A well-connected C++14 Boost.Graph tutorial

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Contents

1 Introduction

1.1 Why this tutorial

I needed this tutorial already 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 [8] and the Boost.Graph website, both did not satisfy these requirements.

This tutorial is intended to take the reader to the level of understanding the book [8] and the Boost.Graph website require.

The chapters of this tutorial are also like a well-connected graph. To allow for quicker learners to skim chapters, or for beginners looking to find the patterns, some chapters are repetitions of each other (for example, getting an edge its name is very similar to getting a vertex its name)[1]. This tutorial is not about being short, but being complete, at the risk of being called bloated.

A pivotal chapter is chapter 5.2, 'Finding the first vertex with a name', as this opens up the door to finding a vertex and manipulating it.

1.2 Code snippets

For every concept, I will show

- the 'do' function: a function that achieves a goal, for example 'create_empty_undirected_graph'
- the 'demo' function: a function that demonstrates how to call the first, for example 'create_empty_undirected_graph_demo'

I enjoy to show concepts by putting those in (long-named) functions. These functions sometimes border the trivial, by, for example, only calling a single Boost.Graph function. On the other hand, these functions have more English-sounding names, resulting in demonstration code that is readable. Additionally, they explicitly mention their return type (in a simpler way), which may be considered informative.

All coding snippets are taken from compiled C++ code. All code is tested to compile cleanly under GCC at the highest warning level. The code, as well as this tutorial, can be downloaded from the GitHub at `www.github.com/richelbilderbeek/BoostGraphTutorial`.

[1] There was even copy-pasting involved!

1.3 Coding style

I use the coding style from the Core C++ Guidelines. At the time of this writing, the Core C++ Guidelines were still in early development, so I can only hope the conventions I then chose to follow are still Good Ideas.

Due to my long function names and the limitation of ≈50 characters per line, sometimes the code does get to look a bit awkward. I am sorry for this.

I prefer to use the keyword auto over doubling the lines of code for using statements. Because the 'do' functions return an explicit data type, these can be used for reference (until 'decltype(auto)' gets into fashion as a return type). If you really want to know a type, you can use the 'get_type_name' function (chapter 17.1).

On the other hand, I am explicit in the namespaces of functions and classes I use, so to distinguish between types like 'std::array' and 'boost::array'. Some functions (for example, 'get') reside in the namespace of the graph to work on. In this tutorial, this is in the global namespace. Thus, I will write 'get', instead of 'boost::get', as the latter does not compile.

1.4 Tutorial style

In the index, I did first put all my long-named functions there literally, but this resulted in a very sloppy layout. Instead, the function 'do_something' can be found as 'Do something' in the index. Functions like 'boost::do_something' and 'boost::do_something' are at named literally in the index.

1.5 Bundled properties

Because I never got these to work, bundled properties are absent in this tutorial. Instead, I add custom edges and vertices, which I did get to work. I would love additional chapters that follow the same structure as the current tutorial that show 'The Bundled Properies Way'.

1.6 Feedback

I have tried hard to strictly follow the style as described above. If you find I deviated from these decisions somewhere, I would be grateful if you'd let know.

1.7 Help

There are some pieces of code I need help with:

- Saving and loading a graph with a name, chapters 13.3, 13.4 and 13.5

I have already put the tests in place, so you/I can easily check if your solution works.

1.8 Outline

This tutorial is highly structured. The starting point is chapter 2, where a graph without properties is created. All basic concepts are introduced where.

[graph here]

2 Building a graph without properties

Boost.Graph is about creating graphs. In this chapter we create the simplest of graphs, in which edges and nodes have no properties (e.g. having a name).

Still, there are two types of graphs that can be constructed: undirected and directed graphs. The difference between directed and undirected graphs is in the edges: in an undirected graph, an edge connects two vertices without any directionality, as displayed in figure 1. In a directed graph, an edge goes from a certain vertex, its source, to another (which may actually be the same), its target. A directed graph is shown in figure 2.

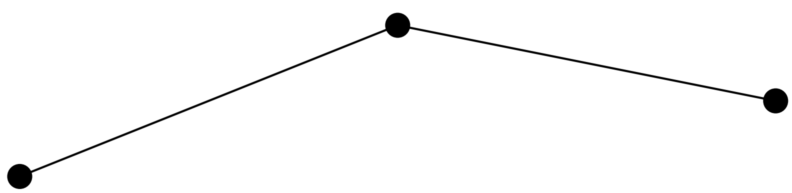

Figure 1: Example of an undirected graph

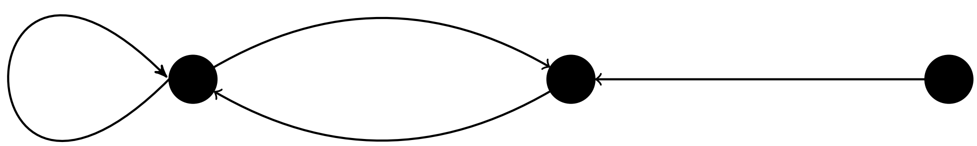

Figure 2: Example of a directed graph

In this chapter, we will build two directed and two undirected graphs:

- An empty (directed) graph, which is the default type: see chapter 2.1

- An empty (undirected) graph: see chapter 2.2
- A two-state Markov chain, a directed graph with two vertices and four edges, chapter 2.14
- K_2, an undirected graph with two vertices and one edge, chapter 2.15

Creating an empty graph may sound trivial, it is not, thanks to the versatility of the Boost.Graph library.

In the process of creating graphs, some basic (sometimes bordering trivial) functions are encountered:

- Counting the number of vertices: see chapter 2.3
- Counting the number of edges: see chapter 2.4
- Adding a vertex: see chapter 2.5
- Getting all vertices: see chapter 2.7
- Getting all vertex descriptors: see chapter 2.8
- Adding an edge: see chapter 2.9
- Getting all edges: see chapter 2.11
- Getting all edge descriptors: see chapter 2.13

These functions are mostly there for completion and showing which data types are used.

The chapter also introduces some important concepts:

- Vertex descriptors: see chapter 2.6
- Edge insertion result: see chapter 2.10
- Edge descriptors: see chapter 2.12

2.1 Creating an empty (directed) graph

Let's create an empty graph!

Algorithm 1 shows the function to create an empty graph.

Algorithm 1 Creating an empty (directed) graph

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

///Create an empty directed graph
boost::adjacency_list<>
create_empty_directed_graph() noexcept
{
  return boost::adjacency_list<>();
}
```

The code consists out of an #include and a function definition. The #include tells the compiler to read the header file 'adjacency_list.hpp'. A header file (often with a '.h' or '.hpp' extension) contains class and functions declarations and/or definitions. The header file 'adjacency_list.hpp' contains the boost::adjacency_list class definition. Without including this file, you will get compile errors like 'definition of boost::adjacency_list unknown'[2]. The function 'create_empty_directed_graph' has:

- a return type: The return type is 'boost::adjacency_list<>', that is a 'boost::adjacency_list with all template arguments set at their defaults
- a noexcept specification: the function should not throw[3], so it is preferred to mark it noexcept ([10] chapter 13.7).
- a function body: all the function body does is create a 'boost::adjacency_list<>' by calling its constructor, by using the round brackets

Algorithm 2 demonstrates the 'create_empty_directed_graph' function. Note that it includes a header file with the same name as the function[4] first, to be able to use it. 'auto' is used, as this is preferred over explicit type declarations ([10] chapter 31.6). The keyword 'auto' lets the compiler figure aut the type itself.

Algorithm 2 Demonstration of 'create_empty_directed_graph'

```
#include "create_empty_directed_graph.h"

void create_empty_directed_graph_demo() noexcept
{
  const auto g = create_empty_directed_graph();
}
```

Congratulations, you've just created a boost::adjacency_list with its default template arguments. We do not do anything with it yet, but still, you've just created a graph, in which:

- The out edges are stored in a std::vector
- The vertices are stored in a std::vector
- The edges have a direction
- The vertices, edges and graph have no properties
- The edges are stored in a std::list

[2] In practice, these compiler error messages will be longer, bordering the unreadable

[3] if the function would throw because it cannot allocate this little piece of memory, you are already in big trouble

[4] I do not think it is important to have creative names

The boost::adjacency_list is the most commonly used graph type, the other is the boost::adjacency_matrix. It stores its edges, out edges and vertices in a two different STL[5] containers. std::vector is the container you should use by default ([10] chapter 31.6, [11] chapter 76), as it has constant time look-up and back insertion. The std::list is used for storing the edges, as it is better suited at inserting elements at any position.

I use const to store the empty graph as we do not modify it. Correct use of const is called const-correct. Prefer to be const-correct ([9] chapter 7.9.3, [10] chapter 12.7, [7] item 3, [3] chapter 3, [11] item 15, [2] FAQ 14.05, [1] item 8, [4] 9.1.6).

2.2 Creating an empty undirected graph

Let's create another empty graph! This time, we even make it undirected!

Algorith 3 shows how to create an undirected graph.

Algorithm 3 Creating an empty undirected graph

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

///Create an empty undirected graph
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS
>
create_empty_undirected_graph() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS
  >();
}
```

Algorithm 4 demonstrates the 'create_empty_undirected_graph' function.

[5] Standard Template Library, the standard library

Algorithm 4 Demonstration of 'create_empty_undirected_graph'

```
#include "create_empty_undirected_graph.h"

void create_empty_undirected_graph_demo() noexcept
{
  const auto g = create_empty_undirected_graph();
}
```

Congratulations, with algorithm 4, you've just created an undirected graph in which:

- The out edges are stored in a std::vector. This way to store out edges is selected by the first 'boost::vecS'
- The vertices are stored in a std::vector. This way to store vertices is selected by the second 'boost::vecS'
- The graph is undirected. This directionality is selected for by the third template argument, 'boost::undirectedS'
- Vertices, edges and graph have no properties
- Edges are stored in a std::list

2.3 Counting the number of vertices

Let's count all zero vertices of an empty graph!

Algorithm 5 Count the number of vertices

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

///Get the number of vertices a graph has
template <class graph>
int get_n_vertices(const graph& g) noexcept
{
  const int n{
    static_cast<int>(boost::num_vertices(g))
  };
  assert(n >= 0);
  return n;
}
```

The function 'get_n_vertices' takes the result of boost::num_vertices, converts it to int and checks if there was no range overflow. We do so, as one should prefer using int (over unsigned int) in an interface ([4] chapter 9.2.2). To do so, in the function body its first stament, the unsigned int[6] produced by boost::num_vertices get converted to an int using a static_cast. This static_cast cannot always be correct, as an unsigned int can have twice as high (but only positive) values. Luckily, this can be detected: if an unsigned int produces a negative int, it was too big to be stored as such. Using an unsigned int over a (signed) int for the sake of gaining that one more bit ([9] chapter 4.4) should be avoided. The integer 'n' is initialized using list-initialization, which is preferred over the other initialization syntaxes ([10] chapter 17.7.6).

The assert statement checks if the conversion from unsigned int to int was successfull. If it was not, the program crashes. Use assert extensively ([9] chapter 24.5.18, [10] chapter 30.5, [11] chapter 68, [6] chapter 8.2, [5] hour 24, [4] chapter 2.6).

The function 'get_n_vertices' is demonstrated in algorithm 6, to measure the number of vertices of both the directed and undirected graph we are already able to create.

Algorithm 6 Demonstration of the 'get_n_vertices' function

```
#include <cassert>

#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_n_vertices.h"

void get_n_vertices_demo() noexcept
{
  const auto g = create_empty_directed_graph();
  assert(get_n_vertices(g) == 0);

  const auto h = create_empty_undirected_graph();
  assert(get_n_vertices(h) == 0);
}
```

Note that the type of graph does not matter here. One can count the number of vertices of every graph, as all graphs have vertices. Boost.Graph is very good at detecting operations that are not allowed, during compile time.

2.4 Counting the number of edges

Let's count all zero edges of an empty graph!

This is very similar to the previous chapter, only it uses boost::num_edges instead:

[6]or '[some type]' to be precise

Algorithm 7 Count the number of edges

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

///Get the number of edges a graph has
template <class graph>
int get_n_edges(const graph& g) noexcept
{
  const int n{
    static_cast<int>(boost::num_edges(g))
  };
  assert(n >= 0);
  return n;
}
```

For the rationale behind this, see the previous chapter.

The function 'get_n_edges' is demonstrated in algorithm 8, to measure the number of edges of an empty directed and undirected graph.

Algorithm 8 Demonstration of the 'get_n_edges' function

```
#include <cassert>

#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_n_edges.h"

void get_n_edges_demo() noexcept
{
  const auto g = create_empty_directed_graph();
  assert(get_n_edges(g) == 0);

  const auto h = create_empty_undirected_graph();
  assert(get_n_edges(h) == 0);
}
```

2.5 Add a vertex

Empty graphs are nice, now its time to add a vertex!

To add a vertex to a graph, the boost::add_vertex function is used as shows in algorithm 9:

Algorithm 9 Adding a vertex to a graph

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

///Add a vertex to a graph
template <typename graph>
void add_vertex(graph& g) noexcept
{
  boost::add_vertex(g);
}
```

Note that boost::add_vertex (in the 'add_vertex' function) returns a vertex descriptor, which is ignored for now. Vertex descriptors are looked at in more details at the chapter 2.6, as we need these to add an edge. Algorithm 10 shows how to add a vertex to a directed and undirected graph.

Algorithm 10 Demonstration of the 'add_vertex' function

```
#include "add_vertex.h"
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"

void add_vertex_demo() noexcept
{
  auto g = create_empty_undirected_graph();
  add_vertex(g);
  assert(boost::num_vertices(g) == 1);

  auto h = create_empty_directed_graph();
  add_vertex(h);
  assert(boost::num_vertices(h) == 1);
}
```

This demonstration code creates two empty graphs, adds one vertex to each and then asserts that the number of vertices in each graph is one. This works for both types of graphs, as all graphs have vertices.

2.6 Vertex descriptors

A vertex descriptor is a handle to a vertex within a graph.

Vertex descriptors can be obtained by dereferencing a vertex iterator (see chapter 2.8). To do so, we first obtain some vertex iterators in chapter 2.7).

Vertex descriptors are used to:

- add and edge between two vertices, see chapter 2.9

- obtain properties of vertex a vertex, for example the vertex its out degrees (chapter 3.1), the vertex its name (chapter 4.4), or a custom vertex property (chapter 8.6)

In this tutorial, vertex descriptors have named prefixed with 'vd_', for example 'vd_1'.

2.7 Get the vertices

You cannot get the vertices. This may sound unexpected, as it must be possible to work on the vertices of a graph. Working on the vertices of a graph is done throught these steps:

- Obtain a vertex iterator pair from the graph
- Dereferencing a vertex iterator to obtain a vertex descriptor

boost::vertices is used to obtain a vertex iterator pair, as shown in algorithm 11. The first vertex iterator points to the first vertex (its descriptor, to be precise), the second points to beyond the last vertex (its descriptor, to be precise). In this tutorial, vertex iterator pairs have named prefixed with 'vip_', for example 'vip_1'.

Algorithm 11 Get the vertex iterators of a graph

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

///Get the vertex iterators of a graph
template <class graph>
std::pair<
  typename graph::vertex_iterator,
  typename graph::vertex_iterator
>
get_vertices(const graph& g) noexcept
{
  return vertices(g); //_not_ boost::vertices!
}
```

This is a somewhat trivial function, as it forwards the function call to boost::vertices.

These vertex iterators can be dereferenced to obtain the vertex descriptors. Note that 'get_vertices' will not be used often in isolation: usually one obtains the vertex descriptors immediatly. Just for your reference, algorithm 12 demonstrates of the 'get_vertices' function, by showing that the vertex iterators of an empty graph point to the same location.

Algorithm 12 Demonstration of 'get_vertices'

```
#include <cassert>
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_vertices.h"

void get_vertices_demo() noexcept
{
  const auto g = create_empty_undirected_graph();
  const auto vip_g = get_vertices(g);
  assert(vip_g.first == vip_g.second);

  const auto h = create_empty_directed_graph();
  const auto vip_h = get_vertices(h);
  assert(vip_h.first == vip_h.second);
}
```

2.8 Get all vertex descriptors

Vertex descriptors are the way to manipulate those vertices. Let's go get the all!

Vertex descriptors are obtained from dereferencing vertex iterators. Algorithm 13 shows how to obtain all vertex descriptors from a graph.

Algorithm 13 Get all vertex descriptors of a graph

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

///Collect all vertex descriptors of a graph
template <class graph>
std::vector<
  typename boost::graph_traits<graph>::vertex_descriptor
> get_vertex_descriptors(const graph& g) noexcept
{
  using boost::graph_traits;
  using vd = typename graph_traits<graph>::
      vertex_descriptor;

  std::vector<vd> vds;
  const auto vis = vertices(g); //_not_ boost::vertices!
  const auto j = vis.second;
  for (auto i = vis.first; i!=j; ++i) {
    vds.emplace_back(*i);
  }
  return vds;
}
```

This is the first more complex piece of code. In the first lines, some 'using' statements allow for shorter type names. The function 'vertices' (not boost::vertices!) returns a vertex iterator pair. The two iterators are extracted, of which the first iterator, 'i', points to the first vertex, and the second, 'j', points to beyond the last vertex. In the for-loop, 'i' loops from begin to end. Dereferencing it produces a vertex descriptor, which is stored in the std::vector using emplace_back. Prefer using emplace_back ([10] chapter 31.6, items 25 and 27).

Algorithm 14 demonstrates that an empty graph has no vertex descriptors:

Algorithm 14 Demonstration of 'get_vertex_descriptors'

```
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_vertex_descriptors.h"

void get_vertex_descriptors_demo() noexcept
{
  const auto g = create_empty_undirected_graph();
  const auto vds_g = get_vertex_descriptors(g);
  assert(vds_g.empty());

  const auto h = create_empty_directed_graph();
  const auto vds_h = get_vertex_descriptors(h);
  assert(vds_h.empty());
}
```

Because all graphs have (vertices and thus) vertex descriptors, the type of graph is unimportant for this code to compile.

2.9 Add an edge

To add an edge to a graph, two vertex descriptors are needed. A vertex descriptor is a handle to the vertex within a graph (vertex descriptors are looked at in more details in chapter 2.6). Algorithm 15 adds two vertices to a graph, and connects these two using boost::add_edge:

Algorithm 15 Adding (two vertices and) an edge to a graph

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

template <typename graph>
void add_edge(graph& g) noexcept
{
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer = boost::add_edge(
    vd_a, // Source/from
    vd_b, // Target/to
    g
  );

  assert(aer.second);
}
```

Algorithm 15 shows how to add an isolated edge to a graph (instead of allowing for graphs with higher connectivities). First, two vertices are created, using the function 'boost::add_vertex'. 'boost::add_vertex' returns a vertex descriptor (which I prefix with 'vd'), both of which are stored. The vertex descriptors are used to add an edge to the graph, using 'boost::add_edge'. 'boost::add_edge' returns returns a std::pair, consisting of an edge descriptor and a boolean success indicator. The success of adding the edge is checked by an assert statement. Here we assert that this insertion was successfull. Insertion can fail if an edge is already present and duplicates are not allowed.

A demonstration of add_edge is shown in algorith 16, in which an edge is added to both a directed and undirected graph.

Algorithm 16 Demonstration of 'add_edge'

```
#include "add_edge.h"
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"

void add_edge_demo() noexcept
{
  auto g = create_empty_undirected_graph();
  add_edge(g);
  assert(boost::num_edges(g) == 1);

  auto h = create_empty_directed_graph();
  add_edge(h);
  assert(boost::num_edges(h) == 1);
}
```

The graph type is unimportant: as all graph types have vertices and edges, edges can be added without possible compile problems.

2.10 boost::add_edge result

When using the function 'boost::add_edge', a 'std::pair<edge_descriptor,bool>' is returned. It contains both the edge descriptor (see chapter 2.12) and a boolean indicating insertion success.

In this tutorial, boost::add_edge results have named prefixed with 'aer_', for example 'aer_1'.

