A well-connected C++11 Boost.Graph tutorial

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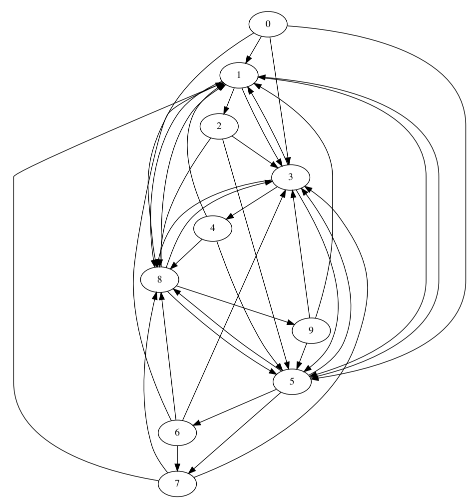

Contents

1 Introduction

This is 'A well-connected C++11 Boost.Graph tutorial', version 1.9.

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. It is about basic graph manipulation, not the more advanced graph algorithms. An analogy with std::vector: it teaches the std::vector member functions, but not the algorithms that work on.

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++11 code. I chose to use C++11 because (1) C++14 was not installable on all my computers (2) the step to C++14 is small. 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`.

1.3 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.

It is important to add comments to code. In this tutorial, however, I have chosen not to put comments in code, as I already describe the function in the tutorial its text. This way, it prevents me from saying the same things twice.

It is good to write generic code. In this tutorial, however, I have chosen my functions to have no templated arguments for conciseness and readability. For example, a vertex name is std::string, the type for if a vertex is selected is a boolean, and the custom vertex type is of type 'my_custom_vertex'. I think these choises are reasonable and that the resulting increase in readability is worth it.

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 21.1).

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.

I try to use STL algorithms wherever I can. Also you should prefer algorithm calls over hand-written for-loops ([9] chapter 18.12.1, [7] item 43). Sometimes using these algorithms becomes a burden on the lines of code. This is because in C++11, a lambda function argument (use by the algorithm) must have its data type specified. It may take multiple lines of 'using' statements being able to do so. In C++14 one can use 'auto' there as well. So, only if it shortens the number of lines significantly, I use raw for-loops, even though you shouldn't.

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. On the other hand, STL and Boost functions like 'std::do_something' and 'boost::do_something' can be found as such in the index.

1.5 License

This tutorial is licensed under Creative Commons license 4.0. All C++ code is licensed under GPL 3.0.

Figure 1: Creative Commons license 4.0

1.6 Feedback

This tutorial is not intended to be perfect yet. For that, I need help and feedback from the community. All referenced feedback is welcome, as well as any constructive 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. Next to this, there are some sections that need to be coded or have its code improved.

1.7 Acknowledgements

These are users that improved this tutorial and/or the code behind this tutorial, in chronological order:

- m-dudley, `http://stackoverflow.com/users/111327/m-dudley`
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- sehe, `http://stackoverflow.com/users/85371/sehe`
- cv_and_me, `http://stackoverflow.com/users/2417774/cv-and-he`

1.8 Outline

The chapters of this tutorial are also like a well-connected graph (as shown in figure 2). 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.

The distinction between the chapter is in the type of edges and vertices. They can have:

- no properties: see chapter 2
- have a name: see chapter 4
- have a bundled property: see chapter 8
- have a custom property: see chapter 12

[1] There was even copy-pasting involved!

The differences between graphs with bundled and custom porties are shown in table 1:

	Bundled	Custom
Meaning	Edges/vertices are of your type	Edges/vertices have an additional custom property
Interface	Directly	Via property map
Class members	Must be public	Can be private
File I/O mechanism	Via public class members	Via stream operators
File I/O success	Fails, please help!	Works, with encoding/decoding

Table 1: Difference between bundled and custom properties

Pivotal chapters are chapters like 'Finding the first vertex with ...', as this opens up the door to finding a vertex and manipulating it.

All chapters have a rather similar structure in themselves, as depicted in figure 3.

There are also some bonus chapters, that I have labeled with a ▶. These chapters are added I needed these functions myself and adding them would not hurt. Just feel free to skip them, as there will be less theory explained.

2 Building graphs 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 4. 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 5.

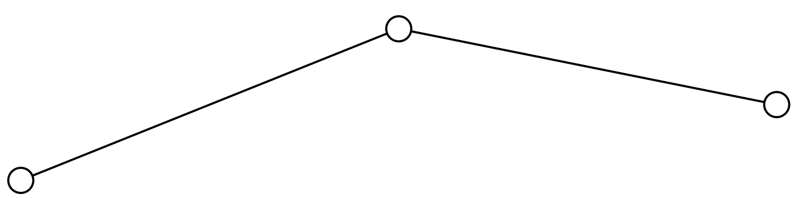

Figure 4: Example of an undirected graph

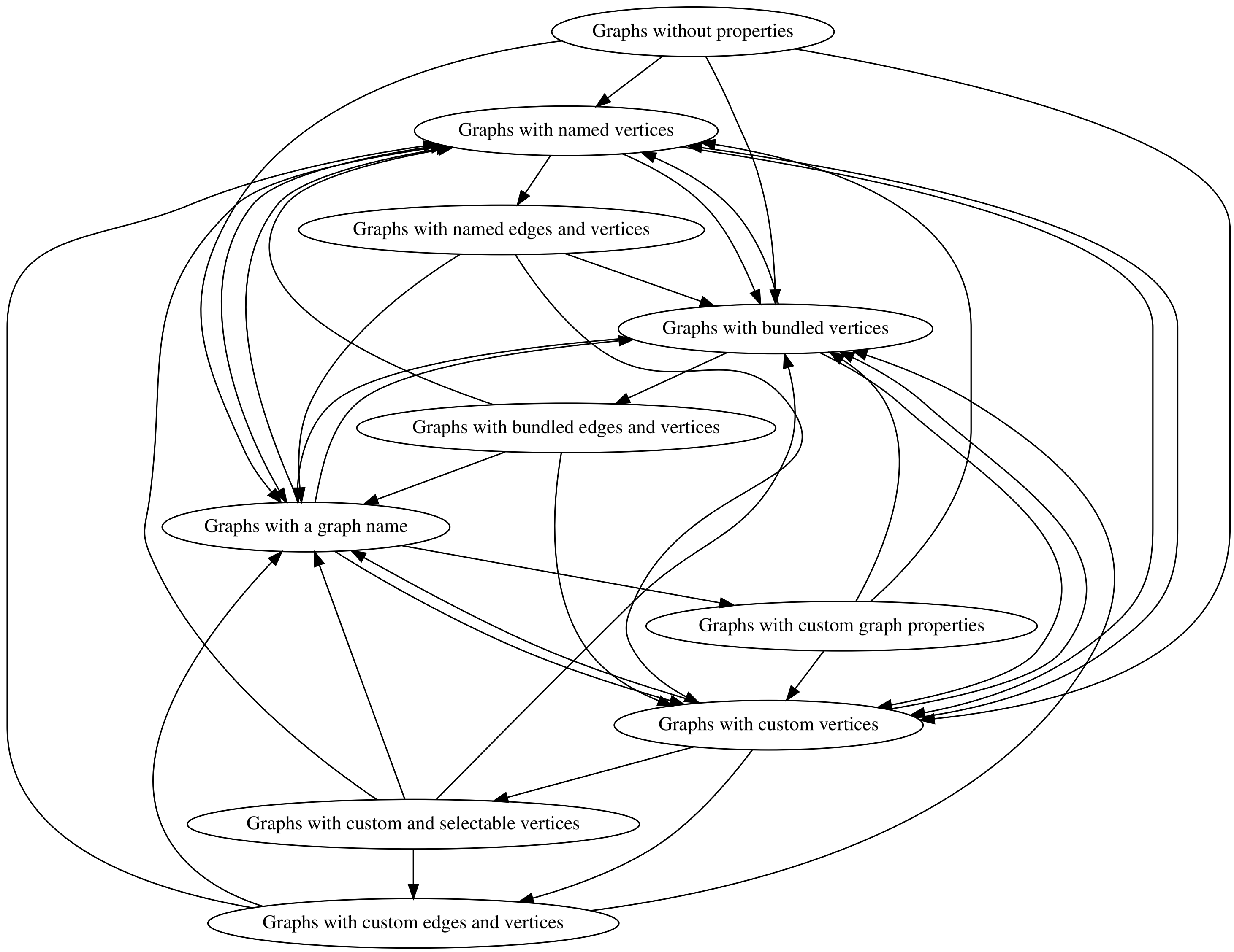

Figure 2: The relations between chapters

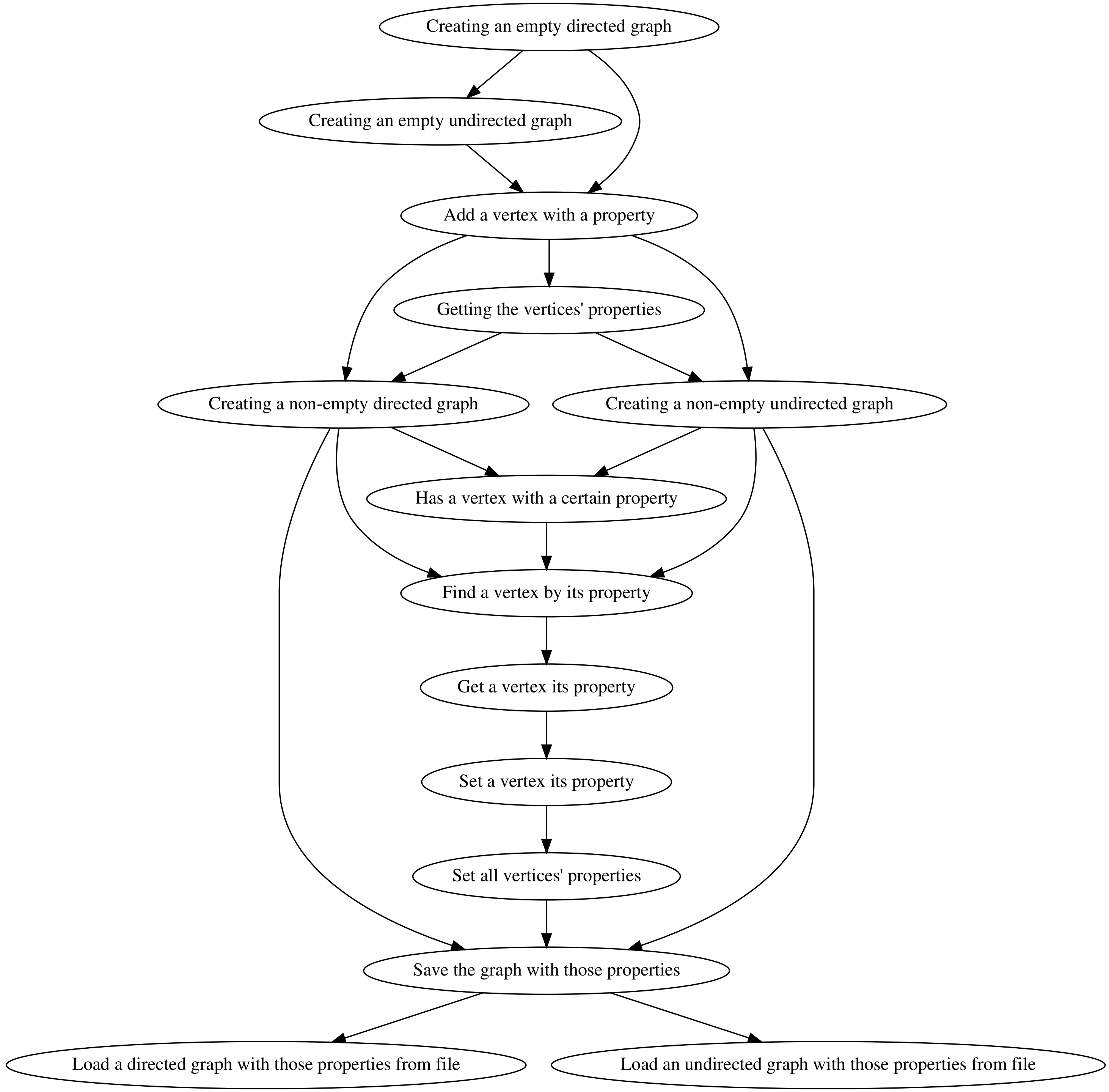

Figure 3: The relations between sub-chapters

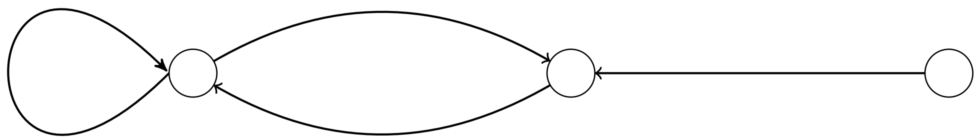

Figure 5: Example of a directed graph

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

After this chapter you may want to:

- Building graphs with named vertices: see chapter 4
- Building graphs with bundled vertices: see chapter 8
- Building graphs with custom vertices: see chapter 12
- Building graphs with a graph name: see chapter 18

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>

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

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).

[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

- a function body: all the function body does is implicitly create its return type by using the '{}'. An alternative syntax would be 'return boost::adjacency_list<>()', which is needlessly longer

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 out 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. The boost::adjacency_list is the most commonly used graph type, the other is the boost::adjacency_matrix. We do not do anything with it yet, but still, you've just created a graph, in which:

- The out edges and 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

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!

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

[5] Standard Template Library, the standard library

Algorith 3 shows how to create an undirected graph.

Algorithm 3 Creating an empty undirected graph

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

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

This algorith differs from the 'create_empty_directed_graph' function (algoritm 1) in that there are three template arguments that need to be specified in the creation of the boost::adjancency_list:

- the first 'boost::vecS': select (that is what the 'S' means) that out edges are stored in a std::vector. This is the default way.
- the second 'boost::vecS': select that the graph vertices are stored in a std::vector. This is the default way.
- 'boost::undirectedS': select that the graph is undirected. This is all we needed to change. By default, this argument is boost::directed

Algorithm 4 demonstrates the 'create_empty_undirected_graph' function.

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 and vertices are stored in a std::vector
- The graph is undirected

- Vertices, edges and graph have no properties
- Edges are stored in a std::list

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>

template <typename graph>
int get_n_vertices(const graph& g) noexcept
{
  const int n{
    static_cast<int>(boost::num_vertices(g))
  };
  assert(static_cast<unsigned long>(n)
    == boost::num_vertices(g)
  );
  return n;
}
```

The function 'get_n_vertices' takes the result of boost::num_vertices, converts it to int and checks if there was conversion error. We do so, as one should prefer using signed data types over unsigned ones in an interface ([4] chapter 9.2.2). To do so, in the function body its first stament, the unsigned long produced by boost::num_vertices get converted to an int using a static_cast. Using an unsigned integer over a (signed) integer 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 checks if the conversion back to unsigned long re-creates the original value, to check if no information has been lost. If information is lost, 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:

Algorithm 7 Count the number of edges

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

template <typename graph>
int get_n_edges(const graph& g) noexcept
{
  const int n{
    static_cast<int>(boost::num_edges(g))
  };
  assert(static_cast<unsigned long>(n)
    == boost::num_edges(g)
  );
  return n;
}
```

This code is similar to the 'get_n_vertices' function (algorithm 5, see rationale there) except 'boost::num_edges' is used, instead of 'boost::num_vertices', which also returns an unsigned long.

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 Adding 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 <type_traits>
#include <boost/graph/adjacency_list.hpp>

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
add_vertex(graph& g) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );
  const auto vd = boost::add_vertex(g);
  return vd;
}
```

The static_assert at the top of the function checks during compiling if the function is called with a non-const graph. One can freely omit this static_assert: you will get a compiler error anyways, be it a less helpful one.

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. To allow for this already, 'add_vertex' also returns a vertex descriptor.

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 12.6)

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

2.7 Get the vertex iterators

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

'vertices' (not '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>

template <typename graph>
std::pair<
  typename graph::vertex_iterator,
  typename graph::vertex_iterator
>
get_vertex_iterators(const graph& g) noexcept
{
  return vertices(g);
}
```

This is a somewhat trivial function, as it forwards the function call to 'vertices' (not 'boost::vertices').

These vertex iterators can be dereferenced to obtain the vertex descriptors. Note that 'get_vertex_iterators' 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_vertex_iterators'

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

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

  const auto h = create_empty_directed_graph();
  const auto vip_h = get_vertex_iterators(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/adjacency_list.hpp>
#include <boost/graph/graph_traits.hpp>

template <typename graph>
std::vector<
  typename boost::graph_traits<graph>::vertex_descriptor
>
get_vertex_descriptors(const graph& g) noexcept
{
  using vd = typename graph::vertex_descriptor;

  std::vector<vd> vds(boost::num_vertices(g));
  const auto vis = vertices(g);
  std::copy(vis.first, vis.second, std::begin(vds));
  return vds;
}
```

This is the first more complex piece of code. In the first lines, some 'using' statements allow for shorter type names[6].

The std::vector to serve as a return value is created at the needed size, which is the number of vertices.

The function 'vertices' (not boost::vertices!) returns a vertex iterator pair. These iterators are used by std::copy to iterator over. std::copy is an STL algorithm to copy a half-open range. Prefer algorithm calls over hand-written for-loops ([9] chapter 18.12.1, [7] item 43).

In this case, we copy all vertex descriptors in the range produced by 'vertices' to the std::vector.

This function will not be used in practice: one iterates over the vertices directly instead, saving the cost of creating a std::vector. This function is only shown as an illustration.

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:

[6] which may be necessary just to create a tutorial with code snippets that are readable

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

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

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
add_edge(graph& g) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );
  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 aer.first;
}
```

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, after which the number of edges and vertices is checked.

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_vertices(g) == 2);
  assert(boost::num_edges(g) == 1);

  auto h = create_empty_directed_graph();
  add_edge(h);
  assert(boost::num_vertices(h) == 2);
  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, which indicates insertion success.

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

2.11 Getting the edge iterators

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>

template <typename graph>
std::pair<
  typename graph::edge_iterator,
  typename graph::edge_iterator
>
get_edge_iterators(const graph& g) noexcept
{
  return edges(g);
}
```

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_edge_iterators' 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_edge_iterators'

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

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

  auto h = create_empty_directed_graph();
  const auto eip_h = get_edge_iterators(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 obtaining all vertex descriptors (algorithm 13), as shown in algorithm 19:

Algorithm 19 Get all edge descriptors of a graph

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

template <typename 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> v(boost::num_edges(g));
  const auto eip = edges(g);
  std::copy(eip.first, eip.second, std::begin(v));
  return v;
}
```

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 non-empty graph!

2.14.1 Graph

This directed graph is a two-state Markov chain, with two vertices and four edges, as depicted in figure 6:

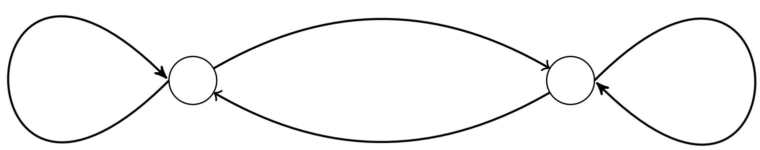

Figure 6: The two-state Markov chain

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 6

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

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;
}
```

Instead of typing the complete type, we call the 'create_empty_directed_graph' function, and let auto figure out the type. 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 "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 the 'save_graph_to_dot' function (algorithm 48). The .dot file 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 48

```
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 7:

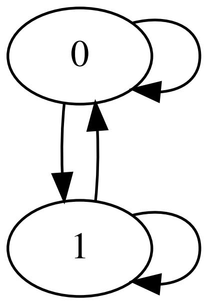

Figure 7: .svg file created from the 'create_markov_chain' function (algorithm 21) its .dot file and converted from .dot file to .svg using algorithm 281

This figure shows that the graph in directed, as the edges have arrow heads. The vertices display the node index, which is the default behavior.

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

Finally, we are going to create an undirected non-empty 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 8.

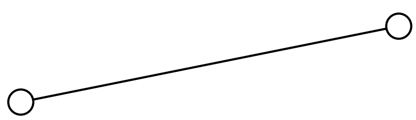

Figure 8: K_2: a fully connected undirected graph with two vertices

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 8

```
#include "create_empty_undirected_graph.h"

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). Instead of typing the graph its type, we call the 'create_empty_undirected_graph' function and let auto figure it out. 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 48

```
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 9:

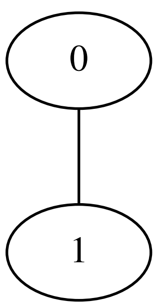

Figure 9: .svg file created from the 'create_k2_graph' function (algorithm 24) its .dot file, converted from .dot file to .svg using algorithm 281

Also this figure shows that the graph in undirected, otherwise the edge would have one or two arrow heads. The vertices display the node index, which is the default behavior.

2.16 ▶ Creating K_3, a fully connected undirected graph with three vertices

This is an extension of the previous chapter

2.16.1 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 10.

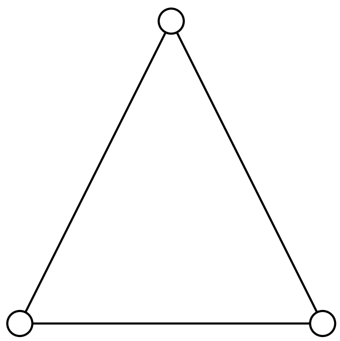

Figure 10: K_3: a fully connected graph with three edges and vertices

2.16.2 Function to create such a graph

To create K_3, the following code can be used:

Algorithm 27 Creating K_3 as depicted in figure 10

```
#include <cassert>
#include "create_empty_undirected_graph.h"
#include "create_k3_graph.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS
>
create_k3_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 vd_c = boost::add_vertex(g);
  const auto aer_a = boost::add_edge(vd_a, vd_b, g);
  assert(aer_a.second);
  const auto aer_b = boost::add_edge(vd_b, vd_c, g);
  assert(aer_b.second);
  const auto aer_c = boost::add_edge(vd_c, vd_a, g);
  assert(aer_c.second);
  return g;
}
```

2.16.3 Creating such a graph

Algorithm 28 demonstrates how to 'create_k2_graph' and checks if it has the correct amount of edges and vertices:

Algorithm 28 Demonstration of 'create_k3_graph'

```
#include "create_k3_graph.h"

void create_k3_graph_demo() noexcept
{
  const auto g = create_k3_graph();
  assert(boost::num_edges(g) == 3);
  assert(boost::num_vertices(g) == 3);
}
```

2.16.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 29:

Algorithm 29 .dot file created from the 'create_k3_graph' function (algorithm 27), converted from graph to .dot file using algorithm 48

```
graph G {
0;
1;
2;
0--1 ;
1--2 ;
2--0 ;
}
```

2.16.5 The .svg file produced

Continuing to running a bit ahead, this .dot file can be converted to the .svg as shown in figure 11:

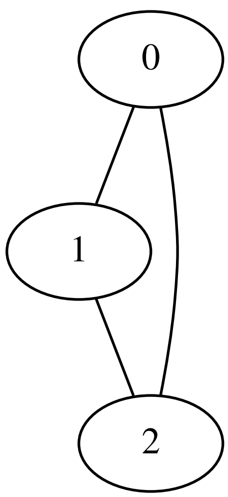

Figure 11: .svg file created from the 'create_k3_graph' function (algorithm 27) its .dot file, converted from .dot file to .svg using algorithm 281

2.17 ▶ Creating a path graph

A path graph is a linear graph without any branches

2.17.1 Graph

Here I show a path graph with four vertices (see figure 12):

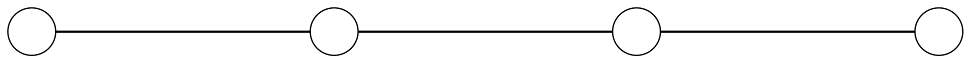

Figure 12: A path graph with four vertices

2.17.2 Function to create such a graph

To create a path graph, the following code can be used:

Algorithm 30 Creating a path graph as depicted in figure 12

```
#include "create_empty_undirected_graph.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS
>
create_path_graph(const int n_vertices) noexcept
{
  assert(n_vertices >= 2);
  auto g = create_empty_undirected_graph();

  auto vd_1 = boost::add_vertex(g);
  for (int i=1; i!=n_vertices; ++i)
  {
    auto vd_2 = boost::add_vertex(g);
    const auto aer = boost::add_edge(vd_1, vd_2, g);
    assert(aer.second);
    vd_1 = vd_2;
  }
  return g;
}
```

2.17.3 Creating such a graph

Algorithm 31 demonstrates how to 'create_k2_graph' and checks if it has the correct amount of edges and vertices:

Algorithm 31 Demonstration of 'create_path_graph'

```
#include <cassert>
#include "create_path_graph.h"

void create_path_graph_demo() noexcept
{
  const auto g = create_path_graph(4);
  assert(boost::num_edges(g) == 3);
  assert(boost::num_vertices(g) == 4);
}
```

2.17.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 32:

Algorithm 32 .dot file created from the 'create_path_graph' function (algorithm 30), converted from graph to .dot file using algorithm 48

```
graph G {
0;
1;
2;
3;
0--1 ;
1--2 ;
2--3 ;
}
```

2.17.5 The .svg file produced

The .dot file can be converted to the .svg as shown in figure 13:

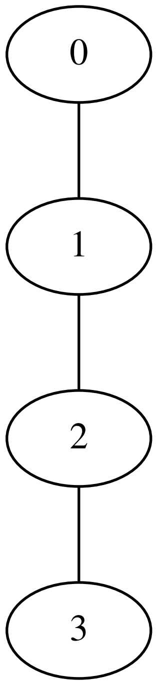

Figure 13: .svg file created from the 'create_path_graph' function (algorithm 30) its .dot file, converted from .dot file to .svg using algorithm 281

2.18 ▶ Creating a Peterson graph

This is an extension of the previous chapter.

