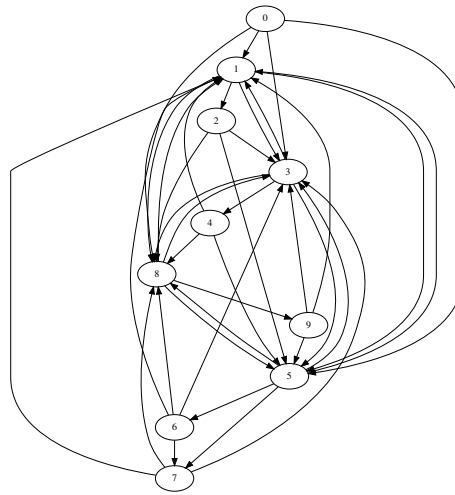


A well-connected C++11 Boost.Graph tutorial

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1 Introduction

This is 'A well-connected C++11 Boost.Graph tutorial', version 1.7.

1.1 Why this tutorial

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

- Orders concepts chronologically
- Increases complexity gradually

- Shows complete pieces of code

What I had were the book [8] and the Boost.Graph website, both did not satisfy these requirements.

This tutorial is intended to take the reader to the level of understanding the book [8] and the Boost.Graph website require. It is about basic graph manipulation, not the more advanced graph algorithms. An analogy with `std::vector`: it teaches the `std::vector` member functions, but not the algorithms that work on.

1.2 Code snippets

For every concept, I will show

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

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

All coding snippets are taken from compiled C++11 code. I chose to use C++11 because (1) C++14 was not installable on all my computers (2) the step to C++14 is small. All code is tested to compile cleanly under GCC at the highest warning level. The code, as well as this tutorial, can be downloaded from the GitHub at www.github.com/richeibilderbeek/BoostGraphTutorial.

1.3 Coding style

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

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

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

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

I prefer to use the keyword `auto` over doubling the lines of code for using statements. Because the `'do'` functions return an explicit data type, these can be used for reference (until `'decltype(auto)'` gets into fashion as a return type). If you really want to know a type, you can use the `'get_type_name'` function (chapter 23.1).

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

1.4 Tutorial style

In the index, I did first put all my long-named functions there literally, but this resulted in a very sloppy layout. Instead, the function `'do_something'` can be found as `'Do something'` in the index. On the other hand, STL and Boost functions like `'std::do_something'` and `'boost::do_something'` can be found as such in the index.

1.5 License

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



Figure 1: Creative Commons license 4.0

1.6 Feedback

This tutorial is not intended to be perfect yet. For that, I need help and feedback from the community. All referenced feedback is welcome, as well as any constructive feedback.

I have tried hard to strictly follow the style as described above. If you find I deviated from these decisions somewhere, I would be grateful if you'd let know. Next to this, there are some sections that need to be coded or have its code improved.

1.7 Help

There are some pieces of code I could use help with:

- Issue #12: Loading a directed graph with a name, function `'load_directed_graph_with_graph_name_fn'` as shown in chapters 19.2. Perhaps the function `'save_graph_with_graph_name_to_dot'` (chapter 19.1) needs to be rewritten as well

I have already put the tests in place, so you/I can easily check if your solution works. If the program crashes with the message 'assertion failed: !"Fixed #"', a problem has been solved.

1.8 Acknowledgements

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

- E. Kawashima

1.9 Outline

The chapters of this tutorial are also like a well-connected graph (as shown in figure 2). To allow for quicker learners to skim chapters, or for beginners looking to find the patterns, some chapters are repetitions of each other (for example, getting an edge its name is very similar to getting a vertex its name)¹. This tutorial is not about being short, but being complete, at the risk of being called bloated.

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

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

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

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

Table 1: Difference between bundled and custom properties

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

¹There was even copy-pasting involved!

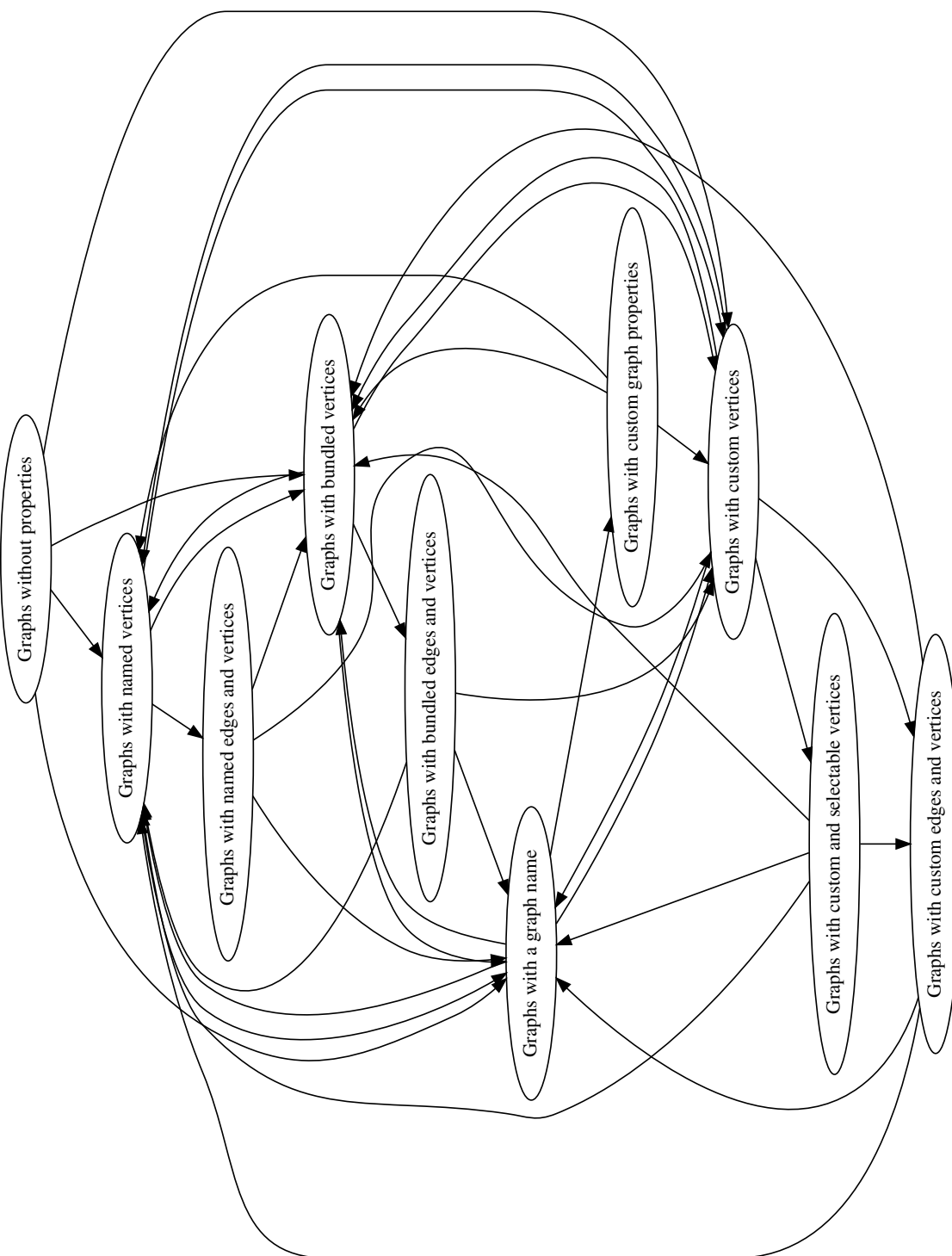


Figure 2: The relations between chapters

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.

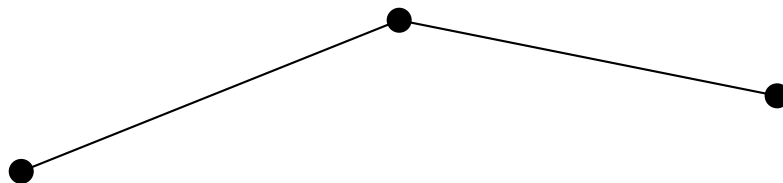


Figure 4: Example of an undirected graph

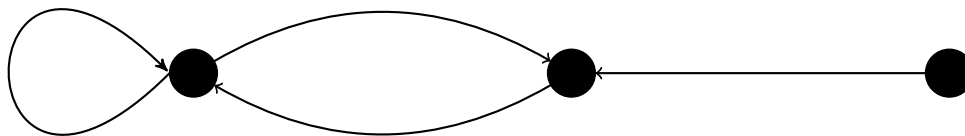


Figure 5: Example of a directed graph

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

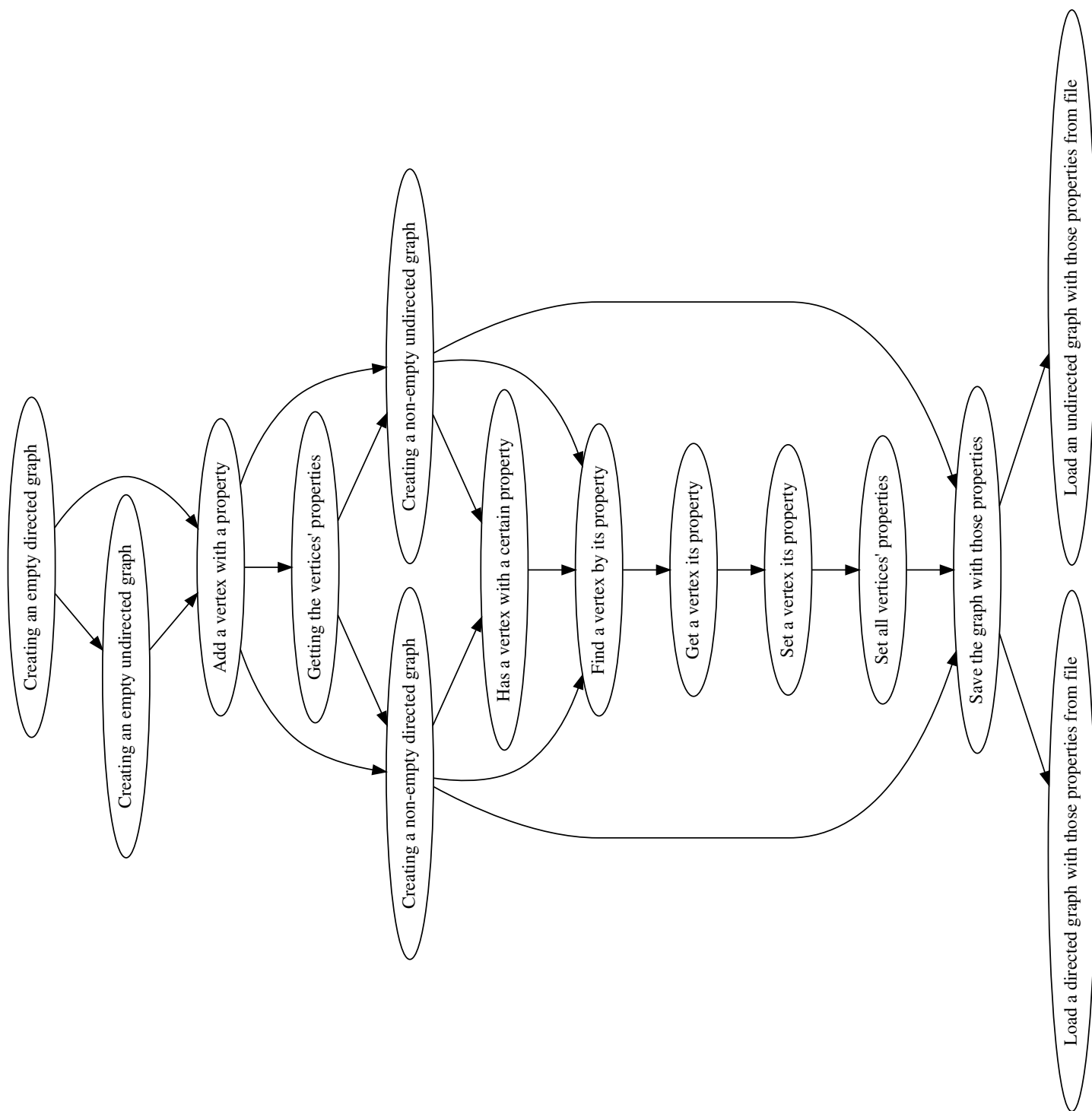


Figure 3: The relations between sub-chapters

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

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

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

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

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

The chapter also introduces some important concepts:

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

After this chapter you may want to:

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

2.1 Creating an empty (directed) graph

Let's create an empty graph!

Algorithm 1 shows the function to create an empty graph.

Algorithm 1 Creating an empty (directed) graph

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

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

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

- a return type: The return type is `'boost::adjacency_list<>'`, that is a `'boost::adjacency_list` with all template arguments set at their defaults
- a `noexcept` specification: the function should not throw³, so it is preferred to mark it `noexcept` ([10] chapter 13.7).
- a function body: all the function body does is create a `'boost::adjacency_list<>'` by calling its constructor, by using the round brackets

Algorithm 2 demonstrates the `'create_empty_directed_graph'` function. Note that it includes a header file with the same name as the function⁴ first, to be able to use it. `'auto'` is used, as this is preferred over explicit type declarations ([10] chapter 31.6). The keyword `'auto'` lets the compiler figure out the type itself.

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

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

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

Algorithm 2 Demonstration of 'create_empty_directed_graph'

```
#include "create_empty_directed_graph.h"

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

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

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

It stores its edges, out edges and vertices in a two different STL⁵ containers. `std::vector` is the container you should use by default ([10] chapter 31.6, [11] chapter 76), as it has constant time look-up and back insertion. The `std::list` is used for storing the edges, as it is better suited at inserting elements at any position.

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

2.2 Creating an empty undirected graph

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

Algorithm 3 shows how to create an undirected graph.

⁵Standard Template Library, the standard library

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 boost::adjacency_list<
        boost::vecS,
        boost::vecS,
        boost::undirectedS
    >();
}
```

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

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

Algorithm 4 demonstrates the 'create_empty_undirected_graph' function.

Algorithm 4 Demonstration of 'create_empty_undirected_graph'

```
#include "create_empty_undirected_graph.h"

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

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

- The out edges and vertices are stored in a `std::vector`

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

2.3 Counting the number of vertices

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

Algorithm 5 Count the number of vertices

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

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

The function 'get_n_vertices' takes the result of `boost::num_vertices`, converts it to `int` and checks if there was conversion error. We do so, as one should prefer using signed data types over unsigned ones in an interface ([4] chapter 9.2.2). To do so, in the function body its first statement, the unsigned long produced by `boost::num_vertices` get converted to an `int` using a `static_cast`. Using an unsigned integer over a (signed) integer for the sake of gaining that one more bit ([9] chapter 4.4) should be avoided. The integer 'n' is initialized using list-initialization, which is preferred over the other initialization syntaxes ([10] chapter 17.7.6).

The `assert` checks if the conversion back to unsigned long re-creates the original value, to check if no information has been lost. If information is lost, the program crashes. Use `assert` extensively ([9] chapter 24.5.18, [10] chapter 30.5, [11] chapter 68, [6] chapter 8.2, [5] hour 24, [4] chapter 2.6).

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

Algorithm 6 Demonstration of the 'get_n_vertices' function

```
#include <cassert>

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

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

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

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

2.4 Counting the number of edges

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

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

Algorithm 7 Count the number of edges

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

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

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

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

Algorithm 8 Demonstration of the 'get_n_edges' function

```
#include <cassert>

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

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

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

2.5 Adding a vertex

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

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

Algorithm 9 Adding a vertex to a graph

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

template <typename graph>
void add_vertex(graph& g) noexcept
{
    static_assert(!std::is_const<graph>::value, "graph_
        cannot_be_const");

    boost::add_vertex(g);
}
```

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. Algorithm 10 shows how to add a vertex to a directed and undirected graph.

Algorithm 10 Demonstration of the `'add_vertex'` function

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

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

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

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

2.6 Vertex descriptors

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

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

Vertex descriptors are used to:

- add an edge between two vertices, see chapter 2.9
- obtain properties of a vertex, for example the vertex's out-degrees (chapter 3.1), the vertex's name (chapter 4.4), or a custom vertex property (chapter 12.6)

In this tutorial, vertex descriptors have names 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 through 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 names 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); //not boost::vertices
}
```

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 immediately. Just for your reference, algorithm 12 demonstrates the 'get_vertices' function, by showing that the vertex iterators of an empty graph point to the same location.

Algorithm 12 Demonstration of 'get_vertex_iterators'

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

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

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

2.8 Get all vertex descriptors

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

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

Algorithm 13 Get all vertex descriptors of a graph

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

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

    std::vector<vd> vds;
    const auto vis = vertices(g); //not boost::vertices
    const auto j = vis.second;
    for (auto i = vis.first; i!=j; ++i) {
        vds.emplace_back(*i);
    }
    return vds;
}
```

This is the first more complex piece of code. In the first lines, some 'using' statements allow for shorter type names⁶. The function 'vertices' (not `boost::vertices`!) returns a vertex iterator pair. The two iterators are extracted, of which the first iterator, 'i', points to the first vertex, and the second, 'j', points to beyond the last vertex. In the for-loop, 'i' loops from begin to end. Dereferencing it produces a vertex descriptor, which is stored in the `std::vector` using `emplace_back`. Prefer using `emplace_back` ([10] chapter 31.6, items 25 and 27).

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

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

Algorithm 14 Demonstration of 'get_vertex_descriptors'

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

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

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

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

2.9 Add an edge

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

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

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

template <typename graph>
void 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, // Source/from
        vd_b, // Target/to
        g
    );

    assert(aer.second);
}
```

Algorithm 15 shows how to add an isolated edge to a graph (instead of allowing for graphs with higher connectivities). First, two vertices are created, using the function 'boost::add_vertex'. 'boost::add_vertex' returns a vertex descriptor (which I prefix with 'vd'), both of which are stored. The vertex descriptors are used to add an edge to the graph, using 'boost::add_edge'. 'boost::add_edge' returns 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 successful. Insertion can fail if an edge is already present and duplicates are not allowed.

A demonstration of add_edge is shown in algorithm 16, in which an edge is added to both a directed and undirected graph, after which the number of edges and vertices is checked.

Algorithm 16 Demonstration of 'add_edge'

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

void add_edge_demo() noexcept
{
    auto g = create_empty_undirected_graph();
    add_edge(g);
    assert(boost::num_vertices(g) == 2);
    assert(boost::num_edges(g) == 1);

    auto h = create_empty_directed_graph();
    add_edge(h);
    assert(boost::num_vertices(h) == 2);
    assert(boost::num_edges(h) == 1);
}
```

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

2.10 boost::add_edge result

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

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

2.11 Getting the edge iterators

You cannot get the edges directly. Instead, working on the edges of a graph is done through 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'. Algorithm 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); //not boost::edges
}
```

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

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

Algorithm 18 Demonstration of 'get_edge_iterators'

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

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

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

2.12 Edge descriptors

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

Edge descriptors are used to obtain the name, or other properties, of an edge. In this tutorial, edge descriptors have names 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/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> eds;

    const auto ei = edges(g); //not boost::edges
    const auto j = ei.second;

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

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

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

Algorithm 20 Demonstration of `get_edge_descriptors`

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

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

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

2.14 Creating a directed graph

Finally, we are going to create a directed non-empty graph!

2.14.1 Graph

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

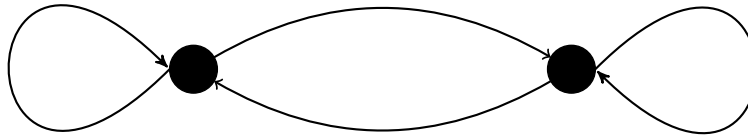


Figure 6: The two-state Markov chain

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

2.14.2 Function to create such a graph

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

Algorithm 21 Creating the two-state Markov chain as depicted in figure 6

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

boost::adjacency_list<>
create_markov_chain() noexcept
{
    auto g = create_empty_directed_graph();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
    assert(aer_aa.second);
    const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
    assert(aer_ab.second);
    const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
    assert(aer_ba.second);
    const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
    assert(aer_bb.second);
    return g;
}
```

Instead of typing the complete type, we call the 'create_empty_directed_graph' function, and let auto figure out the type. The vertex descriptors (see chapter 2.6) created by two boost::add_vertex calls are stored to add an edge to the graph. Then boost::add_edge is called four times. Every time, its return type (see chapter 2.10) is checked for a successful insertion.

