Google Summer of Code Proposal: Boost `static_map`

March 2017

Abstract

This document proposes an addition to `Boost C++ Libraries` – a *compile-time* hash table. There are multiple good implementations of unordered associate containers (e.g. `std::unordered_map`, `Google`'s `sparsehash`). These implementations provide both lookup and insertion/deletion functionality. They are, however, not the perfect fit for the case when the contents of the container are fixed upon construction or even known at compile time. `std::vector` vs. `std::array` is a good analogy here. We propose a `static_map` – an associate container with focus on `constexpr` usage.

1 Personal Details

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Availability	I consider `GSoC` as a full-time job/internship, thus I plan to spend at least 40 hours per week working on the project. I have an exam in April and, in case I fail it, the retake is planned on the 24th of May. 29th (Monday) or 30th of May (the official start date) seems like a good starting point to me. My summer vacation officially starts only on the 1st of July, before that I have some courses to follow, exams to take and a thesis to defend. During this time I plan on working only 4 hours a day, including weekends. However, this does not seem like a big issue to me, because I have no other commitments in July and August and can easily compensate for the lost time. Working 8 hours a day Mon through Fri + 5 hours a day on Sat and Sun would result in more than 40 hours/week, if averaged over the whole work period. End August (the official end of coding) is a nice point to stop, because my summer vacation ends on the 1st of September.

2 Background Information

I'm currently in my third year of Bachelor in Physics program at Radboud University (The Netherlands) and plan on defending my thesis in June. Although I major in physics, I'm quite interested in programming, follow CS courses and plan on obtaining a Bachelor degree in CS while doing a Master program in Physics. By now, I've done the following project-related courses:

- *Imperative Programming 1 & 2* (Introduction to `C++`).
- *Hacking in C* (Memory layout, calling conventions and debugging).
- *Object Orientation.*
- *Algorithms & Datastructures.*
- *Languages and Automata.*
- *Functional Programming 1 & 2.*

For the last two years I've been working as a teaching assistant at Radboud University. I taught both physics and programming. In 2015 I taught `C` to first year physics and math majors; in 2016 — `Python 3`.

Lately, I've been writing code (as part of my Bachelor thesis) for distributed memory systems to perform some physical calculations. I work with quantum mechanical 2D fractal structures that don't exhibit translational symmetry, which makes calculations on them quite challenging. I've been calculating plasmonic properties of some materials using a newly developed method that some people believed to be impossible (too computationally expensive). We plan to publish a paper about it soon. Some code and documentation (both in early state of development) can be found on `https://github.com/twesterhout/plasmon-cpp/`.

Theoretical physicists are usually thinkers rather than doers. Thus in my spare time I've read some books about programming and `C++` in particular, e.g. Scott Meyers' "Effective Modern C++", Andrei Alexandrescu's "Modern C++ Design". This got me interested in the modern part of `C++`, metaprogramming and library development. `Boost` seems a perfect place to apply my knowledge and learn from more experienced people in this area, and the `static_map` project, i.e. "compile-time stuff" + "modern `C++`", is *exactly* what I'm most interested in at the moment. Although I haven't done any work related to this project, I believe myself to be a fast learner. Being highly motivated, I hope to pick up on the background quite soon.

I'd very much like to continue my work in this area even after succeeding with this project, contribute to `Boost` and become a part of the community.

As for my knowledge of the listed languages/technologies/tools, I'd rate it as follows:

`C++ 98/03` ≈ 3;

`C++ 11/14` ≈ 4;

`C++ Standard Library` ≈ 4;

`Boost C++ Libraries` ≈ 3;

`Git` ≈ 2.

I use `Linux` as my primary desktop operating system and have grown used to doing as much as possible via command line. Thus, usually I write code in `Vim` and use `Makefile`s to compile it. For documentation, I've been using `Doxygen`. But it's not the best choice when metaprogramming is involved. I'm open to learning `DocBook` as this is what `Boost` is using.

