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

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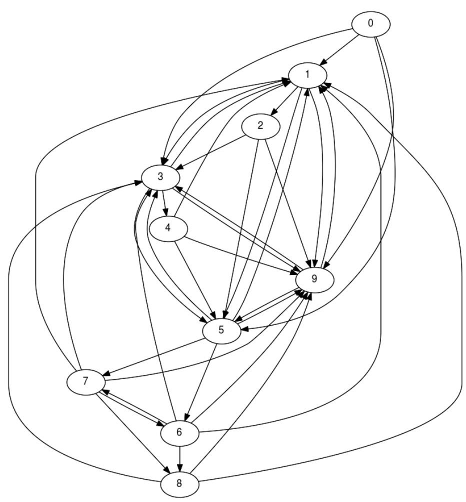


## Contents

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

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

# 1 Introduction

This is 'A well-connected C++14 Boost.Graph tutorial', version 2.0.

## 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.

## 1.2 Tutorial style

**Readable for beginners** This tutorial is aimed at the beginner programmer. 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.

**High verbosity** This tutorial is intended to be as verbose, such that a beginner should be able to follow every step, from reading the tutorial from beginning to end chronologically. Especially in the earlier chapters, the rationale behind the code presented is given, including references to the literature. Chapters marked with '►' are optional, less verbose and bring no new information to the storyline.

**Repetitiveness** This tutorial is intended to be as repetitive, such that a beginner can spot the patterns in the code snippets their increasing complexity. Extending code from this tutorial should be as easy as extending the patterns.

**Index** 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.

## 1.3 Coding style

**Concept** For every concept, I will show

- a function that achieves a goal, for example 'create_empty_undirected_graph'
- a test case of that function, that demonstrates how to use the function, for example 'create_empty_undirected_graph_test'

**C++14** All coding snippets are taken from compiled and tested C++14 code. I chose to use C++14 because it was available to me on all local and remote computers. Next to this, it makes code even shorter then just C++11.

**Coding standard** 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.

**No comments in code** 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.

**Trade-off between generic code and readability** 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.

**Long function names** 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.

**Long function names and readability** 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.

**Use of auto** I prefer to use the keyword auto over doubling the lines of code for using statements. Often the 'do' functions return an explicit data type, these can be used for reference. Sometime I deduce the return type using decltype and a function with the same return type. When C++17 gets accessible, I will use 'decltype(auto)'. If you really want to know a type, you can use the 'get_type_name' function (chapter 23.1).

**Explicity use of namespaces** 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.

**Use of STL algorithms** 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.

**Re-use of functions** The functions I develop in this tutorial are re-used from that moment on. This improves to readability of the code and decreases the number of lines.

**Tested to compile** All functions in this tutorial are tested to compile using Travis CI in both debug and release mode.

**Tested to work** All functions in this tutorial are tested, using the Boost.Test library. Travis CI calls these tests after each push to the repository.

**Availability** The code, as well as this tutorial, can be downloaded from the GitHub at `www.github.com/richelbilderbeek/BoostGraphTutorial`.

## 1.4 License

Figure 1: Creative Commons license 4.0

## 1.5 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.

## 1.6 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`
- E. Kawashima
- mat69, `https://www.reddit.com/user/mat69`
- danielhj, `https://www.reddit.com/user/danieljh`
- sehe, `http://stackoverflow.com/users/85371/sehe`
- cv_and_me, `http://stackoverflow.com/users/2417774/cv-and-he`

## 1.7 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.

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

The differences between graphs with bundled and custom properties 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 constraints | Restricted to Graphviz attributes | Need encoding and 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.

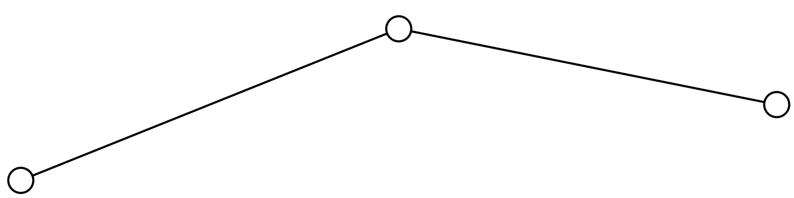

Figure 4: Example of an undirected graph

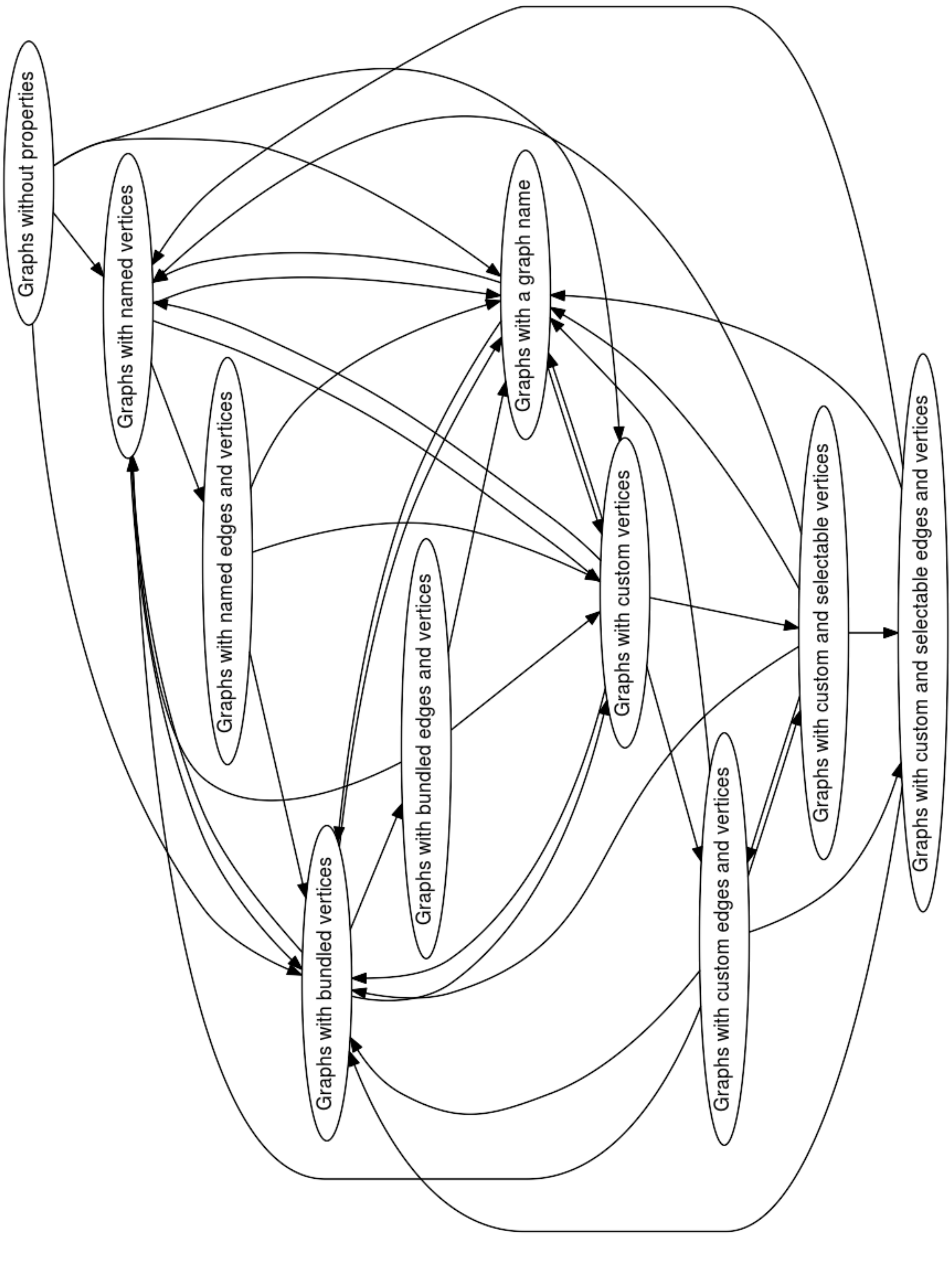


Figure 2: The relations between chapters

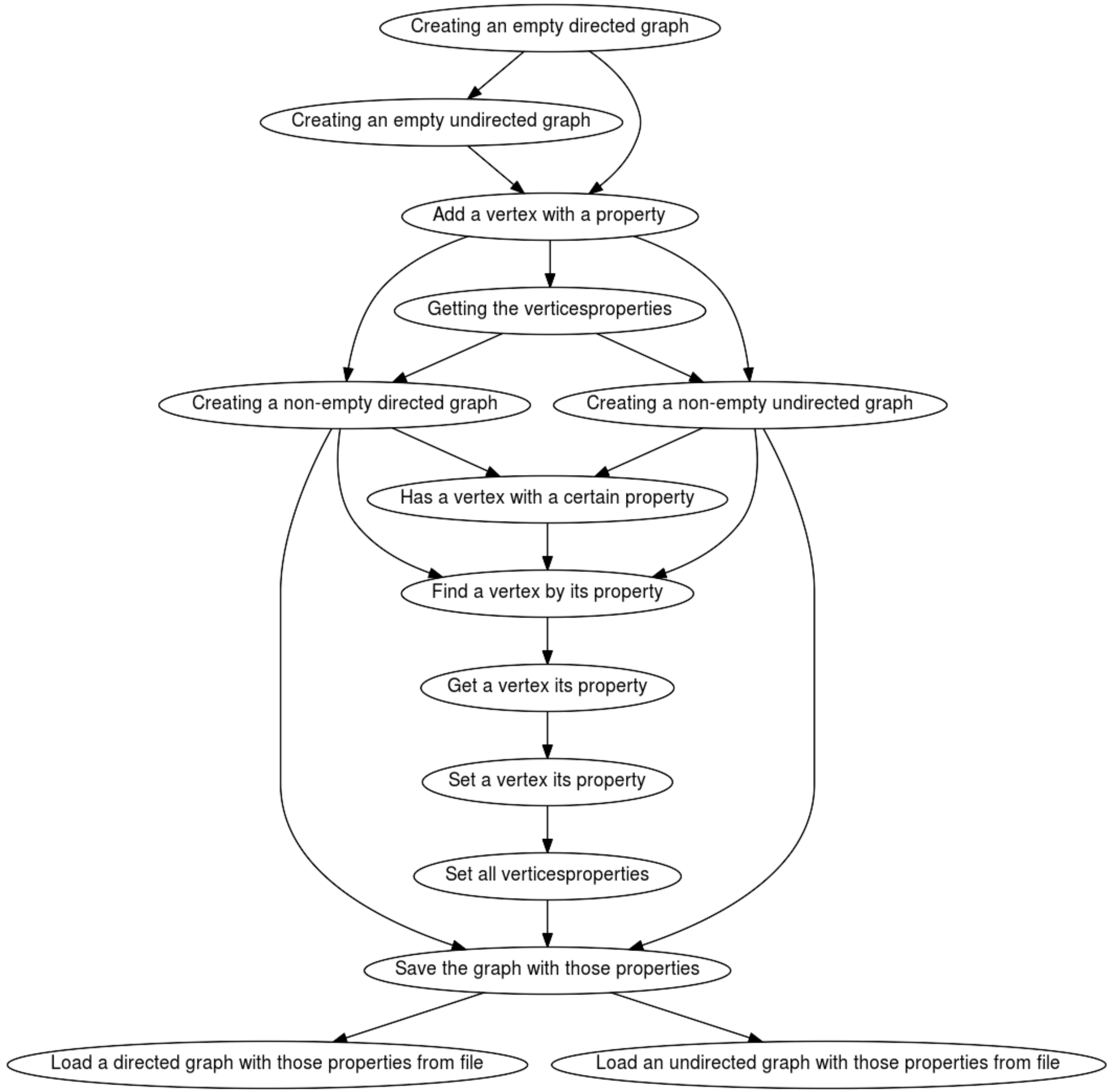


Figure 3: The relations between sub-chapters

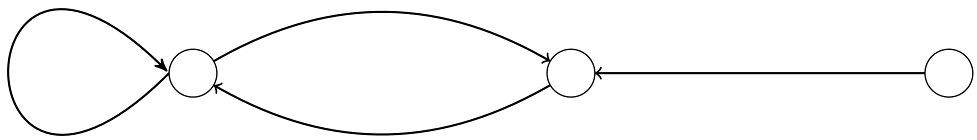

Figure 5: Example of a directed graph

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 20

## 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'[3]. 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[4], so it is preferred to mark it noexcept ([10] chapter 13.7).

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

[4] 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. This demonstration is embedded within a Boost.Test unit testcase. It includes a Boost.Test header to allow to use the Boost.Test framework. Additionally, a header file is included with the same name as the function[5]. This allows use to be able to use the function. The test case creates an empty graph and stores it. Instead of specifying the data type explicitly, 'auto' is used (this is preferred, [10] chapter 31.6), which lets the compiler figure out the type itself.

**Algorithm 2** Demonstration of 'create_empty_directed_graph'

```
#include <boost/test/unit_test.hpp>
#include "create_empty_directed_graph.h"

BOOST_AUTO_TEST_CASE(test_create_empty_directed_graph)
{
  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[6] 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).

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

[6] Standard Template Library, the standard library

## 2.2 Creating an empty undirected graph

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

Algorith 3 shows how to create an undirected graph.

**Algorithm 3** Creating an empty undirected graph

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

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 <boost/test/unit_test.hpp>
#include "create_empty_undirected_graph.h"

BOOST_AUTO_TEST_CASE(test_create_empty_undirected_graph)
{
  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 <boost/test/unit_test.hpp>
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_n_vertices.h"

BOOST_AUTO_TEST_CASE(test_get_n_vertices)
{
  const auto g = create_empty_directed_graph();
  BOOST_CHECK(get_n_vertices(g) == 0);

  const auto h = create_empty_undirected_graph();
  BOOST_CHECK(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 <boost/test/unit_test.hpp>
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_n_edges.h"

BOOST_AUTO_TEST_CASE(test_get_n_edges)
{
  const auto g = create_empty_directed_graph();
  BOOST_CHECK(get_n_edges(g) == 0);

  const auto h = create_empty_undirected_graph();
  BOOST_CHECK(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 <boost/test/unit_test.hpp>
#include "add_vertex.h"
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"

BOOST_AUTO_TEST_CASE(test_add_vertex)
{
  auto g = create_empty_undirected_graph();
  add_vertex(g);
  BOOST_CHECK(boost::num_vertices(g) == 1);

  auto h = create_empty_directed_graph();
  add_vertex(h);
  BOOST_CHECK(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 an 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 <boost/test/unit_test.hpp>
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_vertex_iterators.h"

BOOST_AUTO_TEST_CASE(test_get_vertex_iterators)
{
  const auto g = create_empty_undirected_graph();
  const auto vip_g = get_vertex_iterators(g);
  BOOST_CHECK(vip_g.first == vip_g.second);

  const auto h = create_empty_directed_graph();
  const auto vip_h = get_vertex_iterators(h);
  BOOST_CHECK(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[7].

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 <boost/test/unit_test.hpp>
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_vertex_descriptors.h"

BOOST_AUTO_TEST_CASE(test_get_vertex_descriptors)
{
  const auto g = create_empty_undirected_graph();
  const auto vds_g = get_vertex_descriptors(g);
  BOOST_CHECK(vds_g.empty());

  const auto h = create_empty_directed_graph();
  const auto vds_h = get_vertex_descriptors(h);
  BOOST_CHECK(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:

[7] 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 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 <boost/test/unit_test.hpp>
#include "add_edge.h"
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"

BOOST_AUTO_TEST_CASE(test_add_edge)
{
  auto g = create_empty_undirected_graph();
  add_edge(g);
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(boost::num_edges(g) == 1);

  auto h = create_empty_directed_graph();
  add_edge(h);
  BOOST_CHECK(boost::num_vertices(h) == 2);
  BOOST_CHECK(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 <boost/test/unit_test.hpp>
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_edge_iterators.h"

BOOST_AUTO_TEST_CASE(test_get_edge_iterators)
{
  const auto g = create_empty_undirected_graph();
  const auto eip_g = get_edge_iterators(g);
  BOOST_CHECK(eip_g.first == eip_g.second);

  auto h = create_empty_directed_graph();
  const auto eip_h = get_edge_iterators(h);
  BOOST_CHECK(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 <boost/test/unit_test.hpp>
#include "create_empty_directed_graph.h"
#include "create_empty_undirected_graph.h"
#include "get_edge_descriptors.h"

BOOST_AUTO_TEST_CASE(test_get_edge_descriptors)
{
  const auto g = create_empty_directed_graph();
  const auto eds_g = get_edge_descriptors(g);
  BOOST_CHECK(eds_g.empty());

  const auto h = create_empty_undirected_graph();
  const auto eds_h = get_edge_descriptors(h);
  BOOST_CHECK(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:

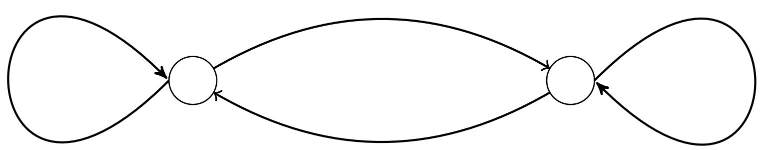

Figure 6: The two-state Markov chain

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);
  boost::add_edge(vd_a, vd_a, g);
  boost::add_edge(vd_a, vd_b, g);
  boost::add_edge(vd_b, vd_a, g);
  boost::add_edge(vd_b, vd_b, g);
  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 <boost/test/unit_test.hpp>
#include "create_markov_chain.h"

BOOST_AUTO_TEST_CASE(test_create_markov_chain)
{
  const auto g = create_markov_chain();
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(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 55). 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 55

```
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:

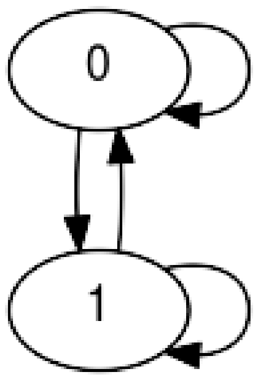


Figure 7: .svg file created from the 'create_markov_chain' function (algorithm 21) its .dot file and converted from .dot file to .svg using algorithm 366

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.

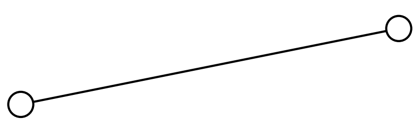

Figure 8: $K_2$: a fully connected undirected graph with two vertices

#### 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);
  boost::add_edge(vd_a, vd_b, g);
  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 <boost/test/unit_test.hpp>
#include "create_k2_graph.h"

BOOST_AUTO_TEST_CASE(test_create_k2_graph)
{
  const auto g = create_k2_graph();
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(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 55

```
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:

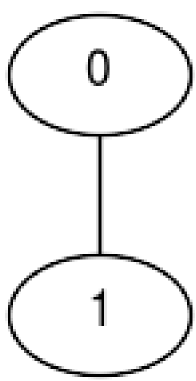


Figure 9: .svg file created from the 'create_k2_graph' function (algorithm 24) its .dot file, converted from .dot file to .svg using algorithm 366

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.

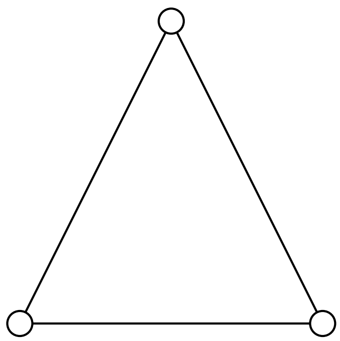

Figure 10: $K_3$: a fully connected graph with three edges and vertices

### 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);
  boost::add_edge(vd_a, vd_b, g);
  boost::add_edge(vd_b, vd_c, g);
  boost::add_edge(vd_c, vd_a, g);
  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 <boost/test/unit_test.hpp>
#include "create_k3_graph.h"

BOOST_AUTO_TEST_CASE(test_create_k3_graph)
{
  const auto g = create_k3_graph();
  BOOST_CHECK(boost::num_edges(g) == 3);
  BOOST_CHECK(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 55

```
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:

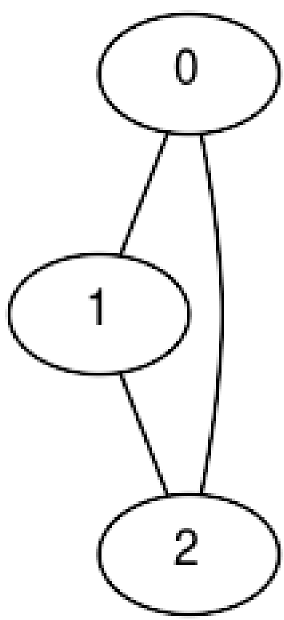


Figure 11: .svg file created from the 'create_k3_graph' function (algorithm 27) its .dot file, converted from .dot file to .svg using algorithm 366

## 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):

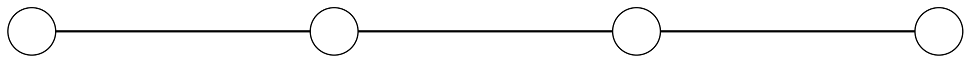

Figure 12: A path graph with four vertices

### 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 size_t n_vertices) noexcept
{
  auto g = create_empty_undirected_graph();
  if (n_vertices == 0) return g;
  auto vd_1 = boost::add_vertex(g);
  if (n_vertices == 1) return g;
  for (size_t i=1; i!=n_vertices; ++i)
  {
    auto vd_2 = boost::add_vertex(g);
    boost::add_edge(vd_1, vd_2, g);
    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 <boost/test/unit_test.hpp>
#include "create_path_graph.h"

BOOST_AUTO_TEST_CASE(test_create_path_graph)
{
  const auto g = create_path_graph(4);
  BOOST_CHECK(boost::num_edges(g) == 3);
  BOOST_CHECK(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 55

```
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:

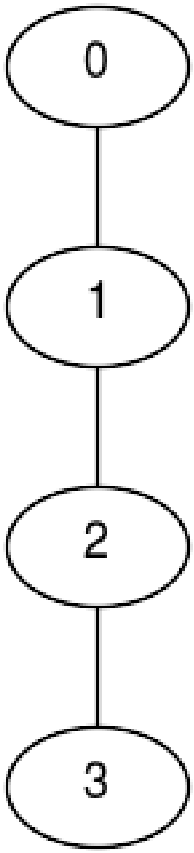


Figure 13: .svg file created from the ‘create_path_graph’ function (algorithm 30) its .dot file, converted from .dot file to .svg using algorithm 366

## 2.18 ▶ Creating a Peterson graph

A Petersen graph is the first graph with interesting properties.

### 2.18.1 Graph

To create a Petersen graph, one needs five vertices and five undirected edges, as depicted in figure 14.

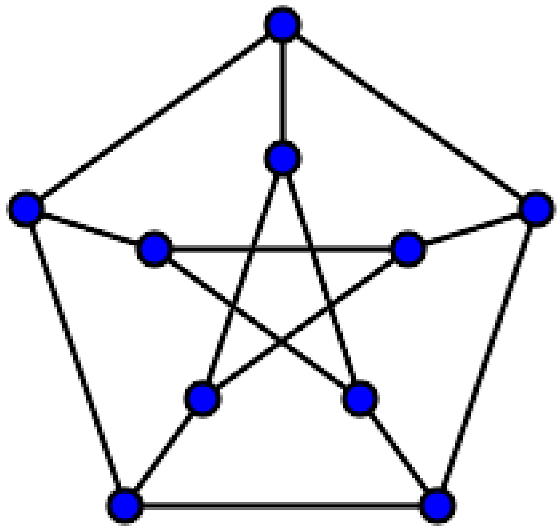

Figure 14: A Petersen graph (from `https://en.wikipedia.org/wiki/Petersen_graph`)

#### 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 = 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) {
    boost::add_edge(v[i], v[(i + 1) % 5], g);
  }
  //Spoke
  for (int i=0; i!=5; ++i) {
    boost::add_edge(v[i], w[i], g);
  }
  //Inner pentagram
  for (int i=0; i!=5; ++i) {
    boost::add_edge(w[i], w[(i + 2) % 5], g);
  }
  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 <boost/test/unit_test.hpp>
#include "create_petersen_graph.h"

BOOST_AUTO_TEST_CASE(test_create_petersen_graph)
{
  const auto g = create_petersen_graph();
  BOOST_CHECK(boost::num_edges(g) == 15);
  BOOST_CHECK(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 55

```
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:

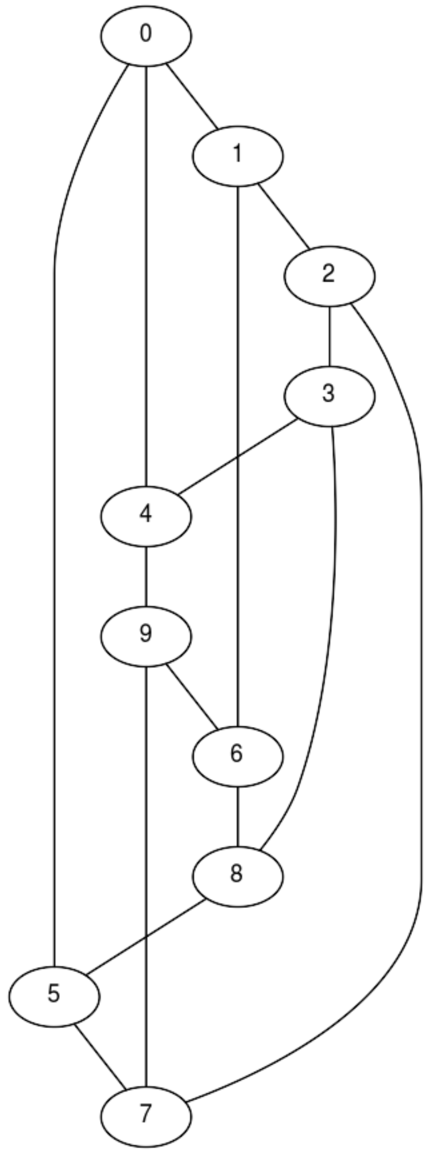


Figure 15: .svg file created from the 'create_petersen_graph' function (algorithm 33) its .dot file, converted from .dot file to .svg using algorithm 366

# 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 3.11
- Loading an undirected graph without properties from .dot file: see chapter 3.13
- Loading a directed graph without properties from .dot file: see chapter 3.12

## 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_degree')
- 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 <boost/test/unit_test.hpp>
#include "create_k2_graph.h"
#include "create_markov_chain.h"
#include "get_vertex_out_degrees.h"

BOOST_AUTO_TEST_CASE(test_get_vertex_out_degrees)
{
  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)
  };
  BOOST_CHECK(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)
  };
  BOOST_CHECK(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 <boost/test/unit_test.hpp>
#include "create_k2_graph.h"
#include "has_edge_between_vertices.h"

BOOST_AUTO_TEST_CASE(test_has_edge_between_vertices)
{
  const auto g = create_k2_graph();
  const auto vd_1 = *vertices(g).first;
  const auto vd_2 = *(++vertices(g).first);
  BOOST_CHECK( has_edge_between_vertices(vd_1, vd_2, g));
  BOOST_CHECK(!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>

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
)
{
  const auto er = edge(vd_from, vd_to, g);
  if (!er.second)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "no edge between these vertices"
    ;
    throw std::invalid_argument(msg.str());
  }
  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 <boost/test/unit_test.hpp>
#include "create_k2_graph.h"
#include "get_edge_between_vertices.h"
#include "has_edge_between_vertices.h"

BOOST_AUTO_TEST_CASE(test_get_edge_between_vertices)
{
  auto g = create_k2_graph();
  const auto vd_1 = *vertices(g).first;
  const auto vd_2 = *(++vertices(g).first);
  BOOST_CHECK(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);
  BOOST_CHECK(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);
    for (auto i = vdsi.first; i != vdsi.second; ++i)
    {
      if (m.find(*i) == m.end())
      {
        const auto vd_h = boost::add_vertex(h);
        m.insert(std::make_pair(*i, 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;
      boost::add_edge(m[vd_from],m[vd_to], h);
    }
  }
  return h;
}
```

This demonstration code shows that the direct-neighbour graph of each vertex of a $K_2$ graphs is ... a $K_2$ graph!

**Algorithm 43** Demo of the 'create_direct_neighbour_subgraph' function

```
#include <boost/test/unit_test.hpp>
#include "create_direct_neighbour_subgraph.h"
#include "create_k2_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_direct_neighbour_subgraph)
{
  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
    );
    BOOST_CHECK(boost::num_vertices(h) == 2);
    BOOST_CHECK(boost::num_edges(h) == 1);
  }
}
```

Note that this algorithm works on both undirectional and directional graphs. If the graph is directional, only the out edges will be copied. To also copy the vertices connected with inward edges, use 3.5

## 3.5 ▶ Create a direct-neighbour subgraph from a vertex descriptor including inward edges

Too bad, this algorithm does not work yet.

**Algorithm 44** Get the direct-neighbour subgraph from a vertex descriptor

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

template <typename graph>
graph create_direct_neighbour_subgraph_including_in_edges
    (
    const typename graph::vertex_descriptor& vd, const
        graph& g)
{
    using vertex_descriptor = typename graph::
        vertex_descriptor;
    using edge_descriptor = typename graph::
        edge_descriptor;
    using vpair = std::pair<vertex_descriptor,
        vertex_descriptor>;

    std::vector<vpair> conn_edges;
    std::unordered_map<vertex_descriptor,
        vertex_descriptor> m;

    vertex_descriptor vd_h = 0;
    m.insert(std::make_pair(vd, vd_h++));

    for (const edge_descriptor ed : boost::
        make_iterator_range(edges(g))) {
      const auto vd_from = source(ed, g);
      const auto vd_to = target(ed, g);
      if (vd == vd_from) {
        conn_edges.emplace_back(vd_from, vd_to);
        m.insert(std::make_pair(vd_to, vd_h++));
      }
      if (vd == vd_to) {
        conn_edges.emplace_back(vd_from, vd_to);
        m.insert(std::make_pair(vd_from, vd_h++));
      }
    }

    for (vpair& vp : conn_edges) {
      vp.first = m[vp.first];
      vp.second = m[vp.second];
    }

    return graph(conn_edges.begin(), conn_edges.end(), m.
        size());
}
```

## 3.6 ▶ 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 45** 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(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 two direct-neighbour graphs of a $K_2$ graphs are ... $K_2$ graphs!

**Algorithm 46** Demo of the 'create_all_direct_neighbour_subgraphs' function

```
#include <boost/test/unit_test.hpp>
#include "create_all_direct_neighbour_subgraphs.h"
#include "create_k2_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_all_direct_neighbour_subgraphs)
{
  const auto v
    = create_all_direct_neighbour_subgraphs(
        create_k2_graph());
  BOOST_CHECK(v.size() == 2);
  for (const auto g: v)
  {
    BOOST_CHECK(boost::num_vertices(g) == 2);
    BOOST_CHECK(boost::num_edges(g) == 1);
  }
}
```

## 3.7 ▶ Are two graphs isomorphic?

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

**Algorithm 47** 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 48** Demo of the 'is_isomorphic' function

```
#include <boost/test/unit_test.hpp>
#include "create_path_graph.h"
#include "create_k3_graph.h"
#include "is_isomorphic.h"

BOOST_AUTO_TEST_CASE(test_is_isomorphic)
{
  const auto g = create_path_graph(3);
  const auto h = create_k3_graph();
  BOOST_CHECK( is_isomorphic(g,g));
  BOOST_CHECK(!is_isomorphic(g,h));
}
```

## 3.8 ▶ Count the number of connected components in an directed graph

A directed graph may consist out of two components, that are connect within each, but unconnected between them. Take for example, a graph of two isolated edges, with four vertices.

