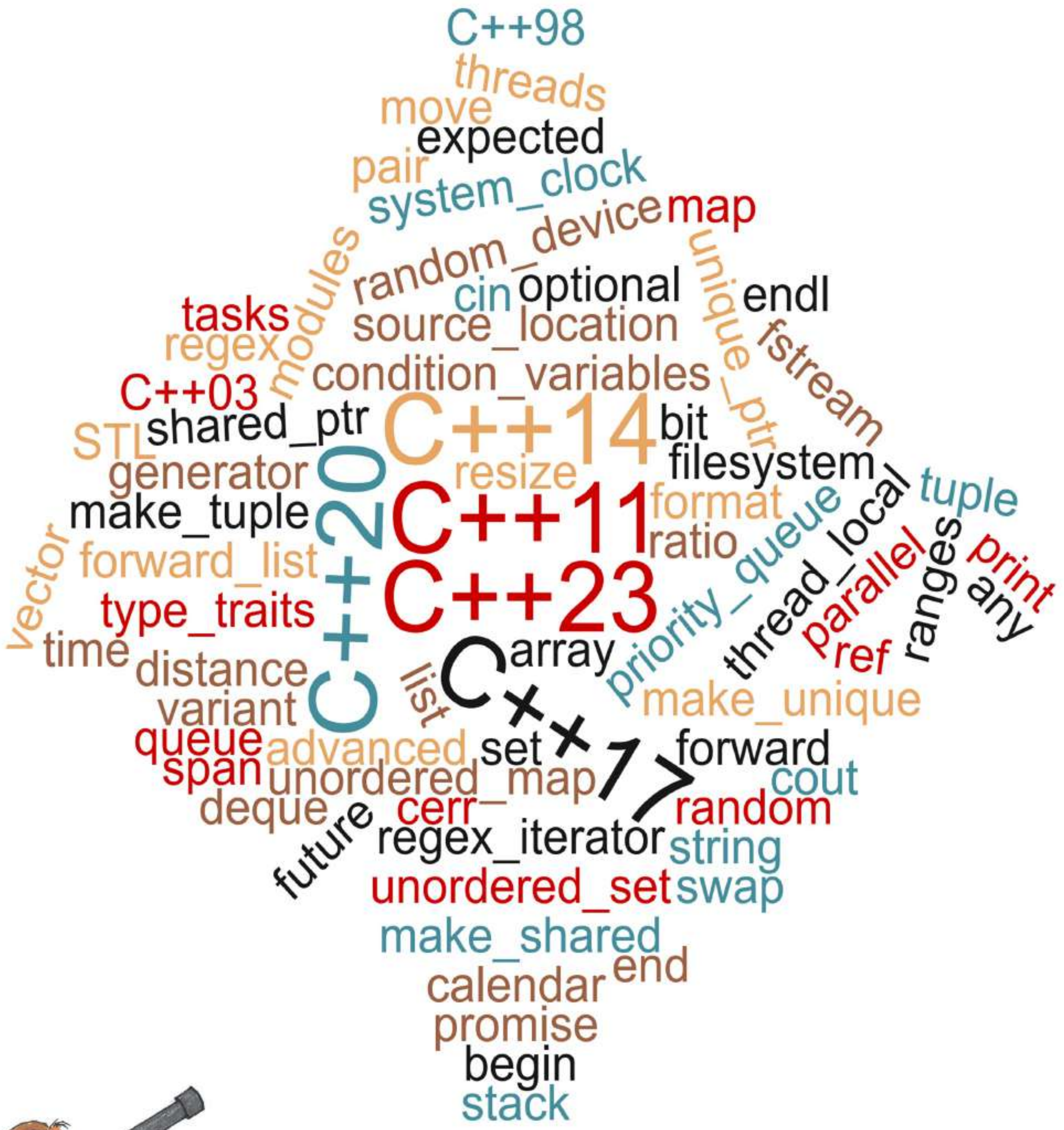
The C++ Standard Library

Fourth Edition includes C++23



Rainer Grimm

ModernesCpp.com

The C++ Standard Library

What every professional C++ programmer should know about the C++ standard library.

Rainer Grimm

This book is for sale at http://leanpub.com/cpplibrary

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Reader Testimonials

English Edition

Rick Audet

Senior Engineer, Dolby Laboratories

"Arguably the quickest and easiest way to get up to speed on
the most important parts of the C++ standard library. Recommended
for any modern C++ programmer."

German Edition

Odin Holmes

CEO/CTO at Auto-Intern GmbH

"Das Buch beinhaltet, wie der Name schon sagt, eine recht
ausführliche Beschreibung der STL. Dabei merkt Mann deutlich dass
der Autor auch selber auf hohem Niveau programmiert. Es gibt oft
den ein oder andere Tipp oder Wink in die richtige Richtung die
bei Bücher von Berufsautoren oft fehlen. Z.B. die Aussage dass
std::vector für 95% aller Fälle die beste Wahl ist oder dass
std::async meistens die erste Wahl sein sollte lenkt der Leser
geschickt in die richtige Richtung.

Auch die Auswahl an Komponente aus der STL ist sehr

gut getroffen
(keiner kann in ein kürzen Buch die ganze STL beschreiben). Oft
sehe ich, vor allem in Deutschsprachige Literatur, dass die Auswahl
eher auf Komponente trifft die leicht zu beschreiben sind und nicht
auf die Nützlichen. Eine gute und dennoch kürze Beschreibung vom
std::regex z.B. ist weiß Gott nicht einfach aber in diesem Fall ist
es der Autor sehr gelungen."

Ramon Wartala

Director Technology at Performance Media GmbH

"Die 215 Seiten plus Index des 'C++ kurz & gut' vom Autor Rainer Grimm
stellen ein gelungene Destillat viel umfangreicherer Texte zum Thema
da. So nimmt das Kapitel über die klassischen Algorithmen der
Standardbibliothek ganze 131 Seiten ein. Selbst kurze Beispiele für die
Anwendung der wichtigsten Bestandteile der Standardbibliothek passen
eng gedruckt in das schmale Büchlein. Auch wenn heute Tools wie Dash
oder entsprechend ausgestattete IDEs, mehr und mehr den Platz derartiger
Desktop-Referenzen einnehmen, ist das 'kurz & gut' zu C++
Standardbibliothek ein leichter und mobiler Begleiter für jeden C++
Entwickler. Und als Kindle Version um so bequemer

mitzunehmen."

Introduction

Purpose of this Book

The C++ Standard Library is a quick reference to the standard library of the current C++23 standard ISO/IEC 14882:2023. C++23 has more than 2100 pages and follows the big C++20 standard. In contrast, C++23 and C++17 are neither a big nor small C++ standards. C++14 is a small addition to C++11. C++11 had more than 1,300 pages and was published in 2011. That was 13 years after the first and only C++ standard, C++98. Of course, there is also C++03, published in 2003. But C++03 is considered a bug-fix release.

This quick reference aims is to provide a concise reference to the C++ standard library. This book assumes that you are familiar with C++. If so, you will get the most benefit out of this book. If C++ is new to you, you should start with a textbook about core C++. Once you have mastered a book about the core language, you can make your next big step by reading this book. To make your job easier, I have provided many short code snippets to connect theory and practice.

Index

The book should be a reference for C++ and should, therefore, have an index. Leanpub does not support the creation of an index. So I've made it based on regular expressions, naming conventions, a lot of python magic, and a long table that I had to split for each page. Here is the problem. The index is only fully available in the pdf format of the book.

Conventions

I promise only a few conventions.

Special Fonts

Italic

I use *Italic* if something is essential.

`Monospace`

I use `Monospace` for code, instructions, keywords, and names of types, variables, functions, and classes.

Special Boxes

I use boxes for unique information, tips, and warning.

Information headline

Information text.

Tip headline

Tip description.

Warning headline

Warning description.

Source Examples

I don't particularly appreciate using directives and declarations because they hide the library's namespace. I use them so that the origin can always be deduced from the using *directive* (`using namespace std;`) or the *using* declaration (`using std::cout;`). Still, because of the limited length of a page, I have to use them from time to time.

Only header files of the featured functionality are shown in the code snippets. `true` or `false` is displayed in the output code snippets for boolean values, and `std::boolalpha` is not used. When your compiler supports the modularized standard library in C++23, you can replace the headers with an `import std` statement.

Source Code

To be concise, I only present short code snippets in this book. The name of the entire program is in the first line of the code snippet.

Value versus Object

I call instances of fundamental data types *values*, which C++ inherited from C. Instances of more advanced types, which often consist of fundamental types, are called *objects*. Objects are typically instances of *user-defined* types or containers.

Acknowledgments

First, I want to thank Alexandra Follenius, the lector at O'Reilly, for the German book C++ Standardbibliothek. The German book is the ancestor of this book. For my book *C++ Standardbibliothek* Karsten Ahnert, Guntram Berti, Dmitry Ganyushin, Sven Johannsen, Torsten Robitzki, Bart Vandewoestyne, and Felix Winter were very valuable proofreaders. A lot of thanks to all of them.

I started a request in my English blog for translating this book to English www.ModernesCpp.com. I received a much higher response than I expected. Special thanks to all of you, including my son Marius, the first proofreader.

Here are the alphabetically ordered names: Mahesh Attarde, Rick Audet, Pete Barrow, Michael Ben-David, Dave Burns, Alvaro Fernandez, Juliette Grimm, George Haake, Clare Macrae, Arne Mertz, Ian Reeve, Jason Turner, Bart Vandewoestyne, Ivan Vergiliev, and Andrzej Warzynski.

Further Information

The idea of the book is relatively easy to paraphrase: "What every professional C++ programmer should know about the C++ standard library." Because of this intention, I left many answers unanswered; therefore, I provide you with the links to the details at the beginning of each new topic. The link will refer to the excellent online resource www.cppreference.com.

Cippi

Let me introduce Cippi. Cippi will accompany you in this book. I hope you like her.

I'm Cippi: curious, clever and - yes - feminine!

About Me

I've worked as a software architect, team lead, and instructor since 1999. In 2002, I created company-intern meetings for further education. I have given training courses since 2002. My first tutorials were about proprietary management software, but I began teaching Python and C++ soon after. I like to write articles about C++, Python, and Haskell in my spare time. I also like to speak at conferences. I publish weekly on my English blog Modernes Cpp, and the German blog, hosted by Heise Developer.

Since 2016, I have been an independent instructor giving seminars about modern C++ and Python. I have published several books in various languages about modern C++ and, in particular, about concurrency. Due to my profession, I always search for the best way to teach modern C++.

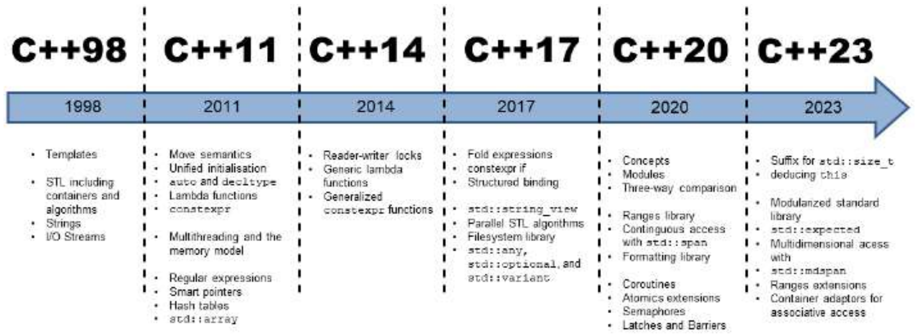
Rainer Grimm

1. The Standard Library

The C++ standard library consists of many components. This chapter serves two purposes. It should give you a quick overview of the features and a first idea of how to use them.

The History

C++ and, therefore, the standard library has a long history. C++ started in the 1980s of the last millennium and ended now in 2023. Anyone who knows about software development knows how fast our domain evolves. So 40 years is a very long period. You may not be so astonished that the first components of C++, like I/O streams, were designed with a different mindset than the modern Standard Template Library (STL). C++ started as an object-oriented language, incorporated generic programming with the STL, and has now adopted many functional programming ideas. This evolution of software development in the last 40 years, which you can observe in the C++ standard library, is also an evolution in how software problems are solved.



C++ timeline

The first **C++98** standard library from 1998 had three components. Those were the previously mentioned I/O streams, mainly for file handling, the string library, and the Standard Template Library. The Standard Template Library facilitates the transparent application of algorithms on containers.

The history continues in 2005 with Technical Report 1 (TR1). The extension to the C++ library ISO/IEC TR 19768 was not an official standard, but almost all components became part of **C++11**. These were, for example, the libraries for regular expressions, smart pointers, hash tables, random numbers, and time, based on the boost libraries (http://www.boost.org/).

In addition to the standardization of TR1, C++11 got one new component: the multithreading library.

C++14 was only a minor update to the C++11 standard. Therefore, C++14 added only a few improvements to existing libraries for smart pointers, tuples, type traits, and multithreading.

C++17 includes libraries for the file system and the two new data types `std::any` and `std::optional`.

C++20 has four outstanding features: concepts, ranges, coroutines, and modules. Besides the big four, there are more pearls in C++20: the three-way comparison operator, the formatting library, and the concurrency-related data types semaphores, latches, and barriers.

C++23 improved the big four of C++20: extended ranges functionality, the coroutine generator `std::generator`, and a modularized C++ standard library.

Overview

As C++ has many libraries, finding the convenient one for each use case is often difficult.

Utilities

Utilities are libraries with a general focus and, therefore, can be applied in many contexts.

Examples of utilities are functions to calculate the minimum or the maximum of values, the midpoint of two values, or to swap or move values. Thanks to save comparison of integers, integral promotion does not kick in.

Other utilities are `std::function`, `std::bind`, or `std:bind_front`. With `std::bind` or `std::bind_front`, you can easily create new functions from existing ones. To bind them to a variable and invoke them later, you have `std::function`.

With `std::pair` and the generalization `std::tuple` you can create heterogeneous pairs and tuples of arbitrary length.

The reference wrappers `std::ref` and `std::cref` are pretty handy. One can use them to create a reference wrapper for a variable, which for `std::cref` is constant.

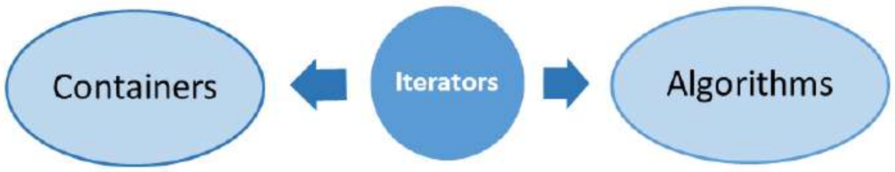
Of course, the highlights of the utilities are the smart pointers. They allow explicit automatic memory management in C++. You can model the concept of explicit ownership with `std::unique_ptr` and model shared ownership with `std::shared_ptr`. `std::shared_ptr` uses reference counting for taking care of its resource. The third one, `std::weak_ptr`, helps to break the cyclic dependencies among `std::shared_ptr`s. Cyclic references are the classic problem of reference counting.

The type traits library can check, compare and manipulate type information at compile time.

The time library is an import addition to the new multithreading capabilities of C++. But it is also quite handy to make performance measurements and includes support for calender and time zone.

With `std::any`, `std::optional`, and `std::variant`, we get with C++17 three special datatypes that can have any, an optional value, or a variant of values.

The Standard Template Library



The three components of the STL

The Standard Template Library (STL) consists of three components from a bird's-eye view. Those are containers, algorithms that run on the containers, and iterators that connect both of them. The containers have only minimal requirements for their elements. This abstraction of generic programming enables you to combine algorithms and containers uniquely.

The C++ Standard Library has a rich collection of containers. We have sequence and associative containers. Associative containers can be classified as ordered or unordered associative containers.

Each of the sequence containers has a unique domain. Still, in 95 % of the use cases, `std::vector` is the right choice. `std::vector` can dynamically adjust its size, automatically manages its memory, and provides you with outstanding performance. In contrast, `std::array` is the only sequence container that cannot adjust its size at runtime. It is optimized for minimal memory and performance overhead. While `std::vector` is good at putting new elements at its end, you should use `std::deque` to put an element also at the beginning. With `std::list` being a doubly-linked list and `std::forward_list` as a singly linked list, we have two additional containers optimized for operations at arbitrary positions in the container, with high performance.

Associative containers are containers of key-value pairs. They provide their values by their respective key. A typical use case for an associative container is a phone book, where you use the key *family name* to retrieve the value *phone number*. C++ has eight different associative containers. On one side are the associative containers with ordered keys: `std::set`, `std::map`, `std::multiset` and `std::multimap`. On the other side, there are the unordered associative containers: `std::unordered_set`, `std::unordered_map`, `std::unordered_multiset`, and `std::unordered_multimap`.

First, look at the ordered associative containers. The difference between `std::set`, and `std::map` is that the former has no associated value. The difference between `std::map` and `std::multimap` is that the latter can have more than one identical key. These naming conventions also hold for the unordered associative containers, which have much in common with the ordered ones. The critical difference is the performance. While the ordered associative containers have a logarithmic access time, the unordered associative containers allow constant access time. Therefore the access time of the unordered associative containers is independent of their size. The same rule applies to `std::unordered_map` as to `std::vector`. In 95 % of all use cases, `std::unordered_map` should be your first choice if you don’t need sorted keys.

Container adapters provide a simplified interface to the sequence containers. C++ has `std::stack`, `std::queue`, and `std::priority_queue`.

C-array, `std::array`, `std::vector`, or `std::string` support views. `std::span` is a view of a contiguous sequence of elements. A view is never an owner.

Iterators are the glue between the containers and the algorithms. The container creates them. As generalized pointers, you can use them to iterate forward and backward or jump to an arbitrary position in the container. The type of iterator you get depends on the container. If you use an iterator adapter, you can directly access a stream.

The STL gives you more than 100 algorithms. Specifying the execution policy, you can run most of the algorithms sequential, parallel, or parallel and vectorized. Algorithms operate on elements or a range of elements. Two iterators define a range. The first one defines the beginning, the second one, called end iterator, defines the end of the range. It’s important to know that the end iterator points to *one element past the end of the range*.

The algorithms can be used in a wide range of applications. You can find elements, count them, find ranges, and compare or transform them. There are algorithms to generate, replace or remove elements from a container. Of course, you can sort, permute or partition a container or determine the minimum or maximum element of it. Many algorithms can be further customized by *callables* like functions, function objects, or lambda-functions. The *callables* provide special criteria for the search or the transformation of elements. They highly increase the power of the algorithm.

The algorithms of the ranges library are lazy, can work directly on the container, and can easily be composed. They extend C++ with functional ideas. Furthermore, most of the classical STL algorithms have ranges pendants, which support projections and provide additional safety guarantees.

Numeric

There are two libraries for numerics in C++: the random numbers library and the mathematical functions, which C++ inherited from C.

The random numbers library consists of two parts. There is the random number generator; the generated random numbers distribution is on the other side. The random number generator generates a stream of numbers between a minimum and a maximum value, which the random number distribution maps onto the concrete distribution.

Because of C, C++ has a lot of mathematical standard functions. For example, there are logarithmic, exponential, and trigonometric functions.

C++ supports basic and advanced mathematical constants such as e, π, or ϕ.

Text Processing

With strings and regular expressions, C++ has two powerful libraries to process text.

`std::string` possesses a rich collection of member functions to analyze and modify its text. Because it has a lot in common with a `std::vector` of characters, you can apply the STL algorithms to `std::string`. `std::string` is the successor of the C string but a lot easier and safer to use. C++ strings manage their memory.

In contrast to a `std::string`, a `std::string_view` is cheap to copy. A `std::string_view` is a non-owning reference to a `std::string`.

Regular expression is a language for describing text patterns. You can use regular expressions to determine whether a text pattern is present once or more times in a text. But that's not all. Regular expressions enable the replacement of a matched pattern with text.

Input and Output

I/O streams library is a library, present from the start of C++, that allows communication with the outside world.

Communication means, in this concrete case, that the extraction operator (>>) enables it to read formatted or unformatted data from the input stream, and the insertion operator (<<) allows it to write the data on the output stream. Data can be formatted using *manipulators*.

The stream classes have an elaborate class hierarchy. Two stream classes are significant: First, string streams allow you to interact with strings and streams. Second, file streams will enable you to read and write files easily. The state of streams is kept in flags, which you can read and manipulate.

By overloading the input operator and output operator, your class can interact with the outside world like a fundamental data type.

The formatting library provides a safe and extensible alternative to the `printf` family and extends the I/O streams library.

In contrast to the I/O streams library, the filesystem library was added to the C++-Standard with C++17. The library is based on three concepts file, file name, and path. Files can be directories, hard links, symbolic links, or regular files. Paths can be absolute or relative.

The filesystem library supports a powerful interface for reading and manipulating the filesystem.

Multithreading

C++ gets with the 2011 published C++ standard a multithreading library. This library has basic building blocks like atomic variables, threads, locks, and condition variables. That's the base on which future C++ standards can build higher abstractions. But C++11 already knows tasks, which provide a higher abstraction than the cited basic building blocks.

At a low level, C++11 provides for the first time a memory model and atomic variables. Both components are the foundation for *well-defined* behavior in multithreading programming.

A new thread in C++ will immediately start its work. It can run in the foreground or background and gets its data by copy or reference. Thanks to the stop token, you can interrupt the improved thread `std::jthread`.

The access of shared variables between threads has to be coordinated. This coordination can be done in different ways with mutexes or locks. But often, it's sufficient to protect the initialization of the data as it will be immutable during its lifetime.

Declaring a variable as thread-local ensures that a thread gets its copy, so there is no conflict.

Condition variables are a classic solution to implement sender-receiver workflows. The key idea is that the sender notifies the receiver when it's done with its work so that the receiver can start.

Semaphores are a synchronization mechanism that controls concurrent access to a shared resource. A semaphore has a counter that is bigger than zero. Acquiring the semaphore decreases the counter, and releasing the semaphore increases the counter. A thread can only acquire the resource when the counter is greater than zero.

Similar to semaphores, `std::latch` and `std::barrier` are coordination types that enable some threads to block until a counter becomes zero. In contrast to a `std::barrier`, you can reuse a `std::latch` for a new iteration and adjust its counter for this new iteration.

Tasks have much in common with threads. But while a programmer explicitly creates a thread, a task will be implicitly created by the C++ runtime. Tasks are like data channels. The data can be a value, an exception, or simply a notification. The promise puts data into the data channel; the future picks the value up.

Coroutines are functions that can suspend and resume their execution while keeping their state. Coroutines are the usual way to write event-driven applications. The event-driven application can be simulations, games, servers, user interfaces, or even algorithms. Coroutines enable cooperative multitasking. The key to cooperative multitasking is that each task takes as much time as it needs.

Use of Libraries

You must perform three steps to use a library in a program. At first, you have to include the header files with the `#include` statement, so the compiler knows the library's names. Alternatively, you can import with C++23 the standard library using `import std;`. Because the C++ standard library names are in the namespace `std`, you can use them in the second step fully qualified, or you have to import them in the global namespace. The third and final step is to specify the libraries for the linker to get an executable. This third step is often optional. The following lines explain the three steps.

Include Header Files

The preprocessor includes the file, following the `#include` statement. That is, most of the time, a header file. The header files are placed in angle brackets:

```
#include <iostream>
#include <vector>
```

Specify all necessary header files

The compiler is free to add additional headers to the header files. So your program may have all the necessary headers, although you didn't specify them. It's not recommended to rely on this feature. All needed headers should always be explicitly specified. Otherwise, a compiler upgrade or code porting may provoke a compilation error.

Import the Standard Library

In C++23, you can import the entire standard library using the `import` statement:

```
import std;
```

The `import std;` statement imports everything in the namespace `std` from C++ headers and C wrapper headers such as `std::printf` from `<cstdio>`. Also `::operator new`, or `::operator delete` from the `<new>` header is imported.

If you also want to import the global namespace counterparts such as `::printf` from the C wrapper header `<stdio.h>`, use the `import std.compat`.

Prefer importing modules to including headers

Modules have many advantages over header files. These advantages hold for the modularized standard library but also user-defined modules.

Modules are imported only once, and this process is literally for free. It makes no difference in which order you import modules, and duplicate names with modules are very unlikely. Modules enable you to express the logical structure of your code because you can explicitly specify names that should be exported or not. Additionally, you can bundle a few modules into a more extensive module and provide them to your customer as a logical package.

Parallel use of header files and modules

I use both syntactic forms: headers files and modules in the following code snippets. You should only use one of them exclusively.

Usage of Namespaces

If you use qualified names, you should use them precisely as defined. For each namespace, you must put the scope resolution operator `::`. More libraries of the C++ standard library use nested namespaces.

```
#include <iostream>                              // either
#include <chrono>                                // either
...
#import std;                                     // or
...
std::cout << "Hello world:" << '\n';
auto timeNow= std::chrono::system_clock::now();
```

Unqualified Use of Names

You can use names in C++ with the `using` declaration and the `using` directive.

Using Declaration

A `using` declaration adds a name to the visibility scope in which you applied the `using` declaration:

```
#include <iostream>                // either
#include <chrono>                  // either
...
#import std;                       // or
...
using std::cout;
using std::endl;
using std::chrono::system_clock;
...
cout << "Hello world:" << endl; // unqualified name
auto timeNow= now();            // unqualified name
```

The application of a `using` declaration has the following consequences:

- An ambiguous lookup and a compiler error occur if the same name was declared in the same visibility scope.
- If the same name was declared in a surrounding visibility scope, it will be hidden by the `using` declaration.

Using Directive

The `using` directive permits it to use all namespace names without qualification.

```
#include <iostream>                          // either
#include <chrono>                            // either
...
#import std;                                 // or
...
using namespace std;
...
cout << "Hello world:" << endl;             // unqualified name
auto timeNow= chrono::system_clock::now(); // partially
qualified name
```

A `using` directive adds no name to the current visibility scope; it only makes the name accessible. That implies:

- An ambiguous lookup and a compiler error occur if the same name was declared in the same visibility scope.
- A name in the local namespace hides a name declared in a surrounding namespace.
- An ambiguous lookup and, therefore, a compiler error occurs if the same name gets visible from different namespaces or if a name in the namespace hides a name in the global scope.

Use `using` directives with great care in source files

`using` directives should be used with great care in source files because by the directive `using namespace std` all names from `std` becomes visible. That includes names which accidentally hide names in the local or surrounding namespace.

Don't use `using` directives in header files. If you include a header with `using namespace std` directive, all names from `std` become visible.

Namespace Alias

A namespace alias defines a synonym for a namespace. It's often convenient to use an alias for a long namespace name or an nested namespaces:

```
#include <chrono>                                   // either
...
#import std;                                        // or
...
namespace sysClock= std::chrono::system_clock;
auto nowFirst= sysClock::now();
auto nowSecond= std::chrono::system_clock::now();
```

Because of the namespace alias, you can address the `now` function qualified, and with the alias. A namespace alias must not hide a name.

Build an Executable

It is only seldom necessary to link explicitly against a library. That sentence is platform-dependent. For example, with the current *g++* or *clang++* compiler, you should link against the `pthread` library to get the multithreading functionality.

```
g++ -std=c++14 thread.cpp -o thread -pthread
```

2. Utilities

Cippi studies the calendar

Utilities are valuable tools that you can use in different contexts. They are not bound to a specific domain. That sentence is valid for the functions and libraries of this chapter. I present functions you can apply to arbitrary values or functions you can use to create new functions and bind them to variables. You can store any value of an arbitrary type in pairs and tuples or build references of any value. Smart pointers are your tool for implementing automatic memory management in C++. To get type information, use the type-traits library.

Useful Functions

You can apply the many variations of the `min`, `max`, and `minmax` functions to values and initializer lists. These functions need the header `<algorithm>`. On the contrary, the functions `std::move`, `std::forward`, `std::to_underlying`, and `std::swap` are defined in the header `<utility>`. You can apply them to arbitrary values.

`std::min`, `std::max`, and `std::minmax`

The functions `std::min`, `std::max`, and `std::minmax`, defined in the header `<algorithm>`, act on values and initializer lists and give you the requested value back as a result. In the case of `std::minmax`, you get a `std::pair`. The first element of the pair is the minimum; the second is the maximum of the values. The less operator (<) is used by default, but you can apply your comparison operator. This function needs two arguments and returns a boolean. Functions that either return `true` or `false` are called predicates.

The functions `std::min`, `std::max`, and `std::minmax`

```
// minMax.cpp
...
#include <algorithm>
...
using std::cout;
...
cout << std::min(2011, 2014);                                // 2011
cout << std::min({3, 1, 2011, 2014, -5});                    // -5
cout << std::min(-10, -5, [](int a, int b)
                { return std::abs(a) < std::abs(b); }); // -5

auto pairInt= std::minmax(2011, 2014);
auto pairSeq= std::minmax({3, 1, 2011, 2014, -5});
auto pairAbs= std::minmax({3, 1, 2011, 2014, -5}, [](int a, int b)
                      { return std::abs(a) < std::abs(b); });

cout << pairInt.first << "," << pairInt.second;  // 2011,2014
cout << pairSeq.first << "," << pairSeq.second;  // -5,2014
cout << pairAbs.first << "," << pairAbs.second;  // 1,2014
```

The table provides an overview of the functions `std::min`, `std::max` and `std::minmax`

The variations of `std::min`, `std::max`, and `std::minmax`

Function	Description
`min(a, b)`	Returns the smaller value of `a` and `b`.
`min(a, b, comp)`	Returns the smaller value of `a` and `b` according to the predicate `comp`.
`min(initialiser list)`	Returns the smallest value of the initializer list.
`min(initialiser list, comp)`	Returns the smallest value of the initializer list according to the predicate `comp`.
`max(a, b)`	Returns the greater value of `a` and `b`.
`max(a, b, comp)`	Returns the greater value of `a` and `b` according to the predicate `comp`.
`max(initialiser list)`	Returns the greates value of the initializer list.
`max(initialiser list, comp)`	Returns the greates value of the initializer list according to the predicate `comp`.
`minmax(a, b)`	Returns the smaller and greater value of `a` and `b`.
`minmax(a, b, comp)`	Returns the smaller and greater value of `a` and `b` according to the predicate `comp`.
`minmax(initialiser list)`	Returns the smallest and the greatest value of the initializer list.
`minmax(initialiser list, comp)`	Returns the smallest and the greatest value of the initializer list according to the predicate `comp`.

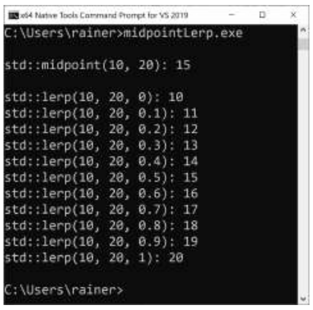
`std::midpoint`, and `std::lerp`

The function `std::midpoint(a, b)` calculates the midpoint between `a` and `b`. `a` and `b` can be integers, floating-point numbers, or pointers. If `a` and `b` are pointers, they must point to the same array object. The function `std::midpoint` requires the header `<numeric>`.

The function `std::lerp(a, b, t)` calculates the linear interpolation of two numbers. It requires the header `<cmath>`. The return value is `a + t(b - a)`.

`std::midpoint`, and `std::lerp`

```
// midpointLerp.cpp

#include <cmath>
#include <numeric>

...

std::cout << "std::midpoint(10, 20): " << std::midpoint(10, 20) <<
'\n';

for (auto v: {0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0})
{
    std::cout << "std::lerp(10, 20, " << v << "): " << std::lerp(10,
20, v) << "\n";
}
```



```
C:\Users\rainer>midpointLerp.exe

std::midpoint(10, 20): 15

std::lerp(10, 20, 0): 10
std::lerp(10, 20, 0.1): 11
std::lerp(10, 20, 0.2): 12
std::lerp(10, 20, 0.3): 13
std::lerp(10, 20, 0.4): 14
std::lerp(10, 20, 0.5): 15
std::lerp(10, 20, 0.6): 16
std::lerp(10, 20, 0.7): 17
std::lerp(10, 20, 0.8): 18
std::lerp(10, 20, 0.9): 19
std::lerp(10, 20, 1): 20

C:\Users\rainer>
```

`std::cmp_equal`, `std::cmp_not_equal`, `std::cmp_less`, `std::cmp_greater`, `std::cmp_less_equal`, and `std::cmp_greater_equal`

The in the header `<utility>` definfined functions `std::cmp_equal`, `std::cmp_not_equal`, `std::cmp_less`, `std::cmp_greater`, `std::cmp_less_equal`, and `std::cmp_greater_equal` provide safe comparison of integers. Safe comparison means that the comparison of a negative signed integer compares less than an unsigned integer, and that the comparison of values other than a signed or unsigned integer gives a compile-time error.

Integer conversion with builtin integers

The following code snippet exemplifies the issue of signed/unsigned comparison.

```
-1 < 0u;                     // true
std::cmp_greater( -1, 0u); // false
```

`-1` as a signed integer is promoted to an unsigned type which causes a surprising result.

`std::move`

The function `std::move`, defined in the header `<utility>`, authorizes the compiler to move the resource. In the so-called *move semantics*, the source object's values are moved to the new object. Afterward, the source is in a *well-defined* but indeterminate state. Most of the time, that is the default state of the source. By using `std::move`, the compiler converts the source `arg` to an rvalue reference: `static_cast<std::remove_reference<decltype(arg)>::type&&> (arg)`. If the compiler can not apply the *move semantics*, it falls back to the *copy semantics*:

```
#include <utility>
...
std::vector<int> myBigVec(10000000, 2011);
std::vector<int> myVec;

myVec = myBigVec;              // copy semantics
myVec = std::move(myBigVec);   // move semantics
```

To move is cheaper than to copy

The move semantics has two advantages. Firstly, it is often a good idea to use cheap moving instead of expensive copying. So there is no extra allocation and deallocation of memory necessary. Secondly, there are objects which can not be copied. E.g., a thread or a lock.

`std::forward`

The function `std::forward`, defined in the header `<utility>`, empowers you to write function templates, which can identically forward their arguments. Typical use cases for `std::forward` are factory functions or constructors. Factory functions create an object and should, therefore, pass their arguments unmodified. Constructors often use their arguments to initialize their base class with identical arguments. So `std::forward` is the perfect tool for authors of generic libraries:

Perfect forwarding

```
// forward.cpp
...
#include <utility>
...
using std::initialiser_list;

struct MyData{
  MyData(int, double, char){};
};

template <typename T, typename...  Args>
  T createT(Args&&... args){
  return T(std::forward<Args>(args)... );
}

...

int a= createT<int>();
int b= createT<int>(1);

std::string s= createT<std::string>("Only for testing.");
MyData myData2= createT<MyData>(1, 3.19, 'a');

typedef std::vector<int> IntVec;
IntVec intVec= createT<IntVec>(initialiser_list<int>({1, 2, 3}));
```

The function template `createT` has to take their arguments as a universal reference: Args&&... args`. A universal reference, or forwarding reference, is an rvalue reference in a type deduction context.

`std::forward` enables completely generic functions in combination with variadic templates

If you use `std::forward` together with variadic templates, you can define fully generic function templates. Your function template can accept an arbitrary number of arguments and forward them unchanged.

`std::to_underlying`

The function `std::to_underlying` in C++23 converts an enumeration `enum` to is underlying type `Enum`. This function is a convenience function for the expression `static_cast<std::underlying_type<Enum>::type>(enum)`, using the type traits function `std::underlying_type`.

`std::swap`

With the function `std::swap` defined in the header `<utility>`, you can easily swap two objects. The generic implementation in the C++ standard library internally uses the function `std::move`.

Move-semantic with `std::swap`

```
// swap.cpp
...
#include <utility>
...
template <typename T>
inline void swap(T& a, T& b) noexcept {
    T tmp(std::move(a));
    a = std::move(b);
    b = std::move(tmp);
}
```

Adaptors for Functions

The three functions `std::bind`, `std::bind_front`, `std::bind_back`, and `std::functions` fit very well together. While `std::bind`, `std::bind_front`, or `std::bind_back` enables you to create new function objects on the fly, `std::function` takes these temporary function objects and binds them to a variable.

`std::bind`, `std::bind_front`, `std::bind_back`, and `std::function` are mostly superfluous

`std::bind` and `std::function`, which were part of TR1, `std::bind_front`, and `std::bind_back` are mostly not necessary in C++. First, you can use lambdas instead of `std::bind`, `std::bind_front`, `std::bind_back`, and second, you can most often use the automatic type deduction with `auto` instead of `std::function`.

`std::bind`

The function `std::bind` is more powerful than `std::bind_front` or `std::bind_back` because `std::bind` allows the arguments to be bound to an arbitrary position. While `std::bind`, `std::bind_front`, and `std::bind_back` enables you to create new function objects on the fly, `std::function` takes these temporary function objects and binds them to a variable. These functions are powerful tools from functional programming and require the header `<functional>`.

Creating and binding function objects

```
// bindAndFunction.cpp
...
#include <functional>
...
// for placehoder _1 and _2
using namespace std::placeholders;

using std::bind;
using std::bind_front;
using std::bind_back;
using std::function
...
double divMe(double a, double b){ return a/b; };

function<double(double, double)> myDiv1 = bind(divMe, _1, _2);  //
200
function<double(double)> myDiv2 = bind(divMe, 2000, _1);         //
200
function<double(double>> myDiv3 = bind_front(divMe, 2000);       //
200
function<double(double)> myDiv4 = bind_back(divMe, 10);          //
200
```

`std::bind`

Because of `std::bind`, you can create function objects in a variety of ways:

- bind the arguments to an arbitrary position,
- change the order of the arguments,
- introduce placeholders for arguments,
- partially evaluate functions,
- invoke the newly created function objects, use them in the STL algorithm, or store them in `std::function`.

`std::bind_front` (C++20)

`std::bind_front` creates a callable wrapper from a callable. A call `std::bind_front(func, arg ...)` binds all arguments `arg` to the front of `func` and returns a callable wrapper.

`std::bind_back` (C++23)

`std::bind_back` creates a callable wrapper from a callable. A call `std::bind_back(func, arg ...)` binds all arguments `arg` to the back of `func` and returns a callable wrapper.

`std::function`

`std::function` can store arbitrary callables in variables. It's a polymorphic function wrapper. A callable may be a lambda function, a function object, or a function. `std::function` is always necessary and can't be replaced by `auto`, if you have to specify the type of the callable explicitly.

A dispatch table with `std::function`

```cpp
// dispatchTable.cpp
...
#include <functional>
...
using std::make_pair;
using std::map;

map<const char, std::function<double(double, double)>> tab;
tab.insert(make_pair('+', [](double a, double b){ return a + b; }));
tab.insert(make_pair('-', [](double a, double b){ return a - b; }));
tab.insert(make_pair('*', [](double a, double b){ return a * b; }));
tab.insert(make_pair('/', [](double a, double b){ return a / b; }));

std::cout << tab['+'](3.5, 4.5);  // 8
std::cout << tab['-'](3.5, 4.5);  // -1
std::cout << tab['*'](3.5, 4.5);  // 15.75
std::cout << tab['/'](3.5, 4.5);  // 0.777778
```

The type parameter of `std::function` defines the type of callables `std::function` will accept.

Return type and type of the arguments

Function type	Return type	Type of the arguments
`double(double, double)`	`double`	`double`
`int()`	`int`	
`double(int, double)`	`double`	`int, double`
`void()`		

Pairs

You can build pairs of arbitrary types with std::pair. The class template std::pair needs the header <utility>. std::pair has a default, copy and move constructor. Pair objects can be swapped: std::swap(pair1, pair2).

Pairs are often used in the C++ library. For example, the function std::minmax returns its result as a pair, the associative container std::map, std::unordered_map, std::multimap and std::unordered_multimap manage their key/value association in pairs.

To get the elements of a pair p, you can access them directly or through an index. So, with p.first or std::get<0>(p), you get the first with p.second or std::get<1>(p), you get the second element of the pair.

Pairs support the comparison operators ==, !=, <, >, <= and >=. When comparing two pairs for identity, members pair1.first and pair2.first are compared first, and then pair1.second and pair2.second. The same strategy holds for the other comparison operators.

std::make_pair

C++ has the practical help function std::make_pair to generate pairs without specifying their types. std::make_pair automatically deduces their types.

The helper function std::make_pair

```
// pair.cpp
...
#include <utility>
...
using namespace std;
...
pair<const char*, double> charDoub("str", 3.14);
pair<const char*, double> charDoub2= make_pair("str", 3.14);
auto charDoub3= make_pair("str", 3.14);

cout << charDoub.first << ", " << charDoub.second;    // str, 3.14
charDoub.first="Str";
get<1>(charDoub)= 4.14;
cout << charDoub.first << ", " << charDoub.second;    // Str, 4.14
```

Tuples

You can create tuples of arbitrary length and types with std::tuple. The class template needs the header <tuple>. std::tuple is a generalization of std::pair. Tuples with two elements and pairs can be converted into each other. Like `std::pair`, the tuple has a default, a copy, and a move constructor. You can swap tuples with the function `std::swap`.

`std::get` can access the i-th element of a tuple: `std::get<i-1>(t)`. By `std::get<type>(t)`, you can directly refer to the element of the type `type`.

Tuples support the comparison operators ==, `!=`, <, >, <= and >=. If you compare two tuples, the elements of the tuples are compared lexicographically. The comparison starts at the index 0.

`std::make_tuple`

The helper function `std::make_tuple` provides a convenient way to create a tuple. You don't have to specify the types. The compiler automatically deduces them.

The helper function `std::make_tuple`

```
// tuple.cpp
...
#include <tuple>
...
using std::get;

std::tuple<std::string, int, float> tup1("first", 3, 4.17f);
auto tup2= std::make_tuple("second", 4, 1.1);

std::cout << get<0>(tup1) << ", " << get<1>(tup1) << ", "
          << get<2>(tup1) << '\n'; // first, 3, 4.17
std::cout << get<0>(tup2) << ", " << get<1>(tup2) << ", "
          << get<2>(tup2) << '\n'; // second, 4, 1.1
std::cout << (tup1 < tup2) << '\n'; // true

get<0>(tup2)= "Second";

std::cout << get<0>(tup2) << "," << get<1>(tup2) << ","
          << get<2>(tup2) << '\n';  // Second, 4, 1.1
std::cout << (tup1 < tup2) << '\n'; // false

auto pair= std::make_pair(1, true);
std::tuple<int, bool> tup= pair;
```

`std::tie` and `std::ignore`

`std::tie` enables you to create tuples that reference variables. You can explicitly ignore tuple elements with `std::ignore`.

The helper functions `std::tie` and `std::ignore`

```
// tupleTie.cpp
...
#include <tuple>
...
```

```
using namespace std;

int first= 1;
int second= 2;
int third= 3;
int fourth= 4;
cout << first << " " << second << " "
     << third << " " << fourth << endl;          // 1 2 3 4

auto tup= tie(first, second, third, fourth)      // bind the tuple
        = std::make_tuple(101, 102, 103, 104);   // create the tuple
                                                 // and assign it
cout << get<0>(tup) << " " << get<1>(tup) << " " << get<2>(tup)
     << " " << get<3>(tup) << endl;              // 101 102 103 104
cout << first << " " << second << " " << third << " "
     << fourth << endl;                          // 101 102 103 104

first= 201;
get<1>(tup)= 202;
cout << get<0>(tup) << " " << get<1>(tup) << " " << get<2>(tup)
     << " " << get<3>(tup) << endl;              // 201 202 103 104
cout << first << " " << second << " " << third << " "
     << fourth << endl;                          // 201 202 103 104

int a, b;
tie(std::ignore, a, std::ignore, b)= tup;
cout << a << " " << b << endl;                   // 202 104
```

Reference Wrappers

A reference wrapper is a copy-constructible and copy-assignable wrapper for an object of type&, which is defined in the header `<functional>`. You have an object that behaves like a reference but can be copied. In opposite to classic references, `std::reference_wrapper` objects support two additional use cases:

- You can use them in containers of the Standard Template Library. `std::vector<std::reference_wrapper<int>> myIntRefVector`
- You can copy instances of classes which have `std::reference_wrapper` objects. That is, in general, not possible with references.

The get member function allows access to the reference: `myInt.get()`. You can use a reference wrapper to encapsulate and invoke a callable.

Reference wrappers

```
// referenceWrapperCallable.cpp
...
#include <functional>
...
void foo(){
  std::cout << "Invoked" << '\n';
}

typedef void callableUnit();
std::reference_wrapper<callableUnit> refWrap(foo);

refWrap();                          // Invoked
```

std::ref and std::cref

With the helper functions `std::ref` and `std::cref`, you can easily create reference wrappers for variables. `std::ref` will create a non-constant reference wrapper, `std::cref` a constant one:

The helper functions `std::ref` and `std::cref`

```
// referenceWrapperRefCref.cpp
...
#include <functional>
...
void invokeMe(const std::string& s){
  std::cout << s << ": const " << '\n';
}

template <typename T>
  void doubleMe(T t){
  t*= 2;
}

std::string s{"string"};

invokeMe(std::cref(s));         // string

int i= 1;
std::cout << i << '\n';    // 1

doubleMe(i);
std::cout << i << '\n';    // 1S

doubleMe(std::ref(i));
std::cout << i << '\n';    // 2
```

It is possible to invoke the function `invokeMe` taking a constant reference to a `std::string` with a non-constant `std::string s` wrapped in a `std::cref(s)`. When I wrap the variable `i` in the helper function `std::ref`, the function template `doubleMe` is invoked with a reference. Consequentially, the variable `i` is doubled.

Smart Pointers

Smart pointers are essential to C++ because they empower you to implement explicit memory management in C++. Besides the *deprecated* `std::auto_ptr`, C++ offers three smart pointers. They are defined in the header `<memory>`.

First, the `std::unique_ptr` models the concept of exclusive ownership. Second, the `std::shared_ptr` models the concept of shared ownership. Finally, the `std::weak_ptr`. `std::weak_ptr` isn't smart because it has a limited interface. Its job is to break cycles of `std::shared_ptr`. It models the concept of temporary ownership.

The smart pointers manage their resource according to the RAII idiom. Therefore, the resource is automatically freed if the smart pointer goes out of scope.

Resource Acquisition Is Initialization

Resource **A**cquisition **I**s **I**nitialization, short RAII, stands for a popular technique in C++, in which the resource acquisition and release are bound to the lifetime of an object. For the smart pointer, the memory is allocated in the constructor and deallocated in the destructor. In C++, the destructor is automatically called when the object goes out of scope.

Overview smart pointers

Name	Standard	Description
`std::auto_ptr` (*deprecated*)	C++98	Owns exclusively the resource. Moves the resource when copying.
`std::unique_ptr`	C++11	Owns exclusively the resource. Cannot be copied.
`std::shared_ptr`	C++11	Has a reference counter for the shared variable. Manages the reference counter automatically. Deletes the resource if the reference counter is 0.
`std::weak_ptr`	C++11	Helps to break cycles of `std::shared_ptr`. Doesn't modify the reference counter.

std::unique_ptr

`std::unique_ptr` exclusively takes care of its resource. It automatically releases the resource if it goes out of scope. If no copy semantics are used, you can use a `std::unique_ptr` in containers and algorithms of the Standard Template Library. `std::unique_ptr` is as cheap and fast as a raw pointer if you use no special deleter.

Don’t use std::auto_ptr

Classical C++03 has a smart pointer `std::auto_ptr`, which exclusively takes care of the lifetime of a resource. But `std::auto_ptr` has a conceptual issue. If you implicitly or explicitly copy a `std::auto_ptr`, the resource is probably moved. So instead of copy semantics, you have hidden move semantics, and therefore, you often have undefined behavior. So `std::auto_ptr` is *deprecated* in C++11, and you should use instead `std::unique_ptr`. You can neither implicitly nor explicitly copy a `std::unique_ptr`. You can only move it:

```
#include <memory>
...
std::auto_ptr<int> ap1(new int(2011));
std::auto_ptr<int> ap2 = ap1;              // OK

std::unique_ptr<int> up1(new int(2011));
std::unique_ptr<int> up2 = up1;            // ERROR
std::unique_ptr<int> up3 = std::move(up1); // OK
```

These are the member functions of `std::unique_ptr`.

Member Functions of `std::unique_ptr`

Name	Description
`get`	Returns a pointer to the resource.
`get_deleter`	Returns the delete function.
`release`	Returns a pointer to the resource and releases it.
`reset`	Resets the resource.
`swap`	Swaps the resources.

In the following code snippet, you can see the application of these member functions:

The `std::unique_ptr`

```
// uniquePtr.cpp
...
#include <utility>
...
using namepace std;

struct MyInt{
  MyInt(int i):i_(i){}
  ~MyInt(){
    cout << "Good bye from " << i_ << endl;
  }
  int i_;
};

unique_ptr<MyInt> uniquePtr1{new MyInt(1998)};
cout << uniquePtr1.get() << endl;                 // 0x15b5010

unique_ptr<MyInt> uniquePtr2{move(uniquePtr1)};
cout << uniquePtr1.get() << endl;                 // 0
cout << uniquePtr2.get() << endl;                 // 0x15b5010
{
  unique_ptr<MyInt> localPtr{new MyInt(2003)};
}                                                 // Good bye from 2003
uniquePtr2.reset(new MyInt(2011));                // Good bye from 1998
MyInt* myInt= uniquePtr2.release();
delete myInt;                                     // Good by from 2011

unique_ptr<MyInt> uniquePtr3{new MyInt(2017)};
unique_ptr<MyInt> uniquePtr4{new MyInt(2022)};
cout << uniquePtr3.get() << endl;                 // 0x15b5030
cout << uniquePtr4.get() << endl;                 // 0x15b5010

swap(uniquePtr3, uniquePtr4);
cout << uniquePtr3.get() << endl;                 // 0x15b5010
cout << uniquePtr4.get() << endl;                 // 0x15b5030
```

`std::unique_ptr` has a specialization for arrays:

`std::unique_ptr` array

```
// uniquePtrArray.cpp
...
#include <memory>
...
using namespace std;

class MyStruct{
public:
  MyStruct():val(count){
    cout << (void*)this << " Hello: " << val << endl;
    MyStruct::count++;
  }
  ~MyStruct(){
    cout << (void*)this << " Good Bye: " << val << endl;
    MyStruct::count--;
  }
private:
  int val;
  static int count;
};

int MyStruct::count= 0;
...
{
  // generates a myUniqueArray with three `MyStructs`
  unique_ptr<MyStruct[]> myUniqueArray{new MyStruct[3]};
}
// 0x1200018 Hello: 0
// 0x120001c Hello: 1
// 0x1200020 Hello: 2
// 0x1200020 GoodBye: 2
// 0x120001c GoodBye: 1
// 0x1200018 GoodBye: 0
```

Special Deleters

`std::unique_ptr` can be parametrized with special deleters: `std::unique_ptr<int, MyIntDeleter> up(new int(2011), myIntDeleter())`. `std::unique_ptr` uses by default the deleter of the resource.

std::make_unique

The helper function [`std::make_unique`](http://en.cppreference.com/w/cpp/memory/unique_ptr/make_unique) was unlike its sibling [`std::make_shared`](http://en.cppreference.com/w/cpp/memory/shared_ptr/make_shared) forgotten in the C++11 standard. `std::make_unique` was, therefore, added with the C++14 standard. `std::make_unique` enables it to create a `std::unique_ptr` in a single step: `std::unique_ptr<int> up= std::make_unique<int>(2014)`.

std::shared_ptr

[`std::shared_ptr`](http://en.cppreference.com/w/cpp/memory/shared_ptr) shares the ownership of the resource. They have two handles. One for the resource and one for the reference counter. By copying a `std::shared_ptr`, the reference count is increased by one. It is decreased by one if the `std::shared_ptr` goes out of scope. If the reference counter becomes the value 0 and there is no `std::shared_ptr` referencing the resource anymore, the C++ runtime automatically releases the resource. The release of the resource occurs precisely when the last `std::shared_ptr` goes out of scope. The C++ runtime guarantees that the call of the reference counter is an atomic operation. Because of this administration overhead, `std::shared_ptr` requires more time and memory than a raw pointer or `std::unique_ptr`.

In the following table are the member functions of `std::shared_ptr`.

Member Functions of `std::shared_ptr`

Name	Description
`get`	Returns a pointer to the resource.
`get_deleter`	Returns the delete function
`reset`	Resets the resource
`swap`	Swaps the resources.
`unique`	Checks if the `std::shared_ptr` is the exclusive owner of the resource.
`use_count`	Returns the value of the reference counter.

std::make_shared

The helper function `std::make_shared` creates the resource, and returns it in a `std::shared_ptr`. You should prefer `std::make_shared` instead of the direct creation of a `std::shared_ptr`, because `std::make_shared` is faster.

The following code sample shows a typical use case of a `std::shared_ptr`.

`std::shared_ptr`

```
// sharedPtr.cpp
...
#include <memory>
...
class MyInt{
public:
  MyInt(int v):val(v){
    std::cout << "Hello: " << val << '\n';
  }
  ~MyInt(){
    std::cout << "Good Bye: " << val << '\n';
  }
private:
  int val;
};

auto sharPtr= std::make_shared<MyInt>(1998);         // Hello: 1998
std::cout << sharPtr.use_count() << '\n';      // 1

{
  std::shared_ptr<MyInt> locSharPtr(sharPtr);
  std::cout << locSharPtr.use_count() << '\n'; // 2
}
std::cout << sharPtr.use_count() << '\n';      // 1
```

```
std::shared_ptr<MyInt> globSharPtr= sharPtr;
std::cout << sharPtr.use_count() << '\n';      // 2

globSharPtr.reset();
std::cout << sharPtr.use_count() << '\n';     // 1
sharPtr= std::shared_ptr<MyInt>(new MyInt(2011));  // Hello:2011
                                                   // Good Bye: 1998
...
// Good Bye: 2011
```

The callable is, in this example, a function object. Therefore you can easily count how many instances of a class are created. The result is in the static variable `count`.

std::shared_ptr from this

You have to derive the class public from `std::enable_shared_from_this`. You can create with the class `std::enable_shared_from_this` objects, which return a `std::shared_ptr` on itself. The class supports the member function `shared_from_this` to return `std::shared_ptr` to this:

`std::shared_ptr` from this

```
// enableShared.cpp
...
#include <memory>
...
class ShareMe: public std::enable_shared_from_this<ShareMe>{
  std::shared_ptr<ShareMe> getShared(){
    return shared_from_this();
  }
};

std::shared_ptr<ShareMe> shareMe(new ShareMe);
std::shared_ptr<ShareMe> shareMe1= shareMe->getShared();

std::cout << (void*)shareMe.get() << '\n';   // 0x152d010
std::cout << (void*)shareMe1.get() << '\n';  // 0x152d010
std::cout << shareMe.use_count() << '\n';    // 2
```

You can see in the code sample that the `get` member functions reference the same object.

std::weak_ptr

`std::weak_ptr` is not a smart pointer. `std::weak_ptr` supports no transparent access to the resource because it only borrows the ressource from a `std::shared_ptr`. `std::weak_ptr` does not change the reference counter:

`std::weak_ptr`

```
// weakPtr.cpp
...
#include <memory>
...
auto sharedPtr= std::make_shared<int>(2011);
std::weak_ptr<int> weakPtr(sharedPtr);

std::cout << weakPtr.use_count() << '\n';        // 1
std::cout << sharedPtr.use_count() << '\n';      // 1

std::cout << weakPtr.expired() << '\n';          // false
if( std::shared_ptr<int> sharedPtr1= weakPtr.lock() ) {
  std::cout << *sharedPtr << '\n'; // 2011
}
else{
  std::cout << "Don't get it!" << '\n';
}

weakPtr.reset();

if( std::shared_ptr<int> sharedPtr1= weakPtr.lock() ) {
  std::cout << *sharedPtr << '\n';
}
else{
  std::cout << "Don't get it!" << '\n';          // Don't get it!
}
```

The table provides an overview of the member functions of `std::weak_ptr`.

Member Functions of `std::weak_ptr`

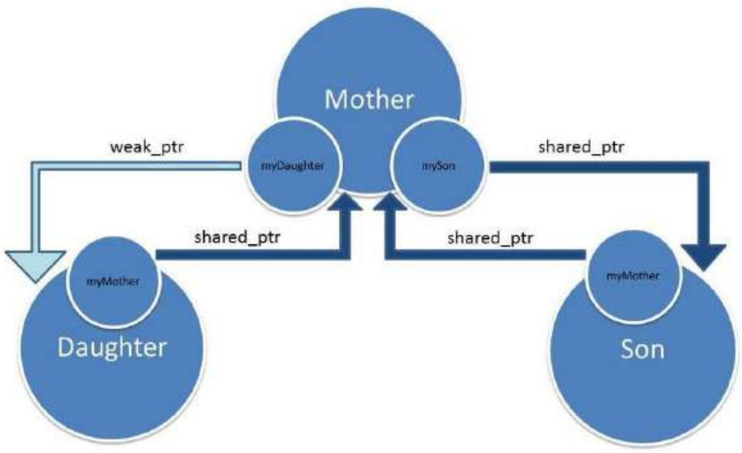
Name	Description
`expired`	Checks if the resource was deleted.
`lock`	Creates a `std::shared_ptr` on the resource.
`reset`	Resets the resource
`swap`	Swaps the resources.
`use_count`	Returns the value of the reference counter.

There is one reason for the existence of `std::weak_ptr`. It breaks the cycle of `std::shared_ptr`.

Cyclic References

You get cyclic references of `std::shared_ptr` if they refer to each other. So, the resource counter never becomes 0, and the resource is not automatically released. You can break this cycle if you embed a `std::weak_ptr` into the cycle. `std::weak_ptr` does not modify the reference counter.