3 Project Proposal

Motivation There's often need for associative containers. `C++ Standard Library` provides `std::map` and `std::unordered_map`. `Google` has `dense_hash_map`. There are many more implementations. These all focus on both insertion/deletion and lookup. However, sometimes we're only interested in the lookup capabilities. For example, when the container is initialised from constant static data or even constexpr data. While a C-style associative array may serve well as a storage for such data, it's inefficient in terms of accessing the data by key. Common associate containers, on the other hand, implement efficient lookup, but use dynamic memory allocation for initialisation which may be undesired in some cases. The following example illustrates this further.

```
#include <iostream>
#include <initializer_list>
#include <map>
#include <unordered_map>
#include <experimental/string_view>
using std::experimental::string_view;

enum class weekday { sunday, monday, tuesday, wednesday
                   , thursday, friday, saturday };

#define STRING_VIEW(str) string_view{ str, sizeof(str)-1 }
constexpr std::initializer_list<std::pair< const string_view
                                         , weekday>> string_to_weekday
    { { STRING_VIEW("sunday"),    weekday::sunday    }
    , { STRING_VIEW("monday"),    weekday::monday    }
    , { STRING_VIEW("tuesday"),   weekday::tuesday   }
    , { STRING_VIEW("wednesday"), weekday::wednesday }
    , { STRING_VIEW("thursday"),  weekday::thursday  }
    , { STRING_VIEW("friday"),    weekday::friday    }
    , { STRING_VIEW("saturday"),  weekday::saturday  }
    };

int main(void)
{
    {
        // Calls malloc() at least 7 times
        static const std::map<string_view, weekday>
            to_weekday1 = string_to_weekday;
        std::cout << "'monday' maps to "
                  << static_cast<int>(to_weekday1.at("monday"))
                  << std::endl;
        std::cout << "'friday' maps to "
                  << static_cast<int>(to_weekday1.at("friday"))
                  << std::endl;
        // Calls free() at least 7 times
    }
    {
        // Calls malloc() at least 8 times
        static const std::unordered_map<string_view, weekday>
            to_weekday2 = string_to_weekday;
        std::cout << "'monday' maps to "
                  << static_cast<int>(to_weekday2.at("monday"))
                  << std::endl;
        std::cout << "'friday' maps to "
                  << static_cast<int>(to_weekday2.at("friday"))
                  << std::endl;
        // Calls free() at least 8 times
    }
    return 0;
}
```

Even though the `string_to_weekday` is `constexpr`, to make use of fast lookups ($\mathcal{O}(1)$ for `unordered_map` and $\mathcal{O}(\log(N))$ for `map` compared to $\mathcal{O}(N)$ of linear searching) we have to copy data at runtime, which involves dynamic memory allocation. And although one may implement stack allocator to prevent dynamic memory allocation for small datasets, initialisation and lookups will still happen at runtime, because they are not marked `constexpr`.

With `C++14` relaxed constraints on `constexpr` functions it is possible to implement an associative container with `constexpr` (whenever possible) key lookups (as a proof, see the toy implementation of such a container in Appendix A). We think that a high quality implementation of such a container would be a worthwhile addition to `Boost`.

Proposal As part of the Google Summer of Code 2017 project we propose to do the following:

- To seek consensus from the Boost Developer's mailing list on a suitable design of a `static_map` class with the following design features:

  1. The number of key–value pairs is fixed upon construction.
  2. All features can be used in constant expressions, i.e. all member functions are marked `constexpr`.
  3. The container can be statically initialised in the mind the compiler or global static storage.
  4. Values, though neither keys nor the number of items, are modifiable.
  5. The container performs constexpr key lookups to the "maximum possible extent".

  This list of requirements is harder to implement than it may seem at first sight. Consider the following example:

```
constexpr std::pair<int, char const*>
    map_data[] = { { 5, "apple" }
                 , { 8, "pear" },
                 , { 0, "banana" }
                 };

// Generates no runtime code. Easy, because the standard requires this to be executed
// at compile-time.
constexpr auto cmap = make_static_map(map_data);
constexpr char const* what_is_5 = cmap[5];

// Generates no runtime code. Easy, because 0 is a non-type template parameter.
char const* what_is_0 = std::get<0>(cmap);

// Challenging: should only generate code loading immediately from a memory location.
// It must NOT generate any additional runtime overhead like hashing or searching.
char const* what_is_8 = cmap[8];

// Challenging: again, should only generate code loading from memory.
auto cmap2 = make_static_map(map_data);
auto& at_0 = map_data[0];
at_0 = "orange";
```

  If all inputs for a `constexpr` operation are constant expressions, but the result is not used as a constant expression, then the compiler in *not required* to execute the operation at compile-time. This is what makes lines 19, 23 and 24 so challenging.

- To implement a `static_map` unordered associative container class which satisfies the above outlined requirements on top of the requirements in the standard. This includes the implementation of utility classes/functions for `constexpr` string comparison and hashing. The implementation should work on at least two major compilers in, hopefully, `C++14` mode.

- To implement a comprehensive unit test suite for the `static_map` class with focus on ensuring no runtime overhead for the challenging cases mentioned above (i.e. when the result of a `constexpr` function is not used as a constant expression).

- To configure a per-commit continuous integration for the unit test suite on at least one of the major public open source CI services (e.g. Travis, Appveyor).

