Boost.Graph tutorial

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1 Introduction

I needed this tutorial in 2006, when I started experimenting with Boost.Graph. More specifically, I needed a tutorial that:

- Orders concepts chronologically
- Increases complexity gradually
- Shows complete pieces of code

What I had were the book [1] and the Boost.Graph website, both did not satisfy these requirements.

1.1 Coding style used

I use the coding style from the Core C++ Guidelines.

I prefer to use the keyword auto over doubling the lines of code for using statements. There are plenty of algorithms that return an explicit data type, which can be used for reference.

All coding snippets are taken from compiled C++ code.

vd: vertex_discriptor

1.2 Pitfalls

The choice between 'boost::get', 'std::get' and 'get'. AFAIKS, when in doubt, use 'get'.

2 Building graphs

Boost.Graph is about creating graphs. In this chapter we create graphs, starting from simple to more complex.

2.1 Creating an empty (directed) graph

Let's create a trivial empty graph:

Algorithm 1 Creating an empty graph

```
#include <boost/graph/adjacency_list.hpp>

boost::adjacency_list<>
create_empty_directed_graph() noexcept
{
  return boost::adjacency_list<>();
}
```

Congratulations, you've just created a boost::adjacency_list in which:

- The out edges are stored in a std::vector
- The vertices are stored in a std::vector
- The graph is directed
- Vertices, edges and graph have no properties
- Edges are stored in a std::list

The boost::adjacency_list is the most commonly used graph type, the other is the boost::adjacency_matrix.

2.2 Creating an empty undirected graph

Let's create a trivial empty graph:

Algorithm 2 Creating an empty graph

```
#include <boost/graph/adjacency_list.hpp>

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS
>
create_empty_undirected_graph() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS
  >();
}
```

Congratulations, you've just created a boost::adjacency_list in which:

- The out edges are stored in a std::vector
- The vertices are stored in a std::vector
- The graph is undirected
- Vertices, edges and graph have no properties
- Edges are stored in a std::list

The boost::adjacency_list is the most commonly used graph type, the other is the boost::adjacency_matrix.

2.3 Add a vertex

To add a vertex to a graph, the boost::add_vertex function is used as such:

Algorithm 3 Adding a vertex to a graph

```
#include <boost/graph/adjacency_list.hpp>

template <typename graph>
void add_vertex(graph& g)
{
  boost::add_vertex(g);
}
```

Note that boost::add_vertex returns a vertex descriptor, which is ignored for now. A vertex descriptor can be used to, for example, connect two vertices by an edge

2.4 Add an edge

To add an edge to a graph, two vertex descriptors are needed. A vertex descriptor is a handle to the vertex with in graph. Algorithm 4 adds two vertices to a graph, and connects these two using boost::add_edge:

Algorithm 4 Adding (two vertices and) an edge to a graph

```
#include <boost/graph/adjacency_list.hpp>

#include <cassert>

template <typename graph>
void add_edge(graph& g)
{
  const auto vertex_descriptor_a = boost::add_vertex(g);
  const auto vertex_descriptor_b = boost::add_vertex(g);
  const auto edge_insertion_result = boost::add_edge(
    vertex_descriptor_a,
    vertex_descriptor_b,
    g
  );

  assert(edge_insertion_result.second);
}
```

This algorithm only shows how to add an isolated edge to a graph, instead of allowing for graphs with higher connectivities. The function boost::add_vertex returns a vertex descriptor, which I prefix with 'vd'. The function boost::add_edge returns a std::pair, consisting of an edge descriptor and a boolean success indi-

cator. In algorithm 4 we assert that this insertion was successfull. Insertion can fail if an edge is already present and duplicates are not allowed.

2.5 Creating K_2, a fully connected graph with two vertices

To create a fully connected graph with two vertices (also called K_2), one needs two vertices and one (undirected) edge, as depicted in figure 1.