2.18.1 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 14.

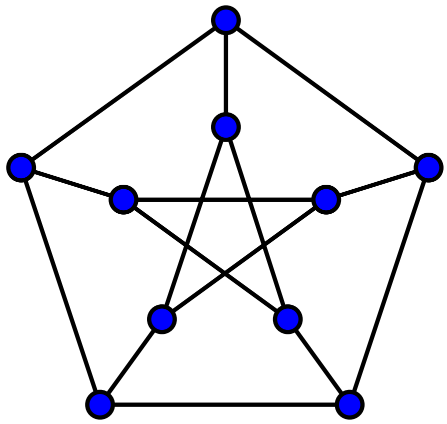

Figure 14: A Petersen graph (from https://en.wikipedia.org/wiki/Petersen_graph)

2.18.2 Function to create such a graph

To create a Petersen graph, the following code can be used:

Algorithm 33 Creating Petersen graph as depicted in figure 14

```
#include <cassert>
#include <vector>
#include "create_empty_undirected_graph.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS
>
create_petersen_graph() noexcept
{
  /*
  using vd = boost::graph_traits<
    boost::adjacency_list<
      boost::vecS,
      boost::vecS,
      boost::undirectedS
    >
  >::vertex_descriptor;
  */
  using vd = decltype(create_empty_undirected_graph())::
     vertex_descriptor;

  auto g = create_empty_undirected_graph();

  std::vector<vd> v; //Outer
  for (int i=0; i!=5; ++i) {
    v.push_back(boost::add_vertex(g));
  }
  std::vector<vd> w; //Inner
  for (int i=0; i!=5; ++i) {
    w.push_back(boost::add_vertex(g));
  }
  //Outer ring
  for (int i=0; i!=5; ++i) {
    const auto aer
      = boost::add_edge(v[i], v[(i + 1) % 5], g);
    assert(aer.second);
  }
  //Spoke
  for (int i=0; i!=5; ++i) {
    const auto aer
      = boost::add_edge(v[i], w[i], g);
    assert(aer.second);
  }
  //Inner pentagram
  for (int i=0; i!=5; ++i) {
    const auto aer
      = boost::add_edge(w[i], w[(i + 2) % 5], g);
    assert(aer.second);
  }
  return g;
}
```

2.18.3 Creating such a graph

Algorithm 34 demonstrates how to use 'create_petersen_graph' and checks if it has the correct amount of edges and vertices:

Algorithm 34 Demonstration of 'create_k3_graph'

```
#include <cassert>
#include "create_petersen_graph.h"

void create_petersen_graph_demo() noexcept
{
  const auto g = create_petersen_graph();
  assert(boost::num_edges(g) == 15);
  assert(boost::num_vertices(g) == 10);
}
```

2.18.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 35:

Algorithm 35 .dot file created from the 'create_petersen_graph' function (algorithm 33), converted from graph to .dot file using algorithm 48

```
graph G {
0;
1;
2;
3;
4;
5;
6;
7;
8;
9;
0--1 ;
1--2 ;
2--3 ;
3--4 ;
4--0 ;
0--5 ;
1--6 ;
2--7 ;
3--8 ;
4--9 ;
5--7 ;
6--8 ;
7--9 ;
8--5 ;
9--6 ;
}
```

2.18.5 The .svg file produced

This .dot file can be converted to the .svg as shown in figure 15:

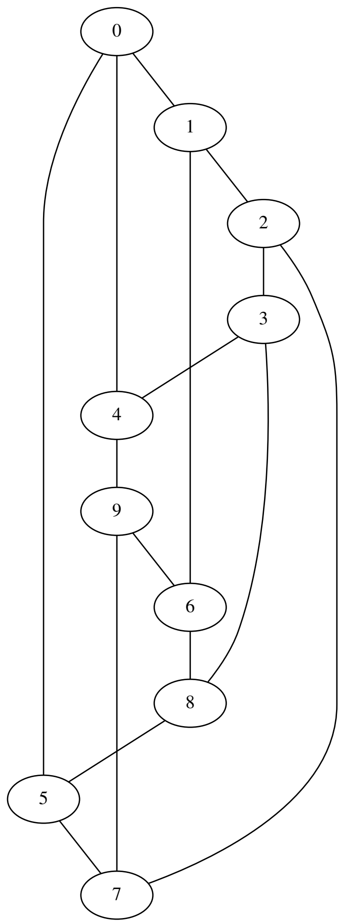

Figure 15: .svg file created from the 'create_petersen_graph' function (algorithm 33) its .dot file, converted from .dot file to .svg using algorithm 281

3 Working on graphs without properties

Now that we can build a graph, there are some things we can do.

- Getting the vertices' out degrees: see chapter 3.1
- Create a direct-neighbour subgraph from a vertex descriptor
- Create all direct-neighbour subgraphs from a graphs
- Saving a graph without properties to .dot file: see chapter 3.7
- Loading an undirected graph without properties from .dot file: see chapter 3.9

- Loading a directed graph without properties from .dot file: see chapter 3.8

3.1 Getting the vertices' out degree

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 'in_degree' (not 'boost::in_edgree')
- out degree: the number of outgoing connections, using 'out_degree' (not 'boost::out_edgree')
- degree: sum of the in degree and out degree, using 'degree' (not 'boost::edgree')

Algorithm 36 shows how to obtain these:

Algorithm 36 Get the vertices' out degrees

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

template <typename graph>
std::vector<int> get_vertex_out_degrees(
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  std::vector<int> v(boost::num_vertices(g));
  const auto vip = vertices(g);
  std::transform(vip.first, vip.second, std::begin(v),
    [g](const vd& d) {
      return out_degree(d,g);
    }
  );
  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 37.

Algorithm 37 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 ▶ Is there an edge between two vertices?

If you have two vertex descriptors, you can check if these are connected by an edge:

Algorithm 38 Check if there exists an edge between two vertices

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

template <typename graph>
bool has_edge_between_vertices(
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd_1,
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd_2,
  const graph& g
) noexcept
{
  return edge(vd_1, vd_2, g).second;
}
```

This code uses the function 'edge' (not boost::edge: it returns a pair consisting of an edge descriptor and a boolean indicating if it is a valid edge descriptor. The boolean will be true if there exists an edge between the two vertices and false if not.

The demo shows that there is an edge between the two vertices of a K_2 graph, but there are no self-loops (edges that original and end at the same vertex).

Algorithm 39 Demonstration of the 'has_edge_between_vertices' function

```
#include <cassert>
#include "create_k2_graph.h"
#include "has_edge_between_vertices.h"

void has_edge_between_vertices_demo() noexcept
{
  const auto g = create_k2_graph();
  const auto vd_1 = *vertices(g).first;
  const auto vd_2 = *(++vertices(g).first);
  assert( has_edge_between_vertices(vd_1, vd_2, g));
  assert(!has_edge_between_vertices(vd_1, vd_1, g));
}
```

3.3 ▶ Get the edge between two vertices

If you have two vertex descriptors, you can use these to find the edge between them.

Algorithm 40 Get the edge between two vertices

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

template <
  typename graph,
  typename vertex_descriptor
>
typename boost::graph_traits<graph>::edge_descriptor
get_edge_between_vertices(
  const vertex_descriptor& vd_from,
  const vertex_descriptor& vd_to,
  const graph& g
) noexcept
{
  assert(has_edge_between_vertices(vd_from, vd_to, g));
  const auto er = edge(vd_from, vd_to, g);
  assert(er.second);
  return er.first;
}
```

This code does assume that there is an edge between the two vertices.

The demo shows how to get the edge between two vertices, deleting it, and checking for success.

Algorithm 41 Demonstration of the 'get_edge_between_vertices' function

```
#include <cassert>
#include "create_k2_graph.h"
#include "get_edge_between_vertices.h"

void get_edge_between_vertices_demo() noexcept
{
  auto g = create_k2_graph();
  const auto vd_1 = *vertices(g).first;
  const auto vd_2 = *(++vertices(g).first);
  assert(has_edge_between_vertices(vd_1, vd_2, g));
  const auto ed = get_edge_between_vertices(vd_1, vd_2, g
    );
  boost::remove_edge(ed, g);
  assert(boost::num_edges(g) == 0);
}
```

3.4 ▶ Create a direct-neighbour subgraph from a vertex descriptor

Suppose you have a vertex of interest its vertex descriptor. Let's say you want to get a subgraph of that vertex and its direct neighbours only. This means that all vertices of that subgraph are adjacent vertices and that the edges go either from focal vertex to its neighbours, or from adjacent vertex to adjacent neighbour.

Here is the 'create_direct_neighbour_subgraph' code:

Algorithm 42 Get the direct-neighbour subgraph from a vertex descriptor

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

template <typename graph, typename vertex_descriptor>
graph create_direct_neighbour_subgraph(
  const vertex_descriptor& vd,
  const graph& g
)
{
  graph h;

  std::map<vertex_descriptor,vertex_descriptor> m;
  {
    const auto vd_h = boost::add_vertex(h);
    m.insert(std::make_pair(vd,vd_h));
  }
  //Copy vertices
  {
    const auto vdsi = boost::adjacent_vertices(vd, g);
    std::transform(vdsi.first, vdsi.second,
      std::inserter(m,std::begin(m)),
      [&h](const vertex_descriptor& d)
      {
        const auto vd_h = boost::add_vertex(h);
        return std::make_pair(d,vd_h);
      }
    );
  }
  //Copy edges
  {
    const auto eip = edges(g);
    const auto j = eip.second;
    for (auto i = eip.first; i!=j; ++i)
    {
      const auto vd_from = source(*i, g);
      const auto vd_to = target(*i, g);
      if (m.find(vd_from) == std::end(m)) continue;
      if (m.find(vd_to) == std::end(m)) continue;
      const auto aer = boost::add_edge(m[vd_from],m[vd_to
        ], h);
      assert(aer.second);
    }
  }
  return h;
}
```

This demonstration code shows that the direct-neighbour graph of each vertex of a K2 graphs is ... a K2 graph!

Algorithm 43 Demo of the 'create_direct_neighbour_subgraph' function

```
#include "create_direct_neighbour_subgraph.h"
#include "create_k2_graph.h"

void create_direct_neighbour_subgraph_demo() noexcept
{
  const auto g = create_k2_graph();
  const auto vip = vertices(g);
  const auto j = vip.second;
  for (auto i=vip.first; i!=j; ++i) {
    const auto h = create_direct_neighbour_subgraph(
      *i,g
    );
    assert(boost::num_vertices(h) == 2);
    assert(boost::num_edges(h) == 1);
  }
}
```

3.5 ▶ Creating all direct-neighbour subgraphs from a graph without properties

Using the previous function, it is easy to create all direct-neighbour subgraphs from a graph without properties:

Algorithm 44 Create all direct-neighbour subgraphs from a graph without properties

```
#include <vector>
#include "create_direct_neighbour_subgraph.h"

template <typename graph>
std::vector<graph> create_all_direct_neighbour_subgraphs(
  const graph g
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  std::vector<graph> v;
  v.resize(boost::num_vertices(g));
  const auto vip = vertices(g);
  std::transform(
    vip.first, vip.second,
    std::begin(v),
    [g](const vd& d)
    {
      return create_direct_neighbour_subgraph(
        d, g
      );
    }
  );
  return v;
}
```

This demonstration code shows that all direct-neighbour graphs of a K2 graphs are ... K2 graphs!

Algorithm 45 Demo of the 'create_all_direct_neighbour_subgraphs' function

```
#include <cassert>
#include "create_all_direct_neighbour_subgraphs.h"
#include "create_k2_graph.h"

void create_all_direct_neighbour_subgraphs_demo()
    noexcept
{
  const auto v
    = create_all_direct_neighbour_subgraphs(
        create_k2_graph());
  assert(v.size() == 2);
  for (const auto g: v)
  {
    assert(boost::num_vertices(g) == 2);
    assert(boost::num_edges(g) == 1);
  }
}
```

3.6 ▶ Are two graphs isomorphic?

You may want to check if two graphs are isomorphic. That is: if they have the same shape.

Algorithm 46 Check if two graphs are isomorphic

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

template <typename graph1, typename graph2>
bool is_isomorphic(
  const graph1 g,
  const graph2 h
) noexcept
{
  return boost::isomorphism(g,h);
}
```

This demonstration code shows that a K_3 graph is not equivalent to a 3-vertices path graph:

Algorithm 47 Demo of the 'is_isomorphic' function

```
#include <cassert>
#include "create_path_graph.h"
#include "create_k3_graph.h"
#include "is_isomorphic.h"

void is_isomorphic_demo() noexcept
{
  const auto g = create_path_graph(3);
  const auto h = create_k3_graph();
  assert( is_isomorphic(g,g));
  assert(!is_isomorphic(g,h));
}
```

3.7 Saving a graph to a .dot file

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 (I show .dot file of every non-empty graph created, e.g. chapters 2.14.4 and 2.15.4)

Algorithm 48 Saving a graph to a .dot file

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

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 49 shows how to use the 'save_graph_to_dot' function:

Algorithm 49 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 48), only the structure of the graph is saved: all other properties like names are not stored. Algorithm 93 shows how to do so.

3.8 Loading a 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 50:

Algorithm 50 Loading a directed graph from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "create_empty_directed_graph.h"
#include "is_regular_file.h"

boost::adjacency_list<>
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 282), after which an std::ifstream is opened. Then an empty directed graph is created, which saves us writing down the template arguments explicitly. Then, 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 22.5). From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 51 shows how to use the 'load_directed_graph_from_dot' function:

Algorithm 51 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.

3.9 Loading an undirected graph from a .dot file

Loading an undirected graph from a .dot file is very similar to loading a directed graph from a .dot file, as shown in chapter 3.8. Algorithm 52 show how to do so:

Algorithm 52 Loading an undirected graph from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "create_empty_undirected_graph.h"
#include "is_regular_file.h"

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;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 3.8 describes the rationale of this function.

Algorithm 53 shows how to use the 'load_undirected_graph_from_dot' function:

Algorithm 53 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.

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 23.1 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

After this chapter you may want to:

- Building graphs with named edges and vertices: see chapter 6
- Building graphs with bundled vertices: see chapter 8
- Building graphs with custom vertices: see chapter 12
- Building graphs with a graph name: see chapter 18

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 54 Creating an empty directed graph with named 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
  >
>
create_empty_directed_named_vertices_graph() noexcept
{
  return {};
}
```

Instead of using a boost::adjacency_list with default template argument, we will now have to specify four template arguments, where we only set the fourth to a non-default value.

Note there is some flexibility in this function: the data type of the vertex names is set to std::string by default, but can be of any other type if desired.

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, which 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 55 shows how to create such a graph:

Algorithm 55 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 56 Creating an empty undirected graph with named 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
  >
>
create_empty_undirected_named_vertices_graph() noexcept
{
  return {};
}
```

This code is very similar to the code described in chapter 4.1, except that the directedness (the third template argument) is undirected (due to the boost::undirectedS). See chapter 4.1 for most of the explanation.

Algorithm 57 shows how to create such a graph:

Algorithm 57 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 58:

Algorithm 58 Adding a vertex with a name

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

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
add_named_vertex(
  const std::string& vertex_name,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  const auto vd = boost::add_vertex(g);
  auto vertex_name_map = get(
      boost::vertex_name, g
    );
  put(vertex_name_map, vd, vertex_name);
  return vd;
}
```

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

First, the static_assert at the top of the function checks during compiling if the function is called with a non-const graph. One can freely omit this static_assert: you will get a compiler error anyways, be it a less helpful one.

When adding a new vertex to the graph, the vertex descriptor (as described in chapter 2.6) is stored.

The name map is obtained from the graph using 'get'. 'get' (not boost::get) allow to obtain a property map. In this case, 'get(boost::vertex_name,g)'), denotes that we want to obtain the property map associated with 'boost::vertex_name' from the graph. 'get' has no 'boost::' prepending it, as it lives in the same (global) namespace the function is in. Using 'boost::get' will not compile.

With a name map and a vertex descriptor, the name of a vertex can be set using 'put' (not boost::put). 'put' is the opposite of 'get'. In this case 'put(vertex_name_map, vd, vertex_name)' is read as: in the vertex name map, look up the spot where the vertex we have the descriptor of, and put the new vertex name there. An alternative syntax is 'vertex_name_map[vd] =

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

vertex_name'. Because 'put' is more general, it is chosen to be the preferred syntax for this tutorial.

Using 'add_named_vertex' is straightforward, as demonstrated by algorithm 59.

Algorithm 59 Demonstration of 'add_named_vertex'

```
#include <cassert>
#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:

Algorithm 60 Get the vertices' names

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

template <typename graph>
std::vector<std::string> get_vertex_names(
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  std::vector<std::string> v(boost::num_vertices(g));
  const auto vip = vertices(g);
  std::transform(vip.first, vip.second, std::begin(v),
    [g](const vd& d)
    {
      const auto vertex_name_map = get(
        boost::vertex_name, g
      );
      return get(vertex_name_map, d);
    }
  );
  return v;
}
```

This code is very similar to 'get_vertex_out_degrees' (algorithm 36), 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.

The order of the vertex names may be different after saving and loading.

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 22.1).

Algorithm 61 shows how to add two named vertices, and check if the added names are retrieved as expected.

Algorithm 61 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

Let's create a directed non-empty graph with named vertices!

4.5.1 Graph

We extend the Markov chain of chapter 2.14 by naming the vertices 'Good' and 'Not bad', as depicted in figure 16:

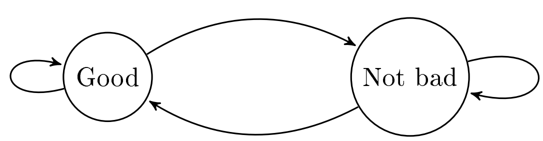

Figure 16: A two-state Markov chain where the vertices have texts

The vertex names are nonsensical, but I choose these for a reason: one name is only one word, the other has two words (as it contains a space). This will have implications for file I/O.

4.5.2 Function to create such a graph

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

Algorithm 62 Creating a Markov chain with named vertices as depicted in figure 16

```
#include <cassert>
#include "add_named_vertex.h"
#include "create_empty_directed_named_vertices_graph.h"

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 = add_named_vertex("Good", g);
  const auto vd_b = add_named_vertex("Not bad", 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;
}
```

Most of the code is a repeat of algorithm 21, 'create_markov_chain_graph'. In the end of the function body, 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 63) is very similar to the demonstration code of the 'create_markov_chain_graph' function (algorithm 22).

Algorithm 63 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{
    "Good", "Not bad"
  };
  const std::vector<std::string> vertex_names{
    get_vertex_names(g)
  };
  assert(expected_names == vertex_names);
}
```

4.5.4 The .dot file produced

Because the vertices now have a name, this should be visible in the .dot file:

Algorithm 64 .dot file created from the 'create_named_vertices_markov_chain' function (algorithm 62), converted from graph to .dot file using algorithm 48

```
digraph G {
0[label=Good];
1[label="Not bad"];
0->0 ;
0->1 ;
1->0 ;
1->1 ;
}
```

As one can see, the names are stored as a label. Note that if a vertex name contains a space, the name will be surrounded by quotes, for example '1[label="Not bad"];'.

4.5.5 The .svg file produced

Now that the vertices have names, this should be reflected in the .svg:

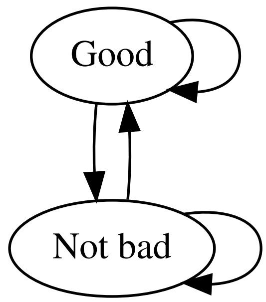

Figure 17: .svg file created from the 'create_named_vertices_markov_chain' function (algorithm 62) its .dot file, converted from .dot file to .svg using algorithm 281

The .svg now shows the vertex names, instead of the vertex indices.

4.6 Creating K_2 with named vertices

Let's create an undirected non-empty graph with named vertices!

4.6.1 Graph

We extend K_2 of chapter 2.15 by naming the vertices 'Me' and 'My computer', as depicted in figure 18:

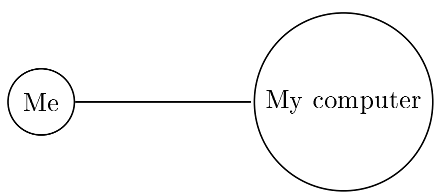

Figure 18: K_2: a fully connected graph with two named vertices

4.6.2 Function to create such a graph

To create K_2, the following code can be used:

Algorithm 65 Creating K_2 with named vertices as depicted in figure 18

```
#include <cassert>
#include "create_empty_undirected_named_vertices_graph.h"
#include "add_named_vertex.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<boost::vertex_name_t,std::string>
>
create_named_vertices_k2_graph() noexcept
{
  auto g
    = create_empty_undirected_named_vertices_graph();
  const auto vd_a = add_named_vertex(
    "Me", g
  );
  const auto vd_b = add_named_vertex(
    "My computer", g
  );
  const auto aer = boost::add_edge(vd_a, vd_b, g);
  assert(aer.second);
  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 66) is very similar to the demonstration code of the 'create_k2_graph function' (algorithm 24).

Algorithm 66 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{"Me", "My
      computer"};
  const std::vector<std::string> vertex_names =
      get_vertex_names(g);
  assert(expected_names == vertex_names);
}
```

4.6.4 The .dot file produced

Because the vertices now have a name, this should be visible in the .dot file:

Algorithm 67 .dot file created from the 'create_named_vertices_k2' function (algorithm 65), converted from graph to .dot file using algorithm 93

```
graph G {
0[label=Me];
1[label="My computer"];
0--1 ;
}
```

As one can see, the names are stored as a label. Note that if a vertex name contains a space, the name will be surrounded by quotes, for example '1[label="My computer"];'.

4.6.5 The .svg file produced

Now that the vertices have names, this should be reflected in the .svg:

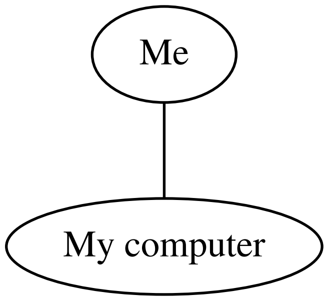

Figure 19: .svg file created from the 'create_named_vertices_k2_graph' function (algorithm 62) its .dot file, converted from .dot file to .svg using algorithm 93

The .svg now shows the vertex names, instead of the vertex indices.

4.7 ► Creating a path graph with named vertices

Here we create a path graph with names vertices

4.7.1 Graph

Here I show a path graph with four vertices (see figure 20):

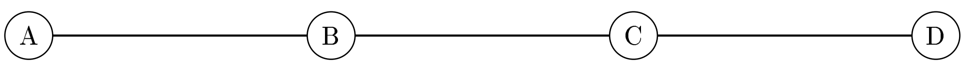

Figure 20: A path graph with four vertices

4.7.2 Function to create such a graph

To create a path graph, the following code can be used:

Algorithm 68 Creating a path graph as depicted in figure 20

```
#include <vector>
#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_name_t, std::string
  >
>
create_named_vertices_path_graph(
  const std::vector<std::string>& names
) noexcept
{
  auto g = create_empty_undirected_named_vertices_graph()
      ;
  if (names.size() == 0) { return g; }
  auto vd_1 = add_named_vertex(*names.begin(), g);
  if (names.size() == 1) return g;
  const auto j = std::end(names);
  auto i = std::begin(names);
  for (++i; i!=j; ++i) //Skip first
  {
    auto vd_2 = add_named_vertex(*i, g);
    const auto aer = boost::add_edge(vd_1, vd_2, g);
    assert(aer.second);
    vd_1 = vd_2;
  }
  return g;
}
```

4.7.3 Creating such a graph

Algorithm 69 demonstrates how to create a path graph with named vertices and checks if it has the correct amount of edges and vertices:

Algorithm 69 Demonstration of 'create_named_vertices_path_graph'

```
#include <cassert>
#include "create_named_vertices_path_graph.h"

void create_named_vertices_path_graph_demo() noexcept
{
  const auto g = create_named_vertices_path_graph(
    {"A", "B", "C", "D"}
  );
  assert(boost::num_edges(g) == 3);
  assert(boost::num_vertices(g) == 4);
}
```

4.7.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 70:

Algorithm 70 .dot file created from the 'create_named_vertices_path_graph' function (algorithm 68), converted from graph to .dot file using algorithm 48

4.7.5 The .svg file produced

The .dot file can be converted to the .svg as shown in figure 21:

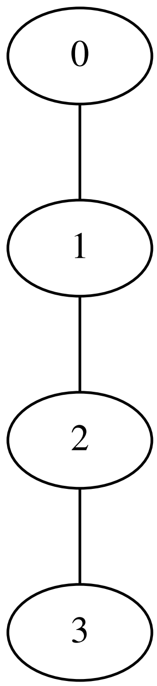

Figure 21: .svg file created from the 'create_named_vertices_path_graph' function (algorithm 68) its .dot file, converted from .dot file to .svg using algorithm 281

5 Working on 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
- Saving an directed/undirected graph with named vertices to a .dot file: chapter 5.12
- Loading a directed graph with named vertices from a .dot file: chapter 5.13
- Loading an undirected graph with named vertices from a .dot file: chapter 5.14

Especially the 'find_first_vertex_by_name' function (chapter 5.2) is important, as it 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 71 Find if there is vertex with a certain name

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

template <typename graph>
bool has_vertex_with_name(
  const std::string& vertex_name,
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  const auto vip = vertices(g);
  return std::find_if(vip.first, vip.second,
    [g, vertex_name](const vd& d)
    {
      const auto vertex_name_map
        = get(boost::vertex_name, g);
      return get(vertex_name_map, d) == vertex_name;
    }
  ) != vip.second;
}
```

This function can be demonstrated as in algorithm 72, where a certain name cannot be found in an empty graph. After adding the desired name, it is found.

Algorithm 72 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 73 shows how to obtain a vertex descriptor to the first (name) vertex found with a specific name.

Algorithm 73 Find the first vertex by its name

```
#include <cassert>
#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
{
  using vd = typename graph::vertex_descriptor;
  const auto vip = vertices(g);
  const auto i = std::find_if(
    vip.first, vip.second,
    [g, name](const vd d) {
      const auto vertex_name_map = get(boost::vertex_name
          , g);
      return get(vertex_name_map, d) == name;
    }
  );
  assert(i != vip.second);
  return *i;
}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 74 shows some examples of how to do so.