- To write documentation to `Boost` quality levels for the `static_map` container class. This includes time and space complexity guarantees and benchmarks, and exception guarantees for each function in the API and each use of each function.

Schedule We propose the following schedule to achieve the goals outlined above:

29th May — 2nd June 5th June — 9th June	Consult Boost Developer's mailing list and do some background reading to come up with a suitable design for `static_map` class and all required utility classes. In the meantime configure the system for development, i.e. get compilers, CI service, doc tools, etc., working.
12th June — 16th June 19th June — 23th June 26th June — 30th June	Implement `static_map` class for the simple case of keys being of integral type. Start writing tests and documentation. It would be nice to have a working implementation (for this simple case) before the first phase evaluation deadline.
3rd July — 7th July 10th July — 14th July 17th July — 21th July 24th July — 28th July	Complete the implementation of `static_map` class and utility classes. Continue working on tests and documentation. It would be nice to have a fully working (on at least two compilers) implementation before the second phase evaluation deadline.
31st July — 4th August 7th August — 11th August	Finish implementing tests. Finish the documentation. Maybe do some work to support other compilers.
14th August — 18th August	Extra
21st August — 25th August	Final touches, submitting results.

4 Programming Competency Test

The initial objective was to reimplement the toy `static_map` provided at `https://goo.gl/e07ooa` so that `GCC` or `VS2017` would execute the non-`constexpr` assignment at compile time.

My first idea was to use SFINAE to detect whether parameters were `constexpr`, and if they were, store the result of the lookup in a `constexpr` variable, thus forcing the compiler to evaluate the operation at compile-time. Detecting `constexpr`ness of parameters, however, proved to be impossible. One could write a macro to detect whether an expression passed to it was actually a constant expression (as it was done in the following answer: `http://stackoverflow.com/a/40413051`), more or less what GCC's `__builtin_constant_p` does. Unfortunately, this only works with one level of indirection:

```
constexpr auto factorial(std::size_t const n) -> std::size_t
{
  if (n == 0 || n == 1) return 1;
  return n * factorial(n - 1);
}

constexpr auto foo(std::size_t const n)
{
  return __builtin_constant_p(factorial(n));
}

int main(void)
{
  static_assert(__builtin_constant_p(factorial(10)), "");
  // This fails!
  static_assert(foo(10), "");
}
```

I've thus come to the conclusion that there is no standard way to force the compiler to evaluate the expression at compile time, we have to rely on compiler's "kindness" to optimise it. After some trial and error I've figured that `GCC` does not like the following:

1. "Difficult" exceptions such as `std::out_of_range`, `std::runtime_error`, etc. I call these exceptions "difficult", because (at least in `GCC-6.3`) the error message is stored in a `class`/`struct` with non-`constexpr` operations.

2. `throw` statements in the function body. I.e. in the following code snippet

```
constexpr auto foo1()
{
    auto x = compute_something();
    if (good_answer(x)) return x;
    throw std::runtime_error{""};
}

constexpr auto foo2()
{
    auto x = compute_something();
    return good_answer(x)
        ? x
        : (throw std::runtime_error{""}, x);
}
```

   `GCC` finds `foo2` easier to optimise. However, this is purely empirical, and compared to Item 1 I don't have a theoretical explanation for it.

3. Multiple return statements. This works well in combination with Item 2. For example, consider the `static_map::at` function in the toy implementation that was provided:

```
constexpr auto at(key_type const& k) const -> mapped_type const&
{
    for (size_t n = 0; n < N; n++)
        if (_values[n].second.first == k)
            return _values[n].second.second;
    throw key_not_found_error{};
}
```

   I've already replaced the "difficult" `std::out_of_range` exceptions with an "easy" one. This doesn't help. `GCC-6.3` still produces runtime code for this function. However, if we follow the rules of Items 2 and 3 and replace the original function with

```
constexpr auto at(key_type const& k) const -> mapped_type const&
{
    size_t n = 0;
    while (n < N && _values[n].second.first != k) {
        ++n;
    }
    return n != N
        ? _values[n].second.second
        : (throw key_not_found_error{}, _values[0].second.second);
}
```

   `GCC-6.3` optimises the function completely, i.e. no runtime code is produced for it. To prove that Item 1 is useful, substitute `key_not_found_error{}` by `std::out_of_range{"Key not found."}` — runtime code is back.

It was a matter of following the described rules of thumb to satisfy the requirements of the competency test. From Niall Douglas I've learned that the test has outgrown its initial requirements and a complete toy implementation of the proposal is now desired.