The code sample result is that the daughter is automatically released, but neither the son nor the mother. The mother refers to her son via a `std::shared_ptr`, and her daughter via a `std::weak_ptr`. Maybe it helps to see the structure of the code in an image.



Cyclic references

Finally, here is the source code.

Cyclic references

```
// cyclicReference.cpp
...
#include <memory>
...
using namespace std;

struct Son, Daughter;

struct Mother{
  ~Mother(){cout << "Mother gone" << endl;}
   void setSon(const shared_ptr<Son> s ){mySon= s;}
   void setDaughter(const shared_ptr<Daughter> d){myDaughter= d;}
   shared_ptr<const Son> mySon;
   weak_ptr<const Daughter> myDaughter;
};

struct Son{
Son(shared_ptr<Mother> m):myMother(m){}
  ~Son(){cout << "Son gone" << endl;}
  shared_ptr<const Mother> myMother;
};

struct Daughter{
Daughter(shared_ptr<Mother> m):myMother(m){}
  ~Daughter(){cout << "Daughter gone" << endl;}
  shared_ptr<const Mother> myMother;
};
```

```
{
  shared_ptr<Mother> mother= shared_ptr<Mother>(new Mother);
  shared_ptr<Son> son= shared_ptr<Son>(new Son(mother) );
  shared_ptr<Daughter> daugh= shared_ptr<Daughter>(new
Daughter(mother));
  mother->setSon(son);
  mother->setDaughter(daugh);
}
                              // Daughter gone
```

Type Traits

The type traits library enables you to check, compare, and modify types at compile time. Consequentially, there is no overhead on the runtime of your program. There are two reasons for using the type traits library: Optimization and Correctness. Optimization because the type traits library's introspection capabilities make it possible to choose the faster code automatically. Correctness because you can specify requirements for your code to be checked at compile time.

The type traits library and static_assert are a powerful pair

The type traits library and the function `static_assert` are a powerful pair. On one side, the type traits library's functions provide the type information at compile time; on the other, the `static_assert` function checks the given information at compile time. These checks cause no run ttime overhead.

```
#include <type_traits>
...
template <typename T>T fac(T a){
 static_assert(std::is_integral<T>::value, "T not integral");
 ...
}
fac(10);
fac(10.1); // with T= double; T not integral
```

The GCC compiler quits the function invocation `fac(10.1)`. The message at compile is that T is of type double and, therefore, no integral type.

Check Type Information

With the type traits library, you can check primary and composite type categories. The attribute `value` gives you the result.

Primary Type Categories

There are 14 different type categories. They are complete and don't overlap. So each type is only a member of one type category. If you check a type category for your type, the request is independent of the `const` or `volatile` qualifiers.

```
template <class T> struct is_void;
template <class T> struct is_integral;
template <class T> struct is_floating_point;
template <class T> struct is_array;
template <class T> struct is_pointer;
template <class T> struct is_null_pointer;
template <class T> struct is_member_object_pointer;
template <class T> struct is_member_function_pointer;
template <class T> struct is_enum;
template <class T> struct is_union;
template <class T> struct is_class;
template <class T> struct is_function;
template <class T> struct is_lvalue_reference;
template <class T> struct is_rvalue_reference;
```

The following code samples show all primary type categories.

All primary type categories

```
// typeCategories.cpp
...
#include <type_traits>
using std::cout;

cout << std::is_void<void>::value;             // true
cout << std::is_integral<short>::value;        // true
cout << std::is_floating_point<double>::value; // true
cout << std::is_array<int [] >::value;         // true
cout << std::is_pointer<int*>::value;          // true
cout << std::is_reference<int&>::value;        // true

struct A{
  int a;
  int f(int){ return 2011; }
};
cout << std::is_member_object_pointer<int A::*>::value;          //
true
cout << std::is_member_function_pointer<int (A::*)(int)>::value; //
true

enum E{
  e= 1,
};
cout << std::is_enum<E>::value;                  // true

union U{
  int u;
};
cout << std::is_union<U>::value;                 // true

cout << std::is_class<std::string>::value;       // true
cout << std::is_function<int * (double)>::value; // true
cout << std::is_lvalue_reference<int&>::value;   // true
cout << std::is_rvalue_reference<int&&>::value;  // true
```

Composite Type Categories

There are seven composite type categories based on the 14 primary type categories.

Composite type categories

Composite type categories	Primary type category
`is_arithmetic`	`is_floating_point` or `is_integral`
`is_fundamental`	`is_arithmetic` or `is_void`
`is_object`	`is_arithmetic` or `is_enum` or `is_pointer` or `is_member_pointer`
`is_reference`	`is_lvalue_reference` or `is_rvalue_reference`
`is_compound`	complement of `is_fundamental`
`is_member_pointer`	`is_member_object_pointer` or `is_member_function_pointer`
`is_scalar`	`is_arithmetic` or `is_enum` or `is_pointer` or `is_is_member_pointer` or `is_null_pointer`

Type Properties

In addition to the primary and composite type categories, there are many type properties.

```
template <class T> struct is_const;
template <class T> struct is_volatile;
template <class T> struct is_trivial;
template <class T> struct is_trivially_copyable;
template <class T> struct is_standard_layout;
template <class T> struct has_unique_object_represenation;
template <class T> struct is_empty;
template <class T> struct is_polymorphic;
template <class T> struct is_abstract;
template <class T> struct is_final;
template <class T> struct is_aggregate;
template <class T> struct is_implicit_lifetime;

template <class T> struct is_signed;
template <class T> struct is_unsigned;

template <class T> struct is_bounded_array;
template <class T> struct is_unbounded_array;
template <class T> struct is_scoped_enum;

template <class T, class... Args> struct is_constructible;
template <class T> struct is_default_constructible;
template <class T> struct is_copy_constructible;
template <class T> struct is_move_constructible;

template <class T, class U> struct is_assignable;
template <class T> struct is_copy_assignable;
template <class T> struct is_move_assignable;
template <class T> struct is_destructible;
template <class T, class... Args> struct is_trivially_constructible;
template <class T> struct is_trivially_default_constructible;
template <class T> struct is_trivially_copy_constructible;
template <class T> struct is_trivially_move_constructible;
template <class T, class U> struct is_trivially_assignable;
template <class T> struct is_trivially_copy_assignable;
template <class T> struct is_trivially_move_assignable;

template <class T> struct is_trivially_destructible;

template <class T, class... Args> struct is_nothrow_constructible;
template <class T> struct is_nothrow_default_constructible;
template <class T> struct is_nothrow_copy_constructible;
template <class T> struct is_nothrow_move_constructible;

template <class T, class U> struct is_nothrow_assignable;
template <class T> struct is_nothrow_copy_assignable;
template <class T> struct is_nothrow_move_assignable;

template <class T> struct is_nothrow_destructible;
template <class T> struct has_virtual_destructor;

template <class T> struct is_swappable_with;
template <class T> struct is_swappable;
template <class T> struct is_nothrow_swappable_with;
template <class T> struct is_nothrow_swappable;
```

Type Relationships

The library supports various kinds of type relationships

Type relationships

Function	Description
`template <class Base, class Derived>` `struct is_base_of`	Checks if `Derived` is derived from `Base`.
`template <class From, class To>` `struct is_convertible` `struct is_nothrow_convertible`	Checks if `From` can be converted to `To`.
`template <class T, class U>` `struct is_same`	Checks if the types `T` and `U` are the same.
`template <class T, class U>` `struct is_layout_compatible`	Checks if the types `T` and `U` are layout compatible.
`template <class Base, class Derived>` `struct is_pointer_interconvertible_base_of`	Checks if a type is a pointer-interconvertible base of another type.
`template <class Fn, class ... ArgTypes>` `struct is_invocable` `struct is_invocable_r` `struct is_nothrow_invocable` `struct is_nothrow_invocable_r`	Checks if a type can be invoked with the given types.

Type Modifications

The type traits library enables you to change types during compile time. You can modify the constness of a type:

Type modifications

```cpp
// typeTraitsModifications.cpp
...
#include <type_traits>
...
using namespace std;

cout << is_const<int>::value;                     // false
cout << is_const<const int>::value;               // true
cout << is_const<add_const<int>::type>::value;    // true

typedef add_const<int>::type myConstInt;
cout << is_const<myConstInt>::value;              //true

typedef const int myConstInt2;
cout << is_same<myConstInt, myConstInt2>::value;  // true

cout << is_same<int,
remove_const<add_const<int>::type>::type>::value;    // true
cout << is_same<const int,
add_const<add_const<int>::type>::type>::value; // true
```

The function `std::add_const` adds the constness to a type, while `std::remove_const` removes it.

There are a lot more functions available in the type traits library. You can modify the const-volatile properties of a type.

```cpp
template <class T> struct remove_const;
template <class T> struct remove_volatile;
template <class T> struct remove_cv;

template <class T> struct add_const;
template <class T> struct add_volatile;
template <class T> struct add_cv;
```

You can change at compile time the sign,

```cpp
template <class T> struct make_signed;
template <class T> struct make_unsigned;
```

or the reference or pointer properties of a type.

```cpp
template <class T> struct remove_reference;
template <class T> struct remove_cvref;
template <class T> struct add_lvalue_reference;
template <class T> struct add_rvalue_reference;

template <class T> struct remove_pointer;
template <class T> struct add_pointer;
```

The following following functions are precious for the writing of generic libraries.

```cpp
template <class B> struct enable_if;
template <class B, class T, class F> struct conditional;
template <class... T> common_type;
template <class... T> common_reference;
template <class... T> basic_common_reference;
template <class... T> void_t;
template <class... T> type_identity;
```

You can conditionally hide with `std::enable_if` a function overload or template specialization from overload resolution. `std::conditional` provides you with the ternary operator at compile time, and `std::common_type` gives you the common type of all types. `std::common_type`, `std::common_reference`, `std::basic_common_reference`, `std::void_t`, and `std::type_identity` are a variadic template. Therefore the number of type parameters can be arbitrary.

Operations on Traits

The functions `std::conjunction`, `std::disjunction`, and `std::negation` enable the logical combinations of the type traits functions. They are variadic templates.

C++ has a shorthand for `::type` and has a shorthand for `::value`

If you want to get a `const int` from an `int` you have to ask for the type: `std::add_const<int>::type`. With the C++14 standard use simply `std::add_const_t<int>` instead of the verbose form: `std::add_const<int>::type`. This rule works for all type traits functions.

Accordingly, with C++17 you can use the shorthand `std::is_integral_v<T>` for the predicate `std::is_integral<T>::value`.

Member Relationships

The function `std::is_pointer_interconvertible_with_class` checks if objects of a type are pointer-interconvertible with the specified subobject of that type, and the function `std::is_corresponding_member` checks if two specified members correspond to each other in the common initial subsequence of two specified types.

Const evaluated Context

The call `std::is_constant_evaluated` allows you to detect if a function call occurs at compile time.

Detect if a function call occurs at compile time

```
// constantEvaluated.cpp
#include <type_traits>
...

constexpr double power(double b, int x) {
    if (std::is_constant_evaluated() && !(b == 0.0 && x < 0)) {

        if (x == 0)
            return 1.0;
        double r = 1.0, p = x > 0 ? b : 1.0 / b;
        auto u = unsigned(x > 0 ? x : -x);
        while (u != 0) {
            if (u & 1) r *= p;
            u /= 2;
            p *= p;
        }
        return r;
    }
    else {
        return std::pow(b, double(x));
    }
}

constexpr double kilo1 = power(10.0, 3);       // execution at compile
time

int n = 3;
double kilo2 = power(10.0, n);                 // execution at runtime
std::cout << "kilo2: " << kilo2 << '\n';
```

Time Library

The time library consists of the three main components, time point, time duration, and clock. Additionally, the library provides the time of day functionality, calendar support, time zone support, and support for in- and output.

Time point
: Time point is defined by a starting point, the so-called epoch, and additional time duration.

Time duration
: Time duration is the difference between two time-points. The number of ticks gives it.

Clock
: A clock consists of a starting point (epoch) and a tick so that the current time point can be calculated.

Time of day
: The duration since midnight split into hours:minutes:seconds.

Calendar
: Calendar stands for various calendar days such as year, a month, a weekday, or the n-th day of a week.

Time zone

Represents time specific to a geographic area.

The time library is a key component for multithreading

The time library is a key component of the new multithreading capabilities of C++. You can put the current thread by `std::this_thread::sleep_for(std::chrono::milliseconds(15)` for 15 milliseconds to sleep, or you try to acquire a lock for 2 minutes: `lock.try_lock_until(now + std::chrono::minutes(2))`.

Time Point

A duration consists of a period of time, defined as some number of ticks of some time unit. A time point consists of a clock and a time duration. This time duration can be positive or negative.

```
template <class Clock, class Duration= typename Clock::duration>
class time_point;
```

The epoch is not defined for the clocks `std::chrono::steady_clock`, `std::chrono::high_resolution_clock` and `std::chrono::system`. But on the popular platform, the epoch of `std::chrono::system` is usually defined as 1.1.1970. You can calculate the time since 1.1.1970 in the resolutions nanoseconds, seconds and minutes.

Time since epoch

```
// epoch.cpp
...
#include <chrono>
...
auto timeNow= std::chrono::system_clock::now();
auto duration= timeNow.time_since_epoch();
std::cout << duration.count() << "ns"       // 1413019260846652ns

typedef std::chrono::duration<double> MySecondTick;
MySecondTick mySecond(duration);
std::cout << mySecond.count() << "s";       // 1413019260.846652s

const int minute= 60;
typedef std::chrono::duration<double, <minute>> MyMinuteTick;
MyMinuteTick myMinute(duration);
std::cout << myMinute.count() << "m";       // 23550324.920572m
```

Thanks to the function `std::chrono::clock_cast`, you can cast time points between various clocks.

Easy performance tests with the time library

Performance measurement

```
// performanceMeasurement.cpp
...
#include <chrono>
...
std::vector<int> myBigVec(10000000, 2011);
std::vector<int> myEmptyVec1;

auto begin= std::chrono::high_resolution_clock::now();
myEmptyVec1 = myBigVec;
auto end= std::chrono::high_resolution_clock::now() - begin;

auto timeInSeconds = std::chrono::duration<double>
(end).count();
std::cout << timeInSeconds << '\n';              //
0.0150688800
```

Time Duration

Time duration is the difference between the two time-points. Time duration is measured in the number of ticks.

```
template <class Rep, class Period = ratio<1>> class duration;
```

If `Rep` is a floating-point number, the time duration supports fractions of ticks. The most important time durations are predefined in the chrono library:

```
typedef duration<signed int, nano> nanoseconds;
typedef duration<signed int, micro> microseconds;
typedef duration<signed int, milli> milliseconds;
typedef duration<signed int> seconds;
typedef duration<signed int, ratio< 60>> minutes;
typedef duration<signed int, ratio<3600>> hours;
```

How long can a time duration be? The C++ standard guarantees that the predefined time durations can store +/- 292 years. You can easily define your time duration like a German school hour: `typedef std::chrono::duration<double, std::ratio<2700>> MyLessonTick`. Time durations in natural numbers must be explicitly converted to time durations in floating pointer numbers. The value will be truncated:

Durations

```
// duration.cpp
...
```

```
#include <chrono>
#include <ratio>

using std::chrono;

typedef duration<long long, std::ratio<1>> MySecondTick;
MySecondTick aSecond(1);

milliseconds milli(aSecond);
std::cout << milli.count() << " milli";        // 1000 milli

seconds seconds(aSecond);
std::cout << seconds.count() << " sec";         // 1 sec

minutes minutes(duration_cast<minutes>(aSecond));
std::cout << minutes.count() << " min";         // 0 min

typedef duration<double, std::ratio<2700>> MyLessonTick;
MyLessonTick myLesson(aSecond);
std::cout << myLesson.count() << " less";       // 0.00037037 less
```

std::ratio

std::ratio supports arithmetic at compile time with rational numbers. A rational number has two template arguments: the nominator and the denominator. C++11 predefines lots of rational numbers.

```
typedef ratio<1, 1000000000000000000> atto;
typedef ratio<1, 1000000000000000> femto;
typedef ratio<1, 1000000000000> pico;
typedef ratio<1, 1000000000> nano;
typedef ratio<1, 1000000> micro;
typedef ratio<1, 1000> milli;
typedef ratio<1, 100> centi;
typedef ratio<1, 10> deci;
typedef ratio< 10, 1> deca;
typedef ratio< 100, 1> hecto;
typedef ratio< 1000, 1> kilo;
typedef ratio< 1000000, 1> mega;
typedef ratio< 1000000000, 1> giga;
typedef ratio< 1000000000000, 1> tera;
typedef ratio< 1000000000000000, 1> peta;
typedef ratio< 1000000000000000000, 1> exa;
```

C++14 has built-in literals for the most used time durations.

Built-in literals for time durations

Type	Suffix	Example
`std::chrono::hours`	h	5h
`std::chrono::minutes`	min	5min
`std::chrono::seconds`	s	5s
`std::chrono::milliseconds`	ms	5ms
`std::chrono::microseconds`	us	5us
`std::chrono::nanoseconds`	ns	5ns

Clock

The clock consists of a starting point and a tick. You can get the current time with the member function `now`.

`std::chrono::system_clock`
: System time, which you can synchronize with the external clock.

`std::chrono::steady_clock`
: Clock, which can not be adjusted.

`std::chrono::high_resolution_clock`
: System time with the greatest accuracy.

`std::chrono::system_clock` refers typically to the 1.1.1970. You can not adjust `std::steady_clock` forward or backward opposite to two other clocks. The member functions `to_time_t` and `from_time_t` can be used to convert between `std::chrono::system_clock` and `std::time_t` objects.

Time of Day

`std::chrono::time_of_day` splits the duration since midnight into hours:minutes:seconds. The functions `std::chrono::is_am` and `std::chrono::is_pm` checks if the time is before midday (ante meridiem) or after midday (post meridiem).

A `std::chrono::time_of_day` object `tOfDay` supports various member functions.

Member functions of `std::chrono::time_of_day`

Member function	Decription
`tOfDay.hours()`	Returns the hour component since midnight.
`tOfDay.minutes()`	Returns the minute component since midnight.
`tOfDay.seconds()`	Returns the second component since midnight.
`tOfDay.subseconds()`	Returns the fractional second component since midnight.
`tOfDay.to_duration()`	Returns the time duration since midnight.
`std::chrono::make12(hr)` `std::chrono::make24(hr)`	Returns the 12-hour (24-hour) equivalent of a 24-hour (12-hour) format time.
`std::chrono::is_am(hr)` `std::chrono::is_pm(hr)`	Detects wether the 24-hour format time is a.m. or p.m. .

Calendar

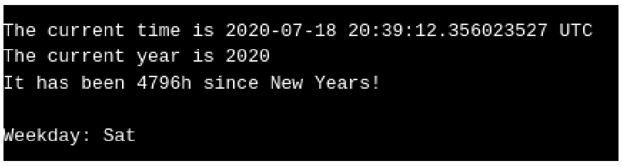
Calendar stands for various calendar dates such as year, a month, a weekday, or the n-th day of a week.

The current time

```
// currentTime.cpp
...
#include <chrono>
using std::chrono;
...
auto now = system_clock::now();
std::cout << "The current time is " << now << " UTC\n";

auto currentYear = year_month_day(floor<days>(now)).year();
```

```
std::cout << "The current year is " << currentYear << '\n';

auto h = floor<hours>(now) - sys_days(January/1/currentYear);
std::cout << "It has been " << h << " since New Years!\n";

std::cout << '\n';

auto birthOfChrist = year_month_weekday(sys_days(January/01/0000));
std::cout << "Weekday: " << birthOfChrist.weekday() << '\n';
```

The output of the program shows information referring to the current time.



```
The current time is 2020-07-18 20:39:12.356023527 UTC
The current year is 2020
It has been 4796h since New Years!

Weekday: Sat
```

The following table gives an overview of the calendar types.

Various calendar types

Class	Decription
`last_spec`	Indicates the last day or weekday in a month.
`day`	Represents a day of a month.
`month`	Represents a month of a year.
`year`	Represents a year in the Gregorian calendar.
`weekday`	Represents a day of the week in the Gregorian calendar.
`weekday_indexed`	Represents the n-th weekday of a month.
`weekday_last`	Represents the last weekday of a month.
`month_day`	Represents a specific day of a specific month.
`month_day_last`	Represents the last day of a specific month.
`month_weekday`	Represents the n-th weekday of a specific month.
`month_weekday_last`	Represents the last weekday of a specific month.
`year_month`	Represents a specific month of a specific year.
`year_month_day`	Represents a specific year, month, and day.

Class	Decription
`year_month_day_last`	Represents the last day of a specific year and month.
`year_month_weekday`	Represents the last day of a specific year and month.
`year_month_weekday_last`	Represents the last weekday of a specific year and month.

Time Zone

Time zones represent time specific to a geographic area. The following program snippet displays the local time in various time zones.

Local time is displayed in various time zones

```
// timezone.cpp
...
#include <chrono>
using std::chrono;
..
auto time = floor<milliseconds>(system_clock::now());
auto localTime = zoned_time<milliseconds>(current_zone(), time);
auto berlinTime = zoned_time<milliseconds>("Europe/Berlin", time);
auto newYorkTime = std::chorno::zoned_time<milliseconds>
("America/New_York", time);
auto tokyoTime = zoned_time<milliseconds>("Asia/Tokyo", time);


std::cout << time << '\n';
std::cout << localTime << '\n';
std::cout << berlinTime << '\n';
std::cout << newYorkTime << '\n';
std::cout << tokyoTime << '\n';
```

The time zone functionality supports the access of the IANA time zone database, enables the operation with various time zones, and provides information about leap seconds.

The following table gives an overview of the time zone functionality. For more detailed information, refer to cpprefere.com.

Time zone information

Type	Description
`tzdb`	Describes the IANA time zone database.
`locate_zone`	Locates a `time_zone` bases on its name..
`current_zone`	Returns the current `time_zone`.
`time_zone`	Represents a time zone.
`sys_info`	Returns information about a time zone at a specific time point.
`local_info`	Represents information about the local time to UNIS time conventions.
`zoned_time`	Represents a time zone and a time point.
`leap_second`	Contains information about a leap second insertion.

Chrono I/O

The function `std::chrono::parse` parses a chrono object from a stream.

Parsing a time point and a time zone

```
std::istringstream inputStream{"1999-10-31 01:30:00 -08:00
US/Pacific"};

std::chrono::local_seconds timePoint;
std::string timeZone;
inputStream >> std::chrono::parse("%F %T %Ez %Z", timePoint,
timeZone);
```

The parsing functionality provides various format specifiers to deal with the time of day and calendar dates such as year, month, week, and day. cppreference.com provides detailed information to the format specifiers.

`std::any`, `std::optional`, and `std::variant`

The new C++17 data types `std::any`, `std::optional`, and `std::variant` are all based on the Boost libraries

`std::any`

`std::any` is a type-safe container for single values of any copy-constructible type. This vocabulary type requires the header `<any>`. There are a few ways to create a `std::any` container `any`. You can use the various constructors or the factory function `std::make_any`. `any.emplace` lets you directly construct one value into `any`. `any.reset` enables you to destroy the contained object. If you want to know whether the container `any` has a value, use the member function `any.has_value`. You can even get the typeid of the container object via `any.type`. Thanks to the generic function `std::any_cast`, you have access to the contained object. If you specify the wrong type, you will get a `std::bad_any_cast` exception.
Here is a code snippet showing the basic usage of `std::any`.

`std::any`

```
// any.cpp
...
#include <any>

struct MyClass{};

...

std::vector<std::any> anyVec{true, 2017, std::string("test"), 3.14,
MyClass()};
std::cout << std::any_cast<bool>(anyVec[0]);                    //
true
int myInt= std::any_cast<int>(anyVec[1]);
std::cout << myInt << '\n';                                     //
2017

std::cout << anyVec[0].type().name();                           // b
std::cout << anyVec[1].type().name();                           // i
```

The program snippet defines a `std::vector<std::any>`. To get one of its elements, you must use `std::any_cast`. As mentioned, if you use the wrong type, you will get a `std::bad_any_cast` `exception`.

The string representation of the typeid

The string representation of the typeid operator is implementation defined. If `anyVec[1]` is of type `int` the expression `anyVec[1].type().name()` will return `i` with the GCC C++ compiler and `int` with the Microsoft Visual C++ compiler.

`std::any` can have objects of arbitrary types; `std::optional` may or may not have a value.

`std::optional`

`std::optional` is quite comfortable for calculations such as database queries that may have a result. This vocabulary type requires the header `<optional>`.

Don't use no-results

Before C++17, it was common practice to use a unique value such as a null pointer, an empty string, or a unique integer to denote a result's absence. For the type system, you must use a regular value, such as an empty string, to define an irregular value. These unique values or no results are error-prone because you must misuse the type system to check the return value.

The various constructors and the convenience function `std::make_optional` let you define an optional object `opt` with or without a value. `opt.emplace` will construct the contained value in-place and `opt.reset` will destroy the container value. You can explicitly ask a `std::optional` container if it has a value, or you can check it in a logical expression. `opt.value` returns the value, and `opt.value_or` returns the value or a default value. If `opt` has no contained value, the call `opt.value` will throw a `std::bad_optional_access` exception.

Here is a short example using `std::optional`.

std::optional

```
// optional.cpp
...
#include <optional>

std::optional<int> getFirst(const std::vector<int>& vec){
  if (!vec.empty()) return std::optional<int>(vec[0]);
  else return std::optional<int>();
}

...
```

```
std::vector<int> myVec{1, 2, 3};
std::vector<int> myEmptyVec;

auto myInt= getFirst(myVec);

if (myInt){
  std::cout << *myInt << '\n';                    // 1
  std::cout << myInt.value() << '\n';             // 1
  std::cout << myInt.value_or(2017) << '\n';      // 1
}

auto myEmptyInt= getFirst(myEmptyVec);

if (!myEmptyInt){
  std::cout << myEmptyInt.value_or(2017) << '\n';   // 2017
}
```

I use `std::optional` in the function `getFirst`. `getFirst` returns the first element if it exists. You will get a `std::optional<int>` object if not. The main function has two vectors. Both invoke `getFirst` and return a `std::optional` object. In the case of `myInt`, the object has a value; in the case of `myEmptyInt`, the object has no value. The program displays the value of `myInt` and `myEmptyInt`. `myInt.value_or(2017)` returns the value, but `myEmptyInt.value_or(2017)` returns the default value.

In C++23, `std::optional` is extended with monadic operations `opt.and_then`, `opt.transform`, and `opt.or_else`. `opt.and_then` returns the result of the given function call if it exists, or an empty `std::optional`. `opt.transform` returns a `std::optional` containing is tranformed value, or an empty `std::optional`. Additionally, `opt.or_else` returns the `std::optional` if it contains a value or the result of the given function otherwise.

These monadic operations enable the composition of operations on `std::optional`:

Monadic operations on `std::optional`

```
// optionalMonadic.cpp

#include <iostream>
#include <optional>
#include <vector>
#include <string>

std::optional<int> getInt(std::string arg) {
    try {
        return {std::stoi(arg)};
    }
    catch (...) {
        return { };
    }
}


```

```
18 int main() {
19 
20     std::vector<std::optional<std::string>> strings = {"66", "foo", "-5"};
21 
22     for (auto s: strings) {
23         auto res = s.and_then(getInt)
24                     .transform( [](int n) { return n + 100;})
25                     .transform( [](int n) { return std::to_string(n); })
26                     .or_else([] { return std::optional{std::string("Error") }; });
27         std::cout << *res << ' ';          // 166 Error 95
28     }
29 
30 }
```

The range-based for-loop (line 22) iterates through the `std::vector<std::optional<std::string>>`. First, the function `getInt` converts each element to an integer (line 23), adds `100` to it (line 24), converts it back to a string (line 25), and finally displays the string (line 27). If the initial conversion to `int` fails, the string `Error` is returned (line 26) and displayed.

`std::variant`

`std::variant` is a type-safe union. This vocabulary type requires the header `<variant>`. An instance of `std::variant` has a value from one of its types. The type must not be a reference, array, or `void`. A `std::variant` can have a type more than once. A default-initialized `std::variant` is initialized with its first type; therefore, its first type must have a default constructor. By using `var.index` you get the zero-based index of the alternative held by the `std::variant var`. `var.valueless_by_exception` returns `false` if the variant holds a value. You can create a new value in-place by using `var.emplace`. A few global functions are used to access a `std:variant`. The function template `var.holds_alternative` lets you check if the `std::variant` holds a specified alternative. You can use `std::get` with an index and a type as an argument. By using an index, you will get the value. If you invoke `std::get` with a type, you only will get the value if it is unique. If you use an invalid index or a non-unique type, you will get a `std::bad_variant_access` exception. In contrast to `std::get`, which eventually returns an exception, `std::get_if` returns a null pointer in the case of an error.

The following code snippet shows you the usage of a `std::variant`.

std::variant

```
// variant.cpp
...
#include <variant>

...

std::variant<int, float> v, w;
v = 12;                              // v contains int
int i = std::get<int>(v);
w = std::get<int>(v);
w = std::get<0>(v);                  // same effect as the previous 
line
w = v;                               // same effect as the previous 
line

//  std::get<double>(v);             // error: no double in [int, 
float]
//  std::get<3>(v);                  // error: valid index values are 
0 and 1

try{
  std::get<float>(w);                // w contains int, not float: 
will throw
}
catch (std::bad_variant_access&) {}

std::variant<std::string> v2("abc"); // converting constructor must 
be unambiguous
v2 = "def";                          // converting assignment must be 
unambiguous
```

`v` and `w` are two variants. Both can have an int and a float value. Their default value is 0. v becomes 12, and the following call `std::get<int>(v)` returns the value. The next three lines show three possibilities to assign the variant `v` to `w`, but you must keep a few rules in mind. You can ask for the value of a variant by type `std::get<double>(v)` or by index: `std::get<3>(v)`. The type must be unique and the index valid. The variant `w` holds an `int` value; therefore, I get a `std::bad_variant_access` exception if I ask for a `float` type. If the constructor call or assignment call is unambiguous, a conversion can take place. This makes it possible to construct a `std::variant<std::string>` from a C-string or assign a new C-string to the variant.

`std::variant` has an interesting non-member function `std::visit` that allows you the execute a callable on a list of variants. A callable is something that you can invoke. Typically this can be a function, a function object, or lambda expression. For simplicity reasons, I use a lambda function in this example.

std::visit

```
// visit.cpp
...
```

```
#include <variant>

...

std::vector<std::variant<char, long, float, int, double, long long>>
           vecVariant = {5, '2', 5.4, 100ll, 2011l, 3.5f, 2017};

for (auto& v: vecVariant){
  std::visit([](auto&& arg){std::cout << arg << " ";}, v);
                                   // 5 2 5.4 100 2011 3.5 2017
}

// display each type
for (auto& v: vecVariant){
  std::visit([](auto&& arg){std::cout << typeid(arg).name() << " ";},
v);
                                  // int char double __int64 long
float int
}

// get the sum
std::common_type<char, long, float, int, double, long long>::type
res{};

std::cout << typeid(res).name() << '\n';        // double

for (auto& v: vecVariant){
  std::visit([&res](auto&& arg){res+= arg;}, v);
}
std::cout << "res: " << res << '\n';            // 4191.9

// double each value
for (auto& v: vecVariant){
  std::visit([&res](auto&& arg){arg *= 2;}, v);
  std::visit([](auto&& arg){std::cout << arg << " ";}, v);
                                // 10 d 10.8 200 4022 7 4034
}
```

Each variant in this example can hold a `char, long, float, int, double`, or `long long`. The first visitor `[](auto&& arg){std::cout << arg << " ";}` will output the various variants. The second visitor `std::cout << typeid(arg).name() << " ";}` will display its types.

Now I want to sum up the elements of the variants. First, I need the correct result type at compile time. `std::common_type` from the type traits library will provide it. `std::common_type` gives the type to which all types `char, long, float, int, double`, and `long long` can implicitly be converted. The final {} in `res{}` causes it to be initialized to 0.0. `res` is of type `double`. The visitor `[&res](auto&& arg){arg *= 2;}` calculates the sum, and the following line displays it.

std::expected

`std::expected<T, E>` provides a way to store either of two values. An instance of `std::expected` always holds a value: either the expected value of type `T`, or the unexpected value of type `E`. This vocabulary type requires the header `<expected>`. Thanks to `std::expected`, you can implement functions that either return a value or an error. The stored value is allocated directly within the storage occupied by the expected object. No dynamic memory allocation takes place.

`std::expected` has a similar interface such as `std::optional`. In contrast to `std::optional`, `std::exptected` can return an error message.

The various constructors let you define an expected object `exp` with an expected value. `exp.emplace` will construct the contained value in-place. You can explicitly ask a `std::expected` container if it has a value, or you can check it in a logical expression. `exp.value` returns the expected value, and `exp.value_or` returns the expected value, or a default value. If `exp` has an unexpected value, the call `exp.value` will throw a `std::bad_expected_access` exception.

`std::unexpected` represents the unexpected value stored in `std::expected`.

`std::expected`

```cpp
// expected.cpp

#include <iostream>
#include <expected>
#include <vector>
#include <string>

std::expected<int, std::string> getInt(std::string arg) {
    try {
        return std::stoi(arg);
    }
    catch (...) {
        return std::unexpected{std::string(arg + ": Error")};
    }
}


int main() {

    std::vector<std::string> strings = {"66", "foo", "-5"};

    for (auto s: strings) {
        auto res = getInt(s);
        if (res) {
            std::cout << res.value() << ' ';      // 66 -5
        }
        else {
            std::cout << res.error() << ' ';      // foo: Error
        }
    }
31
32     std::cout << '\n';
33
34     for (auto s: strings) {
35         auto res = getInt(s);
36         std::cout << res.value_or(2023) << ' ';  // 66 2023 -5
37     }
38
39 }
```

The function `getInt` converts each string to an integer and returns a `std::expected<int, std::string>`. `int` represents the expected, and `std::string` the unexpected value. The two range-based for-loops (lines 22 and 34) iterate through the `std::vector<std::string>`. In the first range-based for-loop (line 22), either the expected (line 25) or the unexpected value (line 28) is displayed. In the second range-based for-loop (line 34), either the expected or the default value `2023` (line 36) is displayed.

`std::exptected` supports monadic operations for convenient function composition: `exp.and_then`, `exp.transform`, `exp.or_else`, and `exp.transform_error`. `exp.and_then` returns the result of the given function call if it exists, or an empty `std::expected`. `exp.transform` returns a `std::exptected` containing is tranformed value, or an empty `std::exptected`. Additionally, `exp.or_else` returns the `std::exptected` if it contains a value or the result of the given function otherwise.

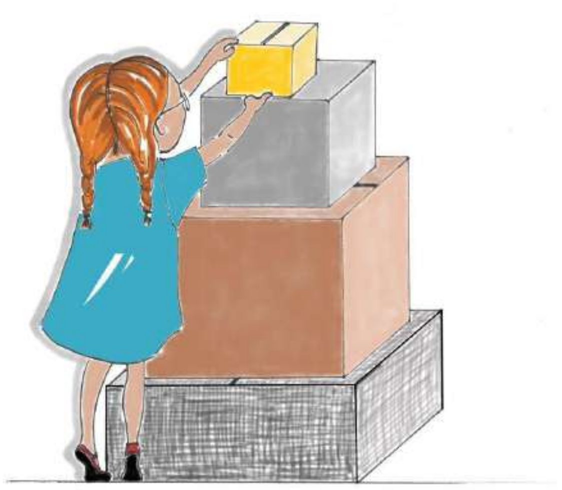
The following program is based on the previous program [optionalMonadic.cpp](). Essentially, the type `std::optional` is replaced with `std::exptected`.

Monadic operations on `std::expected`

```
 1 // expectedMonadic.cpp
 2 ...
 3 #include <expected>
 4
 5 std::expected<int, std::string> getInt(std::string arg) {
 6     try {
 7         return std::stoi(arg);
 8     }
 9     catch (...) {
10         return std::unexpected{std::string(arg + ": Errror")};
11     }
12 }
13
14 std::vector<std::string> strings = {"66", "foo", "-5"};
15
16 for (auto s: strings) {
17     auto res = getInt(s)
18                .transform( [](int n) { return n + 100; })
19                .transform( [](int n) { return std::to_string(n);
});
20     std::cout << *res << ' ';          // 166 foo: Error 95
21 }
```

The range-based for-loop (line 23) iterates through the `std::vector<std::string>`. First, the function `getInt` converts each string to an integer (line 24), adds `100` to it (line 25), converts it back to a string (line 26), and finally displays the string (line 27). If the initial conversion to `int` fails, the string `arg + ": Error"` is returned (line 14) and displayed.

3. Interface of All Containers



Cippi prepares the packages

The sequence and associative containers of the Standard Template library have a lot in common. For example, the operations to create or delete a container, determine its size, access its elements, and assign or swap, are all independent of the type of elements of a container. Each container has at least one type parameter and an allocator for this type. The allocator works in the background most of the time. `std::vector` exemplifies this. The call `std::vector<int>` results in a call `std::vector<int, std::allocator<int>>`. Because of the `std::allocator`, you can adjust except for `std::array` the size of all containers dynamically. However, they have more in common. You can access the elements of a container with an iterator.

Despite the high similarity, the containers differ in details. The chapters Sequence Container and Associative Container provide the details.

With the sequence containers `std::array`, `std::vector`, `std::deque`, `std::list`, and `std::forward_list` C++ has an expert on each domain.

The associative containers can be classified into ordered and unordered ones.

Create and delete

Each container provides various constructors. To delete all container elements `cont`, you can use `cont.clear()`. It makes no difference whether you create a container, you delete them, or you add or remove elements. Each time the container takes care of the memory management.

The table shows you the constructors and destructors of a container. In the following table, `std:vector` often stands for the rest of them.

Creation and deletion of a container

Type	Example
Default	`std::vector<int> vec1`
Range	`std::vector<int> vec2(vec1.begin(), vec1.end())`
Copy	`std::vector<int> vec3(vec2)`
Copy	`std::vector<int> vec3= vec2`
Move	`std::vector<int> vec4(std::move(vec3))`
Move	`std::vector<int> vec4= std::move(vec3)`
Sequence (initializer list)	`std::vector<int> vec5 {1, 2, 3, 4, 5}`
Sequence (initializer list)	`std::vector<int> vec5= {1, 2, 3, 4, 5}`
Destructor	`vec5.~vector()`
Delete elements	`vec5.clear()`

You have to specify the size of a `std::array` at compile time and use aggregate initialization for initialization. `std::array` has no member functions for removing its elements.

I use the different constructors on the various containers in the following example.

Various constructors

```
// containerConstructor.cpp
...
#include <map>
#include <unordered_map>
#include <vector>
...
```

```
using namespace std;

vector<int> vec= {1, 2, 3, 4, 5, 6, 7, 8, 9};
map<string, int> m= {{"bart", 12345}, {"jenne", 34929},
{"huber", 840284} };
unordered_map<string, int> um{m.begin(), m.end()};

for (auto v: vec) cout << v << " "; // 1 2 3 4 5 6 7 8 9
for (auto p: m) cout << p.first << "," << p.second << " ";
                                    // bart,12345 huber,840284
jenne,34929
for (auto p: um) cout << p.first << "," << p.second << " ";
                                    // bart,12345 jenne,34929
huber,840284

vector<int> vec2= vec;
cout << vec.size() << endl; // 9
cout << vec2.size() << endl; // 9

vector<int> vec3= move(vec);
cout << vec.size() << endl; // 0
cout << vec3.size() << endl; // 9

vec3.clear();
cout << vec3.size() << endl; // 0
```

Size

For a container `cont`, you can check with `cont.empty()` if the container is empty. `cont.size()` returns the current number of elements, and `cont.max_size()` returns the maximum number of elements `cont` can have. The maximum number of elements is implementation-defined.

Size of a container

```
// containerSize.cpp
...
#include <map>
#include <set>
#include <vector>
...
using namespace std;

vector<int> intVec{1, 2, 3, 4, 5, 6, 7, 8, 9};
map<string, int> str2Int = {{"bart", 12345},
                            {"jenne", 34929}, {"huber",
840284}};
set<double> douSet{3.14, 2.5};

cout << intVec.empty() << endl;  // false
cout << str2Int.empty() << endl; // false
cout << douSet.empty() << endl;  // false

cout << intVec.size() << endl;  // 9
cout << str2Int.size() << endl; // 3
cout << douSet.size() << endl;  // 2
cout << intVec.max_size() << endl;  // 4611686018427387903
cout << str2Int.max_size() << endl; // 384307168202282325
cout << douSet.max_size() << endl;  // 461168601842738790
```

Use `cont.empty()` instead of `cont.size()`

For a container `cont`, use the member function `cont.empty()` instead of `(cont.size() == 0)` to determine if the container is empty. First, `cont.empty()` is in general faster than `(const.size() == 0)`; second, `std::forward_list` has no member function `size()`.

Access

An iterator allows you to access the elements of a container. If you use a begin and end iterator, you have a range, which you can further process. For a container `cont`, you get with `cont.begin()` the begin iterator and with `cont.end()` the end iterator, which defines a *half-open* range. It is *half-open* because the begin iterator belongs to the range, and the end iterator refers to a position past the range. The iterator pair `cont.begin()` and `cont.end()` enables it to modify the elements of the container.

Creation and deletion of a container

Iterator	Description
`cont.begin()` and `cont.end()`	Pair of iterators to iterate forward.
`cont.cbegin()` and `cont.cend()`	Pair of iterators to iterate const forward.
`cont.rbegin()` and `cont.rend()`	Pair of iterators to iterate backward.
`cont.crbegin()` and `cont.crend()`	Pair of iterators to iterate const backward.

Now I can modify the container.

Access the elements of a container

```
// containerAccess.cpp
...
#include <vector>
...
struct MyInt{
  MyInt(int i): myInt(i){};
  int myInt;
};

std::vector<MyInt> myIntVec;
myIntVec.push_back(MyInt(5));
myIntVec.emplace_back(1);
std::cout << myIntVec.size() << '\n';              // 2

std::vector<int> intVec;
intVec.assign({1, 2, 3});
for (auto v: intVec) std::cout << v << " ";        // 1 2 3

intVec.insert(intVec.begin(), 0);
for (auto v: intVec) std::cout << v << " ";        // 0 1 2 3

intVec.insert(intVec.begin()+4, 4);
for (auto v: intVec) std::cout << v << " ";        // 0 1 2 3 4

intVec.insert(intVec.end(), {5, 6, 7, 8, 9, 10, 11});

for (auto v: intVec) std::cout << v << " ";        // 0 1 2 3 4
5 6 7 8 9 10 11

for (auto revIt= intVec.rbegin(); revIt != intVec.rend();
++revIt)
     std::cout << *revIt << " ";                   // 11 10 9 8
7 6 5 4 3 2 1 0

intVec.pop_back();
for (auto v: intVec ) std::cout << v << " ";       // 0 1 2 3 4
5 6 7 8 9 10
```

Assign and Swap

You can assign new elements to existing containers or swap two containers. For the assignment of a container `cont2` to a container `cont`, there exists the copy assignment `cont = cont2` and the move assignment `cont = std::move(cont2)`. A special form of assignment is the one with an initializer list: `cont= {1, 2, 3, 4, 5}`. That’s not possible for `std::array`. The function `swap` exists in two forms. You have it as a member function `cont(swap(cont2))` or as a function template `std::swap(cont, cont2)`.

Assignment and swap

```
// containerAssignmentAndSwap.cpp
...
#include <set>
...
std::set<int> set1{0, 1, 2, 3, 4, 5};
std::set<int> set2{6, 7, 8, 9};

for (auto s: set1) std::cout << s << " "; // 0 1 2 3 4 5
for (auto s: set2) std::cout << s << " "; // 6 7 8 9

set1= set2;
for (auto s: set1) std::cout << s << " "; // 6 7 8 9
for (auto s: set2) std::cout << s << " "; // 6 7 8 9

set1= std::move(set2);
for (auto s: set1) std::cout << s << " "; // 6 7 8 9
for (auto s: set2) std::cout << s << " "; //

set2= {60, 70, 80, 90};
for (auto s: set1) std::cout << s << " "; // 6 7 8 9
for (auto s: set2) std::cout << s << " "; // 60 70 80 90

std::swap(set1, set2);
for (auto s: set1) std::cout << s << " "; // 60 70 80 90
for (auto s: set2) std::cout << s << " "; // 6 7 8 9
```

Compare

Containers support the comparison operators ==, !=, <, >, <=, >=. The comparison of the two containers applies to the elements of the containers. If you compare associative containers, their keys are compared. Unordered associative containers support only the comparison operator == and !=.

Comparison of a container

```
// containerComparison.cpp
...
#include <array>
#include <set>
#include <unordered_map>
#include <vector>
...
using namespace std;

vector<int> vec1{1, 2, 3, 4};
vector<int> vec2{1, 2, 3, 4};
cout << (vec1 == vec2) << endl;        // true

array<int, 4> arr1{1, 2, 3, 4};
array<int, 4> arr2{1, 2, 3, 4};
cout << (arr1 == arr2) << endl;        // true

set<int> set1{1, 2, 3, 4};
set<int> set2{4, 3, 2, 1};
cout << (set1 == set2) << endl;        // true
```

```
set<int> set3{1, 2, 3, 4, 5};
cout << (set1 < set3) << endl;          // true

set<int> set4{1, 2, 3, -3};
cout << (set1 > set4) << endl;          // true

unordered_map<int, string> uSet1{{1, "one"}, {2, "two"}};
unordered_map<int, string> uSet2{{1, "one"}, {2, "Two"}};
cout << (uSet1 == uSet2) << endl;       // false
```

Erasure

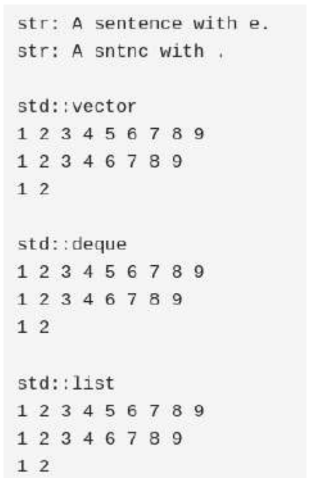
The free functions `std::erase(cont, val)` and `std::erase_if(cont, pred)` erase all container `cont` elements that compare equal to `val` or fulfill the predicate `pred`. Both functions return the number of erased elements.

Consistent container erasure

```
// erase.cpp
...

template <typename Cont>
void eraseVal(Cont& cont, int val) {
    std::erase(cont, val);
}

template <typename Cont, typename Pred>
void erasePredicate(Cont& cont, Pred pred) {
    std::erase_if(cont, pred);
}

template <typename Cont>
void printContainer(Cont& cont) {
    for (auto c: cont) std::cout << c << " ";
    std::cout << '\n';
}

template <typename Cont>
void doAll(Cont& cont) {
    printContainer(cont);
    eraseVal(cont, 5);
    printContainer(cont);
    erasePredicate(cont, [](auto i) { return i >= 3; } );
    printContainer(cont);
}

...

std::string str{"A sentence with e."};
std::cout << "str: " << str << '\n';
std::erase(str, 'e');
std::cout << "str: " << str << '\n';

std::cout << "\nstd::vector " << '\n';
std::vector vec{1, 2, 3, 4, 5, 6, 7, 8, 9};
doAll(vec);
```

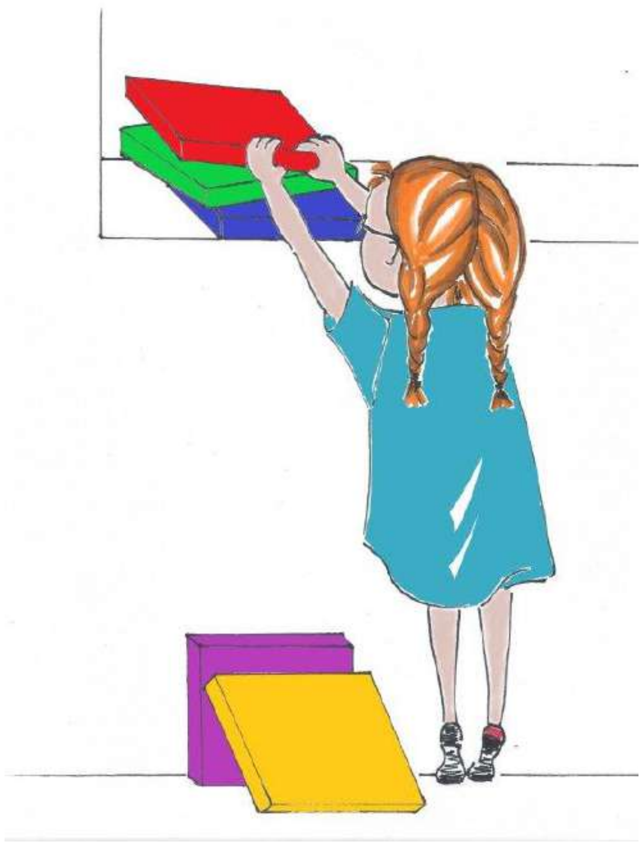
```
std::cout << "\nstd::deque " << '\n';
std::deque deq{1, 2, 3, 4, 5, 6, 7, 8, 9};
doAll(deq);

std::cout << "\nstd::list" << '\n';
std::list lst{1, 2, 3, 4, 5, 6, 7, 8, 9};
doAll(lst);
```

`erase` and `erase_if` can be applied on all STL containers and `std::string`.



```
str: A sentence with e.
str: A sntnc with .

std::vector
1 2 3 4 5 6 7 8 9
1 2 3 4 6 7 8 9
1 2

std::deque
1 2 3 4 5 6 7 8 9
1 2 3 4 6 7 8 9
1 2

std::list
1 2 3 4 5 6 7 8 9
1 2 3 4 6 7 8 9
1 2
```

4. Sequence Containers



Cippi builds a stack

The sequence containers have a lot in common, but each container has its particular domain. Before I dive into the details, I provide an overview of all five sequence containers of the std namespace.

The sequence containers

Criteria	array	vector	deque	list	forward_list
Size	static	dynamic	dynamic	dynamic	dynamic
Implementation	static array	dynamic array	sequence of arrays	doubled linked list	single linked list
Access	random	random	random	forward and backward	forward
Optimized for insert and delete at		end: O(1)	begin and end: O(1)	begin and end: O(1) arbitrary: O(1)	begin(1) arbitrary: O(1)
Memory reservation		yes	no	no	no
Release of memory		`shrink_to_fit`	`shrink_to_fit`	always	always
Strength	no memory allocation; minimal memory requirements	95% solution	insertion and deletion at the begin and end	insertion and deletion at an arbitrary position	fast insertion and deletion; minimal memory requirements
Weakness	no dynamic memory allocation	Insertion and deletion at an arbitrary position: O(n)	Insertion and deletion at an arbitrary position: O(n)	no random access	no random access

I want to make a few additional remarks to the table.

O(i) stands for an operation's complexity (runtime). O(1) means that the runtime of an operation on a container is constant and independent of the container's size. Conversely, O(n) means that the runtime depends linearly on the number of container elements. What does that mean for a `std::vector`? The access time on an element is independent of the size of the `std::vector`, but the insertion or deletion of an arbitrary element with k-times more elements is k-times slower.

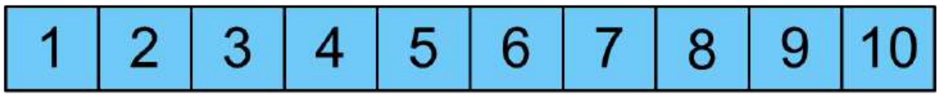
Although the random access on the elements of a `std::vector` has the same complexity O(1) as the random access on the elements of a `std::deque`, that doesn't mean that both operations are equally fast.

The complexity guarantee O(1) for the insertion or deletion into a double (`std::list`) or single linked list (`std::forward_list`) is only guaranteed if the iterator points to the correct element.

`std::string` is like `std::vector<char>`

Of course, `std::string` is no container of the standard template library. From a behavioral perspective, it is like a sequence container, especially like a `std::vector<char>`. Therefore I will treat `std::string` as a `std::vector<char>`.

Arrays



The `std::array` combines the memory and runtime characteristic of a C array with the interface of `std::vector`. `std::array` is a homogeneous container of fixed length. It needs the header `<array>`. This means, in particular, the `std::array` knows its size.

To initialize a `std::array`, you must follow a few special rules.

`std::array<int, 10> arr`
: The 10 elements are not initialized.

`std::array<int, 10> arr{}`
: The 10 elements are default initialized.

`std::array<int, 10> arr{1, 2, 3, 4, 5}`
: The remaining elements are default initialized.

`std::array` supports three types of index access.

```
arr[n];
arr.at(n);
std::get<n>(arr);
```

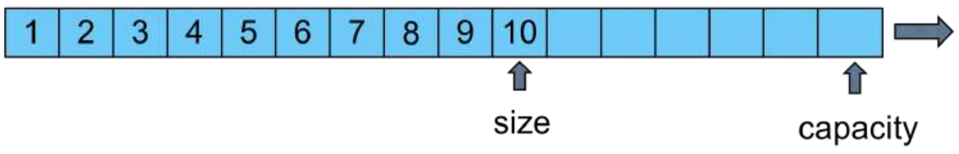
The most often used first type form with angle brackets does not check the boundaries of the `arr`. This is in opposition to `arr.at(n)`. You will eventually get a `std::range-error` exception. The last type shows the relationship of the `std::array` with the `std::tuple` because both are containers of fixed length.

Here is a little bit of arithmetic with `std::array`.

std::array

```
// array.cpp
...
#include <array>
...
std::array<int, 10> arr{1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
for (auto a: arr) std::cout << a << " " ;  // 1 2 3 4 5 6 7 8 9 10

double sum= std::accumulate(arr.begin(), arr.end(), 0);
std::cout << sum << '\n';                  // 55

double mean= sum / arr.size();
std::cout << mean << '\n';                  // 5.5
std::cout << (arr[0] == std::get<0>(arr));  // true
```

Vectors



std::vector is a homogeneous container, which length is automatically adjusted at runtime. `std::vector` needs the header `<vector>`. As it stores its elements contiguously in memory, `std::vector` supports pointer arithmetic.

```
for (int i= 0; i < vec.size(); ++i){
  std::cout << vec[i] == *(vec + i) << '\n'; // true
}
```

Distinguish the round and curly braces when you create a `std::vector`

When constructing a `std::vector`, you must pay attention to a few special rules. The constructor with round braces in the following example creates a `std::vector` with ten elements, and the constructor with curly braces a `std::vector` with element 10.

```
std::vector<int> vec(10);
std::vector<int> vec{10};
```

The same rules hold for the expressions `std::vector<int>(10, 2011)` or `std::vector<int>{10, 2011}`. In the first case, you get a `std::vector` with ten elements initialized to 2011. In the second case, you get a `std::vector` with elements 10 and 2011. The behavior is because curly braces stand for an initializer list; therefore, the sequence constructor is used.

Size versus Capacity

The number of elements a `std::vector` has is usually smaller than the number of elements for which space is already reserved. That is for a simple reason. The size of the `std::vector` can increase without an expensive allocation of new memory.

There are a few operations for using memory intelligently.

Memory management of `std::vector`

Member Functions	Description
`vec.size()`	Number of elements of `vec`.
`vec.capacity()`	Number of elements that `vec` can have without reallocation.
`vec.resize(n)`	`vec` will be increased to n elements.`
`vec.reserve(n)`	Reserve memory for at least n elements.
`vec.shrink_to_fit()`	Reduces capacity of `vec` to its size.

The call `vec.shrink_to_fit()` is not binding. That means the runtime can ignore it. But on popular platforms, I always observed the desired behavior.

So let's use the operations.

std::vector

```
// vector.cpp
...
#include <vector>
...
std::vector<int> intVec1(5, 2011);
intVec1.reserve(10);
std::cout << intVec1.size() << '\n';     // 5
std::cout << intVec1.capacity() << '\n'; // 10

intVec1.shrink_to_fit();
std::cout << intVec1.capacity() << '\n'; // 5

std::vector<int> intVec2(10);
std::cout << intVec2.size() << '\n';     // 10

std::vector<int> intVec3{10};
std::cout << intVec3.size() << '\n';     // 1

std::vector<int> intVec4{5, 2011};
std::cout << intVec4.size() << '\n';     // 2
```

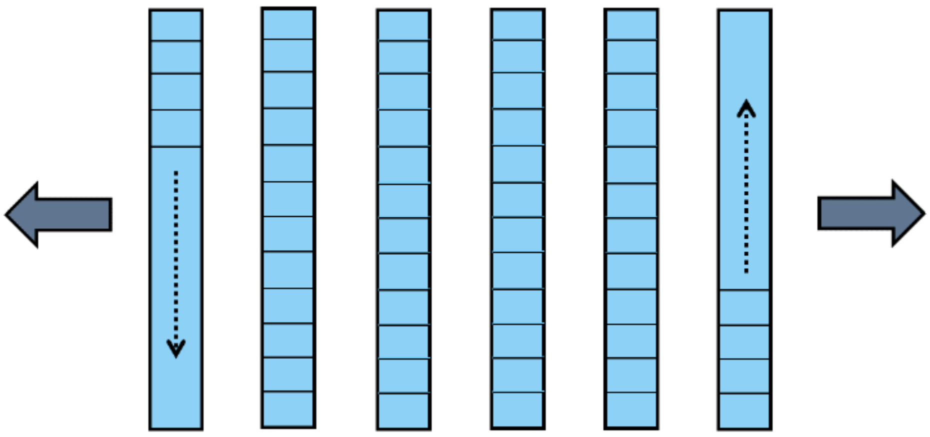
`std::vector vec` has a few member functions to access its elements. With `vec.front()`, you get the first element; with `vec.back()`, you get the last element of `vec`. To read or write the (n+1)-th element of `vec`, you can use the index operator `vec[n]` or the member function `vec.at(n)`. The second one checks the boundaries of `vec`, so that you eventually get a `std::out_of_range` exception.