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

2.14.3 Creating such a graph

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

Algorithm 22 Demonstration of the 'create_markov_chain'

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

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

2.14.4 The .dot file produced

Running a bit ahead, this graph can be converted to a .dot file using the 'save_graph_to_dot' function (algorithm 43). 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 43

```
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:

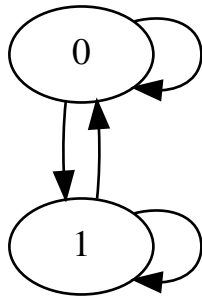


Figure 7: .svg file created from the 'create_markov_chain' function (algorithm 21) its .dot file and converted from .dot file to .svg using algorithm 268

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

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

Finally, we are going to create an undirected non-empty graph!

2.15.1 Graph

To create a fully connected undirected graph with two vertices (also called K_2), one needs two vertices and one (undirected) edge, as depicted in figure 8.



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

2.15.2 Function to create such a graph

To create K_2 , the following code can be used:

Algorithm 24 Creating K_2 as depicted in figure 8

```
#include "create_empty_undirected_graph.h"

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

This code is very similar to the 'add_edge' function (algorithm 15). Instead of typing the graph its type, we call the 'create_empty_undirected_graph' function and let auto figure it out. The vertex descriptors (see chapter 2.6) created by two boost::add_vertex calls are stored to add an edge to the graph. From boost::add_edge its return type (see chapter 2.10), it is only checked that insertion has been successful.

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

2.15.3 Creating such a graph

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

Algorithm 25 Demonstration of 'create_k2_graph'

```
#include <cassert>

#include "create_k2_graph.h"

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

2.15.4 The .dot file produced

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

Algorithm 26 .dot file created from the 'create_k2_graph' function (algorithm 24), converted from graph to .dot file using algorithm 43

```
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:

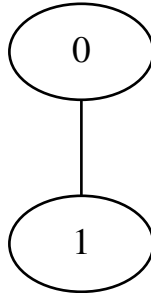


Figure 9: .svg file created from the 'create_k2_graph' function (algorithm 24) its .dot file, converted from .dot file to .svg using algorithm 268

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

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

This is an extension of the previous chapter

2.16.1 Graph

To create a fully connected undirected graph with two vertices (also called K_2), one needs two vertices and one (undirected) edge, as depicted in figure 10.

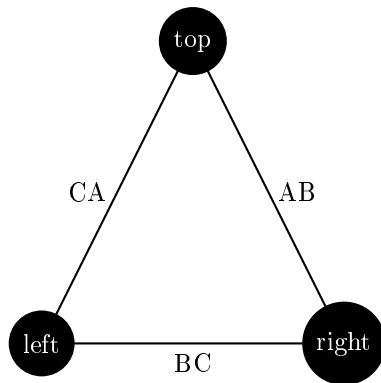


Figure 10: K_3 : a fully connected graph with three edges and vertices

2.16.2 Function to create such a graph

To create K_3 , the following code can be used:

Algorithm 27 Creating K_3 as depicted in figure 10

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS
>
create_k3_graph() noexcept
{
    auto g = create_empty_undirected_graph();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto vd_c = boost::add_vertex(g);
    const auto aer_a = boost::add_edge(vd_a, vd_b, g);
    assert(aer_a.second);
    const auto aer_b = boost::add_edge(vd_b, vd_c, g);
    assert(aer_b.second);
    const auto aer_c = boost::add_edge(vd_c, vd_a, g);
    assert(aer_c.second);
    return g;
}
```

2.16.3 Creating such a graph

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

Algorithm 28 Demonstration of 'create_k3_graph'

```
#include "create_k3_graph.h"

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

2.16.4 The .dot file produced

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

Algorithm 29 .dot file created from the 'create_k3_graph' function (algorithm 27), converted from graph to .dot file using algorithm 43

```
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:

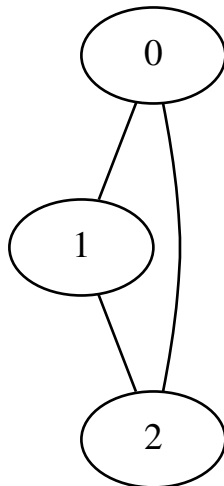


Figure 11: .svg file created from the 'create_k3_graph' function (algorithm 27) its .dot file, converted from .dot file to .svg using algorithm 268

2.17 ► Creating a Peterson graph

This is an extension of the previous chapter.

2.17.1 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 12.

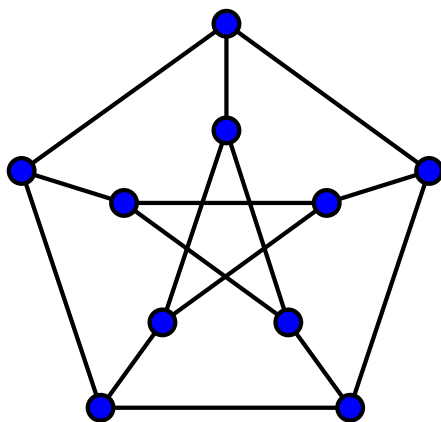


Figure 12: A Petersen graph (from https://en.wikipedia.org/wiki/Petersen_graph)

2.17.2 Function to create such a graph

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

Algorithm 30 Creating Petersen graph as depicted in figure 12

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS
>
create_petersen_graph() noexcept
{
    auto g = create_empty_undirected_graph();

    //Outer pentagon
    const auto vd_oa = boost::add_vertex(g);
    const auto vd_ob = boost::add_vertex(g);
    const auto vd_oc = boost::add_vertex(g);
    const auto vd_od = boost::add_vertex(g);
    const auto vd_oe = boost::add_vertex(g);
    //Inner pentagon
    const auto vd_ia = boost::add_vertex(g);
    const auto vd_ib = boost::add_vertex(g);
    const auto vd_ic = boost::add_vertex(g);
    const auto vd_id = boost::add_vertex(g);
    const auto vd_ie = boost::add_vertex(g);

    const auto aer_1 = boost::add_edge(vd_oa, vd_ob, g);
    const auto aer_2 = boost::add_edge(vd_oa, vd_ia, g);
    const auto aer_3 = boost::add_edge(vd_ob, vd_oc, g);
    const auto aer_4 = boost::add_edge(vd_ob, vd_ib, g);
    const auto aer_5 = boost::add_edge(vd_oc, vd_od, g);
    const auto aer_6 = boost::add_edge(vd_oc, vd_ic, g);
    const auto aer_7 = boost::add_edge(vd_od, vd_oe, g);
    const auto aer_8 = boost::add_edge(vd_od, vd_id, g);
    const auto aer_9 = boost::add_edge(vd_oe, vd_oa, g);
    const auto aer_10 = boost::add_edge(vd_oe, vd_ie, g);
    const auto aer_11 = boost::add_edge(vd_ia, vd_ic, g);
    const auto aer_12 = boost::add_edge(vd_ib, vd_id, g);
    const auto aer_13 = boost::add_edge(vd_ic, vd_ie, g);
    const auto aer_14 = boost::add_edge(vd_id, vd_ia, g);
    const auto aer_15 = boost::add_edge(vd_ie, vd_ib, g);

    assert(aer_1.second);
    assert(aer_2.second);
    assert(aer_3.second);
    assert(aer_4.second);
    assert(aer_5.second);
    assert(aer_6.second);
    assert(aer_7.second);
    assert(aer_8.second);
    assert(aer_9.second);
    assert(aer_10.second);
    assert(aer_11.second);
    assert(aer_12.second);
    assert(aer_13.second);
```

2.17.3 Creating such a graph

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

Algorithm 31 Demonstration of 'create_k3_graph'

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

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

2.17.4 The .dot file produced

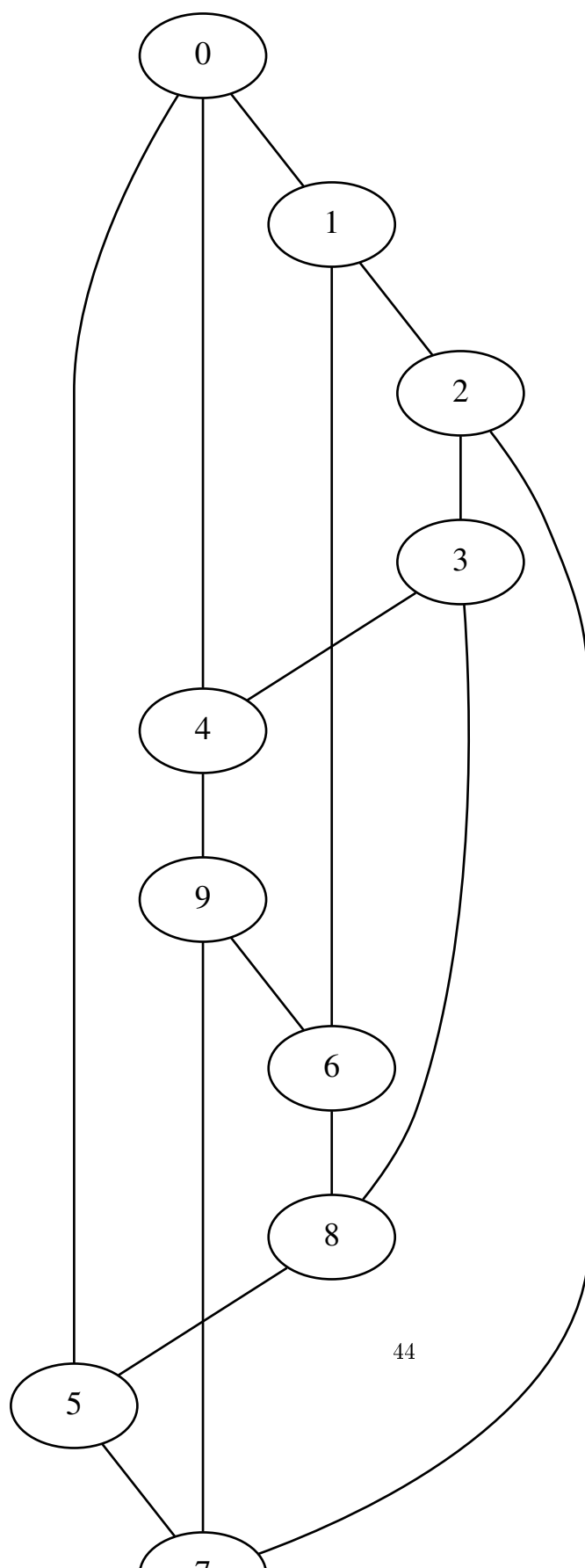
This graph can be converted to the .dot file as shown in algorithm 32:

Algorithm 32 .dot file created from the 'create_petersen_graph' function (algorithm 30), converted from graph to .dot file using algorithm 43

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

2.17.5 The .svg file produced

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



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 3.6
- Loading an undirected graph without properties from .dot file: see chapter 3.8
- Loading a directed graph without properties from .dot file: see chapter 3.7

3.1 Getting the vertices' out degree

Let's measure the out degree of all vertices in a graph!

The out degree of a vertex is the number of edges that originate at it.

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

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

Algorithm 33 shows how to obtain these:

Algorithm 33 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
{
    std::vector<int> v;
    const auto vis
        = vertices(g); //not boost::vertices
    const auto j = vis.second;
    for (auto i = vis.first; i!=j; ++i) {
        v.emplace_back(
            out_degree(*i,g) //not boost::out_degree
        );
    }
    return v;
}
```

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

Albeit that the K_2 graph and the two-state Markov chain are rather simple, we can use it to demonstrate '`get_vertex_out_degrees`' on, as shown in algorithm 34.

Algorithm 34 Demonstration of the 'get_vertex_out_degrees' function

```
#include <cassert>

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

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

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

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

3.2 ► Is there an edge between two vertices?

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

Algorithm 35 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( //not boost::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 36 Demonstration of the 'has_edge_between_vertices' function

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

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

3.3 ► Get the edge between two vertices

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

Algorithm 37 Get the edge between two vertices

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

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

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

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

Algorithm 38 Demonstration of the 'get_edge_between_vertices' function

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

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

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

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

Here is the 'create_direct_neighbour_subgraph' code:

Algorithm 39 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);
        const auto j = vdsi.second;
        for (auto i = vdsi.first; i!=j; ++i)
        {
            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;
            const auto aer = boost::add_edge(m[vd_from], m[vd_to], h);
            assert(aer.second);
        }
    }
    return h;
}
```

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

Algorithm 40 Demo of the 'create_direct_neighbour_subgraph' function

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

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

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

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

Algorithm 41 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
{
    std::vector<graph> v;
    const auto vip = vertices(g);
    const auto j = vip.second;
    for (auto i = vip.first; i!=j; ++i) {
        v.emplace_back(
            create_direct_neighbour_subgraph(
                *i, g
            )
        );
    }
    return v;
}
```

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

Algorithm 42 Demo of the 'create_all_direct_neighbour_subgraphs' function

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

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

3.6 Saving a graph to a .dot file

Graphs 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 43 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 44 shows how to use the 'save_graph_to_dot' function:

Algorithm 44 Demonstration of the 'save_graph_to_dot' function

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

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

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

When using the 'save_graph_to_dot' function (algorithm 43), only the structure of the graph is saved: all other properties like names are not stored. Algorithm 80 shows how to do so.

3.7 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 45:

Algorithm 45 Loading a directed graph from a .dot file

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

boost::adjacency_list<
load_directed_graph_from_dot(
    const std::string& dot_filename
)
{
    assert(is_regular_file(dot_filename));
    std::ifstream f(dot_filename.c_str());
    auto g = create_empty_directed_graph();
    boost::dynamic_properties p(
        boost::ignore_other_properties
    );
    boost::read_graphviz(f, g, p);
    return g;
}
```

In this algorithm, first it is checked if the file to load exists, using the 'is_regular_file' function (algorithm 269), 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 46 shows how to use the 'load_directed_graph_from_dot' function:

Algorithm 46 Demonstration of the 'load_directed_graph_from_dot' function

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

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

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

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

3.8 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 3.7. Algorithm 47 show how to do so:

Algorithm 47 Loading an undirected graph from a .dot file

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS
>
load_undirected_graph_from_dot(
    const std::string& dot_filename
)
{
    assert(is_regular_file(dot_filename));
    std::ifstream f(dot_filename.c_str());
    auto g = create_empty_undirected_graph();
    boost::dynamic_properties p(
        boost::ignore_other_properties
    );
    boost::read_graphviz(f, g, p);
    return g;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 3.7 describes the rationale of this function.

Algorithm 48 shows how to use the 'load_undirected_graph_from_dot' function:

Algorithm 48 Demonstration of the 'load_undirected_graph_from_dot' function

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

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

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

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

4 Building graphs with named vertices

Up until now, the graphs created have had edges and vertices without any property. 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 18

4.1 Creating an empty directed graph with named vertices

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

Algorithm 49 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 boost::adjacency_list<
        boost::vecS,
        boost::vecS,
        boost::directedS,
        boost::property<
            boost::vertex_name_t, std::string
        >
        >
    > ();
}
```

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 50 shows how to create such a graph:

Algorithm	50	Demonstration	of	the	'create_empty_directed_named_vertices_graph' function
------------------	-----------	---------------	----	-----	---

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

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

4.2 Creating an empty undirected graph with named vertices

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

Algorithm 51 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 boost::adjacency_list<
        boost::vecS,
        boost::vecS,
        boost::undirectedS,
        boost::property<
            boost::vertex_name_t, std::string
        >
    > ();
}
```

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 52 shows how to create such a graph:

Algorithm 52 Demonstration of the 'create_empty_undirected_named_vertices_graph' function

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

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

4.3 Add a vertex with a name

Adding a vertex without a name was trivially easy (see chapter 2.5). Adding a vertex with a name takes slightly more work, as shown by algorithm 53:

Algorithm 53 Adding a vertex with a name

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

template <typename graph>
void add_named_vertex(
    const std::string& vertex_name,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value,
        "graph_cannot_be_const");

    const auto vd_a = boost::add_vertex(g);
    auto vertex_name_map
        = get( //not boost::get
            boost::vertex_name, g
        );
    vertex_name_map[vd_a] = vertex_name;
}
```

Instead of calling 'boost::add_vertex' with an additional argument containing the name of the vertex⁷, 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. After obtaining the name map from the graph (using 'get(boost::vertex_name,g)'), the name of the vertex is set using that vertex descriptor. Note that 'get' has no 'boost::' prepending it, as it lives in the same (global) namespace the function is in. Using 'boost::get' will not compile.

Using 'add_named_vertex' is straightforward, as demonstrated by algorithm 54.

Algorithm 54 Demonstration of 'add_named_vertex'

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

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

4.4 Getting the vertices' names

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

⁷I 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.

Algorithm 55 Get the vertices' names

```
#include <string>
#include <vector>
#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
{
    std::vector<std::string> v;

    const auto vertex_name_map = get(
        boost::vertex_name, g
    );
    const auto vip
        = vertices(g); //not boost::vertices
    const auto j = vip.second;

    for (auto i = vip.first; i!=j; ++i) {
        v.emplace_back(
            get( //not boost::get
                vertex_name_map,
                *i
            )
        );
    }
    return v;
}
```

This code is very similar to 'get_vertex_out_degrees' (algorithm 33), 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 56 shows how to add two named vertices, and check if the added names are retrieved as expected.

Algorithm 56 Demonstration of 'get_vertex_names'

```
#include <cassert>

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

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

4.5 Creating a Markov chain with named vertices

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

4.5.1 Graph

We extend the Markov chain of chapter 2.14 by naming the vertices 'Good' and 'Not bad', as depicted in figure 14:

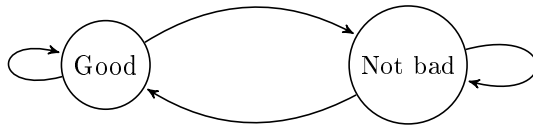


Figure 14: A two-state Markov chain where the vertices have texts

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 57 Creating a Markov chain with named vertices as depicted in figure 14

```
#include <cassert>
#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 = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
    assert(aer_aa.second);
    const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
    assert(aer_ab.second);
    const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
    assert(aer_ba.second);
    const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
    assert(aer_bb.second);

    auto name_map = get( //not boost::get
        boost::vertex_name, g
    );
    name_map[vd_a] = "Good";
    name_map[vd_b] = "Not_bad";

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

Algorithm 58 Demonstrating the 'create_named_vertices_markov_chain' function

```
#include <cassert>

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

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

4.5.4 The .dot file produced

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

Algorithm 59 .dot file created from the 'create_named_vertices_markov_chain' function (algorithm 57), converted from graph to .dot file using algorithm 43

```
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:

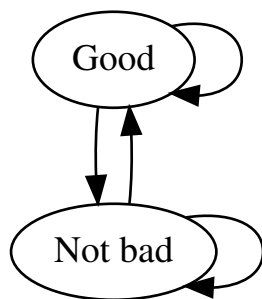


Figure 15: .svg file created from the 'create_named_vertices_markov_chain' function (algorithm 57) its .dot file, converted from .dot file to .svg using algorithm 268

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 16:

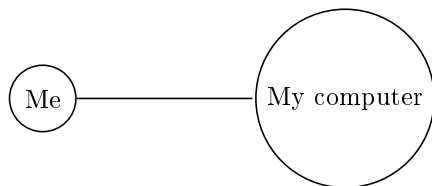


Figure 16: K_2 : a fully connected graph with two named vertices

4.6.2 Function to create such a graph

To create K_2 , the following code can be used:

Algorithm 60 Creating K_2 with named vertices as depicted in figure 16

```
#include <cassert>
#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_k2_graph() noexcept
{
    auto g
        = create_empty_undirected_named_vertices_graph();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer = boost::add_edge(vd_a, vd_b, g);
    assert(aer.second);

    auto name_map = get( //not boost::get
        boost::vertex_name, g
    );
    name_map[vd_a] = "Me";
    name_map[vd_b] = "My_computer";

    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 61) is very similar to the demonstration code of the 'create_k2_graph function' (algorithm 24).

Algorithm 61 Demonstrating the 'create_k2_graph' function

```
#include <cassert>

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

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

4.6.4 The .dot file produced

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

Algorithm 62 .dot file created from the 'create_named_vertices_k2' function (algorithm 60), converted from graph to .dot file using algorithm 80

```
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:

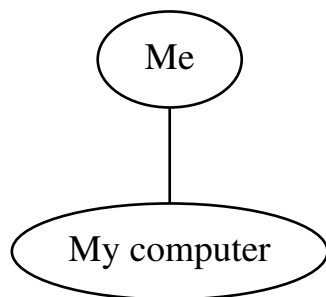


Figure 17: .svg file created from the 'create_named_vertices_k2_graph' function (algorithm 57) its .dot file, converted from .dot file to .svg using algorithm 80

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

5 Working on graphs with named vertices

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

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

Especially 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 obtaining 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 63 Find if there is vertex with a certain name

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

template <typename graph>
bool has_vertex_with_name(
    const std::string& vertex_name,
    const graph& g
) noexcept
{
    const auto vertex_name_map
        = get( //not boost::get
              boost::vertex_name,
              g
            );
    const auto vip
        = vertices(g); //not boost::vertices
    const auto j = vip.second;
    for (auto i = vip.first; i!=j; ++i) {
        if (
            get( //not boost::get
                vertex_name_map,
                *i
            ) == vertex_name
        ) {
            return true;
        }
    }
    return false;
}
```

This function can be demonstrated as in algorithm 64, where a certain name cannot be found in an empty graph. After adding the desired name, it is found.

