

SEMESTER HS2020

C++ Zusammenfassung

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1 Introduction to C++

In C++ gibt es keinen Garbage Collector, wie man es aus anderen Sprachen, wie Java oder C# kennt. Warnung: Wenn Code "falsch" geschrieben wurde, kann **Undefined Behavior** auftreten.

1.1 C++ Compilation Process

*.cpp Files

- Also called Implementation File
- For function implementations (can be in .h as well)
- Source of compilation

*.h File

- Also called Header File
- Declarations and definitions to be used in other implementation files

3 Phases of compilation

- Preprocessor Textual replacement of preprocessor directives (include)
- Compiler Translation of C++ code into machine code (source file to object file)
- Linker Combination of object files and libraries into libraries and executables

1.2 Declarations and Definitions

All things with a name that you use in a C++ program must be declared before you can do so.

One Definition Rule

While a program element can be declared several times without problem there can be only one definition of it. This is called the **One Definition Rule** (ODR)!

Include Guard

Include guards ensure that a header file is only included once. Multiple inclusions could violate the One Definition Rule when the header contains definitions.

```
1  #ifndef SAYHELLO_H_
2  #define SAYHELLO_H_
3
4  #include <iosfwd>
5  struct Greeter { /* Some Code */ };
6
7  #endif /* SAYHELLO_H_ */
```

2 Values and Streams

2.1 Variable Definitions

- Defining a variable consists of specifying its type, its variable name and its initial value. E.g. `int x{42};`
- Empty braces mean default initialization. E.g. `double x{};`
- Using `=` for initialization we can have the compiler determine its type. E.g. `auto const i = 5;`

Constants

- Adding the `const` keyword in front of the name makes the variable a single assignment variable, aka a constant. E.g. `int const x{42};`
 - Must be initialized and immutable
- Use the keyword `constexpr` if the variable is required to be fixed at compile time. E.g. `double constexpr pi{3.14159};`

Why should I use `const`?

- A lot of code needs names for values, but often does not intend to change it
- It helps to avoid reusing the same variable for different purposes (code smell)
- It creates safer code, because a `const` variable cannot be inadvertently changed
- It makes reasoning about code easier
- `Constness` is checked by the compiler
- It improves optimization and parallelization (shared mutable state is dangerous)

Important types for Variable

- `short`, `int`, `long`, `long long` - each also available as unsigned version
- `bool`, `char`, unsigned `char`, signed `char`
- `float`, `double`, `long double`
- `void` is special, it is the type with no values
- class defined: E.g. `std::string`, `std::vector`

2.2 Values and Expressions

Integer to boolean: `0 = False`, every other value = `True`

if (`a < b < c`) → zuerst wird `a < b` ausgewertet (true oder false). Dann wird der Boolean mit einem `int` (`c`) verglichen. Der Bool wird dafür implizit in 0 oder 1 gecastet.

Literal Example	Type	Value
'a'	char	Letter a, value: 97
'\n'	char	<NL> character, value: 10
'\x0a'	char	<NL> character, value: 10
1	int	1
42L	long	42
5LL	long long	5
int{} (not really a literal)	int	0 (default value)
1u	unsigned int	1
42ul	unsigned long	42
5ull	unsigned long long	5
020	int	16 (octal 20)
0x1f	int	31 (hex 1F)
0XFULL	unsigned long long	15 (hex F)
0.f	float	0
.33	double	0.33
1e9	double	1000000000 (10 ⁹)
42.E-12L	long double	0.00000000042 (42*10 ⁻¹²)
.3l	long double	0.3
"hello"	char const [6]	Array of 6 chars: h e l l o <NUL>
"\012\n\\"	char const [4]	Array of 4 chars: <NL> <NL> \ <NUL>

2.3 Strings and Sequences

`std::string` is C++'s type for representing sequences of `char` (which is often only 8 bit) and are mutable. That means, we can modify the content. (Vergleich zu Java: Dort würde ein neues String Objekt erstellt werden)

Grundsätzlich werden Strings also als `char const[]` abgespeichert. Mit dem namespace `std::literals` hat man die Option hinter dem String eine `'s'` anzufügen, um das Objekt effektiv als String zu speichern. z.B. `"ab"s`

toUpper Iterator

```
1 void toUpper(std::string & value) {
2     transform(cbegin(value), cend(value), begin(value), ::toupper);
3 }
```

2.4 Input and Output Streams

Functions taking a stream object must take it as a reference, because they provide a side effect to the stream (i.e., output characters).

Reading from Input

- Reading into a `std::string` always works. Unless the stream is already `!good()` → Spaces werden übersprungen (neues String-Objekt)!
- Reading into other types (e.g. `int`) has no error recovery. A wrong input puts the stream into status fail and the characters remain in the input.
- Post-read check: `if (in » age) { ... }`
- Multiple subsequent reads are possible: `if (in » symbol » count) { ... }`
- Remove fail flag: `in.clear()`
- Ignore one char: `in.ignore();`
- Helpfull for reading: `while (in.good())` um die Leseoperationen setzen.

Robust reading of an int value

```
1 // Use an std::istringstream as intermediate stream
2 int inputAge(std::istream & in)
3 {
4     std::string line{}
5     while (getline(in, line)) {
6         std::istringstream is{line};
7         int age{-1};
8         if (is >> age) {
9             return age;
10        }
11    }
12    return -1;
13 }
```

Stream States

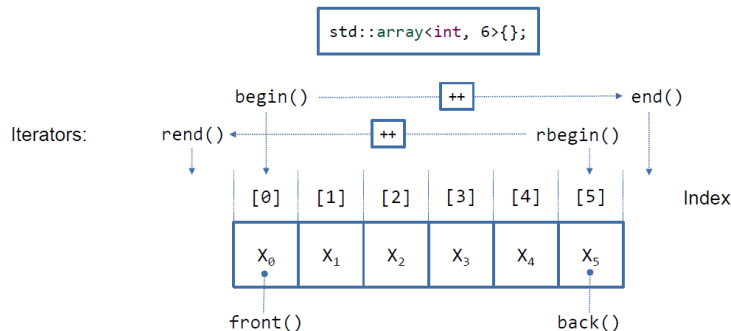
State Bit Set	Query	Entered
<none>	<code>is.good()</code>	initial <code>is.clear()</code>
failbit	<code>is.fail()</code>	formatted input failed
eofbit	<code>is.eof()</code>	trying to read at end of input
badbit	<code>is.bad()</code>	unrecoverable I/O error