Algorithm 74 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(
      "My computer", g
    );
  assert(
    out_degree(vd,g) == 1
  );
  assert(in_degree(vd,g) == 1);
}
```

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 73 shows how to find a vertex, obtain its vertex descriptor and then obtain the out degree from it.

Algorithm 75 Get the first vertex with a certain name its out degree from its vertex descriptor

```
#include <cassert>
#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
{
  const auto vd
    = find_first_vertex_with_name(name, g);
  const int od {
    static_cast<int>(
      out_degree(vd, g)
    )
  };
  assert(static_cast<unsigned long>(od)
    == out_degree(vd, g)
  );
  return od;
}
```

Algorithm 76 shows how to use this function.

Algorithm 76 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(
      "Me", g
    ) == 1
  );
  assert(
    get_first_vertex_with_name_out_degree(
      "My computer", 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.

Algorithm 77 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 get(vertex_name_map, vd);
}
```

To use 'get_vertex_name', one first needs to obtain a vertex descriptor. Algorithm 78 shows a simple example:

Algorithm 78 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 79.

Algorithm 79 Set a vertex its name from its vertex descriptor

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

template <typename graph>
void set_vertex_name(
  const std::string& any_vertex_name,
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  auto vertex_name_map
    = get(boost::vertex_name, g);
  put(vertex_name_map, vd, any_vertex_name);
}
```

To use 'set_vertex_name', one first needs to obtain a vertex descriptor. Algorithm 80 shows a simple example.

Algorithm 80 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 81 Setting the vertices' names

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

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

template <typename graph>
void set_vertex_names(
  graph& g,
  const std::vector<std::string>& names
) noexcept
{
  static_assert(!std::is_const<graph>::value,"graph␣
     cannot␣be␣const");

  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);
  const auto j = vip.second;
  for (auto i = vip.first; i!=j; ++i, ++ni)
  {
    assert(ni != names_end);
    put(vertex_name_map, *i, *ni);
  }
}
```

A new function makes its appearance here: 'put' (not 'boost::put'), which is the opposite of 'get' (not 'boost::get')

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 22.2)

- 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 22.3)

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

Algorithm 82 Clear the first vertex with a certain name

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

template <typename graph>
void clear_first_vertex_with_name(
  const std::string& name,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph␣cannot␣be␣const"
  );

  assert(has_vertex_with_name(name,g));
  const auto vd
    = find_first_vertex_with_name(name,g);
  boost::clear_vertex(vd,g);
}
```

Algorithm 83 shows the clearing of the first named vertex found.

Algorithm 83 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("My␣computer",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 82) 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 5.8:

Algorithm 84 Remove the first vertex with a certain name

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

template <typename graph>
void remove_first_vertex_with_name(
  const std::string& name,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  assert(has_vertex_with_name(name,g));
  const auto vd
    = find_first_vertex_with_name(name,g);
  assert(degree(vd,g) == 0);
  boost::remove_vertex(vd,g);
}
```

Algorithm 85 shows the removal of the first named vertex found.

Algorithm 85 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(
    "My computer",g
  );
  remove_first_vertex_with_name(
    "My computer",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 86.

Algorithm 86 Remove the first edge with a certain name

```
#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
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  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 87 shows the removal of the first named edge found.

Algorithm 87 Demonstration of the 'remove_edge_between_vertices_with_names' function

```
#include <cassert>

#include "create_named_edges_and_vertices_k3_graph.h"
#include "remove_edge_between_vertices_with_names.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 ▶ Count the vertices with a certain name

How often is a vertex with a certain name present? Here we'll find out.

Algorithm 88 Find the first vertex by its name

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

template <typename graph>
int count_vertices_with_name(
  const graph& g,
  const std::string& name
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  const auto vip = vertices(g);
  const auto cnt = std::count_if(
    vip.first, vip.second,
    [g, name](const vd& d)
    {
      const auto vertex_name_map
        = get(boost::vertex_name,g);
      return name
        == get(vertex_name_map, d);
    }
  );
  return static_cast<int>(cnt);
}
```

Here we use the STL std::count_if algorithm to count how many vertices have a name equal to the desired name.

Algorithm 89 shows some examples of how to do so.

Algorithm 89 Demonstration of the 'find_first_vertex_with_name' function

```
#include <cassert>
#include "add_named_vertex.h"
#include "count_vertices_with_name.h"
#include "create_empty_undirected_named_vertices_graph.h"
#include "create_named_vertices_path_graph.h"

void count_vertices_with_name_demo() noexcept
{
  auto g = create_named_vertices_path_graph(
    {"Apple", "Pear", "Apple"}
  );
  assert(count_vertices_with_name(g,"Apple") == 2);
  assert(count_vertices_with_name(g,"Pear") == 1);
  assert(count_vertices_with_name(g,"Banana") == 0);
}
```

5.11 ▶ Are two graphs with named vertices isomorphic?

Strictly speaking, finding isomorphisms is about the shape of the graph, independent of vertex name, and is already done in chapter 3.6.

Here, it is checked if two graphs with named vertices are 'label isomorphic' (please email me a better term if you know one). That is: if they have the same shape with the same vertex names at the same places.

To do this, there are two steps needed:

1. Map all vertex names to an unsigned int.
2. Compare the two graphs with that map

Below the class 'named_vertex_invariant' is shown. Its std::map maps the vertex names to an unsigned integer, which is done in the member function 'collect_names'. The purpose of this, is that is is easier to compare integers that std::strings.

Algorithm 90 The named_vertex_invariant functor

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

template <class graph>
struct named_vertex_invariant {
  using str_to_int_map = std::map<std::string, size_t>;
  using result_type = size_t;
  using argument_type = typename graph::vertex_descriptor
      ;

  const graph& m_graph;
  str_to_int_map& m_mappings;

  size_t operator()(argument_type u) const {
      return m_mappings.at(boost::get(boost::vertex_name,
          m_graph, u));
  }
  size_t max() const noexcept { return m_mappings.size();
      }

  void collect_names() noexcept {
    for (auto vd : boost::make_iterator_range(boost::
        vertices(m_graph))) {
      size_t next_id = m_mappings.size();
      auto ins = m_mappings.insert(
        { boost::get(boost::vertex_name, m_graph, vd),
            next_id}
      );
      if (ins.second) {
      //  std::cout << "Mapped '" << ins.first->first <<
          "' to " << ins.first->second << "\n";
      }
    }
  }
};
```

To check for 'label isomorphism', multiple things need to be put in place for 'boost::isomorphism' to work with:

Algorithm 91 Check if two graphs with named vertices are isomorphic

```
#include "named_vertex_invariant.h"

#include <boost/graph/vf2_sub_graph_iso.hpp>
#include <boost/graph/graph_utility.hpp>

template <typename graph>
bool is_named_vertices_isomorphic(
  const graph &g,
  const graph &h
) noexcept {
  using vd = typename graph::vertex_descriptor;
  auto vertex_index_map = get(boost::vertex_index, g);
  std::vector<vd> iso(boost::num_vertices(g));

  typename named_vertex_invariant<graph>::str_to_int_map
     shared_names;
  named_vertex_invariant<graph> inv1{g, shared_names};
  named_vertex_invariant<graph> inv2{h, shared_names};
  inv1.collect_names();
  inv2.collect_names();

  return boost::isomorphism(g, h,
    boost::isomorphism_map(
      make_iterator_property_map(
        iso.begin(),
        vertex_index_map
      )
    )
    .vertex_invariant1(inv1)
    .vertex_invariant2(inv2)
  );
}
```

This demonstration code creates three path graphs, of which two are 'label isomorphic':

Algorithm 92 Demo of the 'is_named_vertices_isomorphic' function

```
#include <cassert>
#include "create_named_vertices_path_graph.h"
#include "is_named_vertices_isomorphic.h"

void is_named_vertices_isomorphic_demo() noexcept
{
  const auto g = create_named_vertices_path_graph(
    { "Alpha", "Beta", "Gamma" }
  );
  const auto h = create_named_vertices_path_graph(
    { "Gamma", "Beta", "Alpha" }
  );
  const auto i = create_named_vertices_path_graph(
    { "Alpha", "Gamma", "Beta" }
  );
  assert( is_named_vertices_isomorphic(g,h));
  assert(!is_named_vertices_isomorphic(g,i));
}
```

5.12 Saving an directed/undirected graph with named vertices to a .dot file

If you used the 'create_named_vertices_k2_graph' function (algorithm 65) 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

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

The created .dot file is shown at algorithm 67.

You can use all characters in the vertex without problems (for example: comma's, quotes, whitespace). This will not hold anymore for bundled and custom vertices in later chapters.

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.

5.12.1 Using boost::make_label_writer

The first implemention uses boost::make_label_writer, as shown in algorithm 93:

Algorithm 93 Saving a graph with named vertices to a .dot file

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

#include "get_vertex_names.h"

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.

5.12.2 Using a C++11 lambda function

An equivalent algorithm is algorithm 94:

Algorithm 94 Saving a graph with named vertices to a .dot file using a lambda expression

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

#include "get_vertex_names.h"

template <typename graph>
void save_named_vertices_graph_to_dot_using_lambda(
  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 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++17 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 77) and stream it to the out stream.

5.12.3 Demonstration

Algorithm 95 shows how to use (one of) the 'save_named_vertices_graph_to_dot' function(s):

Algorithm 95 Demonstration of the 'save_named_vertices_graph_to_dot' function

```
#include "create_named_vertices_k2_graph.h"
#include "create_named_vertices_markov_chain.h"
#include "save_named_vertices_graph_to_dot.h"

void save_named_vertices_graph_to_dot_demo() noexcept
{
  const auto g = create_named_vertices_k2_graph();
  save_named_vertices_graph_to_dot(
    g, "create_named_vertices_k2_graph.dot"
  );

  const auto h = create_named_vertices_markov_chain();
  save_named_vertices_graph_to_dot(
    h, "create_named_vertices_markov_chain.dot"
  );
}
```

When using the 'save_named_vertices_graph_to_dot' function (algorithm 93), only the structure of the graph and the vertex names are saved: all other properties like edge name are not stored. Algorithm 124 shows how to do so.

5.13 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 96:

Algorithm 96 Loading a directed graph with named vertices from a .dot file

```
#include <fstream>
#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;
  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 97 shows how to use the 'load_directed_graph_from_dot' function:

Algorithm 97 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 60).

5.14 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 98:

Algorithm 98 Loading an undirected graph with named vertices from a .dot file

```
#include <fstream>
#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;
  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;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 5.13 describes the rationale of this function.

Algorithm 99 shows how to use the 'load_undirected_graph_from_dot' function:

Algorithm 99 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 65), 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 60).

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 100 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 {};
}
```

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

Algorithm 101 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 102 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 {};
}
```

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

Algorithm 103 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 104 Add a vertex with a name

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

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
add_named_edge(
  const std::string& edge_name,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );
  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(
      boost::edge_name,g
    );
  put(edge_name_map, aer.first, edge_name);
  return aer.first;
}
```

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 105 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 22.1).

Algorithm 105 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 106 Get the edges' names

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

template <typename graph>
std::vector<std::string> get_edge_names(const graph& g)
    noexcept
{
  using boost::graph_traits;
  using ed = typename graph_traits<graph>::
      edge_descriptor;
  std::vector<std::string> v(boost::num_edges(g));
  const auto eip = edges(g);
  std::transform(eip.first, eip.second, std::begin(v),
    [g](const ed& d)
    {
      const auto edge_name_map = get(boost::edge_name,g);
      return get(edge_name_map, d);
    }
  );
  return v;
}
```

The names of the edges are obtained from a boost::property_map and then put into a std::vector. The algorithm 107 shows how to apply this function.

The order of the edge names may be different after saving and loading.

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 22.1).

Algorithm 107 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:

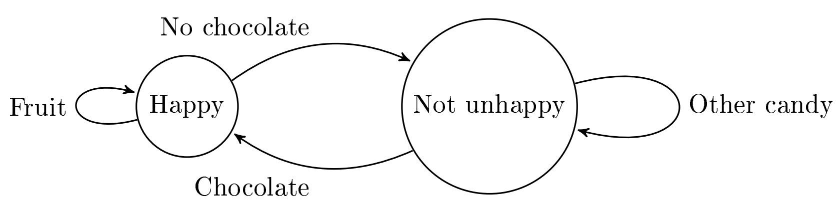

Figure 22: A two-state Markov chain where the edges and vertices have texts

6.5.2 Function to create such a graph

Here is the code:

Algorithm 108 Creating the two-state Markov chain as depicted in figure 22

```
#include <string>
#include "
    create_empty_directed_named_edges_and_vertices_graph.h
    "
#include "add_named_vertex.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 = add_named_vertex("Happy", g);
  const auto vd_b = add_named_vertex("Not unhappy", 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 edge_name_map = get(
    boost::edge_name,g
  );
  put(edge_name_map, aer_aa.first, "Fruit");
  put(edge_name_map, aer_ab.first, "No chocolate");
  put(edge_name_map, aer_ba.first, "Chocolate");
  put(edge_name_map, aer_bb.first, "Other candy");

  return g;
}
```

6.5.3 Creating such a graph

Here is the demo:

Algorithm 109 Demo of the 'create_named_edges_and_vertices_markov_chain' function (algorithm 108)

```
#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{
    "Happy","Not unhappy"
  };
  const strings vertex_names{
    get_vertex_names(g)
  };
  assert(expected_vertex_names == vertex_names);

  const strings expected_edge_names{
    "Fruit","No chocolate","Chocolate","Other candy"
  };

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

6.5.4 The .dot file produced

Algorithm 110 .dot file created from the 'create_named_edges_and_vertices_markov_chain' function (algorithm 108), converted from graph to .dot file using algorithm 48

```
digraph G {
0[label=Happy];
1[label="Not unhappy"];
0->0 [label="Fruit"];
0->1 [label="No chocolate"];
1->0 [label="Chocolate"];
1->1 [label="Other candy"];
}
```

6.5.5 The .svg file produced

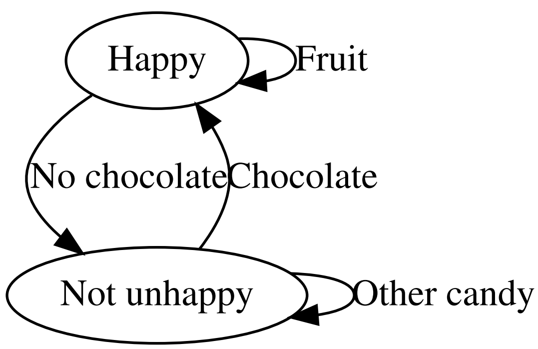

Figure 23: .svg file created from the 'create_named_edges_and_vertices_markov_chain' function (algorithm 108) its .dot file, converted from .dot file to .svg using algorithm 281

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 24:

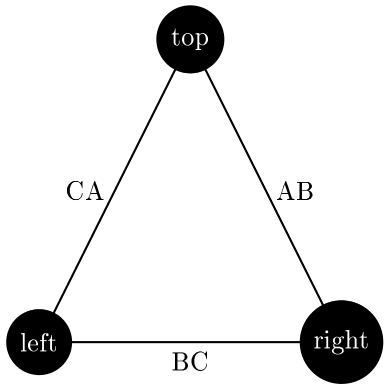

Figure 24: K_3: a fully connected graph with three named edges and vertices

6.6.2 Function to create such a graph

To create K_3, the following code can be used:

Algorithm 111 Creating K_3 as depicted in figure 24

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<boost::vertex_name_t,std::string>,
  boost::property<boost::edge_name_t,std::string>
>
create_named_edges_and_vertices_k3_graph() noexcept
{
  auto g
    =
        create_empty_undirected_named_edges_and_vertices_graph
        ();
  const auto vd_a = add_named_vertex("top", g);
  const auto vd_b = add_named_vertex("right", g);
  const auto vd_c = add_named_vertex("left", 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 edge_name_map = get(boost::edge_name,g);
  put(edge_name_map, aer_ab.first, "AB");
  put(edge_name_map, aer_bc.first, "BC");
  put(edge_name_map, aer_ca.first, "CA");

  return g;
}
```

Most of the code is a repeat of algorithm 65. In the end, the edge names are obtained as a boost::property_map and set.

6.6.3 Creating such a graph

Algorithm 112 shows how to create the graph and measure its edge and vertex names.

Algorithm 112 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 113 .dot file created from the 'create_named_edges_and_vertices_k3_graph' function (algorithm 111), converted from graph to .dot file using algorithm 48

```
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

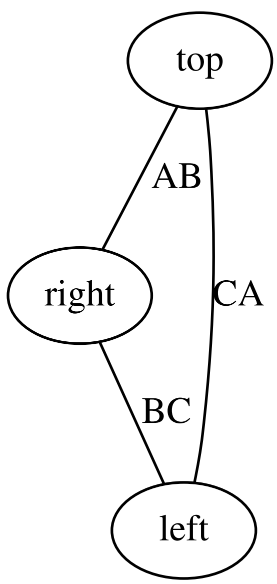

Figure 25: .svg file created from the 'create_named_edges_and_vertices_k3_graph' function (algorithm 111) its .dot file, converted from .dot file to .svg using algorithm 281

7 Working on 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
- Saving a graph with named edges and vertices to 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 114 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& edge_name,
  const graph& g
) noexcept
{
  using ed = typename boost::graph_traits<graph>::
      edge_descriptor;
  const auto eip = edges(g);
  return std::find_if(eip.first, eip.second,
    [edge_name, g](const ed& d)
    {
      const auto edge_name_map
        = get(boost::edge_name, g);
      return get(edge_name_map, d) == edge_name;
    }
  ) != eip.second;
}
```

This function can be demonstrated as in algorithm 115, where a certain name cannot be found in an empty graph. After adding the desired name, it is found.

Algorithm 115 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 116 shows how to obtain an edge descriptor to the first (name) edge found with a specific name.

Algorithm 116 Find the first edge by its name

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

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
find_first_edge_with_name(
  const std::string& name,
  const graph& g
) noexcept
{
  using ed = typename boost::graph_traits<graph>::
      edge_descriptor;
  const auto eip = edges(g);
  const auto i = std::find_if(
    eip.first, eip.second,
    [g, name](const ed d) {
      const auto edge_name_map = get(boost::edge_name, g)
          ;
      return get(edge_name_map, d) == name;
    }
  );
  assert(i != eip.second);
  return *i;
}
```

With the edge descriptor obtained, one can read and modify the graph. Algorithm 117 shows some examples of how to do so.

Algorithm 117 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 118 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& ed,
  const graph& g
) noexcept
{
  const auto edge_name_map
    = get(boost::edge_name,
      g
    );
  return get(edge_name_map, ed);
}
```

To use 'get_edge_name', one first needs to obtain an edge descriptor. Algorithm 119 shows a simple example.

Algorithm 119 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 120.

Algorithm 120 Set an edge its name from its edge descriptor

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

template <typename graph>
void set_edge_name(
  const std::string& any_edge_name,
  const typename boost::graph_traits<graph>::
     edge_descriptor& vd,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  auto edge_name_map = get(boost::edge_name,g);
  put(edge_name_map, vd, any_edge_name);
}
```

To use 'set_edge_name', one first needs to obtain an edge descriptor. Algorithm 121 shows a simple example.

Algorithm 121 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 84:

Algorithm 122 Remove the first edge with a certain name

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

template <typename graph>
void remove_first_edge_with_name(
  const std::string& name,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  assert(has_edge_with_name(name,g));
  const auto vd
    = find_first_edge_with_name(name,g);
  boost::remove_edge(vd,g);
}
```

Algorithm 123 shows the removal of the first named edge found.

Algorithm 123 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 Saving an undirected graph with named edges and vertices as a .dot

If you used the create_named_edges_and_vertices_k3_graph function (algorithm 111) to produce a K_3 graph with named edges and vertices, you can store these names additionally with algorithm 124:

Algorithm 124 Saving an undirected graph with named edges and vertices to 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"

template <typename graph>
void save_named_edges_and_vertices_graph_to_dot(
  const graph& g,
  const std::string& filename
)
{
  using my_edge_descriptor = typename graph::
      edge_descriptor;

  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
        my_edge_descriptor& e) {
      out << "[label=\"" << edge_name_map[e] << "\"]";
    }
  );
}
```

If you created a graph with edges more complex than just a name, you will still just write these to the .dot file. Chapter 13.6 shows how to write custom vertices to a .dot file.

So, the 'save_named_edges_and_vertices_graph_to_dot' function (algorithm 48) 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 125:

Algorithm 125 Loading a directed graph with named edges and vertices from a .dot file

```
#include <fstream>
#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;
  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 126 shows how to use the 'load_directed_graph_from_dot' function:

Algorithm 126 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 108), 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 106, and the 'get_vertex_names' function, algorithm 60).

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 127:

Algorithm 127 Loading an undirected graph with named edges and vertices from a .dot file

```
#include <fstream>
#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;
  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;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 7.7 describes the rationale of this function.

Algorithm 128 shows how to use the 'load_undirected_graph_from_dot' function:

Algorithm 128 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 111), 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 106, and the 'get_vertex_names' function, algorithm 60).

8 Building graphs with bundled 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 bundled 'my_bundled_vertex' type[8]. The following graphs will be created:

- An empty directed graph that allows for bundled vertices: see chapter 130
- An empty undirected graph that allows for bundled vertices: see chapter 8.2
- A two-state Markov chain with bundled vertices: see chapter 8.6
- $K_2$with bundled vertices: see chapter 8.7

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

- Create the vertex class, called 'my_bundled_vertex': see chapter 8.1
- Adding a 'my_bundled_vertex': see chapter 8.4
- Getting the vertices 'my_bundled_vertex'-es: see chapter 8.5

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

8.1 Creating the bundled vertex class

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

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

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

Algorithm 129 Declaration of my_bundled_vertex

```
#include <string>
#include <iosfwd>
#include <boost/property_map/dynamic_property_map.hpp>

struct my_bundled_vertex
{
  explicit my_bundled_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_bundled_vertex& lhs, const
    my_bundled_vertex& rhs) noexcept;
bool operator!=(const my_bundled_vertex& lhs, const
    my_bundled_vertex& rhs) noexcept;
```

'my_bundled_vertex' is a class that has multiple properties:

- It has four public member variables: the double 'm_x' ('m_' stands for member), the double 'm_y', the std::string m_name and the std::string m_description. These variables must be public
- It has a default constructor
- It is copyable
- It is comparable for equality (it has operator==), which is needed for searching

'my_bundled_vertex' does not have to have the stream operators defined for file I/O, as this goes via the public member variables.

8.2 Create the empty directed graph with bundled vertices

Algorithm 130 Creating an empty directed graph with bundled vertices

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  my_bundled_vertex
>
create_empty_directed_bundled_vertices_graph() noexcept
{
  return {};
}
```

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 bundled type, that is of data type 'my_bundled_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 'my_bundled_vertex'. This can be read as: "vertices have the bundled property 'my_bundled_vertex"'. Or simply: "vertices have a bundled type called my_bundled_vertex".

8.3 Create the empty undirected graph with bundled vertices

Algorithm 131 Creating an empty undirected graph with bundled vertices

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

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

This code is very similar to the code described in chapter 8.2, except that the directedness (the third template argument) is undirected (due to the boost::undirectedS).