Algorithm 64 Demonstration of the 'has_vertex_with_name' function

```
#include <cassert>

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

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

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

5.2 Find a vertex by its name

Where STL functions work with iterators, here we obtain a vertex descriptor (see chapter 2.6) to obtain a handle to the desired vertex. Algorithm 65 shows how to obtain a vertex descriptor to the first (name) vertex found with a specific name.

Algorithm 65 Find the first vertex by its name

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

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_vertex_with_name(
    const std::string& name,
    const graph& g
) noexcept
{
    assert(has_vertex_with_name(name, g));
    const auto vertex_name_map
        = get(boost::vertex_name, g);
    const auto vip
        = vertices(g); //not boost::vertices
    const auto j = vip.second;

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

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 66 shows some examples of how to do so.

Algorithm 66 Demonstration of the 'find_first_vertex_with_name' function

```
#include <cassert>

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

void find_first_vertex_with_name_demo() noexcept
{
    const auto g
        = create_named_vertices_k2_graph();
    const auto vd
        = find_first_vertex_with_name(
            "My_computer", g
        );
    assert(
        out_degree(vd, g) == 1 //not boost::out_degree
    );
    assert(in_degree(vd, g) == 1); //not boost::in_degree
}
```

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

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

With a vertex descriptor, we can read a vertex its types of degrees. Algorithm 65 shows how to find a vertex, obtain its vertex descriptor and then obtain the out degree from it.

Algorithm 67 Get the first vertex with a certain name its out degree from its vertex descriptor

```
#include <cassert>
#include "find_first_vertex_with_name.h"
#include "has_vertex_with_name.h"

template <typename graph>
int get_first_vertex_with_name_out_degree(
    const std::string& name,
    const graph& g) noexcept
{
    assert(has_vertex_with_name(name, g));
    const auto vd
        = find_first_vertex_with_name(name, g);
    const int od {
        static_cast<int>(
            out_degree(vd, g) //not boost::out_degree
        )
    };
    assert(static_cast<unsigned long>(od)
        == out_degree(vd, g)
    );

    return od;
}
```

Algorithm 68 shows how to use this function.

Algorithm 68 Demonstration of the 'get_first_vertex_with_name_out_degree' function

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

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

5.4 Get a vertex its name from its vertex descriptor

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

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

Algorithm 69 Get a vertex its name from its vertex descriptor

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

template <typename graph>
std::string get_vertex_name(
    const typename boost::graph_traits<graph>::
        vertex_descriptor& vd,
    const graph& g
) noexcept
{
    const auto vertex_name_map
        = get( //not boost::get
            boost::vertex_name,
            g
        );
    return vertex_name_map[vd];
}
```

To use 'get_vertex_name', one first needs to obtain a vertex descriptor. Algorithm 70 shows a simple example:

Algorithm 70 Demonstration if the 'get_vertex_name' function

```
#include <cassert>

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

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

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

If you know how to get the name from a vertex descriptor, setting it is just as easy, as shown in algorithm 71.

Algorithm 71 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( //not boost::get
            boost::vertex_name,
            g
        );
    vertex_name_map[vd]
        = any_vertex_name;
}
```

To use 'set_vertex_name', one first needs to obtain a vertex descriptor. Algorithm 72 shows a simple example.

Algorithm 72 Demonstration if the 'set_vertex_name' function

```
#include <cassert>

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

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

5.6 Setting all vertices' names

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

Algorithm 73 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); //not boost::vertices
    const auto j = vip.second;
    for (auto i = vip.first; i!=j; ++i, ++ni)
    {
        assert(ni != names_end);
        put(vertex_name_map, *i, *ni);
    }
}
```

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 74 Clear the first vertex with a certain name

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

template <typename graph>
void clear_first_vertex_with_name(
    const std::string& name,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value,
        "graph_cannot_be_const");

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

Algorithm 75 shows the clearing of the first named vertex found.

Algorithm 75 Demonstration of the 'clear_first_vertex_with_name' function

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

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

5.8 Remove a named vertex

A vertex descriptor can be used to remove a vertex from a graph. It is necessary to remove these connections (e.g. using `clear_first_vertex_with_name`, algorithm 74) 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 76 Remove the first vertex with a certain name

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

template <typename graph>
void remove_first_vertex_with_name(
    const std::string& name,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value,
        "graph_cannot_be_const"
    );

    assert(has_vertex_with_name(name, g));
    const auto vd
        = find_first_vertex_with_name(name, g);
    assert(degree(vd, g) == 0); //not degree
    boost::remove_vertex(vd, g);
}
```

Algorithm 77 shows the removal of the first named vertex found.

Algorithm 77 Demonstration of the 'remove_first_vertex_with_name' function

```
#include <cassert>

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

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

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

5.9 Removing the edge between two named vertices

Instead of looking for an edge descriptor, one can also remove an edge from two vertex descriptors (which is: the edge between the two vertices). Removing an edge between two named vertices named edge goes as follows: use the names of the vertices to get both vertex descriptors, then call 'boost::remove_edge' on those two, as shown in algorithm 78.

Algorithm 78 Remove the first edge with a certain name

```
#include "find_first_vertex_with_name.h"
#include "has_vertex_with_name.h"
#include "has_edge_between_vertices.h"

template <typename graph>
void remove_edge_between_vertices_with_names(
    const std::string& name_1,
    const std::string& name_2,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value,
        "graph_cannot_be_const");
    ;

    assert(has_vertex_with_name(name_1, g));
    assert(has_vertex_with_name(name_2, g));
    const auto vd_1
        = find_first_vertex_with_name(name_1, g);
    const auto vd_2
        = find_first_vertex_with_name(name_2, g);
    assert(has_edge_between_vertices(vd_1, vd_2, g));
    boost::remove_edge(vd_1, vd_2, g);
}
```

Algorithm 79 shows the removal of the first named edge found.

Algorithm 79 Demonstration of the 'remove_edge_between_vertices_with_names' function

```
#include <cassert>

#include "create_named_edges_and_vertices_k3_graph.h"
#include "remove_edge_between_vertices_with_names.h"

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

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

If you used the 'create_named_vertices_k2_graph' function (algorithm 60) to produce a K_2 graph with named vertices, you can store these names in multiple ways:

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

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

The created .dot file is shown at algorithm 62.

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.

5.10.1 Using `boost::make_label_writer`

The first implementation uses `boost::make_label_writer`, as shown in algorithm 80:

Algorithm 80 Saving a graph with named vertices to a .dot file

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

#include "get_vertex_names.h"

template <typename graph>
void save_named_vertices_graph_to_dot(
    const graph& g,
    const std::string& filename
) noexcept
{
    std::ofstream f(filename);
    const auto names = get_vertex_names(g);
    boost::write_graphviz(
        f,
        g,
        boost::make_label_writer(&names[0])
    );
}
```

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

5.10.2 Using a C++11 lambda function

An equivalent algorithm is algorithm 81:

Algorithm 81 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 69) and stream it to the out stream.

5.10.3 Demonstration

Algorithm 82 shows how to use (one of) the `'save_named_vertices_graph_to_dot'` function(s):

Algorithm 82 Demonstration of the `'save_named_vertices_graph_to_dot'` function

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

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

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

When using the `'save_named_vertices_graph_to_dot'` function (algorithm 80), only the structure of the graph and the vertex names are saved: all other properties like edge name are not stored. Algorithm 111 shows how to do so.

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

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph with named vertices is loaded, as shown in algorithm 83:

Algorithm 83 Loading a directed graph with named vertices from a .dot file

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

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

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

Algorithm 84 shows how to use the 'load_directed_graph_from_dot' function:

Algorithm 84 Demonstration of the 'load_directed_named_vertices_graph_from_dot' function

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

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

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

This demonstration shows how the Markov chain is created using the 'create_named_vertices_markov_chain' function (algorithm 21), saved and then loaded. The loaded graph is checked to be a directed graph similar to the Markov chain with the same vertex names (using the 'get_vertex_names' function, algorithm 55).

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

When loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph with named vertices is loaded, as shown in algorithm 85:

Algorithm 85 Loading an undirected graph with named vertices from a .dot file

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

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

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 5.11 describes the rationale of this function.

Algorithm 86 shows how to use the 'load_undirected_graph_from_dot' function:

Algorithm 86 Demonstration of the 'load_undirected_graph_from_dot' function

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

#include "save_named_vertices_graph_to_dot.h"
#include "get_vertex_names.h"

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

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

This demonstration shows how K_2 with named vertices is created using the 'create_named_vertices_k2_graph' function (algorithm 60), 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 55).

6 Building graphs with named edges and vertices

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

In this chapter, we will build the following graphs:

- An empty directed graph that allows for edges and vertices with names: see chapter 6.1
- An empty undirected graph that allows for edges and vertices with names: see chapter 6.2
- Markov chain with named edges and vertices: see chapter 6.5
- K_3 with named edges and vertices: see chapter 6.6

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

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

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

6.1 Creating an empty directed graph with named edges and vertices

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

Algorithm 87 Creating an empty directed graph with named edges and vertices

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

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

This graph:

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

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

Algorithm 88 shows how to create this graph. Note that all the earlier functions defined in this tutorial keep working as expected.

Algorithm	88	Demonstration	if	the	'cre-
		ate_empty_directed_named_edges_and_vertices_graph'	function		

```
#include <cassert>
#include "add_named_edge.h"
#include "
    create_empty_directed_named_edges_and_vertices_graph.h
"
#include "get_edge_names.h"
#include "get_vertex_names.h"

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

6.2 Creating an empty undirected graph with named edges and vertices

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

Algorithm 89 Creating an empty undirected graph with named edges and vertices

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

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

This graph:

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

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

Algorithm 90 shows how to create this graph. Note that all the earlier functions defined in this tutorial keep working as expected.

Algorithm	90	Demonstration	if	the	'cre-
		ate_empty_undirected_named_edges_and_vertices_graph'			function

```
#include <cassert>

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

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

6.3 Adding a named edge

Adding an edge with a name:

Algorithm 91 Add a vertex with a name

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

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

    auto edge_name_map
        = get( //not boost::get
            boost::edge_name, g
        );
    edge_name_map[aer.first] = edge_name;
}
```

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

The algorithm 92 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 92 Demonstration of the 'add_named_edge' function

```
#include <cassert>
#include "add_named_edge.h"
#include "
    create_empty_undirected_named_edges_and_vertices_graph
    .h"

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

6.4 Getting the edges' names

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

Algorithm 93 Get the edges' names

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

template <typename graph>
std::vector<std::string> get_edge_names(const graph& g)
    noexcept
{
    std::vector<std::string> v;

    const auto edge_name_map = get(boost::edge_name, g);
    const auto eip = edges(g); //not boost::edges
    const auto j = eip.second;

    for (auto i = eip.first; i!=j; ++i) {
        v.emplace_back(
            get( //not boost::get
                edge_name_map,
                *i
            )
        );
    }
    return v;
}
```

The names of the edges are obtained from a `boost::property_map` and then put into a `std::vector`. The algorithm 94 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 94 Demonstration of the 'get_edge_names' function

```
#include <cassert>

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

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

6.5 Creating Markov chain with named edges and vertices

6.5.1 Graph

We build this graph:

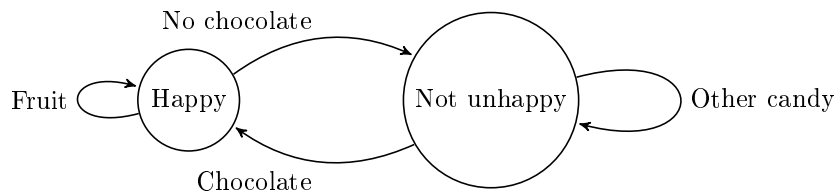


Figure 18: A two-state Markov chain where the edges and vertices have texts

6.5.2 Function to create such a graph

Here is the code:

Algorithm 95 Creating the two-state Markov chain as depicted in figure 18

```
#include <string>
#include "
    create_empty_directed_named_edges_and_vertices_graph.h
"

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

    auto vertex_name_map = get( //not boost::get
        boost::vertex_name, g
    );
    vertex_name_map[vd_a] = "Happy";
    vertex_name_map[vd_b] = "Not_unhappy";

    auto edge_name_map = get( //not boost::get
        boost::edge_name, g
    );
    edge_name_map[aer_aa.first] = "Fruit";
    edge_name_map[aer_ab.first] = "No_chocolate";
    edge_name_map[aer_ba.first] = "Chocolate";
    edge_name_map[aer_bb.first] = "Other_candy";

    return g;
}
```

6.5.3 Creating such a graph

Here is the demo:

Algorithm 96 Demo of the 'create_named_edges_and_vertices_markov_chain' function (algorithm 95)

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

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

    const auto g
        = create_named_edges_and_vertices_markov_chain();

    const strings expected_vertex_names{
        "Happy", "Not_unhappy"
    };
    const strings vertex_names{
        get_vertex_names(g)
    };
    assert(expected_vertex_names == vertex_names);

    const strings expected_edge_names{
        "Fruit", "No_chocolate", "Chocolate", "Other_candy"
    };

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

6.5.4 The .dot file produced

Algorithm 97 .dot file created from the 'create_named_edges_and_vertices_markov_chain' function (algorithm 95), converted from graph to .dot file using algorithm 43

```

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

```

6.5.5 The .svg file produced

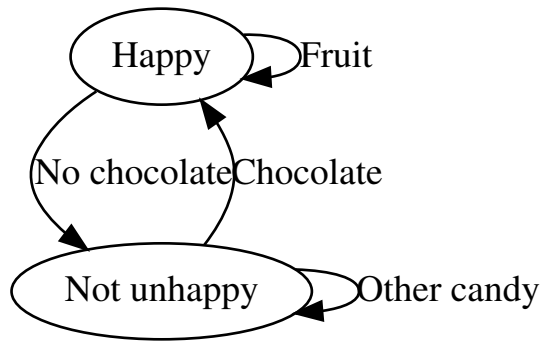


Figure 19: .svg file created from the 'create_named_edges_and_vertices_markov_chain' function (algorithm 95) its .dot file, converted from .dot file to .svg using algorithm 268

6.6 Creating K_3 with named edges and vertices

6.6.1 Graph

We extend the graph K_2 with named vertices of chapter 4.6 by adding names to the edges, as depicted in figure 20:

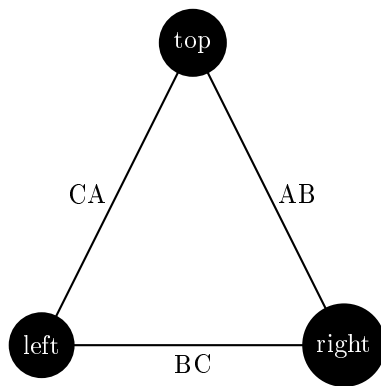


Figure 20: K_3 : a fully connected graph with three named edges and vertices

6.6.2 Function to create such a graph

To create K_3 , the following code can be used:

Algorithm 98 Creating K_3 as depicted in figure 20

```
#include <string>
#include <boost/graph/adjacency_list.hpp>
#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_k3_graph() noexcept
{
    auto g
        =
            create_empty_undirected_named_edges_and_vertices_graph
            ();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto vd_c = boost::add_vertex(g);
    const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
    assert(aer_ab.second);
    const auto aer_bc = boost::add_edge(vd_b, vd_c, g);
    assert(aer_bc.second);
    const auto aer_ca = boost::add_edge(vd_c, vd_a, g);
    assert(aer_ca.second);

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

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

    return g;
}
```

Most of the code is a repeat of algorithm 60. In the end, the edge names are

obtained as a `boost::property_map` and `set`.

6.6.3 Creating such a graph

Algorithm 99 shows how to create the graph and measure its edge and vertex names.

Algorithm 99 Demonstration of the 'create_named_edges_and_vertices_k3' function

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

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

    const auto g
        = create_named_edges_and_vertices_k3_graph();

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

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

6.6.4 The .dot file produced

Algorithm 100 .dot file created from the 'create_named_edges_and_vertices_k3_graph' function (algorithm 98), converted from graph to .dot file using algorithm 43

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

6.6.5 The .svg file produced

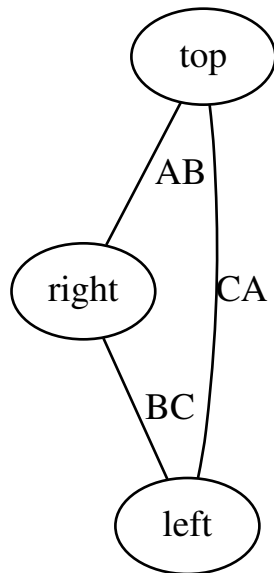


Figure 21: .svg file created from the 'create_named_edges_and_vertices_k3_graph' function (algorithm 98) its .dot file, converted from .dot file to .svg using algorithm 268

7 Working on graphs with named edges and vertices

Working with named edges...

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

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

7.1 Check if there exists an edge with a certain name

Before modifying our edges, let's first determine if we can find an edge by its name in a graph. After obtaining 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 101 Find if there is an edge with a certain name

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

template <typename graph>
bool has_edge_with_name(
    const std::string& name,
    const graph& g
) noexcept
{
    const auto edge_name_map
        = get( //not boost::get
              boost::edge_name,
              g
            );
    const auto eip
        = edges( //not boost::edges
               g
            );
    const auto j = eip.second;
    for (auto i = eip.first; i!=j; ++i) {
        if (get(edge_name_map, *i) == name) {
            return true;
        }
    }
    return false;
}
```

This function can be demonstrated as in algorithm 102, where a certain name cannot be found in an empty graph. After adding the desired name, it is found.

Algorithm 102 Demonstration of the 'has_edge_with_name' function

```
#include <cassert>

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

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

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

7.2 Find an edge by its name

Where STL functions work with iterators, here we obtain an edge descriptor (see chapter 2.12) to obtain a handle to the desired edge. Algorithm 103 shows how to obtain an edge descriptor to the first (name) edge found with a specific name.

Algorithm 103 Find the first edge by its name

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

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

    const auto edge_name_map
        = get( //not boost::get
              boost::edge_name, g
            );
    const auto eip
        = edges(g); //not boost::edges
    const auto j = eip.second;

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

        const std::string s{
            get(edge_name_map, *i)
        };
        if (s == name) { return *i; }
    }
    assert(!"Should_not_get_here");
    throw; //Will crash the program
}
```

With the edge descriptor obtained, one can read and modify the graph. Algorithm 104 shows some examples of how to do so.

Algorithm 104 Demonstration of the 'find_first_edge_by_name' function

```
#include <cassert>

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

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

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

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

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

Algorithm 105 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( //not boost::get
            boost::edge_name,
            g
        );
    return edge_name_map[ed];
}
```

To use 'get_edge_name', one first needs to obtain an edge descriptor. Algorithm 106 shows a simple example.

Algorithm 106 Demonstration if the 'get_edge_name' function

```
#include <cassert>

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

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

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

If you know how to get the name from an edge descriptor, setting it is just as easy, as shown in algorithm 107.

Algorithm 107 Set an edge its name from its edge descriptor

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

template <typename graph>
void set_edge_name(
    const std::string& any_edge_name,
    const typename boost::graph_traits<graph>::
        edge_descriptor& vd,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value,
        "graph_cannot_be_const");

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

To use 'set_edge_name', one first needs to obtain an edge descriptor. Algorithm 108 shows a simple example.