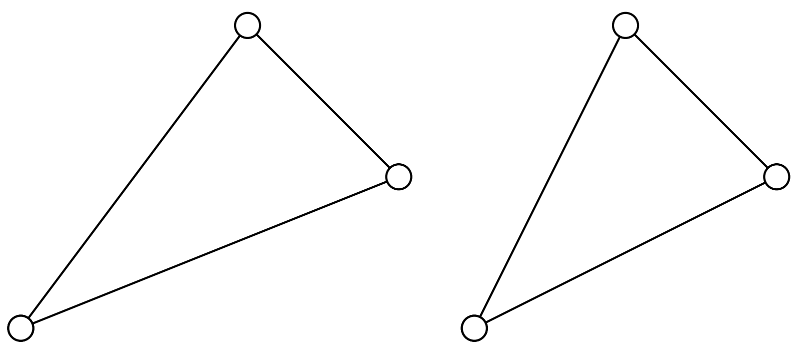

Figure 16: Example of a directed graph with two components

This algorithm counts the number of connected components:

**Algorithm 49** Count the number of connected components

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

template <typename graph>
int count_directed_graph_connected_components(
  const graph& g
) noexcept
{
  std::vector<int> c(boost::num_vertices(g));
  const int n = boost::strong_components(g,
    boost::make_iterator_property_map(
      std::begin(c),
      get(boost::vertex_index, g)
    )
  );
  return n;
}
```

The complexity of this algorithm is $O(|V| + |E|)$.

This demonstration code shows that two solitary edges are correctly counted as being two components:

**Algorithm 50** Demo of the 'count_directed_graph_connected_components' function

```
#include <boost/test/unit_test.hpp>
#include "create_empty_directed_graph.h"
#include "add_edge.h"
#include "count_directed_graph_connected_components.h"

BOOST_AUTO_TEST_CASE(
    test_count_directed_graph_connected_components)
{
  auto g = create_empty_directed_graph();
  BOOST_CHECK(count_directed_graph_connected_components(g
      ) == 0);
  const auto vd_a = boost::add_vertex(g);
  const auto vd_b = boost::add_vertex(g);
  const auto vd_c = boost::add_vertex(g);
  boost::add_edge(vd_a, vd_b, g);
  boost::add_edge(vd_b, vd_c, g);
  boost::add_edge(vd_c, vd_a, g);
  BOOST_CHECK(count_directed_graph_connected_components(g
      ) == 1);
  const auto vd_d = boost::add_vertex(g);
  const auto vd_e = boost::add_vertex(g);
  const auto vd_f = boost::add_vertex(g);
  boost::add_edge(vd_d, vd_e, g);
  boost::add_edge(vd_e, vd_f, g);
  boost::add_edge(vd_f, vd_d, g);
  BOOST_CHECK(count_directed_graph_connected_components(g
      ) == 2);
}
```

## 3.9 ▶ Count the number of connected components in an undirected graph

An undirected graph may consist out of two components, that are connect within each, but unconnected between them. Take for example, a graph of two isolated edges, with four vertices.

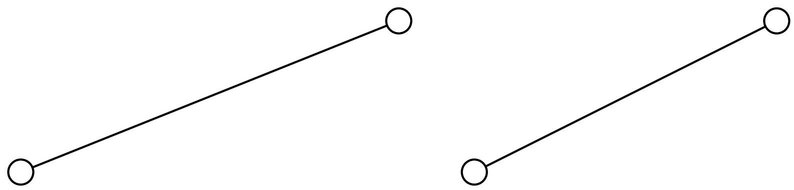

Figure 17: Example of an undirected graph with two components

This algorithm counts the number of connected components:

**Algorithm 51** Count the number of connected components

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

template <typename graph>
int count_undirected_graph_connected_components(
  const graph& g
) noexcept
{
  std::vector<int> c(boost::num_vertices(g));
  return boost::connected_components(g,
    boost::make_iterator_property_map(
      std::begin(c),
      get(boost::vertex_index, g)
    )
  );
}
```

The complexity of this algorithm is $O(|V| + |E|)$.

This demonstration code shows that two solitary edges are correctly counted as being two components:

**Algorithm 52** Demo of the 'count_undirected_graph_connected_components' function

```
#include <boost/test/unit_test.hpp>
#include "create_empty_undirected_graph.h"
#include "add_edge.h"
#include "count_undirected_graph_connected_components.h"

BOOST_AUTO_TEST_CASE(
    test_count_undirected_graph_connected_components)
{
  auto g = create_empty_undirected_graph();
  BOOST_CHECK(count_undirected_graph_connected_components
      (g) == 0);
  add_edge(g);
  BOOST_CHECK(count_undirected_graph_connected_components
      (g) == 1);
  add_edge(g);
  BOOST_CHECK(count_undirected_graph_connected_components
      (g) == 2);
}
```

## 3.10 ▶ Count the number of levels in an undirected graph

Graphs can have a hierarchical structure. From a starting vertex, the number of levels can be counted. A graph of one vertex has zero levels. A graph with one edge has one level. A linear graph of three vertices and two edges has one or two levels, depending on the starting vertex.

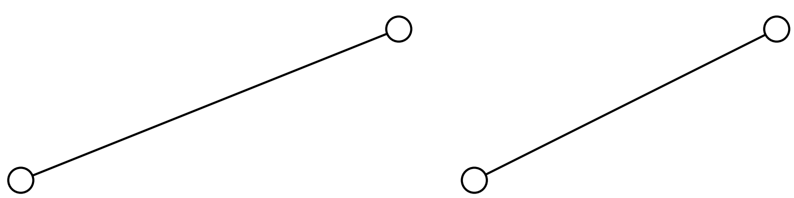

Figure 18: Example of an undirected graph with two components

This algorithm counts the number of levels in an undirected graph, starting at a certain vertex.

It does so, by collecting the neighbours of the traversed vertices. Each sweep, all neighbours of traversed neighbours are added to a set of known vertices. As long as vertices can be added, the algorithm continues. If no vertices can be added, the number of level equals the number of sweeps.

**Algorithm 53** Count the number of levels in an undirected graph

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

// Collect all neighbours
// If there are no new neighbours, the level is found

template <typename graph>
int count_undirected_graph_levels(
  typename boost::graph_traits<graph>::vertex_descriptor
     vd,
  const graph& g
) noexcept
{
  int level = 0;
  // This does not work:
  // std::set<boost::graph_traits<graph>::
     vertex_descriptor> s;
  std::set<int> s;
  s.insert(vd);

  while (1)
  {
    //How many nodes are known now
    const auto sz_before = s.size();

    const auto t = s;

    for (const auto v: t)
    {
      const auto neighbours = boost::adjacent_vertices(v,
          g);
      for (auto n = neighbours.first; n != neighbours.
         second; ++n)
      {
        s.insert(*n);
      }
    }

    //Have new nodes been discovered?
    if (s.size() == sz_before) break;

    //Found new nodes, thus an extra level
    ++level;
  }
  return level;
}
```

This demonstration code shows the number of levels from a certain vertex, while adding edges to form a linear graph. The vertex, when still without edges, has zero levels. After adding one edge, the graph has one level, etc.

**Algorithm 54** Demo of the 'count_undirected_graph_levels' function

```
#include <boost/test/unit_test.hpp>
#include "create_empty_undirected_graph.h"
#include "add_edge.h"
#include "count_undirected_graph_levels.h"

BOOST_AUTO_TEST_CASE(test_count_undirected_graph_levels)
{
  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 vd_d = boost::add_vertex(g);
  BOOST_CHECK(count_undirected_graph_levels(vd_a, g) ==
      0);
  boost::add_edge(vd_a, vd_b, g);
  BOOST_CHECK(count_undirected_graph_levels(vd_a, g) ==
      1);
  boost::add_edge(vd_b, vd_c, g);
  BOOST_CHECK(count_undirected_graph_levels(vd_a, g) ==
      2);
  boost::add_edge(vd_c, vd_d, g);
  BOOST_CHECK(count_undirected_graph_levels(vd_a, g) ==
      3);
}
```

## 3.11 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 55** 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 56 shows how to use the 'save_graph_to_dot' function:

**Algorithm 56** Demonstration of the 'save_graph_to_dot' function

```
#include <boost/test/unit_test.hpp>
#include "create_k2_graph.h"
#include "create_markov_chain.h"
#include "save_graph_to_dot.h"

BOOST_AUTO_TEST_CASE(test_save_graph_to_dot)
{
  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 55), only the structure of the graph is saved: all other properties like names are not stored. Algorithm 112 shows how to do so.

## 3.12 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 57:

**Algorithm 57** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_directed_graph();
  boost::dynamic_properties dp(
    boost::ignore_other_properties
  );
  boost::read_graphviz(f,g,dp);
  return g;
}
```

In this algorithm, first it is checked if the file to load exists, using the 'is_regular_file' function (algorithm 367), 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 24.5). From this and the empty graph, 'boost::read_graphviz' is called to build up the graph.

Algorithm 58 shows how to use the 'load_directed_graph_from_dot' function:

**Algorithm 58** Demonstration of the 'load_directed_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#include "create_markov_chain.h"
#include "load_directed_graph_from_dot.h"
#include "save_graph_to_dot.h"

BOOST_AUTO_TEST_CASE(test_load_directed_graph_from_dot)
{
  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);
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(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.

## 3.13 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 3.12. Algorithm 59 show how to do so:

**Algorithm 59** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  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 3.12 describes the rationale of this function.

Algorithm 60 shows how to use the 'load_undirected_graph_from_dot' function:

**Algorithm 60** Demonstration of the 'load_undirected_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#include "create_k2_graph.h"
#include "load_undirected_graph_from_dot.h"
#include "save_graph_to_dot.h"

BOOST_AUTO_TEST_CASE(test_load_undirected_graph_from_dot)
{
  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);
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(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 25.1 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 20

## 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 61** 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 62 shows how to create such a graph:

**Algorithm 62** Demonstration of the 'create_empty_directed_named_vertices_graph' function

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

BOOST_AUTO_TEST_CASE(
    test_create_empty_named_directed_vertices_graph)
{
  const auto g
    = create_empty_directed_named_vertices_graph();
  BOOST_CHECK(boost::num_vertices(g) == 0);
  BOOST_CHECK(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 63** 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 64 shows how to create such a graph:

**Algorithm 64** Demonstration of the 'create_empty_undirected_named_vertices_graph' function

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

BOOST_AUTO_TEST_CASE(
    test_create_empty_undirected_named_vertices_graph)
{
  const auto g
    = create_empty_undirected_named_vertices_graph();
  BOOST_CHECK(boost::num_vertices(g) == 0);
  BOOST_CHECK(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 65:

**Algorithm 65** Adding a vertex with a name

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

template <typename graph, typename name_type>
typename boost::graph_traits<graph>::vertex_descriptor
add_named_vertex(
  const name_type& 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[8], 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] =

[8] 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 66.

**Algorithm 66** Demonstration of 'add_named_vertex'

```
#include <boost/test/unit_test.hpp>
#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"

BOOST_AUTO_TEST_CASE(test_add_named_vertex)
{
  auto g
    = create_empty_undirected_named_vertices_graph();
  add_named_vertex("Lex", g);
  BOOST_CHECK(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 67** 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 24.1).

Algorithm 68 shows how to add two named vertices, and check if the added names are retrieved as expected.

**Algorithm 68** Demonstration of 'get_vertex_names'

```
#include <boost/test/unit_test.hpp>
#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(test_get_vertex_names)
{
  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)
  };
  BOOST_CHECK(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 19:

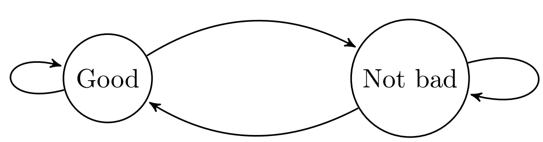


Figure 19: A two-state Markov chain where the vertices have texts

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 69** Creating a Markov chain with named vertices as depicted in figure 19

```
#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);
  boost::add_edge(vd_a, vd_a, g);
  boost::add_edge(vd_a, vd_b, g);
  boost::add_edge(vd_b, vd_a, g);
  boost::add_edge(vd_b, vd_b, g);
  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 70) is very similar to the demonstration code of the 'create_markov_chain_graph' function (algorithm 22).

**Algorithm 70** Demonstrating the 'create_named_vertices_markov_chain' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_markov_chain.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(
    test_create_named_vertices_markov_chain)
{
  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)
  };
  BOOST_CHECK(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 71** .dot file created from the 'create_named_vertices_markov_chain' function (algorithm 69), converted from graph to .dot file using algorithm 55

```
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:

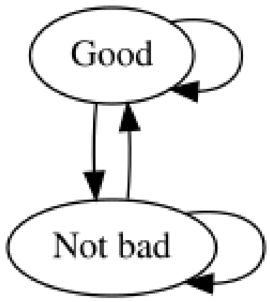


Figure 20: .svg file created from the 'create_named_vertices_markov_chain' function (algorithm 69) its .dot file, converted from .dot file to .svg using algorithm 366

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 21:

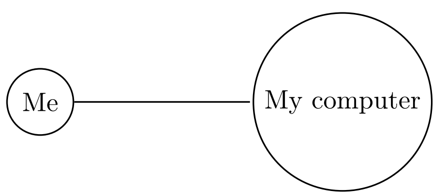


Figure 21: $K_2$: a fully connected graph with two named vertices

### 4.6.2 Function to create such a graph

To create $K_2$, the following code can be used:

**Algorithm 72** Creating $K_2$ with named vertices as depicted in figure 21

```
#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 std::string va("Me");
  const std::string vb("My computer");
  const auto vd_a = add_named_vertex(va, g);
  const auto vd_b = add_named_vertex(vb, g);
  boost::add_edge(vd_a, vd_b, g);
  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 73) is very similar to the demonstration code of the 'create_k2_graph function' (algorithm 24).

**Algorithm 73** Demonstrating the 'create_k2_graph' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_k2_graph.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(test_create_named_vertices_k2_graph)
{
  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);
  BOOST_CHECK(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 74** .dot file created from the 'create_named_vertices_k2' function (algorithm 72), converted from graph to .dot file using algorithm 112

```
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:

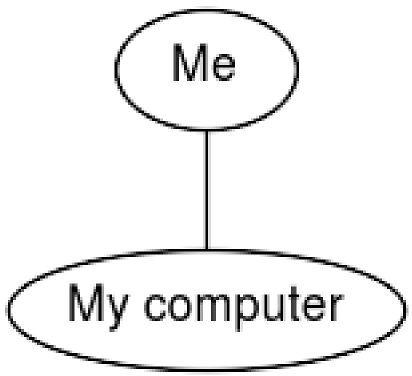


Figure 22: .svg file created from the 'create_named_vertices_k2_graph' function (algorithm 69) its .dot file, converted from .dot file to .svg using algorithm 112

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

## 4.7 ▶ Creating $K_3$ with named vertices

Here we create a $K_3$ graph with names vertices

### 4.7.1 Graph

Here I show a $K_3$ graph with named vertices (see figure 23):

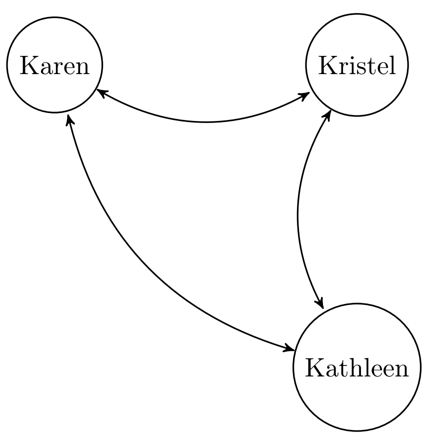


Figure 23: A $K_3$ graph with named vertices

### 4.7.2 Function to create such a graph

To create a $K_3$ graph with named vertices, the following code can be used:

**Algorithm 75** Creating a $K_3$ graph as depicted in figure 23

```
#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_k3_graph() noexcept
{
  auto g
    = create_empty_undirected_named_vertices_graph();
  const std::string a("Karen");
  const std::string b("Kristel");
  const std::string c("Kathleen");
  const auto vd_a = add_named_vertex(a, g);
  const auto vd_b = add_named_vertex(b, g);
  const auto vd_c = add_named_vertex(c, g);
  boost::add_edge(vd_a, vd_b, g);
  boost::add_edge(vd_b, vd_c, g);
  boost::add_edge(vd_c, vd_a, g);
  return g;
}
```

### 4.7.3 Creating such a graph

Algorithm 76 demonstrates how to create a $K_3$ graph with named vertices and checks if it has the correct amount of edges and vertices:

**Algorithm 76** Demonstration of 'create_named_vertices_k3_graph'

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_k3_graph.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(test_create_named_vertices_k3_graph)
{
  const auto g = create_named_vertices_k3_graph();
  const std::vector<std::string> expected_names{
    "Karen", "Kristel","Kathleen"
  };
  const std::vector<std::string> vertex_names =
     get_vertex_names(g);
  BOOST_CHECK(expected_names == vertex_names);
}
```

#### 4.7.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 77:

**Algorithm 77** .dot file created from the 'create_named_vertices_k3_graph' function (algorithm 75), converted from graph to .dot file using algorithm 55

```
graph G {
0[label=Karen];
1[label=Kristel];
2[label=Kathleen];
0--1 ;
1--2 ;
2--0 ;
}
```

#### 4.7.5 The .svg file produced

The .dot file can be converted to the .svg as shown in figure 24:

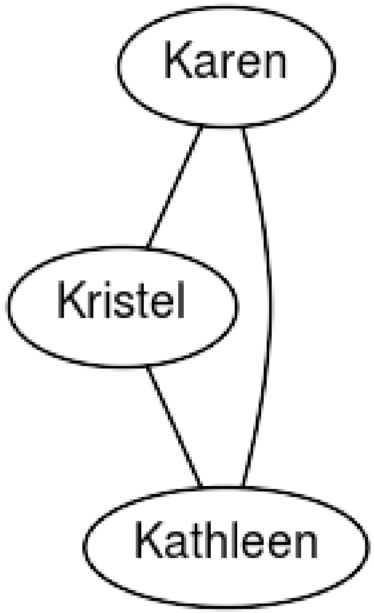


Figure 24: .svg file created from the ‘create_named_vertices_k3_graph’ function (algorithm 75) its .dot file, converted from .dot file to .svg using algorithm 366

## 4.8 ▶ Creating a path graph with named vertices

Here we create a path graph with names vertices

### 4.8.1 Graph

Here I show a path graph with four vertices (see figure 25):

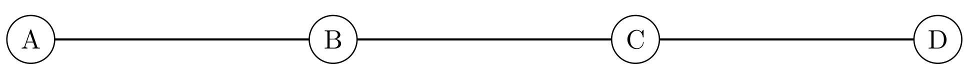


Figure 25: A path graph with four vertices

### 4.8.2 Function to create such a graph

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

**Algorithm 78** Creating a path graph as depicted in figure 25

```
#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);
    boost::add_edge(vd_1, vd_2, g);
    vd_1 = vd_2;
  }
  return g;
}
```

### 4.8.3 Creating such a graph

Algorithm 79 demonstrates how to create a path graph with named vertices and checks if it has the correct amount of edges and vertices:

**Algorithm 79** Demonstration of 'create_named_vertices_path_graph'

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_path_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_named_vertices_path_graph)
{
  const auto g = create_named_vertices_path_graph(
    {"A", "B", "C", "D"}
  );
  BOOST_CHECK(boost::num_edges(g) == 3);
  BOOST_CHECK(boost::num_vertices(g) == 4);
}
```

### 4.8.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 80:

**Algorithm 80** .dot file created from the 'create_named_vertices_path_graph' function (algorithm 78), converted from graph to .dot file using algorithm 55

### 4.8.5 The .svg file produced

The .dot file can be converted to the .svg as shown in figure 26:

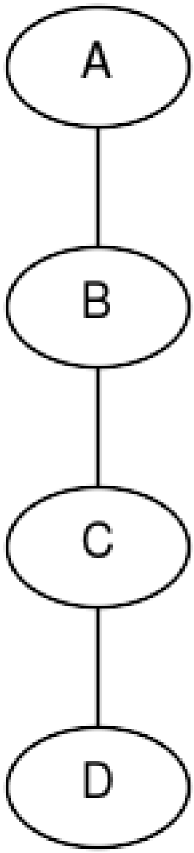


Figure 26: .svg file created from the 'create_named_vertices_path_graph' function (algorithm 78) its .dot file, converted from .dot file to .svg using algorithm 366

## 4.9 ▶ Creating a Petersen graph with named vertices

Here we create a Petersen graph with names vertices.

### 4.9.1 Graph

Here I show a Petersen graph (see figure 27):

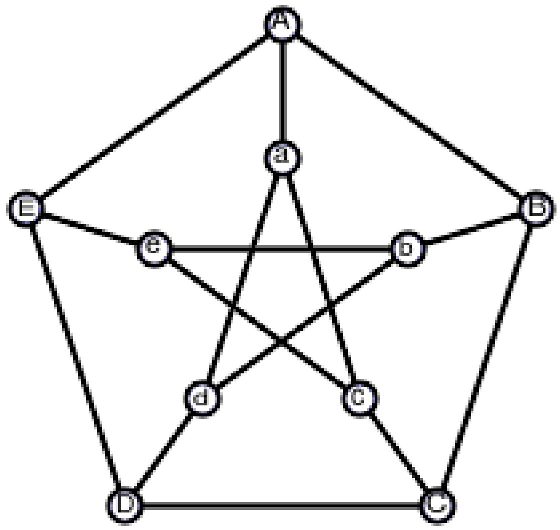


Figure 27: A Petersen graph with named vertices (modified from `https://en.wikipedia.org/wiki/Petersen_graph`)

#### 4.9.2 Function to create such a graph

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

**Algorithm 81** Creating a Petersen graph as depicted in figure 27

```
#include <cassert>
#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_petersen_graph() noexcept
{
  auto g = create_empty_undirected_named_vertices_graph()
      ;
  using vd = decltype(
      create_empty_undirected_named_vertices_graph())::
      vertex_descriptor;


  std::vector<vd> v; //Outer
  for (int i=0; i!=5; ++i) {
    v.push_back(
      add_named_vertex(std::string(1,'A' + i), g)
    );
  }
  std::vector<vd> w; //Inner
  for (int i=0; i!=5; ++i) {
    w.push_back(
      add_named_vertex(std::string(1,'a' + i), g)
    );
  }
  //Outer ring
  for (int i=0; i!=5; ++i) {
    boost::add_edge(v[i], v[(i + 1) % 5], g);
  }
  //Spoke
  for (int i=0; i!=5; ++i) {
    boost::add_edge(v[i], w[i], g);
  }
  //Inner pentagram
  for (int i=0; i!=5; ++i) {
    boost::add_edge(w[i], w[(i + 2) % 5], g);
  }
  return g;
}
```

### 4.9.3 Creating such a graph

Algorithm 82 demonstrates how to create a path graph with named vertices and checks if it has the correct amount of edges and vertices:

**Algorithm 82** Demonstration of 'create_named_vertices_petersen_graph'

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_petersen_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_named_vertices_petersen_graph)
{
  const auto g = create_named_vertices_petersen_graph();
  BOOST_CHECK(boost::num_edges(g) == 15);
  BOOST_CHECK(boost::num_vertices(g) == 10);
}
```

### 4.9.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 83:

**Algorithm 83** .dot file created from the 'create_named_vertices_petersen_graph' function (algorithm 81), converted from graph to .dot file using algorithm 55

```
graph G {
0[label=A];
1[label=B];
2[label=C];
3[label=D];
4[label=E];
5[label=a];
6[label=b];
7[label=c];
8[label=d];
9[label=e];
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 ;
}
```

#### 4.9.5 The .svg file produced

The .dot file can be converted to the .svg as shown in figure 28:

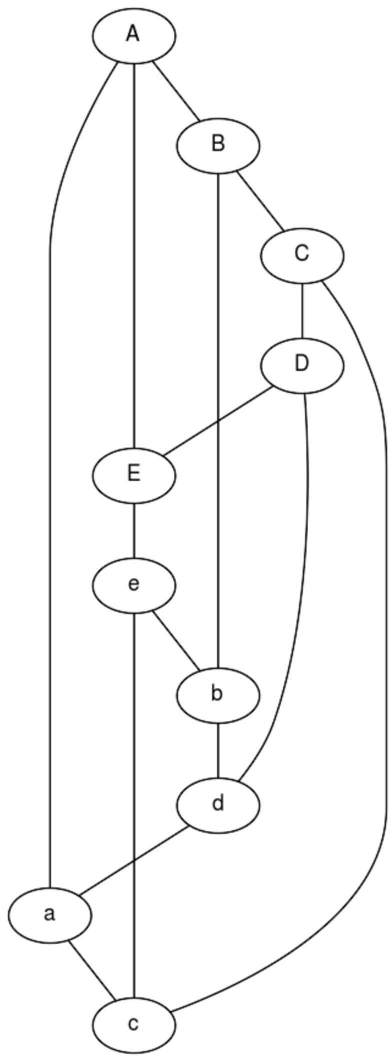


Figure 28: .svg file created from the 'create_named_vertices_petersen_graph' function (algorithm 81) its .dot file, converted from .dot file to .svg using algorithm 366

# 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 5.10
- Saving an directed/undirected graph with named vertices to a .dot file: chapter 5.15
- Loading a directed graph with named vertices from a .dot file: chapter 5.16
- Loading an undirected graph with named vertices from a .dot file: chapter 5.17

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 84** Find if there is vertex with a certain name

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

template <typename graph, typename name_type>
bool has_vertex_with_name(
  const name_type& 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 85, where a certain name cannot be found in an empty graph. After adding the desired name, it is found.

**Algorithm 85** Demonstration of the 'has_vertex_with_name' function

```
#include <boost/test/unit_test.hpp>
#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"
#include "has_vertex_with_name.h"

BOOST_AUTO_TEST_CASE(test_has_vertex_with_name)
{
  auto g
    = create_empty_undirected_named_vertices_graph();
  BOOST_CHECK(!has_vertex_with_name("Felix",g));
  add_named_vertex("Felix",g);
  BOOST_CHECK(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 86 shows how to obtain a vertex descriptor to the first (name) vertex found with a specific name.

**Algorithm 86** Find the first vertex by its name

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

template <typename graph, typename name_type>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_vertex_with_name(
  const name_type& name,
  const graph& g
)
{
  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) {
      return get_vertex_name(d, g) == name;
    }
  );
  if (i == vip.second)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find vertex with name '"
      << name << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  return *i;
}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 87 shows some examples of how to do so.

**Algorithm 87** Demonstration of the 'find_first_vertex_with_name' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_k2_graph.h"
#include "find_first_vertex_with_name.h"

BOOST_AUTO_TEST_CASE(test_find_first_vertex_with_name)
{
  const auto g
    = create_named_vertices_k2_graph();
  const auto vd
    = find_first_vertex_with_name(
      "My computer", g
    );
  BOOST_CHECK(
    out_degree(vd,g) == 1
  );
  BOOST_CHECK(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 86 shows how to find a vertex, obtain its vertex descriptor and then obtain the out degree from it.

**Algorithm 88** 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)
{
  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 89 shows how to use this function.

**Algorithm 89** Demonstration of the 'get_first_vertex_with_name_out_degree' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_k2_graph.h"
#include "get_first_vertex_with_name_out_degree.h"

BOOST_AUTO_TEST_CASE(
    test_get_first_vertex_with_name_out_degree)
{
  const auto g = create_named_vertices_k2_graph();
  BOOST_CHECK(
    get_first_vertex_with_name_out_degree(
      "Me", g
    ) == 1
  );
  BOOST_CHECK(
    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 90** 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>
auto get_vertex_name(
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  const graph& g
) noexcept -> decltype(get(get(boost::vertex_name, g), vd
    ))
{
  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 91 shows a simple example:

**Algorithm 91** Demonstration if the 'get_vertex_name' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_get_vertex_name)
{
  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);
  BOOST_CHECK(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 92.

**Algorithm 92** 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 93 shows a simple example.

**Algorithm 93** Demonstration if the 'set_vertex_name' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_set_vertex_name)
{
  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);
  BOOST_CHECK(get_vertex_name(vd,g) == old_name);
  const std::string new_name{"Diggy"};
  set_vertex_name(new_name, vd, g);
  BOOST_CHECK(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 94** 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)
  {
    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 24.2)

- 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 24.3)

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

**Algorithm 95** Clear the first vertex with a certain name

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

template <typename graph, typename name_type>
void clear_first_vertex_with_name(
  const name_type& name,
  graph& g
)
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );
  if (!has_vertex_with_name(name,g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "unknown vertex name '"
      << name << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  const auto vd
    = find_first_vertex_with_name(name,g);
  boost::clear_vertex(vd,g);
}
```

Algorithm 96 shows the clearing of the first named vertex found.

**Algorithm 96** Demonstration of the 'clear_first_vertex_with_name' function

```
#include <boost/test/unit_test.hpp>
#include "clear_first_vertex_with_name.h"
#include "create_named_vertices_k2_graph.h"

BOOST_AUTO_TEST_CASE(test_clear_first_vertex_with_name)
{
  auto g = create_named_vertices_k2_graph();
  BOOST_CHECK(boost::num_edges(g) == 1);
  clear_first_vertex_with_name("My computer",g);
  BOOST_CHECK(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 95) 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 97** 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
)
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );
  if (!has_vertex_with_name(name,g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "cannot find vertex with name '"
      << name << "'"
    ;
    throw std::invalid_argument(msg.str());
  }

  const auto vd
    = find_first_vertex_with_name(name,g);

  if (degree(vd,g) != 0)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "cannot remove connected vertex with name '"
      << name << "' and degree " << degree(vd,g)
    ;
    throw std::invalid_argument(msg.str());
  }

  boost::remove_vertex(vd,g);
}
```

Algorithm 98 shows the removal of the first named vertex found.

**Algorithm 98** Demonstration of the 'remove_first_vertex_with_name' function

```
#include <boost/test/unit_test.hpp>
#include "clear_first_vertex_with_name.h"
#include "create_named_vertices_k2_graph.h"
#include "remove_first_vertex_with_name.h"

BOOST_AUTO_TEST_CASE(test_remove_first_vertex_with_name)
{
  auto g = create_named_vertices_k2_graph();
  clear_first_vertex_with_name(
    "My computer",g
  );
  remove_first_vertex_with_name(
    "My computer",g
  );
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(boost::num_vertices(g) == 1);
}
```

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

## 5.9 ▶ Adding an edge between two named vertices

Instead of looking for an edge descriptor, one can also add an edge from two vertex descriptors. Adding 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::add_edge' on those two, as shown in algorithm 99.

**Algorithm 99** Adding an edge between two named vertices

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

template <typename graph, typename name_type>
typename boost::graph_traits<graph>::edge_descriptor
add_edge_between_named_vertices(
  const name_type& vertex_name_1,
  const name_type& vertex_name_2,
  graph& g
)
{
  if (!has_vertex_with_name(vertex_name_1, g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find vertex #1 with name '"
      << vertex_name_1 << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  if (!has_vertex_with_name(vertex_name_2, g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find vertex #2 with name '"
      << vertex_name_2 << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  const auto vd_1 = find_first_vertex_with_name(
      vertex_name_1, g);
  const auto vd_2 = find_first_vertex_with_name(
      vertex_name_2, g);
  const auto aer = boost::add_edge(vd_1, vd_2, g);
  if (!aer.second) {
    std::stringstream msg;
    msg << __func__ << ": edge insertion failed";
    throw std::invalid_argument(msg.str());
  }
  return aer.first;
}
```

Algorithm 100 shows how to add an edge between two named vertices:

**Algorithm 100** Demonstration of the 'add_edge_between_named_vertices' function

```
#include <boost/test/unit_test.hpp>
#include "add_edge_between_named_vertices.h"
#include "add_named_vertex.h"
#include "create_empty_undirected_named_vertices_graph.h"

BOOST_AUTO_TEST_CASE(test_add_edge_between_named_vertices
    )
{
  auto g = create_empty_undirected_named_vertices_graph()
      ;
  const std::string name1{"Bert"};
  const std::string name2{"Ernie"};
  add_named_vertex(name1, g);
  add_named_vertex(name2, g);
  add_edge_between_named_vertices(name1, name2, g);
  BOOST_CHECK(boost::num_edges(g) == 1);
}
```

## 5.10 ▶ 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 101.

**Algorithm 101** 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
)
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );
  if (!has_vertex_with_name(name_1,g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "cannot find vertex #1 with name '"
      << name_1 << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  if (!has_vertex_with_name(name_2,g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "cannot find vertex #2 with name '"
      << name_1 << "'"
    ;
    throw std::invalid_argument(msg.str());
  }

  const auto vd_1
    = find_first_vertex_with_name(name_1, g);
  const auto vd_2
    = find_first_vertex_with_name(name_2, g);

  if (!has_edge_between_vertices(vd_1, vd_2, g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "no edge between vertices"
    ;
    throw std::invalid_argument(msg.str());
  }

  boost::remove_edge(vd_1, vd_2, g);
}
```

Algorithm 102 shows the removal of the first named edge found.