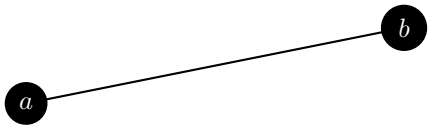

Figure 1: K_2: a fully connected graph with two vertices named a and b

To create K_2, the following code can be used:

Algorithm 5 Creating K_2 as depicted in figure 1

```
#include "create_k2_graph.h"
#include "create_empty_graph.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS
>
create_k2_graph() noexcept
{
  auto g = create_empty_undirected_graph();
  const auto vertex_descriptor_a = boost::add_vertex(g);
  const auto vertex_descriptor_b = boost::add_vertex(g);
  const auto edge_insertion_result
    = boost::add_edge(vertex_descriptor_a,
        vertex_descriptor_b, g);
  assert(edge_insertion_result.second);
  return g;
}
```

Note that this code has more lines of using statements than actual code! In this code, the third template argument of boost::adjacency_list is boost::undirectedS, to select (that is what the S means) for an undirected graph. Adding a vertex with boost::add_vertex results in a vertex descriptor, which is a handle to the vertex added to the graph. Two vertex descriptors are then used to add an edge to the graph. Adding an edge using boost::add_edge returns two things:

an edge descriptor and a boolean indicating success. In the code example, we assume insertion is successfull.

Note that the graph lacks all properties: nodes do not have names, nor do edges.

2.6 Creating an empty graph with named vertices

Let's create a trivial empty graph, in which the vertices can have a name:

Algorithm 6 Creating an empty graph with named vertices

```
#include <boost/graph/adjacency_list.hpp>

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_name_t, std::string
  >
>
create_empty_named_vertices_graph() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::property<
      boost::vertex_name_t, std::string
    >
  > ();
}
```

This graph:

- has its out edges stored in a std::vector (due to the first boost::vecS)
- has its vertices stored in a std::vector (due to the second boost::vecS)
- is undirected (due to the boost::undirectedS)
- The vertices have one property: they have a name, that is of data type std::string (due to the boost::property< boost::vertex_name_t,std::string>')
- Edges and graph have no properties
- Edges are stored in a std::list

The boost::adjacency_list has a new, fourth template argument 'boost::property< boost::vertex_name_t,std::string>'. This can be read as: "vertices have the property 'boost::vertex_name_t', that is of data type 'std::string"'. Or simply: "vertices have a name that is stored as a std::string".

2.7 Add a vertex with a name

Adding a vertex without a name was trivially easy (see chapter 3). Adding a vertex with a name is less easy:

Algorithm 7 Add a vertex with a name

```
#include <boost/graph/adjacency_list.hpp>

template <typename graph>
void add_named_vertex(graph& g, const std::string& name)
{
  const auto vertex_descriptor_a = boost::add_vertex(g);
  auto vertex_name_map = boost::get(boost::vertex_name,g)
      ;
  vertex_name_map[vertex_descriptor_a] = name;
}
```

Instead of calling 'boost::add_vertex' with an additional argument containing the name of the vertex, multiple things need to be done. When adding a new vertex to the graph, the vertex descriptor is stored. After obtaining the name map from the graph (using 'boost::get(boost::vertex_name,g)'), the name of the vertex is set using that vertex descriptor.

2.8 Creating K_2 with named vertices

We extend K_2 of chapter 2.5 by naming the vertices 'from' and 'to', as depicted in figure 2:

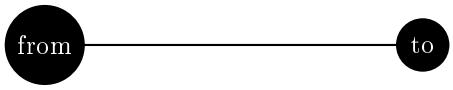

Figure 2: K_2: a fully connected graph with two vertices with the text 'from' and 'to'

To create K_2, the following code can be used:

Algorithm 8 Creating K_2 as depicted in figure 2

```
#include "create_named_vertices_k2_graph.h"
#include "create_empty_named_vertices_graph.h"
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<boost::vertex_name_t,std::string>
>
create_named_vertices_k2_graph() noexcept
{
  auto g = create_empty_named_vertices_graph();
  const auto vertex_descriptor_a = boost::add_vertex(g);
  const auto vertex_descriptor_b = boost::add_vertex(g);
  const auto edge_insertion_result
    = boost::add_edge(
    vertex_descriptor_a,
    vertex_descriptor_b,
    g
  );
  assert(edge_insertion_result.second);

  auto name_map = boost::get(boost::vertex_name,g);
  name_map[vertex_descriptor_a] = "from";
  name_map[vertex_descriptor_b] = "to";

  return g;
}
```

Most of the code is a repeat of algorithm 5. In the end, the names are obtained as a boost::property_map and set.