Algorithm 108 Demonstration if the 'set_edge_name' function

```
#include <cassert>

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

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

7.5 Removing the first edge with a certain name

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

Removing a named edge goes as follows: use the name of the edge to get a first edge descriptor, then call 'boost::remove_edge', shown in algorithm 76:

Algorithm 109 Remove the first edge with a certain name

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

template <typename graph>
void remove_first_edge_with_name(
    const std::string& name,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value,
        "graph_cannot_be_const");

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

Algorithm 110 shows the removal of the first named edge found.

Algorithm 110 Demonstration of the 'remove_first_edge_with_name' function

```
#include <cassert>

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

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

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

If you used the `create_named_edges_and_vertices_k3_graph` function (algorithm 98) to produce a K_3 graph with named edges and vertices, you can store these names additionally with algorithm 111:

Algorithm 111 Saving an undirected graph with named edges and vertices to a .dot file

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

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

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

    std::ofstream f(filename);
    const auto vertex_names = get_vertex_names(g);
    const auto edge_name_map = boost::get(boost::edge_name,
        g);
    boost::write_graphviz(
        f,
        g,
        boost::make_label_writer(&vertex_names[0]),
        [edge_name_map](std::ostream& out, const
            my_edge_descriptor& e) {
            out << "[label=\"" << edge_name_map[e] << "\"]";
        }
    );
}
```

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

So, the 'save_named_edges_and_vertices_graph_to_dot' function (algorithm 43) saves only the structure of the graph and its edge and vertex names.

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

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph with named edges and vertices is loaded, as shown in algorithm 112:

Algorithm 112 Loading a directed graph with named edges and vertices from a .dot file

```

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

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

```

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

Algorithm 113 shows how to use the 'load_directed_graph_from_dot' function:

Algorithm 113 Demonstration of the 'load_directed_named_edges_and_vertices_graph_from_dot' function

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

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

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

This demonstration shows how the Markov chain is created using the 'create_named_edges_and_vertices_markov_chain' function (algorithm 95), 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 93, and the 'get_vertex_names' function, algorithm 55).

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

When loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph with named edges and vertices is loaded, as shown in algorithm 114:

Algorithm 114 Loading an undirected graph with named edges and vertices from a .dot file

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

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

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

Algorithm 115 shows how to use the 'load_undirected_graph_from_dot' function:

Algorithm 115 Demonstration of the 'load_undirected_named_edges_and_vertices_graph_from_dot' function

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

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

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

This demonstration shows how K_3 with named edges and vertices is created using the 'create_named_edges_and_vertices_k3_graph' function (algorithm 98), 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 93, and the 'get_vertex_names'

function, algorithm 55).

8 Building graphs with bundled vertices

Up until now, the graphs created have had edges and vertices with the built-in name property. In this chapter, graphs will be created, in which the vertices can have a bundled 'my_bundled_vertex' type⁸. The following graphs will be created:

- An empty directed graph that allows for bundled vertices: see chapter 117
- 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:

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

Algorithm 116 Declaration of `my_bundled_vertex`

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

struct my_bundled_vertex
{
    explicit my_bundled_vertex(
        const std::string& name = "",
        const std::string& description = "",
        const double x = 0.0,
        const double y = 0.0
    ) noexcept;
    std::string m_name;
    std::string m_description;
    double m_x;
    double m_y;
};

bool operator==(const my_bundled_vertex& lhs, const
    my_bundled_vertex& rhs) noexcept;
bool operator!=(const my_bundled_vertex& lhs, const
    my_bundled_vertex& rhs) noexcept;
```

'my_bundled_vertex' is a class that has multiple properties:

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

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

8.2 Create the empty directed graph with bundled vertices

Algorithm 117 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 boost::adjacency_list<
        boost::vecS,
        boost::vecS,
        boost::directedS,
        my_bundled_vertex
    >();
}
```

This graph:

- has its out edges stored in a `std::vector` (due to the first `boost::vecS`)
- has its vertices stored in a `std::vector` (due to the second `boost::vecS`)
- is directed (due to the `boost::directedS`)
- The vertices have one property: they have a 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 118 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 boost::adjacency_list<
        boost::vecS,
        boost::vecS,
        boost::undirectedS,
        my_bundled_vertex
    >();
}
```

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 119 Add a bundled vertex

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

template <typename graph>
void add_bundled_vertex(const my_bundled_vertex& v, graph
    & g) noexcept
{
    static_assert(!std::is_const<graph>::value,
        "graph_cannot_be_const");
    ;

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

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_vertexes⁹

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

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

Algorithm 120 Get the bundled vertices' my_vertexes

```
#include <vector>
#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_bundled_vertex_my_vertexes(
        const graph& g
    ) noexcept
{
    std::vector<my_bundled_vertex> v;

    const auto vip
        = vertices(g); //not boost::vertices
    const auto j = vip.second;

    for (auto i = vip.first; i!=j; ++i) {
        v.emplace_back(g[*i]);
    }
    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 22 shows the graph that will be reproduced:

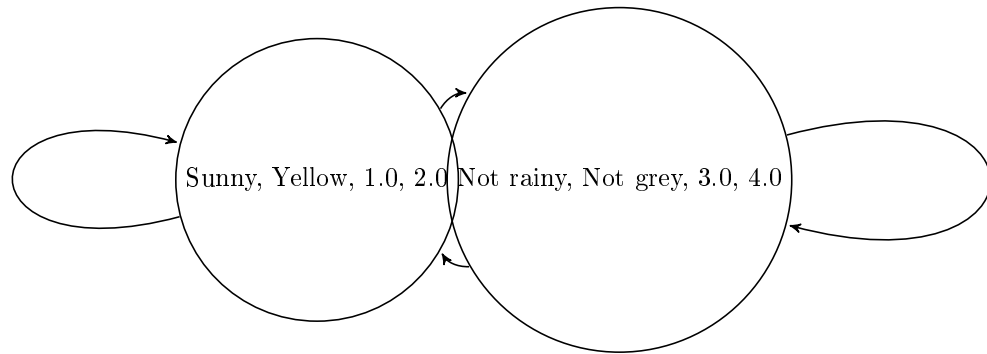


Figure 22: A two-state Markov chain where the vertices have bundled properties and the edges have no properties. The vertices' properties are nonsensical

8.6.2 Function to create such a graph

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

Algorithm 121 Creating the two-state Markov chain as depicted in figure 22

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    my_bundled_vertex
>
create_bundled_vertices_markov_chain() noexcept
{
    auto g
        = create_empty_directed_bundled_vertices_graph();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
    assert(aer_aa.second);
    const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
    assert(aer_ab.second);
    const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
    assert(aer_ba.second);
    const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
    assert(aer_bb.second);

    g[vd_a] = my_bundled_vertex("Sunny",
        "Yellow", 1.0, 2.0
    );
    g[vd_b] = my_bundled_vertex("Not_rainy",
        "Not_grey", 3.0, 4.0
    );

    return g;
}
```

8.6.3 Creating such a graph

Here is the demo:

Algorithm 122 Demo of the 'create_bundled_vertices_markov_chain' function (algorithm 121)

```
#include <cassert>
#include "create_bundled_vertices_markov_chain.h"
#include "get_bundled_vertex_my_vertexes.h"
#include "my_bundled_vertex.h"

void create_bundled_vertices_markov_chain_demo() noexcept
{
    const auto g
        = create_bundled_vertices_markov_chain();
    const std::vector<my_bundled_vertex>
        expected_my_vertexes{
            my_bundled_vertex("Sunny","Yellow",1.0,2.0),
            my_bundled_vertex("Not_rainy","Not_grey",3.0,4.0)
        };
    const std::vector<my_bundled_vertex> vertex_my_vertexes
        {
            get_bundled_vertex_my_vertexes(g)
        };
    assert(expected_my_vertexes == vertex_my_vertexes);
}
```

8.6.4 The .dot file produced

Algorithm 123 .dot file created from the 'create_bundled_vertices_markov_chain' function (algorithm 121), converted from graph to .dot file using algorithm 136

```
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

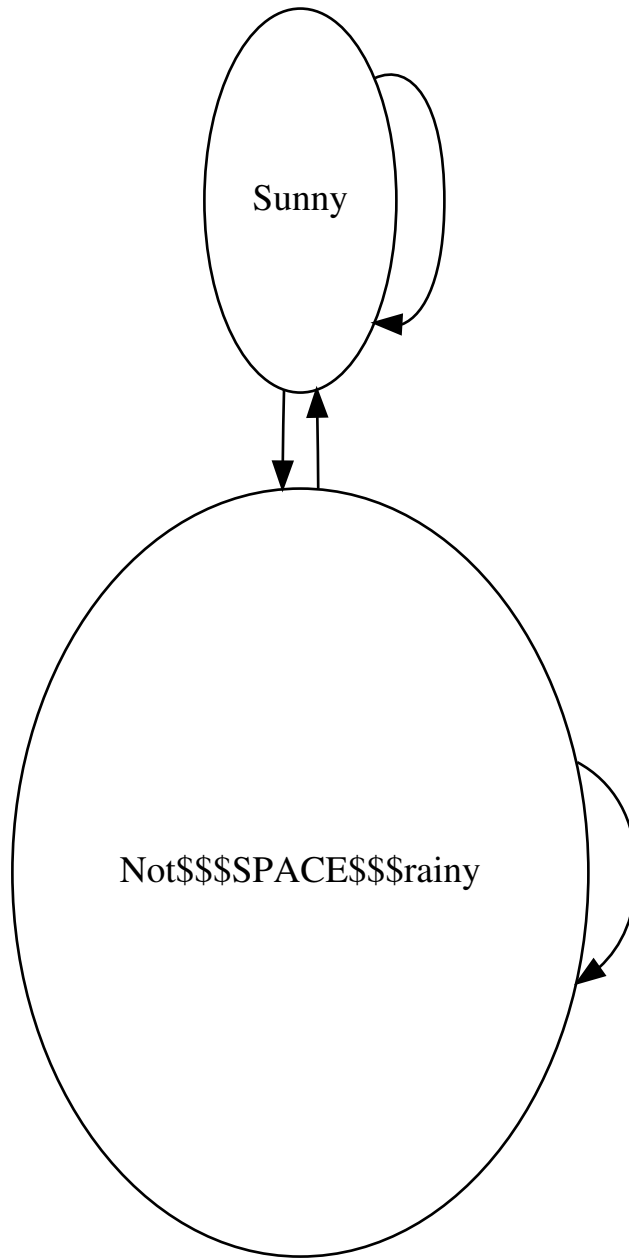


Figure 23: .svg file created from the 'create_bundled_vertices_markov_chain' function (algorithm 121) its .dot file, converted from .dot file to .svg using algorithm 268

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 instead, as show in figure 24:

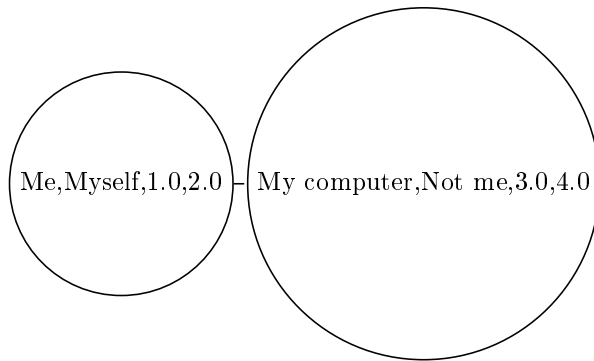


Figure 24: K_2 : a fully connected graph with two bundled vertices

8.7.2 Function to create such a graph

Algorithm 124 Creating K_2 as depicted in figure 16

```
#include "create_empty_undirected_bundled_vertices_graph.h"

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    my_bundled_vertex
>
create_bundled_vertices_k2_graph() noexcept
{
    auto g = create_empty_undirected_bundled_vertices_graph
        ();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer = boost::add_edge(vd_a, vd_b, g);
    assert(aer.second);
    g[vd_a] = my_bundled_vertex(
        "Me", "Myself", 1.0, 2.0
    );
    g[vd_b] = my_bundled_vertex(
        "My_computer", "Not_me", 3.0, 4.0
    );
    return g;
}
```

Most of the code is a slight modification of the 'create_named_vertices_k2_graph' function (algorithm 60). 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 125 Demo of the 'create_bundled_vertices_k2_graph' function (algorithm 124)

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

void create_bundled_vertices_k2_graph_demo() noexcept
{
    const auto g = create_bundled_vertices_k2_graph();
    assert(boost::num_edges(g) == 1);
    assert(boost::num_vertices(g) == 2);
    assert(has_bundled_vertex_with_my_vertex(
        my_bundled_vertex("Me", "Myself", 1.0, 2.0), g)
    );
    assert(has_bundled_vertex_with_my_vertex(
        my_bundled_vertex("My_computer", "Not_me", 3.0, 4.0), g)
    );
}
```

8.7.4 The .dot file produced

Algorithm 126 .dot file created from the 'create_bundled_vertices_k2_graph' function (algorithm 124), converted from graph to .dot file using algorithm 43

8.7.5 The .svg file produced

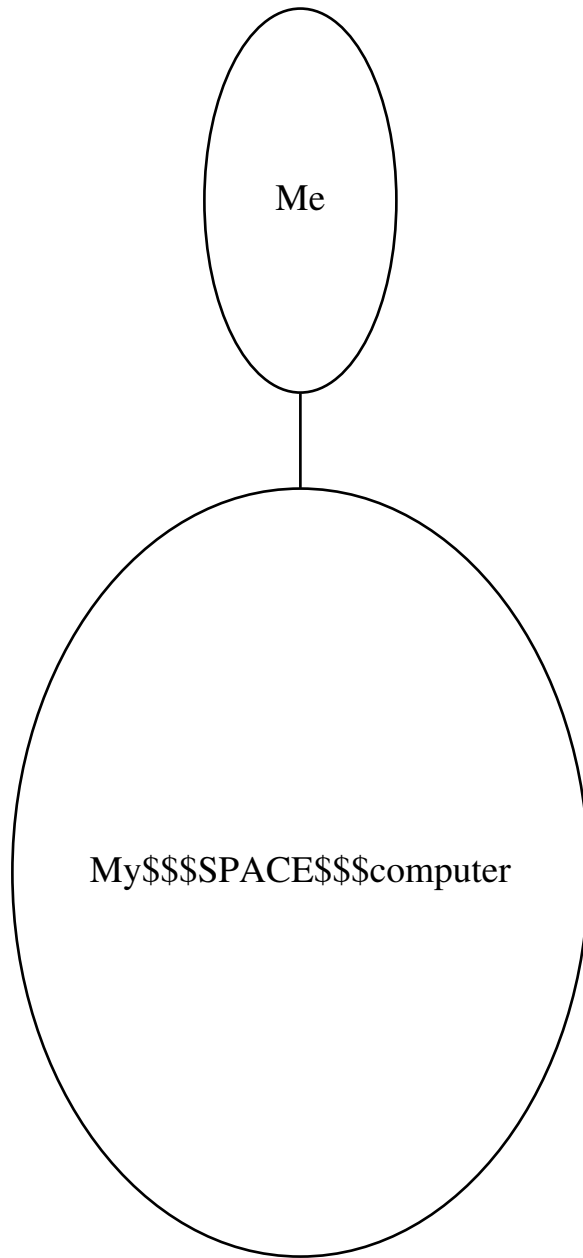


Figure 25: .svg file created from the 'create_bundled_vertices_k2_graph' function (algorithm 124) its .dot file, converted from .dot file to .svg using algorithm 268

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 127 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
{
    const auto vip
        = vertices(g); //not boost::vertices
    const auto j = vip.second;
    for (auto i = vip.first; i!=j; ++i) {
        if (g[*i] == v) {
            return true;
        }
    }
    return false;
}
```

This function can be demonstrated as in algorithm 128, where a certain `my_bundled_vertex` cannot be found in an empty graph. After adding the desired `my_bundled_vertex`, it is found.

Algorithm 128 Demonstration of the 'has_bundled_vertex_with_my_vertex' function

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

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

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

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

9.2 Find a bundled vertex with a certain my_bundled_vertex

Where STL functions work with iterators, here we obtain a vertex descriptor (see chapter 2.6) to obtain a handle to the desired vertex. Algorithm 129 shows how to obtain a vertex descriptor to the first vertex found with a specific 'my_bundled_vertex' value.

Algorithm 129 Find the first vertex with a certain `my_bundled_vertex`

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

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_bundled_vertex_with_my_vertex(
    const my_bundled_vertex& v,
    const graph& g
) noexcept
{
    assert(has_bundled_vertex_with_my_vertex(v, g));
    const auto vip
        = vertices(g); //not boost::vertices
    const auto j = vip.second;

    for (auto i = vip.first; i!=j; ++i) {
        if (g[*i] == v) { return *i; }
    }
    assert(!"Should_not_get_here");
    throw; //Will crash the program
}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 130 shows some examples of how to do so.

Algorithm 130 Demonstration of the 'find_first_bundled_vertex_with_my_vertex' function

```
#include <cassert>

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

void find_first_bundled_vertex_with_my_vertex_demo()
    noexcept
{
    const auto g = create_bundled_vertices_k2_graph();
    const auto vd =
        find_first_bundled_vertex_with_my_vertex(
            my_bundled_vertex("Me", "Myself", 1.0, 2.0),
            g
        );
    assert(out_degree(vd, g) == 1); //not boost::out_degree
    assert(in_degree(vd, g) == 1); //not boost::in_degree
}
```

9.3 Get a bundled vertex its 'my_bundled_vertex'

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

Algorithm 131 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_bundled_vertex_my_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 132 shows a simple example.

Algorithm 132 Demonstration if the 'get_bundled_vertex_my_vertex' function

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

void get_bundled_vertex_my_vertex_demo() noexcept
{
    auto g
        = create_empty_undirected_bundled_vertices_graph();
    const my_bundled_vertex v{"Dex"};
    add_bundled_vertex(v, g);
    const auto vd
        = find_first_bundled_vertex_with_my_vertex(v, g);
    assert(get_bundled_vertex_my_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 133.

Algorithm 133 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_bundled_vertex_my_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 134 shows a simple example.

Algorithm 134 Demonstration if the 'set_bundled_vertex_my_vertex' function

```
#include <cassert>

#include "add_bundled_vertex.h"
#include "create_empty_undirected_bundled_vertices_graph.h"
#include "find_first_bundled_vertex_with_my_vertex.h"
#include "get_bundled_vertex_my_vertex.h"
#include "set_bundled_vertex_my_vertex.h"

void set_bundled_vertex_my_vertex_demo() noexcept
{
    auto g = create_empty_undirected_bundled_vertices_graph();
    const my_bundled_vertex old_name{"Dex"};
    add_bundled_vertex(old_name, g);
    const auto vd =
        find_first_bundled_vertex_with_my_vertex(old_name, g);
    assert(get_bundled_vertex_my_vertex(vd, g) == old_name);
    const my_bundled_vertex new_name{"Diggy"};
    set_bundled_vertex_my_vertex(new_name, vd, g);
    assert(get_bundled_vertex_my_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 135 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_bundled_vertex_my_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); //not boost::vertices
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 124) to produce a K_2 graph with vertices associated with 'my_bundled_vertex' objects, you can store these with algorithm 136:

Algorithm 136 Storing a graph with bundled vertices as a .dot file

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

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

This code looks small, because we call the 'make_bundled_vertices_writer' function, which is shown in algorithm 137:

Algorithm 137 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 138:

Algorithm 138 The 'bundled_vertices_writer' function

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

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

    }

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

private:
    graph m_g;
};
```

Here, some interesting things are happening: the writer needs the bundled property maps to work with and thus copies the whole graph to its internals. I have chosen to map the 'my_bundled_vertex' member variables to Graphviz attributes (see chapter 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 139:

Algorithm 139 Loading a directed graph with bundled vertices from a .dot file

```

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    my_bundled_vertex
>
load_directed_bundled_vertices_graph_from_dot(
    const std::string& dot_filename
)
{
    assert(is_regular_file(dot_filename));
    std::ifstream f(dot_filename.c_str());
    auto g = create_empty_directed_bundled_vertices_graph();
        ;

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

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

    return g;
}

```

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

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

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

Algorithm 140 shows how to use the `'load_directed_bundled_vertices_graph_from_dot'` function:

Algorithm 140 Demonstration of the `'load_directed_bundled_vertices_graph_from_dot'` function

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

#include "save_bundled_vertices_graph_to_dot.h"
#include "get_bundled_vertex_my_vertexes.h"

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

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

This demonstration shows how the Markov chain is created using the `'create_bundled_vertices_markov_chain'` function (algorithm 121), 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 141:

Algorithm 141 Loading an undirected graph with bundled vertices from a .dot file

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    my_bundled_vertex
>
load_undirected_bundled_vertices_graph_from_dot(
    const std::string& dot_filename
)
{
    assert(is_regular_file(dot_filename));
    std::ifstream f(dot_filename.c_str());
    auto g = create_empty_undirected_bundled_vertices_graph
        ();

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

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

    return g;
}
```

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

Algorithm 142 shows how to use the 'load_undirected_bundled_vertices_graph_from_dot' function:

Algorithm 142 Demonstration of the 'load_undirected_bundled_vertices_graph_from_dot' function

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

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

    const auto g
        = create_bundled_vertices_k2_graph();
    const std::string filename{
        "create_bundled_vertices_k2_graph.dot"
    };
    save_bundled_vertices_graph_to_dot(g, filename);
    const auto h
        = load_undirected_bundled_vertices_graph_from_dot(
            filename);
    assert(num_edges(g) == num_edges(h));
    assert(num_vertices(g) == num_vertices(h));
    assert(get_bundled_vertex_my_vertexes(g)
        == get_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 124), 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' type¹⁰.

- 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.