2.11 Getting the edges

You cannot get the edges directly. Instead, working on the edges of a graph is done throught these steps:

- Obtain an edge iterator pair from the graph
- Dereference an edge iterator to obtain an edge descriptor

'edges' (not boost::edges!) is used to obtain an edge iterator pair. The first edge iterator points to the first edge (its descriptor, to be precise), the second points to beyond the last edge (its descriptor, to be precise). In this tutorial, edge iterator pairs have named prefixed with 'eip_', for example 'eip_1'. Algoritm 17 shows how to obtain these:

Algorithm 17 Get the edge iterators of a graph

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

///Get the edge iterators of a graph
template <class graph>
std::pair<
  typename graph::edge_iterator,
  typename graph::edge_iterator
>
get_edges(const graph& g) noexcept
{
  return edges(g); //_not_ boost::edges!
}
```

This is a somewhat trivial function, as all it does is forward to function call to 'edges' (not boost::edges!) These edge iterators can be dereferenced to obtain the edge descriptors. Note that this function will not be used often in isolation: usually one obtains the edge descriptors immediatly.

Algorithm 18 demonstrates 'get_edges' by showing that both iterators of the edge iterator pair point to the same location, when the graph is empty.

Algorithm 18 Demonstration of 'get_edges'

```
#include <cassert>
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_edges.h"

void get_edges_demo() noexcept
{
  const auto g = create_empty_undirected_graph();
  const auto eip_g = get_edges(g);
  assert(eip_g.first == eip_g.second);

  auto h = create_empty_directed_graph();
  const auto eip_h = get_edges(h);
  assert(eip_h.first == eip_h.second);
}
```

2.12 Edge descriptors

An edge descriptor is a handle to an edge within a graph. They are similar to vertex descriptors (chapter 2.6).

Edge descriptors are used to obtain the name, or other properties, of an edge

In this tutorial, edge descriptors have named prefixed with 'ed_', for example 'ed_1'.

2.13 Get all edge descriptors

Obtaining all edge descriptors is similar to getting all vertex descriptors (algorithm 13):

Algorithm 19 Get all edge descriptors of a graph

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

///Get all edge descriptors of a graph
template <class graph>
std::vector<
  typename boost::graph_traits<graph>::edge_descriptor
> get_edge_descriptors(const graph& g) noexcept
{
  using boost::graph_traits;
  using ed = typename graph_traits<graph>::
      edge_descriptor;

  std::vector<ed> eds;

  const auto ei = edges(g); //_not_ boost::edges!
  const auto j = ei.second;

  for (auto i = ei.first; i!=j; ++i) {
    eds.emplace_back(*i);
  }
  return eds;
}
```

The only difference is that instead of the function 'vertices' (not boost::vertices!), 'edges' (not boost::edges!) is used.

Algorithm 20 demonstrates the 'get_edge_descriptor', by showing that empty graphs do not have any edge descriptors.

Algorithm 20 Demonstration of get_edge_descriptors

```
#include <cassert>
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_edge_descriptors.h"

void get_edge_descriptors_demo() noexcept
{
  const auto g = create_empty_directed_graph();
  const auto eds_g = get_edge_descriptors(g);
  assert(eds_g.empty());

  const auto h = create_empty_undirected_graph();
  const auto eds_h = get_edge_descriptors(h);
  assert(eds_h.empty());
}
```

2.14 Creating a directed graph

Finally, we are going to create a directed graph!

2.14.1 Graph

This directed graph is a two-state Markov chain, with two vertices and four edges, as depicted in figure 3:

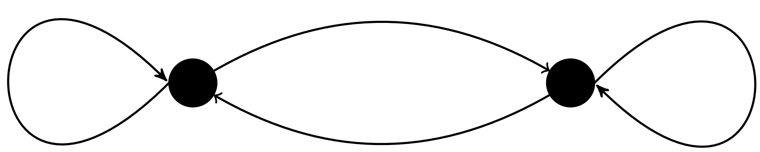

Figure 3: The two-state Markov chain

Note that directed graphs can have edges that start and end in the same vertex. These are called self-loops.

2.14.2 Function to create such a graph

To create this two-state Markov chain, the following code can be used:

Algorithm 21 Creating the two-state Markov chain as depicted in figure 3

```
#include <cassert>
#include <boost/graph/adjacency_list.hpp>
#include "create_empty_directed_graph.h"

///Create a two-state Markov chain
boost::adjacency_list<>
create_markov_chain() noexcept
{
  auto g = create_empty_directed_graph();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
  assert(aer_aa.second);
  const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
  assert(aer_ab.second);
  const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
  assert(aer_ba.second);
  const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
  assert(aer_bb.second);
  return g;
}
```

To save defining the type, we call the 'create_empty_directed_graph' function. The vertex descriptors (see chapter 2.6) created by two boost::add_vertex calls are stored to add an edge to the graph. Then boost::add_edge is called four times. Every time, its return type (see chapter 2.10) is checked for a successfull insertion.

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

2.14.3 Creating such a graph

Algorithm 22 demonstrates the 'create_markov_chain_graph' function and checks if it has the correct amount of edges and vertices.

Algorithm 22 Demonstration of the 'create_markov_chain'

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

#include "create_markov_chain.h"

void create_markov_chain_demo() noexcept
{
  const auto g = create_markov_chain();
  assert(boost::num_vertices(g) == 2);
  assert(boost::num_edges(g) == 4);
}
```

2.14.4 The .dot file produced

Running a bit ahead, this graph can be converted to a .dot file (using algorithm 29) created is displayed in algorithm 23:

Algorithm 23 .dot file created from the 'create_markov_chain_graph' function (algorithm 21), converted from graph to .dot file using algorithm 29

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

From the .dot file one can already see that the graph is directed, because:

- The first word, 'digraph', denotes a directed graph (where 'graph' would have indicated an undirectional graph)
- The edges are written as '->' (where undirected connections would be written as '–')

2.14.5 The .svg file produced

The .svg file of this graph is shown in figure 4:

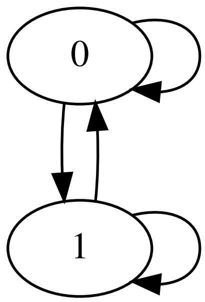

Figure 4: .svg file created from the 'create_markov_chain' function (algorithm 21) its .dot file and converted from .dot file to .svg using algorithm 176

Also this figure shows that the graph in directed, as the edges have arrow heads. Note that the .svg is displayed as if the nodes have names. This is not the case: here, the node indices are shown.

2.15 Creating K_2, a fully connected undirected graph with two vertices

Finally, we are going to create a graph!

2.15.1 Graph

To create a fully connected undirected graph with two vertices (also called K_2), one needs two vertices and one (undirected) edge, as depicted in figure 5.

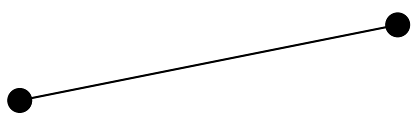

Figure 5: K_2: a fully connected undirected graph with two vertices

2.15.2 Function to create such a graph

To create K_2, the following code can be used:

Algorithm 24 Creating K_2 as depicted in figure 5

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

///Create K2: a fully connected undirected graph with two
    vertices
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS
>
create_k2_graph() noexcept
{
  auto g = create_empty_undirected_graph();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer = boost::add_edge(vd_a, vd_b, g);
  assert(aer.second);
  return g;
}
```

This code is very similar to the 'add_edge' function (algorithm 15). To save defining the type, we call the 'create_empty_undirected_graph' function. The vertex descriptors (see chapter 2.6) created by two boost::add_vertex calls are stored to add an edge to the graph. From boost::add_edge its return type (see chapter 2.10), it is only checked that insertion has been successfull.

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

2.15.3 Creating such a graph

Algorithm 25 demonstrates how to 'create_k2_graph' and checks if it has the correct amount of edges and vertices.

Algorithm 25 Demonstration of 'create_k2_graph'

```
#include <cassert>

#include "create_k2_graph.h"

void create_k2_graph_demo() noexcept
{
  const auto g = create_k2_graph();
  assert(boost::num_vertices(g) == 2);
  assert(boost::num_edges(g) == 1);
}
```

2.15.4 The .dot file produced

Running a bit ahead, this graph can be converted to the .dot file as shown in algorithm 26:

Algorithm 26 .dot file created from the 'create_k2_graph' function (algorithm 24), converted from graph to .dot file using algorithm 29

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

From the .dot file one can already see that the graph is undirected, because:

- The first word, 'graph', denotes an undirected graph (where 'digraph' would have indicated a directional graph)
- The edge between 0 and 1 is written as '–' (where directed connections would be written as '->', '<-' or '<>')

2.15.5 The .svg file produced

Continuing to running a bit ahead, this .dot file can be converted to the .svg as shown in figure 6:

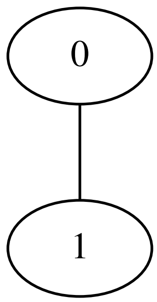

Figure 6: .svg file created from the 'create_k2_graph' function (algorithm 24) its .dot file, converted from .dot file to .svg using algorithm 176

Also this figure shows that the graph in undirected, otherwise the edge would have one or two arrow heads. Note that the .svg is displayed as if the nodes have names. This is not the case: here, the node indices are shown.

3 Working with graphs without vertices

Here we'll do some basic stuff:

- Getting the vertices' out degrees: see chapter 3.1
- Saving a graph without properties to .dot file: see chapter 3.2
- Loading an undirected graph without properties from .dot file: see chapter 3.3
- Loading a directed graph without properties from .dot file: see chapter 3.4

3.1 Getting the vertices' out degree

As a bonus chapter, let's measure the out degree of all vertices in a graph. The out degree of a vertex is the number of edges that originate at it.

The number of connections is called the 'degree' of the vertex. There are three types of degrees:

- in degree: the number of incoming connections, using boost::in_degree
- out degree: the number of outgoing connections, using boost::in_degree
- degree: sum of the in degree and out degree, using boost::in_degree

Algorithm 27 shows how to obtain these:

Algorithm 27 Get the vertices' out degrees

```
#include <vector>

///Get the out degrees of all vertices
template <typename graph>
std::vector<int> get_vertex_out_degrees(const graph& g)
  noexcept
{
  std::vector<int> v;
  const auto vis = vertices(g);
  const auto j = vis.second;
  for (auto i = vis.first; i!=j; ++i) {
    v.emplace_back(
      out_degree(*i,g) //_not_ boost::out_degree!
    );
  }
  return v;
}
```

The structure of this algorithm is similar to get_vertex_descriptors (algorithm 13), except that the out degrees from the vertex descriptors are stored. The out degree of a vertex iterator is obtained from the function 'out_degree' (not boost::out_degree!).

Albeit that the K_2 graph and the two-state Markov chain are rather simple, we can use it to demonstrate 'get_vertex_out_degrees' on, as shown in algorithm 28.

Algorithm 28 Demonstration of the 'get_vertex_out_degrees' function

```
#include <cassert>

#include "create_k2_graph.h"
#include "create_markov_chain.h"
#include "get_vertex_out_degrees.h"

void get_vertex_out_degrees_demo() noexcept
{
  const auto g = create_k2_graph();
  const std::vector<int> expected_out_degrees_g{1,1};
  const std::vector<int> vertex_out_degrees_g{
      get_vertex_out_degrees(g)};
  assert(expected_out_degrees_g == vertex_out_degrees_g);

  const auto h = create_markov_chain();
  const std::vector<int> expected_out_degrees_h{2,2};
  const std::vector<int> vertex_out_degrees_h{
      get_vertex_out_degrees(h)};
  assert(expected_out_degrees_h == vertex_out_degrees_h);
}
```

It is expected that K_2 has one out-degree for every vertex, where the two-state Markov chain is expected to have two out-degrees per vertex.

3.2 Storing a graph as a .dot

Graph are easily saved to a file, thanks to Graphviz. Graphviz (short for Graph Visualization Software) is a package of open-source tools for drawing graphs. It uses the DOT language for describing graphs, and these are commonly stored in (plain-text) .dot files:

Algorithm 29 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
) noexcept
{
  std::ofstream f(filename);
  boost::write_graphviz(f,g);
}
```

All the code does is create an std::ofstream (an output-to-file stream) and use boost::write_graphviz to write the DOT description of our graph to that stream. Instead of 'std::ofstream', one could use std::cout (a related output stream) to display the DOT language on screen directly.

Algorithm 30 shows how to use the 'save_graph_to_dot' function:

Algorithm 30 Demonstration of the 'save_graph_to_dot' function

```
#include "create_k2_graph.h"
#include "create_markov_chain.h"
#include "save_graph_to_dot.h"

void save_graph_to_dot_demo() noexcept
{
  const auto g = create_k2_graph();
  save_graph_to_dot(g,"create_k2_graph.dot");

  const auto h = create_markov_chain();
  save_graph_to_dot(h,"create_markov_chain.dot");
}
```

When using the 'save_graph_to_dot' function (algorithm 29), only the structure of the graph is saved: all other properties like names are not stored. Algorithm 66 shows how to do so.

3.3 Loading an undirected graph from a .dot

Before loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph is loaded, as shown in algorithm 31:

Algorithm 31 Loading an undirected graph from a .dot file

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

#include "create_empty_undirected_graph.h"
#include "is_regular_file.h"

///Load an undirected graph from a .dot file
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS
>
load_undirected_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_undirected_graph();
  boost::dynamic_properties p(
    boost::ignore_other_properties
  );
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists, using the 'is_regular_file' function (algorithm 177), after which a std::ifstream (input-file-stream) is opened. Then an empty undirected graph is created. Next to this, a boost::dynamic_properties is created with the 'boost::ignore_other_properties' in its constructor (using a default constructor here results in the run-time error 'property not found: node_id', see chapter 18.5). From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 32 shows how to use the 'load_undirected_graph_from_dot' function:

Algorithm 32 Demonstration of the 'load_undirected_graph_from_dot' function

```
#include <cassert>
#include "create_k2_graph.h"
#include "load_undirected_graph_from_dot.h"
#include "save_graph_to_dot.h"

void load_undirected_graph_from_dot_demo() noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g = create_k2_graph();
  const std::string filename{"create_k2_graph.dot"};
  save_graph_to_dot(g, filename);
  const auto h
    = load_undirected_graph_from_dot(filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
}
```

This demonstration shows how the K_2 graph is created using the 'create_k2_graph' function (algorithm 24), saved and then loaded. The loaded graph is checked to be a K_2 graph.

3.4 Loading an directed graph from a .dot

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph is loaded, as shown in algorithm 33:

Algorithm 33 Loading a directed graph from a .dot file

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

#include "create_empty_directed_graph.h"
#include "is_regular_file.h"

///Load a directed graph from a .dot file
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS
>
load_directed_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_directed_graph();
  boost::dynamic_properties p(
    boost::ignore_other_properties
  );
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists, using the 'is_regular_file' function (algorithm 177), after which an std::ifstream is opened. Then an empty directed graph is created. Next to this, a boost::dynamic_properties is created with the 'boost::ignore_other_properties' in its constructor (using a default constructor here results in the run-time error 'property not found: node_id', see chapter 18.5). From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 34 shows how to use the 'load_directed_graph_from_dot' function:

Algorithm 34 Demonstration of the 'load_directed_graph_from_dot' function

```
#include <cassert>
#include "create_markov_chain.h"
#include "load_directed_graph_from_dot.h"
#include "save_graph_to_dot.h"

void load_directed_graph_from_dot_demo() noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g = create_markov_chain();
  const std::string filename{
    "create_markov_chain.dot"
  };
  save_graph_to_dot(g, filename);
  const auto h = load_directed_graph_from_dot(filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
}
```

This demonstration shows how the Markov chain is created using the 'create_markov_chain_graph' function (algorithm 21), saved and then loaded. The loaded graph is then checked to be a two-state Markov chain.

4 Building graphs with named vertices

Up until now, the graphs created have had edges and vertices without any propery. In this chapter, graphs will be created, in which the vertices can have a name. This name will be of the std::string data type, but other types are possible as well. There are many more built-in properties edges and nodes can have (see chapter 19.1 for a list).

In this chapter, we will build the following graphs:

- An empty directed graph that allows for vertices with names: see chapter 4.1
- An empty undirected graph that allows for vertices with names: see chapter 4.2
- Two-state Markov chain with named vertices: see chapter 4.5
- K_2 with named vertices: see chapter 4.6

In the process, some basic (sometimes bordering trivial) functions are shown:

- Adding a named vertex: see chapter 4.3
- Getting the vertices' names: see chapter 4.4

These functions are mostly there for completion and showing which data types are used.

4.1 Creating an empty directed graph with named vertices

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

Algorithm 35 Creating an empty directed graph with named vertices

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

///Create an empty directed graph with named vertices
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_name_t,std::string
  >
>
create_empty_directed_named_vertices_graph() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    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 directed (due to the boost::directedS)
- 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".

Algorithm 36 shows how to create this graph. Note that all the earlier functions defined in this tutorial keep working as expected.

Algorithm 36 Demonstration of the 'create_empty_directed_named_vertices_graph' function

```
#include <cassert>
#include <boost/graph/adjacency_list.hpp>
#include "create_empty_directed_named_vertices_graph.h"

void create_empty_named_directed_vertices_graph_demo()
    noexcept
{
  const auto g
    = create_empty_directed_named_vertices_graph();
  assert(boost::num_vertices(g) == 0);
  assert(boost::num_edges(g) == 0);
}
```

4.2 Creating an empty undirected graph with named vertices

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

Algorithm 37 Creating an empty undirected graph with named vertices

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

///Create an empty undirected graph with named vertices
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_name_t,std::string
  >
>
create_empty_undirected_named_vertices_graph() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::property<
      boost::vertex_name_t,std::string
    >
  >();
}
```

There is not much happening in this code, except for returning a boost::adjacency_list of the correct type.

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".

Algorithm 38 shows how to create this graph:

Algorithm 38 Demonstration of the 'create_empty_undirected_named_vertices_graph' function

```
#include <cassert>
#include <boost/graph/adjacency_list.hpp>
#include "create_empty_undirected_named_vertices_graph.h"

void create_empty_undirected_named_vertices_graph_demo()
    noexcept
{
  const auto g
    = create_empty_undirected_named_vertices_graph();
  assert(boost::num_vertices(g) == 0);
  assert(boost::num_edges(g) == 0);
}
```

4.3 Add a vertex with a name

Adding a vertex without a name was trivially easy (see chapter 2.5). Adding a vertex with a name takes slightly more work, as shown by algorithm 39:

Algorithm 39 Adding a vertex with a name

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

///Add a named vertex to the graph
template <typename graph>
void add_named_vertex(
  const std::string& name,
  graph& g
) noexcept
{
  const auto vd_a = boost::add_vertex(g);
  auto vertex_name_map
    = get( //_not_ boost::get!
      boost::vertex_name,g
    );
  vertex_name_map[vd_a] = name;
}
```

Instead of calling 'boost::add_vertex' with an additional argument containing the name of the vertex[7], multiple things need to be done. When adding a new

[7] I am unsure if this would have been a good interface. I am sure I expected this interface myself. I do see a problem with multiple properties and the order of initialization, but

vertex to the graph, the vertex descriptor (as describes in chapter 2.6) is stored. After obtaining the name map from the graph (using 'get(boost::vertex_name,g)'), the name of the vertex is set using that vertex descriptor. Note that 'get' has no 'boost::' prepending it, as it lives in the same (global) namespace the function is in. Using 'boost::get' will not compile.

Using add_named_vertex is straightforward, as demonstrated by algorithm 40.

Algorithm 40 Demonstration of 'add_named_vertex'

```
#include <cassert>
#include <boost/graph/adjacency_list.hpp>
#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"

void add_named_vertex_demo() noexcept
{
  auto g
    = create_empty_undirected_named_vertices_graph();
  add_named_vertex("Lex", g);
  assert(boost::num_vertices(g) == 1);
}
```

4.4 Getting the vertices' names

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

initialization could simply follow the same order as the the property list.

Algorithm 41 Get the vertices' names

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

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

  const auto vertex_name_map = get(boost::vertex_name,g);
  const auto vip = vertices(g);
  const auto j = vip.second;
  for (auto i = vip.first; i!=j; ++i) {

    v.emplace_back(
      get( //_not_ boost::get!
        vertex_name_map,
        *i
      )
    );
  }
  return v;
}
```

This code is very similar to 'get_vertex_out_degrees' (algorithm 27), as also there we iterated through all vertices, accessing all vertex descriptors sequentially.

The names of the vertices are obtained from a boost::property_map and then put into a std::vector. Note that the std::vector has element type 'std::string', instead of extracting the type from the graph. If you know how to do so, please email me.

When trying to get the vertices' names from a graph without vertices with names, you will get the error 'formed reference to void' (see chapter 18.1).

