EDAF30 – Programming in C++

8. More about resource management, classes and the standard library.

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Outline

Lvalues and rvalues

- Applies to *expressions*
- An *lvalue* is a named object (persists beyond an expression)
- Examples:
  - `x`
  - `*p`
  - `arr[4]`
- An *rvalue* is a temporary value
- Examples:
  - `123`
  - `a+b`
- you can take the address of it ⇒ *lvalue*
- Better rule than the old "Can it be the left hand side of an assignment?" (because of **`const`**)

Lvalues and rvalues
references

- An *lvalue reference* can only refer to a named object
- An **`const`** *lvalue reference* can also refer to a temporary
  - Extends the lifetime of the temporary to the lifetime of the reference
- An *rvalue reference* can only refer to a temporary
- Syntax:

  (lvalue) reference: `T&`
  rvalue reference: `T&&` (C++11)

Move semantics
Making value semantics efficient

- Copying is unnecessary if the source will not be used again e.g. if
  - it is a *temporary value* ,e.g.
    - (implicitly) converted function arguments
    - function return values
    - `a + b`
  - the programmer explicitly specifies it
    `std::move()` is a *type cast* to *rvalue-reference* (`T&&`)
    (include `<utility>`)
- Better to "steal" the contents
- Makes *resource handles* even more efficient
- Some objects may/can not be copied
  - e.g., `std::unique_ptr`
  - use `std::move`

rule-of-thumb: "if it has a name, it is an lvalue"

"Rule of ~~three~~ five"
Canonical construction idiom, in C++11

If a class owns a resource, it should implement

1. Destructor
2. Copy constructor
3. Copy assignment operator
4. *Move* constructor
5. *Move* assignment operator

Move constructor
Example: Vector

Move constructor (C++-11)

```
Vector::Vector(Vector&& v) : elem{v.elem}, sz{v.sz}
{
    v.elem = nullptr;
    v.sz = 0;          // v has no elements
}
```


Copy control: (Move semantics – C++11)
Example: Vector

Move assignment

```
Vector& Vector::operator=(Vector&& v) {
    if(this != &v) {
        delete[] elem;      // delete current array
        elem = v.elem;      // "move" the array from v
        v.elem = nullptr;   // mark v as an "empty hulk"
        sz = v.sz;
        v.sz = 0;
    }
    return *this;
}
```


Resource management
copy assignment: `operator=`

Declaration (in the class definition of Vector)

```
const Vector& operator=(const Vector& v);
```

Definition (outside the class definition)

```
Vector& Vector::operator=(const Vector& v)
{
    if (this != &v) {
        auto tmp = new int[sz];
        for (int i=0; i<sz; i++)
            tmp[i] = v.elem[i];
        sz = v.sz;
        delete[] elem;
        elem = tmp;
    }
    return *this;
}
```

1. check "self assignment"
2. Allocate new resources
3. Copy values
4. Free old resources

For error handling, better to allocate and copy first and only **`delete`** *if copying succeded.*

We can (often) do better

- Code complexity
  - Both copy and move assignment operators
  - Code duplication
  - Brittle, manual code
    - self-assignment check
    - copying
    - memory management

alternative: The copy-and-swap idiom.

Copy assignment
The copy and swap idiom

Copy-assignment

```
Vector& Vector::operator=(Vector v) {
   swap(*this, v);
   return *this;
}
```

- Call by value
  - let the compiler do the copy
  - works for both copy assign and move assign
    - called with *lvalue* ⇒ copy construction
    - called with *rvalue* ⇒ move construction
- No code duplication
- Less error-prone
- Needs an overloaded `swap()`
- Slightly less efficient (one additional assignment)

Swapping – `std::swap`

The standard library defines a function (template) for swapping the values of two variables:

Example implementation (C++11)

```
template <typename T>
void swap(T& a, T& b)
{
  T tmp = a;
  a = b;
  b = tmp;
}
```

```
template <typename T>
void swap(T& a, T& b)
{
  T tmp = std::move(a);
  a = std::move(b);
  b = std::move(tmp);
}
```

The generic version does unnecessary copying, for `Vector` we can simply swap the members.

Overload for Vector (needs to be **`friend`**)

```
void swap(Vector& a, Vector& b) noexcept
{
  using std::swap;
  swap(a.sz, b.sz);
  swap(a.elem, b.elem);
}
```

common idiom:

- use **`using`** to make `std::swap` visible
- call swap unqualified to allow ADL to find an overloaded swap for the argument type

Swapping – `std::swap`

- The swap function can be both declared as a friend and *defined inside the class definition*.
- Still a free function
- In the same namespace as the class
  - Good for ADL

Overload for Vector ("inline" `friend`)

```
class Vector {
  ...

  friend void swap(Vector& a, Vector& b) noexcept
  {
    using std::swap;
    swap(a.sz, b.sz);
    swap(a.elem, b.elem);
  }
}
```


Argument Dependent Lookup (ADL)

Name lookup is done in *enclosing scopes*, but...

```
namespace test{
    struct Foo{
        Foo(int v) :x{v} {}
        int x;
    };
    std::ostream& operator<<(std::ostream& o, const Foo& f) {
        return o << "Foo(" << f.x << ")";
    }
} // namespace test

int main()
{
    test::Foo f(17);
    cout << f << endl;
}
```

- The function **operator**<<(ostream&, **const** Foo&) is not visible in `main()`.
- Through ADL it is found in the namespace of its argument (`test`).