8.4 Add a bundled vertex

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

Algorithm 132 Add a bundled vertex

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

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
add_bundled_vertex(const my_bundled_vertex& v, graph& g)
   noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  const auto vd = boost::add_vertex(g);
  g[vd] = v;
  return vd;
}
```

When having added a new (abstract) vertex to the graph, the vertex descriptor is used to set the 'my_bundled_vertex' in the graph.

8.5 Getting the bundled vertices' my_vertexes[9]

When the vertices of a graph have any bundled 'my_bundled_vertex', one can extract these as such:

Algorithm 133 Get the bundled vertices' my_vertexes

```
#include <vector>
#include <boost/graph/adjacency_list.hpp>
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>
#include "my_bundled_vertex.h"

template <typename graph>
std::vector<my_bundled_vertex> get_my_bundled_vertexes(
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  std::vector<my_bundled_vertex> v(boost::num_vertices(g)
    );
  const auto vip = vertices(g);
  std::transform(vip.first, vip.second, std::begin(v),
    [g](const vd& d) { return g[d]; }
  );
  return v;
}
```

The 'my_bundled_vertex' bundled in each vertex is obtained from a vertex descriptor and then put into a std::vector.

The order of the 'my_bundled_vertex' objects may be different after saving and loading.

When trying to get the vertices' my_bundled_vertex from a graph without these, you will get the error 'formed reference to void' (see chapter 22.1).

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

8.6 Creating a two-state Markov chain with bundled vertices

8.6.1 Graph

Figure 26 shows the graph that will be reproduced:

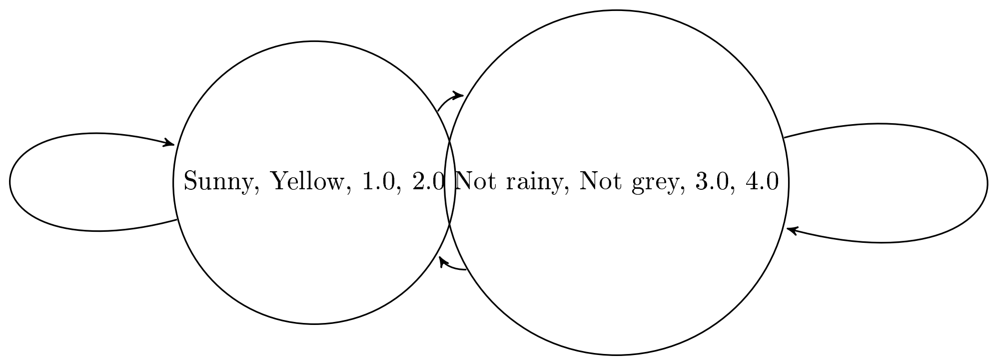

Figure 26: A two-state Markov chain where the vertices have bundled properies and the edges have no properties. The vertices' properties are nonsensical

8.6.2 Function to create such a graph

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

Algorithm 134 Creating the two-state Markov chain as depicted in figure 26

```
#include <cassert>
#include "create_empty_directed_bundled_vertices_graph.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  my_bundled_vertex
>
create_bundled_vertices_markov_chain() noexcept
{
  auto g
    = create_empty_directed_bundled_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);

  g[vd_a] = my_bundled_vertex("Sunny",
    "Yellow",1.0,2.0
  );
  g[vd_b] = my_bundled_vertex("Not rainy",
    "Not grey",3.0,4.0
  );

  return g;
}
```

8.6.3 Creating such a graph

Here is the demo:

Algorithm 135 Demo of the 'create_bundled_vertices_markov_chain' function (algorithm 134)

```
#include <cassert>
#include "create_bundled_vertices_markov_chain.h"
#include "get_my_bundled_vertexes.h"
#include "get_my_bundled_vertex.h"

void create_bundled_vertices_markov_chain_demo() noexcept
{
  const auto g
    = create_bundled_vertices_markov_chain();
  const std::vector<my_bundled_vertex> expected{
    my_bundled_vertex("Sunny","Yellow",1.0,2.0),
    my_bundled_vertex("Not rainy","Not grey",3.0,4.0)
  };
  const auto found = get_my_bundled_vertexes(g);
  assert(expected == found);
}
```

8.6.4 The .dot file produced

Algorithm 136 .dot file created from the 'create_bundled_vertices_markov_chain' function (algorithm 134), converted from graph to .dot file using algorithm 149

```
digraph G {
0[label="Sunny",comment="Yellow",width=1,height=2];
1[label="Not$$$SPACE$$$rainy",comment="Not$$$SPACE$$$grey",width=3,height=4];
0->0 ;
0->1 ;
1->0 ;
1->1 ;
}
```

8.6.5 The .svg file produced

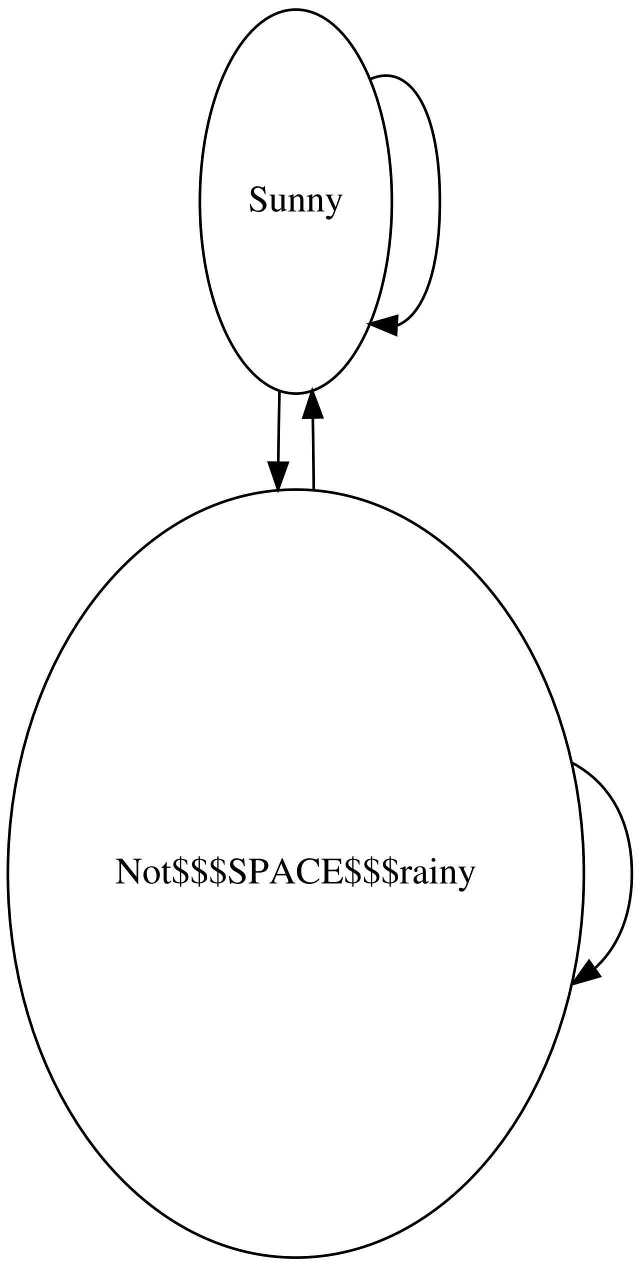

Figure 27: .svg file created from the 'create_bundled_vertices_markov_chain' function (algorithm 134) its .dot file, converted from .dot file to .svg using algorithm 281

8.7 Creating K_2 with bundled vertices

8.7.1 Graph

We reproduce the K_2 with named vertices of chapter 4.6 , but with our bundled vertices intead, as show in figure 28:

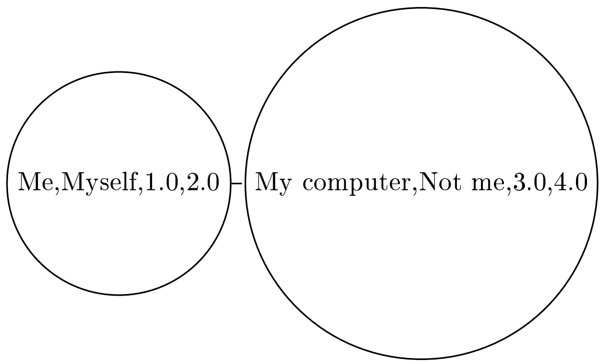

Figure 28: K_2: a fully connected graph with two bundled vertices

8.7.2 Function to create such a graph

Algorithm 137 Creating K_2 as depicted in figure 18

```
#include "create_empty_undirected_bundled_vertices_graph.
    h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  my_bundled_vertex
>
create_bundled_vertices_k2_graph() noexcept
{
  auto g = create_empty_undirected_bundled_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);
  g[vd_a] = my_bundled_vertex(
    "Me","Myself",1.0,2.0
  );
  g[vd_b] = my_bundled_vertex(
    "My computer","Not me",3.0,4.0
  );
  return g;
}
```

Most of the code is a slight modification of the 'create_named_vertices_k2_graph' function (algorithm 65). In the end, (references to) the my_bundled_vertices are obtained and set with two bundled my_bundled_vertex objects.

8.7.3 Creating such a graph

Demo:

Algorithm 138 Demo of the 'create_bundled_vertices_k2_graph' function (algorithm 137)

```
#include <cassert>
#include "create_bundled_vertices_k2_graph.h"
#include "has_bundled_vertex_with_my_vertex.h"

void create_bundled_vertices_k2_graph_demo() noexcept
{
  const auto g = create_bundled_vertices_k2_graph();
  assert(boost::num_edges(g) == 1);
  assert(boost::num_vertices(g) == 2);
  assert(has_bundled_vertex_with_my_vertex(
    my_bundled_vertex("Me","Myself",1.0,2.0), g)
  );
  assert(has_bundled_vertex_with_my_vertex(
    my_bundled_vertex("My computer","Not me",3.0,4.0), g)
  );
}
```

8.7.4 The .dot file produced

Algorithm 139 .dot file created from the 'create_bundled_vertices_k2_graph' function (algorithm 137), converted from graph to .dot file using algorithm 48

8.7.5 The .svg file produced

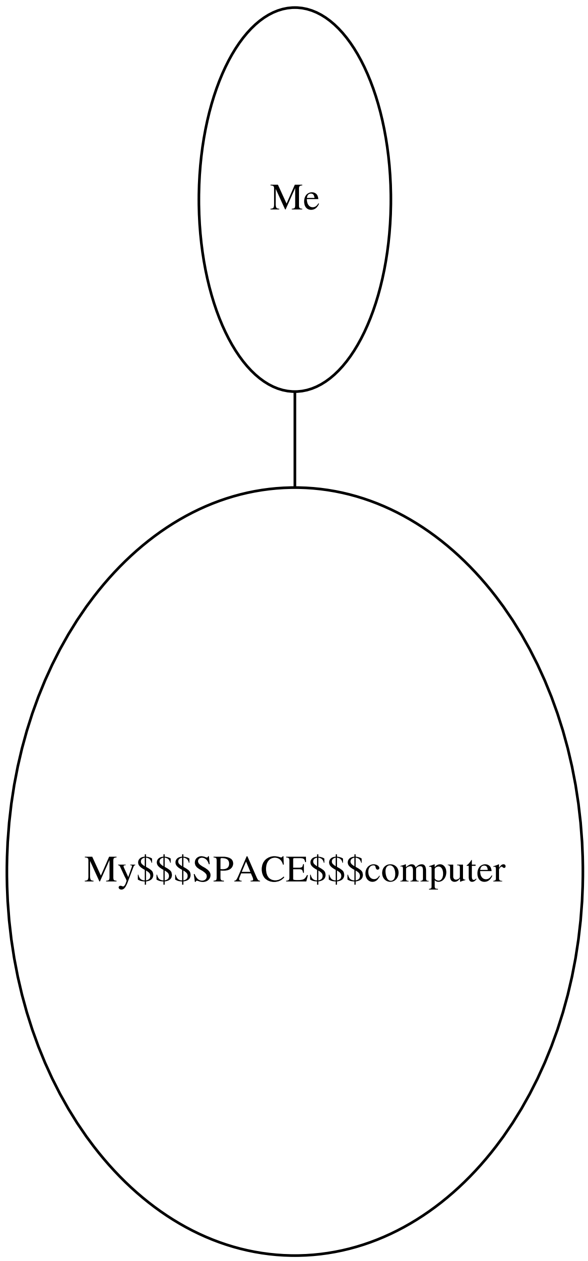

Figure 29: .svg file created from the 'create_bundled_vertices_k2_graph' function (algorithm 137) its .dot file, converted from .dot file to .svg using algorithm 281

9 Working on graphs with bundled vertices

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

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

9.1 Has a bundled vertex with a my_bundled_vertex

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

Algorithm 140 Find if there is vertex with a certain my_bundled_vertex

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

template <typename graph>
bool has_bundled_vertex_with_my_vertex(
  const my_bundled_vertex& v,
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  const auto vip = vertices(g);
  return std::find_if(vip.first, vip.second,
    [v, g](const vd& d)
    {
      return g[d] == v;
    }
  ) != vip.second;
}
```

This function can be demonstrated as in algorithm 141, where a certain my_bundled_vertex cannot be found in an empty graph. After adding the desired my_bundled_vertex, it is found.

Algorithm 141 Demonstration of the 'has_bundled_vertex_with_my_vertex' function

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

#include "add_bundled_vertex.h"
#include "create_empty_undirected_bundled_vertices_graph.
    h"
#include "has_bundled_vertex_with_my_vertex.h"
#include "my_bundled_vertex.h"

void has_bundled_vertex_with_my_vertex_demo() noexcept
{
  auto g = create_empty_undirected_bundled_vertices_graph
      ();
  assert(!has_bundled_vertex_with_my_vertex(
      my_bundled_vertex("Felix"),g));
  add_bundled_vertex(my_bundled_vertex("Felix"),g);
  assert(has_bundled_vertex_with_my_vertex(
      my_bundled_vertex("Felix"),g));
}
```

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

9.2 Find a bundled vertex with a certain my_bundled_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 142 shows how to obtain a vertex descriptor to the first vertex found with a specific 'my_bundled_vertex' value.

Algorithm 142 Find the first vertex with a certain my_bundled_vertex

```
#include <cassert>
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>
#include "has_bundled_vertex_with_my_vertex.h"
#include "my_bundled_vertex.h"

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_bundled_vertex_with_my_vertex(
  const my_bundled_vertex& v,
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;
  const auto vip = vertices(g);
  const auto i = std::find_if(
    vip.first, vip.second,
    [v,g](const vd d) { return g[d] == v; }
  );
  assert(i != vip.second);
  return *i;
}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 143 shows some examples of how to do so.

Algorithm 143 Demonstration of the 'find_first_bundled_vertex_with_my_vertex' function

```
#include <cassert>

#include "create_bundled_vertices_k2_graph.h"
#include "find_first_bundled_vertex_with_my_vertex.h"

void find_first_bundled_vertex_with_my_vertex_demo()
   noexcept
{
  const auto g = create_bundled_vertices_k2_graph();
  const auto vd =
     find_first_bundled_vertex_with_my_vertex(
    my_bundled_vertex("Me","Myself",1.0,2.0),
    g
  );
  assert(out_degree(vd,g) == 1);
  assert(in_degree(vd,g) == 1);
}
```

9.3 Get a bundled vertex its 'my_bundled_vertex'

To obtain the 'my_bundled_vertex' from a vertex descriptor is simple:

Algorithm 144 Get a bundled vertex its my_vertex from its vertex descriptor

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

template <typename graph>
my_bundled_vertex get_my_bundled_vertex(
  const typename boost::graph_traits<graph>::
     vertex_descriptor& vd,
  const graph& g
) noexcept
{
  return g[vd];
}
```

One can just use the graph as a property map and let it be looked-up.

To use 'get_bundled_vertex_my_vertex', one first needs to obtain a vertex descriptor. Algorithm 145 shows a simple example.

Algorithm 145 Demonstration if the 'get_bundled_vertex_my_vertex' function

```
#include <cassert>
#include "add_bundled_vertex.h"
#include "create_empty_undirected_bundled_vertices_graph.
    h"
#include "find_first_bundled_vertex_with_my_vertex.h"
#include "get_my_bundled_vertex.h"

void get_my_bundled_vertex_demo() noexcept
{
  auto g
    = create_empty_undirected_bundled_vertices_graph();
  const my_bundled_vertex v{"Dex"};
  add_bundled_vertex(v, g);
  const auto vd
    = find_first_bundled_vertex_with_my_vertex(v, g);
  assert(get_my_bundled_vertex(vd, g) == v);
}
```

9.4 Set a bundled vertex its my_vertex

If you know how to get the 'my_bundled_vertex' from a vertex descriptor, setting it is just as easy, as shown in algorithm 146.

Algorithm 146 Set a bundled vertex its my_vertex from its vertex descriptor

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

template <typename graph>
void set_my_bundled_vertex(
  const my_bundled_vertex& v,
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,"graph␣
      cannot␣be␣const");
  g[vd] = v;
}
```

To use 'set_bundled_vertex_my_vertex', one first needs to obtain a vertex descriptor. Algorithm 147 shows a simple example.

Algorithm 147 Demonstration if the 'set_bundled_vertex_my_vertex' function

```
#include <cassert>

#include "add_bundled_vertex.h"
#include "create_empty_undirected_bundled_vertices_graph.
    h"
#include "find_first_bundled_vertex_with_my_vertex.h"
#include "get_my_bundled_vertex.h"
#include "set_my_bundled_vertex.h"

void set_my_bundled_vertex_demo() noexcept
{
  auto g = create_empty_undirected_bundled_vertices_graph
      ();
  const my_bundled_vertex old_name{"Dex"};
  add_bundled_vertex(old_name, g);
  const auto vd =
      find_first_bundled_vertex_with_my_vertex(old_name,g)
      ;
  assert(get_my_bundled_vertex(vd, g) == old_name);
  const my_bundled_vertex new_name{"Diggy"};
  set_my_bundled_vertex(new_name, vd, g);
  assert(get_my_bundled_vertex(vd, g) == new_name);
}
```

9.5 Setting all bundled vertices' my_vertex objects

When the vertices of a graph are 'my_bundled_vertex' objects, one can set these as such:

Algorithm 148 Setting the bundled vertices' 'my_bundled_vertex'-es

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

template <typename graph>
void set_my_bundled_vertexes(
  graph& g,
  const std::vector<my_bundled_vertex>& my_vertexes
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  auto my_vertexes_begin = std::begin(my_vertexes);
  const auto my_vertexes_end = std::end(my_vertexes);
  const auto vip = vertices(g);
  const auto j = vip.second;
  for (
    auto i = vip.first;
    i!=j; ++i,
    ++my_vertexes_begin
  ) {
    assert(my_vertexes_begin != my_vertexes_end);
    g[*i] = *my_vertexes_begin;
  }
}
```

9.6 Storing a graph with bundled vertices as a .dot

If you used the 'create_bundled_vertices_k2_graph' function (algorithm 137) to produce a K_2 graph with vertices associated with 'my_bundled_vertex' objects, you can store these with algorithm 149:

Algorithm 149 Storing a graph with bundled vertices as a .dot file

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

template <typename graph>
void save_bundled_vertices_graph_to_dot(
  const graph& g,
  const std::string& filename
)
{
  std::ofstream f(filename);
  write_graphviz(f, g,
    make_bundled_vertices_writer(g)
  );
}
```

This code looks small, because we call the 'make_bundled_vertices_writer' function, which is shown in algorithm 150:

Algorithm 150 The 'make_bundled_vertices_writer' function

```
template <typename graph>
inline bundled_vertices_writer<graph>
make_bundled_vertices_writer(
  const graph& g
)
{
  return bundled_vertices_writer<
    graph
  >(g);
}
```

Also this function is forwarding the real work to the 'bundled_vertices_writer', shown in algorithm 151:

Algorithm 151 The 'bundled_vertices_writer' function

```
#include <ostream>
#include "graphviz_encode.h"

template <
  typename graph
>
class bundled_vertices_writer {
public:
  bundled_vertices_writer(
    graph g
  ) : m_g{g}
  {

  }
  template <class vertex_descriptor>
  void operator()(
    std::ostream& out,
    const vertex_descriptor& vd
  ) const noexcept {
    out
      << "[label=\""
        << graphviz_encode(
          m_g[vd].m_name
        )
      << "\",comment=\""
        << graphviz_encode(
          m_g[vd].m_description
        )
      << "\",width="
        << m_g[vd].m_x
      << ",height="
        << m_g[vd].m_y
      << "]"
    ;
  }
private:
  graph m_g;
};
```

Here, some interesting things are happening: the writer needs the bundled property maps to work with and thus copies the whole graph to its internals. I have chosen to map the 'my_bundled_vertex' member variables to Graphviz attributes (see chapter 23.2 for most Graphviz attributes) as shown in table 2:

my_bundled_vertex variable	C++ data type	Graphviz data type	Graphviz attribute
m_name	std::string	string	label
m_description	std::string	string	comment
m_x	double	double	width
m_y	double	double	height

Table 2: Mapping of my_bundled_vertex member variable and Graphviz attributes

Important in this mapping is that the C++ and the Graphviz data types match. I also chose attributes that matched as closely as possible.

The writer also encodes the std::string of the name and description to a Graphviz-friendly format. When loading the .dot file again, this will have to be undone again.

9.7 Loading a directed graph with bundled 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 bundled vertices is loaded, as shown in algorithm 152:

Algorithm 152 Loading a directed graph with bundled vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "create_empty_directed_bundled_vertices_graph.h"
#include "graphviz_decode.h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  my_bundled_vertex
>
load_directed_bundled_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_bundled_vertices_graph()
    ;

  boost::dynamic_properties p;
  p.property("node_id",get(&my_bundled_vertex::m_name, g)
    );
  p.property("label",get(&my_bundled_vertex::m_name, g));
  p.property("comment", get(&my_bundled_vertex::
    m_description, g));
  p.property("width", get(&my_bundled_vertex::m_x, g));
  p.property("height", get(&my_bundled_vertex::m_y, g));
  boost::read_graphviz(f,g,p);

  //Decode vertices
  const auto vip = vertices(g);
  const auto j = vip.second;
  for (auto i = vip.first; i!=j; ++i)
  {
    g[*i].m_name = graphviz_decode(g[*i].m_name);
    g[*i].m_description = graphviz_decode(g[*i].
      m_description);
  }

  return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created, to save typing the typename explicitly.

Then a boost::dynamic_properties is created with its default constructor, after which we set it to follow the same mapping as in the previous chapter. From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

At the moment the graph is created, all 'my_bundled_vertex' their names and description are in a Graphviz-friendly format. By obtaining all vertex iterators and vertex descriptors, the encoding is made undone.

Algorithm 153 shows how to use the 'load_directed_bundled_vertices_graph_from_dot' function:

Algorithm 153 Demonstration of the 'load_directed_bundled_vertices_graph_from_dot' function

```
#include "create_bundled_vertices_markov_chain.h"
#include "load_directed_bundled_vertices_graph_from_dot.h
   "
#include "save_bundled_vertices_graph_to_dot.h"
#include "get_my_bundled_vertexes.h"

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

  const auto g
    = create_bundled_vertices_markov_chain();
  const std::string filename{
    "create_bundled_vertices_markov_chain.dot"
  };
  save_bundled_vertices_graph_to_dot(g, filename);
  const auto h
    = load_directed_bundled_vertices_graph_from_dot(
        filename);
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_my_bundled_vertexes(g) ==
      get_my_bundled_vertexes(h));
}
```

This demonstration shows how the Markov chain is created using the 'create_bundled_vertices_markov_chain' function (algorithm 134), saved and then loaded. The loaded graph is checked to be the same as the original.

9.8 Loading an undirected graph with bundled 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 bundled vertices is loaded, as shown in algorithm 154:

Algorithm 154 Loading an undirected graph with bundled vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "create_empty_undirected_bundled_vertices_graph.
    h"
#include "graphviz_decode.h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  my_bundled_vertex
>
load_undirected_bundled_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_bundled_vertices_graph
      ();

  boost::dynamic_properties p;
  p.property("node_id",get(&my_bundled_vertex::m_name, g)
      );
  p.property("label",get(&my_bundled_vertex::m_name, g));
  p.property("comment", get(&my_bundled_vertex::
      m_description, g));
  p.property("width", get(&my_bundled_vertex::m_x, g));
  p.property("height", get(&my_bundled_vertex::m_y, g));
  boost::read_graphviz(f,g,p);

  //Decode vertices
  const auto vip = vertices(g);
  const auto j = vip.second;
  for (auto i = vip.first; i!=j; ++i)
  {
    g[*i].m_name = graphviz_decode(g[*i].m_name);
    g[*i].m_description = graphviz_decode(g[*i].
        m_description);
  }

  return g;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 9.7 describes the rationale of this function.

Algorithm 155 shows how to use the 'load_undirected_bundled_vertices_graph_from_dot' function:

Algorithm 155 Demonstration of the 'load_undirected_bundled_vertices_graph_from_dot' function

```
#include <cassert>
#include "create_bundled_vertices_k2_graph.h"
#include "load_undirected_bundled_vertices_graph_from_dot
    .h"
#include "save_bundled_vertices_graph_to_dot.h"
#include "get_my_bundled_vertexes.h"

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

  const auto g
    = create_bundled_vertices_k2_graph();
  const std::string filename{
    "create_bundled_vertices_k2_graph.dot"
  };
  save_bundled_vertices_graph_to_dot(g, filename);
  const auto h
    = load_undirected_bundled_vertices_graph_from_dot(
        filename);
  assert(get_my_bundled_vertexes(g)
    == get_my_bundled_vertexes(h)
  );
}
```

This demonstration shows how K_2 with bundled vertices is created using the 'create_bundled_vertices_k2_graph' function (algorithm 137), saved and then loaded. The loaded graph is checked to be the same as the original.

10 Building graphs with bundled edges and vertices

Up until now, the graphs created have had only bundled vertices. In this chapter, graphs will be created, in which both the edges and vertices have a bundled 'my_bundled_edge' and 'my_bundled_edge' type[10].

- An empty directed graph that allows for bundled edges and vertices: see chapter 10.2
- An empty undirected graph that allows for bundled edges and vertices: see chapter 10.3
- A two-state Markov chain with bundled edges and vertices: see chapter 10.6
- $K_3$with bundled edges and vertices: see chapter 10.7

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

- Creating the 'my_bundled_edge' class: see chapter 10.1
- Adding a bundled 'my_bundled_edge': see chapter 10.4

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

10.1 Creating the bundled edge class

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

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

Algorithm 156 Declaration of my_bundled_edge

```
#include <string>
#include <iosfwd>

class my_bundled_edge
{
public:
  explicit my_bundled_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_bundled_edge& lhs, const
    my_bundled_edge& rhs) noexcept;
bool operator!=(const my_bundled_edge& lhs, const
    my_bundled_edge& rhs) noexcept;
```

my_bundled_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_bundled_edge' is copyable, but cannot trivially be converted to a std::string.' 'my_bundled_edge' is comparable for equality (that is, operator== is defined).

'my_bundled_edge' does not have to have the stream operators defined for file I/O, as this goes via the public member variables.

10.2 Create an empty directed graph with bundled edges and vertices

Algorithm 157 Creating an empty directed graph with bundled edges and vertices

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  my_bundled_vertex,
  my_bundled_edge
>
create_empty_directed_bundled_edges_and_vertices_graph()
   noexcept
{
  return {};
}
```

This code is very similar to the code described in chapter 12.3, except that there is a new, fifth template argument:

```
boost::property<boost::edge_bundled_type_t, my_edge>
```

This can be read as: “edges have the property 'boost::edge_bundled_type_t', which is of data type 'my_bundled_edge”'. Or simply: “edges have a bundled type called my_bundled_edge”.

Demo:

Algorithm 158 Demonstration of the 'create_empty_directed_bundled_edges_and_vertices_graph' function

```
#include "
    create_empty_directed_bundled_edges_and_vertices_graph
    .h"

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

10.3 Create an empty undirected graph with bundled edges and vertices

Algorithm 159 Creating an empty undirected graph with bundled edges and vertices

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

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

This code is very similar to the code described in chapter 10.2, except that the directedness (the third template argument) is undirected (due to the boost::undirectedS).