3 Sequences and Iterators

3.1 Std::array and std::vector

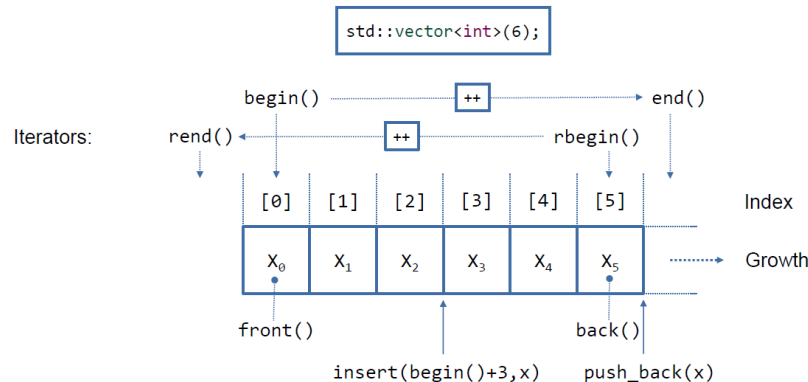
Array

- C++'s `std::array<T, N>` is a fixed size Container
 - T is a template type parameter. N is a positive integer parameter
- `std::array` can be initialized with a list of elements
 - The size of an array must be known at compile time and cannot be changed
 - Otherwise it contains N default constructed elements: `std::array<int, 5> emptyArray`
- The size is bound to the array object and can be queried using `.size()`
- Avoid plain C Array whenever possible: `int arr []{1, 2, 3, 4, 5};`



Vector

- C++'s `std::vector<T>` is a Container: contains its elements of type T (no need to allocate them)
 - `java.util.ArrayList<T>` is a collection = keeps references to T objects
 - T is a template parameter
- `std::vector` can be initialized with a list of elements
 - Otherwise it is empty: `std::vector<double> vd{ };`
 - Other construction means might need parentheses (legacy)
- When an initializer is given, the element type can be deduced! `std::vector{1, 2, 3, 4, 5};`



Parenthesis at definition allow providing initial size, when type of elements is a number:

`std::vector<string> words{6};` → Um sicher zu gehen die Grösse mit runden Klammern angeben.

Für beide Datentypen:

Element access using subscript operator `[]` or `at()`:

`at` throws an exception and `[]` has undefined behavior on invalid access.

Speicherort:

Generell werden alle Elemente einer Klasse auf dem Stack abgelegt. So auch der Vector. Fügt man dem Vector ein Element hinzu, wird davon eine unabhängige Kopie auf dem Heap erstellt. Der Vector referenziert auf das neue Objekt.

3.2 Iteration

Element Iteration (Range-Based for-Loop)

	const: • element cannot be changed	non-const: • element can be changed
reference: • element in vector is accessed	<pre>for (auto const & cref : v) { std::cout << cref << '\n'; }</pre>	<pre>for (auto & ref : v) { ref *= 2; }</pre>
copy: • loop has own copy of the element	<pre>for (auto const ccopy : v) { std::cout << ccopy << '\n'; }</pre>	<pre>for (auto copy : v) { copy *= 2; std::cout << copy << '\n'; }</pre>

Iteration with Iterators

```

1 // Changing the element in a non-const container is possible in this way
2 for (auto it = std::begin(v); it != std::end(v); ++it) {
3     std::cout << (*it)++ << ", ";
4 // Guarantee to just have read-only access with std::cbegin() and std::cend()
5 for (auto it = std::cbegin(v); it != std::cend(v); ++it) {
6     std::cout << *it << ", ";

```

3.3 Iterators with Algorithms

```

1 // Counting values: std::count
2 size_t count_blanks (std::string s) {
3     return std::count(s.begin(), s.end(), ' ');
4 }
5 // Summing up all values in a vector: std::accumulate
6 std::vector<int> v{5, 4, 3, 2, 1};
7 std::cout << std::accumulate(std::begin(v), std::end(v), 0) << " = sum\n";
8
9 // Number of elements in range: std::distance
10 void printDistanceAndLength (std::string s) {
11     std::cout << "distance: " << std::distance(s.begin(), s.end()) << '\n';
12     std::cout << "in a string of length: " << s.size() << '\n';
13 }
14
15 // std::for_each
16 void printAll(std::vector<int> v) {
17     std::for_each(cbegin(v), std::cend(v), print);
18 }
19 // std::for_each with Lambda
20 void printAll(std::vector<int> v, std::ostream & out) {
21     std::for_each(cbegin(v), std::cend(v), [&out](auto x) {
22         out << "print: " << x << '\n';
23     });
24 }
25 // std::copy (target needs to be an iterator too. target.end() would not work)
26 std::vector<int> source{1, 2, 3}, target{};
27 std::copy(source.begin(), source.end(), std::back_inserter target(target));
28
29 // Filling a vector with std::fill
30 std::vector<int> v(10);
31 std::fill(std::begin(v), std::end(v), 2);
32 // Or even easier:
33 std::vector v(10, 2);
34
35 // std::generate()
36 std::vector<double> powerOfTwos(5);
37 double x{1.0};
38 std::generate(powerOfTwos.begin(), powerOfTwos.end(), [&x] {return x *= 2.0; });
39 // std::generate_n
40 std::vector<double> powerOfTwos();
41 double x{1.0};

```

```

42 std::generate(std::back_inserter(powerOfTwos), 5, [&x] {return x *= 2.0; });
43
44 // fills a range with subsequent values (1,2,3,...): std::iota()
45 std::vector<int> v(100);
46 std::iota(std::begin(v), std::end(v), 1);
47
48 // std::find(), std::find_if() - If no match exists the end of the range is returned
49 auto zero_it = std::find(std::begin(v), std::end(v), 0);
50 if (zero_it == std::end(v)) { std::cout << "no zero found \n"; }
51 // std::count_if()
52 std::cout << std::count_if(begin(v), end(v), [](int x) { return isEven(x); }) << " even
    numbers\n";

```

3.4 Iterators for I/O

- `std::ostream_iterator<T>`
 - outputs values of type T to the given `std::ostream`
 - No `end()` marker needed for output, it ends when the input range ends
- `std::istream_iterator<T>`
 - reads values of type T from the given `std::istream`
 - End iterator is the default constructed `std::istream_iterator<T>{}`
 - It ends when the Stream is no longer good()

Shorter types with the keyword `using`.

```

1 // Copy Strings from standard input to standard output
2 // Skips white space !!
3 using input = std::istream_iterator<string>;
4 input eof{};
5 input in{std::cin};
6 std::ostream_iterator<string> out{std::cout, " "};
7 std::copy(in, eof, out);
8
9 // std::istreambuf_iterator<char> uses std::istream::get to get every character
10 // Only works with char-like types
11 using input = std::istreambuf_iterator<char>;
12 input eof{};
13 input in{std::cin};
14 std::ostream_iterator<char> out{std::cout, " "};
15 std::copy(in, eof, out);
16
17 // Fill a vector from a stream (copy with back_inserter)
18 using input = std::istream_iterator<int>;
19 input eof{};
20 std::vector<int> v{};
21 std::copy(input{std::cin}, eof, std::back_inserter(v));
22
23 // Fill a vector from a stream (directly from two iterators)
24 using input = std::istream_iterator<int>;
25 input eof{};
26 std::vector<int> const v{input{std::cin}, eof};

