Modern C++ Programming

7. C++ Object Oriented Programming I

Federico Busato

University of Verona, Dept. of Computer Science

2021, v3.04

Table of Context

Table of Context

C++ Classes

C/C++ Structure

A **structure** (`struct`) is a collection of variables of different data types under a single name

C++ Class

A **class** (`class`) extends the concept of structure to hold data members and also functions as members

`struct` vs. `class`

Structures and classes are *semantically* equivalent. In general, `struct` represents *passive* objects, while `class` *active* objects

Class Member/Field

The data within a class are called *data members* or *class field*.
Functions within a class are called *function members* or *methods* of the class

Holding a resource is a class invariant, and is tied to object lifetime

RAII Idiom consists in three steps:

- Encapsulate a resource into a class (constructor)
- Use the resource via a local instance of the class
- The resource is automatically releases when the object gets out of scope (destructor)

Implication 1: C++ programming language does not require the garbage collector!!

Implication 2 :The programmer has the responsibility to manage the resources

struct/class Declaration and Definition

struct declaration and definition

```
struct A;       // struct declaration

struct A {      // struct definition
    int x;      // data member
    void f();   // function member
};
```

class declaration and definition

```
class A;        // class declaration

class A {       // class definition
    int x;      // data member
    void f();   // function member
};
```

`struct/class` Function Declaration and Definition

```cpp
struct A {
   void g();          // function member declaration

   void f() {         // function member declaration
       cout << "f";   // inline definition
   }
};

void A::g() {         // function member definition
    cout << "g";      // out-of-line definition
}
```

Class Fields

```
struct B {
    void g() { cout << "g"; }
};

struct A {
    int  x;
    B    b;
    void f() { cout << "f"; }
    using T = B;
};

A a;
a.x;
a.f();
a.b.g();
A::T obj; // equal to "B obj"
```

Class Hierarchy

Child/Derived Class or Subclass

A new class that inheriting variables and functions from another class is called a **derived** or **child** class

Parent/Base Class

The *closest* class providing variables and function of a derived class is called **parent** or **base** class

Extend a base class refers to creating a new class which retains characteristics of the base class and *on top it can add* (and never remove) its own members

Syntax:

```
class DerivedClass : [<inheritance attribute>] BaseClass {
```

Class Hierarchy


```
struct A {          // base class
    int value = 3;
    void g() {}
};

struct B : A {      // B is a derived class of A (B extends A)
    int data = 4;   // B inherits from A
    int f() { return data; }
};

A a;
B b;
a.value;
b.g();
```

Access specifiers

The **access specifiers** define the visibility of inherited members of the subsequent base class. The keywords `public`, `private`, and `protected` specify the sections of visibility

The goal of the *access specifiers* is to prevent a direct access to the internal representation of the class for avoiding wrong usage and potential inconsistency (access control)

- **`public:`** No restriction (*function members*, *derived classes*, *outside the class*)
- **`protected:`** *Function members* and *derived classes* access
- **`private:`** *Function members* only access (internal)

`struct` has default `public` members
`class` has default `private` members

```cpp
struct A1 {
    int value;   // public (by default)
protected:
    void f1() {} // protected
private:
    void f2() {} // private
};

class A2 {
    int data;   // private (by default)
};

struct B : A1 {
   void h1() { f1(); } // ok, "f1" is visible in B
// void h2() { f2(); } // compile error "f2" is private in A1
};

A1 a;
a.value;  // ok
// a.f1() // compile error protected
// a.f2() // compile error private
```

Inheritance Access Specifiers

The **access specifiers** are also used for defining how the visibility is propagated from the *base class* to a *specific derived class* in the inheritance

Member declaration		Inheritance		Derived classes

`public`
`protected`
`private`
	$\rightarrow$	**`public`**	$\rightarrow$	`public`
				`protected`
				$\backslash$

`public`
`protected`
`private`
	$\rightarrow$	**`protected`**	$\rightarrow$	`protected`
				`protected`
				$\backslash$

`public`
`protected`
`private`
	$\rightarrow$	**`private`**	$\rightarrow$	`private`
				`private`
				$\backslash$

```cpp
struct A {
    int var1; // public
protected:
    int var2; // protected
};

struct B : protected A {
    int var3; // public
};

B b;
// b.var1; // compile error, var1 is protected in B
// b.var2; // compile error, var2 is protected in B
b.var3;    // ok, var3 is public in B
```

```cpp
class A {
public:
    int var1;
protected:
    int var2;
};

class B1 : A {};        // private inheritance

class B2 : public A {}; // public inheritance

B1 b;
// b.var1; // compile error, var1 is private in B
// b.var2; // compile error, var2 is private in B

B2 b;
// b.var1; // ok, var1 is public in B
// b.var2; // compile error, var2 is protected in B
```