Demo:

Algorithm 160 Demonstration of the 'create_empty_undirected_bundled_edges_and_vertices_graph' function

```
#include <cassert>
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"

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

10.4 Add a bundled edge

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

Algorithm 161 Add a bundled edge

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

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
add_bundled_edge(
  const my_bundled_edge& v,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,"graph␣
     cannot␣be␣const");

  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);
  g[aer.first] = v;
  return aer.first;
}
```

When having added a new (abstract) edge to the graph, the edge descriptor is used to set the my_edge in the graph.

Here is the demo:

Algorithm 162 Demo of 'add_bundled_edge'

```
#include <cassert>
#include "add_bundled_edge.h"
#include "
    create_empty_directed_bundled_edges_and_vertices_graph
    .h"
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"

void add_bundled_edge_demo() noexcept
{
  auto g =
      create_empty_directed_bundled_edges_and_vertices_graph
      ();
  add_bundled_edge(my_bundled_edge("X"), g);
  assert(boost::num_vertices(g) == 2);
  assert(boost::num_edges(g) == 1);

  auto h =
      create_empty_undirected_bundled_edges_and_vertices_graph
      ();
  add_bundled_edge(my_bundled_edge("Y"), h);
  assert(boost::num_vertices(h) == 2);
  assert(boost::num_edges(h) == 1);
}
```

10.5 Getting the bundled edges my_edges

When the edges of a graph are 'my_bundled_edge' objects, one can extract these all as such:

Algorithm 163 Get the edges' my_bundled_edges

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

template <typename graph>
std::vector<my_bundled_edge> get_my_bundled_edges(
  const graph& g
) noexcept
{
  using ed = typename boost::graph_traits<graph>::
      edge_descriptor;
  std::vector<my_bundled_edge> v(boost::num_edges(g));
  const auto eip = edges(g);
  std::transform(eip.first, eip.second, std::begin(v),
    [g](const ed e) { return g[e]; }
  );
  return v;
}
```

The 'my_bundled_edge' object associated with the edges are obtained from the graph its property_map and then put into a std::vector.

Note: the order of the my_bundled_edge objects may be different after saving and loading.

When trying to get the edges' my_bundled_edge objects from a graph without bundled edges objects associated, you will get the error 'formed reference to void' (see chapter 22.1).

10.6 Creating a Markov-chain with bundled edges and vertices

10.6.1 Graph

Figure 30 shows the graph that will be reproduced:

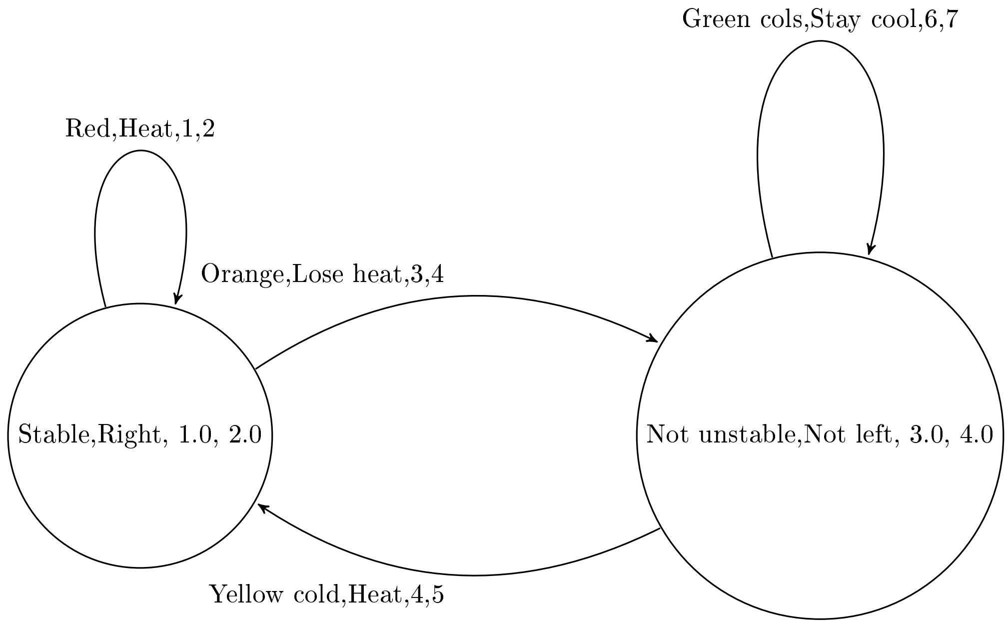

Figure 30: A two-state Markov chain where the edges and vertices have bundled properies. The edges' and vertices' properties are nonsensical

10.6.2 Function to create such a graph

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

Algorithm 164 Creating the two-state Markov chain as depicted in figure 30

```
#include <cassert>
#include "
    create_empty_directed_bundled_edges_and_vertices_graph
    .h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  my_bundled_vertex,
  my_bundled_edge
>
create_bundled_edges_and_vertices_markov_chain() noexcept
{
  auto g
    =
        create_empty_directed_bundled_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);

  g[vd_a]
    = my_bundled_vertex("Stable","Right",1.0,2.0);
  g[vd_b]
    = my_bundled_vertex("Not unstable","Not left"
        ,3.0,4.0);

  g[aer_aa.first]
    = my_bundled_edge("Red","Heat",1.0,2.0);
  g[aer_ab.first]
    = my_bundled_edge("Orange","Lose heat",3.0,4.0);
  g[aer_ba.first]
    = my_bundled_edge("Yellow cold","Heat",5.0,6.0);
  g[aer_bb.first]
    = my_bundled_edge("Green cold","Stay cool",7.0,8.0);

  return g;
}
```

10.6.3 Creating such a graph

Here is the demo:

Algorithm 165 Demo of the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 164)

```
#include <cassert>
#include "create_bundled_edges_and_vertices_markov_chain.
    h"
#include "get_my_bundled_edges.h"
#include "my_bundled_vertex.h"

void create_bundled_edges_and_vertices_markov_chain_demo
    () noexcept
{
  const auto g =
      create_bundled_edges_and_vertices_markov_chain();
  const std::vector<my_bundled_edge> edge_my_edges{
    get_my_bundled_edges(g)
  };
  const std::vector<my_bundled_edge> expected_my_edges{
    my_bundled_edge("Red","Heat",1.0,2.0),
    my_bundled_edge("Orange","Lose heat",3.0,4.0),
    my_bundled_edge("Yellow cold","Heat",5.0,6.0),
    my_bundled_edge("Green cold","Stay cool",7.0,8.0)
  };
  assert(edge_my_edges == expected_my_edges);
}
```

10.6.4 The .dot file produced

Algorithm 166 .dot file created from the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 164), converted from graph to .dot file using algorithm 48

```
digraph G {
0[label="Stable",comment="Right",width=1,height=2];
1[label="Not$$$SPACE$$$unstable",comment="Not$$$SPACE$$$left",width=3,height=4];
0->0 [label="Red",comment="Heat",width=1,height=2];
0->1 [label="Orange",comment="Lose$$$SPACE$$$heat",width=3,height=4];
1->0 [label="Yellow$$$SPACE$$$cold",comment="Heat",width=5,height=6];
1->1 [label="Green$$$SPACE$$$cold",comment="Stay$$$SPACE$$$cool",width=7,height=8];
}
```

10.6.5 The .svg file produced

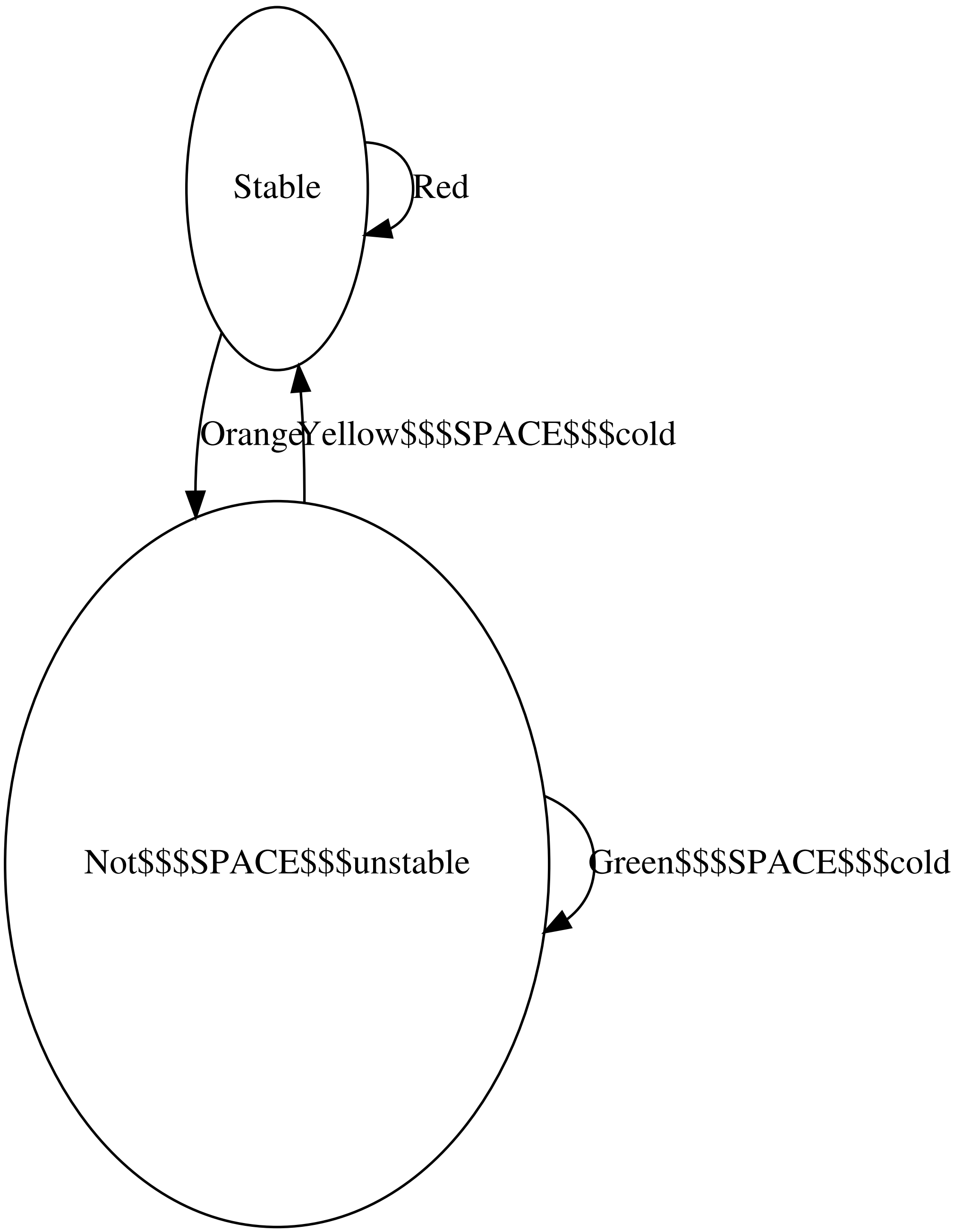

Figure 31: .svg file created from the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 193) its .dot file, converted from .dot file to .svg using algorithm 281

10.7 Creating K_3 with bundled edges and vertices

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

10.7.1 Graph

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

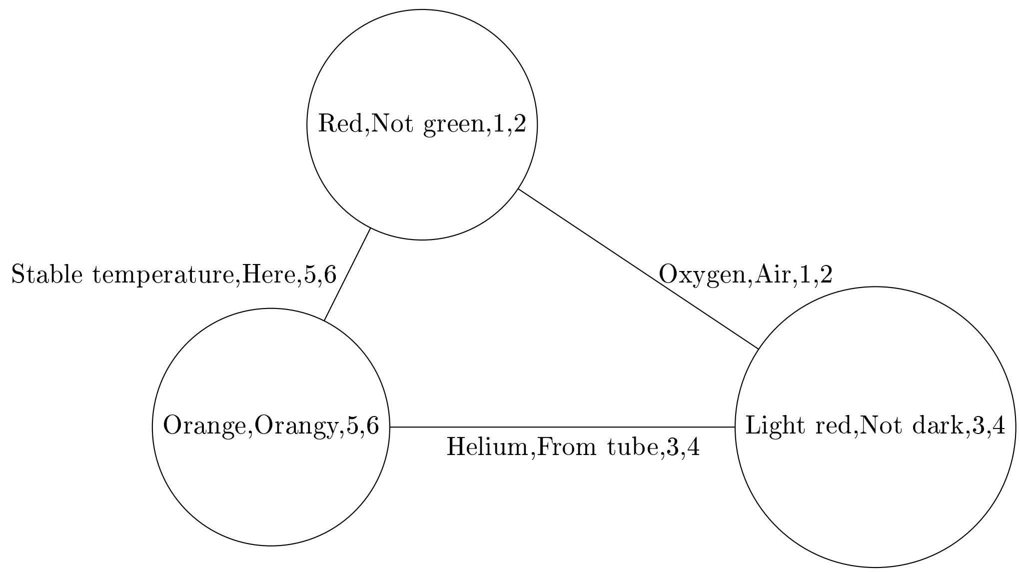

Figure 32: K_3: a fully connected graph with three named edges and vertices

10.7.2 Function to create such a graph

Algorithm 167 Creating K_3 as depicted in figure 24

```
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  my_bundled_vertex,
  my_bundled_edge
>
create_bundled_edges_and_vertices_k3_graph() noexcept
{
  auto g
    =
        create_empty_undirected_bundled_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);

  g[vd_a]
    = my_bundled_vertex("Red","Not green",1.0,2.0);
  g[vd_b]
    = my_bundled_vertex("Light red","Not dark",3.0,4.0);
  g[vd_c]
    = my_bundled_vertex("Orange","Orangy",5.0,6.0);

  g[aer_a.first]
    = my_bundled_edge("Oxygen","Air",1.0,2.0);
  g[aer_b.first]
    = my_bundled_edge("Helium","From tube",3.0,4.0);
  g[aer_c.first]
    = my_bundled_edge("Stable temperature","Here"
        ,5.0,6.0);

  return g;
}
```

Most of the code is a slight modification of algorithm 111. In the end, the my_edges and my_vertices are obtained as the graph its property_map and set with the 'my_bundled_edge' and 'my_bundled_vertex' objects.

10.7.3 Creating such a graph

Here is the demo:

Algorithm 168 Demo of the 'create_bundled_edges_and_vertices_k3_graph' function (algorithm 167)

```
#include <cassert>
#include "add_bundled_edge.h"
#include "add_bundled_vertex.h"
#include "create_bundled_edges_and_vertices_k3_graph.h"

void create_bundled_edges_and_vertices_k3_graph_demo()
    noexcept
{
  auto g
    = create_bundled_edges_and_vertices_k3_graph();
  assert(boost::num_edges(g) == 3);
  assert(boost::num_vertices(g) == 3);
  add_bundled_vertex(my_bundled_vertex("v"), g);
  add_bundled_edge(my_bundled_edge("e"), g);
}
```

10.7.4 The .dot file produced

Algorithm 169 .dot file created from the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 167), converted from graph to .dot file using algorithm 48

```
graph G {
0[label="Red",comment="Not$$$SPACE$$$green",width=1,height=2];
1[label="Light$$$SPACE$$$red",comment="Not$$$SPACE$$$dark",width=3,height=4];
2[label="Orange",comment="Orangy",width=5,height=6];
0--1 [label="Oxygen",comment="Air",width=1,height=2];
1--2 [label="Helium",comment="From$$$SPACE$$$tube",width=3,height=4];
2--0 [label="Stable$$$SPACE$$$temperature",comment="Here",width=5,height=6];
}
```

10.7.5 The .svg file produced

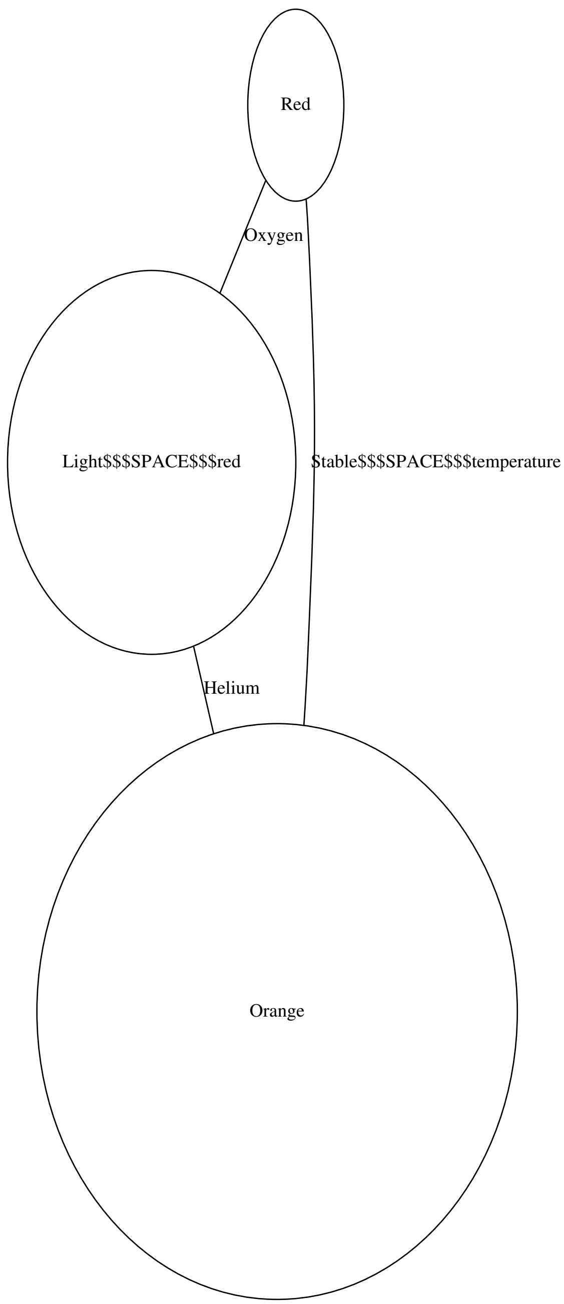

Figure 33: .svg file created from the 'create_bundled_edges_and_vertices_k3_graph' function (algorithm 193) its .dot file, converted from .dot file to .svg using algorithm 281

11 Working on graphs with bundled edges and vertices

11.1 Has a my_bundled_edge

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

Algorithm 170 Find if there is a bundled edge with a certain my_bundled_edge

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

template <typename graph>
bool has_bundled_edge_with_my_edge(
  const my_bundled_edge& e,
  const graph& g
) noexcept
{
  using ed = typename boost::graph_traits<graph>::
      edge_descriptor;
  const auto eip = edges(g);
  return std::find_if(eip.first, eip.second,
    [e, g](const ed& d)
    {
      return g[d] == e;
    }
  ) != eip.second;
}
```

This function can be demonstrated as in algorithm 171, where a certain 'my_bundled_edge' cannot be found in an empty graph. After adding the desired my_bundled_edge, it is found.

Algorithm 171 Demonstration of the 'has_bundled_edge_with_my_edge' function

```
#include <cassert>
#include "add_bundled_edge.h"
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"
#include "has_bundled_edge_with_my_edge.h"

void has_bundled_edge_with_my_edge_demo() noexcept
{
  auto g
    =
        create_empty_undirected_bundled_edges_and_vertices_graph
        ();
  assert(
    !has_bundled_edge_with_my_edge(
      my_bundled_edge("Edward"),g
    )
  );
  add_bundled_edge(my_bundled_edge("Edward"),g);
  assert(
    has_bundled_edge_with_my_edge(
      my_bundled_edge("Edward"),g
    )
  );
}
```

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

11.2 Find a my_bundled_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 172 shows how to obtain an edge descriptor to the first edge found with a specific my_bundled_edge value.

Algorithm 172 Find the first bundled edge with a certain my_bundled_edge

```
#include <cassert>
#include <boost/graph/graph_traits.hpp>
#include "has_bundled_edge_with_my_edge.h"
#include "has_custom_edge_with_my_edge.h"
#include "my_bundled_edge.h"

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
find_first_bundled_edge_with_my_edge(
  const my_bundled_edge& e,
  const graph& g
) noexcept
{
  using ed = typename boost::graph_traits<graph>::
      edge_descriptor;
  const auto eip = edges(g);
  const auto i = std::find_if(
    eip.first, eip.second,
    [e,g](const ed d) { return g[d] == e; }
  );
  assert(i != eip.second);
  return *i;
}
```

With the edge descriptor obtained, one can read and modify the edge and the vertices surrounding it. Algorithm 173 shows some examples of how to do so.

Algorithm 173 Demonstration of the 'find_first_bundled_edge_with_my_edge' function

```
#include <cassert>

#include "create_bundled_edges_and_vertices_k3_graph.h"
#include "find_first_bundled_edge_with_my_edge.h"

void find_first_bundled_edge_with_my_edge_demo() noexcept
{
  const auto g
    = create_bundled_edges_and_vertices_k3_graph();
  const auto ed
    = find_first_bundled_edge_with_my_edge(
    my_bundled_edge("Oxygen","Air",1.0,2.0),
    g
  );
  assert(boost::source(ed,g)
    != boost::target(ed,g)
  );
}
```

11.3 Get an edge its my_bundled_edge

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

Algorithm 174 Get a vertex its my_bundled_vertex from its vertex descriptor

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

template <typename graph>
my_bundled_edge get_my_bundled_edge(
  const typename boost::graph_traits<graph>::
      edge_descriptor& ed,
  const graph& g
) noexcept
{
  return g[ed];
}
```

To use 'get_my_bundled_edge', one first needs to obtain an edge descriptor. Algorithm 175 shows a simple example.

Algorithm 175 Demonstration if the 'get_my_bundled_edge' function

```
#include <cassert>

#include "add_bundled_edge.h"
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"
#include "find_first_bundled_edge_with_my_edge.h"
#include "get_my_bundled_edge.h"

void get_my_bundled_edge_demo() noexcept
{
  auto g
    =
        create_empty_undirected_bundled_edges_and_vertices_graph
        ();
  const my_bundled_edge edge{"Dex"};
  add_bundled_edge(edge, g);
  const auto ed
    = find_first_bundled_edge_with_my_edge(edge, g);
  assert(get_my_bundled_edge(ed,g) == edge);
}
```

11.4 Set an edge its my_bundled_edge

If you know how to get the my_bundled_edge from an edge descriptor, setting it is just as easy, as shown in algorithm 176.

Algorithm 176 Set a bundled edge its my_bundled_edge from its edge descriptor

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

template <typename graph>
void set_my_bundled_edge(
  const my_bundled_edge& name,
  const typename boost::graph_traits<graph>::
      edge_descriptor& ed,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );
  g[ed] = name;
}
```

To use 'set_bundled_edge_my_edge', one first needs to obtain an edge descriptor. Algorithm 177 shows a simple example.

Algorithm 177 Demonstration if the 'set_bundled_edge_my_edge' function

```
#include <cassert>

#include "add_bundled_edge.h"
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"
#include "find_first_bundled_edge_with_my_edge.h"
#include "get_my_bundled_edge.h"
#include "set_my_bundled_edge.h"

void set_my_bundled_edge_demo() noexcept
{
  auto g
    =
        create_empty_undirected_bundled_edges_and_vertices_graph
        ();
  const my_bundled_edge old_edge{"Dex"};
  add_bundled_edge(old_edge, g);
  const auto vd
    = find_first_bundled_edge_with_my_edge(old_edge,g);
  assert(get_my_bundled_edge(vd,g)
    == old_edge
  );
  const my_bundled_edge new_edge{"Diggy"};
  set_my_bundled_edge(new_edge, vd, g);
  assert(get_my_bundled_edge(vd,g)
    == new_edge
  );
}
```

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

If you used the 'create_bundled_edges_and_vertices_k3_graph' function (algorithm 167) to produce a K_3 graph with edges and vertices associated with my_bundled_edge and my_bundled_vertex objects, you can store these my_bundled_edges and my_bundled_vertex-es additionally with algorithm 178:

Algorithm 178 Storing a graph with bundled edges and vertices as a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "make_bundled_vertices_writer.h"
#include "make_bundled_edges_writer.h"

template <typename graph>
void save_bundled_edges_and_vertices_graph_to_dot(
  const graph& g,
  const std::string& filename
)
{
  std::ofstream f(filename);
  write_graphviz(
    f,
    g,
    make_bundled_vertices_writer(g),
    make_bundled_edges_writer(g)
  );
}
```

11.6 Load a directed graph with bundled 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 bundled edges and vertices is loaded, as shown in algorithm 179:

Algorithm 179 Loading a directed graph with bundled edges and vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "
    create_empty_directed_bundled_edges_and_vertices_graph
    .h"
#include "is_regular_file.h"
#include "graphviz_decode.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  my_bundled_vertex,
  my_bundled_edge
>
load_directed_bundled_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_bundled_edges_and_vertices_graph
      ();

  boost::dynamic_properties p;
  p.property("node_id",get(&my_bundled_vertex::m_name, g)
      );
  p.property("label",get(&my_bundled_vertex::m_name, g));
  p.property("comment", get(&my_bundled_vertex::
      m_description, g));
  p.property("width", get(&my_bundled_vertex::m_x, g));
  p.property("height", get(&my_bundled_vertex::m_y, g));
  p.property("edge_id",get(&my_bundled_edge::m_name, g));
  p.property("label",get(&my_bundled_edge::m_name, g));
  p.property("comment", get(&my_bundled_edge::
      m_description, g));
  p.property("width", get(&my_bundled_edge::m_width, g));
  p.property("height", get(&my_bundled_edge::m_height, g)
      );
  boost::read_graphviz(f,g,p);

  //Decode vertices
  {
    const auto vip = vertices(g);
    const auto j = vip.second;
    for (auto i = vip.first; i!=j; ++i)
    {
      g[*i].m_name = graphviz_decode(g[*i].m_name);
      g[*i].m_description = graphviz_decode(g[*i].
          m_description);
    }
  }
```

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 180 shows how to use the 'load_directed_bundled_edges_and_vertices_graph_from_dot' function:

Algorithm 180 Demonstration of the 'load_directed_bundled_edges_and_vertices_graph_from_dot' function

```
#include "create_bundled_edges_and_vertices_markov_chain.
    h"
#include "get_sorted_bundled_vertex_my_vertexes.h"
#include "
    load_directed_bundled_edges_and_vertices_graph_from_dot
    .h"
#include "save_bundled_edges_and_vertices_graph_to_dot.h"

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

  const auto g
    = create_bundled_edges_and_vertices_markov_chain();
  const std::string filename{
    "create_bundled_edges_and_vertices_markov_chain.dot"
  };
  save_bundled_edges_and_vertices_graph_to_dot(g,
     filename);
  const auto h
    =
        load_directed_bundled_edges_and_vertices_graph_from_dot
        (
      filename
    );
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_sorted_bundled_vertex_my_vertexes(g)
    == get_sorted_bundled_vertex_my_vertexes(h)
  );
}
```

This demonstration shows how the Markov chain is created using the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 164), saved and then loaded.