```

4 Functions and Exceptions

4.1 Functions

	const: • Parameter cannot be changed	non-const: • Parameter can be changed
reference: • Argument on call-site is accessed	<pre>void f(std::string const & s) { //no modification //efficient for large objects }</pre>	<pre>void f(std::string & s) { //modification possible //side-effect also at call-site }</pre>
copy: • Function has its own copy of the parameter	<pre>void f(std::string const s) { //no modification //used for maximum constness }</pre>	<pre>void f(std::string s) { //modification possible //side-effect only locally }</pre>

When to use & and const Parameters:

- Value Parameter:
 - Default case
- Reference Parameter
 - When side-effect is required at call-site
- Const-Reference Parameter
 - Possible optimization, when type is large (costly to copy) and no side effects desired at call site
 - For non-copyable objects
- Const Value Parameter
 - The coding style guide of your project this might prefer this over non const value parameters
 - Could prevent changing the parameter in the function inadvertently

Function Overloading

The same function name can be used for different functions if parameter number or types differ

→ Functions cannot be overloaded just by their return type

→ If only the parameter type is different there might be ambiguities

Default Arguments

- A function declaration can provide default arguments for its parameters from the right.
 - E.g: `void incr(int & var, unsigned delta = 1);`
- Implicit overload of the function with fewer parameters
 - If n default arguments are provided, n+1 versions of the function are declared
- Default arguments can be omitted when calling the function

Functions as Parameters

Functions are "first class" objects in C++

→ You can pass them as argument, or keep them in reference variables.

```

1 // As Argument (No Lambdas/Captures before function allowed)
2 void applyAndPrint(double x, double f(double)) {
3     std::cout << "f(" << x << ") = " << f(x) << '\n'; }
4
5 // As reference variable
6 double (&h)(double);
7
8 // std::function: template for Lambdas --> #include <functional>
9 void applyAndPrint(double x, std::function<double(double)> f) {
10    std::cout << "f(" << x << ") = " << f(x) << '\n'; }
11 int main() {
12     double factor{3.0};
13     auto const multiply = [factor](double value) { // Lambda Function
14         return factor * value; };
15     applyAndPrint(1.5, multiply);

```

4.2 Failing Functions

What should you do, if a function cannot fulfill its purpose?

- Ignore the error and provide potentially **undefined behavior**
- Return a standard result to cover the error
- Return an error code or error value
- Provide an error status as a side-effect
- Throw an exception

Ignore the error:

- Relies on the caller to satisfy all preconditions
- Most efficient implementation (no unnecessary checks)
- Simple for implementer, harder for caller
- Should be done consciously and consistently!

Return standard result:

- Reliefs the caller from the need to care if it can continue with the default value
- Can hide underlying problems
- Often better if caller can specify its own default value

Error Value

- Only feasible if result domain is smaller than return type
- E.g: Error Value for strings: `std::string::npos`
- Optional as return type can contain no value.
→ `#include <optional>`
E.g: `std::optional<std::string>`
- caller side: has to check with: `var.has_value()`

Error Status

- Requires reference parameter
- Alternative: Global Variable (BAD decision)
- E.g: `std::istream`'s states (`good()`, `fail()`) is changed as a side-effect of input

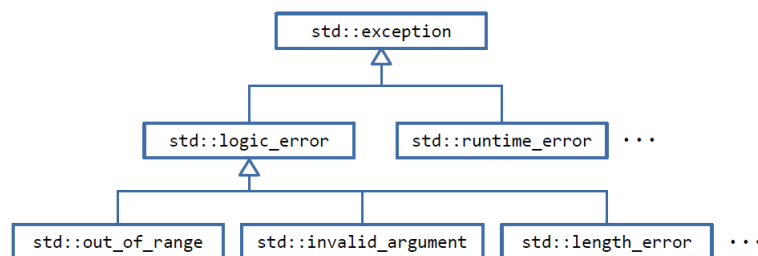
Exceptions

- Prevent execution of invalid logic by throwing an exception

4.3 Exceptions

Principle: Throw by value, catch by const reference.

Functions can be declared to explicitly not throw an exception with the keyword `noexcept`
`#include <stdexcept>`



```

1 // Throw an Exception
2 if (x < 0) {
3     throw std::invalid_argument{"square_root imaginary"};
4 }
5
6 // Catch an Exception
7 try {
8     throwingCall();
9 } catch (type const & e) { /* Handle type exception */
10 } catch (type2 const & e) { /* Handle type2 exception */
11 } catch (...) { /* Handle other exception types */
12 } // Caught exceptions can be rethrown with throw;
13
14 //CUTE
15 void testSquareRootNegativeThrows() {
16     ASSERT_THROWS(square_root(-1.0), std::invalid_argument);
17 }
  
```

5 Classes and Operators

5.1 Classes

- A class defines a new type
- A class is usually defined in a header file
- At the end of a class definition a semicolon is required
- Include guard in header file
- Keyword: `class` or `struct`
 - Default visibility: `Class`: private, `struct`: public
- Access specifiers:
 - `private`: visible only inside the class; for hidden data members
 - `protected`: also visible in subclasses
 - `public`: visible everywhere; for the interface of the class
- Constructor: Initializer list for member initialization

```

1  #ifndef DATE_H_                                     #include "Date.h"
2  #define DATE_H_
3  class Date {                                         Date::Date(int year, int month, int day)
4      int year, month, day;                           : year {year}, month {month}, day {day} {
5  public:                                              /* ... */
6      Date(int year, int month, int day);             }
7
8      static bool isLeapYear(int year);               bool Date::isLeapYear(int year) {
9
10     private:                                         /* ... */
11         bool isValidDate() const;                   }
12     };                                              bool Date::isValidDate() const {
13 #endif /* DATE_H_ */                               /* ... */

```

Special Constructors

- Default Constructor
 - No parameters. Implicitly available if there are no other explicit constructors. Has to initialize member variables with default values.
- Copy Constructor
 - Has one `<own-type> const &` parameter. Implicitly available (unless there is an explicit move constructor or assignment operator). Copies all member variables.
- Move Constructor
 - Has one `<own-type> &&` parameter. Implicitly available (unless there is an explicit copy constructor or assignment operator). Moves all members
- Typeconversion Constructor
 - Has one `<other-type> const &` parameter. Converts the input type if possible. Declare explicit to avoid unexpected conversions.
- Initializer List Constructor
 - Has one `std::initializer_list` parameter. Does not need to be explicit, implicit conversion is usually desired. Initializer List constructors are preferred if a variable is initialized with `{ }`
- Destructor
 - Named like the default constructor but with a `~`. Must release all resources. Implicitly available. Must not throw an exception. Called automatically at the end of the block for local instances.

```

1  class Date {
2  public:
3      Date(int year, int month, int day);
4      Date(); // Default-Constructor
5      Date(Date const &); // Copy-Constructor
6      Date(Date &&); // Move-Constructor
7      explicit Date(std::string const &); // Typeconversion-Constructor
8      Date(std::initializer_list<Element> elements); // Initializer List-Constructor
9      ~Date(); // Destructor
10 };