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

Algorithm 143 Declaration of `my_bundled_edge`

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

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

bool operator==(const my_bundled_edge& lhs, const
    my_bundled_edge& rhs) noexcept;
bool operator!=(const my_bundled_edge& lhs, const
    my_bundled_edge& rhs) noexcept;
```

`my_bundled_edge` is a class that has multiple properties: two doubles `'m_width'` (`'m_'` stands for member) and `'m_height'`, and two `std::string`s `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 144 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 boost::adjacency_list<
        boost::vecS,
        boost::vecS,
        boost::directedS,
        my_bundled_vertex,
        my_bundled_edge
    >();
}
```

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 145 Demonstration of the 'create_empty_directed_bundled_edges_and_vertices_graph' function

```
#include "
    create_empty_directed_bundled_edges_and_vertices_graph
    .h"

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

10.3 Create an empty undirected graph with bundled edges and vertices

Algorithm 146 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 boost::adjacency_list<
        boost::vecS,
        boost::vecS,
        boost::undirectedS,
        my_bundled_vertex,
        my_bundled_edge
    >();
}
```

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 147 Demonstration of the 'create_empty_undirected_bundled_edges_and_vertices_graph' function

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

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

10.4 Add a bundled edge

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

Algorithm 148 Add a bundled edge

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

template <typename graph>
void add_bundled_edge(
    const my_bundled_edge& v,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value, "graph_
        cannot_be_const");

    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);

    const auto aer = boost::add_edge(vd_a, vd_b, g);
    assert(aer.second);
    g[aer.first] = v;
}
```

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 149 Demo of 'add_bundled_edge'

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

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

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

10.5 Getting the bundled edges my_edges

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

Algorithm 150 Get the edges' my_bundled_edges

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

template <typename graph>
std::vector<my_bundled_edge> get_bundled_edge_my_edges(
    const graph& g
) noexcept
{
    std::vector<my_bundled_edge> v;

    const auto vip
        = edges(g); //not boost::edges
    const auto j = vip.second;

    for (auto i = vip.first; i!=j; ++i) {
        v.emplace_back(g[*i]);
    }
    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 26 shows the graph that will be reproduced:

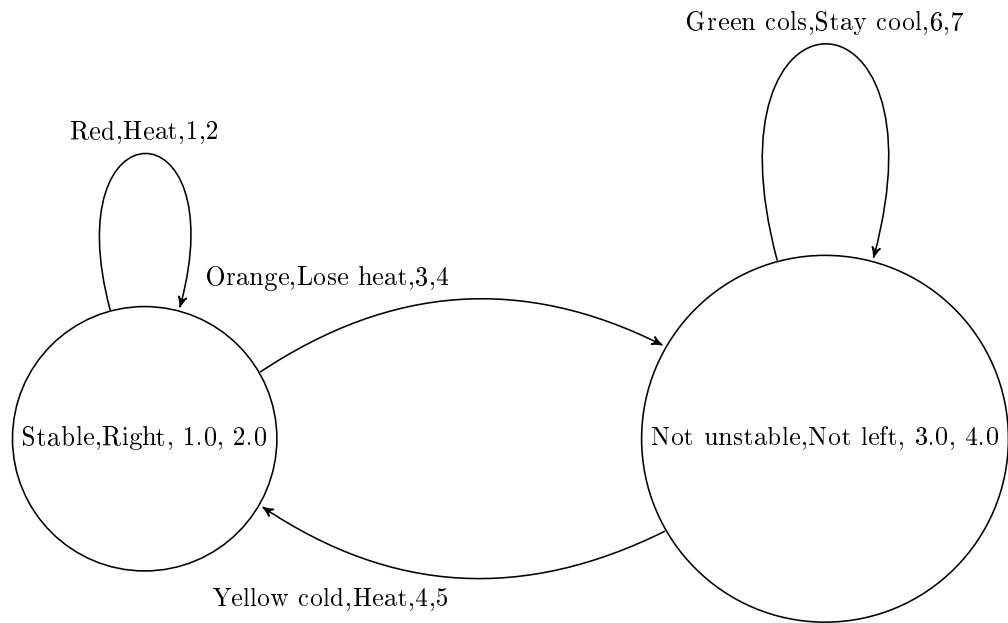


Figure 26: A two-state Markov chain where the edges and vertices have bundled properties. The edges' and vertices' properties are nonsensical

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

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    my_bundled_vertex,
    my_bundled_edge
>
create_bundled_edges_and_vertices_markov_chain() noexcept
{
    auto g
        =
            create_empty_directed_bundled_edges_and_vertices_graph
            ();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
    assert(aer_aa.second);
    const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
    assert(aer_ab.second);
    const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
    assert(aer_ba.second);
    const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
    assert(aer_bb.second);

    g[vd_a]
        = my_bundled_vertex("Stable", "Right", 1.0, 2.0);
    g[vd_b]
        = my_bundled_vertex("Not_unstable", "Not_left",
            , 3.0, 4.0);

    g[aer_aa.first]
        = my_bundled_edge("Red", "Heat", 1.0, 2.0);
    g[aer_ab.first]
        = my_bundled_edge("Orange", "Lose_heat", 3.0, 4.0);
    g[aer_ba.first]
        = my_bundled_edge("Yellow_cold", "Heat", 5.0, 6.0);
    g[aer_bb.first]
        = my_bundled_edge("Green_cold", "Stay_cool", 7.0, 8.0);

    return g;
}
```

10.6.3 Creating such a graph

Here is the demo:

Algorithm 152 Demo of the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 151)

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

void create_bundled_edges_and_vertices_markov_chain_demo
() noexcept
{
    const auto g =
        create_bundled_edges_and_vertices_markov_chain();
    const std::vector<my_bundled_edge> edge_my_edges{
        get_bundled_edge_my_edges(g)
    };
    const std::vector<my_bundled_edge> expected_my_edges{
        my_bundled_edge("Red","Heat",1.0,2.0),
        my_bundled_edge("Orange","Lose_heat",3.0,4.0),
        my_bundled_edge("Yellow_cold","Heat",5.0,6.0),
        my_bundled_edge("Green_cold","Stay_cool",7.0,8.0)
    };
    assert(edge_my_edges == expected_my_edges);
}
```

10.6.4 The .dot file produced

Algorithm 153 .dot file created from the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 151), converted from graph to .dot file using algorithm 43

```
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

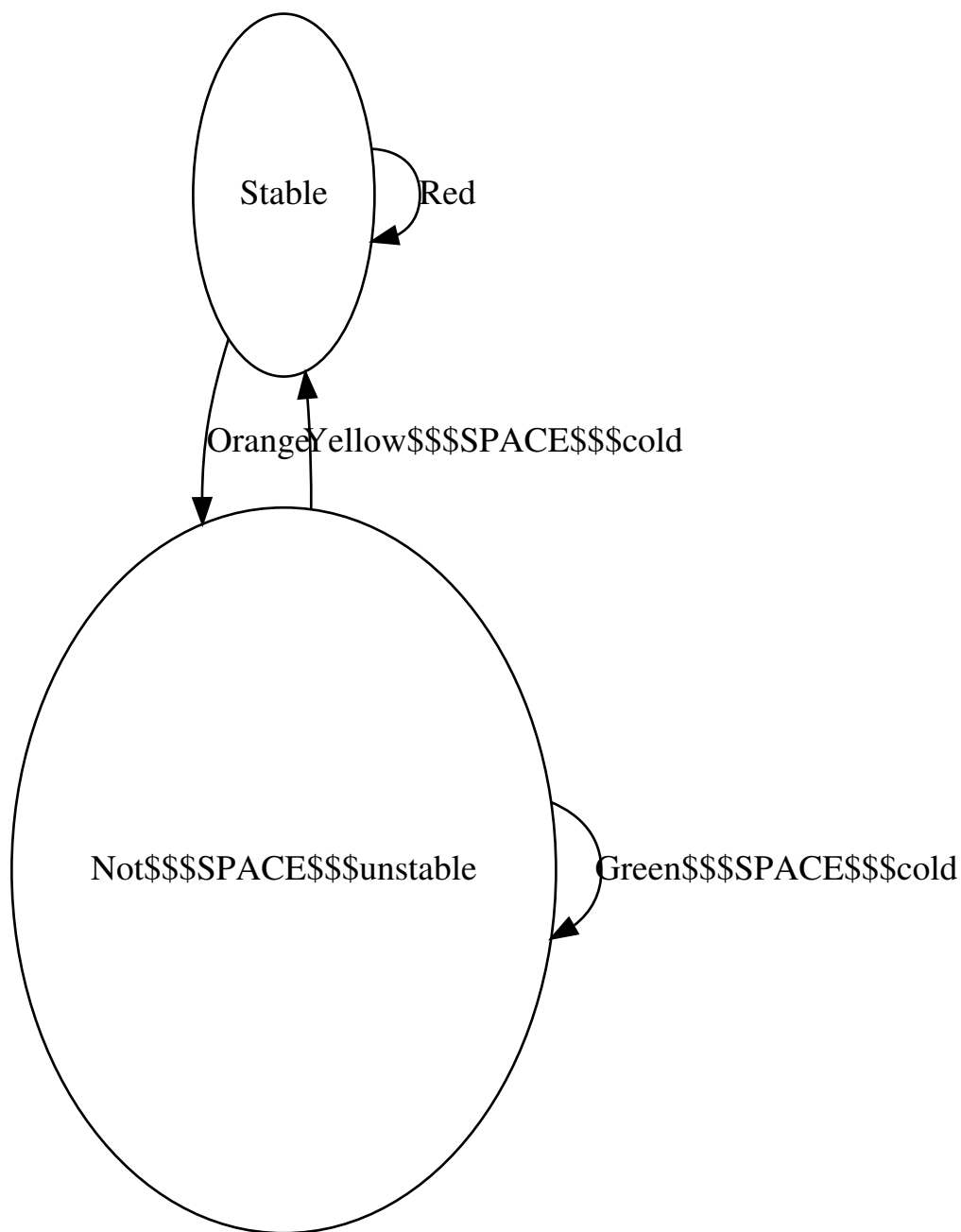


Figure 27: .svg file created from the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 180) its .dot file, converted from .dot file to .svg using algorithm 268

10.7 Creating K_3 with bundled edges and vertices

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

10.7.1 Graph

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

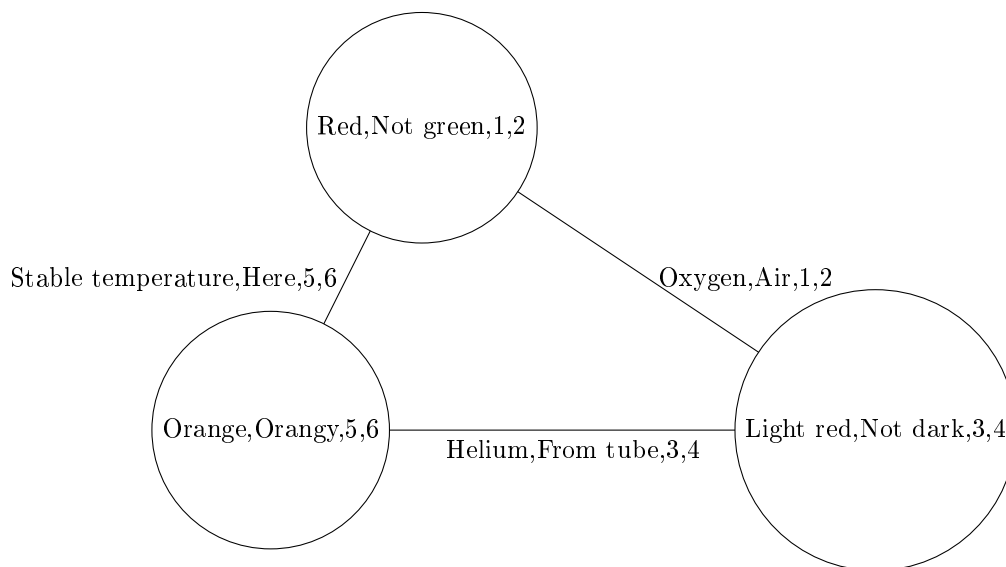


Figure 28: K_3 : a fully connected graph with three named edges and vertices

10.7.2 Function to create such a graph

Algorithm 154 Creating K_3 as depicted in figure 20

```
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    my_bundled_vertex,
    my_bundled_edge
>
create_bundled_edges_and_vertices_k3_graph() noexcept
{
    auto g
        =
            create_empty_undirected_bundled_edges_and_vertices_graph
            ();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto vd_c = boost::add_vertex(g);
    const auto aer_a = boost::add_edge(vd_a, vd_b, g);
    const auto aer_b = boost::add_edge(vd_b, vd_c, g);
    const auto aer_c = boost::add_edge(vd_c, vd_a, g);
    assert(aer_a.second);
    assert(aer_b.second);
    assert(aer_c.second);

    g[vd_a]
        = my_bundled_vertex("Red", "Not_green", 1.0, 2.0);
    g[vd_b]
        = my_bundled_vertex("Light_red", "Not_dark", 3.0, 4.0);
    g[vd_c]
        = my_bundled_vertex("Orange", "Orangy", 5.0, 6.0);

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

    return g;
}
```

Most of the code is a slight modification of algorithm 98. 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 155 Demo of the `'create_bundled_edges_and_vertices_k3_graph'` function (algorithm 154)

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

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

10.7.4 The .dot file produced

Algorithm 156 .dot file created from the `'create_bundled_edges_and_vertices_markov_chain'` function (algorithm 154), converted from graph to .dot file using algorithm 43

```
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

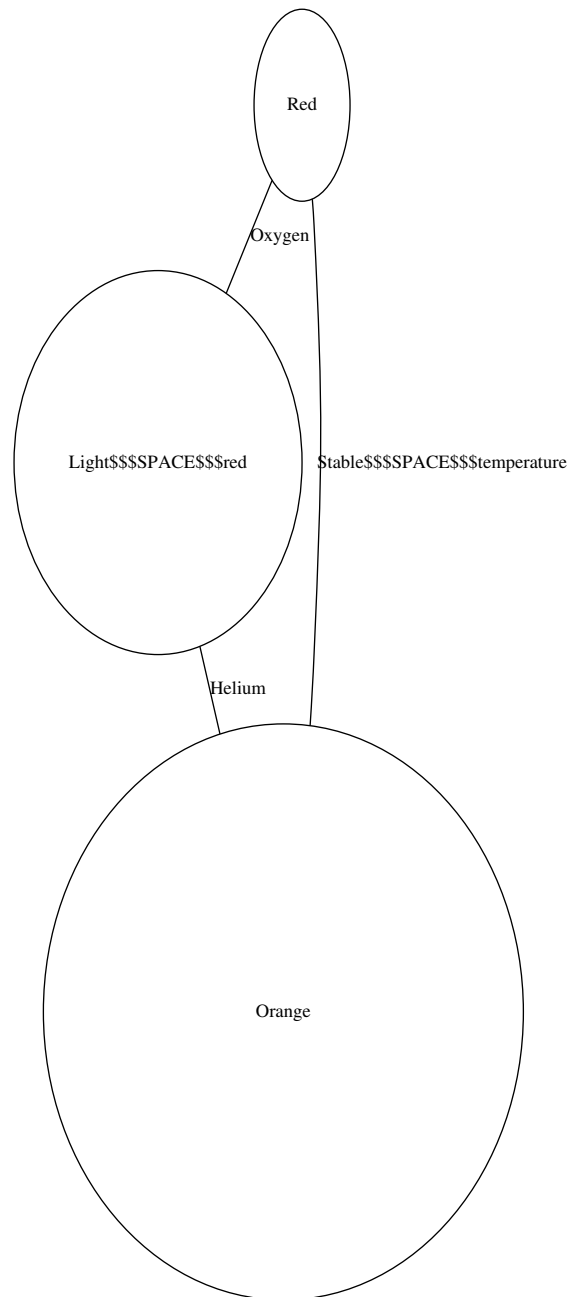


Figure 29: .svg file created from the 'create_bundled_edges_and_vertices_k3_graph' function (algorithm 180) its .dot file, converted from .dot file to .svg using algorithm 268

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 obtaining 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 157 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
{
    const auto eip
        = edges(g); //not boost::edges
    const auto j = eip.second;

    for (auto i = eip.first; i!=j; ++i) {
        if (g[*i] == e) {
            return true;
        }
    }
    return false;
}
```

This function can be demonstrated as in algorithm 158, where a certain 'my_bundled_edge' cannot be found in an empty graph. After adding the desired my_bundled_edge, it is found.

Algorithm 158 Demonstration of the 'has_bundled_edge_with_my_edge' function

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

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

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

11.2 Find a my_bundled_edge

Where STL functions work with iterators, here we obtain an edge descriptor (see chapter 2.12) to obtain a handle to the desired edge. Algorithm 159 shows how to obtain an edge descriptor to the first edge found with a specific my_bundled_edge value.

Algorithm 159 Find the first bundled edge with a certain `my_bundled_edge`

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

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
find_first_bundled_edge_with_my_edge(
    const my_bundled_edge& e,
    const graph& g
) noexcept
{
    assert(has_bundled_edge_with_my_edge(e, g));
    const auto eip = edges(g); //not boost::edges
    const auto j = eip.second;

    for (auto i = eip.first; i!=j; ++i) {
        if (g[*i] == e) {
            return *i;
        }
    }
    assert(!"Should_not_get_here");
    throw; //Will crash the program
}
```

With the edge descriptor obtained, one can read and modify the edge and the vertices surrounding it. Algorithm 160 shows some examples of how to do so.

Algorithm 160 Demonstration of the 'find_first_bundled_edge_with_my_edge' function

```
#include <cassert>

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

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

11.3 Get an edge its my_bundled_edge

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

Algorithm 161 Get a vertex its `my_bundled_vertex` from its vertex descriptor

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

template <typename graph>
my_custom_edge get_custom_edge_my_edge(
    const typename boost::graph_traits<graph>::
        edge_descriptor& vd,
    const graph& g
) noexcept
{
    const auto my_edge_map
        = get( //not boost::get
            boost::edge_custom_type,
            g
        );
    return my_edge_map[vd];
}
```

To use '`get_bundled_edge_my_bundled_edge`', one first needs to obtain an edge descriptor. Algorithm 162 shows a simple example.

Algorithm 162 Demonstration if the 'get_bundled_edge_my_edge' function

```
#include <cassert>

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

void get_bundled_edge_my_edge_demo() noexcept
{
    auto g
        =
            create_empty_undirected_bundled_edges_and_vertices_graph
            ();
    const my_bundled_edge edge{"Dex"};
    add_bundled_edge(edge, g);
    const auto ed
        = find_first_bundled_edge_with_my_edge(edge, g);
    assert(get_bundled_edge_my_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 163.

Algorithm 163 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_bundled_edge_my_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 164 shows a simple example.

Algorithm 164 Demonstration if the 'set_bundled_edge_my_edge' function

```
#include <cassert>

#include "add_bundled_edge.h"
#include "
    create_empty_undirected_bundled_edges_and_vertices_graph
    .h"
#include "find_first_bundled_edge_with_my_edge.h"
#include "get_bundled_edge_my_edge.h"
#include "set_bundled_edge_my_edge.h"

void set_bundled_edge_my_edge_demo() noexcept
{
    auto g
        =
            create_empty_undirected_bundled_edges_and_vertices_graph
            ();
    const my_bundled_edge old_edge{"Dex"};
    add_bundled_edge(old_edge, g);
    const auto vd
        = find_first_bundled_edge_with_my_edge(old_edge, g);
    assert(get_bundled_edge_my_edge(vd, g)
        == old_edge
    );
    const my_bundled_edge new_edge{"Diggy"};
    set_bundled_edge_my_edge(new_edge, vd, g);
    assert(get_bundled_edge_my_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 154) 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 165:

Algorithm 165 Storing a graph with bundled edges and vertices as a .dot file

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

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

/*
#include <fstream>
#include <string>
#include <boost/graph/graphviz.hpp>
#include <boost/graph/properties.hpp>
#include "get_bundled_edge_my_edge.h"
#include "get_bundled_vertex_my_vertexes.h"

template <typename graph>
void save_bundled_edges_and_vertices_graph_to_dot(
    const graph& g,
    const std::string& filename
)
{
    using my_vertex_descriptor = typename graph::
        vertex_descriptor;
    using my_edge_descriptor = typename graph::
        edge_descriptor;
    std::ofstream f(filename);
    boost::write_graphviz(
        f,
        g,
        [g](
            std::ostream& out,
            const my_vertex_descriptor& v
        ) {
            const my_bundled_vertices& m{g[v]};
            out << "[label="
                << m.m_name
                << ", "
                << m.m_description
                << ", "
                << m.m_x
                << ", "

```

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 166:

Algorithm 166 Loading a directed graph with bundled edges and vertices from a .dot file

```

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    my_bundled_vertex,
    my_bundled_edge
>
load_directed_bundled_edges_and_vertices_graph_from_dot(
    const std::string& dot_filename
)
{
    assert(is_regular_file(dot_filename));
    std::ifstream f(dot_filename.c_str());
    auto g =
        create_empty_directed_bundled_edges_and_vertices_graph
        ();

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

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

```


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

Algorithm 167 shows how to use the `'load_directed_bundled_edges_and_vertices_graph_from_dot'` function:

Algorithm 167 Demonstration of the 'load_directed_bundled_edges_and_vertices_graph_from_dot' function

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

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

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

This demonstration shows how the Markov chain is created using the 'create_bundled_edges_and_vertices_markov_chain' function (algorithm 151), 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 168:

Algorithm 168 Loading an undirected graph with bundled edges and vertices from a .dot file

```

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    my_bundled_vertex,
    my_bundled_edge
>
load_undirected_bundled_edges_and_vertices_graph_from_dot
(
    const std::string& dot_filename
)
{
    assert(is_regular_file(dot_filename));
    std::ifstream f(dot_filename.c_str());
    auto g =
        create_empty_undirected_bundled_edges_and_vertices_graph
        ();

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

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

```

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

Algorithm 169 shows how to use the 'load_undirected_bundled_vertices_graph_from_dot' function:

Algorithm 169 Demonstration of the 'load_undirected_bundled_edges_and_vertices_graph_from_dot' function

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

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

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

This demonstration shows how K_2 with bundled vertices is created using the 'create_bundled_vertices_k2_graph' function (algorithm 183), 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 172
- 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 170 Declaration of `my_custom_vertex`

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

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

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

'`my_custom_vertex`' is a class that has multiple properties:

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

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

Special characters like comma's, quotes and whitespace cannot be streamed without problems. The function 'graphviz_encode' (algorithm 265) can convert the elements to be streamed to a Graphviz-friendly version, which can be decoded by 'graphviz_decode' (algorithm 266).