Besides the index operator, `std::vector` offers additional member functions to assign, insert, create, or remove elements. See the following overview.

Modify the elements of a `std::vector`

Member Functions	Description
`vec.assign( ... )`	Assigns one or more elements, a range, or an initializer list.
`vec.clear()`	Removes all elements from `vec`.
`vec.emplace(pos, args ... )`	Creates a new element before `pos'with the` args `in` vec` and returns the new position of the element.
`vec.emplace_back(args ... )`	Creates a new element in `vec` with `args ...`.
`vec.erase( ... )`	Removes one element or a range and returns the next position.
`vec.insert(pos, ... )`	Inserts one or more elements, a range, or an initializer list and returns the new position of the element.
`vec.pop_back()`	Removes the last element.
`vec.push_back(elem)`	Adds a copy of `elem` at the end of `vec`.

Deques

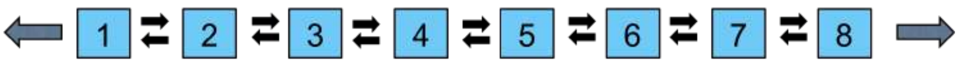


std::deque, which typically consists of a sequence of fixed-sized arrays, is quite similar to `std::vector`. `std::deque` need the header `<deque>`. The `std::deque` has three additional member functions, `deq.push_front(elem)`, `deq.pop_front()` and `deq.emplace_front(args... )` to add or remove elements at its beginning.

std::deque

```
// deque.cpp
...
#include <deque>
...
struct MyInt{
  MyInt(int i): myInt(i){};
  int myInt;
};

std::deque<MyInt> myIntDeq;

myIntDeq.push_back(MyInt(5));
myIntDeq.emplace_back(1);
std::cout << myIntDeq.size() << '\n';          // 2

std::deque<MyInt> intDeq;

intDeq.assign({1, 2, 3});
for (auto v: intDeq) std::cout << v << " ";   // 1 2 3

intDeq.insert(intDeq.begin(), 0);
for (auto v: intDeq) std::cout << v << " ";   // 0 1 2 3

intDeq.insert(intDeq.begin()+4, 4);
for (auto v: intDeq) std::cout << v << " ";   // 0 1 2 3 4

intDeq.insert(intDeq.end(), {5, 6, 7, 8, 9, 10, 11});
for (auto v: intDeq) std::cout << v << " ";   // 0 1 2 3 4 5 6 7 8 9 10 11

for (auto revIt= intDeq.rbegin(); revIt != intDeq.rend(); ++revIt)
     std::cout << *revIt << " ";                     // 11 10 9 8 7 6 5 4 3 2 1 0

intDeq.pop_back();
for (auto v: intDeq) std::cout << v << " ";   // 0 1 2 3 4 5 6 7 8 9 10

intDeq.push_front(-1);
for (auto v: intDeq) std::cout << v << " ";   // -1 0 1 2 3 4 5 6 7 8 9 10
```

Lists



std::list is a doubly linked list. std::list needs the header <list>.

Although it has a similar interface to std::vector or std::deque, std::list is quite different from both. That's due to its structure.

std::list makes the following points unique:

- It supports no random access.
- Access to an arbitrary element is slow because you have to iterate in the worst case through the whole list.
- To add or remove an element is fast if the iterator points to the right place.
- If you add or remove an element, the iterator keeps valid.

Because of its unique structure, std::list has a few special member functions.

Special member functions of std::list

Member Functions	Description
lis.merge(c)	Merges the sorted list c into the sorted list lis, so that lis keeps sorted.
lis.merge(c, op)	Merges the sorted list c into the sorted list lis, so that lis keeps sorted. It uses op as sorting criterion.
lis.remove(val)	Removes all elements from lis with value val.
lis.remove_if(pre)	Removes all elements from lis, fulfilling the predicate pre.
lis.splice(pos, ...)	Splits the elements in lis before pos. The elements can be single elements, ranges, or lists.
lis.unique()	Removes adjacent element with the same value.
lis.unique(pre)	Removes adjacent elements, fulfilling the predicate pre.

Here are a few of the member functions in a code snippet.

std::list

```
// list.cpp
...
#include <list>
...
std::list<int> list1{15, 2, 18, 19, 4, 15, 1, 3, 18, 5,
                      4, 7, 17, 9, 16, 8, 6, 6, 17, 1, 2};

list1.sort();
for (auto l: list1) std::cout << l << " ";
     // 1 1 2 2 3 4 4 5 6 6 7 8 9 15 15 16 17 17 18 18 19

list1.unique();
for (auto l: list1) std::cout << l << " ";
     // 1 2 3 4 5 6 7 8 9 15 16 17 18 19

std::list<int> list2{10, 11, 12, 13, 14};
list1.splice(std::find(list1.begin(), list1.end(), 15), list2);
for (auto l: list1) std::cout << l << " ";
     // 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
```

Forward Lists

`std::forward_list` is a singly linked list, which needs the header `<forward_list>`. `std::forward_list` has a drastically reduced interface and is optimized for minimal memory requirements.

`std::forward_list` has a lot in common with `std::list`:

- It supports no random access.
- Access to an arbitrary element is slow because you have to iterate forward through the whole list in the worst case.
- To add or remove an element is fast if the iterator points to the right place.
- If you add or remove an element, the iterator keeps valid.
- Operations always refer to the beginning of the `std::forward_list` or the position past the current element.

The characteristic that you can iterator a `std::forward_list` forward has a significant impact. So the iterators cannot be decremented, so operations like `It--` on iterators are not supported. For the same reason, `std::forward_list` has no backward iterator. `std::forward_list` is the only sequence container that doesn't know its size.

`std::forward_list` has an exceptional domain

`std::forward_list` is the replacement for singly-linked lists. It's optimized for minimal memory management and performance if insertion, extraction, or movement of elements only affects adjacent elements. This is typical for the sort algorithm.

The special member functions of `std::forward_list`.

Special member functions of `std::forward_list`

Member functions	Description
`forw.before_begin()`	Returns an iterator before the first element.
`forw.emplace_after(pos, args... )`	Creates an element after `pos` with the arguments `args...`.
`forw.emplace_front(args... )`	Creates an element at the beginning of `forw` with the arguments `args...`.
`forw.erase_after( pos, ... )`	Removes from `forw` the element `pos` or a range of elements, starting with `pos`.
`forw.insert_after(pos, ... )`	Inserts after `pos` new elements. These elements can be single elements, ranges, or initializer lists.
`forw.merge(c)`	Merges the sorted forward list c into the sorted forward list `forw`, so that `forw` keeps sorted.
`forw.merge(c, op)`	Merges the forward sorted list c into the forward sorted list `forw`, so that `forw` keeps sorted. Uses `os` as sorting criteria.
`forw.splice_after(pos, ... )`	Splits the elements in `forw` before `pos`. The elements can be single elements, ranges, or lists.
`forw.unique()`	Removes adjacent elements with the same value.
`forw.unique(pre)`	Removes adjacent elements, fulfilling the predicate `pre`.

Let's look at the unique member functions of `std::forward_list`.

`std::forward_list`

```
// forwardList.cpp
...
#include<forward_list>
...
using std::cout;

std::forward_list<int> forw;
std::cout << forw.empty() << '\n'; // true

forw.push_front(7);
forw.push_front(6);
forw.push_front(5);
forw.push_front(4);
forw.push_front(3);
forw.push_front(2);
forw.push_front(1);
for (auto i: forw) cout << i << " "; // 1 2 3 4 5 6 7

forw.erase_after(forw.before_begin());
cout<< forw.front(); // 2

std::forward_list<int> forw2;
forw2.insert_after(forw2.before_begin(), 1);
forw2.insert_after(++forw2.before_begin(), 2);
forw2.insert_after(++(++forw2.before_begin()), 3);
forw2.push_front(1000);
```

```
for (auto i= forw2.cbegin();i != forw2.cend(); ++i) cout << *i << " ";
    // 1000 1 2 3

auto IteratorTo5= std::find(forw.begin(), forw.end(), 5);
forw.splice_after(IteratorTo5, std::move(for2));
for (auto i= forw.cbegin(); i != forw.cend(); ++i) cout << *i << " ";
     // 2 3 4 5 1000 1 2 3 6 7

forw.sort();
for (auto i= forw.cbegin(); i != forw.cend(); ++i) cout << *i << " ";
    // 1 2 2 3 3 4 5 6 7 1000

forw.reverse();
for (auto i= forw.cbegin(); i != forw.cend(); ++i) cout << *i << " ";
    // 1000 7 6 5 4 3 3 2 2 1

forw.unique();
for (auto i= forw.cbegin(); i != forw.cend(); ++i) cout << *i << " ";
    // 1000 7 6 5 4 3 2 1
```

5. Associative Containers

Cippi searches in the phone book

C++ has eight different associative containers. Four associative containers with sorted keys: `std::set`, `std::map`, `std::multiset`, and `std::multimap`. The other four are associative containers with unsorted keys: `std::unordered_set`, `std::unordered_map`, `std::unordered_multiset`, and `std::unordered_multimap`. The associative containers are special containers. That means they support all of the operations described in the chapter Interface of all containers.

Overview

All eight ordered and unordered containers have in common that they associate a key with a value. You can use the key to get the value. To classify the associative containers, you have to answer three simple questions:

- Are the keys sorted?
- Does the key have an associated value?
- Can a key appear more than once?

The following table with 2^3= 8 rows gives the answers to the three questions. I answer a fourth question in the table. How fast is the access time of a key in the best case?

Characteristics for associative containers

Associative Container	Sorted	Associated Value	More Identical Keys	Access Time
`std::set`	yes	no	no	logarithmic
`std::unordered_set`	no	no	no	constant
`std::map`	yes	yes	no	logarithmic
`std::unordered_map`	no	yes	no	constant
`std::multiset`	yes	no	yes	logarithmic
`std::unordered_multiset`	no	no	yes	constant
`std::multimap`	yes	yes	yes	logarithmic
`std::unordered_multimap`	no	yes	yes	constant

Since C++98, C++ has ordered associative containers; with C++11, C++ has, in addition, unordered associative containers. Both classes have a very similar interface. That's why the following code sample is identical for `std::map` and `std::unordered_map`. To be more precise, the interface of `std::unordered_map` is a superset of the interface of `std::map`. The same holds for the remaining three unordered associative containers. So, porting your code from the ordered to unordered containers is relatively easy.

You can initialize the containers with an initializer list and add new elements with the index operator. To access the first element of the key/value pair `p`, you have `p.first`, and for the second element, you have `p.second`. `p.first` is the key, and `p.second` is the associated value of the pair.

`std::map` versus `std::unordered_map`

```
// orderedUnorderedComparison.cpp
...
#include <map>
#include <unordered_map>

// std::map

std::map<std::string, int> m {{"Dijkstra", 1972}, {"Scott", 1976}};
m["Ritchie"]= 1983;
```

```
std::cout << m["Ritchie"];             // 1983
for(auto p : m) std::cout << "{" << p.first << "," << p.second << "}";
                // {Dijkstra,1972},{Ritchie,1983},{Scott,1976}
m.erase("Scott");
for(auto p : m) std::cout << "{" << p.first << "," << p.second << "}";
                // {Dijkstra,1972},{Ritchie,1983}
m.clear();
std::cout << m.size() << '\n';    // 0

// std::unordered_map

std::unordered_map<std::string, int> um {{"Dijkstra", 1972}, {"Scott",
1976}};
um["Ritchie"]= 1983;
std::cout << um["Ritchie"];           // 1983
for(auto p : um) std::cout << "{" << p.first << "," << p.second <<
"}";
                 // {Ritchie,1983},{Scott,1976},{Dijkstra,1972}
um.erase("Scott");
for(auto p : um) std::cout << "{" << p.first << "," << p.second <<
"}";
                 // {Ritchie,1983},{Dijkstra,1972}
um.clear();
std::cout << um.size() << '\n';   // 0
```

There is a subtle difference between the two program executions: The keys of the `std::map` are ordered, and the keys of the `std::unordered_map` are unordered. The question is: Why do we have such similar containers in C++? I already pointed it out in the table. The answer is typically for C++: performance. The access time to the keys of an unordered associative container is constant and, therefore, independent of the container's size. If the containers are big enough, the performance difference is significant. Look at the section about the performance.

Contains

The member function `associativeContainer.contains(ele)` checks if `associativeContainer` has the element `ele`.

Check if an associative container has an element

```
// containsElement.cpp
...
template <typename AssozCont>
bool containsElement5(const AssozCont& assozCont) {
    return assozCont.contains(5);
}

std::set<int> mySet{1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
std::cout << "containsElement5(mySet): "
          << containsElement5(mySet);               // true

std::unordered_set<int> myUnordSet{1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
std::cout << "containsElement5(myUnordSet): "
          << containsElement5(myUnordSet);          // true
```

```
std::map<int, std::string> myMap{ {1, "red"}, {2, "blue"}, {3,
"green"} };
std::cout << "containsElement5(myMap): "
          << containsElement5(myMap);               // false

std::unordered_map<int, std::string> myUnordMap{ {1, "red"}, {2,
"blue"},
                                                 {3, "green"} };
std::cout << "containsElement5(myUnordMap): "
          << containsElement5(myUnordMap);          // false
```

Insertion and Deletion

The insertion (`insert` and `emplace`) and deletion (`erase`) of elements in associative containers are similar to the rules of a [`std::vector`](). For an associative container that can have a key only once, the insertion fails if the key is already in the container. Additionally, ordered associative containers support a particular function `ordAssCont.erase(key)`, which removes all pairs with the `key` and returns their number.

Insertion and Deletion

```
// associativeContainerModify.cpp
...
#include <set>
...
std::multiset<int> mySet{3, 1, 5, 3, 4, 5, 1, 4, 4, 3, 2, 2, 7, 6, 4,
3, 6};

for (auto s: mySet) std::cout << s << " ";
      // 1 1 2 2 3 3 3 3 4 4 4 4 5 5 6 6 7

mySet.insert(8);
std::array<int, 5> myArr{10, 11, 12, 13, 14};
mySet.insert(myArr.begin(), myArr.begin()+3);
mySet.insert({22, 21, 20});
for (auto s: mySet) std::cout << s << " ";
     // 1 1 2 2 3 3 3 3 4 4 4 4 5 5 6 6 7 10 11 12 20 21 22

std::cout << mySet.erase(4);  // 4
mySet.erase(mySet.lower_bound(5), mySet.upper_bound(15));
for (auto s: mySet) std::cout << s << " ";
    // 1 1 2 2 3 3 3 3 20 21 22
```

Ordered Associative Containers

Overview

The ordered associative containers `std::map` and `std::multimap` associate their key with a value. Both are defined in the header `<map>`. `std::set` and `std::multiset` need the header `<set>`. This [Table]() gives you the details.

All four ordered containers are parametrized by their type, their allocator, and their comparison function. Depending on the type, the containers have default values for the allocator and the comparison function. The declaration of `std::map` and `std::set` shows this very nicely.

```
template < class key, class val, class Comp= less<key>,
           class Alloc= allocator<pair<const key, val> >
class map;

template < class T, class Comp = less<T>,
           class Alloc = allocator<T> >
class set;
```

The declaration of both associative containers shows that `std::map` has an associated value. The key and the value are used for the default allocator: `allocator<pair<const key, val>>`. With a little more imagination, you can derive more from the allocator. `std::map` has pairs of the type `std::pair< const key, val>`. The associated value `val` does not matter for the sort criteria: `less<key>`. All observations also hold for `std::multimap` and `std::multiset`.

Keys and Values

There are special rules for the key and the value of an ordered associative container.

The key has to be

- sortable (by default <),
- copyable and moveable.

The value has to be

- default constructible,
- copyable and moveable.

The key associated value builds a pair `p` to get with the member `p.first` the value `p.second`.

```
#include <map>
...
std::multimap<char, int> multiMap= {{'a', 10}, {'a', 20}, {'b', 30}};
for (auto p: multiMap) std::cout << "{" << p.first << "," << p.second
<< "} ";
                                // {a,10} {a,20} {b,30}
```

The Comparison Criterion

The default comparison criterion of the ordered associative containers is `std::less`. If you want to use a *user-defined* type as the key, you must overload the operator `<`. It's sufficient to overload the operator `<` for your data type because the C++ runtime compares, with the help of the relation `(! (elem1<elem2 || elem2<elem1))`, two elements for equality.

You can specify the sorting criterion as a template argument. This sorting criterion must implement a *strict weak ordering*.

Strict weak ordering

Strict weak ordering for a sorting criterion on a set `S` is given if the following requirements are met.

- For `s` from `S` has to hold, that's < s` is impossible.
- For all `s1` and `s2` from `S` must hold: If `s1 < s2`, then `s2 < s1` is impossible.
- For all `s1`, `s2` and `s3` with `s1 < s2` and `s2 < s3` must hold: `s1 < s3`.
- For all `s1`, `s2` and `s3` with `s1` not comparable with `s2` and `s2` not comparable with `s3` must hold: `s1` is not comparable with `s3`.

In contrast to the definition of *strict weak ordering*, using a comparison criterion with *strict weak ordering* is much simpler for a `std::map`.

```
#include <map>
...
std::map<int, std::string, std::greater<int>> int2Str{
         {5, "five"}, {1, "one"}, {4, "four"}, {3, "three"},
         {2, "two"}, {7, "seven"}, {6, "six"} };
for (auto p: int2Str) std::cout << "{" << p.first << "," << p.second
<< "} ";
         // {7,seven} {6,six} {5,five} {4,four} {3,three} {2,two}
{1,one}
```

Special Search Functions

Ordered associative containers are optimized for search. So they offer unique search functions.

Special search functions of the ordered associative containers

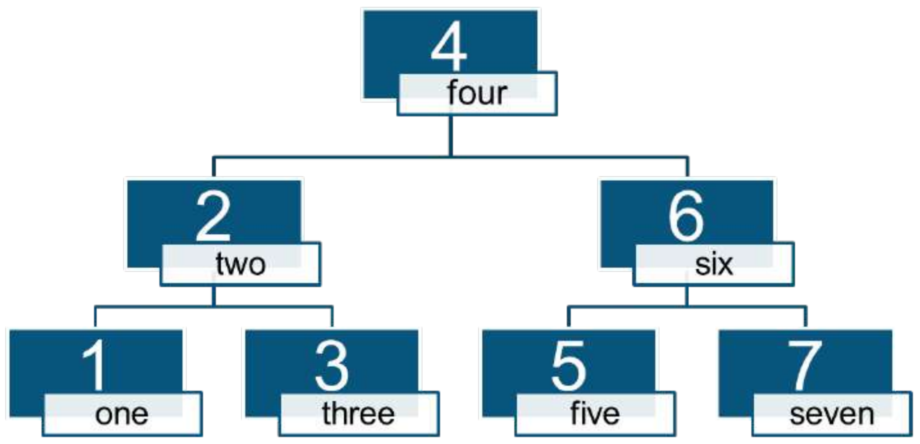
Search function	Description
`ordAssCont.count(key)`	Returns the number of values with the `key`.
`ordAssCont.find(key)`	Returns the iterator of `key` in `ordAssCont`. If there is no `key` in `ordAssCont`, it returns `ordAssCont.end()`.
`ordAssCont.lower_bound(key)`	Returns the iterator to the first `key` in `ordAssCont` in which `key` would be inserted.
`ordAssCont.upper_bound(key)`	Returns the last position of `key` in `ordAssCont` where `key` would be inserted.
`ordAssCont.equal_range(key)`	Returns the range `ordAssCont.lower bound(key)` and `ordAssCont.upper_bound(key)` in a `std::pair`.

Now, the application of the particular search functions.

Search in an associative container

```
// associativeContainerSearch.cpp
...
#include <set>
...
std::multiset<int> mySet{3, 1, 5, 3, 4, 5, 1, 4, 4, 3, 2, 2, 7, 6, 4,
3, 6};

for (auto s: mySet) std::cout << s << " ";
     // 1 1 2 2 3 3 3 3 4 4 4 4 5 5 6 6 7

mySet.erase(mySet.lower_bound(4), mySet.upper_bound(4));
for (auto s: mySet) std::cout << s << " ";
     // 1 1 2 2 3 3 3 3 5 5 6 6 7
std::cout << mySet.count(3) << '\n'; // 4
std::cout << *mySet.find(3) << '\n'; // 3
std::cout << *mySet.lower_bound(3) << '\n'; // 3
std::cout << *mySet.upper_bound(3) << '\n'; // 5
auto pair= mySet.equal_range(3);
std::cout << "(" << *pair.first << "," << *pair.second << ")"; //
(3,5)
```

`std::map`



`std::map` is the most frequently used associative container. The reason is simple. It combines an often sufficient enough performance with a very convenient interface. You can access its elements via the index operator. If the key doesn't exist, `std:map` creates a key/value pair. For the value, the default constructor is used.

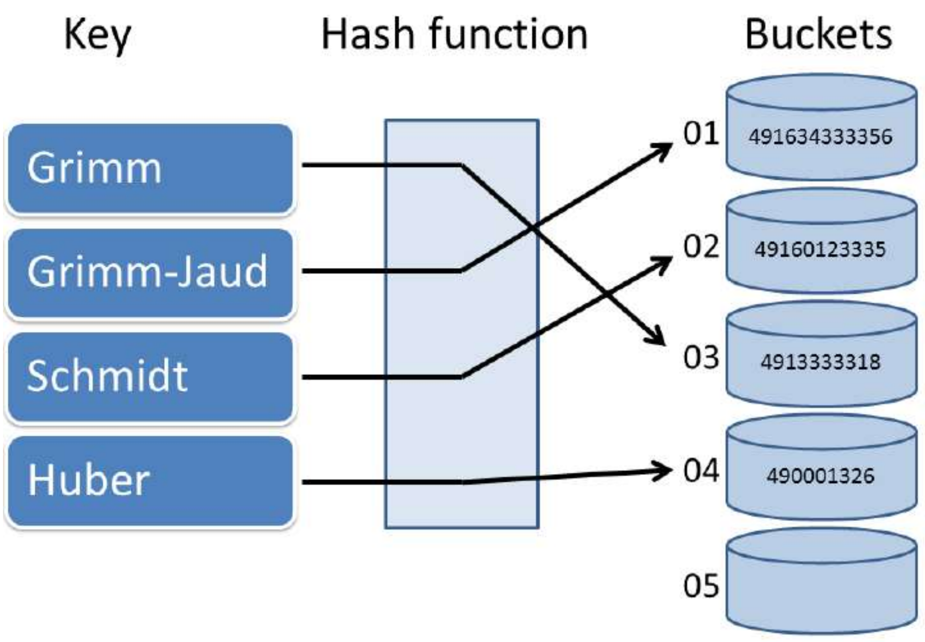
Consider `std::map` as a generalization of `std::vector`

Often, `std::map` is called an associative array, because `std::map` supports the index operator like a sequence container. The subtle difference is that its index is not restricted to a number like in the case of `std::vector`. Its index can be almost any arbitrary type.

The same observations hold for its namesake `std::unordered_map`.

In addition to the index operator, `std::map` supports the `at` member function. The access via `at` is checked. So if the request key doesn't exist in the `std::map`, a `std::out_of_range` exception is thrown.

Unordered Associative Containers



Overview

With the new C++11 standard, C++ has four unordered associative containers: `std::unordered_map`, `std::unordered_multimap`, `std::unordered_set`, and `std::unordered_multiset`. They have a lot in common with their namesakes, the ordered associative containers. The difference is that the unordered ones have a richer interface, and their keys are not sorted.

This shows the declaration of a `std::unordered_map`.

```
template< class key, class val, class Hash= std::hash<key>,
          class KeyEqual= std::equal_to<key>,
          class Alloc= std::allocator<std::pair<const key, val>>>
class unordered_map;
```

Like `std::map`, `std::unordered_map` has an allocator, but `std::unordered_map` needs no comparison function. Instead, `std::unordered_map` needs two additional functions: One, to determine the hash value of its key: `std::has<key>` and second, to compare the keys for equality: `std::equal_to<key>`. Because of the three default template parameters, you only have to provide the key type and the value of the `std::unordered_map`: `std::unordered_map<char,int> unordMap`.

Keys and Values

There are special rules for the key and the value of an unordered associative container.

The key has to be

- equal comparable,
- available as hash value,
- copyable or moveable.

The value has to be

- default constructible,
- copyable or moveable.

Performance

Performance - that's the simple reason - why the unordered associative containers were so long missed in C++. In the example below, one million randomly created values are read from a 10 million big `std::map` and `std::unordered_map`. The impressive result is that the linear access time of an unordered associative container is 20 times faster than an ordered associative container's access time. That is just the difference between these operations' constant and logarithmic complexity *O(log n)*.

Performancecomparison

```
// associativeContainerPerformance.cpp
...
#include <map>
#include <unordered_map>
...
using std::chrono::duration;
static const long long mapSize= 10000000;
static const long long accSize= 1000000;
...
// read 1 million arbitrary values from a std::map
// with 10 million values from randValues
auto start= std::chrono::system_clock::now();
for (long long i= 0; i < accSize; ++i){myMap[randValues[i]];}
duration<double> dur= std::chrono::system_clock::now() - start;
std::cout << dur.count() << " sec";     // 9.18997 sec


// read 1 million arbitrary values from a std::unordered_map
// with 10 million values
auto start2= std::chrono::system_clock::now();
for (long long i= 0; i < accSize; ++i){
myUnorderedMap[randValues[i]];}
duration<double> dur2= std::chrono::system_clock::now() - start2;
std::cout << dur2.count() << " sec";    // 0.411334 sec
```

The Hash Function

The reason for the constant access time of the unordered associative container is the hash function, which is schematically shown here. The hash function maps the key to its value, the so-called hash value. A hash function is good if it produces as few collisions as possible and equally distributes the keys onto the buckets. Because the execution of the hash function takes a constant amount of time, the access of the elements is, in the base case, also constant.

The hash function

- is already defined for the built-in types like boolean, natural numbers, and floating-point numbers,
- is available for `std::string` and `std::wstring`,
- generates for a C string `const char` a hash value of the pointer address,
- can be defined for *user-defined* data types.

For *user-defined* types used as a key for an unordered associative container, you must keep two requirements in mind. They need a hash function and have to be comparable to equal.

A custom hash function

```
// unorderedMapHash.cpp
...
#include <unordered_map>
...
struct MyInt{
  MyInt(int v):val(v){}
  bool operator== (const MyInt& other) const {
    return val == other.val;
  }
  int val;
};

struct MyHash{
  std::size_t operator()(MyInt m) const {
    std::hash<int> hashVal;
    return hashVal(m.val);
  }
};

std::ostream& operator << (std::ostream& st, const MyInt& myIn){
  st << myIn.val ;
  return st;
}

typedef std::unordered_map<MyInt, int, MyHash> MyIntMap;
MyIntMap myMap{{MyInt(-2), -2}, {MyInt(-1), -1}, {MyInt(0), 0},
{MyInt(1), 1}};

for(auto m : myMap) std::cout << "{" << m.first << "," << m.second <<
"} ";
    // {MyInt(1),1} {MyInt(0),0} {MyInt(-1),-1} {MyInt(-2),-2}

std::cout << myMap[MyInt(-2)] << '\n';      // -2
```

The Details

The unordered associative containers store their indices in buckets. Which bucket the index goes to is due to the hash function, which maps the key to the index. If different keys are mapped to the same index, it’s called a collision. The hash function tries to avoid this.

Indices are typically stored in the bucket as a linked list. The access to the bucket is constant; the access in the bucket is linear. The number of buckets is called capacity. The average number of elements for each bucket is called the load factor. In general, the C++ runtime generates new buckets if the load factor exceeds 1. This process is called rehashing and can also explicitly be triggered:

Details to the hash function

```
// hashInfo.cpp
...
#include <unordered_set>
...
using namespace std;

void getInfo(const unordered_set<int>& hash){
  cout << "hash.bucket_count(): " << hash.bucket_count();
  cout << "hash.load_factor(): " << hash.load_factor();
}

unordered_set<int> hash;
cout << hash.max_load_factor() << endl; // 1

getInfo(hash);
    // hash.bucket_count(): 1
    // hash.load_factor(): 0

hash.insert(500);
cout << hash.bucket(500) << endl; // 5

// add 100 abitrary values
fillHash(hash, 100);

getInfo(hash);
    // hash.bucket_count(): 109
    // hash.load_factor(): 0.88908

hash.rehash(500);

getInfo(hash);
    // hash.bucket_count(): 541
    // hash.load_factor(): 0.17298
cout << hash.bucket(500); // 500
```

With the member function `max_load_factor`, you can read and set the load factor. So you can influence the probability of collisions and rehashing. I emphasize one point in the short example above. The key 500 is first in the 5th bucket, but after rehashing is in the 500th bucket.

6. Container Adaptors

Cippi puts Shapes into a Box

Linear Containers

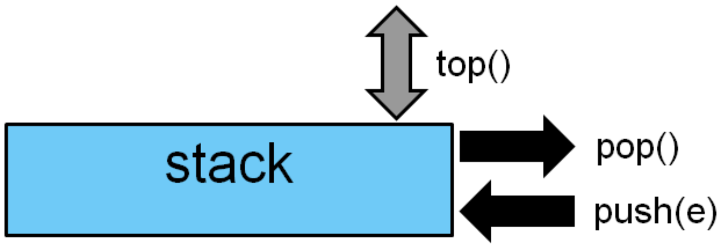
C++ has `std::stack`, `std::queue` and `std::priority_queue` as three special sequence containers. Most of you know these classic data structures from your education.

The adaptors for containers

- support a reduced interface for existing sequence containers,
- can not be used with algorithms of the Standard Template Library,
- are class templates that are parametrized by their data type and their container (`std::vector`, `std::list`, and `std::deque`),
- use by default `std::deque` as the internal sequence container:

```
template <typename T, typename Container= deque<T>>
class stack;
```

Stack



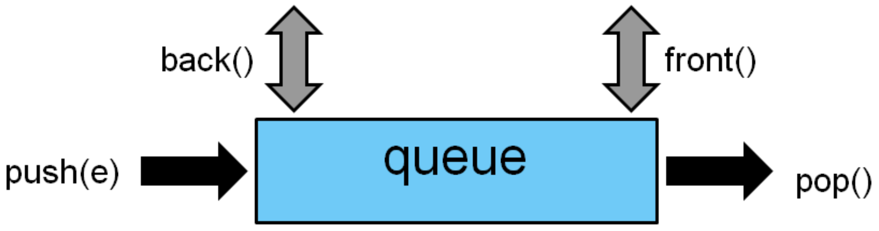
The std::stack follows the LIFO principle (**L**ast **I**n **F**irst **O**ut). The stack sta, which needs the header <stack>, has three special member functions.

With sta.push(e), you can insert a new element e at the top of the stack, remove it from the top with sta.pop() and reference it with sta.top(). The stack supports the comparison operators and knows its size. The stack operations have constant complexity.

std::stack

```
// stack.cpp
...
#include <stack>
...
std::stack<int> myStack;

std::cout << myStack.empty() << '\n';    // true
std::cout << myStack.size() << '\n';     // 0

myStack.push(1);
myStack.push(2);
myStack.push(3);
std::cout << myStack.top() << '\n';      // 3

while (!myStack.empty()){
  std::cout << myStack.top() << " ";
  myStack.pop();
}                                        // 3 2 1

std::cout << myStack.empty() << '\n';    // true
std::cout << myStack.size() << '\n';     // 0
```

Queue



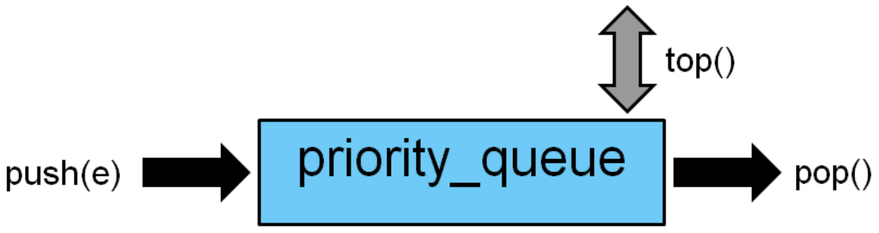
The std::queue follows the FIFO principle (**F**irst **I**n **F**irst **O**ut). The queue `que`, which needs the header `<queue>`, has four special member functions.

With `que.push(e)`, you can insert an element `e` at the end of the queue and remove the first element from the queue with `que.pop()`. `que.back()` enables you to refer to the last component of the `que`, `que.front()` to the first element in the `que`. `std::queue` has similar characteristics as std::stack. So you can compare `std::queue` instances and get their sizes. The queue operations have constant complexity.

std::queue

```
// queue.cpp
...
#include <queue>
...
std::queue<int> myQueue;

std::cout << myQueue.empty() << '\n';     // true
std::cout << myQueue.size() << '\n';      // 0

myQueue.push(1);
myQueue.push(2);
myQueue.push(3);
std::cout << myQueue.back() << '\n';      // 3
std::cout << myQueue.front() << '\n';     // 1

while (!myQueue.empty()){
  std::cout << myQueue.back() << " ";
  std::cout << myQueue.front() << " : ";
  myQueue.pop();
}                                         // 3 1 : 3 2 : 3 3

std::cout << myQueue.empty() << '\n';     // true
std::cout << myQueue.size() << '\n';      // 0
```

Priority Queue



The std::priority_queue is a reduced std::queue. It needs the header <queue>.

The difference to the std::queue is that their greatest element is always at the top of the priority queue. std::priority_queue pri uses by default the comparison operator std::less. Similar to std::queue, pri.push(e) inserts a new element e into the priority queue. pri.pop() removes the first element of the pri, but does that with logarithmic complexity. With pri.top(), you can reference the first element in the priority queue, which is the greatest one. The std::priority_queue knows its size but doesn't support the comparison operator on their instances.

std::priority_queue

```
// priorityQueue.cpp
...
#include <queue>
...
std::priority_queue<int> myPriorityQueue;

std::cout << myPriorityQueue.empty() << '\n';    // true
std::cout << myPriorityQueue.size() << '\n';     // 0

myPriorityQueue.push(3);
myPriorityQueue.push(1);
myPriorityQueue.push(2);
std::cout << myPriorityQueue.top() << '\n';      // 3

while (!myPriorityQueue.empty()){
  std::cout << myPriorityQueue.top() << " ";
  myPriorityQueue.pop();
}                                                // 3 2 1

std::cout << myPriorityQueue.empty() << '\n';    // true
std::cout << myPriorityQueue.size() << '\n';     // 0

std::priority_queue<std::string, std::vector<std::string>,
                    std::greater<std::string>> myPriorityQueue2;

myPriorityQueue2.push("Only");
myPriorityQueue2.push("for");
myPriorityQueue2.push("testing");
```

```
myPriorityQueue2.push("purpose");
myPriorityQueue2.push(".");

while (!myPriorityQueue2.empty()){
  std::cout << myPriorityQueue2.top() << " ";
  myPriorityQueue2.pop();
}                                 // . Only for purpose testing
```

Associative Containers

The four associative containers `std::flat_map`, `std::flat_multimap`, `std::flat_set`, and `std::set_multiset` in C++23 are a drop-in replacement for the ordered associative containers `std::map`, `std::multimap`, `std::set`, and `std::multiset`. To be more precise, a `std::flat_map` is a drop-in replacement for a `std::map`, a `std::flat_multimap` is a drop-in replacement for a `std::multimap`, and so forth.

The flat-ordered associative containers require separate sequence containers for their keys and values. This sequence container must support a random access iterator. By default, a `std::vector` is used, but a `std::array`, or a `std::deque` is also valid.

The following code snippet shows the declaration of `std::flat_map`, and `std::flat_set`.

```
template<class Key, class T,
        class Compare = less<Key>,
        class KeyContainer = vector<Key>, class MappedContainer
= vector<T>>
class flat_map;

template<class Key,
         class Compare = less<Key>,
         class KeyContainer = vector<Key>>
class flat_set;
```

The flat-ordered associative containers provide different time and space complexities than the ordered associative containers. The flat variants require less memory and are faster to read than their non-flat-ordered pendants. The following comparison goes more into the details about the flat and the non-flat-ordered associative containers.

Comparison of the Flat Ordered Associative Container and their Non-Flat Pendants

The flat variants provide better reading performance, such as iterating through the container, and require less memory. They also need that the elements must either be copyable or moveable. The flat variants support a random access iterator.

The non-flat variants improve writing performance if you insert or delete elements. Additionally, the non-flat variants guarantee that the iterators stay valid after inserting or deleting elements. The non-flat variants support a bidirectional iterator.

`std::sorted_unique`

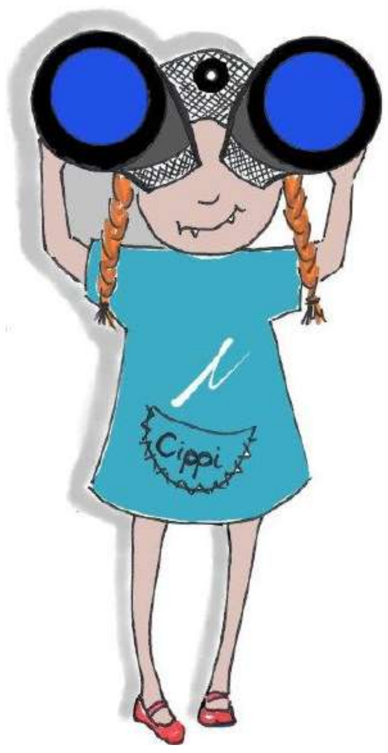
You can use the constant `std::sorted_unique` in a constructor call or in the member functions `insert` to specify that the elements are already sorted. This improves the performance of creating a flat-ordered associative container or inserting elements.

The following code snippet creates a `std::flat_map` from a sorted initializer list `{1, 2, 3, 4, 5}`.

```
std::flat_map myFlatMap = { std::sorted_unique, {1, 2, 3, 4, 5},
{10, 11, 1, 5, -4} };
```

Using the constant `std::sorted_unique` with non-sorted elements is undefined behavior.

7. Views



Cippi observes

Contiguous Access

A `std::span` stands for an object that refers to a contiguous sequence of objects. A `std::span`, sometimes also called a view, is never an owner. This contiguous sequence of objects can be a plain C-array, a pointer with a size, a `std::array`, a`std::vector`, or a `std::string`. You can also access subsequences.

`std::span` does not decay

When you invoke a function taking a C-array, decay occurs. The function takes the C-array via a pointer to its first element. The C-array to pointer conversion is error-prone because all length information to the C-array is lost.

In contrast, a `std::span` knows its length.

```
// copySpanArray.cpp
...
#include <span>

template <typename T>
void copy_n(const T* p, T* q, int n){}

template <typename T>
void copy(std::span<const T> src, std::span<T> des){}


int arr1[] = {1, 2, 3};
int arr2[] = {3, 4, 5};

copy_n(arr1, arr2, 3);      // (1)
copy<int>(arr1, arr2);      // (2)
```

In contrast to the C-array (1), a function taking a C-array via a `std::span` (2) does not need an explicit argument for its length.

A `std::span` can have a *static extent* or a *dynamic extent*. A typical implementation of `std::span` with a *dynamic extent* holds a pointer to its first element and length. By default, `std::span` has a *dynamic extent*:

Definition of `std::span`

```
template <typename T, std::size_t Extent = std::dynamic_extent>
class span;
```

The following table presents the functions of a `std::span`.

Functions of a `std::span sp`

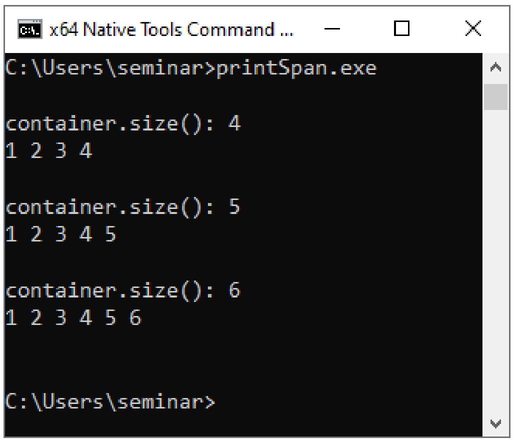
Function	Description
`sp.front()`	Access the first element.
`sp.back()`	Access the last element.
`sp[i]`	Access the `i`-th element.
`sp.data()`	Returns a pointer to the beginning of the sequence.
`sp.size()`	Returns the number of elements of the sequence.
`sp.size_bytes()`	Returns the size of the sequence in bytes.
`sp.empty()`	Returns `true` if the sequence is empty.
`sp.first<count>()` `sp.first(count)`	Returns a subspan consisting of the first count elements of the sequence.
`sp.last<count>()` `sp.last(count)`	Returns a subspan consisting of the last count elements of the sequence.
`sp.subspan<first, count>()` `sp.subspan(first, count)`	Returns a subspan consisting of count elements starting at first.

`std::span` taking different arguments

```
// printSpan.cpp
...
#include <span>

void printMe(std::span<int> container) {
    std::cout << "container.size(): " << container.size() <<
'\n';
```

```
    for(auto e : container) std::cout << e << ' ';
    std::cout << "\n\n";
}

std::cout << '\n';

int arr[]{1, 2, 3, 4};
printMe(arr);                          // (1)

std::vector vec{1, 2, 3, 4, 5};
printMe(vec);                          // (2)

std::array arr2{1, 2, 3, 4, 5, 6};
printMe(arr2);                         // (3)
```

A `std::span` can be initialized with a C-array, a `std::vector` (1), or a `std::array` (2).



```
C:\Users\seminar>printSpan.exe

container.size(): 4
1 2 3 4

container.size(): 5
1 2 3 4 5

container.size(): 6
1 2 3 4 5 6


C:\Users\seminar>
```

Automatic size deduction of a std::span

Prefer `std::string_view` to `std::span`

A `std::string` is a contiguous sequence of characters. Consequently, you could initialize a `std::span` with a `std::string`. You should prefer `std::string_view` to `std::span` because a `std::string_view` represents a view of a sequence of characters and not a sequence of objects such as `std::span`. The interface of a `std::string_view` is string-like, but the interface of a `std::span` is quite generic.

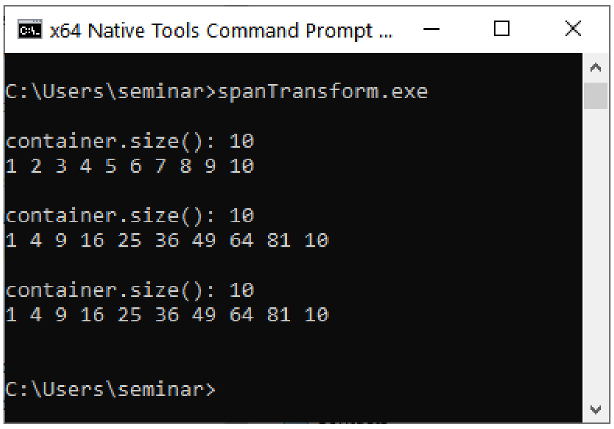
You can modify an entire span or only a subspan. When you modify a span, you modify the referenced objects.

Modify the objects referenced by a `std::span`

```
// spanTransform.cpp
...
#include <span>
```

```
std::vector vec{1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
printMe(vec);

std::span span1(vec);                                     // (1)
std::span span2{span1.subspan(1, span1.size() - 2)};     // (2)

std::transform(span2.begin(), span2.end(),               // (3)
               span2.begin(),
               [](int i){ return i * i; });

printMe(vec);
printMe(span1);
```

I defined the function `printMe` in the previous example `quadSpan.cpp`. `span1` references the `std::vector vec` (1). In contrast, `span2` references only the underlying `vec` elements, excluding the first and the last element (2). Consequently, mapping each element to its square only addresses those elements (3).



```
C:\Users\seminar>spanTransform.exe

container.size(): 10
1 2 3 4 5 6 7 8 9 10

container.size(): 10
1 4 9 16 25 36 49 64 81 10

container.size(): 10
1 4 9 16 25 36 49 64 81 10


C:\Users\seminar>
```

Modify the objects referenced by a `std::span`

Multidimensional Access

A `std::mdspan` is a non-owning multidimensional view of a contiguous sequence of objects. Often, this multidimensional view is called a multidimensional array. The contiguous sequence of objects can be a plain C-array, a pointer with a size, a `std::array`, a `std::vector`, or a `std::string`.

The number of dimensions and the size of each dimension determine the shape of the multidimensional array. The number of dimensions is called rank, and the size of each dimension extension. The size of the `std::mdspan` is the product of all dimensions that are not 0. You can access the elements of a `std::mdspan` using the multidimensional index operator `[]`.

Each dimension of a `std::mdspan` can have a *static extent* or a *dynamic extent*. *static extent* means that its length is specified at compile time; *dynamic extent* means that its length is specified at run time.

Definition of `std::mdspan`

```
template<
    class T,
    class Extents,
    class LayoutPolicy = std::layout_right,
    class AccessorPolicy = std::default_accessor<T>
> class mdspan;
```

- `T`: the contiguous sequence of objects
- `Extents`: specifies the number of dimensions as their size; each dimension can have a *static extent* or a *dynamic extent*
- `LayoutPolicy`: specifies the layout policy to access the underlying memory
- `AccessorPolicy`: specifies how the underlying elements are referenced

Thanks to class template argument deduction (CTAG) in C++17, the compiler can often automatically deduce the template arguments.

Two 2-dimensional arrays

```
// mdspan.cpp

#include <mdspan>
#include <iostream>
#include <vector>

int main() {

    std::vector myVec{1, 2, 3, 4, 5, 6, 7, 8};

    std::mdspan m{myVec.data(), 2, 4};
    std::cout << "m.rank(): " << m.rank() << '\n';

    for (std::size_t i = 0; i < m.extent(0); ++i) {
        for (std::size_t j = 0; j < m.extent(1); ++j) {
            std::cout << m[i, j] << ' ';
        }
        std::cout << '\n';
19       }
20
21       std::cout << '\n';
22
23       std::mdspan m2{myVec.data(), 4, 2};
24       std::cout << "m2.rank(): " << m2.rank() << '\n';
25
26       for (std::size_t i = 0; i < m2.extent(0); ++i) {
27           for (std::size_t j = 0; j < m2.extent(1); ++j) {
28           std::cout << m2[i, j] << ' ';
29       }
30       std::cout << '\n';
31     }
32
33 }
```

I apply class template argument deduction three times in this example. Line 9 uses it for a `std::vector`, and lines 11 and 23 for a `std::mdspan`. The first 2-dimensional array `m` has a shape of (2, 4), the second one `m2` a shape of (4, 2). Lines 12 and 24 display the ranks of both `std::mdspan`. Thanks to the extent of each dimension (lines 14 and 15), and the index operator in line 16, it is straightforward to iterate through multidimensional arrays.

```
m.rank(): 2
1 2 3 4
5 6 7 8

m2.rank(): 2
1 2
3 4
5 6
7 8
```

Two 2-dimensional arrays

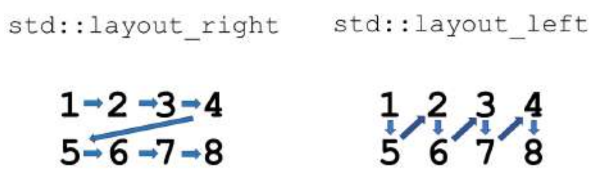
If your multidimensional array should have a *static extent*, you have to specify the template arguments.

Explicitly specifying the template arguments of a `std::mdspan`

```
// staticDynamicExtent.cpp

#include <mdspan>
...

std::mdspan<int, std::extents<std::size_t, 2, 4>>
m{myVec.data()};   // (1)
std::cout << "m.rank(): " << m.rank() << '\n';

for (std::size_t i = 0; i < m.extent(0); ++i) {
    for (std::size_t j = 0; j < m.extent(1); ++j) {
        std::cout << m[i, j] << ' ';
    }
    std::cout << '\n';
}

std::mdspan<int, std::extents<std::size_t,
std::dynamic_extent, std::dynamic_extent>>
               m2{myVec.data(), 4, 2};
// (2)
std::cout << "m2.rank(): " << m2.rank() << '\n';

for (std::size_t i = 0; i < m2.extent(0); ++i) {
    for (std::size_t j = 0; j < m2.extent(1); ++j) {
        std::cout << m2[i, j] << ' ';
    }
std::cout << '\n';
}
```

The program `staticDynamicExtent.cpp` is based on the previous program `mdspan.cpp`, and produces the same output. The difference is, that the `std::mdspan m` (1) has a *static extent*. For completeness, `std::mdspan m2` (2) has a *dynamic extent*. Consequentially, the shape of `m` is specified with template arguments, but the shape of `m2` is with function arguments.

A `std::mdspan` allows you to specify the layout policy to access the underlying memory. By default, `std::layout_right` (C, C++ or Python style) is used, but you can also specify `std::layout_left` (Fortran or MATLAB style). The following graphic exemplifies, in which sequence the elements of the `std::mdspan` are accessed.



`std::layout_right` and `std::layout_left`

Traversing two `std::mdspan` with the layout policy `std::layout_right` and `std::layout_left` shows the difference.

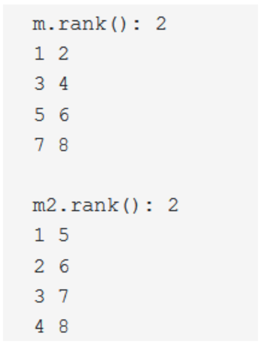
Using a `std::mdspan` with `std::layout_right` and `std::layout_left`

```
// mdspanLayout.cpp
...
#include <mdspan>
```

```cpp

std::vector myVec{1, 2, 3, 4, 5, 6, 7, 8};

std::mdspan<int,                                                   // (1)
    std::extents<std::size_t, std::dynamic_extent, std::dynamic_extent>,
    std::layout_right> m2{myVec.data(), 4, 2};

std::cout << "m.rank(): " << m.rank() << '\n';

for (std::size_t i = 0; i < m.extent(0); ++i) {
    for (std::size_t j = 0; j < m.extent(1); ++j) {
        std::cout << m[i, j] << ' ';
    }
    std::cout << '\n';
}

std::cout << '\n';

std::mdspan<int,
    std::extents<std::size_t, std::dynamic_extent, std::dynamic_extent>,
    std::layout_left> m2{myVec.data(), 4, 2};                      // (2)
std::cout << "m2.rank(): " << m2.rank() << '\n';

for (std::size_t i = 0; i < m2.extent(0); ++i) {
    for (std::size_t j = 0; j < m2.extent(1); ++j) {
        std::cout << m2[i, j] << ' ';
    }
    std::cout << '\n';
}
```

The `std::mdspan` `m` uses `std::layout_right` (1), the other `std::mdspan` `std::layout_left` (1). Thanks to class template argument deduction, the constructor call of `std::mdspan` (1) needs no explicit template arguments and is equivalent to the following expression: `std::mdspan m2{myVec.data(), 4, 2}`.

The output of the program shows the two different layout strategies.



```
m.rank(): 2
1 2
3 4
5 6
7 8

m2.rank(): 2
1 5
2 6
3 7
4 8
```

`std::mdspan` with `std::layout_left`

The following table presents an overview of `std::mdspan`'s interface.

Functions of a `std::mdspan md`

Function	Description
`md[ind]`	Access the `ind`-th element.
`md.size`	Returns the size of the multidimensional array.
`md.rank`	Returns the dimension of the multidimensional array.
`md.extents(i)`	Returns the size of the `i`-th dimension.
`md.data_handle`	Returns a pointer to the contiguous sequence of elements.

8. Iterators

Cippi makes giant steps

On the one hand, iterators are generalizations of pointers representing positions in a container. On the other hand, they provide powerful iteration and random access in a container.

Iterators are the glue between the generic containers and the generic algorithms of the Standard Template Library.

Iterators support the following operations:

- `*`: returns the element at the current position
- `==, !=`: compares two positions
- `=`: assigns a new value to an iterator

The range-based for-loop uses the iterators implicitly.

Because iterators are not checked, they have the same issues as pointers.

```
std::vector<int> verc{1, 23, 3, 3, 3, 4, 5};
std::deque<int> deq;

// Start iterator bigger than end iterator
std::copy(vec.begin()+2, vec.begin(), deq.begin());
```

```
// Target container too small
std::copy(vec.begin(), vec.end(), deq.end());
```

Categories

Their capabilities can categorize iterators. The category of an iterator depends on the type of container used. C++ has forward, bidirectional, random access, and contiguous iterators. With the forward iterator, you can iterate the container forward, with the bidirectional iterator, in both directions. The random access iterator allows it to directly access an arbitrary element. In particular, the random iterator enables iterator arithmetic and ordering comparisons (e.g.: <). A contiguous iterator is a random access iterator and requires that the elements of the container are stored contiguously in memory.

The table below is a representation of containers and their iterator categories. The bidirectional iterator includes the forward iterator functionalities. The random access iterator includes the forward and the bidirectional iterator functionalities. `It` and `It2` are iterators, `n` is a natural number.

The iterator categories of the container

Iterator category	Properties	Containers

Forward iterator	`++It, It++, *It`
	`It == It2, It != It2`
		`std::unordered_set`
		`std::unordered_map`
		`std::unordered_multiset`
		`std::unordered_multimap`
		`std::forward_list`

Bidirectional iterator	`--It, It--`	`std::set`
		`std::map`
		`std::multiset`
		`std::multimap`
		`std::list`

Random access iterator	`It[i]`
	`It+= n, It-= n`
	`It+n, It-n`
	`n+It`
	`It-It2`
	`It < It2, It <= It2, It > It2`
	`It >= It2`
		`std::deque`

Contiguous iterator		`std::array`
		`std::vector`
		`std::string`

The input iterator and the output iterator are special forward iterators: they can read and write their pointed element only once.

Iterator Creation

Each container generates its suitable iterator on request. For example, an `std::unordered_map` generates constant and non-constant forward iterators.

```
std::unordered_map<std::string, int>::iterator unMapIt=
unordMap.begin();
std::unordered_map<std::string, int>::iterator unMapIt=
unordMap.end();

std::unordered_map<std::string, int>::const_iterator unMapIt=
unordMap.cbegin();
std::unordered_map<std::string, int>::const_iterator unMapIt=
unordMap.cend();
```

In addition, `std::map` supports the backward iterators:

```
std::map<std::string, int>::reverse_iterator mapIt= map.rbegin();
std::map<std::string, int>::reverse_iterator mapIt= map.rend();

std::map<std::string, int>::const_reverse_iterator mapIt=
map.crbegin();
std::map<std::string, int>::const_reverse_iterator mapIt=
map.crend();
```

Use `auto` for iterator definition

Iterator definition is very labor intensive. The automatic type deduction with `auto` reduces the writing to the bare minimum.

```
std::map<std::string, int>::const_reverse_iterator
mapIt= map.crbegin();
auto mapIt2= map.crbegin();
```

The final example:

Iterator creation

```
// iteratorCreation.cpp
...
using namespace std;
...
map<string, int> myMap{{"Rainer", 1966}, {"Beatrix", 1966},
{"Juliette", 1997},
                      {"Marius", 1999}};

auto endIt= myMap.end();
for (auto mapIt= myMap.begin(); mapIt != endIt; ++mapIt)
     cout << "{" << mapIt->first << "," << mapIt->second << "}";
         // {Beatrix,1966},{Juliette,1997},{Marius,1999},
{Rainer,1966}

vector<int> myVec{1, 2, 3, 4, 5, 6, 7, 8, 9};
vector<int>::const_iterator vecEndIt= myVec.end();
vector<int>::iterator vecIt;
```

```
for (vecIt= myVec.begin(); vecIt != vecEndIt; ++vecIt) cout <<
*vecIt << " ";
        // 1 2 3 4 5 6 7 8 9

vector<int>::const_reverse_iterator vecEndRevIt= myVec.rend();
vector<int>::reverse_iterator revIt;
for (revIt= myVec.rbegin(); revIt != vecEndRevIt; ++revIt) cout
<< *revIt << " ";
        // 9 8 7 6 5 4 3 2 1
```

Useful Functions

The global functions `std::begin`, `std::end`, `std::prev`, `std::next`, `std::distance`, and `std::advance` make your handling of the iterators a lot easier. Only the function `std::prev` requires a bidirectional iterator. All functions need the header `<iterator>`. The table gives you an overview.

Useful functions for iterators

Global function	Description
`std::begin(cont)`	Returns a begin iterator to the container `cont`.
`std::end(cont)`	Returns an end iterator to the container `cont`.
`std::rbegin(cont)`	Returns a reverse begin iterator to the container `cont`.
`std::rend(cont)`	Returns a reverse end iterator to the container `cont`.
`std::cbegin(cont)`	Returns a constant begin iterator to the container `cont`.
`std::cend(cont)`	Returns a constant end iterator to the container `cont`.
`std::crbegin(cont)`	Returns a reverse constant begin iterator to the container `cont`.
`std::crend(cont)`	Returns a reverse constant end iterator to the container `cont`.
`std::prev(it)`	Returns an iterator, which points to a position before `it`
`std::next(it)`	Returns an iterator, which points to a position after `it`.
`std::distance(fir, sec)`	Returns the number of elements between `fir` and `sec`.
`std::advance(it, n)`	Puts the iterator `it` n positions further.

