Graph and Path Search Library Design Document

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1 Introduction

We've built a graph and path searching library, built in C++. The library is designed to make it really easy for users to use their own vertex and edge data structures and get going using graphs and running algorithms on them right away. Currently the library supports the following graphs: DG (directed graph), DAG (directed acyclic graph), DT (directed tree), Matrix(undirected). The idea is that users define their own vertex and edge data types, and then the library handles everything else under the hood. We also provide very generic path searching code that can be used in many domains.

2 Motivation

Conceptually, a graph is made up of a bunch of vertices and edges. At a minimum there must be some way to distinguish between vertices, distinguish between edges, and define edges as made up of two vertices. Nonetheless, users often want to embed extra information in these ADTs. For example, a user may want a graph representing cities and the highways between them. The user may have a City class; cities must of course have some unique id (e.g. city name), but they may also have extra information such as population, GDP, etc. The same goes for edges; maybe a Road class is used, and the class also has miles, age of road etc.

We wanted to design a library that made it super easy for users to user their *own* vertex and edge data types. The philosophy of the library was that it should be really easy for users to be able to use their own vertex and edge data structures, and that the the library would handle everything else under the hood. In order to make it easy to use the library, we designed the library with minimal requirements when it came to the user defined vertex and edge types.

3 General Graph Design

3.1 Graph Data Types

We provide the following graph types: DG (adjacency list), DAG (adjacency list), DT (adjacency list), and Matrix (undirected). All of these types are represented by simple structs. Each struct holds certain information about the graph it is representing. For example, the adjacency list structs will point to lists of vertices, while the matrix struct will point to some sort of matrix. An important member type of each struct is `graph_type`. This member type is set to one of: `DAG, DG, DT, Matrix_graph`. Concepts (described below) use this member type to determine what graph type is being used, and thus be able to determine, at compile type, which function to call. This is important as fundamentally there is no structural difference between a DT and DG; by using this member type we can have a function that works on a DT (and checks to make sure the tree structure invariant is maintained) and another function that works on a DG (and doesn't have to check that tree structure is maintained).

3.2 User Defined Data Structures

The library was designed so that users are able to design their own vertex and edge data structures. All that is required of the users is the following:

- Vertex and Edge must be comparable (that is they must implement the == operator for their types)

- Vertex and Edge must be hashable

- Edge must have two fields v_1 and v_2, that are of the same type as the Vertex that they defined.

- To use the path algorithms, Edge must have a cost field that is numeric. If the user does not define a cost, the library will automatically given an edge a cost of 1.

- Vertex must have a to_string function that returns a string representation of the vertex.

3.3 Wrappers

Because minimal requirements are imposed on the user when it comes to his/her vertex and edge type, we needed to wrap the users data types in our own struct for certain bookkeeping reasons. Thus, under the hood the graph library stores each vertex in a vertex_wrapper and each edge in a edge_wrapper. Both wrappers also store a field of type Value which is a pair consisting of a string and an int. This lets the user set some sort of value for each vertex and/or edge, without their own data type knowing about such a value. Lastly, the wrapper also stores a unique id (of type int) that the user is again completely oblivious to. This id is generated by the graph library for internal bookkeeping (for example, it's used as the index when a matrix graph representation is used). The following image illustrates this.

vertex_wrapper

```
int unique_id;
V vertex_data;
Value value
```

The idea is the same for the edge_wrapper

vertex_data points to the user provided vertex data. This vertex_wrapper is the fundamental data type of our graph library. Whether a DAG, DG, DT or matrix graph representation is used, each vertex is stored in this struct.

3.4 Graph Interface

Because all graphs are represented by structs, pretty much every graph library function requires such a graph struct as a formal argument. The remaining arguments are almost always one of the user defined vertex or edge. Thus, users do not need to know about wrappers at all. The wrappers are handled by the library. Furthermore, shared_ptr<>s are required when using the API. That is, the library requires every formal argument to be of type shared_ptr<>