Adding support for iterators and custom hash and equals functions is a matter of doing. The only challenging part is initialisation of the `static_map`. In the original solution initialisation goes as follows: the user passes a `C`-style array to `make_static_map` function, it expands the array into a parameter pack and passes it to the `static_map` constructor which

initialises the underlying storage type (again a C-array) using list initialisation. To make use of hashing, elements in the underlying array must appear in a certain order. Sorting the array after initialisation seems like a bad solution, because keys are constant. Storing keys as non-const would make static_map inconsistent with other associate containers, and using const_casts seems like a dirty hack is this case. A good place to sort the array would be the make_static_map function. In the original implementation this function expands the array il using std::index_sequence<_Is...> as il[_Is]... . Thus sorting can be achieved by expanding il as il[σ(_Is)]..., where σ is some permutation. My implementation of this idea can be found in Appendix A.

Another interesting thing about the original implementation is that it uses an array of std::pair<std::size_t, std::pair<key_type const, mapped_type> as underlying storage. I found the extra std::size_t unnecessary and decided to use an array of std::pair<key_type const, mapped_type> as the underlying storage. But then, as indicated by Niall, my solution stopped working with Clang. Thus I've decided to follow the "convention" used in libstdc++ and created an inner storage class that allows the static_map to be implemented independent of the underlying storage type. Addition of this inner class turned out to be crutial as now even Clang was happy to optimise code without the extra std::size_t.

My complete toy implementation of static_map can be found in Appendix A or online on https://github.com/twesterhout/GSoC17-proposal/blob/master/static_map.cpp (easier to copy-paste into Compiler Explorer). The "challenging cases" work with both GCC-6+ and Clang-3.9+.

A Code

```
#include <utility>
#include <cassert>
#include <stdexcept>
#include <type_traits>
#include <experimental/string_view>

struct key_not_found_error : std::exception {
  auto what() const noexcept -> char const* override
  { return _msg; }
private:
  static constexpr char const* _msg = "Key not found.";
};

constexpr char const* key_not_found_error::_msg;


namespace {

template < class _Static_map
         , bool _is_const
         >
struct map_iterator {
  using type              = map_iterator<_Static_map, _is_const>;
  using difference_type   = typename _Static_map::difference_type;
  using value_type        =
    std::conditional_t< _is_const
                      , std::add_const_t<typename _Static_map::value_type>
                      , typename _Static_map::value_type >;
  using iterator_category = std::random_access_iterator_tag;
  using reference         =
    std::conditional_t< _is_const
                      , typename _Static_map::const_reference
                      , typename _Static_map::reference >;
  using pointer           = std::add_pointer_t<value_type>;
  using size_type         = typename _Static_map::size_type;

private:
  using _const_iterator   = map_iterator<_Static_map, /*is_const =*/ true>;
  using _storage_type     =
    std::conditional_t< _is_const
                      , std::add_const_t<typename _Static_map::storage_type>
                      , typename _Static_map::storage_type >;

  static constexpr size_type _size = _Static_map::size();
  _storage_type* _data;
  size_type      _i;

  constexpr auto _to_same_object( map_iterator const& x
                                , map_iterator const& y ) const noexcept -> bool
  { return x._data == y._data; }

public:
  constexpr map_iterator() noexcept : _data{ nullptr }, _i{ 0 } {}

  constexpr map_iterator(_storage_type& data, size_type const pos) noexcept
    : _data{ &data }, _i{ pos }
  {}

  constexpr map_iterator(map_iterator const& other) noexcept = default;
  constexpr map_iterator& operator=(map_iterator const& other) noexcept = default;

  __attribute__((always_inline))
  constexpr auto operator*() const -> reference
  {
    return _data != nullptr
      ? ( _i < _size
          ? _data->value(_i)
          : (throw std::out_of_range{"Iterator not dereferenceable."}, _data->value(0))
        )
      : (throw std::invalid_argument{"Iterator not dereferenceable."}, _data->value(0));
  }

  constexpr auto operator->() const -> pointer { return &(*(*this)); }

  constexpr auto operator++() noexcept -> map_iterator& { ++_i; return *this; }

  constexpr auto operator++(int) noexcept -> map_iterator
  {
    map_iterator saved{ *this };
    ++(*this);
    return saved;
  }

  constexpr auto operator-(map_iterator const& other) const -> difference_type
  {
    return _to_same_object(*this, other)
      ? (static_cast<difference_type>(_i) - static_cast<difference_type>(other._i))
      : (throw std::invalid_argument{"Iterators not comparable."}, 0);
  }