Now, here is the application of the valuable functions.

Helper functions for iterators

```
// iteratorUtilities.cpp
...
#include <iterator>
...
using std::cout;

std::unordered_map<std::string, int> myMap{{"Rainer", 1966},
{"Beatrix", 1966},
                                           {"Juliette", 1997},
{"Marius", 1999}};

for (auto m: myMap) cout << "{" << m.first << "," << m.second <<
"} ";
     // {Juliette,1997},{Marius,1999},{Beatrix,1966},
{Rainer,1966}

auto mapItBegin= std::begin(myMap);
cout << mapItBegin->first << " " << mapItBegin->second; //
Juliette 1997

auto mapIt= std::next(mapItBegin);
cout << mapIt->first << " " << mapIt->second;            //
Marius 1999
cout << std::distance(mapItBegin, mapIt);                 // 1

std::array<int, 10> myArr{0, 1, 2, 3, 4, 5, 6, 7, 8, 9};
for (auto a: myArr) std::cout << a << " ";                // 0 1
2 3 4 5 6 7 8 9

auto arrItEnd= std::end(myArr);
auto arrIt= std::prev(arrItEnd);
cout << *arrIt << '\n';                             // 9

std::advance(arrIt, -5);
cout << *arrIt;                                     // 4
```

Adaptors

Iterator adaptors enable the use of iterators in insert mode or with streams. They need the header `<iterator>`.

Insert iterators

With the three insert iterators `std::front_inserter`, `std::back_inserter` and `std::inserter`, you can insert an element into a container at the beginning, at the end, or an arbitrary position, respectively. The three map their functionality on the container `cont` underlying member functions. The memory for the elements will automatically be provided.

The table below gives you two pieces of information: Which member function of the containers are internally used and which iterators can be used depends on the container's type.

The three insert iterators

Name	**internally used member function**	**Container**
`std::front_inserter(val)`	`cont.push_front(val)`	`std::deque` `std::list`

`std::back_inserter(val)`	`cont.push_back(val)`	`std::vector`
		`std::deque`
		`std::list`
		`std::string`

`std::inserter(val, pos)`	`cont.insert(pos, val)`	`std::vector`
		`std::deque`
		`std::list`
		`std::string`
		`std::map`
		`std::set`

You can combine the algorithms in the STL with the three insert iterators.

```
#include <iterator>
...
std::deque<int> deq{5, 6, 7, 10, 11, 12};
std::vector<int> vec{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13,
14, 15};

std::copy(std::find(vec.begin(), vec.end(), 13),
          vec.end(), std::back_inserter(deq));

for (auto d: deq) std::cout << d << " ";
                    // 5 6 7 10 11 12 13 14 15

std::copy(std::find(vec.begin(), vec.end(), 8),
std::find(vec.begin(), vec.end(), 10),
std::inserter(deq,
std::find(deq.begin(), deq.end(), 10)));d
for (auto d: deq) std::cout << d << " ";
                    // 5 6 7 8 9 10 11 12 13 14 15

std::copy(vec.rbegin()+11, vec.rend(),
std::front_inserter(deq));
```

```
for (auto d: deq) std::cout << d << " ";
                        // 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
```

Stream Iterators

Stream iterator adaptors can use streams as a data source or data sink. C++ offers two functions to create istream iterators and two to create ostream iterators. The created istream iterators behave like input iterators, the ostream iterators act like insert iterators.

The four stream iterators

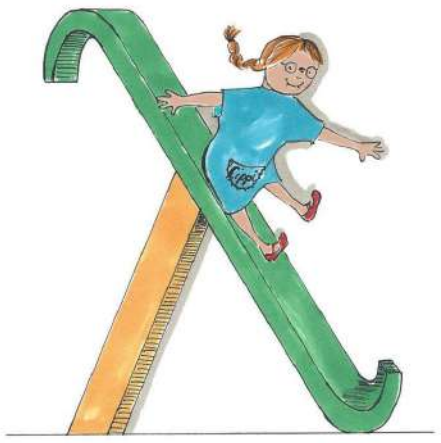
Function	Description
`std::istream_iterator<T>`	Creates an end-of-stream iterator.
`std::istream_iterator<T>(istream)`	Creates an istream iterator for `istream`.
`std::ostream_iterator<T>(ostream)`	Creates an ostream iterator for `ostream`
`std::ostream_iterator<T>(ostream, delim)`	Creates an ostream iterator for `ostream` with the delimiter `delim`.

Thanks to the stream iterator adapter, you can directly read from or write to a stream.

The following interactive program fragment reads natural numbers from `std::cin` in an endless loop and pushes them onto the vector `myIntVec`. If the input is not a natural number, an error in the input stream will occur. All numbers in `myIntVec` are copied to `std::cout`, separated by `:`. Now you can see the result on the console.

```
#include <iterator>
...
std::vector<int> myIntVec;
std::istream_iterator<int> myIntStreamReader(std::cin);
std::istream_iterator<int> myEndIterator;

// Possible input
// 1
// 2
// 3
// 4
// z
while(myIntStreamReader != myEndIterator){
  myIntVec.push_back(*myIntStreamReader);
  ++myIntStreamReader;
}

std::copy(myIntVec.begin(), myIntVec.end(),
          std::ostream_iterator<int>(std::cout, ":"));
          // 1:2:3:4:
```

9. Callable Units



Cippi slides down the slide

This chapter is intentionally not exhaustive

This book is about the C++ Standard library. Therefore, I will not go into the details of callable units. I provide as much information as necessary to use them in the Standard Template Library algorithms correctly. An exhaustive discussion of callable units should be part of a book about the C++ core language.

Many STL algorithms and containers can be parametrized with callable units (short callable). A callable is something that behaves like a function. Not only are these functions but also function objects and lambda functions. Predicates are special functions that return a boolean as a result. If a predicate has one argument, it's called a unary predicate. If a predicate has two arguments, it's called a binary predicate. The same holds for functions. A function taking one argument is a unary function; a function taking two arguments is a binary function.

To change the elements of a container, your algorithm should take them by reference

Callables can receive their arguments by value or reference from their container. To modify the container elements, they must address them directly, so the callable must get them by reference.

Functions

Functions are the simplest callables. They can have - apart from static variables - no state. Because the definition of a function is often widely separated from its use or even in a different translation unit, the compiler has fewer opportunities to optimize the resulting code.

```
void square(int& i){ i = i*i; }
std::vector<int> myVec{1, 2, 3, 4, 5, 6, 7, 8, 9, 10};

std::for_each(myVec.begin(), myVec.end(), square);
for (auto v: myVec) std::cout << v << " ";      // 1 4 9 16 25
36 49 64 81 100
```

Function Objects

At first, don't call them functors. That's a *well-defined* term from the category theory.

Function objects are objects that behave like functions. As function objects are objects, they can have attributes and, therefore, state. They achieve this due to their call operator being implemented.

```
struct Square{
  void operator()(int& i){i= i*i;}
};

std::vector<int> myVec{1, 2, 3, 4, 5, 6, 7, 8, 9, 10};

std::for_each(myVec.begin(), myVec.end(), Square());

for (auto v: myVec) std::cout << v << " "; // 1 4 9 16 25 36 49
64 81 100
```

Instantiate function objects to use them

It’s a common error that only the name of the function object (**`Square`**) and not the instance of the function object (**`Square()`**) is used in an algorithm: `std::for_each(myVec.begin(), myVec.end(), Square)`. That’s, of course, an error. You have to use the instance: `std::for_each(myVec.begin(), myVec.end(), Square())`

Predefined Function Objects

C++ offers a bunch of predefined function objects. They need the header `<functional>`. These predefined function objects are beneficial to change the default behavior of the containers. For example, the ordered associative containers’ keys are by default sorted using the predefined function object `std::less`. But you may want to use `std::greater` instead:

```
std::map<int, std::string> myDefaultMap;                    // 
std::less<int>
std::map<int, std::string, std::greater<int> mySpecialMap>;  // 
std::greater<int>
```

There are function objects in the Standard Template Library for arithmetic, logic, bitwise operations, negation, and comparison.

Predefined function objects

Function object for	Representative
Negation	`std::negate<T>()`
Arithmetic	`std::plus<T>(), std::minus<T>()` `std::multiplies<T>(),` `std::divides<T>()` `std::modulus<T>()`
Comparison	`std::equal_to<T>(),` `std::not_equal_to<T>()` `std::less<T>(), std::greater<T>()` `std::less_equal<T>(),` `std::greater_equal<T>()`
Logical	`std::logical_not<T>()` `std::logical_and<T>(),` `std::logical_or<T>()`
Bitwise	`std::bit_and<T>(), std::bit_or<T>()` `std::bit_xor<T>()`

Lambda Functions

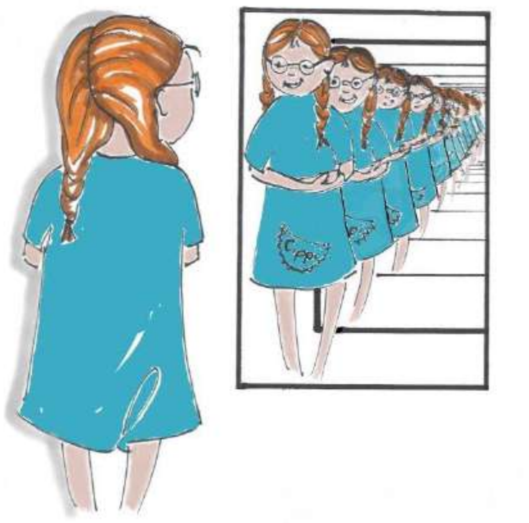
Lambda functions provide in-place functionality. Lambda functions can receive their arguments by value or by reference. They can capture their environment by value, reference, and with C++14 by move. The compiler gets a lot of insight and has excellent optimization potential.

```
std::vector<int> myVec{1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
std::for_each(myVec.begin(), myVec.end(), [](int& i){ i= i*i;
});
                                        // 1 4 9 16 25 36 49 64
81 100
```

Lambda functions should be your first choice

If the functionality of your callable is short and self-explanatory, use a lambda function. A lambda function is, in general, faster and easier to understand.

10. Algorithms



Cippi clones herself

The Standard Template Library has many algorithms to work with containers and their elements. As the algorithms are function templates, they are independent of the type of container elements. The glue between the containers and algorithms are their iterators. If your container supports the STL container's interface, you can apply the algorithms to your container.

Generic programming with the algorithmn

```
// algorithm.cpp
...
#include <algorithm>
...
template <typename Cont, typename T>
void doTheSame(Cont cont, T t){
  for (const auto c: cont) std::cout << c << " ";
  std::cout << cont.size() << '\n';
  std::reverse(cont.begin(), cont.end());
  for (const auto c: cont) std::cout << c << " ";
  std::reverse(cont.begin(), cont.end());
  for (const auto c: cont) std::cout << c << " ";
  auto It= std::find(cont.begin(), cont.end(), t);
  std::reverse(It, cont.end());
  for (const auto c: cont) std::cout << c << " ";
}

std::vector<int> myVec{1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
std::deque<std::string> myDeq({"A", "B", "C", "D", "E", "F", "G", "H", "I"});
std::list<char> myList({'a', 'b', 'c', 'd', 'e', 'f', 'g', 'h'});

doTheSame(myVec, 5);
  // 1 2 3 4 5 6 7 8 9 10
  // 10
  // 10 9 8 7 6 5 4 3 2 1
  // 1 2 3 4 5 6 7 8 9 10
  // 1 2 3 4 10 9 8 7 6 5

doTheSame(myDeq, "D");
  // A B C D E F G H I
  // 9
  // I H G F E D C B A
  // A B C D E F G H I
  // A B C I H G F E D

doTheSame(myList, 'd');
  // a b c d e f g h
  // 8
  // h g f e d c b a
  // a b c d e f g h
  // a b c h g f e d
```

Conventions

You must keep a few rules in your head to use the algorithms.

The algorithms are defined in various headers.

`<algorithm>`
: Contains the general algorithms.

`<numeric>`
: Contains the numeric algorithms.

Many algorithms have the name suffix `_if` and `_copy`.

`_if`
: The algorithm can be parametrized by a predicate.

`_copy`
: The algorithm copies its elements in another range.

Algorithms like `auto num= std::count(InpIt first, InpIt last, const T& val)` return the number of elements equal to `val`. `num` is of type `iterator_traits<InpIt>::difference_type`. You have the guarantee that `num` is sufficient to hold the result. Because of the automatic return type deduction with `auto`, the compiler will give you the right types.

If the container uses an additional range, it has to be valid

The algorithm `std::copy_if` uses an iterator to the beginning of its destination range. This destination range has to be valid.

Naming conventions for the algorithms

I use a few naming conventions for the type of arguments and the algorithms' return type to make them easier to read.

Signature of the algorithms

Name	Description
`InIt`	Input iterator
`FwdIt`	Forward iterator
`BiIt`	Bidirectional iterator
`UnFunc`	Unary callable
`BiFunc`	Binary callable
`UnPre`	Unary predicate
`BiPre`	Binary predicate
`Search`	The searcher encapsulates the search algorithm.
`ValType`	From the input range, automatically deduced value type.
`Num`	typename std::iterator_traits<ForwardIt>::difference_type
`ExePol`	Execution policy

Iterators are the Glue

Iterators define the range of the container on which the algorithms work. They describe a *half-open* range. In a *half-open* range, the begin iterator points to the beginning, and the end iterator points to one position after the range.

The iterators can be categorized based on their capabilities. See the Categories section of the Iterators chapter. The algorithms provide conditions to the iterators. Like in the case of `std::rotate`, most of the time, a forward iterator is sufficient. But that doesn't hold for `std::reverse`. `std::reverse` requires a bidirectional iterator.

Sequential, Parallel, or Parallel Execution with Vectorisation

Using an execution policy in C++17, you can specify whether the algorithm should run sequentially, in parallel, or parallel with vectorization.

Availability of the Parallel STL

In 2023, only the Microsoft Compiler implements the STL algorithm's parallel version natively. With the GCC or Clang compiler, you have to install and use the Threading Building Blocks. The TBB is a C++ template library developed by Intel for parallel programming on multi-core processors.

Execution Policies

The policy tag specifies whether an algorithm should run sequentially, in parallel, or in parallel with vectorization.

- **`std::execution::seq`**: runs the algorithm sequentially
- **`std::execution::par`**: runs the algorithm in parallel on multiple threads
- **`std::execution::par_unseq`**: runs the algorithm in parallel on multiple threads and allows the interleaving of individual loops; permits a vectorized version with SIMD (**S**ingle **I**nstruction **M**ultiple **D**ata) extensions.

The following code snippet shows all execution policies.

The execution policy

```
std::vector<int> v = {1, 2, 3, 4, 5, 6, 7, 8, 9};

// standard sequential sort
std::sort(v.begin(), v.end());

// sequential execution
std::sort(std::execution::seq, v.begin(), v.end());

// permitting parallel execution
std::sort(std::execution::par, v.begin(), v.end());

// permitting parallel and vectorized execution
std::sort(std::execution::par_unseq, v.begin(), v.end());
```

The example shows that you can still use the classic `std::sort` variant without an execution policy. Also, in C++17, you can specify explicitly whether the sequential, parallel, or the parallel and vectorized version should be used.

Parallel and Vectorised Execution

Whether an algorithm runs in a parallel and vectorized way depends on many factors. For example, it depends on whether the CPU and the operating system support SIMD instructions. Additionally, it depends on the compiler and the optimization level to compile your code.

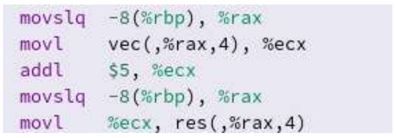
The following example shows a simple loop for creating a new vector.

```
const int SIZE= 8;

int vec[] = {1, 2, 3, 4, 5, 6, 7, 8};
int res[] = {0, 0, 0, 0, 0, 0, 0};

int main(){
  for (int i = 0; i < SIZE; ++i) {
    res[i] = vec[i] + 5;
  }
}
```

The expression `res[i] = vec[i] + 5` is the critical line in this small example. Thanks to the Compiler Explorer, we can look closely at the assembler instructions generated by x86-64 clang 3.6.

Without Optimisation

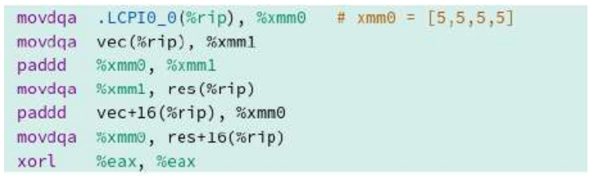
Here are the assembler instructions. Each addition is done sequentially.



```
movslq  -8(%rbp), %rax
movl    vec(,%rax,4), %ecx
addl    $5, %ecx
movslq  -8(%rbp), %rax
movl    %ecx, res(,%rax,4)
```

With Maximum Optimisation

Using the highest optimization level, `-O3`, special registers such as `xmm0` that can hold 128 bits or 4 `int's are used. This means that the addition takes place in parallel on four vector elements.



```
movdqa  .LCPI0_0(%rip), %xmm0   # xmm0 = [5,5,5,5]
movdqa  vec(%rip), %xmm1
paddd   %xmm0, %xmm1
movdqa  %xmm1, res(%rip)
paddd   vec+16(%rip), %xmm0
movdqa  %xmm0, res+16(%rip)
xorl    %eax, %eax
```

77 of the STL algorithms can be parametrized by an execution policy.

Algorithms with parallelized versions

Here are the 77 algorithms with parallelized versions.

The 77 algorithms with parallelized versions

std::adjacent_difference	std::adjacent_find	std::all_of
std::any_of	std::copy	std::copy_if
std::copy_n	std::count	std::count_if
std::equal	std::exclusive_scan	std::fill
std::fill_n	std::find	std::find_end
std::find_first_of	std::find_if	std::find_if_not
std::for_each	std::for_each_n	std::generate
std::generate_n	std::includes	std::inclusive_scan
std::inner_product	std::inplace_merge	std::is_heap
std::is_heap_until	std::is_partitioned	std::is_sorted
std::is_sorted_until	std::lexicographical_compare	std::max_element
std::merge	std::min_element	std::minmax_element
std::mismatch	std::move	std::none_of
std::nth_element	std::partial_sort	std::partial_sort_copy
std::partition	std::partition_copy	std::reduce
std::remove	std::remove_copy	std::remove_copy_if
std::remove_if	std::replace	std::replace_copy
std::replace_copy_if	std::replace_if	std::reverse
std::reverse_copy	std::rotate	std::rotate_copy
std::search	std::search_n	std::set_difference
std::set_intersection	std::set_symmetric_difference	std::set_union
std::sort	std::stable_partition	std::stable_sort
std::swap_ranges	std::transform	std::transform_exclusive_s
std::transform_inclusive_scan	std::transform_reduce	std::uninitialized_copy
std::uninitialized_copy_n	std::uninitialized_fill	std::uninitialized_fill_n
std::unique	std::unique_copy	

`constexpr` Container and Algorithms

C++20 supports the constexpr containers std::vector and std::string. constexpr means that you can apply the member functions of both containers at compile time. Additionally, the more than 100 algorithms of the Standard Template Library are declared as `constexpr`.

for_each

`std::for_each` applies a unary callable to each element of its range. The input iterators provide the range.

```
UnFunc std::for_each(InpIt first, InpIt second, UnFunc func)
void std::for_each(ExePol pol, FwdIt first, FwdIt second, UnFunc func)
```

`std::for_each`, when used without an explicit execution policy, is a special algorithm because it returns its callable argument. If you invoke `std::for_each` with a function object, you can store the result of the function call directly in the function object.

```
InpIt std::for_each_n(InpIt first, Size n, UnFunc func)
FwdIt std::for_each_n(ExePol pol, FwdIt first, Size n, UnFunc func)
```

`std::for_each_n` is new with C++17 and applies a unary callable to its range's first n elements. An input iterator and a size provide the range.

`std::for_each`

```
// forEach.cpp
...
#include <algorithm>
...
template <typename T>
class ContInfo{
public:
  void operator()(T t){
    num++;
    sum+= t;
  }
  int getSum() const{ return sum; }
  int getSize() const{ return num; }
  double getMean() const{
    return static_cast<double>(sum)/static_cast<double>(num);
  }
private:
  T sum{0};
  int num{0};
};

std::vector<double> myVec{1.1, 2.2, 3.3, 4.4, 5.5, 6.6, 7.7, 8.8, 9.9};
auto vecInfo= std::for_each(myVec.begin(), myVec.end(), ContInfo<double>());

std::cout << vecInfo.getSum() << '\n';    // 49
std::cout << vecInfo.getSize() << '\n';   // 9
std::cout << vecInfo.getMean() << '\n';   // 5.5

std::array<int, 100> myArr{1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
auto arrInfo= std::for_each(myArr.begin(), myArr.end(), ContInfo<int>());

std::cout << arrInfo.getSum() << '\n';    // 55
std::cout << arrInfo.getSize() << '\n';   // 100
std::cout << arrInfo.getMean() << '\n';   // 0.55
```

Non-Modifying Algorithms

Non-modifying algorithms are algorithms for searching and counting elements. However, you can also check properties on ranges, compare ranges, or search for ranges within ranges.

Search Elements

You can search for elements in three different ways.

Returns an element in a range:

```
InpIt find(InpIt first, InpI last, const T& val)
InpIt find(ExePol pol, FwdIt first, FwdIt last, const T& val)

InpIt find_if(InpIt first, InpIt last, UnPred pred)
InpIt find_if(ExePol pol, FwdIt first, FwdIt last, UnPred pred)

InpIt find_if_not(InpIt first, InpIt last, UnPred pre)
InpIt find_if_not(ExePol pol, FwdIt first, FwdIt last, UnPred pre)
```

Returns the first element of a range in a range:

```
FwdIt1 find_first_of(InpIt1 first1, InpIt1 last1,
                     FwdIt2 first2, FwdIt2 last2)
FwdIt1 find_first_of(ExePol pol, FwdIt1 first1, FwdIt1 last1,
                    FwdIt2 first2, FwdIt2 last2)

FwdIt1 find_first_of(InpIt1 first1, InpIt1 last1,
                     FwdIt2 first2, FwdIt2 last2, BiPre pre)
FwdIt1 find_first_of(ExePol pol, FwdIt1 first1, FwdIt1 last1,
                     FwdIt2 first2, FwdIt2 last2, BiPre pre)
```

Returns identical, adjacent elements in a range:

```
FwdIt adjacent_find(FwdIt first, FwdIt last)
FwdIt adjacent_find(ExePol pol, FwdIt first, FwdIt last)
FwdIt adjacent_find(FwdIt first, FwdI last, BiPre pre)
FwdIt adjacent_find(ExePol pol, FwdIt first, FwdI last, BiPre pre)
```

The algorithms require input or forward iterators as arguments and return an iterator on the element when successfully found. If the search is not successful, they return an end iterator.

`std::find`, `std::find_if`, `std::find_if_not`, `std::find_of`, and `std::adjacent_fint`

```
// find.cpp
...
#include <algorithm>
...
using namespace std;

bool isVowel(char c){
  string myVowels{"aeiouäöü"};
  set<char> vowels(myVowels.begin(), myVowels.end());
  return (vowels.find(c) != vowels.end());
}

list<char> myCha{'a', 'b', 'c', 'd', 'e', 'f', 'g', 'h', 'i', 'j'};
int cha[]= {'A', 'B', 'C'};

cout << *find(myCha.begin(), myCha.end(), 'g');             // g
cout << *find_if(myCha.begin(), myCha.end(), isVowel);      // a
cout << *find_if_not(myCha.begin(), myCha.end(), isVowel);  // b

auto iter= find_first_of(myCha.begin(), myCha.end(), cha, cha + 3);
if (iter == myCha.end()) cout << "None of A, B or C.";      // None of A, B or C.
auto iter2= find_first_of(myCha.begin(), myCha.end(), cha, cha+3,
            [](char a, char b){ return toupper(a) == toupper(b); });

if (iter2 != myCha.end()) cout << *iter2;                   // a
auto iter3= adjacent_find(myCha.begin(), myCha.end());
if (iter3 == myCha.end()) cout << "No same adjacent chars.";
                                         // No same adjacent chars.

auto iter4= adjacent_find(myCha.begin(), myCha.end(),
            [](char a, char b){ return isVowel(a) == isVowel(b); });
if (iter4 != myCha.end()) cout << *iter4;                   // b
```

Count Elements

You can count elements with the STL with and without a predicate.

Returns the number of elements:

```
Num count(InpIt first, InpIt last, const T& val)
Num count(ExePol pol, FwdIt first, FwdIt last, const T& val)

Num count_if(InpIt first, InpIt last, UnPred pre)
Num count_if(ExePol pol, FwdIt first, FwdIt last, UnPred pre)
```

Count algorithms take input iterators as arguments and return the number of elements matching `val` or the predicate.

`std::count`, and `std::count_if`

```
// count.cpp
...
#include <algorithm>
...
std::string str{"abcdabAAAaefaBqeaBCQEaadsfdewAAQAaafbd"};
std::cout << std::count(str.begin(), str.end(), 'a');              // 9
std::cout << std::count_if(str.begin(), str.end(),
                           [](char a){ return std::isupper(a); }); // 12
```

Check Conditions on Ranges

The three functions `std::all_of`, `std::any_of`, and `std::none_of` answer the question if all, at least one, or no element of a range satisfies the condition. The functions need as arguments input iterators and a unary predicate and return a boolean.

Checks if all elements of the range satisfy the condition:

```
bool all_of(InpIt first, InpIt last, UnPre pre)
bool all_of(ExePol pol, FwdIt first, FwdIt last, UnPre pre)
```

Checks if at least one element of the range satisfies the condition:

```
bool any_of(InpIt first, InpIt last, UnPre pre)
bool any_of(ExePol pol, FwdIt first, FwdIt last, UnPre pre)
```

Checks if no element of the range satisfies the condition:

```
bool none_of(InpIt first, InpIt last, UnPre pre)
bool none_of(ExePol pol, FwdIt first, FwdIt last, UnPre pre)
```

As promised, the example:

`std::all_of`, `std::any_of`, and `std::none_of`

```
// allAnyNone.cpp
...
#include <algorithm>
...
auto even= [](int i){ return i%2; };
std::vector<int> myVec{1, 2, 3, 4, 5, 6, 7, 8, 9};
std::cout << std::any_of(myVec.begin(), myVec.end(), even);  // true
std::cout << std::all_of(myVec.begin(), myVec.end(), even);  // false
std::cout << std::none_of(myVec.begin(), myVec.end(), even); // false
```

Compare Ranges

With `std::equal`, you can compare ranges on equality. With `std::lexicographical_compare`, `std:: lexicographical_compare_three_way`, and `std::mismatch`, you discover the smaller range.

Checks if both ranges are equal:

```
bool equal(InpIt first1, InpIt last1, InpIt first2)
bool equal(ExePol pol, FwdIt first1, FwdIt last1, FwdIt first2)

bool equal(InpIt first1, InpIt last1, InpIt first2, BiPre pred)
bool equal(ExePol pol, FwdIt first1, FwdIt last1, FwdIt first2, BiPre pred)

bool equal(InpIt first1, InpIt last1,
           InpIt first2, InpIt last2)
bool equal(ExePol pol, FwdIt first1, FwdIt last1,
           FwdIt first2, FwdIt last2)

bool equal(InpIt first1, InpIt last1,
           InpIt first2, InpIt last2, BiPre pred)
bool equal(ExePol pol, FwdIt first1, FwdIt last1,
           FwdIt first2, FwdIt last2, BiPre pred)
```

Checks if the first range is smaller than the second:

```
bool lexicographical_compare(InpIt first1, InpIt last1,
                             InpIt first2, InpIt last2)
bool lexicographical_compare(ExePol pol, FwdIt first1, FwdIt last1,
                             FwdIt first2, FwdIt last2)

bool lexicographical_compare(InpIt first1, InpIt last1,
                             InpIt first2, InpIt last2, BiPre pred)
bool lexicographical_compare(ExePol pol, FwdIt first1, FwdIt last1,
                             FwdIt first2, FwdIt last2, BiPre pred)
```

Checks if the first range is smaller than the second. Applies three-way comparison. It returns the strongest applicable comparison category type.

```
bool lexicographical_compare_three_way(InpIt first1, InpIt last1,
                                       InpIt first2, InpIt last2)
bool lexicographical_compare_three_way(InpIt first1, InpIt last1,
                                       InpIt first2, InpIt last2,
                                       BiPre pre)
```

Finds the first position at which both ranges are not equal:

```
pair<InpIt, InpIt> mismatch(InpIt first1, InpIt last1,
                            InpIt first2)
pair<InpIt, InpIt> mismatch(ExePol pol, FwdIt first1, FwdIt last1,
                            FwdIt first2)

pair<InpIt, InpIt> mismatch(InpIt first1, InpIt last1,
                            InpIt first2, BiPre pred)
pair<InpIt, InpIt> mismatch(ExePol pol, FwdIt first1, FwdIt last2,
                            FwdIt first2, BiPre pred)

pair<InpIt, InpIt> mismatch(InpIt first1, InpIt last1,
                            InpIt first2, InpIt last2)
pair<InpIt, InpIt> mismatch(ExePol pol, FwdIt first1, FwdIt last1,
                            FwdIt first2, FwdIt last2)

pair<InpIt, InpIt> mismatch(InpIt first1, InpIt last1,
                            InpIt first2, InpIt last2, BiPre pred)
pair<InpIt, InpIt> mismatch(ExePol pol, FwdIt first1, FwdIt last1,
                            FwdIt first2, FwdIt last2, BiPre pred)
```

The algorithms take input iterators and eventually a binary predicate. `std::mismatch` returns as its result a pair `pa` of input iterators. `pa.first` holds an input iterator for the first element that is not equal. `pa.second` holds the corresponding input iterator for the second range. If both ranges are identical, you get two end iterators.

`std::equal`, `std::lexicographical_compare`, and `std::mismatch`

```
// equalLexicographicalMismatch.cpp
...
#include <algorithm>
...
using namespace std;

string str1{"Only For Testing Purpose." };
string str2{"only for testing purpose." };
cout << equal(str1.begin(), str1.end(), str2.begin());  // false
cout << equal(str1.begin(), str1.end(), str2.begin(),
              [](char c1, char c2){ return toupper(c1) == toupper(c2);} );
                                                         // true

str1= {"Only for testing Purpose." };
str2= {"Only for testing purpose." };
auto pair= mismatch(str1.begin(), str1.end(), str2.begin());
if (pair.first != str1.end()){
  cout << distance(str1.begin(), pair.first)
       << "at (" << *pair.first << "," << *pair.second << ")";  // 17 at (P,p)
}
auto pair2= mismatch(str1.begin(), str1.end(), str2.begin(),
                     [](char c1, char c2){ return toupper(c1) == toupper(c2); });
if (pair2.first == str1.end()){
  cout << "str1 and str2 are equal";  // str1 and str2 are equal
}
```

Search for Ranges within Ranges

`std::search` searches for a range in another range from the beginning, `std::find_end` from the end. `std::search_n` searches for n consecutive elements in the range.

All algorithms take a forward iterator, can be parametrized by a binary predicate, and return an end iterator for the first range, if the search is unsuccessful.

Searches the second range in the first one and returns the position. It starts at the beginning:

```
FwdIt1 search(FwdIt1 first1, FwdIt1 last1, FwdIt2 first2, FwdIt2 last2)
FwdIt1 search(ExePol pol, FwdIt1 first1, FwdIt1 last1,
              FwdIt2 first2, FwdIt2 last2)

FwdIt1 search(FwdIt1 first1, FwdIt1 last1,
              FwdIt2 first2, FwdIt2 last2, BiPre pre)
FwdIt1 search(ExePol pol, FwdIt1 first1, FwdIt1 last1,
              FwdIt2 first2, FwdIt2 last2, BiPre pre)
```

```
FwdIt1 search(FwdIt1 first, FwdIt last1, Search search)
```

Searches the second range in the first one and returns the positions. It starts at the end:

```
FwdIt1 find_end(FwdIt1 first1, FwdIt1 last1, FwdIt2 first2 FwdIt2 last2)
FwdIt1 find_end(ExePol pol, FwdIt1 first1, FwdIt1 last1,
                FwdIt2 first2 FwdIt2 last2)

FwdIt1 find_end(FwdIt1 first1, FwdIt1 last1, FwdIt2 first2, FwdIt2 last2,
                BiPre pre)
FwdIt1 find_end(ExePol pol, FwdIt1 first1, FwdIt1 last1,
                FwdIt2 first2, FwdIt2 last2, BiPre pre)
```

Searches `count` consecutive values in the first range:

```
FwdIt search_n(FwdIt first, FwdIt last, Size count, const T& value)
FwdIt search_n(ExePol pol, FwdIt first, FwdIt last, Size count, const T& value)

FwdIt search_n(FwdIt first, FwdIt last, Size count, const T& value, BiPre pre)
FwdIt search_n(ExePol pol, FwdIt first,
               FwdIt last, Size count, const T& value, BiPre pre)
```

The algorithm `search_n` is very special

The algorithm `FwdIt search_n(FwdIt first, FwdIt last, Size count, const T& value, BiPre pre)` is very special. The binary predicate `BiPre` uses as the first argument the values of the range and as the second argument the value `value`.

`std::find`, `std::find_end`, and `std::search_n`

```
// search.cpp
...
#include <algorithm>
...

using std::search;

std::array<int, 10> arr1{0, 1, 2, 3, 4, 5, 6, 7, 8, 9};
std::array<int, 5> arr2{3, 4, -5, 6, 7};

auto fwdIt= search(arr1.begin(), arr1.end(), arr2.begin(), arr2.end());
if (fwdIt == arr1.end()) std::cout << "arr2 not in arr1.";  // arr2 not in arr1.

auto fwdIt2= search(arr1.begin(), arr1.end(), arr2.begin(), arr2.end(),
                    [](int a, int b){ return std::abs(a) == std::abs(b); });
if (fwdIt2 != arr1.end()) std::cout << "arr2 at position "
                    << std::distance(arr1.begin(), fwdIt2) << " in arr1.";
                                                 // arr2 at position 3 in arr1.
```

Modifying Algorithms

C++ has many algorithms to modify elements and ranges.

Copy Elements and Ranges

You can copy ranges forward with `std::copy`, backward with `std::copy_backward`, and conditionally with `std::copy_if`. If you want to copy n elements, you can use `std::copy_n`.

Copies the range:

```
OutIt copy(InpIt first, InpIt last, OutIt result)
FwdIt2 copy(ExePol pol, FwdIt first, FwdIt last, FowdIt2 result)
```

Copies n elements:

```
OutIt copy_n(InpIt first, Size n, OutIt result)
FwdIt2 copy_n(ExePol pol, FwdIt first, Size n, FwdIt2 result)
```

Copies the elements dependent on the predicate `pre`.

```
OutIt copy_if(InpIt first, InpIt last, OutIt result, UnPre pre)
FwdIt2 copy_if(ExePol pol, FwdIt first, FwdIt last, FwdIt2 result, UnPre pre)
```

Copies the range backward:

```
BiIt copy_backward(BiIt first, BiIt last, BiIt result)
```

The algorithms need input iterators and copy their elements to `result`. They return an end iterator to the destination range.

Copy elements and ranges

```
// copy.cpp
...
#include <algorithm>
...

std::vector<int> myVec{0, 1, 2, 3, 4, 5, 6, 7, 9};
std::vector<int> myVec2(10);

std::copy_if(myVec.begin(), myVec.end(), myVec2.begin()+3,
             [](int a){ return a%2; });

for (auto v: myVec2) std::cout << v << " ";     // 0 0 0 1 3 5 7 9 00

std::string str{"abcdefghijklmnop"};
std::string str2{"---------------------"};

std::cout << str2;                             // ---------------------
std::copy_backward(str.begin(), str.end(), str2.end());
std::cout << str2;                             // -----abcdefghijklmnop
std::cout << str;                              // abcdefghijklmnop

std::copy_backward(str.begin(), str.begin() + 5, str.end());
std::cout << str;                              // abcdefghijkabcde
```

Replace Elements and Ranges

You have with `std::replace`, `std::replace_if`, `std::replace_copy`, and `std::replace_copy_if` four variations to replace elements in a range. The algorithms differ in two aspects. First, does the algorithm need a predicate? Second, does the algorithm copy the elements in the destination range?

Replaces the old elements in the range with `newValue`, if the old element has the value `old`.

```
void replace(FwdIt first, FwdIt last, const T& old, const T& newValue)
void replace(ExePol pol, FwdIt first, FwdIt last, const T& old,
             const T& newValue)
```

Replaces the old elements of the range with `newValue`, if the old element fulfills the predicate `pred`:

```
void replace_if(FwdIt first, FwdIt last, UnPred pred, const T& newValue)
void replace_if(ExePol pol, FwdIt first, FwdIt last, UnPred pred,
                const T& newValue)
```

Replaces the old elements in the range with `newValue` if the old element has the value `old`. Copies the result to `result`:

```
OutIt replace_copy(InpIt first, InpIt last, OutIt result, const T& old,
                   const T& newValue)
FwdIt2 replace_copy(ExePol pol, FwdIt first, FwdIt last,
                    FwdIt2 result, const T& old, const T& newValue)
```

Replaces the old elements of the range with `newValue`, if the old element fulfills the predicate `pred`. Copies the result to `result`:

```
OutIt replace_copy_if(InpIt first, InpIt last, OutIt result, UnPre pred,
                      const T& newValue)
FwdIt2 replace_copy_if(ExePol pol, FwdIt first, FwdIt last,
                       FwdIt2 result, UnPre pred, const T& newValue)
```

The algorithms in action.

Replace elements and ranges

```
// replace.cpp
...
#include <algorithm>
...

std::string str{"Only for testing purpose." };
std::replace(str.begin(), str.end(), ' ', '1');
std::cout << str; // Only1for1testing1purpose.

std::replace_if(str.begin(), str.end(), [](char c){ return c == '1'; }, '2');
std::cout << str; // Only2for2testing2purpose.

std::string str2;
std::replace_copy(str.begin(), str.end(), std::back_inserter(str2), '2', '3');
std::cout << str2; // Only3for3testing3purpose.

std::string str3;
std::replace_copy_if(str2.begin(), str2.end(),
std::back_inserter(str3), [](char c){ return c == '3'; }, '4');
std::cout << str3; // Only4for4testing4purpose.
```

Remove Elements and Ranges

The four variations `std::remove, std::remove_if, std::remove_copy` and `std::remove_copy_if` support two kinds of operations. On the one hand, remove elements with and without a predicate from a range. On the other hand, copy the result of your modification to a new range.

Removes the elements from the range, having the value `val`:

```
FwdIt remove(FwdIt first, FwdIt last, const T& val)
FwdIt remove(ExePol pol, FwdIt first, FwdIt last, const T& val)
```

Removes the elements from the range, fulfilling the predicate `pred`:

```
FwdIt remove_if(FwdIt first, FwdIt last, UnPred pred)
FwdIt remove_if(ExePol pol, FwdIt first, FwdIt last, UnPred pred)
```

Removes the elements from the range, having the value `val`. Copies the result to `result`:

```
OutIt remove_copy(InpIt first, InpIt last, OutIt result, const T& val)
FwdIt2 remove_copy(ExePol pol, FwdIt first, FwdIt last,
                   FwdIt2 result, const T& val)
```

Removes the elements from the range which fulfill the predicate `pred`. It copies the result to `result`.

```
OutIt remove_copy_if(InpIt first, InpIt last, OutIt result, UnPre pred)
FwdIt2 remove_copy_if(ExePol pol, FwdIt first, FwdIt last,
                      FwdIt2 result, UnPre pred)
```

The algorithms need input iterators for the source range and an output iterator for the destination range. They return, as a result, an end iterator for the destination range.

Apply the erase-remove idiom

The remove variations don't remove an element from the range. They return the new *logical* end of the range. You have to adjust the size of the container with the erase-remove idiom.

Remove elements and ranges

```
// remove.cpp
...
#include <algorithm>
...
std::vector<int> myVec{0, 1, 2, 3, 4, 5, 6, 7, 8, 9};

auto newIt= std::remove_if(myVec.begin(), myVec.end(),
                          [](int a){ return a%2; });
for (auto v: myVec) std::cout << v << " ";    // 0 2 4 6 8 5 6 7 8 9

myVec.erase(newIt, myVec.end());
for (auto v: myVec) std::cout << v << " ";    // 0 2 4 6 8

std::string str{"Only for Testing Purpose." };
str.erase( std::remove_if(str.begin(), str.end(),
          [](char c){ return std::isupper(c); }, str.end() ) );
std::cout << str << '\n';                    // nly for esting urpose.
```

Fill and Create Ranges

You can fill a range with `std::fill` and `std::fill_n`; you can generate new elements with `std::generate` and `std::generate_n`.

Fills a range with elements:

```
void fill(FwdIt first, FwdIt last, const T& val)
void fill(ExePol pol, FwdIt first, FwdIt last, const T& val)
```

Fills a range with n new elements:

```
OutIt fill_n(OutIt first, Size n, const T& val)
FwdIt fill_n(ExePol pol, FwdIt first, Size n, const T& val)
```

Generates a range with a generator `gen`:

```
void generate(FwdIt first, FwdIt last, Generator gen)
void generate(ExePol pol, FwdIt first, FwdIt last, Generator gen)
```

Generates n elements of a range with the generator `gen`:

```
OutIt generate_n(OutIt first, Size n, Generator gen)
FwdIt generate_n(ExePol pol, FwdIt first, Size n, Generator gen)
```

The algorithms expect the value `val` or generator `gen` as an argument. `gen` has to be a function taking no argument and returning the new value. The return value of the algorithms `std::fill_n` and `std::generate_n` is an output iterator, pointing to the last created element.

Fill and create ranges

```
// fillAndCreate.cpp
...
#include <algorithm>
...

int getNext(){
  static int next{0};
  return ++next;
}

std::vector<int> vec(10);
std::fill(vec.begin(), vec.end(), 2011);
```

```
for (auto v: vec) std::cout << v << " ";
                      // 2011 2011 2011 2011 2011 2011 2011 2011 2011 2011

std::generate_n(vec.begin(), 5, getNext);
for (auto v: vec) std::cout << v << " ";
                      // 1 2 3 4 5 2011 2011 2011 2011 2011
```

Move Ranges

`std::move` moves the ranges forward; `std::move_backward` moves the ranges backward.

Moves the range forward:

```
OutIt move(InpIt first, InpIt last, OutIt result)
FwdIt2 move(ExePol pol, FwdIt first, FwdIt last, Fwd2It result)
```

Moves the range backward:

```
BiIt move_backward(BiIt first, BiIt last, BiIt result)
```

Both algorithms need a destination iterator `result`, to which the range is moved. In the case of the `std::move` algorithm, this is an output iterator. In the case of the `std::move_backward` algorithm, this is a bidirectional iterator. The algorithms return an output or a bidirectional iterator, pointing to the initial position in the destination range.

The source range may be changed

`std::move` and `std::move_backward` apply move semantics. Therefore the source range is valid but has not necessarily the same elements afterward.

Move ranges

```
// move.cpp
...
#include <algorithm>
...

std::vector<int> myVec{0, 1, 2, 3, 4, 5, 6, 7, 9};
std::vector<int> myVec2(myVec.size());
std::move(myVec.begin(), myVec.end(), myVec2.begin());
for (auto v: myVec2) std::cout << v << " ";    // 0 1 2 3 4 5 6 7 9 0

std::string str{"abcdefghijklmnop"};
std::string str2{"---------------------"};
std::move_backward(str.begin(), str.end(), str2.end());
std::cout << str2;                             // -----abcdefghijklmnop
```

Swap Ranges

`std::swap` and `std::swap_ranges` can swap objects and ranges.

Swaps objects:

```
void swap(T& a, T& b)
```

Swaps ranges:

```
FwdIt swap_ranges(FwdIt1 first1, FwdIt1 last1, FwdIt first2)
FwdIt swap_ranges(ExePol pol, FwdIt1 first1, FwdIt1 last1, FwdIt first2)
```

The returned iterator points to the last swapped element in the destination range.

The ranges must not overlap

Swap algorithms

```
// swap.cpp
...
#include <algorithm>
...

std::vector<int> myVec{0, 1, 2, 3, 4, 5, 6, 7, 9};
std::vector<int> myVec2(9);
std::swap(myVec, myVec2);
for (auto v: myVec) std::cout << v << " ";     // 0 0 0 0 0 0 0 0 0
for (auto v: myVec2) std::cout << v << " ";    // 0 1 2 3 4 5 6 7 9

std::string str{"abcdefghijklmnop"};
std::string str2{"---------------------"};
std::swap_ranges(str.begin(), str.begin()+5, str2.begin()+5);
std::cout << str << '\n';                 // -----fghijklmnop
std::cout << str2 << '\n';                // -----abcde-----------
```

Transform Ranges

The `std::transform` algorithm applies a unary or binary callable to a range and copies the modified elements to the destination range.

Applies the unary callable `fun` to the elements of the input range and copies the result to `result`:

```
OutIt transform(InpIt first1, InpIt last1, OutIt result, UnFun fun)
FwdIt2 transform(ExePol pol, FwdIt first1, FwdIt last1, FwdIt2 result, UnFun fun)
```

Applies the binary callable `fun` to both input ranges and copies the result to `result`:

```
OutIt transform(InpIt1 first1, InpIt1 last1, InpIt2 first2, OutIt result,
                BiFun fun)
FwdIt3 transform(ExePol pol, FwdIt1 first1, FwdIt1 last1,
                 FwdIt2 first2, FwdIt3 result, BiFun fun)
```

The difference between the two versions is that the first version applies the callable to each element of the range; the second version applies the callable to pairs of both ranges in parallel. The returned iterator points to one position after the last transformed element.

Transform algorithms

```
// transform.cpp
...
#include <algorithm>
...

std::string str{"abcdefghijklmnopqrstuvwxyz"};
std::transform(str.begin(), str.end(), str.begin(),
               [](char c){ return std::toupper(c); });
std::cout << str;         // ABCDEFGHIJKLMNOPQRSTUVWXYZ

std::vector<std::string> vecStr{"Only", "for", "testing", "purpose", "." };
std::vector<std::string> vecStr2(5, "-");
std::vector<std::string> vecRes;
std::transform(vecStr.begin(), vecStr.end(),
               vecStr2.begin(), std::back_inserter(vecRes),
               [](std::string a, std::string b){ return std::string(b)+a+b; });
for (auto str: vecRes) std::cout << str << " ";
                           // -Only- -for- -testing- -purpose- -.-
```

Reverse Ranges

`std::reverse` and `std::reverse_copy` invert the order of the elements in their range.

Reverses the order of the elements in the range:

```
void reverse(BiIt first, BiIt last)
void reverse(ExePol pol, BiIt first, BiIt last)
```

Reverses the order of the elements in the range and copies the result to `result`:

```
OutIt reverse_copy(BiIt first, BiIt last, OutIt result)
FwdIt reverse_copy(ExePol pol, BiIt first, BiIt last, FwdIt result)
```

Both algorithms require bidirectional iterators. The returned iterator points to the output range `result` position before the elements are copied.

Reverse range algorithms

```
// algorithmen.cpp
...
#include <algorithm>
...

std::string str{"123456789"};
std::reverse(str.begin(), str.begin()+5);
std::cout << str;            // 543216789
```

Rotate Ranges

`std::rotate` and `std::rotate_copy` rotate their elements.

Rotates the elements in such a way that `middle` becomes the new first element:

```
FwdIt rotate(FwdIt first, FwdIt middle, FwdIt last)
FwdIt rotate(ExePol pol, FwdIt first, FwdIt middle, FwdIt last)
```

Rotates the elements so that `middle` becomes the new first element. Copies the result to `result`:

```
OutIt rotate_copy(FwdIt first, FwdIt middle, FwdIt last, OutIt result)
FwdIt2 rotate_copy(ExePol pol, FwdIt first, FwdIt middle, FwdIt last,
                   FwdIt2 result)
```

Both algorithms need forward iterators. The returned iterator is an end iterator for the copied range.

Rotate algorithms

```
// rotate.cpp
...
#include <algorithm>
...

std::string str{"12345"};
for (auto i= 0; i < str.size(); ++i){
  std::string tmp{str};
  std::rotate(tmp.begin(), tmp.begin()+i , tmp.end());
  std::cout << tmp << " ";
}                           // 12345 23451 34512 45123 51234
```

Shift Ranges

The C++20 function `std::shift_left` and `std::shift_right` shift elements in a range. Both algorithm return a forward iterator.

Shift the elements of a range towards the beginning of the range by `n`. Returns the end of the resulting range.

```
FwdIt shift_left(FwdIt first, FwdIt last, Num n)
FwdIt shift_left(ExePol pol, FwdIt first, FwdIt last, Num n)
```

Shift the elements of a range towards the end of the range by `n`. Returns the beginning of the resulting range.

```
FwdIt shift_right(FwdIt first, FwdIt last, Num n)
FwdIt shift_right(ExePol pol, FwdIt first, FwdIt last, Num n)
```

The operation on `std::shift_left` and `std::shift_right` has no effect if `n == 0 || n >= last - first`. The elements of the range are moved.

Shift elements of a range

```
// shiftRange.cpp
...
#include <algorithm>
...

std::vector<int> myVec{1, 2, 3, 4, 5, 6, 7};
for (auto v: myVec) std::cout << v << " ";        // 1 2 3 4 5 6 7

auto newEnd = std::shift_left(myVec.begin(), myVec.end(), 2);
myVec.erase(newEnd, myVec.end());
for (auto v: myVec) std::cout << v << " ";        // 3 4 5 6 7

auto newBegin = std::shift_right(myVec.begin(), myVec.end(), 2);
myVec.erase(myVec.begin(), newBegin);
for (auto v: myVec) std::cout << v << " ";        // 3 4 5
```

Randomly Shuffle Ranges

You can randomly shuffle ranges with `std::random_shuffle` and `std::shuffle`.

Randomly shuffles the elements in a range:

```
void random_shuffle(RanIt first, RanIt last)
```

Randomly shuffles the elements in the range by using the random number generator `gen`:

```
void random_shuffle(RanIt first, RanIt last, RanNumGen&& gen)
```

Randomly shuffles the elements in a range, using the uniform random number generator `gen`:

```
void shuffle(RanIt first, RanIt last, URNG&& gen)
```

The algorithms need random access iterators. `RanNumGen&& gen` has to be a callable, taking an argument and returning a value within its arguments. `URNG&& gen` has to be a *uniform random number generator*.

Prefer `std::shuffle`

Use `std::shuffle` instead of `std::random_shuffle`. `std::random_shuffle` has been *deprecated* since C++14 and removed in C++17 because it uses the C function `rand` internally.

Randomly shuffle algorithms

```
// shuffle.cpp
...
#include <algorithm>
...

using std::chrono::system_clock;
using std::default_random_engine;
std::vector<int> vec1{0, 1, 2, 3, 4, 5, 6, 7, 8, 9};
std::vector<int> vec2(vec1);

std::random_shuffle(vec1.begin(), vec1.end());
for (auto v: vec1) std::cout << v << " ";      // 4 3 7 8 0 5 2 1 6 9
```

```
unsigned seed= system_clock::now().time_since_epoch().count();
std::shuffle(vec2.begin(), vec2.end(), default_random_engine(seed));
for (auto v: vec2) std::cout << v << " ";      // 4 0 2 3 9 6 5 1 8 7
```

`seed` initializes the random number generator.

Remove Duplicates

With the algorithms `std::unique` and `std::unique_copy`, you have more opportunities to remove adjacent duplicates. You can do this with and without a binary predicate.

Removes adjacent duplicates:

```
FwdIt unique(FwdIt first, FwdIt last)
FwdIt unique(ExePol pol, FwdIt first, FwdIt last)
```

Removes adjacent duplicates, satisfying the binary predicate:

```
FwdIt unique(FwdIt first, FwdIt last, BiPred pre)
FwdIt unique(ExePol pol, FwdIt first, FwdIt last, BiPred pre)
```

Removes adjacent duplicates and copies the result to `result`:

```
OutIt unique_copy(InpIt first, InpIt last, OutIt result)
FwdIt2 unique_copy(ExePol pol, FwdIt first, FwdIt last, FwdIt2 result)
```

Removes adjacent duplicates, satisfying the binary predicate, and copies the result to `result`:

```
OutIt unique_copy(InpIt first, InpIt last, OutIt result, BiPred pre)
FwdIt2 unique_copy(ExePol pol, FwdIt first, FwdIt last,
                   FwdIt2 result, BiPred pre)
```

The `unique` algorithms return the new logical end iterator

The `unique` algorithms return the logical end iterator of the range. The elements must be be removed with the erase-remove idiom.

Remove duplicates algorithms

```
// removeDuplicates.cpp
...
#include <algorithm>
...

std::vector<int> myVec{0, 0, 1, 1, 2, 2, 3, 4, 4, 5,
                       3, 6, 7, 8, 1, 3, 3, 8, 8, 9};

myVec.erase(std::unique(myVec.begin(), myVec.end()), myVec.end());
for (auto v: myVec) std::cout << v << "";      // 0 1 2 3 4 5 3 6 7 8 1 3 8 9

std::vector<int> myVec2{1, 4, 3, 3, 3, 5, 7, 9, 2, 4, 1, 6, 8,
                        0, 3, 5, 7, 8, 7, 3, 9, 2, 4, 2, 5, 7, 3};
std::vector<int> resVec;
resVec.reserve(myVec2.size());
std::unique_copy(myVec2.begin(), myVec2.end(), std::back_inserter(resVec),
                 [](int a, int b){ return (a%2) == (b%2); } );
for(auto v: myVec2) std::cout << v << " ";
                      // 1 4 3 3 3 5 7 9 2 4 1 6 8 0 3 5 7 8 7 3 9 2 4 2 5 7 3
for(auto v: resVec) std::cout << v << " ";        // 1 4 3 2 1 6 3 8 7 2 5
```

Partition

What is a partition?

A partition of a set is a decomposition of a set in subsets so that each element of the set is precisely in one subset. A binary predicate defines the subset so that the members of the first subset fulfill the predicate. The remaining elements are in the second subset.

C++ offers a few functions for dealing with partitions. They all need a unary predicate `pre`. `std::partition` and `std::stable_partition` partition a range and return the partition point. With `std::partition_point`, you can get the partition point of a partition. Afterward, you can check the partition with `std::is_partitioned` or copy it with `std::partition_copy`.

Checks if the range is partitioned:

```
bool is_partitioned(InpIt first, InpIt last, UnPre pre)
bool is_partitioned(ExePol pol, FwdIt first, FwdIt last, UnPre pre)
```

Partitions the range:

```
FwdIt partition(FwdIt first, FwdIt last, UnPre pre)
FwdIt partition(ExePol pol, FwdIt first, FwdIt last, UnPre pre)
```

Partitions the range (stable):

```
BiIt stable_partition(FwdIt first, FwdIt last, UnPre pre)
BiIt stable_partition(ExePol pol, FwdIt first, FwdIt last, UnPre pre)
```

Copies a partition in two ranges:

```
pair<OutIt1, OutIt2> partition_copy(InIt first, InIt last,
                     OutIt1 result_true, OutIt2 result_false, UnPre pre)
pair<FwdIt1, FwdIt2> partition_copy(ExePol pol, FwdIt1 first, FwdIt1 last,
                     FwdIt2 result_true, FwdIt3 result_false, UnPre pre)
```

Returns the partition point:

```
FwdIt partition_point(FwdIt first, FwdIt last, UnPre pre)
```

A `std::stable_partition` guarantees, contrary to a `std::partition` that the elements preserve their relative order. The returned iterator `FwdIt` and `BiIt` point to the second subset of the partition's initial position. The pair `std::pair<OutIt, OutIt>` of the algorithm `std::partition_copy` contains the end iterator of the subsets `result_true` and `result_false`. The behavior of `std::partition_point` is undefined if the range is not partitioned.

Partition algorithms

```
// partition.cpp
...
#include <algorithm>
...
using namespace std;

bool isOdd(int i){ return (i%2) == 1; }
vector<int> vec{1, 4, 3, 4, 5, 6, 7, 3, 4, 5, 6, 0, 4,
                8, 4, 6, 6, 5, 8, 8, 3, 9, 3, 7, 6, 4, 8};

auto parPoint= partition(vec.begin(), vec.end(), isOdd);
for (auto v: vec) cout << v << " ";
                    // 1 7 3 3 5 9 7 3 3 5 5 0 4 8 4 6 6 6 8 8 4 6 4 4 6 4 8

for (auto v= vec.begin(); v != parPoint; ++v) cout << *v << " ";
                    // 1 7 3 3 5 9 7 3 3 5 5
for (auto v= parPoint; v != vec.end(); ++v) cout << *v << " ";
                    // 4 8 4 6 6 6 8 8 4 6 4 4 6 4 8

cout << is_partitioned(vec.begin(), vec.end(), isOdd);     // true
list<int> le;
```

```
list<int> ri;
partition_copy(vec.begin(), vec.end(), back_inserter(le), back_inserter(ri),
               [](int i) { return i < 5; });
for (auto v: le) cout << v << "";    // 1 3 3 3 3 0 4 4 4 4 4 4
for (auto v: ri) cout << v << "";    // 7 5 9 7 5 5 8 6 6 6 8 8 6 6 8
```

Sort

You can sort a range with `std::sort` or `std::stable_sort` or sort until a position with `std::partial_sort`. In addition, `std::partial_sort_copy` copies the partially sorted range. With `std::nth_element`, you can assign an element the *sorted* position in the range. You can check with `std::is_sorted` if a range is sorted. If you want to know until which position a range is sorted, use `std::is_sorted_until`.