```

5.2 Operator Overloading

- Custom operators can be overloaded for user-defined types.
- Declared like a function, with a special name: `<returntype> operator op(<parameters>);`
- Non-Overloadable Operators: `::`, `.*`, `..`, `?:`
- Keyword `inline` when defined in header file. But: Problem with private variables.
→ Define operator in class

`std::tie` creates a tuple and binds the argument with lvalue references. `std::tuple` provides comparison operators: `==`, `!=`, `<`, `<=`, `>`, `>=`

```

1  class Date {
2      int year, month, day; // private
3
4      bool operator<(Date const & rhs) const {
5          return year < rhs.year ||
6              (year == rhs.year && (month < rhs.month ||
7                  (month == rhs.month && day == rhs.day)));
8      }
9  };
10
11 // With std::tie
12 #include <tuple>
13 bool operator<(Date const & rhs) const {
14     return std::tie(year, month, day) < std::tie(rhs.year, rhs.month, rhs.day);
15 }
16
17 // Sending Date to std::ostream
18 class Date {
19     int year, month, day;
20 public:
21     std::ostream & print(std::ostream & os) const {
22         os << year << "/" << month << "/" << day;
23         return os;
24     }
25 };
26 inline std::ostream & operator<<(std::ostream & os, Date const & date) {
27     return date.print(os);
28 }
29
30 // Reading Date from std::istream
31 class Date {
32     int year, month, day;
33 public:
34     std::istream & read(std::istream & is) {
35         // Logic for reading values and verifying correctness
36         return is;
37     }
38 };
39 inline std::istream & operator>>(std::istream & is, Date & date) {
40     return date.read(is);
41 }
42
43 /* Keyword friend, um Kapselung zwischen private/public zu brechen. --> Dann ist es mö
44    glich die read/print Operatoren ohne inline Hilfsfunktionen zu schreiben. */
45 // Header File:
46 class Date {
47     int year, month, day;
48 public:
49     friend std::istream & operator>>(std::istream & is, Date & date);
50     friend std::ostream & operator<<(std::ostream & os, Date const & date);
51 };
52 // .cpp File:
53 std::istream & operator<<(std::istream & is, Date & date) {
54     // read logic
55     return is;
56 }
57 std::ostream & operator<<(std::ostream & os, Date const & date) {
58     // print logic
59     return os;
60 }

```

6 Namespaces and Enums

6.1 Namespaces

- Namespaces are scopes for grouping and preventing name clashes
- Global namespace has the `::` prefix
- Nesting of namespaces is possible
- Nesting of scopes allows hiding names
- Anonymous namespaces (without a name) are only accessible in the current file
- Keyword `using` to use a defined namespace in your file.

E.g: after typing `using std::string;` you can write: `string s{"my string"};`

Argument Dependent Lookup

When the compiler encounters an unqualified function or operator call with an argument of a user defined type it looks into the namespace in which that type is defined to resolve the function/operator.

```

1 namespace one {                               #include "adl.h"
2     struct type_one{};
3     void f(type_one) { /* ... */ } /* 1 */
4 }
5
6 namespace two {
7     struct type_two{};
8     void f(type_two) { /* ... */ } /* 2 */
9     void g(one::type_one) { /* ... */ } /* 3 */
10    void h(one::type_one) { /* ... */ } /* 4 */
11 }
12 void g(two::type_two) { /* ... */ } /* 5 */

```

```

int main() {
    one::type_one t1{};
    f(t1); // Function 1
    two::type_two t2{};
    f(t2); // Function 2
    h(t1); // No Function found
    two::g(t1); // Function 3
    g(t1); // No Function found
    // (5 gefunden, aber arg passt nicht)
    g(t2) // Function 5

```

6.2 Enums

- Enumerations are useful to represent types with only a few values
- An enumeration creates a new type that can easily be converted to an integral type (unscoped enumeration only)
- The individual values (enumerators) are specified in the type
- Unless specified explicitly, the values start with 0 and increase by 1

```

1 // Unscoped enumeration
2 enum DayOfWeek {
3     Mon, Tue, Wed, Thu, Fri, Sat, Sun
4 }; // 0 1 2 3 4 5 6
5 // Implicit conversion:
6 int day = Sun;
7
8 // Scoped enumeration (class keyword)
9 enum class DayOfWeek {
10    Mon, Tue, Wed, Thu, Fri, Sat, Sun
11 }; // 0 1 2 3 4 5 6
12 // No implicit conversion to int, requires static_cast:
13 int day = static_cast<int>(DayOfWeek::Sun);
14
15 // Conversion from int to enum always requires a static_cast:
16 DayOfWeek tuesday = static_cast<DayOfWeek>(1);

```

→ Beispiel im Anhang unter Woche06

6.3 Arithmetic Types

- Arithmetic types must be equality comparable
- Boost can be used to get `!=` operator → `boost::equality_comparable`
- It might be convenient to have the output operator
- Result must be in a specific range (Modulo)

→ Beispiel im Anhang unter Woche06

7 Standard Container & Iterators

7.1 STL Containers: General API

- Sequence Containers
 - Elements are accessible in order as they were inserted created
 - Find in linear time through the algorithm find
- Associative Containers
 - Elements are accessible in sorted order
 - find as member function in logarithmic time
- Hashed Containers
 - Elements are accessible in unspecified order
 - find as member function in constant time

Member Function	Purpose
<code>begin()</code> <code>end()</code>	Get iterators for algorithms and iteration in general
<code>erase(iter)</code>	Removes the element at position the iterator <code>iter</code> points to
<code>insert(iter, value)</code>	Inserts <code>value</code> at the position the iterator <code>iter</code> points to
<code>size()</code> <code>empty()</code>	Check the size of the container

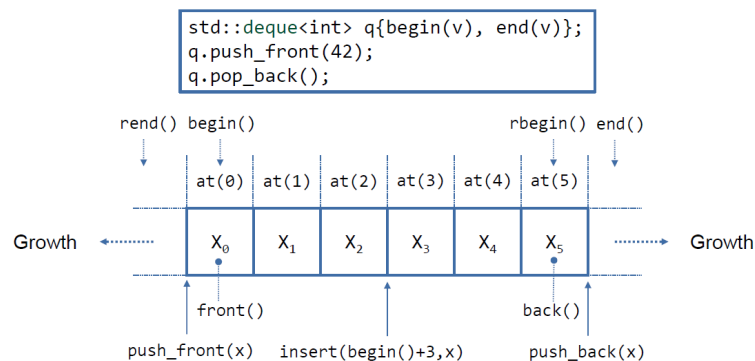
7.2 Sequence Containers

`std::vector` & `std::array`

Siehe Kapitel3: Sequences and Iterators (Seite 6)

