Modern C++ Programming

5. C++ Object Oriented Programming

Federico Busato

University of Verona, Dept. of Computer Science
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C++ Classes

C++ Classes

C++ Class

Classes extend the concept of data structures: they can contain data members and also functions as members

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

`struct` vs. `class`

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

C++ Classes

```
struct A;     // class declaration (incomplete type)

class B {
    void g() { cout << "g"; } // function member definition
};
struct A {   // class definition
   int x;    // field/variable member
   void f(); // function member (declaration)

   B b;          // b class is a field of A
   using T = B; // alias of B inside A
};

void A::f() { cout << "f"; } // function member definition

int main() {
    A a;
    std::cout << a.x;
    a.f();
    a.b.g();
    A::T obj; // equal to B obj;
}
```

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** class

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

```cpp
#include <iostream>
using namespace std;

struct A {  // base class
    int value = 3;
};

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

int main() {
    A base;
    B derived1;
    C derived2;
    cout << base.value;     // print 3
    cout << derived1.data; // print 4
    cout << derived2.f();  // print 4
}
```

`private`, `public`, and `protected` inheritance

- **`public:`** The public members can be accessed without any restriction
- **`protected:`** The protected members of a base class can be accessed by its derived class
- **`private:`** The private members of a class can only be accessed by function members of that class

Inheritance Attributes

member declaration	inheritance	derived classes
`public` protected private	public	public protected \
public protected private	protected	protected protected \
public protected private	private	private private \

- structs have default **`public`** members
- classes have default **`private`** members

Inheritance Attributes


```cpp
#include <iostream>
using namespace std;

class A {
public:
    int var1 = 3;
    int f() { return var1; }
protected:
    int b;
};

class B : public A { // without public, B inherits
};                   // the data member "var1" and f()
                     // as private members
int main() {
    B derived;
    cout << derived.f(); // print 3
//  cout << derived.b;   // compile error!! protected
}
```

Constructor [ctor]

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

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

Class constructors are never inherited. *Derived* class must call a *Base* constructor before the current class constructor

Class constructors are called in order of declaration
(C++ objects are constructed like onions)

```cpp
#include <iostream>
class A {
    int x;
public:
    A(int x1) : x(x1) {    // constructor
        std::cout << "A";
    }
};

class B : A {
public:
    B(int b1) : A(b1) { std::cout << "B"; }
};

int main() {
    A a(1);     // print "A"
    B b(2);     // print "A", then print "B"
    A c = {1};  // direct initialization, print "A"
    A d {1};    // uniform initialization (C++11), print "A"
}
```

Default Constructor

A **default constructor** is a constructor with no arguments

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

Note: in `class` the implicit default constructor is marked as `private`

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

- It has a member of reference/`const` type
- It has a user-defined constructor
- It has a member/base class which has a deleted (or inaccessible, or ambiguous) default constructor
- It has a base class which has a deleted (or inaccessible, or ambiguous) destructor

```cpp
struct A {};  // implicit-declared public default constructor

class B {};  // implicit-declared private default constructor

class C {
public:
    C() {   // user-defined default constructor
        std::cout << "C";
    }
};
struct D {
    int& a; // implicit-deleted default constructor
};

int main() {
    A a1;       // call the default constructor
//  A a2();     // interpreted as a function declaration!!
//  B b;        // compile error!! private
    C c;        // ok, print "C"
    C array[3]; // print three times "C"
//  D d;        // compile error!! deleted
}
```

(Any) Member data <u>should</u> be initialized by constructors with the **initialization lists** or by using **brace-or-equal-initializer** syntax

`const` and *reference* data members <u>must</u> be initialized by using the *initialization lists*

```
struct A {
    char        a;
    const float b;
    const int   c = 3;          // default initialization
    int*        ptr { nullptr }; // default initialization(C++11)

    A(char a1) : a(a1), b(1.2f) {}  // direct initilization

    A() : a{'x'}, b{1.2f} {} // uniform initialization(C++11)

// A() : c('a') {}          // compile error!! "b" is const
};
```

