CSCE 221 Cover Page
Programming Assignment #5

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Programming Assignment 5

Consider a directed graph without cycles called **a directed acyclic graph** (DAG). In this assignment you are going to find a topological ordering in a DAG. There are many real life problems that can be modeled by such graphs and solved by the topological ordering algorithm. Read the section 9.2, pp. 382-385 in the textbook to learn more about the algorithm.

- The assignment consists of three parts:
  - **Part 1** – implementation of the graph data structure
  - **Part 2** – implementation of the topological ordering for a DAG. Please notice that we take a DAG as an input and the topological ordering for the DAG is returned; or the exception message is displayed: "*There are cycles in the graph*".
  - **Part 3** – preparing a report:
    - * discussing the implementation of the Part 1 and 2 and the running time of the algorithms used to solve the problem.
    - * providing testing cases for correctness
- **Part 1 (40 points)**

  In this part you should implement a graph data structure which is defined based on an additional type `Vertex`. You can download the supplementary (zipped) file with a code skeleton from the eCampus. The implementation of the `Graph` class should be based on adjacency lists, see the file `graph.h`.

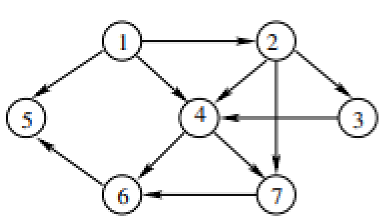
  You should implement the following functions (`T` can be `int`, `char` or `string`):

  - ```
    void buildGraph(istream &input)
    //takes an istream and build the graph according to the specification below
    ```
  - ```
    void displayGraph(ostream &o)
    //prints the graph according to the specification into ostream,
    // nodes can be printed in any order
    ```
  - ```
    Vertex<T> at(T label)
    //returns the Vertex with the given label,
    // throws an exception if it is not present
    ```
  - ```
    int size()
    //returns the number of Vertices in the graphs
    ```

  You are encouraged to use a hash table to store the nodes in the graph. `std::unordered_map` is one such a data structure. Using this library is covered at the end of the document.

  The graph is populated by reading data from a text file with fixed format, see the example below. At each row, the first number is the label of the start vertex of a directed edge. Other numbers in this row are the end vertices accessed from the start vertex.

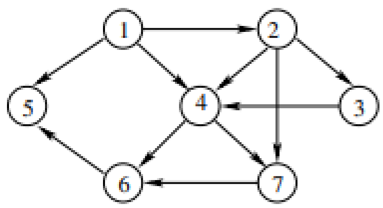
  Example. The first row starts with the vertex 1 and provides information about three directed edges to vertices 2, 4 and 5. In the case when there is no edge for a certain vertex, for example for the vertex 5, the list is empty. This input file is called `input.data` in the supplementary file.




```
1 2 4 5
2 3 4 7
3 4
4 6 7
5
6 5
7 6
```

  - The purpose of this part is to read in the data from an input file with a given format, build a graph data structure, and display the graph on the screen in text format.

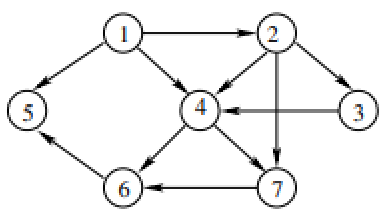
- We assume that the graph we are dealing with is sparse and unweighted. Then, adjacency lists will be a natural choice to store the connection between two nodes. The class `Graph` is used to store the graph and implements the necessary operations such as `buildGraph`, and so on. Furthermore, a `Vertex` class can be implemented to store the basic information about a graph node such as a label which in our case is an integer.
- The nodes are not necessarily numbered consecutively, making a hash table a logical choice data structure for storing Vertices with labels as keys
- You may assume that the graph is fully specified by the input stream and will not be changed after building the graph
- `displayGraph()` should print out each vertex and its adjacency list on the screen. For example, consider the graph G and its corresponding adjacency linked lists for an input sample graph (`input.data`). Test your program by reading a graph from an input file and use the function `displayGraph()` to display the generated graph in text format on the screen, see the format of the output below.



1 : 2 4 5
2 : 3 4 7
3 : 4
4 : 6 7
5 :
6 : 5
7 : 6

- You can compile your code using this command line:
`make`
- And you can run your program by executing:
`./main input.data`

- **Part 2 (40 points)**
  - The formal definition of a topological sort:
  Let G be a DAG with n vertices. A **topological ordering** of G is the ordering $v_1, v_2, \ldots, v_n$ of the vertices of G such that for every edge (v_i, v_j) of G, $i < j$.
  - The illustration of the definition of the topological sort ordering gives a sequence of vertices:



`1 2 3 4 7 6 5`

  The topological sort ordering places vertices of the graph along the horizontal line with the following property: if there is an edge from the vertex v_i to the vertex v_j then the vertex v_i precedes v_j in the topological ordering.
  - Topological sort algorithm:
    1. The input is a DAG
    2. Algorithm – see the textbook, Fig. 9.7, p. 385.
       * You can use `topNum` (`top_num`) as in Fig. 9.7, and then traverse the graph to initialize the topological sort ordering vector.
    3. The output of the program should be a vector of vertices (or their labels) set in topological sort order.
       * You need to print the topological sort ordering vector by printing the labels of vertices.

  You should implement the following functions:

* `bool topological_sort()`
  `//performs the topological sort which returns true`
  `//if a topological ordering is found, otherwise returns false.`
* `void compute_indegree()`
  `//assigns the indegree, the number of inbound edges, for each node.`
* `void print_top_sort(ostream& o, bool addNewline=true)`
  `//prints the topological ordering into the ostream`
  `//if the second parameter is true, insert a newline at the end.`

This may require another data structure, such as `std::priority_queue`, which may alter the runtime.