```

```
  constexpr auto operator==(map_iterator const& other) const noexcept -> bool
  { return _to_same_object(*this, other) && (_i == other._i); }

  constexpr auto operator!=(map_iterator const& other) const noexcept -> bool
  { return !(*this == other); }

  constexpr auto operator< (map_iterator const& other) const -> bool
  { return (*this - other) <  0; }

  constexpr auto operator<=(map_iterator const& other) const -> bool
  { return (*this - other) <= 0; }

  constexpr auto operator> (map_iterator const& other) const -> bool
  { return (*this - other) >  0; }

  constexpr auto operator>=(map_iterator const& other) const -> bool
  { return (*this - other) >= 0; }

  constexpr auto operator[](difference_type const n) const -> reference
  { return *(*this + n); }

  constexpr operator _const_iterator() const noexcept { return {_data, _i}; }

  friend
  constexpr auto swap(map_iterator& lhs, map_iterator& rhs) noexcept -> void
  {
    auto const _temp_idx = lhs._i;
    lhs._i = rhs._i;
    rhs._i = _temp_idx;

    auto const _temp_data = lhs._data;
    lhs._data = rhs._data;
    rhs._data = _temp_data;
  }

  friend
  constexpr auto operator+ ( map_iterator    const& x
                           , difference_type const  n ) noexcept -> map_iterator
  { return {*(x._data), x._i + n}; }

  friend
  constexpr auto operator+ ( difference_type const  n
                           , map_iterator    const& x ) noexcept -> map_iterator
  { return x + n; }

  friend
  constexpr auto operator- ( map_iterator    const& x
                           , difference_type const  n ) noexcept -> map_iterator
  { return {*(x._data), x._i - n}; }

  friend
  constexpr auto operator+=( map_iterator         & x
                           , difference_type const  n ) noexcept -> map_iterator&
  { return x = x + n; }

  friend
  constexpr auto operator-=( map_iterator         & x
                           , difference_type const  n ) noexcept -> map_iterator&
  { return x = x - n; }
};

template <class _Static_map, bool _is_const>
constexpr typename _Static_map::size_type map_iterator<_Static_map, _is_const>::_size;

} // unnamed namespace


struct equal_c {
  template <class _Char>
  constexpr auto operator()(_Char const* const a, _Char const* const b) const
    noexcept( noexcept(std::declval<_Char>() == std::declval<_Char>())
           && noexcept(std::declval<_Char>() != std::declval<_Char>()) )
  {
    std::size_t i = 0;
    while (a[i] != _Char{} && a[i] == b[i]) {
      ++i;
    }
    return a[i] == _Char{} && b[i] == _Char{};
  }
};


namespace {

template <class _Char>
inline constexpr auto length_c(_Char const* const str) noexcept -> std::size_t
{
  std::size_t i = 0;
  while (str[i] != _Char{}) {
    ++i;
  }
  return (i == 0) ? 0 : (i - 1);
}