C++11

Uniform Initialization

Uniform 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

To not confuse with narrowing conversion

Full details:
`mbevin.wordpress.com/2012/11/16/uniform-initialization/`

```
struct A {
    int a1, a2;
};
class B {
    int b1, b2;
public:
    B(A a) {}
    B(int x1, int x2) : b1(x1), b2(x2) {}
};

A f() {
    return { 1, 2 }; // ok, works also for B (call B(int, int))
}
B g(A a) {
    B b( A() ); // interpreted as function declaration
//  return b;   // 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
};
```

C++11

The `explicit` keyword specifies that a constructor or conversion function doesn't allow implicit conversions or copy-initialization

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

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

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

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

Copy Constructor

A **copy constructor** 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

Note: in `class` the implicit copy constructor is marked as `private`

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

- Every non-static class type (or array of class type) member has a valid (accessible, not deleted, not ambiguous) copy constructor
- Every base classes has a valid (accessible, not deleted, not ambiguous) copy constructor
- It has a base class with a deleted or inaccessible destructor
- The class has no move constructor (next slides)

Copy Constructor (example)


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

    A(int size1) : size(size1) {
        y = new int[size];
    }

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

int main() {
    A x(100), y(10);
    x = y;    // call "A::A(const A&)" copy constructor
}
```

```cpp
struct A {
    int x;
    A(const A& obj) : x(obj.x) {} // user-defined copy constructor
                                  // -> delete default ctor
    A() {}   // user-defined
};
struct B : A {
    int array[3];
    B() : A(), array{1, 2, 3} {}
//  B(const B& obj) ...   // implicitly-declared copy constructor
};

int main() {
    B x;
    B y = x;   // call "A" user-declared copy constructor, then
               // call "B" implicitly-declared copy constructor
//  the value of y.array[0] is 1
    B z = B(); // ok, call "B" implicitly-declared copy ctor
}
```

The copy constructor is used to:

- Initialize one object from another having the same type
  - Direct constructor
  - Assignment operator
- Copy an object which is passed by value as input parameter of a function
- Copy an object which is returned as result from a function

```cpp
class A {
public:
    A() {}
    A(const A& obj) {}
};

void f(A a) {}

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

```cpp
int main() {
    A a;
    A b = a; // copy constructor (assignment)

    A c(b);  // copy constructor (direct)

    f(b);    // copy constructor (argument)
   // copy constructor (return value)
    A d = g();  // but see RVO optimization
}
```

Class Constructor (`default` keyword) 1/2

In C++11, we can use the compiler-generated version of default/copy constructors

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

When compiler-generated constructor is useful:

- Define any constructor different from the default constructor disables implicitly-generated default constructor
- Default/copy constructors from classes are marked `private`

Class Constructor (`default` keyword) 2/2

```
struct A {
   int v;
   A(int v1) : v(v1){} // delete implicitly-defined default ctor
   A() = default;      // now A has the default constructor
};

class B {  // default/copy constructor marked private
public:
   B()          = default; // default constructor now is public
   B(const B&) = default; // copy constructor now is public
};                // "B() = default" equal to "B() : A() {}"
                  // "B(const B&) = default" equal to
int main() {      //    "B(const B& b) : A(b.x) {}"
   B x, y;
   x.v = 4 ;
   y = x;      // "y.x" has value 3
}
```

Default vs. Copy Constructor

```
struct A{
    A()          { std::cout << "default"; }
    A(const A&) { std::cout << "copy"; }
};

void f(A a) {}
void g(A& a) {}
A h() { return A(); } // default constructor "default"

int main() {
    A x, y;  // default constructor "default"
    A z = x; // copy constructor    "copy"
    x = y;   // copy assignment operator (see next slides)
    f(x);    // copy constructor    "copy"
    g(x);    // nothing
    A j = h(); // copy constructor, but RVO (copy elision)
}
```