- **Part 3 (20 points)**
  - Submit to Mimir the source code
  - Submit to eCampus an electronic version of your report including
    * (15 points) description of your implementation, C++ features used, assumptions on input data.
      · Why does the topological sort algorithm use a queue? Can we use a stack instead?
      · Can you explain why the algorithm detects cycles?
      · What is the running time for each function? Use the Big-O notation asymptotic notation and justify your answer.
    * (5 points) test your program for correctness using the four cases below:

Case 1: Use the example (`input.data`) provided in the description of the problem.

Case 2: Samantha plans her course schedule. She is interested in the following eight courses: CSCE121, CSCE222, CSCE221, CSCE312, CSCE314, CSCE313, CSCE315, and CSCE411. The course prerequisites are:

course	#	prerequisites	
CSCE121:	1	(none)	
CSCE222:	2	(none)	
CSCE221:	3	CSCE121	CSCE222
CSCE312:	4	CSCE221	
CSCE314:	5	CSCE221	
CSCE313:	6	CSCE221	
CSCE315:	7	CSCE312	CSCE314
CSCE411:	8	CSCE222	CSCE221

Find a sequence of courses that allows Samantha to satisfy all the prerequisites. Assume that she can only take one class at a time. The input file for this case is provided (`input2.data`)

Case 3: Samantha loves foreign languages and wants to plan her course schedule. She is interested in the following nine courses: LA15, LA16, LA22, LA31, LA32, LA126, LA127, LA141, and LA169. The course prerequisite are:

course	#	prerequisites	
LA15:	1	(none)	
LA16:	2	LA15	
LA22:	3	(none)	
LA31:	4	LA15	
LA32:	5	LA16	LA31
LA126:	6	LA22	LA32
LA127:	7	LA16	
LA141:	8	LA22	LA16
LA169:	9	LA32	

Find a sequence of courses that allows Samantha to satisfy all the prerequisites. Assume that she can only take one class at a time.

Case 4. Create a directed graph with cycles and test your program. There is one such a file provided (`input-cycle.data`).

- **Using the C++ Standard Library:**

  There are several C++ standard library containers that are of note:

  - `std::unordered_set`
  - `std::unordered_map`
  - `std::set`
  - `std::map`

  The former two use a hash table, the latter two use red-black trees. The set elements are immutable whereas map elements are mutable. The other key difference is that the unordered data structures require the elements to have an ordering (`operator<` defined). This allows the in-order traversal of nodes based on this ordering. This would be great for `print_top_sort()`, however, as the topological ordering is not known at insertion time, this cannot be used for ordering; `std::unordered_map` is the preferable data structure. To aid in working with this data structure, the following code is provided:

```
//create the unordered_map object
//the two template types are for key and value type
unordered_map<T, Vertex<T>> node_set;

//create and insert a new object with key token
//  if a key in the table with this item exists,
//  the new object is not inserted
//returns a pair<unordered_map<T, Vertex<T>>::iterator, bool>
//  where iterator is a reference to the object in the hash table,
//  bool is true if this is the first time insert, false otherwise
auto pair = node_set.insert(make_pair(label, Vertex<T>{label, 0}));

bool newItem = pair.second; //true if this is the first item with the given key

unordered_map<T, Vertex<T>>::iterator iter = pair.first;

//the iterator can be dereferenced to get the object back
Vertex<T> v = *iter; //create a copy of the v object
Vertex<T>& v = *iter; //create a reference to v in the map

//WARNING: references are only valid until the next insert is made
//  - they should never be stored in variables
//  - pointers to them should never be made


//Working with STL data structures require considering when references and copies are used
//The trivial solution is here:
Vertex<T> v = node_set.at(label); //copy assignment for v
v.top_num = 0; //or other changes to v
node_set.at(label) = v;


//Alternatively, using references can save some copies
//top_num is 0 by default
cout << node_set.at(label).top_num << endl;   // outputs 0
Vertex<T>& vRef = node_set.at(label);         // by reference
vRef.top_num += 1;                            //incrementing the object in the map
cout << node_set.at(label).top_num << endl;   // outputs 1
Vertex<T> vCopy = node_set.at(label);         //copy assignment
vCopy.top_num += 1;                           // increments the copy
cout << node_set.at(label).top_num << endl;   // outputs 1 again
node_set.at(label).top_num += 1;              //incrementing the object in the map
cout << node_set.at(label).top_num << endl;   // outputs 2
```

```
//much of the same applies to iterating the map object
//elements by reference, updates within the map
for(auto& v: node_set){
  v.second.indegree = 0;
}
//elements by copy, no updates to the item in the map
for(auto v: node_set){
  v.second.indegree = 0;
}
//in both the cases auto is pair<T,Vertex<T>> type object
//in case this is a new syntax for you:
// these for loops are iterating over all objects in the map
```

Another data structure you may be using for the first time is `std::priority_queue`, implemented via a binary heap. It takes one or three template parameters: `<Type, ContainerType, Functor>`. The priority queue orders maximizing, meaning that the greatest priority element is returned first. The stored type or the functor should implement the `operator<()`. The Container type is unimportant, `std::vector<Vertex<T>>` can be used. The code for declaring a functor class is show below. Recall, that the implementation of topological ordering likely assigns the first ordered elements a lower value.

```
// syntax for a custom comparator
template<class T>
class VertexCompare {
public:
  //will be called as a < operator
  bool operator()(Vertex<T> v1, Vertex<T> v2){
    //TODO - implement
        return false;
  }
};
...
priority_queue<Vertex<T>, vector<Vertex<T>>, VertexCompare<T>> pq;
```