.4 Display

In [8]:

```

1 # display modules
2 def display_policy(policy_map: np.ndarray, des=((15, 16), (15, 15), (16, 15), (16, 16))):
3     """
4     Display policy in a vector field
5     :param des: destination, for dying quiver
6     :param policy_map: your policy map where each position is a number standing for an action
7     :return:
8     """
9
10    def phrase_action(action: int):
11        if action == 0:
12            return 0, 1
13        if action == 1:
14            return 1, 0
15        if action == 2:
16            return 0, -1
17        if action == 3:
18            return -1, 0
19        return 0, 0
20
21    des = np.asarray(np.copy(des))
22
23    X, Y = policy_map.shape
24    grid_X = np.arange(X).reshape(-1, 1).repeat(Y, axis=1)
25    grid_Y = np.arange(Y).reshape(1, -1).repeat(X, axis=0)
26    direct_X, direct_Y = [], []
27    C = []
28    for x_row in list(zip(grid_X, grid_Y)):
29        for p in tuple(zip(x_row[0], x_row[1])):
30            direct_x, direct_y = phrase_action(policy_map[p[0], p[1]])
31            direct_X.append(direct_x)
32            direct_Y.append(direct_y)
33            if des is not None:
34                C.append(np.sum(np.abs(p - des)))
35    fig = plt.figure(figsize=(8, 8))
36    ax = plt.gca()
37    ax.xaxis.set_ticks_position('top') #将X坐标轴移到上面
38    ax.invert_yaxis() #反转Y坐标轴
39    plt.quiver(grid_X, grid_Y, direct_X, direct_Y, 0 if len(C) == 0 else C)
40    plt.show()
41
42
43 def display_v(V: np.ndarray, map_m: np.ndarray):
44     """
45     display state value in heat map
46     :param map_m: 2D map matrix corresponding to v
47     :param V: state value, 1D
48     :return:
49     """
50
51    heatmap = V.reshape(map_m.shape[0:2])
52    plt.imshow(heatmap, cmap=plt.cm.autumn)
53    plt.colorbar()
54    plt.show()
55
56
57 def display_path(policy_map, map_m, departure, des, max_iter=100):
58     """
59

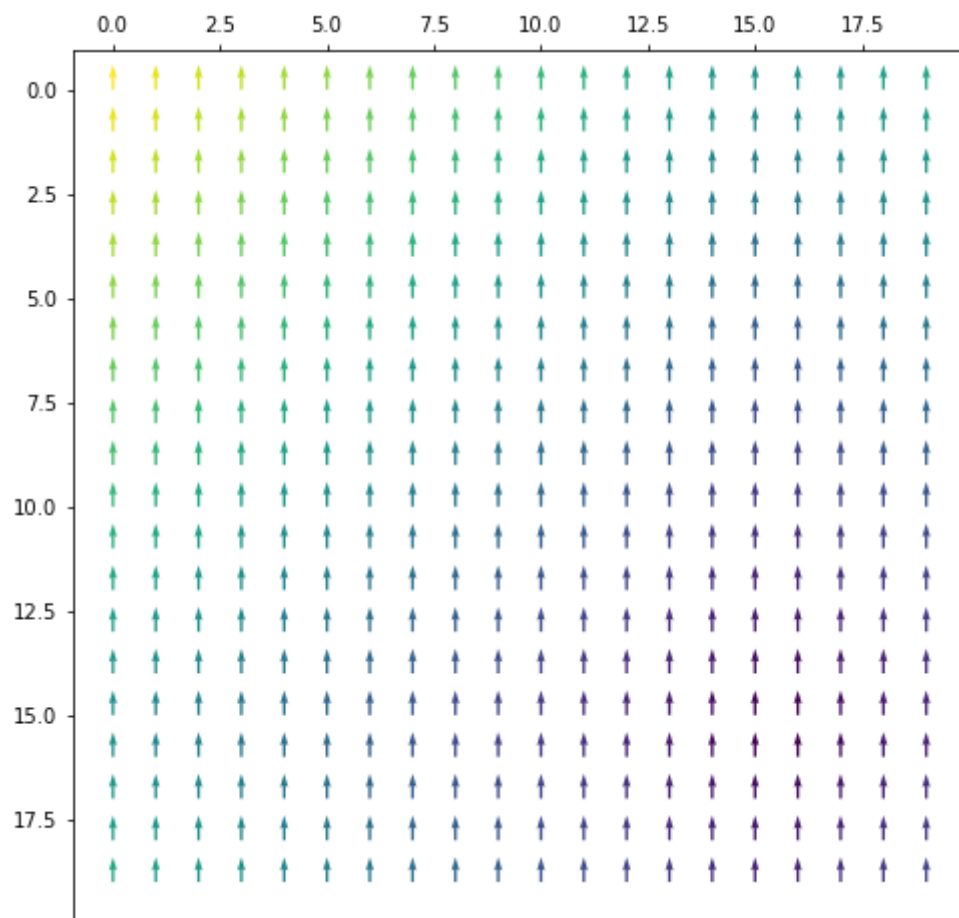
```

```
60 :param policy_map: policy
61 :param map_m: map
62 :param departure: start point
63 :param des: destination
64 :return:
65 """
66 map_m = np.copy(map_m)
67
68 now_y, now_x = departure
69 iter_n = 0
70 while now_y * MAX_X + now_x not in des:
71     if iter_n > max_iter:
72         break
73     map_matrix[now_y, now_x, :] = np.array([151, 255, 255])
74     if UP == policy_map[now_y, now_x]:
75         now_y = now_y - 1
76     elif RIGHT == policy_map[now_y, now_x]:
77         now_x = now_x + 1
78     elif DOWN == policy_map[now_y, now_x]:
79         now_y = now_y + 1
80     elif LEFT == policy_map[now_y, now_x]:
81         now_x = now_x - 1
82     now_y = (now_y + MAX_Y) % MAX_Y
83     now_x = (now_x + MAX_X) % MAX_X
84     map_m[now_y, now_x, :] = 120
85     plt.imshow(map_m)
86     plt.show()
87     display.clear_output(wait=True)
88
89     iter_n += 1
```