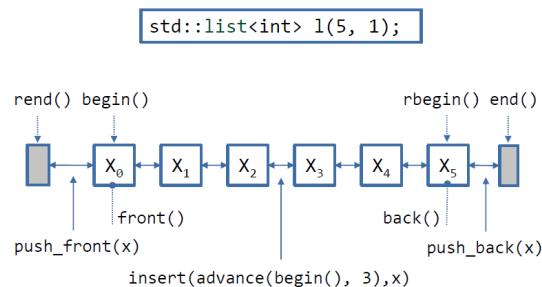
`std::deque<T>` → `#include<deque>`

`std::deque` is like `std::vector` but with additional, efficient front insertion/removal



`std::list<T>` → `#include<list>`

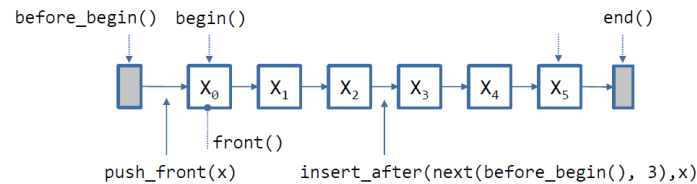
Efficient insertion in any position. Lower efficiency in bulk operations. Requires member function call for sort etc. Only bi directional iterators no index access



std::forward_list<T> → #include<forward_list>

Efficient insertion AFTER any position, but clumsy with iterator to get "before" position. Only forward iterators, clumsy to search and remove, use member functions not algorithms.

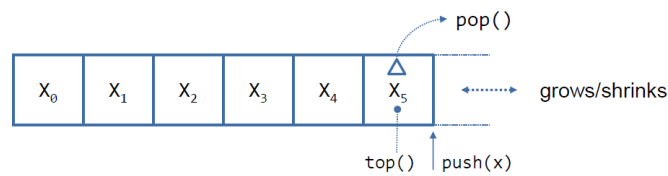
```
std::forward_list<int> l{1, 2, 3, 4, 5, 6};
```



std::stack → #include<stack>

Uses `std::deque` (or `std::vector`, `std::list`) and limits its functionality to stack operations. Iteration not possible.

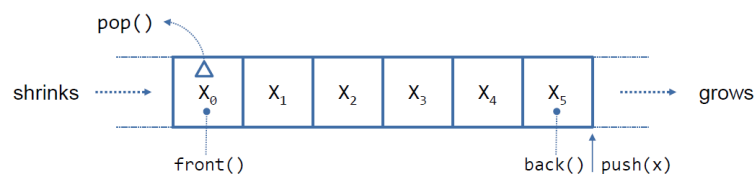
```
std::stack<int> s{};
s.push(42);
std::cout << s.top();
s.pop();
```



std::queue → #include<queue>

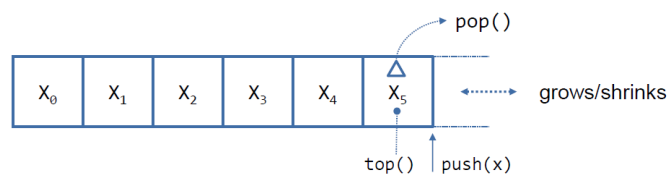
Uses `std::deque` (or `std::list`) and limits its functionality to queue operations. Iteration not possible.

```
std::queue<int> q{};
q.push(42);
std::cout << q.front();
q.pop();
```



std::priority_queue → #include<stack>

Uses `std::deque` (or `std::vector`) and limits its functionality to stack operations. `top()` element is always the smallest.



7.3 Associative Containers

	Key Only	Key-Value Pair
Key Unique	<code>std::set<T></code>	<code>std::map<K, V></code>
Multiple Equivalent Keys	<code>std::multiset<T></code>	<code>std::multimap<K, V></code>

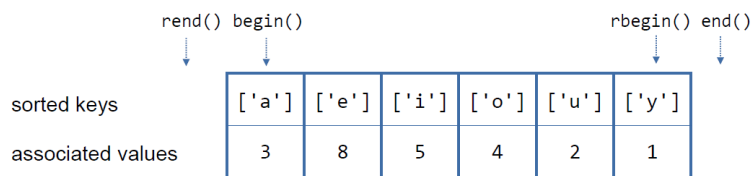
std::set → **#include <set>**

- `std::set<int>` values{7, 1, 4, 3, 2, 5, 6}
- Stores elements in sorted order (ascending by default)
- Iteration walks over the elements in order
- Member functions to check if element exists: `.find(element)` or `.count(element)`

std::map → **#include <map>**

Stores key-value pairs in sorted order. Default: By key ascending.
Use `.first()` for key and `.second()` for value.

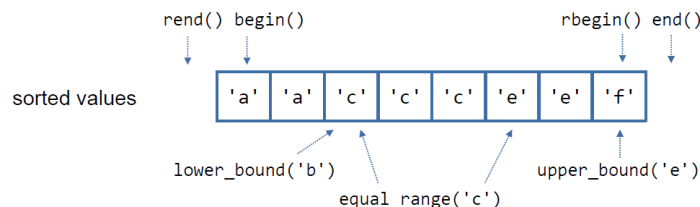
```
std::map<char, size_t> vowels{{'a', 3}, {'e', 8}, {'i', 5}, {'o', 4}, {'u', 2}, {'y', 1}};
```



std::multiset → **#include <set>**, **std::multimap** → **#include <map>**

Multiple equivalent keys allowed. Use `equal_range()` or `lower_bound()/upper_bound()` member functions to find boundaries of equivalent keys.

```
std::multiset<char> letters{'a', 'a', 'c', 'c', 'c', 'e', 'e', 'f'};
```



7.4 Hashed Containers

std::unordered_set → **#include <unordered_set>**, **std::unordered_map** → **#include <unordered_map>**

Usage is almost equivalent to `std::set/std::map`. Except for the lack of ordering.

7.5 Iterators

What are these Iterator Categories for?

- Some algorithms only work with powerful iterators, e.g: `std::sort()` requires a pair of random access iterators (it needs to jump forward and backward)
- Some algorithms can be implemented better with more powerful iterators, e.g: `std::advance()` or `std::distance()`

Input Iterator

- Supports reading the current element (of type `Element`)
- Allows for one-pass input algorithms (cannot step backwards)
- Models the `std::istream_iterator` and `std::istream`
- Can be compared with `==` and `!=` to other iterator objects of the same type: `It`
- Can be copied (after increment all other copies are invalid!)