Per default, the predefined function object `std::less` is used as a sorting criterion. However, you can use your sorting criterion. This has to obey the strict weak ordering.

Sorts the elements in the range:

```
void sort(RaIt first, RaIt last)
void sort(ExePol pol, RaIt first, RaIt last)

void sort(RaIt first, RaIt last, BiPre pre)
void sort(ExePol pol, RaIt first, RaIt last, BiPre pre)
```

Sorts the elements in the range (stable):

```
void stable_sort(RaIt first, RaIt last)
void stable_sort(ExePol pol, RaIt first, RaIt last)

void stable_sort(RaIt first, RaIt last, BiPre pre)
void stable_sort(ExePol pol, RaIt first, RaIt last, BiPre pre)
```

Sorts partially the elements in the range until `middle`:

```
void partial_sort(RaIt first, RaIt middle, RaIt last)
void partial_sort(ExePol pol, RaIt first, RaIt middle, RaIt last)

void partial_sort(RaIt first, RaIt middle, RaIt last, BiPre pre)
void partial_sort(ExePol pol, RaIt first, RaIt middle, RaIt last, BiPre pre)
```

Sorts partially the elements in the range and copies them in the destination ranges `result_first` and `result_last`:

```
RaIt partial_sort_copy(InIt first, InIt last,
                       RaIt result_first, RaIt result_last)
RaIt partial_sort_copy(ExePol pol, FwdIt first, FwdIt last,
                       RaIt result_first, RaIt result_last)

RaIt partial_sort_copy(InIt first, InIt last,
                       RaIt result_first, RaIt result_last, BiPre pre)
RaIt partial_sort_copy(ExePol pol, FwdIt first, FwdIt last,
                       RaIt result_first, RaIt result_last, BiPre pre)
```

Checks if a range is sorted:

```
bool is_sorted(FwdIt first, FwdIt last)
bool is_sorted(ExePol pol, FwdIt first, FwdIt last)

bool is_sorted(FwdIt first, FwdIt last, BiPre pre)
bool is_sorted(ExePol pol, FwdIt first, FwdIt last, BiPre pre)
```

Returns the position to the first element that doesn't satisfy the sorting criterion:

```
FwdIt is_sorted_until(FwdIt first, FwdIt last)
FwdIt is_sorted_until(ExePol pol, FwdIt first, FwdIt last)

FwdIt is_sorted_until(FwdIt first, FwdIt last, BiPre pre)
FwdIt is_sorted_until(ExePol pol, FwdIt first, FwdIt last, BiPre pre)
```

Reorders the range so that the n-th element has the right (sorted) position:

```
void nth_element(RaIt first, RaIt nth, RaIt last)
void nth_element(ExePol pol, RaIt first, RaIt nth, RaIt last)

void nth_element(RaIt first, RaIt nth, RaIt last, BiPre pre)
void nth_element(ExePol pol, RaIt first, RaIt nth, RaIt last, BiPre pre)
```

Here is a code snippet.

Sort algorithms

```
// sort.cpp
...
#include <algorithm>
...

std::string str{"RUdAjdDkaACsdfjwldXmnEiVSEZTiepfgOIkue"};
std::cout << std::is_sorted(str.begin(), str.end());        // false

std::partial_sort(str.begin(), str.begin()+30, str.end());
std::cout << str;           // AACDEEIORSTUVXZaddddeeffgiijjkwspnmluk

auto sortUntil= std::is_sorted_until(str.begin(), str.end());
std::cout << *sortUntil;                                   // s
for (auto charIt= str.begin(); charIt != sortUntil; ++charIt)
    std::cout << *charIt;           // AACDEEIORSTUVXZaddddeeffgiijjkw

std::vector<int> vec{1, 0, 4, 3, 5};
auto vecIt= vec.begin();
while(vecIt != vec.end()){
  std::nth_element(vec.begin(), vecIt++, vec.end());
  std::cout << std::distance(vec.begin(), vecIt) << "-th ";
  for (auto v: vec) std::cout << v << "/";
}
// 1-th 01435/2-th 01435/3-th 10345/4-th 30145/5-th 10345
```

Binary Search

The binary search algorithms use the fact that the ranges are already sorted. To search for an element, use `std::binary_search`. With `std::lower_bound`, you get an iterator for the first element, being no smaller than the given value. With `std::upper_bound`, you get an iterator back for the first element, which is bigger than the given value. `std:::equal_range` combines both algorithms.

If the container has n elements, you need on average `log2(n)` comparisons for the search. The binary search requires you to use the same comparison criterion you used for sorting the container. The default comparison criterion is `std::less`, but you can adjust it. Your sorting criterion has to obey the strict weak ordering. If not, the program is undefined.

The member functions of an unordered associative container are, in general, faster.

Searches the element `val` in the range:

```
bool binary_search(FwdIt first, FwdIt last, const T& val)
bool binary_search(FwdIt first, FwdIt last, const T& val, BiPre pre)
```

Returns the position of the first element of the range, being not smaller than `val`:

```
FwdIt lower_bound(FwdIt first, FwdIt last, const T& val)
FwdIt lower_bound(FwdIt first, FwdIt last, const T& val, BiPre pre)
```

Returns the position of the first element of the range, being bigger than `val`:

```
FwdIt upper_bound(FwdIt first, FwdIt last, const T& val)
FwdIt upper_bound(FwdIt first, FwdIt last, const T& val, BiPre pre)
```

Returns the pair `std::lower_bound` and `std::upper_bound` for the element `val`:

```
pair<FwdIt, FwdIt> equal_range(FwdIt first, FwdIt last, const T& val)
pair<FwdIt, FwdIt> equal_range(FwdIt first, FwdIt last, const T& val, BiPre pre)
```

Finally, here is the code snippet.

Binary search algorithms

```
// binarySearch.cpp
...
#include <algorithm>
...
using namespace std;

bool isLessAbs(int a, int b){
  return abs(a) < abs(b);
}
vector<int> vec{-3, 0, -3, 2, -3, 5, -3, 7, -0, 6, -3, 5,
                -6, 8, 9, 0, 8, 7, -7, 8, 9, -6, 3, -3, 2};

sort(vec.begin(), vec.end(), isLessAbs);
for (auto v: vec) cout << v << " ";
     // 0 0 0 2 2 -3 -3 -3 -3 -3 3 -3 5 5 -6 -6 6 7 -7 7 8 8 8 9 9
cout << binary_search(vec.begin(), vec.end(), -5, isLessAbs); // true
cout << binary_search(vec.begin(), vec.end(), 5, isLessAbs);  // true

auto pair= equal_range(vec.begin(), vec.end(), 3, isLessAbs);
cout << distance(vec.begin(), pair.first);                    // 5
cout << distance(vec.begin(), pair.second)-1;                 // 11

for (auto threeIt= pair.first;threeIt != pair.second; ++threeIt)
     cout << *threeIt << " ";                  // -3 -3 -3 -3 -3 3 -3
```

Merge Operations

Merge operations empower you to merge sorted ranges in a new sorted range. The algorithm requires that the ranges and the algorithm use the same sorting criterion. If not, the program has undefined behavior. Per default, the predefined sorting criterion `std::less` is used. If you use your sorting criterion, it has to obey the strict weak ordering. If not, the program is undefined.

You can merge two sorted ranges with `std::inplace_merge` and `std::merge`. You can check with `std::includes` if one sorted range is in another sorted range. You can merge with `std::set_difference`, `std::set_intersection`, `std::set_symmetric_difference` and `std::set_union` two sorted ranges in a new sorted range.

Merges in place two sorted sub-ranges `[first, mid)` and `[mid, last)`:

```
void inplace_merge(BiIt first, BiIt mid, BiIt last)
void inplace_merge(ExePol pol, BiIt first, BiIt mid, BiIt last)

void inplace_merge(BiIt first, BiIt mid, BiIt last, BiPre pre)
void inplace_merge(ExePol pol, BiIt first, BiIt mid, BiIt last, BiPre pre)
```

Merges two sorted ranges and copies the result to `result`:

```
OutIt merge(InpIt first1, InpIt last1, InpIt first2, InpIt last2, OutIt result)
FwdIt3 merge(ExePol pol, FwdIt1 first1, FwdIt1 last1,
             FwdIt2 first2, FwdIt2 last2, FwdIt3 result)

OutIt merge(InpIt first1, InpIt last1, InpIt first2, InpIt last2, OutIt result,
            BiPre pre)
FwdIt3 merge(ExePol pol, FwdIt1 first1, FwdIt1 last1,
             FwdpIt2 first2, FwdIt2 last2, FwdIt3 result, BiPre pre)
```

Checks if all elements of the second range are in the first range:

```
bool includes(InpIt first1, InpIt last1, InpIt1 first2, InpIt1 last2)
bool includes(ExePol pol, FwdIt first1, FwdIt last1, FwdIt1 first2, FwdIt1 last2)

bool includes(InpIt first1, InpIt last1, InpIt first2, InpIt last2, BinPre pre)
bool includes(ExePol pol, FwdIt first1, FwdIt last1,
              FwdIt1 first2, FwdIt1 last2, BinPre pre)
```

Copies these elements of the first range to `result`, being not in the second range:

```
OutIt set_difference(InpIt first1, InpIt last1, InpIt1 first2, InpIt2 last2,
                     OutIt result)
FwdIt2 set_difference(ExePol pol, FwdIt first1, FwdIt last1,
                     FWdIt1 first2, FwdIt1 last2, FwdIt2 result)

OutIt set_difference(InpIt first1, InpIt last1, InpIt1 first2, InpIt2 last2,
                     OutIt result, BiPre pre)
FwdIt2 set_difference(ExePol pol, FwdIt first1, FwdIt last1,
                      FwdIt1 first2, FwdIt1 last2, FwdIt2 result, BiPre pre)
```

Determines the intersection of the first with the second range and copies the result to `result`:

```
OutIt set_intersection(InpIt first1, InpIt last1, InpIt1 first2, InpIt2 last2,
                       OutIt result)
FwdIt2 set_intersection(ExePol pol, FwdIt first1, FwdIt last1,
                        FWdIt1 first2, FwdIt1 last2, FwdIt2 result)

OutIt set_intersection(InpIt first1, InpIt last1, InpIt1 first2, InpIt2 last2,
                       OutIt result, BiPre pre)
FwdIt2 set_intersection(ExePol pol, FwdIt first1, FwdIt last1,
                        FwdIt1 first2, FwdIt1 last2, FwdIt2 result, BiPre pre)
```

Determines the symmetric difference of the first with the second range and copies the result to `result`:

```
OutIt set_symmetric_difference(InpIt first1, InpIt last1,
                               InpIt1 first2, InpIt2 last2, OutIt result)
FwdIt2 set_symmetric_difference(ExePol pol, FwdIt first1, FwdIt last1,
                                FWdIt1 first2, FwdIt1 last2, FwdIt2 result)

OutIt set_symmetric_difference(InpIt first1, InpIt last1,
                               InpIt1 first2, InpIt2 last2, OutIt result,
                               BiPre pre)
FwdIt2 set_symmetric_difference(ExePol pol, FwdIt first1, FwdIt last1,
                                FwdIt1 first2, FwdIt1 last2, FwdIt2 result,
                                BiPre pre)
```

Determines the union of the first with the second range and copies the result to `result`:

```
OutIt set_union(InpIt first1, InpIt last1,
                InpIt1 first2, InpIt2 last2, OutIt result)
FwdIt2 set_union(ExePol pol, FwdIt first1, FwdIt last1,
                 FWdIt1 first2, FwdIt1 last2, FwdIt2 result)

OutIt set_union(InpIt first1, InpIt last1,
               InpIt1 first2, InpIt2 last2, OutIt result, BiPre pre)
FwdIt2 set_union(ExePol pol, FwdIt first1, FwdIt last1,
                 FwdIt1 first2, FwdIt1 last2, FwdIt2 result, BiPre pre)
```

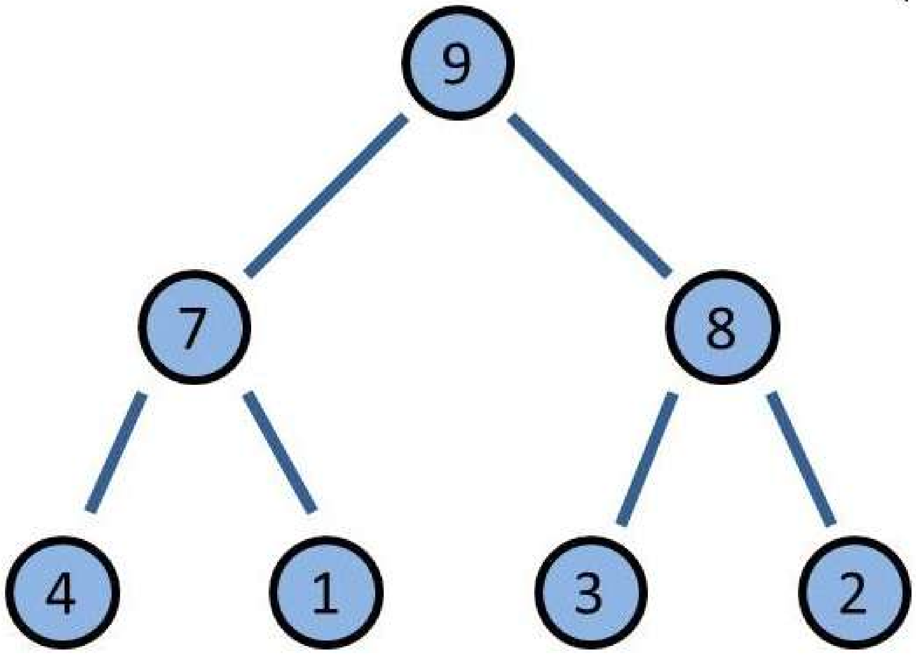
The returned iterator is an end iterator for the destination range. The destination range of `std::set_difference` has all the elements in the first but not the second range. On the contrary, the destination range of `std::symmetric_difference` has only the elements that are elements of one range but not both. `std::union` determines the union of both sorted ranges.

Merge algorithms

```
// merge.cpp
...
#include <algorithm>
...

std::vector<int> vec1{1, 1, 4, 3, 5, 8, 6, 7, 9, 2};
std::vector<int> vec2{1, 2, 3};

std::sort(vec1.begin(), vec1.end());
std::vector<int> vec(vec1);

vec1.reserve(vec1.size() + vec2.size());
vec1.insert(vec1.end(), vec2.begin(), vec2.end());
for (auto v: vec1) std::cout << v << " ";       // 1 1 2 3 4 5 6 7 8 9 1 2 3
```

```
std::inplace_merge(vec1.begin(), vec1.end()-vec2.size(), vec1.end());
for (auto v: vec1) std::cout << v << " ";        //  1 1 1 2 2 3 3 4 5 6 7 8 9

vec2.push_back(10);
for (auto v: vec) std::cout << v << " ";         // 1 1 2 3 4 5 6 7 8 9
for (auto v: vec2) std::cout << v << " ";        // 1 2 3 10

std::vector<int> res;
std::set_symmetric_difference(vec.begin(), vec.end(), vec2.begin(), vec2.end(),
                              std::back_inserter(res));
for (auto v : res) std::cout << v << " ";        // 1 4 5 6 7 8 9 10

res= {};
std::set_union(vec.begin(), vec.end(), vec2.begin(), vec2.end(),
std::back_inserter(res));
for (auto v : res) std::cout << v << "";        // 1 1 2 3 4 5 6 7 8 9 10
```

Heaps



What is a heap?
A heap is a binary search tree in which parent elements are always bigger than their child elements. Heap trees are optimized for the efficient sorting of elements.

You can create with `std::make_heap` a heap. You can push with `std::push_heap` new elements on the heap. On the contrary, you can pop the largest element with `std::pop_heap` from the heap. Both operations respect the heap characteristics. `std::push_heap` moves the last element of the range on the heap; `std::pop_heap` moves the biggest element of the heap to the last position in the range. You can check with `std::is_heap` if a range is a heap. You can determine with `std::is_heap_until` until which position the range is a heap. `std::sort_heap` sorts the heap.

The heap algorithms require that the ranges and the algorithm use the same sorting criterion. If not, the program has undefined behavior. Per default, the predefined sorting criterion `std::less` is used. If you use your sorting criterion, it has to obey the strict weak ordering. If not, the program has undefined behavior.

Creates a heap from the range:

```
void make_heap(RaIt first, RaIt last)
void make_heap(RaIt first, RaIt last, BiPre pre)
```

Checks if the range is a heap:

```
bool is_heap(RaIt first, RaIt last)
bool is_heap(ExePol pol, RaIt first, RaIt last)

bool is_heap(RaIt first, RaIt last, BiPre pre)
bool is_heap(ExePol pol, RaIt first, RaIt last, BiPre pre)
```

Determines until which position the range is a heap:

```
RaIt is_heap_until(RaIt first, RaIt last)
RaIt is_heap_until(ExePol pol, RaIt first, RaIt last)

RaIt is_heap_until(RaIt first, RaIt last, BiPre pre)
RaIt is_heap_until(ExePol pol, RaIt first, RaIt last, BiPre pre)
```

Sorts the heap:

```
void sort_heap(RaIt first, RaIt last)
void sort_heap(RaIt first, RaIt last, BiPre pre)
```

It pushes the last element of the range onto the heap. `[first, last-1)` has to be a heap.

```
void push_heap(RaIt first, RaIt last)
void push_heap(RaIt first, RaIt last, BiPre pre)
```

Removes the biggest element from the heap and puts it to the end of the range:

```
void pop_heap(RaIt first, RaIt last)
void pop_heap(RaIt first, RaIt last, BiPre pre)
```

With `std::pop_heap`, you can remove the greatest element from the heap. Afterward, the greatest element is the last element of the range. To remove the element from the heap `h`, use `h.pop_back`.

Heap algorithms

```
// heap.cpp
...
#include <algorithm>
...

std::vector<int> vec{4, 3, 2, 1, 5, 6, 7, 9, 10};
std::make_heap(vec.begin(), vec.end());
for (auto v: vec) std::cout << v << " ";                  // 10 9 7 4 5 6 2 3 1
std::cout << std::is_heap(vec.begin(), vec.end());         // true

vec.push_back(100);
std::cout << std::is_heap(vec.begin(), vec.end());         // false
std::cout << *std::is_heap_until(vec.begin(), vec.end());  // 100
for (auto v: vec) std::cout << v << " ";                  // 10 9 7 4 5 6 2 3 1 100

std::push_heap(vec.begin(), vec.end());
std::cout << std::is_heap(vec.begin(), vec.end());        // true
for (auto v: vec) std::cout << v << " ";                 // 100 10 7 4 9 6 2 3 1 5

std::pop_heap(vec.begin(), vec.end());
for (auto v: vec) std::cout << v << " ";                 // 10 9 7 4 5 6 2 3 1 100
std::cout << *std::is_heap_until(vec.begin(), vec.end()); // 100

vec.resize(vec.size()-1);
std::cout << std::is_heap(vec.begin(), vec.end());        // true
std::cout << vec.front() << '\n';                    // 10
```

Min and Max

You can determine the minimum, maximum, minimum, and maximum pair of a range with the algorithms `std::min_element`, `std::max_element`, and `std::minmax_element`. Each algorithm can invoked with a binary predicate. Additionally, C++17 enables it to clamp a value between a pair of boundary values.

Returns the minimum element of the range:

```
constexpr FwdIt min_element(FwdIt first, FwdIt last)
FwdIt min_element(ExePol pol, FwdIt first, FwdIt last)

constexpr FwdIt min_element(FwdIt first, FwdIt last, BinPre pre)
FwdIt min_element(ExePol pol, FwdIt first, FwdIt last, BinPre pre)
```

Returns the maximum element of the range:

```
constexpr FwdIt max_element(FwdIt first, FwdIt last)
FwdIt max_element(ExePol pol, FwdIt first, FwdIt last)

constexpr FwdIt max_element(FwdIt first, FwdIt last, BinPre pre)
FwdIt max_element(ExePol pol, FwdIt first, FwdIt last, BinPre pre)
```

Returns the pair `std::min_element` and `std::max_element` of the range:

```
constexpr pair<FwdIt, FwdIt> minmax_element(FwdIt first, FwdIt last)
pair<FwdIt, FwdIt> minmax_element(ExePol pol, FwdIt first, FwdIt last)

constexpr pair<FwdIt, FwdIt> minmax_element(FwdIt first, FwdIt last, BinPre pre)
pair<FwdIt, FwdIt> minmax_element(ExePol pol, FwdIt first, FwdIt last,
                                  BinPre pre)
```

The first one is returned if the range has more than one minimum or maximum element.

Minimum and maximum algorithms

```
// minMax.cpp
...
#include <algorithm>
...

int toInt(const std::string& s){
  std::stringstream buff;
  buff.str("");
  buff << s;
  int value;
  buff >> value;
  return value;
}

std::vector<std::string> myStrings{"94", "5", "39", "-4", "-49", "1001", "-77",
                                   "23", "0", "84", "59", "96", "6", "-94"};
auto str= std::minmax_element(myStrings.begin(), myStrings.end());
std::cout << *str.first << ":" << *str.second;              // -4:96

auto asInt= std::minmax_element(myStrings.begin(), myStrings.end(),
            [](std::string a, std::string b){ return toInt(a) < toInt(b); });
std::cout << *asInt.first << ":" << *asInt.second;          // -94:1001
```

`std::clamp` clamps a value between a pair of boundary values:

```
constexpr const T& clamp(const T& v, const T& lo, const T& hi);
constexpr const T& clamp(const T& v, const T& lo, const T& hi, BinPre pre);
```

Returns a reference to `v` if `lo` is less than `v` and `v` is less than `hi`. Otherwise, it returns a reference to `lo` or `hi`. By default, < is used as the comparison criteria but you can also provide a binary predicate `pre`.

Clamp a value

```
// clamp.cpp
...
#include <algorithm>
...

auto values = {1, 2, 3, 4, 5, 6, 7};
for (auto v: values) std::cout << v << ' ';                     // 1 2 3 4 5 6 7
```

```
auto lo = 3;
auto hi = 6;
for (auto v: values) std::cout << std::clamp(v, lo, hi) << ' '; // 3 3 3 4 5 6 6
```

Permutations

`std::prev_permutation` and `std::next_permutation` return the previous smaller or next greater permutation of the newly ordered range. If a smaller or greater permutation is unavailable, the algorithms return false. Both algorithms need bidirectional iterators. Per default, the predefined sorting criterion `std::less` is used. If you use your sorting criterion, it has to obey the strict weak ordering. If not, the program has undefined behavior.

Applies the previous permutation to the range:

```
bool prev_permutation(BiIt first, BiIt last)
bool prev_permutation(BiIt first, BiIt last, BiPred pre)
```

Applies the next permutation to the range:

```
bool next_permutation(BiIt first, BiIt last)
bool next_permutation(BiIt first, BiIt last, BiPred pre)
```

You can generate with both algorithms all permutations of the range.

Permutation algorithms

```
// permutation.cpp
...
#include <algorithm>
...

std::vector<int> myInts{1, 2, 3};
do{
  for (auto i: myInts) std::cout << i;
  std::cout << " ";
} while(std::next_permutation(myInts.begin(), myInts.end()));
                                    // 123 132 213 231 312 321

std::reverse(myInts.begin(), myInts.end());
do{
  for (auto i: myInts) std::cout << i;
  std::cout << " ";
} while(std::prev_permutation(myInts.begin(), myInts.end()));
                                    // 321 312 231 213 132 123
```

Numeric

The numeric algorithms `std::accumulate`, `std::adjacent_difference`, `std::partial_sum`, `std::inner_product` and `std::iota` and the six additional C++17 algorithms `std::exclusive_scan`, `std::inclusive_scan`, `std::transform_exclusive_scan`, `std::transform_inclusive_scan`, `std::reduce`, and `std::transform_reduce` are special. All of them are defined in the header `<numeric>`. They are widely applicable because they can invoked with a callable.

Accumulates the elements of the range. `init` is the start value:

```
T accumulate(InpIt first, InpIt last, T init)
T accumulate(InpIt first, InpIt last, T init, BiFun fun)
```

Calculates the difference between adjacent elements of the range and stores the result in `result`:

```
OutIt adjacent_difference(InpIt first, InpIt last, OutIt result)
FwdIt2 adjacent_difference(ExePol pol, FwdIt first, FwdIt last, FwdIt2 result)

OutIt adjacent_difference(InpIt first, InpIt last, OutIt result, BiFun fun)
```

```
FwdIt2 adjacent_difference(ExePol pol, FwdIt first, FwdIt last,
                           FwdIt2 result, BiFun fun)
```

Calculates the partial sum of the range:

```
OutIt partial_sum(InpIt first, InpIt last, OutIt result)
OutIt partial_sum(InpIt first, InpIt last, OutIt result, BiFun fun)
```

Calculates the inner product (scalar product) of the two ranges and returns the result:

```
T inner_product(InpIt first1, InpIt last1, OutIt first2, T init)
T inner_product(InpIt first1, InpIt last1, OutIt first2, T init,
                BiFun fun1, BiFun fun2)
```

Assigns each element of the range a by one sequentially increasing value. The start value is `val`:

```
void iota(FwdIt first, FwdIt last, T val)
```

The algorithms are more challenging to get.

`std::accumulate` without callable uses the following strategy:

```
result = init;
result += *(first+0);
result += *(first+1);
...
```

`std::adjacent_difference` without callable uses the following strategy:

```
*(result) = *first;
*(result+1) = *(first+1) - *(first);
*(result+2) = *(first+2) - *(first+1);
...
```

`std::partial_sum` without callable uses the following strategy:

```
*(result) = *first;
*(result+1) = *first + *(first+1);
*(result+2) = *first + *(first+1) + *(first+2)
...
```

The challenging algorithm variation `inner_product(InpIt, InpIt, OutIt, T, BiFun fun1, BiFun fun2)` with two binary callables uses the following strategy: The second callable `fun2` is applied to each pair of the ranges to generate the temporary destination range `tmp`, and the first callable is applied to each element of the destination range `tmp` for accumulating them and therefore generating the final result.

Numeric algorithms

```
// numeric.cpp
...
#include <numeric>
...

std::array<int, 9> arr{1, 2, 3, 4, 5, 6, 7, 8, 9};
std::cout << std::accumulate(arr.begin(), arr.end(), 0);               // 45
std::cout << std::accumulate(arr.begin(), arr.end(), 1,
                             [](int a, int b){ return a*b; } );        // 362880

std::vector<int> vec{1, 2, 3, 4, 5, 6, 7, 8, 9};
std::vector<int> myVec;
std::adjacent_difference(vec.begin(), vec.end(),
                 std::back_inserter(myVec), [](int a, int b){ return a*b; });
for (auto v: myVec) std::cout << v << " ";             // 1 2 6 12 20 30 42 56 72
std::cout << std::inner_product(vec.begin(), vec.end(), arr.begin(), 0);  // 285

myVec= {};
std::partial_sum(vec.begin(), vec.end(), std::back_inserter(myVec));
for (auto v: myVec) std::cout << v << " ";             // 1 3 6 10 15 21 28 36 45

std::vector<int> myLongVec(10);
std::iota(myLongVec.begin(), myLongVec.end(), 2000);
```

```
for (auto v: myLongVec) std::cout << v << " ";
                            // 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
```

New Parallel Algorithms with C++17

The six new algorithms typically used for parallel execution are known as prefix sum. The behavior of the algorithms is undefined if the given binary callables are not associative and commutative.

`reduce`: reduces the elements of the range. `init` is the start value.

- Behaves the same as `std::accumulate`, but the range may be rearranged.

```
ValType reduce(InpIt first, InpIt last)
ValType reduce(ExePol pol, InpIt first, InpIt last)

T reduce(InpIt first, InpIt last, T init)
T reduce(ExePol pol, InpIt first, InpIt last, T init)

T reduce(InpIt first, InpIt last, T init, BiFun fun)
T reduce(ExePol pol, InpIt first, InpIt last, T init, BiFun fun)
```

`transform_reduce`: transforms and reduces the elements of one or two ranges. `init` is the start value.

- Behaves similar to `std::inner_product`, but the range may be rearranged.
- If applied to two ranges
  - if not provided, multiplication is used for transforming the ranges into one range, and addition is used to reduce the intermediate range into the result
  - if provided, `fun1` is used for the transforming step, and `fun2` is used for the reducing step
- If applied to a single range
  - `fun2` is used for transforming the given range

```
T transform_reduce(InpIt first, InpIt last, InpIt first2, T init)
T transform_reduce(InpIt first, InpIt last,
                   InpIt first2, T init, BiFun fun1, BiFun fun2)

T transform_reduce(FwdIt first, FwdIt last, FwdIt first2, T init)
T transform_reduce(ExePol pol, FwdIt first, FwdIt last,
                  FwdIt first2, T init, BiFun fun1, BiFun fun2)


T transform_reduce(InpIt first, InpIt last, T init, BiFun fun1, UnFun fun2)
T transform_reduce(ExePol pol, FwdIt first, FwdIt last,
                   T init, BiFun fun1, UnFun fun2)
```

MapReduce in C++17

The Haskell function `map` is called std::transform in C++. When you substitute `transform` with `map` in the name std::transform_reduce, you will get `std::map_reduce`. MapReduce is the well-known parallel framework that first maps each value to a new value then reduces in the second phase all values to the result.

The algorithm is directly applicable in C++17. Each word is mapped to its length in the map phase, and the lengths of all words are then reduced to their sum during the reduce phase. The result is the sum of the length of all words.

```
std::vector<std::string> str{"Only", "for", "testing", "purpose"};


std::size_t result= std::transform_reduce(std::execution::par,
                   str.begin(), str.end(), 0,
                   [](std::size_t a, std::size_t b){ return a + b; },
                   [](std::string s){ return s.length(); });

std::cout << result << '\n';      //   21
```

`exclusive_scan`: computes the exclusive prefix sum using a binary operation.

- Behaves similar to std::reduce, but provides a range of all prefix sums
- excludes the last element in each iteration

```
OutIt exclusive_scan(InpIt first, InpIt last, OutIt first, T init)
FwdIt2 exclusive_scan(ExePol pol, FwdIt first, FWdIt last,
                      FwdIt2 first2, T init)

OutIt exclusive_scan(InpIt first, InpIt last, OutIt first, T init, BiFun fun)
FwdIt2 exclusive_scan(ExePol pol, FwdIt first, FwdIt last,
                     FwdIt2 first2, T init, BiFun fun)
```

`inclusive_scan`: computes the inclusive prefix sum using a binary operation.

- Behaves similar to std::reduce, but provides a range of all prefix sums
- includes the last element in each iteration

```
OutIt inclusive_scan(InpIt first, InpIt last, OutIt first2)
FwdIt2 inclusive_scan(ExePol pol, FwdIt first, FwdIt last, FwdIt2 first2)

OutIt inclusive_scan(InpIt first, InpIt last, OutIt first, BiFun fun)
FwdIt2 inclusive_scan(ExePol pol, FwdIt first, FwdIt last,
                      FwdIt2 first2, BiFun fun)

OutIt inclusive_scan(InpIt first, InpIt last, OutIt firs2t, BiFun fun, T init)
FwdIt2 inclusive_scan(ExePol pol, FwdIt first, FwdIt last,
                      FwdIt2 first2, BiFun fun, T init)
```

`transform_exclusive_scan`: first transforms each element and then computes the exclusive prefix sums. {lang=”C++”} OutIt transform_exclusive_scan(InpIt first, InpIt last, OutIt first2, T init, BiFun fun, UnFun fun2)

FwdIt2 transform_exclusive_scan(ExePol pol, FwdIt first, FwdIt last, FwdIt2 first2, T init, BiFun fun, UnFun fun2)

`transform_inclusive_scan`: first transforms each element of the input range and then computes the inclusive prefix sums.

```
OutIt transform_inclusive_scan(InpIt first, InpIt last, OutIt first2,
                               BiFun fun, UnFun fun2)

FwdIt2 transform_inclusive_scan(ExePol pol, FwdIt first, FwdIt last,
                                FwdIt first2,
                                BiFun fun, UnFun fun2)

OutIt transform_inclusive_scan(InpIt first, InpIt last, OutIt first2,
                               BiFun fun, UnFun fun2,
                               T init)

FwdIt2 transform_inclusive_scan(ExePol pol, FwdIt first, FwdIt last,
                                FwdIt first2,
                                BiFun fun, UnFun fun2,
                                T init)
```

The following example illustrates the usage of the six algorithms using the parallel execution policy.

The new algorithms

```
// newAlgorithms.cpp
...
#include <execution>
#include <numeric>

...

std::vector<int> resVec{1, 2, 3, 4, 5, 6, 7, 8};
std::exclusive_scan(std::execution::par,
                    resVec.begin(), resVec.end(), resVec.begin(), 1,
                    [](int fir, int sec){ return fir * sec; });

for (auto v: resVec) std::cout << v << " "; // 1 1 2 6 24 120 720 5040

std::vector<int> resVec2{1, 2, 3, 4, 5, 6, 7, 8};

std::inclusive_scan(std::execution::par,
                    resVec2.begin(), resVec2.end(), resVec2.begin(),
                    [](int fir, int sec){ return fir * sec; }, 1);

for (auto v: resVec2) std::cout << v << " "; // 1 2 6 24 120 720 5040 40320

std::vector<int> resVec3{1, 2, 3, 4, 5, 6, 7, 8};
std::vector<int> resVec4(resVec3.size());
std::transform_exclusive_scan(std::execution::par,
                              resVec3.begin(), resVec3.end(),
                              resVec4.begin(), 0,
                              [](int fir, int sec){ return fir + sec; },
                              [](int arg){ return arg *= arg; });

for (auto v: resVec4) std::cout << v << " "; // 0 1 5 14 30 55 91 140

std::vector<std::string> strVec{"Only", "for", "testing", "purpose"};
std::vector<int> resVec5(strVec.size());

std::transform_inclusive_scan(std::execution::par,
                              strVec.begin(), strVec.end(),
                              resVec5.begin(),
                              [](auto fir, auto sec){ return fir + sec; },
                              [](auto s){ return s.length(); }, 0);

for (auto v: resVec5) std::cout << v << " "; // 4 7 14 21

std::vector<std::string> strVec2{"Only", "for", "testing", "purpose"};

std::string res = std::reduce(std::execution::par,
                  strVec2.begin() + 1, strVec2.end(), strVec2[0],
                  [](auto fir, auto sec){ return fir + ":" + sec; });

std::cout << res;      // Only:for:testing:purpose

std::size_t res7 = std::transform_reduce(std::execution::par,
                   strVec2.begin(), strVec2.end(), 0,
                   [](std::size_t a, std::size_t b){ return a + b; },
                   [](std::string s){ return s.length(); });

std::cout << res7;    // 21
```

Unitialized Memory

The following functions in the header `<memory>` operate on uninitialized memory.

Copy a range of objects to an unitialized area of memory.

```
FwdIt uninitialized_copy(InIt first, InIt last, FwdIt out)
FwdIt uninitialized_copy(ExePol pol, FwdIt first, FwdIt last, FwdIt out)
```

Copy `count` objects to an unitialized area of memory.

```
FwdIt uninitialized_copy_n(InIt first, Size count, FwdIt out)
FwdIt uninitialized_copy_n(ExePol pol, FwdIt first, Size count, FwdIt out)
```

Copy an object `value` to an unitialized area of memory.

```
void uninitialized_fill(FwdIt first, FwdIt last, const T& value)
void uninitialized_fill(ExePol pol, FwdIt first, FwdIt last, const T& value)
```

Copy `count` object to an unitialized area of memory, starting with `first`.

```
void uninitialized_fill_n(FwdIt first, Size count, const T& value)
FwdIt uninitialized_fill_n(FwdIt first, Size count, const T& value)
FwdIt uninitialized_fill_n(ExePol pol, FwdIt first, Size count, const T& value)
```

Move a range of objects to an unitialized area of memory.

```
FwdIt uninitialized_move(InIt first, InIt last, FwItout)
FwdIt uninitialized_move(ExePol pol, FwdIt first, FwdIt last, FwIt out)
```

Move `count` objects to an unitialized area of memory.

```
std::pair<InIt, FwdIt> uninitialized_move_n(InIt first, Size count, FwIt out)
std::pair<FwdIt, FwdIt> uninitialized_move_n(ExePol pol, FwdIt first, Size count,
                                             FwIt out)
```

Construct objects by default initialization an unitialized area of memory.

```
void uninitialized_default_construct(FwdIt first, FwdIt last)
void uninitialized_default_construct(ExePol pol, FwdIt first, FwdIt last)
```

Construct `n`objects by default initialization an unitialized area of memory.

```
FwdIt uninitialized_default_construct_n(FwdIt first, Size n)
FwdIt uninitialized_default_construct_n(ExePol pol, FwdIt first, Size n)
```

Construct objects by value initialization an unitialized area of memory.

```
void uninitialized_value_construct(FwdIt first, FwdIt last)
void uninitialized_value_construct(ExePol pol, FwdIt first, FwdIt last)
```

Construct `n` objects by value initialization an unitialized area of memory.

```
FwdIt uninitialized_value_construct_n(FwdIt first, Size n)
FwdIt uninitialized_value_construct_n(ExePol pol, FwdIt first, Size n)
```

Destroy objects.

```
constexpr void destroy(FwdIt first, FwdIt last)
void destroy(ExePol pol, FwdIt first, FwdIt last)
```

Destroy `n` objects.

```
constexpr void destroy_n(FwdIt first, Size n)
void destroy_n(ExePol pol, FwdIt first, Size n)
```

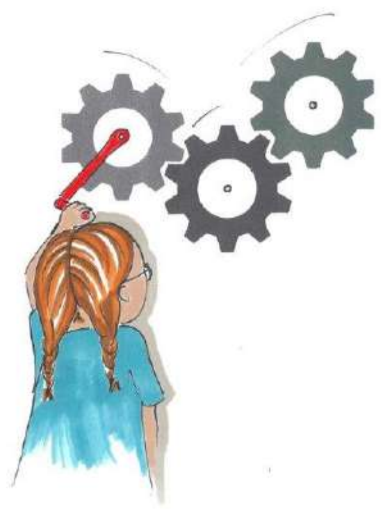
Destroy an object at a given address `p`.

```
constexpr void destroy_at(T* p)
```

Create an object at a given address `p`.

```
constexpr T* construct_at(T* p, Args&& ... args)
```

11. Ranges



Cippi starts the pipeline job

The ranges library was added with C++20, but has powerful extensions with C++23. The algorithms of the ranges library are lazy, operate directly on the container, and can be composed. Furthermore, most of the classical STL algorithms have ranges pendants, which support projections and provide additional safety guarantees.

Composing of ranges

```
// rangesFilterTransform.cpp
...
#include <ranges>

std::vector<int> numbers = {1, 2, 3, 4, 5, 6};

auto results = numbers | std::views::filter([](int n){ return n % 2
== 0; })
                       | std::views::transform([](int n){ return n *
2; });

for (auto v: results) std::cout << v << " ";      // 4 8 12
```

You have to read the expression from left to right. The pipe symbol `|` stands for function composition: First, all numbers can pass which are even (`std::views::filter([](int n){ return n % 2 == 0; })`). Afterward, each remaining number is mapped to its double (`std::views::transform([](int n){ return n * 2; })`). T

Range

Ranges and views are concepts. C++20 supports various kinds of ranges:

`std::range`
: A range is a group of items that you can iterator over. It provides a begin iterator and an end sentinel. End iterators are special sentinels.

There are further refinements of `std::range`:

Refinements of `std::range`

Range (namespace `std` omitted)	Description
`ranges::input_range`	Specifies a range whose iterator type satisfies `input_iterator`
`ranges::output_range`	Specifies a range whose iterator type satisfies `output_iterator`
`ranges::forward_range`	Specifies a range whose iterator type satisfies `forward_iterator`
`ranges::bidirectional_range`	Specifies a range whose iterator type satisfies `bidirectional_iterator`
`ranges::random_access_range`	Specifies a range whose iterator type satisfies `random_access_iterator`
`ranges::contiguous_range`	Specifies a range whose iterator type satisfies `contiguous_iterator`

A `random_access_iterator` provides random access to its elements and is implicit a `bidirectional_iterator`; a `bidirection_iterator` enables iterating in both directions and is implicit a `forward_iterator`; a `forward_iterator` iteration in one direction. The interface of a `contigiuous_iterator` is the same, such as a `bidirectional_iterator` interface. The `contiguous_iterator` guarantees that the iterator refers to contiguous storage.

Sentinel

The sentinel specifies the end of a range. For the containers of the STL, the end iterator is the sentinel. With C++20, the type of the sentinel can be different from the type of the begin iterator. The following example uses a space as a sentinel.

Composing of ranges

```
// sentinelSpace.cpp
...
#include <algorithm>

...

struct Space {
bool operator== (auto pos) const {
    return *pos == ' ';
}

...

const char* rainerGrimm = "Rainer Grimm";
std::ranges::for_each(rainerGrimm, Space{}, [] (char c) { std::cout
<< c; }); // Rainer
```

Due to the space as sentinel, only `Rainer` is displayed in the last line.

`ranges::to`

`std::ranges::to` is a convenient way in C++23 to construct a container from a range:

```
std::vector<int> range(int begin, int end, int stepsize = 1) {
    auto boundary = [end](int i){ return i < end; };
    std::vector<int> result = std::ranges::views::iota(begin)
                              | std::views::stride(stepsize)
                              | std::views::take_while(boundary)
                              | std::ranges::to<std::vector>();
    return result;
}
```

The function `range` creates a `std::vector<int>` consisting of all elements for `begin` to `end` with the stepsize `stepsize`. `begin` must be smaller than `end`.

View

Views are lightweight ranges. A view allows you to access ranges, iterate through ranges, or modify or filter elements of a range. A view does not own data, and its time complexity to copy, move, or assign is constant.

Range Adaptors

A range adaptor transforms a range into a view.

```
std::vector<int> numbers = {1, 2, 3, 4, 5, 6};

auto results = numbers | std::views::filter([](int n){ return n % 2
== 0; })
                       | std::views::transform([](int n){ return n *
2; });
```

In this code snippet, `numbers` is the range, and `std::views::filter` and `std::views::transform` are the views.

The ranges library in C++20 has a rich set of views.

Views in C++20

View	Description

`std::views::all_t`
 `std::views::all`
	Takes all elements.

`std::ranges::ref_view`	Takes all elements of another range.

`std::ranges::filter_view`
 `std::views::filter`
	Takes the elements which satisfy the predicate.

`std::ranges::transform_view`
 `std::views::transform`
	Transforms each element.

`std::ranges::take_view`
 `std::views::take`
	Takes the first `n` elements of another view.

`std::ranges::take_while_view`
 `std::views::take_while`
	Takes the elements of another view as long as the predicate returns `true`.

`std::ranges::drop_view`
 `std::views::drop`
	Skips the first `n` elements of another view.

`std::ranges::drop_while_view`
 `std::views::drop_while`
	Skips the initial elements of another view until the predicate returns `false`.

`std::ranges::join_view`
 `std::views::join`
	Joins a view of ranges.

`std::ranges::split_view`
 `std::views::split`
	Splits a view by using a delimiter.

View	Description

`std::ranges::common_view`
 `std::views::common`
	Converts a view into a `std::ranges::common_range`.

`std::ranges::reverse_view`
 `std::views::reverse`
	Iterates in reverse order.

`std::ranges::basic_istream_view`
 `std::ranges::istream_view`
	Applies `operator>>` on the view.

`std::ranges::elements_view`
 `std::views::elements`
	Creates a view on the `n`-th element of tuples.

`std::ranges::keys_view`
 `std::views::keys`
	Creates a view on the first element of pair-like values.

`std::ranges::values_view`
 `std::views::values`
	Creates a view on the second element of pair-like values.

In general, you can use a view such as `std::views::transform` with the alternative name `std:: ranges:: transform_view`.

Thanks to the ranges library, algorithms can be directly applied to the containers, can be composed, and are lazy.

C++23 supports additional views:

Views in C++23

View	Description
`std::ranges::zip_view` `std::views::zip`	Creates a view of tuples.
`std::ranges::zip_transform_view` `std::views::zip_transform`	Creates a view of tuples by applying the transformation function.
`std::ranges::adjacent_view` `std::views::adjacent`	Creates a view of adjacent elements.
`std::ranges::adjacent_transform_view` `std::views::adjacent_transform`	Creates a view of adjacent elements by applying the transformation function.
`std::ranges::join_with_view` `std::views::join_with`	Joins existing ranges into a view by applying a delimiter.
`std::ranges::slide_view` `std::views::slide`	Creates N-tuples by taking a view and a number N.
`std::ranges::chunk_view` `std::views::chunk`	Creates N-chunks of a view and a number N.
`std::ranges::chunk_by_view` `std::views::chunk_by`	Creates chunks of a view based on a predicate.
`std::ranges::as_const_view` `std::views::as_const`	Converts a view into a constant range.

View	Description
`std::ranges::as_rvalue_view` `std::views::as_rvalue`	Casts each element into an rvalue.
`std::ranges::stride_view` `std::views::stride`	Creates a view of the N-th elements of another view.

The following code snippet applies the C++23 views.

New views in C++23

```cpp
// cpp23Ranges.cpp
...
#include <ranges>
...

std::vector vec = {1, 2, 3, 4};

for (auto i : vec | std::views::adjacent<2>) {
  std::cout << '(' << i.first << ", " << i.second << ") "; // (1, 2)
(2, 3) (3, 4)
}

for (auto i : vec | std::views::adjacent_transform<2>
(std::multiplies())) {
  std::cout << i << ' ';                                  // 2 6 12
}

std::print("{}\n", vec | std::views::chunk(2));          // [[1, 2],
[3, 4],
std::print("{}\n", vec | std::views::slide(2));          // [[1, 2],
[2, 3], [3, 4]

for (auto i : vec | std::views::slide(2)) {
    std::cout << '[' << i[0] << ", " << i[1] << "] ";  // [1, 2] [2,
3] [3, 4] [4, 5]
}

std::vector vec2 = {1, 2, 3, 0, 5, 2};
std::print("{}\n", vec2 |
std::views::chunk_by(std::ranges::less_equal{}));
                                                         // [[1, 2,
3], [0, 5], [2]]

for (auto i : vec | std::views::slide(2)) {
    std::cout << '[' << i[0] << ", " << i[1] << "] ";  // [1, 2] [2,
3] [3, 4] [4, 5]
}
```

`generator`

`std::generator` in C++23 is the first concrete coroutine generator. A `std::generator` generates a sequence of elements by repeatedly resuming the coroutine from which is was paused.

The coroutine generator `std::generator`

```
// generator.cpp
...
#include <generator>
#include <ranges>

...

std::generator<int> fib() {
    co_yield 0;                                 // 1
    auto a = 0;
    auto b = 1;
    for(auto n : std::views::iota(0)) {
        auto next = a + b;
        a = b;
        b = next;
        co_yield next;                          // 2
    }
}

...

for (auto f : fib() | std::views::take(10)) {   // 3
    std::cout << f << " ";                      //  0 1 1 2 3 5 8 13
21 34
}
```

The function `fib` return a coroutine. This coroutine creates an infinite stream of Fibonacci numbers. The stream of numbers starts with 0 (1) and continues with the following Fibonacci number (2). The ranges-based for-loop requests explicitly the first 10 Fibonacci numbers (3).

Direct on the Containers

The algorithms of the Standard Template Library need a begin iterator and an end iterator.

```
std::vector<int> myVec{1, 2, 3, 4, 5, 6, 7, 8, 9};
auto res = std::accumulate(std::begin(myVec), std::end(myVec), 0);
std::cout << res << '\n';       //  45
```

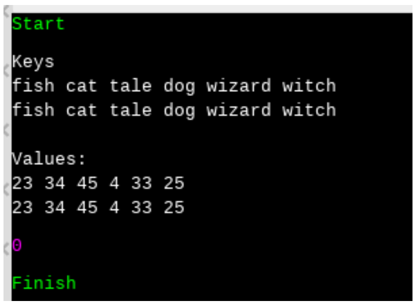
The ranges library allows it to directly create a view on the keys (1) or values (3) of a `std::unordered_map`.

Ranges work directly on the container

```
// rangesEntireContainer.cpp
...
#include <ranges>
```

```
std::unordered_map<std::string, int> freqWord{ {"witch", 25},
{"wizard", 33},
                                               {"tale", 45}, {"dog",
4},
                                               {"cat", 34}, {"fish",
23} };
std::cout << "Keys" << '\n';
auto names = std::views::keys(freqWord);
// (1)
for (const auto& name : names){ std::cout << name << " "; };

for (const auto& na : std::views::keys(freqWord)){ std::cout << na
<< " "; }; // (2)

std::cout << "Values: " << '\n';
auto values = std::views::values(freqWord);
// (3)
for (const auto& value : values){ std::cout << value << " "; };

for (const auto& value : std::views::values(freqWord)){
// (4)
    std::cout << value << " ";
}
```

Of course, the keys and values can be displayed directly ((2) and (4)). The output is identical.



```
Start

Keys
fish cat tale dog wizard witch
fish cat tale dog wizard witch

Values:
23 34 45 4 33 25
23 34 45 4 33 25

0

Finish
```

Function Composition

The ranges library supports function composition using the | symbol.

Ranges work directly on the container

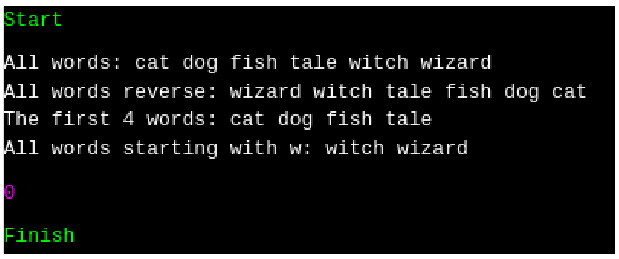
```
// rangesComposition.cpp
...
#include <ranges>

std::map<std::string, int> freqWord{ {"witch", 25}, {"wizard", 33},
{"tale", 45},
                                     {"dog", 4}, {"cat", 34},
{"fish", 23} };

std::cout << "All words: ";                          // (1)
for (const auto& name : std::views::keys(freqWord)) { std::cout <<
name << " "; }         \
std::cout << "All words reverse: ";                     // (2)
for (const auto& name : std::views::keys(freqWord) |
std::views::reverse) {
    std::cout << name << " ";
}

std::cout << "The first 4 words: ";                     // (3)
for (const auto& name : std::views::keys(freqWord) |
std::views::take(4)) {
    std::cout << name << " ";
}

std::cout << "All words starting with w: ";             // (4)
auto firstw = [](const std::string& name){ return name[0] == 'w'; };
for (const auto& name : std::views::keys(freqWord) |
std::views::filter(firstw)) {
    std::cout << name << " ";
}
```

In this case, I'm only interested in the keys. I display all of them (1), all of them reversed (2), the first four (3), and the keys starting with the letter 'w' (4).

The pipe symbol `|` is syntactic sugar for function composition. Instead of `C(R)`, you can write `R | C`. Consequentially, the next three lines are equivalent.

```
auto rev1 = std::views::reverse(std::views::keys(freqWord));
auto rev2 = std::views::keys(freqWord) | std::views::reverse;
auto rev3 = freqWord | std::views::keys | std::views::reverse;
```

Finally, here is the output of the program:



```
Start

All words: cat dog fish tale witch wizard
All words reverse: wizard witch tale fish dog cat
The first 4 words: cat dog fish tale
All words starting with w: witch wizard

0

Finish
```

Lazy Evaluation

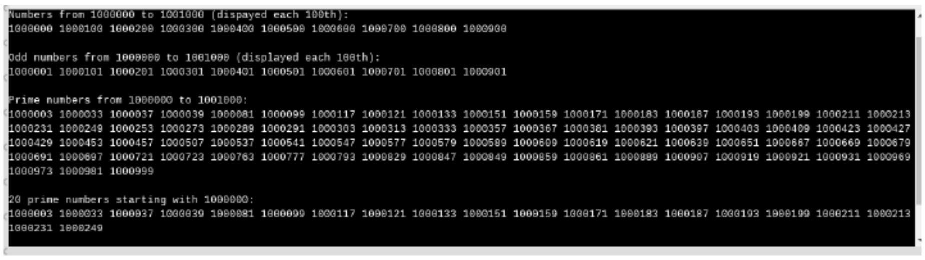
`std::views::iota` is a range factory for creating a sequence of elements by successively incrementing an initial value. This sequence can be finite or infinite. Thanks to the function, I can find the first 20 prime numbers starting with 1000000.

Finding 20 prime numbers starting with 1000000

```
// rangesLazy.cpp
...
#include <ranges>

bool isPrime(int i) {
    for (int j=2; j*j <= i; ++j){
        if (i % j == 0) return false;
    }
    return true;
}
                                        // (1)
std::cout << "Numbers from 1000000 to 1001000 (displayed each
100th): " << "\n";
for (int i: std::views::iota(1000000, 1001000)) {
    if (i % 100 == 0) std::cout << i << " ";
}
                                        // (2)
auto odd = [](int i){ return i % 2 == 1; };
std::cout << "Odd numbers from 1000000 to 1001000 (displayed each
100th): " << "\n";
for (int i: std::views::iota(1000000, 1001000) |
std::views::filter(odd)) {
    if (i % 100 == 1) std::cout << i << " ";
}
                                        // (3)
std::cout << "Prime numbers from 1000000 to 1001000: " << '\n';
for (int i: std::views::iota(1000000, 1001000) |
std::views::filter(odd)
                                                |
std::views::filter(isPrime)) {
    std::cout << i << " ";
}
                                         // (4)
std::cout << "20 prime numbers starting with 1000000: " << '\n';
for (int i: std::views::iota(1000000) | std::views::filter(odd)
                                      | std::views::filter(isPrime)
                                      | std::views::take(20)) {
    std::cout << i << " ";
}
```

Here is my iterative strategy:

1. I don't know when I have 20 primes greater than 1000000. To be on the safe side, I create 1000 numbers. I displayed only each 100th.
2. A prime is an odd number; therefore, I remove the even numbers.
3. The predicate `isPrime` returns if a number is a prime. I get 75 primes, but I only want to have 20.
4. I use `std::iota` as an infinite number factory, starting with 1000000, and ask precisely for 20 primes.



```
Numbers from 1000000 to 1001000 (dispayed each 100th):
1000000 1000100 1000200 1000300 1000400 1000500 1000600 1000700 1000800 1000900

Odd numbers from 1000000 to 1001000 (displayed each 100th):
1000001 1000101 1000201 1000301 1000401 1000501 1000601 1000701 1000801 1000901

Prime numbers from 1000000 to 1001000:
1000003 1000033 1000037 1000039 1000081 1000099 1000117 1000121 1000133 1000151 1000159 1000171 1000183 1000187 1000193 1000199 1000211 1000213
1000231 1000249 1000253 1000273 1000289 1000291 1000303 1000313 1000333 1000357 1000367 1000381 1000393 1000397 1000403 1000409 1000423 1000427
1000429 1000453 1000457 1000507 1000537 1000541 1000547 1000577 1000579 1000589 1000609 1000619 1000621 1000639 1000651 1000667 1000669 1000679
1000691 1000697 1000721 1000723 1000763 1000777 1000793 1000829 1000847 1000849 1000859 1000861 1000889 1000907 1000919 1000921 1000931 1000969
1000973 1000981 1000999

20 prime numbers starting with 1000000:
1000003 1000033 1000037 1000039 1000081 1000099 1000117 1000121 1000133 1000151 1000159 1000171 1000183 1000187 1000193 1000199 1000211 1000213
1000231 1000249
```

`std` Algorithms versus `std::ranges` Algorithms

The algorithms of the algorithm library and the memory libray have ranges pendants. They start with the namespace `std::ranges`. The numeric library does not have a ranges pendant. In the following listing, I display one of the five overloads of the `std::sort` algorithm and one of the two overloads of the new `std::ranges::sort` algorithm.

```
template< class ExecutionPolicy, class RandomIt, class Compare >
void sort( ExecutionPolicy&& policy,
           RandomIt first, RandomIt last, Compare comp );

template <std::random_access_iterator I, std::sentinel_for<I> S,
         class Comp = ranges::less, class Proj = std::identity>
requires std::sortable<I, Comp, Proj>
constexpr I sort(I first, S last, Comp comp = {}, Proj proj = {});
```

First, `std::sort` takes a range given by a begin and end iterator. The iterators must be a random access iterator. It requires an execution policy. `Compare` lets you specify the sorting strategy of `std::sort`.

Furthermore, when you study the overload of `std::ranges::sort`, you notice that it takes a range defined by a random-access begin iterator and a sentinel. Additionally, this overload takes a predicate `Comp`, and a projection `Proj`. The predicate `Comp` uses for default less, and the projection `Proj` the identity `std::identity`. A projection is a mapping of a set into a subset:

```
struct PhoneBookEntry{
    std::string name;
    int number;
};

std::vector<PhoneBookEntry> phoneBook{ {"Brown", 111}, {"Smith",
444}, {"Grimm", 666},
                            {"Butcher", 222}, {"Taylor", 555},
{"Wilson", 333} };
```

```
std::ranges::sort(phoneBook, std::ranges::greater(),
&PhoneBookEntry::name);
```

The `phoneBook` is sorted in a descending order based on the projection `&PhoneBookEntry::name`.

The `std::random_access_iterator`, `std::sortable`, and `std::sentinel_for` are concepts.