Concepts allow us to use the same function name for different graph types. For example, there is a different function add_edge(G g, E e) for each graph type.

```
template<typename G, typename E>
requires Graph<G> && Edge_ptr<E>
bool add_edge(G g, E e)
{
        bool added_edge = add_edge_blindly_w_edge(g, e);
        return added_edge;
```

```
}

template<typename G, typename E>
requires DAG_Graph<G> && Edge_ptr<E>
bool add_edge(G g, E e)
{
        typedef typename G::element_type::vertex_type vertex_type;
        shared_ptr<vertex_type> tmp_v1 = make_shared<vertex_type>(e->v1);
        shared_ptr<vertex_type> tmp_v2 = make_shared<vertex_type>(e->v2);
        bool path_ex = path_exists(g, tmp_v2, tmp_v1);
        if (path_ex == true) {
                return false;
        }
        bool added_edge = add_edge_blindly_w_edge(g, e);
        return added_edge;
}

template<typename G, typename E>
requires DT_Graph<G> && Edge_ptr<E>
bool add_edge(G g, E e)
{
        typedef typename G::element_type::vertex_type vertex_type;
        shared_ptr<vertex_type> tmp_v1 = make_shared<vertex_type>(e->v1);
        shared_ptr<vertex_type> tmp_v2 = make_shared<vertex_type>(e->v2);
        bool path_ex = path_exists(g, tmp_v2, tmp_v1);
        if (path_ex == true) {
                return false;
        }
        bool has_par = has_parent(g, tmp_v2);
        if (has_par == true) {
                return false;
        }
        bool added_edge = add_edge_blindly_w_edge(g, e);
        return added_edge;
}
```

4   Adjacency List Design

4.1

DAG, DG and DT are are represented using adjacency lists. In order to implement an adjacency list, we actually created another data type to wrap `vertex_wrapper`, which we call `vertex_header`. The `vertex_header` is the head of a vertex's adjacency list. Thus, the difference between a `vertex_header` and `vertex_wrapper`, is that the `vertex_header` is the conceptual head of a vertex's adjacency list and points to a list of `vertex_wrapper`.