Forward Iterator

- Can do whatever an input iterator can, plus: Supports changing the current element
- Allows only for one-pass input algorithms
- Models the `std::forward_list` iterators

Bidirectional Iterator

- Can do whatever a forward iterator can, plus: Can go backwards
- Allows for forward-backward-pass algorithms
- Models the `std::set` iterators

Random Access Iterator

- Can do whatever a bidirectional iterator can, plus:
 - Directly access element at index
 - Go n steps forward or backward
 - Subtract two iterators to get the distance
 - Compare with relational operators (`<`, `<=`, `>`, `>=`)
- Allows random access in algorithms
- Models the `std::vector` iterators

Output Iterator

- Can write value to current element, but only once
- Modeled after `std::ostream_iterator`

Iterator Functions → `#include <iterator>`

```
std::distance(start, goal);
std::advance(itr, n);
```

- `std::distance()` counts the number of hops iterator start must make until it reaches goal
- `std::advance()` lets itr hop n times

`std::advance` vs. `std::next`

```

1  int main() {
2      std::vector<int> primes{2, 3, 5, 7, 11, 13};
3
4      auto current = std::begin(primes);
5      auto afterNext = std::next(current);
6      std::cout << "current: " << *current << " afterNext: " << *afterNext << '\n';
7
8      std::advance(current, 1);
9      std::cout << "current: " << *current << " afterNext: " << *afterNext << '\n';
10 }
```

8 STL Algorithms

Why should we use Algorithms?

- Correctness: It is much easier to use an algorithm correctly than implementing loops correctly
- Readability: Applying the correct algorithm expresses your intention much better than a loop
- Performance: Algorithms might perform better than handwritten loops

8.1 Functor

A functor is a type (class) that provides a call operator: `operator()`.

```

1  struct Accumulator {
2      int count{0};
3      int accumulatedValue{0}
4      void operator()(int value) {
5          count++;
6          accumulatedValue += value;
7      }
8      int average() const; // To implement
9      int sum() const;
10 };
11
12 int average(std::vector<int> values) {
13     Accumulator acc{};
14     return std::for_each(begin(values), end(values), acc).average();
15 }
```

Standard Functor Template Classes → `#include <functional>`

```

1  // Lambda to transform
2  transform(v.begin(), v.end(), v.begin(), [](int x){ return -x; } );
3  // Standard Library's Functor: std::negate
4  transform(v.begin(), v.end(), v.begin(), std::negate<int>{} );
5  // Sorting with Standard Library Functor: std::greater
6  sort(v.begin(), v.end(), std::greater<>{} );
```

Standard Functor Classes → `#include <functional>`

1 // Binary arithmetic and logical	Unary
2 plus<> (+)	negate<> (-)
3 minus<> (-)	logical_not<> (!)
4 divides<> (/)	
5 multiplies<> (*)	//Binary comparison
6 modulus<> (%)	less<> (<)
7 logical_and<> (&&)	less_equal<> (<=)
8 logical_or<> ()	equal_to<> (==)
9	greater_equal<> (>=)
10	greater<> (>)
11	not_equal_to<> (!=)

8.2 Algorithm Examples

- transform: Lambda, function or functor for map
- merge: ranges must to be sorted
- remove/erase: Remove does not actually delete element, it moves the not-removed elements to the front
- accumulate: Sums elements that are addable (+ operator)
- `_if` versions: Take a predicate (instead of value) to provide a condition
- `_n` versions: algorithm is related to a number (e.g: instead of last iterator)
 - `search_n`, `copy_n`, `fill_n`, `generate_n`, `for_each_n`

```

1 // transform
2 // combined contains: | "ggg" | "" | "u" | "yyyy" | "" | "oo" |
3 std::vector<int> counts{3, 0, 1, 4, 0, 2};
4 std::vector<char> letters{'g', 'a', 'u', 'y', 'f', 'o'};
5 std::vector<std::string> combined{};
6 auto times = [](int i, char c) { return std::string(i, c); };
7 std::transform(begin(counts), end(counts), begin(letters), std::back_inserter(combined),
8               times);
9
10 // merge
11 std::vector<int> r1{9, 12, 17, 23, 54, 57, 85, 95};
12 std::vector<int> r2{2, 30, 32, 41, 49, 63, 72, 88};
13 std::vector<int> d(r1.size() + r2.size(), 0);
14 std::merge(begin(r1), end(r1), begin(r2), end(r2), begin(d));
15
16 // remove
17 std::vector<unsigned> values{54, 13, 17, 95, 2, 57, 12, 9};
18 auto is_prime = [](unsigned u) { /* ... */ };
19 auto removed = std::remove_if(begin(values), end(values), is_prime);
20
21 // accumulate
22 std::vector<std::string> longMonths {"Jan", "Mar", "May", "Jul", "Aug", "Oct", "Dec"};
23 std::string accumulatedString = std::accumulate(
24     next(begin(longMonths)), // Second element
25     end(longMonths), // End
26     longMonths.at(0), //First element, usually the neutral element
27     [](std::string const & acc, std::string const & element) {
28         return acc + ", " + element;
29     }); //Jan, Mar, May, Jul, Aug, Oct, Dec
30
31 // count_if
32 std::set<unsigned> numbers{1, 2, 3, 4, 5, 6, 7, 8, 9};
33 auto isPrime = [](unsigned u) { /* ... */ };
34 auto nOfPrimes = std::count_if(begin(numbers), end(numbers), isPrime);
35
36 // copy_n
37 std::set<unsigned> numbers{1, 2, 3, 4, 5, 6, 7, 8, 9};
38 std::vector<unsigned> top5(5);
39 std::copy_n(rbegin(numbers), 5, begin(top5));

```

Heap Algorithms

- Implementing a binary heap on a sequenced container
- Requires random access iterator
- Guarantees: Top element is the largest (max), Adding and removing performance guarantees
- Used for implementing priority queues
- Heap operations: [make_heap](#), [pop_heap](#), [push_heap](#), [sort_heap](#)

```

1 // create heap
2 std::vector<int> v{3, 1, 4, 1, 5, 9, 2, 6}
3 make_heap(v.begin(), v.end()); // create tree order
4 // remove largest element
5 pop_heap(v.begin(), v.end()); // reorder
6 v.pop_back();
7 // add element
8 v.push_back(8);
9 push_heap(v.begin(), v.end()); // reorder
10 sort_heap(v.begin(), v.end()); // smallest element first in vector