2.9 Creating an empty graph with named edges and vertices

Let's create a trivial empty graph, in which the both the edges and vertices can have a name:

Algorithm 9 Creating an empty graph with named edges and vertices

```
#include <string>
#include <boost/graph/adjacency_list.hpp>

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<boost::vertex_name_t,std::string>,
  boost::property<boost::edge_name_t,std::string>
>
create_empty_named_edges_and_vertices_graph() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::property<
      boost::vertex_name_t,std::string
    >,
    boost::property<
      boost::edge_name_t,std::string
    >
  >();
}
```

This graph:

- has its out edges stored in a std::vector (due to the first boost::vecS)
- has its vertices stored in a std::vector (due to the second boost::vecS)
- is undirected (due to the boost::undirectedS)
- The vertices have one property: they have a name, that is of data type std::string (due to the boost::property< boost::vertex_name_t,std::string>')
- The edges have one property: they have a name, that is of data type std::string (due to the boost::property< boost::edge_name_t,std::string>')
- The graph has no properties
- Edges are stored in a std::list

The boost::adjacency_list has a new, fifth template argument 'boost::property< boost::edge_name_t,std::string>'. This can be read as: "edges have the property 'boost::edge_name_t', that is of data type 'std::string"'. Or simply: "edges have a name that is stored as a std::string".

2.10 Add an edge with a name

Adding an edge with a name:

Algorithm 10 Add a vertex with a name

```
#include <boost/graph/adjacency_list.hpp>

#include <cassert>

template <typename graph>
void add_named_edge(graph& g, const std::string&
    edge_name)
{
  const auto vertex_descriptor_a = boost::add_vertex(g);
  const auto vertex_descriptor_b = boost::add_vertex(g);
  const auto edge_insertion_result
    = boost::add_edge(vertex_descriptor_a,
        vertex_descriptor_b, g);

  assert(edge_insertion_result.second);

  auto edge_name_map = boost::get(boost::edge_name,g);
  edge_name_map[edge_insertion_result.first] = edge_name;
}
```

In this code snippet, the edge descriptor when using 'boost::add_edge' is used as a key to change the edge name map.

2.11 Creating K_3 with named edges and vertices

We extend the graph K_2 with named vertices of chapter 2.8 by adding names to the edges, as depicted in figure 3:

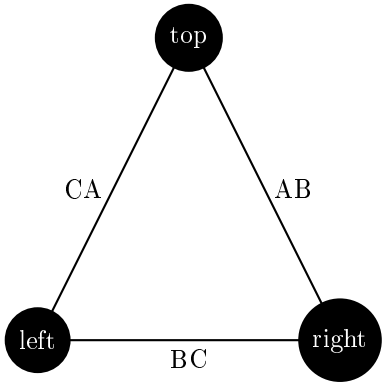

Figure 3: K_3: a fully connected graph with three named edges and vertices

To create K_3, the following code can be used:

Algorithm 11 Creating K_3 as depicted in figure 3

```
#include "create_named_edges_and_vertices_k3_graph.h"

#include "create_empty_named_edges_and_vertices_graph.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<boost::vertex_name_t,std::string>,
  boost::property<boost::edge_name_t,std::string>
>
create_named_edges_and_vertices_k3_graph() noexcept
{
  auto g = create_empty_named_edges_and_vertices_graph();
  const auto vertex_descriptor_a = boost::add_vertex(g);
  const auto vertex_descriptor_b = boost::add_vertex(g);
  const auto vertex_descriptor_c = boost::add_vertex(g);
  const auto edge_insertion_result_ab
    = boost::add_edge(vertex_descriptor_a,
        vertex_descriptor_b, g);
  assert(edge_insertion_result_ab.second);
  const auto edge_insertion_result_bc
    = boost::add_edge(vertex_descriptor_b,
        vertex_descriptor_c, g);
  assert(edge_insertion_result_bc.second);
  const auto edge_insertion_result_ca
    = boost::add_edge(vertex_descriptor_c,
        vertex_descriptor_a, g);
  assert(edge_insertion_result_ca.second);

  //Add vertex names
  auto vertex_name_map = boost::get(boost::vertex_name,g)
      ;
  vertex_name_map[vertex_descriptor_a] = "top";
  vertex_name_map[vertex_descriptor_b] = "right";
  vertex_name_map[vertex_descriptor_c] = "left";

  //Add edge names
  auto edge_name_map = boost::get(boost::edge_name,g);
  edge_name_map[edge_insertion_result_ab.first] = "AB";
  edge_name_map[edge_insertion_result_bc.first] = "BC";
  edge_name_map[edge_insertion_result_ca.first] = "CA";

  return g;

}
```

Most of the code is a repeat of algorithm 8. In the end, the edge names are obtained as a boost::property_map and set.