11.7 Load an undirected graph with bundled 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 bundled edges and vertices is loaded, as shown in algorithm 181:

Algorithm 181 Loading an undirected graph with bundled edges and vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"
#include "is_regular_file.h"
#include "graphviz_decode.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  my_bundled_vertex,
  my_bundled_edge
>
load_undirected_bundled_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_bundled_edges_and_vertices_graph
      ();

  boost::dynamic_properties p;
  p.property("node_id",get(&my_bundled_vertex::m_name, g)
      );
  p.property("label",get(&my_bundled_vertex::m_name, g));
  p.property("comment", get(&my_bundled_vertex::
      m_description, g));
  p.property("width", get(&my_bundled_vertex::m_x, g));
  p.property("height", get(&my_bundled_vertex::m_y, g));
  p.property("edge_id",get(&my_bundled_edge::m_name, g));
  p.property("label",get(&my_bundled_edge::m_name, g));
  p.property("comment", get(&my_bundled_edge::
      m_description, g));
  p.property("width", get(&my_bundled_edge::m_width, g));
  p.property("height", get(&my_bundled_edge::m_height, g)
      );
  boost::read_graphviz(f,g,p);

  //Decode vertices
  {
    const auto vip = vertices(g);
    const auto j = vip.second;
    for (auto i = vip.first; i!=j; ++i)
    {
      g[*i].m_name = graphviz_decode(g[*i].m_name);
      g[*i].m_description = graphviz_decode(g[*i].
          m_description);
    }
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 11.6 describes the rationale of this function.

Algorithm 182 shows how to use the 'load_undirected_bundled_vertices_graph_from_dot' function:

Algorithm 182 Demonstration of the 'load_undirected_bundled_edges_and_vertices_graph_from_dot' function

```
#include "create_bundled_edges_and_vertices_k3_graph.h"
#include "get_sorted_bundled_vertex_my_vertexes.h"
#include "
    load_undirected_bundled_edges_and_vertices_graph_from_dot
    .h"
#include "save_bundled_edges_and_vertices_graph_to_dot.h"

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

  const auto g
    = create_bundled_edges_and_vertices_k3_graph();
  const std::string filename{
    "create_bundled_edges_and_vertices_k3_graph.dot"
  };
  save_bundled_edges_and_vertices_graph_to_dot(g,
      filename);
  const auto h
    =
        load_undirected_bundled_edges_and_vertices_graph_from_dot
        (
      filename
    );
  assert(num_edges(g) == num_edges(h));
  assert(num_vertices(g) == num_vertices(h));
  assert(get_sorted_bundled_vertex_my_vertexes(g)
    == get_sorted_bundled_vertex_my_vertexes(h)
  );
}
```

This demonstration shows how K_2 with bundled vertices is created using the 'create_bundled_vertices_k2_graph' function (algorithm 196), saved and then loaded. The loaded graph is checked to be a graph similar to the original.

12 Building graphs with custom vertices

Instead of using bundled properties, you can also add a new custom property. The difference is that instead of having a class *as* a vertex, vertices have *an additional property* where the 'my_custom_vertex' is stored, next to properties like vertex name, edge delay (see chapter 23.1 for all properties). The following graphs will be created:

- An empty directed graph that allows for custom vertices: see chapter 185
- An empty undirected graph that allows for custom vertices: see chapter 12.3
- A two-state Markov chain with custom vertices: see chapter 12.7
- $K_2$with custom vertices: see chapter 12.8

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

- Installing a new vertex property, called 'vertex_custom_type': chapter 12.2
- Adding a custom vertex: see chapter 12.5
- Getting the custom vertices my_vertex-es: see chapter 12.6

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

12.1 Creating the vertex class

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

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

Algorithm 183 Declaration of my_custom_vertex

```
#include <string>
#include <iosfwd>

class my_custom_vertex
{
public:
  explicit my_custom_vertex(
    const std::string& name = "",
    const std::string& description = "",
    const double x = 0.0,
    const double y = 0.0
  ) noexcept;
  const std::string& get_description() const noexcept;
  const std::string& get_name() const noexcept;
  double get_x() const noexcept;
  double get_y() const noexcept;
private:
  std::string m_name;
  std::string m_description;
  double m_x;
  double m_y;
};

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

'my_custom_vertex' is a class that has multiple properties:

- It has four private member variables: the double 'm_x' ('m_' stands for member), the double 'm_y', the std::string m_name and the std::string m_description. These variables are private, but there are getters supplied
- It has a default constructor
- It is copyable
- It is comparable for equality (it has operator==), which is needed for searching

- It can be streamed (it has both operator<< and operator>>), which is needed for file I/O.

Special characters like comma's, quotes and whitespace cannot be streamed without problems. The function 'graphviz_encode' (algorithm 278) can convert the elements to be streamed to a Graphviz-friendly version, which can be decoded by 'graphviz_decode' (algorithm 279).

12.2 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 184 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.

12.3 Create the empty directed graph with custom vertices

Algorithm 185 Creating an empty directed graph with custom vertices

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex
  >
>
create_empty_directed_custom_vertices_graph() noexcept
{
  return {};
}
```

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".

The demo:

Algorithm 186 Demo how to create an empty directed graph with custom vertices

```
#include "create_empty_directed_custom_vertices_graph.h"

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

12.4 Create the empty undirected graph with custom vertices

Algorithm 187 Creating an empty undirected graph with custom vertices

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

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

This code is very similar to the code described in chapter 12.3, except that the directedness (the third template argument) is undirected (due to the boost::undirectedS).

The demo:

Algorithm 188 Demo how to create an empty undirected graph with custom vertices

```
#include "create_empty_undirected_custom_vertices_graph.h
    "

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

12.5 Add a custom vertex

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

Algorithm 189 Add a custom vertex

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

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
add_custom_vertex(
  const my_custom_vertex& v,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  const auto vd = boost::add_vertex(g);
  const auto my_custom_vertex_map
    = get(boost::vertex_custom_type, g);
  put(my_custom_vertex_map, vd, v);
  return vd;
}
```

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)').

Here is the demo:

Algorithm 190 Demo of 'add_custom_vertex'

```
#include <cassert>
#include "add_custom_vertex.h"
#include "create_empty_directed_custom_vertices_graph.h"
#include "create_empty_undirected_custom_vertices_graph.h
    "

void add_custom_vertex_demo() noexcept
{
  auto g
    = create_empty_directed_custom_vertices_graph();
  assert(boost::num_vertices(g) == 0);
  assert(boost::num_edges(g) == 0);
  add_custom_vertex(my_custom_vertex("X"), g);
  assert(boost::num_vertices(g) == 1);
  assert(boost::num_edges(g) == 0);

  auto h
    = create_empty_undirected_custom_vertices_graph();
  assert(boost::num_vertices(h) == 0);
  assert(boost::num_edges(h) == 0);
  add_custom_vertex(my_custom_vertex("X"), h);
  assert(boost::num_vertices(h) == 1);
  assert(boost::num_edges(h) == 0);
}
```

12.6 Getting the vertices' my_vertexes[11]

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

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

Algorithm 191 Get the my_custom_vertex objects

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

template <typename graph>
std::vector<my_custom_vertex> get_my_custom_vertexes(
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  std::vector<my_custom_vertex> v(boost::num_vertices(g))
     ;
  const auto vip = vertices(g);
  std::transform(vip.first, vip.second, std::begin(v),
    [g](const vd& d)
    {
      const auto my_custom_vertexes_map
        = get(boost::vertex_custom_type,g
      );
      return get(my_custom_vertexes_map, d);
    }
  );
  return v;
}
```

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

The order of the 'my_custom_vertex' objects may be different after saving and loading.

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 22.1).

Demo:

Algorithm 192 Demo how to the vertices' my_custom_vertex objects

```
#include <cassert>
#include "create_custom_vertices_k2_graph.h"
#include "get_my_custom_vertexes.h"

void get_my_custom_vertexes_demo() noexcept
{
  const auto g = create_custom_vertices_k2_graph();
  const std::vector<my_custom_vertex>
      expected_my_custom_vertexes{
    my_custom_vertex("A","source",0.0,0.0),
    my_custom_vertex("B","target",3.14,3.14)
  };
  const std::vector<my_custom_vertex> vertexes{
    get_my_custom_vertexes(g)
  };
  assert(expected_my_custom_vertexes == vertexes);
}
```

12.7 Creating a two-state Markov chain with custom vertices

12.7.1 Graph

Figure 34 shows the graph that will be reproduced:

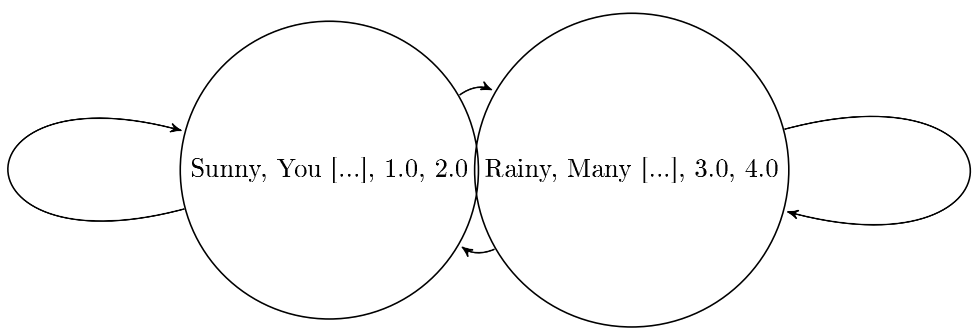

Figure 34: A two-state Markov chain where the vertices have custom properies and the edges have no properties. The vertices' properties are nonsensical

12.7.2 Function to create such a graph

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

Algorithm 193 Creating the two-state Markov chain as depicted in figure 34

```
#include <cassert>
#include "create_empty_directed_custom_vertices_graph.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_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 my_custom_vertex_map = get(
    boost::vertex_custom_type,g
  );
  put(my_custom_vertex_map, vd_a,
    my_custom_vertex("Sunny","Yellow thing",1.0,2.0)
  );
  put(my_custom_vertex_map, vd_b,
    my_custom_vertex("Rainy", "Grey things",3.0,4.0)
  );
  return g;
}
```

12.7.3 Creating such a graph

Here is the demo:

Algorithm 194 Demo of the 'create_custom_vertices_markov_chain' function (algorithm 193)

```
#include <cassert>
#include "create_custom_vertices_markov_chain.h"
#include "get_my_custom_vertexes.h"

void create_custom_vertices_markov_chain_demo() noexcept
{
  const auto g
    = create_custom_vertices_markov_chain();
  const std::vector<my_custom_vertex>
    expected_my_custom_vertexes{
    my_custom_vertex("Sunny","Yellow thing",1.0,2.0),
    my_custom_vertex("Rainy","Grey things",3.0,4.0)
  };
  const std::vector<my_custom_vertex>
    vertex_my_custom_vertexes{
    get_my_custom_vertexes(g)
  };
  assert(expected_my_custom_vertexes
    == vertex_my_custom_vertexes
  );
}
```

12.7.4 The .dot file produced

Algorithm 195 .dot file created from the 'create_custom_vertices_markov_chain' function (algorithm 193), converted from graph to .dot file using algorithm 208

```
digraph G {
0[label="Sunny,Yellow$$$SPACE$$$thing,1,1"];
1[label="Rainy,Grey$$$SPACE$$$things,3,3"];
0->0 ;
0->1 ;
1->0 ;
1->1 ;
}
```

This .dot file may look unexpectedly different: instead of a space, there is this '[[:SPACE:]]' thing. This is because the function 'graphviz_encode' (algorithm 278) made this conversion. In this example, I could have simply surrounded the content by quotes, and this would have worked. I chose to use 'graphviz_encode' because it works in all contexts.

12.7.5 The .svg file produced

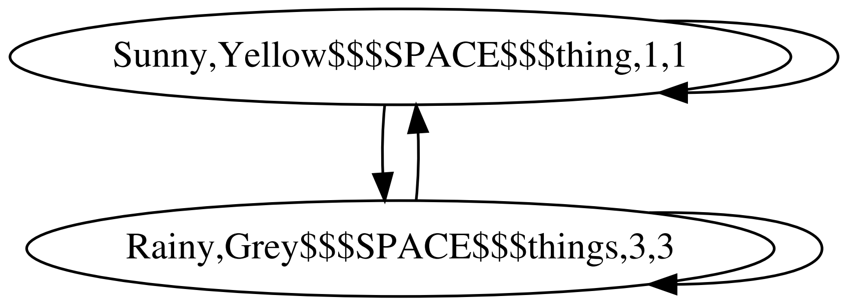

Figure 35: .svg file created from the 'create_custom_vertices_markov_chain' function (algorithm 193) its .dot file, converted from .dot file to .svg using algorithm 281

This .svg file may look unexpectedly different: instead of a space, there is this '[[:SPACE:]]' thing. This is because the function 'graphviz_encode' (algorithm 278) made this conversion.

12.8 Creating K_2 with custom vertices

12.8.1 Graph

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

12.8.2 Function to create such a graph

Algorithm 196 Creating K_2 as depicted in figure 18

```
#include "create_empty_undirected_custom_vertices_graph.h
    "

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_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_custom_vertex_map = get(
    boost::vertex_custom_type,g
  );
  put(my_custom_vertex_map, vd_a,
    my_custom_vertex("A","source",0.0,0.0)
  );
  put(my_custom_vertex_map, vd_b,
    my_custom_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 65). In the end, the my_vertices are obtained as a boost::property_map and set with two custom my_vertex objects.

12.8.3 Creating such a graph

Demo:

Algorithm 197 Demo of the 'create_custom_vertices_k2_graph' function (algorithm 196)

```
#include <cassert>
#include <iostream>
#include "create_custom_vertices_k2_graph.h"
#include "has_custom_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_custom_vertex_with_my_custom_vertex(
    my_custom_vertex("A", "source" ,0.0, 0.0), g)
  );
  assert(has_custom_vertex_with_my_custom_vertex(
    my_custom_vertex("B", "target" ,3.14, 3.14), g)
  );
}
```

12.8.4 The .dot file produced

Algorithm 198 .dot file created from the 'create_custom_vertices_k2_graph' function (algorithm 196), converted from graph to .dot file using algorithm 48

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

12.8.5 The .svg file produced

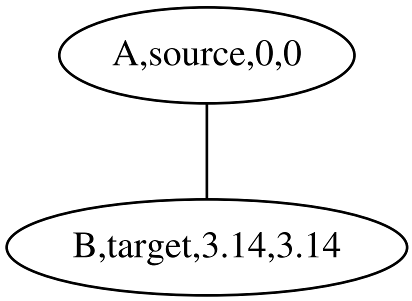

Figure 36: .svg file created from the 'create_custom_vertices_k2_graph' function (algorithm 196) its .dot file, converted from .dot file to .svg using algorithm 281

13 Working on graphs with custom vertices (as a custom property)

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 13.1
- Find a vertex with a certain 'my_vertex': chapter 13.2
- Get a vertex its 'my_vertex' from its vertex descriptor: chapter 13.3
- Set a vertex its 'my_vertex' using its vertex descriptor: chapter 13.4
- Setting all vertices their 'my_vertex'es: chapter 13.5
- Storing an directed/undirected graph with custom vertices as a .dot file: chapter 13.6
- Loading a directed graph with custom vertices from a .dot file: chapter 13.7
- Loading an undirected directed graph with custom vertices from a .dot file: chapter 13.8

13.1 Has a custom vertex with 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 199 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_custom_vertex.h"

template <typename graph>
bool has_custom_vertex_with_my_custom_vertex(
  const my_custom_vertex& v,
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  const auto vip = vertices(g);
  return std::find_if(vip.first, vip.second,
    [v, g](const vd& d)
    {
      const auto my_custom_vertexes_map
        = get(boost::vertex_custom_type, g);
      return get(my_custom_vertexes_map, d) == v;
    }
  ) != vip.second;
}
```

This function can be demonstrated as in algorithm 200, where a certain my_vertex cannot be found in an empty graph. After adding the desired my_vertex, it is found.

Algorithm 200 Demonstration of the 'has_custom_vertex_with_my_vertex' function

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

#include "add_custom_vertex.h"
#include "create_empty_undirected_custom_vertices_graph.h
    "
#include "has_custom_vertex_with_my_vertex.h"
#include "install_vertex_custom_type.h"
#include "my_custom_vertex.h"

void has_custom_vertex_with_my_custom_vertex_demo()
    noexcept
{
  auto g = create_empty_undirected_custom_vertices_graph
      ();
  assert(!has_custom_vertex_with_my_custom_vertex(
      my_custom_vertex("Felix"),g));
  add_custom_vertex(my_custom_vertex("Felix"),g);
  assert(has_custom_vertex_with_my_custom_vertex(
      my_custom_vertex("Felix"),g));
}
```

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

13.2 Find a custom 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 201 shows how to obtain a vertex descriptor to the first vertex found with a specific my_vertex value.

Algorithm 201 Find the first vertex with a certain my_vertex

```
#include <cassert>
#include <boost/graph/graph_traits.hpp>
#include <boost/graph/properties.hpp>
#include "has_custom_vertex_with_my_vertex.h"
#include "install_vertex_custom_type.h"
#include "my_custom_vertex.h"

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_custom_vertex_with_my_vertex(
  const my_custom_vertex& v,
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;
  const auto vip = vertices(g);
  const auto i = std::find_if(
    vip.first, vip.second,
    [v,g](const vd d) {
      const auto my_vertex_map = get(boost::
          vertex_custom_type, g);
      return get(my_vertex_map, d) == v;
    }
  );
  assert(i != vip.second);
  return *i;
}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 202 shows some examples of how to do so.

Algorithm 202 Demonstration of the 'find_first_custom_vertex_with_my_vertex' function

```
#include <cassert>

#include "create_custom_vertices_k2_graph.h"
#include "find_first_custom_vertex_with_my_vertex.h"

void find_first_custom_vertex_with_my_vertex_demo()
    noexcept
{
  const auto g = create_custom_vertices_k2_graph();
  const auto vd = find_first_custom_vertex_with_my_vertex
      (
    my_custom_vertex("A","source",0.0,0.0),
    g
  );
  assert(out_degree(vd,g) == 1);
  assert(in_degree(vd,g) == 1);
}
```

13.3 Get a custom vertex its my_vertex

To obtain the name from a vertex descriptor, one needs to pull out the my_vertexes[12] map and then look up the vertex of interest.

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

Algorithm 203 Get a my_custom_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_custom_vertex.h"

template <typename graph>
my_custom_vertex get_my_custom_vertex(
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  const graph& g
) noexcept
{
  const auto my_custom_vertexes_map
    = get(boost::vertex_custom_type,
       g
    );
  return get(my_custom_vertexes_map, vd);
}
```

To use 'get_custom_vertex_my_vertex', one first needs to obtain a vertex descriptor. Algorithm 204 shows a simple example.

Algorithm 204 Demonstration if the 'get_my_custom_vertex' function

```
#include <cassert>
#include "add_custom_vertex.h"
#include "create_empty_undirected_custom_vertices_graph.h
   "
#include "find_first_custom_vertex_with_my_vertex.h"
#include "get_my_custom_vertex.h"

void get_my_custom_vertex_demo() noexcept
{
  auto g = create_empty_undirected_custom_vertices_graph
      ();
  const my_custom_vertex name{"Dex"};
  add_custom_vertex(name, g);
  const auto vd
    = find_first_custom_vertex_with_my_vertex(name,g);
  assert(get_my_custom_vertex(vd,g) == name);
}
```

13.4 Set a custom 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 205.

Algorithm 205 Set a custom 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_custom_vertex.h"

template <typename graph>
void set_my_custom_vertex(
  const my_custom_vertex& v,
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  const auto my_custom_vertexes_map
    = get(boost::vertex_custom_type, g);
  put(my_custom_vertexes_map, vd, v);
}
```

To use 'set_my_custom_vertex', one first needs to obtain a vertex descriptor. Algorithm 206 shows a simple example.

Algorithm 206 Demonstration if the 'set_my_custom_vertex' function

```
#include <cassert>

#include "add_custom_vertex.h"
#include "create_empty_undirected_custom_vertices_graph.h
    "
#include "find_first_custom_vertex_with_my_vertex.h"
#include "get_my_custom_vertex.h"
#include "set_my_custom_vertex.h"

void set_my_custom_vertex_demo() noexcept
{
  auto g
    = create_empty_undirected_custom_vertices_graph();
  const my_custom_vertex old_vertex{"Dex"};
  add_custom_vertex(old_vertex, g);
  const auto vd
    = find_first_custom_vertex_with_my_vertex(old_vertex,
        g);
  assert(get_my_custom_vertex(vd,g)
    == old_vertex
  );
  const my_custom_vertex new_vertex{"Diggy"};
  set_my_custom_vertex(
    new_vertex, vd, g
  );
  assert(get_my_custom_vertex(vd,g)
    == new_vertex
  );
}
```

13.5 Setting all custom 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 207 Setting the custom 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_custom_vertex.h"

template <typename graph>
void set_my_custom_vertexes(
  graph& g,
  const std::vector<my_custom_vertex>& my_custom_vertexes
) noexcept
{
  static_assert(!std::is_const<graph>::value,"graph␣
      cannot␣be␣const");

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

  auto my_custom_vertexes_begin = std::begin(
      my_custom_vertexes);
  const auto my_custom_vertexes_end = std::end(
      my_custom_vertexes);
  const auto vip = vertices(g);
  const auto j = vip.second;
  for (
    auto i = vip.first;
    i!=j; ++i,
    ++my_custom_vertexes_begin
  ) {
    assert(my_custom_vertexes_begin !=
        my_custom_vertexes_end);
    put(my_custom_vertex_map, *i,*
        my_custom_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.

13.6 Storing a graph with custom vertices as a .dot

If you used the create_custom_vertices_k2_graph function (algorithm 196) to produce a K_2 graph with vertices associated with my_vertex objects, you can store these my_vertexes additionally with algorithm 208:

Algorithm 208 Storing a graph with custom vertices as a .dot file

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

template <typename graph>
void save_custom_vertices_graph_to_dot(
  const graph& g,
  const std::string& filename
) noexcept
{
  using vd = typename graph::vertex_descriptor;

  std::ofstream f(filename);
  boost::write_graphviz(
    f,
    g,
    [g](std::ostream& out, const vd& v) {
      const auto my_custom_vertexes_map
        = get(boost::vertex_custom_type,g)
      ;
      const my_custom_vertex m{get(my_custom_vertexes_map
          ,v)};
      out << "[label=\"" << m << "\"]";
    }
  );
}
```

13.7 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 209:

Algorithm 209 Loading a directed graph with custom vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "create_empty_directed_custom_vertices_graph.h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex
  >
>
load_directed_custom_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_custom_vertices_graph();
  boost::dynamic_properties p;
  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 210 shows how to use the 'load_directed_custom_vertices_graph_from_dot' function:

Algorithm 210 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_my_custom_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_my_custom_vertexes(g)
    == get_my_custom_vertexes(h)
  );
}
```

This demonstration shows how the Markov chain is created using the 'create_custom_vertices_markov_chain' function (algorithm 193), saved and then loaded. The loaded graph is then checked to be identical to the original.

13.8 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 211:

Algorithm 211 Loading an undirected graph with custom vertices from a .dot file

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

#include "create_empty_undirected_custom_vertices_graph.h
    "
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex
  >
>
load_undirected_custom_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_custom_vertices_graph
      ();
  boost::dynamic_properties p;
  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;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 13.7 describes the rationale of this function.

Algorithm 212 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

Algorithm 212 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_my_custom_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_my_custom_vertexes(g) ==
      get_my_custom_vertexes(h));
}
```

This demonstration shows how K_2 with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 196), saved and then loaded. The loaded graph is then checked to be identical to the original.

14 Building graphs with custom and selectable vertices

We have added one custom vertex property, here we add a second: if the vertex is selected.

- An empty directed graph that allows for custom and selectable vertices: see chapter 14.2
- An empty undirected graph that allows for custom and selectable vertices:

see chapter 14.3

- A two-state Markov chain with custom and selectable vertices: see chapter 14.5
- $K_3$with custom and selectable vertices: see chapter 14.6

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

- Installing the new edge property: see chapter 14.1
- Adding a custom and selectable vertex: see chapter 14.4

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

14.1 Installing the new is_selected 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 213 Installing the vertex_is_selected property

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

namespace boost {
  enum vertex_is_selected_t { vertex_is_selected = 31416
      };
  BOOST_INSTALL_PROPERTY(vertex, is_selected);
}
```

The enum value 31415 must be unique.