Destructor [dtor]

A **destructor** is a member function of a class that is executed whenever an object is out-of-scope or whenever the delete expression is applied to a pointer to the object of that class

- A destructor will have exact same name as the class prefixed with a tilde ($\sim$)
- A destructor does not have any return type
- Each object has exactly one destructor
- A destructor is useful for releasing resources before the class instance goes out of scope or it is deleted

```
struct A {
    int* array;

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

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

int main() {
   A a;     // call the constructor
   for (int i = 0; i < 5; i++)
       A b; // call 5 times the constructor and the 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() { std::cout << "A"; }
};
struct B {
    ~B() { std::cout << "B"; }
};
struct C : A {
    B b;            // call ~B()
    ~C() { std::cout << "C"; }
};

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

RAII Idiom - Resource Acquisition is Initialization

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

Implication1: C++ programming language does not require the garbage collector!!
Implication2 :The programmer has the responsibility to manage the resources

RAII Idiom consists in three steps:

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

Class Keywords

`this` Keyword

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

The `this` const pointer an implicit variable added to any member function. In general, it is not needed

`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 access only *static* class members
- A *non-static* member function can access *static* class members
- All *static* data is initialized to zero/default useless if no user-initialization is provided
- It can be initialized (defined) only once
- Static data members cannot be `inline` initialized

```
struct A {
    int y = 2;
//  static int x = 3;     // compile error!! inline initialization
    static int x;         // declaration
    static int z[];       // array declaration (incomplete type)
    static int g();       // function 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;              // static variable definition
int A::z[] = {1, 2, 3};      // static array definition
int A::g() { return z[1]; } // static function definition

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

Constant static members

If a static data member is declared as `const` or `constexpr`, then it can be initialized inline and only through a constant expression

```
constexpr int f(int a) { return a * 2}

struct A {
    static const int   x = f(3);         // ok
    static const float y;                // ok, declaration
//  static const char* z    = "ab";      // compile error!! "static const"
//  static const int   w[] = {1, 2};     // cannot be initilizaed "inline"
//  static const float v    = 3.3f;      // with arrays, pointers,
                                         // and floating-point
    static constexpr char* z    = "ab";      // ok, but must be initilized
    static constexpr int   w[] = {1, 2};     // "inline"
    static constexpr float v    = 3.3f;      //
};
const float A::y = 3.3f;      // ok, definition
```

Const member functions

Const member functions, or (**inspectors**), do not change the object state

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

The compiler prevent callers from inadvertently mutating/changing the object data members with functions marked as `const`

```
class A {
    int x = 3;
public:
    int get() const {
      // x = 2;    // compile error!! class variables cannot
        return x;                    //  be modified
    }
};
```

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; }
    int get1() const { return x; }
    int get2()       { return x; }
};
int main() {
   A a1;
   std::cout << a1.get1();   // ok
   std::cout << a1.get2();   // ok
   const A a2;
   std::cout << a2.get1();   // ok
// std::cout << a2.get2();   // compile error!! "a2" is const
}
```

`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 your class interface*

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

int main() {
    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;
};

int main() {
    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);
};

class A {
    friend class B;
    int x = 3;  // private
    int f(B b);
};

int B::f(A a) { return a.x; } // ok, B is friend of A
int A::f(B b) { return b.y; } // compile error!! (no symmetric)

class C : B {
    int f(A a) { return a.x; } // compile error!! (no 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 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
int main() {
//  f(A());     // compile error!! (marked as deleted)
}
```

Polymorphism

Polymorphism

In object-oriented programming, **polymorphism** (meaning "having multiple forms") is the capability of an object of *mutating* its behavior in accordance with a specific usage *context*

