人工智慧 Lab3 - Pacman Agents

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實驗內容描述:

此次實驗透過修改 search.zip 裡面的 search.py 跟 searchAgenets.py 裡頭的程式碼片段, 程式碼的撰寫部分主要包含:

- searchAgents.py 中的:
  - **class CornerProblem(search.SearchProblem) 底下的 __init__()、getStartState()、isGoalState()、getSuccessors()。**

```python
class CornersProblem(search.SearchProblem):
    """
    This search problem finds paths through all four corners of a layout.

    You must select a suitable state space and successor function
    """

    def __init__(self, startingGameState):
        """
        Stores the walls, pacman's starting position and corners.
        """
        self.walls = startingGameState.getWalls()
        self.startingPosition = startingGameState.getPacmanPosition()
        top, right = self.walls.height-2, self.walls.width-2
        self.corners = ((1,1), (1,top), (right, 1), (right, top))
        for corner in self.corners:
            if not startingGameState.hasFood(*corner):
                print('Warning: no food in corner ' + str(corner))
        self._expanded = 0 # DO NOT CHANGE; Number of search nodes expanded
        # Please add any code here which you would like to use
        # in initializing the problem
        "*** YOUR CODE HERE ***"
        self.startState = (self.startingPosition, tuple())
```

```python
class CornersProblem(search.SearchProblem):

    def getStartState(self):
        """
        Returns the start state (in your state space, not the full Pacman state
        space)
        """
        "*** YOUR CODE HERE ***"
        return self.startState

    def isGoalState(self, state):
        """
        Returns whether this search state is a goal state of the problem.
        """
        "*** YOUR CODE HERE ***"
        return len(state[1]) == 4
```

```python
class CornersProblem(search.SearchProblem):
    def getSuccessors(self, state):
        Returns successor states, the actions they require, and a cost of 1.

            As noted in search.py:
            For a given state, this should return a list of triples, (successor,
            action, stepCost), where 'successor' is a successor to the current
            state, 'action' is the action required to get there, and 'stepCost'
            is the incremental cost of expanding to that successor
        """

        successors = []
        for action in [Directions.NORTH, Directions.SOUTH, Directions.EAST, Directions.WEST]:
            # Add a successor state to the successor list if the action is legal
            # Here's a code snippet for figuring out whether a new position hits a wall:
            #   x,y = currentPosition
            #   dx, dy = Actions.directionToVector(action)
            #   nextx, nexty = int(x + dx), int(y + dy)
            #   hitsWall = self.walls[nextx][nexty]

            "*** YOUR CODE HERE ***"
            x, y = state[0]
            dx, dy = Actions.directionToVector(action)
            nextx, nexty = int(x + dx), int(y + dy)
            if not self.walls[nextx][nexty]:
                nextPosition = (nextx, nexty)
                visitedCorners = list(state[1])
                if nextPosition in self.corners and nextPosition not in visitedCorners:
                    visitedCorners.append(nextPosition)
                successors.append( ( (nextPosition, tuple(visitedCorners)), action, 1 ) )

        self._expanded += 1 # DO NOT CHANGE
        return successors
```

- **class ClosestDotSearchAgent(SearchAgent)** 底下的 **findPathToClosestDot()**。

```python
class ClosestDotSearchAgent(SearchAgent):
    def findPathToClosestDot(self, gameState):
        """
        Returns a path (a list of actions) to the closest dot, starting from
        gameState.
        """
        # Here are some useful elements of the startState
        startPosition = gameState.getPacmanPosition()
        food = gameState.getFood()
        walls = gameState.getWalls()
        problem = AnyFoodSearchProblem(gameState)

        "*** YOUR CODE HERE ***"
        return search.bfs(problem)
```

- **class AnyFoodSearchProblem(PositionSearchProblem)** 底下的 **isGoalState()**。

```python
class AnyFoodSearchProblem(PositionSearchProblem):
    def isGoalState(self, state):
        """
        The state is Pacman's position. Fill this in with a goal test that will
        complete the problem definition.
        """
        x,y = state

        "*** YOUR CODE HERE ***"
        return self.food[x][y]
```