**Algorithm 102** Demonstration of the 'remove_edge_between_vertices_with_names' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_edges_and_vertices_k3_graph.h"
#include "remove_edge_between_vertices_with_names.h"

BOOST_AUTO_TEST_CASE(
    test_remove_edge_between_vertices_with_names)
{
  auto g = create_named_edges_and_vertices_k3_graph();
  BOOST_CHECK(boost::num_edges(g) == 3);
  remove_edge_between_vertices_with_names("top","right",g
      );
  BOOST_CHECK(boost::num_edges(g) == 2);
}
```

## 5.11 ▶ Count the vertices with a certain name

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

**Algorithm 103** Find the first vertex by its name

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

template <typename graph, typename name_type>
int count_vertices_with_name(
  const name_type& name,
  const graph& g
) 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 104 shows some examples of how to do so.

**Algorithm 104** Demonstration of the 'find_first_vertex_with_name' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_count_vertices_with_name)
{
  auto g = create_named_vertices_path_graph(
    {"Apple", "Pear", "Apple"}
  );
  BOOST_CHECK(count_vertices_with_name("Apple", g) == 2);
  BOOST_CHECK(count_vertices_with_name("Pear", g) == 1);
  BOOST_CHECK(count_vertices_with_name("Banana", g) == 0)
      ;
}
```

## 5.12 ▶ Create a direct-neighbour subgraph from a vertex descriptor of a graph with named vertices

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 105** Get the direct-neighbour named vertices subgraph from a vertex descriptor

```
#include <map>
#include <boost/graph/adjacency_list.hpp>
#include "add_named_vertex.h"
#include "get_vertex_name.h"
template <typename graph, typename vertex_descriptor>
graph create_direct_neighbour_named_vertices_subgraph(
  const vertex_descriptor& vd,
  const graph& g
)
{
  graph h;

  std::map<vertex_descriptor,vertex_descriptor> m;
  {
    const auto vd_h = add_named_vertex(
      get_vertex_name(vd, g), 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)),
      [g, &h](const vertex_descriptor& d)
      {
        const auto vd_h = add_named_vertex(
          get_vertex_name(d,g), 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;
      boost::add_edge(m[vd_from],m[vd_to], h);
    }
  }
  return h;
}
```

This demonstration code shows that the direct-neighbour graph of each vertex of a $K_2$ graphs is ... a $K_2$ graph!

**Algorithm 106** Demo of the 'create_direct_named_vertices_neighbour_subgraph' function

```
#include <boost/test/unit_test.hpp>
#include "create_direct_neighbour_named_vertices_subgraph
    .h"
#include "create_named_vertices_k2_graph.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(
    test_create_direct_neighbour_named_vertices_subgraph)
{
  const auto g = create_named_vertices_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_named_vertices_subgraph(
      *i,g
    );
    BOOST_CHECK(boost::num_vertices(h) == 2);
    BOOST_CHECK(boost::num_edges(h) == 1);
    const auto v = get_vertex_names(h);
    std::set<std::string> names(std::begin(v),std::end(v)
        );
    BOOST_CHECK(names.count("Me") == 1);
    BOOST_CHECK(names.count("My computer") == 1);
  }
}
```

## 5.13 ► Creating all direct-neighbour subgraphs from a graph with named vertices

Using the previous function, it is easy to create all direct-neighbour subgraphs from a graph with named vertices:

**Algorithm 107** Create all direct-neighbour subgraphs from a graph with named vertices

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

template <typename graph>
std::vector<graph>
    create_all_direct_neighbour_named_vertices_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_named_vertices_subgraph(
        d, g
      );
    }
  );
  return v;
}
```

This demonstration code shows that all two direct-neighbour graphs of a $K_2$ graphs are ... $K_2$ graphs!

**Algorithm 108** Demo of the 'create_all_direct_neighbour_named_vertices_subgraphs' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_all_direct_neighbour_named_vertices_subgraphs.h
    "
#include "create_named_vertices_path_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_all_direct_neighbour_named_vertices_subgraphs
    )
{
  const auto v
    =
        create_all_direct_neighbour_named_vertices_subgraphs
        (
      create_named_vertices_path_graph( {"A","B","C"} )
    );
  BOOST_CHECK(v.size() == 3);
}
```

The sub-graphs are shown here:

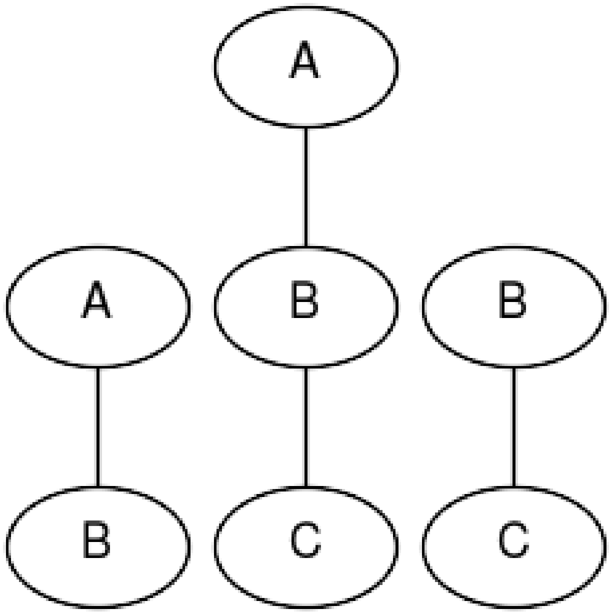


Figure 29: All subgraphs created

## 5.14 ▶ 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 3.7.

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 than std::strings.

**Algorithm 109** 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 (const auto vd : boost::make_iterator_range(boost
        ::vertices(m_graph))) {
      const size_t next_id = m_mappings.size();
      const 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 110** 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 111** Demo of the 'is_named_vertices_isomorphic' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_path_graph.h"
#include "is_named_vertices_isomorphic.h"

BOOST_AUTO_TEST_CASE(test_is_named_vertices_isomorphic)
{
  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" }
  );
  BOOST_CHECK( is_named_vertices_isomorphic(g,h));
  BOOST_CHECK(!is_named_vertices_isomorphic(g,i));
}
```

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

If you used the 'create_named_vertices_k2_graph' function (algorithm 72) to produce a $K_2$ graph with named vertices, you can store these names in multiple ways:

- Using boost::make_label_writer
- Using a lambda function

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

The created .dot file is shown at algorithm 74.

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.

### 5.15.1 Using boost::make_label_writer

The first implemention uses boost::make_label_writer, as shown in algorithm 112:

**Algorithm 112** 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"
#include "is_graphviz_friendly.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); //Can be Graphviz-unfriendly
  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.

### 5.15.2 Using a lambda function

An equivalent algorithm is algorithm 113:

**Algorithm 113** 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 90) and stream it to the out stream.

### 5.15.3 Demonstration

Algorithm 114 shows how to use (one of) the 'save_named_vertices_graph_to_dot' function(s):

**Algorithm 114** Demonstration of the 'save_named_vertices_graph_to_dot' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_k2_graph.h"
#include "create_named_vertices_markov_chain.h"
#include "save_named_vertices_graph_to_dot.h"

BOOST_AUTO_TEST_CASE(
    test_save_named_vertices_graph_to_dot)
{
  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 112), only the structure of the graph and the vertex names are saved: all other properties like edge name are not stored. Algorithm 158 shows how to do so.

## 5.16 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 115:

**Algorithm 115** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_directed_named_vertices_graph();
  boost::dynamic_properties dp(boost::
      ignore_other_properties);
  dp.property("label", get(boost::vertex_name, g));
  boost::read_graphviz(f,g,dp);
  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 116 shows how to use the 'load_directed_graph_from_dot' function:

**Algorithm 116** Demonstration of the 'load_directed_named_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_directed_named_vertices_graph_from_dot)
{
  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
    );
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 67).

## 5.17 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 117:

**Algorithm 117** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_undirected_named_vertices_graph()
     ;
  boost::dynamic_properties dp(boost::
     ignore_other_properties);
  dp.property("label", get(boost::vertex_name, g));
  boost::read_graphviz(f,g,dp);
  return g;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 5.16 describes the rationale of this function.

Algorithm 118 shows how to use the 'load_undirected_graph_from_dot' function:

**Algorithm 118** Demonstration of the 'load_undirected_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_undirected_named_vertices_graph_from_dot)
{
  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
    );
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 72), 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 67).

# 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 6.6
- $K_3$ with named edges and vertices: see chapter 6.8

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 6.5

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 119** 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 120 shows how to create this graph. Note that all the earlier functions defined in this tutorial keep working as expected.

**Algorithm 120** Demonstration if the 'create_empty_directed_named_edges_and_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_create_empty_directed_named_edges_and_vertices_graph
    )
{
  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);
  BOOST_CHECK(expected_vertex_names == vertex_names);
  const strings expected_edge_names{"Reed"};
  const strings edge_names = get_edge_names(g);
  BOOST_CHECK(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 121** 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 122 shows how to create this graph. Note that all the earlier functions defined in this tutorial keep working as expected.

**Algorithm 122** Demonstration if the 'create_empty_undirected_named_edges_and_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_create_empty_undirected_named_edges_and_vertices_graph
    )
{
  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);
  BOOST_CHECK(expected_vertex_names == vertex_names);
  const strings expected_edge_names{"Reed"};
  const strings edge_names = get_edge_names(g);
  BOOST_CHECK(expected_edge_names == edge_names);
}
```

## 6.3 Adding a named edge

Adding an edge with a name:

**Algorithm 123** Add a vertex with a name

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

template <typename graph, typename name_type>
typename boost::graph_traits<graph>::edge_descriptor
add_named_edge(
  const name_type& 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 124 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 24.1).

**Algorithm 124** Demonstration of the 'add_named_edge' function

```
#include <boost/test/unit_test.hpp>
#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(test_add_named_edge)
{
  auto g
    =
        create_empty_undirected_named_edges_and_vertices_graph
        ();
  add_named_edge("Richards", g);
  BOOST_CHECK(boost::num_edges(g) == 1);
}
```

## 6.4 Adding a named edge between vertices

When having two vertex descriptors, you can add a named edge between those.

**Algorithm 125** Add a vertex with a name between vertices

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

template <
  typename graph,
  typename vertex_descriptor,
  typename name_type
>
typename boost::graph_traits<graph>::edge_descriptor
add_named_edge_between_vertices(
  const name_type& edge_name,
  const vertex_descriptor from,
  const vertex_descriptor to,
  graph& g
)
{
  const auto aer = boost::add_edge(from, to, g);
  if (!aer.second) {
    std::stringstream msg;
    msg << __func__ << ": edge insertion failed";
    throw std::invalid_argument(msg.str());
  }
  set_edge_name(edge_name, aer.first , g);
  return aer.first;
}
```

In this code snippet, the edge is added between the two vertex descriptors, after which the name of the edge is set.

A demonstration is given by algorithm 126:

**Algorithm 126** Demonstration of the 'add_named_edge_between_vertices' function

```
#include <boost/test/unit_test.hpp>
#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(test_add_named_edge)
{
  auto g
    =
        create_empty_undirected_named_edges_and_vertices_graph
        ();
  add_named_edge("Richards", g);
  BOOST_CHECK(boost::num_edges(g) == 1);
}
```

## 6.5 Getting the edges' names

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

**Algorithm 127** 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 128 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 24.1).

**Algorithm 128** Demonstration of the 'get_edge_names' function

```
#include <boost/test/unit_test.hpp>
#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "get_edge_names.h"

BOOST_AUTO_TEST_CASE(test_get_edge_names)
{
  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)
  };
  BOOST_CHECK(expected_names == edge_names);
}
```

## 6.6 Creating Markov chain with named edges and vertices

### 6.6.1 Graph

We build this graph:

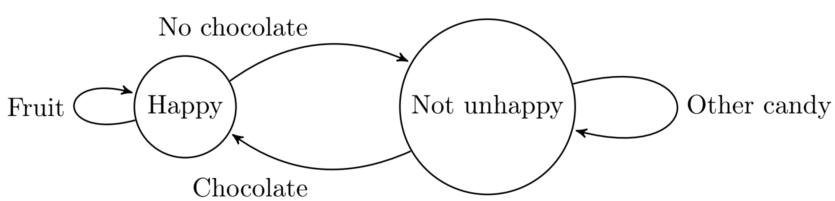


Figure 30: A two-state Markov chain where the edges and vertices have texts

### 6.6.2 Function to create such a graph

Here is the code:

**Algorithm 129** Creating the two-state Markov chain as depicted in figure 30

```
#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;
}
```

### 6.6.3 Creating such a graph

Here is the demo:

**Algorithm 130** Demo of the 'create_named_edges_and_vertices_markov_chain' function (algorithm 129)

```
#include <boost/test/unit_test.hpp>
#include "create_named_edges_and_vertices_markov_chain.h"
#include "get_edge_names.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(
    test_create_named_edges_and_vertices_markov_chain)
{
  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)
  };
  BOOST_CHECK(expected_vertex_names == vertex_names);

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

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

### 6.6.4 The .dot file produced

**Algorithm 131** .dot file created from the 'create_named_edges_and_vertices_markov_chain' function (algorithm 129), converted from graph to .dot file using algorithm 55

```
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"];
}
```

### 6.6.5 The .svg file produced

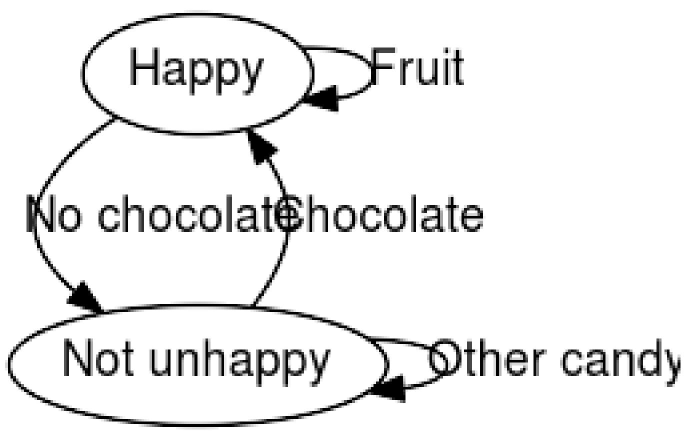


Figure 31: .svg file created from the 'create_named_edges_and_vertices_markov_chain' function (algorithm 129) its .dot file, converted from .dot file to .svg using algorithm 366

## 6.7 Creating $K_2$ with named edges and vertices

### 6.7.1 Graph

We extend the graph $K_2$ with named vertices of chapter 4.6 by adding names to the edges, as depicted in figure 32:

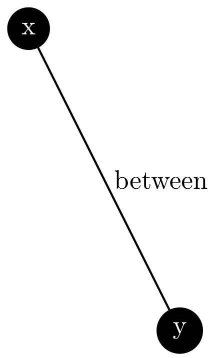


Figure 32: $K_2$: a fully connected graph with three named edges and vertices

### 6.7.2 Function to create such a graph

To create $K_2$, the following code can be used:

**Algorithm 132** Creating $K_2$ as depicted in figure 32

```
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "add_named_vertex.h"
#include "add_named_edge_between_vertices.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_k2_graph()
{
  auto g
    =
        create_empty_undirected_named_edges_and_vertices_graph
        ();
  const std::string va("x");
  const std::string vb("y");
  const std::string ea("between");
  const auto vd_a = add_named_vertex(va, g);
  const auto vd_b = add_named_vertex(vb, g);
  add_named_edge_between_vertices(ea,vd_a,vd_b, g);
  return g;
}
```

Most of the code is a repeat of algorithm 72. In the end, the edge names are obtained as a boost::property_map and set.

### 6.7.3 Creating such a graph

Algorithm 133 shows how to create the graph and measure its edge and vertex names.

**Algorithm 133** Demonstration of the 'create_named_edges_and_vertices_k2' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_edges_and_vertices_k2_graph.h"
#include "get_edge_names.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(
    test_create_named_edges_and_vertices_k2_graph)
{
  using strings = std::vector<std::string>;

  const auto g
    = create_named_edges_and_vertices_k2_graph();

  const strings expected_vertex_names{
    "x", "y"
  };
  const strings vertex_names{
    get_vertex_names(g)
  };
  BOOST_CHECK(expected_vertex_names == vertex_names);

  const strings expected_edge_names{
    "between"
  };
  const strings edge_names{get_edge_names(g)};
  BOOST_CHECK(expected_edge_names == edge_names);
}
```

### 6.7.4 The .dot file produced

**Algorithm 134** .dot file created from the 'create_named_edges_and_vertices_k2_graph' function (algorithm 132), converted from graph to .dot file using algorithm 55

```
graph G {
0[label=x];
1[label=y];
0--1 [label="between"];
}
```

#### 6.7.5 The .svg file produced

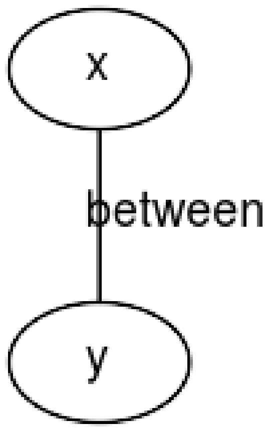


Figure 33: .svg file created from the 'create_named_edges_and_vertices_k2_graph' function (algorithm 132) its .dot file, converted from .dot file to .svg using algorithm 366

### 6.8 Creating $K_3$ with named edges and vertices

#### 6.8.1 Graph

We extend the graph $K_2$ with named vertices of chapter 4.6 by adding names to the edges, as depicted in figure 34:

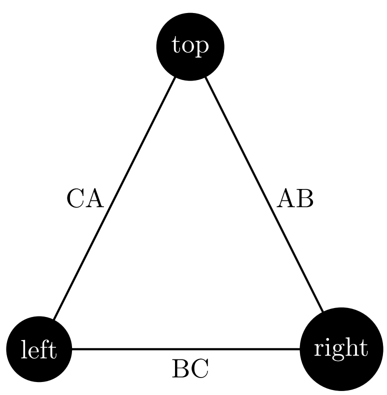


Figure 34: $K_3$: a fully connected graph with three named edges and vertices

#### 6.8.2 Function to create such a graph

To create $K_3$, the following code can be used:

**Algorithm 135** Creating $K_3$ as depicted in figure 34

```
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "add_named_vertex.h"
#include "add_named_edge_between_vertices.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()
{
  auto g
    =
        create_empty_undirected_named_edges_and_vertices_graph
        ();
  const std::string va("top");
  const std::string vb("right");
  const std::string vc("left");
  const std::string ea("AB");
  const std::string eb("BC");
  const std::string ec("CA");
  const auto vd_a = add_named_vertex(va, g);
  const auto vd_b = add_named_vertex(vb, g);
  const auto vd_c = add_named_vertex(vc, g);
  add_named_edge_between_vertices(ea, vd_a, vd_b, g);
  add_named_edge_between_vertices(eb, vd_b, vd_c, g);
  add_named_edge_between_vertices(ec, vd_c, vd_a, g);
  return g;
}
```

Most of the code is a repeat of algorithm 72. In the end, the edge names are obtained as a boost::property_map and set.

### 6.8.3 Creating such a graph

Algorithm 136 shows how to create the graph and measure its edge and vertex names.

**Algorithm 136** Demonstration of the 'create_named_edges_and_vertices_k3' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_edges_and_vertices_k3_graph.h"
#include "get_edge_names.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(
    test_create_named_edges_and_vertices_k3_graph)
{
  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)
  };
  BOOST_CHECK(expected_vertex_names == vertex_names);

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

#### 6.8.4 The .dot file produced

**Algorithm 137** .dot file created from the 'create_named_edges_and_vertices_k3_graph' function (algorithm 135), converted from graph to .dot file using algorithm 55

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

#### 6.8.5 The .svg file produced

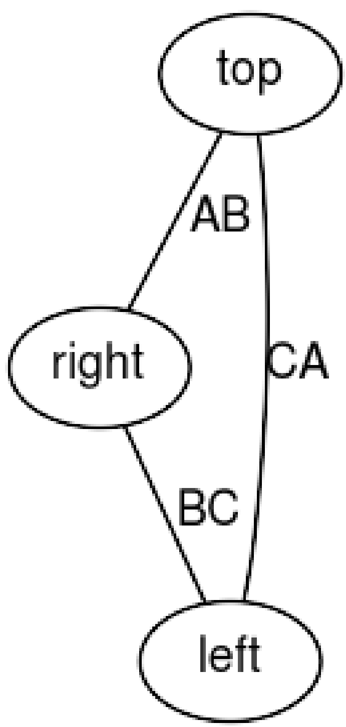


Figure 35: .svg file created from the 'create_named_edges_and_vertices_k3_graph' function (algorithm 135) its .dot file, converted from .dot file to .svg using algorithm 366

## 6.9 ▶ Creating a path graph with named edges and vertices

Here we create a path graph with names edges and vertices

### 6.9.1 Graph

Here I show a path graph with four vertices (see figure 36):

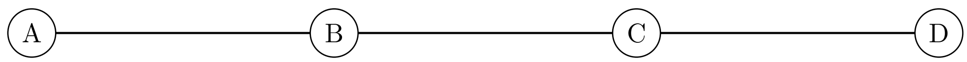


Figure 36: A path graph with four vertices

### 6.9.2 Function to create such a graph

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

**Algorithm 138** Creating a path graph as depicted in figure 36

```
#include <vector>
#include "add_named_edge_between_vertices.h"
#include "add_named_vertex.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  boost::property<boost::vertex_name_t,std::string>,
  boost::property<boost::edge_name_t,std::string>
>
create_named_edges_and_vertices_path_graph(
  const std::vector<std::string>& edge_names,
  const std::vector<std::string>& vertex_names
)
{
  if (!vertex_names.empty()
    && vertex_names.size() - 1 != edge_names.size())
  {
    std::stringstream msg;
    msg << __func__ << ": need n_vertices == n_edges + 1,
         supplied "
      << "n_vertices: " << vertex_names.size() << ", "
      << "n_edges: " << edge_names.size()
    ;
    throw std::invalid_argument(msg.str());
  }
  auto g =
     create_empty_undirected_named_edges_and_vertices_graph
     ();
  if (vertex_names.size() == 0) { return g; }
  auto vd_1 = add_named_vertex(*vertex_names.begin(), g);
  if (vertex_names.size() == 1) return g;
  const auto j = std::end(vertex_names);
  auto vertex_name = std::begin(vertex_names);
  auto edge_name = std::begin(edge_names);
  for (++vertex_name; vertex_name!=j; ++vertex_name, ++
     edge_name) //Skip first vertex name
  {
    auto vd_2 = add_named_vertex(*vertex_name, g);
    add_named_edge_between_vertices(
      *edge_name,vd_1, vd_2, g
    );
    vd_1 = vd_2;
  }
  return g;
}
```

### 6.9.3 Creating such a graph

Algorithm 139 demonstrates how to create a path graph with named edges and vertices and checks if it has the correct amount of edges and vertices:

**Algorithm 139** Demonstration of 'create_named_edges_and_vertices_path_graph'

```
#include <boost/test/unit_test.hpp>
#include "create_named_edges_and_vertices_path_graph.h"
#include "get_edge_names.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(
    test_create_named_edges_and_vertices_path_graph)
{
  const std::vector<std::string> vertex_names
    = {"A", "B", "C", "D"};
  const std::vector<std::string> edge_names
    = { "1", "2", "3" };
  const auto g =
      create_named_edges_and_vertices_path_graph(
    edge_names, vertex_names
  );
  BOOST_CHECK(boost::num_edges(g) == 3);
  BOOST_CHECK(boost::num_vertices(g) == 4);
  BOOST_CHECK(get_edge_names(g) == edge_names);
  BOOST_CHECK(get_vertex_names(g) == vertex_names);
}
```

### 6.9.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 140:

**Algorithm 140** .dot file created from the 'create_named_edges_and_vertices_path_graph' function (algorithm 138), converted from graph to .dot file using algorithm 55

### 6.9.5 The .svg file produced

The .dot file can be converted to the .svg as shown in figure 37:

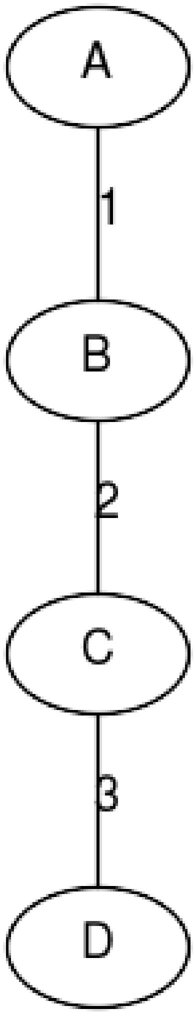


Figure 37: .svg file created from the 'create_named_edges_and_vertices_path_graph' function (algorithm 138) its .dot file, converted from .dot file to .svg using algorithm 366

## 6.10 ▶ Creating a Petersen graph with named edges and vertices

Here we create a Petersen graph with named edges and vertices.

### 6.10.1 Graph

Here I show a Petersen graph (see figure 38):

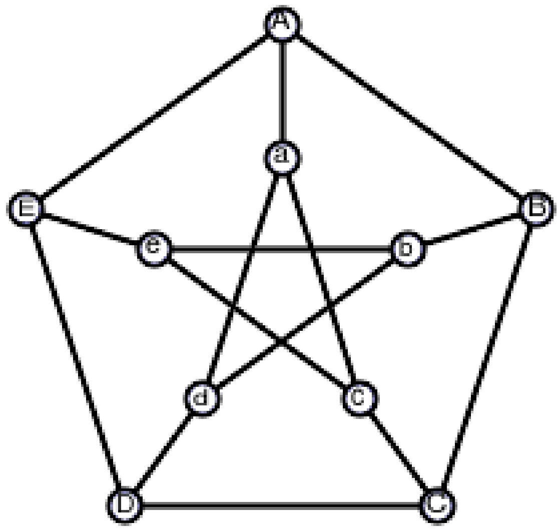


Figure 38: A Petersen graph with named edges and vertices (modified from `https://en.wikipedia.org/wiki/Petersen_graph`)

### 6.10.2 Function to create such a graph

To create a Petersen graph with named edges and vertices, the following code can be used:

**Algorithm 141** Creating a Petersen graph as depicted in figure 38

```
#include <cassert>
#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_petersen_graph() noexcept
{
  auto g = create_empty_undirected_named_vertices_graph()
      ;
  using vd = decltype(
      create_empty_undirected_named_vertices_graph())::
      vertex_descriptor;


  std::vector<vd> v; //Outer
  for (int i=0; i!=5; ++i) {
    v.push_back(
      add_named_vertex(std::string(1,'A' + i), g)
    );
  }
  std::vector<vd> w; //Inner
  for (int i=0; i!=5; ++i) {
    w.push_back(
      add_named_vertex(std::string(1,'a' + i), g)
    );
  }
  //Outer ring
  for (int i=0; i!=5; ++i) {
    boost::add_edge(v[i], v[(i + 1) % 5], g);
  }
  //Spoke
  for (int i=0; i!=5; ++i) {
    boost::add_edge(v[i], w[i], g);
  }
  //Inner pentagram
  for (int i=0; i!=5; ++i) {
    boost::add_edge(w[i], w[(i + 2) % 5], g);
  }
  return g;
}
```

### 6.10.3 Creating such a graph

Algorithm 142 demonstrates how to create a path graph with named vertices and checks if it has the correct amount of edges and vertices:

**Algorithm 142** Demonstration of 'create_named_vertices_petersen_graph'

```
#include <boost/test/unit_test.hpp>
#include "create_named_vertices_petersen_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_named_vertices_petersen_graph)
{
  const auto g = create_named_vertices_petersen_graph();
  BOOST_CHECK(boost::num_edges(g) == 15);
  BOOST_CHECK(boost::num_vertices(g) == 10);
}
```

### 6.10.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 143:

**Algorithm 143** .dot file created from the 'create_named_edges_and_vertices_petersen_graph' function (algorithm 141), converted from graph to .dot file using algorithm 55

```
graph G {
0[label=A];
1[label=B];
2[label=C];
3[label=D];
4[label=E];
5[label=a];
6[label=b];
7[label=c];
8[label=d];
9[label=e];
0--1 [label="F"];
1--2 [label="G"];
2--3 [label="H"];
3--4 [label="I"];
4--0 [label="J"];
0--5 [label="0"];
1--6 [label="1"];
2--7 [label="2"];
3--8 [label="3"];
4--9 [label="4"];
5--7 [label="f"];
6--8 [label="g"];
7--9 [label="h"];
8--5 [label="i"];
9--6 [label="j"];
}
```

#### 6.10.5 The .svg file produced

The .dot file can be converted to the .svg as shown in figure 39:

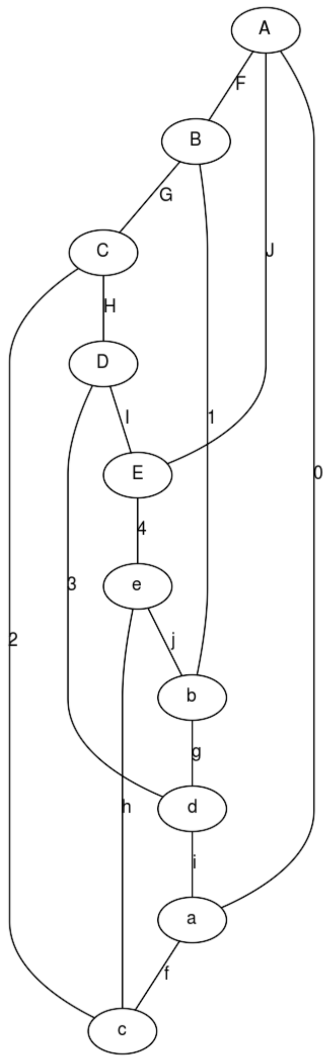


Figure 39: .svg file created from the 'create_named_edges_and_vertices_petersen_graph' function (algorithm 141) its .dot file, converted from .dot file to .svg using algorithm 366

# 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 7.8
- Loading a directed graph with named edges and vertices from a .dot file: chapter 7.9
- Loading an undirected graph with named edges and vertices from a .dot file: chapter 7.10

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 144** 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 145, where a certain name cannot be found in an empty graph. After adding the desired name, it is found.

**Algorithm 145** Demonstration of the 'has_edge_with_name' function

```
#include <boost/test/unit_test.hpp>
#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"
#include "has_edge_with_name.h"

BOOST_AUTO_TEST_CASE(test_has_edge_with_name)
{
  auto g =
      create_empty_undirected_named_edges_and_vertices_graph
      ();
  BOOST_CHECK(!has_edge_with_name("Edward",g));
  add_named_edge("Edward",g);
  BOOST_CHECK(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 146 shows how to obtain an edge descriptor to the first (name) edge found with a specific name.