2.12 Create an empty graph with custom vertices

Say we want to use our own vertex class as graph nodes. This is done in multiple steps:

1. Create a custom vertex class, called 'my_vertex'
2. Install a new property, called 'vertex_custom_type'
3. Use the new property in creating a boost::adjacency_list

2.12.1 Creating the custom vertex class

In this example, I create a custom vertex class. Here I will show the header file of it, as the implementation of it is not important yet.

Algorithm 12 Declaration of my_vertex

```
#ifndef MY_VERTEX_H
#define MY_VERTEX_H

#include <string>

class my_vertex
{
public:
  my_vertex(
    const std::string& name = "",
    const std::string& description = "",
    const double x = 0.0,
    const double y = 0.0
  );
  std::string m_name;
  std::string m_description;
  double m_x;
  double m_y;
};

bool operator==(const my_vertex& lhs, const my_vertex&
    rhs) noexcept;

#endif // MY_VERTEX_H
```

my_vertex is a class that has multiple properties: two doubles 'm_x' ('m_' stands for member) and 'm_y', and two std::strings m_name and m_description. my_vertex is copyable, but cannot trivially be converted to a std::string.

2.12.2 Installing the new property

Installing a new property would have been easier, if 'more C++ compilers were standards conformant' ([1], chapter 3.6, footnote at page 52). Boost.Graph uses the BOOST_INSTALL_PROPERTY macro to allow using a custom property:

Algorithm 13 Installing the vertex_custom_type property

```
#include <boost/graph/properties.hpp>

namespace boost {
  enum vertex_custom_type_t { vertex_custom_type = 314 };
  BOOST_INSTALL_PROPERTY(vertex,custom_type);
}
```

The enum value 314 must be unique.

2.12.3 Create the empty graph with custom vertices

Algorithm 14 Creating an empty graph with custom vertices

```
#include <boost/graph/adjacency_list.hpp>
#include "install_vertex_custom_type.h"
#include "my_vertex.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t,my_vertex
  >
>
create_empty_custom_vertices_graph() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::property<
      boost::vertex_custom_type_t,my_vertex
    >
  >();
}
```

This graph:

- has its out edges stored in a std::vector (due to the first boost::vecS)
- has its vertices stored in a std::vector (due to the second boost::vecS)
- is undirected (due to the boost::undirectedS)
- The vertices have one property: they have a custom type, that is of data type my_vertex (due to the boost::property< boost::vertex_custom_type_t,my_vertex>')
- The edges and graph have no properties
- Edges are stored in a std::list

The boost::adjacency_list has a new, fourth template argument 'boost::property< boost::vertex_custom_type_t,my_vertex>'. This can be read as: "vertices have the property 'boost::vertex_custom_type_t', which is of data type 'my_vertex"'. Or simply: "vertices have a custom type called my_vertex".

2.13 Add a custom vertex

Adding a custom vertex is very similar to adding a named vertex (chapter 7).

Algorithm 15 Add a vertex with a name

```
#include <boost/graph/adjacency_list.hpp>
#include "install_vertex_custom_type.h"
#include "my_vertex.h"

template <typename graph>
void add_custom_vertex(graph& g, const my_vertex& v)
{
  const auto vertex_descriptor_a = boost::add_vertex(g);
  const auto my_vertex_map = boost::get(boost::
      vertex_custom_type,g);
  my_vertex_map[vertex_descriptor_a] = v;
}
```

When having added a new (abstract) vertex to the graph, the vertex descriptor is used to set the my_vertex in the graph its my_vertex map (using 'boost::get(boost::vertex_custom_type,g)').