- At run-time, objects of a *derived class* may be treated as objects of a *base class*
- **Base** classes may define and implement polymorphic (`virtual`) methods, and **derived** classes can `override` them, which means they provide their own implementations which are invoked at run-time depending on the context

Overloading is a form of static polymorphism (compile-time polymorphism)

In C++ the term *polymorphic* is strongly associated with dynamic polymorphism (overriding)

Polymorphism (the problem)

```
struct A {
    void f()  { std::cout << "A"; }
};

struct B : A { // B extends A (B does something more than A)
    void f() { std::cout << "B"; }
};

void g(A& a) { a.f(); } // accepts A and B

void h(B& b) { b.f(); } // accepts only B

int main() {
    A a; B b;
    g(a);    // print "A"
    g(b);    // print "A" not "B"!!!
//  h(a);    // compile error!!
    h(b);    // print "B"
}
```

Function Binding

Connecting the function call to the function body is called *Binding*

- In **Early Binding** or *Static Binding* or *Compile-time Binding*, the compiler identifies the type of object at compile-time
- In **Late Binding** or *Dynamic Binding* or *Run-time binding*, the compiler identifies the type of object at run-time and *then* matches the function call with the correct function definition

In C++ **late binding** can be can be achieved by declaring a `virtual` function

- *Early binding*: the program can jump directly to the function address
- *Late binding*: the program has to read the address held in the pointer and then jump to that address (less efficient since it involves an extra level of indirection)

Polymorphism (`virtual` method)

```
struct A {
    virtual void f() { std::cout << "A"; }
}; // now "f()" is virtual, evaluated at run-time

struct B : A { // B extends A (B does something more than A)
    void f() { std::cout << "B"; }
}; // now "B::f()" override "A::f()", evaluated at run-time

void g(A& a) { a.f(); } // accepts A and B

void h(B& b) { b.f(); } // accepts only B

int main() {
    A a; B b;
    g(a);     // print "A"
    g(b);     // NOW, print "B"!!!
    h(b);     // print "B"
}
```

When `virtual` works

```cpp
struct A {
    virtual void f() { std::cout << "A"; }
    virtual void g() {} // see next slide
};
struct B : A {
    void f() { std::cout << "B"; }
};
void g(A  a) { a.f();  }
void h(A& a) { a.f();  }
void p(A* a) { a->f(); }

int main() {
    A a; B b;
    a.f();        // print "A"
    b.f();        // print "B"
    A* ax1 = &b;  // memory address conversion
    ax1->f();     // print "B"
    g(b);         // print "A"
    h(b);         // print "B"
    p(&b);        // print "B"
}
```

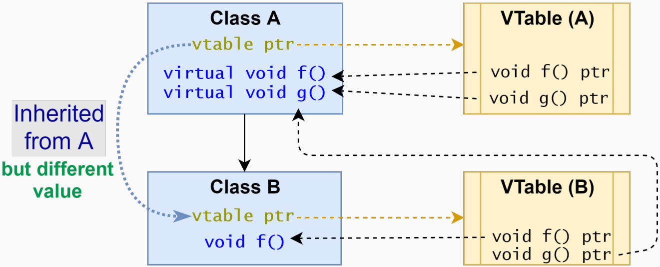
Virtual Table

vtable

The **virtual table** (`vtable`) is a lookup table of functions used to resolve function calls and support *dynamic dispatch* (late binding)

A virtual table contains one entry for each `virtual` function that can be called by objects of the class. Each entry in this table is simply a function pointer that points to the most-derived function accessible by that class

The compiler adds a *hidden* pointer to the base class which points to the virtual table for that class (`sizeof` considers the `vtable` pointer)



Virtual Method Notes

`virtual` classes allocate one extra pointer (hidden)

```
class A {
    double x;
    virtual void f1();
    virtual void f2();
}

class B : A {
    virtual void f1();
}

sizeof(A) = sizeof(double) + 1 * sizeof(pointer) // 16
sizeof(B) = sizeof(A)                            // 16
```

