Modern C++ Programming

7. C++ Object Oriented Programming I

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C++ Classes

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. In general, `struct` represents *passive* objects, while `class` *active* objects

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 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

```cpp
struct A;       // struct declaration

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

`class` declaration and definition

```cpp
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

```cpp
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 {
```

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();
```

```cpp
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

Access specifiers


```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`
				\

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

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

```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
```

Inheritance Access Specifiers 3/3

```cpp
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
```

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*

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

```cpp
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

```cpp
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 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)
```

In-Class Member Initializer

C++11 **In-class non-static data members** can be initialized where they are declared (NSDMI). A constructor can be used when run-time initialization is needed

```
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 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]} {}
        // 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

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

Minimizing Redundant Typenames

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

C++03

```cpp
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

```cpp
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 ★

```
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 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 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

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

```
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)
```

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

```
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&)` 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

```cpp
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 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 *implictly* or *explicitly* declared
- C++20 The *destructor* can be `constexpr`

```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. 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 Members (`= default`)

C++11 The compiler can generate **default/copy/move constructors**, **destructor**, **copy/move assignment operators**, and **spaceship operator**

syntax: `A() = default`

implies `constexpr`

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`)
- Make explicit and clear the declarations of such members

Defaulted Members (= `default`)

```
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

    B(const B&) = default; // now it is protected
};
```

Class Keywords

`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 all objects of the class

- A `static` member function can only access `static` class members
- A non-`static` member function can access `static` class members
- Non-const `static` data members cannot be *directly* initialized inline (see `Translation Units` lecture)...before C++17

Mutable `static` members

```
// "static" means the same value for all instances
struct A {
// static int         a = 4;     // compiler error
   static int         a;         // ok, (declaration)
   static inline int b = 4;     // from C++17
};
int A::a = 4; // ok, without definition -> undefined reference
```

Constant `static` members

```
struct A {
   static const int         c = 4;     // also C++03
// static const float       d = 4.2f; // only GNU extension (GCC)
   static constexpr float e = 4.2f; // ok, C++11
};
```

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

    static int f() { return x * 2; }
//  static int f() { return y;     } // compile 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 (**inspectors** or **observer**) 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 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

```cpp
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 objects 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*

```
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` Keyword 1/3

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`

`friend` Keyword 2/3

```
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
```