2.14 Creating K_2 with custom vertices

We reproduce the K_2 with named vertices of chapter 2.8 , but with our custom vertices intead:

Algorithm 16 Creating K_2 as depicted in figure 2

```
#include "install_vertex_custom_type.h"
#include "my_vertex.h"
#include "create_empty_custom_vertices_graph.h"

#include <boost/graph/adjacency_list.hpp>

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t,my_vertex
  >
>
create_custom_vertices_k2_graph() noexcept
{
  auto g = create_empty_custom_vertices_graph();
  const auto vertex_descriptor_a = boost::add_vertex(g);
  const auto vertex_descriptor_b = boost::add_vertex(g);
  const auto edge_insertion_result
    = boost::add_edge(vertex_descriptor_a,
        vertex_descriptor_b, g);
  assert(edge_insertion_result.second);

  //Add names
  auto my_vertex_name_map = boost::get(boost::
      vertex_custom_type,g);
  my_vertex_name_map[vertex_descriptor_a]
    = my_vertex("from","source",0.0,0.0);
  my_vertex_name_map[vertex_descriptor_b]
    = my_vertex("to","target",3.14,3.14);

  return g;
}
```

Most of the code is a slight modification of algorithm 8. In the end, the my_vertices are obtained as a boost::property_map and set with two custom my_vertex objects.

2.15 Create an empty graph with custom edges and vertices

2.16 Add a custom edge

2.17 Creating K_2 with custom edges and vertices

Instead of using edges with a name, or other properties, here we use a custom edge class called 'my_edge'.

3 Measuring simple graphs traits

Measuring simple traits of the graphs created allows you to deb ug your code.

3.1 Getting the vertices

You can use boost::vertices to obtain an iterator pair. The first iterator points to the first vertex, the second points to beyond the last vertex.

3.2 Getting the edges

You can use boost::edges to obtain an iterator pair. The first iterator points to the first edge, the second points to beyond the last edge.

3.3 Counting the number of vertices

Use boost::num_vertices, as shown here:

Algorithm 17 Count the numbe of vertices

```
#include <boost/graph/adjacency_list.hpp>

///Get the number of vertices a graph has
template <class graph>
int get_n_vertices(const graph& g)
{
  return static_cast<int>(boost::num_vertices(g));
}
```

3.4 Counting the number of edges

Use boost::num_edges, as shown here:

Algorithm 18 Count the number of edges

```
#include <boost/graph/adjacency_list.hpp>

///Get the number of edges a graph has
template <class graph>
int get_n_edges(const graph& g)
{
  return static_cast<int>(boost::num_edges(g));
}
```

3.5 Getting the vertices' names

When the vertices of a graph have named vertices, one can extract them as such:

Algorithm 19 Get the vertices' names

```
#include <string>
#include <vector>
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>

//TODO: generalize to return any type
template <typename graph>
std::vector<std::string> get_vertex_names(const graph& g)
{
  std::vector<std::string> v;

  const auto vertex_name_map = get(boost::vertex_name,g);

  for (auto p = vertices(g);
    p.first != p.second;
    ++p.first) {
    v.emplace_back(get(vertex_name_map, *p.first));
  }
  return v;
}
```

The names of the vertices are obtained from a boost::property_map and then put into a std::vector.

When trying to get the vertices' names from a graph without vertices with names, you will get the error 'formed reference to void' (for example, with the code 'get_vertex_names(create_k2_graph());').

3.6 Getting the edges' names

When the edges of a graph have named vertices, one can extract them as such:

Algorithm 20 Get the edges' names

```
#include <string>
#include <vector>
#include <boost/graph/adjacency_list.hpp>
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>

//TODO: generalize to return any type
template <typename graph>
std::vector<std::string> get_edge_names(const graph& g)
{
  std::vector<std::string> v;

  const auto edge_name_map = get(boost::edge_name,g);

  for (auto p = boost::edges(g);
    p.first != p.second;
    ++p.first) {
    v.emplace_back(get(edge_name_map, *p.first));
  }
  return v;
}
```

The names of the edges are obtained from a boost::property_map and then put into a std::vector.

When trying to get the edges' names from a graph without vertices with names, you will get the error 'formed reference to void' (for example, with the code 'get_vertex_names(create_k2_graph());').