The `virtual` keyword is *not necessary* in derived classes, but it improves *readability* and clearly advertises the fact to the user that the function is `virtual`

C++11

`override` Keyword

The `override` keyword ensures that the function is `virtual` and is overriding a `virtual` function from a base class

It force the compiler to check the base class to see if there is a `virtual` function with this exact signature

- `override` implies `virtual` (`virtual` should be omitted)

```
struct A {
    virtual void f(int a);          // a "float" value is casted to "int"
};                                  // see*

struct B : A {
    void f(int a) override;         // ok
    void f(float a);                // (still) very dangerous!! see*
//  void f(float a) override;       // compile error!! not safe
//  void f(int a) const override; // compile error!! not safe
};
// *f(3.3f) has different behavior between A and B
```

`final` Keyword

C++11

`final` Keyword

The `final` keyword prevent inheriting from classes or prevent overriding methods in derived classes

```
struct A {
    virtual void f(int a) final;  // "final" method
};

struct B : A {
//  void f(int a);    // compile error!! f(int) is "final"
    void f(float a); // dangerous!! (still possible)
};                   // "override" prevents these errors

struct C final {    // cannot be extended
};
// struct D : C {  // compile error!! C is "final"
// };
```

Virtual Methods (Common Error 1)

All classes with at least one `virtual` method should declare a `virtual` *destructor*

```
struct A {
    ∼A() { std::cout << "A"; }   // <-- here the problem (not virtual)
    virtual void f(int a) {}
};
struct B : A {
    int* array;
    B() { array = new int[1000000]; }
    ∼B() {
        delete[] array;
        std::cout << "B";
    }
};
void g(A* a) {
    delete a;    // call ∼A()
}
int main() {
    B* b = new B;
    g(b);      // without virtual, ∼B() is not called
}              // g() prints only "A" -> huge memory leak!!
```

Virtual Methods (Common Error 2)

Don't call virtual methods in constructor and destructor

- *Constructor*: The derived class is not ready until constructor is completed
- *Destructor*: The derived class could be already destroyed

```cpp
struct A {
    A() { f(); }  // what instance is called? "B" is not ready
                  // it calls A::f(), even though A::f() is virtual
    virtual void f() { std::cout << "A"; }
};

struct B : A {
    B() : A() {}  // call A()     (A() call may be also implicit)

    void f() { std::cout << "B"; }
};

int main() {
    B b;      // call B()
}             // print "A", not "B"!!
```

Virtual Methods (Common Error 3)

Don't use default parameters in virtual methods

Default parameters are not inherited

```
struct A {
    virtual void f(int i = 5) { std::cout << "A::" << i << "\n"; }
    virtual void g(int i = 5) { std::cout << "A::" << i << "\n"; }
};
struct B : A {
    void f(int i = 3) { std::cout << "B::" << i << "\n"; }
    void g(int i)     { std::cout << "B::" << i << "\n"; }
};

int main() {
    A* a = new A();
    a->f();           // ok, print "A::5"
    B* b = new B();
    b->f();           // ok, print "B::3"
    A* zz = new B();
    zz->f();          // !!!, print "B::5"  // the virtual table of A
    A* ww = new B();                        // contains f(int i = 5) and
    ww->g();          // !!!, print "B::5"  // g(int i = 5) but it points
}                                           // to B implementations
```

Pure Virtual Method

Pure Virtual Method

A **pure virtual method** is a function that must be implemented in derived classes (concrete implementation)

Pure virtual functions can have or not have a body

```
struct A {
    virtual void f(int x) = 0; // pure virtual without body
    virtual void g(int x) = 0; // pure virtual with body
};

void A::g(int x) {} // pure virtual implementation (body) for g()

struct B : A {
    void f(int x) {}  // must be implemented
    void g(int x) {}  // must be implemented
};
```