**Algorithm 146** 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
)
{
  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;
    }
  );
  if (i == eip.second)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find edge with name '"
      << name << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  return *i;
}
```

With the edge descriptor obtained, one can read and modify the graph. Algorithm 147 shows some examples of how to do so.

**Algorithm 147** Demonstration of the 'find_first_edge_by_name' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_edges_and_vertices_k3_graph.h"
#include "find_first_edge_with_name.h"

BOOST_AUTO_TEST_CASE(test_find_first_edge_with_name)
{
  const auto g
    = create_named_edges_and_vertices_k3_graph();
  const auto ed
    = find_first_edge_with_name("AB", g);
  BOOST_CHECK(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 6.5 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 148** 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 149 shows a simple example.

**Algorithm 149** Demonstration if the 'get_edge_name' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_get_edge_name)
{
  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);
  BOOST_CHECK(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 150.

**Algorithm 150** Set an edge its name from its edge descriptor

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

template <typename graph, typename name_type>
void set_edge_name(
  const name_type& 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 151 shows a simple example.

**Algorithm 151** Demonstration if the 'set_edge_name' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_set_edge_name)
{
  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);
  BOOST_CHECK(get_edge_name(vd,g) == old_name);
  const std::string new_name{"Diggy"};
  set_edge_name(new_name, vd, g);
  BOOST_CHECK(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 97:

**Algorithm 152** 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
)
{
  static_assert(!std::is_const<graph>::value,
    "graph cannot be const"
  );

  if (!has_edge_with_name(name, g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "cannot find edge with name '"
      << name << "'"
    ;
    throw std::invalid_argument(msg.str());
  }

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

Algorithm 153 shows the removal of the first named edge found.

**Algorithm 153** Demonstration of the 'remove_first_edge_with_name' function

```
#include <boost/test/unit_test.hpp>
#include "create_named_edges_and_vertices_k3_graph.h"
#include "remove_first_edge_with_name.h"

BOOST_AUTO_TEST_CASE(test_remove_first_edge_with_name)
{
  auto g = create_named_edges_and_vertices_k3_graph();
  BOOST_CHECK(boost::num_edges(g) == 3);
  BOOST_CHECK(boost::num_vertices(g) == 3);
  remove_first_edge_with_name("AB",g);
  BOOST_CHECK(boost::num_edges(g) == 2);
  BOOST_CHECK(boost::num_vertices(g) == 3);
}
```

## 7.6 ▶ Create a direct-neighbour subgraph from a vertex descriptor of a graph with named edges and vertices

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 154** Get the direct-neighbour named edges and vertices subgraph from a vertex descriptor

```
#include <map>
#include <boost/graph/adjacency_list.hpp>
#include "add_named_edge_between_vertices.h"
#include "add_named_vertex.h"
#include "get_edge_name.h"
#include "get_vertex_name.h"
template <typename graph, typename vertex_descriptor>
graph
    create_direct_neighbour_named_edges_and_vertices_subgraph
    (
  const vertex_descriptor& vd,
  const graph& g
)
{
  graph h;

  std::map<vertex_descriptor,vertex_descriptor> vds;
  {
    const auto vd_h = add_named_vertex(get_vertex_name(vd
        ,g),h);
    vds.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(vds,std::begin(vds)),
      [g, &h](const vertex_descriptor& d)
      {
        const auto vd_h = add_named_vertex(
            get_vertex_name(d,g), 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 (vds.find(vd_from) == std::end(vds)) continue;
      if (vds.find(vd_to) == std::end(vds)) continue;
      add_named_edge_between_vertices(
        get_edge_name(*i, g),
        vds[vd_from],vds[vd_to], h
      );
    }
  }
  return h;
}
```

This demonstration code shows that the direct-neighbour graph of each vertex of a $K_2$ graphs is ... a $K_2$ graph!

**Algorithm 155** Demo of the 'create_direct_neighbour_named_edges_and_vertices_subgraph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_direct_neighbour_named_edges_and_vertices_subgraph
    .h"
#include "create_named_edges_and_vertices_k2_graph.h"
#include "get_edge_names.h"
#include "get_vertex_names.h"

BOOST_AUTO_TEST_CASE(
    test_create_direct_neighbour_named_edges_and_vertices_subgraph
    )
{
  const auto g = create_named_edges_and_vertices_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_named_edges_and_vertices_subgraph
        (
      *i,g
    );
    BOOST_CHECK(boost::num_vertices(h) == 2);
    BOOST_CHECK(boost::num_edges(h) == 1);
    const auto v = get_vertex_names(h);
    std::set<std::string> vs(std::begin(v),std::end(v));
    BOOST_CHECK(vs.count("x") == 1);
    BOOST_CHECK(vs.count("y") == 1);
    const auto e = get_edge_names(h);
    std::set<std::string> es(std::begin(e),std::end(e));
    BOOST_CHECK(es.count("between") == 1);
  }
}
```

## 7.7 ▶ Creating all direct-neighbour subgraphs from a graph with named edges and vertices

Using the previous function, it is easy to create all direct-neighbour subgraphs from a graph with named edges and vertices:

**Algorithm 156** Create all direct-neighbour subgraphs from a graph with named edges and vertices

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

template <typename graph>
std::vector<graph>
    create_all_direct_neighbour_named_edges_and_vertices_subgraphs
    (
  const graph g
)
{
  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_named_edges_and_vertices_subgraph
          (
        d, g
      );
    }
  );
  return v;
}
```

This demonstration code shows that all two direct-neighbour graphs of a $K_2$ graphs are ... $K_2$ graphs!

**Algorithm 157** Demo of the 'create_all_direct_neighbour_named_edges_and_vertices_subgraphs' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_all_direct_neighbour_named_edges_and_vertices_subgraphs
    .h"
#include "create_named_edges_and_vertices_k2_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_all_direct_neighbour_named_edges_and_vertices_subgraphs
    )
{
  const auto v
    =
        create_all_direct_neighbour_named_edges_and_vertices_subgraphs
        (create_named_edges_and_vertices_k2_graph());
  BOOST_CHECK(v.size() == 2);
  for (const auto g: v)
  {
    BOOST_CHECK(boost::num_vertices(g) == 2);
    BOOST_CHECK(boost::num_edges(g) == 1);
  }
}
```

All sub-graphs of a path graph are shown here:

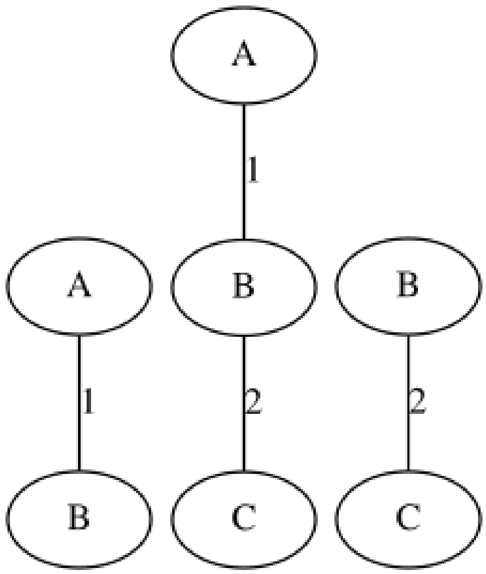


Figure 40: All subgraphs created

## 7.8 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 135) to produce a $K_3$ graph with named edges and vertices, you can store these names additionally with algorithm 158:

**Algorithm 158** 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 13.10 shows how to write custom vertices to a .dot file.

So, the 'save_named_edges_and_vertices_graph_to_dot' function (algorithm 55) saves only the structure of the graph and its edge and vertex names.

## 7.9 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 159:

**Algorithm 159** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g =
     create_empty_directed_named_edges_and_vertices_graph
     ();
  boost::dynamic_properties dp(boost::
     ignore_other_properties);
  dp.property("label", get(boost::vertex_name, g));
  dp.property("edge_id", get(boost::edge_name, g));
  dp.property("label", get(boost::edge_name, g));
  boost::read_graphviz(f,g,dp);
  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 160 shows how to use the 'load_directed_graph_from_dot' function:

**Algorithm 160** Demonstration of the 'load_directed_named_edges_and_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_directed_named_edges_and_vertices_graph_from_dot
    )
{
  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
    );
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 129), 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 127, and the 'get_vertex_names' function, algorithm 67).

## 7.10 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 161:

**Algorithm 161** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g =
      create_empty_undirected_named_edges_and_vertices_graph
      ();
  boost::dynamic_properties dp(boost::
      ignore_other_properties);
  dp.property("label", get(boost::vertex_name, g));
  dp.property("edge_id", get(boost::edge_name, g));
  dp.property("label", get(boost::edge_name, g));
  boost::read_graphviz(f,g,dp);
  return g;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 7.9 describes the rationale of this function.

Algorithm 162 shows how to use the 'load_undirected_graph_from_dot' function:

**Algorithm 162** Demonstration of the 'load_undirected_named_edges_and_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_undirected_named_edges_and_vertices_graph_from_dot
    )
{
  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
    );
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 135), 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 127, and the 'get_vertex_names' function, algorithm 67).

# 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[9]. The following graphs will be created:

- An empty directed graph that allows for bundled vertices: see chapter 164
- 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:

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

**Algorithm 163** 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;
};

std::ostream& operator<<(std::ostream& os, const
    my_bundled_vertex& e) noexcept;
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 164** 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 165** 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 166** Add a bundled vertex

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

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

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[10]

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

**Algorithm 167** 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 24.1).

## 8.6 Creating a two-state Markov chain with bundled vertices

### 8.6.1 Graph

Figure 41 shows the graph that will be reproduced:

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

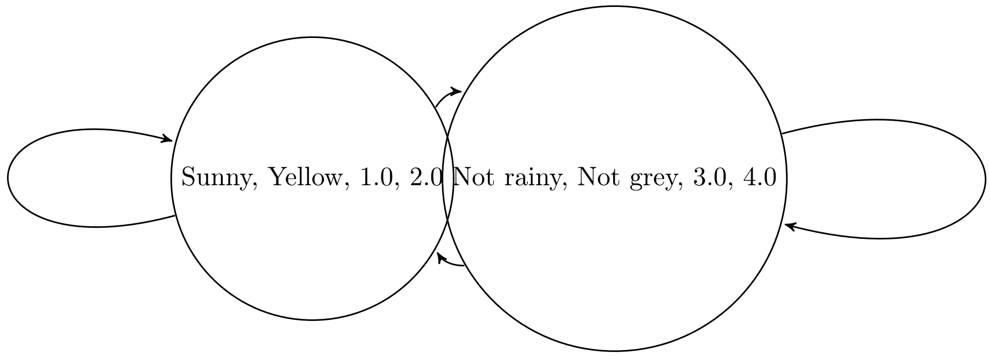


Figure 41: A two-state Markov chain where the vertices have bundled properies and the edges have no properties. The vertices' properties are nonsensical

### 8.6.2 Function to create such a graph

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

**Algorithm 168** Creating the two-state Markov chain as depicted in figure 41

```
#include "add_bundled_vertex.h"
#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 my_bundled_vertex a("Sunny",
    "Yellow",1.0,2.0
  );
  const my_bundled_vertex b("Not rainy",
    "Not grey",3.0,4.0
  );
  const auto vd_a = add_bundled_vertex(a, g);
  const auto vd_b = add_bundled_vertex(b, g);
  boost::add_edge(vd_a, vd_a, g);
  boost::add_edge(vd_a, vd_b, g);
  boost::add_edge(vd_b, vd_a, g);
  boost::add_edge(vd_b, vd_b, g);
  return g;
}
```

### 8.6.3 Creating such a graph

Here is the demo:

**Algorithm 169** Demo of the 'create_bundled_vertices_markov_chain' function (algorithm 168)

```
#include <boost/test/unit_test.hpp>
#include "create_bundled_vertices_markov_chain.h"
#include "get_my_bundled_vertexes.h"
#include "get_my_bundled_vertex.h"

BOOST_AUTO_TEST_CASE(
    test_create_bundled_vertices_markov_chain)
{
  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);
  BOOST_CHECK(expected == found);
}
```

### 8.6.4 The .dot file produced

**Algorithm 170** .dot file created from the 'create_bundled_vertices_markov_chain' function (algorithm 168), converted from graph to .dot file using algorithm 183

```
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

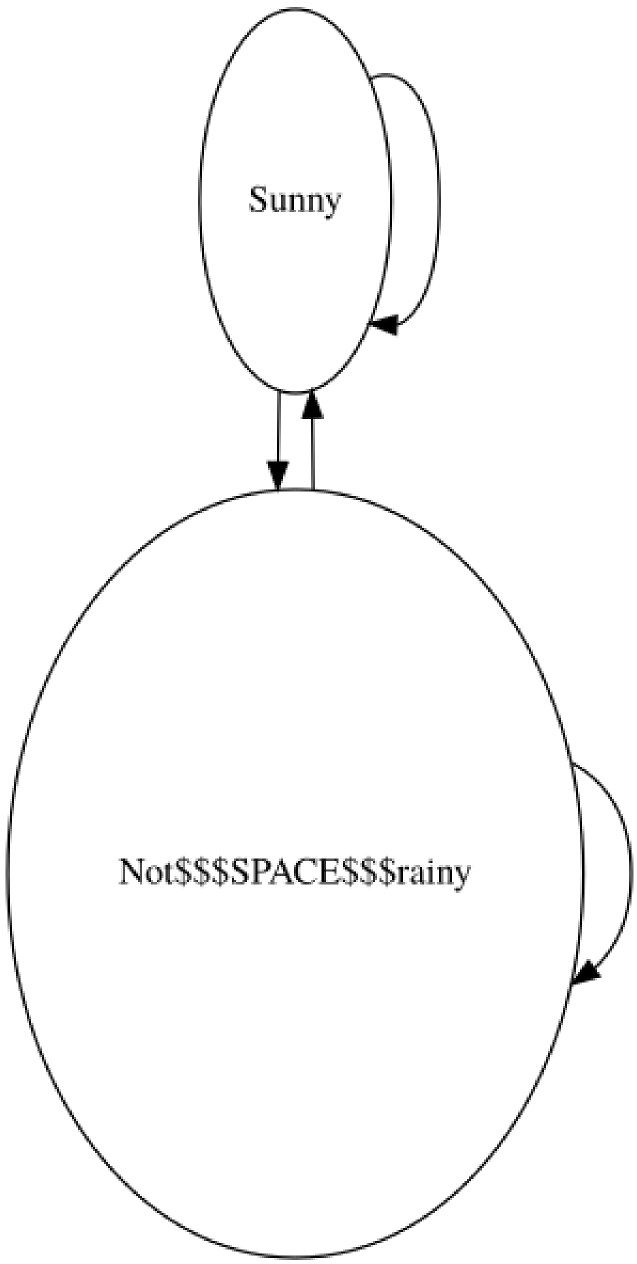


Figure 42: .svg file created from the 'create_bundled_vertices_markov_chain' function (algorithm 168) its .dot file, converted from .dot file to .svg using algorithm 366

## 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 43:

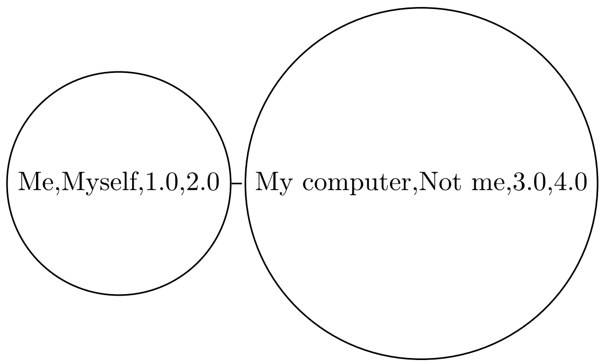


Figure 43: $K_2$: a fully connected graph with two bundled vertices

### 8.7.2 Function to create such a graph

**Algorithm 171** Creating $K_2$ as depicted in figure 21

```
#include "create_empty_undirected_bundled_vertices_graph.
    h"
#include "add_bundled_vertex.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 my_bundled_vertex a(
    "Me","Myself",1.0,2.0
  );
  const my_bundled_vertex b(
    "My computer","Not me",3.0,4.0
  );
  const auto vd_a = add_bundled_vertex(a, g);
  const auto vd_b = add_bundled_vertex(b, g);
  boost::add_edge(vd_a, vd_b, g);
  return g;
}
```

Most of the code is a slight modification of the 'create_named_vertices_k2_graph' function (algorithm 72). 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 172** Demo of the 'create_bundled_vertices_k2_graph' function (algorithm 171)

```
#include <boost/test/unit_test.hpp>
#include "create_bundled_vertices_k2_graph.h"
#include "has_bundled_vertex_with_my_vertex.h"

BOOST_AUTO_TEST_CASE(
    test_create_bundled_vertices_k2_graph)
{
  const auto g = create_bundled_vertices_k2_graph();
  BOOST_CHECK(boost::num_edges(g) == 1);
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(has_bundled_vertex_with_my_vertex(
    my_bundled_vertex("Me","Myself",1.0,2.0), g)
  );
  BOOST_CHECK(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 173** .dot file created from the 'create_bundled_vertices_k2_graph' function (algorithm 171), converted from graph to .dot file using algorithm 55

### 8.7.5 The .svg file produced

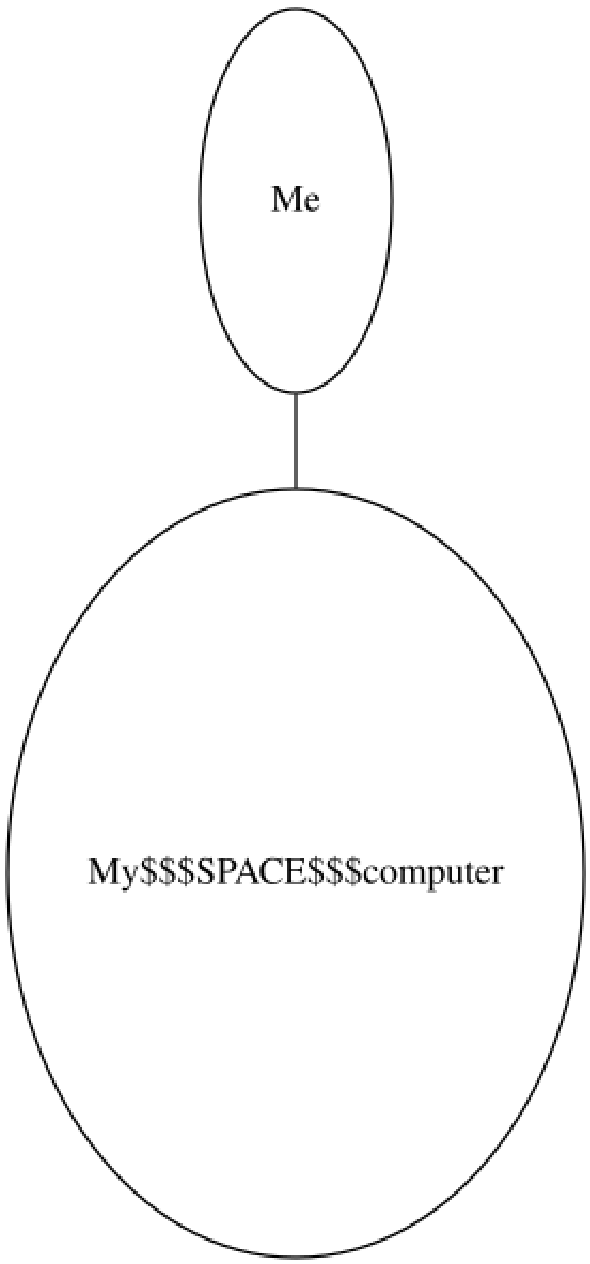


Figure 44: .svg file created from the 'create_bundled_vertices_k2_graph' function (algorithm 171) its .dot file, converted from .dot file to .svg using algorithm 366

# 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 174** 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 175, where a certain my_bundled_vertex cannot be found in an empty graph. After adding the desired my_bundled_vertex, it is found.

**Algorithm 175** Demonstration of the 'has_bundled_vertex_with_my_vertex' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_has_bundled_vertex_with_my_vertex)
{
  auto g = create_empty_undirected_bundled_vertices_graph
      ();
  BOOST_CHECK(!has_bundled_vertex_with_my_vertex(
      my_bundled_vertex("Felix"),g));
  add_bundled_vertex(my_bundled_vertex("Felix"),g);
  BOOST_CHECK(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 176 shows how to obtain a vertex descriptor to the first vertex found with a specific 'my_bundled_vertex' value.

**Algorithm 176** 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 bundled_vertex_t>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_bundled_vertex_with_my_vertex(
  const bundled_vertex_t& v,
  const graph& g
)
{
  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; }
  );
  if (i == vip.second)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find my_bundled_vertex '"
      << v << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  return *i;
}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 177 shows some examples of how to do so.

Algorithm 177 Demonstration of the 'find_first_bundled_vertex_with_my_vertex' function

```
#include <boost/test/unit_test.hpp>
#include "create_bundled_vertices_k2_graph.h"
#include "find_first_bundled_vertex_with_my_vertex.h"

BOOST_AUTO_TEST_CASE(
    test_find_first_bundled_vertex_with_my_vertex)
{
  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
  );
  BOOST_CHECK(out_degree(vd,g) == 1);
  BOOST_CHECK(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 178 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 179 shows a simple example.

**Algorithm 179** Demonstration if the 'get_bundled_vertex_my_vertex' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_get_my_bundled_vertex)
{
  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);
  BOOST_CHECK(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 180.

**Algorithm 180** 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 181 shows a simple example.

**Algorithm 181** Demonstration if the 'set_bundled_vertex_my_vertex' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_set_my_bundled_vertex)
{
  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)
      ;
  BOOST_CHECK(get_my_bundled_vertex(vd, g) == old_name);
  const my_bundled_vertex new_name{"Diggy"};
  set_my_bundled_vertex(new_name, vd, g);
  BOOST_CHECK(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 182** 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 171) to produce a $K_2$ graph with vertices associated with 'my_bundled_vertex' objects, you can store these with algorithm 183:

**Algorithm 183** 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);
  boost::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 184:

**Algorithm 184** 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 185:

**Algorithm 185** The 'bundled_vertices_writer' function

```
#include <ostream>
#include "graphviz_encode.h"
#include "is_graphviz_friendly.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 25.2 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 186:

**Algorithm 186** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_directed_bundled_vertices_graph()
    ;

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

  //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 187 shows how to use the 'load_directed_bundled_vertices_graph_from_dot' function:

**Algorithm 187** Demonstration of the 'load_directed_bundled_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_directed_bundled_vertices_graph_from_dot)
{
  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);
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 168), 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 188:

**Algorithm 188** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_undirected_bundled_vertices_graph
      ();

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

  //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 189 shows how to use the 'load_undirected_bundled_vertices_graph_from_dot' function:

**Algorithm 189** Demonstration of the 'load_undirected_bundled_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_undirected_bundled_vertices_graph_from_dot)
{
  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);
  BOOST_CHECK(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 171), 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[11].

- 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.

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

**Algorithm 190** 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;
};

std::ostream& operator<<(std::ostream& os, const
    my_bundled_edge& e) noexcept;
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 191** 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 192** Demonstration of the 'create_empty_directed_bundled_edges_and_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_empty_directed_bundled_edges_and_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_directed_bundled_edges_and_vertices_graph
    )
{
  const auto g =
      create_empty_directed_bundled_edges_and_vertices_graph
      ();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(boost::num_vertices(g) == 0);
}
```

## 10.3 Create an empty undirected graph with bundled edges and vertices

**Algorithm 193** 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 194** Demonstration of the 'create_empty_undirected_bundled_edges_and_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_undirected_bundled_edges_and_vertices_graph
    )
{
  const auto g
    =
        create_empty_undirected_bundled_edges_and_vertices_graph
        ();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(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 195** Add a bundled edge

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

template <typename graph, typename bundled_edge>
typename boost::graph_traits<graph>::edge_descriptor
add_bundled_edge(
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd_from,
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd_to,
  const bundled_edge& edge,
  graph& g
)
{
  static_assert(!std::is_const<graph>::value,"graph␣
      cannot␣be␣const");
  if (has_edge_between_vertices(vd_from, vd_to, g))
  {
    std::stringstream msg;
    msg << __func__ << ":␣already␣an␣edge␣there";
    throw std::invalid_argument(msg.str());
  }
  const auto aer = boost::add_edge(vd_from, vd_to, g);
  assert(aer.second);
  g[aer.first] = edge;
  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 196** Demo of 'add_bundled_edge'

```
#include <boost/test/unit_test.hpp>
#include "add_bundled_edge.h"
#include "add_bundled_vertex.h"
#include "
    create_empty_directed_bundled_edges_and_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(test_add_bundled_edge)
{
  auto g =
      create_empty_directed_bundled_edges_and_vertices_graph
      ();
  const auto vd_from = add_bundled_vertex(
      my_bundled_vertex("From"), g);
  const auto vd_to = add_bundled_vertex(my_bundled_vertex
      ("To"), g);
  add_bundled_edge(vd_from, vd_to, my_bundled_edge("X"),
      g);
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(boost::num_edges(g) == 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 197** 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 24.1).

## 10.6 Creating a Markov-chain with bundled edges and vertices

### 10.6.1 Graph

Figure 45 shows the graph that will be reproduced:

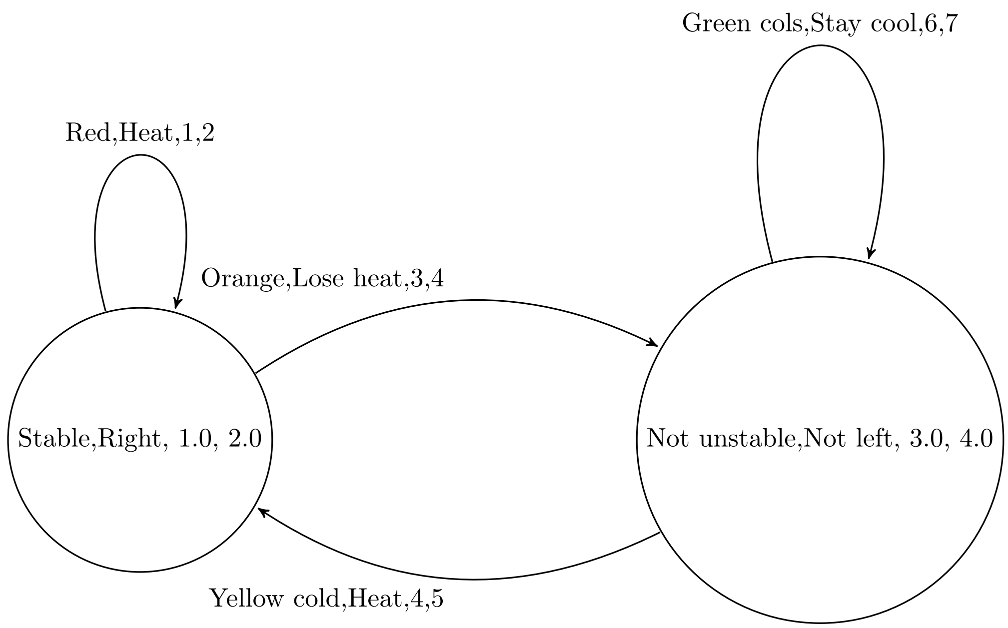


Figure 45: A two-state Markov chain where the edges and vertices have bundled properies. The edges' and vertices' properties are nonsensical

### 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 198** Creating the two-state Markov chain as depicted in figure 45

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

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::directedS,
  my_bundled_vertex,
  my_bundled_edge
>
create_bundled_edges_and_vertices_markov_chain()
{
  auto g
    =
        create_empty_directed_bundled_edges_and_vertices_graph
        ();
  const auto va = my_bundled_vertex("Stable","Right"
      ,1.0,2.0);
  const auto vb = my_bundled_vertex("Not unstable","Not 
      left",3.0,4.0);
  const auto vd_a = add_bundled_vertex(va, g);
  const auto vd_b = add_bundled_vertex(vb, g);
  const auto e_aa = my_bundled_edge("Red","Heat",1.0,2.0)
      ;
  const auto e_ab = my_bundled_edge("Orange","Lose heat"
      ,3.0,4.0);
  const auto e_ba = my_bundled_edge("Yellow cold","Heat"
      ,5.0,6.0);
  const auto e_bb = my_bundled_edge("Green cold","Stay 
      cool",7.0,8.0);
  add_bundled_edge(vd_a, vd_a, e_aa, g);
  add_bundled_edge(vd_a, vd_b, e_ab,  g);
  add_bundled_edge(vd_b, vd_a, e_ba,  g);
  add_bundled_edge(vd_b, vd_b, e_bb,  g);
  return g;
}
```

### 10.6.3 Creating such a graph

Here is the demo:

**Algorithm 199** Demo of the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 198)

```
#include <boost/test/unit_test.hpp>
#include "create_bundled_edges_and_vertices_markov_chain.
    h"
#include "get_my_bundled_edges.h"
#include "my_bundled_vertex.h"

BOOST_AUTO_TEST_CASE(
    test_create_bundled_edges_and_vertices_markov_chain)
{
  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)
  };
  BOOST_CHECK(edge_my_edges == expected_my_edges);
}
```

### 10.6.4 The .dot file produced

**Algorithm 200** .dot file created from the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 198), converted from graph to .dot file using algorithm 55