3.7 Getting the vertices' my_vertexes[1]

When the vertices of a graph have any associated my_vertex, one can extract these as such:

[1] the name 'my_vertexes' is chosen to indicate this function returns a container of my_vertex

Algorithm 21 Get the vertices' my_vertexes

```
#include <vector>
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>
#include "install_vertex_custom_type.h"
#include "my_vertex.h"

//TODO: generalize to return any type
template <typename graph>
std::vector<my_vertex> get_vertex_my_vertexes(const graph
    & g)
{
  std::vector<my_vertex> v;

  const auto my_vertexes_map = get(boost::
      vertex_custom_type,g);

  for (auto p = vertices(g);
    p.first != p.second;
    ++p.first) {
    v.emplace_back(get(my_vertexes_map, *p.first));
  }
  return v;
}
```

The my_vertex object associated with the vertices are obtained from a boost::property_map and then put into a std::vector.

When trying to get the vertices' my_vertex from a graph without my_vertex objects associated, you will get the error 'formed reference to void' (for example, with the code 'get_vertex_my_vertexes(create_k2_graph());').

3.8 Count vertex name

count_vertices_with_name

3.9 Find a vertex by its name

find_vertex_with_name

3.10 Get a named vertex its in-degree

get_named_vertex_in_degree

- degree_size_type in_degree(vertex_descriptor u, const adjacency_list& g) . Returns the in-degree of a vertex

3.11 Get a named vertex its out-degree

get_named_vertex_out_degree

- degree_size_type in_degree(vertex_descriptor u, const adjacency_list& g) . Returns the in-degree of a vertex

3.12 Count vertex my_vertex

count_vertex_my_vertex

3.13 Find a my_vertex

find_my_vertex

3.14 Find the vertices connected to a certain my_vertex

find_vertices_connected_to_my_vertex

4 Modifying simple graphs traits

It is useful to be able to modify every aspect of a graph. Adding nodes and edges are found in earlier chapters.

4.1 Setting all vertices' names

When the vertices of a graph have named vertices, one set their names as such:

Algorithm 22 Setting the vertices' names

```
#include <string>
#include <vector>

#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>

//TODO: generalize 'names'
template <typename graph>
void set_vertex_names(
  graph& g,
  const std::vector<std::string>& names
)
{
  const auto vertex_name_map = get(boost::vertex_name,g);

  auto names_begin = std::begin(names);
  const auto names_end = std::end(names);
  for (auto vi = vertices(g);
    vi.first != vi.second;
    ++vi.first, ++names_begin)
  {
    assert(names_begin != names_end);
    put(vertex_name_map, *vi.first,*names_begin);
  }
}
```

An impressive feature is that getting the property map holding the graph its names is not a copy, but a reference. Otherwise, modifying 'name_map' (obtained by non-reference) would only modify a copy.

4.2 Setting all vertices' my_vertex objects

When the vertices of a graph are associated with my_vertex objects, one can set these my_vertexes as such:

Algorithm 23 Setting the vertices' my_vertexes

```
#include <string>
#include <vector>

#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>

#include "install_vertex_custom_type.h"
#include "my_vertex.h"

//TODO: generalize 'my_vertexes'
template <typename graph>
void set_vertex_my_vertexes(
  graph& g,
  const std::vector<my_vertex>& my_vertexes
)
{
  const auto my_vertex_map = get(boost::
      vertex_custom_type,g);

  auto my_vertexes_begin = std::begin(my_vertexes);
  const auto my_vertexes_end = std::end(my_vertexes);
  for (auto vi = vertices(g);
    vi.first != vi.second;
    ++vi.first, ++my_vertexes_begin)
  {
    assert(my_vertexes_begin != my_vertexes_end);
    put(my_vertex_map, *vi.first,*my_vertexes_begin);
  }
}
```

An impressive feature is that getting the property map holding the graph its names is not a copy, but a reference. Otherwise, modifying 'my_vertexes_map' (obtained by non-reference) would only modify a copy.

4.3 Replace a vertex its name

rename_vertex

4.4 Replace an edge its name

rename_edge

4.5 Replace a my_vertex

replace_my_vertex

4.6 Clear a named vertex

clear_named_vertex

- void clear_vertex(vertex_descriptor u, adjacency_list& g) . Removes all edges to and from u
- void clear_out_edges(vertex_descriptor u, adjacency_list& g) . Removes all outgoing edges from vertex u in the directed graph g (not applicable for undirected graphs)
- void clear_in_edges(vertex_descriptor u, adjacency_list& g) . Removes all incoming edges from vertex u in the directed graph g (not applicable for undirected graphs)

4.7 Remove a named vertex

remove_named_vertex

4.8 Remove a named edge

remove_named_vertex

- void remove_edge(vertex_descriptor u, vertex_descriptor v, adjacency_list& g) . Removes an edge from g
- void remove_edge(edge_descriptor e, adjacency_list& g) . Removes an edge from g

4.9 Remove a my_vertex

remove_my_vertex

- void remove_vertex(vertex_descriptor u, adjacency_list& g) . Removes a vertex from graph g (It is expected that all edges associated with this vertex have already been removed using clear_vertex or another appropriate function.)

