

Modern C++ Programming

7. OBJECT-ORIENTED PROGRAMMING I

CLASS CONCEPTS

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2023-12-11

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C++ Classes

C/C++ Structure

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

C++ Class

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

struct vs. class

Structures and *classes* are *semantically* equivalent.

- `struct` represents *passive* objects, namely the *physical state* (set of data)
- `class` represents *active* objects, namely the *logical state* (data abstraction)

Class Members - Data and Function Members

Data Member

Data within a class are called **data members** or **class fields**

Function Member

Functions within a class are called **function members** or **methods**

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 released 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

```
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  
}
```

struct/class Members

```
struct B {  
    void g() { cout << "g"; } // function member  
};  
  
struct A {  
    int x; // data member  
    B b; // data member  
    void f() { cout << "f"; } // function member  
};  
  
A a;  
a.x;  
a.f();  
a.b.g();
```

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 functions 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 {
```

```
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();
```

```
struct A {};  
struct B : A {};  
  
void f(A a) {}      // copy  
void g(B b) {}      // copy  
  
void f_ref(A& a) {} // the same for A*  
void g_ref(B& b) {} // the same for B*  
  
A a;  
B b;  
f(a); // ok, also f(b), f_ref(a), g_ref(b)  
g(b); // ok, also g_ref(b), but not g(a), g_ref(a)  
  
A a1 = b;    // ok, also A& a2 = b  
// B b1 = a; // compile error
```


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

```
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
```

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	→	public	→	public protected \ protected protected \ private private \ private
public protected private	→	protected	→	protected protected \ private private \ private
public protected private	→	private	→	private private \ private

```
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
```

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

class B1 : A {};           // private inheritance

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

B1 b1;
// b1.var1; // compile error, var1 is private in B1
// b1.var2; // compile error, var2 is private in B1

B2 b2;
b2.var1;    // ok, var1 is public in B2
```

When Use `public/protected/private/` for Data Members?

When use `protected/private` data members:

- They are not part of the interface, namely the *logical state* of the object (not useful for the user)
- They must preserve the `const` correctness (e.g. for pointer), see Advanced Concepts I

When use `public` data members:

- They can potentially change any time
- `const` correctness is preserved for values and references, as opposite to pointers. *Data members* should be preferred to *member functions* in this case

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*

Syntax: `T(...)` same named of the class and no return type

- A *constructor* is supposed to initialize all data members
- We can define *multiple constructors* with different signatures
- Any *constructor* can be `constexpr`

Default Constructor

Default Constructor

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

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

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

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

- An *implicit* default constructor is `constexpr`

Default Constructor Examples

```
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 (C++11)  
  
A array[3];    // print "AAA"  
  
A* ptr = new A[4]; // print "AAAA"
```

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

- It has any user-defined constructor

```
struct A {  
    A(int x) {}  
};  
  
// A a; // compile error
```

- It has a non-static member/base class of reference/const type

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

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

```
struct A {  
    NoDefault var;      // deleted default constructor  
};  
struct B : NoDefault {}; // deleted default constructor
```

- It has a non-static member/base class with a deleted or inaccessible destructor

```
struct A {  
private:  
    ~A() {}  
};
```

Initializer List

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

In-Class Member_INITIALIZER

C++11 In-class non-static data members initialization (NSDMI) allows to initialize the data members where they are declared. A user-defined constructor can be used to override the their default values

```
struct A {  
    int      x      = 0;          // in-class member initializer  
    const char* str = nullptr; // in-class member initializer  
  
    A() {} // "x" and "str" are well-defined if  
           // the default constructor is called  
  
    A(const char* str1) : str{str1} {}  
};
```

Data Member Initialization

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

```
struct A {  
    int      x;  
    const char y;    // must be initialized  
    int&     z;      // must be initialized  
  
    int&     v = x;  // equal-initializer (C++11)  
    const int w{4}; // brace initializer (C++11)  
  
    A() : x(3), y('a'), z(x) {}  
};
```


Initialization Order

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

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

    ArrayWrapper(int user_size) :
        size{user_size},
        array{new int[size]} {}
        // wrong!!: "size" is still undefined
};

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

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

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
```

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