Class Constructor

Class Constructor

Constructor [ctor]

A **constructor** is a *special* member function of a class that is executed when a new instance of that class is created

Goals: *initialization* and *resource acquisition*

- A constructor is always named as the class
- A constructor have no return type
- A constructor is supposed to initialize *all* data members
- We can define multiple constructors (different signatures)

Default Constructor

The **default constructor** `T()` is a constructor with no arguments

Every class has always either an *implicit* or *explicit* default constructor

```
struct A {
    A()    {} // explicit default constructor
    A(int) {} // user-defined constructor
};
```

```
struct A {
    int x = 3; // implicit default constructor
};
```

Default Constructor Examples

```cpp
struct A {
    A() { cout << "A"; }  // default constructor
};

A  a1;             // call the default constructor
// A a2();         // interpreted as a function declaration!!
A a3{};            // ok, call the default constructor
                   // direct-list initialization

A  array[3];       // print "B B B"

A* ptr = new A[4]; // print "B B B B"
```

Default Constructor Notes

In `class`, the *implicit default constructor* has `private` visibility

```
class A {
    int x = 3;
};
// A a; // compile error
```

If a *user-provided constructor* is defined, the *implicit default constructor* is marked as deleted

```
struct B {
    B(int x) {}
};
// B b; // compile error
```

Deleted Default Constructor

The *implicit* default constructor of a class is marked as **deleted** if (simplified):

- It has any user-defined constructor (see previous slide)
- It has a member of reference/`const` type

```
struct A { // deleted default constructor
    int&      x;
    const int y;
};
```

- It has a member/base class which has a deleted (or inaccessible) default constructor

```
struct A {
    int& x;
};
struct B : A {}; // deleted default constructor
```

- It has a Base class with a deleted or inaccessible destructor

Initializer List

The **Initializer list** is used for *initializing the data members* of a class or explicitly call the base class constructor before entering in the constructor body

(Not to be confused with `std::initializer_list`)

```
struct A {
    int x, y;

    A(int x1) : x(x1) {}  // ": x(x1)" is the Initializer list
                          // direct initialization syntax

    A(int x1, int y1) :   // ": x{x1}, y{y1}"
        x{x1},            // is the Initializer list
        y{y1} {}          // direct-list initialization syntax
};                        // (C++11)
```

Data Member Initialization

const and **reference** data members <u>must</u> be initialized by using the *initialization list* or by using *brace-or-equal-initializer* syntax (C++11)

```
struct A {
    int        x;
    const char y;  // must be initilizated
    int&       z;  // must be initilizated
    A() : x(3), y('a'), z(x) {}
};

struct B {
    int        x = 3;   // equal-initializer (C++11)
    int        y{4};    // brace initializer (C++11)
    const char z = 'a'; // equal-initializer (C++11)
    int&       w = x;   // equal-initializer (C++11)
};
```

Initialization Order ★

Class members initialization follows the order of declarations and *not* the order in the initialization list

```
struct ArrayWrapper {
    int* array;
    int  size;

    A(int user_size) :
        size{user_size},
        array{new int[size]} {}
        // very dangerous: "size" is still undefined
};

ArrayWrapper a(10);
cout << a.array[4]; // segmentation fault
```

Uniform Initialization

Uniform Initialization (C++11)

Uniform Initialization $\{\}$, also called *list-initialization*, is a way to fully initialize any object independently from its data type

- **Minimizing Redundant Typenames**
  - In function arguments
  - In function returns
- Solving the **"Most Vexing Parse" problem**
  - Constructor interpreted as function prototype

mbevin.wordpress.com/2012/11/16/uniform-initialization

Minimizing Redundant Typenames

```
struct Point {
    int x, y;
    Point(int x1, int y1) : x(x1), y(y1) {}
};
```

C++03

```
Point add(Point a, Point b) {
    return Point(a.x + b.x, a.y + b.y);
}
Point c = add(Point(1, 2), Point(3, 4));
```