5 Visualizing graphs

Before graphs are visualized, they are stored as a file first. Here, I use the .dot file format.

5.1 Storing a graph as a .dot

Graph are easily saved to a .dot file:

Algorithm 24 Storing a graph as a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>

///Save a graph to a .dot file
template <typename graph>
void save_graph_to_dot(const graph& g, const std::string&
    filename)
{
  std::ofstream f(filename);
  boost::write_graphviz(f,g);
}
```

Using the create_k2_graph function (algorithm 5) to create a K_2 graph, the .dot file created is displayed in algorithm 25:

Algorithm 25 .dot file created from the create_k2_graph function (algorithm 5)

```
digraph G {
0;
1;
0->1 ;
}
```

This .dot file corresponds to figure 4:

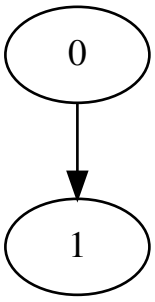

Figure 4: .svg file created from the create_k2_graph function (algorithm 5)

If you used the create_named_vertices_k2_graph function (algorithm 8) to produce a K_2 graph with named vertices, you see that the .dot file does not have stored the vertex names:

Algorithm 26 .dot file created from the create_named_vertices_k2_graph function (algorithm 8)

```
graph G {
0;
1;
0--1 ;
}
```

So, the 'save_graph_to_dot' function (algorithm 24) saves the structure of the graph.

5.2 Storing a graph with named vertices as a .dot

If you used the create_named_vertices_k2_graph function (algorithm 8) to produce a K_2 graph with named vertices, you can store these names additionally with algorithm 27:

Algorithm 27 Storing a graph with named vertices as a .dot file

```
#include <string>
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include <boost/graph/properties.hpp>

#include "get_vertex_names.h"

///Save a graph with named vertices to a .dot file
template <typename graph>
void save_named_vertices_graph_to_dot(const graph& g,
    const std::string& filename)
{
  std::ofstream f(filename);
  const auto names = get_vertex_names(g);
  boost::write_graphviz(f,g,boost::make_label_writer(&
      names[0]));
}
```

The .dot file created is displayed in algorithm 28:

Algorithm 28 .dot file created from the create_named_vertices_k2_graph function (algorithm 8)

```
graph G {
0[label=from];
1[label=to];
0--1 ;
}
```

This .dot file corresponds to figure 5:

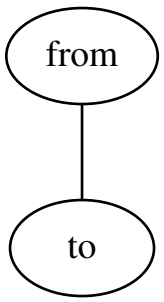

Figure 5: .svg file created from the create_k2_graph function (algorithm 8)

If you used the create_named_edges_and_vertices_k3_graph function (algorithm 11) to produce a K_3 graph with named edges and vertices, you see that the .dot file does not have stored the edge names:

Algorithm 29 .dot file created from the create_named_edges_and_vertices_k3_graph function (algorithm 11)

```
graph G {
0[label=top];
1[label=right];
2[label=left];
0--1 ;
1--2 ;
2--0 ;
}
```

So, the 'save_named_vertices_graph_to_dot' function (algorithm 24) saves only the structure of the graph and its vertex names.

5.3 Storing a graph with named vertices and edges as a .dot

If you used the create_named_edges_and_vertices_k3_graph function (algorithm 11) to produce a K_3 graph with named edges and vertices, you can store these names additionally with algorithm 30:

Algorithm 30 Storing a graph with named edges and vertices as a .dot file

```
#include <string>
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include <boost/graph/properties.hpp>

#include "get_edge_names.h"
#include "get_vertex_names.h"