Algorithm 42 shows how to add two named vertices, and check if the added names are retrieved as expected.

Algorithm 42 Demonstration of 'get_vertex_names'

```
#include <cassert>

#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"
#include "get_vertex_names.h"

void get_vertex_names_demo() noexcept
{
  auto g
    = create_empty_undirected_named_vertices_graph();
  const std::string vertex_name_1{"Chip"};
  const std::string vertex_name_2{"Chap"};
  add_named_vertex(vertex_name_1, g);
  add_named_vertex(vertex_name_2, g);
  const std::vector<std::string> expected_names{
    vertex_name_1, vertex_name_2
  };
  const std::vector<std::string> vertex_names{
    get_vertex_names(g)
  };
  assert(expected_names == vertex_names);
}
```

4.5 Creating a Markov chain with named vertices

4.5.1 Graph

We extend the Markov chain of chapter 2.14 by naming the vertices *Sunny* and *Rainy*, as depicted in figure 7:

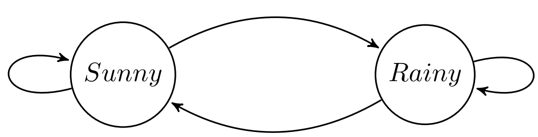

Figure 7: A two-state Markov chain where the vertices have texts *Sunny* and *Rainy*

4.5.2 Function to create such a graph

To create this Markov chain, the following code can be used:

Algorithm 43 Creating a Markov chain with named vertices as depicted in figure 7

```
#include <cassert>
#include <boost/graph/adjacency_list.hpp>
#include "create_empty_directed_named_vertices_graph.h"

///Create a two-state Markov chain with named vertices
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<boost::vertex_name_t,std::string>
>
create_named_vertices_markov_chain() noexcept
{
  auto g
    = create_empty_directed_named_vertices_graph();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
  assert(aer_aa.second);
  const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
  assert(aer_ab.second);
  const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
  assert(aer_ba.second);
  const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
  assert(aer_bb.second);

  auto name_map = get( //_not_ boost::get!
    boost::vertex_name,g
  );
  name_map[vd_a] = "Sunny";
  name_map[vd_b] = "Rainy";

  return g;
}
```

Most of the code is a repeat of algorithm 21, 'create_markov_chain_graph'. In the end, the names are obtained as a boost::property_map and set to the desired values.

4.5.3 Creating such a graph

Also the demonstration code (algorithm 44) is very similar to the demonstration code of the 'create_markov_chain_graph' function (algorithm 22).

Algorithm 44 Demonstrating the 'create_named_vertices_markov_chain' function

```
#include <cassert>

#include "create_named_vertices_markov_chain.h"
#include "get_vertex_names.h"

void create_named_vertices_markov_chain_demo() noexcept
{
  const auto g
    = create_named_vertices_markov_chain();
  const std::vector<std::string> expected_names{
    "Sunny", "Rainy"
  };
  const std::vector<std::string> vertex_names{
    get_vertex_names(g)
  };
  assert(expected_names == vertex_names);
}
```

4.5.4 The .dot file produced

Algorithm 45 .dot file created from the 'create_named_vertices_markov_chain' function (algorithm 43), converted from graph to .dot file using algorithm 29

```
digraph G {
0[label=Sunny];
1[label=Rainy];
0->0 ;
0->1 ;
1->0 ;
1->1 ;
}
```

4.5.5 The .svg file produced

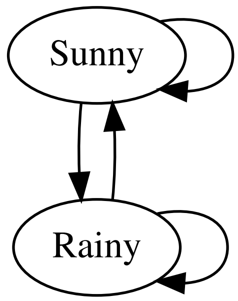

Figure 8: .svg file created from the 'create_named_vertices_markov_chain' function (algorithm 43) its .dot file, converted from .dot file to .svg using algorithm 176

4.6 Creating K_2 with named vertices

4.6.1 Graph

We extend K_2 of chapter 2.15 by naming the vertices A and B, as depicted in figure 9:

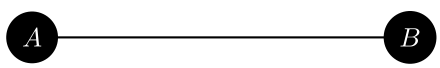

Figure 9: K_2: a fully connected graph with two vertices with the text A and B

4.6.2 Function to create such a graph

To create K_2, the following code can be used:

Algorithm 46 Creating K_2 with named vertices as depicted in figure 9

```
#include <cassert>
#include <boost/graph/adjacency_list.hpp>
#include "create_empty_undirected_named_vertices_graph.h"

///Create a K2 graph with named vertices
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_undirected_named_vertices_graph();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer = boost::add_edge(vd_a, vd_b, g);
  assert(aer.second);

  auto name_map = get( //_not_ boost::get!
    boost::vertex_name,g
  );
  name_map[vd_a] = "A";
  name_map[vd_b] = "B";

  return g;
}
```

Most of the code is a repeat of algorithm 24. In the end, the names are obtained as a boost::property_map and set to the desired names.

4.6.3 Creating such a graph

Also the demonstration code (algorithm 47) is very similar to the demonstration code of the create_k2_graph function (algorithm 24).

Algorithm 47 Demonstrating the 'create_k2_graph' function

```
#include <cassert>

#include "create_named_vertices_k2_graph.h"
#include "get_vertex_names.h"

void create_named_vertices_k2_graph_demo() noexcept
{
  const auto g = create_named_vertices_k2_graph();
  const std::vector<std::string> expected_names{"A", "B"
      };
  const std::vector<std::string> vertex_names =
      get_vertex_names(g);
  assert(expected_names == vertex_names);
}
```

4.6.4 The .dot file produced

Algorithm 48 .dot file created from the 'create_named_vertices_k2' function (algorithm 46), converted from graph to .dot file using algorithm 29

4.6.5 The .svg file produced

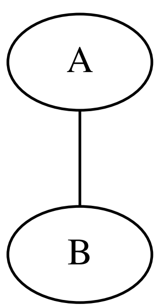

Figure 10: .svg file created from the 'create_named_vertices_k2_graph' function (algorithm 43) its .dot file, converted from .dot file to .svg using algorithm 176

5 Working with graphs with named vertices

When vertices have names, this name gives a way to find a vertex and working with it. This chapter shows some basic operations on graphs with named vertices.

- Check if there exists a vertex with a certain name: chapter 5.1
- Find a vertex by its name: chapter 5.2
- Get a named vertex its degree, in degree and out degree: chapter: 5.3
- Get a vertex its name from its vertex descriptor: chapter 5.4
- Set a vertex its name using its vertex descriptor: chapter 5.5
- Setting all vertices' names: chapter 5.6
- Clear a named vertex its edges: chapter 5.7
- Remove a named vertex: chapter 5.8
- Removing an edge between two named vertices: chapter 5.9
- Storing an directed/undirected graph with named vertices as a .dot file: chapter 5.10
- Loading a directed graph with named vertices from a .dot file: chapter 5.11
- Loading an undirected graph with named vertices from a .dot file: chapter 5.12

Especially chapter 5.2 is important: 'find_first_vertex_by_name' shows how to obtain a vertex descriptor, which is used in later algorithms.

5.1 Check if there exists a vertex with a certain name

Before modifying our vertices, let's first determine if we can find a vertex by its name in a graph. After obtaing a name map, we obtain the vertex iterators, dereference these to obtain the vertex descriptors and then compare each vertex its name with the one desired.

Algorithm 49 Find if there is vertex with a certain name

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

template <typename graph>
bool has_vertex_with_name(
  const std::string& name,
  const graph& g
) noexcept
{
  const auto vertex_name_map
    = get(boost::vertex_name, g);
  const auto vip
    = vertices(g); //_not_ boost::vertices!
  const auto j = vip.second;

  for (auto i = vip.first; i!=j; ++i) {
    if (
      get( //_not_ boost::get!
        vertex_name_map,
        *i
      ) == name
    ) {
      return true;
    }
  }
  return false;
}
```

This function can be demonstrated as in algorithm 50, where a certain name cannot be found in an empty graph. After adding the desired name, it is found.

Algorithm 50 Demonstration of the 'has_vertex_with_name' function

```
#include <cassert>

#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"
#include "has_vertex_with_name.h"

void has_vertex_with_name_demo() noexcept
{
  auto g
    = create_empty_undirected_named_vertices_graph();
  assert(!has_vertex_with_name("Felix",g));
  add_named_vertex("Felix",g);
  assert(has_vertex_with_name("Felix",g));
}
```

Note that this function only finds if there is at least one vertex with that name: it does not tell how many vertices with that name exist in the graph.

5.2 Find a vertex by its name

Where STL functions work with iterators, here we obtain a vertex descriptor (see chapter 2.6) to obtain a handle to the desired vertex. Algorithm 51 shows how to obtain a vertex descriptor to the first (name) vertex found with a specific name.

Algorithm 51 Find the first vertex by its name

```
#include <string>
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>
#include "has_vertex_with_name.h"

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_vertex_with_name(
  const std::string& name,
  const graph& g
) noexcept
{
  assert(has_vertex_with_name(name, g));
  const auto vertex_name_map
    = get(boost::vertex_name,g);
  const auto vip
    = vertices(g); //_not_ boost::vertices!
  const auto j = vip.second;

  for (auto i = vip.first; i!=j; ++i) {
    const std::string s{
      get( //_not_ boost::get!
        vertex_name_map,
        *i
      )
    };
    if (s == name) { return *i; }
  }
  assert(!"Should not get here");
  throw; //Will crash the program
}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 52 shows some examples of how to do so.

Algorithm 52 Demonstration of the 'find_first_vertex_with_name' function

```
#include <cassert>

#include "create_named_vertices_k2_graph.h"
#include "find_first_vertex_with_name.h"

void find_first_vertex_with_name_demo() noexcept
{
  const auto g = create_named_vertices_k2_graph();
  const auto vd = find_first_vertex_with_name("A", g);
  assert(out_degree(vd,g) == 1); //_not_ boost::
     out_degree!
  assert(in_degree(vd,g) == 1); //_not_ boost::in_degree!
}
```

5.3 Get a (named) vertex its degree, in degree and out degree

We already obtained all out degrees of all vertices in chapter 3.1 by just collecting all vertex descriptors. Here, we will search for a vertex with a certain name, obtain its vertex descriptor and find the number of connections it has.

With a vertex descriptor, we can read a vertex its types of degrees. Algorithm 51 shows how to find a vertex, obtain its vertex descriptor and then obtain the out degree from it.

Algorithm 53 Get the first vertex with a certain name its out degree from its vertex descriptor

```
#include <cassert>
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include "find_first_vertex_with_name.h"
#include "has_vertex_with_name.h"

template <typename graph>
int get_first_vertex_with_name_out_degree(
  const std::string& name,
  const graph& g) noexcept
{
  assert(has_vertex_with_name(name, g));
  const auto vd
    = find_first_vertex_with_name(name, g);
  const int od {
    static_cast<int>(
      out_degree(vd, g) //_not_ boost::out_degree!
    )
  };
  assert(od >= 0);
  return od;
}
```

Algorithm 54 shows how to use this function.

Algorithm 54 Demonstration of the 'get_first_vertex_with_name_out_degree' function

```
#include <cassert>
#include "create_named_vertices_k2_graph.h"
#include "get_first_vertex_with_name_out_degree.h"

void get_first_vertex_with_name_out_degree_demo()
  noexcept
{
  const auto g = create_named_vertices_k2_graph();
  assert(
    get_first_vertex_with_name_out_degree("A", g)
    == 1
  );
  assert(
    get_first_vertex_with_name_out_degree("B", g)
    == 1
  );
}
```

5.4 Get a vertex its name from its vertex descriptor

This may seem a trivial paragraph, as chapter 4.4 describes the 'get_vertex_names' algorithm, in which we get all vertices' names. But it does not allow to first find a vertex of interest and subsequently getting only that one its name.

To obtain the name from a vertex descriptor, one needs to pull out the name map and then look up the vertex of interest (I like to compare it as such: the vertex descriptor is a last name, the name map is a phone book, the desired info a phone number).

Algorithm 55 Get a vertex its name from its vertex descriptor

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

template <typename graph>
std::string get_vertex_name(
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  const graph& g
) noexcept
{
  const auto vertex_name_map
    = get(boost::vertex_name,g);
  return vertex_name_map[vd];
}
```

To use 'get_vertex_name', one first needs to obtain a vertex descriptor. Algorithm 56 shows a simple example:

Algorithm 56 Demonstration if the 'get_vertex_name' function

```
#include <cassert>

#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"
#include "find_first_vertex_with_name.h"
#include "get_vertex_name.h"

void get_vertex_name_demo() noexcept
{
  auto g
    = create_empty_undirected_named_vertices_graph();
  const std::string name{"Dex"};
  add_named_vertex(name, g);
  const auto vd
    = find_first_vertex_with_name(name,g);
  assert(get_vertex_name(vd,g) == name);
}
```

5.5 Set a (named) vertex its name from its vertex descriptor

If you know how to get the name from a vertex descriptor, setting it is just as easy, as shown in algorithm 57.

Algorithm 57 Set a vertex its name from its vertex descriptor

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

template <typename graph>
void set_vertex_name(
  const std::string& name,
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  graph& g
) noexcept
{
  auto vertex_name_map
    = get(boost::vertex_name,g);
  vertex_name_map[vd] = name;
}
```

To use 'set_vertex_name', one first needs to obtain a vertex descriptor. Algorithm 58 shows a simple example.

Algorithm 58 Demonstration if the 'set_vertex_name' function

```
#include <cassert>

#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"
#include "find_first_vertex_with_name.h"
#include "get_vertex_name.h"
#include "set_vertex_name.h"

void set_vertex_name_demo() noexcept
{
  auto g
    = create_empty_undirected_named_vertices_graph();
  const std::string old_name{"Dex"};
  add_named_vertex(old_name, g);
  const auto vd
    = find_first_vertex_with_name(old_name,g);
  assert(get_vertex_name(vd,g) == old_name);
  const std::string new_name{"Diggy"};
  set_vertex_name(new_name, vd, g);
  assert(get_vertex_name(vd,g) == new_name);
}
```

5.6 Setting all vertices' names

When the vertices of a graph have named vertices and you want to set all their names at once:

Algorithm 59 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
) noexcept
{
  const auto vertex_name_map = get(boost::vertex_name,g);
  auto ni = std::begin(names);
  const auto names_end = std::end(names);
  const auto vip
    = vertices(g); //_not_ boost::vertices!
  const auto j = vip.second;
  for (auto i = vip.first; i!=j; ++i, ++ni)
  {
    assert(ni != names_end);
    put(vertex_name_map, *i,*ni);
  }
}
```

This is not a very usefull function if the graph is complex. But for just creating graphs for debugging, it may come in handy.

5.7 Clear the edges of a named vertex

A vertex descriptor can be used to clear all in/out/both edges connected to a vertex. It is necessary to remove these connections before the vertex itself can be removed. There are three functions to remove the edges connected to a vertex:

- boost::clear_vertex: removes all edges to and from the vertex
- boost::clear_out_edges: removes all outgoing edges from the vertex (in directed graphs only, else you will get a 'error: no matching function for call to clear_out_edges', as described in chapter 18.2)
- boost::clear_in_edges: removes all incoming edges from the vertex (in directed graphs only, else you will get a 'error: no matching function for call to clear_in_edges', as described in chapter 18.3)

In the algorithm 'clear_first_vertex_with_name' the 'boost::clear_vertex' algorithm is used, as the graph used is undirectional:

Algorithm 60 Clear the first vertex with a certain name

```
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include "find_first_vertex_with_name.h"
#include "has_vertex_with_name.h"

template <class graph>
void clear_first_vertex_with_name(
  const std::string& name,
  graph& g
) noexcept
{
  assert(has_vertex_with_name(name,g));
  const auto vd
    = find_first_vertex_with_name(name,g);
  boost::clear_vertex(vd,g);
}
```

Algorithm 61 shows the clearing of the first named vertex found.

Algorithm 61 Demonstration of the 'clear_first_vertex_with_name' function

```
#include <cassert>
#include "clear_first_vertex_with_name.h"
#include "create_named_vertices_k2_graph.h"


void clear_first_vertex_with_name_demo() noexcept
{
  auto g = create_named_vertices_k2_graph();
  assert(boost::num_edges(g) == 1);
  clear_first_vertex_with_name("A",g);
  assert(boost::num_edges(g) == 0);
}
```

5.8 Remove a named vertex

A vertex descriptor can be used to remove a vertex from a graph. It is necessary to remove these connections (e.g. using clear_first_vertex_with_name', algorithm 60) before the vertex itself can be removed.

Removing a named vertex goes as follows: use the name of the vertex to get a first vertex descriptor, then call 'boost::remove_vertex', shown in algorithm 60.

Algorithm 62 Remove the first vertex with a certain name

```
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include "find_first_vertex_with_name.h"
#include "has_vertex_with_name.h"

template <class graph>
void remove_first_vertex_with_name(
  const std::string& name,
  graph& g
) noexcept
{
  assert(has_vertex_with_name(name,g));
  const auto vd = find_first_vertex_with_name(name,g);
  assert(boost::degree(vd,g) == 0);
  boost::remove_vertex(vd,g);
}
```

Algorithm 63 shows the removal of the first named vertex found.

Algorithm 63 Demonstration of the 'remove_first_vertex_with_name' function

```
#include <cassert>

#include "clear_first_vertex_with_name.h"
#include "create_named_vertices_k2_graph.h"
#include "remove_first_vertex_with_name.h"

void remove_first_vertex_with_name_demo() noexcept
{
  auto g = create_named_vertices_k2_graph();
  clear_first_vertex_with_name("A",g);
  remove_first_vertex_with_name("A",g);
  assert(boost::num_edges(g) == 0);
  assert(boost::num_vertices(g) == 1);
}
```

Again, be sure that the vertex removed does not have any connections!

5.9 Removing the edge between two named vertices

Instead of looking for an edge descriptor, one can also remove an edge from two vertex descriptors (which is: the edge between the two vertices). Removing an edge between two named vertices named edge goes as follows: use the names of the vertices to get both vertex descriptors, then call 'boost::remove_edge' on those two, as shown in algorithm 64.

Algorithm 64 Remove the first edge with a certain name

```
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include "find_first_vertex_with_name.h"
#include "has_vertex_with_name.h"
#include "has_edge_between_vertices.h"

template <typename graph>
void remove_edge_between_vertices_with_names(
  const std::string& name_1,
  const std::string& name_2,
  graph& g
) noexcept
{
  assert(has_vertex_with_name(name_1, g));
  assert(has_vertex_with_name(name_2, g));
  const auto vd_1 = find_first_vertex_with_name(name_1, g
    );
  const auto vd_2 = find_first_vertex_with_name(name_2, g
    );
  assert(has_edge_between_vertices(vd_1, vd_2, g));
  boost::remove_edge(vd_1, vd_2, g);
}
```

Algorithm 65 shows the removal of the first named edge found.

Algorithm 65 Demonstration of the 'remove_edge_between_vertices_with_names' function

```
#include <cassert>

#include "create_named_edges_and_vertices_k3_graph.h"


void remove_edge_between_vertices_with_names_demo()
    noexcept
{
  auto g = create_named_edges_and_vertices_k3_graph();
  assert(boost::num_edges(g) == 3);
  remove_edge_between_vertices_with_names("top","right",g
      );
  assert(boost::num_edges(g) == 2);
}
```

5.10 Storing an directed/undirected graph with named vertices as a .dot

If you used the 'create_named_vertices_k2_graph' function (algorithm 46) to produce a K_2 graph with named vertices, you can store these names in multiple ways:

- Using boost::make_label_writer
- Using a C++11 lambda function
- Using a C++14 lambda function

I show all three ways, because you may need all of them.

The created .dot file is shown at algorithm 48. Note that the 'save_named_vertices_graph_to_dot' functions below only save the structure of the graph and its vertex names. It ignores other edge and vertex properties.

5.10.1 Using boost::make_label_writer

additionally with algorithm 66:

Algorithm 66 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
) noexcept
{
  std::ofstream f(filename);
  const auto names = get_vertex_names(g);
  boost::write_graphviz(
    f,
    g,
    boost::make_label_writer(&names[0])
  );
}
```

Here, the function boost::write_graphviz is called with a new, third argument. After collecting all names, these are used by boost::make_label_writer to write the names as labels.