14.2 Create an empty directed graph with custom and selectable vertices

Algorithm 214 Creating an empty directed graph with custom and selectable vertices

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex,
    boost::property<
      boost::vertex_is_selected_t, bool
    >
  >
>
create_empty_directed_custom_and_selectable_vertices_graph
    () noexcept
{
  return {};
}
```

This code is very similar to the code described in chapter 12.3, except that there is a new, fourth template argument:

```
boost::property<boost::vertex_custom_type_t, my_custom_vertex,
  boost::property<boost::vertex_is_selected_t, bool,
>
```

This can be read as: “vertices have two properties: an associated custom type (of type my_custom_vertex) and an associated is_selected property (of type bool)”.

Demo:

Algorithm 215 Demonstration of the 'create_empty_directed_custom_and_selectable_vertices_graph' function

```
#include "
    create_empty_directed_custom_and_selectable_vertices_graph
    .h"

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

14.3 Create an empty undirected graph with custom and selectable vertices

Algorithm 216 Creating an empty undirected graph with custom and selectable vertices

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex,
    boost::property<
      boost::vertex_is_selected_t, bool
    >
  >
>
create_empty_undirected_custom_and_selectable_vertices_graph
    () noexcept
{
  return {};
}
```

This code is very similar to the code described in chapter 14.2, except that the directedness (the third template argument) is undirected (due to the boost::undirectedS).

Demo:

Algorithm 217 Demonstration of the 'create_empty_undirected_custom_and_selectable_vertices_graph' function

```
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"

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

14.4 Add a custom and selectable vertex

Adding a custom and selectable vertex is very similar to adding a custom vertex (chapter 12.5).

Algorithm 218 Add a custom and selectable vertex

```
#include <type_traits>
#include <boost/graph/adjacency_list.hpp>
#include "install_vertex_custom_type.h"
#include "install_vertex_is_selected.h"
#include "my_custom_vertex.h"

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
add_custom_and_selectable_vertex(
  const my_custom_vertex& v,
  const bool is_selected,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  const auto vd = boost::add_vertex(g);

  const auto my_custom_vertex_map
    = get(boost::vertex_custom_type,
      g
    );
  put(my_custom_vertex_map, vd, v);

  const auto is_selected_map
    = get(boost::vertex_is_selected,
      g
    );
  put(is_selected_map, vd, is_selected);
  return vd;
}
```

When having added a new (abstract) vertex to the graph, the vertex descriptor is used to set the my_custom_vertex and the selectedness in the graph its my_custom_vertex and is_selected map .

Here is the demo:

Algorithm 219 Demo of 'add_custom_and_selectable_vertex'

```
#include <cassert>
#include "add_custom_and_selectable_vertex.h"
#include "
    create_empty_directed_custom_and_selectable_vertices_graph
    .h"
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"

void add_custom_and_selectable_vertex_demo() noexcept
{
  auto g
    =
        create_empty_directed_custom_and_selectable_vertices_graph
        ();
  assert(boost::num_vertices(g) == 0);
  assert(boost::num_edges(g) == 0);
  add_custom_and_selectable_vertex(
    my_custom_vertex("X"),
    true,
    g
  );
  assert(boost::num_vertices(g) == 1);
  assert(boost::num_edges(g) == 0);

  auto h
    =
        create_empty_undirected_custom_and_selectable_vertices_graph
        ();
  assert(boost::num_vertices(h) == 0);
  assert(boost::num_edges(h) == 0);
  add_custom_and_selectable_vertex(
    my_custom_vertex("X"),
    false,
    h
  );
  assert(boost::num_vertices(h) == 1);
  assert(boost::num_edges(h) == 0);
}
```

14.5 Creating a Markov-chain with custom and selectable vertices

14.5.1 Graph

Figure 37 shows the graph that will be reproduced:

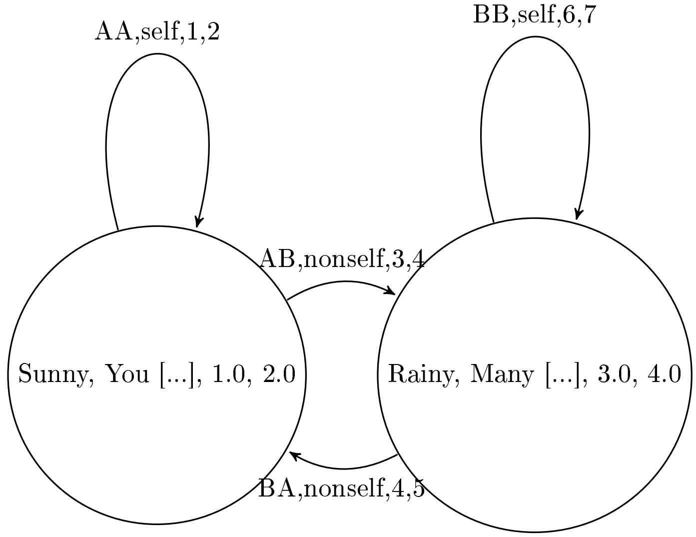

Figure 37: A two-state Markov chain where the edges and vertices have custom properies. The edges' and vertices' properties are nonsensical

14.5.2 Function to create such a graph

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

Algorithm 220 Creating the two-state Markov chain as depicted in figure 37

```
#include <cassert>
#include "
    create_empty_directed_custom_and_selectable_vertices_graph
    .h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex,
    boost::property<
      boost::vertex_is_selected_t, bool
    >
  >
>
create_custom_and_selectable_vertices_markov_chain()
    noexcept
{
  auto g
    =
        create_empty_directed_custom_and_selectable_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_custom_vertex_map = get(
    boost::vertex_custom_type,g
  );
  put(my_custom_vertex_map, vd_a,
    my_custom_vertex("Sunny","Yellow thing",1.0,2.0)
  );
  put(my_custom_vertex_map, vd_b,
    my_custom_vertex("Rainy", "Grey things",3.0,4.0)
  );
  auto is_selected_map = get(
    boost::vertex_is_selected, g
  );
  put(is_selected_map, vd_a, true);
  put(is_selected_map, vd_b, false);
  return g;
}
```

14.5.3 Creating such a graph

Here is the demo:

Algorithm 221 Demo of the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 220)

```
#include <cassert>
#include "
    create_custom_and_selectable_vertices_markov_chain.h"
#include "get_vertex_selectednesses.h"

void
    create_custom_and_selectable_vertices_markov_chain_demo
    () noexcept
{
  const auto g
    = create_custom_and_selectable_vertices_markov_chain
        ();
  const std::vector<bool>
    expected_selectednesses{
    true, false
  };
  const std::vector<bool>
    vertex_selectednesses{
    get_vertex_selectednesses(g)
  };
  assert(expected_selectednesses
    == vertex_selectednesses
  );
}
```

14.5.4 The .dot file produced

Algorithm 222 .dot file created from the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 220), converted from graph to .dot file using algorithm 48

```
digraph G {
0[label="Sunny,Yellow$$$SPACE$$$thing,1,1", regular="1"];
1[label="Rainy,Grey$$$SPACE$$$things,3,3", regular="0"];
0->0 ;
0->1 ;
1->0 ;
1->1 ;
}
```

14.5.5 The .svg file produced

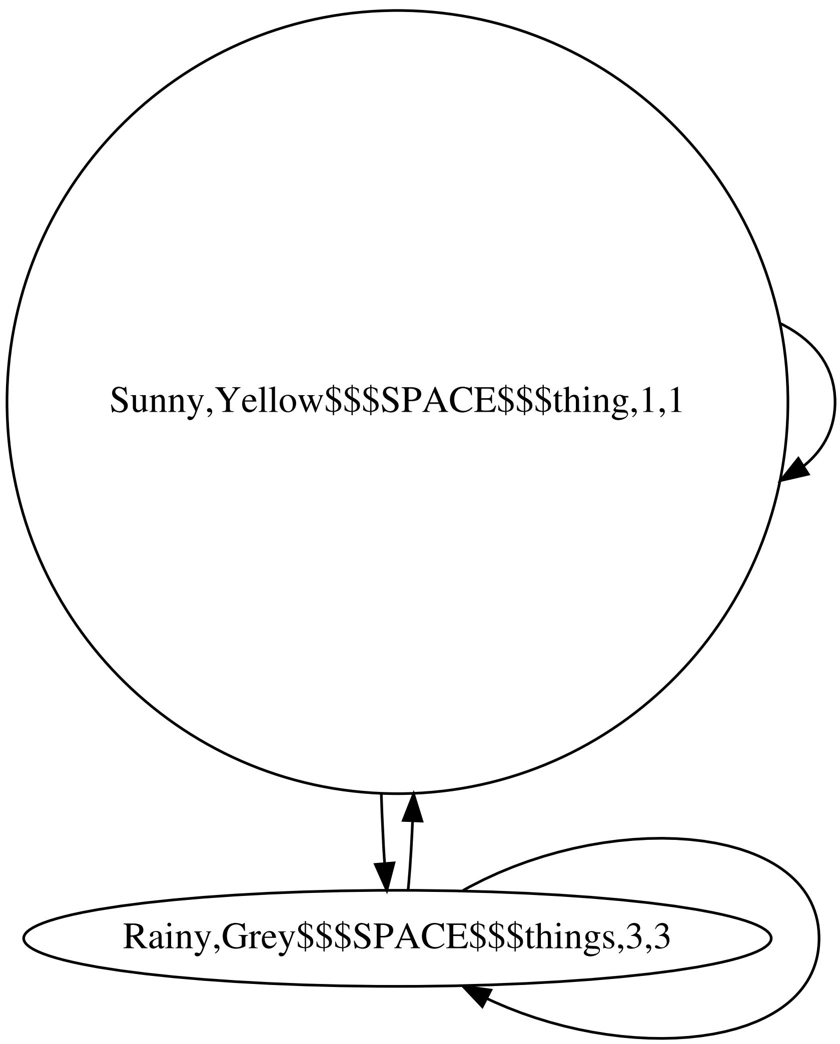

Figure 38: .svg file created from the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 193) its .dot file, converted from .dot file to .svg using algorithm 281

Note how the .svg changed it appearance due to the Graphviz 'regular' property (see chapter 23.2): the vertex labeled 'Sunny' is drawn according to the Graphviz 'regular' attribute, which makes it a circle. The other vertex, labeled 'Rainy' is not drawn as such and retained its ellipsoid appearance.

14.6 Creating K_2 with custom and selectable vertices

14.6.1 Graph

We reproduce the K_2 with custom vertices of chapter 12.8 , but now are vertices can be selected as well:

[graph here]

14.6.2 Function to create such a graph

Algorithm 223 Creating K_3 as depicted in figure 24

```
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex,
    boost::property<
      boost::vertex_is_selected_t, bool
    >
  >
>
create_custom_and_selectable_vertices_k2_graph() noexcept
{
  auto g
    =
        create_empty_undirected_custom_and_selectable_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_custom_vertexes_map = get(
    boost::vertex_custom_type,
    g
  );
  put(my_custom_vertexes_map, vd_a,
    my_custom_vertex("A","source",0.0,0.0)
  );
  put(my_custom_vertexes_map, vd_b,
    my_custom_vertex("B","target",3.14,3.14)
  );

  auto is_selected_map = get(
    boost::vertex_is_selected,
    g
  );
  put(is_selected_map, vd_a, true);
  put(is_selected_map, vd_b, false);
  return g;
}
```

Most of the code is a slight modification of algorithm 196. In the end, the associated my_custom_vertex and is_selected properties are obtained as boost::property_maps and set with the desired my_custom_vertex objects and selectednesses.

14.6.3 Creating such a graph

Here is the demo:

Algorithm 224 Demo of the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 223)

```
#include <cassert>
#include "create_custom_and_selectable_vertices_k2_graph.
    h"
#include "has_custom_vertex_with_my_vertex.h"

void create_custom_and_selectable_vertices_k2_graph_demo
    () noexcept
{
  const auto g =
      create_custom_and_selectable_vertices_k2_graph();
  assert(boost::num_edges(g) == 1);
  assert(boost::num_vertices(g) == 2);
  assert(has_custom_vertex_with_my_custom_vertex(
    my_custom_vertex("A", "source" ,0.0, 0.0), g)
  );
  assert(has_custom_vertex_with_my_custom_vertex(
    my_custom_vertex("B", "target" ,3.14, 3.14), g)
  );
}
```

14.6.4 The .dot file produced

Algorithm 225 .dot file created from the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 223), converted from graph to .dot file using algorithm 48

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

14.6.5 The .svg file produced

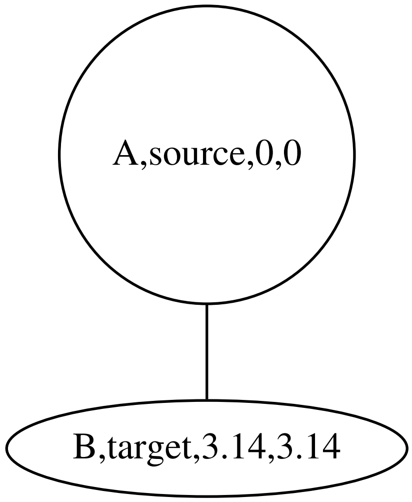

Figure 39: .svg file created from the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 193) its .dot file, converted from .dot file to .svg using algorithm 281

Note how the .svg changed it appearance due to the Graphviz 'regular' property (see chapter 23.2): the vertex labeled 'A' is drawn according to the Graphviz 'regular' attribute, which makes it a circle. The other vertex, labeled 'B' is not drawn as such and retained its ellipsoid appearance.

15 Working on graphs with custom and selectable vertices

This chapter shows some basic operations to do on graphs with custom and selectable vertices.

- Storing an directed/undirected graph with custom and selectable vertices as a .dot file: chapter 15.1
- Loading a directed graph with custom and selectable vertices from a .dot file: chapter 15.2
- Loading an undirected directed graph with custom and selectable vertices from a .dot file: chapter 15.3

15.1 Storing a graph with custom and selectable vertices as a .dot

If you used the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 223) to produce a K_2 graph with vertices associated with (1) my_custom_vertex objects, and (2) a boolean indicating its selectedness, you can store such graphs with algorithm 226:

Algorithm 226 Storing a graph with custom and selectable vertices as a .dot file

```
#include <fstream>
#include <string>
#include <boost/graph/graphviz.hpp>
#include "install_vertex_custom_type.h"
#include "install_vertex_is_selected.h"
#include "make_custom_and_selectable_vertices_writer.h"
#include "my_custom_vertex.h"

template <typename graph>
void save_custom_and_selectable_vertices_graph_to_dot(
  const graph& g,
  const std::string& filename
)
{
  std::ofstream f(filename);
  write_graphviz(f, g,
    make_custom_and_selectable_vertices_writer(
      get(boost::vertex_custom_type,g),
      get(boost::vertex_is_selected,g)
    )
  );
}
```

This code looks small, because we call the 'make_custom_and_selectable_vertices_writer' function, which is shown in algorithm 227:

Algorithm 227 The 'make_custom_and_selectable_vertices_writer' function

```
template <
  typename my_custom_vertex_map,
  typename is_selected_map
>
inline custom_and_selectable_vertices_writer<
  my_custom_vertex_map,
  is_selected_map
>
make_custom_and_selectable_vertices_writer(
  const my_custom_vertex_map& any_my_custom_vertex_map,
  const is_selected_map& any_is_selected_map
)
{
  return custom_and_selectable_vertices_writer<
    my_custom_vertex_map,
    is_selected_map
  >(
    any_my_custom_vertex_map,
    any_is_selected_map
  );
}
```

Also this function is forwarding the real work to the 'custom_and_selectable_vertices_writer', shown in algorithm 228:

Algorithm 228 The 'custom_and_selectable_vertices_writer' function

```
#include <ostream>

template <
  typename my_custom_vertex_map,
  typename is_selected_map
>
class custom_and_selectable_vertices_writer {
public:
  custom_and_selectable_vertices_writer(
    my_custom_vertex_map any_my_custom_vertex_map,
    is_selected_map any_is_selected_map
  ) : m_my_custom_vertex_map{any_my_custom_vertex_map},
      m_is_selected_map{any_is_selected_map}
  {

  }
  template <class vertex_descriptor>
  void operator()(
    std::ostream& out,
    const vertex_descriptor& vd
  ) const noexcept {
    out << "[label=\"" << m_my_custom_vertex_map[vd]
      << "\", regular=\"" << m_is_selected_map[vd]
      << "\"]"
    ;
  }
private:
  my_custom_vertex_map m_my_custom_vertex_map;
  is_selected_map m_is_selected_map;
};
```

Here, some interesting things are happening: the writer needs both property maps to work with (that is, the 'my_custom_vertex' and is_selected maps). The 'my_custom_vertex' are written to the Graphviz 'label' attribute, and the is_selected is written to the 'regular' attribute (see chapter 23.2 for most Graphviz attributes).

15.2 Loading a directed graph with custom and selectable 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 and selectable vertices is loaded, as shown in algorithm 229:

Algorithm 229 Loading a directed graph with custom vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "
    create_empty_directed_custom_and_selectable_vertices_graph
    .h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex,
    boost::property<
      boost::vertex_is_selected_t, bool
    >
  >
>
load_directed_custom_and_selectable_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_custom_and_selectable_vertices_graph
      ();
  boost::dynamic_properties p;
  p.property("node_id", get(boost::vertex_custom_type, g)
      );
  p.property("label", get(boost::vertex_custom_type, g));
  p.property("regular", get(boost::vertex_is_selected, 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. Then, a boost::dynamic_properties is created with its default constructor, after which

- The Graphviz attribute 'node_id' (see chapter 23.2 for most Graphviz attributes) is connected to a vertex its 'my_custom_vertex' property

- The Graphviz attribute 'label' is connected to a vertex its 'my_custom_vertex' property
- The Graphviz attribute 'regular' is connected to a vertex its 'is_selected' vertex property

Algorithm 230 shows how to use the 'load_directed_custom_vertices_graph_from_dot' function:

Algorithm 230 Demonstration of the 'load_directed_custom_and_selectable_vertices_graph_from_dot' function

```
#include <cassert>
#include "
    create_custom_and_selectable_vertices_markov_chain.h"
#include "is_regular_file.h"
#include "
    save_custom_and_selectable_vertices_graph_to_dot.h"

void
    load_directed_custom_and_selectable_vertices_graph_from_dot_demo
    () noexcept
{
  const auto g
    = create_custom_and_selectable_vertices_markov_chain
        ();
  const std::string filename{
    "create_custom_and_selectable_vertices_markov_chain.
        dot"
  };
  save_custom_and_selectable_vertices_graph_to_dot(
    g,
    filename
  );
  assert(is_regular_file(filename));
}
```

This demonstration shows how the Markov chain is created using the 'create_custom_vertices_markov_chain' function (algorithm 193), saved and then checked to exist.

15.3 Loading an undirected graph with custom and selectable 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 and selectable vertices is loaded, as shown in algorithm 231:

Algorithm 231 Loading an undirected graph with custom vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"
#include "install_vertex_custom_type.h"
#include "is_regular_file.h"
#include "my_custom_vertex.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex,
    boost::property<
      boost::vertex_is_selected_t, bool
    >
  >
>
load_undirected_custom_and_selectable_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_custom_and_selectable_vertices_graph
      ();
  boost::dynamic_properties p;
  p.property("node_id", get(boost::vertex_custom_type, g)
      );
  p.property("label", get(boost::vertex_custom_type, g));
  p.property("regular", get(boost::vertex_is_selected, g)
      );
  boost::read_graphviz(f,g,p);
  return g;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 15.2 describes the rationale of this function.

Algorithm 232 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

Algorithm 232 Demonstration of the 'load_undirected_custom_and_selectable_vertices_graph_from_dot' function

```
#include <cassert>
#include "create_custom_and_selectable_vertices_k2_graph.
    h"
#include "is_regular_file.h"
#include "
    save_custom_and_selectable_vertices_graph_to_dot.h"

void
    load_undirected_custom_and_selectable_vertices_graph_from_dot_demo
    () noexcept
{
  const auto g
    = create_custom_and_selectable_vertices_k2_graph();
  const std::string filename{
    "create_custom_and_selectable_vertices_k2_graph.dot"
  };
  save_custom_and_selectable_vertices_graph_to_dot(
    g,
    filename
  );
  assert(is_regular_file(filename));
}
```

This demonstration shows how K_2 with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 196), saved and then checked to exist.

16 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_custom_edge' and 'my_custom_edge' type[13].

- An empty directed graph that allows for custom edges and vertices: see chapter 16.3

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

- An empty undirected graph that allows for custom edges and vertices: see chapter 16.4
- A two-state Markov chain with custom edges and vertices: see chapter 16.7
- $K_3$with custom edges and vertices: see chapter 16.8

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

- Creating the custom edge class: see chapter 16.1
- Installing the new edge property: see chapter 16.2
- Adding a custom edge: see chapter 16.5

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

16.1 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.

Algorithm 233 Declaration of my_custom_edge

```
#include <string>
#include <iosfwd>

class my_custom_edge
{
public:
  explicit my_custom_edge(
    const std::string& name = "",
    const std::string& description = "",
    const double width = 1.0,
    const double height = 1.0
  ) noexcept;
  const std::string& get_description() const noexcept;
  const std::string& get_name() const noexcept;
  double get_width() const noexcept;
  double get_height() const noexcept;
  private:
  std::string m_name;
  std::string m_description;
  double m_width;
  double m_height;
};

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

my_custom_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_custom_edge' is copyable, but cannot trivially be converted to a std::string.' 'my_custom_edge' is comparable for equality (that is, operator== is defined).

Special characters like comma's, quotes and whitespace cannot be streamed without problems. The function 'graphviz_encode' (algorithm 278) can convert the elements to be streamed to a Graphviz-friendly version, which can be decoded by 'graphviz_decode' (algorithm 279).

16.2 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 234 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.

16.3 Create an empty directed graph with custom edges and vertices

Algorithm 235 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_custom_edge.h"
#include "my_custom_vertex.h"

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

This code is very similar to the code described in chapter 12.3, except that there is 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_custom_edge”'. Or simply: “edges have a custom type called my_custom_edge”.

Demo:

Algorithm 236 Demonstration of the 'create_empty_directed_custom_edges_and_vertices_graph' function

```
#include "
    create_empty_directed_custom_edges_and_vertices_graph.
    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);
}
```

16.4 Create an empty undirected graph with custom edges and vertices

Algorithm 237 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_custom_vertex.h"
#include "my_custom_edge.h"

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

This code is very similar to the code described in chapter 16.3, except that the directedness (the third template argument) is undirected (due to the boost::undirectedS).

Demo:

Algorithm 238 Demonstration of the 'create_empty_undirected_custom_edges_and_vertices_graph' function

```
#include <cassert>
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .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);
}
```

16.5 Add a custom edge

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

Algorithm 239 Add a custom edge

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

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
add_custom_edge(
  const my_custom_edge& v,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,"graph␣
     cannot␣be␣const");

  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(boost::edge_custom_type, g);
  put(my_edge_map, aer.first, v);
  return aer.first;
}
```

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_custom_edge map (using 'get(boost::edge_custom_type,g)').

Here is the demo:

Algorithm 240 Demo of 'add_custom_edge'

```
#include <cassert>
#include "add_custom_edge.h"
#include "
    create_empty_directed_custom_edges_and_vertices_graph.
    h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"

void add_custom_edge_demo() noexcept
{
  auto g =
     create_empty_directed_custom_edges_and_vertices_graph
     ();
  add_custom_edge(my_custom_edge("X"), g);
  assert(boost::num_vertices(g) == 2);
  assert(boost::num_edges(g) == 1);

  auto h =
     create_empty_undirected_custom_edges_and_vertices_graph
     ();
  add_custom_edge(my_custom_edge("Y"), h);
  assert(boost::num_vertices(h) == 2);
  assert(boost::num_edges(h) == 1);
}
```

16.6 Getting the custom edges my_edges

When the edges of a graph have an associated 'my_custom_edge', one can extract these all as such:

Algorithm 241 Get the edges' my_custom_edges

```
#include <vector>
#include <boost/graph/adjacency_list.hpp>
#include "install_edge_custom_type.h"
#include "my_custom_edge.h"

template <typename graph>
std::vector<my_custom_edge> get_my_custom_edges(
  const graph& g
) noexcept
{
  using ed = typename boost::graph_traits<graph>::
      edge_descriptor;
  std::vector<my_custom_edge> v(boost::num_edges(g));
  const auto eip = edges(g);
  std::transform(eip.first, eip.second, std::begin(v),
    [g](const ed d)
    {
      const auto my_custom_edges_map
        = get(boost::edge_custom_type,g);
      return get(my_custom_edges_map, d);
    }
  );
  return v;
}
```

The 'my_custom_edge' object associated with the edges are obtained from a boost::property_map and then put into a std::vector.

Note: the order of the my_custom_edge objects may be different after saving and loading.

When trying to get the edges' my_custom_edge objects from a graph without custom edges objects associated, you will get the error 'formed reference to void' (see chapter 22.1).