`std::ranges::sort` does not support execution policies.

12. Numeric

Cippi studies arithmetic

C++ inherits the numeric functions from C and has a random number library.

Random Numbers

Random numbers are necessary for many domains, e.g., test software, generate cryptographic keys, or computer games. The random number facility of C++ consists of two components. There is the generation of the random numbers and the distribution of these random numbers. Both parts need the header `<random>`.

Random Number Generator

The random number generator generates a random number stream between a minimum and maximum value. This stream is initialized by a "so-called" *seed*, guaranteeing different random number sequences.

```
#include <random>
...
std::random_device seed;
std::mt19937 generator(seed());
```

A random number generator `gen` of type `Generator` supports four different requests:

`Generator::result_type`
: Data type of the generated random number.

`gen()`
: Returns a random number.

`gen.min()`
: Returns the minimum random number that can be returned by `gen()`.

`gen.max()`
: Returns the maximum random number that can be returned by `gen`.

The random number library supports several random number generators. The best known are the Mersenne Twister, the `std::default_random_engine` chosen by the implementation, and `std::random_device`. `std::random_device` is the only true random number generator, but not all platforms offer it.

Random Number Distribution

The random number distribution maps the random number with the random number generator `gen` to the selected distribution.

```
#include <random>
...

std::random_device seed;
std::mt19937 gen(seed());
std::uniform_int_distribution<> unDis(0, 20); // distribution
between 0 and 20
unDis(gen);                                   // generates a
random number
```

C++ has several discrete and continuous random number distributions. The discrete random number distribution generates integers. The continuous random number distribution generates floating-point numbers.

```
class bernoulli_distribution;
template<class T = int> class uniform_int_distribution;
template<class T = int> class binomial_distribution;
template<class T = int> class geometric_distribution;
template<class T = int> class negative_binomial_distribution;
template<class T = int> class poisson_distribution;
template<class T = int> class discrete_distribution;
template<class T = double> class exponential_distribution;
template<class T = double> class gamma_distribution;
```

```
template<class T = double> class weibull_distribution;
template<class T = double> class extreme_value_distribution;
template<class T = double> class normal_distribution;
template<class T = double> class lognormal_distribution;
template<class T = double> class chi_squared_distribution;
template<class T = double> class cauchy_distribution;
template<class T = double> class fisher_f_distribution;
template<class T = double> class student_t_distribution;
template<class T = double> class
piecewise_constant_distribution;
template<class T = double> class piecewise_linear_distribution;
template<class T = double> class uniform_real_distribution;
```

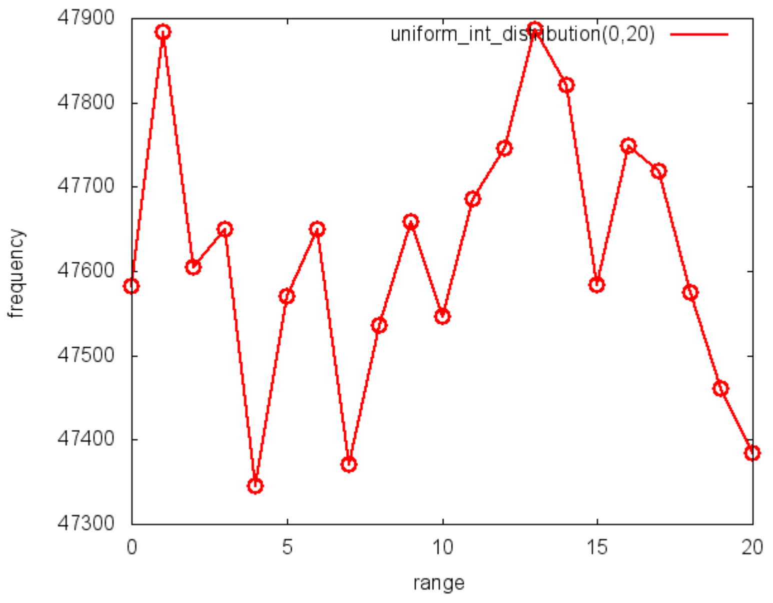
Class templates with a default template argument `int` are discrete. The Bernoulli distribution generates booleans.

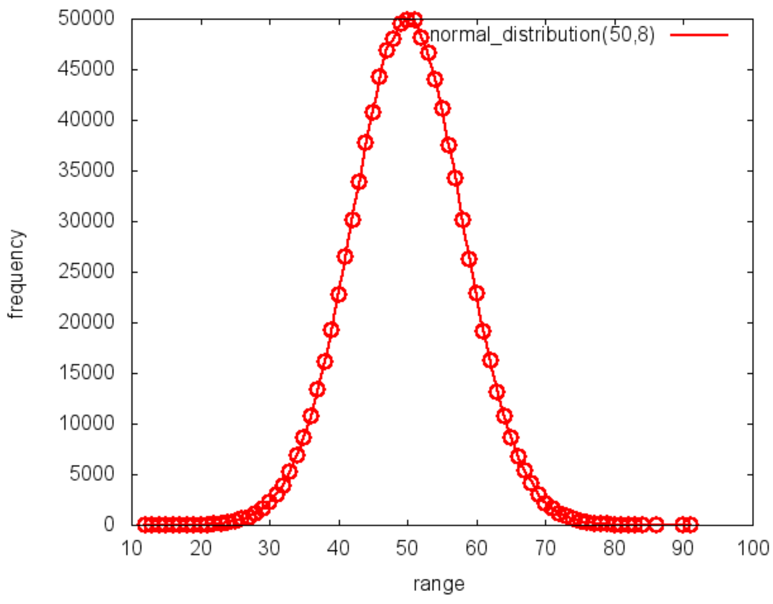
Here is an example using the Mersenne Twister `std::mt19937` as the pseudo-random number generator for generating one million random numbers. The random number stream is mapped to the uniform and normal (or Gaussian) distribution.

Random numbers

```
// random.cpp
...
#include <random>
...

static const int NUM= 1000000;
std::random_device seed;
std::mt19937 gen(seed());
std::uniform_int_distribution<> uniformDist(0, 20); // min= 0;
max= 20
std::normal_distribution<> normDist(50, 8);         // mean= 50;
sigma= 8

std::map<int, int> uniformFrequency;
std::map<int, int> normFrequency;
for (int i= 1; i <= NUM; ++i){
  ++uniformFrequency[uniformDist(gen)];
  ++normFrequency[round(normDist(gen))];
}
```

The following pictures show the uniform and the normal distribution of the one million random numbers as a plot.





Numeric Functions Inherited from C

C++ inherited many numeric functions from C. They need the header `<cmath>`. The table below shows the names of these functions.

Mathematical functions in `<cmath>`

pow	sin	tanh	asinh	fabs
exp	cos	asin	aconsh	fmod
sqrt	tan	acos	atanh	frexp
log	sinh	atan	ceil	ldexp
log10	cosh	atan2	floor	modf

Additionally, C++ inherits mathematical functions from C. They are defined in the header `<cstdlib>`. Once more, here are the names.

Mathematical functions in `<cstdlib>`

abs	llabs	ldiv	srand
labs	div	lldiv	rand

All functions for integers are available for the types `int`, `long`, and ‘long long`; all functions for floating-point numbers are available for the types `float`, `double`, and 'long double`.

The numeric functions need to be qualified with the namespace `std`.

Mathematic functions

```
// mathFunctions.cpp
...
#include <cmath>
#include <cstdlib>
...

std::cout << std::pow(2, 10);     // 1024
std::cout << std::pow(2, 0.5);    // 1.41421
std::cout << std::exp(1);         // 2.71828
std::cout << std::ceil(5.5);      // 6
std::cout << std::floor(5.5);     // 5
std::cout << std::fmod(5.5, 2);   // 1.5

double intPart;
auto fracPart= std::modf(5.7, &intPart);
std::cout << intPart << " + " << fracPart;           // 5 + 0.7
std::div_t divresult= std::div(14, 5);
std::cout << divresult.quot << " " << divresult.rem; // 2 4

// seed
std::srand(time(nullptr));
for (int i= 0;i < 10; ++i) std::cout << (rand()%6 + 1) << " ";
                                                // 3 6 5 3 6 5 6 3 1 5
```

Mathematical Constants

C++ supports basic and advanced mathematical constants. The mathematical constants have the data type `double`. They are in the namespace `std::number` and part of the header `<numbers>`.

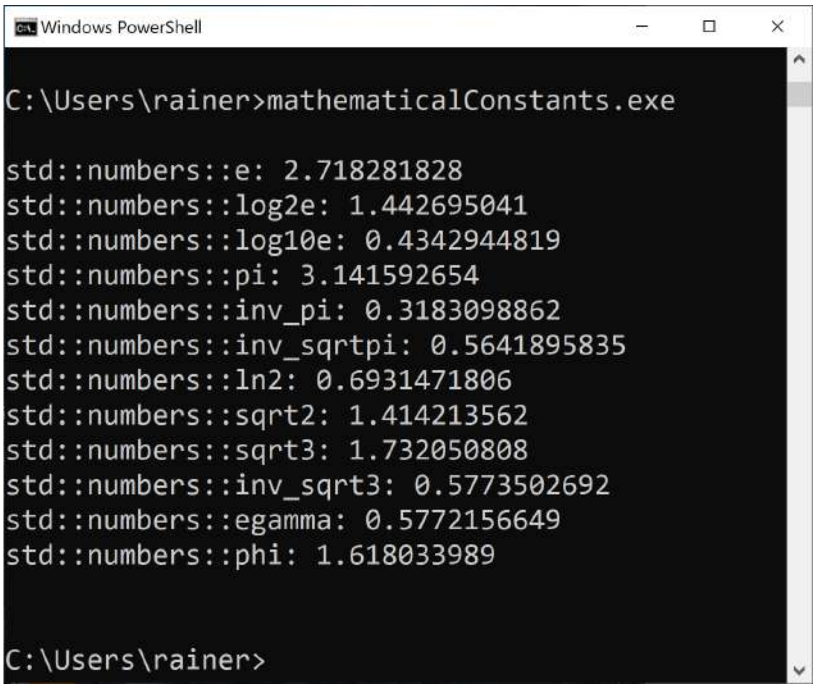
The mathematical constants

Mathematical Constant	Meaning
`std::numbers::e`	e
`std::numbers::log2e`	$\log_2 e$
`std::numbers::log10e`	$\log_{10} e$
`std::numbers::pi`	π
`std::numbers::inv_pi`	$\frac{1}{\pi}$
`std::numbers::inv_sqrtpi`	$\frac{1}{\sqrt{\pi}}$
`std::numbers::ln2`	$\ln 2$
`std::numbers::ln10`	$\ln 10$
`std::numbers::sqrt2`	$\sqrt{2}$
`std::numbers::sqrt3`	$\sqrt{3}$
`std::numbers::inv_sqrt3`	$\frac{1}{\sqrt{3}}$
`std::numbers::egamma`	Euler-Mascheroni constant
`std::numbers::phi`	ϕ

The following code snippet displays all mathematical constants.

Mathematic functions

```
// mathematicalConstants.cpp
#include <numbers>
...

std::cout<< std::setprecision(10);

std::cout << "std::numbers::e: " <<  std::numbers::e << '\n';
std::cout << "std::numbers::log2e: " <<  std::numbers::log2e <<
'\n';
std::cout << "std::numbers::log10e: " <<  std::numbers::log10e
<< '\n';
std::cout << "std::numbers::pi: " <<  std::numbers::pi << '\n';
std::cout << "std::numbers::inv_pi: " <<  std::numbers::inv_pi
<< '\n';
std::cout << "std::numbers::inv_sqrtpi: " <<
std::numbers::inv_sqrtpi << '\n';
std::cout << "std::numbers::ln2: " <<  std::numbers::ln2 <<
'\n';
std::cout << "std::numbers::sqrt2: " <<  std::numbers::sqrt2 <<
'\n';
std::cout << "std::numbers::sqrt3: " <<  std::numbers::sqrt3 <<
'\n';
std::cout << "std::numbers::inv_sqrt3: " <<
std::numbers::inv_sqrt3 << '\n';
std::cout << "std::numbers::egamma: " <<  std::numbers::egamma
<< '\n';
std::cout << "std::numbers::phi: " <<  std::numbers::phi <<
'\n';
```

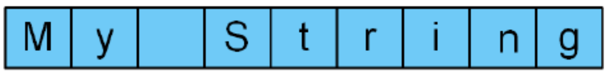


```
C:\Users\rainer>mathematicalConstants.exe

std::numbers::e: 2.718281828
std::numbers::log2e: 1.442695041
std::numbers::log10e: 0.4342944819
std::numbers::pi: 3.141592654
std::numbers::inv_pi: 0.3183098862
std::numbers::inv_sqrtpi: 0.5641895835
std::numbers::ln2: 0.6931471806
std::numbers::sqrt2: 1.414213562
std::numbers::sqrt3: 1.732050808
std::numbers::inv_sqrt3: 0.5773502692
std::numbers::egamma: 0.5772156649
std::numbers::phi: 1.618033989


C:\Users\rainer>
```

13. Strings

Cippi plays with a snake

A string is a sequence of characters. C++ has many member functions to analyze or change a string. C++-strings are the safe replacement for C Strings: `const char*`. Strings need the header `<string>`.



A string is similar to a `std::vector`

A string feels like a `std::vector` containing characters. It supports a very similar interface. This means that you have the algorithms of the Standard Template Library to operate on a string.

The following code snippet has the `std::string name` with the value `RainerGrimm`. I use the STL algorithm `std::find_if` to get the upper letter and then extract my first and last name into the variables `firstName` and `lastName`. The expression `name.begin()+1` shows, that strings support random access iterators:

string versus vector

```
// string.cpp
...
#include <algorithm>
#include <string>

std::string name{"RainerGrimm"};
auto strIt= std::find_if(name.begin()+1, name.end(),
                          [](char c){ return
std::isupper(c); });
if (strIt != name.end()){
  firstName= std::string(name.begin(), strIt);
  lastName= std::string(strIt, name.end());
}
```

Strings are class templates parametrized by their character, character trait, and allocator. The character trait and the allocator have defaults.

```
template <typename charT,
          typename traits= char_traits<charT>,
          typename Allocator= allocator<charT> >
class basic_string;
```

C++ has synonyms for the character types `char`, `wchar_t`, `char16_t` and `char32_t`

```
typedef basic_string<char> string;
typedef basic_string<wchar_t> wstring;
typedef basic_string<char16_t> u16string;
typedef basic_string<char32_t> u32string;
```

`std::string` is the string

If we speak in C++ about a string, we refer with 99 % probability to the specialization `std::basic_string` for the character type `char`. This statement is also true for this book.

Create and Delete

C++ offers many member functions to create strings from C or C++-strings. Under the hood, a C string is always involved for creating a C++-string. That changes with C++14, because the new C++ standard support C++-string literals: `std::string str{"string"s}`. The C string literals `"string literal"` becomes with the suffix `s` a C++-string literal: `"string literal"s`.

The table gives an overview of the member functions to create and delete a C++-string.

Member Functions to create and delete a string

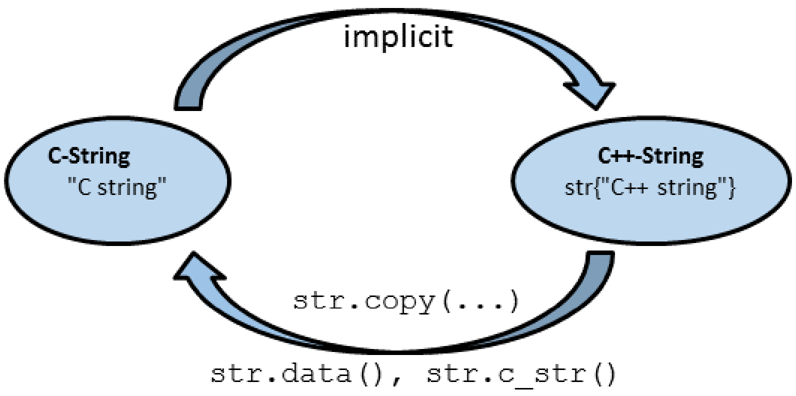
Member Functions	Example
Default	`std::string str`
Copies from a C++-string	`std::string str(oth)`
Moves from a C++-string	`std::string str(std::move(oth))`
From the range of a C++-string	`std::string(oth.begin(), oth.end())`
From a substring of a C++-string	`std::string(oth, otherIndex)`
From a substring of a C++-string	`std::string(oth, otherIndex, strlen)`
From a C string	`std::string str("c-string")`
From a C array	`std::string str("c-array", len)`
From characters	`std::string str(num, 'c')`
From an initializer list	`std::string str({'a', 'b', 'c', 'd'})`
From a substring	`str= other.substring(3, 10)`
Destructor	`str.~string()`

Creation of a string

```
// stringConstructor.cpp
...
```

```
#include <string>
...
std::string defaultString;
std::string other{"123456789"};
std::string str1(other);                      // 123456789
std::string tmp(other);                       // 123456789
std::string str2(std::move(tmp));             // 123456789
std::string str3(other.begin(), other.end()); // 123456789
std::string str4(other, 2);                   // 3456789
std::string str5(other, 2, 5);                // 34567
std::string str6("123456789", 5);             // 12345
std::string str7(5, '1');                     // 11111
std::string str8({'1', '2', '3', '4', '5'});  // 12345
std::cout << str6.substr();                   // 12345
std::cout << str6.substr(1);                  // 2345
std::cout << str6.substr(1, 2);               // 23
```

Conversion Between C++ and C Strings



While the conversion of a C string into a C++-string id done implicitly, you must explicitly request the conversion from a C++-string into a C string. `str.copy()` copies the content of a C++-string without the terminating `\0` character. `str.data()` and `str.c_str()` includes the terminating null character.

Be careful with `str.data()` and `str.c_str()`

The return value of the two member functions `str.data()` and `std.c_str()` is invalid, if you modify the `str`.

C versus C++-strings

```
// stringCversusC++.cpp
...
#include<string>
...

std::string str{"C++-String"};
str += " C-String";
std::cout << str;                  // C++-String C-String
const char* cString= str.c_str();
char buffer[10];
str.copy(buffer, 10);
str+= "works";
// const char* cString2= cString; // ERROR
std::string str2(buffer, buffer+10);
std::cout<< str2;                  // C++-String
```

Size versus Capacity

The number of elements a string has (`str.size()`) is in general, smaller than the number of elements for which space is reserved: `str.capacity()`. Therefore if you add elements to a string, there will not automatically be new memory allocated. `std:max_size()` return how many elements a string can maximal have. For the three member functions the following relation holds: `str.size() <= str.capacity() <= str.max_size()`.

The following table shows the member functions for dealing with the memory management of the string.

Member Functions to create and delete a string

Member Functions	**Description**
`str.empty()`	Checks if `str` has elements.
`str.size()`, `str.length()`	Number of elements of the `str`.
`str.capacity()`	Number of elements `str` can have without reallocation.
`str.max_size()`	Number of elements `str` can maximal have.
`str.resize(n)`	Resize `str` to `n` elements.
`str.resize_and_overwrite(n, op)`	Resize `str` to `n` elements and applies the operation `op` to its elements.
`str.reserve(n)`	Reserve memory for a least `n` elements.
`str.shrink_to_fit()`	Adjusts the capacity of the string to it's size.

The request `str.shrink_to_fit()` is, as in the case of [`std::vector`](), non-binding.

Size versus capacity

```
// stringSizeCapacity.cpp
...
#include <string>
...
```

```
void showStringInfo(const std::string& s){
  std::cout << s << ": ";
  std::cout << s.size() << " ";
  std::cout << s.capacity() << " ";
  std::cout << s.max_size() << " ";
}

std::string str;
showStringInfo(str);  // "": 0 0 4611686018427387897

str +="12345";
showStringInfo(str);  // "12345": 5 5 4611686018427387897

str.resize(30);
showStringInfo(str);  // "12345": 30 30 4611686018427387897

str.reserve(1000);
showStringInfo(str);  // "12345": 30 1000 4611686018427387897

str.shrink_to_fit();
showStringInfo(str);  // "12345": 30 30 4611686018427387897
```

Comparison

Strings support the well-known comparison operators `==`, `!=`, `<`, `>`, `>=`. The comparison of two strings takes place on their elements.

String comparison

```
// stringComparisonAndConcatenation.cpp
...
#include <string>
...

std::string first{"aaa"};
std::string second{"aaaa"};

std::cout << (first < first) << '\n';  // false
std::cout << (first <= first) << '\n'; // true
std::cout << (first < second) << '\n'; // true
```

String Concatenation

The + operator is overloaded for strings, so you can *add* strings.

The + operator is only overloaded for C++-strings

The C++ type system permits it to concatenate C++ and C strings to C++-strings, but not to concatenate C++ and C strings to C strings. The reason is that the + operator is overloaded for C++-strings. Therefore only the second line is valid C++ because the C is implicitly converted to a C++-string:

String Concatenation

```
// stringComparisonAndConcatenation.cpp
...
#include <string>
...
std::string wrong= "1" + "1"; // ERROR
std::string right= std::string("1") + "1"; // 11
```

Element Access

Access to the elements of a string `str` is very convenient because the string supports random access iterators. You can access with `str.front()` the first character, and with `str.back()` the last character of the string. With `str[n]` and `str.at(n)`, you get the n-th element by index.

The following table provides an overview.

Access the elements of the string

Member Functions	Example
`str.front()`	Returns the first character of `str`.
`str.back()`	Returns the last character of `str`.
`str[n]`	Returns the n-th character of `str`. The string boundaries **will not be checked**.
`str.at(n)`	Returns the n-th character of `str`. The string boundaries **will be checked**. If the boundaries are violated, a `std::out_of_range` exception is thrown.

```
// stringAccess.cpp
...
#include <string>
...

std::string str= {"0123456789"};
std::cout << str.front() << '\n';             // 0
std::cout << str.back() << '\n';              // 9
for (int i= 0; i <= 3; ++i){
  std::cout << "str[" << i << "]:" << str[i] << "; ";
} // str[0]: 0; str[1]: 1; str[2]: 2; str[3]: 3;

std::cout << str[10] << '\n';                 // undefined
behaviour
try{
  str.at(10);
}
catch (const std::out_of_range& e){
  std::cerr << "Exception: " << e.what() << '\n';
} // Exception: basic_string::at

std::cout << *(&str[0]+5) << '\n';           // 5
std::cout << *(&str[5]) << '\n';             // 5
std::cout << str[5] << '\n';                 // 5
```

It is exciting to see in the example that the compiler performs the invocation `str[10]`. The access outside the string boundaries is *undefined behavior*. On the contrary, the compiler complains about the call `str.at(10)`.

Input and Output

A string can read from an input stream via >> and write to an output stream via <<.

The global function `getline` empowers you to read from an input stream line by line until the *end-of-file* character.

There are four variations of the `getline` function available. The first two arguments are the input stream `is` and the string `line` holding the line read. Optionally you can specify a special line separator. The function returns by reference to the input stream.

```
istream& getline (istream& is, string& line, char delim);
istream& getline (istream&& is, string& line, char delim);
istream& getline (istream& is, string& line);
istream& getline (istream&& is, string& line);
```

`getline` consumes the whole line, including empty spaces. Only the line separator is ignored. The function needs the header `<string>`.

Input and output with strings

```
// stringInputOutput.cpp
...
#include <string>
...

std::vector<std::string> readFromFile(const char* fileName){
  std::ifstream file(fileName);
  if (!file){
    std::cerr << "Could not open the file " << fileName << ".";
    exit(EXIT_FAILURE);
  }
  std::vector<std::string> lines;
  std::string line;
  while (getline(file , line)) lines.push_back(line);
  return lines;
}

std::string fileName;
std::cout << "Your filename: ";
std::cin >> fileName;
std::vector<std::string> lines= readFromFile(fileName.c_str());
int num{0};
for (auto line: lines) std::cout << ++num << ": " << line <<
'\n';
```

The program displays the lines of an arbitrary file, including their line number. The expression `std::cin >> fileName` reads the file name. The function `readFromFile` reads with `getline` all file lines and pushes them onto the vector.

Search

C++ offers the ability to search in a string in many variations. Each variation exists in various overloaded forms.

Search is called find

Odd enough, the algorithms for searching in a string start with the name find. If the search was successful, you get the index of type `std::string::size_type`. If not, you get the constant `std::string::npos`. The first character has index 0.

The find algorithms support:

- search for a character, a C String, or a C++-string,
- search for a character from a C or C++-string,
- search forward and backward,
- search positive (does contain) or negative(does not contain) for characters from a C or C++-string,
- start the search at an arbitrary position in the string.

The arguments of all six variations of the find functions follow a similar pattern. The first argument is the text you are searching for. The second argument holds the start position of the search, and the third the number of characters starting from the second argument.

Here are the six variations.

Find variations of the string

Member Functions	Description
`str.find(...)`	Returns the first position of a character, a C or C++-string in `str`.
`str.rfind(...)`	Returns the last position of a character, a C or C++-string in `str`.
`str.find_first_of(...)`	Returns the first position of a character from a C or C++-string in `str`.
`str.find_last_of(...)`	Returns the last position of a character from a C or C++-string in `str`.
`str.find_first_not_of(...)`	Returns the first position of a character in `str`, which is not from a C or C++-string.
`str.find_last_not_of(...)`	Returns the last position of a character in `str`, which is not from a C or C++-string.

Find(search) in a string

```
// stringFind.cpp
...
#include <string>
...

std::string str;

auto idx= str.find("no");
if (idx == std::string::npos) std::cout << "not found";   // not
found

str= {"dkeu84kf8k48kdj39kdj74945du942"};
std::string str2{"84"};

std::cout << str.find('8');                               // 4
std::cout << str.rfind('8');                              // 11
std::cout << str.find('8', 10);                           // 11
```

```
std::cout << str.find(str2);                              // 4
std::cout << str.rfind(str2);                             // 4
std::cout << str.find(str2, 10);                          //
18446744073709551615

str2="0123456789";

std::cout << str.find_first_of("678");                     // 4
std::cout << str.find_last_of("678");                      // 20
std::cout << str.find_first_of("678", 10);                 // 11
std::cout << str.find_first_of(str2);                      // 4
std::cout << str.find_last_of(str2);                       // 29
std::cout << str.find_first_of(str2, 10);                  // 10
std::cout << str.find_first_not_of("678");                 // 0
std::cout << str.find_last_not_of("678");                  // 29
std::cout << str.find_first_not_of("678", 10);             // 10
std::cout << str.find_first_not_of(str2);                  // 0
std::cout << str.find_last_not_of(str2);                   // 26
std::cout << str.find_first_not_of(str2, 10);              // 12
```

The call `std::find(str2, 10)` returns `std::string::npos`. If I display that value, I get on my platform `18446744073709551615`.

Check for a substring

The C++20 member function `str.starts_with(prefix)` and `str.end_with(suffix)` check for a string `str` if it begins with a `prefix` or ends with a `suffix`. Additionally, in C++23 you can check with `str.contains` if a string has a substring.

Check for a Prefix or a Suffix

The member function `str.starts_with(prefix)` and `str.end_with(suffix)` check for a given string `str` if it begins with a `prefix` or ends with a `suffix`. The substring can be a `std::string_view`, a single character, or a string.

Check if the string starts with or ends with a prefix or suffix

```
// startWithEndsWith.cpp
...
#include <string>
...
std::string helloWorld = "hello world";

std::cout << helloWorld.starts_with("hello") << '\n'; // true
std::cout << helloWorld.starts_with("llo") << '\n';   // false

std::cout << helloWorld.ends_with("world") << '\n';   // true
std::cout << helloWorld.ends_with("wo") << '\n';      // false
```

Check for a Containing Substring

`str.contains` checks with if a string has a substring. The substring can be a `std::string_view`, a single character, or a string.

Check if the string contains a substring

```
// containsString.cpp
...
#include <string>
...
std::string helloWorld = "hello world";

std::cout << helloWorld.contains("hello") << '\n'; // true
std::cout << helloWorld.contains("llo") << '\n';   // true
std::cout << helloWorld.contains('w') << '\n';     // true
std::cout << helloWorld.contains('W') << '\n';     // false
```

Modifying Operations

Strings have many operations to modify them. `str.assign` assigns a new string to the string `str`. With `str.swap` you can swap two strings. To remove a character from a string, use `str.pop_back` or `str.erase`. On contrary, `str.clear` or `str.erase` deletes the whole string. To append new characters to a string, use `+=`, `std.append` or `str.push_back`. You can use `str.insert` to insert new characters or `str.replace` to replace characters.

Member Functions for modifying a string

Member Functions	Description
`str= str2`	Assigns `str2` to `str`.
`str.assign(...)`	Assigns to `str`a new string.
`str.swap(str2)`	Swaps `str` and `str2`.
`str.pop_back()`	Removes the last character from `str`.
`str.erase(...)`	Removes characters from `str`.
`str.clear()`	Clears the `str`.
`str.append(...)`	Appends characters to `str`.
`str.push_back(s)`	Appends the character `s` to `str`.
`str.insert(pos, ...)`	Inserts characters in `str` starting at `pos`.
`str.replace(pos, len, ...)`	Replaces the `len` characters from `str` starting at `pos`

The operations are available in many overloaded versions. The member functions `str.assign`, `str.append`, `str.insert`, and `str.replace` are very similar. All four can be invoked with C++-strings and substrings, characters, C strings, C string arrays, ranges, and initializer lists. `str.erase` can erase a single character, ranges, and many characters starting at a given position.

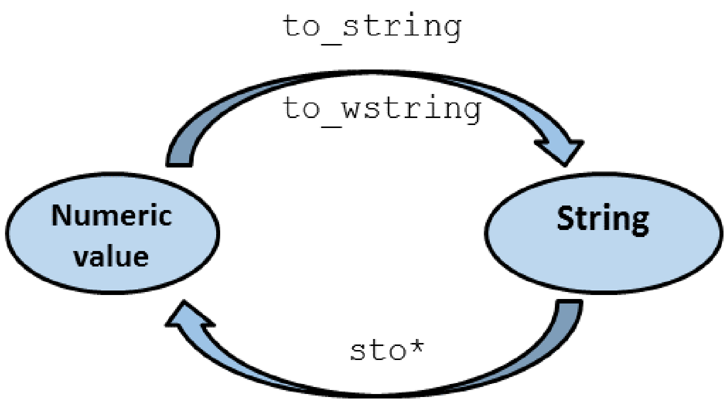
The following code snippet shows many of the variations. For simplicity reasons, only the effects of the strings modifications are displayed:

Modifying strings

```
// stringModification.cpp
...
```

```
#include <string>
...

std::string str{"New String"};
std::string str2{"Other String"};

str.assign(str2, 4, std::string::npos); // r String
str.assign(5, '-');                     // -----

str= {"0123456789"};
str.erase(7, 2);                        // 01234569
str.erase(str.begin()+2, str.end()-2);  // 012
str.erase(str.begin()+2, str.end());    // 01
str.pop_back();                         // 0
str.erase();                            //

str= "01234";
str+= "56";                      // 0123456
str+= '7';                       // 01234567
str+= {'8', '9'};                // 0123456789
str.append(str);                 // 01234567890123456789
str.append(str, 2, 4);           // 012345678901234567892345
str.append(3, '0');              // 012345678901234567892345000
str.append(str, 10, 10);         //
01234567890123456789234500001234567989
str.push_back('9');              //
012345678901234567892345000012345679899

str= {"345"};
str.insert(3, "6789");                // 3456789
str.insert(0, "012");                 // 0123456789

str= {"only for testing purpose."};
str.replace(0, 0, "0");               // Only for testing
purpose.
str.replace(0, 5, "Only", 0, 4);      // Only for testing
purpose.
str.replace(16, 8, "");               // Only for testing.
str.replace(4, 0, 5, 'y');            // Onlyyyyyy for testing.
str.replace(str.begin(), str.end(), "Only for testing
purpose.");
                                      // Only for testing
purpose.
str.replace(str.begin()+4, str.end()-8, 10, '#');
                                      //
Only############purpose.
```

Numeric Conversions



You can convert with `std::to_string(val)` and `std::to_wstring(val)` numbers or floating-point numbers to the corresponding `std::string` or `std::wstring`. You have the function family of the `sto`* functions for the opposite direction for converting numbers or floating-point numbers to strings. All functions need the header `<string>`.

Read `sto*` as string to

The seven ways to convert a string into a natural or floating-point number follow a simple pattern. All functions start with `sto` and add other characters, denoting the type to which the strings should be converted to. E.g. `stol` stands for a string to `long` or `stod` for a string to `double`.

The `sto` functions all have the same interface. The example shows it for the type `long`.

```
std::stol(str, idx= nullptr, base= 10)
```

The function takes a string and determines the `long` representation to the base `base`. `stol` ignores leading spaces and optionally returns the index of the first invalid character in `idx`. By default, the base is 10. Valid values for the base are 0 and 2 until 36. If you use base 0 the compiler automatically determines the type based on the format of the string. If the base is greater than ten, the compiler encodes them in the characters `a` until `z`. The representation is analogous to the representation of hexadecimal numbers.

The table gives an overview of all functions.

Numeric conversion of strings

Member Function	Description
`std::to_string(val)`	Converts `val` into a `std::string`.
`std::to_wstring(val)`	Converts `val` into a `std::wstring`.
`std::stoi(str)`	Returns an `int` value.
`std::stol(str)`	Returns a `long` value.
`std::stoll(str)`	Returns a `long long` value.
`std::stoul(str)`	Returns an `unsigned long` value.
`std::stoull(str)`	Returns an `unsigned long long` value.
`std::stof(str)`	Returns a `float` value.
`std::stod(str)`	Returns a `double` value.
`std::stold(str)`	Returns an `long double` value.

Where is the `stou` function?

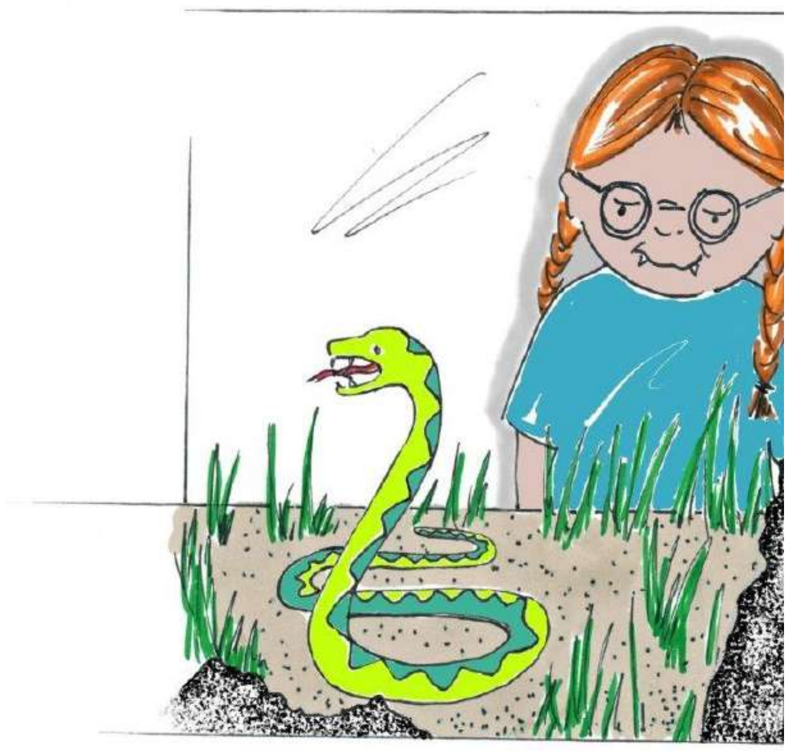
In case you're curious, the C++ `sto` functions are thin wrappers around the C `strto*` functions, but there is no `strtou` function in C. Therefore, C++ has no `stou` function.

The functions throw a `std::invalid_argument` exception if the conversion is impossible. If the determined value is too big for the destination type you get a `std::out_of_range` exception.

Numeric conversion

```
stringNumericConversion.cpp
...
#include <string>
...

std::string maxLongLongString=
            std::to_string(std::numeric_limits<long
long>::max());
std::wstring maxLongLongWstring=
            std::to_wstring(std::numeric_limits<long
long>::max());

std::cout << std::numeric_limits<long long>::max();     //
9223372036854775807
std::cout << maxLongLongString;                         //
9223372036854775807
std::wcout << maxLongLongWstring;                       //
9223372036854775807

std::string str("10010101");
std::cout << std::stoi(str);                            //
10010101
std::cout << std::stoi(str, nullptr, 16);               //
268501249
std::cout << std::stoi(str, nullptr, 8);                //
2101313
std::cout << std::stoi(str, nullptr, 2);                // 149

std::size_t idx;
std::cout << std::stod(" 3.5 km", &idx);                 // 3.5
std::cout << idx;                                        // 6

try{
  std::cout << std::stoi(" 3.5 km") << '\n';             // 3
  std::cout << std::stoi(" 3.5 km", nullptr, 2) << '\n';
}
catch (const std::exception& e){
  std::cerr << e.what() << '\n';
}                                                        // stoi
```

14. String Views



Cippi ovserves a Snake

A string view is a non-owning reference to a string. It represents a view of a sequence of characters. This sequence of characters can be a C++-string or a C-string. A string view needs the header `<string_view>`.

A string view is a for copying optimized string

From a birds-eye perspective, the purpose of `std::string_view` is to avoid copying data that is already owned by someone else and to allow immutable access to a `std::string` like object. The string view is a restricted string that supports only immutable operations. Additionally, a string view `sv` has two additional mutating operations: `sv.remove_prefix` and `sv.remove_suffix`.

String views are class templates parameterized by their character and their character trait. The character trait has a default. In contrast to a string, a string view is non-owner and, therefore, needs no allocator.

```
template<
    class CharT,
    class Traits = std::char_traits<CharT>
> class basic_string_view;
```

According to strings, string views exist four synonyms for the underlying character types `char`, `wchar_t`, `char16_t`, and `char32_t`.

```
typedef std::string_view std::basic_string_view<char>
typedef std::wstring_view std::basic_string_view<wchar_t>
typedef std::u16string_view std::basic_string_view<char16_t>
typedef std::u32string_view std::basic_string_view<char32_t>
```

std::string_view is the string view

If we speak in C++ about a string view, we refer with 99% probability to the specialization `std::basic_string_view` for the character type `char`. This statement is also true for this book.

Create and Initialise

You can create an empty string view. You can also create a string view from an existing string, character array, or string view.

The table below gives you an overview of the various ways of creating a string view.

Member Functions to create and set a string view

Member Functions	Example
Empty string view	`std::string_view str_view`
From a C-string	`std::string_view str_view2("C-string")`
From a string view	`std::string_view str_view3(str_view2)`
From a C array	`std::string_view str_view4(arr, sizeof arr)`
From a string_view	`str_view4= str_view3.substring(2, 3)`
From a string view	`std::string_view str_view5 = str_view4`

Non-modifying operations

To make this chapter concise and avoid repeating the detailed descriptions from the chapter on strings, I only mention the non-modifying operations of the string view. Please use the link to the associated documentation in the string chapter for further details.

- *Element access*: `operator[], at, front, back, data` (see string: element access)
- *Capacity*: `size, length, max_size, empty` (see string: size versus capacity)
- *Find*: `find, rfind, find_first_of, find_last_of, find_first_not_of, find_last_not_of` (see string: search)
- *Copy*: `copy` (see string: conversion between a C++-string and a C-String)

Modifying operations

The call `stringView.swap(stringView2)` swaps the content of the two string views. The member functions `remove_prefix` and `remove_suffix` are unique to a string view because a string supports neither. `remove_prefix` shrinks its start forward; `remove_suffix` shrinks its end backward.

Non-modifying operations

```
// string_view.cpp
...
#include <string_view>

...

using namespace std;
string str = "   A lot of space";
string_view strView = str;
strView.remove_prefix(min(strView.find_first_not_of(" "),
strView.size()));
cout << str << endl       // "   A lot of space
     << strView << endl; // "A lot of space"

char arr[] = {'A',' ','l','o','t',' ','o','f',' ',
              's','p','a','c','e','\0', '\0', '\0'};
string_view strView2(arr, sizeof arr);
auto trimPos = strView2.find('\0');
if(trimPos != strView2.npos)
strView2.remove_suffix(strView2.size() - trimPos);
cout << arr << ": " << sizeof arr << endl             // A lot
of space: 17
     << strView2 << ": " << strView2.size() << endl;  // A lot
of space: 14
```

No memory allocation with a string view

If you create a string view or copy a string view, no memory allocation is necessary. This contrasts with a string; creating or copying a string requires memory allocation.

Memory allocation

```
// stringView.cpp
...
include <string_view>

...

void* operator new(std::size_t count){
   std::cout << "   " << count << " bytes" << '\n';
   return malloc(count);
}

void getString(const std::string&){}

void getStringView(std::string_view){}

std::string large = "012345678901234567890"
                   "1234567890123456789";  // 41 bytes
allocated
std::string substr = large.substr(10);      // 31 bytes
allocated

std::string_view largeStringView{large.c_str(), // 0
bytes allocated
                                large.size()};
largeStringView.remove_prefix(10);              // 0
bytes allocated

getString(large);
getString("012345678901234567890"
         "1234567890123456789");            // 41 bytes
allocated
const char message []=
"0123456789012345678901234567890123456789";
getString(message);                         // 41 bytes
allocated

getStringView(large);                   // 0 bytes
allocated
getStringView("012345678901234567890"
             "1234567890123456789");    // 0 bytes
allocated
getStringView(message);                 // 0 bytes
allocated
```

Thanks to the global overload `operator new`, I can observe each memory allocation.

15. Regular Expressions

Cippi analysis tracks in the Snow

Regular expression is a language for describing text patterns. They need the header `<regex>`.

Regular expressions are a powerful tool for the following tasks:

- Check if a text matches a text pattern: `std::regex_match`
- Search for a text pattern in a text: `std::regex_search`
- Replace a text pattern with a text: `std::regex_replace`
- Iterate through all text patterns in a text: `std::regex_iterator` and `std::regex_token_iterator`

C++ supports six different grammar for regular expressions. By default, the ECMAScript grammar is used. This one is the most powerful grammar of the six grammars and is quite similar to the grammar used in Perl 5. The other five grammars are the basic, extended, awk, grep, and egrep grammars.

Use raw strings

Use raw string literals in regular expressions. The regular expression for the text C++ is quite ugly: `C\\+\\+`. You have to use two backslashes for each + sign. First, the + sign is a unique character in a regular expression. Second, the backslash is a special character in a string. Therefore one backslash escapes the + sign; the other backslash escapes the backslash. By using a raw string literal, the second backslash is not necessary anymore because the backslash is not interpreted in the string.

```
#include <regex>
...
std::string regExpr("C\\+\\+");
std::string regExprRaw(R"(C\+\+)");
```

Dealing with regular expressions is typically done in three steps:

I. Define the regular expression:

```
std::string text="C++ or c++.";
std::string regExpr(R"(C\+\+)");
std::regex rgx(regExpr);
```

II. Store the result of the search:

```
std::smatch result;
std::regex_search(text, result, rgx);
```

III. Process the result:

```
std::cout << result[0] << '\n';
```

Character Types

The text type determines the character type of the regular expression and the type of the search result.

The table shows the four different combinations.

Combinations of type of text, regular expression, search result and action

Text type	Regular expression type	Result type
`const char*`	`std::regex`	`std::cmatch`
`std::string`	`std::regex`	`std::smatch`
`const wchar_t*`	`std::wregex`	`std::wcmatch`
`std::wstring`	`std::wregex`	`std::wsmatch`

The program shown in the Search section of this chapter provides the four combinations in detail.

Regular Expression Objects

Objects of type regular expression are instances of the class template `template <class charT, class traits= regex_traits <charT>> class basic_regex` parametrized by their character type and traits class. The traits class defines the interpretation of the properties of regular grammar. There are two type synonyms in C++:

```
typedef basic_regex<char> regex;
typedef basic_regex<wchar_t> wregex;
```

You can further customize the object of type regular expression. Therefore you can specify the grammar used or adapt the syntax. As mentioned, C++ supports the basic, extended, awk, grep, and egrep grammars. A regular expression qualified by the `std::regex_constants::icase` flag is case insensitive. If you want to adopt the syntax, you have to specify the grammar explicitly.

Specify the grammar

```
// regexGrammar.cpp
...
#include <regex>
...
using std::regex_constants::ECMAScript;
using std::regex_constants::icase;

std::string theQuestion="C++ or c++, that's the question.";
std::string regExprStr(R"(c\+\+)");
```

```
std::regex rgx(regExprStr);
std::smatch smatch;

if (std::regex_search(theQuestion, smatch, rgx)){
  std::cout << "case sensitive: " << smatch[0];       // c++
}

std::regex rgxIn(regExprStr, ECMAScript|icase);
if (std::regex_search(theQuestion, smatch, rgxIn)){
  std::cout << "case insensitive: " << smatch[0];     // C++
}
```

If you use the case-sensitive regular expression `rgx`, the result of the search in the text `theQuestion` is `c++`. That's not the case if your case-insensitive regular expression `rgxIn` is applied. Now you get the match string `C++`.

The Search Result match_results

The object of type `std::match_results` is the result of a `std::regex_match` or `std::regex_search`. `std::match_results` is a sequence container having at least one capture group of a `std::sub_match` object. The `std::sub_match` objects are sequences of characters.

What is a capture group?

Capture groups allow it to further analyze the search result in a regular expression. They are defined by a pair of parentheses `( )`. The regular expression `((a+)(b+)(c+))` has four capture groups: `((a+)(b+)(c+))`, `(a+)`, `(b+)` and `(c+)` The total result is the 0-th capture group.

C++ has four types of synonyms of type `std::match_results`:

```
typedef match_results<const char*> cmatch;
typedef match_results<const wchar_t*> wcmatch;
typedef match_results<string::const_iterator> smatch;
typedef match_results<wstring::const_iterator> wsmatch;
```

The search result `std::smatch smatch` has a powerful interface.

Interface of std::smatch

Member Function	Description
`smatch.size()`	Returns the number of capture groups.
`smatch.empty()`	Returns if the search result has a capture group.
`smatch[i]`	Returns the ith capture group.
`smatch.length(i)`	Returns the length of the ith capture group.
`smatch.position(i)`	Returns the position of the ith capture group.
`smatch.str(i)`	Returns the ith capture group as string.
`smatch.prefix()` and `smatch.suffix()`	Returns the string before and after the capture group.
`smatch.begin()` and `smatch.end()`	Returns the begin and end iterator for the capture groups.
`smatch.format(...)`	Formats `std::smatch` objects for the output.

The following program shows the output of the first four capture groups for different regular expressions.

Capture groups

```
// captureGroups.cpp
...
#include<regex>
...
using namespace std;

void showCaptureGroups(const string& regEx, const string& text){
  regex rgx(regEx);
  smatch smatch;
  if (regex_search(text, smatch, rgx)){
    cout << regEx << text << smatch[0] << " " << smatch[1]
         << " "<< smatch[2] << " " << smatch[3] << endl;
  }
}

showCaptureGroups("abc+", "abccccc");
showCaptureGroups("(a+)(b+)", "aaabccc");
showCaptureGroups("((a+)(b+))", "aaabccc");
showCaptureGroups("(ab)(abc)+", "ababcabc");
...

reg Expr            text        smatch[0]     smatch[1]
smatch[2]     smatch[3]
abc+                abccccc     abccccc
(a+)(b+)(c+)        aaabccc     aaabccc       aaa           b
ccc
((a+)(b+)(c+))      aaabccc     aaabccc       aaabccc       aaa
b
(ab)(abc)+          ababcabc    ababcabc      ab            abc
```

`std::sub_match`

The capture groups are of type `std::sub_match`. As with [std::match_results]() C++ defines the following four type synonyms.

```
typedef sub_match<const char*> csub_match;
typedef sub_match<const wchar_t*> wcsub_match;
typedef sub_match<string::const_iterator> ssub_match;
typedef sub_match<wstring::const_iterator> wssub_match;
```

You can further analyze the capture group `cap`.

The `std::sub_match` object

Member Function	Description
`cap.matched()`	Indicates if this match was successful.
`cap.first()` and `cap.end()`	Returns the begin and end iterator of the character sequence.
`cap.length()`	Returns the length of the capture group.
`cap.str()`	Returns the capture group as string.
`cap.compare(other)`	Compares the current capture group with the other capture group.

Here is a code snippet showing the interplay between the search result `std::match_results` and its capture groups `std::sub_match`.

std::sub_match

```
// subMatch.cpp
...
#include <regex>
...

using std::cout;

std::string privateAddress="192.168.178.21";
std::string regEx(R"((\d{1,3})\.(\d{1,3})\.(\d{1,3})\.
(\d{1,3}))");
std::regex rgx(regEx);
std::smatch smatch;

if (std::regex_match(privateAddress, smatch, rgx)){
  for (auto cap: smatch){
  cout << "capture group: " << cap << '\n';
  if (cap.matched){
    std::for_each(cap.first, cap.second, [](int v){
      cout << std::hex << v << " ";});
      cout << '\n';
    }
  }
}
...

capture group: 192.168.178.21
31 39 32 2e 31 36 38 2e 31 37 38 2e 32 31

capture group: 192
31 39 32

capture group: 168
31 36 38

capture group: 178
31 37 38

capture group: 21
32 31
```

The regular expression `regEx` stands for an IPv4 address. `regEx` extracts the address’s components using capture groups. Finally, the capture groups and the characters in ASCII are displayed in hexadecimal values.

Match

`std::regex_match` determines if the text matches a text pattern. You can further analyze the search result of type std::match_results.

The code snippet below shows three simple applications of std::regex_match: a C string, a C++ string, and a range returning only a boolean. The three variants are available for std::match_results objects, respectively.

std::match

```
// match.cpp
...
#include <regex>
...

std::string numberRegEx(R"([-+]?([0-9]*\.[0-9]+|[0-9]+))");
std::regex rgx(numberRegEx);
const char* numChar{"2011"};

if (std::regex_match(numChar, rgx)){
  std::cout << numChar << "is a number." << '\n';
}                                            // 2011 is a
number.

const std::string numStr{"3.14159265359"};
if (std::regex_match(numStr, rgx)){
  std::cout << numStr << " is a number." << '\n';
}                                           // 3.14159265359 is
a number.

const std::vector<char> numVec{{'-', '2', '.', '7', '1', '8',
'2',
                                '8', '1', '8', '2', '8'}};
if (std::regex_match(numVec.begin(), numVec.end(), rgx)){
    for (auto c: numVec){ std::cout << c ;};
    std::cout << "is a number." << '\n';
}                                           // -2.718281828 is a
number.
```

Search

std::regex_search checks if the text contains a text pattern. You can use the function with and without a std::match_results object and apply it to a C string, a C++ string, or a range.

The example below shows how to use std::regex_search with texts of type const char*, std::string, const wchar_t*, and std::wstring.

std::search

```
// search.cpp
...
#include <regex>
...
```

```
// regular expression holder for time
std::regex crgx("([01]?[0-9]|2[0-3]):[0-5][0-9]");

// const char*
std::cmatch cmatch;

const char* ctime{"Now it is 23:10." };
if (std::regex_search(ctime, cmatch, crgx)){
  std::cout << ctime << '\n';                    // Now it is
23:10.
  std::cout << "Time: " << cmatch[0] << '\n';    // Time: 23:10
}

// std::string
std::smatch smatch;

std::string stime{"Now it is 23:25." };
if (std::regex_search(stime, smatch, crgx)){
  std::cout << stime << '\n';                    // Now it is
23:25.
  std::cout << "Time: " << smatch[0] << '\n';    // Time: 23:25
}

// regular expression holder for time
std::wregex wrgx(L"([01]?[0-9]|2[0-3]):[0-5][0-9]");

// const wchar_t*
std::wcmatch wcmatch;

const wchar_t* wctime{L "Now it is 23:47." };
if (std::regex_search(wctime, wcmatch, wrgx)){
  std::wcout << wctime << '\n';                  // Now it is
23:47.
  std::wcout << "Time: " << wcmatch[0] << '\n'; // Time: 23:47
}

// std::wstring
std::wsmatch wsmatch;

std::wstring  wstime{L "Now it is 00:03." };
if (std::regex_search(wstime, wsmatch, wrgx)){
  std::wcout << wstime << '\n';                   // Now it is
00:03.
  std::wcout << "Time: " << wsmatch[0] << '\n';   // Time: 00:03
}
```

Replace

`std::regex_replace` replaces sequences in a text matching a text pattern. It returns in the simple form `std::regex_replace(text, regex, replString)` its result as string. The function replaces an occurrence of `regex` in `text` with `replString`.

`std::replace`

```
// replace.cpp
...
#include <regex>
...
using namespace std;

string future{"Future"};
string unofficialName{"The unofficial name of the new C++
standard is C++0x."};

regex rgxCpp{R"(C\+\+0x)"};
string newCppName{"C++11"};
string newName{regex_replace(unofficialName, rgxCpp,
newCppName)};

regex rgxOff{"unofficial"};
string makeOfficial{"official"};
string officialName{regex_replace(newName, rgxOff,
makeOfficial)};

cout << officialName << endl;
                          // The official name of the new C++
standard is C++11.
```

In addition to the simple version, C++ has a version of `std::regex_replace` working on ranges. It enables you to push the modified string directly into another string:

```
typedef basic_regex<char> regex;
std::string str2;
std::regex_replace(std::back_inserter(str2),
                   text.begin(), text.end(), regex,replString);
```

All variants of `std::regex_replace` have an additional optional parameter. If you set the parameter to `std::regex_constants::format_no_copy`, you will get the part of the text matching the regular expression. The unmatched text is not copied. If you set the parameter to `std::regex_constants::format_first_only` `std::regex_replace` will only be applied once.

Format

`std::regex_replace` and `std::match_results.format` in combination with capture groups enables you to format text. You can use a format string together with a placeholder to insert the value.

Here are both possibilities:

Formatting with regex

```
// format.cpp
...
#include <regex>
...

std::string future{"Future"};
const std::string unofficial{"unofficial, C++0x"};
const std::string official{"official, C++11"};

std::regex regValues{"(.*),(.*)"};
std::string standardText{"The $1 name of the new C++ standard is
$2."};
std::string textNow= std::regex_replace(unofficial, regValues,
standardText);
std::cout << textNow << '\n';
                        // The unofficial name of the new C++
standard is C++0x.

std::smatch smatch;
if (std::regex_match(official, smatch, regValues)){
  std::cout << smatch.str();
// official,C++11
  std::string textFuture= smatch.format(standardText);
  std::cout << textFuture << '\n';
}                       // The official name of the new C++
standard is C++11.
```

In the function call `std::regex_replace(unoffical, regValues, standardText)`, the text matching the first and second capture group of the regular expression `regValues` is extracted from the string `unofficial`. The placeholders `$1` and `$2` in the text `standardText` are then replaced by the extracted values. The strategy of `smatch.format(standardTest)` is similar, but there is a difference:

The creation of the search results `smatch` is separated from their usage when formatting the string.

In addition to capture groups, C++ supports additional format escape sequences. You can use them in format strings:

Format escape sequences

Format escape sequence	Description
`$&`	Returns the total match (0th capture group).
`$$`	Returns $.
`` $` `` (backward tic)	Returns the text before the total match.
`$Â´` (forward tic)	Returns the text after the total match.
`$ i’	Returns the ith capture group.