5.10.2 Using a C++11 lambda function

An equivalent algorithm is algorithm 67:

Algorithm 67 Storing a graph with named vertices as a .dot file using a lambda expression and C++11

```
#include <string>
#include <ostream>
#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
///using a lambda and C++11
template <typename graph>
void save_named_vertices_graph_to_dot_using_lambda_cpp11(
  const graph& g,
  const std::string& filename
) noexcept
{
  using vd_t = typename graph::vertex_descriptor;
  std::ofstream f(filename);
  const auto name_map = get(boost::vertex_name,g);
  boost::write_graphviz(
    f,
    g,
    [name_map](std::ostream& os, const vd_t& vd) {
      const std::string s{name_map[vd]};
      if (s.find(' ') == std::string::npos) {
        //No space, no quotes around string
        os << "[label=" << s << "]";
      }
      else {
        //Has space, put quotes around string
        os << "[label=\"" << s << "\"]";
      }
    }
  );
}
```

In this C++11 code, a lambda function is used as a third argument. A lambda function is an on-the-fly function that has these parts:

- the capture brackets '[]', to take variables within the lambda function
- the function argument parentheses '()', to put the function arguments in
- the function body '{}', where to write what it does

First we create a shorthand for the vertex descriptor type, that we'll need to use a lambda function argument (in C++14 you can use auto).

We then create a vertex name map at function scope (in C++14 this can be at lambda function scope) and pass it to the lambda function using its capture section.

The lambda function arguments need to be two: a std::ostream& (a reference to a general out-stream) and a vertex descriptor. In the function body, we get the name of the vertex the same as the 'get_vertex_name' function (algorithm 55) and stream it to the out stream.

5.10.3 Using a C++14 lambda function

Algorithm 68 Storing a graph with named vertices as a .dot file using a lambda expression and C++14

```
#include <string>
#include <ostream>
#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
///using a lambda and C++14
template <typename graph>
void save_named_vertices_graph_to_dot_using_lambda_cpp14(
  const graph& g,
  const std::string& filename
) noexcept
{
  const auto name_map = get(boost::vertex_name,g);
  std::ofstream f(filename);
  boost::write_graphviz(
    f,
    g,
    [name_map]
    (std::ostream& os, const auto& vd) {
      const std::string s{name_map[vd]};
      if (s.find(' ') == std::string::npos) {
        //No space, no quotes around string
        os << "[label=" << s << "]";
      }
      else {
        //Has space, put quotes around string
        os << "[label=\"" << s << "\"]";
      }
    }
  );
}
```

In this C++14 code, a lambda function is used as a third argument.

A lambda function is an on-the-fly function that has these parts:

- the capture brackets '[]', to take variables within the lambda function
- the function argument parentheses '()', to put the function arguments in

- the function body '{}', where to write what it does

We create a vertex name map at lambda function scope in its capture section.

The lambda function arguments need to be two: a std::ostream& (a reference to a general out-stream) and a vertex descriptor. In the function body, we get the name of the vertex the same as the 'get_vertex_name' function (algorithm 55) and stream it to the out stream.

5.11 Loading a directed graph with named vertices from a .dot

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph with named vertices is loaded, as shown in algorithm 69:

Algorithm 69 Loading a directed graph with named vertices from a .dot file

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

#include "create_empty_directed_named_vertices_graph.h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_name_t,std::string
  >
>
load_directed_named_vertices_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_directed_named_vertices_graph();
  boost::dynamic_properties p; //_do_ default construct
  p.property("node_id", get(boost::vertex_name, g));
  p.property("label", get(boost::vertex_name, g));
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created. Next to this, a boost::dynamic_properties is created with its default constructor, after which we direct the boost::dynamic_properties to find a 'node_id' and 'label' in the vertex name map. From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 70 shows how to use the 'load_directed_graph_from_dot' function:

Algorithm 70 Demonstration of the 'load_directed_named_vertices_graph_from_dot' function

```
#include "create_named_vertices_markov_chain.h"
#include "load_directed_named_vertices_graph_from_dot.h"
#include "save_named_vertices_graph_to_dot.h"
#include "get_vertex_names.h"

void load_directed_named_vertices_graph_from_dot_demo()
    noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g
    = create_named_vertices_markov_chain();
  const std::string filename{
    "create_named_vertices_markov_chain.dot"
  };
  save_named_vertices_graph_to_dot(g, filename);
  const auto h
    = load_directed_named_vertices_graph_from_dot(
        filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_vertex_names(g) == get_vertex_names(h));
}
```

This demonstration shows how the Markov chain is created using the 'create_named_vertices_markov_chain' function (algorithm 21), saved and then loaded. The loaded graph is checked to be a directed graph similar to the Markov chain with the same vertex names (using the 'get_vertex_names' function, algorithm 41).

5.12 Loading an undirected graph with named vertices from a .dot

When loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph with named vertices is loaded, as shown in algorithm 71:

Algorithm 71 Loading an undirected graph with named vertices from a .dot file

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

#include "create_empty_undirected_named_vertices_graph.h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_name_t,std::string
  >
>
load_undirected_named_vertices_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_undirected_named_vertices_graph()
    ;
  boost::dynamic_properties p; //_do_ default construct
  p.property("node_id", get(boost::vertex_name, g));
  p.property("label", get(boost::vertex_name, g));
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created. Next to this, a boost::dynamic_properties is created with its default constructor, after which we direct the boost::dynamic_properties to find a 'node_id' and 'label' in the vertex name map. From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 72 shows how to use the 'load_undirected_graph_from_dot' function:

Algorithm 72 Demonstration of the 'load_undirected_graph_from_dot' function

```
#include "create_named_vertices_k2_graph.h"
#include "load_undirected_named_vertices_graph_from_dot.h
  "
#include "save_named_vertices_graph_to_dot.h"
#include "get_vertex_names.h"

void load_undirected_named_vertices_graph_from_dot_demo()
    noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g
    = create_named_vertices_k2_graph();
  const std::string filename{
    "create_named_vertices_k2_graph.dot"
  };
  save_named_vertices_graph_to_dot(g, filename);
  const auto h
    = load_undirected_named_vertices_graph_from_dot(
        filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_vertex_names(g) == get_vertex_names(h));
}
```

This demonstration shows how K_2 with named vertices is created using the 'create_named_vertices_k2_graph' function (algorithm 46), saved and then loaded. The loaded graph is checked to be an undirected graph similar to K_2 , with the same vertex names (using the 'get_vertex_names' function, algorithm 41).

6 Building graphs with named edges and vertices

Up until now, the graphs created have had edges and vertices without any propery. In this chapter, graphs will be created, in which edges vertices can have a name. This name will be of the std::string data type, but other types are possible as well. There are many more built-in properties edges and nodes can have (see the boost/graph/properties.hpp file for these).

In this chapter, we will build the following graphs:

- An empty directed graph that allows for edges and vertices with names:

see chapter 6.1

- An empty undirected graph that allows for edges and vertices with names: see chapter 6.2
- Markov chain with named edges and vertices: see chapter 6.5
- $K_3$with named edges and vertices: see chapter 6.6

In the process, some basic (sometimes bordering trivial) functions are shown:

- Adding an named edge: see chapter 6.3
- Getting the edges' names: see chapter 6.4

These functions are mostly there for completion and showing which data types are used.

6.1 Creating an empty directed graph with named edges and vertices

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

Algorithm 73 Creating an empty directed graph with named edges and vertices

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<boost::vertex_name_t,std::string>,
  boost::property<boost::edge_name_t,std::string>
>
create_empty_directed_named_edges_and_vertices_graph()
    noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    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 directed (due to the boost::directedS)
- 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".

Algorithm 74 shows how to create this graph. Note that all the earlier functions defined in this tutorial keep working as expected.

Algorithm 74 Demonstration if the 'create_empty_directed_named_edges_and_vertices_graph' function

```
#include <cassert>

#include "add_named_edge.h"
#include "
    create_empty_directed_named_edges_and_vertices_graph.h
    "
#include "get_edge_names.h"
#include "get_vertex_names.h"

void
    create_empty_directed_named_edges_and_vertices_graph_demo
    () noexcept
{
  using strings = std::vector<std::string>;
  auto g
    =
        create_empty_directed_named_edges_and_vertices_graph
        ();
  add_named_edge("Reed", g);
  const strings expected_vertex_names{"",""};
  const strings vertex_names = get_vertex_names(g);
  assert(expected_vertex_names == vertex_names);
  const strings expected_edge_names{"Reed"};
  const strings edge_names = get_edge_names(g);
  assert(expected_edge_names == edge_names);
}
```

6.2 Creating an empty undirected graph with named edges and vertices

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

Algorithm 75 Creating an empty undirected 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_undirected_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".

Algorithm 76 shows how to create this graph. Note that all the earlier functions defined in this tutorial keep working as expected.

Algorithm 76 Demonstration if the 'create_empty_undirected_named_edges_and_vertices_graph' function

```
#include <cassert>

#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "get_edge_names.h"
#include "get_vertex_names.h"

void
    create_empty_undirected_named_edges_and_vertices_graph_demo
    () noexcept
{
  using strings = std::vector<std::string>;
  auto g
    =
        create_empty_undirected_named_edges_and_vertices_graph
        ();
  add_named_edge("Reed", g);
  const strings expected_vertex_names{"",""};
  const strings vertex_names = get_vertex_names(g);
  assert(expected_vertex_names == vertex_names);
  const strings expected_edge_names{"Reed"};
  const strings edge_names = get_edge_names(g);
  assert(expected_edge_names == edge_names);
}
```

6.3 Adding a named edge

Adding an edge with a name:

Algorithm 77 Add a vertex with a name

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

#include <cassert>

template <typename graph>
void add_named_edge(
  const std::string& edge_name,
  graph& g
) noexcept
{
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer = boost::add_edge(vd_a, vd_b, g);
  assert(aer.second);

  auto edge_name_map
    = get( //_not_ boost::get!
      boost::edge_name,g
    );
  edge_name_map[aer.first] = edge_name;
}
```

In this code snippet, the edge descriptor (see chapter 2.12 if you need to refresh your memory) when using 'boost::add_edge' is used as a key to change the edge its name map.

The algorithm 78 shows how to add a named edge to an empty graph. When trying to add named vertices to graph without this property, you will get the error 'formed reference to void' (see chapter 18.1).

Algorithm 78 Demonstration of the 'add_named_edge' function

```
#include <cassert>

#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"


void add_named_edge_demo() noexcept
{
  auto g
    =
        create_empty_undirected_named_edges_and_vertices_graph
        ();
  add_named_edge("Richards", g);
  assert(boost::num_edges(g) == 1);
}
```

6.4 Getting the edges' names

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

Algorithm 79 Get the edges' names

```
#include <string>
#include <vector>
#include <boost/graph/adjacency_list.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)
    noexcept
{
  std::vector<std::string> v;

  const auto edge_name_map = get(boost::edge_name,g);
  const auto eip = edges(g); //_not_ boost::edges!
  const auto j = eip.second;

  for (auto i = eip.first; i!=j; ++i) {
    v.emplace_back(
      get( //_not_ boost::get!
        edge_name_map,
        *i
      )
    );
  }
  return v;
}
```

The names of the edges are obtained from a boost::property_map and then put into a std::vector. The algorithm 80 shows how to apply this function.

Would you dare to try to get the edges' names from a graph without vertices with names, you will get the error 'formed reference to void' (see chapter 18.1).

Algorithm 80 Demonstration of the 'get_edge_names' function

```
#include <cassert>

#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "get_edge_names.h"

void get_edge_names_demo() noexcept
{
  auto g
    =
        create_empty_undirected_named_edges_and_vertices_graph
        ();
  const std::string edge_name_1{"Eugene"};
  const std::string edge_name_2{"Another␣Eugene"};
  add_named_edge(edge_name_1, g);
  add_named_edge(edge_name_2, g);
  const std::vector<std::string> expected_names{
    edge_name_1, edge_name_2
  };
  const std::vector<std::string> edge_names{
    get_edge_names(g)
  };
  assert(expected_names == edge_names);
}
```

6.5 Creating Markov chain with named edges and vertices

6.5.1 Graph

We build this graph:

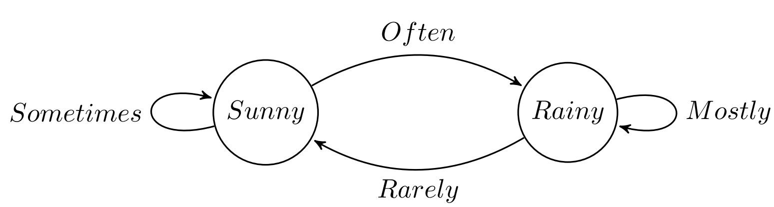

Figure 11: A two-state Markov chain where the vertices have texts *Sunny* and *Rainy*, and the edges have texts *Sometimes*, *Often*, *Rarely* and *Mostly*

6.5.2 Function to create such a graph

Here is the code:

Algorithm 81 Creating the two-state Markov chain as depicted in figure 11

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<boost::vertex_name_t,std::string>,
  boost::property<boost::edge_name_t,std::string>
>
create_named_edges_and_vertices_markov_chain() noexcept
{
  auto g
    =
        create_empty_directed_named_edges_and_vertices_graph
        ();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
  assert(aer_aa.second);
  const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
  assert(aer_ab.second);
  const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
  assert(aer_ba.second);
  const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
  assert(aer_bb.second);

  auto vertex_name_map = get( //_not_ boost::get!
    boost::vertex_name,g
  );
  vertex_name_map[vd_a] = "Sunny";
  vertex_name_map[vd_b] = "Rainy";

  auto edge_name_map = get( //_not_ boost::get!
    boost::edge_name,g
  );
  edge_name_map[aer_aa.first] = "Sometimes";
  edge_name_map[aer_ab.first] = "Often";
  edge_name_map[aer_ba.first] = "Rarely";
  edge_name_map[aer_bb.first] = "Mostly";

  return g;
}
```

6.5.3 Creating such a graph

Here is the demo:

Algorithm 82 Demo of the 'create_named_edges_and_vertices_markov_chain' function (algorithm 81)

```
#include <cassert>
#include <iostream>
#include "create_named_edges_and_vertices_markov_chain.h"
#include "get_edge_names.h"
#include "get_vertex_names.h"

void create_named_edges_and_vertices_markov_chain_demo()
    noexcept
{
  using strings = std::vector<std::string>;

  const auto g
    = create_named_edges_and_vertices_markov_chain();

  const strings expected_vertex_names{
    "Sunny", "Rainy"
  };
  const strings vertex_names{
    get_vertex_names(g)
  };
  assert(expected_vertex_names == vertex_names);

  const strings expected_edge_names{
    "Sometimes", "Often", "Rarely", "Mostly"
  };

  const strings edge_names{get_edge_names(g)};
  assert(expected_edge_names == edge_names);
}
```

6.5.4 The .dot file produced

Algorithm 83 .dot file created from the 'create_named_edges_and_vertices_markov_chain' function (algorithm 81), converted from graph to .dot file using algorithm 29

```
digraph G {
0[label=Sunny];
1[label=Rainy];
0->0 [label="Sometimes"];
0->1 [label="Often"];
1->0 [label="Rarely"];
1->1 [label="Mostly"];
}
```

6.5.5 The .svg file produced

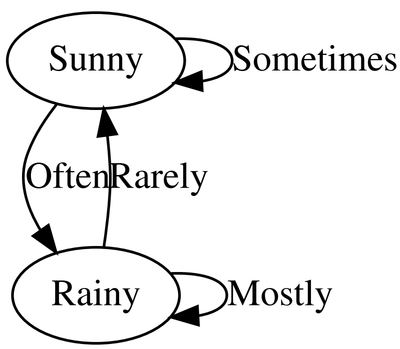

Figure 12: .svg file created from the 'create_named_edges_and_vertices_markov_chain' function (algorithm 81) its .dot file, converted from .dot file to .svg using algorithm 176

6.6 Creating K_3 with named edges and vertices

6.6.1 Graph

We extend the graph K_2 with named vertices of chapter 4.6 by adding names to the edges, as depicted in figure 13:

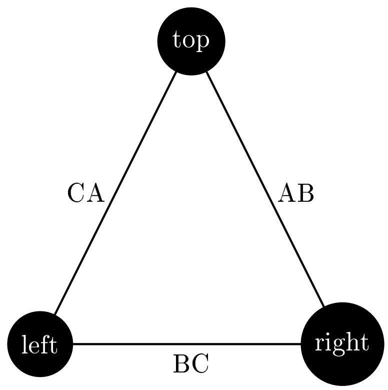

Figure 13: K_3: a fully connected graph with three named edges and vertices

6.6.2 Function to create such a graph

To create K_3, the following code can be used:

Algorithm 84 Creating K_3 as depicted in figure 13

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

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_undirected_named_edges_and_vertices_graph
      ();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto vd_c = boost::add_vertex(g);
  const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
  assert(aer_ab.second);
  const auto aer_bc = boost::add_edge(vd_b, vd_c, g);
  assert(aer_bc.second);
  const auto aer_ca = boost::add_edge(vd_c, vd_a, g);
  assert(aer_ca.second);

  auto vertex_name_map = get(boost::vertex_name,g);
  vertex_name_map[vd_a] = "top";
  vertex_name_map[vd_b] = "right";
  vertex_name_map[vd_c] = "left";

  auto edge_name_map = get(boost::edge_name,g);
  edge_name_map[aer_ab.first] = "AB";
  edge_name_map[aer_bc.first] = "BC";
  edge_name_map[aer_ca.first] = "CA";

  return g;
}
```

Most of the code is a repeat of algorithm 46. In the end, the edge names are obtained as a boost::property_map and set.

6.6.3 Creating such a graph

Algorithm 85 shows how to create the graph and measure its edge and vertex names.

Algorithm 85 Demonstration of the 'create_named_edges_and_vertices_k3' function

```
#include <cassert>
#include <iostream>
#include "create_named_edges_and_vertices_k3_graph.h"
#include "get_edge_names.h"
#include "get_vertex_names.h"

void create_named_edges_and_vertices_k3_graph_demo()
    noexcept
{
  using strings = std::vector<std::string>;

  const auto g
    = create_named_edges_and_vertices_k3_graph();

  const strings expected_vertex_names{
    "top", "right", "left"
  };
  const strings vertex_names{
    get_vertex_names(g)
  };
  assert(expected_vertex_names == vertex_names);

  const strings expected_edge_names{
    "AB", "BC", "CA"
  };
  const strings edge_names{get_edge_names(g)};
  assert(expected_edge_names == edge_names);
}
```

6.6.4 The .dot file produced

Algorithm 86 .dot file created from the 'create_named_edges_and_vertices_k3_graph' function (algorithm 84), converted from graph to .dot file using algorithm 29

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

6.6.5 The .svg file produced

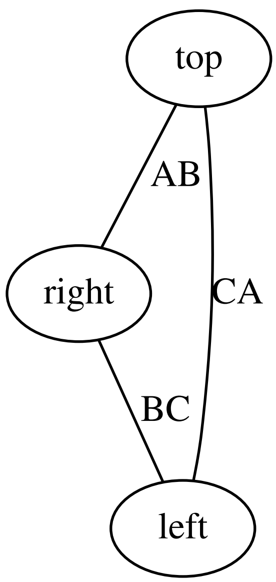

Figure 14: .svg file created from the 'create_named_edges_and_vertices_k3_graph' function (algorithm 84) its .dot file, converted from .dot file to .svg using algorithm 176

7 Working with graphs with named edges and vertices

Working with named edges...

- Check if there exists an edge with a certain name: chapter 7.1
- Find a (named) edge by its name: chapter 7.2
- Get a (named) edge its name from its edge descriptor: chapter 7.3
- Set a (named) edge its name using its edge descriptor: chapter 7.4
- Remove a named edge: chapter 7.5
- Storing a graph with named edges and vertices as a .dot file: chapter 7.6
- Loading a directed graph with named edges and vertices from a .dot file: chapter 7.7
- Loading an undirected graph with named edges and vertices from a .dot file: chapter 7.8

Especially chapter 7.2 with the 'find_first_edge_by_name' algorithm shows how to obtain an edge descriptor, which is used in later algorithms.

7.1 Check if there exists an edge with a certain name

Before modifying our edges, let's first determine if we can find an edge by its name in a graph. After obtaing a name map, we obtain the edge iterators, dereference these to obtain the edge descriptors and then compare each edge its name with the one desired.

Algorithm 87 Find if there is an edge with a certain name

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

template <typename graph>
bool has_edge_with_name(
  const std::string& name,
  const graph& g
) noexcept
{
  const auto edge_name_map = get(boost::edge_name,g);

  for (auto p = edges(g);
    p.first != p.second;
    ++p.first) {
    if (get(edge_name_map, *p.first) == name) {
      return true;
    }
  }
  return false;
}
```

This function can be demonstrated as in algorithm 88, where a certain name cannot be found in an empty graph. After adding the desired name, it is found.

