

EDAF30 – Programming in C++

4. The standard library. Algorithms and containers.

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Outline

- 1 More on constructors
 - Copying objects
- 2 Generic programming
- 3 The standard library
 - Algorithms
 - Containers
 - Sequences
 - Associative containers
 - Pairs and tuples
- 4 Container adapters

User-defined types

Concrete classes

A concrete type

- ▶ “behaves just like a built-in type”
- ▶ the representation is part of the definition,
That allows us to
 - ▶ place objects
 - ▶ on the stack (i.e., in local variables)
 - ▶ in other objects
 - ▶ in statically allocated memory (e.g., global variables)
 - ▶ copy objects
 - ▶ assignment of a variable
 - ▶ copy-constructing an object
 - ▶ value parameter of a function
 - ▶ refer to objects directly (not just using pointers or references)
 - ▶ initialize objects directly and completely (with a *constructor*)

Copy Constructor

- ▶ Is called when initializing an object
- ▶ Is *not called* on assignment
- ▶ Can be defined, otherwise a standard copy constructor is generated (=default, =delete)

```
void function(Bar); // by-value parameter
```

```
Bar b1(10, false);
```

```
Bar b2{b1};           // the copy constructor is called
```

```
Bar b3(b2);          // the copy constructor is called
```

```
Bar b4 = b2;         // the copy constructor is called
```

```
function(b2);        // the copy constructor is called
```

Copy Constructors

default

- ▶ Declaration:

```
class C {  
public:  
    C(const C&) =default;  
};
```

- ▶ default copy constructor

- ▶ Is automatically generated if not defined in the code
 - ▶ exception: if there are members that cannot be copied
- ▶ But do declare it **=default** when you want it.
- ▶ *shallow copy* of each member
 - ▶ Works for member variables of built-in types,
 - ▶ or *classes that behave like built-in types* (RAII-types)
 - ▶ *Does not work* for classes which manage resources “manually”
(More on this later)

Classes

Example: Copying the Vector class

```
class Vector{  
public:  
    Vector(int sz) :sz{sz},elem{new double[sz]} {}  
    ~Vector() {delete[] elem;}  
    double& operator[](int i) {return elem[i];}  
    int size() {return sz;}  
private:  
    int sz;  
    double* elem;  
};
```

Vector vec:



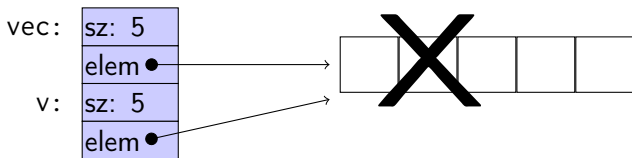
No copy constructor defined \Rightarrow default generated.

Classes

Default copy construction: shallow copy

```
void f(Vector v);

void test()
{
    Vector vec(5);
    f(vec); // call by value -> copy
    // ... other uses of vec
}
```



- ▶ The parameter `v` is default copy constructed: the value of each member variable is copied
- ▶ When `f()` returns, the destructor of `v` is executed:
`delete[] elem;`
- ▶ The array pointed to *by both copies* is deleted. Disaster!

Constructors

Special cases: zero or one argument

Copy Constructor

- ▶ Has the same class as parameter: `Bar::Bar(const Bar& b);`

Converting constructor

- ▶ A constructor that can be called with one argument defines an *implicit type conversion* from the type of the parameter

```
class ComplexNumber {
public:
    ComplexNumber():re{0},im{0} {}
    ComplexNumber(const ComplexNumber& k) :re{k.re},im{k.im} {}
    ComplexNumber(double x, double i=0):re{x},im{i} {}
    //...
private:
    double re;
    double im;
};
```

default constructor

copy constructor

converting constructor

Converting constructor

Warning - implicit conversion

```
class Vector{
public:
    Vector(int s);    // create Vector with size s
    ...
    int size() const; // return size of Vector
    ...
};

void example_vector()
{
    Vector v = 7;

    std::cout << "v.size(): " << v.size() << std::endl;
}

v.size(): 7
```

In `std::vector` the corresponding constructor is declared

```
explicit vector( size_type count );
```