```

9 Function Templates

9.1 Templates Syntax

- Keyword `template` for declaring a template
- Template parameter list: Contains one or more template parameters
 - A template parameter is a placeholder for a type, which can be used within the template as a type
 - A type template parameter is introduced with the typename (or class) keyword

```

1 // min.h
2 template <typename T>
3 T min(T left, T right) {
4     return left < right ? left : right;
5 }
6
7 // smaller.cpp
8 #include "min.h"
9 #include <iostream>
10 int main() {
11     int first;
12     int second;
13     if (std::cin >> first >> second) {
14         auto const smaller = min(first, second);
15         std::cout << "Smaller of " << first << " and " << second << " is: " << smaller << '\n';
16     }
17 }

```

Template Definition

- Templates are usually defined in a header file. They are implicitly `inline`
- The definition in a source file is possible, but then it can only be used in that translation unit
- Type checking happens twice: When the template is defined, when template is instantiated (used)

9.2 Variadic Templates

- For function templates with an arbitrary number of parameters
- Needs at least one pack parameter
- Pack Expansion: For each argument in that pack an instance of the pattern is created
- In an instance of the pattern the parameter pack name is replaced by an argument of the pack
- Needs a base case for the recursion (after the last parameter is done, it would call the function without a parameter, which is invalid) → Base case must be written before the template function.

```

1 void printAll() { } // Base Case
2 template<typename First, typename...Types>
3 void printAll(First const & first, Types const &... rest) {
4     std::cout << first;
5     if (sizeof...(Types))
6         std::cout << ", ";
7 }
8 printAll(rest...);
9 }

```

9.3 Overloading

Problem: Wenn Pointer als Argument übergeben werden, werden die Pointer-Adressen miteinander verglichen und nicht die Objekte selbst.

Lösung: Mehrere function templates mit dem Selben Namen können existieren. Spezifischere/Normale Funktionen werden den function templates aber bevorzugt.

```

1 // other template function in min.h
2 template <typename T>
3 T * min(T * left, T * right) {
4     return *left < *right ? left : right;
5 }

```

10 Class Templates

A class template provides a type with compile-time parameters.

→ Data members can depend on template parameters.

→ Function members are template functions with the class' template parameters

Rules

- Define class templates completely in header files
- Member functions of class templates: Either in class template directly, or as inline function template in the same header file
- When using language elements depending directly or indirectly on a template parameter, you must specify typename when it is naming a type
- static member variables of a template class can be defined in header without violating ODR, even if included in several compilation units

Type Aliases & Dependent Names

- It is common for template definitions to define type aliases in order to ease their use
- Within the template definition you might use names that are directly or indirectly depending on the template parameter.
- Dependent Name: Compiler geht standardmässig davon aus, dass es sich um eine Variable, oder eine Funktion handelt. Wenn es ein Typ ist (wie `size_type`), muss das keyword `typename` verwendet werden.

Members Outside of Class Template

Must have: template declaration, keyword `inline`, member signature, template ID as namespace.

→ Example im Anhang

Class Template that Inherit

Rule: Always use `this->variable` (or `className::`) to refer to inherited members in a template class.

Template (Partial) Specialization

partial: still using a template parameter, but provide (some) arguments

Explicit: providing all arguments with concrete types.

→ Must declare non-specialized template first. Most specialized version that fits is used.

<pre> 1 // Partial Specialization 2 template <typename T> 3 struct Sack<T *>; 4 5 // Prevent Creation of Sack<int *> --> Delete Destructor 6 template <typename T> 7 struct Sack<T *> { 8 ~Sack() = delete; 9 }</pre>	<pre> Explicit Specialization template <> struct Sack<char const *>;</pre>
--	--

Extending Sack<T>

Implementation im Anhang Kapitel Übungen Woche 10

- Create a `Sack<T>` using iterators to fill it
- Create a `Sack<T>` of multiple default values
- Create a `Sack<T>` from initializer list
- Obtain copy of contents in a `std::vector` (for iteration and inspection)
- Auto-deducting `T` for a `Sack<T>` from initializer list → User Provided Deduction Guides
- Allow to vary the type of the container to be used

11 Heap Memory Management

12 Woche12

13 Woche13

14 Anhang

14.1 Übungen Woche XX

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14.2 Übungen Woche 06

Enumeration Example

```

1  // statemachine.h
2  #ifndef STATEMACHINE_H_
3  #define STATEMACHINE_H_
4
5  struct Statemachine {
6      Statemachine();
7      void processInput(char c);
8      bool isDone() const;
9  private:
10     enum class State : unsigned short;
11     State theState;
12 };
13
14 #endif /* STATEMACHINE_H_ */
15
16 // statemachine.cpp
17 #include "Statemachine.h"
18 #include <cctype>
19 enum class Statemachine::State : unsigned short {
20     begin, middle, end
21 };
22 Statemachine::Statemachine()
23 : theState {State::begin} {}
24 void Statemachine::processInput(char c) {
25     switch (theState) {
26     case State::begin:
27         if (!isspace(c)) { theState = State::middle; }
28         break;
29     case State::middle:
30         if (isspace(c)) { theState = State::end; }
31         break;
32     case State::end:
33         break; // ignore input
34     }
35 }
36 bool Statemachine::isDone() const {
37     return theState == State::end;
38 }

```

14.3 Übungen Woche 07

Example: Stack and Queue

```

1  #include <stack>
2  #include <queue>
3  #include <iostream>
4  #include <string>
5
6  int main() {
7      std::stack<std::string> lifo{};

```

```

8     std::queue<std::string> fifo{};
9     for (std::string s : { "Fall", "leaves", "after", "leaves", "fall" }) {
10         lifo.push(s);
11         fifo.push(s);
12     }
13     while (!lifo.empty()) { // fall leaves after leaves Fall
14         std::cout << lifo.top () << ' ';
15         lifo.pop();
16     }
17     std::cout << '\n';
18     while (!fifo.empty()) { // Fall leaves after leaves fall
19         std::cout << fifo.front() << ' ';
20         fifo.pop();
21     }
22 }

```

Example Code using std::set

```

1  #include <set>
2  #include <iostream>
3
4  void filterVowels(std::istream & in, ostream & out) {
5      std::set<const char> vowels{'a', 'e', 'o', 'u', 'i', 'y'};
6      char c{};
7      while (in >> c) {
8          if (!vowels.count(c)) { // returns 0 (false) or 1 (true)
9              out << c;
10          }
11      }
12  }
13  int main () {
14      filterVowels(std::cin, std::cout);
15  }