Adjacency List Representation
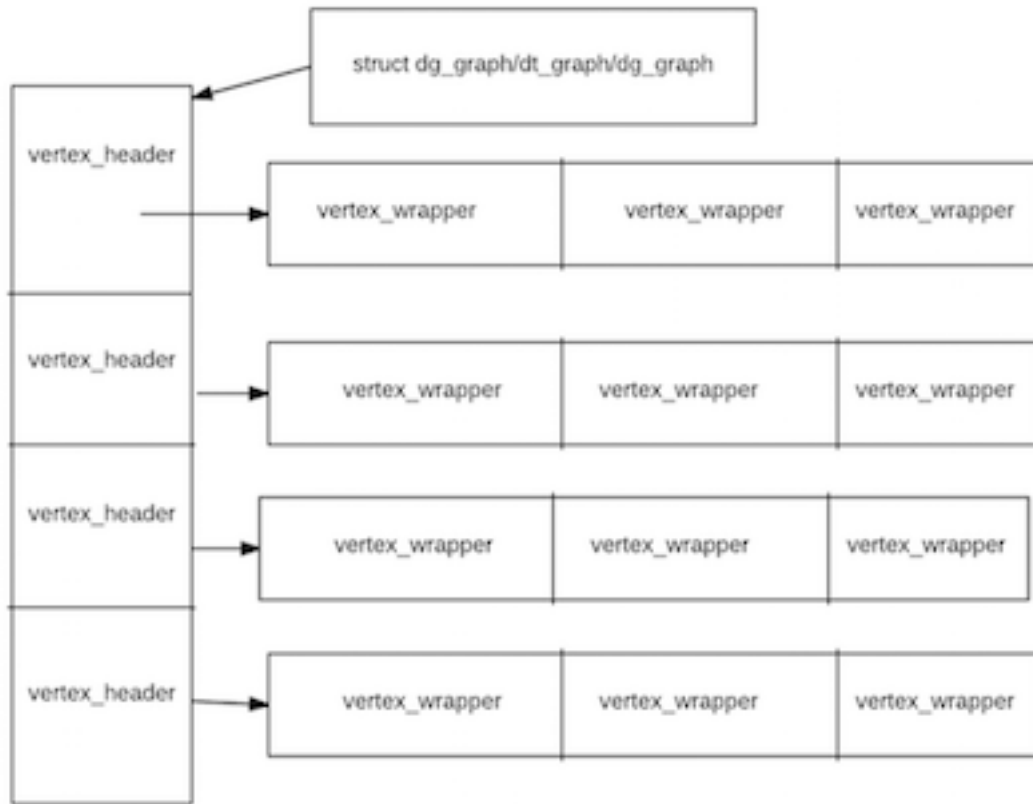
The image above shows the `vertex_header` pointing to a list of `vertex_wrapper`. `vertex_header` actually also points to a list of `edge_wrapper` too.
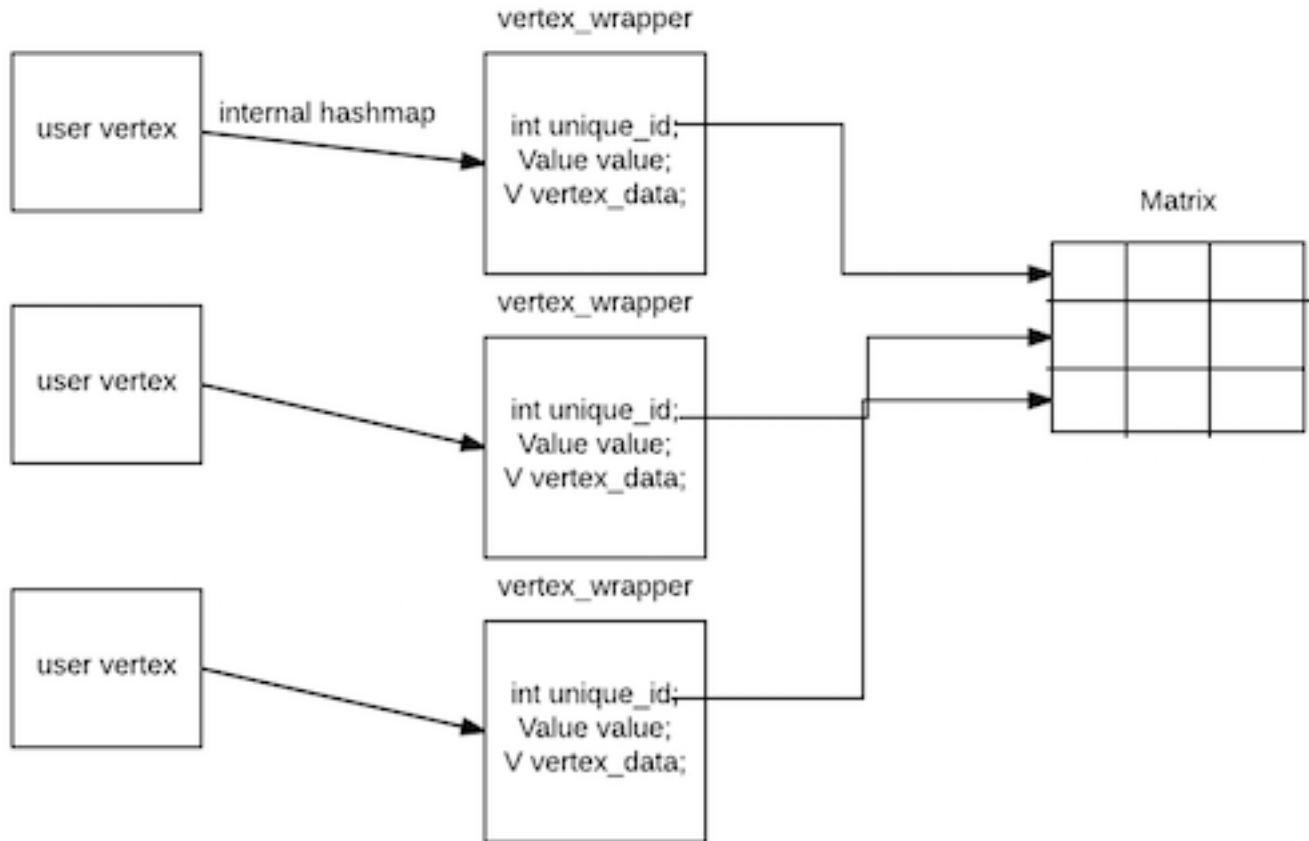
4.2 Data Structures

The list of vertex headers is stored in a vector. The list of neighbors (aka `vertex_wrapper` is also stored in a vector. The list of edges (aka `edge_wrapper` is also stored in a vector).