```

```
template <class _Char>
inline constexpr auto crc32_hash(_Char const* const str) noexcept -> std::uint32_t
{
  constexpr std::uint32_t INITXOR  = 0xFFFFFFFF;
  constexpr std::uint32_t FINALXOR = 0xFFFFFFFF;
  constexpr std::uint32_t CRCPOLY  = 0xEDB88320;

  auto const l = length_c(str);
  auto crcreg  = INITXOR;

  for (std::size_t j = 0; j < l; ++j) {
    auto b = static_cast<std::make_unsigned_t<_Char>>(str[j]);
    for (std::size_t i = 0; i < 8 * sizeof(_Char); ++i) {
      if ((crcreg ^ b) & 1) {
        crcreg = (crcreg >> 1) ^ CRCPOLY;
      }
      else {
        crcreg >>= 1;
      }
      b >>= 1;
    }
  }

  return crcreg ^ FINALXOR;
}

template <class _Char>
inline constexpr auto simple_hash(_Char const* const str) noexcept
{
  std::size_t hash = 0;
  std::size_t i = 0;
  while (str[i] != _Char{}) {
    hash = 37 * hash + str[i];
    ++i;
  }
  return hash;
}

} // unnamed namespace


template <class _T, std::size_t _N, class = void>
struct hash_c;

template <class _T, std::size_t _N>
struct hash_c<_T, _N, std::enable_if_t<std::is_integral<_T>::value>> {
  constexpr auto operator()(_T const x) const noexcept -> std::size_t
  { return static_cast<std::size_t>(x) % _N; }
};

template <std::size_t _N>
struct hash_c<char const*, _N> {
  constexpr auto operator()(char const* const x) const noexcept -> std::size_t
  {
    // return simple_hash(x) % _N;
    return static_cast<std::size_t>(crc32_hash(x)) % _N;
  }
};

template <std::size_t _N>
struct hash_c<std::experimental::string_view, _N> {
  constexpr auto operator()(std::experimental::string_view const& x) const noexcept
  { return hash_c<char const*, _N>{}(x.data()); }
};


template < class _RAIterator, class _Pred>
inline constexpr auto find_if_c( _RAIterator&& first, _RAIterator&& last, _Pred&& p )
  noexcept( noexcept(std::declval<_RAIterator>() - std::declval<_RAIterator>())
         && noexcept(std::declval<_RAIterator&>() = std::declval<_RAIterator>())
         && noexcept(*std::declval<_RAIterator>())
         && noexcept(++std::declval<_RAIterator>()) )
{
  auto const _count = last - first;
  auto i = first;
  std::remove_const_t<decltype(_count)> n = 0;
  while (n < _count && !p(*i)) {
    ++n; ++i;
  }
  return n == _count ? last : i;
}


namespace {
template <bool... _Bs> struct _all;
template <> struct _all<> : std::true_type {};

template <bool _B, bool... _Bs>
struct _all<_B, _Bs...> : std::conditional_t<_B, _all<_Bs...>, std::false_type> {};
} // unnamed namespace


template < class _Key
         , class _Tp
```

```
          , size_t _N
          , class _Pred   = std::equal_to<_Key>
          , class _Hasher = hash_c<_Key, _N>
          >
class static_map {

public:
  using type                = static_map<_Key, _Tp, _N, _Pred, _Hasher>;
  using key_type            = _Key;
  using mapped_type         = _Tp;
  using key_equal           = _Pred;
  using hasher              = _Hasher;
  using value_type          = std::pair<key_type const, mapped_type>;
  using reference           = value_type &;
  using const_reference     = value_type const&;
  using iterator            = map_iterator<type, /*is_const =*/ false>;
  using const_iterator      = map_iterator<type, /*is_const =*/ true>;
  using difference_type     = std::ptrdiff_t;
  using size_type           = std::size_t;

private:
  struct _Storage {
  private:
    using _actual_value_type = value_type;
    _actual_value_type _vs[_N];

    static constexpr auto make_node(const_reference value)
      noexcept( std::is_nothrow_copy_constructible<key_type>::value
             && std::is_nothrow_copy_constructible<mapped_type>::value )
    { return std::make_pair(value.first, value.second); }


  public:
    template <class... _Pair>
    constexpr _Storage(_Pair const&... values)
      noexcept(_all<noexcept(make_node(std::declval<_Pair const&>()))...>::value)
      : _vs{ make_node(values)... }
    {}

    constexpr auto value(size_type const i) const noexcept -> const_reference
    { return _vs[i]; }

    constexpr auto value(size_type const i)       noexcept -> reference
    { return _vs[i]; }
  };

public:
  using storage_type = _Storage;

private:
  key_equal    const _eq;
  hasher       const _hf;
  storage_type       _data;

private:
  __attribute__((always_inline))
  constexpr auto _lookup(key_type const& k) const
    noexcept( noexcept(std::declval<hasher>()(std::declval<key_type>()))
           && noexcept(std::declval<key_equal>()( std::declval<key_type>()
                                                , std::declval<key_type>())) )
  {
    auto const guess = _hf(k);
    auto       i     = guess;

    while (i < _N && !_eq(_data.value(i).first, k)) { ++i; }
    if (i == _N) {
      i = 0;
      while (i < guess && !_eq(_data.value(i).first, k)) { ++i; }
      if (i == guess) return _N;
    }
    return i;
  }

public:
  template <class... _K, class... _V>
  constexpr static_map(std::pair<_K, _V> const&... values)
    noexcept( std::is_nothrow_constructible< storage_type
                                           , std::pair<_K, _V> const&...>::value