```
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

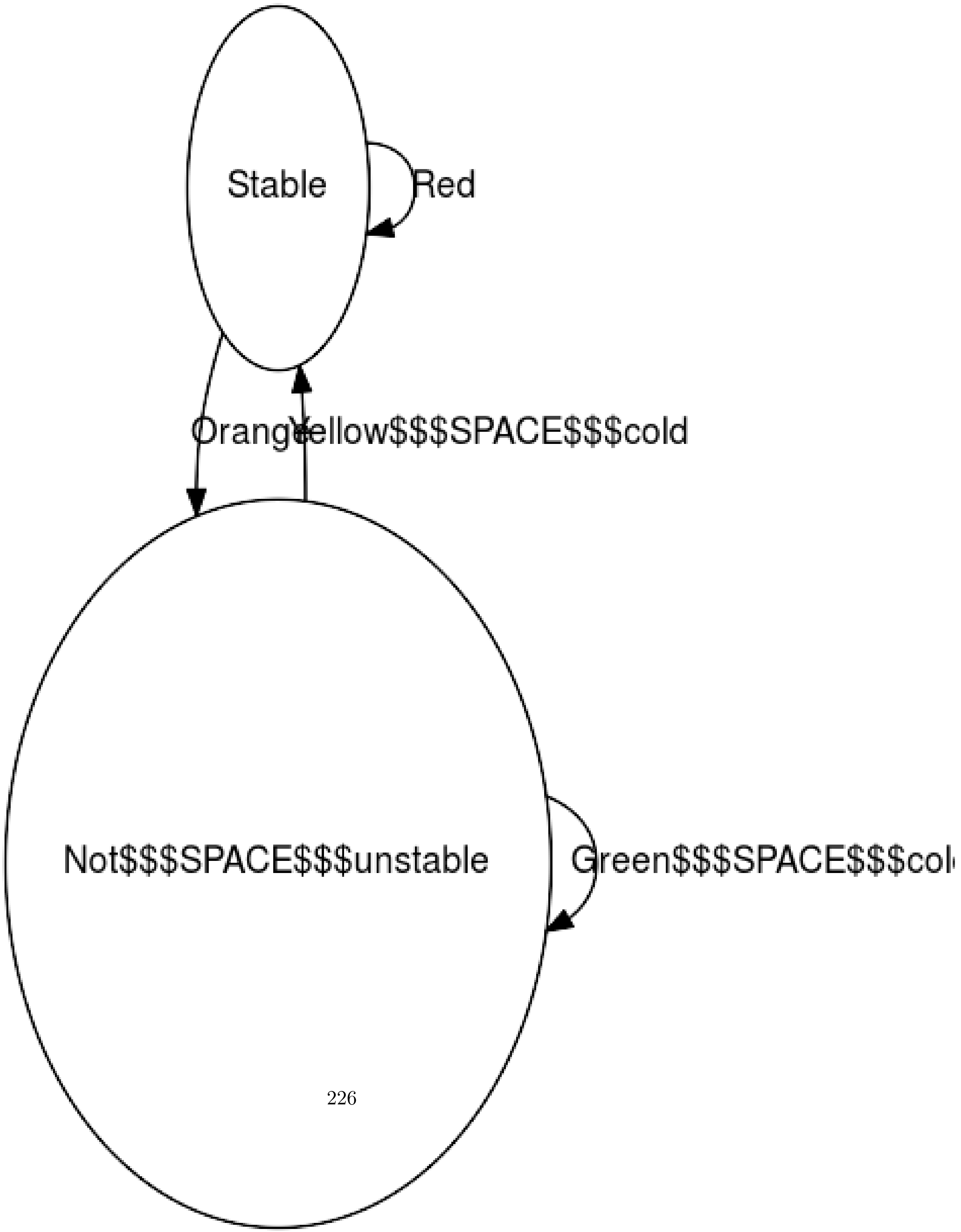




Figure 46: .svg file created from the 'cre-

## 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 6.8 , but with our bundled edges and vertices intead:

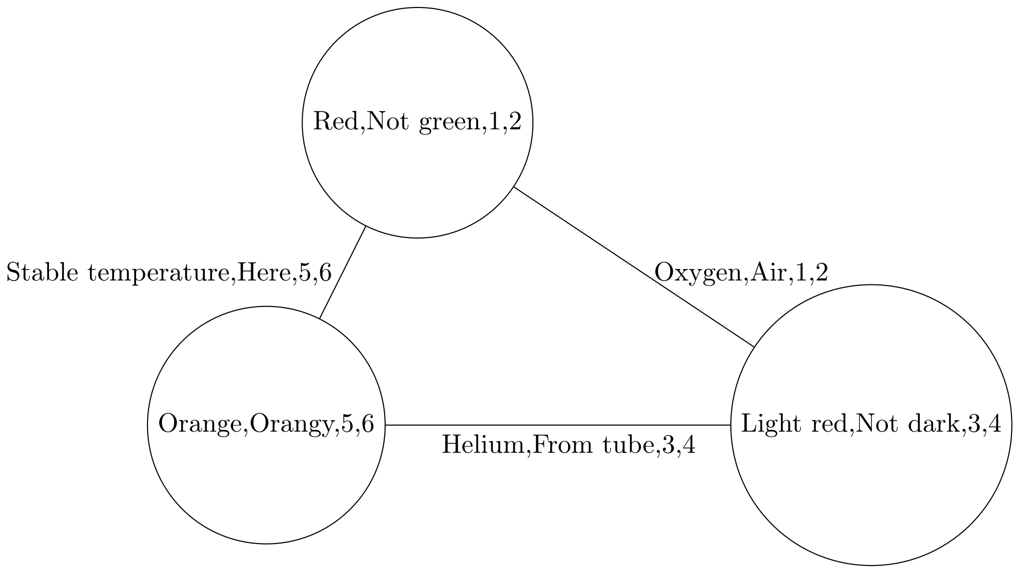


Figure 47: $K_3$: a fully connected graph with three named edges and vertices

### 10.7.2 Function to create such a graph

**Algorithm 201** Creating $K_3$ as depicted in figure 34

```
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"
#include "add_bundled_edge.h"
#include "add_bundled_vertex.h"

boost::adjacency_list<
  boost::vecS,
  boost::vecS,
  boost::undirectedS,
  my_bundled_vertex,
  my_bundled_edge
>
create_bundled_edges_and_vertices_k3_graph()
{
  auto g
    =
        create_empty_undirected_bundled_edges_and_vertices_graph
        ();
  const auto vd_a = add_bundled_vertex(
    my_bundled_vertex("Red","Not green",1.0,2.0),
    g
  );
  const auto vd_b = add_bundled_vertex(
    my_bundled_vertex("Light red","Not dark",3.0,4.0),
    g
  );
  const auto vd_c = add_bundled_vertex(
    my_bundled_vertex("Orange","Orangy",5.0,6.0),
    g
  );
  add_bundled_edge(vd_a, vd_b,
    my_bundled_edge("Oxygen","Air",1.0,2.0),
    g
  );
  add_bundled_edge(vd_b, vd_c,
    my_bundled_edge("Helium","From tube",3.0,4.0),
    g
  );
  add_bundled_edge(vd_c, vd_a,
    my_bundled_edge("Stable temperature","Here",5.0,6.0),
    g
  );
  return g;
}
```

Most of the code is a slight modification of algorithm 135. 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 202** Demo of the 'create_bundled_edges_and_vertices_k3_graph' function (algorithm 201)

```
#include <boost/test/unit_test.hpp>
#include "create_bundled_edges_and_vertices_k3_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_bundled_edges_and_vertices_k3_graph)
{
  auto g
    = create_bundled_edges_and_vertices_k3_graph();
  BOOST_CHECK(boost::num_edges(g) == 3);
  BOOST_CHECK(boost::num_vertices(g) == 3);
}
```

### 10.7.4 The .dot file produced

**Algorithm 203** .dot file created from the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 201), converted from graph to .dot file using algorithm 55

```
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

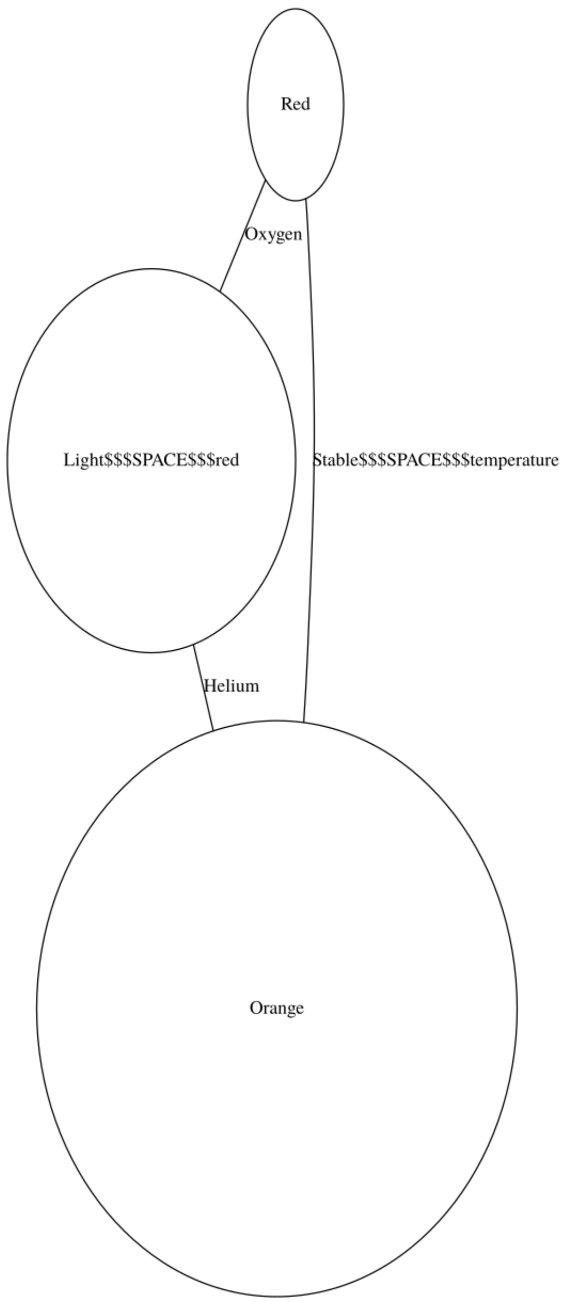


Figure 48: .svg file created from the 'create_bundled_edges_and_vertices_k3_graph' function (algorithm 227) its .dot file, converted from .dot file to .svg using algorithm 366

# 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 204** 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 205, where a certain 'my_bundled_edge' cannot be found in an empty graph. After adding the desired my_bundled_edge, it is found.

**Algorithm 205** Demonstration of the 'has_bundled_edge_with_my_edge' function

```
#include <boost/test/unit_test.hpp>
#include "create_bundled_edges_and_vertices_k3_graph.h"
#include "has_bundled_edge_with_my_edge.h"

BOOST_AUTO_TEST_CASE(test_has_bundled_edge_with_my_edge)
{
  auto g
    = create_bundled_edges_and_vertices_k3_graph();
  BOOST_CHECK(
    has_bundled_edge_with_my_edge(
      my_bundled_edge("Oxygen","Air",1.0,2.0),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 206 shows how to obtain an edge descriptor to the first edge found with a specific my_bundled_edge value.

**Algorithm 206** Find the first bundled edge with a certain my_bundled_edge

```cpp
#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
)
{
  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; }
  );
  if (i == eip.second)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find my_bundled_edge '"
      << e << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  return *i;
}
```

With the edge descriptor obtained, one can read and modify the edge and the vertices surrounding it. Algorithm 207 shows some examples of how to do so.

**Algorithm 207** Demonstration of the 'find_first_bundled_edge_with_my_edge' function

```
#include <boost/test/unit_test.hpp>
#include "create_bundled_edges_and_vertices_k3_graph.h"
#include "find_first_bundled_edge_with_my_edge.h"

BOOST_AUTO_TEST_CASE(
    test_find_first_bundled_edge_with_my_edge)
{
  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
  );
  BOOST_CHECK(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 208** 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 209 shows a simple example.

**Algorithm 209** Demonstration if the 'get_my_bundled_edge' function

```
#include <boost/test/unit_test.hpp>
#include "add_bundled_edge.h"
#include "add_bundled_vertex.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"

BOOST_AUTO_TEST_CASE(test_get_my_bundled_edge)
{
  auto g
    =
        create_empty_undirected_bundled_edges_and_vertices_graph
        ();
  const my_bundled_edge edge{"Dex"};
  const auto vd_a = add_bundled_vertex(
    my_bundled_vertex("A"), g
  );
  const auto vd_b = add_bundled_vertex(
    my_bundled_vertex("B"), g
  );
  add_bundled_edge(vd_a, vd_b, edge, g);
  const auto ed
    = find_first_bundled_edge_with_my_edge(edge, g);
  BOOST_CHECK(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 210.

**Algorithm 210** 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 211 shows a simple example.

**Algorithm 211** Demonstration if the 'set_bundled_edge_my_edge' function

```
#include <boost/test/unit_test.hpp>
#include "add_bundled_edge.h"
#include "add_bundled_vertex.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"

BOOST_AUTO_TEST_CASE(test_set_my_bundled_edge)

{
  auto g
    =
        create_empty_undirected_bundled_edges_and_vertices_graph
        ();
  const auto vd_a = add_bundled_vertex(my_bundled_vertex{
      "A"}, g);
  const auto vd_b = add_bundled_vertex(my_bundled_vertex{
      "B"}, g);
  const my_bundled_edge old_edge{"Dex"};
  add_bundled_edge(vd_a, vd_b, old_edge, g);
  const auto vd
    = find_first_bundled_edge_with_my_edge(old_edge,g);
  BOOST_CHECK(get_my_bundled_edge(vd,g)
    == old_edge
  );
  const my_bundled_edge new_edge{"Diggy"};
  set_my_bundled_edge(new_edge, vd, g);
  BOOST_CHECK(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 201) 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 212:

**Algorithm 212** 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);
  boost::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 213:

**Algorithm 213** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g =
      create_empty_directed_bundled_edges_and_vertices_graph
      ();

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

  //Decode vertices
  {
```

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 214 shows how to use the 'load_directed_bundled_edges_and_vertices_graph_from_dot' function:

**Algorithm 214** Demonstration of the 'load_directed_bundled_edges_and_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_directed_bundled_edges_and_vertices_graph_from_dot
    )
{
  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
    );
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 198), 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 215:

**Algorithm 215** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g =
      create_empty_undirected_bundled_edges_and_vertices_graph
      ();

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

  //Decode vertices
```

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 216 shows how to use the 'load_undirected_bundled_vertices_graph_from_dot' function:

**Algorithm 216** Demonstration of the 'load_undirected_bundled_edges_and_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_undirected_bundled_edges_and_vertices_graph_from_dot
    )
{
  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
    );
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 230), 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 25.1 for all properties). The following graphs will be created:

- An empty directed graph that allows for custom vertices: see chapter 219
- 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 217** 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
  );
  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;
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);
```

'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 362) can convert the elements to be streamed to a Graphviz-friendly version, which can be decoded by 'graphviz_decode' (algorithm 363).

## 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 218** 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 219** 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 220** Demo how to create an empty directed graph with custom vertices

```
#include <boost/test/unit_test.hpp>
#include "create_empty_directed_custom_vertices_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_directed_custom_vertices_graph)
{
  const auto g
    = create_empty_directed_custom_vertices_graph();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(boost::num_vertices(g) == 0);
}
```

## 12.4 Create the empty undirected graph with custom vertices

**Algorithm 221** 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 222** Demo how to create an empty undirected graph with custom vertices

```
#include <boost/test/unit_test.hpp>
#include "create_empty_undirected_custom_vertices_graph.h
  "

BOOST_AUTO_TEST_CASE(
  test_create_empty_undirected_custom_vertices_graph)
{
  const auto g
    = create_empty_undirected_custom_vertices_graph();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(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 223** Add a custom vertex

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

template <typename graph, typename vertex_t>
typename boost::graph_traits<graph>::vertex_descriptor
add_custom_vertex(
  const vertex_t& 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 224** Demo of 'add_custom_vertex'

```
#include <boost/test/unit_test.hpp>
#include "add_custom_vertex.h"
#include "create_empty_directed_custom_vertices_graph.h"
#include "create_empty_undirected_custom_vertices_graph.h
    "

BOOST_AUTO_TEST_CASE(test_add_custom_vertex)
{
  auto g
    = create_empty_directed_custom_vertices_graph();
  BOOST_CHECK(boost::num_vertices(g) == 0);
  BOOST_CHECK(boost::num_edges(g) == 0);
  add_custom_vertex(my_custom_vertex("X"), g);
  BOOST_CHECK(boost::num_vertices(g) == 1);
  BOOST_CHECK(boost::num_edges(g) == 0);

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

## 12.6 Getting the vertices' my_vertexes[12]

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

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

**Algorithm 225** 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"
#include "get_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) {
      return get_my_custom_vertex(d, g);
    }
  );
  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 24.1).

Demo:

**Algorithm 226** Demo how to the vertices' my_custom_vertex objects

```
#include <boost/test/unit_test.hpp>
#include "create_custom_vertices_k2_graph.h"
#include "get_my_custom_vertexes.h"

BOOST_AUTO_TEST_CASE(test_get_my_custom_vertexes)
{
  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)
  };
  BOOST_CHECK(expected_my_custom_vertexes == vertexes);
}
```

## 12.7 Creating a two-state Markov chain with custom vertices

### 12.7.1 Graph

Figure 49 shows the graph that will be reproduced:

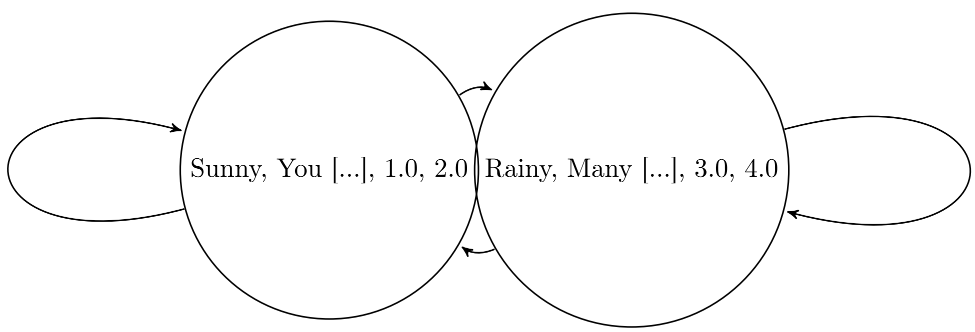


Figure 49: A two-state Markov chain where the vertices have custom properies and the edges have no properties. The vertices' properties are nonsensical

### 12.7.2 Function to create such a graph

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

**Algorithm 227** Creating the two-state Markov chain as depicted in figure 49

```
#include "add_custom_vertex.h"
#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 my_custom_vertex a("Sunny","Yellow thing"
      ,1.0,2.0);
  const my_custom_vertex b("Rainy", "Grey things"
      ,3.0,4.0);

  const auto vd_a = add_custom_vertex(a, g);
  const auto vd_b = add_custom_vertex(b, g);
  boost::add_edge(vd_a, vd_a, g);
  boost::add_edge(vd_a, vd_b, g);
  boost::add_edge(vd_b, vd_a, g);
  boost::add_edge(vd_b, vd_b, g);
  return g;
}
```

### 12.7.3 Creating such a graph

Here is the demo:

**Algorithm 228** Demo of the 'create_custom_vertices_markov_chain' function (algorithm 227)

```
#include <boost/test/unit_test.hpp>
#include "create_custom_vertices_markov_chain.h"
#include "get_my_custom_vertexes.h"

BOOST_AUTO_TEST_CASE(
    test_create_custom_vertices_markov_chain)
{
  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)
  };
  BOOST_CHECK(expected_my_custom_vertexes
    == vertex_my_custom_vertexes
  );
}
```

### 12.7.4 The .dot file produced

**Algorithm 229** .dot file created from the 'create_custom_vertices_markov_chain' function (algorithm 227), converted from graph to .dot file using algorithm 254

```
digraph G {
0[label="Sunny,Yellow$$$SPACE$$$thing,1,2"];
1[label="Rainy,Grey$$$SPACE$$$things,3,4"];
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 362) 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

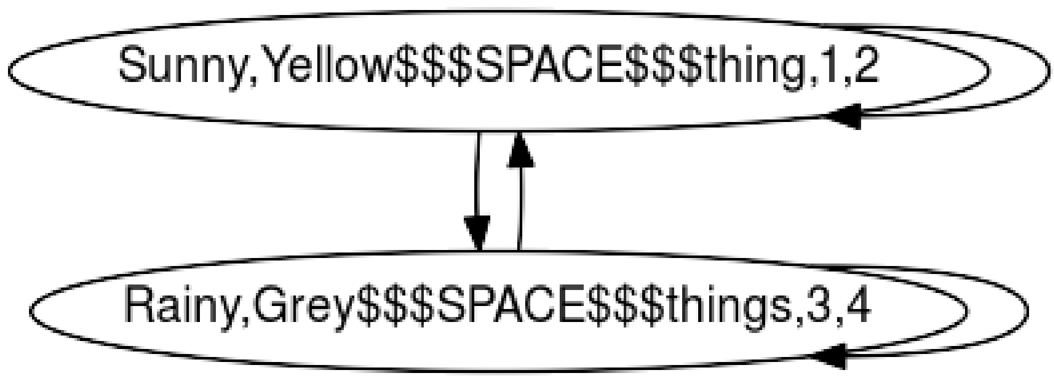


Figure 50: .svg file created from the 'create_custom_vertices_markov_chain' function (algorithm 227) its .dot file, converted from .dot file to .svg using algorithm 366

This .svg file may look unexpectedly different: instead of a space, there is this '[[:SPACE:]]' thing. This is because the function 'graphviz_encode' (algorithm 362) 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 230** Creating $K_2$ as depicted in figure 21

```
#include "create_empty_undirected_custom_vertices_graph.h
    "
#include "add_custom_vertex.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 = add_custom_vertex(
    my_custom_vertex("A","source",0.0,0.0), g
  );
  const auto vd_b = add_custom_vertex(
    my_custom_vertex("B","target",3.14,3.14), g
  );
  boost::add_edge(vd_a, vd_b, g);
  return g;
}
```

Most of the code is a slight modification of the 'create_named_vertices_k2_graph' function (algorithm 72). 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 231** Demo of the 'create_custom_vertices_k2_graph' function (algorithm 230)

```
#include <boost/test/unit_test.hpp>
#include "create_custom_vertices_k2_graph.h"
#include "has_custom_vertex_with_my_vertex.h"

BOOST_AUTO_TEST_CASE(test_create_custom_vertices_k2_graph
    )
{
  const auto g = create_custom_vertices_k2_graph();
  BOOST_CHECK(boost::num_edges(g) == 1);
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(has_custom_vertex_with_my_vertex(
    my_custom_vertex("A", "source" ,0.0, 0.0), g)
  );
  BOOST_CHECK(has_custom_vertex_with_my_vertex(
    my_custom_vertex("B", "target" ,3.14, 3.14), g)
  );
}
```

#### 12.8.4 The .dot file produced

**Algorithm 232** .dot file created from the 'create_custom_vertices_k2_graph' function (algorithm 230), converted from graph to .dot file using algorithm 55

```
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

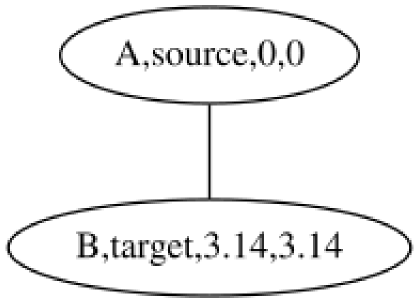


Figure 51: .svg file created from the 'create_custom_vertices_k2_graph' function (algorithm 230) its .dot file, converted from .dot file to .svg using algorithm 366

## 12.9 ▶ Creating a path graph with custom vertices

Here we create a path graph with custom vertices

### 12.9.1 Graph

Here I show a path graph with four vertices (see figure 52):

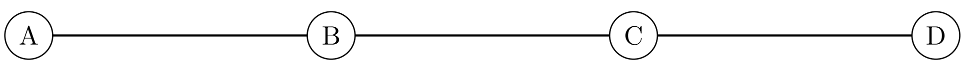


Figure 52: A path graph with four vertices

### 12.9.2 Function to create such a graph

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

**Algorithm 233** Creating a path graph as depicted in figure 52

```
#include <vector>
#include "add_custom_vertex.h"
#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_path_graph(
  const std::vector<my_custom_vertex>& names
) noexcept
{
  auto g = create_empty_undirected_custom_vertices_graph
      ();
  if (names.size() == 0) { return g; }
  auto vd_1 = add_custom_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_custom_vertex(*i, g);
    boost::add_edge(vd_1, vd_2, g);
    vd_1 = vd_2;
  }
  return g;
}
```

### 12.9.3 Creating such a graph

Algorithm 234 demonstrates how to create a path graph with named vertices and checks if it has the correct amount of edges and vertices:

**Algorithm 234** Demonstration of 'create_named_vertices_path_graph'

```
#include <boost/test/unit_test.hpp>
#include "create_custom_vertices_path_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_custom_vertices_path_graph)
{
  const auto g = create_custom_vertices_path_graph(
    {
      my_custom_vertex("A"),
      my_custom_vertex("B"),
      my_custom_vertex("C")
    }
  );
  BOOST_CHECK(boost::num_edges(g) == 2);
  BOOST_CHECK(boost::num_vertices(g) == 3);
}
```

### 12.9.4 The .dot file produced

This graph can be converted to the .dot file as shown in algorithm 235:

**Algorithm 235** .dot file created from the 'create_named_vertices_path_graph' function (algorithm 233), converted from graph to .dot file using algorithm 55

### 12.9.5 The .svg file produced

The .dot file can be converted to the .svg as shown in figure 53:

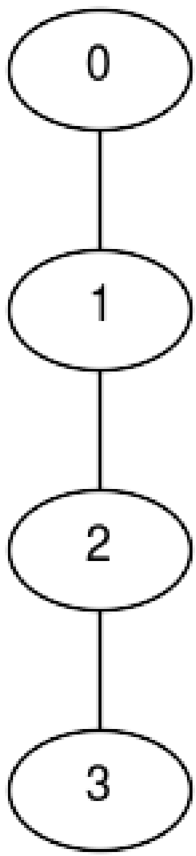


Figure 53: .svg file created from the 'create_named_vertices_path_graph' function (algorithm 233) its .dot file, converted from .dot file to .svg using algorithm 366

# 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 13.10
- Loading a directed graph with custom vertices from a .dot file: chapter 13.11
- Loading an undirected directed graph with custom vertices from a .dot file: chapter 13.12

## 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 236** Find if there is vertex with a certain my_vertex

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

template <typename graph, typename custom_vertex>
bool has_custom_vertex_with_my_vertex(
  const 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 237, where a certain my_vertex cannot be found in an empty graph. After adding the desired my_vertex, it is found.

**Algorithm 237** Demonstration of the 'has_custom_vertex_with_my_vertex' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
   test_has_custom_vertex_with_my_vertex)
{
  auto g = create_empty_undirected_custom_vertices_graph
     ();
  BOOST_CHECK(!has_custom_vertex_with_my_vertex(
     my_custom_vertex("Felix"),g));
  add_custom_vertex(my_custom_vertex("Felix"),g);
  BOOST_CHECK(has_custom_vertex_with_my_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 238 shows how to obtain a vertex descriptor to the first vertex found with a specific my_vertex value.

**Algorithm 238** 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 custom_vertex>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_custom_vertex_with_my_vertex(
  const custom_vertex& v,
  const graph& g
)
{
  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;
    }
  );
  if (i == vip.second)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find custom_vertex '"
      << v << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  return *i;
}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 239 shows some examples of how to do so.

**Algorithm 239** Demonstration of the 'find_first_custom_vertex_with_my_vertex' function

```
#include <boost/test/unit_test.hpp>
#include "create_custom_vertices_k2_graph.h"
#include "find_first_custom_vertex_with_my_vertex.h"

BOOST_AUTO_TEST_CASE(
    test_find_first_custom_vertex_with_my_vertex)
{
  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
  );
  BOOST_CHECK(out_degree(vd,g) == 1);
  BOOST_CHECK(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[13] map and then look up the vertex of interest.

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

**Algorithm 240** 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>
auto get_my_custom_vertex(
  const typename boost::graph_traits<graph>::
      vertex_descriptor& vd,
  const graph& g
) noexcept -> decltype(get(get(boost::vertex_custom_type,
    g), vd))
{
  const auto my_custom_vertexes_map
    = get(boost::vertex_custom_type,
      g
    );
  return get(my_custom_vertexes_map, vd);
}
```

This function creates a property map from the graph, using the 'boost::vertex_custom_type' tag. Then it uses the vertex descriptor to obtain the custom vertex associated with that vertex.

Note how this function deduces the date type of its return value using decltype.

To use 'get_custom_vertex_my_vertex', one first needs to obtain a vertex descriptor. Algorithm 241 shows a simple example.

**Algorithm 241** Demonstration if the 'get_my_custom_vertex' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_get_my_custom_vertex)
{
  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);
  BOOST_CHECK(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 242.

**Algorithm 242** 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, typename my_custom_vertex>
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 243 shows a simple example.

**Algorithm 243** Demonstration if the 'set_my_custom_vertex' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_set_my_custom_vertex)
{
  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);
  BOOST_CHECK(get_my_custom_vertex(vd,g)
    == old_vertex
  );
  const my_custom_vertex new_vertex{"Diggy"};
  set_my_custom_vertex(
    new_vertex, vd, g
  );
  BOOST_CHECK(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 244** 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, typename custom_vertex>
void set_my_custom_vertexes(
  graph& g,
  const std::vector<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 vip = vertices(g);
  const auto j = vip.second;
  for (
    auto i = vip.first;
    i!=j; ++i,
    ++my_custom_vertexes_begin
  ) {
    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 ▶ Adding an edge between two custom vertices

Instead of looking for an edge descriptor, one can also add an edge from two vertex descriptors. Adding an edge between two selected vertices goes as follows:

use the my_custom_vertex of the vertices to get both vertex descriptors, then call 'boost::add_edge' on those two, as shown in algorithm 245.

**Algorithm 245** Add an edge between two custom vertices

```
#include <cassert>
#include <string>
#include <sstream>
#include <stdexcept>
#include <boost/graph/adjacency_list.hpp>
#include "has_vertex_with_my_vertex.h"
#include "find_first_custom_vertex_with_my_vertex.h"

template <typename graph, typename custom_vertex>
typename boost::graph_traits<graph>::edge_descriptor
add_edge_between_custom_vertices(
  const custom_vertex& vertex_from,
  const custom_vertex& vertex_to,
  graph& g
)
{
  if (!has_vertex_with_my_vertex(vertex_from, g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find vertex_with_my_vertex 'from' with value '"
      << vertex_from << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  if (!has_vertex_with_my_vertex(vertex_to, g))
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find vertex_with_my_vertex 'to' with value '"
      << vertex_to << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  const auto vd_1 =
    find_first_custom_vertex_with_my_vertex(vertex_from, g);
  const auto vd_2 =
    find_first_custom_vertex_with_my_vertex(vertex_to, g);
  if (edge(vd_1, vd_2, g).second)
  {
    std::stringstream msg;
    msg << __func__ << ": edge is already present";
    throw std::invalid_argument(msg.str());
  }

  const auto aer = boost::add_edge(vd_1, vd_2, g);
  assert(aer.second);
  return aer.first;
}
```

Algorithm 246 shows how the edges can be added:

**Algorithm 246** Demonstration of the 'add_edge_between_selected_vertices' function

```
#include <boost/test/unit_test.hpp>
#include "add_edge_between_custom_vertices.h"
#include "add_custom_vertex.h"
#include "create_empty_undirected_custom_vertices_graph.h
  "

BOOST_AUTO_TEST_CASE(
   test_add_edge_between_custom_vertices)
{
  auto g = create_empty_undirected_custom_vertices_graph
     ();
  const my_custom_vertex va("Bert");
  const my_custom_vertex vb("Ernie");
  add_custom_vertex(va, g);
  add_custom_vertex(vb, g);
  add_edge_between_custom_vertices(va, vb, g);
  BOOST_CHECK(boost::num_edges(g) == 1);
}
```

## 13.7 ▶ Create a direct-neighbour subgraph from a vertex descriptor of a graph with custom vertices

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 code that does exactly that:

**Algorithm 247** Get the direct-neighbour custom vertices subgraph from a vertex descriptor

```
#include <map>
#include <boost/graph/adjacency_list.hpp>
#include "add_custom_vertex.h"
#include "get_my_custom_vertex.h"
template <typename graph, typename vertex_descriptor>
graph create_direct_neighbour_custom_vertices_subgraph(
  const vertex_descriptor& vd,
  const graph& g
)
{
  graph h;

  std::map<vertex_descriptor,vertex_descriptor> m;
  {
    const auto vd_h = add_custom_vertex(
      get_my_custom_vertex(vd, g), 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)),
      [g, &h](const vertex_descriptor& d)
      {
        const auto vd_h = add_custom_vertex(
          get_my_custom_vertex(d,g), 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;
      boost::add_edge(m[vd_from],m[vd_to], h);
    }
  }
  return h;
}
```

This demonstration code shows that the direct-neighbour graph of each vertex of a $K_2$ graphs is ... a $K_2$ graph!