- **cornerHeuristic()**：尋找四格角落的 searchAgent 使用 A* 演算法時的啟發函式，這部分依照註解要求，可以比較粗略的估計，因此我僅讓他去計算從當前點開始到最近的未被拜訪的角落，再從該角落去到相對於當前角落最近的其他角落，以此類推所累計

的總距離做為啟發函式的回傳值。

```python
def cornersHeuristic(state, problem):
    corners = problem.corners # These are the corner coordinates
    walls = problem.walls # These are the walls of the maze, as a Grid (game.py)

    "*** YOUR CODE HERE ***"
    x, y = state[0]
    visited = state[1]
    unvisited = [corner for corner in corners if corner not in visited]
    if not unvisited:
        return 0

    totalDistance = 0
    unvisitedCorners = unvisited.copy()
    while unvisitedCorners:
        dists = [(abs(x - c[0]) + abs(y - c[1]), c) for c in unvisitedCorners]
        minDist, closestCorner = min(dists)
        totalDistance += minDist
        x, y = closestCorner
        unvisitedCorners.remove(closestCorner)
    return totalDistance
```

- **foodHeuristic()**：尋找食物的 searchAgent 使用 A* 演算法時的啟發函式，這部分依照註解要求，需要符合 admissible 跟 consistency，因此需要比較複雜的算法來得到夠精確，且不能高估的可接受的解，因此我把啟發值分成兩部分計算，一部分計算與當前最近的 food 的距離，另一部分我先假設 Pacman 先去吃離他最近的食物，之後再從該食物開始去找其他食物，因此這涉及食物跟食物之間的距離計算，我透過「利用所有 **food** 之間的距離製作成一個 **Graph**，節點就是所有的 **food**，節點跟節點之間的邊就是任意兩個 **food** 之間的曼哈頓距離，並裡用 **Kruskal** 演算法求這個 **Graph** 所形成的最小生成樹」。為此，Kruskal 演算法是以邊為主的 Greedy 演算法來獲取最小生成樹，故我使用了原始的 util.py 裡面提供的 PriorityQueue 來讓儲存所有的邊，並將最小邊逐一拿出，接著，為了效率，我在 util.py 裡面實作了自己的 DisjointSet 來維護每次加入邊不能使得當前的最小生成樹形成 Cycle 的限制（透過檢查 parent[x] != parent[y] 之後才把 x 跟 y 加到最小生成樹裡面）。

```python
def foodHeuristic(state, problem):
    # Try Kruskal's Algorithm for MST(Minimum Spanning Tree) (using manhattan distance)
    # the minimal distance from pacman to all the food in food list
    position, foodGrid = state
    "*** YOUR CODE HERE ***"
    foodList = foodGrid.asList()
    if not foodList:
        return 0

    minDist = min([abs(position[0] - food[0]) + abs(position[1] - food[1]) for food in foodList])

    # Kruskal's Algorithm for MST (using Manhattan distance)
    vertex = foodList
    pq = util.PriorityQueue()   # storing the edges in priority queue in ascending order
    for i in range(len(vertex)):
        for j in range(i + 1, len(vertex)):
            vi, vj = vertex[i], vertex[j]
            dist = abs(vi[0] - vj[0]) + abs(vi[1] - vj[1])
            pq.push((dist, i, j), dist)  # use dist as the priority

    disjointSet = util.DisjointSet(n=len(vertex))
    mstCost = 0 # the cost of the MST(Minimum Spanning Tree)
    count = 0   # the count the number of edges in MST
    while not pq.isEmpty():
        dist, x, y = pq.pop()   # extracting the current minimum edge in the priority queue
        rootX, rootY = disjointSet.find(x), disjointSet.find(y)

        if rootX != rootY: # check if there's cycle after we add this edge to the MST
            disjointSet.union(rootX, rootY)
            mstCost += dist
            count += 1
            if count == len(vertex) - 1:    # break if we already have the MST with n - 1 edges
                break

    # heuristic = the distance from pacman to the closest food + the MST of all the other foods
    return minDist + mstCost
```

```python
# Custom a data structure of disjoint set for food heuristic function
class DisjointSet:
    def __init__(self, n):
        self.rank = [0] * n
        self.parent = [0] * n
        self.n = n
        for i in range(n): self.parent[i] = i

    def find(self, x):
        if x >= self.n: return x
        while self.parent[x] != x:
            self.parent[x] = self.parent[self.parent[x]]
            x = self.parent[x]
        return x

    def union(self, x, y):
        if x >= self.n: return False
        rootX, rootY = self.parent[x], self.parent[y]
        if rootX == rootY: return;

        if self.rank[rootX] < self.rank[rootY]:
            self.parent[rootX] = rootY
        elif self.rank[rootY] < self.rank[rootX]:
            self.parent[rootY] = rootX
        else:
            self.parent[rootY] = rootX
            self.rank[rootX] += 1

        return True
```

