EDAF30 – Programming in C++

4. The standard library. Algorithms and containers.

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Outline

User-defined types
Concrete classes

A concrete type

- "behaves just like a built-in type"
- the representation is part if 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*)

Constructors

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
  - *shallow copy* of each member
    - Works for members variables with 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)

Constructors
Special cases: zero or one parameter

Copy Constructor

- Has a **const** & as parameter: `Bar::Bar(const Bar& b);`

Converting constructor

- A constructor with one parameter 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):re{x},im{0} {}
    //...
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 `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

Constructors
Initialization and assignment

*An object is initialized **before** the body of the constructor is run*

It is (often) *possible* to write like in Java, but

- it is less efficient
- the members must be *assignable*

Java-style: assignment in constructor

```
class Foo {
public:
    Foo(const Bar& v) {
        value = v;  NB! assignment, not initialization
    }
private:
    Bar value; is default constructed before the body of the constructor
};
```

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

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 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
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:
    ...
    int* begin() {return sz > 0 ? elem : nullptr;}
    int* end() {return begin()+sz;}
    const int* begin() const {return sz > 0 ? elem : nullptr;}
    const int* end() const {return begin()+sz;}
private:
    int sz;
    T* elem;
};
```

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

Generic programming

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;
}
```

Algorithms

Standard libray algorithms

```
#include <algorithm>
```

Numeric algorithms:

```
#include <numeric>
```

Random number generation

```
#include <random>
```

Appendix A.2 in Lippman gives an overview

Standard algorithms

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

Standard 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
```

Standard containers

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

- Contigous in memory
- Grows at the back

std::deque
: Double ended queue

- Piecewise contigous 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.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()
```

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 sizes, and {} for list of elements.

The classes vector and deque
The member function assign, example

```
vector<int> v{3,3};
print_seq(v);          length = 2: [3][3]

v.assign(3,3);
print_seq(v);          length = 3: [3][3][3]


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();
```

pop_X(), front() and back()

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

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`

Sets and maps

Associative containers

`map<Key,Value>`	Unique keys
`multimap<Key,Value>`	Can contain duplicate keys
`set<Key>`	Unique keys
`multiset<Key>`	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
Nisse not found
```

Sets and maps

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*.

Queues and stacks

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

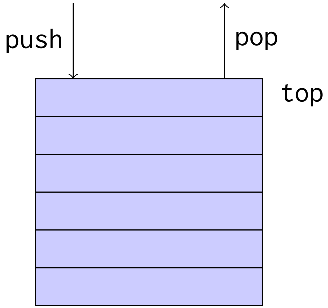
Has a default underlying container. E.g., for `stack`:

```
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()`.

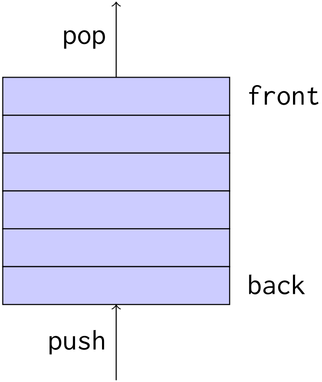
Queues and stacks

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



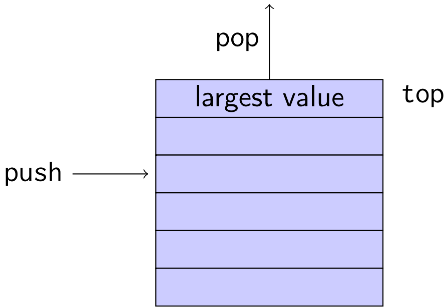
Queues and stacks

- 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