CSE221 Data Structures (Fall 2019)
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Due date: Dec 21st, 2019, 11:59 pm. [**No later than** Dec 24th, 2019, 11:59 pm.]

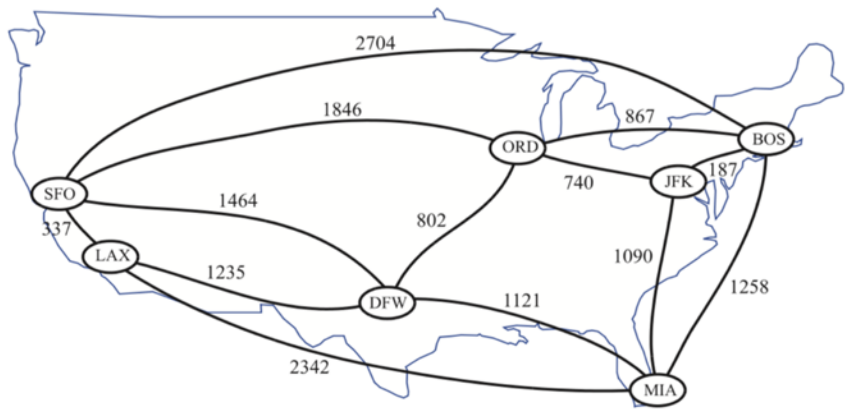
Notes: Check correctness of your program using **uni-server** before final submission. (See the last page.) Plus, do not change the given skeletons at all. In this final assignment, we cannot give you a full late-submission period because of the grading schedules. Thus, we will not accept your submission after the LAST-LAST submission point, which is Dec 24th, 2019, 11:59 pm. (Don't get confused: the due date is still Dec 21st, 2019, 11:59 pm.)

Assignment 5: Directed Graphs and Dijkstra's Algorithm

Many problems in computer science, especially Artificial Intelligence, involve finding the shortest paths in a directed graph. How to correctly implement the shortest path algorithms such as the famous Dijkstra's algorithm is an essential skill for computer science students. The performance of these algorithms heavily depends on the choice of container classes for storing directed graphs. In this exercise, you will learn how to implement the adjacency list structure for directed graphs and Dijkstra's algorithm for solving the single-source, shortest-path problems. At the end, you will write a program to help travelers to solve their shortest path problems they encounter in real life.

Our Goal: Finding the Shortest Routes in a Flight Map

Let's take a look at the following map in Figure 13.13 of the textbook:



This figure shows a map of the flight connections in the major airports in the United States. As you can see, there are some airports that do not have direct flights between them (e.g., BOS and LAX). A passenger would have to choose a route with multiple connecting flights to get to his destination if there is no direct flight to his destination. The question for the passenger is: what is the shortest route to reach the destination? The problem faced by the passenger is the single-source, shortest paths problem, a classic problem in graph theory. In this exercise, you will write a program to help the passenger to solve this problem. Your program will load the data of flight connections from a file and run the Dijkstra's algorithm to find the shortest route between two airports.

1. Implementing Adjacency Lists of Directed Graphs (50 pts)

While the example in Figure 13.13 assumes the graph of flight connections is undirected, a more realistic assumption is that the flight map is a directed graph in which the flight distance of the two directions between two airports can be different. While there are many ways to implement an adjacency list structure for directed graphs, we want you to implement the one as described in Section 13 in the textbook, as its operations can achieve the running times in Table 13.2 of the textbook. To achieve the O(1) running time of eraseEdge() and O(deg(v)) of eraseVertex(), it is necessary to maintain the positions (i.e., iterators) of the collections of vertices and edges in the graph. Other simple implementations of adjacency list structures without maintaining these positions may not guarantee the time complexity of the above operations.

In this exercise, you will implement the adjacency list structure as described in Sections 13.1.1, 13.2.2, and 13.4 of our textbook to store flight maps. Your implementation should faithfully follow the description in the textbook. On Page 599, the textbook has provided all the details the interface of a Graph ADT, which includes the following member functions:

Vertex::operator*(), Vertex::incidentEdges(), Vertex::isAdjacentTo(), Edge::operator*(), Edge::endVertices(), Edge::opposite(), Edge::isAdjacentTo(), Edge::isIncidentOn(), vertices(), edges(), insertVertex(), eraseVertex(), and eraseEdge(). Since we will implement a directed graph, the Graph ADT should also include the following member functions as described on Page 626: Edge::isDirected(), Edge::origin(), Edge::dest(), and insertDirectedEdge(). Notice that we will omit insertEdge() as it is replaced by insertDirectedEdge() as discussed in Section 13.4.