**Algorithm 248** Demo of the 'create_direct_custom_vertices_neighbour_subgraph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_direct_neighbour_custom_vertices_subgraph.h"
#include "create_custom_vertices_k2_graph.h"
#include "get_my_custom_vertexes.h"

BOOST_AUTO_TEST_CASE(
    test_create_direct_neighbour_custom_vertices_subgraph)
{
  const auto g = create_custom_vertices_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_custom_vertices_subgraph(
      *i,g
    );
    BOOST_CHECK(boost::num_vertices(h) == 2);
    BOOST_CHECK(boost::num_edges(h) == 1);
    const auto v = get_my_custom_vertexes(h);
    std::set<my_custom_vertex> vertexes(std::begin(v),std
        ::end(v));
    const my_custom_vertex a("A","source",0.0,0.0);
    const my_custom_vertex b("B","target",3.14,3.14);
    BOOST_CHECK(vertexes.count(a) == 1);
    BOOST_CHECK(vertexes.count(b) == 1);
  }
}
```

## 13.8 ▶ Creating all direct-neighbour subgraphs from a graph with custom vertices

Using the previous function, it is easy to create all direct-neighbour subgraphs from a graph with custom vertices:

**Algorithm 249** Create all direct-neighbour subgraphs from a graph with custom vertices

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

template <typename graph>
std::vector<graph>
    create_all_direct_neighbour_custom_vertices_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_custom_vertices_subgraph
          (
        d, g
      );
    }
  );
  return v;
}
```

This demonstration code shows how to extract the subgraphs from a path graph:

**Algorithm 250** Demo of the 'create_all_direct_neighbour_custom_vertices_subgraphs' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_all_direct_neighbour_custom_vertices_subgraphs.
    h"
#include "create_custom_vertices_k2_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_all_direct_neighbour_custom_vertices_subgraphs
    )
{
  const auto v
    =
        create_all_direct_neighbour_custom_vertices_subgraphs
        (create_custom_vertices_k2_graph());
  BOOST_CHECK(v.size() == 2);
  for (const auto g: v)
  {
    BOOST_CHECK(boost::num_vertices(g) == 2);
    BOOST_CHECK(boost::num_edges(g) == 1);
  }
}
```

The sub-graphs are shown here:

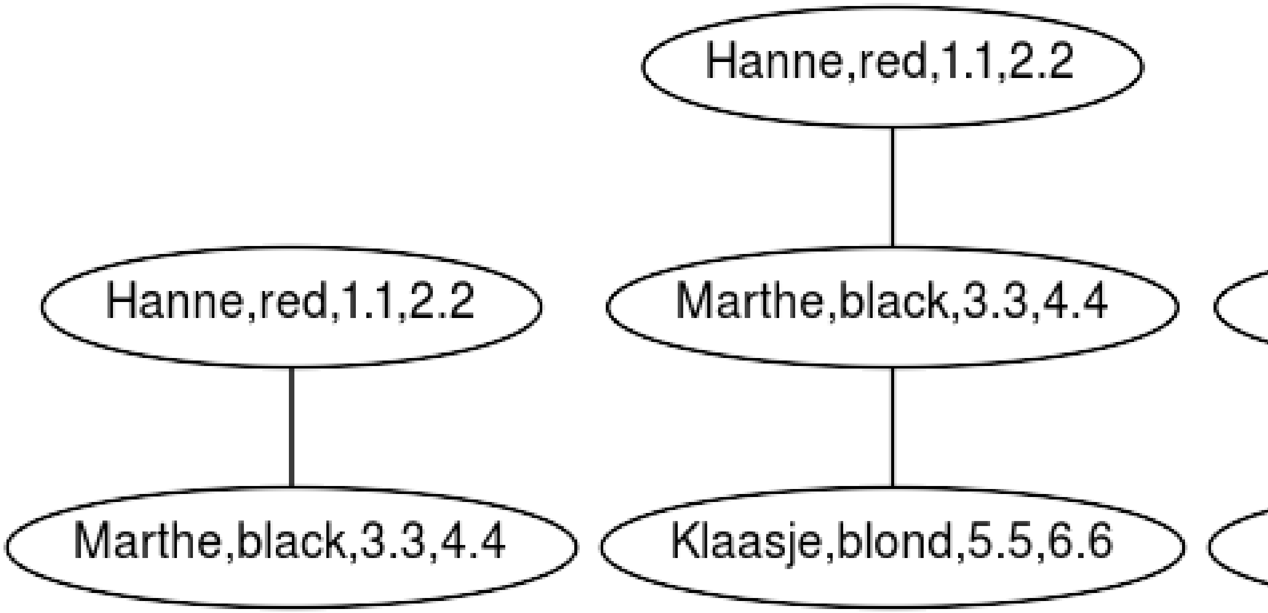


Figure 54: All subgraphs created

### 13.9 ▶ Are two graphs with custom vertices isomorphic?

Algorithm 5.14 checked if two graphs with named vertices are 'label isomorphic'. Here, we do the same for custom vertices.

To do this, there are two steps needed:

1. Map all my_custom_vertex objects to an unsigned int.

2. Compare the two graphs with that map

Below the class 'my_custom_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 than custom vertices. Note that operator< must be implemented for the custom class for this to compile.

**Algorithm 251** The 'custom_vertex_invariant' functor

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

template <class graph>
struct custom_vertex_invariant {
  using custom_vertex_to_int_map = std::map<
      my_custom_vertex, size_t >;
  using result_type = size_t;
  using argument_type = typename graph::vertex_descriptor
      ;

  const graph& m_graph;
  custom_vertex_to_int_map& m_mappings;

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

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

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

**Algorithm 252** Check if two graphs with custom vertices are isomorphic

```
#include "custom_vertex_invariant.h"

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

template <typename graph>
bool is_custom_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 custom_vertex_invariant<graph>::
     custom_vertex_to_int_map shared_custom;
  custom_vertex_invariant<graph> inv1{g, shared_custom};
  custom_vertex_invariant<graph> inv2{h, shared_custom};
  inv1.collect_custom();
  inv2.collect_custom();

  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 253** Demo of the 'is_named_vertices_isomorphic' function

```
#include <boost/test/unit_test.hpp>
#include "create_custom_vertices_path_graph.h"
#include "is_custom_vertices_isomorphic.h"

BOOST_AUTO_TEST_CASE(test_is_custom_vertices_isomorphic)
{
  const auto g = create_custom_vertices_path_graph(
    {
      my_custom_vertex("Alpha"),
      my_custom_vertex("Beta"),
      my_custom_vertex("Gamma")
    }
  );
  const auto h = create_custom_vertices_path_graph(
    {
      my_custom_vertex("Gamma"),
      my_custom_vertex("Beta"),
      my_custom_vertex("Alpha")
    }
  );
  const auto i = create_custom_vertices_path_graph(
    {
      my_custom_vertex("Alpha"),
      my_custom_vertex("Gamma"),
      my_custom_vertex("Beta")
    }
  );
  BOOST_CHECK( is_custom_vertices_isomorphic(g,h));
  BOOST_CHECK(!is_custom_vertices_isomorphic(g,i));
}
```

## 13.10 Storing a graph with custom vertices as a .dot

If you used the create_custom_vertices_k2_graph function (algorithm 230) to produce a $K_2$ graph with vertices associated with my_vertex objects, you can store these my_vertexes additionally with algorithm 254:

**Algorithm 254** 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 auto m = get(my_custom_vertexes_map,v);
      out << "[label=\"" << m << "\"]";
    }
  );
}
```

## 13.11 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 255:

**Algorithm 255** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_directed_custom_vertices_graph();
  boost::dynamic_properties dp(boost::
      ignore_other_properties);
  dp.property("label", get(boost::vertex_custom_type, g))
      ;
  boost::read_graphviz(f,g,dp);
  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 256 shows how to use the 'load_directed_custom_vertices_graph_from_dot' function:

**Algorithm 256** Demonstration of the 'load_directed_custom_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_directed_custom_vertices_graph_from_dot)
{
  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);
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 227), saved and then loaded. The loaded graph is then checked to be identical to the original.

## 13.12 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 257:

**Algorithm 257** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g = create_empty_undirected_custom_vertices_graph
      ();
  boost::dynamic_properties dp(boost::
      ignore_other_properties);
  dp.property("label", get(boost::vertex_custom_type, g))
      ;
  boost::read_graphviz(f,g,dp);
  return g;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 13.11 describes the rationale of this function.

Algorithm 258 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

**Algorithm 258** Demonstration of the 'load_undirected_custom_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_undirected_custom_vertices_graph_from_dot)
{
  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);
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 230), 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 259** 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 260** 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 261** Demonstration of the 'create_empty_directed_custom_and_selectable_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_empty_directed_custom_and_selectable_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_directed_custom_and_selectable_vertices_graph
    )
{
  const auto g
    =
        create_empty_directed_custom_and_selectable_vertices_graph
        ();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(boost::num_vertices(g) == 0);
}
```

## 14.3 Create an empty undirected graph with custom and selectable vertices

**Algorithm 262** 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 263** Demonstration of the 'create_empty_undirected_custom_and_selectable_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_undirected_custom_and_selectable_vertices_graph
    )
{
  const auto g
    =
        create_empty_undirected_custom_and_selectable_vertices_graph
        ();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(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 264** 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"

template <typename graph, typename vertex_t>
typename boost::graph_traits<graph>::vertex_descriptor
add_custom_and_selectable_vertex(
  const vertex_t& 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 265** Demo of 'add_custom_and_selectable_vertex'

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_add_custom_and_selectable_vertex)
{
  auto g
    =
        create_empty_directed_custom_and_selectable_vertices_graph
        ();
  BOOST_CHECK(boost::num_vertices(g) == 0);
  BOOST_CHECK(boost::num_edges(g) == 0);
  add_custom_and_selectable_vertex(
    my_custom_vertex("X"),
    true,
    g
  );
  BOOST_CHECK(boost::num_vertices(g) == 1);
  BOOST_CHECK(boost::num_edges(g) == 0);

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

## 14.5 Creating a Markov-chain with custom and selectable vertices

### 14.5.1 Graph

Figure 55 shows the graph that will be reproduced:

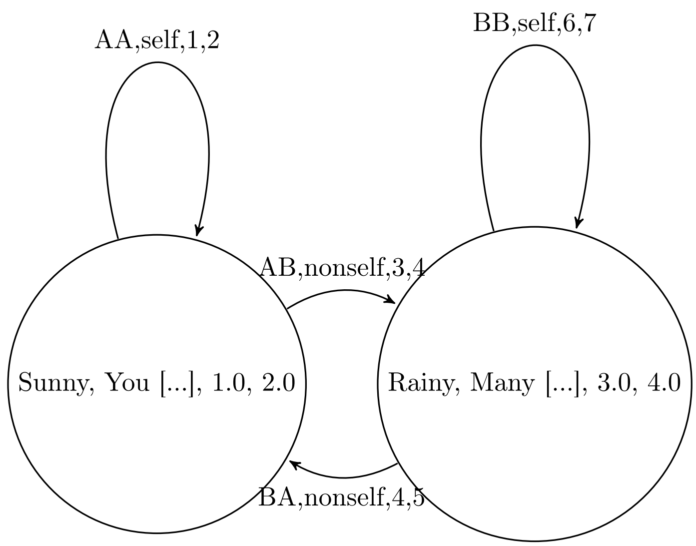


Figure 55: A two-state Markov chain where the edges and vertices have custom properies. The edges' and vertices' properties are nonsensical

### 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 266** Creating the two-state Markov chain as depicted in figure 55

```
#include "add_custom_and_selectable_vertex.h"
#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 my_custom_vertex a("Sunny","Yellow thing"
      ,1.0,2.0);
  const my_custom_vertex b("Rainy", "Grey things"
      ,3.0,4.0);
  const auto vd_a = add_custom_and_selectable_vertex(a,
      true, g);
  const auto vd_b = add_custom_and_selectable_vertex(b,
      false, g);
  boost::add_edge(vd_a, vd_a, g);
  boost::add_edge(vd_a, vd_b, g);
  boost::add_edge(vd_b, vd_a, g);
  boost::add_edge(vd_b, vd_b, g);
  return g;
}
```

### 14.5.3 Creating such a graph

Here is the demo:

**Algorithm 267** Demo of the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 266)

```
#include <boost/test/unit_test.hpp>
#include "
    create_custom_and_selectable_vertices_markov_chain.h"
#include "get_vertex_selectednesses.h"

BOOST_AUTO_TEST_CASE(
    test_create_custom_and_selectable_vertices_markov_chain
    )
{
  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)
  };
  BOOST_CHECK(expected_selectednesses
    == vertex_selectednesses
  );
}
```

### 14.5.4 The .dot file produced

**Algorithm 268** .dot file created from the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 266), converted from graph to .dot file using algorithm 55

```
digraph G {
0[label="Sunny,Yellow$$$SPACE$$$thing,1,2", regular="1"];
1[label="Rainy,Grey$$$SPACE$$$things,3,4", regular="0"];
0->0 ;
0->1 ;
1->0 ;
1->1 ;
}
```

#### 14.5.5 The .svg file produced

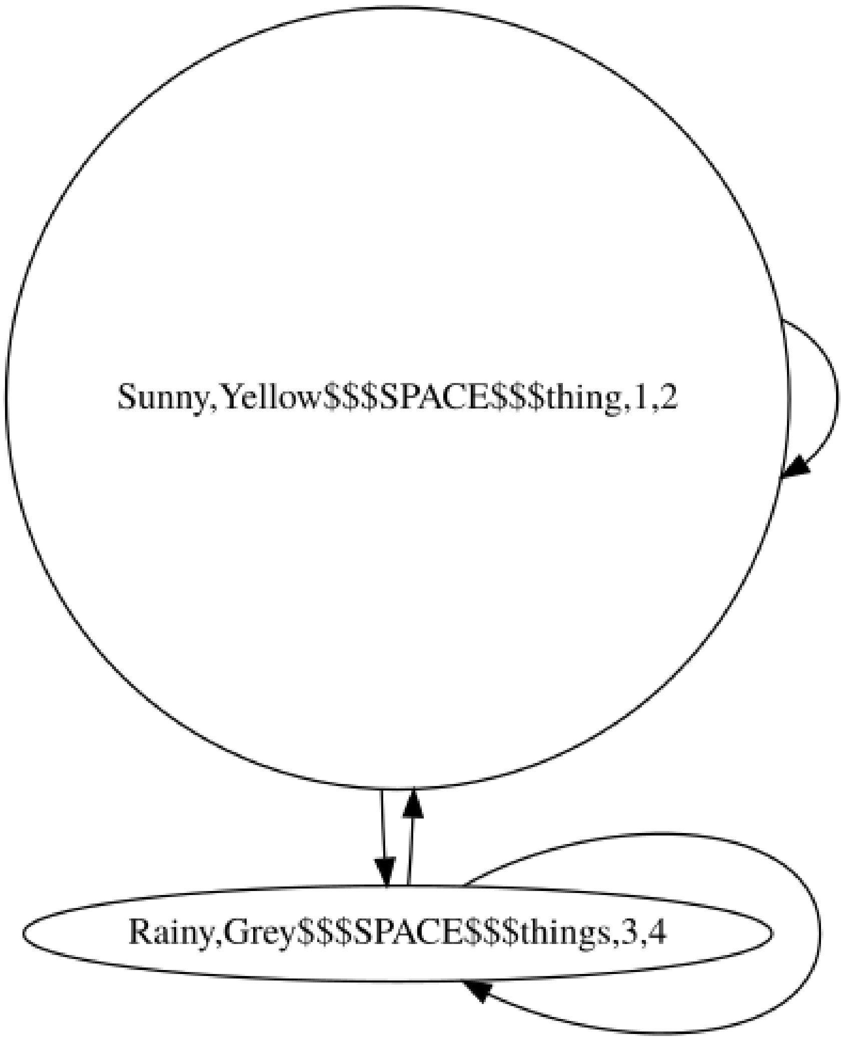


Figure 56: .svg file created from the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 227) its .dot file, converted from .dot file to .svg using algorithm 366

Note how the .svg changed it appearance due to the Graphviz 'regular' property (see chapter 25.2): 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 269** Creating $K_3$ as depicted in figure 34

```
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"
#include "add_custom_and_selectable_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_custom_and_selectable_vertices_k2_graph() noexcept
{
  auto g
    =
        create_empty_undirected_custom_and_selectable_vertices_graph
        ();
  const my_custom_vertex a("A","source",0.0,0.0);
  const my_custom_vertex b("B","target",3.14,3.14);
  const auto vd_a = add_custom_and_selectable_vertex(a,
      true, g);
  const auto vd_b = add_custom_and_selectable_vertex(b,
      false, g);
  boost::add_edge(vd_a, vd_b, g);
  return g;
}
```

Most of the code is a slight modification of algorithm 230. 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 270** Demo of the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 269)

```
#include <boost/test/unit_test.hpp>
#include "create_custom_and_selectable_vertices_k2_graph.
    h"
#include "has_custom_vertex_with_my_vertex.h"

BOOST_AUTO_TEST_CASE(
    test_create_custom_and_selectable_vertices_k2_graph)
{
  const auto g =
      create_custom_and_selectable_vertices_k2_graph();
  BOOST_CHECK(boost::num_edges(g) == 1);
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(has_custom_vertex_with_my_vertex(
    my_custom_vertex("A", "source" ,0.0, 0.0), g)
  );
  BOOST_CHECK(has_custom_vertex_with_my_vertex(
    my_custom_vertex("B", "target" ,3.14, 3.14), g)
  );
}
```

### 14.6.4 The .dot file produced

**Algorithm 271** .dot file created from the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 269), converted from graph to .dot file using algorithm 55

```
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

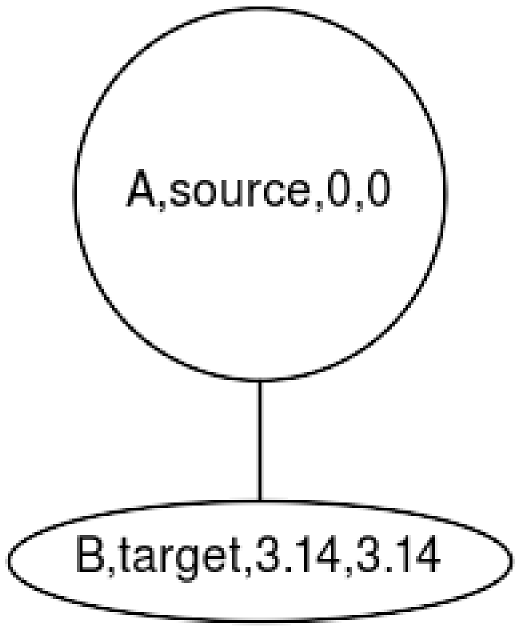


Figure 57: .svg file created from the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 227) its .dot file, converted from .dot file to .svg using algorithm 366

Note how the .svg changed it appearance due to the Graphviz 'regular' property (see chapter 25.2): 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 15.6
- Loading a directed graph with custom and selectable vertices from a .dot file: chapter 15.7
- Loading an undirected directed graph with custom and selectable vertices from a .dot file: chapter 15.8

## 15.1 ▶ Getting the vertices with a certain selectedness

## 15.2 ▶ Counting the vertices with a certain selectedness

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

**Algorithm 272** Count the vertices with a certain selectedness

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

template <typename graph>
int count_vertices_with_selectedness(
  const bool selectedness,
  const graph& g
) noexcept
{
  using vd = typename graph::vertex_descriptor;

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

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

Algorithm 273 shows some examples of how to do so.

**Algorithm 273** Demonstration of the 'count_vertices_with_selectedness' function

```
#include <boost/test/unit_test.hpp>
#include "add_custom_and_selectable_vertex.h"
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(
    test_count_vertices_with_selectedness)
{
  auto g =
      create_empty_undirected_custom_and_selectable_vertices_graph
      ();
  add_custom_and_selectable_vertex(
    my_custom_vertex("A"), true, g
  );
  add_custom_and_selectable_vertex(
    my_custom_vertex("B"), false, g
  );
  add_custom_and_selectable_vertex(
    my_custom_vertex("C"), true, g
  );
  BOOST_CHECK(count_vertices_with_selectedness( true, g)
      == 2);
  BOOST_CHECK(count_vertices_with_selectedness(false, g)
      == 1);

}
```

## 15.3 ▶ Adding an edge between two selected vertices

Instead of looking for an edge descriptor, one can also add an edge from two vertex descriptors. Adding an edge between two selected vertices goes as follows: use the selectedness of the vertices to get both vertex descriptors, then call 'boost::add_edge' on those two, as shown in algorithm 274.

**Algorithm 274** Add an edge between two selected vertices

```
#include <cassert>
#include <sstream>
#include <stdexcept>
#include <string>
#include <boost/graph/adjacency_list.hpp>
#include "get_vertices_with_selectedness.h"
#include "count_vertices_with_selectedness.h"

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
add_edge_between_selected_vertices(graph& g)
{
  if (count_vertices_with_selectedness(true, g) != 2)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "need exactly two selected vertices, "
      << "to add an edge in between, instead of "
      << count_vertices_with_selectedness(true, g)
    ;
    throw std::invalid_argument(msg.str());
  }
  const auto vds = get_vertices_with_selectedness(true, g
    );
  assert(vds.size() == 2);
  const auto aer = boost::add_edge(vds[0], vds[1], g);
  if (!aer.second) {
    std::stringstream msg;
    msg << __func__ << ": edge insertion failed";
    throw std::invalid_argument(msg.str());
  }
  return aer.first;
}
```

Algorithm 275 shows how the edges can be added:

**Algorithm 275** Demonstration of the 'add_edge_between_selected_vertices' function

```
#include <boost/test/unit_test.hpp>
#include "add_edge_between_selected_vertices.h"
#include "add_custom_and_selectable_vertex.h"
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(
    test_add_edge_between_selected_vertices)
{
  auto g =
      create_empty_undirected_custom_and_selectable_vertices_graph
      ();
  add_custom_and_selectable_vertex(my_custom_vertex("Bert
      "),true, g);
  add_custom_and_selectable_vertex(my_custom_vertex("
      Ernie"),true, g);
  add_edge_between_selected_vertices(g);
  BOOST_CHECK(boost::num_edges(g) == 1);
}
```

## 15.4 ▶ Create a direct-neighbour subgraph from a vertex descriptor of a graph with custom and selectable vertices

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 code that does exactly that:

**Algorithm 276** Get the direct-neighbour custom and selectable vertices subgraph from a vertex descriptor

```
#include <map>
#include <boost/graph/adjacency_list.hpp>
#include "add_custom_and_selectable_vertex.h"
#include "get_my_custom_vertex.h"
template <typename graph, typename vertex_descriptor>
graph
    create_direct_neighbour_custom_and_selectable_vertices_subgraph
    (
  const vertex_descriptor& vd,
  const graph& g
)
{
  graph h;

  std::map<vertex_descriptor,vertex_descriptor> m;
  {
    const auto vd_h = add_custom_and_selectable_vertex(
      get_my_custom_vertex(vd, g), false, 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)),
      [g, &h](const vertex_descriptor& d)
      {
        const auto vd_h =
            add_custom_and_selectable_vertex(
          get_my_custom_vertex(d,g), false, 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;
      boost::add_edge(m[vd_from],m[vd_to], h);
    }
  }
  return h;
}
```

Demo:

**Algorithm 277** Demo of the 'create_direct_custom_and_selectable_vertices_neighbour_subgraph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_direct_neighbour_custom_and_selectable_vertices_subgraph
    .h"
#include "create_custom_and_selectable_vertices_k2_graph.
    h"
#include "get_my_custom_vertexes.h"

BOOST_AUTO_TEST_CASE(
    test_create_direct_neighbour_custom_and_selectable_vertices_subgraph
    )
{
  const auto g =
      create_custom_and_selectable_vertices_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_custom_and_selectable_vertices_subgraph
        (
      *i,g
    );
    BOOST_CHECK(boost::num_vertices(h) == 2);
    BOOST_CHECK(boost::num_edges(h) == 1);
    const auto v = get_my_custom_vertexes(h);
    std::set<my_custom_vertex> vertexes(std::begin(v),std
        ::end(v));
    const my_custom_vertex a("A","source",0.0,0.0);
    const my_custom_vertex b("B","target",3.14,3.14);
    BOOST_CHECK(vertexes.count(a) == 1);
    BOOST_CHECK(vertexes.count(b) == 1);
  }
}
```

## 15.5 ▶ Creating all direct-neighbour subgraphs from a graph with custom and selectable vertices

Using the previous function, it is easy to create all direct-neighbour subgraphs from a graph with custom vertices:

**Algorithm 278** Create all direct-neighbour subgraphs from a graph with custom vertices

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

template <typename graph>
std::vector<graph>
    create_all_direct_neighbour_custom_and_selectable_vertices_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_custom_and_selectable_vertices_subgraph
          (
        d, g
      );
    }
  );
  return v;
}
```

This demonstration code shows how to extract the subgraphs from a path graph:

**Algorithm 279** Demo of the 'create_all_direct_neighbour_custom_vertices_subgraphs' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_all_direct_neighbour_custom_and_selectable_vertices_subgraphs
    .h"
#include "create_custom_and_selectable_vertices_k2_graph.
    h"

BOOST_AUTO_TEST_CASE(
    test_create_all_direct_neighbour_custom_and_selectable_vertices_subgraphs
    )
{
  const auto v
    =
      create_all_direct_neighbour_custom_and_selectable_vertices_subgraphs
      (
       create_custom_and_selectable_vertices_k2_graph()
    );
  BOOST_CHECK(v.size() == 2);
  for (const auto g: v)
  {
    BOOST_CHECK(boost::num_vertices(g) == 2);
    BOOST_CHECK(boost::num_edges(g) == 1);
  }
}
```

The sub-graphs created from a path graph are shown here:

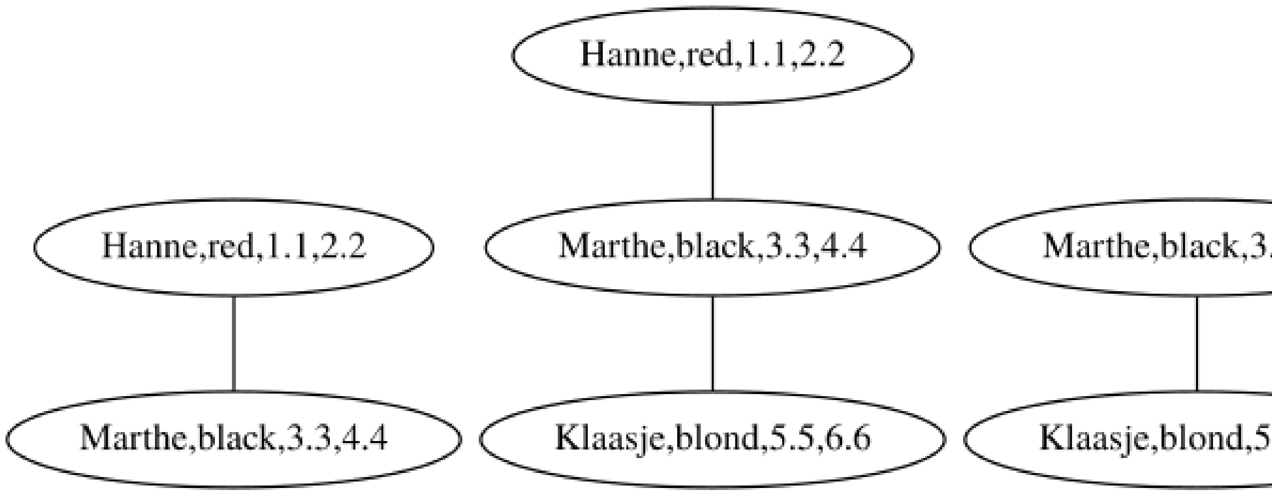


Figure 58: All subgraphs created

### 15.6 Storing a graph with custom and selectable vertices as a .dot

If you used the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 269) 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 280:

**Algorithm 280** 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);
  boost::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 281:

**Algorithm 281** 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 282:

**Algorithm 282** The 'custom_and_selectable_vertices_writer' function

```
#include <ostream>
#include <boost/lexical_cast.hpp>
#include "is_graphviz_friendly.h"
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=\""
      << get(m_my_custom_vertex_map, vd) //Can be
           Graphviz unfriendly
      << "\", regular=\""
      << get(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 25.2 for most Graphviz attributes).

Special about this, is that even for Graphviz-unfriendly input, it still works.

## 15.7 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 283:

**Algorithm 283** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g =
      create_empty_directed_custom_and_selectable_vertices_graph
      ();
  boost::dynamic_properties dp(
    boost::ignore_other_properties
  );
  dp.property("label", get(boost::vertex_custom_type, g))
      ;
  dp.property("regular", get(boost::vertex_is_selected, g
      ));
  boost::read_graphviz(f,g,dp);
  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 25.2 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 284 shows how to use the 'load_directed_custom_vertices_graph_from_dot' function:

**Algorithm 284** Demonstration of the 'load_directed_custom_and_selectable_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_custom_and_selectable_vertices_markov_chain.h"
#include "is_regular_file.h"
#include "
    save_custom_and_selectable_vertices_graph_to_dot.h"

BOOST_AUTO_TEST_CASE(
    test_load_directed_custom_and_selectable_vertices_graph_from_dot
    )
{
  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
  );
  BOOST_CHECK(is_regular_file(filename));
}
```

This demonstration shows how the Markov chain is created using the 'create_custom_vertices_markov_chain' function (algorithm 227), saved and then checked to exist.

## 15.8 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 285:

**Algorithm 285** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g =
      create_empty_undirected_custom_and_selectable_vertices_graph
      ();
  boost::dynamic_properties dp(boost::
      ignore_other_properties);
  dp.property("label", get(boost::vertex_custom_type, g))
      ;
  dp.property("regular", get(boost::vertex_is_selected, g
      ));
  boost::read_graphviz(f,g,dp);
  return g;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 15.7 describes the rationale of this function.

Algorithm 286 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

**Algorithm 286** Demonstration of the 'load_undirected_custom_and_selectable_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#include "create_custom_and_selectable_vertices_k2_graph.
    h"
#include "is_regular_file.h"
#include "
    save_custom_and_selectable_vertices_graph_to_dot.h"

BOOST_AUTO_TEST_CASE(
    test_load_undirected_custom_and_selectable_vertices_graph_from_dot
    )
{
  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
  );
  BOOST_CHECK(is_regular_file(filename));
}
```

This demonstration shows how $K_2$ with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 230), 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[14].

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

- An empty directed graph that allows for custom edges and vertices: see chapter 16.3
- 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 287** 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
  );
  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;
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);
```

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 362) can convert the elements to be streamed to a Graphviz-friendly version, which can be decoded by 'graphviz_decode' (algorithm 363).

## 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 288** 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 289** 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 290** Demonstration of the 'create_empty_directed_custom_edges_and_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_empty_directed_custom_edges_and_vertices_graph.
    h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_directed_custom_edges_and_vertices_graph
    )
{
  const auto g =
      create_empty_directed_custom_edges_and_vertices_graph
      ();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(boost::num_vertices(g) == 0);
}
```

## 16.4 Create an empty undirected graph with custom edges and vertices

**Algorithm 291** 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 292** Demonstration of the 'create_empty_undirected_custom_edges_and_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_undirected_custom_edges_and_vertices_graph
    )
{
  const auto g
    =
        create_empty_undirected_custom_edges_and_vertices_graph
        ();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(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 293** Add a custom edge

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

template <typename graph, typename custom_edge>
typename boost::graph_traits<graph>::edge_descriptor
add_custom_edge(
  const custom_edge& edge,
  graph& g
)
{
  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);
  return add_custom_edge_between_vertices(edge, vd_a,
     vd_b, g);
}
```

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 294** Demo of 'add_custom_edge'

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_add_custom_edge)
{
  auto g =
     create_empty_directed_custom_edges_and_vertices_graph
     ();
  add_custom_edge(my_custom_edge("X"), g);
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(boost::num_edges(g) == 1);

  auto h =
     create_empty_undirected_custom_edges_and_vertices_graph
     ();
  add_custom_edge(my_custom_edge("Y"), h);
  BOOST_CHECK(boost::num_vertices(h) == 2);
  BOOST_CHECK(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 295** 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"
#include "get_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) {
      return get_my_custom_edge(d, g);
    }
  );
  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 24.1).