- search.py 中的:

- **depthFirstSearch()。**

```python
def depthFirstSearch(problem):
    """
    Search the deepest nodes in the search tree first.

    Your search algorithm needs to return a list of actions that reaches the
    goal. Make sure to implement a graph search algorithm.

    To get started, you might want to try some of these simple commands to
    understand the search problem that is being passed in:

    print("Start:", problem.getStartState())
    print("Is the start a goal?", problem.isGoalState(problem.getStartState()))
    print("Start's successors:", problem.getSuccessors(problem.getStartState()))
    """
    "*** YOUR CODE HERE ***"
    stack = util.Stack()
    startState = problem.getStartState()
    stack.push((startState, []))
    visited = set()

    while not stack.isEmpty():
        state, path = stack.pop()
        if problem.isGoalState(state):
            return path
        if state not in visited:
            visited.add(state)
            for successor, action, stepCost in problem.getSuccessors(state):
                stack.push((successor, path + [action]))

    return []
```

- **breadthFirstSearch()。**

```python
def breadthFirstSearch(problem):
    """Search the shallowest nodes in the search tree first."""
    "*** YOUR CODE HERE ***"
    queue = util.Queue()
    startState = problem.getStartState()
    queue.push((startState, []))
    visited = set()

    while not queue.isEmpty():
        state, path = queue.pop()
        if problem.isGoalState(state):
            return path
        if state not in visited:
            visited.add(state)
            for successor, action, stepCost in problem.getSuccessors(state):
                queue.push((successor, path + [action]))

    return []
```

- **uniformCostSearch()**。

```python
def uniformCostSearch(problem):
    """Search the node of least total cost first."""
    "*** YOUR CODE HERE ***"
    pq = util.PriorityQueue()
    startState = problem.getStartState()
    pq.push((startState, [], 0), 0) # (state, path, cost), priority
    visited = dict() # state: lowerest cost

    while not pq.isEmpty():
        state, path, cost = pq.pop()
        if problem.isGoalState(state):
            return path
        if state not in visited or cost < visited[state]:
            visited[state] = cost
            for successor, action, stepCost in problem.getSuccessors(state):
                newCost = cost + stepCost
                pq.push((successor, path + [action], newCost), newCost)

    return []
```

- **aStarSearch()**。

```python
def aStarSearch(problem, heuristic=nullHeuristic):
    """Search the node that has the lowest combined cost and heuristic first."""
    "*** YOUR CODE HERE ***"
    pq = util.PriorityQueue()
    startState = problem.getStartState()
    pq.push((startState, [], 0), heuristic(startState, problem))
    visited = dict()

    while not pq.isEmpty():
        state, path, cost = pq.pop()
        if problem.isGoalState(state):
            return path
        if state not in visited or cost < visited[state]:
            visited[state] = cost
            for successor, action, stepCost in problem.getSuccessors(state):
                newCost = cost + stepCost
                priority = newCost + heuristic(successor, problem)
                pq.push((successor, path + [action], newCost), priority)

    return []
```

- Addition：由於當初開啟 search.zip 時發現裡頭的 autograder.py（用於在第二步驟測試運行結果的程式碼）出現許多非單一種類的複雜問題，因此有額外花了一些時間修正並研究和修改其片段損壞的程式碼，這部分也花了一些功夫...，主要是 imp 模組在 3.12 以上的 Python 版本中已被棄用，於是我把運行環境改到 3.11.4，接著又有一些程式碼其實 autograder.py 在運行時不會用到，因此將其註解掉，接著在運行後發現 grading.py 裡面原先的 cgi 函式也有問題，找了一些資料發現 cgi 僅適用於 3.8 以前的 Python 版本，但 Python 官網已經沒有提供下載