16.7 Creating a Markov-chain with custom edges and vertices

16.7.1 Graph

Figure 40 shows the graph that will be reproduced:

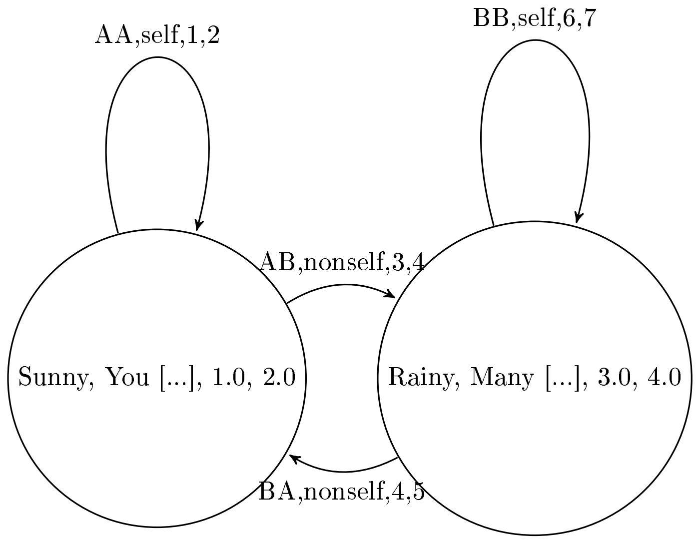

Figure 40: A two-state Markov chain where the edges and vertices have custom properies. The edges' and vertices' properties are nonsensical

16.7.2 Function to create such a graph

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

Algorithm 242 Creating the two-state Markov chain as depicted in figure 40

```
#include <cassert>
#include "
    create_empty_directed_custom_edges_and_vertices_graph.
    h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex
  >,
  boost::property<
    boost::edge_custom_type_t, my_custom_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_custom_vertexes_map = get(
    boost::vertex_custom_type,g
  );
  put(my_custom_vertexes_map, vd_a,
    my_custom_vertex("Sunny","Yellow␣thing",1.0,2.0)
  );
  put(my_custom_vertexes_map, vd_b,
    my_custom_vertex("Rainy","Grey␣things",3.0,4.0)
  );

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

16.7.3 Creating such a graph

Here is the demo:

Algorithm 243 Demo of the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 242)

```
#include <cassert>
#include "create_custom_edges_and_vertices_markov_chain.h
    "
#include "get_my_custom_vertexes.h"
#include "install_vertex_custom_type.h"
#include "my_custom_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_custom_vertex>
    expected_my_custom_vertexes{
    my_custom_vertex("Sunny",
      "Yellow thing",1.0,2.0
    ),
    my_custom_vertex("Rainy",
      "Grey things",3.0,4.0
    )
  };
  const std::vector<my_custom_vertex>
    vertex_my_custom_vertexes{
    get_my_custom_vertexes(g)
  };
  assert(expected_my_custom_vertexes
    == vertex_my_custom_vertexes
  );
}
```

16.7.4 The .dot file produced

Algorithm 244 .dot file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 242), converted from graph to .dot file using algorithm 48

```
digraph G {
0[label="Sunny,Yellow$$$SPACE$$$thing,1,1"];
1[label="Rainy,Grey$$$SPACE$$$things,3,3"];
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"];
}
```

16.7.5 The .svg file produced

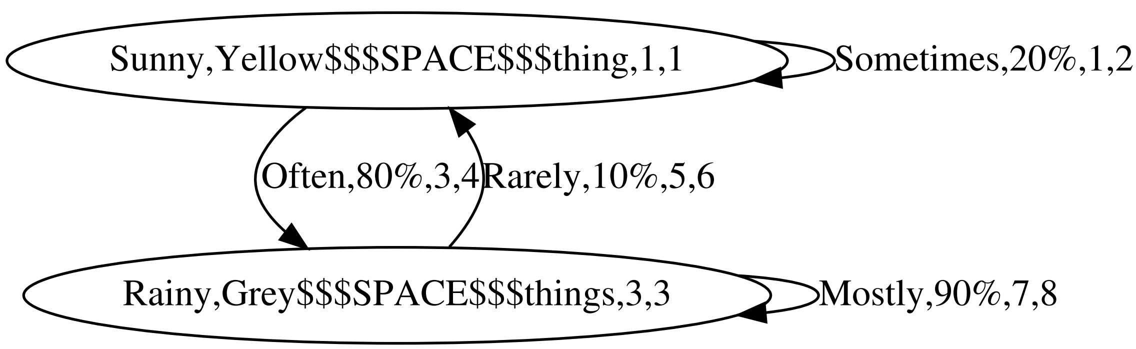

Figure 41: .svg file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 193) its .dot file, converted from .dot file to .svg using algorithm 281

16.8 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_custom_edge'.

16.8.1 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]

16.8.2 Function to create such a graph

Algorithm 245 Creating K_3 as depicted in figure 24

```
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex
  >,
  boost::property<
    boost::edge_custom_type_t, my_custom_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_custom_vertex_map  = get(
      boost::vertex_custom_type,g
    );
  put(my_custom_vertex_map,vd_a,
    my_custom_vertex("top","source",0.0,0.0)
  );
  put(my_custom_vertex_map, vd_b,
    my_custom_vertex("right","target",3.14,0)
  );
  put(my_custom_vertex_map, vd_c,
    my_custom_vertex("left","target",0,3.14)
  );

  auto my_edge_map = get(boost::edge_custom_type,g);
  put(my_edge_map, aer_a.first,
    my_custom_edge("AB","first",0.0,0.0)
  );
  put(my_edge_map, aer_b.first,
    my_custom_edge("BC","second",3.14,3.14)
  );
  put(my_edge_map, aer_c.first,
```

Most of the code is a slight modification of algorithm 111. In the end, the my_edges and my_vertices are obtained as a boost::property_map and set with the 'my_custom_edge' and 'my_custom_vertex' objects.

16.8.3 Creating such a graph

Here is the demo:

Algorithm 246 Demo of the 'create_custom_edges_and_vertices_k3_graph' function (algorithm 245)

```
#include <cassert>
#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_custom_vertex("v"), g);
  add_custom_edge(my_custom_edge("e"), g);
}
```

16.8.4 The .dot file produced

Algorithm 247 .dot file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 245), converted from graph to .dot file using algorithm 48

```
graph G {
0[label="top,source,0,0"];
1[label="right,target,3.14,3.14"];
2[label="left,target,0,0"];
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"];
}
```

16.8.5 The .svg file produced

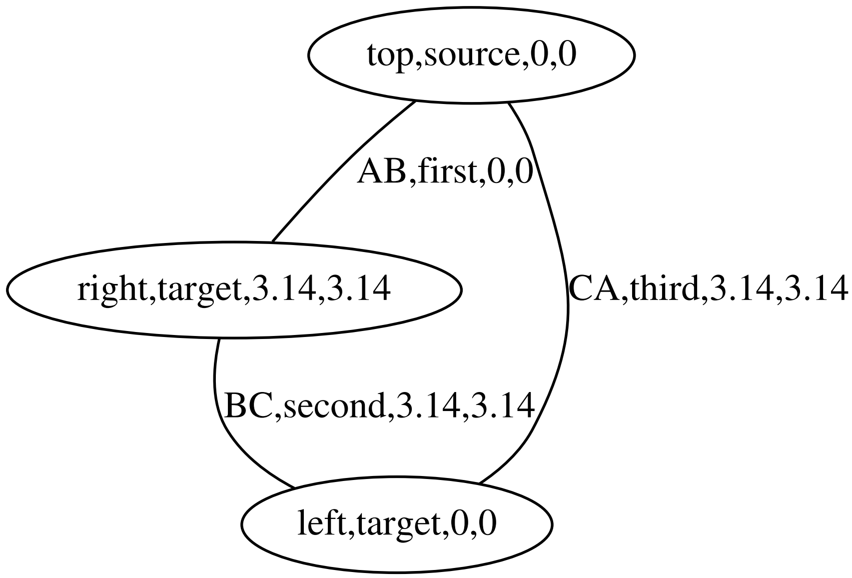

Figure 42: .svg file created from the 'create_custom_edges_and_vertices_k3_graph' function (algorithm 193) its .dot file, converted from .dot file to .svg using algorithm 281

17 Working on graphs with custom edges and vertices

17.1 Has a my_custom_edge

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

Algorithm 248 Find if there is a custom edge with a certain my_custom_edge

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

template <typename graph>
bool has_custom_edge_with_my_edge(
  const my_custom_edge& e,
  const graph& g
) noexcept
{
  using ed = typename boost::graph_traits<graph>::
      edge_descriptor;
  const auto eip = edges(g);
  return std::find_if(eip.first, eip.second,
    [e, g](const ed& d)
    {
      const auto my_edges_map
        = get(boost::edge_custom_type,g);
      return get(my_edges_map, d) == e;
    }
  ) != eip.second;
}
```

This function can be demonstrated as in algorithm 249, where a certain 'my_custom_edge' cannot be found in an empty graph. After adding the desired my_custom_edge, it is found.

Algorithm 249 Demonstration of the 'has_custom_edge_with_my_edge' function

```
#include <cassert>
#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "has_custom_edge_with_my_edge.h"

void has_custom_edge_with_my_edge_demo() noexcept
{
  auto g
    =
        create_empty_undirected_custom_edges_and_vertices_graph
        ();
  assert(
    !has_custom_edge_with_my_edge(
      my_custom_edge("Edward"),g
    )
  );
  add_custom_edge(my_custom_edge("Edward"),g);
  assert(
    has_custom_edge_with_my_edge(
      my_custom_edge("Edward"),g
    )
  );
}
```

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

17.2 Find a my_custom_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 250 shows how to obtain an edge descriptor to the first edge found with a specific my_custom_edge value.

Algorithm 250 Find the first custom edge with a certain my_custom_edge

```
#include <cassert>
#include <boost/graph/graph_traits.hpp>
#include "has_custom_edge_with_my_edge.h"
#include "install_edge_custom_type.h"
#include "my_custom_edge.h"

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
find_first_custom_edge_with_my_edge(
  const my_custom_edge& e,
  const graph& g
) noexcept
{
  using ed = typename boost::graph_traits<graph>::
      edge_descriptor;
  const auto eip = edges(g);
  const auto i = std::find_if(
    eip.first, eip.second,
    [e,g](const ed d) {
      const auto my_edges_map = get(boost::
          edge_custom_type, g);
      return get(my_edges_map, d) == e;
    }
  );
  assert(i != eip.second);
  return *i;
}
```

With the edge descriptor obtained, one can read and modify the edge and the vertices surrounding it. Algorithm 251 shows some examples of how to do so.

Algorithm 251 Demonstration of the 'find_first_custom_edge_with_my_edge' function

```
#include <cassert>

#include "create_custom_edges_and_vertices_k3_graph.h"
#include "find_first_custom_edge_with_my_edge.h"

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

17.3 Get an edge its my_custom_edge

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

Algorithm 252 Get a vertex its my_custom_vertex from its vertex descriptor

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

template <typename graph>
my_custom_edge get_my_custom_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 get(my_edge_map, vd);
}
```

To use 'get_custom_edge_my_custom_edge', one first needs to obtain an edge descriptor. Algorithm 253 shows a simple example.

Algorithm 253 Demonstration if the 'get_custom_edge_my_edge' function

```
#include <cassert>

#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "find_first_custom_edge_with_my_edge.h"
#include "get_my_custom_edge.h"

void get_my_custom_edge_demo() noexcept
{
  auto g
    =
        create_empty_undirected_custom_edges_and_vertices_graph
        ();
  const my_custom_edge edge{"Dex"};
  add_custom_edge(edge, g);
  const auto ed
    = find_first_custom_edge_with_my_edge(edge, g);
  assert(get_my_custom_edge(ed,g) == edge);
}
```

17.4 Set an edge its my_custom_edge

If you know how to get the my_custom_edge from an edge descriptor, setting it is just as easy, as shown in algorithm 254.

Algorithm 254 Set a custom edge its my_custom_edge from its edge descriptor

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

template <typename graph>
void set_my_custom_edge(
  const my_custom_edge& name,
  const typename boost::graph_traits<graph>::
      edge_descriptor& vd,
  graph& g
) noexcept
{
  static_assert(!std::is_const<graph>::value,"graph␣
      cannot␣be␣const");

  auto my_edge_map = get(boost::edge_custom_type, g);
  put(my_edge_map, vd, name);
}
```

To use 'set_my_custom_edge', one first needs to obtain an edge descriptor. Algorithm 255 shows a simple example.

Algorithm 255 Demonstration if the 'set_my_custom_edge' function

```
#include <cassert>

#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "find_first_custom_edge_with_my_edge.h"
#include "get_my_custom_edge.h"
#include "set_my_custom_edge.h"

void set_my_custom_edge_demo() noexcept
{
  auto g
    =
        create_empty_undirected_custom_edges_and_vertices_graph
        ();
  const my_custom_edge old_edge{"Dex"};
  add_custom_edge(old_edge, g);
  const auto vd
    = find_first_custom_edge_with_my_edge(old_edge,g);
  assert(get_my_custom_edge(vd,g)
    == old_edge
  );
  const my_custom_edge new_edge{"Diggy"};
  set_my_custom_edge(new_edge, vd, g);
  assert(get_my_custom_edge(vd,g)
    == new_edge
  );
}
```

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

If you used the create_custom_edges_and_vertices_k3_graph function (algorithm 245) to produce a K_3 graph with edges and vertices associated with my_custom_edge and my_custom_vertex objects, you can store these my_custom_edges and my_custom_vertex-es additionally with algorithm 256:

Algorithm 256 Storing a graph with custom edges and vertices as a .dot file

```
#include <fstream>
#include <string>
#include <boost/graph/graphviz.hpp>
#include <boost/graph/properties.hpp>
#include "get_my_custom_edge.h"
#include "get_my_custom_vertex.h"

template <typename graph>
void save_custom_edges_and_vertices_graph_to_dot(
  const graph& g,
  const std::string& filename
)
{
  using vd = typename graph::vertex_descriptor;
  using ed = typename graph::edge_descriptor;

  std::ofstream f(filename);
  boost::write_graphviz(
    f,
    g,
    [g](
      std::ostream& out, const vd& d) {
      const my_custom_vertex& m{
        get_my_custom_vertex(d, g)
      };
      out << "[label=\"" << m << "\"]";
    },
    [g](std::ostream& out, const ed& d) {
      const my_custom_edge& m{
        get_my_custom_edge(d, g)
      };
      out << "[label=\"" << m << "\"]";
    }
  );
}
```

17.6 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 257:

Algorithm 257 Loading a directed graph with custom edges and vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "
    create_empty_directed_custom_edges_and_vertices_graph.
    h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex
  >,
  boost::property<
    boost::edge_custom_type_t, my_custom_edge
  >
>
load_directed_custom_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_custom_edges_and_vertices_graph
      ();
  boost::dynamic_properties p;
  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 258 shows how to use the 'load_directed_custom_edges_and_vertices_graph_from_dot' function:

Algorithm 258 Demonstration of the 'load_directed_custom_edges_and_vertices_graph_from_dot' function

```
#include "create_custom_edges_and_vertices_markov_chain.h
    "
#include "get_my_custom_vertexes.h"
#include "
    load_directed_custom_edges_and_vertices_graph_from_dot
    .h"
#include "save_custom_edges_and_vertices_graph_to_dot.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_my_custom_vertexes(g)
    == get_my_custom_vertexes(h)
  );
}
```

This demonstration shows how the Markov chain is created using the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 242), saved and then loaded.

17.7 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 259:

Algorithm 259 Loading an undirected graph with custom edges and vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "is_regular_file.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<
    boost::vertex_custom_type_t, my_custom_vertex
  >,
  boost::property<
    boost::edge_custom_type_t, my_custom_edge
  >
>
load_undirected_custom_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_custom_edges_and_vertices_graph
      ();
  boost::dynamic_properties p;
  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;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 17.6 describes the rationale of this function.

Algorithm 260 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

Algorithm 260 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_my_custom_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_my_custom_vertexes(g) ==
      get_my_custom_vertexes(h));
}
```

This demonstration shows how K_2 with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 196), saved and then loaded. The loaded graph is checked to be a graph similar to the original.

18 Building graphs with a graph name

Up until now, the graphs created have had no properties themselves. Sure, the edges and vertices have had properties, but the graph itself has had none. Until now.

In this chapter, graphs will be created with a graph name of type std::string

- An empty directed graph with a graph name: see chapter
- An empty undirected graph with a graph name: see chapter
- A two-state Markov chain with a graph name: see chapter
- $K_3$with a graph name: see chapter

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

- Getting a graph its name: see chapter
- Setting a graph its name: see chapter

18.1 Create an empty directed graph with a graph name property

Algorithm 261 shows the function to create an empty directed graph with a graph name.

Algorithm 261 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 {};
}
```

This boost::adjacency_list is of the following type:

- the first 'boost::vecS': select (that is what the 'S' means) that out edges are stored in a std::vector. This is the default way.
- the second 'boost::vecS': select that the graph vertices are stored in a std::vector. This is the default way.
- 'boost::directedS': select that the graph is directed. This is the default selectedness

- the first 'boost::no_property': the vertices have no properties. This is the default (non-)property
- the second 'boost::no_property': the vertices have no properties. This is the default (non-)propert
- 'boost::property<boost::graph_name_t, std::string>': the graph itself has a single property: its boost::graph_name has type std::string

Algorithm 262 demonstrates the 'create_empty_directed_graph_with_graph_name' function.

Algorithm 262 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);
}
```

18.2 Create an empty undirected graph with a graph name property

Algorithm 263 shows the function to create an empty undirected graph with a graph name.

Algorithm 263 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 {};
}
```

This code is very similar to the code described in chapter 261, except that the directedness (the third template argument) is undirected (due to the boost::undirectedS).

Algorithm 264 demonstrates the 'create_empty_undirected_graph_with_graph_name' function.

Algorithm 264 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);
}
```

18.3 Get a graph its name property

Algorithm 265 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(
    g, boost::graph_name
  );
}
```

Algorithm 266 demonstrates the 'get_graph_name' function.

Algorithm 266 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);
}
```

18.4 Set a graph its name property

Algorithm 267 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
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );
  get_property(g, boost::graph_name) = name;
}
```

Algorithm 268 demonstrates the 'set_graph_name' function.

Algorithm 268 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);
}
```

18.5 Create a directed graph with a graph name property

18.5.1 Graph

See figure 6.

18.5.2 Function to create such a graph

Algorithm 269 shows the function to create an empty directed graph with a graph name.

Algorithm 269 Creating a two-state Markov chain with a graph name

```
#include <cassert>
#include "create_empty_directed_graph_with_graph_name.h"
#include "set_graph_name.h"

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;
}
```

18.5.3 Creating such a graph

Algorithm 270 demonstrates the 'create_markov_chain_with_graph_name' function.

Algorithm 270 Demonstration of 'create_markov_chain_with_graph_name'

```
#include <cassert>
#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");
}
```

18.5.4 The .dot file produced

Algorithm 271 .dot file created from the 'create_markov_chain_with_graph_name' function (algorithm 269), converted from graph to .dot file using algorithm 48

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

18.5.5 The .svg file produced

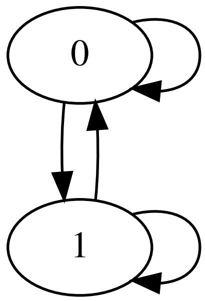

Figure 43: .svg file created from the 'create_markov_chain_with_graph_name' function (algorithm 269) its .dot file, converted from .dot file to .svg using algorithm 281

18.6 Create an undirected graph with a graph name property

18.6.1 Graph

See figure 8.

18.6.2 Function to create such a graph

Algorithm 272 shows the function to create K2 graph with a graph name.

Algorithm 272 Creating a K2 graph with a graph name

```
#include "create_empty_undirected_graph_with_graph_name.h
    "

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(g,boost::graph_name) = "K2";

  return g;
}
```

18.6.3 Creating such a graph

Algorithm 273 demonstrates the 'create_k2_graph_with_graph_name' function.

Algorithm 273 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");
}
```

18.6.4 The .dot file produced

Algorithm 274 .dot file created from the 'create_k2_graph_with_graph_name' function (algorithm 272), converted from graph to .dot file using algorithm 48

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

18.6.5 The .svg file produced

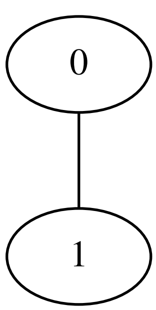

Figure 44: .svg file created from the 'create_k2_graph_with_graph_name' function (algorithm 272) its .dot file, converted from .dot file to .svg using algorithm 281

19 Working on graphs with a graph name

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

This works:

Algorithm 275 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"

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";
    }
  );
}
```

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

This will result in a directed graph with a name:

Algorithm 276 Loading a directed graph with a graph name from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
//#include "create_empty_directed_graph_with_graph_name.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
)
{
  using graph = boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    boost::no_property,
    boost::no_property,
    boost::property<
      boost::graph_name_t, std::string
    >
  >;

  assert(is_regular_file(dot_filename));

  graph g;

  boost::ref_property_map<graph*,std::string>
  graph_name{
    get_property(g,boost::graph_name)
  };
  boost::dynamic_properties dp{
    boost::ignore_other_properties
  };
  dp.property("name",graph_name);


  std::ifstream f(dot_filename.c_str());
  boost::read_graphviz(f,g,dp);
  return g;
}
```

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

This will result in an undirected graph with a name:

Algorithm 277 Loading an undirected graph with a graph name from a .dot file

```
#include <fstream>
#include <string>
#include <boost/graph/graphviz.hpp>
#include "create_empty_undirected_graph_with_graph_name.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
)
{
  using graph = boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::no_property,
    boost::no_property,
    boost::property<
      boost::graph_name_t, std::string
    >
  >;

  assert(is_regular_file(dot_filename));

  graph g;

  boost::ref_property_map<graph*,std::string>
  graph_name{
    get_property(g,boost::graph_name)
  };
  boost::dynamic_properties dp{
    boost::ignore_other_properties
  };
  dp.property("name",graph_name);
```



```
  std::ifstream f(dot_filename.c_str());
  boost::read_graphviz(f,g,dp);
  return g;

  /*
  assert(is_regular_file(dot_filename));
  std::ifstream f(dot_filename.c_str());
```

20 Other graph functions

Some functions that did not fit in.

20.1 Encode a std::string to a Graphviz-friendly format

You may want to use a label with spaces, comma's and/or quotes. Saving and loading these, will result in problem. This function replaces these special characters by a rare combination of ordinary characters.

Algorithm 278 Encode a std::string to a Graphviz-friendly format

```
#include <boost/algorithm/string/replace.hpp>

std::string graphviz_encode(std::string s) noexcept
{
  boost::algorithm::replace_all(s,",","$$$COMMA$$$");
  boost::algorithm::replace_all(s," ","$$$SPACE$$$");
  boost::algorithm::replace_all(s,"\"","$$$QUOTE$$$");
  return s;
}
```

20.2 Decode a std::string from a Graphviz-friendly format

This function undoes the 'graphviz_encode' function (algorithm 278) and thus converts a Graphviz-friendly std::string to the original human-friendly std::string.

Algorithm 279 Decode a std::string from a Graphviz-friendly format to a human-friendly format

```
#include <boost/algorithm/string/replace.hpp>

std::string graphviz_decode(std::string s) noexcept
{
  boost::algorithm::replace_all(s,"$$$COMMA$$$",",");
  boost::algorithm::replace_all(s,"$$$SPACE$$$"," ");
  boost::algorithm::replace_all(s,"$$$QUOTE$$$","\"");
  return s;
}
```

21 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.

21.1 Getting a data type as a std::string

This function will only work under GCC. I found this code at: `http://stackoverflow.com/questions/1055452/c-get-name-of-type-in-template`. Thanks to 'm-dudley' (Stack Overflow userpage at `http://stackoverflow.com/users/111327/m-dudley`).

Algorithm 280 Getting a data type its name as a std::string

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

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;
}
```

21.2 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 281 Convert a .dot file to a .svg

```
#include <cassert>
#include <string>
#include <sstream>
#include "has_dot.h"
#include "is_regular_file.h"
#include "is_valid_dot_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.

21.3 Check if a file exists

Not the most smart way perhaps, but it does only use the STL.

Algorithm 282 Check if a file exists

```
#include <fstream>

bool is_regular_file(const std::string& filename)
   noexcept
{
  std::fstream f;
  f.open(filename.c_str(),std::ios::in);
  return f.is_open();
}
```

22 Errors

Some common errors.

22.1 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 283:

Algorithm 283 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 283 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.

22.2 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 284 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;
  boost::clear_in_edges(vd,g);
}
```

In algorithm 284 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.

22.3 No matching function for call to 'clear_in_edges'

See chapter 22.2.

22.4 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
```

22.5 Property not found: node_id

When loading a graph from file (as in chapter 3.9) 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 285 shows how to trigger this run-time error.

Algorithm 285 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");
}
```

23 Appendix

23.1 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

23.2 Graphviz attributes

List created from `www.graphviz.org/content/attrs`, where only the attributes that are supported by all formats are listed:

Edge	Graph	Vertex
arrowhead	_background	color
arrowsize	bgcolor	colorscheme
arrowtail	center	comment
color	charset	distortion
colorscheme	color	fillcolor
comment	colorscheme	fixedsize
decorate	comment	fontcolor
dir	concentrate	fontname
fillcolor	fillcolor	fontsize
fontcolor	fontcolor	gradientangle
fontname	fontname	height
fontsize	fontpath	image
gradientangle	fontsize	imagescale
headclip	forcelabels	label
headlabel	gradientangle	labelloc
headport	imagepath	layer
label	label	margin
labelangle	labeljust	nojustify
labeldistance	labelloc	orientation
labelfloat	landscape	penwidth
labelfontcolor	layerlistsep	peripheries
labelfontname	layers	pos
labelfontsize	layerselect	regular
layer	layersep	samplepoints
nojustify	layout	shape
penwidth	margin	shapefile
pos	nodesep	sides
style	nojustify	skew
tailclip	orientation	sortv
taillabel	outputorder	style
tailport	pack	width
weight	packmode	xlabel
xlabel	pad	z
	page	
	pagedir	
	penwidth	
	quantum	
	ratio	
	rotate	
	size	
	sortv	
	splines	
	style	
	viewport	

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