           && std::is_nothrow_default_constructible<key_equal>::value
           && std::is_nothrow_default_constructible<hasher>::value )
    : _eq{}, _hf{}, _data{ values... }
  {}

  template <class... _K, class... _V>
  constexpr static_map( key_equal equal, hasher hash_function
                      , std::pair<_K, _V> const&... values )
    noexcept( std::is_nothrow_constructible< storage_type
                                           , std::pair<_K, _V> const&...>::value
           && std::is_nothrow_move_constructible<key_equal>::value
           && std::is_nothrow_move_constructible<hasher>::value )
    : _eq{ std::move(equal) }
    , _hf{ std::move(hash_function) }
    , _data{ values... }
  {}
```

```
374   static constexpr auto size() noexcept -> size_type
      { return _N; }
376
      constexpr auto begin() noexcept -> iterator
378   { return {_data, 0}; }

380   constexpr auto   end() noexcept -> iterator
      { return {_data, size()}; }
382
      constexpr auto cbegin() const noexcept -> const_iterator
384   { return {_data, 0}; }

386   constexpr auto   cend() const noexcept -> const_iterator
      { return {_data, size()}; }
388
      __attribute__((always_inline))
390   constexpr auto find(key_type const& k) const
        noexcept(noexcept(std::declval<static_map>()._lookup(std::declval<key_type>())))
392     -> const_iterator
      {
394     auto i = _lookup(k);
        return i == _N
396       ? cend()
          : const_iterator{_data, i};
398   }

400   constexpr auto count(key_type const& k) const
        noexcept(noexcept(std::declval<static_map>().find(std::declval<key_type>())))
402     -> size_type
      { return find(k) == cend() ? 0 : 1; }
404
      __attribute__((always_inline))
406   constexpr auto at(key_type const& k) const -> mapped_type const&
      {
408     auto i = _lookup(k);
        return i != _N
410       ? _data.value(i).second
          : (throw key_not_found_error{}, _data.value(0).second);
412   }

414   __attribute__((always_inline))
      constexpr auto at(key_type const& k) -> mapped_type&
416   {
        auto i = _lookup(k);
418     return i != _N
          ? _data.value(i).second
420       : (throw key_not_found_error{}, _data.value(0).second);
      }
422
      constexpr auto operator[](key_type const& k) const -> mapped_type const&
424   { return at(k); }

426   constexpr auto operator[](key_type const& k) -> mapped_type &
      { return at(k); }
428 };

430

432 namespace {

434 template <std::size_t _N>
    __attribute__((always_inline))
436 inline constexpr auto _insert( std::size_t const index, std::size_t const guess
                                 , std::size_t (&indices)[_N] ) noexcept
438 {
      auto i = guess;
440   while (i < _N && indices[i] != _N) { ++i; }
      if (i == _N) {
442     i = 0;
        while (i < guess && indices[i] != _N) { ++i; }
444   }
      indices[i] = index;
446 }

448 template <std::size_t _N>
    __attribute__((always_inline))
450 inline constexpr auto _init_impl( std::size_t (&indices)[_N]
                                    , std::pair<std::size_t, std::size_t> const& x ) noexcept
452 { _insert(x.first, x.second, indices); }

454 template <std::size_t _N, class... _I>
    __attribute__((always_inline))
456 inline constexpr auto _init_impl( std::size_t (&indices)[_N]
                                    , std::pair<std::size_t, std::size_t> const& x
458                                 , std::pair<_I, _I> const&... xs ) noexcept
    {
460   _insert(x.first, x.second, indices);
      _init_impl(indices, xs...);
462 }

464

    template <std::size_t, class _T>
```

```
using _transform = _T;

template < class _K
         , class _V
         , class _Pred
         , class _Hasher
         , std::size_t _N
         , std::size_t... _Is
     >
__attribute__((always_inline))
inline constexpr auto _initialise( std::pair<_K const, _V> const (&il)[_N]
                                 , _Pred&& equal, _Hasher&& hf
                                 , std::index_sequence<_Is...> )
  noexcept( noexcept(std::declval<_Hasher>()(std::declval<_K>()))
         && noexcept(std::is_nothrow_constructible
                     < static_map<_K, _V, _N, _Pred, _Hasher>
                     , _Pred, _Hasher, _transform<_Is, std::pair<_K const, _V> const&>...
                     >::value) )
{
  std::size_t indices[_N] = {((void)_Is, _N)...};
  _init_impl(indices, std::make_pair(_Is, hf(il[_Is].first))...);

  return static_map<_K, _V, _N, _Pred, _Hasher>{ std::forward<_Pred>(equal)
                                               , std::forward<_Hasher>(hf)
                                               , il[indices[_Is]]... };
}

} // unnamed namespace

template < class _K
         , class _V
         , std::size_t _N
         , class _Pred = std::equal_to<_K>
         , class _Hasher = hash_c<_K, _N>
     >
__attribute__((always_inline))
inline
constexpr
auto make_static_map( std::pair<_K const, _V> const (&il)[_N]
                    , _Pred&& equal = _Pred{}
                    , _Hasher&& hf = _Hasher{} )
  noexcept( noexcept(_initialise( std::declval<decltype(il)>()