Converting constructor and `explicit`

`explicit` specifies that a constructor does not allow implicit type conversion.

```
struct A                struct B
{
    A(int);             {
    // ...              explicit B(int);
};                      // ...
};

A a1(2);               // OK          B b1(2);           // OK
A a2 = 1;              // OK          B b2 = 1;          // Error! [2]
A a3 = (A)1;           // OK          B b3 = (B)1;       // OK: explicit cast

a3 = 17;               // OK [1]      b3 = 17;           // Error! [3]
```

[1]: construct an A(17), **and** then copy

[2]: conversion from 'int' to non-scalar type 'B' requested

[3]: no match for 'operator=' (operand types are 'B' and 'int')

Copying objects

Difference between *construction* and *assignment*

```
void function(Bar); // by-value parameter

Bar b1(10, false);

Bar b2{b1};           // the copy constructor is called
Bar b3(b2);          // the copy constructor is called
Bar b4 = b2;         // the copy constructor is called

function(b2);        // the copy constructor is called

b4 = b3;             // the copy constructor is not called
```

copy assignment – not construction

Copying objects

the *copy assignment* operator: `operator=`

The *copy assignment operator* is implicitly defined

- ▶ with the type `T&` `T::operator=(const T&)`
- ▶ if no copy assignment operator is declared for the type
- ▶ if all member variables can be copied
 - ▶ i.e., define a copy-assignment operator
- ▶ If all members are of built-in (and RAII) types the default variant works (same problems as with copy ctor).
- ▶ More on copy control when we discuss resource management

Preventing copying

- ▶ Declaration:

```
class C {  
public:  
    C(const C&) =delete;  
    C& operator=(const C&) =delete;  
};
```

- ▶ A class without copy constructor and copy assignment operator cannot be copied.
 - ▶ C++-98: declare private and don't define

Generic programming

Templates (mallar)

- ▶ Uses *type parameters* to write more generic classes and functions
- ▶ No need to manually write a new class/function for each data type to be handled
- ▶ static polymorphism
- ▶ A template is *instantiated* by the compiler for the type(s) it is used for
 - ▶ each instance is a separate class/function
 - ▶ *different from java*: a `java.util.ArrayList<T>` holds `java.lang.Object` references
 - ▶ at compile-time: no runtime overhead
 - ▶ increases code size

Generic programming

Function templates

Example:
instead of

```
void print(int);  
void print(double);  
void print(const std::string&);  
  
template <typename T> print(const T&);
```

Templates

Template compilation

- ▶ The compiler *instantiates* the template at the call site
- ▶ The entire *definition* of the template is needed
 - ▶ place template definitions in header files
- ▶ *Duck typing: if it walks like a duck, and quacks like a duck, it is a duck.*
 - ▶ cf. dynamically typed languages like python
- ▶ Requirements on the *use* of an object rather than its *type*
 - ▶ instead of “**class** T must have a function foo(U)”
 - ▶ “for objects t and u, the expression t.foo(u) is well-formed.”
 - ▶ operator overloading: a+b or a < b is well-formed
 - ▶ a template can work for both built-in and user-defined types
- ▶ Independent of class hierarchies
 - ▶ E.g., in Java: a class must implement Comparable
 - ▶ in C++, a < b must be well-formed

Generic programming

A class for a vector of doubles

```
class Vector{
public:
    explicit Vector(int s);
    ~Vector() {delete[] elem;}
    double& operator[](int i) {return elem[i];}
    int size() const {return sz;}
private:
    int sz;
    double* elem;
};
```

can be generalized to hold any type:

```
template <typename T>
class Vector{
public:
    ...
    T& operator[](int i) const {return elem[i];}
private:
    int sz;
    T* elem;
};
```

Generic programming

example: find an element in a Vector

```
template <typename T>
T& find(const Vector<T>& v, const T& val)
{
    if(v.size() == 0) throw std::invalid_argument("empty vector");
    for(int i=0; i < v.size(); ++i){
        if(v[i] == val) return v[i];
    }
    throw std::runtime_error("not found");
}
```

- ▶ specific to Vector
- ▶ returning a reference is problematic: cannot return null
 - ▶ special handling of empty vector
 - ▶ special handling of element not found
- ▶ returning by value not a solution:
 - ▶ most types do not have a “not found” value
 - ▶ sometimes we need a reference to the actual found element, and not a copy.