C++11

```
Point add(Point a, Point b) {
    return { a.x + b.x, a.y + b.y }; // here
}
auto c = add({1, 2}, {3, 4});        // here
```

“Most Vexing Parse” problem ★

```cpp
struct A {};

struct B {
    B(A a) {}
    B(int x, int y) {}
    void f() {}
};
//--------------------------------------------------------------------

B b( A() );  // "b" is interpreted as function declaration
             //  with a single argument A (*)() (func. pointer)
// b.f()     // compile error "Most Vexing Parse" problem
             // solved with B b{ A{} };

//--------------------------------------------------------------------

struct C {
// B b (1, 2);   // compile error (struct)! It works in a function scope
   B b {1, 2}; // ok, call the constructor
};
```

Constructors and Inheritance

Class constructors are <u>never</u> inherited

A *Derived* class <u>must</u> call *implicitly* or *explicitly* a *Base* constructor before the current class constructor

Class constructors are called <u>in order</u> from the top Base class to the most Derived class (C++ objects are constructed like onions)

```
struct A {
    A() { cout << "A" };
};
struct B1 : A { // call "A()" implicitly
    int y = 3;  // then, "y = 3"
};
struct B2 : A { // call "A()" explicitly
    B2() : A() { cout << "B"; }
};
B1 b1; // print "A"
B2 b2; // print "A", then print "B"
```

Delegate Constructor

The problem:

Most constructors usually perform identical initialization steps before executing individual operations

A **delegate constructor** (C++11) calls another constructor of the same class to reduce the repetitive code by adding a function that does all of the initialization steps

```
struct A {
    int   a1;
    float b1;
    bool  c1;
    // standard constructor:
    A(int a1, float b1, bool c1) : a(a1), b(b1), c(c1) {
        // do a lot of work
    }

    A(int a1, float b1) : A(a1, b1, false)  {} // delegate construtor
    A(float b1)         : A(100, b1, false) {} // delegate construtor
};
```

`explicit` Keyword

`explicit`

The `explicit` keyword specifies that a *constructor* or *conversion function* does not allow implicit conversions or copy-initialization

```cpp
struct A {
    A(int) {}
    A(int, int) {}
};
```

```cpp
A a1(2);       // ok
A a2 = 1;      // ok (implicit)
A a3{4, 5};    // ok. Selected A(int, int)
A a4 = {4, 5}; // ok. Selected A(int, int)
```

```cpp
struct B {
    explicit B(int) {}
    explicit B(int, int) {}
};
```

```cpp
B b1(2);          // ok
// B b2 = 1;      // error implicit conversion
B b3{4, 5};       // ok. Selected B(int, int)
// B b4 = {4, 5}; // error implicit conversion
B b5 = (B) 1;     // OK: explicit cast
```

Copy Constructor

Copy Constructor

Copy Constructor

A **copy constructor** `T(const T&)` is a constructor used to create a new object as a *copy* of an existing object

Every class always define an *implicit* or *explicit* copy constructors

```
struct A {
    A()          {} // default constructor
    A(int)       {} // user-provided constructor
    A(const A&) {} // copy constructor
}
```

In `class`, the implicit copy constructor is marked as `private`

Also the copy constructor implicitly calls the default Base class constructor

Copy Constructor Example

```
struct ArrayWrapper {
    int  size;
    int* array;

    ArrayWrapper(int size1) : size{size1} {
        array = new int[size];
    }

    // copy constructor
    ArrayWrapper(const A& obj) : size{obj.size} {
        array = new int[size];
        for (int i = 0; i < size; i++)
            array[i] = obj.array[i];
    }
};

A x{100}; // do something with x.array ...
A y{x};   // call "A::A(const A&)" copy constructor
```

Copy Constructor Usage

The copy constructor is used to:

- Initialize one object from another having the same type
  - Direct constructor
  - Assignment operator

```
A a1;
A a2(a1);  // Direct copy-constructor
A a3 = a1; // Copy-initialization
```

- Copy an object which is *passed by-value* as input parameter of a function

```
void f(A a);
```

- Copy an object which is returned as result from a function*

```
A f() {
    return A(3); // * see RVO optimization
}
```

Copy Constructor Usage Examples

```
struct A {
    A() {}
    A(const A& obj) { cout << "copy"; }
};

void f(A a) {} // pass by-value

A g() { return A(); };

A a;
A b = a;     // copy constructor (assignment)   "copy"
A c(b);      // copy constructor (direct)       "copy"
f(b);        // copy constructor (argument)     "copy"
g();         // copy constructor (return value) "copy"
A d = g();   // * see RVO optimization         (depends)
```