Repeated Search

It’s pretty convenient to iterate with `std::regex_iterator` and `std::regex_token_iterator` through the matched texts. `std::regex_iterator` supports the matches and their capture groups. `std::regex_token_iterator` supports more. You can address the components of each capture. Using a negative index enables it to access the text between the matches.

std::regex_iterator

C++ defines the following four type synonyms for `std::regex_iterator`.

```
typedef cregex_iterator     regex_iterator<const char*>
typedef wcregex_iterator    regex_iterator<const wchar_t*>
typedef sregex_iterator
regex_iterator<std::string::const_iterator>
typedef wsregex_iterator
regex_iterator<std::wstring::const_iterator>
```

You can use `std::regex_iterator` to count the occurrences of the words in a text:

`std::regex_iterator`

```
// regexIterator.cpp
...
#include <regex>
...

using std::cout;
std::string text{"That's a (to me) amazingly frequent question.
It may be the most freque\
ntly asked question. Surprisingly, C++11 feels like a new
language: The pieces just fit t\
ogether better than they used to, and I find a higher-level
style of programming more nat\
ural than before and as efficient as ever." };

std::regex wordReg{R"(\w+)"};
std::sregex_iterator wordItBegin(text.begin(), text.end(),
wordReg);
const std::sregex_iterator wordItEnd;
std::unordered_map<std::string, std::size_t> allWords;
for (; wordItBegin != wordItEnd; ++wordItBegin){
  ++allWords[wordItBegin->str()];
}
for (auto wordIt: allWords) cout << "(" << wordIt.first << ":"
                                        << wordIt.second << ")";
                  // (as:2)(of:1)(level:1)(find:1)(ever:1)
(and:2)(natural:1) ...
```

A word consists of a least one character `(\w+)`. This regular expression is used to define the begin iterator `wordItBegin` and the end iterator `wordItEnd`. The iteration through the matches happens in the for loop. Each word increments the counter: `++allWords[wordItBegin]->str()]`. A word with counter equals to 1 is created if it is not already in `allWords`.

std::regex_token_iterator

C++ defines the following four type synonyms for `std::regex_token_iterator`.

```
typedef cregex_iterator     regex_iterator<const char*>
typedef wcregex_iterator    regex_iterator<const wchar_t*>
typedef sregex_iterator
regex_iterator<std::string::const_iterator>
typedef wsregex_iterator
regex_iterator<std::wstring::const_iterator>
```

`std::regex_token_iterator` enables you to use indexes to explicitly specify which capture groups you are interested in. If you don’t specify the index, you will get all capture groups, but you can also request specific capture groups using their respective index. The -1 index is particular: You can use -1 to address the text between the matches:

std::regex_token_iterator

```
// tokenIterator.cpp
...
using namespace std;

  std::string text{"Pete Becker, The C++ Standard Library 
Extensions, 2006:"
                    "Nicolai Josuttis, The C++ Standard Library, 
1999:"
                    "Andrei Alexandrescu, Modern C++ Design, 
2001"};

regex regBook(R"((\w+)\s(\w+),([\w\s\+]*),(\d{4}))");
sregex_token_iterator bookItBegin(text.begin(), text.end(), 
regBook);

const sregex_token_iterator bookItEnd;
while (bookItBegin != bookItEnd){
  cout << *bookItBegin++ << endl;
}                          // Pete Becker,The C++ Standard 
Library Extensions,2006
                           // Nicolai Josuttis,The C++ Standard 
Library,1999

sregex_token_iterator bookItNameIssueBegin(text.begin(), 
text.end(),
                                           regBook, {{2,4}});
const sregex_token_iterator bookItNameIssueEnd;
```

16. Input and Output Streams

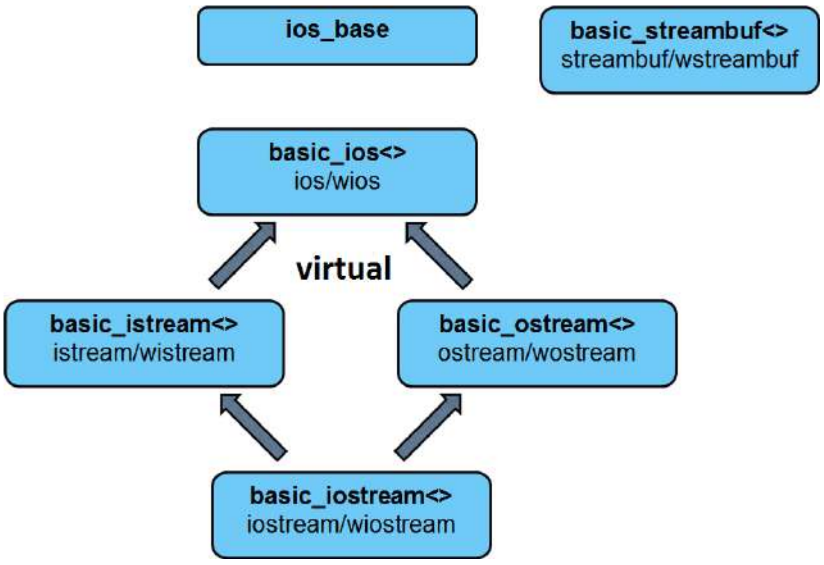
Cippi goes by Boat on a Raging River

The input and output streams enable you to communicate with the outside world. A stream is an infinite character stream on which you can push or pull data. Push is called writing; pull is called reading.

The input and output streams

- were used long before the first C++ standard (C++98) in 1998,
- are designed for extensibility,
- are implemented according to the object-oriented and generic paradigms.

Hierarchy



`basic_streambuf<>`
: Reads and writes the data.

`ios_base`
: Properties of all stream classes independent of the character type.

`basic_ios<>`
: Properties of all stream classes dependent on the character type.

`basic_istream<>`
: Base for the stream classes for the reading of the data.

`basic_ostream<>`
: Base for the stream classes for the writing of the data.

`basic_iostream<>`
: Base for the stream classes for the reading and writing of the data.

The class hierarchy has type synonyms for the character types `char` and `wchar_t`. Names not beginning with `w` are type synonyms for `char`; names beginning with `w` for `wchar_t`.

The base classes of the class `std::basic_iostream<>` are virtually derived from `std::basic_ios<>`, therefore `std::basic_iostream<>` has only one instance of `std::basic_ios`.

Input and Output Functions

The stream classes `std::istream` and `std::ostream` are often used for the reading and writing of data. Use of `std::istream` classes requires the `<istream>` header; use of `std::ostream` classes requires the `<ostream>` header. You can have both with the header `<iostream>`. `std::istream` is a typedef for the class `basic_istream` and the character type `char`, `std::ostream` for the class `basic_ostream` respectively:

```
typedef basic_istream<char> istream;
typedef basic_ostream<char> ostream;
```

C++ has four predefined stream objects for the convenience of dealing with the keyboard and the monitor.

The four predefined stream objects

Stream object	C pendant	Device	Buffered
`std::cin`	`stdin`	keyboard	yes
`std::cout`	`stdout`	console	yes
`std::cerr`	`stderr`	console	no
`std::clog`		monitor	yes

The stream objects are also available for `wchar_t`

The four stream objects for `wchar_t`, `std::wcin`, `std::wcout`, `std::wcerr`, and `std::wclog` are by far not so heavily used as their `char` pendants. Therefore I treat them only marginally.

The stream objects are sufficient to write a program that reads from the command line and returns the sum.

The stream objects

```
// IOStreams.cpp
...
#include <iostream>

int main(){
  std::cout << "Type in your numbers";
  std::cout << "(Quit with an arbitrary character): " << std::endl;
                // 2000 <Enter> 11 <a>
  int sum{0};
  int val;
  while (std::cin >> val) sum += val;
  std::cout << "Sum: " << sum;                          // Sum: 2011
}
```

The minor program above uses the stream operators << and >> and the stream manipulator `std::endl`.

The insert operator << pushes characters onto the output stream `std::cout`; the extract operator >> pulls the characters from the input stream `std::cin`. You can build chains of insert or extract operators because both operators return a reference to themselves.

`std::endl` is a stream manipulator because it puts a '`\n`' character onto `std::cout` and flushes the output buffer.

Here are the most frequently used stream manipulators.

The most frequently used stream manipulators

Manipulator	Stream type	Description
`std::endl`	output	Inserts a new-line character and flushes the stream.
`std::flush`	output	Flushes the stream.
`std::ws`	input	Discards leading whitespace.

Input

You can read in C++ in two ways from the input stream: Formatted with the extractor >> and unformatted with explicit member functions.

Formatted Input

The extraction operator >>

- is predefined for all built-in types and strings,
- can be implemented for user-defined data types,
- can be configured by format specifiers.

`std::cin` ignores by default leading whitespace

```
#include <iostream>
...
int a, b;
std::cout << "Two natural numbers: " << '\n';
std::cin >> a >> b; // < 2000 11>
std::cout << "a: " << a << " b: " << b;
```

Unformatted Input

There are many member functions for the unformatted input from an input stream `is`.

Unformatted input from an input stream

Member Function	Description
`is.get(ch)`	Reads one character into `ch`.
`is.get(buf, num)`	Reads at most `num` characters into the buffer `buf`.
`is.getline(buf, num[, delim])`	Reads at most `num` characters into the buffer `buf`. Uses the line-delimiter `delim` (default `\n`) optionally.
`is.gcount()`	Returns the number of last extracted characters from `is` by an unformatted operation.
`is.ignore(streamsize sz= 1, int delim= end-of-file)`	Ignores `sz` characters until `delim`.
`is.peek()`	Gets one character from `is` without consuming it.
`is.unget()`	Pushes the last read character back to `is`.
`is.putback(ch)`	Pushes the character `ch` onto the stream `is`.

`std::string` has a `getline` function

The `getline` function of std::string has a big advantage above the `getline` function of the `istream`. The std::string automatically takes care of its memory. On the contrary, you must reserve the memory for the buffer `buf` in the `is.get(buf, num)` function.

```
// inputUnformatted.cpp
...
#include <iostream>
...
std::string line;
std::cout << "Write a line: " << '\n';
```

```
std::getline(std::cin, line);            // <Only for testing
purpose.>
std::cout << line << '\n';               // Only for testing
purpose.

std::cout << "Write numbers, separated by;" << '\n';
while (std::getline(std::cin, line, ';') ) {
  std::cout << line << " ";
}                                       // <2000;11;a>
                                        // 2000 11
```

Output

You can push characters with the insert operator << onto the output stream.

The insert operator <<

- is predefined for all built-in types and strings,
- can be implemented for user-defined data types,
- can be adjusted by format specifiers.

Format Specifier

Format specifiers enable you to adjust the input and output data explicitly.

I use manipulators as format specifiers

The format specifiers are available as manipulators and flags. I only present manipulators in this book because their functionality is quite similar, and manipulators are more comfortable to use.

Manipulators as format specifiers

```
// formatSpecifier.cpp
...
#include <iostream>
...
int num{2011};

std::cout.setf(std::ios::hex, std::ios::basefield);
std::cout << num << '\n'; // 7db
std::cout.setf(std::ios::dec, std::ios::basefield);
std::cout << num << '\n'; // 2011

std::cout << std::hex << num << '\n';  // 7db
std::cout << std::dec << num << '\n';  // 2011
```

The following tables present the important format specifiers. The format specifiers are sticky except for the field width, which is reset after each application.

The manipulators without arguments require the header `<iostream>`; the manipulators with arguments require the header `<iomanip>`.

Displaying of boolean values

Manipulator	Stream type	Description
`std::boolalpha`	input and output	Displays the boolean as a word.
`std::noboolalpha`	input and output	Displays the boolean as a number (default).

Set the field width and the fill character

Manipulator	Stream type	Description
`std::setw(val)`	input and output	Sets the field width to `val`.
`std::setfill(c)`	output stream	Sets the fill character to `c` (default: spaces).

Alignment of the text

Manipulator	Stream type	Description
`std::left`	output	Aligns the output left.
`std::right`	output	Aligns the output right.
`std::internal`	output	Aligns the signs of numbers left, the values right.

Positive signs and upper or lower case

Manipulator	Stream type	Description
`std::showpos`	output	Displays positive signs.
`std::noshowpos`	output	Doesn’t display positive signs (default).
`std::uppercase`	output	Uses upper case characters for numeric values (default).
`std::lowercase`	output	Uses lowercase characters for numeric values.

Display of the numeric base

Manipulator	Stream type	Description
`std::oct`	input and output	Uses natural numbers in octal format.
`std::dec`	input and output	Uses natural numbers in decimal format (default).
`std::hex`	input and output	Uses natural numbers in hexadecimal format.
`std::showbase`	output	Displays the numeric base.
`std::noshowbase`	output	Doesn’t display the numeric base (default).

There are special rules for floating-point numbers:

- The number of significant digits (digits after the comma) is, by default, six.
- If the number of significant digits is not big enough, the number is displayed in scientific notation.
- Leading and trailing zeros are not displayed.
- If possible, the decimal point is not displayed.

Floating point numbers

Manipulator	Stream type	Description
`std::setprecision(val)`	output	Adjusts the precision of the output to `val`.
`std::showpoint`	output	Displays the decimal point.
`std::noshowpoint`	output	Doesn't display the decimal point (default).
`std::fixed`	output	Displays the floating-point number in decimal format.
`std::scientific`	output	Displays the floating-point number in scientific format.
`std::hexfloat`	output	Displays the floating-point number in hexadecimal format.
`std::defaultfloat`	output	Displays the floating-point number in default floating-point notation.

Format specifier

```cpp
// formatSpecifierOutput.cpp
...
#include <iomanip>
#include <iostream>
...

std::cout.fill('#');
std::cout << -12345;
std::cout << std::setw(10) << -12345;                    // ####-12345
std::cout << std::setw(10) << std::left << -12345;     // -12345####
std::cout << std::setw(10) << std::right << -12345;    // ####-12345
std::cout << std::setw(10) << std::internal << -12345; //-####12345

std::cout << std::oct << 2011;  // 3733
std::cout << std::hex << 2011;  // 7db

std::cout << std::showbase;
std::cout << std::dec << 2011; // 2011
std::cout << std::oct << 2011; // 03733
std::cout << std::hex << 2011; // 0x7db

std::cout << 123.456789;                          // 123.457
```

```
std::cout << std::fixed;
std::cout << std::setprecision(3) << 123.456789;  // 123.457
std::cout << std::setprecision(6) << 123.456789;  // 123.456789
std::cout << std::setprecision(9) << 123.456789;  // 123.456789000

std::cout << std::scientific;
std::cout << std::setprecision(3) << 123.456789;  // 1.235e+02
std::cout << std::setprecision(6) << 123.456789;  // 1.234568e+02
std::cout << std::setprecision(9) << 123.456789;  // 1.234567890e+02

std::cout << std::hexfloat;
std::cout << std::setprecision(3) << 123.456789;  //
0x1.edd3c07ee0b0bp+6
std::cout << std::setprecision(6) << 123.456789;  //
0x1.edd3c07ee0b0bp+6
std::cout << std::setprecision(9) << 123.456789;  //
0x1.edd3c07ee0b0bp+6

std::cout << std::defaultfloat;
std::cout << std::setprecision(3) << 123.456789;  // 123
std::cout << std::setprecision(6) << 123.456789;  // 123.457
std::cout << std::setprecision(9) << 123.456789;  // 123.456789
```

Streams

A stream is an infinite data stream on which you can push or pull data. String streams and file streams enable strings and files to interact with the stream directly.

String Streams

String streams need the header `<sstream>`. They are not connected to an input or output stream and store their data in a string.

Whether you use a string stream for input or output or with the character type `char` or `wchar_t`, there are various string stream classes:

`std::istringstream` and `std::wistringstream`
: String stream for the input data of type `char` and `wchar_t`.

`std::ostringstream` and `std::wostringstream`
: String stream for the output data of type `char` and `wchar_t`.

`std::stringstream` and `std::wstringstream`
: String stream for the input or output data of type `char` and `wchar_t`.

Typical operations on a string stream are:

- Write data in a string stream:

```
std::stringstream os;
os << "New String";
os.str("Another new String");
```

- Read data from a string stream:

```
std::stringstream os;
std::string str;
os >> str;
str= os.str();
```

- Clear a string stream:

```
std::stringstream os;
os.str("");
```

String streams are often used for the type-safe conversion between strings and numeric values:

String streams

```
// stringStreams.cpp
...
#include <sstream>
...

template <typename T>
T StringTo ( const std::string& source ){
  std::istringstream iss(source);
  T ret;
  iss >> ret;
  return ret;
}

template <typename T>
  std::string ToString(const T& n){
  std::ostringstream tmp ;
  tmp << n;
  return tmp.str();
}

std::cout << "5= " << StringTo<int>("5");                          //
5
std::cout << "5 + 6= " << StringTo<int>("5") + 6;                  //
11
std::cout << ToString(StringTo<int>("5") + 6 );                    //
"11"
std::cout << "5e10: " << std::fixed << StringTo<double>("5e10");   //
50000000000
```

File Streams

File streams enable you to work with files. The file streams automatically manage the lifetime of their file. They need the header `<fstream>`.

Whether you use a file stream for input or output or with the character type `char` or `wchar_t`, there are various file stream classes:

`std::ifstream` and `std::wifstream`
: File stream for the input data of type `char` and `wchar_t`.

`std::ofstream` and `std::wofstream`
: File stream for the output data of type `char` and `wchar_t`.

`std::fstream` and `std::wfstream`
: File stream for the input and output data of type `char` and `wchar_t`.

`std::filebuf` and `std::wfilebuf`
: Data buffer of type `char` and `wchar_t`.

Set the file position pointer

File streams used for reading and writing must set the file position pointer after the contests change.

Flags enable you to set the opening mode of a file stream.

Flags for the opening of a file stream

Flag	Description
`std::ios::in`	Opens the file stream for reading (default for `std::ifstream` and `std::wifstream`).
`std::ios::out`	Opens the file stream for writing (default for `std::ofstream` and `std::wofstream`).
`std::ios::app`	Appends the character to the end of the file stream.
`std::ios::ate`	Sets the initial position of the file position pointer at the end of the file stream.
`std::ios::trunc`	Deletes the original file.
`std::ios::binary`	Suppresses the interpretation of an escape sequence in the file stream.

It’s pretty easy to copy the file named `in` to the file named `out` with the file buffer `in.rdbuf()`. Error handling needs to be included in this short example.

```
#include <fstream>
...
std::ifstream in("inFile.txt");
std::ofstream out("outFile.txt");
out << in.rdbuf();
```

In the following table, I compare the C++ mode and the C mode to open a file.

Opening of a file with C++ and C

C++ mode	Description	C mode
`std::ios::in`	Reads the file.	`"r"`
`std::ios::out`	Writes the file.	`"w"`
`std::ios::out|std::ios::app`	Appends to the file.	`"a"`
`std::ios::in|std::ios::out`	Reads and writes the file.	`"r+"`
`std::ios::in|std::ios::out|std::ios::trunc`	Writes and reads the file.	`"w+"`

The file must exist with the modes `"r"` and `"r+"`. On the contrary, the file is created with `"a"` and `"w+"`. The file is overwritten with `"w"`.

You can explicitly manage the lifetime of a file stream.

Managing the lifetime of a file stream

Flag	Description
`infile.open(name)`	Opens the file `name` for reading.
`infile.open(name, flags)`	Opens the file `name` with the flags `flags` for reading.
`infile.close()`	Closes the file `name`.
`infile.is_open()`	Checks if the file is open.

Random Access

Random access enables you to set the file position pointer arbitrarily.

When a file stream is constructed, the file's position pointer points to the beginning of the file. You can adjust the position with the member functions of the file stream `file`.

Navigate in a file stream

Member Function	Description
`file.tellg()`	Returns the read position of `file`.
`file.tellp()`	Returns the write position of `file`.
`file.seekg(pos)`	Sets the read position of `file` to `pos`.
`file.seekp(pos)`	Sets the write position of `file` to `pos`.
`file.seekg(off, rpos)`	Sets the read position of `file` to the offset `off` relative to `rpos`.
`file.seekp(off, rpos)`	Sets the write position of `file` to the offset `off` relative to `rpos`.

`off` has to be a number. `rpos` can have three values:

`std::ios::beg`

Position at the beginning of the file.

`std::ios::cur`
: Position at the current position.

`std::ios::end`
: Position at the end of the file.

Respect the file boundaries

If you randomly access a file, the C++ runtime does not check the file boundaries. Reading or writing data outside the boundaries is *undefined behavior*.

Random access

```
// randomAccess.cpp
...
#include <fstream>
...

void writeFile(const std::string name){
  std::ofstream outFile(name);
  if (!outFile){
    std::cerr << "Could not open file " << name << '\n';
    exit(1);
  }
  for (unsigned int i= 0; i < 10 ; ++i){
    outFile << i << "          0123456789" << '\n';
  }
}

std::string random{"random.txt"};
writeFile(random);
std::ifstream inFile(random);

if (!inFile){
  std::cerr << "Could not open file " << random << '\n';
  exit(1);
}

std::string line;

std::cout << inFile.rdbuf();
// 0          0123456789
// 1          0123456789
...
// 9          0123456789

std::cout << inFile.tellg() << '\n';   // 200

inFile.seekg(0);   // inFile.seekg(0, std::ios::beg);
getline(inFile, line);
std::cout << line;                        // 0          0123456789

inFile.seekg(20, std::ios::cur);
getline(inFile, line);
std::cout << line;                        // 2          0123456789
```

```
inFile.seekg(-20, std::ios::end);
getline(inFile, line);
std::cout << line;                              // 9         0123456789
```

State of the Stream

Flags represent the state of the stream `stream`. The member functions for dealing with these flags need the header `<iostream>`.

State of a stream

Flag	Query of the flag	Description
`std::ios::goodbit`	`stream.good()`	No bit set.
`std::ios::eofbit`	`stream.eof()`	end-of-file bit set.
`std::ios::failbit`	`stream.fail()`	Error.
`std::ios::badbit`	`stream.bad()`	Undefined behaviour.

Here are examples of conditions causing the different states of a stream:

`std::ios::eofbit`

- Reading beyond the last valid character.

`std::ios::failbit`

- False formatted reading.
- Reading beyond the last valid character.
- Opening of a file went wrong.

`std::ios::badbit`

- Size of the stream buffer cannot be adjusted.
- Code conversion of the stream buffer went wrong.
- A part of the stream threw an exception.

`stream.fail()` returns whether `std::ios::failbit` or `std::ios::badbit` is set.

The state of a stream can be read and set.

`stream.clear()`
: Initializes the flags and sets the stream in the `goodbit` state.

`stream.clear(sta)`
: Initializes the flags and set the stream into `sta` state.

`stream.rdstate()`
: Returns the current state.

`stream.setstate(fla)`
: Sets the additional flag `fla`.

Operations on a stream only work if the stream is in the `goodbit` state. If the stream is in the `badbit` state, you cannot set it back to `goodbit` state.

State of a stream

```
// streamState.cpp
...
#include <iostream>
...
std::cout << std::cin.fail() << '\n';     // false

int myInt;

while (std::cin >> myInt){                // <a>
  std::cout << myInt << '\n';             //
  std::cout << std::cin.fail() << '\n';   //
}

std::cin.clear();
std::cout << std::cin.fail() << '\n';     // false
```

The input of the character `a` causes the stream `std::cin` to be in `std::ios::failbit` state. Therefore `a' and` std::cin.fail() `cannot be displayed. First, you have to initialize the stream` std::cin`.

User-defined Data Types

If you overload the input and output operators, your data type behaves like a built-in data type.

```
friend std::istream& operator>> (std::istream& in, Fraction& frac);
friend std::ostream& operator<< (std::ostream& out, const Fraction&
frac);
```

For overloading the input and output operators, you have to keep a few rules in mind:

- To support the chaining of input and output operations, you have to get and return the input and output streams by non-constant reference.
- To access the private members of the class, the input and output operators have to be *friends* of your data type.
- The input operator >> takes its data type as a non-constant reference.
- The output operator << takes its data type as a constant reference.

Overloading input and output operator

```
// overloadingInOutput.cpp
class Fraction{
public:
  Fraction(int num= 0, int denom= 0):numerator(num),
denominator(denom){}
  friend std::istream& operator>> (std::istream& in, Fraction&
frac);
  friend std::ostream& operator<< (std::ostream& out, const
Fraction& frac);
private:
  int numerator;
  int denominator;
};

std::istream& operator>> (std::istream& in, Fraction& frac){
  in >> frac.numerator;
  in >> frac.denominator;
  return in;
}

std::ostream& operator<< (std::ostream& out, const Fraction& frac){
  out << frac.numerator << "/" << frac.denominator;
  return out;
}

Fraction frac(3, 4);
std::cout << frac;                    // 3/4

std::cout << "Enter two numbers: ";
Fraction fracDef;

std::cin >> fracDef;                  // <1 2>
std::cout << fracDef;                 // 1/2
```

17. Formatting Library

Cippi forms a cup

The formatting library in C++20 provides a safe and extensible alternative to the `printf` family and extends the Input and Output streams. The library requires the `<format>`, and the format string syntax follows the Python syntax.

Thanks to the formatting library, you can specify format specifications using a format string for

- the fill character and alignment of text.
- the sign, the width, and the precision of numbers.
- the data type.

Formatting Functions

C++ supports various formatting functions. The elementary compile-time formatting functions `std::format`, `std::format_to`, and `std::format_to_n`. The run-time formatting functions `std::vformat` and `std::vformat_to` in combination with the function `std::make_format_args`. Finally, the convenience functions `std::print` and `std::println`.

The formatting library has three elementary formatting functions.

`std::format`

Returns the formatted string

`std::format_to`
: Writes the formatted string via an output iterator

`std::format_to_n`
: Writes the formatted string via an output iterator but not more than `n` characters

```
#include <format>
....
std::format("{1} {0}!", "world", "Hello");  // Hello world!

std::string buffer;
std::format_to(std::back_inserter(buffer),
    "Hello, C++{}!\n", "20");                // Hello, C++20!
```

`std::vformat`, `std::vformat_to`, and `std::make_format_args`

The three formatting functions `std::format`, `std::format_to`, and `std::format_to_n` use a format string to create a formatted string. This format string must be a compile-time value. Consequentially, an invalid format string causes a compile-time error.

For run-time format strings, there are the alternative functions `std::vformat` and `std:: vformat_to`, which you have to use in combination with `std::make_format_args`.

```
#include <format>
...
std::string formatString = "{1} {0}!";
std::vformat(formatString, std::make_format_args("world",
"Hello"));  // Hello world
```

`std::print`, and `std::println`

The convenience functions `std::print` and `std::println` write to the output console. `std::println` adds a newline character to the output. Additionally, both functions enable it to write to an output file stream and support Unicode. You have to include the header `<print>`.

```
#include <print>
...
std::print("{1} {0}!", "world", "Hello");  // prints "Hello
world!"

std::ofstream outFile("testfile.txt");
std::print(outFile, "{1} {0}!", "world", "Hello");  // writes
```

```
"Hello world!" into the out\
File
```

I use `std::format` for the rest of this chapter

The compile-time formatting functions `std::format`, `std::format_to`, and `std::format_to_n`, the run-time formatting functions `std::vformat`, and `std::vformat_n`, and the convenience functions `std::print`, and `std::println` apply the same syntax for the format string. For simplicity, I use `std::format` for the rest of this chapter.

Syntax

`std::format`has the following syntax:
std::format(FormatString, Args)

The format string **FormatString** consists of

- Ordinary characters (except `{` and `}`)
- Escape sequences `{{` and `}}` that are replaced by `{` and `}`
- Replacement fields

A replacement field has the format

- Beginning character `{`
  - Argument-ID (optional)
  - Colon `:` followed by a format specification (optional)
- Closing character `}`

The argument-id allows you to specify the index of the arguments in **Args**. The id's start with 0. When you don't provide the argument-id, the arguments are used as given. Either all replacement fields have to use an argument-id or none.

`std::formatter` and its specializations define the **format specification** for the arguments.

- basic types and string types: standard format specification based on Python's format specification.

- chrono types: chrono format specification
- other types: user-defined format specification

Format specification

You can specify the fill character and alignment of the text, the sign, the width, the precision of numbers, and the data type.

Fill characters and alignment of text

- Fill character: per default space
- Alignment:
  - <: left
  - >: right
  - ^: centered

```
char c = 120;

std::format("{:7}", 42);      // "     42"
std::format("{:7}", 'x');     // "x      "
std::format("{:*<7}", 'x');   // "x******"
std::format("{:*>7}", 'x');   // "******x"
std::format("{:*^7}", 'x');   // "***x***"
std::format("{:7d}", c);      // "    120"
std::format("{:7}", true);    // "true   "
```

Sign, width, and precision of numbers

- Sign
  - +: number gets a sign symbol
  - -: negative numbers get a sign (default)
  - space: positive numbers get a space

```
double inf = std::numeric_limits<double>::infinity();
double nan = std::numeric_limits<double>::quiet_NaN();

std::format("{0:},{0:+},{0:-},{0: }", 1);   // "1,+1,1, 1"
std::format("{0:},{0:+},{0:-},{0: }", -1);  // "-1,-1,-1,-1"
std::format("{0:},{0:+},{0:-},{0: }", inf); // "inf,+inf,inf,
inf"
std::format("{0:},{0:+},{0:-},{0: }", nan); // "nan,+nan,nan,
nan"
```

- #:
  - uses the alternative format

    - integrals:
        - binary numbers: `0b`
        - octal numbers: `0`
        - hexadecimal numbers: `0x`
- `0`: fills with leading zeros

```
std::format("{:+06d}", 120);    // "+00120"
std::format("{:#0f}", 120));    // "120.000000"
std::format("{:0>15f}", 120)); // "00000120.000000"
std::format("{:#06x}", 0xa);    // "0x000a"
```

- Width: specifies the minimal width
- Precision: can be applied to floating-point numbers and strings
    - Floating-point number: place after the decimal point
    - Strings: maximal number of characters

```
double d = 20.11;

std::format("{}", d));                // " 20.11 "
std::format("{:10}", d));             // " 20.11 "
std::format("{:10.3}", d));           // " 20.1 "
std::format("{:.3}", "Only a test."); // " Onl "
```

Data types

The values are copied to the output if not other specified. You can explicitly specify the presentation of a value:

- String presentation: `s`
- Integer presentation:
    - `b`, `B`: binary
    - `d`: decimal
    - `o`: octal
    - `x`, `X`: hexadecimal
- Character presentation:
    - `b`, `B`, `d`, `o`, `x`, `X`: integer
- Bool:
    - `s`: `true` or `false`
    - `b`, `B`, `d`, `o`, `x`, `X`: integer
- Floating point:
    - `e`, `E`: scientific
    - `f`, `F`: decimal

User-defined formatter

To format a user-defined type, I have to specialize the class `std::formatter` for my user-defined type. This means, in particular, I have to implement the member functions `parse` and `format`.

- **parse**:
    - Accepts the parse context
    - Parses the parse context
    - Returns an iterator to the end of the format specification
    - Throws a `std::format_error` in case of an error
- **format**:
    - Gets the value `t`, which should be formatted, and the format context `fc`
    - Formats `t` according to the format context
    - Writes the output to `fc.out()`
    - Returns an iterator that represents the end of the output

Let me put the theory into practice and format a `std::vector`.

Formatting a `std::vector`

The specialization of the class `std::formatter` is as straightforward as possible. I specify a format specification which is applied to each element of the container.

```
// formatVector.cpp

#include <format>

...

template <typename T>
struct std::formatter<std::vector<T>> {

  std::string formatString;

  auto constexpr parse(format_parse_context& ctx) {
// (3)
    formatString = "{:";
    std::string parseContext(std::begin(ctx), std::end(ctx));
    formatString += parseContext;
    return std::end(ctx) - 1;
  }

  template <typename FormatContext>
  auto format(const std::vector<T>& v, FormatContext& ctx) {
    auto out= ctx.out();
    std::format_to(out, "[");
    if (v.size() > 0) std::format_to(out, formatString, v[0]);
    for (int i= 1; i < v.size(); ++i) {
      std::format_to(out, ", " + formatString, v[i]);
// (1)
    }
    std::format_to(out, "]");
// (2)
    return std::format_to(out,  "\n" );
  }

};

...

std::vector<int> myInts{1, 2, 3, 4, 5};
std::cout << std::format("{:}", myInts);     // [1, 2, 3, 4, 5]
// (4)
std::cout << std::format("{:+}", myInts);    // [+1, +2, +3, +4,
+5]
std::cout << std::format("{:03d}", myInts);  // [001, 002, 003,
004, 005]
std::cout << std::format("{:b}", myInts);    // [1, 10, 11, 100,
101]  // (5)

std::vector<std::string> myStrings{"Only", "for", "testing"};
std::cout << std::format("{:}", myStrings);    // [Only, for,
testing]
std::cout << std::format("{:.3}", myStrings);  // [Onl, for,
tes]
```

The specialization for `std::vector` has the member functions `parse` and `format`. `parse` essentially creates the `formatString` applied to each element of the `std::vector` (1 and 2). The parse context `ctx` (3) contains the characters between the colon (`:`) and the closing curly braces (`}`). The function returns an iterator to the closing curly braces (`}`). The job of the member function `format` is more interesting. The format context returns the output iterator. Thanks to the output iterator and the function `std::format_to`, the elements of a `std::vector` are nicely displayed.

The elements of the `std::vector` are formatted in a few ways. The first line (4) displays the numbers. The following line writes a sign before each number, aligns them to 3 characters, and uses the `0` as a fill character. Line (5) displays them in binary format. The remaining two lines output each string of the `std::vector`. The last line truncates each string to three characters.

18. Filesystem

Cippi sorts here painting stuff

The filesystem is based on boost::filesystem. Some of its components are optional. This means not all functionality of std::filesytem is available on each implementation of the filesystem library. For example, FAT-32 does not support symbolic links.

The library is based on three concepts: file, file name, and path.

- A *file* is an object that holds data that you can write to or read from. A file has a name and a file type. A file type can be a directory, hard link, symbolic link, or regular file.
    - A *directory* is a container for holding other files. The current directory is represented by a dot `"."`; two dots represent the parent directory`".."`.
    - A *hard link* associates a name with an existing file.
    - A *symbolic link* associates a name with a path that may exist.
    - A *regular file* is a directory entry that is neither a directory, a hard link, nor a symbolic link.
- A *file name* is a string that represents a file. It is implementation-defined which characters are allowed, how

long the name could be, or if the name is case sensitive.

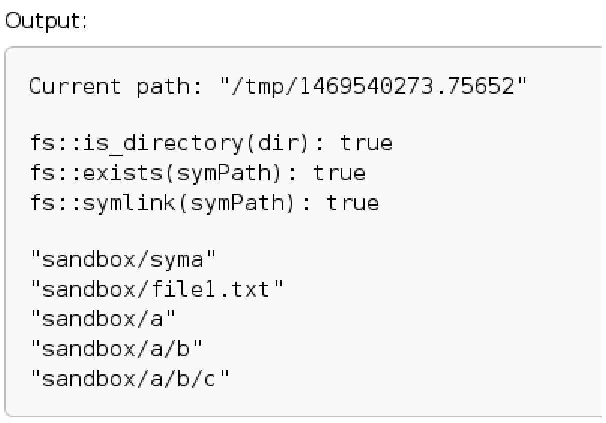
- A *path* is a sequence of entries that identifies the location of a file. It has an optional root-name such a “C:” on Windows, followed by a root-directory such a “/” on Unix. Additional parts can be directories, hard links, symbolic links, or regular files. A path can be absolute, canonical, or relative.
    - An *absolute path* is a path that identifies a file.
    - A *canonical path* is a path that includes neither a symbolic link nor the relative paths `"."` (current directory) or `".."`(parent directory).
    - A *relative path* specifies a path relative to a location in the file system. Paths such as `"."` (current directory), `".."`(parent directory), or `"home/rainer"` are relative paths. On Unix, they do not start at the root-directory `"/"`.

Here is an introductory example of the filesystem.

Overview to the filesystem library

```
// filesystem.cpp
...
#include <filesystem>

...

namespace fs = std::filesystem;

std::cout << "Current path: " << fs::current_path() << '\n';   //
(1)

std::string dir= "sandbox/a/b";
fs::create_directories(dir);
// (2)

std::ofstream("sandbox/file1.txt");
fs::path symPath= fs::current_path() /=  "sandbox";
// (3)
symPath /= "syma";
fs::create_symlink("a", "symPath");
// (4)

std::cout << "fs::is_directory(dir): " << fs::is_directory(dir) <<
'\n';
std::cout << "fs::exists(symPath): "  << fs::exists(symPath) <<
'\n';
std::cout << "fs::symlink(symPath): " << fs::is_symlink(symPath)
<< '\n';

for(auto& p: fs::recursive_directory_iterator("sandbox")){
// (5)
  std::cout << p << '\n';
}
fs::remove_all("sandbox");
```

`fs::current_path()` (1) returns the current path. You can create a directory hierarchy (2) with `std::filesystem::create_directories`. The `/=` operator is overloaded for a path (3). Therefore, I can directly create a symbolic link (4) or check a file's properties. The call `recursive_directory_iterator` (5) allows you to traverse directories recursively.


Output:

```
Current path: "/tmp/1469540273.75652"

fs::is_directory(dir): true
fs::exists(symPath): true
fs::symlink(symPath): true

"sandbox/syma"
"sandbox/file1.txt"
"sandbox/a"
"sandbox/a/b"
"sandbox/a/b/c"
```

Classes

Many classes encapsulate a specific aspect of the filesystem.

The various classes the filesystem

Class	Description
`path`	Represents a path.
`filesystem_error`	Defines an exception object.
`directory_entry`	Represents a directory entry.
`directory_iterator`	Defines a directory iterator.
`recursive_directory_iterator`	Defines a recursive directory iterator.
`file_status`	Stores information about the file.
`space_info`	Represents filesystem information.
`file_type`	Indicates the type of a file.
`perms`	Represents file access permissions.
`perm_options`	Represents options for the function `permissions`.
`copy_options`	Represents options for the functions `copy` and `copy_file`.
`directory_options`	Represents options for the functions `directory_iterator` and `recursive_directory_iterator`.
`file_time_type`	Represents file time.

Manipulating the permissions of a file

The permissions for a file are represented by the class `std::filesystem::perms`. It is a BitmaskType and can, therefore, be manipulated by bitwise operations. The access permissions are based on POSIX.

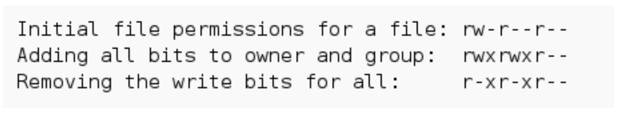
The program from en.cppreference.com shows how you can read and manipulate the owner, group, and other (world) bits of a file.

Permissions of a file

```
// perms.cpp
...
#include <filesystem>

...

namespace fs = std::filesystem;

void printPerms(fs::perms perm){
  std::cout << ((perm & fs::perms::owner_read) != fs::perms::none
? "r" : "-")
            << ((perm & fs::perms::owner_write) != fs::perms::none
? "w" : "-")
            << ((perm & fs::perms::owner_exec) != fs::perms::none
? "x" : "-")
            << ((perm & fs::perms::group_read) != fs::perms::none
? "r" : "-")
            << ((perm & fs::perms::group_write) != fs::perms::none
? "w" : "-")
            << ((perm & fs::perms::group_exec) != fs::perms::none
? "x" : "-")
            << ((perm & fs::perms::others_read) != fs::perms::none
? "r" : "-")
            << ((perm & fs::perms::others_write) !=
fs::perms::none ? "w" : "-")
            << ((perm & fs::perms::others_exec) != fs::perms::none
? "x" : "-")
            << '\n';
}

...

std::ofstream("rainer.txt");

std::cout << "Initial file permissions for a file: ";
printPerms(fs::status("rainer.txt").permissions());
// (1)

fs::permissions("rainer.txt", fs::perms::add_perms |
// (2)
                fs::perms::owner_all | fs::perms::group_all);
std::cout << "Adding all bits to owner and group:  ";
printPerms(fs::status("rainer.txt").permissions());

fs::permissions("rainer.txt", fs::perms::remove_perms |
// (3)
  fs::perms::owner_write | fs::perms::group_write |
fs::perms::others_write);
```

```
std::cout << "Removing the write bits for all:     ";
printPerms(fs::status("rainer.txt").permissions());
```

Thanks to the call `fs::status("rainer.txt").permissions()`, I get the permissions of the file `rainer.txt` and can display them in the function `printPerms` (1). By setting the type `std::filesystem::add_perms`, I can add permissions to the owner and the group of the file (2). Alternatively, I can set the constant `std::filesystem::remove_perms` for removing permissions (3).



```
Initial file permissions for a file: rw-r--r--
Adding all bits to owner and group:  rwxrwxr--
Removing the write bits for all:     r-xr-xr--
```

Non-member functions

Many non-member functions exist for manipulating the filesystem.

The non-member functions for manipulating the filesystem

Non-member functions	Description
`absolute`	Composes an absolute path.
`canonical` and `weakly_canonical`	Composes a canonical path.
`relative` and `proximate`	Composes a relative path.
`copy`	Copies files or directories.
`copy_file`	Copies file contents.
`copy_symlink`	Copies a symbolic link.
`create_directory` and `create_directories`	Creates a new directory.
`create_hard_link`	Creates a hard link.
`create_symlink` and `create_directory_symlink`	Creates a symbolic link.
`current_path`	Returns the current working directory.
`exists`	Checks if the path refers to an existing file.
`equivalent`	Checks if two paths refer to the same file.
`file_size`	Returns the size of the file.
`hard_link_count`	Returns the number of hard links to a file.

Non-member functions	**Description**
`last_write_time`	Gets and sets the time of the last file modification.
`permissions`	Modifies the file access permissions.
`read_symlink`	Gets the target of the symbolic link.
`remove`	Removes a file or an empty directory.
`remove_all`	Removes a file or a directory with all its content recursively.
`rename`	Moves or renames a file or directory.
`resize_file`	Changes the size of a file by truncation.
`space`	Returns the free space on the filesystem.
`status`	Determines the file attributes.
`symlink_status`	Determines the file attributes and checks the symlink target.
`temp_directory_path`	Returns a directory for temporary files.

Read and set the last write time of a file

Thanks to the global function `std::filesystem::last_write_time`, you can read and set the last write time of a file. Here is an example based on the `last_write_time` example from en.cppreference.com.

Write time of a file

```
// fileTime.cpp
...
#include <filesystem>

...

namespace fs = std::filesystem;
using namespace std::chrono_literals;

...

fs::path path = fs::current_path() / "rainer.txt";
std::ofstream(path.c_str());
const auto fTime = fs::last_write_time(path);
// (1)
const auto sTime =
std::chrono::clock_cast<std::chrono::system_clock>(fTime);   //
(2)


std::time_t cftime = std::chrono::system_clock::to_time_t(sTime);
std::cout << "Write time on server "
// (3)
          << std::asctime(std::localtime(&cftime));
std::cout << "Write time on server "
// (4)
          << std::asctime(std::gmtime(&cftime)) << '\n';

const auto fTime2 =  fTime + 2h;
// (5)
const auto sTime2 =
std::chrono::clock_cast<std::chrono::system_clock>(fTime2); // (6)

std::time_t cftime2 =
std::chrono::system_clock::to_time_t(sTime2);
std::cout << "Local time on client "
          << std::asctime(std::localtime(&cftime2)) << '\n';
```

Line (1) gives the write time of the newly created file. You can use `fTime` in (2) to cast it in a real time wall clock `sTime`. This `sTime` initializes `std::chrono::system_clock` in the following line. `cftime` is of type `std::filesystem::file_time_type`, which is, in this case, an alias for `std::chrono::system_clock`; therefore, you can initialize `std::localtime` in (3) and present the calendar time in a textual representation. Nothing will change if you use `std::gmtime` (4) instead of `std::localtime`. This puzzled me because the Coordinated Universal Time (UTC) differs 2 hours from Germany's local time. That's due to the server for the online compiler on en.cppreference.com. UTC and local time are set to the same time on the server.

Here is the output of the program. I moved the write time of the file 2 hours to the future (5) and read it back from the filesystem (6). This adjusts the time, so it corresponds to the local time in Germany.

```
Write time on server Tue Oct 10 06:28:04 2017
Write time on server Tue Oct 10 06:28:04 2017

Local time on client Tue Oct 10 08:28:04 2017
```

Space Information on the Filesystem

The global function `std::filesystem::space` returns a `std::filesystem::space_info` object with three members: capacity, free, and available.

- *capacity*: total size of the filesystem
- *free*: free space on the filesystem
- *available*: free space to a non-privileged process (equal or less than free)

All sizes are in bytes.

The output of the following program is from cppreference.com. All paths I tried were on the same filesystem; therefore, I always get the same answer.

Space information

```
// space.cpp
...
#include <filesystem>

...

namespace fs = std::filesystem;

...

fs::space_info root = fs::space("/");
fs::space_info usr = fs::space("/usr");

std::cout << ".        Capacity       Free       Available\n"
          << "/       " << root.capacity << "    "
          << root.free << "    " << root.available << "\n"
          << "usr   "  << usr.capacity << "    "
          << usr.free <<  "    " << usr.available;
```

```
       Capacity       Free        Available
/    42140499968   18342744064   17054289920
usr  42140499968   18342744064   17054289920
```

File types

By using the following predicates, you can easily ask for the file type.

The file types of the filesystem

file types	Description
`is_block_file`	Checks if the path refers to a block file.
`is_character_file`	Checks if the path refers to a character file.
`is_directory`	Checks if the path refers to a directory.
`is_empty`	Checks if the path refers to an empty file or directory.
`is_fifo`	Checks if the path refers to a named pipe.
`is_other`	Checks if the path refers to another file.
`is_regular_file`	Checks if the path refers to a regular file.
`is_socket`	Checks if the path refers to an IPC socket.
`is_symlink`	Checks if the path refers to a symbolic link.
`status_known`	Checks if the file status is known.

Getting the type of a file

The predicates give you information on the file type. More than one predicate may be right for one file. A symbolic link referencing a regular file is both a regular file and a symbolic link.

Type of a file

```
// fileType.cpp
...
#include <filesystem>

...

namespace fs = std::filesystem;

void printStatus(const fs::path& path_){
  std::cout << path_;
  if(!fs::exists(path_)) std::cout << " does not exist";
  else{
    if(fs::is_block_file(path_)) std::cout << " is a block
file\n";
    if(fs::is_character_file(path_)) std::cout << " is a character
device\n";
    if(fs::is_directory(path_)) std::cout << " is a directory\n";
    if(fs::is_fifo(path_)) std::cout << " is a named pipe\n";
    if(fs::is_regular_file(path_)) std::cout << " is a regular
file\n";
    if(fs::is_socket(path_)) std::cout << " is a socket\n";
    if(fs::is_symlink(path_)) std::cout << "          is a
symlink\n";
  }
}

...

fs::create_directory("rainer");
printStatus("rainer");

std::ofstream("rainer/regularFile.txt");
printStatus("rainer/regularFile.txt");

fs::create_directory("rainer/directory");
printStatus("rainer/directory");

mkfifo("rainer/namedPipe", 0644);
printStatus("rainer/namedPipe");

struct sockaddr_un addr;
addr.sun_family = AF_UNIX;
std::strcpy(addr.sun_path, "rainer/socket");
int fd = socket(PF_UNIX, SOCK_STREAM, 0);
bind(fd, (struct sockaddr*)&addr, sizeof addr);
printStatus("rainer/socket");

fs::create_symlink("rainer/regularFile.txt", "symlink");
printStatus("symlink");

printStatus("dummy.txt");

fs::remove_all("rainer");
```

```
"rainer" is a directory
"rainer/regularFile.txt" is a regular file
"rainer/directory" is a directory
"rainer/namedPipe" is a named pipe
"rainer/socket" is a socket
"symlink" is a regular file
          is a symlink
"dummy.txt" does not exist
```

19. Multithreading

Cippi ties a braid

For the first time with C++11, C++ supports native multithreading. This support consists of two parts: A *well-defined* memory model and a standardized threading interface.

Memory Model

The foundation of multithreading is a *well-defined* memory model. This memory model has to deal with the following points:

- Atomic operations: Operations that can be performed without interruption.
- Partial ordering of operations: Sequence of operations that must not be reordered.
- Visible effects of operations: Guarantees when operations on shared variables are visible in other threads.

The C++ memory model has a lot in common with its predecessor: the Java memory model. Additionally, C++ permits the breaking of sequential consistency. Sequential consistency is the default behavior of atomic operations.

Sequential consistency provides two guarantees.

1. The instructions of a program are executed in source code order.
2. There is a global order of all operations on all threads.

Atomic Data Types

C++ has a set of atomic data types. First, there is `std::atomic_flag`, and second the class template `std::atomic`. Additionally, you can define your atomic datatype using `std::atomic`.

`std::atomic_flag`

`std::atomic_flag` is an atomic boolean. It has a clear and a set state. For simplicity reasons, I call the clear state `false` and the set state `true`. Its `clear` member function enables you to set its value to `false`. With the `test_and_set` member functions, you can set the value back to `true` and return the previous value. There is no member functions to ask for the current value. This changes with C++20. With C++20, a `std::atomic_flag` has a `test` member function and can be used for thread synchronization via the member functions `notify_one`, `notify_all`, and `wait`.

All operations of `std::atomic_flag atomicFlag`

Member functions	Description
`atomicFlag.clear()`	Clears the atomic flag.
`atomicFlag.test_and_set()`	Sets the atomic flag and returns the old value.
`atomicFlag.test()` (C++20)	Returns the value of the flag.
`atomicFlag.notify_one()` (C++20)	Notifies one thread waiting on the atomic flag.
`atomicFlag.notify_all()` (C++20)	Notifies all threads waiting on the atomic flag.
`atomicFlag.wait(b)` (C++20)	Blocks the thread until notified and the atomic value changes.

The call `atomicFlag.test()` returns the `atomicFlag` value without changing it. Further on, you can use `std::atomic_flag` for thread-synchronization: `atomicFlag.wait()`, `atomicFlag.notify_one()`, and `atomicFlag.notify_all()`. The member functions `notify_one` or `notify_all` notify one or all of the waiting atomic flags. `atomicFlag.wait(boo)` needs a boolean `b`. The call `atomicFlag.wait(b)` blocks until notified. It checks if the value of `atomicFlag` is equal to `b` and unblocks if not.

You must initialize a `std::atomic_flag` explicitly using `ATOMIC_FLAG_INIT:` std::atomic_flag flag(ATOMIC_FLAG_INIT)`. In C++20, a default-constructed `std::atomic_flag `is in its` false` state.

`std::atomic_flag` has one outstanding property because it is the only guaranteed lock-free atomic. The remaining powerful atomics can provide their functionality by using a locking mechanism such as `std::mutex`.

`std::atomic`

There are various specializations of the class template `std::atomic` available. They require the header `<atomic>`. `std::atomic<bool>` and `std::atomic<user-defined type>` use the primary template. Partial specializations are available for pointers `std::atomic<T*>`, and with C++20 for smart pointers `std::atomic<smart T*>`, full specializations for integral types `std::atomic<integral type>`, and with C++20 for floating-point types `std::atomic<floating-point>`. You can define your atomic data type using `std::atomic`.

Fundamental Atomic Interface

The three partial specializations `std::atomic<bool>`, `std::atomic<user-defined type>`, and `std::atomic<smart T*>` support the fundamental atomic interface.

Member functions	Description
`is_lock_free`	Checks if the atomic object is lock free.
`atomic_ref<T>::is_always_lock_free`	Checks at compile time if the atomic type is always lock free.
`load`	Atomically returns the value of the atomic.
`operator T`	Atomically returns the value of the atomic. Equivalent to `atom.load()`.
`store`	Atomically replace the atomic value with the non-atomic.
`exchange`	Atomically replace the value with the new value. Returns the old value.
`compare_exchange_strong` `compare_exchange_weak`	Atomically compares and eventually exchanges the value.
`notify_one` (C++20)	Notifies one atomic wait operation.
`notify_all` (C++20)	Notifies all atomic wait operations.
`wait` (C++20)	Blocks until it is notified. If the `old` value compares to unequal returns.

`compare_exchange_strong` has the following syntax: `bool compare_exchange_strong(T& expected, T& desired)`. Here is its behavior:

- If the atomic comparison of `atomicValue` with `expected` returns `true`, `atomicValue` is set in the same atomic operation to `desired`.
- If the comparison returns `false`, `expected` is set to `atomicValue`.

User Defined Atomics `std::atomic<user-defined type>`

Thanks to the class template `std::atomic`, you can define your user-defined atomic type.

There are many substantial restrictions on a user-defined type if you use it for an atomic type `std::atomic<user-defined type>`. The atomic type `std::atomic<user-defined type>` supports the same interface as `std::atomic<bool>`.

Here are the restrictions for a user-defined type to become an atomic type:

- The copy assignment operator for a user-defined type must be trivial for all its base classes and non-static members. You must not define the copy assignment operator, but you can request it from the compiler using `default`.
- a user-defined type must not have virtual member functions or virtual base classes
- a user-defined type must be bitwise comparable so that the C functions memcpy or memcmp can be applied

Most popular platforms can use atomic operations for `std::atomic<user-defined type>` if the size of the `user-defined type` is not bigger than an `int`.

Atomic Smart Pointers `std::atomic<smart T*>` (C++20)

A `std::shared_ptr` consists of a control block and its resource. The control block is thread-safe, but access to the resource is not. This means modifying the reference counter is an atomic operation, and you have the guarantee that the resource is deleted precisely once. These are the guarantees `std::shared_ptr` gives you. Using the partial template specialization `std::atomic<std::shared_ptr<T>>` and `std::atomic<std::weak_ptr<T>>` gives you the additionally guarantee that the access of the underlying object is thread-safe. In 2022, all operations on atomic smart pointers are not lock free.

`std::atomic<floating-point type>` (C++20)

Additionally to the fundamental atomic interface, `std::atomic<floating-point type>` supports addition and subtraction.

Additional operations to the fundamental atomic interface

Member functions	Description

`fetch_add`, `+=`
`fetch_sub`, `-=`
	Atomically adds (subtracts) the value.
	Returns the old value.

Full specializations for the types `float`, `double`, and `long double` are available.

`std::atomic<T*>`

`std::atomic<T*>` is a partial specialization of the class template `std::atomic`. It behaves like a plain pointer `T*`. Additionally to `std::atomic<floating-point type>`, `std::atomic<T*>` supports pre- and post-increment or pre- and post-decrement operations.

Additional operations to the `std::atomic<floating-point type`

Member functions	Description
`++`, `--`	Increments or decrements (pre- and post-increment) the atomic.

Have a look at the short example.

```
int intArray[5];
std::atomic<int*> p(intArray);
p++;
assert(p.load() == &intArray[1]);
p+=1;
assert(p.load() == &intArray[2]);
--p;
assert(p.load() == &intArray[1]);
```

`std::atomic<integral type>`

For each integral type there is a full specialization `std::atomic<integral type>` of `std::atomic`. `std::atomic<integral type>` supports all operations that `std::atomic<T*>` or `std::atomic<floating-point type>` supports. Additionally, `std::atomic<integral type` supports the bitwise logical operators `AND`, `OR`, and `XOR`.

All operations on `atomic`

Member functions	Description

`fetch_or`, `|=`
`fetch_and`, `&=`
`fetch_xor`, `^=`
	Atomically performs bitwise (AND, OR, and XOR) operation with the value.
	Returns the old value.

There is a slight difference between the composite bitwise-assignment operation and the fetch version. The composite bitwise-assignment operation returns the new value; the fetch variation returns the old value.

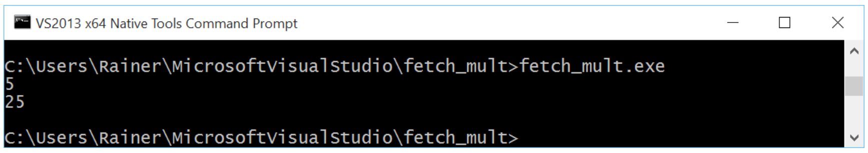
A more in-depth look provides more insight: no atomic multiplication, atomic division, or atomic shift operation is available. This is not a significant limitation because these operations are seldom needed and can easily be implemented. Here is an example of an atomic `fetch_mult` function.

An atomic multiplication with `compare_exchange_strong`

```
// fetch_mult.cpp

#include <atomic>
#include <iostream>

template <typename T>
T fetch_mult(std::atomic<T>& shared, T mult){
  T oldValue = shared.load();
  while (!shared.compare_exchange_strong(oldValue, oldValue * mult));
  return oldValue;
}
```

```
12
13 int main(){
14   std::atomic<int> myInt{5};
15   std::cout << myInt << '\n';
16   fetch_mult(myInt,5);
17   std::cout << myInt << '\n';
18 }
```

One point worth mentioning is that the multiplication in line 9 only happens if the relation `oldValue == shared` holds. I put the multiplication in a while loop to be sure that the multiplication always takes place because there are two instructions for the reading of `oldValue` in line 8 and its usage in line 9. Here is the result of the atomic multiplication.



```
C:\Users\Rainer\MicrosoftVisualStudio\fetch_mult>fetch_mult.exe
5
25

C:\Users\Rainer\MicrosoftVisualStudio\fetch_mult>
```

An atomic multiplication

`std::atomic_ref`

Additionally, the class template `std::atomic_ref` applies atomic operations to the referenced object. Concurrent writing and reading of atomic objects is thread-safe. The lifetime of the referenced object must exceed the lifetime of the `atomic_ref`. `std::atomic_ref` supports the same types and operations such as `std::atomic` does it for its underlying type.

```
struct Counters {
    int a;
    int b;
};

Counter counter;
std::atomic_ref<Counters> cnt(counter);
```

All Atomic Operations

The following table shows all atomic operations. To get further information about the operations, refer to the previous chapters on atomic data types.

	All atomic operations depending on the atomic type				
Member functions	**atomic_flag**	**atomic<bool> atomic<user> atomic<smart T*>**	**atomic<float>**	**atomic<T*>**	**atomic<**
`test_and_set`	yes				
`clear`	yes				
`is_lock_free`		yes	yes	yes	yes
`atomic<T>::is_always_lock_free`		yes	yes	yes	yes
`load`		yes	yes	yes	yes
`operator T`		yes	yes	yes	yes
`store`		yes	yes	yes	yes
`exchange`		yes	yes	yes	yes
`compare_exchange_strong`		yes	yes	yes	yes
`compare_exchange_weak`		yes	yes	yes	yes
`fetch_add, +=`			yes	yes	yes
`fetch_sub, -=`			yes	yes	yes
`fetch_or, |=`					yes
`fetch_and, &=`					yes
`fetch_xor, ^=`					yes
`++, --`				yes	yes
`notify_one` (C++20)	yes	yes	yes	yes	yes
`notify_all` (C++20)	yes	yes	yes	yes	yes
`wait` (C++20)	yes	yes	yes	yes	yes

`std::atomic<float>` stands for atomic floating point types, and `std::atomic<int>` for atomic integral types.

Threads

To use the multithreading interface of C++, you need the header `<thread>`. C++ supports with C++11 a `std::thread` and with C++20 an improved `std::jthread`.

`std::thread`

Creation

A thread `std::thread` represents an executable unit. This executable unit, which the thread immediately starts, gets its work package as a callable unit. A callable unit can be a function, a function object, or a lambda function:

Thread creation

```
// threadCreate.cpp
...
#include <thread>
...
using namespace std;

void helloFunction(){
  cout << "function" << endl;
}

class HelloFunctionObject {
public:
  void operator()() const {
    cout << "function object" << endl;
  }
};

thread t1(helloFunction);                      // function

HelloFunctionObject helloFunctionObject;
thread t2(helloFunctionObject);                // function object

thread t3([]{ cout << "lambda function"; });   // lambda function
```

Lifetime

The creator of a thread has to take care of the lifetime of its created thread. The executable unit of the created thread ends with the end of the callable. Either the creator is waiting until the created thread `t` is done (`t.join()`) or the creator detaches itself from the created thread: `t.detach()`. A thread `t` is *joinable* if no call `t.join()` or `t.detach()` was performed on it. A *joinable* thread throws in its destructor the exception `std::terminate`, and the program terminates.