In addition, you need to implement five more member functions for directed graphs:

- Vertex::isOutgoingTo(v) : constructor. This function returns true if and only if there is a directed edge connecting the current vertex to the given vertex v.
- Vertex::outgoingEdge(v) : This function returns the directed edge connecting the current vertex to the given vertex v. If there is no such edge, it throws an exception.
- Vertex::outgoingEdges() : This function returns the set of all directed edges connecting the current vertex to any vertex in the graph.
- Vertex::operator==(v) : This function returns true if and only if the current vertex is the same as the given vertex v.
- Edge::operator==(e) : This function returns true if and only if the current edge is the same as the given edge v.

We provide you a skeleton of the AdjacencyListDirectedGraph class in AdjacencyListDirectedGraph.h, which contains the headers of all of the above member functions. All you need is do is to implement these member functions according to the adjacency list structure in the textbook.

An overview of the adjacency list structures is shown in Figure 13.4 on Page 603 in Section 13.2.2. Your implementation should exactly implement the structure in this figure. Notice that this adjacency list structure is built on top of the edge list structure in Section 13.2.1, which means that you will have to understand the edge list structure as well. To facilitate a correct understanding of the implementation, we have already defined the classes for vertex objects and edge objects in AdjacencyListDirectedGraph.h for you. You just need to take a look at the classes to see how they correspond to the description in the textbook. The classes have included all the member variables as described in Section 13.2.

In the code we provide in AdjacencyListDirectedGraph.h, all vertex objects, edge objects, and incidence collections are stored in these member variables: vertex_collection, edge_collection, and inc_edges_collection, which are list objects in STL. These are all the member variables you need, and you should not declare any other member variables, even a private one, in the AdjacencyListDirectedGraph class. Notice that these variables are defined as list objects because other container classes such as vectors in STL may not guarantee that their iterators remain valid after you modify the containers. In fact, the list container class in STL is one of the few that does guarantee that its iterator will continue to point to the same objects after you modify the container.

In this exercise, all you need to do is to implement the member functions in AdjacencyListDirectedGraph. You should not modify any code that are given in AdjacencyListDirectedGraph.h, and you should not add any other member variables and member functions. To simplify the implementation, you are allowed to assume that vertices and edges passed as arguments to the member functions are never "NULL" (i.e., they always refer to a vertex object or an edge object). This assumption can save you some codes for error handling. There is also no need to define the constructor and the destructor as the list member variables will automatically free their own memory.

2. Implementing Dijkstra's Algorithm (50 pts)

We also provide you FlightMap.h, in which we define the FlightMap class that is used in main.cpp. The FlightMap class contains all the functionalities that are needed in our application—there is no need to extend it to add more public member functions. However, you are allowed to add some private member functions to FlightMap.h if you want.

For each member function of the FlightMap class, we have written a detailed description of its inputs, its outputs, and its function in the comments in FlightMap.h. Please take a look at the comments to learn what these member functions are. We have also implemented most of the member functions in FlightMap.cpp. We strongly recommend you to read the codes in FlightMap.cpp to learn about how to use the AdjacencyListDirectedGraph class.

There are three member functions of the FlightMap class that are not implemented in FlightMap.cpp:

- FlightMap::calcRouteDistance(route) : Calculate the total distance of a route.
- FlightMap::findShortestRoute(airport1, airport2) : Find the shortest route between two airports.
- FlightMap::printAllShortestRoutes(airport) : Print all shortest routes to all airports reachable from a given airport.

Please notice that you must implement these member functions in assignment5.cpp (not in FlightMap.cpp). The comments in FlightMap.h provide the detailed description of the inputs, the outputs, and the functions of these member functions. You should also take a look at the outputs of the sample program called flight-map-sample to see exactly how they work.

