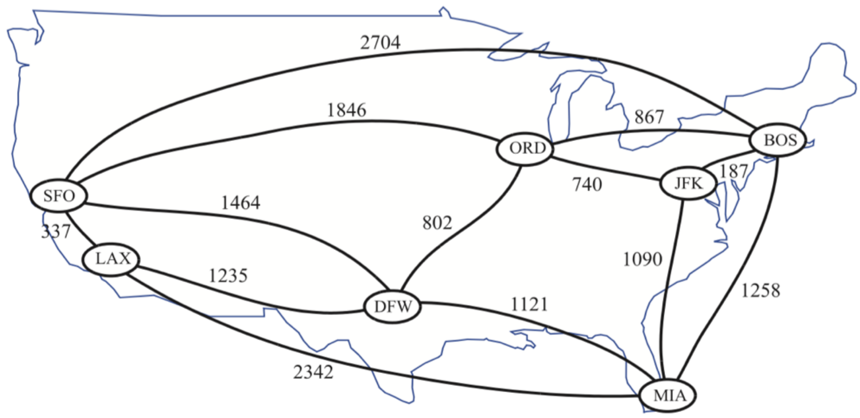
CSE221 Data Structures (Fall 2017)
Instructor: Prof. Tsz-Chiu Au
Due date: Dec. 12, 2017, 11:59 pm

Assignment 4: 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.

Task 1: Implementing Adjacency List Structure for Directed Graphs

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 `eraseEge()` 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)`

  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.

Please make sure that your code can be compiled using the gcc compiler on our submission server. Please write your name, your student ID, and your email as a comment at the top of the file. You should also briefly describe your implementation at the top of the file.

Task 2: Implementing Five Member Functions of FlightMap in assignment4.cpp

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 (see below).

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 five member functions of the `FlightMap` class that are not implemented in `FlightMap.cpp`:

- `FlightMap::calcRouteDistance(route)`

  Calculate the total distance of a route.

- `FlightMap::findRoute(airport1, airport2)`

  Find a route between two airports, which must be a simple path with no cycle.

- `FlightMap::findReachableAirports(airport)`

  Find the set of all airports reachable from an airport.

- `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.

We ask you to implement these member functions in `assignment4.cpp` (not in `FlightMap.cpp`). Once again, 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.

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 `assignment4.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."

Task 3: Implementing Dijkstra's Algorithm

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 on our submission server supports a rather old version of C++ compiler only. Hence, you should use the features of C++98 of these STL classes only, and avoid using the features in C++03, C++11, or C++14.

Testing and Submission

All files that you need in this assignment are put in a zip file called `prog4.zip`, which contains the following files:

- `handout-4.pdf` — the handout of this assignment (i.e., this file).
- `ChangeLog.txt` — the change log.
- `FAQ.txt` — the answers to some frequently asked questions.
- `flight-map-sample` — the sample program.
- `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`.
- `assignment4.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.
- `README.TXT` — your readme file. You will submit this file.

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 `assignment4.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.

To compile your program on our submission servers, use this command:

```
g++ -o flight-map FlightMap.cpp assignment4.cpp main.cpp
```

Before you submit your program, please check whether your program can be compiled correctly using this command on our submission server. We do not grade your program using other compilers.

Please also submit a plain text file called "`README.TXT`" to tell us the extent of your implementation, more specifically which parts have been implemented and which parts have not. Also, if there are some known bugs in your program, you should state them in the plain text file. An empty `README.TXT` is included in `prog4.zip`.

You will submit only four files: (1) **`AdjacencyListDirectedGraph.h`**, (2) **`FlightMap.h`**, (3) **`assignment4.h`**, and (4) **`README.TXT`**. These files should be self-contained and you cannot submit additional files. Please put these files in a zip file called **`assign4.zip`**, and submit it using the `dssubmit` script on our submission servers (`uni06~10.unist.ac.kr`). The command for creating the zip file on our server is:

```
zip assign4.zip AdjacencyListDirectedGraph.h FlightMap.h
                assignment4.h README.TXT
```

Note that you should not put the files in a subdirectory inside the zip file. Otherwise, our grading script cannot find your files

The submission command is

```
dssubmit assign4 assign4s.zip
```

The `dssubmit` script is located at `/home/cse221/bin`. Therefore, your PATH variable of your login shell should contain `/home/cse221/bin` in order to gain access to the script. Check whether your PATH variable has already included `/home/cse221/bin`. If not, please add the following line at the end of your shell's startup scripts (which is `.bashrc` if you are using bash) at your home directory:

```
export PATH=$PATH:/home/cse221/bin
```

Then you will find the command after you log out and then login to the server.

You should test the above `dssubmit` command long before the deadline in order to see whether you will encounter any issue during submission. Please email **Sangwoo Ha** at **swha@unist.ac.kr** if you fail to use this command.

Automatic Grading and Late Submission Penalty

We developed shell scripts to grade your programs automatically without human intervention. In the past, many students didn't read this handout carefully and implemented their programs with wrong function names or filenames, etc., causing compilation errors. Our TAs spent too much time to help students to fix these issues in the past. In order to avoid wasting our TAs' time, we decide to give students opportunities to see the results of the grading script running with their programs *before* the deadline, such that students can fix any issues *themselves* before the final submission. We will start running the grading scripts at every midnight at least three days before the deadline. If you submit your program earlier, you will see the grading report generated by the grading script in the home directory in your account. Please fix any problems in your program according to the grading report, especially those that are caused by incorrect naming. *There will be a 10% penalty if our TA needs to help you to fix any issues related to the submission and automatic grading after the deadline.*

The scores in the pre-deadline grading reports are not final and they will not be recorded. However, the grading reports after the deadline are final. In fact, we will grade your programs three times after the deadline in order implement our late submission policy as described on our course webpage. The first real grading report will be generated right after the deadline. The second real grading report will be exactly one day after the deadline with a penalty of 15%. The third real grading report will be exactly third day after the deadline with a penalty of 30%. We will select the highest scores among these three real grading reports as your final score of this assignment. Clearly, if you do not update and resubmit your program after the deadline, the highest score will be the one right after the deadline. However, if you are not happy with the score on the first real grading report, you still have the chance to improve it by submitting your programs again. Notice that late submission will never decrease your final score.

Our grading script is evolving and hence we reserve rights to regrade your programs with a different script in a later time. Hence, the scores you see in the grading reports may not be final. Please report any bugs in our grading script if you find them.

Bug Reports

Please report any bugs in the codes we provide as well as any typos and errors in this handout and the grading reports to **Prof. Tsz-Chiu Au** at **chiu@unist.ac.kr**. We will look into the bug reports and fix the problems. For any other problems, please do not contact the instructor directly; instead, please email our TA who should be able to help you. Please cc the email to the instructor so that he also knows what is going on between you and the TA. Notice all emails between you, the TA, and the instructor should be written in English.

If we have to release a new version of the codes to fix the bugs, we will announce it on our course webpage. Before submitting your program, you should check the announcement to see whether the codes have been updated. Please make sure that your program works with the latest version of the codes we provide.