Python3.8 了，因此我把 cgi 全面改用 html 這個 Python library，最後成功透過 **python3.11 autograder.py --code-directory /Users/jeff/Desktop/Coding/Machine_Learning/Pacman_Agent --student-code search.py,searchAgents.py** 運行了（--code-directory 後我提供了我當前執行該檔案的 Project Folder 位置）。註解：使用 python3.11 來指定在當前 PC 環境直接運行 3.11 版本的 Python

實驗結果：

運行上面提到的指令去執行 autograder.py 後，得到了經過 q1, q2, … q8 的所有測試結果，包含各個測試檔案裡面的小測試案件，可以看到總共有 25 項測試，最後的結果是全部都通過了（可於最後一張截圖查看對於所有測試的總結 log）。

```
jeff@Jack Pacman_Agent % python3.11 autograder.py --code-directory /Users/jeff
/Desktop/Coding/Machine_Learning/Pacman_Agent --student-code search.py,searchA
gents.py
/Users/jeff/Desktop/Coding/Machine_Learning/Pacman_Agent/autograder.py:17: Dep
recationWarning: the imp module is deprecated in favour of importlib and slate
d for removal in Python 3.12; see the module's documentation for alternative u
ses
  import imp
Starting on 5-20 at 22:18:12

Question q1
===========
*** PASS: test_cases/q1/graph_backtrack.test
***     solution:               ['1:A->C', '0:C->G']
***     expanded_states:        ['A', 'D', 'C']
*** PASS: test_cases/q1/graph_bfs_vs_dfs.test
***     solution:               ['2:A->D', '0:D->G']
***     expanded_states:        ['A', 'D']
*** PASS: test_cases/q1/graph_infinite.test
***     solution:               ['0:A->B', '1:B->C', '1:C->G']
***     expanded_states:        ['A', 'B', 'C']
*** PASS: test_cases/q1/graph_manypaths.test
***     solution:               ['2:A->B2', '0:B2->C', '0:C->D', '2:D->E2', '0
:E2->F', '0:F->G']
***     expanded_states:        ['A', 'B2', 'C', 'D', 'E2', 'F']
*** PASS: test_cases/q1/pacman_1.test
***     pacman layout:          mediumMaze
***     solution length: 130
***     nodes expanded:         146

### Question q1: 3/3 ###
```

```
Question q2
===========
*** PASS: test_cases/q2/graph_backtrack.test
***     solution:               ['1:A->C', '0:C->G']
***     expanded_states:        ['A', 'B', 'C', 'D']
*** PASS: test_cases/q2/graph_bfs_vs_dfs.test
***     solution:               ['1:A->G']
***     expanded_states:        ['A', 'B']
*** PASS: test_cases/q2/graph_infinite.test
***     solution:               ['0:A->B', '1:B->C', '1:C->G']
***     expanded_states:        ['A', 'B', 'C']
*** PASS: test_cases/q2/graph_manypaths.test
***     solution:               ['1:A->C', '0:C->D', '1:D->F', '0:F->G']
***     expanded_states:        ['A', 'B1', 'C', 'B2', 'D', 'E1', 'F', 'E2']
*** PASS: test_cases/q2/pacman_1.test
***     pacman layout:          mediumMaze
***     solution length: 68
***     nodes expanded:         269

### Question q2: 3/3 ###
```

```
Question q3
===========
*** PASS: test_cases/q3/graph_backtrack.test
***     solution:               ['1:A->C', '0:C->G']
***     expanded_states:        ['A', 'B', 'C', 'D']
*** PASS: test_cases/q3/graph_bfs_vs_dfs.test
***     solution:               ['1:A->G']
***     expanded_states:        ['A', 'B']
*** PASS: test_cases/q3/graph_infinite.test
***     solution:               ['0:A->B', '1:B->C', '1:C->G']
***     expanded_states:        ['A', 'B', 'C']
*** PASS: test_cases/q3/graph_manypaths.test
***     solution:               ['1:A->C', '0:C->D', '1:D->F', '0:F->G']
***     expanded_states:        ['A', 'B1', 'C', 'B2', 'D', 'E1', 'F', 'E2']
*** PASS: test_cases/q3/ucs_0_graph.test
***     solution:               ['Right', 'Down', 'Down']
***     expanded_states:        ['A', 'B', 'D', 'C', 'G']
*** PASS: test_cases/q3/ucs_1_problemC.test
***     pacman layout:          mediumMaze
***     solution length: 68
***     nodes expanded:         269
*** PASS: test_cases/q3/ucs_2_problemE.test
***     pacman layout:          mediumMaze
***     solution length: 74
***     nodes expanded:         260
*** PASS: test_cases/q3/ucs_3_problemW.test
***     pacman layout:          mediumMaze
***     solution length: 152
***     nodes expanded:         173
*** PASS: test_cases/q3/ucs_4_testSearch.test
***     pacman layout:          testSearch
***     solution length: 7
***     nodes expanded:         14
*** PASS: test_cases/q3/ucs_5_goalAtDequeue.test
***     solution:               ['1:A->B', '0:B->C', '0:C->G']
***     expanded_states:        ['A', 'B', 'C']

### Question q3: 3/3 ###
```

```
Question q4
===========
*** PASS: test_cases/q4/astar_0.test
***     solution:               ['Right', 'Down', 'Down']
***     expanded_states:        ['A', 'B', 'D', 'C', 'G']
*** PASS: test_cases/q4/astar_1_graph_heuristic.test
***     solution:               ['0', '0', '2']
***     expanded_states:        ['S', 'A', 'D', 'C']
*** PASS: test_cases/q4/astar_2_manhattan.test
***     pacman layout:          mediumMaze
***     solution length: 68
***     nodes expanded:         221
*** PASS: test_cases/q4/astar_3_goalAtDequeue.test
***     solution:               ['1:A->B', '0:B->C', '0:C->G']
***     expanded_states:        ['A', 'B', 'C']
*** PASS: test_cases/q4/graph_backtrack.test
***     solution:               ['1:A->C', '0:C->G']
***     expanded_states:        ['A', 'B', 'C', 'D']
*** PASS: test_cases/q4/graph_manypaths.test
***     solution:               ['1:A->C', '0:C->D', '1:D->F', '0:F->G']
***     expanded_states:        ['A', 'B1', 'C', 'B2', 'D', 'E1', 'F', 'E2']

### Question q4: 3/3 ###
```