```
struct A {};  
  
struct B {  
    B(A a) {}  
    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{} };
```

Constructors and Inheritance

Class constructors are never inherited

A *Derived* class must call *implicitly* or *explicitly* a *Base* constructor before the current class constructor

Class constructors are called in order 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

C++11 A **delegate constructor** 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 a;
    float b;
    bool c;
    // 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 constructor
    A(float b1) : A(100, b1, false) {} // delegate constructor
};
```

explicit

The `explicit` keyword specifies that a *constructor* or *conversion operator* (C++11) does not allow implicit conversions or copy-initialization from single arguments or braced initializers

The problem:

```
struct MyString {  
    MyString(int n);           // (1) allocate n bytes for the string  
    MyString(const char *p);  // (2) initializes starting from a raw string  
};  
MyString string = 'a';       // call (1), implicit conversion!!
```

`explicit` cannot be applied to *copy/move-constructors*


```
struct A {  
    A() {}  
    A(int) {}  
    A(int, int) {}  
};  
void f(const A&) {}
```

```
A a1 = {};           // ok  
A a2(2);             // ok  
A a3 = 1;            // ok (implicit)  
A a4{4, 5};          // ok. Selected A(int, int)  
A a5 = {4, 5};       // ok. Selected A(int, int)  
f({});               // ok  
f(1);                 // ok  
f({1});               // ok
```

```
struct B {  
    explicit B() {}  
    explicit B(int) {}  
    explicit B(int, int) {}  
};  
void f(const B&) {}
```

```
// B b1 = {};           // error implicit conversion  
B b2(2);               // ok  
// B b3 = 1;            // error implicit conversion  
B b4{4, 5};           // ok. Selected B(int, int)  
// B b5 = {4, 5};       // error implicit conversion  
B b6 = (B) 1;         // OK: explicit cast  
// f({});               // error implicit conversion  
// f(1);                 // error implicit conversion  
// f({1});               // error implicit conversion  
f(B{1});               // ok
```

[[nodiscard]] and Classes

C++17 allows to set `[[nodiscard]]` for the entire `class/struct`

```
[[nodiscard]] struct A {};  
A f() { return A{}; }  
  
auto x = f(); // ok  
f();          // compiler warning
```

C++20 allows to set `[[nodiscard]]` for constructors

```
struct A {  
    [[nodiscard]] A() {} // C++20 also allows [[nodiscard]] with a reason  
};  
void f(A {})  
  
A a{}; // ok  
f(A{}); // ok  
A{};   // compiler warning
```

Copy Constructor

Copy Constructor

A **copy constructor** `T(const T&)` creates a new object as a *deep copy* of an existing object

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

- Every class always defines an *implicit* or *explicit* copy constructor
- Even the copy constructor implicitly calls the *default* Base class constructor
- Even the copy constructor is considered a non-default constructor

Copy Constructor Example

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

    Array(int size1) : size{size1} {
        array = new int[size];
    }
    // copy constructor, ": size{obj.size}" initializer list
    Array(const Array& obj) : size{obj.size} {
        array = new int[size];
        for (int i = 0; i < size; i++)
            array[i] = obj.array[i];
    }
};

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

Copy Constructor Usage

The copy constructor is used to:

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

```
A a1;  
A a2(a1);    // Direct copy initialization  
A a3{a1};    // Direct copy initialization  
A a4 = a1;   // Copy initialization  
A a5 = {a1}; // Copy list 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 g1(A& a) { return a; }  
  
A g2()      { return A(); }  
  
A a;  
A b = a;    // copy constructor (assignment) "copy"  
A c(b);     // copy constructor (direct)    "copy"  
f(b);      // copy constructor (argument)   "copy"  
g1();      // copy constructor (return value) "copy"  
A d = g2(); // * see RVO optimization (Advanced Concepts I)
```

Pass by-value and Copy Constructor

```
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 non-static member/base class of reference/const type

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

- It has a non-static member/base class which has a deleted (or inaccessible) copy constructor

```
struct B { // deleted copy constructor
    NonDefault a;
};
struct B : NonDefault {}; // delete copy constructor
```

- It has a non-static member/base class with a deleted or inaccessible destructor
- The class has the move constructor (next lectures)

Class Destructor

Destructor [dtor]

A **destructor** 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*

Syntax: `~T()` same name of the class and no return type

- Any object has exactly one *destructor*, which is always *implicitly* or *explicitly* declared
- **C++20** The *destructor* can be `constexpr`

```
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 never inherited. *Base* class destructor is invoked *after* the current class destructor