```

Example Code using std::map

```

1  // Example 1
2  void countVowels(std::istream &in, ostream &out) {
3      std::map<char, size_t> vowels{{'a', 0}, {'e', 0}, {'i', 0}, {'o', 0}, {'u', 0}, {'y', 0}};
4      char c{};
5      while (in >> c) {
6          if (vowels.count(c)) { // only count those chars that are already in the map
7              ++vowels[c];
8              for_each(cbegin(vowels), cend(vowels), [&out](auto const & entry) {
9                  // entry is a pair<char, size_t>
10                 out << entry.first << " = " << entry.second << '\n';
11             });
12          }
13      }
14  }
15
16  // Example 2
17  void countStrings(std::istream & in, std::ostream & out) {
18      std::map<std::string, size_t> occurrences{};
19      std::istream_iterator<std::string> inputBegin{in};
20      std::istream_iterator<std::string> inputEnd{};
21      for_each(inputBegin, inputEnd, [&occurrences](auto const & str) {
22          ++occurrences[str]; // inserts new entry with value 1, if not existst, else:
23          counts ++
24      });
25      for(auto const & occurrence : occurrences) {
26          out << occurrence.first << " = " << occurrence.second << '\n'
27      }
28  }

```

Example Code using std::multiset

```

1  void sortedStringList(std::istream & in, std::ostream & out) {
2      using inIter = std::istream_iterator<std::string>;

```

```

3     using outIter = std::ostream_iterator<std::string>;
4     std::multiset<std::string> words{inIter{in}, inIter{}};
5     copy(cbegin(words), cend(words), outIter(out, "\n"));
6     auto current = cbegin(words);
7     while (current != cend(words)) {
8         auto endOfRange = words.upper_bound(*current);
9         copy(current, endOfRange, outIter(out, " "));
10        out << '\n'; // next range on new line
11        current = endOfRange;
12    }
13 }

```

Example Code using std::unordered_set

```

1  #include <algorithm>
2  #include <iostream>
3  #include <iterator>
4  #include <unordered_set>
5
6  int main () {
7      std::unordered_set<char> const vowels{'a', 'e', 'i', 'o', 'u'};
8      using in = std::istreambuf_iterator<char>;
9      using out = std::ostreambuf_iterator<char>;
10     remove_copy_if(in{std::cin}, in{}, out{std::cout}, [&](char c) {
11         return vowels.count(c);
12     });
13 }

```

Example Code using std::unordered_map

```

1  #include <unordered_map>
2  #include <iostream>
3  #include <string>
4  int main() {
5      std::unordered_map<std::string, int> words{};
6      std::string s{};
7      while (std::cin >> s) { ++words[s]; }
8      for (auto const & p : words) {
9          std::cout << p.first << " = " << p.second << '\n';
10     }
11 }

```

14.4 Übungen Woche 10

Adapting Standard Containers

```

1  template<typename T>
2  struct safeVector : std::vector<T> {
3      using container = std::vector<T>;
4      using container::container; // or using std::vector<T>::vector; --> Inherits
5      using size_type = typename container::size_type; // Type Alias
6      using reference = typename container::reference; // Type Alias
7      using const_reference = typename container::const_reference; // Type Alias
8
9      reference operator[](size_type index) {
10         return this->at(index); // this-> for member access
11     }
12
13     const_reference operator[](size_type index) const {
14         return this->at(index);
15     }
16     // should also provide front/back with empty() check
17 };

```

Template Sack

```

1 // sack.h
2 template<typename T> // Class template with one typename parameter
3 class Sack {
4     using SackType = std::vector<T>; // Alias type: SackType
5     using size_type = typename SackType::size_type; // Dependent name: size_type
6     SackType theSack{};
7
8 public:
9     bool empty() const {
10         return theSack.empty();
11     }
12     size_type size() const {
13         return theSack.size();
14     }
15     void putInto(T const & item) {
16         theSack.push_back(item);
17     }
18     T getOut(); // Member function forward declaration
19 };
20
21 template <typename T> // implementing member function outside of a class
22 inline T Sack<T>::getOut() {
23     if (empty()) {
24         throw std::logic_error{"Empty Sack"};
25     }
26     auto index = static_cast<size_type>(rand() % size()); // Pick random element
27     T retval{theSack.at(index)};
28     theSack.erase(theSack.begin() + index);
29     return retval;
30 }

```

Extending Sack<T>

```

1 template <typename T>
2 class Sack {
3     //...
4 public:
5     Sack() = default; // Retain default constructor
6
7     // Add constructor template for iterators
8     template <typename Iter>
9     Sack(Iter begin, Iter end) : theSack(begin, end) {}
10
11     // Add constructor for initializer_list
12     Sack(std::initializer_list<T> values) : theSack(values) {}
13
14     // Add constructor for Deduction Guide
15     Sack(size_type n, T const & value) : theSack(n, value) {}
16
17     // extracting a std::vector<T> from a Sack<T>
18     template <typename Elt>
19     explicit operator std::vector<Elt>() const {
20         return std::vector<Elt>(theSack.begin(), theSack.end());
21     }
22
23 };
24
25 // User Provided Deduction Guide for Sack<T> (after template definition)
26 template <typename Iter>
27 Sack(Iter begin, Iter end) -> Sack<typename std::iterator_traits<Iter>::value_type>;

```

Template/Default/Non-Type Template Parameter

```

1 // A template can take templates as parameters
2 template<typename T, template<typename...> typename Container> // ... for unspecified
3     amount of parameters
4 class Sack;
5
6 // with default argument:
7 template<typename T, template<typename...> typename Container = std::vector>
8 class Sack;
9
10 // Templates can have non type parameters

```

```
10 template <typename T, auto n>
11 auto average(std::array<T, n> const & values) {
12     auto sumOfValues = accumulate(begin(values), end(values), 0);
13     return sumOfValues / n;
14 }
```

14.5 Includes

```
1 // Only the declaration for input and output streams
2 #include <iosfwd>
3
4 // Implementation of input stream
5 #include <istream>
6
7 // Implementation of output stream
8 #include <ostream>
9
10 // Declaration of both streams and additionally std::cout, std::cin, std::cerr
11 #include <iostream>
12
13 // Functions: std::tolower(c), std::isupper(c)
14 #include <cctype>
15
16 // Strings
17 #include <string>
18
19 // Arrays
20 #include <array>
21
22 // Vectors (ArrayList)
23 #include <vector>
24
25 // Iterators: std::count, std::accumulate, std::distance, std::for_each
26 #include <iterator>
27
28 // std::iota
29 #include <numeric>
30
31 // function template, which allows passing lambdas (with capture)
32 #include <functional>
33
34 // std::tie (creates tuple)
35 #include <tuple>
36
37 // std::deque<T>
38 #include <deque>
39
40 // std::list<T>
41 #include <list>
42
43 // std::forward_list<T>
44 #include <forward_list>
45
46 // std::stack
47 #include <stack>
48
49 // std::queue
50 #include <queue>
51
52 // std::priority_queue
53 #include <stack>
54
55 // std::set
56 #include <set>
57
58 // std::map
59 #include <map>
60
61 // std::unordered_set --> Hashed
62 #include <unordered_set>
63
64 // std::unordered_map --> Hashed
65 #include <unordered_map>
```