```
Question q5
===========
*** PASS: test_cases/q5/corner_tiny_corner.test
***     pacman layout:          tinyCorner
***     solution length:                28

### Question q5: 3/3 ###
```

```
Question q6
===========
*** PASS: heuristic value less than true cost at start state
*** PASS: heuristic value less than true cost at start state
*** PASS: heuristic value less than true cost at start state
path: ['North', 'East', 'East', 'East', 'East', 'North', 'North', 'West', 'Wes
t', 'West', 'West', 'North', 'North', 'North', 'North', 'North', 'North', 'Nor
th', 'North', 'West', 'West', 'West', 'West', 'South', 'South', 'East', 'East'
, 'East', 'East', 'South', 'South', 'South', 'South', 'South', 'South', 'West'
, 'West', 'South', 'South', 'South', 'West', 'West', 'East', 'East', 'North',
'North', 'North', 'East', 'East', 'East', 'East', 'East', 'East', 'East', 'Eas
t', 'South', 'South', 'East', 'East', 'East', 'East', 'East', 'North', 'North'
, 'East', 'East', 'North', 'North', 'East', 'East', 'North', 'North', 'East',
'East', 'East', 'East', 'South', 'South', 'South', 'South', 'East', 'East', 'N
orth', 'North', 'East', 'East', 'South', 'South', 'South', 'South', 'South', '
North', 'North', 'North', 'North', 'North', 'North', 'North', 'West', 'West',
'North', 'North', 'East', 'East', 'North', 'North']
path length: 106
*** PASS: Heuristic resulted in expansion of 901 nodes

### Question q6: 3/3 ###
```

```
Question q7
===========
*** PASS: test_cases/q7/food_heuristic_1.test
*** PASS: test_cases/q7/food_heuristic_10.test
*** PASS: test_cases/q7/food_heuristic_11.test
*** PASS: test_cases/q7/food_heuristic_12.test
*** PASS: test_cases/q7/food_heuristic_13.test
*** PASS: test_cases/q7/food_heuristic_14.test
*** PASS: test_cases/q7/food_heuristic_15.test
*** PASS: test_cases/q7/food_heuristic_16.test
*** PASS: test_cases/q7/food_heuristic_17.test
*** PASS: test_cases/q7/food_heuristic_2.test
*** PASS: test_cases/q7/food_heuristic_3.test
*** PASS: test_cases/q7/food_heuristic_4.test
*** PASS: test_cases/q7/food_heuristic_5.test
*** PASS: test_cases/q7/food_heuristic_6.test
*** PASS: test_cases/q7/food_heuristic_7.test
*** PASS: test_cases/q7/food_heuristic_8.test
*** PASS: test_cases/q7/food_heuristic_9.test
*** FAIL: test_cases/q7/food_heuristic_grade_tricky.test
***     expanded nodes: 7137
***     thresholds: [15000, 12000, 9000, 7000]

### Question q7: 4/4 ###
```

```
Question q8
===========
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_1.test
***     pacman layout:          Test 1
***     solution length:                1
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_10.test
***     pacman layout:          Test 10
***     solution length:                1
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_11.test
***     pacman layout:          Test 11
***     solution length:                2
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_12.test
***     pacman layout:          Test 12
***     solution length:                3
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_13.test
***     pacman layout:          Test 13
***     solution length:                1
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_2.test
***     pacman layout:          Test 2
***     solution length:                1
```

```
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_4.test
***     pacman layout:          Test 4
***     solution length:                3
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_5.test
***     pacman layout:          Test 5
***     solution length:                1
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_6.test
***     pacman layout:          Test 6
***     solution length:                2
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_7.test
***     pacman layout:          Test 7
***     solution length:                1
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_8.test
***     pacman layout:          Test 8
***     solution length:                1
[SearchAgent] using function depthFirstSearch
[SearchAgent] using problem type PositionSearchProblem
*** PASS: test_cases/q8/closest_dot_9.test
***     pacman layout:          Test 9
***     solution length:                1

### Question q8: 3/3 ###
```

```
Finished at 22:18:13

Provisional grades
==================
Question q1: 3/3
Question q2: 3/3
Question q3: 3/3
Question q4: 3/3
Question q5: 3/3
Question q6: 3/3
Question q7: 4/4
Question q8: 3/3
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Total: 25/25

Your grades are NOT yet registered.  To register your grades, make sure
to follow your instructor's guidelines to receive credit on your project.
```