Generic programming

example: find an element in an int array

```
int* find(int* first, int* last, int val)
{
    while(first != last && *first != val) ++first;
    return first;
}
```

Generalize to any array (pointer to ~~int~~ type parameter T).

```
template <typename T>
T* find(T* first, T* last, const T& val)
{
    while(first != last && *first != val) ++first;
    return first;
}
```

Generic programming

Iterators

The standard library uses an abstraction for an element of a collection – *iterator*

- ▶ “points to” an element
- ▶ can be dereferenced
- ▶ can be incremented (to point to the following element)
- ▶ can be compared to another iterator

and two functions

`begin()` get an iterator to the first element of a collection

`end()` get an one-past-end iterator

Generic programming

example: find an element in a collection

find using pair of pointers

```
template <typename T>
T* find(T* first, T* last, const T& val)
{
    while(first != last && *first != val) ++first;
    return first;
}
```

Pointers are iterators for built-in arrays.

Find for any iterator range

```
template <typename Iter, typename T>
Iter find(Iter first, Iter last, const T& val)
{
    while(first != last && *first != val) ++first;
    return first;
}
```

Generic programming

A generic Vector class

Example implementation of begin() and end():

```
template <typename T>
class Vector{
public:
    ...
    T* begin() {return sz > 0 ? elem : nullptr;}
    T* end() {return begin()+sz;}
    const T* begin() const {return sz > 0 ? elem : nullptr;}
    const T* end() const {return begin()+sz;}
private:
    int sz;
    T* elem;
};
```

The standard function template `std::begin()` has an overload for classes with `begin()` and `end()` member functions.

Generic user code

```
using std::begin;
using std::end;
void example1()
{
    int a[] {1,2,3,4,5,6,7};

    auto f5= find(begin(a), end(a), 5);
    if(f5 != end(a)) *f5 = 10;
}

void example2()
{
    Vector<int> a{1,2,3,4,5,6,7};

    auto f5= find(begin(a), end(a), 5);
    if(f5 != end(a)) *f5 = 10;
}
```

Generic user code

```
template <typename Iter>
void change_five_to_ten(Iter first, Iter last)
{
    auto f5= find(first, last, 5);
    if(f5 != last) *f5 = 10;
}

using std::begin;
using std::end;
void example1()
{
    int a[] {1,2,3,4,5,6,7};
    change_five_to_ten(begin(a), end(a));
}

void example2()
{
    Vector<int> a{1,2,3,4,5,6,7};
    change_five_to_ten(begin(a), end(a));
}
```


Standard library algorithms

```
#include <algorithm>
```

Numeric algorithms:

```
#include <numeric>
```

Random number generation

```
#include <random>
```

Appendix A.2 in Lippman gives an overview

Main categories of algorithms

- 1 Search, count
- 2 Compare, iterate
- 3 Generate new data
- 4 Copying and moving elements
- 5 Changing and reordering elements
- 6 Sorting
- 7 Operations on sorted sequences
- 8 Operations on sets
- 9 Numeric algorithms

Algorithms operate on iterators.

Algorithm limitations

- ▶ Algorithms may *modify container elements*. E.g.,
 - ▶ `std::sort`
 - ▶ `std::replace`
 - ▶ `std::copy`
 - ▶ `std::remove` (sic!)
- ▶ No algorithm *inserts or removes container elements*.
 - ▶ That requires operating on the actual container object
 - ▶ or using an *insert iterator* that knows about the container (cf. `std::back_inserter`)

Algorithms

Example: find

```
template <class InputIterator, class T>
InputIterator find (InputIterator first, InputIterator last,
                  const T& val);
```

Example:

```
vector<std::string> s{"Kalle", "Pelle", "Lisa", "Kim"};

auto it = std::find(s.begin(), s.end(), "Pelle");

if(it != s.end())
    cout << "Found " << *it << endl;
else
    cout << "Not found"<< endl;
```

Found Pelle

Sequences (homogeneous)

- ▶ `vector<T>`
- ▶ `deque<T>`
- ▶ `list<T>`

Associative containers (also *unordered*)

- ▶ `map<K,V>`, `multimap<K,V>`
- ▶ `set<T>`, `multiset<T>`

Heterogeneous sequences (not “containers”)

- ▶ `tuple<T1, T2, ...>`
- ▶ `pair<T1,T2>`

The classes `vector` and `deque`

The standard library has two main sequence data types

`std::vector` your default sequence type

- ▶ Contiguous in memory
- ▶ Grows at the back

`std::deque` Double ended queue

- ▶ Piecewise contiguous in memory
- ▶ Grows at front and back

The classes `vector` and `deque`

Operations in the class `vector`

```
v.clear(), v.size(), v.empty()  
v.push_back(), v.pop_back(), v.emplace_back()  
v.front(), v.back(), v.at(i), v[i]  
v.assign(), v.insert(), v.emplace()  
v.resize(), v.reserve()
```