In FlightMap::findShortestRoute() and FlightMap::printAllShortestRoutes(), you will implement a shortest path algorithm to find the shortest routes. In this exercise, we ask you to implement Dijkstra's algorithm for finding the single-source, shortest-paths in a directed graph. Section 13.5.2 in the textbook is dedicated to the discussion of the algorithm. More specifically, the Code Fragment 13.24 is the pseudo-code of Dijkstra's algorithm. Please read the pseudo-code to learn how the algorithm works. While the discussion in Section 13.5.2 is for undirected graphs, the same algorithm will work for directed graph with very little modification.

In fact, there are many different ways to implement Dijkstra's algorithm, and you are free to explore other options. Most implementations use a priority queue to store the current frontier (i.e., the set of vertices that will soon be expanded) in Dijkstra's algorithm. Instead of implementing your own priority queue, we allow you to use priority_queue in STL to implement the algorithm. However, there is one drawback of using priority_queue in STL: Dijkstra's algorithm requires the modification of keys in the priority queue in the relaxation step, but priority_queue in STL does not support the modification of a key of an element in a priority queue, and you cannot remove any non-top element from the priority queue. Fortunately, there is an implementation of Dijkstra's algorithm that does not require modifying the keys of non-top elements. The idea is that a vertex can be inserted into a priority queue *multiple* times whenever its cost is getting lower, without removing any of them from the priority queue. The algorithm also maintains the set of vertices that have been *visited* (i.e., their shortest paths have been found). When popping from the priority queue, the algorithm ignores the vertices that have been visited. The effect will be the same as modifying the keys of non-top elements in the priority queue.

There is a high chance that you will use list, vector, and priority_queue in STL to implement your algorithm. We expect you to learn how to use these STL classes yourself by reading some online materials. Notice that the C++ compiler we will use on evaluations is C++11 standard of our uni-server. Hence, you should use the features of C++11 of these STL classes only.

You are allowed to include some private member functions to help you implement the above member functions. You will have to declare them in FlightMap.h, and submit the file along with assignment5.cpp. However, we insist that you should not modify the existing codes in FlightMap.h. You should not add any member variables and public member functions in FlightMap.h. Please take a look at FlightMap.h and locate the line: "You should not modify anything above this line in this class."

Testing

All files that you need in this assignment are the following files:

- FAQ.txt — the answers to some frequently asked questions before.
- flight-map-sample — the sample program. The option j and k in the sample program is out of the scope and thus will not be tested.
- main.cpp — the main function of your program.
- AdjacencyListDirectedGraph.h — your implementation of adjacency list structure for directed graphs. You will submit this file.
- FlightMap.h — the FlightMap class. You will submit this file.
- FlightMap.cpp — the definition of some member functions in FlightMap.h.
- assignment5.cpp — your implementation of the member functions in FlightMap.h that have not been implemented in FlightMap.cpp. You will submit this file.
- graph1.txt — the data of the graph in Figure 13.15 of the textbook.

We provide you a sample program called "flight-map-sample" that implements all functionalities of this program. We also provide you a graph data file called graph1.txt, which contains the data of the graph in Figure 13.15 of the textbook. Please run the sample program with the graph data file on our submission server to see the output it generates. Please make sure that the output of your program is the same as the output of the sample program (except the white spaces and the error messages in the exceptions).

You can check the correctness of Dijkstra's algorithm in your program by comparing your solution with the one in Figure 13.15. Apart from graph1.txt, we recommend you to write a few more graph data files of your own to test your program.

In this exercise, you are allowed to use these container classes in the Standard Template Library: list, vector, queue, map, set, and pair. However, you should not use other data structures in STL except the iterators of these container classes and some common exceptions such as runtime_error. If in doubt, please contact the instructor to ask whether a data structure in STL can be used.

We will test your implementation of AdjacencyListDirectedGraph using a different main function that is different from the one in main.cpp. We will test the completeness and correctness of your implementation, including whether your code will throw all necessary exceptions. We will also check whether your program will cause memory leak. We will also test whether assignment5.cpp uses the member functions in AdjacencyListDirectedGraph correctly by replacing AdjacencyListDirectedGraph.h with the instructor's implementation of AdjacencyListDirectedGraph.h.

The error messages in runtime_error exceptions do not have to be exactly the same as the messages in the sample program we provided. You can write the error messages in your own sentences. However, we will check whether your algorithm have thrown the exceptions when necessary.

Try this for your compilation:

```
$ g++ -o output assignment5.cpp FlightMap.cpp main.cpp -std=c++11 -O3
```

Those compile options are what we are going to use for the actual evaluation.