Pure Virtual Method

If a virtual method is not implemented in derived class, it is implicitly declared pure virtual

```
struct A {
    virtual void f(int x) = 0;
};

struct B : A {
//  virtual void f(int x) = 0; // implicitly declared
};

struct C : B {
    void f(int x) override {}  // implemented
};

int main() {
   C c;
   c.f(3); // ok
}
```

Abstract Class and Interface

- A class is **abstract** if it has at least one *pure virtual* function
- A class is **interface** if it has only *pure virtual* functions and optionally (*suggested*) a virtual destructor. Interfaces don't have implementation or data

```
struct A {          // INTERFACE
    virtual ~A();   // to implement
    virtual void f(int x) = 0;
};

struct B {          // ABSTRACT CLASS
   B() {}           // abstract classes may have a contructor
   virtual void g(int x) = 0; // at least one pure virtual
protected:
   int x;           // additional data
};
```

Virtual Methods (Virtual Contructor)

Virtual Constructor is not supported in C++, but can be emulated by using other `virtual` methods

```
struct A {
   virtual ~A() { }              // A virtual destructor
   virtual A clone()  const = 0; // Uses the copy constructor
   virtual A create() const = 0; // Uses the default constructor
};

struct B : A {
    B clone() const {       // Covariant Return Types
        return B(*this);    // (different from A::clone())
    }

    B create() const {     // Covariant Return Types
        return B();        // (different from A::create())
    }
};

void f(A& a) {
    B b = a.clone();  // ok
}
```

Operator Overloading

Operator Overloading

Operator overloading is a specific case of polymorphism in which some operators are treated as polymorphic functions and have different behaviors depending on the type of its arguments

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

    Point operator+(const Point& p) const {
        return Point(x + p.x, y + p.x);
    }
};

int main() {
    Point a(1, 2);
    Point b(5, 3);
    Point c = a + b; // "c" is (6, 5)
}
```

Operator Overloading

Syntax: `operator@`

Categories not in bold are rarely used in practice

Arithmetic:	`+ - * \ % ++ --`
Comparison:	`== != < <= > >=`
Bitwise:	`| & ^ ~ << >>`
Logical:	`! && ||`
Compound assignment:	`+= <<= *=`, etc.
Subscript:	`[]`
Address-of, Reference, Dereferencing:	`& -> ->* *`
Memory:	`new new[] delete delete[]`
Comma:	`,`

Operators which cannot be overloaded: `? . .* :: sizeof typeof`

Notes

- Increment, Decrement: *Prefix* and *Postfix* notation

```
struct A {
    A& operator++() {  // prefix:  ++obj
        ...
        return *this;
    }
    A& operator++(const A& a); // postfix:  obj++
};
```

- Array subscript operator accepts anything (not only integer)

```
struct A {
    some_t&       operator[](char a);       // write
    const some_t& operator[](char a) const; // read
};
```

- Operators preserve precedence and short-circuit properties (e.g. ^)
- `operator<` is used in comparison procedures (`std::sort`)

Binary Operators

Binary Operators should be implemented as `friend` methods

```
class A {};

class B : public A {
    bool operator==(const A& a) { return true; }
};

class C : public A {
    friend bool operator==(const A& a, const A& b);
};
bool C::operator==(const A& a, const A& b); { return true; }

int main() {
    A a;  B b;  C c;
    b == a; // ok
//  a == b; // compile error!! // friend is useful to access
    c == a; // ok              // private fields
    a == c; // ok
}
```

Special Operators (iostream `operator<<`)

The **stream operations** can be overloaded to perform input and output for user-defined types

```cpp
#include <iostream>
struct Point {
    int x, y;

    // may be also directly defined inside Point
    friend std::ostream& operator<<(std::ostream& stream,
                                    const Point& point);
};

std::ostream& operator<<(std::ostream& stream,
                         const Point& point) {
    stream << "(" << point.x << "," << point.y << ")";
    return stream;
}

int main() {
    Point point { 1, 2 };
    std::cout << point;  // print "(1, 2)"
}
```

Special Operators (function call `operator()`)

The **function call operator** is generally overloaded to create objects which behave like functions, or for classes that have a primary operation

Many algorithms (included `std` library) accept objects of such types to customize behavior