結果討論與實驗心得：

這次的實驗做得很累，有點心力憔悴，但是完成後的感覺很棒、很有成就感，在這次專題中，我訓練了自己透過 Python 撰寫大量演算法（過去都是使用 C++ 在 LeetCode 上面練習），我覺得最核心且最關鍵部分還是撰寫 foodHeuristic() 的過程，因為要保持註解裡面提到的 admissble 跟 consistency，否則在執行 autograder.py 時會卡在 q7，我原先為了讓距離可接受，嘗試透過同個檔案底下提供的 mazeDistance()（其內部調用 bfs）來完成，但是這會導致其中一項測資顯示擴展的點超過可接受的值，因此後來改成粗略的計算各食物的距離（透過曼哈頓距離），結果這也導致 q7 跳出啟發函式不符合 consistency 的問題，故我最後採用了一個可以更加精確且執行速度不會太慢的方式，過程中非常煎熬，只是剛好最近在準備研究所考試的資料結構上到最小生成樹，跟認識的同學討論一陣子後決定至少試試看，於是便在 util.py 裡面寫出一個簡單的 DisjointSet（有 rank 的功能保障路經壓縮不會花費太多時間），並使用 Kruskal 演算法，過程如同實驗內容描述，可去上方的 foodHeuristic() 裡面查看。總之，這次讓我更加熟悉資料結構和圖論演算法，也讓我更熟悉 Python 函式庫跟 Python，最重要的是讓我面對問題的解決能力和信心大幅提升。
另外，如果有需要程式碼，請聯絡我，可以透過 gmail 或是其他方式，我定會提供我的心血。