Algorithm 88 Demonstration of the 'has_edge_with_name' function

```
#include <cassert>

#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "has_edge_with_name.h"

void has_edge_with_name_demo() noexcept
{
  auto g =
      create_empty_undirected_named_edges_and_vertices_graph
      ();
  assert(!has_edge_with_name("Edward",g));
  add_named_edge("Edward",g);
  assert(has_edge_with_name("Edward",g));
}
```

Note that this function only finds if there is at least one edge with that name: it does not tell how many edges with that name exist in the graph.

7.2 Find an edge by its name

Where STL functions work with iterators, here we obtain an edge descriptor (see chapter 2.12) to obtain a handle to the desired edge. Algorithm 89 shows how to obtain an edge descriptor to the first (name) edge found with a specific name.

Algorithm 89 Find the first edge by its name

```
#include <string>
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>
#include "has_edge_with_name.h"

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
find_first_edge_with_name(
  const std::string& name,
  const graph& g
) noexcept
{
  assert(has_edge_with_name(name, g));

  const auto edge_name_map
    = get(boost::edge_name,g);
  const auto eip
    = edges(g); //_not_ boost::edges!
  const auto j = eip.second;

  for (auto i = eip.first; i!=j; ++i) {

    const std::string s{
      get(edge_name_map, *i)
    };
    if (s == name) { return *i; }
  }
  assert(!"Should not get here");
  throw; //Will crash the program
}
```

With the edge descriptor obtained, one can read and modify the graph. Algorithm 90 shows some examples of how to do so.

Algorithm 90 Demonstration of the 'find_first_edge_by_name' function

```
#include <cassert>

#include "create_named_edges_and_vertices_k3_graph.h"
#include "find_first_edge_with_name.h"

void find_first_edge_with_name_demo() noexcept
{
  const auto g
    = create_named_edges_and_vertices_k3_graph();
  const auto ed
    = find_first_edge_with_name("AB", g);
  assert(boost::source(ed,g) != boost::target(ed,g));
}
```

7.3 Get a (named) edge its name from its edge descriptor

This may seem a trivial paragraph, as chapter 6.4 describes the 'get_edge_names' algorithm, in which we get all edges' names. But it does not allow to first find an edge of interest and subsequently getting only that one its name.

To obtain the name from an edgedescriptor, one needs to pull out the name map and then look up the edge of interest.

Algorithm 91 Get an edge its name from its edge descriptor

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

template <typename graph>
std::string get_edge_name(
  const typename boost::graph_traits<graph>::
      edge_descriptor& vd,
  const graph& g
) noexcept
{
  const auto edge_name_map
    = get( //_not_ boost::get!
      boost::edge_name,
      g
    );
  return edge_name_map[vd];
}
```

To use 'get_edge_name', one first needs to obtain an edge descriptor. Algorithm 92 shows a simple example.

Algorithm 92 Demonstration if the 'get_edge_name' function

```
#include <cassert>

#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "find_first_edge_with_name.h"
#include "get_edge_name.h"

void get_edge_name_demo() noexcept
{
  auto g =
      create_empty_undirected_named_edges_and_vertices_graph
      ();
  const std::string name{"Dex"};
  add_named_edge(name, g);
  const auto ed = find_first_edge_with_name(name,g);
  assert(get_edge_name(ed,g) == name);
}
```

7.4 Set a (named) edge its name from its edge descriptor

If you know how to get the name from an edge descriptor, setting it is just as easy, as shown in algorithm 93.

Algorithm 93 Set an edge its name from its edge descriptor

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

template <typename graph>
void set_edge_name(
  const std::string& name,
  const typename boost::graph_traits<graph>::
      edge_descriptor& vd,
  graph& g
) noexcept
{
  auto edge_name_map = get(boost::edge_name,g);
  edge_name_map[vd] = name;
}
```

To use 'set_edge_name', one first needs to obtain an edge descriptor. Algorithm 94 shows a simple example.

Algorithm 94 Demonstration if the 'set_edge_name' function

```
#include <cassert>

#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "find_first_edge_with_name.h"
#include "get_edge_name.h"
#include "set_edge_name.h"

void set_edge_name_demo() noexcept
{
  auto g =
      create_empty_undirected_named_edges_and_vertices_graph
      ();
  const std::string old_name{"Dex"};
  add_named_edge(old_name, g);
  const auto vd = find_first_edge_with_name(old_name,g);
  assert(get_edge_name(vd,g) == old_name);
  const std::string new_name{"Diggy"};
  set_edge_name(new_name, vd, g);
  assert(get_edge_name(vd,g) == new_name);
}
```

7.5 Removing the first edge with a certain name

An edge descriptor can be used to remove an edge from a graph.

Removing a named edge goes as follows: use the name of the edge to get a first edge descriptor, then call 'boost::remove_edge', shown in algorithm 62:

Algorithm 95 Remove the first edge with a certain name

```
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include "find_first_edge_with_name.h"
#include "has_edge_with_name.h"

template <class graph>
void remove_first_edge_with_name(
  const std::string& name,
  graph& g
) noexcept
{
  assert(has_edge_with_name(name,g));
  const auto vd = find_first_edge_with_name(name,g);
  boost::remove_edge(vd,g);
}
```

Algorithm 96 shows the removal of the first named edge found.

Algorithm 96 Demonstration of the 'remove_first_edge_with_name' function

```
#include <cassert>

#include "create_named_edges_and_vertices_k3_graph.h"
#include "remove_first_edge_with_name.h"

void remove_first_edge_with_name_demo() noexcept
{
  auto g = create_named_edges_and_vertices_k3_graph();
  assert(boost::num_edges(g) == 3);
  assert(boost::num_vertices(g) == 3);
  remove_first_edge_with_name("AB",g);
  assert(boost::num_edges(g) == 2);
  assert(boost::num_vertices(g) == 3);
}
```

7.6 Storing an undirected graph with named edges and vertices as a .dot

If you used the create_named_edges_and_vertices_k3_graph function (algorithm 84) to produce a K_3 graph with named edges and vertices, you can store these names additionally with algorithm 97:

Algorithm 97 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 98:

Algorithm 98 .dot file created from the create_named_edges_and_vertices_k3_graph function (algorithm 46)

```
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 15:

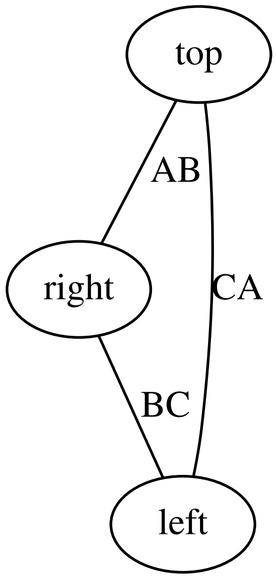

Figure 15: .svg file created from the create_named_edges_and_vertices_k3_graph function (algorithm 46) and converted to .svg using the 'convert_dot_to_svg' function (algorithm 176)

If you created a graph with edges more complex than just a name, you will still just write these to the .dot file. Chapter 9.6 shows how to write custom vertices to a .dot file.

So, the 'save_named_edges_and_vertices_graph_to_dot' function (algorithm 29) saves only the structure of the graph and its edge and vertex names.

7.7 Loading a directed graph with named edges and vertices from a .dot

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph with named edges and vertices is loaded, as shown in algorithm 99:

Algorithm 99 Loading a directed graph with named edges and vertices from a .dot file

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

#include "
    create_empty_directed_named_edges_and_vertices_graph.h
    "
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_name_t,std::string
  >,
  boost::property<
    boost::edge_name_t,std::string
  >
>
load_directed_named_edges_and_vertices_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  std::ifstream f(dot_filename.c_str());
  auto g =
      create_empty_directed_named_edges_and_vertices_graph
      ();
  boost::dynamic_properties p; //_do_ default construct
  #ifdef USE_FAILING
  p.property("node_id", get(boost::vertex_name, g));
  p.property("label", get(boost::vertex_name, g));
  #else
  p.property("node_id", get(boost::vertex_name, g));
  p.property("label", get(boost::vertex_name, g));
  p.property("edge_id", get(boost::edge_name, g));
  p.property("label", get(boost::edge_name, g));
  #endif
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created. Next to this, a boost::dynamic_properties is created with its default constructor, after which we direct the boost::dynamic_properties to find a 'node_id' and 'label' in the vertex name map, 'edge_id' and 'label to the edge name map. From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 100 shows how to use the 'load_directed_graph_from_dot' function:

Algorithm 100 Demonstration of the 'load_directed_named_edges_and_vertices_graph_from_dot' function

```
#include "create_named_edges_and_vertices_markov_chain.h"
#include "
    load_directed_named_edges_and_vertices_graph_from_dot.
    h"
#include "save_named_edges_and_vertices_graph_to_dot.h"
#include "get_vertex_names.h"

void
    load_directed_named_edges_and_vertices_graph_from_dot_demo
    () noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g
    = create_named_edges_and_vertices_markov_chain();
  const std::string filename{
    "create_named_edges_and_vertices_markov_chain.dot"
  };
  save_named_edges_and_vertices_graph_to_dot(g, filename)
      ;
  const auto h
    =
        load_directed_named_edges_and_vertices_graph_from_dot
        (filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_vertex_names(g) == get_vertex_names(h));
}
```

This demonstration shows how the Markov chain is created using the 'create_named_edges_and_vertices_markov_chain' function (algorithm 81), saved and then loaded. The loaded graph is checked to be a directed graph similar to the Markov chain with the same edge and vertex names (using the 'get_edge_names' function , algorithm 79, and the 'get_vertex_names' function, algorithm 41).

7.8 Loading an undirected graph with named edges and vertices from a .dot

When loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph with named edges and vertices is loaded, as shown in algorithm 101:

Algorithm 101 Loading an undirected graph with named edges and vertices from a .dot file

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

#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "is_regular_file.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
  >
>
load_undirected_named_edges_and_vertices_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  std::ifstream f(dot_filename.c_str());
  auto g =
      create_empty_undirected_named_edges_and_vertices_graph
      ();
  boost::dynamic_properties p; //_do_ default construct
  p.property("node_id", get(boost::vertex_name, g));
  p.property("label", get(boost::vertex_name, g));
  p.property("edge_id", get(boost::edge_name, g));
  p.property("label", get(boost::edge_name, g));
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created. Next to this, a boost::dynamic_properties is created with its default constructor, after which we direct the boost::dynamic_properties to find a 'node_id' and 'label' in the vertex name map, 'edge_id' and 'label to the edge name map. From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 102 shows how to use the 'load_undirected_graph_from_dot' function:

Algorithm 102 Demonstration of the 'load_undirected_named_edges_and_vertices_graph_from_dot' function

```
#include "create_named_edges_and_vertices_k3_graph.h"
#include "
    load_undirected_named_edges_and_vertices_graph_from_dot
    .h"
#include "save_named_edges_and_vertices_graph_to_dot.h"
#include "get_vertex_names.h"

void
    load_undirected_named_edges_and_vertices_graph_from_dot_demo
    () noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g
    = create_named_edges_and_vertices_k3_graph();
  const std::string filename{
    "create_named_edges_and_vertices_k3_graph.dot"
  };
  save_named_edges_and_vertices_graph_to_dot(g, filename)
      ;
  const auto h
    =
        load_undirected_named_edges_and_vertices_graph_from_dot
        (filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_vertex_names(g) == get_vertex_names(h));
}
```

This demonstration shows how K_3 with named edges and vertices is created using the 'create_named_edges_and_vertices_k3_graph' function (algorithm 84), saved and then loaded. The loaded graph is checked to be an undirected graph similar to K_3 , with the same edge and vertex names (using the 'get_edge_names' function , algorithm 79, and the 'get_vertex_names' function, algorithm 41).

8 Building graphs with custom vertices

Up until now, the graphs created have had edges and vertices with the built-in name propery. In this chapter, graphs will be created, in which the vertices can have a custom 'my_vertex' type[8]. The following graphs will be created:

- An empty directed graph that allows for custom vertices: see chapter 105
- An empty undirected graph that allows for custom vertices: see chapter 8.3
- A two-state Markov chain with custom vertices: see chapter 8.7
- $K_2$with custom vertices: see chapter 8.8

In the process, some basic (sometimes bordering trivial) functions are shown:

- Create the custom vertex class, called 'my_vertex': see chapter 8.1
- Installing the new vertex type as a vertex property, called 'vertex_custom_type': chapter 8.2
- Adding a custom vertex: see chapter 8.5
- Getting the vertices my_vertex-es: see chapter 8.6

These functions are mostly there for completion and showing which data types are used.

8.1 Creating the custom vertex class

Before creating an empty graph with custom vertices, that custom vertex class must be created. In this tutorial, the 'my_vertex' class is nonsensical, but it can be replaced by any other class type.

Here I will show the header file of 'my_vertex', as the implementation of it is not important:

[8]I do not intend to be original in naming my data types

Algorithm 103 Declaration of my_vertex

```
#ifndef MY_VERTEX_H
#define MY_VERTEX_H

#include <string>
#include <iostream>

class my_vertex
{
public:
  my_vertex(
    const std::string& name = "",
    const std::string& description = "",
    const double x = 0.0,
    const double y = 0.0
  ) noexcept;
  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;
bool operator!=(const my_vertex& lhs, const my_vertex&
    rhs) noexcept;
std::ostream& operator<<(std::ostream& os, const
    my_vertex& v) noexcept;
std::istream& operator>>(std::istream& os, my_vertex& v)
    noexcept;

void my_vertex_test() 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. 'my_vertex' is comparable for equality (that is, operator== is defined).

For the class to be saved to file and/or read from file, one needs to define both the in- and outstream operators. One can use the 'is_read_graphviz_correct' function (algorithm 174) to check this.

8.2 Installing the new vertex property

Before creating an empty graph with custom vertices, this type must be installed as a vertex property. Installing a new property would have been easier, if 'more C++ compilers were standards conformant' ([8] chapter 3.6). Boost.Graph uses the BOOST_INSTALL_PROPERTY macro to allow using a custom property:

Algorithm 104 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.

8.3 Create the empty directed graph with custom vertices

Algorithm 105 Creating an empty directed 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::directedS,
  boost::property<
    boost::vertex_custom_type_t,my_vertex
  >
>
create_empty_directed_custom_vertices_graph() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    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 directed (due to the boost::directedS)
- 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".

8.4 Create the empty undirected graph with custom vertices

Algorithm 106 Creating an empty undirected 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_undirected_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".

8.5 Add a custom vertex

Adding a custom vertex is very similar to adding a named vertex (chapter 4.3).

Algorithm 107 Add a custom vertex

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

template <typename graph>
void add_custom_vertex(const my_vertex& v, graph& g)
    noexcept
{
  const auto vd_a = boost::add_vertex(g);
  const auto my_vertex_map
    = get( //_not_ boost::get!
      boost::vertex_custom_type,g
    );
  my_vertex_map[vd_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 'get(boost::vertex_custom_type,g)').

8.6 Getting the vertices' my_vertexes[9]

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

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

Algorithm 108 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) noexcept
{
  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' (see chapter 18.1).

8.7 Creating a two-state Markov chain with custom vertices

8.7.1 Graph

Figure 16 shows the graph that will be reproduced:

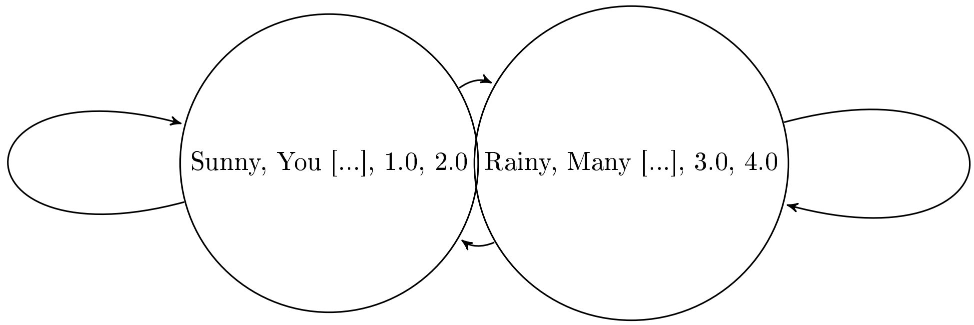

Figure 16: A two-state Markov chain where the vertices have custom properies and the edges have no properties. The vertices' properties are nonsensical

Having spaces in a vertex label is not supported (yet), and the spaces are replaced by underscores.

8.7.2 Function to create such a graph

Here is the code creating a two-state Markov chain with custom vertices:

Algorithm 109 Creating the two-state Markov chain as depicted in figure 16

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

///Create a two-state Markov chain with named vertices
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t,my_vertex
  >
>
create_custom_vertices_markov_chain() noexcept
{
  auto g
    = create_empty_directed_custom_vertices_graph();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
  assert(aer_aa.second);
  const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
  assert(aer_ab.second);
  const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
  assert(aer_ba.second);
  const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
  assert(aer_bb.second);

  auto name_map = get( //_not_ boost::get!
    boost::vertex_custom_type,g
  );
  name_map[vd_a] = my_vertex("Sunny","You can see the 
     yellow thing",1.0,2.0);
  name_map[vd_b] = my_vertex("Rainy","Many grey fluffy 
     things",3.0,4.0);

  return g;
}
```

8.7.3 Creating such a graph

Here is the demo:

Algorithm 110 Demo of the 'create_custom_vertices_markov_chain' function (algorithm 109)

```
#include <cassert>
#include "create_custom_vertices_markov_chain.h"
#include "get_vertex_my_vertexes.h"
#include "install_vertex_custom_type.h"
#include "my_vertex.h"

void create_custom_vertices_markov_chain_demo() noexcept
{
  const auto g
    = create_custom_vertices_markov_chain();
  const std::vector<my_vertex> expected_my_vertexes{
    my_vertex("Sunny","You can see the yellow thing"
        ,1.0,2.0),
    my_vertex("Rainy","Many grey fluffy things",3.0,4.0)
  };
  const std::vector<my_vertex> vertex_my_vertexes{
    get_vertex_my_vertexes(g)
  };
  assert(expected_my_vertexes == vertex_my_vertexes);
}
```

8.7.4 The .dot file produced

Algorithm 111 .dot file created from the 'create_custom_vertices_markov_chain' function (algorithm 109), converted from graph to .dot file using algorithm 29

```
digraph G {
0[label="Sunny,You_can_see_the_yellow_thing,1,2"];
1[label="Rainy,Many_grey_fluffy_things,3,4"];
0->0 ;
0->1 ;
1->0 ;
1->1 ;
}
```

8.7.5 The .svg file produced

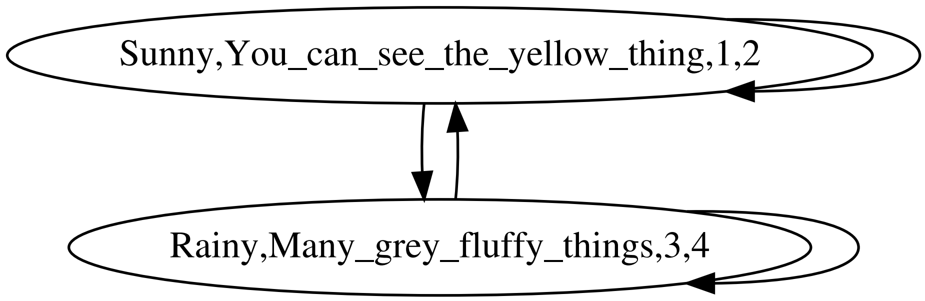

Figure 17: .svg file created from the 'create_custom_vertices_markov_chain' function (algorithm 109) its .dot file, converted from .dot file to .svg using algorithm 176

8.8 Creating K_2 with custom vertices

8.8.1 Graph

We reproduce the K_2 with named vertices of chapter 4.6 , but with our custom vertices intead.

8.8.2 Function to create such a graph

Algorithm 112 Creating K_2 as depicted in figure 9