Class destructors are called in reverse order. From the most Derived to the top Base class

```
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
Constructors,
Destructor, and
Operators
(=default)**

C++11 The compiler can automatically generate

- **default/copy/move constructors**

 - `A() = default`

 - `A(const A&) = default`

 - `A(A&&) = default`

- **destructor**

 - `A() = default`

- **copy/move assignment operators** `A& operator=(const A&) = default`

 - `A& operator=(A&&) = default`

- **spaceship operator**

 - `auto operator<=>(const A&) = default`

`= default` implies `constexpr`, but not `noexcept` or `explicit`

When the compiler-generated constructors, destructors, and operators are useful:

- Change the visibility of non-user provided constructors and assignment operators (`public`, `protected`, `private`)
 - Make visible the declarations of such members
-

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

When the compiler-generated constructor is useful:

- Any user-provided constructor disables implicitly-generated default constructor
- Force the default values for the class data members


```
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  
};
```

```
struct B {  
protected:  
    B() = default; // now it is protected  
};
```

```
struct C {  
    int x;  
    // C() {}    // 'x' is undefined  
    C() = default; // 'x' is zero  
};
```

Class Keywords

this Keyword

`this`

Every object has access to its own address through the 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 all objects of the class

```
struct A {  
    int x;  
  
    int f() { return x; }  
  
    static int g() { return 3; } // g() cannot access 'x' as it is associated with  
};                               // class instances  
A a{4};  
a.f(); // call the class instance method  
A::g(); // call the static class method  
a.g(); // as an alternative, a class instance can access static class members  
      // (less common)
```

```
struct A {  
    static const int      a = 4;           // C++03  
    static constexpr float b = 4.2f;     // better, C++11  
    // static const float  c = 4.2f;     // only GNU extension (GCC)  
  
    static constexpr int f() { return 1; } // ok, C++11  
    // static const int    g() { return 1; } // 'const' refers to the return type  
};
```

Non-`const` `static` data members cannot be *directly* initialized inline (see Translation Units lecture)...before C++17

```
struct A {  
    // static int      a = 4; // compiler error  
    static int      a;      // ok, declaration only  
    static inline int b = 4; // ok from C++17  
  
    static int f() { return 2; }  
    static int g();        // ok, declaration only  
};  
  
int A::a = 4;              // ok, undefined reference without this definition  
int A::g() { return 3; }  // ok, undefined reference without this definition
```

```
struct A {  
    static int x; // declaration  
  
    static int f() { return x; }  
  
    static int& g() { return x; }  
};  
int A::x = 3; // definition  
  
//-----  
  
A::f();    // return 3  
A::x++;  
A::f();    // return 4  
A::g() = 7;  
A::f();    // return 7
```

- A `static` member function can only access `static` class members
- A non-`static` member function can access `static` class members

```
struct A {  
    int          x = 3;  
    static inline int y = 4;  
  
    int          f1() { return x; } // ok  
// static int f2() { return x; } // compiler error, 'x' is not visible  
    int          g1() { return y; } // ok  
    static int g2() { return y; } // ok  
  
    struct B {  
        int h() { return y + g2(); } // ok  
}; // 'x', 'f1()', 'g1()' are not visible within 'B'  
};
```


Const member functions

Const member functions (**inspectors** or **observer**) are functions marked with `const` that are not allowed to change the object logical state (to not confuse with the *physical 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 be modified  
        return x;  
    }  
};
```

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

`mutable` data members of *const* class instances are modifiable. They should be part of the object *physical state*, but not of the *logical state*

- 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

```
struct A {  
    int      x = 3;  
    mutable int y = 5;  
};  
const A a;  
// a.x = 3; // compiler error const  
a.y = 5;    // ok
```

using Keyword for type declaration

The `using` keyword is used to declare a *type alias* tied to a specific class

```
struct A {  
    using type = int;  
};  
  
typename A::type x = 3; // "typename" keyword is needed when we refer to types  
  
struct B : A {};  
  
typename B::type x = 4; // B can use "type" as it is public in A
```

using Keyword for Inheritance

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

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

```
class B;    // class declaration

class A {
    friend class B;
    int x;    // private
};

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

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); // friendship declaration, no implementation  
};  
  
// 'f' is not a member function of any class  
int f(A a) {  
    return a.x; // A is friend of f(A)  
}
```

friend methods are commonly used for implementing the stream operator **operator<<**

delete Keyword

delete Keyword (C++11)

The `delete` keyword 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()          = default;
    A(const A&) = delete; // e.g. deleted because unsafe or expensive
};
void f(A a) {} // implicit call to copy constructor

A a;
// f(a);      // compile error marked as deleted
```