Argument Dependent Lookup (ADL)

```
namespace test{
    struct Foo;
    std::ostream& operator<<(std::ostream& o, const Foo& f);

    void print(const Foo& f)
    {
        cout << f << endl;
    }
    void print(int i)
    {
        cout << i << endl;
    }
} // namespace test

int main()
{
    test::Foo f(17);

    print(f);
    print(17);
    test::print(17);
}
```

- The functions `test::`**operator**`<<()` and `test::print(`**const** `Foo&)` are found through ADL.
- The function `test::print(`**int**`)` is not found.
- unless **using** `test::print`.

Swapping – `std::swap_ranges` (from `<algorithm>`)

```
template< class ForwardIt1, class ForwardIt2 >
ForwardIt2 swap_ranges( ForwardIt1 first1, ForwardIt1 last1,
                        ForwardIt2 first2 );
```

Returns an iterator one past the last element swapped in the range beginning with `first2`

Container and resource management

- Containers have value semantics
- Elements are copied into the container

The classes `vector` and `deque`
Insertion with `insert` and `emplace`

insert: copying (or moving)

```
iterator insert (const_iterator pos, const value_type& val);
iterator insert (const_iterator pos, size_type n,
                 const value_type& val);
template <class InputIterator>
iterator insert (const_iterator pos, InputIterator first,
                 InputIterator last);
iterator insert (const_iterator pos,
                 initializer_list<value_type> il);
```

emplace: construction *"in-place"*

```
template <class... Args>
iterator emplace (const_iterator position, Args&&... args);

template <class... Args>
void emplace_back (Args&&... args);
```

The classes vector and deque
Example with insert and emplace

```
struct Foo {
  int x;
  int y;
  Foo(int a=0,int b=0) :x{a},y{b} {cout<<*this <<"\n";}
  Foo(const Foo& f) :x{f.x},y{f.y} {cout<<"**Copying Foo\n";}
};
std::ostream& operator<<(std::ostream& os, const Foo& f)
{
  return os << "Foo("<< f.x << ","<<f.y<<")";
}
vector<Foo> v;
v.reserve(4);
v.insert(v.begin(), Foo(17,42)); Foo(17,42)
                                 **Copying Foo
print_seq(v);  length = 1: [Foo(17,42)]
v.insert(v.end(), Foo(7,2));     Foo(7,2)
                                 **Copying Foo
print_seq(v);  length = 2: [Foo(17,42)][Foo(7,2)]
v.emplace_back();                Foo(0,0)
print_seq(v);  length = 3: [Foo(17,42)][Foo(7,2)][Foo(0,0)]
v.emplace_back(10);              Foo(10,0)
print_seq(v);  length = 4: [Foo(17,42)][Foo(7,2)][Foo(0,0)][Foo(10,0)]
```


Container and resource management

- Containers have value semantics
- Elements are copied into the container
- When an element is removed, it is destroyed
- The destructor of a container destroys all elements
- Usually a bad idea to store owning raw pointers in a container
  - Requires explicit destruction of the elements
  - Prefer smart pointers

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

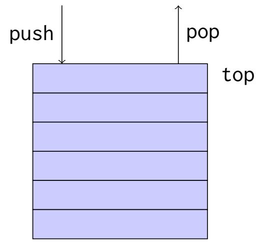
Has a default underlying container. E.g., for stack:

```
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().

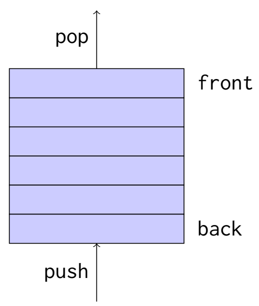
Queues and stacks

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



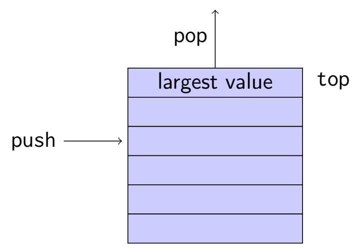
Queues and stacks

- 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.

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

Using std::tie to unpack a pair (or tuple)

```
bool inserted;
std::tie(std::ignore, inserted) = set.insert(value);
```


pairs and std::tie
Example: explicit element access

Getting the elements of a pair

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

    int i = t.first;
    string s = t.second;

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


pairs and std::tie
Example: using std::tie

Getting the elements of a pair

```
void example1b()
{
    auto t = std::make_pair(10, "Hello");

    int i;
    string s;

    std::tie(i,s) = t;