```
#include "install_vertex_custom_type.h"
#include "my_vertex.h"
#include "create_empty_undirected_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_undirected_custom_vertices_graph
     ();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer = boost::add_edge(vd_a, vd_b, g);
  assert(aer.second);

  auto my_vertexes_map = get(boost::vertex_custom_type,g)
     ;
  my_vertexes_map[vd_a]
    = my_vertex("A","source",0.0,0.0);
  my_vertexes_map[vd_b]
    = my_vertex("B","target",3.14,3.14);

  return g;
}
```

Most of the code is a slight modification of the 'create_named_vertices_k2_graph' function (algorithm 46). In the end, the my_vertices are obtained as a boost::property_map and set with two custom my_vertex objects.

8.8.3 Creating such a graph

Demo:

Algorithm 113 Demo of the 'create_custom_vertices_k2_graph' function (algorithm 112)

```
#include <cassert>
#include <iostream>
#include "create_custom_vertices_k2_graph.h"
#include "has_vertex_with_my_vertex.h"

void create_custom_vertices_k2_graph_demo() noexcept
{
  const auto g = create_custom_vertices_k2_graph();
  assert(boost::num_edges(g) == 1);
  assert(boost::num_vertices(g) == 2);
  assert(has_vertex_with_my_vertex(
    my_vertex("A", "source" ,0.0, 0.0), g)
  );
  assert(has_vertex_with_my_vertex(
    my_vertex("B", "target" ,3.14, 3.14), g)
  );
}
```

8.8.4 The .dot file produced

Algorithm 114 .dot file created from the 'create_custom_vertices_k2_graph' function (algorithm 112), converted from graph to .dot file using algorithm 29

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

8.8.5 The .svg file produced

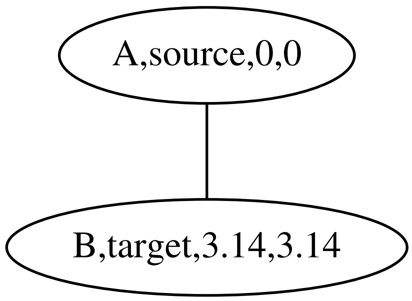

Figure 18: .svg file created from the 'create_custom_vertices_k2_graph' function (algorithm 112) its .dot file, converted from .dot file to .svg using algorithm 176

9 Working with graphs with custom vertices

When using graphs with custom vertices, their state gives a way to find a vertex and working with it. This chapter shows some basic operations on graphs with custom vertices.

- Check if there exists a vertex with a certain 'my_vertex': chapter 9.1
- Find a vertex with a certain 'my_vertex': chapter 9.2
- Get a vertex its 'my_vertex' from its vertex descriptor: chapter 9.3
- Set a vertex its 'my_vertex' using its vertex descriptor: chapter 9.4
- Setting all vertices their 'my_vertex'es: chapter 9.5
- Storing an directed/undirected graph with custom vertices as a .dot file: chapter 9.6
- Loading a directed graph with custom vertices from a .dot file: chapter 9.7
- Loading an undirected directed graph with custom vertices from a .dot file: chapter 9.8

9.1 Has a my_vertex

Before modifying our vertices, let's first determine if we can find a vertex by its custom type ('my_vertex') in a graph. After obtaing a my_vertex map, we obtain the vertex iterators, dereference these to obtain the vertex descriptors and then compare each vertex its my_vertex with the one desired.

Algorithm 115 Find if there is vertex with a certain my_vertex

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


template <typename graph>
bool has_vertex_with_my_vertex(
  const my_vertex& v,
  const graph& g
) noexcept
{
  const auto my_vertexes_map = get(boost::
      vertex_custom_type, g);

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

This function can be demonstrated as in algorithm 116, where a certain my_vertex cannot be found in an empty graph. After adding the desired my_vertex, it is found.

Algorithm 116 Demonstration of the 'has_vertex_with_my_vertex' function

```
#include <cassert>
#include <iostream>

#include "add_custom_vertex.h"
#include "create_empty_undirected_custom_vertices_graph.h
    "
#include "has_vertex_with_my_vertex.h"
#include "install_vertex_custom_type.h"
#include "my_vertex.h"

void has_vertex_with_my_vertex_demo() noexcept
{
  auto g = create_empty_undirected_custom_vertices_graph
      ();
  assert(!has_vertex_with_my_vertex(my_vertex("Felix"),g)
      );
  add_custom_vertex(my_vertex("Felix"),g);
  assert(has_vertex_with_my_vertex(my_vertex("Felix"),g))
      ;
}
```

Note that this function only finds if there is at least one vertex with that my_vertex: it does not tell how many vertices with that my_vertex exist in the graph.

9.2 Find a vertex with a certain my_vertex

Where STL functions work with iterators, here we obtain a vertex descriptor (see chapter 2.6) to obtain a handle to the desired vertex. Algorithm 117 shows how to obtain a vertex descriptor to the first vertex found with a specific my_vertex value.

Algorithm 117 Find the first vertex with a certain my_vertex

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

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_vertex_with_my_vertex(
  const my_vertex& v,
  const graph& g
) noexcept
{
  assert(has_vertex_with_my_vertex(v, g));
  const auto my_vertexes_map = get(boost::
      vertex_custom_type, g);

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

}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 118 shows some examples of how to do so.

Algorithm 118 Demonstration of the 'find_first_vertex_with_my_vertex' function

```
#include <cassert>

#include "create_custom_vertices_k2_graph.h"
#include "find_first_vertex_with_my_vertex.h"

void find_first_vertex_with_my_vertex_demo() noexcept
{
  const auto g = create_custom_vertices_k2_graph();
  const auto vd = find_first_vertex_with_my_vertex(
    my_vertex("A","source",0.0,0.0),
    g
  );
  assert(out_degree(vd,g) == 1); //_not_ boost::
      out_degree!
  assert(in_degree(vd,g) == 1); //_not_ boost::in_degree!
}
```

9.3 Get a vertex its my_vertex

To obtain the name from a vertex descriptor, one needs to pull out the my_vertexes[10] map and then look up the vertex of interest.

[10] Bad English intended: my_vertexes = multiple my_vertex objects, vertices = multiple graph nodes

Algorithm 119 Get a vertex its my_vertex from its vertex descriptor

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

template <typename graph>
my_vertex get_vertex_my_vertex(
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  const graph& g
) noexcept
{
  const auto my_vertexes_map = get(boost::
      vertex_custom_type, g);
  return my_vertexes_map[vd];
}
```

To use 'get_vertex_my_vertex', one first needs to obtain a vertex descriptor. Algorithm 120 shows a simple example.

Algorithm 120 Demonstration if the 'get_vertex_my_vertex' function

```
#include <cassert>

#include "add_custom_vertex.h"
#include "create_empty_undirected_custom_vertices_graph.h
    "
#include "find_first_vertex_with_my_vertex.h"
#include "get_vertex_my_vertex.h"

void get_vertex_my_vertex_demo() noexcept
{
  auto g = create_empty_undirected_custom_vertices_graph
      ();
  const my_vertex name{"Dex"};
  add_custom_vertex(name, g);
  const auto vd = find_first_vertex_with_my_vertex(name,g
      );
  assert(get_vertex_my_vertex(vd,g) == name);
}
```

9.4 Set a vertex its my_vertex

If you know how to get the my_vertex from a vertex descriptor, setting it is just as easy, as shown in algorithm 121.

Algorithm 121 Set a vertex its my_vertex from its vertex descriptor

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

template <typename graph>
void set_vertex_my_vertex(
  const my_vertex& v,
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  graph& g
) noexcept
{
  const auto my_vertexes_map = get(boost::
      vertex_custom_type, g);
  my_vertexes_map[vd] = v;
}
```

To use 'set_vertex_my_vertex', one first needs to obtain a vertex descriptor. Algorithm 122 shows a simple example.

Algorithm 122 Demonstration if the 'set_vertex_my_vertex' function

```
#include <cassert>

#include "add_custom_vertex.h"
#include "create_empty_undirected_custom_vertices_graph.h
   "
#include "find_first_vertex_with_my_vertex.h"
#include "get_vertex_my_vertex.h"
#include "set_vertex_my_vertex.h"

void set_vertex_my_vertex_demo() noexcept
{
  auto g = create_empty_undirected_custom_vertices_graph
      ();
  const my_vertex old_name{"Dex"};
  add_custom_vertex(old_name, g);
  const auto vd = find_first_vertex_with_my_vertex(
      old_name,g);
  assert(get_vertex_my_vertex(vd,g) == old_name);
  const my_vertex new_name{"Diggy"};
  set_vertex_my_vertex(new_name, vd, g);
  assert(get_vertex_my_vertex(vd,g) == new_name);
}
```

9.5 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 123 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
) noexcept
{
  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.

9.6 Storing a graph with custom vertices as a .dot

If you used the create_custom_vertices_k2_graph function (algorithm 112) to produce a K_2 graph with vertices associated with my_vertex objects, you can store these my_vertexes additionally with algorithm 124:

Algorithm 124 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++14.

The .dot file created is displayed in algorithm 125:

Algorithm 125 .dot file created from the create_custom_vertices_k2_graph function (algorithm 46)

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

This .dot file corresponds to figure 125:

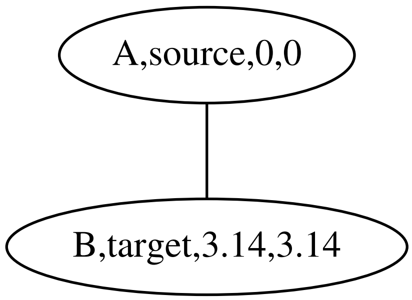

Figure 19: .svg file created from the create_custom_vertices_k2_graph function (algorithm 112) and converted to .svg using the 'convert_dot_to_svg' function (algorithm 176)

9.7 Loading a directed graph with custom vertices from a .dot

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph with custom vertices is loaded, as shown in algorithm 126:

Algorithm 126 Loading a directed graph with custom vertices from a .dot file

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

#include "create_empty_directed_custom_vertices_graph.h"
#include "install_vertex_custom_type.h"
#include "is_regular_file.h"
#include "my_vertex.h"
#include "is_read_graphviz_correct.h"
#include "get_vertex_my_vertexes.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t,my_vertex
  >
>
load_directed_custom_vertices_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  assert(is_read_graphviz_correct<my_vertex>());
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_directed_custom_vertices_graph();
  boost::dynamic_properties p; //_do_ default construct
  p.property("node_id", get(boost::vertex_custom_type, g)
     );
  p.property("label", get(boost::vertex_custom_type, g));
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created. Next to this, a boost::dynamic_properties is created with its default constructor, after which we direct the boost::dynamic_properties to find a 'node_id' and 'label' in the vertex name map, 'edge_id' and 'label to the edge name map. From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 127 shows how to use the 'load_directed_custom_vertices_graph_from_dot' function:

Algorithm 127 Demonstration of the 'load_directed_custom_vertices_graph_from_dot' function

```
#include "create_custom_vertices_markov_chain.h"
#include "load_directed_custom_vertices_graph_from_dot.h"
#include "save_custom_vertices_graph_to_dot.h"
#include "get_vertex_my_vertexes.h"

void load_directed_custom_vertices_graph_from_dot_demo()
    noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g
    = create_custom_vertices_markov_chain();
  const std::string filename{
    "create_custom_vertices_markov_chain.dot"
  };
  save_custom_vertices_graph_to_dot(g, filename);
  const auto h
    = load_directed_custom_vertices_graph_from_dot(
        filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_vertex_my_vertexes(g) ==
      get_vertex_my_vertexes(h));
}
```

This demonstration shows how the Markov chain is created using the 'create_custom_vertices_markov_chain' function (algorithm 109), saved and then loaded. The loaded graph is checked to be a directed graph similar to the Markov chain with the same vertex my_vertex instances (using the 'get_vertex_my_vertexes' function).

9.8 Loading an undirected graph with custom vertices from a .dot

When loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph with custom vertices is loaded, as shown in algorithm 128:

Algorithm 128 Loading an undirected graph with custom vertices from a .dot file

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

#include "create_empty_undirected_custom_vertices_graph.h
   "
#include "install_vertex_custom_type.h"
#include "is_regular_file.h"
#include "my_vertex.h"
#include "is_read_graphviz_correct.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t,my_vertex
  >
>
load_undirected_custom_vertices_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  assert(is_read_graphviz_correct<my_vertex>());
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_undirected_custom_vertices_graph
     ();
  boost::dynamic_properties p; //_do_ default construct
  p.property("node_id", get(boost::vertex_custom_type, g)
     );
  p.property("label", get(boost::vertex_custom_type, g));
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created. Next to this, a boost::dynamic_properties is created with its default constructor, after which we direct the boost::dynamic_properties to find a 'node_id' and 'label' in the vertex name map, 'edge_id' and 'label to the edge name map. From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 129 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

Algorithm 129 Demonstration of the 'load_undirected_custom_vertices_graph_from_dot' function

```
#include <cassert>
#include "create_custom_vertices_k2_graph.h"
#include "load_undirected_custom_vertices_graph_from_dot.
    h"
#include "save_custom_vertices_graph_to_dot.h"
#include "get_vertex_my_vertexes.h"

void load_undirected_custom_vertices_graph_from_dot_demo
    () noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g
    = create_custom_vertices_k2_graph();
  const std::string filename{
    "create_custom_vertices_k2_graph.dot"
  };
  save_custom_vertices_graph_to_dot(g, filename);
  const auto h
    = load_undirected_custom_vertices_graph_from_dot(
        filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_vertex_my_vertexes(g) ==
      get_vertex_my_vertexes(h));
}
```

This demonstration shows how K_2 with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 112), saved and then loaded. The loaded graph is checked to be a graph similar to the original, with the same vertex my_vertex instances (using the 'get_vertex_my_vertexes' function).

10 Building graphs with custom edges and vertices

Up until now, the graphs created have had edges and vertices with the built-in name propery. In this chapter, graphs will be created, in which the edges and vertices can have a custom 'my_edge' and 'my_edge' type[11].

- An empty directed graph that allows for custom edges and vertices: see chapter
- An empty undirected graph that allows for custom edges and vertices: see chapter **??**
- A two-state Markov chain with custom edges and vertices: see chapter
- $K_3$with custom edges and vertices: see chapter 10.7

In the process, some basic (sometimes bordering trivial) functions are shown:

- Creating the custom edge class: see chapter
- Installing the new edge property: see chapter
- Adding a custom edge: see chapter 10.5

These functions are mostly there for completion and showing which data types are used.

10.1 Creating the custom edge class

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

[11] I do not intend to be original in naming my data types

Algorithm 130 Declaration of my_edge

```
#ifndef MY_EDGE_H
#define MY_EDGE_H

#include <string>

class my_edge
{
public:
  my_edge(
    const std::string& name = "",
    const std::string& description = "",
    const double width = 1.0,
    const double height = 1.0
  ) noexcept;
  std::string m_name;
  std::string m_description;
  double m_width;
  double m_height;
};

bool operator==(const my_edge& lhs, const my_edge& rhs)
    noexcept;
bool operator!=(const my_edge& lhs, const my_edge& rhs)
    noexcept;
std::ostream& operator<<(std::ostream& os, const my_edge&
    v) noexcept;
std::istream& operator>>(std::istream& os, my_edge& v)
    noexcept;

void my_edge_test() noexcept;

#endif // MY_EDGE_H
```

my_edge is a class that has multiple properties: two doubles 'm_width' ('m_' stands for member) and 'm_height', and two std::strings m_name and m_description. 'my_edge' is copyable, but cannot trivially be converted to a std::string.' 'my_edge' is comparable for equality (that is, operator== is defined).

For the class to be saved to file and/or read from file, one needs to define both the in- and outstream operators. One can use the 'is_read_graphviz_correct' function (algorithm 174) to check this.

10.2 Installing the new edge property

Installing a new property would have been easier, if 'more C++ compilers were standards conformant' ([8], chapter 3.6, footnote at page 52). Boost.Graph uses the BOOST_INSTALL_PROPERTY macro to allow using a custom property:

Algorithm 131 Installing the edge_custom_type property

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

namespace boost {
  enum edge_custom_type_t { edge_custom_type = 3142 };
  BOOST_INSTALL_PROPERTY(edge,custom_type);
}
```

The enum value 3142 must be unique.

10.3 Create an empty directed graph with custom edges and vertices

Algorithm 132 Creating an empty directed graph with custom edges and vertices

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t,my_vertex
  >,
  boost::property<
    boost::edge_custom_type_t,my_edge
  >
>
create_empty_directed_custom_edges_and_vertices_graph()
   noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    boost::property<
      boost::vertex_custom_type_t,my_vertex
    >,
    boost::property<
      boost::edge_custom_type_t,my_edge
    >
  >();
}
```

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 directed (due to the boost::directedS)

- 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 have one property: they have a custom type, that is of data type my_edge (due to the boost::property< boost::edge_custom_type_t, my_edge>')
- 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_custom_type_t, my_edge>'. This can be read as: "edges have the property 'boost::edge_custom_type_t', which is of data type 'my_edge"'. Or simply: "edges have a custom type called my_edge".

Demo:

Algorithm 133 Demonstration of the XXX function

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

void
    create_empty_directed_custom_edges_and_vertices_graph_demo
    () noexcept
{
  const auto g =
      create_empty_directed_custom_edges_and_vertices_graph
      ();
  assert(boost::num_edges(g) == 0);
  assert(boost::num_vertices(g) == 0);
}
```

10.4 Create an empty undirected graph with custom edges and vertices

Algorithm 134 Creating an empty undirected graph with custom edges and vertices

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

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

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 have one property: they have a custom type, that is of data type my_edge (due to the boost::property< boost::edge_custom_type_t, my_edge>')
- 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_custom_type_t, my_edge>'. This can be read as: "edges have the property 'boost::edge_custom_type_t', which is of data type 'my_edge"'. Or simply: "edges have a custom type called my_edge".

Demo:

Algorithm 135 Demonstration of the XXX function

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

void
    create_empty_undirected_custom_edges_and_vertices_graph_demo
    () noexcept
{
  const auto g =
      create_empty_undirected_custom_edges_and_vertices_graph
      ();
  assert(boost::num_edges(g) == 0);
  assert(boost::num_vertices(g) == 0);
}
```

10.5 Add a custom edge

Adding a custom edge is very similar to adding a named edge (chapter 6.3).

Algorithm 136 Add a custom edge

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

template <typename graph>
void add_custom_edge(const my_edge& v, graph& g) noexcept
{
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);

  const auto aer = boost::add_edge(vd_a, vd_b, g);
  assert(aer.second);
  const auto my_edge_map
    = get( //_not_ boost::get!
      boost::edge_custom_type, g
    );
  my_edge_map[aer.first] = v;
}
```

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

10.6 Creating a Markov-chain with custom edges and vertices

10.6.1 Graph

Figure 20 shows the graph that will be reproduced:

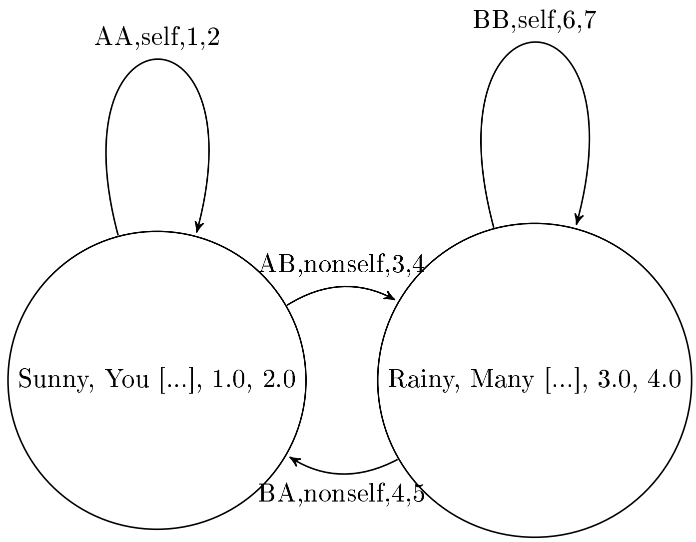

Figure 20: A two-state Markov chain where the edges and vertices have custom properies. The edges' and vertices' properties are nonsensical

Having spaces in a vertex label is not supported (yet), and the spaces are replaced by underscores.