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 171 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 172 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 boost::adjacency_list<
        boost::vecS,
        boost::vecS,
        boost::directedS,
        boost::property<
            boost::vertex_custom_type_t, my_custom_vertex
        >
    >();
}
```

This graph:

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

The `boost::adjacency_list` has a new, fourth template argument '`boost::property< boost::vertex_custom_type_t, my_vertex>`'. This can be read as: "vertices

have the property 'boost::vertex_custom_type_t', which is of data type 'my_vertex'.
Or simply: "vertices have a custom type called my_vertex".

The demo:

Algorithm 173 Demo how to create an empty directed graph with custom vertices

```
#include "create_empty_directed_custom_vertices_graph.h"

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

12.4 Create the empty undirected graph with custom vertices

Algorithm 174 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 boost::adjacency_list<
        boost::vecS,
        boost::vecS,
        boost::undirectedS,
        boost::property<
            boost::vertex_custom_type_t, my_custom_vertex
        >
    >();
}
```

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 175 Demo how to create an empty undirected graph with custom vertices

```
#include "create_empty_undirected_custom_vertices_graph.h"

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

12.5 Add a custom vertex

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

Algorithm 176 Add a custom vertex

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

template <typename graph>
void add_custom_vertex(
    const my_custom_vertex& v,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value,
        "graph_cannot_be_const");

    const auto vd_a = boost::add_vertex(g);
    const auto my_custom_vertex_map
        = get( //not boost::get
            boost::vertex_custom_type,
            g
        );
    my_custom_vertex_map[vd_a] = v;
}
```

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

Here is the demo:

Algorithm 177 Demo of `'add_custom_vertex'`

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

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

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

12.6 Getting the vertices' `my_vertexes`¹¹

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

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

Algorithm 178 Get the vertices' my_vertexes

```
#include <vector>
#include "install_vertex_custom_type.h"
#include "my_custom_vertex.h"

template <typename graph>
std::vector<my_custom_vertex>
    get_custom_vertex_my_vertexes(
        const graph& g
    ) noexcept
{
    std::vector<my_custom_vertex> v;

    const auto my_custom_vertexes_map
        = get( //not boost::get
              boost::vertex_custom_type, g
            );
    const auto vip
        = vertices(g); //not boost::vertices
    const auto j = vip.second;

    for (auto i = vip.first; i!=j; ++i) {
        v.emplace_back(
            get( //not boost::get
                my_custom_vertexes_map, *i
            )
        );
    }
    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 179 Demo how to the vertices' my_custom_vertex objects

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

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

12.7 Creating a two-state Markov chain with custom vertices

12.7.1 Graph

Figure 30 shows the graph that will be reproduced:

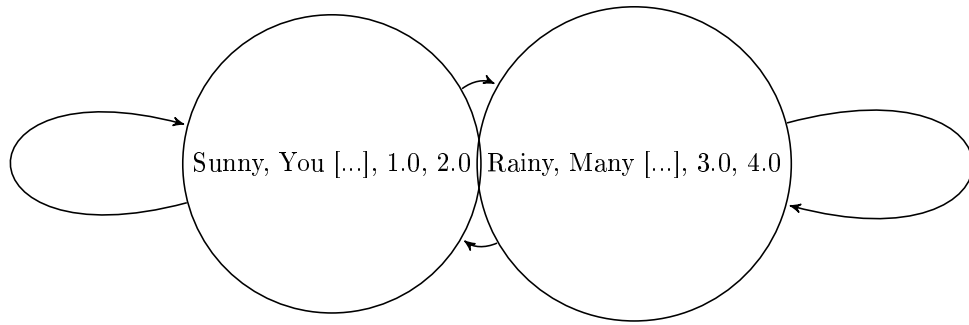


Figure 30: A two-state Markov chain where the vertices have custom properties and the edges have no properties. The vertices' properties are nonsensical

12.7.2 Function to create such a graph

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

Algorithm 180 Creating the two-state Markov chain as depicted in figure 30

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    boost::property<
        boost::vertex_custom_type_t, my_custom_vertex
    >
>
>
create_custom_vertices_markov_chain() noexcept
{
    auto g
        = create_empty_directed_custom_vertices_graph();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
    assert(aer_aa.second);
    const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
    assert(aer_ab.second);
    const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
    assert(aer_ba.second);
    const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
    assert(aer_bb.second);

    auto my_custom_vertex_map = get( //not boost::get
        boost::vertex_custom_type, g
    );
    my_custom_vertex_map[vd_a] = my_custom_vertex("Sunny",
        "Yellow_thing", 1.0, 2.0
    );
    my_custom_vertex_map[vd_b] = my_custom_vertex("Rainy",
        "Grey_things", 3.0, 4.0
    );

    return g;
}
```

12.7.3 Creating such a graph

Here is the demo:

Algorithm 181 Demo of the 'create_custom_vertices_markov_chain' function (algorithm 180)

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

void create_custom_vertices_markov_chain_demo() noexcept
{
    const auto g
        = create_custom_vertices_markov_chain();
    const std::vector<my_custom_vertex>
        expected_my_custom_vertexes{
            my_custom_vertex("Sunny", "Yellow_thing", 1.0, 2.0),
            my_custom_vertex("Rainy", "Grey_things", 3.0, 4.0)
        };
    const std::vector<my_custom_vertex>
        vertex_my_custom_vertexes{
            get_custom_vertex_my_vertexes(g)
        };
    assert(expected_my_custom_vertexes
        == vertex_my_custom_vertexes
    );
}
```

12.7.4 The .dot file produced

Algorithm 182 .dot file created from the 'create_custom_vertices_markov_chain' function (algorithm 180), converted from graph to .dot file using algorithm 195

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

This .dot file may look unexpectedly different: instead of a space, there is this '[:SPACE:]' thing. This is because the function 'graphviz_encode' (algorithm 265) 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

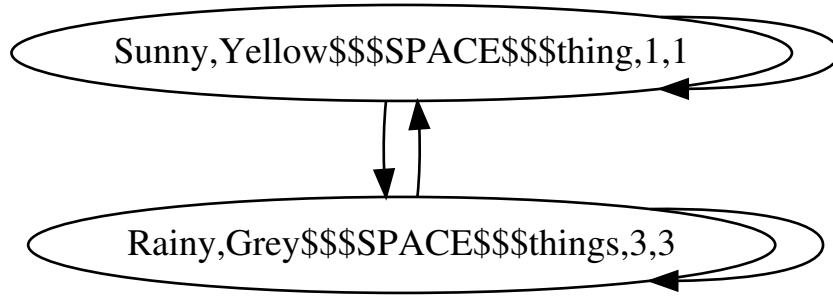


Figure 31: .svg file created from the 'create_custom_vertices_markov_chain' function (algorithm 180) its .dot file, converted from .dot file to .svg using algorithm 268

This .svg file may look unexpectedly different: instead of a space, there is this '[:SPACE:]' thing. This is because the function 'graphviz_encode' (algorithm 265) 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 instead.

12.8.2 Function to create such a graph

Algorithm 183 Creating K_2 as depicted in figure 16

```
#include "create_empty_undirected_custom_vertices_graph.h"
"

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::property<
        boost::vertex_custom_type_t, my_custom_vertex
    >
>
>
create_custom_vertices_k2_graph() noexcept
{
    auto g = create_empty_undirected_custom_vertices_graph
        ();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer = boost::add_edge(vd_a, vd_b, g);
    assert(aer.second);

    auto my_custom_vertex_map = get( //not boost::get
        boost::vertex_custom_type, g
    );
    my_custom_vertex_map[vd_a]
        = my_custom_vertex("A", "source", 0.0, 0.0);
    my_custom_vertex_map[vd_b]
        = my_custom_vertex("B", "target", 3.14, 3.14);

    return g;
}
```

Most of the code is a slight modification of the 'create_named_vertices_k2_graph' function (algorithm 60). 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 184 Demo of the 'create_custom_vertices_k2_graph' function (algorithm 183)

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

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

12.8.4 The .dot file produced

Algorithm 185 .dot file created from the 'create_custom_vertices_k2_graph' function (algorithm 183), converted from graph to .dot file using algorithm 43

```
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

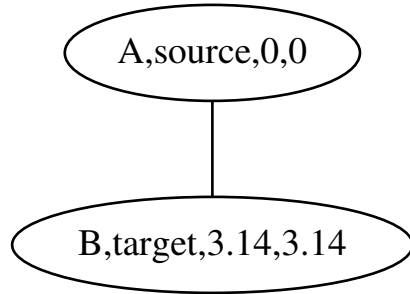


Figure 32: .svg file created from the 'create_custom_vertices_k2_graph' function (algorithm 183) its .dot file, converted from .dot file to .svg using algorithm 268

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

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

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

13.1 Has a custom vertex with a my_vertex

Before modifying our vertices, let's first determine if we can find a vertex by its custom type ('my_vertex') in a graph. After obtaining 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 186 Find if there is vertex with a certain `my_vertex`

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

template <typename graph>
bool has_custom_vertex_with_my_custom_vertex(
    const my_custom_vertex& v,
    const graph& g
) noexcept
{
    const auto my_custom_vertexes_map
        = get(boost::vertex_custom_type, g);
    const auto vip
        = vertices(g); //not boost::vertices
    const auto j = vip.second;
    for (auto i = vip.first; i!=j; ++i) {
        if (
            get( //not boost::get
                my_custom_vertexes_map,
                *i
            ) == v) {
            return true;
        }
    }
    return false;
}
```

This function can be demonstrated as in algorithm 187, where a certain `my_vertex` cannot be found in an empty graph. After adding the desired `my_vertex`, it is found.

Algorithm 187 Demonstration of the 'has_custom_vertex_with_my_vertex' function

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

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

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

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

13.2 Find a custom vertex with a certain my_vertex

Where STL functions work with iterators, here we obtain a vertex descriptor (see chapter 2.6) to obtain a handle to the desired vertex. Algorithm 188 shows how to obtain a vertex descriptor to the first vertex found with a specific my_vertex value.

Algorithm 188 Find the first vertex with a certain `my_vertex`

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

template <typename graph>
typename boost::graph_traits<graph>::vertex_descriptor
find_first_custom_vertex_with_my_vertex(
    const my_custom_vertex& v,
    const graph& g
) noexcept
{
    assert(has_custom_vertex_with_my_custom_vertex(v, g));
    const auto my_custom_vertexes_map = get(boost::
        vertex_custom_type, g);
    const auto vip
        = vertices(g); //not boost::vertices
    const auto j = vip.second;

    for (auto i = vip.first; i!=j; ++i) {
        const auto w
            = get( //not boost::get
                my_custom_vertexes_map,
                *i
            );
        if (w == v) { return *i; }
    }
    assert(!"Should_not_get_here");
    throw; //Will crash the program
}
```

With the vertex descriptor obtained, one can read and modify the vertex and the edges surrounding it. Algorithm 189 shows some examples of how to do so.

Algorithm 189 Demonstration of the 'find_first_custom_vertex_with_my_vertex' function

```
#include <cassert>

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

void find_first_custom_vertex_with_my_vertex_demo()
    noexcept
{
    const auto g = create_custom_vertices_k2_graph();
    const auto vd = find_first_custom_vertex_with_my_vertex
        (
            my_custom_vertex("A", "source", 0.0, 0.0),
            g
        );
    assert(out_degree(vd, g) == 1); //not boost::out_degree
    assert(in_degree(vd, g) == 1); //not boost::in_degree
}
```

13.3 Get a custom vertex its my_vertex

To obtain the name from a vertex descriptor, one needs to pull out the my_vertexes¹² map and then look up the vertex of interest.

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

Algorithm 190 Get 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>
my_custom_vertex get_custom_vertex_my_custom_vertex(
    const typename boost::graph_traits<graph>::
        vertex_descriptor& vd,
    const graph& g
) noexcept
{
    const auto my_custom_vertexes_map
        = get( //not boost::get
            boost::vertex_custom_type,
            g
        );
    return my_custom_vertexes_map[vd];
}
```

To use 'get_custom_vertex_my_vertex', one first needs to obtain a vertex descriptor. Algorithm 191 shows a simple example.

Algorithm 191 Demonstration if the 'get_custom_vertex_my_vertex' function

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

void get_custom_vertex_my_custom_vertex_demo() noexcept
{
    auto g = create_empty_undirected_custom_vertices_graph
        ();
    const my_custom_vertex name{"Dex"};
    add_custom_vertex(name, g);
    const auto vd
        = find_first_custom_vertex_with_my_vertex(name, g);
    assert(get_custom_vertex_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 192.

Algorithm 192 Set a custom vertex its `my_vertex` from its vertex descriptor

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

template <typename graph>
void set_custom_vertex_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( //not boost::get
        boost::vertex_custom_type, g
    );
my_custom_vertexes_map[vd] = v;
}
```

To use 'set_vertex_my_vertex', one first needs to obtain a vertex descriptor. Algorithm 193 shows a simple example.

Algorithm 193 Demonstration if the 'set_custom_vertex_my_vertex' function

```
#include <cassert>

#include "add_custom_vertex.h"
#include "create_empty_undirected_custom_vertices_graph.h"
#include "find_first_custom_vertex_with_my_vertex.h"
#include "get_custom_vertex_my_vertex.h"
#include "set_custom_vertex_my_vertex.h"

void set_custom_vertex_my_custom_vertex_demo() noexcept
{
    auto g
        = create_empty_undirected_custom_vertices_graph();
    const my_custom_vertex old_vertex{"Dex"};
    add_custom_vertex(old_vertex, g);
    const auto vd
        = find_first_custom_vertex_with_my_vertex(old_vertex,
            g);
    assert(get_custom_vertex_my_custom_vertex(vd, g)
        == old_vertex
    );
    const my_custom_vertex new_vertex{"Diggy"};
    set_custom_vertex_my_custom_vertex(
        new_vertex, vd, g
    );
    assert(get_custom_vertex_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 194 Setting the custom vertices' my_vertexes

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

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

#include "install_vertex_custom_type.h"
#include "my_custom_vertex.h"

template <typename graph>
void set_custom_vertex_my_custom_vertexes(
    graph& g,
    const std::vector<my_custom_vertex>& my_custom_vertexes
) noexcept
{
    static_assert(!std::is_const<graph>::value, "graph_
        cannot_be_const");

    const auto my_custom_vertex_map
        = get( //not boost::get
            boost::vertex_custom_type, g
        );

    auto my_custom_vertexes_begin = std::begin(
        my_custom_vertexes);
    const auto my_custom_vertexes_end = std::end(
        my_custom_vertexes);
    const auto vip = vertices(g); //not boost::vertices
    const auto j = vip.second;
    for (
        auto i = vip.first;
        i!=j; ++i,
        ++my_custom_vertexes_begin
    ) {
        assert(my_custom_vertexes_begin !=
            my_custom_vertexes_end);
        put(my_custom_vertex_map, *i, *
            my_custom_vertexes_begin);
    }
}
```

An impressive feature is that getting the property map holding the graph its names is not a copy, but a reference. Otherwise, modifying 'my_vertexes_map'

(obtained by non-reference) would only modify a copy.

13.6 Storing a graph with custom vertices as a .dot

If you used the `create_custom_vertices_k2_graph` function (algorithm 183) to produce a K_2 graph with vertices associated with `my_vertex` objects, you can store these `my_vertexes` additionally with algorithm 195:

Algorithm 195 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_custom_vertex_my_vertexes.h"

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

    const auto my_custom_vertexes_map
        = get( //not boost::get
              boost::vertex_custom_type, g
            );
    boost::write_graphviz(
        f,
        g,
        [my_custom_vertexes_map](
            std::ostream& out,
            const my_custom_vertex_descriptor& v
        ) {
            const my_custom_vertex m{my_custom_vertexes_map[v]};
            out << "[label=\"" << m << "\"]";
        }
    );
}
```

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

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph with custom vertices is loaded, as shown in algorithm 196:

Algorithm 196 Loading a directed graph with custom vertices from a .dot file

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

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

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

Algorithm 197 shows how to use the 'load_directed_custom_vertices_graph_from_dot' function:

Algorithm 197 Demonstration of the 'load_directed_custom_vertices_graph_from_dot' function

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

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

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

This demonstration shows how the Markov chain is created using the 'create_custom_vertices_markov_chain' function (algorithm 180), saved and then loaded. The loaded graph is then checked to be identical to the original.

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

When loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph with custom vertices is loaded, as shown in algorithm 198:

Algorithm 198 Loading an undirected graph with custom vertices from a .dot file

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

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

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

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

Algorithm 199 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

Algorithm 199 Demonstration of the 'load_undirected_custom_vertices_graph_from_dot' function

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

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

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

This demonstration shows how K_2 with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 183), 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 200 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 201 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 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
            >
        >
    >
    >();
}
```

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 202 Demonstration of the ‘create_empty_directed_custom_and_selectable_vertices_graph’ function

```
#include "
    create_empty_directed_custom_and_selectable_vertices_graph
    .h"

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

14.3 Create an empty undirected graph with custom and selectable vertices

Algorithm 203 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 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
            >
        >
    >
    >()
};
}
```

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 204 Demonstration of the 'create_empty_undirected_custom_and_selectable_vertices_graph' function

```
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"

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

14.4 Add a custom and selectable vertex

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

Algorithm 205 Add a custom and selectable vertex

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

template <typename graph>
void add_custom_and_selectable_vertex(
    const my_custom_vertex& v,
    const bool is_selected,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value,
        "graph_cannot_be_const");
};

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

const auto my_custom_vertex_map
    = get( //not boost::get
        boost::vertex_custom_type,
        g
    );
my_custom_vertex_map[vd_a] = v;

const auto is_selected_map
    = get( //not boost::get
        boost::vertex_is_selected,
        g
    );
is_selected_map[vd_a] = is_selected;
}
```

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 206 Demo of 'add_custom_and_selectable_vertex'

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

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

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

14.5 Creating a Markov-chain with custom and selectable vertices

14.5.1 Graph

Figure 33 shows the graph that will be reproduced:

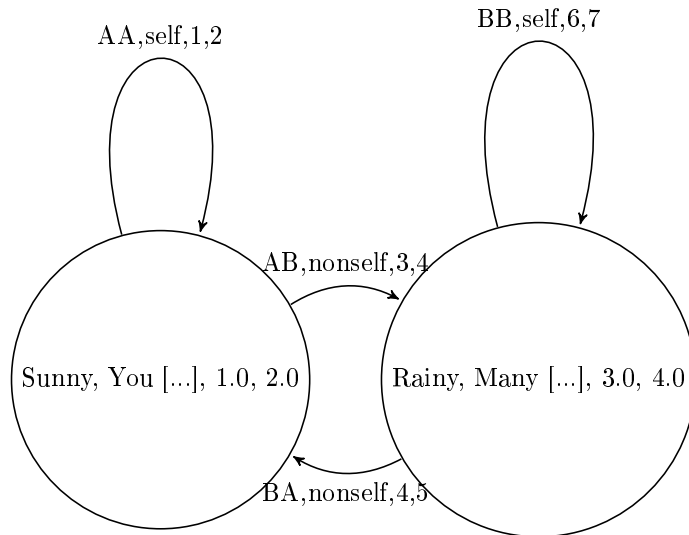


Figure 33: A two-state Markov chain where the edges and vertices have custom properties. The edges' and vertices' properties are nonsensical

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 207 Creating the two-state Markov chain as depicted in figure 33

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    boost::property<
        boost::vertex_custom_type_t, my_custom_vertex,
        boost::property<
            boost::vertex_is_selected_t, bool
        >
    >
>
>
>
create_custom_and_selectable_vertices_markov_chain()
    noexcept
{
    auto g
        =
            create_empty_directed_custom_and_selectable_vertices_graph
            ();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
    assert(aer_aa.second);
    const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
    assert(aer_ab.second);
    const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
    assert(aer_ba.second);
    const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
    assert(aer_bb.second);

    auto my_custom_vertex_map
        = get( //not boost::get
            boost::vertex_custom_type, g
        );
    my_custom_vertex_map[vd_a] = my_custom_vertex("Sunny",
        "Yellow_thing", 1.0, 2.0
    );
    my_custom_vertex_map[vd_b] = my_custom_vertex("Rainy",
        "Grey_things", 3.0, 4.0
    );

    auto is_selected_map
        = get( //not boost::get 228
            boost::vertex_is_selected, g
        );
    is_selected_map[vd_a] = true;
    is_selected_map[vd_b] = false;

    return g;
}
```