In [9]:

```
1 print("Grid Policy (0=up, 1=right, 2=down, 3=left):")
2 grid_policy = np.reshape(np.argmax(policy, axis=1), map_matrix.shape[0:2])
3 display_policy(grid_policy.T)
```

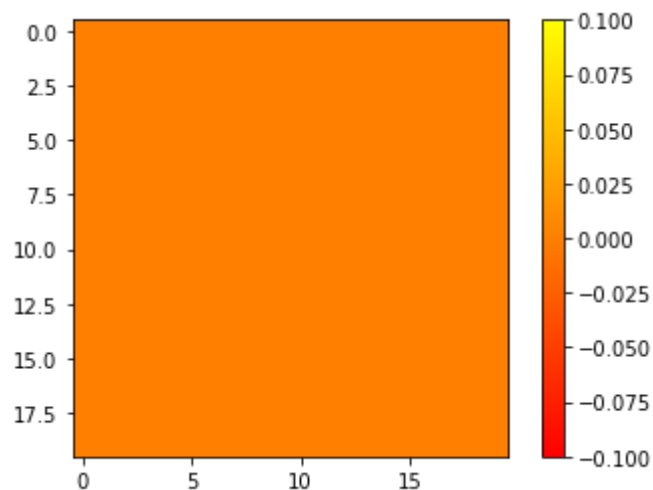
Grid Policy (0=up, 1=right, 2=down, 3=left):



In [10]:

```
1 print("State value:")
2 display_v(v, map_matrix)
```

State value:

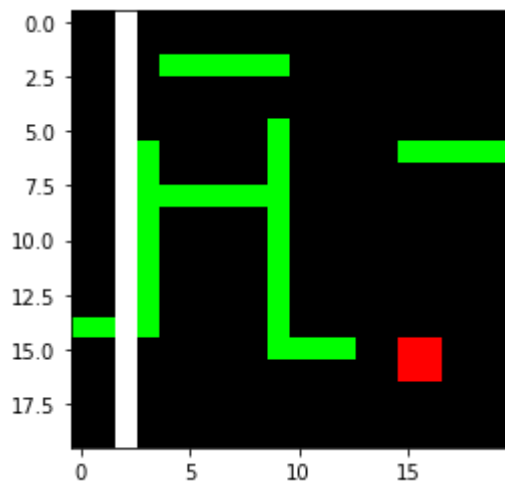




In [11]:

```
1 %matplotlib inline
2 display_path(grid_policy, map_matrix, start, goal)
```

Clipping input data to the valid range for imshow with RGB data ([0..1] for floats or [0..255] for integers).



In [11]:

```
1
```