[graph here]

10.6.2 Function to create such a graph

Here is the code creating a two-state Markov chain with custom edges and vertices:

Algorithm 137 Creating the two-state Markov chain as depicted in figure 20

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

///Create a two-state Markov chain with named vertices
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_vertex
  >,
  boost::property<
    boost::edge_custom_type_t, my_edge
  >
>
create_custom_edges_and_vertices_markov_chain() noexcept
{
  auto g
    =
      create_empty_directed_custom_edges_and_vertices_graph
      ();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
  assert(aer_aa.second);
  const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
  assert(aer_ab.second);
  const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
  assert(aer_ba.second);
  const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
  assert(aer_bb.second);

  auto my_vertexes_map = get( //_not_ boost::get!
    boost::vertex_custom_type,g
  );
  my_vertexes_map[vd_a] = my_vertex("Sunny","You can see 
     the yellow thing",1.0,2.0);
  my_vertexes_map[vd_b] = my_vertex("Rainy","Many grey 
     fluffy things",3.0,4.0);

  auto my_edges_map = get( //_not_ boost::get!
    boost::edge_custom_type,g
  );
  my_edges_map[aer_aa.first] = my_edge("Sometimes","20%"
     ,1.0,2.0);
  my_edges_map[aer_ab.first] = my_edge("Often","80%"
     ,3.0,4.0);
  my_edges_map[aer_ba.first] = my_edge("Rarely","10%"
     ,5.0,6.0);
```

10.6.3 Creating such a graph

Here is the demo:

Algorithm 138 Demo of the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 137)

```
#include <cassert>
#include "create_custom_edges_and_vertices_markov_chain.h
    "
#include "get_vertex_my_vertexes.h"
#include "install_vertex_custom_type.h"
#include "my_vertex.h"

void create_custom_edges_and_vertices_markov_chain_demo()
     noexcept
{
  const auto g
    = create_custom_edges_and_vertices_markov_chain();
  const std::vector<my_vertex> expected_my_vertexes{
    my_vertex("Sunny","You can see the yellow thing"
        ,1.0,2.0),
    my_vertex("Rainy","Many grey fluffy things",3.0,4.0)
  };
  const std::vector<my_vertex> vertex_my_vertexes{
    get_vertex_my_vertexes(g)
  };
  assert(expected_my_vertexes == vertex_my_vertexes);
}
```

10.6.4 The .dot file produced

Algorithm 139 .dot file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 137), converted from graph to .dot file using algorithm 29

```
digraph G {
0[label="Sunny,You_can_see_the_yellow_thing,1,2"];
1[label="Rainy,Many_grey_fluffy_things,3,4"];
0->0 [label="Sometimes,20%,1,2"];
0->1 [label="Often,80%,3,4"];
1->0 [label="Rarely,10%,5,6"];
1->1 [label="Mostly,90%,7,8"];
}
```

10.6.5 The .svg file produced

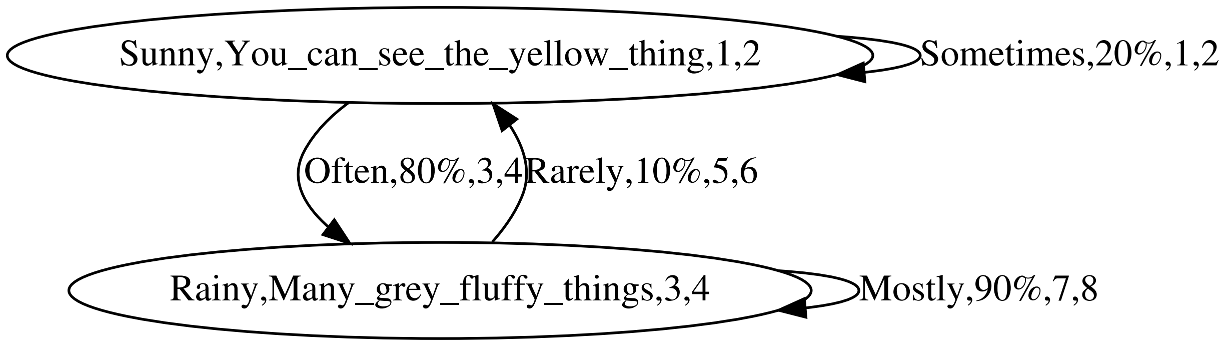

Figure 21: .svg file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 109) its .dot file, converted from .dot file to .svg using algorithm 176

10.7 Creating K_3 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'.

10.7.1 Graph

We reproduce the K_3 with named edges and vertices of chapter 6.6 , but with our custom edges and vertices intead:

[graph here]

10.7.2 Function to create such a graph

Algorithm 140 Creating K_3 as depicted in figure 13

```
#include "install_vertex_custom_type.h"
#include "my_vertex.h"
#include "
    create_empty_undirected_custom_edges_and_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
  >,
  boost::property<
    boost::edge_custom_type_t,my_edge
  >
>
create_custom_edges_and_vertices_k3_graph() noexcept
{
  auto g =
      create_empty_undirected_custom_edges_and_vertices_graph
      ();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto vd_c = boost::add_vertex(g);
  const auto aer_a = boost::add_edge(vd_a, vd_b, g);
  const auto aer_b = boost::add_edge(vd_b, vd_c, g);
  const auto aer_c = boost::add_edge(vd_c, vd_a, g);
  assert(aer_a.second);
  assert(aer_b.second);
  assert(aer_c.second);

  auto my_vertex_map = get(boost::vertex_custom_type,g);
  my_vertex_map[vd_a]
    = my_vertex("top","source",0.0,0.0);
  my_vertex_map[vd_b]
    = my_vertex("right","target",3.14,0);
  my_vertex_map[vd_c]
    = my_vertex("left","target",0,3.14);

  auto my_edge_map = get(boost::edge_custom_type,g);
  my_edge_map[aer_a.first]
    = my_edge("AB","first",0.0,0.0);
  my_edge_map[aer_b.first]
    = my_edge("BC","second",3.14,3.14);
  my_edge_map[aer_c.first]
    = my_edge("CA","third",3.14,3.14);

  return g;
}
```

Most of the code is a slight modification of algorithm 84. In the end, the my_edges and my_vertices are obtained as a boost::property_map and set with the custom my_edge and my_vertex objects.

10.7.3 Creating such a graph

Here is the demo:

Algorithm 141 Demo of the 'create_custom_edges_and_vertices_k3_graph' function (algorithm 140)

```
#include <cassert>
#include <boost/graph/adjacency_list.hpp>
#include "add_custom_edge.h"
#include "add_custom_vertex.h"
#include "create_custom_edges_and_vertices_k3_graph.h"

void create_custom_edges_and_vertices_k3_graph_demo()
    noexcept
{
  auto g = create_custom_edges_and_vertices_k3_graph();
  assert(boost::num_edges(g) == 3);
  assert(boost::num_vertices(g) == 3);
  add_custom_vertex(my_vertex("v"), g);
  add_custom_edge(my_edge("e"), g);
}
```

10.7.4 The .dot file produced

Algorithm 142 .dot file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 140), converted from graph to .dot file using algorithm 29

```
graph G {
0[label="top,source,0,0"];
1[label="right,target,3.14,0"];
2[label="left,target,0,3.14"];
0--1 [label="AB,first,0,0"];
1--2 [label="BC,second,3.14,3.14"];
2--0 [label="CA,third,3.14,3.14"];
}
```

10.7.5 The .svg file produced

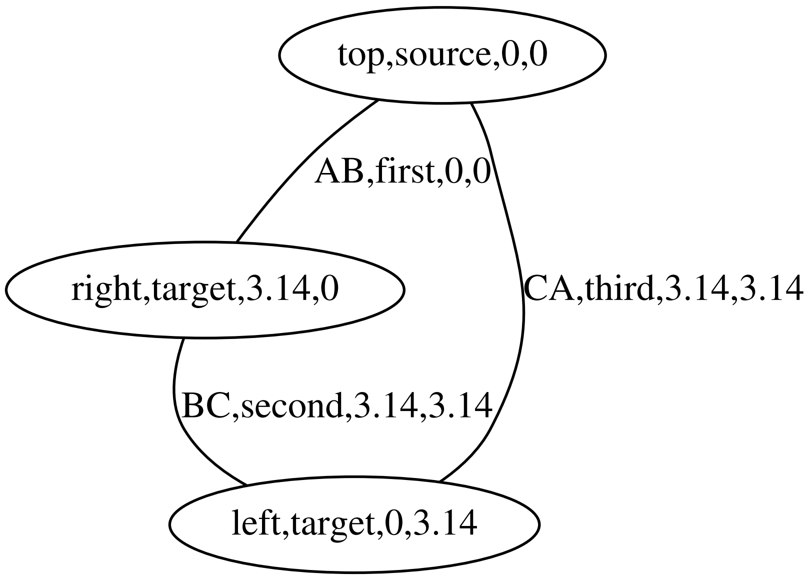

Figure 22: .svg file created from the 'create_custom_edges_and_vertices_k3_graph' function (algorithm 109) its .dot file, converted from .dot file to .svg using algorithm 176

11 Working with graphs with custom edges and vertices

11.1 Has a my_edge

Before modifying our edges, let's first determine if we can find an edge by its custom type ('my_edge') in a graph. After obtaing a my_edge map, we obtain the edge iterators, dereference these to obtain the edge descriptors and then compare each edge its my_edge with the one desired.

Algorithm 143 Find if there is an edge with a certain my_edge

```
#include <boost/graph/properties.hpp>
#include "install_edge_custom_type.h"
#include "my_edge.h"

template <typename graph>
bool has_edge_with_my_edge(
  const my_edge& e,
  const graph& g
) noexcept
{
  const auto my_edges_map = get(boost::edge_custom_type,g
     );

  for (auto p = edges(g);
    p.first != p.second;
    ++p.first) {
    if (get(my_edges_map, *p.first) == e) {
      return true;
    }
  }
  return false;
}
```

This function can be demonstrated as in algorithm 144, where a certain my_edge cannot be found in an empty graph. After adding the desired my_edge, it is found.

Algorithm 144 Demonstration of the 'has_edge_with_my_edge' function

```
#include <cassert>

#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "has_edge_with_my_edge.h"

void has_edge_with_my_edge_demo() noexcept
{
  auto g =
      create_empty_undirected_custom_edges_and_vertices_graph
      ();
  assert(!has_edge_with_my_edge(my_edge("Edward"),g));
  add_custom_edge(my_edge("Edward"),g);
  assert(has_edge_with_my_edge(my_edge("Edward"),g));
}
```

Note that this function only finds if there is at least one edge with that my_edge: it does not tell how many edges with that my_edge exist in the graph.

11.2 Find a my_edge

Where STL functions work with iterators, here we obtain an edge descriptor (see chapter 2.12) to obtain a handle to the desired edge. Algorithm 145 shows how to obtain an edge descriptor to the first edge found with a specific my_edge value.

Algorithm 145 Find the first edge with a certain my_edge

```
#include <cassert>
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>
#include "has_edge_with_my_edge.h"
#include "install_edge_custom_type.h"
#include "my_edge.h"

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
find_first_edge_with_my_edge(
  const my_edge& e,
  const graph& g
) noexcept
{
  assert(has_edge_with_my_edge(e, g));
  const auto my_edges_map = get(boost::edge_custom_type,
     g);

  for (auto p = edges(g);
    p.first != p.second;
    ++p.first) {

    if (get(my_edges_map, *p.first) == e) {
      return *p.first;
    }
  }
  return *edges(g).second;
}
```

With the edge descriptor obtained, one can read and modify the edge and the vertices surrounding it. Algorithm 146 shows some examples of how to do so.

Algorithm 146 Demonstration of the 'find_first_edge_with_my_edge' function

```
#include <cassert>

#include "create_custom_edges_and_vertices_k3_graph.h"
#include "find_first_edge_with_my_edge.h"

void find_first_edge_with_my_edge_demo() noexcept
{
  const auto g =
      create_custom_edges_and_vertices_k3_graph();
  const auto ed = find_first_edge_with_my_edge(
    my_edge("AB","first",0.0,0.0),
    g
  );
  assert(boost::source(ed,g) != boost::target(ed,g));
}
```

11.3 Get an edge its my_edge

To obtain the my_edeg from an edge descriptor, one needs to pull out the my_edges map and then look up the my_edge of interest.

Algorithm 147 Get a vertex its my_vertex from its vertex descriptor

```
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>
#include "install_edge_custom_type.h"
#include "my_edge.h"

template <typename graph>
my_edge get_edge_my_edge(
  const typename boost::graph_traits<graph>::
      edge_descriptor& vd,
  const graph& g
) noexcept
{
  const auto my_edge_map = get(boost::edge_custom_type, g
      );
  return my_edge_map[vd];
}
```

To use 'get_edge_my_edge', one first needs to obtain an edgedescriptor. Algorithm 148 shows a simple example.

Algorithm 148 Demonstration if the 'get_edge_my_edge' function

```
#include <cassert>

#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "find_first_edge_with_my_edge.h"
#include "get_edge_my_edge.h"

void get_edge_my_edge_demo() noexcept
{
  auto g =
      create_empty_undirected_custom_edges_and_vertices_graph
      ();
  const my_edge name{"Dex"};
  add_custom_edge(name, g);
  const auto ed = find_first_edge_with_my_edge(name,g);
  assert(get_edge_my_edge(ed,g) == name);
}
```

11.4 Set an edge its my_edge

If you know how to get the my_edge from an edge descriptor, setting it is just as easy, as shown in algorithm 149.

Algorithm 149 Set an edge its my_edge from its edge descriptor

```
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>
#include "install_edge_custom_type.h"
#include "my_edge.h"

template <typename graph>
void set_edge_my_edge(
  const my_edge& name,
  const typename boost::graph_traits<graph>::
      edge_descriptor& vd,
  graph& g
) noexcept
{
  auto my_edge_map = get(boost::edge_custom_type, g);
  my_edge_map[vd] = name;
}
```

To use 'set_edge_my_edge', one first needs to obtain an edgedescriptor. Algorithm 150 shows a simple example.

Algorithm 150 Demonstration if the 'set_edge_my_edge' function

```
#include <cassert>

#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "find_first_edge_with_my_edge.h"
#include "get_edge_my_edge.h"
#include "set_edge_my_edge.h"

void set_edge_my_edge_demo() noexcept
{
  auto g =
      create_empty_undirected_custom_edges_and_vertices_graph
      ();
  const my_edge old_name{"Dex"};
  add_custom_edge(old_name, g);
  const auto vd = find_first_edge_with_my_edge(old_name,g
      );
  assert(get_edge_my_edge(vd,g) == old_name);
  const my_edge new_name{"Diggy"};
  set_edge_my_edge(new_name, vd, g);
  assert(get_edge_my_edge(vd,g) == new_name);
}
```

11.5 Storing a graph with custom edges and vertices as a .dot

If you used the create_custom_edges_and_vertices_k3_graph function (algorithm 140) to produce a K_3 graph with edges and vertices associated with my_edge and my_vertex objects, you can store these my_edges and my_vertexes additionally with algorithm 151:

Algorithm 151 Storing a graph with custom edges and 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_edges_and_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++14.

The .dot file created is displayed in algorithm 152:

Algorithm 152 .dot file created from the create_custom_edges_and_vertices_k3_graph function (algorithm 46)

```
graph G {
0[label="top,source,0,0"];
1[label="right,target,3.14,0"];
2[label="left,target,0,3.14"];
0--1 [label="AB,first,0,0"];
1--2 [label="BC,second,3.14,3.14"];
2--0 [label="CA,third,3.14,3.14"];
}
```

This .dot file corresponds to figure 152:

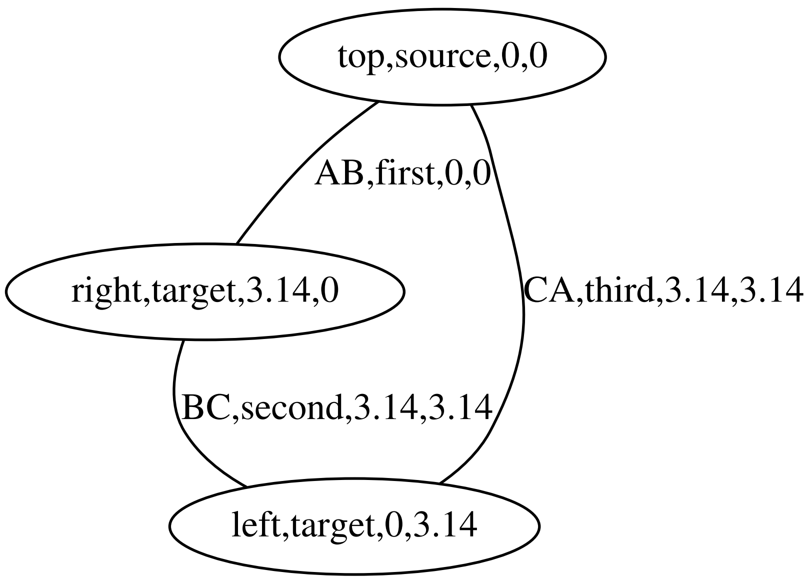

Figure 23: .svg file created from the create_custom_edges_and_vertices_k3_graph function (algorithm 140) and converted to .svg using the 'convert_dot_to_svg' function (algorithm 176)

11.6 Load a directed graph with custom edges and vertices from a .dot file

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph with custom edges and vertices is loaded, as shown in algorithm 153:

Algorithm 153 Loading a directed graph with custom edges and vertices from a .dot file

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

#include "
    create_empty_directed_custom_edges_and_vertices_graph.
    h"
#include "get_vertex_my_vertexes.h"
#include "install_edge_custom_type.h"
#include "install_vertex_custom_type.h"
#include "is_read_graphviz_correct.h"
#include "is_regular_file.h"
#include "my_edge.h"
#include "my_vertex.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_vertex
  >,
  boost::property<
    boost::edge_custom_type_t, my_edge
  >
>
load_directed_custom_edges_and_vertices_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  assert(is_read_graphviz_correct<my_edge>());
  assert(is_read_graphviz_correct<my_vertex>());
  std::ifstream f(dot_filename.c_str());
  auto g =
      create_empty_directed_custom_edges_and_vertices_graph
      ();
  boost::dynamic_properties p; //_do_ default construct
  p.property("node_id", get(boost::vertex_custom_type, g)
      );
  p.property("label", get(boost::vertex_custom_type, g));
  p.property("edge_id", get(boost::edge_custom_type, g));
  p.property("label", get(boost::edge_custom_type, g));
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created. Next to this, a boost::dynamic_properties is created with its default constructor, after which we direct the boost::dynamic_properties to find a 'node_id' and 'label' in the vertex name map, 'edge_id' and 'label to the edge name map. From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 154 shows how to use the 'load_directed_custom_edges_and_vertices_graph_from_dot' function:

Algorithm 154 Demonstration of the 'load_directed_custom_edges_and_vertices_graph_from_dot' function

```
#include "create_custom_edges_and_vertices_markov_chain.h
    "
#include "
    load_directed_custom_edges_and_vertices_graph_from_dot
    .h"
#include "save_custom_edges_and_vertices_graph_to_dot.h"
#include "get_vertex_my_vertexes.h"

void
    load_directed_custom_edges_and_vertices_graph_from_dot_demo
    () noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g
    = create_custom_edges_and_vertices_markov_chain();
  const std::string filename{
    "create_custom_edges_and_vertices_markov_chain.dot"
  };
  save_custom_edges_and_vertices_graph_to_dot(g, filename
      );
  const auto h
    =
        load_directed_custom_edges_and_vertices_graph_from_dot
        (filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_vertex_my_vertexes(g) ==
      get_vertex_my_vertexes(h));
}
```

This demonstration shows how the Markov chain is created using the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 137), saved and then loaded. The loaded graph is checked to be a directed graph similar to the Markov chain with the same vertex 'my_vertex' instances (using the 'get_vertex_my_vertexes' function) and the same edge 'my_edge' instances (using the 'get_edge_my_edges' function)

11.7 Load an undirected graph with custom edges and vertices from a .dot file

When loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph with custom edges and vertices is loaded, as shown in algorithm 155:

Algorithm 155 Loading an undirected graph with custom edges and vertices from a .dot file

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

#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "get_vertex_my_vertexes.h"
#include "install_edge_custom_type.h"
#include "install_vertex_custom_type.h"
#include "is_read_graphviz_correct.h"
#include "is_regular_file.h"
#include "my_edge.h"
#include "my_vertex.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t, my_vertex
  >,
  boost::property<
    boost::edge_custom_type_t, my_edge
  >
>
load_undirected_custom_edges_and_vertices_graph_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  assert(is_read_graphviz_correct<my_edge>());
  assert(is_read_graphviz_correct<my_vertex>());
  std::ifstream f(dot_filename.c_str());
  auto g =
      create_empty_undirected_custom_edges_and_vertices_graph
      ();
  boost::dynamic_properties p; //_do_ default construct
  p.property("node_id", get(boost::vertex_custom_type, g)
      );
  p.property("label", get(boost::vertex_custom_type, g));
  p.property("edge_id", get(boost::edge_custom_type, g));
  p.property("label", get(boost::edge_custom_type, g));
  boost::read_graphviz(f,g,p);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created. Next to this, a boost::dynamic_properties is created with its default constructor, after which we direct the boost::dynamic_properties to find a 'node_id' and 'label' in the vertex name map, 'edge_id' and 'label to the edge name map. From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 156 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

Algorithm 156 Demonstration of the 'load_undirected_custom_edges_and_vertices_graph_from_dot' function

```
#include "create_custom_edges_and_vertices_k3_graph.h"
#include "
    load_undirected_custom_edges_and_vertices_graph_from_dot
    .h"
#include "save_custom_edges_and_vertices_graph_to_dot.h"
#include "get_vertex_my_vertexes.h"

void
    load_undirected_custom_edges_and_vertices_graph_from_dot_demo
    () noexcept
{
  using boost::num_edges;
  using boost::num_vertices;

  const auto g
    = create_custom_edges_and_vertices_k3_graph();
  const std::string filename{
    "create_custom_edges_and_vertices_k3_graph.dot"
  };
  save_custom_edges_and_vertices_graph_to_dot(g, filename
      );
  const auto h
    =
        load_undirected_custom_edges_and_vertices_graph_from_dot
        (filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_vertex_my_vertexes(g) ==
      get_vertex_my_vertexes(h));
}
```

This demonstration shows how K_2 with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 112), saved and then loaded. The loaded graph is checked to be a graph similar to the original, with the same vertex my_vertex instances (using the 'get_vertex_my_vertexes' function) and with the same edge my_edge instances (using the 'get_edge_my_edges' function).

12 Building graphs with a graph name

12.1 Create an empty directed graph with a graph name property

Algorithm 157 shows the function to create an empty directed graph with a graph name.

Algorithm 157 Creating an empty directed graph with a graph name

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::no_property,
  boost::no_property,
  boost::property<
    boost::graph_name_t, std::string
  >
>
create_empty_directed_graph_with_graph_name() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    boost::no_property,
    boost::no_property,
    boost::property<
      boost::graph_name_t, std::string
    >
  >();
}
```

Algorithm 158 demonstrates the 'create_empty_directed_graph_with_graph_name' function.