///Save a graph with named vertices to a .dot file
template <typename graph>
void save_named_edges_and_vertices_graph_to_dot(const
    graph& g, const std::string& filename)
{
  std::ofstream f(filename);
  const auto vertex_names = get_vertex_names(g);
  const auto edge_name_map = boost::get(boost::edge_name,
      g);
  boost::write_graphviz(
    f,
    g,
    boost::make_label_writer(&vertex_names[0]),
    [edge_name_map](std::ostream& out, const auto& e) {
      out << "[label=\"" << edge_name_map[e] << "\"]";
    }
  );
}
```

Note that this algorithm uses C++17.
The .dot file created is displayed in algorithm 31:

Algorithm 31 .dot file created from the create_named_edges_and_vertices_k3_graph function (algorithm 8)

```
graph G {
0[label=top];
1[label=right];
2[label=left];
0--1 [label="AB"];
1--2 [label="BC"];
2--0 [label="CA"];
}
```

This .dot file corresponds to figure 6:

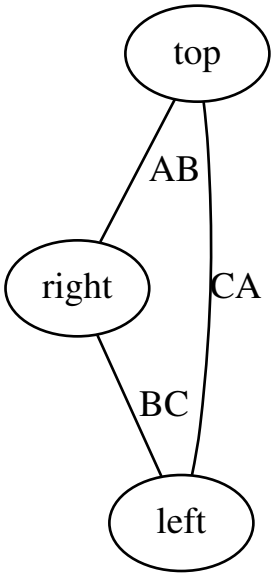

Figure 6: .svg file created from the create_named_edges_and_vertices_k3_graph function (algorithm 8)

If you used the MORE_COMPLEX_create_named_edges_and_vertices_k3_graph function (algorithm 11) to produce a K_3 graph with named edges and vertices, you see that the .dot file does not have stored the edge names:

Algorithm 32 .dot file created from the MORE_COMPLEX_create_named_edges_and_vertices_k3_graph function (algorithm 11)

```
graph G {
0[label=top];
1[label=right];
2[label=left];
0--1 [label="AB"];
1--2 [label="BC"];
2--0 [label="CA"];
}
```

So, the 'save_named_edges_and_vertices_graph_to_dot' function (algorithm 24) saves only the structure of the graph and its edge and vertex names.

5.4 Storing a graph with custom vertices as a .dot

If you used the create_custom_vertices_k2_graph function (algorithm 16) to produce a K_2 graph with vertices associated with my_vertex objects, you can store these my_vertexes additionally with algorithm 33:

Algorithm 33 Storing a graph with custom vertices as a .dot file

```
#include <string>
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include <boost/graph/properties.hpp>

#include "get_vertex_my_vertexes.h"

///Save a graph with named vertices to a .dot file
template <typename graph>
void save_custom_vertices_graph_to_dot(const graph& g,
    const std::string& filename)
{
  std::ofstream f(filename);
  const auto my_vertexes = get_vertex_my_vertexes(g);
  boost::write_graphviz(
    f,
    g,
    [my_vertexes](std::ostream& out, const auto& v) {
      const my_vertex m{my_vertexes[v]};
      out << "[label=\""
        << m.m_name
        << ","
        << m.m_description
        << ","
        << m.m_x
        << ","
        << m.m_y
        << "\"]";
    }
  );
}
```

Note that this algorithm uses C++17.
The .dot file created is displayed in algorithm 34:

Algorithm 34 .dot file created from the create_custom_vertices_k2_graph function (algorithm 8)

```
graph G {
0[label="from,source,0,0"];
1[label="to,target,3.14,3.14"];
0--1 ;
}
```

This .dot file corresponds to figure 34:

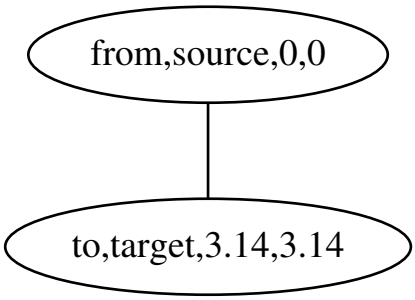

Figure 7: .svg file created from the create_custom_vertices_k2_graph function (algorithm 16)

6 Measuring more complex graphs traits

6.1 Count the number of self-loops

References

[1] Jeremy G Siek, Lie-Quan Lee, and Andrew Lumsdaine. *Boost Graph Library: User Guide and Reference Manual, The*. Pearson Education, 2001.

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