Additional operations in `deque`

```
d.push_front(), d.pop_front(), d.emplace_front()
```

The classes `vector` and `deque`

Constructors and the function `assign`

Constructors and `assign` have three overloads:

- ▶ *fill*: `n` elements with the same value

```
void assign (size_type n, const value_type& val);
```

- ▶ *initializer list*

```
void assign (initializer_list<value_type> il);
```

- ▶ *range*: copies the elements in the interval $[first, last)$ (i.e., from `first` to `last`, excl. `last`)

```
template <class InputIterator>  
void assign (InputIterator first, InputIterator last);
```

Use `()` for ctor arguments (e.g., sizes), and `{}` for list of elements.

The classes `vector` and `deque`

The member function `assign`, example

```
vector<int> v{3,4};  
print_seq(v);          length = 2: [3][4]  
  
v.assign(3,4);  
print_seq(v);          length = 3: [4][4][4]  
  
int a[]{0,1,2,3,4,5,6,7,8,9};  
  
v.assign(a, a+5);  
print_seq(v);          length = 5: [0][1][2][3][4]  
  
std::deque<int> d;  
d.assign(v.begin(), v.end());  
print_seq(d);          length = 5: [0][1][2][3][4]
```

Examples of iterators

The classes `vector` and `deque`

Member functions `push` and `pop`

`push` adds an element, increasing size

`pop` removes an element, decreasing size

`front`, `back` get a reference to the first (last) element

`*_back` operates at the end, available in both

```
void push_back (const value_type& val);    //copy
void pop_back();
reference front();
reference back();
```

only in `deque`: `*_front`

```
void push_front (const value_type& val);    //copy
void pop_front();
```

NB! The return type of pop_back() is **void**.

```
auto val = v.back();  
v.pop_back();
```

Why separate functions?

- ▶ Don't pay for what you don't need.
 - ▶ A non-void pop() has to return by value (copy).
 - ▶ front()/back() can return a reference.
 - ▶ Let the caller decide if it wants a copy.

Growing a vector

Size and capacity

A container has a *size* and a *capacity*.

On a `push_back`, if `size == capacity` the vector grows

- ▶ New storage is allocated
- ▶ The elements are copied

If you know how many `push_back` calls you will make,

- ▶ first use `reserve()` to (at least) the expected final size.
- ▶ then do a series of `push_back`

Associative containers

<code>map<Key, Value></code>	Unique keys
<code>multimap<Key, Value></code>	Can contain duplicate keys
<code>set<Key></code>	Unique keys
<code>multiset<Key></code>	Can contain duplicate keys

set is in principle a map without values.

- ▶ By default orders elements with **operator<**

```
template<class Key, class Compare = std::less<Key>>
class set{
    explicit set( const Compare& comp = Compare());
    ...
};
```

- ▶ A custom comparator can be provided

Sets and maps

<set>: std::set

```
void test_set()
{
    std::set<int> ints{1,3,7};

    ints.insert(5);
    for(auto x : ints) {
        cout << x << " ";
    }
    cout << endl;
    auto has_one = ints.find(1);

    if(has_one != ints.end()){
        cout << "one is in the set\n";
    } else {
        cout << "one is not in the set\n";
    }
}
```

1 3 5 7

one is in the set

Or

if(ints.count(1))

Sets and maps

<map>: std::map

```
map<string, int> msi;
msi.insert(make_pair("Kalle", 1));
msi.emplace("Lisa", 2);
msi["Kim"]= 5;

for(const auto& a: msi) {
    cout << a.first << " : " << a.second << endl;
}

cout << "Lisa --> " << msi.at("Lisa") << endl;
cout << "Hasse --> " << msi["Hasse"] << endl;

auto nisse = msi.find("Nisse");
if(nisse != msi.end()) {
    cout << "Nisse : " << nisse->second << endl;
} else {
    cout << "Nisse not found\n";
}

Kalle : 1
Kim : 5
Lisa : 2
Lisa --> 2
Hasse --> 0      NB! operator[] default constructs values for new keys
Nisse not found
```