Lifetime of a thread

```
// threadLifetime.cpp
...
#include <thread>
...

thread t1(helloFunction);                    // function

HelloFunctionObject helloFunctionObject;
thread t2(helloFunctionObject);              // function object

thread t3([]{ cout << "lambda function"; }); // lambda function

t1.join();
t2.join();
t3.join();
```

A from its creator detached thread is typically called a daemon thread because it runs in the background.

Move threads with caution

Threads can be moved but not copied.

```
#include <thread>
...
std::thread t([]{ cout << "lambda function"; });
std::thread t2;
t2 = std::move(t);

std::thread t3([]{ cout << "lambda function"; });
t2 = std::move(t3);                         // std::terminate
```

By performing `t2 = std::move(t)` thread `t2` gets the callable of thread `t`. Assuming thread `t2` already had a callable and is *joinable*, the C++ runtime would call `std::terminate`. This happens exactly in `t2 = std::move(t3)` because `t2` neither executed `t2.join()` nor `t2.detach()` before.

Arguments

A `std::thread` is a variadic template. This means that it can get an arbitrary number of arguments by copy or reference. Either the callable or the thread can get the arguments. The thread delegates them to the callable: `tPerCopy2` and `tPerReference2`.

```
#include <thread>
...

using namespace std;

void printStringCopy(string s){ cout << s; }
void printStringRef(const string& s){ cout << s; }

string s{"C++"};
```

```
thread tPerCopy([=]{ cout << s; });            // C++
thread tPerCopy2(printStringCopy, s);          // C++
tPerCopy.join();
tPerCopy2.join();

thread tPerReference([&]{ cout << s; });        // C++
thread tPerReference2(printStringRef, s);       // C++
tPerReference.join();
tPerReference2.join();
```

The first two threads get their argument `s` by copy, the second two by reference.

By default, threads should get their arguments by copy

Arguments of a thread

```
// threadArguments.cpp
...
#include <thread>
...

using std::this_thread::sleep_for;
using std::this_thread::get_id;

struct Sleeper{
 Sleeper(int& i_):i{i_}{};
 void operator() (int k){
   for (unsigned int j= 0; j <= 5; ++j){
     sleep_for(std::chrono::milliseconds(100));
     i += k;
   }
   std::cout << get_id();           // undefined behaviour
 }
private:
 int& i;
};

int valSleeper= 1000;

std::thread t(Sleeper(valSleeper), 5);
t.detach();

std::cout << valSleeper;            // undefined behaviour
```

This program snippet has undefined behavior. First, the lifetime of `std::cout` is bound to the lifetime of the main thread, and the created thread gets its variable `valSleeper` by reference. The issue is that the created thread could live longer than its creator, therefore, `std::cout` and `valSleeper` lose their validity if the main thread is done. Second, `valSleeper` is a shared, mutable variable which is concurrently used by the main thread and the child thread. Consequently, this is a data race.

Operations

You can perform many operations on a thread `t`.

Operations with a `std::thread`

Member Function	Description
`t.join()`	Waits until thread `t` has finished its executable unit.
`t.detach()`	Executes the created thread `t` independent of the creator.
`t.joinable()`	Checks if thread `t` supports the calls `join` or `detach`.
`t.get_id()` and `std::this_thread::get_id()`	Returns the identity of the thread.
`std::thread::hardware_concurrency()`	Indicates the number of threads that can run in parallel.
`std::this_thread::sleep_until(absTime)`	Puts the thread `t` to sleep until time `absTime`.
`std::this_thread::sleep_for(relTime)`	Puts the thread `t` to sleep for the duration `relTime`.
`std::this_thread::yield()`	Offers the system to run another thread.
`t.swap(t2)` and `std::swap(t1, t2)`	Swaps the threads.

You can only call `t.join()` or `t.detach()` once on a thread `t`. If you attempt to call these more than once, you get the exception `std::system_error`. `std::thread::hardware_concurrency` returns the number of cores or 0 if the runtime cannot determine the number. The `sleep_until` and `sleep_for` operations need a time point or a time duration as an argument.

Threads cannot be copied but can be moved. A swap operation performs a move when possible.

Operations on a thread

```
// threadMember Functions.cpp
...
#include <thread>
...

using std::this_thread::get_id;

std::thread::hardware_concurrency();      // 4

std::thread t1([]{ get_id(); });            // 139783038650112
std::thread t2([]{ get_id(); });            // 139783030257408
t1.get_id();                                // 139783038650112
t2.get_id();                                // 139783030257408

t1.swap(t2);

t1.get_id();                                // 139783030257408
t2.get_id();                                // 139783038650112
get_id();                                   // 140159896602432
```

`std::jthread`

`std::jthread` stands for joining thread. In addition to `std::thread` from C++11, `std::jthread` can automatically join the started thread and signal an interrupt.

Automatically Joining

The *non-intuitive* behavior of `std::thread` is the following: when a `std::thread` is still joinable, `std::terminate` is called in its destructor.

On the contrary, a `std::jthread thr` automatically joins in its destructor if `thr` is still joinable.

Terminating a still joinable `std::jthread`

```
// jthreadJoinable.cpp
...
#include <thread>
...

std::jthread thr{[]{ std::cout << "std::jthread" << "\n"; }}; // std::jthread

std::cout << "thr.joinable(): " << thr.joinable() << "\n"; // thr.joinable(): true
```

Additionally to the std::thread, a `std::jthread` is interuptible.

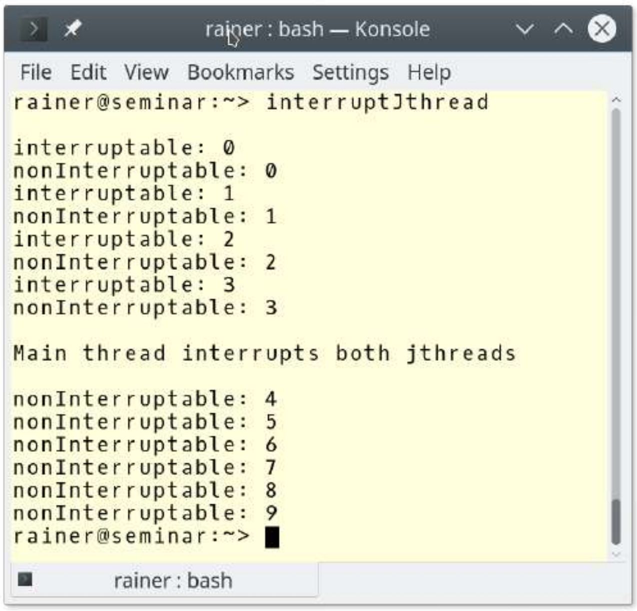
Stop Token

The additional functionality of the cooperatively joining thread is based on the `std::stop_token`, the `std::stop_callback`, and the `std::stop_source`. The following program should give you a general idea.

Interrupt an non-interruptable and interruptable `std::jthread`

```
// interruptJthread.cpp

...

#include <thread>
#include <stop_token

using namespace::std::literals;

...


std::jthread nonInterruptable([]{                          // (1)
    int counter{0};
    while (counter < 10){
        std::this_thread::sleep_for(0.2s);
        std::cerr << "nonInterruptable: " << counter << '\n';
        ++counter;
    }
});

std::jthread interruptable([](std::stop_token stoken){   // (2)
    int counter{0};
    while (counter < 10){
        std::this_thread::sleep_for(0.2s);
        if (stoken.stop_requested()) return;              // (3)
        std::cerr << "interruptable: " << counter << '\n';
        ++counter;
    }
});

std::this_thread::sleep_for(1s);

std::cerr << "Main thread interrupts both jthreads" << std:: endl;
nonInterruptable.request_stop();                          // (4)
interruptable.request_stop();

...
```

I start in the main program the two threads `nonInterruptable` and `interruptable` ((1) and (2)). In contrast to the thread `nonInterruptable`, the thread `interruptable` gets a `std::stop_token` and uses it in (3) to check if it was interrupted: `stoken.stop_requested()`. In case of an interrupt, the lambda function returns, and the thread ends. The call `interruptable.request_stop()` (4) triggers the end of the thread. This does not hold for the previous call `nonInterruptable.request_stop()`, which does not have an effect.



```
rainer@seminar:~> interruptJthread

interruptable: 0
nonInterruptable: 0
interruptable: 1
nonInterruptable: 1
interruptable: 2
nonInterruptable: 2
interruptable: 3
nonInterruptable: 3

Main thread interrupts both jthreads

nonInterruptable: 4
nonInterruptable: 5
nonInterruptable: 6
nonInterruptable: 7
nonInterruptable: 8
nonInterruptable: 9
rainer@seminar:~> 
```

`std::stop_token`, `std::stop_source`, and `std::stop_callback`

A `stop_token`, a `std::stop_callback`, or a `std::stop_source` enables it to asynchronously request execution to stop or ask if an execution gets a stop signal. The `std::stop_token` can be passed to an operation and afterward be used to actively poll the token for a stop request or to register a callback via `std::stop_callback`. The `std::stop_source` sents the stop request. This signal affects all associated `std::stop_token`. The three classes `std::stop_source`, `std::stop_token`, and `std::stop_callback` share the ownership of an associated stop state. The calls `request_stop()`, `stop_requested()`, and `stop_possible()` are atomic operations.

The components `std::stop_source` and `std::stop_token` provide the following attributes for stop handling.

Constructors of `std::stop_source`

```
stop_source();
explicit stop_source(std::nostopstate_t) noexcept;
```

The default-constructed `std::stop_source` gets a stop-source. The constructor taking `std::nostopstate_t` constructs an empty `std::stop_source` without an associated stop-state.

Member functions of `std::stop_source src`

Member function	Description
`src.get_token()`	If `stop_possible()`, returns a `stop_token` for the associated stop-state. Otherwise, it returns a default-constructed (empty) `stop_token`.
`src.stop_possible()`	`true` if `src` can be requested to stop.
`src.stop_requested()`	`true` if `stop_possible()` and `request_stop()` was called by one of the owners.
`src.request_stop()`	Calls a stop request if `stop_possible()` and `!stop_requested()`. Otherwise, the call has no effect.

`src.stop_possible()` means that `src` has an associated stop-state. `src.stop_requested()` returns `true` when `src` has an associated stop-state and was requested to stop before. `src.request_stop()` is successful and returns `true` if `src` has an associated stop-state and has received a stop request.

The call `src.get_token()` returns the stop token `stoken`. Thanks to `stoken`, you can check if a stop request has been made or can be made for its associated stop source `src`. The stop token `stoken` observes the stop source `src`.

Member functions of `std::stop_token stoken`

Member function	Description
`stoken.stop_possible()`	Returns `true` if `stoken` has an associated stop-state.
`stoken.stop_requested()`	`true` if `request_stop()` was called on the associated `std::stop_source src`, otherwise `false`.

A default-constructed stop token has no associated stop state. `stoken.stop_possible` also returns `true` if the stop request has already been made. `stoken.stop_requested()` returns `true` when the stop token has an associated stop-state and has already received a stop request.

If the `std::stop_token` should be temporarily disabled, you can replace it with a default constructed token. A default constructed token has no associated stop-state. The following code snippet shows how to disable and enable a thread's capability to accept stop requests.

Temporarily disable a stop token

```
std::jthread jthr([](std::stop_token stoken) {
    ...
    std::stop_token interruptDisabled;
    std::swap(stoken, interruptDisabled);  // (1)
    ...                                    // (2)
    std::swap(stoken, interruptDisabled);
    ...
}
```

`std::stop_token interruptDisabled` has no associated stop-state. This means the thread `jthr` can accept stop requests in all lines except lines (1) and (2).

Shared Variables

If more than one thread shares a variable, you must coordinate the access. That's the job for mutexes and locks in C++.

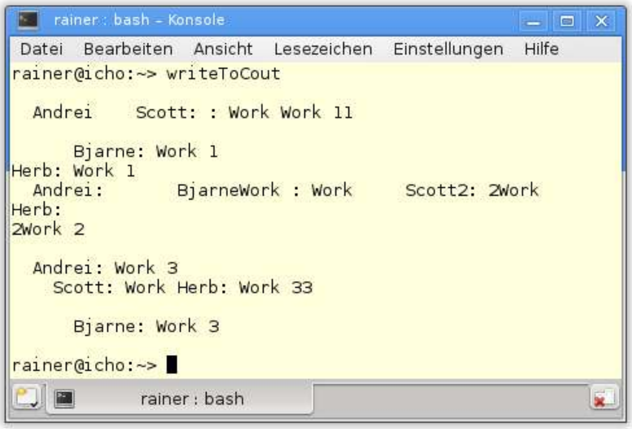
Data race

A data race
: A data race is a state in which at least two threads access shared data simultaneously, and at least one of the threads is a writer. Therefore the program has undefined behavior.

You can observe very well the interleaving of threads if a few threads write to `std::cout`. In this case, the output stream `std::cout` is the shared variable.

Unsychronised writing to `std::cout`

```
// withoutMutex.cpp
...
#include <thread>
...

using namespace std;

struct Worker{
  Worker(string n):name(n){};
  void operator() (){
    for (int i= 1; i <= 3; ++i){
      this_thread::sleep_for(chrono::milliseconds(200));
      cout << name << ": " << "Work " << i << endl;
    }
  }
private:
  string name;
};

thread herb= thread(Worker("Herb"));
thread andrei= thread(Worker(" Andrei"));
thread scott= thread(Worker ("    Scott"));
thread bjarne= thread(Worker("      Bjarne"));
```



```
rainer@icho:~> writeToCout

  Andrei     Scott: : Work Work 11

      Bjarne: Work 1
Herb: Work 1
  Andrei:       BjarneWork : Work      Scott2: 2Work
Herb:
2Work 2

  Andrei: Work 3
    Scott: Work Herb: Work 33

      Bjarne: Work 3

rainer@icho:~> 
```

The output on `std::cout` is not coordinated.

The streams are *thread-safe*

The C++11 standard guarantees that the characters are written atomically. Therefore you don't need to protect them. You only have to protect the interleaving of the threads on the stream if the entire read operation is not interleaved. That guarantee holds for the input and output streams.

With C++20, we have synchronized output streams such as `std::osyncstream` and `std::wosyncstream`. The guarantee that the writing to one output stream is synchronized. The output is written to an internal buffer and flushed when it goes out of scope. A synchronized output stream can have a name such as `synced_out` or be without a name.

Synchronized outputstreams

```
{
   std::osyncstream synced_out(std::cout);
   synced_out << "Hello, ";
   synced_out << "World!";
   synced_out << '\n'; // no effect
   synced_out << "and more!\n";
} // destroys the synced_output and emits the internal buffer

std::osyncstream(std::cout) << "Hello, " << "World!" << "\n";
```

`std::cout` is, in the example, the shared variable, which should have exclusive access to the stream.

Mutexes

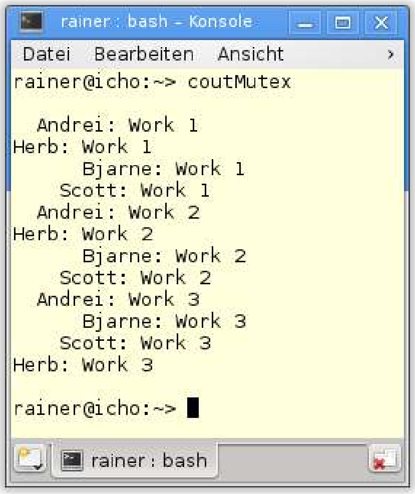
Mutex (*mutual exclusion*) `m' guarantees that only one thread can access the critical region at one time. They need the header` <mutex>`. A mutex` m' locks the critical section by the call `m.lock()` and unlocks it by `m.unlock()`.

Synchronisation with `std::mutex`

```
// mutex.cpp
...
#include <mutex>
#include <thread>
...

using namespace std;

std::mutex mutexCout;

struct Worker{
  Worker(string n):name(n){};
  void operator() (){
    for (int i= 1; i <= 3; ++i){
      this_thread::sleep_for(chrono::milliseconds(200));
      mutexCout.lock();
      cout << name << ": " << "Work " << i << endl;
      mutexCout.unlock();
    }
  }
private:
  string name;
};
```

```
thread herb= thread(Worker("Herb"));
thread andrei= thread(Worker("  Andrei"));
thread scott= thread(Worker ("    Scott"));
thread bjarne= thread(Worker("      Bjarne"));
```

Each thread after each other writes coordinated to `std::cout` because it uses the same mutex `mutexCout`.



```
rainer@icho:~> coutMutex

  Andrei: Work 1
Herb: Work 1
      Bjarne: Work 1
    Scott: Work 1
  Andrei: Work 2
Herb: Work 2
      Bjarne: Work 2
    Scott: Work 2
  Andrei: Work 3
      Bjarne: Work 3
    Scott: Work 3
Herb: Work 3

rainer@icho:~>
```

C++ has five different mutexes. They can lock recursively, tentatively with and without time constraints.

Mutex variations

Member Function	mutex	recursive_mutex	timed_mutex	recursive_timed_mutex	shared_timed_
`m.lock`	yes	yes	yes	yes	yes
`m.unlock`	yes	yes	yes	yes	yes
`m.try_lock`	yes	yes	yes	yes	yes
`m.try_lock_for`			yes	yes	yes
`m.try_lock_until`			yes	yes	yes

The `std::shared_time_mutex` enables it to implement reader-writer locks. The Member Function `m.try_lock_for(relTime)` needs a relative time duration; the Member Function `m.try_lock_until(absTime)` a absolute time point.

Deadlocks

Deadlocks
: A deadlock is a state in which two or more threads are blocked because each thread waits for the release of a resource before it releases its resource.

You can quickly get a deadlock if you forget to call `m.unlock()`. That happens, for example, in the case of an exception in the function `getVar()`.

```
m.lock();
sharedVar= getVar();
m.unlock()
```

Don't call an unknown function while holding a lock

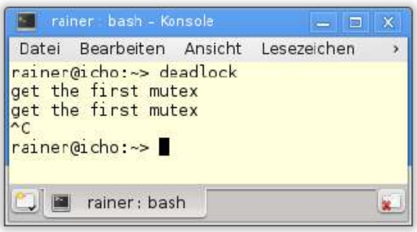
If the function `getVar` tries to get the same lock by calling `m.lock()`, you will get a deadlock because it will not be successful, and the call will block forever.

Locking two mutexes in the wrong order is another typical reason for a deadlock.

A deadlock

```
// deadlock.cpp
...
#include <mutex>
...

struct CriticalData{
  std::mutex mut;
};

void deadLock(CriticalData& a, CriticalData& b){
  a.mut.lock();
  std::cout << "get the first mutex\n";
  std::this_thread::sleep_for(std::chrono::milliseconds(1));
  b.mut.lock();
  std::cout << "get the second mutex\n";
  a.mut.unlock(), b.mut.unlock();
}

CriticalData c1;
CriticalData c2;

std::thread t1([&]{ deadLock(c1, c2); });
std::thread t2([&]{ deadLock(c2, c1); });
```

The short time window of one millisecond (`std::this_thread::sleep_for(std::chrono::milliseconds(1))`) is enough to produce with high probability a deadlock because each thread is waiting forever on the other mutex. The result is a standstill.



```
rainer@icho:~> deadlock
get the first mutex
get the first mutex
^C
rainer@icho:~> 
```

Encapsulate a mutex in a lock

It's very easy to forget to unlock a mutex or lock mutexes in a different order. To overcome most of the problems with a mutex, encapsulate it in a lock.

Locks

You should encapsulate a mutex in a lock to release the mutex automatically. A lock is an implementation of the RAII idiom because the lock binds the lifetime of the mutex to its lifetime. C++11 has `std::lock_guard` for the simple and `std::unique_lock` for the advanced use case, respectively. Both need the header `<mutex>`. With C++14 C++ has a `std::shared_lock`, which is in the combination with the mutex `std::shared_time_mutex` the base for reader-writer locks.

`std::lock_guard`

`std::lock_guard` supports only the simple use case. Therefore it can only bind its mutex in the constructor and release it in the destructor. So the synchronization of the worker example is reduced to the call of the constructor.

Synchronisation with `std::lock_guard`

```
// lockGuard.cpp
...
std::mutex coutMutex;

struct Worker{
  Worker(std::string n):name(n){};
  void operator() (){
    for (int i= 1; i <= 3; ++i){
      std::this_thread::sleep_for(std::chrono::milliseconds(200));
      std::lock_guard<std::mutex> myLock(coutMutex);
      std::cout << name << ": " << "Work " << i << '\n';
    }
  }
private:
  std::string name;
};
```

std::unique_lock

The usage of `std::unique_lock` is more expensive than that of `std::lock_guard`. On the contrary, a `std::unique_lock` can be created with and without a mutex, explicitly lock or release its mutex, or delay its mutex's lock.

The following table shows the Member Functions of a `std::unique_lock lk`.

The interface of std::unique_lock

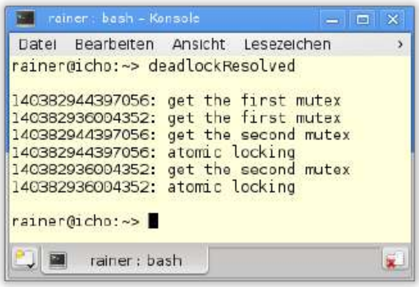
Member Function	Description
`lk.lock()`	Locks the associated mutex.
`std::lock(lk1, lk2, ...)`	Locks atomically the arbitrary number of associated mutexes.
`lk.try_lock()` and `lk.try_lock_for(relTime)` and `lk.try_lock_until(absTime)`	Tries to lock the associated mutex.
`lk.release()`	Release the mutex. The mutex remains locked.
`lk.swap(lk2)` and `std::swap(lk, lk2)`	Swaps the locks.
`lk.mutex()`	Returns a pointer to the associated mutex.
`lk.owns_lock()`	Checks if the lock has a mutex.

Deadlocks caused by acquiring locks in a different order can easily be solved by `std::atomic`.

`std::unique_lock`

```
// deadLockResolved. cpp
...
#include <mutex>
...

using namespace std;
struct CriticalData{
  mutex mut;
};

void deadLockResolved(CriticalData& a, CriticalData& b){
  unique_lock<mutex>guard1(a.mut, defer_lock);
  cout << this_thread::get_id() << ": get the first lock" << endl;
  this_thread::sleep_for(chrono::milliseconds(1));
  unique_lock<mutex>guard2(b.mut, defer_lock);
  cout << this_thread::get_id() << ": get the second lock" << endl;
  cout << this_thread::get_id() << ": atomic locking";
  lock(guard1, guard2);
}

CriticalData c1;
CriticalData c2;

thread t1([&]{ deadLockResolved(c1, c2); });
thread t2([&]{ deadLockResolved(c2, c1); });
```

Because of the argument `std::defer_lock` of the `std::unique_lock`, the locking of `a.mut` and `b.mut` is deferred. The locking takes place atomically in the call `std::lock(guard1, guard2)`.



```
rainer@icho:~> deadlockResolved

140382944397056: get the first mutex
140382936004352: get the first mutex
140382944397056: get the second mutex
140382944397056: atomic locking
140382936004352: get the second mutex
140382936004352: atomic locking

rainer@icho:~>
```

`std::shared_lock`

`std::shared_lock` has the same interface as `std::unique_lock`. Also, a `std::shared_lock` supports the case where multiple threads share the same locked mutex. For this special use case, you must use a `std::shared_lock` in combination with a `std::shared_timed_mutex`. However, if multiple threads use the same `std::shared_time_mutex` in a `std::unique_lock`, only one thread can own it.

```
#include <mutex>
...

std::shared_timed_mutex sharedMutex;

std::unique_lock<std::shared_timed_mutex> writerLock(sharedMutex);

std::shared_lock<std::shared_time_mutex> readerLock(sharedMutex);
std::shared_lock<std::shared_time_mutex> readerLock2(sharedMutex);
```

The example presents the typical reader-writer lock scenario. The `writerLock` of type `std::unique_lock<std::shared_timed_mutex>` can only exclusively have the `sharedMutex`. Both of the reader locks `readerLock` and `readerLock2` of type `std::shared_lock<std::shared_time_mutex>` can share the same mutex `sharedMutex`.

Thread-safe Initialization

If you don't modify the data, it's sufficient to initialize them in a *thread-safe* way. C++ offers various ways to achieve this: using a constant expression, using static variables with block scope, or using the function `std::call_once` combined with the flag `std::once::flag`.

Constant Expressions

A constant expression is initialized at compile time. Therefore they are per se *thread-safe*. By using the keyword `constexpr` before a variable, the variable becomes a constant expression. Instances of *user-defined* type can also be a constant expression and therefore be initialized in a *thread-safe* way if the Member Functions are declared as constant expressions.

```
struct MyDouble{
  constexpr MyDouble(double v):val(v){};
  constexpr double getValue(){ return val; }
private:
  double val
};

constexpr MyDouble myDouble(10.5);
std::cout << myDouble.getValue();             // 10.5
```

Static Variables Inside a Block

If you define a static variable in a block, the C++11 runtime guarantees that it is initialized in a *thread-safe* way.

```
void blockScope(){
  static int MySharedDataInt= 2011;
}
```

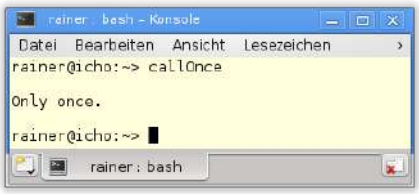
`std::call_once` and `std::once_flag`

`std::call_once` takes two arguments: the flag `std::once_flag` and a callable. The C++ runtime guarantees with the help of the flag `std::once_flag` that the callable is executed exactly once.

Thread-safe initialisation

```
// callOnce.cpp
...
#include <mutex>
...

using namespace std;

once_flag onceFlag;
void do_once(){
  call_once(onceFlag, [](){ cout << "Only once." << endl; });
}
thread t1(do_once);
thread t2(do_once);
```

Although both threads executed the function `do_once`, only one of them is successful, and the lambda function `[]{cout << "Only once." << endl;}` is executed exactly once.



```
rainer@icho:~> callOnce

Only once.

rainer@icho:~> 
```

You can use the same `std::once_flag` to register different callables, and only one of these callables is called.

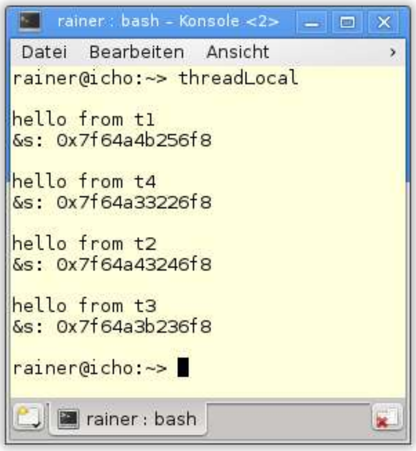
Thread Local Data

Using the keyword `thread_local`, you have thread-local data, also known as thread-local storage. Each thread has its copy of the data. *Thread-local* data behave like static variables. They are created at their first usage, and their lifetime is bound to the lifetime of their thread.

Thread local data

```
// threadLocal.cpp
...
std::mutex coutMutex;
thread_local std::string s("hello from ");

void addThreadLocal(std::string const& s2){
  s+= s2;
  std::lock_guard<std::mutex> guard(coutMutex);
  std::cout << s << '\n';
  std::cout << "&s: " << &s << '\n';
  std::cout << '\n';
}

std::thread t1(addThreadLocal, "t1");
std::thread t2(addThreadLocal, "t2");
std::thread t3(addThreadLocal, "t3");
std::thread t4(addThreadLocal, "t4");
```

Each thread has its copy of the `thread_local` string. Therefore, each string `s` modifies its string independently, and each string has its unique address:



```
rainer@icho:~> threadLocal

hello from t1
&s: 0x7f64a4b256f8

hello from t4
&s: 0x7f64a33226f8

hello from t2
&s: 0x7f64a43246f8

hello from t3
&s: 0x7f64a3b236f8

rainer@icho:~>
```

Condition Variables

Condition variables enable threads to be synchronized via messages. They need the header `<condition_variable>`. One thread acts as a sender, and the other as a receiver of the message. The receiver waits for the notification of the sender. Typical use cases for condition variables are producer-consumer workflows.

A condition variable can be the sender and receiver of the message.

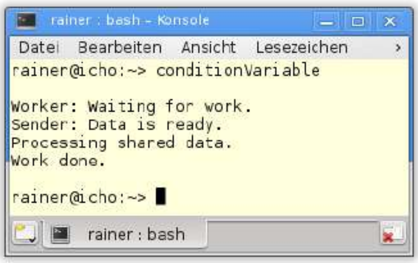
The Member Functions of the condition variable cv

Member Function	Description
`cv.notify_one()`	Notifies a waiting thread.
`cv.notify_all()`	Notifies all waiting threads.
`cv.wait(lock, ...)`	Waits for the notification while holding a `std::unique_lock`.
`cv.wait_for(lock, relTime, ...)`	Waits for a time duration for the notification while holding a `std::unique_lock`.
`cv.wait_until(lock, absTime, ...)`	Waits until a time for the notification while holding a `std::unique_lock`.

The sender and receiver need a lock. In the case of the sender, a `std::lock_guard` is sufficient because it only once calls lock and unlock. In the case of the receiver, a `std::unique_lock` is necessary because it typically locks and unlocks its mutex a few times.

Condition variable

```
// conditionVariable.cpp
...
#include <condition_variable>
...

std::mutex mutex_;
std::condition_variable condVar;
bool dataReady= false;

void doTheWork(){
  std::cout << "Processing shared data." << '\n';
}

void waitingForWork(){
  std::cout << "Worker: Waiting for work." << '\n';
  std::unique_lock<std::mutex> lck(mutex_);
  condVar.wait(lck, []{ return dataReady; });
  doTheWork();
  std::cout << "Work done." << '\n';
}

void setDataReady(){
  std::lock_guard<std::mutex> lck(mutex_);
  dataReady=true;
  std::cout << "Sender: Data is ready." << '\n';
  condVar.notify_one();
}

std::thread t1(waitingForWork);
std::thread t2(setDataReady);
```



```
rainer@icho:~> conditionVariable

Worker: Waiting for work.
Sender: Data is ready.
Processing shared data.
Work done.

rainer@icho:~>
```

Using a condition variable may sound easy but there a two critical issues.

Protection against spurious wakeup

To protect itself against spurious wakeup, the `wait` call of the condition variable should use an additional predicate. The predicate ensures that the notification is indeed from the sender. I use the lambda function `[]{ return dataReady; }` as the predicate. `dataReady` is set to `true` by the sender.

Protection against lost wakeup

To protect itself against lost wakeup, the `wait` call of the condition variable should use an additional predicate. The predicate ensures that the notification of the sender is not lost. The notification is lost if the sender notifies the receiver before the receiver is waiting. Therefore the receiver waits forever. The receiver now checks at first its predicate: `[]{ return dataReady; }`.

Semaphores

Semaphores are a synchronization mechanism that controls concurrent access to a shared resource. A counting semaphore is a special semaphore with a counter greater than zero. The counter is initialized in the constructor. Acquiring the semaphore decreases the counter, and releasing the semaphore increases the counter. If a thread tries to acquire the semaphore when the counter is zero, the thread will block until another thread increments the counter by releasing the semaphore.

C++20 supports a `std::binary_semaphore`, which is an alias for a `std::counting_semaphore<1>`. In this case, the least maximal value is 1.

```
using binary_semaphore = std::counting_semaphore<1>;
```

In contrast to a `std::mutex`, a `std::counting_semaphore` is not bound to a thread. This means that the acquire and release call can happen on different threads. The following table presents the interface of a `std::counting_semaphore`.

Member Functions of a semaphore `sem`

Member Function	Description
`counting_semaphore::max()`	Return the maximum value of the `counter`.
`sem.release(upd = 1)`	Atomically increases `counter` by `upd`.
`sem.acquire()`	Performs `sem.try_acquire` and blocks until `counter` is greater than zero.
`sem.try_acquire()`	Atomically decrements the `counter`.
`sem.try_acquire_for(relTime)`	Performs `sem.try_acquire` for the time duration.
`sem.try_acquire_until(absTime)`	Performs `sem.try_acquire` until the time point.

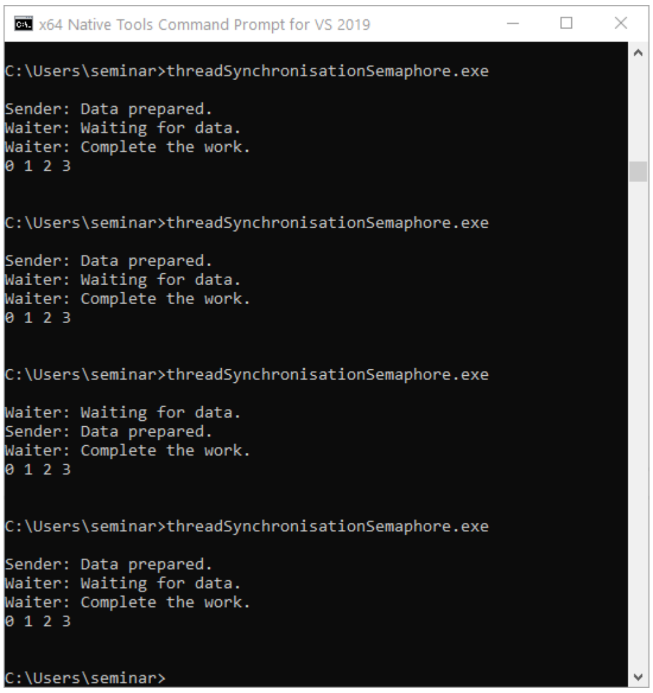
The Member Function `sem.try_lock_for(relTime)` requires a relative time duration; the Member Function `sem.try_lock_until(absTime)` requires an absolute time point.

Semaphores are often the safer and faster alternative to condition variables:

`std::counting_semaphore`

```
// threadSynchronisationSemaphore.cpp

#include <semaphore>

...

std::counting_semaphore<1> prepareSignal(0);              // (1)

void prepareWork() {

    myVec.insert(myVec.end(), {0, 1, 0, 3});
    std::cout << "Sender: Data prepared."  << '\n';
    prepareSignal.release();                              // (2)
}

void completeWork() {

    std::cout << "Waiter: Waiting for data." << '\n';
    prepareSignal.acquire();                              // (3)
    myVec[2] = 2;
    std::cout << "Waiter: Complete the work." << '\n';
    for (auto i: myVec) std::cout << i << " ";
    std::cout << '\n';

}

...

std::thread t1(prepareWork);
std::thread t2(completeWork);

t1.join();
t2.join();
```

The `std::counting_semaphore prepareSignal` (line 1) can have the values 0 and 1. In the concrete example, it's initialized with 0. This means that the call `prepareSignal.release()` sets the value to 1 (line 2) and unblocks the call `prepareSignal.acquire()` (line 3).



```
C:\Users\seminar>threadSynchronisationSemaphore.exe

Sender: Data prepared.
Waiter: Waiting for data.
Waiter: Complete the work.
0 1 2 3


C:\Users\seminar>threadSynchronisationSemaphore.exe

Sender: Data prepared.
Waiter: Waiting for data.
Waiter: Complete the work.
0 1 2 3


C:\Users\seminar>threadSynchronisationSemaphore.exe

Waiter: Waiting for data.
Sender: Data prepared.
Waiter: Complete the work.
0 1 2 3


C:\Users\seminar>threadSynchronisationSemaphore.exe

Sender: Data prepared.
Waiter: Waiting for data.
Waiter: Complete the work.
0 1 2 3


C:\Users\seminar>
```

Coordination Types

Latches and barriers are coordination types that enable some threads to block until a counter becomes zero. With C++20, we have latches and barriers in two variations: `std::latch`, and `std::barrier`.

`std::latch`

Now, I have a closer look at the interface of a `std::latch`.

Member function of a `std::latch lat`

Member function	Description
`lat.count_down(upd = 1)`	Atomically decrements the counter by `upd` without blocking the caller.
`lat.try_wait()`	Returns true if `counter == 0`.
`lat.wait()`	Returns immediately if `counter == 0`. If not, blocks until `counter == 0`.
`lat.arrive_and_wait(upd = 1)`	Equivalent to `count_down(upd); wait();`.

The default value for `upd` is `1`. When `upd` is greater than the counter or negative, the program has undefined behavior. The call `lat.try_wait()` does never wait as its name suggests.

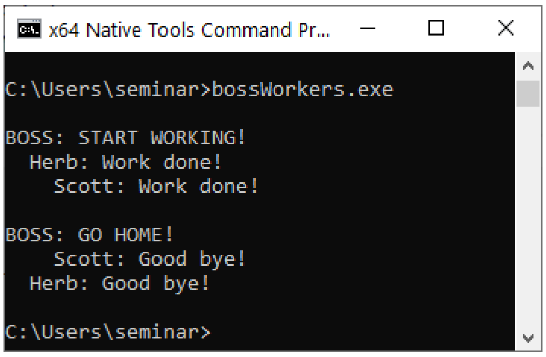
The following program uses two `std::latch` to build a boss-workers workflow. I synchronized the output to `std::cout` using the function `synchronizedOut` (line 13). This synchronization makes it easier to follow the workflow.

std::latch

```
// bossWorkers.cpp

#include <latch>

...
```

```
std::latch workDone(2);
std::latch goHome(1);                   // (5)

void synchronizedOut(const std::string s) {
    std::lock_guard<std::mutex> lo(coutMutex);
    std::cout << s;
}

class Worker {
 public:
     Worker(std::string n): name(n) { };

      void operator() (){
          // notify the boss when work is done
          synchronizedOut(name + ": " + "Work done!\n");
          workDone.count_down();      // (3)

          // waiting before going home
          goHome.wait();
          synchronizedOut(name + ": " + "Good bye!\n");
      }
 private:
    std::string name;
};

...

std::cout << "BOSS: START WORKING! " << '\n';

Worker herb("  Herb");               // (1)
std::thread herbWork(herb);

Worker scott("    Scott");           // (2)
std::thread scottWork(scott);

workDone.wait();                     // (4)

std::cout << '\n';

goHome.count_down();

std::cout << "BOSS: GO HOME!" << '\n';

herbWork.join();
scottWork.join();
```

The idea of the workflow is straightforward. The two workers, `herb`, and `scott` (lines 1 and 2), must fulfill their job. When they finished their job (line 3), they count down the `std::latch workDone`. The boss (main-thread) is blocked in line (4) until the counter becomes 0. When the counter is 0, the boss uses the second `std::latch goHome` to signal its workers to go home. In this case, the initial counter is 1 (line 5). The call `goHome.wait(0)` blocks until the counter becomes 0.



```
C:\Users\seminar>bossWorkers.exe

BOSS: START WORKING!
  Herb: Work done!
    Scott: Work done!

BOSS: GO HOME!
    Scott: Good bye!
  Herb: Good bye!

C:\Users\seminar>
```

A `std::barrier` is similar to a `std::latch`.

std::barrier

There are two differences between a `std::latch` and a `std::barrier`. First, you can use a `std::barrier` more than once, and second, you can set the counter for the next step (iteration). Immediately after the counter becomes zero, the so-called completion step starts. In this completion step, a callable is invoked. The `std::barrier` gets its callable in its constructor.

The completion step performs the following steps:

1. All threads are blocked.
2. An arbitrary thread is unblocked and executes the callable.
3. If the completion step is done, all threads are unblocked.

Member functions of a `std::barrier` bar

Member function	Description
`bar.arrive(upd)`	Atomically decrements counter by `upd`.
`bar.wait()`	Blocks at the synchronization point until the completion step is done.
`bar.arrive_and_wait()`	Equivalent to `wait(arrive())`
`bar.arrive_and_drop()`	Decrements the counter for the current and the subsequent phase by one.
`std::barrier::max`	Maximum value supported by the implementation.

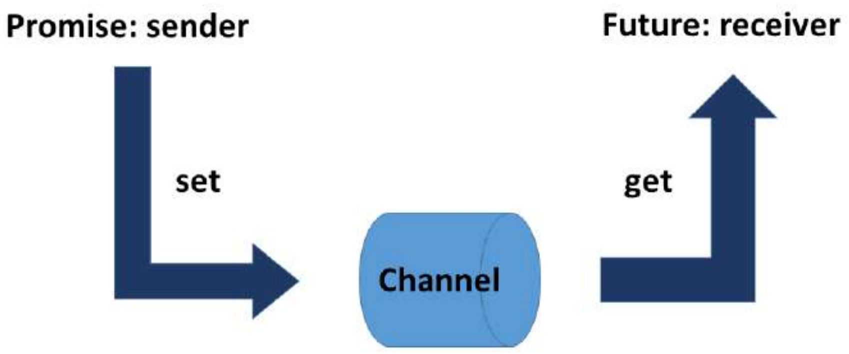
The `bar.arrive_and_drop()` call essentially means that the counter is decremented by one for the next phase.

Tasks

In addition to threads, C++ has tasks to perform work asynchronously. Tasks need the header `<future>`. A task is parameterized with a work package consisting of two associated components: a promise and a future. Both are connected via a data channel. The promise executes the work packages and puts the result in the data channel; the associated future picks up the result. Both communication endpoints can run in separate threads. It is special that the future can pick up the result later. Therefore, the calculation of the result by the promise is independent of the query of the result by the associated future.

Regard tasks as data channels

Tasks behave like data channels. The promise puts its result in the data channel. The future waits for it and picks it up.



Threads versus Tasks

Threads are very different from tasks.

You have to use a shared variable for the communication between the creator thread and the created thread. The task communicates via its data channel, which is implicitly protected. Therefore a task must not use a protection mechanism like a mutex.

The creator thread is waiting for its child with the `join` call. The `future fut` is using the `fut.get() call which is blocking if no result is there.

If an exception happens in the created thread, the created thread, the creator, and the whole process terminates. On the contrary, the promise can send exceptions to the future, which has to handle the exception.

A promise can serve one or many futures. It can send a value, an exception, or only a notification. You can use a task as a safe replacement for a condition variable.

```
#include <future>
#include <thread>
...

int res;
std::thread t([&]{ res= 2000+11;});
t.join();
std::cout << res << '\n';             // 2011

auto fut= std::async([]{ return 2000+11; });
std::cout << fut.get() << '\n';       // 2011
```

The child thread `t` and the asynchronous function call `std::async` calculates the sum of `2000` and `11`. The creator thread gets the result from its child thread `t` via the shared variable `res`. The call `std::async` creates the data channel between the sender (promise) and the receiver (future). The future asks the data channel with `fut.get()` for the calculation result. The `fut.get` call is blocking.

`std::async`

`std::async` behaves like an asynchronous function call. This function call takes a callable and its arguments. `std::async` is a variadic template and can, therefore, take an arbitrary number of arguments. The call of `std::async` returns a future object `fut`. That's your handle for getting the result via `fut.get()`. Optionally you can specify a start policy for `std::async`. You can explicitly determine with the start policy if the asynchronous operation should be executed in the same thread (`std::launch::deferred`) or another thread (`std::launch::async`).

The call `auto fut= std::async(std::launch::deferred, ... )` will not immediately be executed. The call `fut.get()` starts the promise lazily.

Lazy and eager with `std::async`

```
// asyncLazyEager.cpp
...
#include <future>
...
using std::chrono::duration;
using std::chrono::system_clock;
using std::launch;

auto begin= system_clock::now();

auto asyncLazy= std::async(launch::deferred, []{ return system_clock::now(); });
auto asyncEager= std::async(launch::async, []{ return system_clock::now(); });
std::this_thread::sleep_for(std::chrono::seconds(1));

auto lazyStart= asyncLazy.get() - begin;
auto eagerStart= asyncEager.get() - begin;

auto lazyDuration= duration<double>(lazyStart).count();
auto eagerDuration= duration<double>(eagerStart).count();

std::cout << lazyDuration << " sec";                 // 1.00018 sec.
std::cout << eagerDuration << " sec";                // 0.00015489 sec.
```

The program's output shows that the promise associated with the future `asyncLazy` is executed one second later than the promise associated with the future `asyncEager`. One second is precisely the time duration the creator is sleeping before the future `asyncLazy` asks for its result.

`std::async` should be your first choice

The C++ runtime determines if `std::async` is executed in a separate thread. The decision of the C++ runtime may depend on the number of your cores, the utilization of your system, or the size of your work package.

`std::packaged_task`

`std::packaged_task` enables you to build a simple wrapper for a callable, which can later be executed on a separate thread.

Therefore four steps are necessary.

I. Wrap your work:

```
std::packaged_task<int(int, int)> sumTask([](int a, int b){ return a+b; });
```

II. Create a future:

```
std::future<int> sumResult= sumTask.get_future();
```

III. Perform the calculation:

```
sumTask(2000, 11);
```

IV. Query the result:

```
sumResult.get();
```

You can move either the `std::package_task` or the `std::future` in a separate thread.

`std::packaged_task`

```
// packaged_task.cpp
...
#include <future>
...

using namespace std;

struct SumUp{
  int operator()(int beg, int end){
    for (int i= beg; i < end; ++i ) sum += i;
    return sum;
  }
private:
  int beg;
  int end;
  int sum{0};
};

SumUp sumUp1, sumUp2;

packaged_task<int(int, int)> sumTask1(sumUp1);
packaged_task<int(int, int)> sumTask2(sumUp2);

future<int> sum1= sumTask1.get_future();
future<int> sum2= sumTask2.get_future();

deque< packaged_task<int(int, int)>> allTasks;
allTasks.push_back(move(sumTask1));
allTasks.push_back(move(sumTask2));

int begin{1};
int increment{5000};
int end= begin + increment;

while (not allTasks.empty()){
  packaged_task<int(int, int)> myTask= move(allTasks.front());
  allTasks.pop_front();
  thread sumThread(move(myTask), begin, end);
  begin= end;
  end += increment;
  sumThread.detach();
}

auto sum= sum1.get() + sum2.get();
cout << sum;                                    // 50005000
```

The promises (`std::packaged_task`) are moved into the `std::deque allTasks`. The program iterates in the `while` loop through all promises. Each promise runs in its thread and performs its addition in the background (`sumThread.detach()`). The result is the sum of all numbers from 1 to 100000.

`std::promise` and `std::future`

The pair `std::promise` and `std::future` provide the full control over the task.

The Member Functions of the promise prom

Member Function	Description
`prom.swap(prom2)` and `std::swap(prom, prom2)`	Swaps the promises.
`prom.get_future()`	Returns the future.
`prom.set_value(val)`	Sets the value.
`prom.set_exception(ex)`	Sets the exception.
`prom.set_value_at_thread_exit(val)`	Stores the value and makes it ready if the promise exits.
`prom.set_exception_at_thread_exit(ex)`	Stores the exception and makes it ready if the promise exits.

If the promise sets the value or the exception more than once a `std::future_error` exception is thrown.

The Member Functions of the future fut

Member Function	Description
`fut.share()`	Returns a `std::shared_future`.
`fut.get()`	Returns the result, which can be a value or an exception.
`fut.valid()`	Checks if the result is available. Returns after the call `fut.get()` false.
`fut.wait()`	Waits for the result.
`fut.wait_for(relTime)`	Waits for a time duration for the result.
`fut.wait_until(absTime)`	Waits until a time for the result.

If a future `fut` asks more than once for the result, a `std::future_error` exception is thrown. The future creates a shared future by the call `fut.share()`. Shared futures are associated with their promise, and can ask for the result independently. A shared future has the same interface as a future.

Here is the usage of promise and future.

Promise and future

```
// promiseFuture.cpp
...
#include <future>
...

void product(std::promise<int>&& intPromise, int a, int b){
  intPromise.set_value(a*b);
}

int a= 20;
int b= 10;

std::promise<int> prodPromise;
std::future<int> prodResult= prodPromise.get_future();

std::thread prodThread(product, std::move(prodPromise), a, b);
std::cout << "20*10= " << prodResult.get();                // 20*10= 200
```

The promise `prodPromise` is moved into a separate thread and performs its calculation. The future gets the result by `prodResult.get()`.

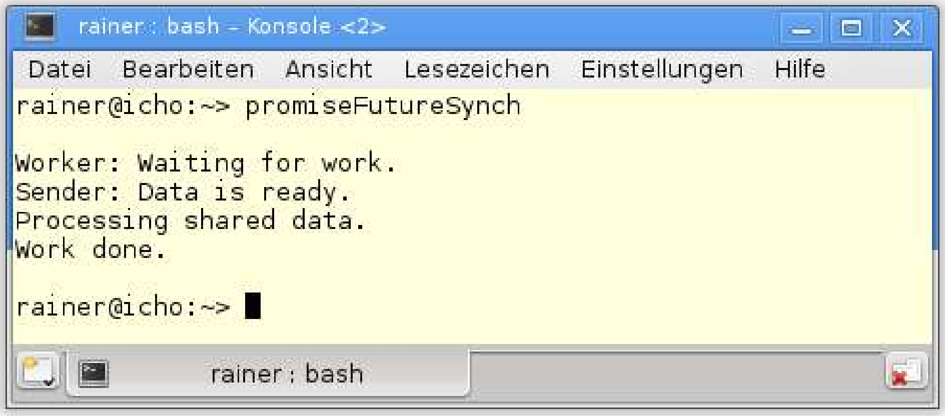
Synchronization

A future `fut` can be synchronized with is associated promise by the call `fut.wait()`. Contrary to condition variables, you need no locks and mutexes, and spurious and lost wakeups are impossible.

Tasks for synchronisation

```
// promiseFutureSynchronise.cpp
...
#include <future>
...

void doTheWork(){
  std::cout << "Processing shared data." << '\n';
}

void waitingForWork(std::future<void>&& fut){
  std::cout << "Worker: Waiting for work." <<
  '\n';
  fut.wait();
  doTheWork();
  std::cout << "Work done." << '\n';
}

void setDataReady(std::promise<void>&& prom){
  std::cout << "Sender: Data is ready." <<
  '\n';
  prom.set_value();
}

std::promise<void> sendReady;
auto fut= sendReady.get_future();

std::thread t1(waitingForWork, std::move(fut));
std::thread t2(setDataReady, std::move(sendReady));
```

The call of the promise `prom.set_value()` wakes up the future, which then can perform its work.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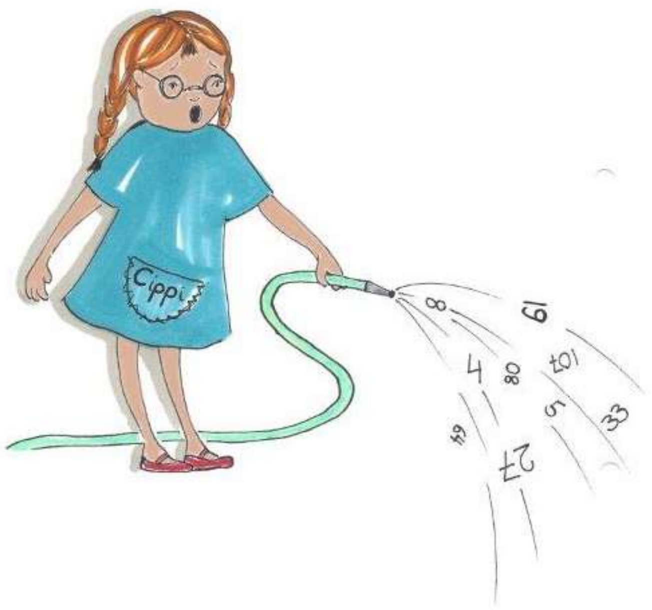
Datei Bearbeiten Ansicht Lesezeichen Einstellungen Hilfe
rainer : bash

```
rainer@icho:~> promiseFutureSynch

Worker: Waiting for work.
Sender: Data is ready.
Processing shared data.
Work done.

rainer@icho:~> 
```

20. Coroutines



Cippi waters the flowers

We don't get with C++20 concrete coroutines; we have with C++20 a framework for implementing coroutines. In C++23, we have the first concrete coroutine with `std::generator` in the ranges library. This chapter gives you only a rough idea of the challenging coroutine framework.

Coroutines are functions that can suspend and resume their execution while keeping their state. To achieve this, a coroutine consists of three parts: the promise object, the coroutine handle, and the coroutine frame.

- The promise object is manipulated from within the coroutine and returns its result via the promise object.
- The coroutine handle is a non-owning handle to resume or destroy the coroutine frame from the outside.
- The coroutine frame is an internal, typically heap-allocated state. It consists of the already mentioned promise object, the coroutine's copied parameters, the representation of the suspensions point, local variables whose lifetime ends before the current suspension point,

and local variables whose lifetime exceeds the current suspension point.

Two requirements are necessary to optimize the allocation of the coroutine:

A function that uses the keywords `co_return` instead of `return`, `co_yield`, or `co_await` becomes a coroutine implicitly.

The new keywords extend the execution of C++ functions with two new concepts.

`co_yield expression`
: Allows it to write a generator function. The generator function returns a new value each time. A generator function is a data stream from which you can pick values. The data stream can be infinite.

A generator

```
Generator<int> getNext(int start = 0, int step = 1) noexcept {
    auto value = start;
    for (int i = 0;; ++i){
        co_yield value;
        value += step;
    }
}
```

`co_await expression`
: Suspends and resumes the execution of the expression. If you use the `co_await` expression in a function `func`, the call `auto getResult = func()` does not block if the function's result is unavailable. Instead of resource-consuming blocking, you have resource-friendly waiting. The expression has to be a so-called awaitable expression and must support the following three functions `await_ready`, `await_suspend`, and `await_resume`.

A coroutine

```
Acceptor acceptor{443};

while (true){
    Socket socket= co_await acceptor.accept();
    auto request= co_await socket.read();
    auto response= handleRequest(request);
    co_await socket.write(response);
}
```

The awaitable expression `expr` in the `co_await expr` has to implement the functions `await_ready`, `await_suspend`, and `await_resume`.

Awaitables

The C++20 standard already defines two awaitables as basic-building blocks: `std::suspend_always`, and `std::suspend_never`.

The predefined awaitables

```
struct suspend_always {
    constexpr bool await_ready() const noexcept { return false;
}
    constexpr void await_suspend(coroutine_handle<>) const
noexcept {}
    constexpr void await_resume() const noexcept {}
};

struct suspend_never {
    constexpr bool await_ready() const noexcept { return true; }
    constexpr void await_suspend(coroutine_handle<>) const
noexcept {}
    constexpr void await_resume() const noexcept {}
};
```

An Infinite Data Stream with `co_yield`

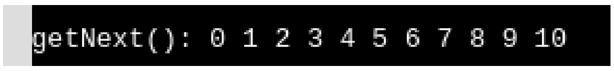
The following program produces an infinite data stream. The coroutine `getNext` uses `co_yield` to create a data stream that starts at `start` and gives on request the next value, incremented by `step`.

An infinite data stream

```
// infiniteDataStream.cpp

...

#include <coroutine>

template<typename T>
struct Generator {

    struct promise_type;
    using handle_type = std::coroutine_handle<promise_type>;

    Generator(handle_type h): coro(h) {}
// (3)
    handle_type coro;
    ~Generator() {
        if ( coro ) coro.destroy();
    }
    Generator(const Generator&) = delete;
    Generator& operator = (const Generator&) = delete;
    Generator(Generator&& oth) noexcept : coro(oth.coro) {
        oth.coro = nullptr;
    }
    Generator& operator = (Generator&& oth) noexcept {
        coro = oth.coro;
        oth.coro = nullptr;
        return *this;
    }
    T getValue() {
        return coro.promise().current_value;
    }
    bool next() {
// (5)
        coro.resume();
        return not coro.done();
    }
    struct promise_type {
        promise_type()  = default;
// (1)

        ~promise_type() = default;

        auto initial_suspend() {
// (4)
            return std::suspend_always{};
        }
        auto final_suspend() noexcept {
            return std::suspend_always{};
        }
        auto get_return_object() {
// (2)
            return Generator{handle_type::from_promise(*this)};
        }
        auto return_void() {
            return std::suspend_never{};
        }

        auto yield_value(const T value) {
// (6)
            current_value = value;
            return std::suspend_always{};
        }
        void unhandled_exception() {
            std::exit(1);
        }
        T current_value;
    };

};

Generator<int> getNext(int start = 0, int step = 1){
    auto value = start;
    for (int i = 0;; ++i){
        co_yield value;
        value += step;
    }
}
```

```
int main() {

    std::cout << '\n';

    std::cout << "getNext():";
    auto gen = getNext();
    for (int i = 0; i <= 10; ++i) {
        gen.next();
        std::cout << " " << gen.getValue();
// (7)
    }

    std::cout << '\n';

}
```

The `main` program creates a coroutine. The coroutine `gen` (7) returns the values from 0 to 10.



```
getNext(): 0 1 2 3 4 5 6 7 8 9 10
```

An infinite data stream

The numbers in the program `infiniteDataStream.cpp` stand for the first iteration of the workflow.

1. creates the promise
2. calls `promise.get_return_object()` and keeps the result in a local variable
3. creates the generator
4. calls `promise.initial_suspend()`. The generator is lazy and, therefore, always suspends.
5. asks for the next value and returns if the generator is consumed
6. triggered by the `co_yield` call. The next value is afterward available.
7. gets the next value

In additional iterations, only steps 5 and 6 are performed.

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