Pass by-value and Copy Constructor

```cpp
struct A {
    A() {}
    A(const A& obj) { cout << "expensive copy"; }
};

struct B : A {
    B() {}
    B(const B& obj) { cout << "cheap copy"; }
};

void f1(B b) {}
void f2(A a) {}

B b1;
f1(b1); // cheap copy
f2(b1); // expensive copy!! It calls A(const A&) implicitly
```

Deleted Copy Constructor

The *implicit* copy constructor of a class is marked as **deleted** if (simplified):

- It has a member of reference/`const` type

```
struct A {  int& x; }; // deleted copy constructor
```

- Every non-static data member has a valid (accessible and not deleted) copy constructor

```
struct B { // deleted copy constructor
    A a;
};
```

- Every base classes has a valid (accessible, not deleted, not ambiguous) copy constructor

```
struct B : A {}; // delete copy constructor
```

- It has a base class with a deleted or inaccessible destructor
- The class has no move constructor (next lectures)

Class Destructor

Destructor [dtor]

A **destructor** `~T()` is a special member function that is executed whenever an object is out-of-scope or whenever the `delete` `/delete[]` expression is applied to a pointer of that class

Goals: *resources releasing*

- A destructor will have the same name as the class prefixed with a tilde (~)
- A destructor does not have any return type
- Each object has exactly one destructor

```cpp
struct Array {
    int* array;

    Array() {   // constructor
        array = new int[10];
    }

    ~Array() {  // destructor
        delete[] array;
    }
};

int main() {
   Array a;      // call the constructor
   for (int i = 0; i < 5; i++)
       Array b; // call 5 times the constructor + destructor
} // call the destructor of "a"
```

Class destructor is <u>never</u> inherited. *Base* class destructor is invoked *after* the current class destructor

Class destructors are called in reverse order

```
struct A {
    ~A() { cout << "A"; }
};
struct B {
    ~B() { cout << "B"; }
};
struct C : A {
    B b;             // call ~B()
    ~C() { cout << "C"; }
};

int main() {
    C b;  // print "C", then "B", then "A"
}
```

Defaulted Members

Defaulted Constructor (= `default`) 1/2

In C++11, the compiler can generate default/copy/move constructors and copy/more assignment operators

syntax: `A() = default`

The **defaulted** default constructor has a similar effect as a user-defined constructor with empty body and empty initializer list

When compiler-generated constructor is useful:

- Any user-provided constructor disables implicitly-generated default constructor
- Change the visibility of non-user provided constructors and assignment operators (`public` , `protected` , `private`)

Defaulted Constructor (= `default`) 2/2

```
struct A {
    A(int v1) {}   // delete implicitly-defined default ctor
                   // because a user-provided constructor is
                   // defined

    A() = default; // now, A has the default constructor
};

//-------------------------------------------------------------

class B : A {      // default/copy constructor marked private
                   // because B is a class
public:
     B()         = default; // default constructor is now public

     B(const B&) = default; // default constructor is now public
};
```

Defaulted Constructor and Inheritance

```
struct A {
    int x = 3;

    B() = default;
    // "B()" initializes its members

    B(const B&) = default;
    // "B(const B&)" copies its members
};

A b1;       // x = 3;
b1   = 4;   // x = 4
A b2 = b1; // b2.x = 4
```

Defaulted vs. User-Provided Default Constructor

```
struct A {
    int x;
};
struct B {
    int x;
    B() {}  // User-Provided
};
struct C {
    int x;
    C() = default; // Compiler-Provided
};

A a1, a2{}; // a1.x, a2.x is undefined
B b;        // b.x is undefined
C c;        // c.x is zero
A a3{0};    // a3.x is zero
```

Class Keywords

this Keyword

this

Every object has access to its own address through the const pointer `this`

Explicit usage is not mandatory (and not suggested)

`this` is necessary when:

- The name of a local variable is equal to some member name
- Return reference to the calling object

```
struct A {
    int x;
    void f(int x) {
        this->x = x; // without "this" has no effect
    }
    const A& g() {
        return *this;
    }
};
```

`static` Keyword

The keyword `static` declares members (fields or methods) that are not bound to class instances. A **static** member is shared by <u>all</u> objects of the class