```
#include <iostream>
#include <numeric>  // for std::accumulate
struct Multiply {
    int operator()(int a, int b) const {
        return a * b;
    }
};
int main() {
    int array[] = { 2, 3 ,4 };
    int mul = std::accumulate(arrray, array + 3, 0, Multiply());
    std::cout << mul;  // 24
}
```

Special Operators (conversion `operator type()`)

Conversion operators enable objects of a class to be either implicitly (coercion) or explicitly (casting) converted to another type

```
class MyBool {
    int a;
public:
    MyBool(int a1) : a(a1) {}

    operator bool()(const MyBool& b) const {
        return b.a == 0;    // implicit return type
    }
};

int main() {
    MyBool my_bool { 3 };
    bool b = my_bool;  // b = false, call operator bool()
}
```

Special Operators (conversion `operator type()` + `explicit`)

Conversion operators can be marked `explicit` to prevent implicit conversions:

```cpp
struct A {
    operator bool() { return true; }
};

struct B {
    explicit operator bool() { return true; }
};

int main() {
    A a;
    B b;
    bool c = a;
//  bool c = b;  // compile error!! explicit
    bool c = static_cast<bool>(b);
}
```

Special Operators (assignment `operator=`)

The **assignment operator** (`operator=`) is used to copy values from one object to another *already existing* object

```
#include <algorithm> //std::fill, std::copy
struct A {
    char* array;
    int   size;

    A(int size1, char value) : size(size1) {
        array = new char[size];
        std::fill(array, array + size, value);
    }
    ~A() { delete[] array; }

    A& operator=(const A& x) { .... } // see next slide
};

int main() {
     A obj(5, 'o');  // ["ooooo"]
     A a(3, 'b');    // ["bbb"]
     obj = a;        // obj = ["bbb"]
}
```

Special Operators (assignment `operator=`)

- First option:

```
A& operator=(const A& x) {
    if (this == &x)         // Check for self assignment
        return *this;
    delete[] array;         // delete everything from this
    array = new int[x.size];
    std::copy(x.array, x.array + size, array);  // copy
    return *this;
}
```

- Second option (less intuitive):

```
A& operator=(A x) {  // pass by value: need a copy constructor
    swap(this, x);   // now we need a swap function for A
    return *this;    //    see next slide
}                    // x is destroyed at the end
```

Special Operators (assignment `operator=`)

- Swap method:

```
friend void swap(A& x, A& y) {
    using std::swap;
    swap(x.size, y.size);
    swap(x.array, y.Array);
}
```

  - **why using `std::swap`?** if `swap(x, y)` finds a better match, it will use that instead of `std::swap`
  - **why `friend`?** it allows the function to be used from outside the structure/class scope

Full story: `stackoverflow.com/questions/5695548`

C++ Special Objects

Aggregate

An **aggregate** is a type which supports *aggregate initialization* (form of list-initialization) through curly braces syntax {}

An aggregate is an *array* or a *class* with

- No user-provided constructors (all)
- No private/protected non-static data members
- No base classes
- No virtual functions (standard functions allowed)

* No *brace-or-equal-initializers* for non-static data members (until C++14)

No restrictions:

- Non-static data member (can be also not aggregate)
- Static data members

Full story: `stackoverflow.com/questions/4178175`

```
struct NotAggregate1 {
    NotAggregate1();     // No constructors
    virtual void f();    // No virtual functions
};

class NotAggregate2 : NotAggregate1 { // No base class
    int x;              // x is private
};

struct Aggregate1 {
    int x;
    int y[3];
    int z { 3 };        // only C++14
};

struct Aggregate2 {
    Aggregate1() = default; // ok, defaulted constructor
    NotAggregate2 x;        // ok, public member
    Aggregate2& operator=(const& Aggregate2 obj); // ok
private:                                          // copy-assignment
    void f() {} // ok, private function (no data member)
};
```

Aggregate (examples) 3/3