                                , std::declval<_Pred>()
                                , std::declval<_Hasher>()
                  , std::make_index_sequence<_N>{})) )
{
  return _initialise( il
                    , std::forward<_Pred>(equal)
                    , std::forward<_Hasher>(hf)
                    , std::make_index_sequence<_N>{} );
}


enum class weekday { sunday
                   , monday
                   , tuesday
                   , wednesday
                   , thursday
                   , friday
                   , saturday };

using std::experimental::string_view;
#define STRING_VIEW(str) std::experimental::string_view{str, sizeof(str)-1}

struct equal_string_view {
  constexpr
  auto operator()( string_view const& a
                 , string_view const& b ) const noexcept -> bool
  { return equal_c{}(a.data(), b.data()); }
};

int main(void)
{
  {
    // Compile-time stuff
    constexpr std::pair<int const, const char *> map_data[] =
      { { 5, "apple"  }
      , { 8, "pear"   }
      , { 0, "banana" }
      };
    // Initialisation
    constexpr auto cmap = make_static_map(map_data);

    // No abort call in assembly
    if (!cmap[8]) abort();

    // These operations use hashing
    static_assert(equal_c{}(cmap[5], "apple"), "");
    static_assert(equal_c{}(cmap[8], "pear"), "");
    static_assert(equal_c{}(cmap[0], "banana"), "");

    // This fails to compile -- as expected.
    // constexpr auto foo = cmap[-1];
```

```
560     // We need this because GCC does not support constexpr lambdas, yet.
562     struct is_eight {
562       constexpr auto operator()(std::pair<int, char const*> const& x)
564         const noexcept
564       { return x.first == 8; }
566     };
566
568     // Iterators
568     static_assert( find_if_c(cmap.cbegin(), cmap.cend(), is_eight{})
570                    != cmap.cend(), "" );
570   }
572   {
572     // Run-time stuff
574     constexpr std::pair<int const, const char *> map_data[] =
574       { { 5, "apple"  }
576       , { 8, "pear"   }
576       , { 0, "banana" }
578       };
578     auto cmap = make_static_map(map_data);
580     // No abort in assembly
580      if (!cmap.count(5)) abort();
582
584     // Values are mutable !!
584     auto& i = cmap.at(8);
586     i = "orange";
586     assert(equal_c{}(i, "orange"));
588     // Iterators
590     auto const it1 = cmap.find(8);
590     assert(it1->first == 8);
592   }
594   {
594     // Working with string_view
594     constexpr std::pair<const std::experimental::string_view, weekday>
596       string_to_weekday[]
596         { { STRING_VIEW("sunday"),    weekday::sunday }
598         , { STRING_VIEW("monday"),    weekday::monday }
598         , { STRING_VIEW("tuesday"),   weekday::tuesday }
600         , { STRING_VIEW("wednesday"), weekday::wednesday }
600         , { STRING_VIEW("thursday"),  weekday::thursday }
602         , { STRING_VIEW("friday"),    weekday::friday }
602         , { STRING_VIEW("saturday"),  weekday::saturday }
604         };
604     constexpr auto to_weekday = make_static_map( string_to_weekday
606                                                , equal_string_view{} );
608     static_assert(to_weekday[STRING_VIEW("sunday")] == weekday::sunday, "");
608     static_assert(to_weekday[STRING_VIEW("monday")] == weekday::monday, "");
610     static_assert(to_weekday[STRING_VIEW("tuesday")] == weekday::tuesday, "");
610     static_assert(to_weekday[STRING_VIEW("wednesday")] == weekday::wednesday, "");
612     static_assert(to_weekday[STRING_VIEW("thursday")] == weekday::thursday, "");
612     static_assert(to_weekday[STRING_VIEW("friday")] == weekday::friday, "");
614     static_assert(to_weekday[STRING_VIEW("saturday")] == weekday::saturday, "");
616     if (!to_weekday.count(STRING_VIEW("sunday"))) abort();
618     struct is_friday {
618       constexpr auto operator()(std::pair< string_view const
620                                          , weekday > const& x)
620         const noexcept -> bool
622       { return equal_c{}(x.first.data(), "friday"); }
622     };
624     // Lookup
626     static_assert(to_weekday.find(STRING_VIEW("friday")) != to_weekday.cend(), "");
626     static_assert(to_weekday.find(STRING_VIEW("__friday__")) == to_weekday.cend(), "" );
628     // Linear search
628     static_assert( find_if_c( to_weekday.cbegin(), to_weekday.cend()
630                             , is_friday{} ) != to_weekday.cend(), "" );
630   }
632   {
632     // C-strings
634     constexpr std::pair<char const* const, weekday>
634       string_to_weekday[]
636         { { "sunday",    weekday::sunday }
636         , { "monday",    weekday::monday }
638         , { "tuesday",   weekday::tuesday }
638         , { "wednesday", weekday::wednesday }
640         , { "thursday",  weekday::thursday }
640         , { "friday",    weekday::friday }
642         , { "saturday",  weekday::saturday }
642         };
644     constexpr auto to_weekday = make_static_map( string_to_weekday
644                                                , equal_c{} );
646   }
646   return 0;
}
```

static_map.cpp