A `std::set` is in principle a `std::map` without values

Operations on `std::map`

```
insert, emplace, [], at, find, count,  
erase, clear, size, empty,  
lower_bound, upper_bound, equal_range
```

Operations on `std::set`

```
insert, emplace, find, count,  
erase, clear, size, empty,  
lower_bound, upper_bound, equal_range
```

*Use the member functions, not algorithms like `std::find()`
(It works, but is less efficient – linear time complexity instead of logarithmic.)*

Sets and maps

The return value of insert

`insert()` returns a pair

```
std::pair<iterator, bool> insert( const value_type& value );
```

The `insert` member function returns two things:

- ▶ An iterator to the inserted value
 - ▶ or to the element that prevented insertion
- ▶ A **bool**: **true** if the element was inserted

`insert()` in `multiset` and `multimap` just returns an iterator.

Getting the result of an insert

```
auto result = set.insert(value);  
bool inserted = result.second;
```

pair and tuple

- ▶ fixed-size heterogenous container
- ▶ can be used to return multiple values

`std::pair` is defined in `<utility>`

`std::tuple` is defined in `<tuple>`

pairs

Example: explicit element access

Getting the elements of a pair

```
void example1()
{
    auto t = std::make_pair(10, "Hello");

    auto i = t.first;
    auto s = t.second;

    cout << "i: " << i << ", s: " << s << endl;
}
```

tuples

Example: using `std::get(std::tuple)`

Getting the elements of a tuple

```
void example2()
{
    auto t = std::make_tuple(10, "Hello", 4.2);

    auto i = std::get<0>(t);
    auto s = std::get<1>(t);
    auto d = std::get<2>(t);

    cout << "i: " << i << ", s: " << s << ", d: " << d << endl;
}
```

NB! `std::get(std::tuple)` takes the index as a *template parameter*.

- ▶ *adapter classes*, providing a limited interface to one of the standard containers: `stack`, `queue`, `priority_queue`
 - ▶ fewer operations
 - ▶ do not have iterators

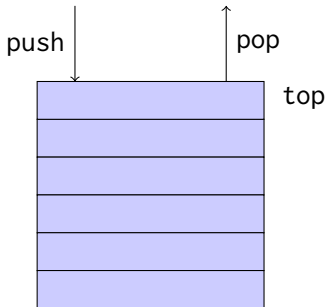
Has a default underlying container. E.g., for `stack`:

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

but `stack` can be instantiated with any class that has `push_back()`, `pop_back()` and `back()`.

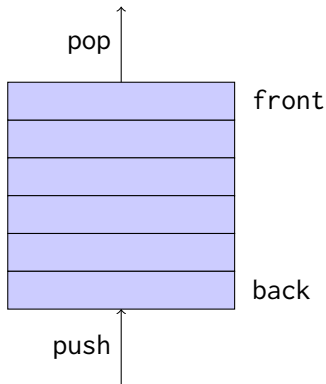
Queues and stacks

- ▶ Stack: LIFO queue (Last In First Out)
- ▶ Operations: push, pop, top, size and empty



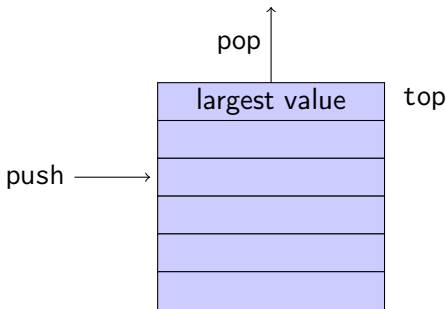
Queues and stacks

- ▶ Queue: FIFO-queue (First In First Out)
- ▶ Operations: push, pop, front, back, size and empty



Queues and stacks

- ▶ Priority queue: sorted queue. The element highest priority is first in the queue.
- ▶ Operations: push, pop, top, size and empty



*Compares elements with `std::less<T>` by default.
A custom comparator can be used. E.g., using `std::greater<T>`
would cause the smallest element to be first.*

Suggested reading

References to sections in Lippman

Iterators 3.4

Sequential containers 9.1 – 9.3

Algorithms 10.1

Associative containers chapter 11

Pairs 11.2.3

Tuples 17.1

Next lecture

References to sections in Lippman

Function templates 16.1.1

Algorithms 10 – 10.3.1, 10.5

Iterators 10.4

Function objects 14.8

Random numbers 17.4.1