Algorithm 158 Demonstration of 'create_empty_directed_graph_with_graph_name'

```
#include <cassert>

#include "create_empty_directed_graph_with_graph_name.h"



void create_empty_directed_graph_with_graph_name_demo()
    noexcept
{
  auto g = create_empty_directed_graph_with_graph_name();
  assert(boost::num_edges(g) == 0);
  assert(boost::num_vertices(g) == 0);
}
```

12.2 Create an empty undirected graph with a graph name property

Algorithm 159 shows the function to create an empty undirected graph with a graph name.

Algorithm 159 Creating an empty undirected graph with a graph name

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::no_property,
  boost::no_property,
  boost::property<
    boost::graph_name_t,std::string
  >
>
create_empty_undirected_graph_with_graph_name() noexcept
{
  return boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::no_property,
    boost::no_property,
    boost::property<
      boost::graph_name_t,std::string
    >
  >();
}
```

Algorithm 160 demonstrates the 'create_empty_undirected_graph_with_graph_name' function.

Algorithm 160 Demonstration of 'create_empty_undirected_graph_with_graph_name'

```
#include <cassert>

#include "create_empty_undirected_graph_with_graph_name.h
    "



void create_empty_undirected_graph_with_graph_name_demo()
    noexcept
{
  auto g = create_empty_undirected_graph_with_graph_name
      ();
  assert(boost::num_edges(g) == 0);
  assert(boost::num_vertices(g) == 0);
}
```

12.3 Create a directed graph with a graph name property

12.3.1 Graph

See figure 3.

12.3.2 Function to create such a graph

Algorithm 161 shows the function to create an empty directed graph with a graph name.

Algorithm 161 Creating a two-state Markov chain with a graph name

```
#include <cassert>
#include <boost/graph/adjacency_list.hpp>
#include "create_empty_directed_graph_with_graph_name.h"
#include "set_graph_name.h"

///Create a two-state Markov chain with a graph name
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::no_property,
  boost::no_property,
  boost::property<boost::graph_name_t,std::string>
>
create_markov_chain_with_graph_name() noexcept
{
  auto g = create_empty_directed_graph_with_graph_name();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
  assert(aer_aa.second);
  const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
  assert(aer_ab.second);
  const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
  assert(aer_ba.second);
  const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
  assert(aer_bb.second);

  set_graph_name("Two-state Markov chain", g);
  return g;
}
```

12.3.3 Creating such a graph

Algorithm 162 demonstrates the 'create_markov_chain_with_graph_name' function.

Algorithm 162 Demonstration of 'create_markov_chain_with_graph_name'

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

#include "create_markov_chain_with_graph_name.h"
#include "get_graph_name.h"

void create_markov_chain_with_graph_name_demo() noexcept
{
  const auto g = create_markov_chain_with_graph_name();
  assert(boost::num_vertices(g) == 2);
  assert(boost::num_edges(g) == 4);
  assert(get_graph_name(g) == "Two-state Markov chain");
}
```

12.3.4 The .dot file produced

Algorithm 163 .dot file created from the 'create_markov_chain_with_graph_name' function (algorithm 161), converted from graph to .dot file using algorithm 29

```
digraph G {
name="Two-state Markov chain";
0;
1;
0->0 ;
0->1 ;
1->0 ;
1->1 ;
}
```

12.3.5 The .svg file produced

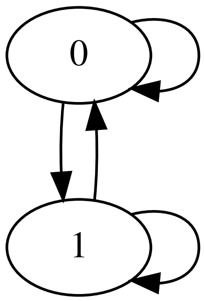

Figure 24: .svg file created from the 'create_markov_chain_with_graph_name' function (algorithm 161) its .dot file, converted from .dot file to .svg using algorithm 176

12.4 Create an undirected graph with a graph name property

12.4.1 Graph

See figure 5.

12.4.2 Function to create such a graph

Algorithm 164 shows the function to create K2 graph with a graph name.

Algorithm 164 Creating a K2 graph with a graph name

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

///Create K2 with a graph name
boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::no_property,
  boost::no_property,
  boost::property<boost::graph_name_t,std::string>
>
create_k2_graph_with_graph_name() noexcept
{
  auto g = create_empty_undirected_graph_with_graph_name
      ();
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto aer = boost::add_edge(vd_a, vd_b, g);
  assert(aer.second);

  get_property( //_not_ boost::get_property
    g,boost::graph_name
  ) = "K2";

  return g;
}
```

12.4.3 Creating such a graph

Algorithm 165 demonstrates the 'create_k2_graph_with_graph_name' function.

Algorithm 165 Demonstration of 'create_k2_graph_with_graph_name'

```
#include <cassert>

#include "create_k2_graph_with_graph_name.h"
#include "get_graph_name.h"

void create_k2_graph_with_graph_name_demo() noexcept
{
  const auto g = create_k2_graph_with_graph_name();
  assert(boost::num_vertices(g) == 2);
  assert(boost::num_edges(g) == 1);
  assert(get_graph_name(g) == "K2");
}
```

12.4.4 The .dot file produced

Algorithm 166 .dot file created from the 'create_k2_graph_with_graph_name' function (algorithm 164), converted from graph to .dot file using algorithm 29

```
graph G {
name="K2";
0;
1;
0--1 ;
}
```

12.4.5 The .svg file produced

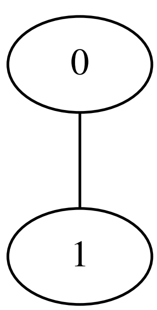

Figure 25: .svg file created from the 'create_k2_graph_with_graph_name' function (algorithm 164) its .dot file, converted from .dot file to .svg using algorithm 176

13 Working with graphs with a graph name

13.1 Set a graph its name property

Algorithm 167 Set a graph its name

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

template <typename graph>
void set_graph_name(
  const std::string& name,
  graph& g
) noexcept
{
  get_property( //_not_ boost::get_property
    g, boost::graph_name
  ) = name;
}
```

Algorithm 168 demonstrates the 'set_graph_name' function.

Algorithm 168 Demonstration of 'set_graph_name'

```
#include <cassert>

#include "create_empty_directed_graph_with_graph_name.h"
#include "get_graph_name.h"
#include "set_graph_name.h"

void set_graph_name_demo() noexcept
{
  auto g = create_empty_directed_graph_with_graph_name();
  const std::string name{"Dex"};
  set_graph_name(name, g);
  assert(get_graph_name(g) == name);
}
```

13.2 Get a graph its name property

Algorithm 169 Get a graph its name

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

template <typename graph>
std::string get_graph_name(
  const graph& g
) noexcept
{
  return
    get_property( //_not_ boost::get_property
      g, boost::graph_name
    );
}
```

Algorithm 170 demonstrates the 'get_graph_name' function.

Algorithm 170 Demonstration of 'get_graph_name'

```
#include <cassert>

#include "create_empty_directed_graph_with_graph_name.h"
#include "get_graph_name.h"
#include "set_graph_name.h"

void get_graph_name_demo() noexcept
{
  auto g = create_empty_directed_graph_with_graph_name();
  const std::string name{"Dex"};
  set_graph_name(name, g);
  assert(get_graph_name(g) == name);
}
```

13.3 Storing a graph with a graph name property as a .dot file

I am unsure if this results in a .dot file that can produce a graph with a graph name, but this is what I came up with.

Algorithm 171 Storing a graph with a graph name as a .dot file

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

#include "get_graph_name.h"

///Save a graph with a graph name to a .dot file
template <typename graph>
void save_graph_with_graph_name_to_dot(
  const graph& g,
  const std::string& filename
)
{
  std::ofstream f(filename);
  boost::write_graphviz(
    f,
    g,
    boost::default_writer(),
    boost::default_writer(),
    //Unsure if this results in a graph
    //that can be loaded correctly
    //from a .dot file
    [g](std::ostream& os) {
      os << "name=\""
        << get_graph_name(g)
        << "\";\n";
    }
  );
}
```

13.4 Loading a directed graph with a graph name property from a .dot file

This will result in a directed graph without a name. Please email me if you know how to do this correctly.

Algorithm 172 Loading a directed graph with a graph name from a .dot file

```
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include <boost/graph/graphviz.hpp>
#include <boost/graph/properties.hpp>
#include "create_empty_directed_graph_with_graph_name.h"
#include "is_read_graphviz_correct.h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::no_property,
  boost::no_property,
  boost::property<
    boost::graph_name_t, std::string
  >
>
load_directed_graph_with_graph_name_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_directed_graph_with_graph_name();

  #ifdef TODO_KNOW_HOW_TO_LOAD_A_GRAPH_ITS_NAME
  boost::dynamic_properties p; //_do_ default construct
  p.property("name",get_property(g,boost::graph_name));
     //AFAIK, this should work
  #else
  boost::dynamic_properties p(
    boost::ignore_other_properties
  );
  #endif
  boost::read_graphviz(f,g,p);
  return g;
}
```

Note the part that I removed using #ifdef: I read that that is a valid approach, according to the Boost.Graph documentation (see `http://www.boost.org/doc/libs/1_60_0/libs/graph/doc/read_graphviz.html`), but it failed to compile.

13.5 Loading an undirected graph with a graph name property from a .dot file

This will result in an undirected graph without a name. Please email me if you know how to do this correctly.

Algorithm 173 Loading an undirected graph with a graph name from a .dot file

```
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include <boost/graph/graphviz.hpp>
#include <boost/graph/properties.hpp>
#include "create_empty_undirected_graph_with_graph_name.h
  "
#include "is_read_graphviz_correct.h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::no_property,
  boost::no_property,
  boost::property<
    boost::graph_name_t, std::string
  >
>
load_undirected_graph_with_graph_name_from_dot(
  const std::string& dot_filename
)
{
  assert(is_regular_file(dot_filename));
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_undirected_graph_with_graph_name
    ();

  #ifdef TODO_KNOW_HOW_TO_LOAD_A_GRAPH_ITS_NAME
  boost::dynamic_properties p; //_do_ default construct
  p.property("name",get_property(g,boost::graph_name));
    //AFAIK, this should work
  #else
  boost::dynamic_properties p(
    boost::ignore_other_properties
  );
  #endif
  boost::read_graphviz(f,g,p);
  return g;
}
```

Note the part that I removed using #ifdef: I read that that is a valid approach, according to the Boost.Graph documentation (see `http://www.boost.org/doc/libs/1_60_0/libs/graph/doc/read_graphviz.html`), but it failed to compile.

14 Building graphs with custom graph property

I will write this chapter if and only if I can save and load a graph with a graph name (as in chapter 12).

15 Working with graphs with a custom graph property

I will write this chapter if and only if I can save and load a graph with a graph name (as in chapter 12).

16 Other graph functions

Some functions that did not fit in

16.1 Check if a custom class can be used with boost::read_graphviz

For a custom class to be saved to a .dot file and then loaded from it, it needs to have these properties:

- When the class is sent to a stream, and a copy is created from that stream, that copy must be identical
- When the class is sent to a stream, and then converted to a std::string, there must not be spaces in the std::string. Note: it may be that surrounding the string in quotes also suffices

To checks if a custom class can be used with boost::read_graphviz, see the function 'is_read_graphviz_correct' (algorithm 174):

Algorithm 174 Check if a custom class can be used with boost::graph_viz

```
#include <sstream>
#include <string>

///Determines if a class can be used with boost::
    read_graphviz
template <class any_class>
bool is_read_graphviz_correct(const any_class& in =
    any_class()) noexcept
{
  //any_class must be streamable, that is,
  //when sent to stream, then read from stream,
  //must result in an identical object
  {
    //any_class in;
    std::stringstream s;
    s << in;
    any_class out;
    s >> out;
    if (in != out) return false;
  }
  //When converting any_class to a std::string,
  //there may not be spaces
  {
    //any_class in;
    std::stringstream s;
    s << in;
    const std::string t{s.str()};
    if (t.find(' ') != std::string::npos) return false;
  }
  return true;
}
```

17 Misc functions

These are some function I needed for creating this tutorial. Although they are not important for working with graphs, I used these heavily. These functions may be compiler-dependent, platform-dependent and/or there may be superior alternatives. I just add them for completeness.

17.1 Getting a data type as a std::string

This function will only work under GCC.

Algorithm 175 Getting a data type its name as a std::string

```
#include <cstdlib>
#include <string>
#include <typeinfo>
#include <cxxabi.h>

//From http://stackoverflow.com/questions/1055452/c-get-
    name-of-type-in-template
//Thanks to m-dudley ( http://stackoverflow.com/users
    /111327/m-dudley )
template<typename T>
std::string get_type_name() noexcept
{
  std::string tname = typeid(T).name();
  int status = -1;
  char * const demangled_name{
    abi::__cxa_demangle(
      tname.c_str(), NULL, NULL, &status
    )
  };
  if(status == 0) {
    tname = demangled_name;
    std::free(demangled_name);
  }
  return tname;
}
```

17.2 Convert a .dot to .svg

All illustrations in this tutorial are created by converting .dot to a .svg ('Scalable Vector Graphic') file. This function assumes the program 'dot' is installed, which is part of Graphviz.

Algorithm 176 Convert a .dot file to a .svg

```
#include <cassert>
#include <string>
#include <sstream>

#include "has_dot.h"
#include "is_valid_dot_file.h"
#include "is_regular_file.h"

void convert_dot_to_svg(
  const std::string& dot_filename,
  const std::string& svg_filename
)
{
  assert(has_dot());
  assert(is_valid_dot_file(dot_filename));
  std::stringstream cmd;
  cmd << "dot -Tsvg " << dot_filename << " -o " <<
      svg_filename;
  std::system(cmd.str().c_str());
  assert(is_regular_file(svg_filename));
}
```

'convert_dot_to_svg' makes a system call to the prgram 'dot' to convert the .dot file to an .svg file.

17.3 Check if a file exists

Not the most smart way perhaps, but it does only use the STL.

Algorithm 177 Check if a file exists

```
#include <fstream>

///Determines if a filename is a regular file
///From http://www.richelbilderbeek.nl/CppIsRegularFile.
    htm
bool is_regular_file(const std::string& filename)
    noexcept
{
  std::fstream f;
  f.open(filename.c_str(),std::ios::in);
  return f.is_open();
}
```

18 Errors

Some common errors.

18.1 Formed reference to void

This compile-time error occurs when you create a graph without a certain property, then subsequently reading that property, as in algorithm 178:

Algorithm 178 Creating the error 'formed reference to void'

```
#include "create_k2_graph.h"
#include "get_vertex_names.h"

void formed_reference_to_void() noexcept
{
  get_vertex_names(create_k2_graph());
}
```

In algorithm 178 a graph is created with vertices of no properties. Then the names of these vertices, which do not exists, are tried to be read. If you want to read the names of the vertices, supply a graph that has this property.

18.2 No matching function for call to 'clear_out_edges'

This compile-time error occurs when you want to clear the outward edges from a vertex in an undirected graph.

Algorithm 179 Creating the error 'no matching function for call to clear_out_edges'

```
#include "create_k2_graph.h"

void no_matching_function_for_call_to_clear_out_edges()
    noexcept
{
  auto g = create_k2_graph();
  const auto vd = *vertices(g).first; //_not_ boost::
      vertices!
  boost::clear_in_edges(vd,g);
}
```

In algorithm 179 an undirected graph is created, a vertex descriptor is obtained, then its out edges are tried to be cleared. Either use a directed graph (which has out edges), or use the 'boost::clear_vertex' function instead.

18.3 No matching function for call to 'clear_in_edges'

See chapter 18.2.

18.4 Undefined reference to boost::detail::graph::read_graphviz_new

You will have to link against the Boost.Graph and Boost.Regex libraries. In Qt Creator, this is achieved by adding these lines to your Qt Creator project file:

```
LIBS += -lboost_graph -lboost_regex
```

18.5 Property not found: node_id

When loading a graph from file (as in chapter 3.3) you will be using boost::read_graphviz. boost::read_graphviz needs a third argument, of type boost::dynamic_properties. When a graph does not have properties, do not use a default constructed version, but initializate with 'boost::ignore_other_properties' as a constructor argument instead. Algorithm 180 shows how to trigger this run-time error.

Algorithm 180 Creating the error 'Property not found: node_id'

```
#include <cassert>
#include <fstream>
#include "is_regular_file.h"
#include "create_empty_undirected_graph.h"
#include "create_k2_graph.h"
#include "save_graph_to_dot.h"

void property_not_found_node_id() noexcept
{
  const std::string dot_filename{"
     property_not_found_node_id.dot"};
  //Create a file
  {
    const auto g = create_k2_graph();
    save_graph_to_dot(g, dot_filename);
    assert(is_regular_file(dot_filename));
  }

  //Try to read that file
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_undirected_graph();

  //Line below should have been
  //  boost::dynamic_properties p(boost::
     ignore_other_properties);
  boost::dynamic_properties p; //Error

  try {
    boost::read_graphviz(f,g,p);
  }
  catch (std::exception&) {
    return; //Should get here
  }
  assert(!"Should␣not␣get␣here");
}
```

19 Appendix

19.1 List of all edge, graph and vertex properties

The following list is obtained from the file 'boost/graph/properties.hpp'.

Edge	Graph	Vertex
edge_all	graph_all	vertex_all
edge_bundle	graph_bundle	vertex_bundle
edge_capacity	graph_name	vertex_centrality
edge_centrality	graph_visitor	vertex_color
edge_color		vertex_current_degree
edge_discover_time		vertex_degree
edge_finished		vertex_discover_time
edge_flow		vertex_distance
edge_global		vertex_distance2
edge_index		vertex_finish_time
edge_local		vertex_global
edge_local_index		vertex_in_degree
edge_name		vertex_index
edge_owner		vertex_index1
edge_residual_capacity		vertex_index2
edge_reverse		vertex_local
edge_underlying		vertex_local_index
edge_update		vertex_lowpoint
edge_weight		vertex_name
edge_weight2		vertex_out_degree
		vertex_owner
		vertex_potential
		vertex_predecessor
		vertex_priority
		vertex_rank
		vertex_root
		vertex_underlying
		vertex_update

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