14.5.3 Creating such a graph

Here is the demo:

Algorithm 208 Demo of the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 207)

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

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

14.5.4 The .dot file produced

Algorithm 209 .dot file created from the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 207), converted from graph to .dot file using algorithm 43

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

14.5.5 The .svg file produced

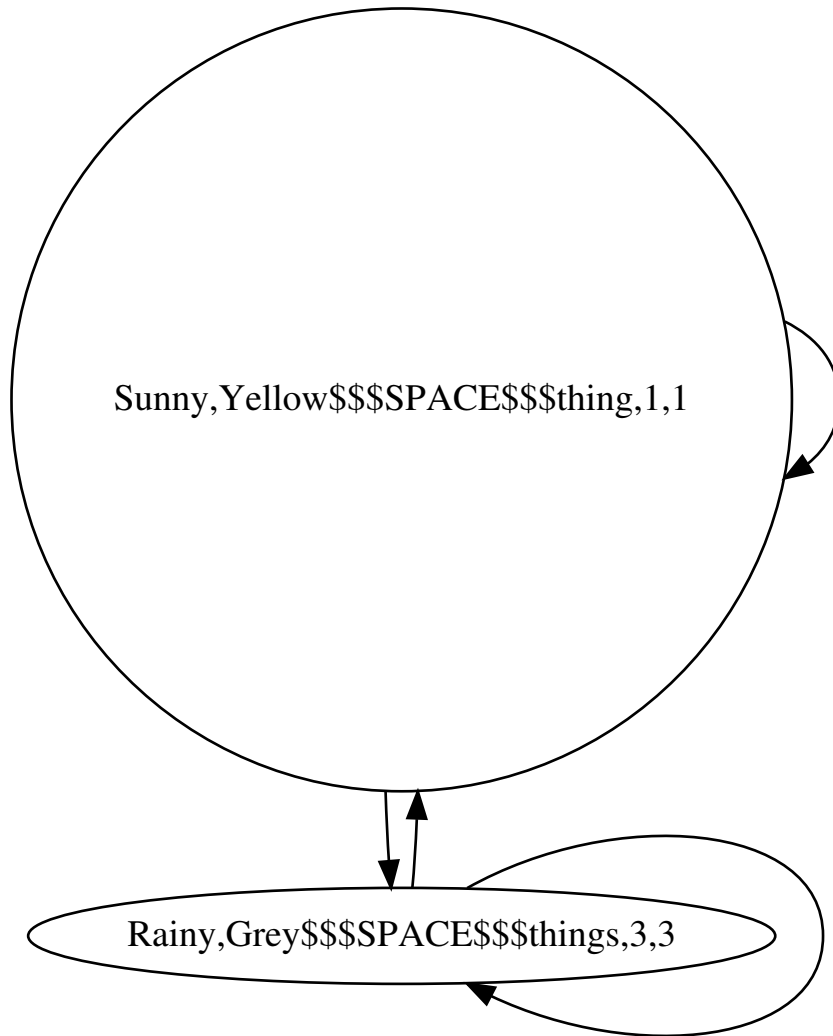


Figure 34: .svg file created from the 'create_custom_and_selectable_vertices_markov_chain' function (algorithm 180) its .dot file, converted from .dot file to .svg using algorithm 268

Note how the .svg changed its 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 210 Creating K_3 as depicted in figure 20

```
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::property<
        boost::vertex_custom_type_t, my_custom_vertex,
        boost::property<
            boost::vertex_is_selected_t, bool
        >
    >
>
>
>
create_custom_and_selectable_vertices_k2_graph() noexcept
{
    auto g
        =
            create_empty_undirected_custom_and_selectable_vertices_graph
            ();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer = boost::add_edge(vd_a, vd_b, g);
    assert(aer.second);

    auto my_custom_vertexes_map
        = get( //not boost::get
            boost::vertex_custom_type,
            g
        );
    my_custom_vertexes_map[vd_a]
        = my_custom_vertex("A", "source", 0.0, 0.0);
    my_custom_vertexes_map[vd_b]
        = my_custom_vertex("B", "target", 3.14, 3.14);

    auto is_selected_map
        = get( //not boost::get
            boost::vertex_is_selected,
            g
        );
    is_selected_map[vd_a] = true;
    is_selected_map[vd_b] = false;

    return g;
}
```

Most of the code is a slight modification of algorithm 183. 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 211 Demo of the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 210)

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

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

14.6.4 The .dot file produced

Algorithm 212 .dot file created from the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 210), converted from graph to .dot file using algorithm 43

```
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

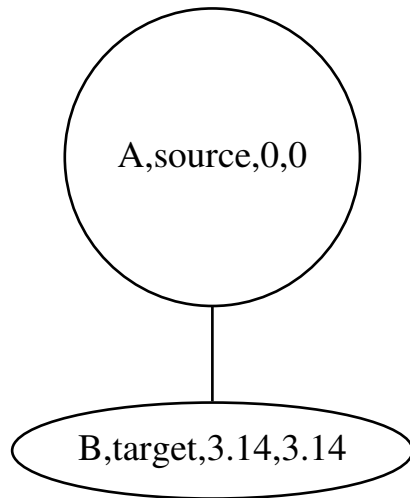


Figure 35: .svg file created from the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 180) its .dot file, converted from .dot file to .svg using algorithm 268

Note how the .svg changed its 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 15.1
- Loading a directed graph with custom and selectable vertices from a .dot file: chapter 15.2
- Loading an undirected directed graph with custom and selectable vertices from a .dot file: chapter 15.3

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

If you used the 'create_custom_and_selectable_vertices_k2_graph' function (algorithm 210) 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 213:

Algorithm 213 Storing a graph with custom and selectable vertices as a .dot file

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

template <typename graph>
void save_custom_and_selectable_vertices_graph_to_dot(
    const graph& g,
    const std::string& filename
)
{
    std::ofstream f(filename);

    write_graphviz(f, g,
        make_custom_and_selectable_vertices_writer(
            get(boost::vertex_custom_type, g),
            get(boost::vertex_is_selected, g)
        )
    );
}
```

This code looks small, because we call the 'make_custom_and_selectable_vertices_writer' function, which is shown in algorithm 214:

Algorithm 214 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 215:

Algorithm 215 The 'custom_and_selectable_vertices_writer' function

```
#include <ostream>

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

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

Here, some interesting things are happening: the writer needs both property maps to work with (that is, the 'my_custom_vertex' and is_selected maps). The 'my_custom_vertex' are written to the Graphviz 'label' attribute, and the is_selected is written to the 'regular' attribute (see chapter 25.2 for most Graphviz attributes).

15.2 Loading a directed graph with custom and selectable vertices from a .dot

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph with custom and selectable vertices is loaded, as shown in algorithm 216:

Algorithm 216 Loading a directed graph with custom vertices from a .dot file

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

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    boost::property<
        boost::vertex_custom_type_t, my_custom_vertex,
        boost::property<
            boost::vertex_is_selected_t, bool
        >
    >
>
>
load_directed_custom_and_selectable_vertices_graph_from_dot
(
    const std::string& dot_filename
)
{
    assert(is_regular_file(dot_filename));
    std::ifstream f(dot_filename.c_str());
    auto g =
        create_empty_directed_custom_and_selectable_vertices_graph
        ();
    boost::dynamic_properties p; //_do_ default construct
    p.property("node_id", get(boost::vertex_custom_type, g)
    );
    p.property("label", get(boost::vertex_custom_type, g));
    p.property("regular", get(boost::vertex_is_selected, g)
    );
    boost::read_graphviz(f, g, p);
    return g;
}
```

In this algorithm, first it is checked if the file to load exists. Then an empty directed graph is created. Then, a `boost::dynamic_properties` is created with its default constructor, after which

- The Graphviz attribute 'node_id' (see chapter 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 217 shows how to use the 'load_directed_custom_vertices_graph_from_dot' function:

Algorithm 217 Demonstration of the 'load_directed_custom_and_selectable_vertices_graph_from_dot' function

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

void
load_directed_custom_and_selectable_vertices_graph_from_dot_demo
() noexcept
{
    const auto g
        = create_custom_and_selectable_vertices_markov_chain
          ();
    const std::string filename{
        "create_custom_and_selectable_vertices_markov_chain.
        dot"
    };
    save_custom_and_selectable_vertices_graph_to_dot(
        g,
        filename
    );
    assert(is_regular_file(filename));
}
```

This demonstration shows how the Markov chain is created using the 'create_custom_vertices_markov_chain' function (algorithm 180), saved and then checked to exist.

15.3 Loading an undirected graph with custom and selectable vertices from a .dot

When loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph with custom and selectable vertices is loaded, as shown in algorithm 218:

Algorithm 218 Loading an undirected graph with custom vertices from a .dot file

```
#include <fstream>
#include <boost/graph/graphviz.hpp>
#include "
    create_empty_undirected_custom_and_selectable_vertices_graph
    .h"
#include "install_vertex_custom_type.h"
#include "is_regular_file.h"
#include "my_custom_vertex.h"

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::property<
        boost::vertex_custom_type_t, my_custom_vertex,
        boost::property<
            boost::vertex_is_selected_t, bool
        >
    >
>
>
load_undirected_custom_and_selectable_vertices_graph_from_dot
(
    const std::string& dot_filename
)
{
    assert(is_regular_file(dot_filename));
    std::ifstream f(dot_filename.c_str());
    auto g =
        create_empty_undirected_custom_and_selectable_vertices_graph
        ();
    boost::dynamic_properties p; //_do_ default construct
    p.property("node_id", get(boost::vertex_custom_type, g)
    );
    p.property("label", get(boost::vertex_custom_type, g));
    p.property("regular", get(boost::vertex_is_selected, g)
    );
    boost::read_graphviz(f, g, p);
    return g;
}
```

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 15.2 describes the rationale of this func-

tion.

Algorithm 219 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

Algorithm 219 Demonstration of the 'load_undirected_custom_and_selectable_vertices_graph_from_dot' function

```
#include <cassert>
#include "create_custom_and_selectable_vertices_k2_graph.h"
#include "is_regular_file.h"
#include "save_custom_and_selectable_vertices_graph_to_dot.h"

void
load_undirected_custom_and_selectable_vertices_graph_from_dot_demo
() noexcept
{
    const auto g
        = create_custom_and_selectable_vertices_k2_graph();
    const std::string filename{
        "create_custom_and_selectable_vertices_k2_graph.dot"
    };
    save_custom_and_selectable_vertices_graph_to_dot(
        g,
        filename
    );
    assert(is_regular_file(filename));
}
```

This demonstration shows how K_2 with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 183), 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 property. In this chapter, graphs will be created, in which the edges and vertices can have a custom 'my_custom_edge' and 'my_custom_edge' type¹³.

- An empty directed graph that allows for custom edges and vertices: see chapter 16.3

¹³I do not intend to be original in naming my data types

- An empty undirected graph that allows for custom edges and vertices: see chapter 16.4
- A two-state Markov chain with custom edges and vertices: see chapter 16.7
- K_3 with custom edges and vertices: see chapter 16.8

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

- Creating the custom edge class: see chapter 16.1
- Installing the new edge property: see chapter 16.2
- Adding a custom edge: see chapter 16.5

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

16.1 Creating the custom edge class

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

Algorithm 220 Declaration of `my_custom_edge`

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

class my_custom_edge
{
public:
    explicit my_custom_edge(
        const std::string& name = "",
        const std::string& description = "",
        const double width = 1.0,
        const double height = 1.0
    ) noexcept;
    const std::string& get_description() const noexcept;
    const std::string& get_name() const noexcept;
    double get_width() const noexcept;
    double get_height() const noexcept;
private:
    std::string m_name;
    std::string m_description;
    double m_width;
    double m_height;
};

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

`my_custom_edge` is a class that has multiple properties: two doubles '`m_width`' (`'m_'` stands for member) and '`m_height`', and two `std::string`s `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 265) can convert the elements to be streamed to a Graphviz-friendly version, which can be decoded by '`graphviz_decode`' (algorithm 266).

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 221 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 222 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 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
        >
    >();
}
```

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 223 Demonstration of the 'create_empty_directed_custom_edges_and_vertices_graph' function

```
#include "
    create_empty_directed_custom_edges_and_vertices_graph.
h"

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

16.4 Create an empty undirected graph with custom edges and vertices

Algorithm 224 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 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
        >
    >();
}
```

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 225 Demonstration of the 'create_empty_undirected_custom_edges_and_vertices_graph' function

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

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

16.5 Add a custom edge

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

Algorithm 226 Add a custom edge

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

template <typename graph>
void add_custom_edge(
    const my_custom_edge& v,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value, "graph_
        cannot_be_const");

    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);

    const auto aer
        = boost::add_edge(vd_a, vd_b, g);
    assert(aer.second);
    const auto my_edge_map
        = get( //not boost::get
            boost::edge_custom_type, g
        );
    my_edge_map[aer.first] = v;
}
```

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

Here is the demo:

Algorithm 227 Demo of 'add_custom_edge'

```
#include <cassert>
#include "add_custom_edge.h"
#include "
    create_empty_directed_custom_edges_and_vertices_graph.
    h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"

void add_custom_edge_demo() noexcept
{
    auto g =
        create_empty_directed_custom_edges_and_vertices_graph
        ();
    add_custom_edge(my_custom_edge("X"), g);
    assert(boost::num_vertices(g) == 2);
    assert(boost::num_edges(g) == 1);

    auto h =
        create_empty_undirected_custom_edges_and_vertices_graph
        ();
    add_custom_edge(my_custom_edge("Y"), h);
    assert(boost::num_vertices(h) == 2);
    assert(boost::num_edges(h) == 1);
}
```

16.6 Getting the custom edges my_edges

When the edges of a graph have an associated 'my_custom_edge', one can extract these all as such:

Algorithm 228 Get the edges' my_custom_edges

```
#include <vector>
#include "install_edge_custom_type.h"
#include "my_custom_edge.h"

template <typename graph>
std::vector<my_custom_edge> get_custom_edge_my_edges(
    const graph& g
) noexcept
{
    std::vector<my_custom_edge> v;

    const auto my_custom_edges_map
        = get( //not boost::get
              boost::edge_custom_type, g
            );
    const auto vip
        = edges(g); //not boost::edges
    const auto j = vip.second;

    for (auto i = vip.first; i!=j; ++i) {
        v.emplace_back(
            get( //not boost::get
                my_custom_edges_map, *i
            )
        );
    }
    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 36 shows the graph that will be reproduced:

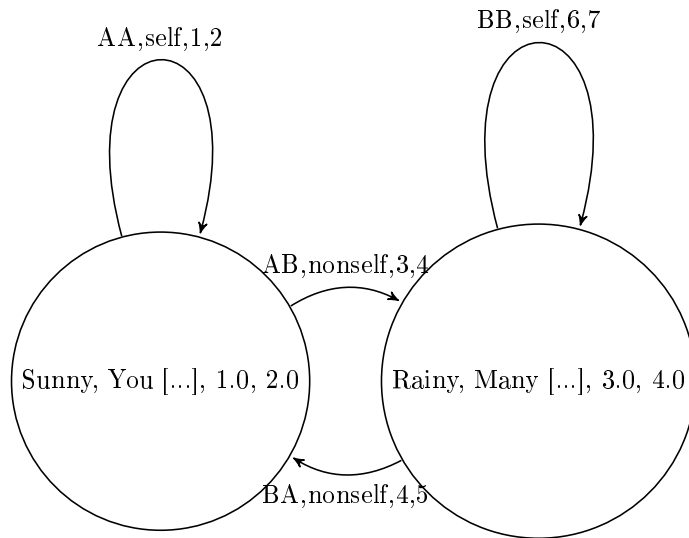


Figure 36: A two-state Markov chain where the edges and vertices have custom properties. The edges' and vertices' properties are nonsensical

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 229 Creating the two-state Markov chain as depicted in figure 36

```
#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( //not boost::get
        boost::vertex_custom_type, g
    );
    my_custom_vertexes_map[vd_a]
        = my_custom_vertex("Sunny", "Yellow_thing", 1.0, 2.0);
    my_custom_vertexes_map[vd_b]
        = my_custom_vertex("Rainy", "Grey_things", 3.0, 4.0);

    auto my_edges_map = get( //not boost::get
        boost::edge_custom_type, g
    );
    my_edges_map[aer_aa.first]
        = my_custom_edge("Sometimes", "20%", 1.0, 2.0);
    my_edges_map[aer_ab.first]254
        = my_custom_edge("Often", "80%", 3.0, 4.0);
    my_edges_map[aer_ba.first]
        = my_custom_edge("Rarely", "10%", 5.0, 6.0);
    my_edges_map[aer_bb.first]
        = my_custom_edge("Mostly", "90%", 7.0, 8.0);

    return g;
}
```

16.7.3 Creating such a graph

Here is the demo:

Algorithm 230 Demo of the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 229)

```
#include <cassert>
#include "create_custom_edges_and_vertices_markov_chain.h"
"
#include "get_custom_vertex_my_vertexes.h"
#include "install_vertex_custom_type.h"
#include "my_custom_vertex.h"

void create_custom_edges_and_vertices_markov_chain_demo()
    noexcept
{
    const auto g
        = create_custom_edges_and_vertices_markov_chain();
    const std::vector<my_custom_vertex>
        expected_my_custom_vertexes{
            my_custom_vertex("Sunny",
                "Yellow_thing",1.0,2.0
            ),
            my_custom_vertex("Rainy",
                "Grey_things",3.0,4.0
            )
        };
    const std::vector<my_custom_vertex>
        vertex_my_custom_vertexes{
            get_custom_vertex_my_vertexes(g)
        };
    assert(expected_my_custom_vertexes
        == vertex_my_custom_vertexes
    );
}
```

16.7.4 The .dot file produced

Algorithm 231 .dot file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 229), converted from graph to .dot file using algorithm 43

```

digraph G {
0[label="Sunny,Yellow$$$$SPACE$$$thing,1,1"];
1[label="Rainy,Grey$$$$SPACE$$$things,3,3"];
0->0 [label="Sometimes,20%,1,2"];
0->1 [label="Often,80%,3,4"];
1->0 [label="Rarely,10%,5,6"];
1->1 [label="Mostly,90%,7,8"];
}

```

16.7.5 The .svg file produced

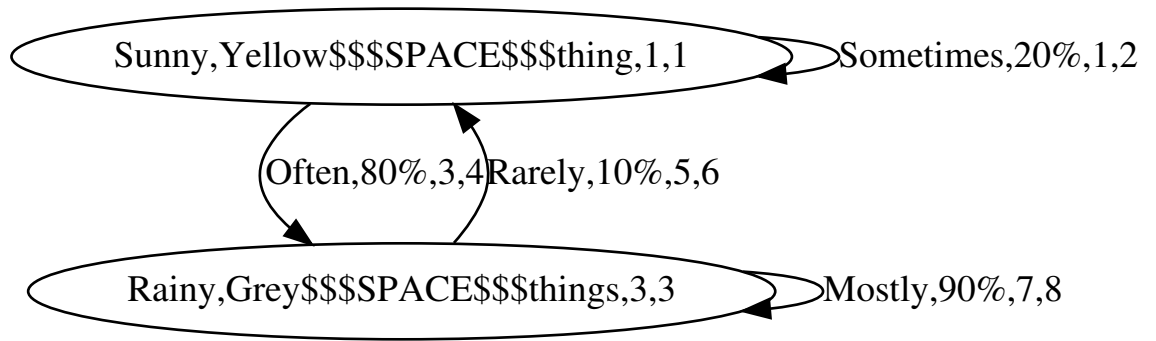


Figure 37: .svg file created from the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 180) its .dot file, converted from .dot file to .svg using algorithm 268

16.8 Creating K_3 with custom edges and vertices

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

16.8.1 Graph

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

[graph here]