## 16.7 Creating a Markov-chain with custom edges and vertices

### 16.7.1 Graph

Figure 59 shows the graph that will be reproduced:

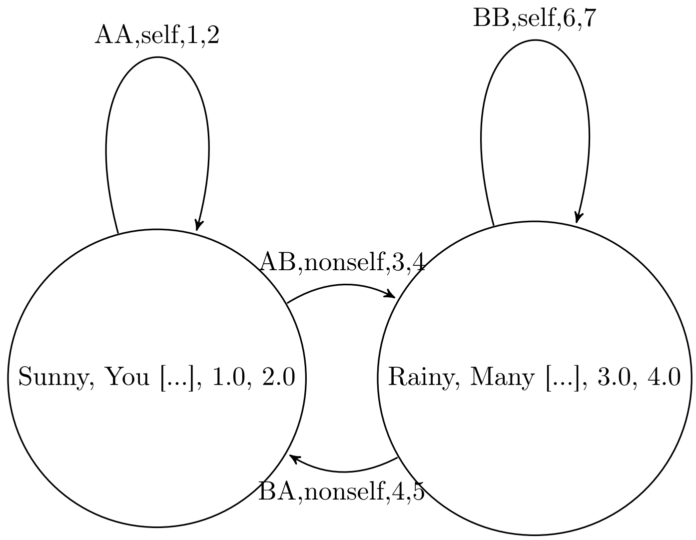


Figure 59: A two-state Markov chain where the edges and vertices have custom properies. The edges' and vertices' properties are nonsensical

### 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 296** Creating the two-state Markov chain as depicted in figure 59

```
#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 297** Demo of the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 296)

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
  test_create_custom_edges_and_vertices_markov_chain)
{
  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)
  };
  BOOST_CHECK(expected_my_custom_vertexes
    == vertex_my_custom_vertexes
  );
}
```

### 16.7.4 The .dot file produced

**Algorithm 298** .dot file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 296), converted from graph to .dot file using algorithm 55

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

### 16.7.5 The .svg file produced

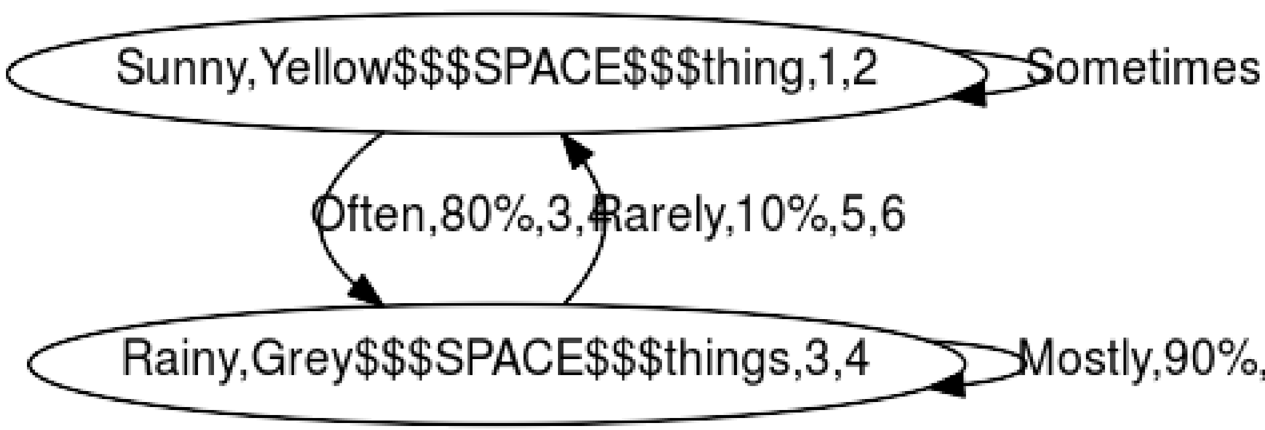


Figure 60: .svg file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 227) its .dot file, converted from .dot file to .svg using algorithm 366

## 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 6.8 , but with our custom edges and vertices intead:

[graph here]

### 16.8.2 Function to create such a graph

**Algorithm 299** Creating $K_3$ as depicted in figure 34

```
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "add_custom_vertex.h"
#include "add_custom_edge_between_vertices.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()
{
  auto g
    =
        create_empty_undirected_custom_edges_and_vertices_graph
        ();

  const my_custom_vertex va("top","source",0.0,0.0);
  const my_custom_vertex vb("right","target",3.14,0);
  const my_custom_vertex vc("left","target",0,3.14);
  const my_custom_edge ea("AB","first",0.0,0.0);
  const my_custom_edge eb("BC","second",3.14,3.14);
  const my_custom_edge ec("CA","third",3.14,3.14);
  const auto vd_a = add_custom_vertex(va, g);
  const auto vd_b = add_custom_vertex(vb, g);
  const auto vd_c = add_custom_vertex(vc, g);
  add_custom_edge_between_vertices(ea, vd_a, vd_b, g);
  add_custom_edge_between_vertices(eb, vd_b, vd_c, g);
  add_custom_edge_between_vertices(ec, vd_c, vd_a, g);
  return g;
}
```

Most of the code is a slight modification of algorithm 135. 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 300** Demo of the ‘create_custom_edges_and_vertices_k3_graph’ function (algorithm 299)

```
#include <boost/test/unit_test.hpp>
#include "add_custom_edge.h"
#include "add_custom_vertex.h"
#include "create_custom_edges_and_vertices_k3_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_custom_edges_and_vertices_k3_graph)
{
  auto g
    = create_custom_edges_and_vertices_k3_graph();
  BOOST_CHECK(boost::num_edges(g) == 3);
  BOOST_CHECK(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 301** .dot file created from the ‘create_custom_edges_and_vertices_markov_chain’ function (algorithm 299), converted from graph to .dot file using algorithm 55

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

#### 16.8.5 The .svg file produced

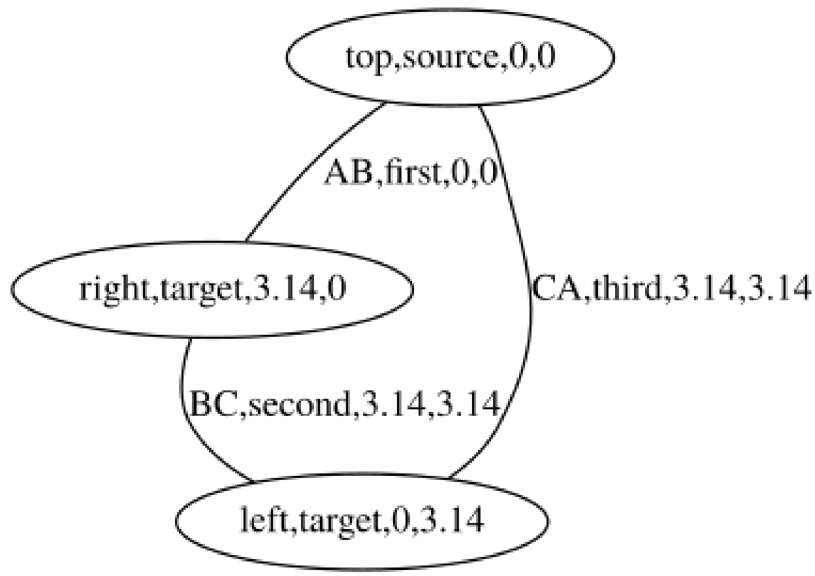


Figure 61: .svg file created from the 'create_custom_edges_and_vertices_k3_graph' function (algorithm 227) its .dot file, converted from .dot file to .svg using algorithm 366

# 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 302** 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, typename custom_edge>
bool has_custom_edge_with_my_edge(
  const 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 303, where a certain 'my_custom_edge' cannot be found in an empty graph. After adding the desired my_custom_edge, it is found.

**Algorithm 303** Demonstration of the 'has_custom_edge_with_my_edge' function

```
#include <boost/test/unit_test.hpp>
#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "has_custom_edge_with_my_edge.h"

BOOST_AUTO_TEST_CASE(test_has_custom_edge_with_my_edge)
{
  auto g
    =
        create_empty_undirected_custom_edges_and_vertices_graph
        ();
  BOOST_CHECK(
    !has_custom_edge_with_my_edge(
      my_custom_edge("Edward"),g
    )
  );
  add_custom_edge(my_custom_edge("Edward"),g);
  BOOST_CHECK(
    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 first my_custom_edge satisfying a predicate

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 304 shows how to obtain an edge descriptor to the first edge found that satisfies a predicate.

**Algorithm 304** Find the first custom edge satisfying a predicate

```
#include <cassert>
#include <boost/graph/graph_traits.hpp>
#include "install_edge_custom_type.h"
#include "my_custom_edge.h"

/// @param predicate a function that returns a boolean,
///   and takes a custom edge as an argument
template <typename graph, typename predicate>
typename boost::graph_traits<graph>::edge_descriptor
find_first_custom_edge(
  const predicate& p,
  const graph& g
)
{
  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,p](const ed d) {
      const auto my_edges_map = get(boost::
          edge_custom_type, g);
      const auto edge = get(my_edges_map, d);
      return p(edge);
    }
  );
  if (i == eip.second)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find a custom edge satisfying the 
          predicate"
    ;
    throw std::invalid_argument(msg.str());
  }
  return *i;
}
```

With the edge descriptor obtained, one can read and modify the edge and the vertices surrounding it. Algorithm 305 shows some examples of how to do so.

**Algorithm 305** Demonstration of the 'find_first_custom_edge' function

```
#include <boost/test/unit_test.hpp>
#include "create_custom_edges_and_vertices_k3_graph.h"
#include "find_first_custom_edge.h"
#include "my_custom_edge.h"
#include "get_my_custom_edge.h"

BOOST_AUTO_TEST_CASE(test_find_first_custom_edge)
{
  const auto g =
     create_custom_edges_and_vertices_k3_graph();
  const auto predicate = [](const my_custom_edge& e) {
     return e.get_name() == "BC"; };
  const auto ed = find_first_custom_edge(predicate, g);
  BOOST_CHECK(get_my_custom_edge(ed, g).get_name() == "BC
     ");
}
```

## 17.3 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 306 shows how to obtain an edge descriptor to the first edge found with a specific my_custom_edge value.

**Algorithm 306** 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 custom_edge>
typename boost::graph_traits<graph>::edge_descriptor
find_first_custom_edge_with_my_edge(
  const custom_edge& e,
  const graph& g
)
{
  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;
    }
  );
  if (i == eip.second)
  {
    std::stringstream msg;
    msg << __func__ << ": "
      << "could not find custom_edge '"
      << e << "'"
    ;
    throw std::invalid_argument(msg.str());
  }
  return *i;
}
```

With the edge descriptor obtained, one can read and modify the edge and the vertices surrounding it. Algorithm 307 shows some examples of how to do so.

**Algorithm 307** Demonstration of the 'find_first_custom_edge_with_my_edge' function

```
#include <boost/test/unit_test.hpp>
#include "create_custom_edges_and_vertices_k3_graph.h"
#include "find_first_custom_edge_with_my_edge.h"

BOOST_AUTO_TEST_CASE(
    test_find_first_custom_edge_with_my_edge)
{
  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
  );
  BOOST_CHECK(boost::source(ed,g)
    != boost::target(ed,g)
  );
}
```

## 17.4 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 308** 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>
auto get_my_custom_edge(
  const typename boost::graph_traits<graph>::
     edge_descriptor& ed,
  const graph& g
) noexcept -> decltype(get(get(boost::edge_custom_type,g)
    , ed))
{
  const auto my_edge_map
    = get(boost::edge_custom_type, g);
  return get(my_edge_map, ed);
}
```

To use ‘get_custom_edge_my_custom_edge’, one first needs to obtain an edge descriptor. Algorithm 309 shows a simple example.

**Algorithm 309** Demonstration if the ‘get_custom_edge_my_edge’ function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_get_my_custom_edge)
{
  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);
  BOOST_CHECK(get_my_custom_edge(ed,g) == edge);
}
```

## 17.5 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 310.

**Algorithm 310** 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, typename custom_edge>
void set_my_custom_edge(
  const custom_edge& edge,
  const typename boost::graph_traits<graph>::
      edge_descriptor& ed,
  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, ed, edge);
}
```

To use 'set_my_custom_edge', one first needs to obtain an edge descriptor. Algorithm 311 shows a simple example.

**Algorithm 311** Demonstration if the 'set_my_custom_edge' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(test_set_my_custom_edge)
{
  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);
  BOOST_CHECK(get_my_custom_edge(vd,g)
    == old_edge
  );
  const my_custom_edge new_edge{"Diggy"};
  set_my_custom_edge(new_edge, vd, g);
  BOOST_CHECK(get_my_custom_edge(vd,g)
    == new_edge
  );
}
```

## 17.6 ▶ Counting the edges with a certain selectedness

How often is an edge with a certain selectedness present? Here we'll find out.

**Algorithm 312** Count the edges with a certain selectedness

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

template <typename graph>
int count_edges_with_selectedness(
  const bool selectedness,
  const graph& g
) noexcept
{
  using ed = typename graph::edge_descriptor;

  const auto eip = edges(g);
  const auto cnt = std::count_if(
    eip.first, eip.second,
    [g, selectedness](const ed& d)
    {
      const auto is_selected_map
        = get(boost::edge_is_selected, g);
      return selectedness
        == get(is_selected_map, d);
    }
  );
  return static_cast<int>(cnt);
}
```

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

Algorithm 313 shows some examples of how to do so.

**Algorithm 313** Demonstration of the 'count_edges_with_selectedness' function

```
#include <boost/test/unit_test.hpp>
#include "count_edges_with_selectedness.h"
#include "
    create_empty_directed_custom_and_selectable_edges_and_vertices_graph
    .h"
#include "add_custom_and_selectable_edge.h"

BOOST_AUTO_TEST_CASE(test_count_edges_with_selectedness)
{
  auto g =
      create_empty_directed_custom_and_selectable_edges_and_vertices_graph
      ();
  add_custom_and_selectable_edge(
    my_custom_edge("AB"), true, g
  );
  add_custom_and_selectable_edge(
    my_custom_edge("AA"), false, g
  );
  BOOST_CHECK(count_edges_with_selectedness( true, g) ==
      1);
  BOOST_CHECK(count_edges_with_selectedness(false, g) ==
      1);
}
```

## 17.7 ▶ Create a direct-neighbour subgraph from a vertex descriptor of a graph with custom edges and vertices

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 code that does exactly that:

**Algorithm 314** Get the direct-neighbour custom edges and vertices subgraph from a vertex descriptor

```
#include <map>
#include <boost/graph/adjacency_list.hpp>
#include "add_custom_vertex.h"
#include "add_custom_edge_between_vertices.h"
#include "get_my_custom_edge.h"
#include "get_my_custom_vertex.h"
template <typename graph, typename vertex_descriptor>
graph
    create_direct_neighbour_custom_edges_and_vertices_subgraph
    (
  const vertex_descriptor& vd,
  const graph& g
)
{
  graph h;

  std::map<vertex_descriptor,vertex_descriptor> m;
  {
    const auto vd_h = add_custom_vertex(
      get_my_custom_vertex(vd, g), 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)),
      [g, &h](const vertex_descriptor& d)
      {
        const auto vd_h = add_custom_vertex(
          get_my_custom_vertex(d,g), 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;
      add_custom_edge_between_vertices(
        get_my_custom_edge(*i, g),
        m[vd_from],
        m[vd_to],
        h
      );
```

This demonstration code shows that the direct-neighbour graph of each vertex of a $K_2$ graphs is ... a $K_2$ graph!

**Algorithm 315** Demo of the 'create_direct_custom_edges_and_vertices_neighbour_subgraph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_direct_neighbour_custom_edges_and_vertices_subgraph
    .h"
#include "create_custom_edges_and_vertices_k2_graph.h"
#include "get_my_custom_vertexes.h"

BOOST_AUTO_TEST_CASE(
    test_create_direct_neighbour_custom_edges_and_vertices_subgraph
    )
{
  const auto g =
      create_custom_edges_and_vertices_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_custom_edges_and_vertices_subgraph
        (
      *i,g
    );
    BOOST_CHECK(boost::num_vertices(h) == 2);
    BOOST_CHECK(boost::num_edges(h) == 1);
    const auto v = get_my_custom_vertexes(h);
    std::set<my_custom_vertex> vertexes(std::begin(v),std
        ::end(v));
    const my_custom_vertex a("A","source",0.0,0.0);
    const my_custom_vertex b("B","target",3.14,3.14);
    BOOST_CHECK(vertexes.count(a) == 1);
    BOOST_CHECK(vertexes.count(b) == 1);
  }
}
```

## 17.8 ▶ Creating all direct-neighbour subgraphs from a graph with custom edges and vertices

Using the previous function, it is easy to create all direct-neighbour subgraphs from a graph with custom vertices:

**Algorithm 316** Create all direct-neighbour subgraphs from a graph with custom edges and vertices

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

template <typename graph>
std::vector<graph>
    create_all_direct_neighbour_custom_edges_and_vertices_subgraphs
    (
  const graph g
)
{
  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_custom_edges_and_vertices_subgraph
          (
        d, g
      );
    }
  );
  return v;
}
```

This demonstration code shows how to extract the subgraphs from a path graph:

**Algorithm 317** Demo of the 'create_all_direct_neighbour_custom_edges_and_vertices_subgraphs' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_all_direct_neighbour_custom_edges_and_vertices_subgraphs
    .h"
#include "create_custom_edges_and_vertices_k2_graph.h"

BOOST_AUTO_TEST_CASE(
    test_create_all_direct_neighbour_custom_edges_and_vertices_subgraphs
    )
{
  const auto v
    =
        create_all_direct_neighbour_custom_edges_and_vertices_subgraphs
        (
         create_custom_edges_and_vertices_k2_graph()
       );
  BOOST_CHECK(v.size() == 2);
  for (const auto g: v)
  {
    BOOST_CHECK(boost::num_vertices(g) == 2);
    BOOST_CHECK(boost::num_edges(g) == 1);
  }
}
```

The sub-graphs are shown here:

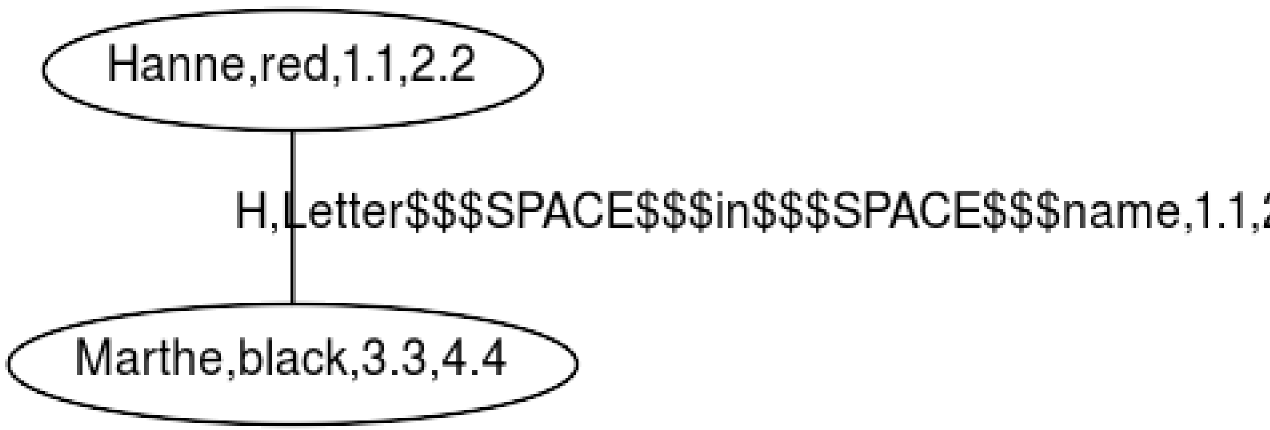


Figure 62: All subgraphs created

### 17.9 Storing a graph with custom edges and vertices as a .dot

If you used the create_custom_edges_and_vertices_k3_graph function (algorithm 299) 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 318:

**Algorithm 318** 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"
#include "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 auto& m = get_my_custom_vertex(d, g);
      out << "[label=\"" << m << "\"]";
    },
    [g](std::ostream& out, const ed& d) {
      const auto& m = get_my_custom_edge(d, g);
      out << "[label=\"" << m << "\"]";
    }
  );
}
```

## 17.10 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 319:

**Algorithm 319** 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
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  auto g =
    create_empty_directed_custom_edges_and_vertices_graph
    ();
  boost::dynamic_properties dp(boost::
    ignore_other_properties);
  dp.property("label", get(boost::vertex_custom_type, g))
    ;
  dp.property("edge_id", get(boost::edge_custom_type, g))
    ;
  dp.property("label", get(boost::edge_custom_type, g));
  boost::read_graphviz(f,g,dp);
  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 320 shows how to use the 'load_directed_custom_edges_and_vertices_graph_from_dot' function:

**Algorithm 320** Demonstration of the 'load_directed_custom_edges_and_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_directed_custom_edges_and_vertices_graph_from_dot
    )
{
  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
    );
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 296), saved and then loaded.

## 17.11 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 321:

**Algorithm 321** 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"

template <class graph = decltype(
    create_empty_undirected_custom_edges_and_vertices_graph
    ())>
graph
    load_undirected_custom_edges_and_vertices_graph_from_dot
    (
  const std::string& dot_filename
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  graph g;
  boost::dynamic_properties dp(boost::
      ignore_other_properties);
  dp.property("label", get(boost::vertex_custom_type, g))
      ;
  dp.property("edge_id", get(boost::edge_custom_type, g))
      ;
  dp.property("label", get(boost::edge_custom_type, g));
  boost::read_graphviz(f,g,dp);
  return g;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 17.10 describes the rationale of this function.

Algorithm 322 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

**Algorithm 322** Demonstration of the 'load_undirected_custom_edges_and_vertices_graph_from_dot' function

```
#include <boost/test/unit_test.hpp>
#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"

BOOST_AUTO_TEST_CASE(
    test_load_undirected_custom_edges_and_vertices_graph_from_dot
    )
{
  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);
  BOOST_CHECK(num_edges(g) == num_edges(h));
  BOOST_CHECK(num_vertices(g) == num_vertices(h));
  BOOST_CHECK(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 230), saved and then loaded. The loaded graph is checked to be a graph similar to the original.

# 18 Building graphs with custom and selectable edges and vertices

Now also the edge can be selected

- An empty directed graph that allows for custom and selectable vertices:

see chapter 18.2

- An empty undirected graph that allows for custom and selectable vertices: see chapter 18.3
- A two-state Markov chain with custom and selectable vertices: see chapter 18.5
- $K_3$with custom and selectable vertices: see chapter 18.6

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

- Installing the new edge property: see chapter 18.1
- Adding a custom and selectable vertex: see chapter 18.4

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

## 18.1 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 323** Installing the edge_is_selected property

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

namespace boost {
  enum edge_is_selected_t { edge_is_selected = 314159 };
  BOOST_INSTALL_PROPERTY(edge, is_selected);
}
```

The enum value 31415 must be unique.

## 18.2 Create an empty directed graph with custom and selectable edges and vertices

**Algorithm 324** Creating an empty directed graph with custom and selectable edges and vertices

```
#include <boost/graph/adjacency_list.hpp>
#include "install_edge_custom_type.h"
#include "install_edge_is_selected.h"
#include "install_vertex_custom_type.h"
#include "install_vertex_is_selected.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::vertex_is_selected_t, bool
    >
  >,
  boost::property<
    boost::edge_custom_type_t, my_custom_edge,
    boost::property<
      boost::edge_is_selected_t, bool
    >
  >
>
create_empty_directed_custom_and_selectable_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_custom_edge,
  boost::property<boost::edge_is_selected_t, bool,
>
```

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

Demo:

**Algorithm 325** Demonstration of the 'create_empty_directed_custom_and_selectable_edges_and_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_empty_directed_custom_and_selectable_edges_and_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_directed_custom_and_selectable_edges_and_vertices_graph
    )
{
  const auto g
    =
      create_empty_directed_custom_and_selectable_edges_and_vertices_graph
      ();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(boost::num_vertices(g) == 0);
}
```

## 18.3 Create an empty undirected graph with custom and selectable edges and vertices

**Algorithm 326** Creating an empty undirected graph with custom and selectable edges and vertices

```
#include <boost/graph/adjacency_list.hpp>
#include "install_edge_custom_type.h"
#include "install_edge_is_selected.h"
#include "install_vertex_custom_type.h"
#include "install_vertex_is_selected.h"
#include "my_custom_edge.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
    >
  >,
  boost::property<
    boost::edge_custom_type_t, my_custom_edge,
    boost::property<
      boost::edge_is_selected_t, bool
    >
  >
>
create_empty_undirected_custom_and_selectable_edges_and_vertices_graph
   () noexcept
{
  return {};
}
```

This code is very similar to the code described in chapter 18.2, except that the directedness (the third template argument) is undirected (due to the boost::undirectedS).

Demo:

**Algorithm 327** Demonstration of the 'create_empty_undirected_custom_and_selectable_edges_and_vertices_graph' function

```
#include <boost/test/unit_test.hpp>
#include "
    create_empty_undirected_custom_and_selectable_edges_and_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_undirected_custom_and_selectable_edges_and_vertices_graph
    )
{
  const auto g
    =
        create_empty_undirected_custom_and_selectable_edges_and_vertices_graph
        ();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(boost::num_vertices(g) == 0);
}
```

## 18.4 Add a custom and selectable edge

Adding a custom and selectable edge is very similar to adding a custom and selectable vertex (chapter 14.4).

**Algorithm 328** Add a custom and selectable edge

```
#include <type_traits>
#include <boost/graph/adjacency_list.hpp>
#include "install_edge_custom_type.h"
#include "install_edge_is_selected.h"
#include "install_edge_custom_type.h"
#include "add_custom_and_selectable_edge_between_vertices
    .h"

template <typename graph, typename custom_edge>
typename boost::graph_traits<graph>::edge_descriptor
add_custom_and_selectable_edge(
  const custom_edge& edge,
  const bool is_selected,
  graph& g
)
{
  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);
  return add_custom_and_selectable_edge_between_vertices(
    edge, is_selected, vd_a, vd_b, g
  );
}
```

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

Here is the demo:

**Algorithm 329** Demo of 'add_custom_and_selectable_vertex'

```
#include <boost/test/unit_test.hpp>
#include "add_custom_and_selectable_edge.h"
#include "
    create_empty_directed_custom_and_selectable_edges_and_vertices_graph
    .h"
#include "
    create_empty_undirected_custom_and_selectable_edges_and_vertices_graph
    .h"

BOOST_AUTO_TEST_CASE(test_add_custom_and_selectable_edge)
{
  auto g =
     create_empty_directed_custom_and_selectable_edges_and_vertices_graph
     ();
  BOOST_CHECK(boost::num_vertices(g) == 0);
  BOOST_CHECK(boost::num_edges(g) == 0);
  add_custom_and_selectable_edge(
    my_custom_edge("X"),
    true,
    g
  );
  BOOST_CHECK(boost::num_edges(g) == 1);
}
```

## 18.5 Creating a Markov-chain with custom and selectable vertices

### 18.5.1 Graph

Figure 63 shows the graph that will be reproduced:

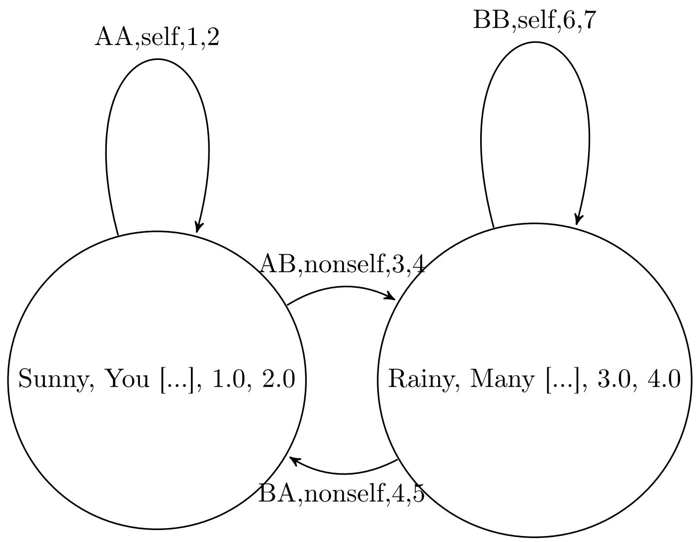


Figure 63: A two-state Markov chain where the edges and vertices have custom properies. The edges' and vertices' properties are nonsensical

#### 18.5.2 Function to create such a graph

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

**Algorithm 330** Creating the two-state Markov chain as depicted in figure 63

```
#include <cassert>
#include "
    create_empty_directed_custom_and_selectable_edges_and_vertices_graph
    .h"
#include "add_custom_and_selectable_edge_between_vertices
    .h"
#include "add_custom_and_selectable_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
    >
  >,
  boost::property<
    boost::edge_custom_type_t, my_custom_edge,
    boost::property<
      boost::edge_is_selected_t, bool
    >
  >
>
create_custom_and_selectable_edges_and_vertices_markov_chain
    ()
{
  auto g
    =
        create_empty_directed_custom_and_selectable_edges_and_vertices_graph
        ();
  const auto vd_a = add_custom_and_selectable_vertex(
    my_custom_vertex("Sunny","Yellow␣thing",1.0,2.0),
    true,
    g
  );
  const auto vd_b = add_custom_and_selectable_vertex(
    my_custom_vertex("Rainy", "Grey␣things",3.0,4.0),
    false,
    g
  );
  add_custom_and_selectable_edge_between_vertices(
    my_custom_edge("A␣to␣A"),
    true,
    vd_a, vd_a,
    g
  );
  add_custom_and_selectable_edge_between_vertices(
    my_custom_edge("A␣to␣B"),
    false,
    vd_a, vd_b,
    g
  );
```

### 18.5.3 Creating such a graph

Here is the demo:

**Algorithm 331** Demo of the 'create_custom_and_selectable_edges_and_vertices_markov_chain' function (algorithm 330)

```
#include <boost/test/unit_test.hpp>
#include "
    create_custom_and_selectable_edges_and_vertices_markov_chain
    .h"
#include "get_vertex_selectednesses.h"

BOOST_AUTO_TEST_CASE(
    test_create_custom_and_selectable_edges_and_vertices_markov_chain
    )
{
  const auto g
    =
        create_custom_and_selectable_edges_and_vertices_markov_chain
        ();
  const std::vector<bool>
    expected_selectednesses{
    true, false
  };
  const std::vector<bool>
    vertex_selectednesses{
    get_vertex_selectednesses(g)
  };
  BOOST_CHECK(expected_selectednesses
    == vertex_selectednesses
  );
}
```

### 18.5.4 The .dot file produced

**Algorithm 332** .dot file created from the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 330), converted from graph to .dot file using algorithm 55