5 Matrix Design

5.1

As with the adjacency list representation, `vertex_wrapper` is a fundamental data type to our matrix implementation. As emphasized, we wanted the user to be able to use his/her own vertex and edge types. In order to be as flexible as possible we did *not* require the user to assign each vertex a unique integer id. Nonetheless, in order to use matrix graph representations we need some way to index each vertex into the matrix. We decided to use the internal id embedded in each `vertex_wrapper` for this purpose. However, using this unique id wasn't enough. The whole point of using a matrix representation is the access efficiency; we needed some way to immediately map an incoming vertex to its unique id without iterating over *all* vertices. Thus, to make the matrix representation work we maintain a hashmap pointing from a vertex to its `vertex_wrapper`, which contains it's unique id.

vertex_wrapper

user vertex — internal hashmap — int unique_id;
Value value;
V vertex_data;

Matrix

vertex_wrapper

user vertex

int unique_id;
Value value;
V vertex_data;

vertex_wrapper

user vertex

int unique_id;
Value value;
V vertex_data;

5.2 Data Structures

We use a vector of vectors to represent the matrix. Since the internal id is an int, the matrix is thus a vector of vector of ints. We also maintain a hashmap pointing from a vertex to its wrapper.

6 Path Searching algorithms

6.1 Algorithms Supported

We support the following path searching algorithms:

- BFS

- DFS

- UCS

- A*

6.2 Implementation

6.2.1 User Defined State

We designed the path algorithms such that they only require a "start" state and "goal" state, where "state" is an abstract type. The user simply defines his/her own start and goal state, and the code handles the rest.

Of course the semantics of path finding require that any given state must adhere to some requirements; we use concepts to enforce these:

- a state must be comparable

- a state must be hashable

- a state must have a `to_string()` member function

- a state must have a field called parent that is of type `shared_ptr<state>`

- a state must have a field called cost that is numeric

- a state must have a member function called "expand" that returns a vector of states

- if A* is used, a member function called `heuristic_func()` is required that returns a numeric type

As long as the user provides a type that adheres to these properties, any of our algorithms can be run

6.2.2 Path Code

We designed the path searching part of the library such that *all* algorithms actually run on the same while loop. The function that eventually gets called accepts a few parameters that determine which algorithm gets run. For example, if we want to run DFS we send the path code a stack to be used as the frontier set. If we want to run BFS we send it a queue for the frontier set. Thus, all the different algorithms actually run on the same code; it's the inputs that decide which algorithm gets run.

Obviously we wouldn't want the user to know or worry about such details. Thus, the user simply calls `find_path_ast(s, g)`, and under the hood the library creates the appropriate frontier set and calls the generic code from there.

6.3 Path Interface

As mentioned above, the path searching algorithms requires only a start state and goal state. Both states must be wrapped in a `shared_ptr<>`

6.4 Graph Library Integration

The core graph library doesn't know anything about a "start" state and a "goal" state. A vertex is not the same thing as a state; for example, a vertex does not have the concept of a parent pointer. In order to use the path searching code, we therefore has to create state wrappers that integrated with the pre-existing graph data types. This made sure we could still use code described above, while also making sure the user did not have to worry about such transformations.

7 Concepts

7.1 What are concepts?

Concepts are essentially compile time predicates. That is, they are requirements on the types that are passed into functions. If an argument doesn't satisfy the concept, the compiler will immediately report an error. This makes debugging much easier when using templates. Without concepts, debugging can be very tricky when using templates, as it's often late in the compilation process that the compiler realizes a type is no good. As a result error messages can be extremely long, making dubugging tricky.

7.2   Library Usage

In terms of this library, there are two main ways we use concepts.

The first is to make debugging easier; user defined vertices and edges must satisfy certain properties and concepts are used to enforce these and catch bugs earlier in the compilation process. For example, an Edge must point to two vertices; an Edge must be comparable; a Vertex must have a unique identifier.

Perhaps more importantly, we use concepts to support function overloading. The names of the functions that work on different graph types are all the same; thus the user can call the same function whether he or she is working with a matrix or adjacency list. Concepts determine which function should be called at *compile* time, not runtime.

7.3   References

- Concepts reference: `http://www.stroustrup.com/good_concepts.pdf`

- The complete project is located at `https://github.com/andyg7/Graph-Library`.

- The core graph library code is located at `https://github.com/andyg7/Graph-Library/src`