- A *static* member function can access <u>only</u> *static* class members
- A *non-static* member function can access *static* class members
- Non-const static data members <u>cannot</u> be *directly* initialized inline

```cpp
// "static" means the same value for all instances

struct A {
// static int                a = 4;     // compiler error

   static int                a;         // ok

   static const int          b = 4;     // also C++03

   static const float        c = 4.2f; // only GNU extension (GCC)

   static constexpr float d = 4.2f; // ok
};

int A::a = 4; // ok, without definition -> undefined reference
```

```
struct A {
    int        y = 2;
    static int x; // declaration

    static int f() { return x * 2; }
//  static int f() { return y;     } // error "y" is non-static
    int h()        { return x;     } // ok, "x" is static
};

int A::x = 3;    // definition
//-----------------------------------------------------------------

A a;
a.h();           // return 3
A::x++;
cout << A::x;    // print 4
cout << A::f();  // print 8
```

Const member functions

Const member functions, or **inspectors**, are functions marked with `const` that are not allowed to change the object state

Member functions without a `const` suffix are called *non-const member functions* or *mutators*

The compiler prevents from inadvertently mutating/changing the data members of *observer* functions

```
struct A {
    int x = 3;

    int get() const {
     // x = 2;    // compile error class variables cannot
        return x; //               be modified
    }
};
```

`const` Keyword - `const` Overloading 2/2

The `const` keyword is part of the functions signature. Therefore a class can implement two similar methods, one which is called when the object is `const`, and one that is not

```
class A {
    int x = 3;
public:
    int& get1()       { return x; } // read and write
    int  get1() const { return x; } // read only
    int& get2()       { return x; } // read and write
};

A a1;
cout << a1.get1();    // ok
cout << a1.get2();    // ok
a1.get1() = 4;        // ok

const A a2;
cout << a2.get1();    // ok
// cout << a2.get2(); // compile error "a2" is const
//a2.get1() = 5;      // compile error only "get1() const" is available
```

`mutable` Keyword

mutable

`mutable` members of *const* class instances are modifiable

Constant references or pointers to objects cannot modify that object in any way, except for data members marked `mutable`

- It is particularly useful if most of the members should be constant but a few need to be modified
- *Conceptually,* `mutable` *members should not change anything that can be retrieved from the class interface*

```cpp
struct A {
    int         x = 3;
    mutable int y = 5;
};

const A a;
// a.x = 3; // compiler error const
a.y = 5;    // ok
```

`using` Keyword

The `using` keyword can be used to change the *inheritance attribute* of member data or functions

```
class A {
protected:
    int x = 3;
};

class B : A {
public:
    using A::x;
};

B b;
b.x = 3;  // ok, "b.x" is public
```

friend Class

A `friend` class can access the `private` and `protected` members of the class in which it is declared as a `friend`

Friendship properties:

- **Not Symmetric**: if class `A` is a friend of class `B`, class `B` is not automatically a friend of class `A`
- **Not Transitive**: if class `A` is a friend of class `B`, and class `B` is a friend of class `C`, class `A` is not automatically a friend of class `C`
- **Not Inherited**: if class `Base` is a friend of class `X`, subclass `Derived` is not automatically a friend of class `X`; and if class `X` is a friend of class `Base`, class `X` is not automatically a friend of subclass `Derived`

```cpp
class A;    // class declaration

class B {
    int y = 3;  // private
    int f(A a) { return a.x; } // ok, B is friend of A
};

class A {
    friend class B;
    int x = 3;  // private
//  int f(B b) { return b.y; } // compile error not symmetric
};

class C : B {
//  int f(A a) { return a.x; } // compile error not inherited
};
```

`friend` Method

A *non-member function* can access the `private` and `protected` members of a class if it is declared a `friend` of that class

```
class A {
    int x = 3;  // private

    friend int f(A a);
};

//'f' is not a member function of any class
int f(A a) {
    return a.x;  // A is friend of f(A)
}
```

`delete` Keyword

The `delete` keyword (C++11) explicitly marks a member function as deleted and any use results in a compiler error. When it is applied to *copy/move constructor* or *assignment*, it prevents the compiler from implicitly generating these functions

The default copy/move functions for a class can produce unexpected results. The keyword `delete` prevents these errors

```
struct A {
    A(const A& a) = delete;
};
                // e.g. if a class uses heap memory
void f(A a) {}  // the copy construct should be
                // written by the user -> expensive copy
A a;
// f(a);        // compile error marked as deleted
```