```
digraph G {
0[label="Sunny,Yellow$$$SPACE$$$thing,1,2", regular="1"];
1[label="Rainy,Grey$$$SPACE$$$things,3,4", regular="0"];
0->0 [label="A$$$SPACE$$$to$$$SPACE$$$A,,1,1", regular="1"];
0->1 [label="A$$$SPACE$$$to$$$SPACE$$$B,,1,1", regular="0"];
1->0 [label="B$$$SPACE$$$to$$$SPACE$$$A,,1,1", regular="0"];
1->1 [label="B$$$SPACE$$$to$$$SPACE$$$B,,1,1", regular="1"];
}
```

### 18.5.5 The .svg file produced

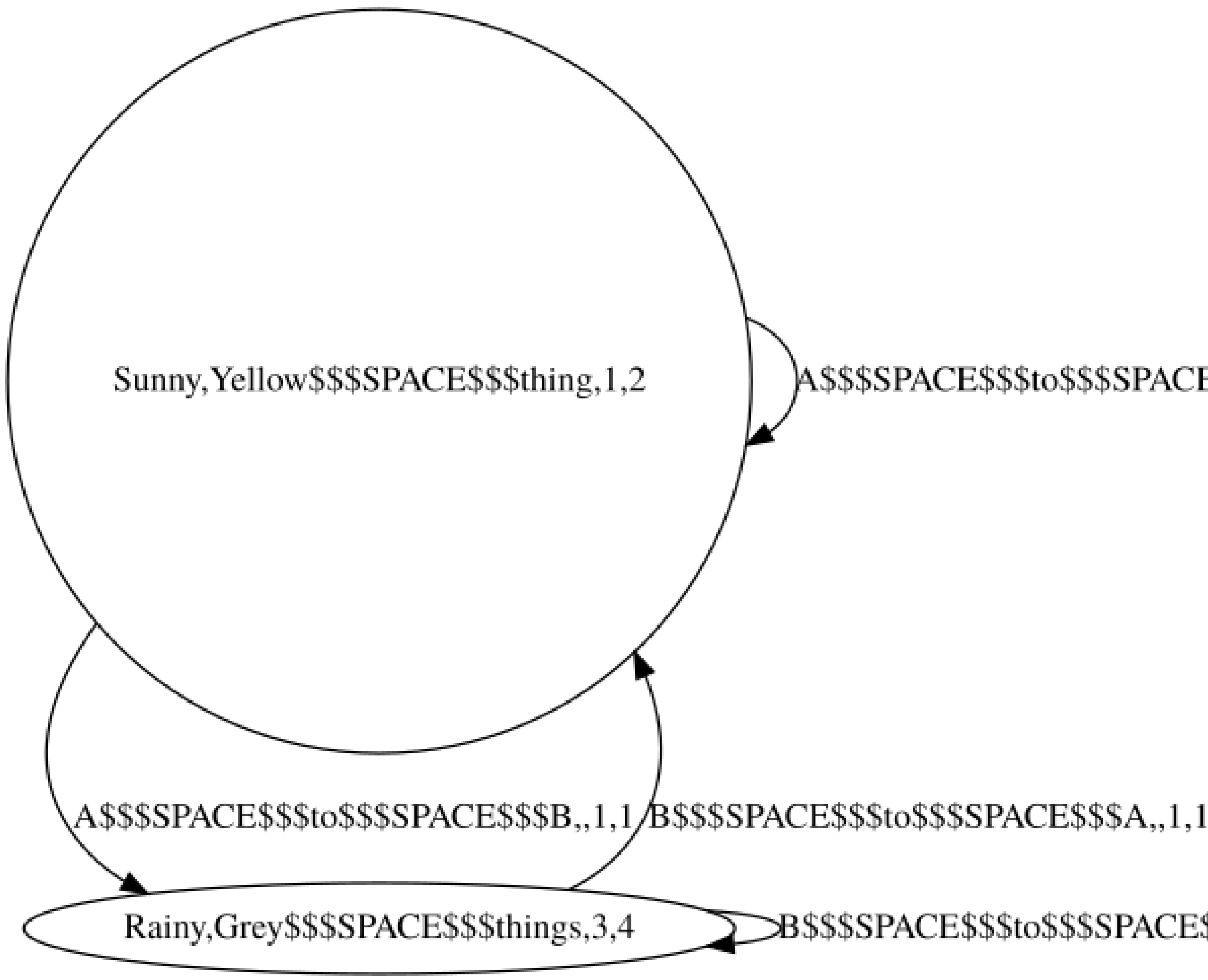


Figure 64: .svg file created from the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 227) its .dot file, converted from .dot file to .svg using algorithm 366

Note how the .svg changed it appearance due to the Graphviz 'regular' property (see chapter 25.2): 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.

## 18.6 Creating $K_2$ with custom and selectable edges and vertices

### 18.6.1 Graph

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

[graph here]

### 18.6.2 Function to create such a graph

**Algorithm 333** Creating $K_3$ as depicted in figure 34

```
#include "
    create_empty_undirected_custom_and_selectable_edges_and_vertices_graph
    .h"
#include "add_custom_and_selectable_vertex.h"
#include "add_custom_and_selectable_edge_between_vertices
    .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
    >
  >,
  boost::property<
    boost::edge_custom_type_t, my_custom_edge,
    boost::property<
      boost::edge_is_selected_t, bool
    >
  >
>
create_custom_and_selectable_edges_and_vertices_k2_graph
    ()
{
  auto g
    =
        create_empty_undirected_custom_and_selectable_edges_and_vertices_graph
        ();
  const my_custom_vertex va("A","source",0.0,0.0);
  const my_custom_vertex vb("B","target",3.14,3.14);
  const my_custom_edge ea("between");
  const auto vd_a = add_custom_and_selectable_vertex(va,
      true, g);
  const auto vd_b = add_custom_and_selectable_vertex(vb,
      false, g);
  add_custom_and_selectable_edge_between_vertices(ea,
      false, vd_a, vd_b, g);
  return g;
}
```

Most of the code is a slight modification of algorithm 230. 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.

### 18.6.3 Creating such a graph

Here is the demo:

**Algorithm 334** Demo of the 'create_custom_and_selectable_edges_and_vertices_k2_graph' function (algorithm 333)

```
#include <boost/test/unit_test.hpp>
#include "
    create_custom_and_selectable_edges_and_vertices_k2_graph
    .h"
#include "has_custom_vertex_with_my_vertex.h"

BOOST_AUTO_TEST_CASE(
    test_create_custom_and_selectable_edges_and_vertices_k2_graph
    )
{
  const auto g =
      create_custom_and_selectable_edges_and_vertices_k2_graph
      ();
  BOOST_CHECK(boost::num_edges(g) == 1);
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(has_custom_vertex_with_my_vertex(
    my_custom_vertex("A", "source" ,0.0, 0.0), g)
  );
  BOOST_CHECK(has_custom_vertex_with_my_vertex(
    my_custom_vertex("B", "target" ,3.14, 3.14), g)
  );
}
```

### 18.6.4 The .dot file produced

**Algorithm 335** .dot file created from the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 333), converted from graph to .dot file using algorithm 55

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

### 18.6.5 The .svg file produced

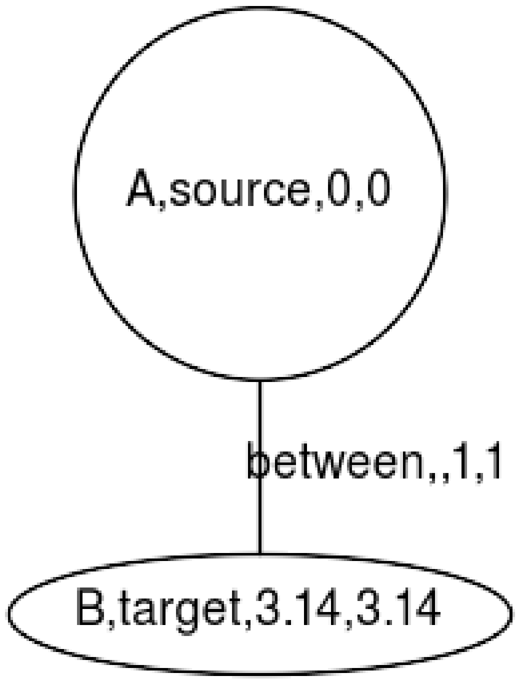


Figure 65: .svg file created from the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 227) its .dot file, converted from .dot file to .svg using algorithm 366

Note how the .svg changed it appearance due to the Graphviz 'regular' property (see chapter 25.2): 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.

# 19 Working on graphs with custom and selectable edges and vertices

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

- Storing an directed/undirected graph with custom and selectable edges and vertices as a .dot file: chapter 19.3
- Loading a directed graph with custom and selectable edges and vertices from a .dot file: chapter 19.4

- Loading an undirected directed graph with custom and selectable edges amd vertices from a .dot file: chapter 19.5

## 19.1 ▶ Create a direct-neighbour subgraph from a vertex descriptor of a graph with custom and selectable edges and vertices

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 code that does exactly that:

**Algorithm 336** Get the direct-neighbour custom edges and vertices subgraph from a vertex descriptor

```
#include <map>
#include <boost/graph/adjacency_list.hpp>
#include "add_custom_and_selectable_edge_between_vertices
    .h"
#include "add_custom_and_selectable_vertex.h"
#include "get_edge_selectedness.h"
#include "get_my_custom_edge.h"
#include "get_my_custom_vertex.h"
#include "get_vertex_selectedness.h"
template <typename graph, typename vertex_descriptor>
graph
    create_direct_neighbour_custom_and_selectable_edges_and_vertices_subgraph
    (
  const vertex_descriptor& vd,
  const graph& g
)
{
  graph h;

  std::map<vertex_descriptor,vertex_descriptor> m;
  {
    const auto vd_h = add_custom_and_selectable_vertex(
      get_my_custom_vertex(vd, g),
      get_vertex_selectedness(vd, g),
      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)),
      [g, &h](const vertex_descriptor& d)
      {
        const auto vd_h =
            add_custom_and_selectable_vertex(
          get_my_custom_vertex(d,g),
          get_vertex_selectedness(d, g),
          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);
```

This demonstration code shows that the direct-neighbour graph of each vertex of a $K_2$ graphs is ... a $K_2$ graph!

**Algorithm 337** Demo of the 'create_direct_custom_and_selectable_edges_and_vertices_neighbour_subgr function

```
#include <boost/test/unit_test.hpp>
#include "
    create_direct_neighbour_custom_and_selectable_edges_and_vertices_subgraph
    .h"
#include "
    create_custom_and_selectable_edges_and_vertices_k2_graph
    .h"
#include "get_my_custom_vertexes.h"

BOOST_AUTO_TEST_CASE(
    test_create_direct_neighbour_custom_and_selectable_edges_and_vertices_subgrap
    )
{
  const auto g =
      create_custom_and_selectable_edges_and_vertices_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_custom_and_selectable_edges_and_vertices_subgraph
        (
      *i,g
    );
    BOOST_CHECK(boost::num_vertices(h) == 2);
    BOOST_CHECK(boost::num_edges(h) == 1);
    const auto v = get_my_custom_vertexes(h);
    std::set<my_custom_vertex> vertexes(std::begin(v),std
        ::end(v));
    const my_custom_vertex a("A","source",0.0,0.0);
    const my_custom_vertex b("B","target",3.14,3.14);
    BOOST_CHECK(vertexes.count(a) == 1);
    BOOST_CHECK(vertexes.count(b) == 1);
  }
}
```

## 19.2 ▶ Creating all direct-neighbour subgraphs from a graph with custom and selectable edges and vertices

Using the previous function, it is easy to create all direct-neighbour subgraphs from a graph with custom vertices:

**Algorithm 338** Create all direct-neighbour subgraphs from a graph with custom and selectable edges and vertices

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

template <typename graph>
std::vector<graph>
    create_all_direct_neighbour_custom_and_selectable_edges_and_vertices_subgraph
    (
  const graph& g
)
{
  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_custom_and_selectable_edges_and_vertices_subgra
          (
        d, g
      );
    }
  );
  return v;
}
```

This demonstration code shows how to extract the subgraphs from a path graph:

**Algorithm 339** Demo of the 'create_all_direct_neighbour_custom_and_selecteable_edges_and_vertices_s function

```
#include <boost/test/unit_test.hpp>
#include "
    create_all_direct_neighbour_custom_and_selectable_edges_and_vertices_subgraph
    .h"
#include "
    create_custom_and_selectable_edges_and_vertices_k2_graph
    .h"

BOOST_AUTO_TEST_CASE(
    demo_create_all_direct_neighbour_custom_and_selectable_edges_and_vertices_sub
    )
{
  const auto v
    =
        create_all_direct_neighbour_custom_and_selectable_edges_and_vertices_subg
        (
         create_custom_and_selectable_edges_and_vertices_k2_graph
             ()
      );
  BOOST_CHECK(v.size() == 2);
  for (const auto g: v)
  {
    BOOST_CHECK(boost::num_vertices(g) == 2);
    BOOST_CHECK(boost::num_edges(g) == 1);
  }
}
```

The sub-graphs are shown here:

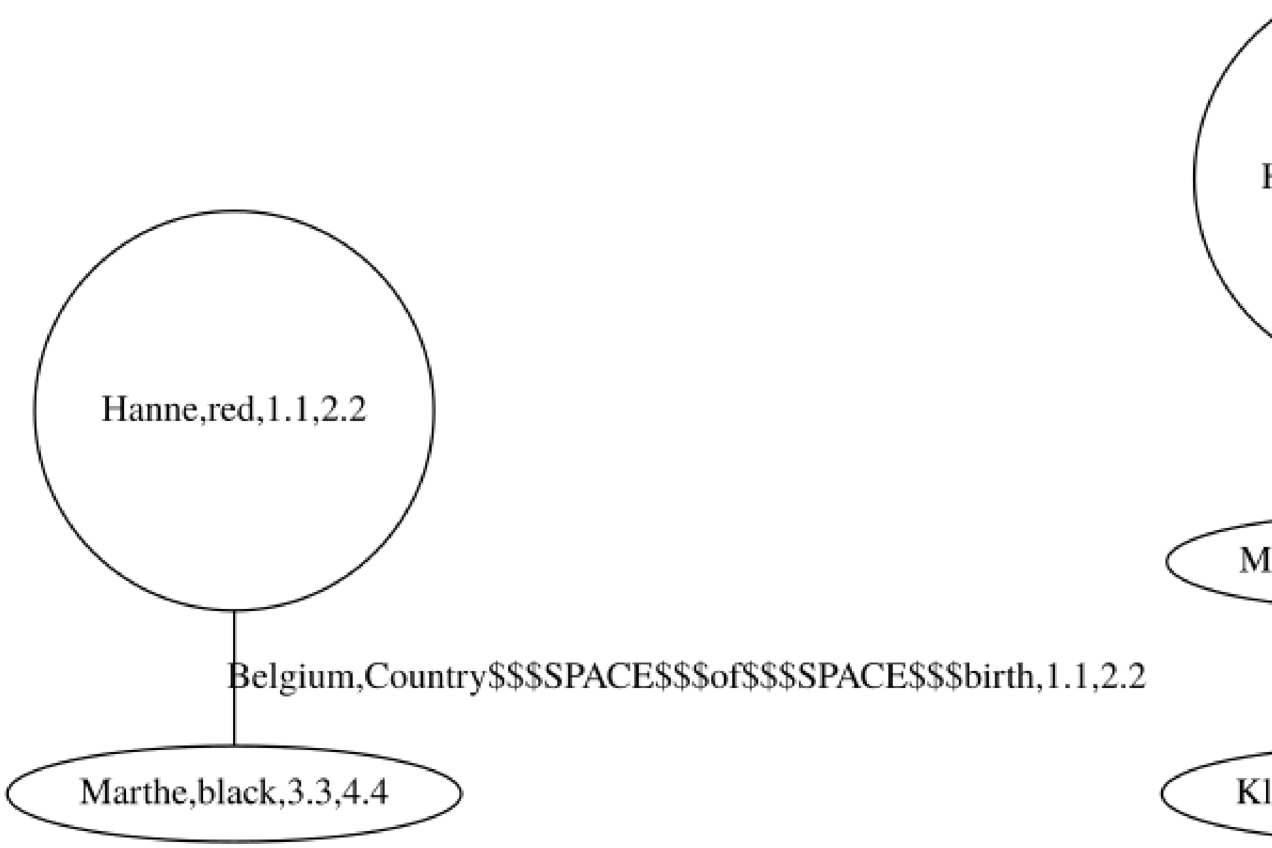


Figure 66: All subgraphs created

### 19.3 Storing a graph with custom and selectable edges and vertices as a .dot

If you used the 'create_custom_and_selectable_edges_and_vertices_k2_graph' function (algorithm 333) to produce a $K_2$ graph with edges and vertices associated with (1) my_custom_edge/my_custom_vertex objects, and (2) a boolean indicating its selectedness, you can store such graphs with algorithm 340:

**Algorithm 340** Storing a graph with custom and selectable edges and vertices as a .dot file

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

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

We re-use the writer.

Special about this, is that even for Graphviz-unfriendly input, it still works.

## 19.4 Loading a directed graph with custom and selectable 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 custom and selectable edges and vertices is loaded, as shown in algorithm 341:

**Algorithm 341** Loading a directed graph with custom and selectable edges and vertices from a .dot file

```
#include <fstream>
#include <sstream>
#include <stdexcept>
#include <boost/graph/graphviz.hpp>
#include "
    create_empty_directed_custom_and_selectable_edges_and_vertices_graph
    .h"
#include "install_edge_custom_type.h"
#include "install_edge_is_selected.h"
#include "install_vertex_custom_type.h"
#include "install_vertex_is_selected.h"
#include "is_regular_file.h"

template <class graph = decltype(
    create_empty_directed_custom_and_selectable_edges_and_vertices_graph
    ())>
graph
    load_directed_custom_and_selectable_edges_and_vertices_graph_from_dot
    (
  const std::string& dot_filename
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": filename '"
      << dot_filename << "' is not the name"
      << " of a regular file"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  graph g;
  boost::dynamic_properties dp(
    boost::ignore_other_properties
  );
  dp.property("label", get(boost::vertex_custom_type, g))
      ;
  dp.property("regular", get(boost::vertex_is_selected, g
      ));
  dp.property("label", get(boost::edge_custom_type, g));
  dp.property("regular", get(boost::edge_is_selected, g))
      ;
  boost::read_graphviz(f,g,dp);
  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 25.2 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 342 shows how to use the 'load_directed_custom_vertices_graph_from_dot' function:

**Algorithm 342** Demonstration of the 'load_directed_custom_and_selectable_edges_and_vertices_graph_ function

```
#include <boost/test/unit_test.hpp>
#include "
    create_custom_and_selectable_edges_and_vertices_markov_chain
    .h"
#include "is_regular_file.h"
#include "
    save_custom_and_selectable_edges_and_vertices_graph_to_dot
    .h"

BOOST_AUTO_TEST_CASE(
    test_load_directed_custom_and_selectable_edges_and_vertices_graph_from_dot
    )
{
  const auto g
    =
        create_custom_and_selectable_edges_and_vertices_markov_chain
        ();
  const std::string filename{
    "
        create_custom_and_selectable_edges_and_vertices_markov_chain
        .dot"
  };
  save_custom_and_selectable_edges_and_vertices_graph_to_dot
      (
    g,
    filename
  );
  BOOST_CHECK(is_regular_file(filename));
}
```

This demonstration shows how the Markov chain is created using the 'create_custom_vertices_markov_chain' function (algorithm 227), saved and then checked to exist.

## 19.5 Loading an undirected graph with custom and selectable 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 custom and selectable vertices is loaded, as shown in algorithm 343:

**Algorithm 343** 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_edges_and_vertices_graph
    .h"
#include "is_regular_file.h"

template <class graph = decltype(
    create_empty_undirected_custom_and_selectable_edges_and_vertices_graph
    ())>
graph
    load_undirected_custom_and_selectable_edges_and_vertices_graph_from_dot
    (
  const std::string& dot_filename
)
{
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::ifstream f(dot_filename.c_str());
  graph g;
  boost::dynamic_properties dp(
    boost::ignore_other_properties
  );
  dp.property("label", get(boost::vertex_custom_type, g))
     ;
  dp.property("regular", get(boost::vertex_is_selected, g
     ));
  dp.property("label", get(boost::edge_custom_type, g));
  dp.property("regular", get(boost::edge_is_selected, g))
     ;
  boost::read_graphviz(f,g,dp);
  return g;
}

/*
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
    >
  >,
  boost::property<
    boost::edge_custom_type_t, my_custom_edge,
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 19.4 describes the rationale of this function.

Algorithm 344 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

**Algorithm 344** Demonstration of the 'load_undirected_custom_and_selectable_edges_and_vertices_graph function

```
#include <boost/test/unit_test.hpp>
#include "
    create_custom_and_selectable_edges_and_vertices_k2_graph
    .h"
#include "is_regular_file.h"
#include "
    save_custom_and_selectable_edges_and_vertices_graph_to_dot
    .h"

BOOST_AUTO_TEST_CASE(
    test_load_undirected_custom_and_selectable_edges_and_vertices_graph_from_dot
    )
{
  const auto g
    =
        create_custom_and_selectable_edges_and_vertices_k2_graph
        ();
  const std::string filename{
    "
        create_custom_and_selectable_edges_and_vertices_k2_graph
        .dot"
  };
  save_custom_and_selectable_edges_and_vertices_graph_to_dot
      (
    g,
    filename
  );
  BOOST_CHECK(is_regular_file(filename));
}
```

This demonstration shows how $K_2$ with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 230), saved and then checked to exist.

# 20 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

## 20.1 Create an empty directed graph with a graph name property

Algorithm 345 shows the function to create an empty directed graph with a graph name.

**Algorithm 345** 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 346 demonstrates the ‘create_empty_directed_graph_with_graph_name’ function.

**Algorithm 346** Demonstration of ‘create_empty_directed_graph_with_graph_name’

```
#include <boost/test/unit_test.hpp>
#include "create_empty_directed_graph_with_graph_name.h"

BOOST_AUTO_TEST_CASE(
    test_create_empty_directed_graph_with_graph_name)
{
  auto g
    = create_empty_directed_graph_with_graph_name();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(boost::num_vertices(g) == 0);
}
```

## 20.2 Create an empty undirected graph with a graph name property

Algorithm 347 shows the function to create an empty undirected graph with a graph name.

**Algorithm 347** 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 345, except that the directedness (the third template argument) is undirected (due to the boost::undirectedS).

Algorithm 348 demonstrates the 'create_empty_undirected_graph_with_graph_name' function.

**Algorithm 348** Demonstration of 'create_empty_undirected_graph_with_graph_name'

```
#include <boost/test/unit_test.hpp>
#include "create_empty_undirected_graph_with_graph_name.h
    "

BOOST_AUTO_TEST_CASE(
    test_create_empty_undirected_graph_with_graph_name)
{
  auto g = create_empty_undirected_graph_with_graph_name
      ();
  BOOST_CHECK(boost::num_edges(g) == 0);
  BOOST_CHECK(boost::num_vertices(g) == 0);
}
```

## 20.3 Get a graph its name property

**Algorithm 349** 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 350 demonstrates the 'get_graph_name' function.

**Algorithm 350** Demonstration of 'get_graph_name'

```
#include <boost/test/unit_test.hpp>
#include "create_empty_directed_graph_with_graph_name.h"
#include "get_graph_name.h"
#include "set_graph_name.h"

BOOST_AUTO_TEST_CASE(test_get_graph_name)
{
  auto g = create_empty_directed_graph_with_graph_name();
  const std::string name{"Dex"};
  set_graph_name(name, g);
  BOOST_CHECK(get_graph_name(g) == name);
}
```

## 20.4 Set a graph its name property

**Algorithm 351** 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 352 demonstrates the 'set_graph_name' function.

**Algorithm 352** Demonstration of 'set_graph_name'

```
#include <boost/test/unit_test.hpp>
#include "create_empty_directed_graph_with_graph_name.h"
#include "get_graph_name.h"
#include "set_graph_name.h"

BOOST_AUTO_TEST_CASE(test_set_graph_name)
{
  auto g = create_empty_directed_graph_with_graph_name();
  const std::string name{"Dex"};
  set_graph_name(name, g);
  BOOST_CHECK(get_graph_name(g) == name);
}
```

## 20.5 Create a directed graph with a graph name property

### 20.5.1 Graph

See figure 6.

### 20.5.2 Function to create such a graph

Algorithm 353 shows the function to create an empty directed graph with a graph name.

**Algorithm 353** 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);
  boost::add_edge(vd_a, vd_a, g);
  boost::add_edge(vd_a, vd_b, g);
  boost::add_edge(vd_b, vd_a, g);
  boost::add_edge(vd_b, vd_b, g);

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

### 20.5.3 Creating such a graph

Algorithm 354 demonstrates the 'create_markov_chain_with_graph_name' function.

**Algorithm 354** Demonstration of 'create_markov_chain_with_graph_name'

```
#include <boost/test/unit_test.hpp>
#include "create_markov_chain_with_graph_name.h"
#include "get_graph_name.h"

BOOST_AUTO_TEST_CASE(
    test_create_markov_chain_with_graph_name)
{
  const auto g = create_markov_chain_with_graph_name();
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(boost::num_edges(g) == 4);
  BOOST_CHECK(get_graph_name(g) == "Two-state Markov 
      chain");
}
```

### 20.5.4 The .dot file produced

**Algorithm 355** .dot file created from the 'create_markov_chain_with_graph_name' function (algorithm 353), converted from graph to .dot file using algorithm 55

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

#### 20.5.5 The .svg file produced

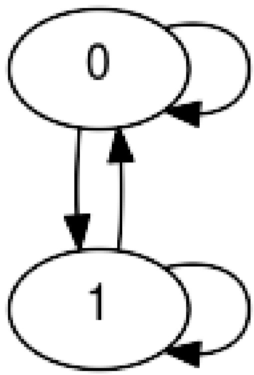


Figure 67: .svg file created from the 'create_markov_chain_with_graph_name' function (algorithm 353) its .dot file, converted from .dot file to .svg using algorithm 366

### 20.6 Create an undirected graph with a graph name property

#### 20.6.1 Graph

See figure 8.

#### 20.6.2 Function to create such a graph

Algorithm 356 shows the function to create K2 graph with a graph name.

**Algorithm 356** 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);
  boost::add_edge(vd_a, vd_b, g);
  get_property(g,boost::graph_name) = "K2";

  return g;
}
```

### 20.6.3 Creating such a graph

Algorithm 357 demonstrates the 'create_k2_graph_with_graph_name' function.

**Algorithm 357** Demonstration of 'create_k2_graph_with_graph_name'

```
#include <boost/test/unit_test.hpp>
#include "create_k2_graph_with_graph_name.h"
#include "get_graph_name.h"

BOOST_AUTO_TEST_CASE(test_create_k2_graph_with_graph_name
    )
{
  const auto g = create_k2_graph_with_graph_name();
  BOOST_CHECK(boost::num_vertices(g) == 2);
  BOOST_CHECK(boost::num_edges(g) == 1);
  BOOST_CHECK(get_graph_name(g) == "K2");
}
```

### 20.6.4 The .dot file produced

**Algorithm 358** .dot file created from the 'create_k2_graph_with_graph_name' function (algorithm 356), converted from graph to .dot file using algorithm 55

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

### 20.6.5 The .svg file produced

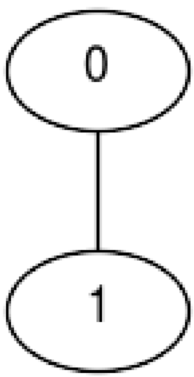


Figure 68: .svg file created from the 'create_k2_graph_with_graph_name' function (algorithm 356) its .dot file, converted from .dot file to .svg using algorithm 366

# 21 Working on graphs with a graph name

## 21.1 Storing a graph with a graph name property as a .dot file

This works:

**Algorithm 359** 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";
    }
  );
}
```

## 21.2 Loading a directed graph with a graph name property from a .dot file

This will result in a directed graph with a name:

**Algorithm 360** Loading a directed graph with a graph name from a .dot file

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

  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }

  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;
}
```

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

This will result in an undirected graph with a name:

**Algorithm 361** 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
    >
  >;
  if (!is_regular_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '"
      << dot_filename << "' not found"
    ;
    throw std::invalid_argument(msg.str());
  }
  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;
}
```

# 22 Other graph functions

Some functions that did not fit in.

## 22.1 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 362** 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;
}
```

## 22.2 Decode a std::string from a Graphviz-friendly format

This function undoes the 'graphviz_encode' function (algorithm 362) and thus converts a Graphviz-friendly std::string to the original human-friendly std::string.

**Algorithm 363** 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;
}
```

## 22.3 Check if a std::string is Graphviz-friendly

There are pieces where I check if a std::string is Graphviz-friendly. This is done only where it matters. If it is tested not to matter, 'is_graphviz_friendly' is absent.

**Algorithm 364** Check if a std::string is Graphviz-friendly

```
#include "graphviz_encode.h"

bool is_graphviz_friendly(const std::string& s) noexcept
{
  return graphviz_encode(s) == s;
}
```

# 23 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.

## 23.1 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 365** 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;
}
```

## 23.2 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 366** Convert a .dot file to a .svg

```
#include <cassert>
#include <string>
#include <iostream>
#include <sstream>
#include <stdexcept>
#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
)
{
  if (!has_dot())
  {
    std::stringstream msg;
    msg << __func__ << ": 'dot' cannot be found. "
      << "type 'sudo apt-get install graphviz' in the 
          command line"
    ;
    throw std::runtime_error(msg.str());
  }
  if (!is_valid_dot_file(dot_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": file '" << dot_filename
      << "' is not a valid DOT language"
    ;
    throw std::invalid_argument(msg.str());
  }
  std::stringstream cmd;
  cmd << "dot -Tsvg " << dot_filename << " -o " <<
     svg_filename;
  const int error {
    std::system(cmd.str().c_str())
  };
  if (error)
  {
    std::cerr << __func__ << ": warning: command '"
      << cmd.str() << "' resulting in error "
      << error;
  }
  if (!is_regular_file(svg_filename))
  {
    std::stringstream msg;
    msg << __func__ << ": failed to create SVG output 
        file '"
      << svg_filename << "'"
    ;
    throw std::runtime_error(msg.str());
  }
}
```

‘convert_dot_to_svg’ makes a system call to the prgram ‘dot’ to convert the .dot file to an .svg file.

### 23.3 Check if a file exists

Not the most smart way perhaps, but it does only use the STL.

**Algorithm 367** 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();
}
```

## 24 Errors

Some common errors.

### 24.1 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 368:

**Algorithm 368** 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 368 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.

## 24.2 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 369** 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 369 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.

## 24.3 No matching function for call to ‘clear_in_edges’

See chapter 24.2.

## 24.4 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
```

## 24.5 Property not found: node_id

When loading a graph from file (as in chapter 3.13) 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 370 shows how to trigger this run-time error.

**Algorithm 370** 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 dp(boost::
     ignore_other_properties);
  boost::dynamic_properties dp; //Error

  try {
    boost::read_graphviz(f,g,dp);
  }
  catch (std::exception&) {
    return; //Should get here
  }
  assert(!"Should␣not␣get␣here");
}
```

## 24.6 Stream zeroes

When loading a graph from a .dot file, in operator>>, I encountered reading zeroes, where I expected an XML formatted string:

```
std::istream& ribi::cmap::operator>>(std::istream& is, my_class& any_class) noex
{
  std::string s;
```

```
  is >> s; //s has an XML format
  assert(s != "0");
  any_class = my_class(s);
  return is;
}
```

This was because I misconfigured the reader. I did (heavily simplified code):

```
graph load_from_dot(const std::string& dot_filename)
{
  std::ifstream f(dot_filename.c_str());
  graph g;
  boost::dynamic_properties dp;
  dp.property("node_id", get(boost::vertex_custom_type, g));
  dp.property("label", get(boost::vertex_custom_type, g));
  boost::read_graphviz(f,g,dp);
  return g;
}
```

Where it should have been:

```
graph load_from_dot(const std::string& dot_filename)
{
  std::ifstream f(dot_filename.c_str());
  graph g;
  boost::dynamic_properties dp(boost::ignore_other_properties);
  dp.property("label", get(boost::vertex_custom_type, g));
  boost::read_graphviz(f,g,dp);
  return g;
}
```

The explanation is that by setting the boost::dynamic_property 'node_id' to 'boost::vertex_custom_type', operator>> will receive the node indices.

An alternative, but less clean solution, is to let operator>> ignore the node indices:

```
std::istream& ribi::cmap::operator>>(std::istream& is, my_class& any_class) noex
{
  std::string s;
  is >> s; //s has an XML format
  if (!is_xml(s)) { //Ignore node index
    any_class_class = my_class();
  }
  else {
    any_class_class = my_class(s);
  }
  return is;
}
```

# 25 Appendix

## 25.1 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 |

## 25.2 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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