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


tuples and std::tie
Example: using std::get(std::tuple)

Getting the elements of a tuple

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

    int i;
    string s;
    double d;

    i = std::get<0>(t);
    s = std::get<1>(t);
    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*.

tuples and std::tie
Example: using std::tie

Getting the elements of a tuple

```
void example2b()
{
    auto t = std::make_tuple(10, "Hello",4.2);

    int i;
    string s;
    double d;

    std::tie(i,s,d) = t;

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


std::tie
Example: ignoring values with std::ignore

Getting the elements of a tuple

```
void example2c()
{
    auto t = std::make_tuple(10, "Hello",4.2);

    int i;
    double d;

    std::tie(i,std::ignore,d) = t;

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

`std::ignore` is *an object of unspecified type such that assigning any value to it has no effect.*

std::tie
Example: implementation sketch

tie for a `pair<int, string>`

```
std::pair<int&, string&> mytie(int& x, string& y)
{
    return std::pair<int&, string&>(x,y);
}
```

- returns a *temporary* pair of *lvalue references*
- the assignment operator of pair assigns each member
- the references are *aliases for the variables* passed as arguments
- assigning to the references is the same as assigning to the variables

```
int i;
string s;

mytie(i,s) = t;
```


std::tie
Comments

possible implementation

```
template <typename... Args>
std::tuple<Args&...> tie(Args&... args)
{
    return std::tuple<Args&...>(args...);
}
```

- `std::tie` can be used on both `std::pair` and `std::tuple`, as a tuple has an implicit conversion from pair.
- The variables used with `std::tie` must have been declared.
- C++17 introduces *structured bindings* that lets you write code like `const auto& [i,s,d] = some_tuple;`
  - No need to declare variables before
  - Cannot use `std::ignore`: compiler warning if you don't use all variables.

Static members

static members: shared by all objects of the type (like Java)

- *declared* in the class definition
- *defined* outside class definition (if not **const**)
- can be **public** or **private** (or **protected**)

Static members
Example: count allocations and deallocations

```
class Foo {
private:
    static int created;
    static int alive;
public:
    Foo() {++created; ++alive;}
    ~Foo() {--alive;}

    static void print_counts();
};
```

Definitions: *NB! without static*

```
int Foo::created{0};
int Foo::alive{0};

void Foo::print_counts()
{
    cout << alive << " / ";
    cout << created << endl;
}
```

```
void test_lifetimes()
{
    {
        Foo a;
        a.print_counts();

        Foo b;
        b.print_counts();
    }

    {
        Foo c;
        Foo::print_counts();
    }
    Foo::print_counts();
}
```

```
1 / 1
2 / 2
1 / 3
0 / 3
```


Static members
Example: count allocations and deallocations

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```

Definitions: *NB! without static*

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int Foo::created{0};
int Foo::alive{0};

void Foo::print_counts()
{
    cout << alive << " / ";
    cout << created << endl;
}
```

```
void test_lifetimes()
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    {
        Foo a;
        a.print_counts();

        Foo b;
        b.print_counts();
    }

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        Foo c;
        Foo::print_counts();
    }
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1 / 1
2 / 2
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int Foo::created{0};
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1 / 1
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```
int Foo::created{0};
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    cout << created << endl;
}
```

```
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    {
        Foo a;
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        b.print_counts();
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        Foo c;
        Foo::print_counts();
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    Foo::print_counts();
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```
1 / 1
2 / 2
1 / 3
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```


Static members
Example: count allocations and deallocations

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    static int created;
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    Foo() {++created; ++alive;}
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};
```

Definitions: *NB! without static*

```
int Foo::created{0};
int Foo::alive{0};

void Foo::print_counts()
{
    cout << alive << " / ";
    cout << created << endl;
}
```

```
void test_lifetimes()
{
    {
        Foo a;
        a.print_counts();

        Foo b;
        b.print_counts();
    }

    {
        Foo c;
        Foo::print_counts();
    }
    Foo::print_counts();
}
```

```
1 / 1
2 / 2
1 / 3
0 / 3
```

Static and inline : Static members 8. More about resource management, classes and the standard library. 34/39

Class definitions
Member functions and `inline`

Function *inlining*:

- Replace a function call with the code in the function body
  - `inline` is a hint to the compiler
- Only suitable for (very) small functions
- Implicit if the function definition is in the class definition
- If the function is defined outside the class definition, use the keyword `inline`

Class definitions
Member functions and `inline`, example

Inline in the class definition:

```
class Foo {
public:
    int getValue() {return value;}
    // ...
private:
    int value;
};
```

Inline outside the class definition:

```
inline int Foo::getValue()
{
    return value;
}
```


Suggested reading

References to sections in Lippman

swap	13.3
Copying and moving objects	13.4, 13.6
(allocators)	12.2.2
(Classes, dynamic memory allocation)	13.5
Container Adapters	9.6
Pairs	11.2.3
Tuples	17.1