```
struct Aggregate1 {
    int x;
    struct Aggregate2 {
        int a;
        int b[3];
    } y;
};

int main() {
    int array1[3] = { 1, 2, 3 };
    int array2[3]   { 1, 2, 3 };
    Aggregate1 agg1 = { 1, { 2, { 3, 4, 5} } };
    Aggregate1 agg2   { 1, { 2, { 3, 4, 5} } };
    Aggregate1 agg3 = { 1, 2, 3, 4, 5 };
}
```

A **Trivial Class** is a class *trivial copyable* (supports `memcpy`)

Trivial copyable:

- No user-provided copy/move/default *constructors* and *destructor*
- No user-provided copy/move *assignment* operators
- No virtual functions (standard functions allowed) or virtual base classes
- No *brace-or-equal-initializers* for non-static data members
- All non-static members are trivial (recursively for members)

No restrictions:

- Other user-declared constructors different from default
- Static data members
- Protected/Private members

Trivial Class (examples)


```
struct NonTrivial1 {
    int y { 3 };      // brace-or-equal-initializers

    NonTrivial1();    // user-provided constructor
    virtual void f(); // virtual function
};

struct Trivial1 {
    Trivial1() = default;    // defaulted constructor
    int x;
    void f();
private:
    int z; // ok, private
};

struct Trivial2 : Trivial1 { // base class is trivial
    int Trivial1[3];         // array of trivials is trivial
};
```

A **standard-layout class** is a class with the same memory layout of the equivalent C `struct` or `union` (useful for communicating with other languages)

Standard-layout class

- No virtual functions or virtual base classes
- Recursively on non-static members, base and derived classes
- Only one control access (public/protected/private) for non-static data members
- No base classes of the same type as the first non-static data member

(a) No non-static data members in the *most derived* class and *at most one base* class with non-static data members

(b) No base classes with non-static data members

```
struct StandardLayout1 {
    StandardLayout2(); // user-provided contructors
    int x;
    void f();          // non-virtual function
};

class StandardLayout2 : StandardLayout1 {
    int x, y;          // both are private
    StandardLayout1 y; // can have members of base type
                       // if they are not the first
};

struct StandardLayout3 { } //empty

struct StandardLayout4 : StandardLayout2, StandardLayout3 {
    // can use multiple inheritance as long only
    // one class in the hierarchy has non-static data members
};
```

Plain Old Data (POD)

C++11, C++14 Standard-Layout (s) + Trivial copyable (t)

- **(t)** No user-provided copy/move/default constructors and destructor
- **(t)** No user-provided copy/move assignment operators
- **(t)** No virtual functions or virtual base classes
- **(t)** No *brace-or-equal-initializers* for non-static data member
- **(s)** Recursively on non-static members, base and derived classes
- **(s)** Only one control access (public/protected/private) for non-static data members
- **(s)** No base classes of the same type as the first non-static data member
- **(s)a** No non-static data members in the *most derived* class and *at most one base* class with non-static data members
- **(s)b** No base classes with non-static data members

C++ std Utilities

C++11 provides three utilities to check if a type is POD, Trivial Copyable, Standard-Layout

- `std::is_pod` checks for POD
- `std::is_trivially_copyable` checks for trivial copyable
- `std::is_standard_layout` checks for standard-layout

```
#include <type_traits>
struct A {
    int x;
private:
    int y;
};
int main() {
    std::cout << std::is_trivial_copyable<A>::value; // true
    std::cout << std::is_standard_layout<A>::value;  // false
    std::cout << std::is_pod<A>::value;              // false
}
```

Special Objects Hierarchy