16.8.2 Function to create such a graph

Algorithm 232 Creating K_3 as depicted in figure 20

```
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::undirectedS,
    boost::property<
        boost::vertex_custom_type_t, my_custom_vertex
    >,
    boost::property<
        boost::edge_custom_type_t, my_custom_edge
    >
>
create_custom_edges_and_vertices_k3_graph() noexcept
{
    auto g
        =
            create_empty_undirected_custom_edges_and_vertices_graph
            ();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto vd_c = boost::add_vertex(g);
    const auto aer_a = boost::add_edge(vd_a, vd_b, g);
    const auto aer_b = boost::add_edge(vd_b, vd_c, g);
    const auto aer_c = boost::add_edge(vd_c, vd_a, g);
    assert(aer_a.second);
    assert(aer_b.second);
    assert(aer_c.second);

    auto my_custom_vertex_map
        = get( //not boost::get
            boost::vertex_custom_type, g
        );
    my_custom_vertex_map[vd_a]
        = my_custom_vertex("top", "source", 0.0, 0.0);
    my_custom_vertex_map[vd_b]
        = my_custom_vertex("right", "target", 3.14, 0);
    my_custom_vertex_map[vd_c]
        = my_custom_vertex("left", "target", 0, 3.14);

    auto my_edge_map = get(boost::edge_custom_type, g);
    my_edge_map[aer_a.first] 257
        = my_custom_edge("AB", "first", 0.0, 0.0);
    my_edge_map[aer_b.first]
        = my_custom_edge("BC", "second", 3.14, 3.14);
    my_edge_map[aer_c.first]
        = my_custom_edge("CA", "third", 3.14, 3.14);

    return g;
}
```

Most of the code is a slight modification of algorithm 98. 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 233 Demo of the `'create_custom_edges_and_vertices_k3_graph'` function (algorithm 232)

```
#include <cassert>
#include "add_custom_edge.h"
#include "add_custom_vertex.h"
#include "create_custom_edges_and_vertices_k3_graph.h"

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

16.8.4 The .dot file produced

Algorithm 234 .dot file created from the `'create_custom_edges_and_vertices_markov_chain'` function (algorithm 232), converted from graph to .dot file using algorithm 43

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

16.8.5 The .svg file produced

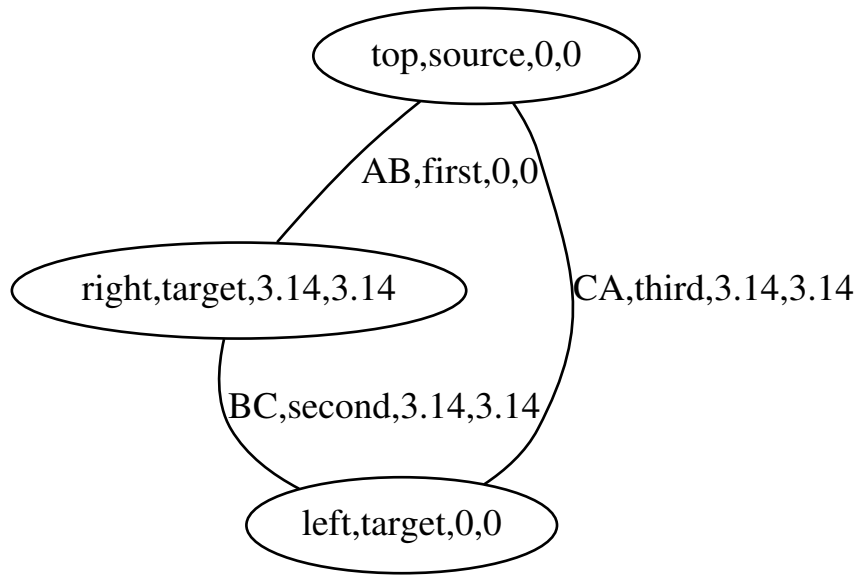


Figure 38: .svg file created from the 'create_custom_edges_and_vertices_k3_graph' function (algorithm 180) its .dot file, converted from .dot file to .svg using algorithm 268

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 obtaining 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 235 Find if there is a custom edge with a certain `my_custom_edge`

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

template <typename graph>
bool has_custom_edge_with_my_edge(
    const my_custom_edge& e,
    const graph& g
) noexcept
{
    const auto my_edges_map
        = get(boost::edge_custom_type, g);
    const auto eip
        = edges(g); //not boost::edges
    const auto j = eip.second;

    for (auto i = eip.first; i!=j; ++i) {
        if (
            get( //not boost::get
                my_edges_map,
                *i
            ) == e) {
            return true;
        }
    }
    return false;
}
```

This function can be demonstrated as in algorithm 236, where a certain 'my_custom_edge' cannot be found in an empty graph. After adding the desired my_custom_edge, it is found.

Algorithm 236 Demonstration of the 'has_custom_edge_with_my_edge' function

```
#include <cassert>
#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "has_custom_edge_with_my_edge.h"

void has_custom_edge_with_my_edge_demo() noexcept
{
    auto g
        =
            create_empty_undirected_custom_edges_and_vertices_graph
                ();
    assert (
        !has_custom_edge_with_my_edge(
            my_custom_edge("Edward"), g
        )
    );
    add_custom_edge(my_custom_edge("Edward"), g);
    assert (
        has_custom_edge_with_my_edge(
            my_custom_edge("Edward"), g
        )
    );
}
```

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

17.2 Find a my_custom_edge

Where STL functions work with iterators, here we obtain an edge descriptor (see chapter 2.12) to obtain a handle to the desired edge. Algorithm 237 shows how to obtain an edge descriptor to the first edge found with a specific my_custom_edge value.

Algorithm 237 Find the first custom edge with a certain `my_custom_edge`

```
#include <cassert>
#include <boost/graph/graph_traits.hpp>
#include "has_custom_edge_with_my_edge.h"
#include "install_edge_custom_type.h"
#include "my_custom_edge.h"

template <typename graph>
typename boost::graph_traits<graph>::edge_descriptor
find_first_custom_edge_with_my_edge(
    const my_custom_edge& e,
    const graph& g
) noexcept
{
    assert(has_custom_edge_with_my_edge(e, g));
    const auto my_edges_map = get(boost::edge_custom_type,
        g);
    const auto eip = edges(g); //not boost::edges
    const auto j = eip.second;

    for (auto i = eip.first; i!=j; ++i) {
        if (
            get( //not boost::get
                my_edges_map,
                *i
            ) == e) {
            return *i;
        }
    }
    assert(!"Should_not_get_here");
    throw; //Will crash the program
}
```

With the edge descriptor obtained, one can read and modify the edge and the vertices surrounding it. Algorithm 238 shows some examples of how to do so.

Algorithm 238 Demonstration of the 'find_first_custom_edge_with_my_edge' function

```
#include <cassert>

#include "create_custom_edges_and_vertices_k3_graph.h"
#include "find_first_custom_edge_with_my_edge.h"

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

17.3 Get an edge its my_custom_edge

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

Algorithm 239 Get a vertex its `my_custom_vertex` from its vertex descriptor

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

template <typename graph>
my_custom_edge get_custom_edge_my_edge(
    const typename boost::graph_traits<graph>::
        edge_descriptor& vd,
    const graph& g
) noexcept
{
    const auto my_edge_map
        = get( //not boost::get
              boost::edge_custom_type,
              g
            );
    return my_edge_map[vd];
}
```

To use 'get_custom_edge_my_custom_edge', one first needs to obtain an edge descriptor. Algorithm 240 shows a simple example.

Algorithm 240 Demonstration if the 'get_custom_edge_my_edge' function

```
#include <cassert>

#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "find_first_custom_edge_with_my_edge.h"
#include "get_custom_edge_my_edge.h"

void get_custom_edge_my_edge_demo() noexcept
{
    auto g
        =
            create_empty_undirected_custom_edges_and_vertices_graph
            ();
    const my_custom_edge edge{"Dex"};
    add_custom_edge(edge, g);
    const auto ed
        = find_first_custom_edge_with_my_edge(edge, g);
    assert(get_custom_edge_my_edge(ed, g) == edge);
}
```

17.4 Set an edge its my_custom_edge

If you know how to get the my_custom_edge from an edge descriptor, setting it is just as easy, as shown in algorithm 241.

Algorithm 241 Set a custom edge its `my_custom_edge` from its edge descriptor

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

template <typename graph>
void set_custom_edge_my_edge(
    const my_custom_edge& name,
    const typename boost::graph_traits<graph>::
        edge_descriptor& vd,
    graph& g
) noexcept
{
    static_assert(!std::is_const<graph>::value, "graph_
        cannot_be_const");

    auto my_edge_map = get(boost::edge_custom_type, g);
    my_edge_map[vd] = name;
}
```

To use 'set_custom_edge_my_edge', one first needs to obtain an edge descriptor. Algorithm 242 shows a simple example.

Algorithm 242 Demonstration if the 'set_custom_edge_my_edge' function

```
#include <cassert>

#include "add_custom_edge.h"
#include "
    create_empty_undirected_custom_edges_and_vertices_graph
    .h"
#include "find_first_custom_edge_with_my_edge.h"
#include "get_custom_edge_my_edge.h"
#include "set_custom_edge_my_edge.h"

void set_custom_edge_my_edge_demo() noexcept
{
    auto g
        =
            create_empty_undirected_custom_edges_and_vertices_graph
            ();
    const my_custom_edge old_edge{"Dex"};
    add_custom_edge(old_edge, g);
    const auto vd
        = find_first_custom_edge_with_my_edge(old_edge, g);
    assert(get_custom_edge_my_edge(vd, g)
        == old_edge
    );
    const my_custom_edge new_edge{"Diggy"};
    set_custom_edge_my_edge(new_edge, vd, g);
    assert(get_custom_edge_my_edge(vd, g)
        == new_edge
    );
}
```

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

If you used the `create_custom_edges_and_vertices_k3_graph` function (algorithm 232) 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 243:

Algorithm 243 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_custom_edge_my_edge.h"
#include "get_custom_vertex_my_vertexes.h"

template <typename graph>
void save_custom_edges_and_vertices_graph_to_dot(
    const graph& g,
    const std::string& filename
)
{
    using my_vertex_descriptor = typename graph::
        vertex_descriptor;
    using my_edge_descriptor = typename graph::
        edge_descriptor;
    std::ofstream f(filename);
    const auto my_custom_vertexes =
        get_custom_vertex_my_vertexes(g);
    boost::write_graphviz(
        f,
        g,
        [my_custom_vertexes](
            std::ostream& out,
            const my_vertex_descriptor& v
        ) {
            const my_custom_vertex m{my_custom_vertexes[v]};
            out << "[label=\"" << m << "\"]";
        },
        [g](std::ostream& out,
            const my_edge_descriptor& e
        ) {
            const my_custom_edge m{get_custom_edge_my_edge(e,g)};
            out << "[label=\"" << m << "\"]";
        }
    );
}
```

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

When loading a graph from file, one needs to specify a type of graph. In this example, an directed graph with custom edges and vertices is loaded, as shown in algorithm 244:

Algorithm 244 Loading a directed graph with custom edges and vertices from a .dot file

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

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

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

called to build up the graph.

Algorithm 245 shows how to use the 'load_directed_custom_edges_and_vertices_graph_from_dot' function:

Algorithm 245 Demonstration of the 'load_directed_custom_edges_and_vertices_graph_from_dot' function

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

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

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

This demonstration shows how the Markov chain is created using the 'create_custom_edges_and_vertices_markov_chain' function (algorithm 229), saved and then loaded.

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

When loading a graph from file, one needs to specify a type of graph. In this example, an undirected graph with custom edges and vertices is loaded, as shown in algorithm 246:

Algorithm 246 Loading an undirected graph with custom edges and vertices from a .dot file

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

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

The only difference with loading a directed graph, is that the initial empty graph is undirected instead. Chapter 17.6 describes the rationale of this function.

Algorithm 247 shows how to use the 'load_undirected_custom_vertices_graph_from_dot' function:

Algorithm 247 Demonstration of the 'load_undirected_custom_edges_and_vertices_graph_from_dot' function

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

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

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

This demonstration shows how K_2 with custom vertices is created using the 'create_custom_vertices_k2_graph' function (algorithm 183), saved and then loaded. The loaded graph is checked to be a graph similar to the original.

18 Building graphs with a graph name

Up until now, the graphs created have had no properties themselves. Sure, the edges and vertices have had properties, but the graph itself has had none. Until now.

In this chapter, graphs will be created with a graph name of type `std::string`

- An empty directed graph with a graph name: see chapter
- An empty undirected graph with a graph name: see chapter
- A two-state Markov chain with a graph name: see chapter
- K_3 with a graph name: see chapter

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

- Getting a graph its name: see chapter
- Setting a graph its name: see chapter

18.1 Create an empty directed graph with a graph name property

Algorithm 248 shows the function to create an empty directed graph with a graph name.

Algorithm 248 Creating an empty directed graph with a graph name

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

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

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-)property
- '`boost::property<boost::graph_name_t, std::string>`': the graph itself has a single property: its `boost::graph_name` has type `std::string`

Algorithm 249 demonstrates the '`create_empty_directed_graph_with_graph_name`' function.

Algorithm 249 Demonstration of '`create_empty_directed_graph_with_graph_name`'

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

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

18.2 Create an empty undirected graph with a graph name property

Algorithm 250 shows the function to create an empty undirected graph with a graph name.

Algorithm 250 Creating an empty undirected graph with a graph name

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

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

This code is very similar to the code described in chapter 248, except that the directedness (the third template argument) is undirected (due to the `boost::undirectedS`).

Algorithm 251 demonstrates the 'create_empty_undirected_graph_with_graph_name' function.

Algorithm 251 Demonstration of 'create_empty_undirected_graph_with_graph_name'

```
#include <cassert>

#include "create_empty_undirected_graph_with_graph_name.h"
"

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

18.3 Get a graph its name property

Algorithm 252 Get a graph its name

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

template <typename graph>
std::string get_graph_name(
    const graph& g
) noexcept
{
    return
        get_property( //not boost::get_property
            g, boost::graph_name
        );
}
```

Algorithm 253 demonstrates the 'get_graph_name' function.

Algorithm 253 Demonstration of 'get_graph_name'

```
#include <cassert>

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

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

18.4 Set a graph its name property

Algorithm 254 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( //not boost::get_property
        g, boost::graph_name
    ) = name;
}
```

Algorithm 255 demonstrates the 'set_graph_name' function.

Algorithm 255 Demonstration of 'set_graph_name'

```
#include <cassert>

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

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

18.5 Create a directed graph with a graph name property

18.5.1 Graph

See figure 6.

18.5.2 Function to create such a graph

Algorithm 256 shows the function to create an empty directed graph with a graph name.

Algorithm 256 Creating a two-state Markov chain with a graph name

```
#include <cassert>
#include "create_empty_directed_graph_with_graph_name.h"
#include "set_graph_name.h"

boost::adjacency_list<
    boost::vecS,
    boost::vecS,
    boost::directedS,
    boost::no_property,
    boost::no_property,
    boost::property<boost::graph_name_t, std::string>
>
create_markov_chain_with_graph_name() noexcept
{
    auto g = create_empty_directed_graph_with_graph_name();
    const auto vd_a = boost::add_vertex(g);
    const auto vd_b = boost::add_vertex(g);
    const auto aer_aa = boost::add_edge(vd_a, vd_a, g);
    assert(aer_aa.second);
    const auto aer_ab = boost::add_edge(vd_a, vd_b, g);
    assert(aer_ab.second);
    const auto aer_ba = boost::add_edge(vd_b, vd_a, g);
    assert(aer_ba.second);
    const auto aer_bb = boost::add_edge(vd_b, vd_b, g);
    assert(aer_bb.second);

    set_graph_name("Two-state_Markov_chain", g);
    return g;
}
```

18.5.3 Creating such a graph

Algorithm 257 demonstrates the 'create_markov_chain_with_graph_name' function.

Algorithm 257 Demonstration of 'create_markov_chain_with_graph_name'

```
#include <cassert>
#include "create_markov_chain_with_graph_name.h"
#include "get_graph_name.h"

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

18.5.4 The .dot file produced

Algorithm 258 .dot file created from the 'create_markov_chain_with_graph_name' function (algorithm 256), converted from graph to .dot file using algorithm 43

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

18.5.5 The .svg file produced

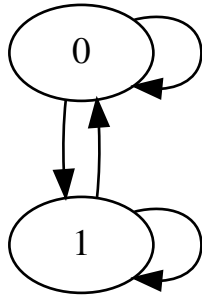


Figure 39: .svg file created from the 'create_markov_chain_with_graph_name' function (algorithm 256) its .dot file, converted from .dot file to .svg using algorithm 268

18.6 Create an undirected graph with a graph name property

18.6.1 Graph

See figure 8.

18.6.2 Function to create such a graph

Algorithm 259 shows the function to create K2 graph with a graph name.

Algorithm 259 Creating a K2 graph with a graph name

```
#include "create_empty_undirected_graph_with_graph_name.h"

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

    get_property( //not boost::get_property
        g, boost::graph_name
    ) = "K2";

    return g;
}
```

18.6.3 Creating such a graph

Algorithm 260 demonstrates the 'create_k2_graph_with_graph_name' function.

Algorithm 260 Demonstration of 'create_k2_graph_with_graph_name'

```
#include <cassert>

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

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

18.6.4 The .dot file produced

Algorithm 261 .dot file created from the 'create_k2_graph_with_graph_name' function (algorithm 259), converted from graph to .dot file using algorithm 43

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

18.6.5 The .svg file produced

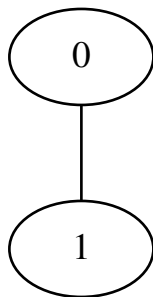


Figure 40: .svg file created from the 'create_k2_graph_with_graph_name' function (algorithm 259) its .dot file, converted from .dot file to .svg using algorithm 268

19 Working on graphs with a graph name

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

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

Algorithm 262 Storing a graph with a graph name as a .dot file

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

#include "get_graph_name.h"

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

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

This will result in a directed graph without a name [ISSUE #12]. Please email me if you know how to do this correctly.

Algorithm 263 Loading a directed graph with a graph name from a .dot file

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

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

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

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

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

This will result in an undirected graph without a name. [ISSUE #12] Please email me if you know how to do this correctly.

Algorithm 264 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
)
{
    assert(is_regular_file(dot_filename));
    std::ifstream f(dot_filename.c_str());
    auto g = create_empty_undirected_graph_with_graph_name
        ();

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

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

to compile.

20 Building graphs with custom graph properties

I will write this chapter if and only if I can save and load a graph with a graph name (as in chapter 18). That is, if Issue #12 is fixed.

21 Working on graphs with custom graph properties

I will write this chapter if and only if I can save and load a graph with a graph name (as in chapter 18). That is, if Issue #12 is fixed.

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 265 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 265) and thus converts a Graphviz-friendly `std::string` to the original human-friendly `std::string`.

Algorithm 266 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;
}
```

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 267 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 268 Convert a .dot file to a .svg

```
#include <cassert>
#include <string>
#include <sstream>
#include "has_dot.h"
#include "is_regular_file.h"
#include "is_valid_dot_file.h"

void convert_dot_to_svg(
    const std::string& dot_filename,
    const std::string& svg_filename
)
{
    assert(has_dot());
    assert(is_valid_dot_file(dot_filename));
    std::stringstream cmd;
    cmd << "dot -Tsvg " << dot_filename << ".o" <<
        svg_filename;
    std::system(cmd.str().c_str());
    assert(is_regular_file(svg_filename));
}
```

'convert_dot_to_svg' makes a system call to the program '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 269 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 270:

Algorithm 270 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 270 a graph is created with vertices of no properties. Then the names of these vertices, which do not exist, 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 271 Creating the error 'no matching function for call to clear_out_edges'

```
#include "create_k2_graph.h"

void no_matching_function_for_call_to_clear_out_edges()
    noexcept
{
    auto g = create_k2_graph();
    const auto vd = *vertices(g).first; //not boost::
        vertices
    boost::clear_in_edges(vd,g);
}
```

In algorithm 271 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 3.8) 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 initialize with `'boost::ignore_other_properties'` as a constructor argument instead. Algorithm 272 shows how to trigger this run-time error.

Algorithm 272 Creating the error 'Property not found: node_id'

```
#include <cassert>
#include <fstream>
#include "is_regular_file.h"
#include "create_empty_undirected_graph.h"
#include "create_k2_graph.h"
#include "save_graph_to_dot.h"

void property_not_found_node_id() noexcept
{
    const std::string dot_filename{"
        property_not_found_node_id.dot"};
    // Create a file
    {
        const auto g = create_k2_graph();
        save_graph_to_dot(g, dot_filename);
        assert(is_regular_file(dot_filename));
    }

    // Try to read that file
    std::ifstream f(dot_filename.c_str());
    auto g = create_empty_undirected_graph();

    // Line below should have been
    // boost::dynamic_properties p(boost::
    ignore_other_properties);
    boost::dynamic_properties p; // Error

    try {
        boost::read_graphviz(f, g, p);
    }
    catch (std::exception&) {
        return; // Should get here
    }
    assert(!"Should_not_get_here");
}
```

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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