# Lecture 15-16: Classes in C++

## Subtype Polymorphism

Subtype relation is an “IS-A” relationship.

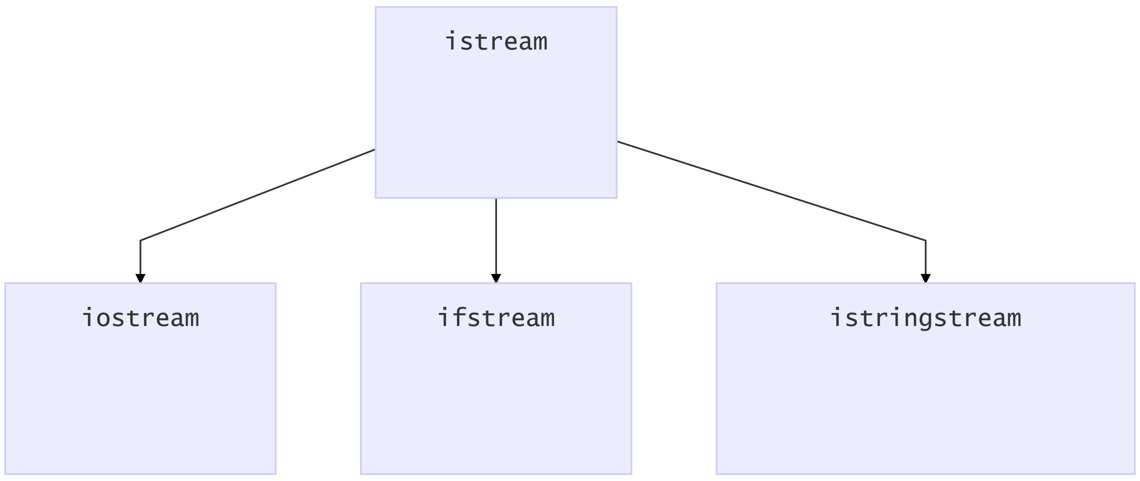
For examples, a Swan **is a** Bird, thus a class Swan is a subtype of class Bird. A bird can fly, can quake and can lay eggs. A swan can also do these. It might do these better, but as far as we are concerned, we don’t care. Bird is the super-type of the Swan.

### Liskov Substitution Principle

If $S$ is a subtype of $T$ or $T$ is a supertype of $S$, written $S <: T$, then for any instance where an object of type $T$ is expected, an object of type $S$ can be supplied without changing the correctness of the original computation.

- Functions written to operate on elements of the supertype can also operate on elements of the subtype.
- Benefits: code reuse.

An example would be the input streams of c++:



## Compare: Type Coercion

Consider the following examples.

- Example 1:

  Can we use an `ifstream` where an `istream` is expected? Is there ant type conversion happening in this piece of code?

```cpp
void add(istream &source) {
    double n1, n2;
    source >> n1 >> n2;
    cout << n1 + n2;
}

int main(){
    ifstream inFile;
    inFile.open("test.in")
    add(inFile);
    inFile.close();
}
```

- Example 2: Coercion.

  Can we use an `int` where a `double` is expected? Is there ant type conversion happening in this piece of code?

```cpp
void add(double n1, double n2) {
    cout << n1 + n2;
}

int main(){
    int n1 = 1;
    int n2 = 2;
    add(n1, n2);
}
```

## Creating Subtypes

In an Abstract Data Type, there are three ways to create a subtype from a supertype:

1. Add operations.
2. Strengthen the postconditions

- Postconditions include:
  - The EFFECTS clause
  - The return type

3. Weaken the preconditions

- Preconditions include:
  - The REQUIRES clause
  - The argument types

# Inheritance Mechanism

When a class (called derived, child class or subclass) inherits from another class (base, parent class, or superclass), the derived class is automatically populated with almost everything from the base class.

- This includes member variables, functions, types, and even static members.
- The only thing that does not come along is friendship-ness.
- We will specifically discuss the constructors and destructors later.

The basic syntax of inheritance is:

```cpp
class Derived : /* access */ Base1, Base2, ... {
private:
    /* Contents of class Derived */
public:
    /* Contents of class Derived */
};
```

## Access Specifier

There are a three choices of access specifiers, namely `private`, `public` and `protected`.

The accessibility of members are as follows:

| specifier | private | protected | public |
|---|---|---|---|
| **self** | Yes | Yes | Yes |
| **derived classes** | No | No | Yes |
| **outsiders** | No | No | Yes |

When declaring inheritance with access specifiers, the status of member in the derived classes are as follows:

| Inheritance \ Member | private | protected | public |
|---|---|---|---|
| **private** | inaccessible | private | private |
| **protected** | inaccessible | protected | protected |
| **public** | inaccessible | protected | public |

When you omit the access specifier, the access specifier is assumed to be `private`, and the inheritance is assumed to be `private` as well.

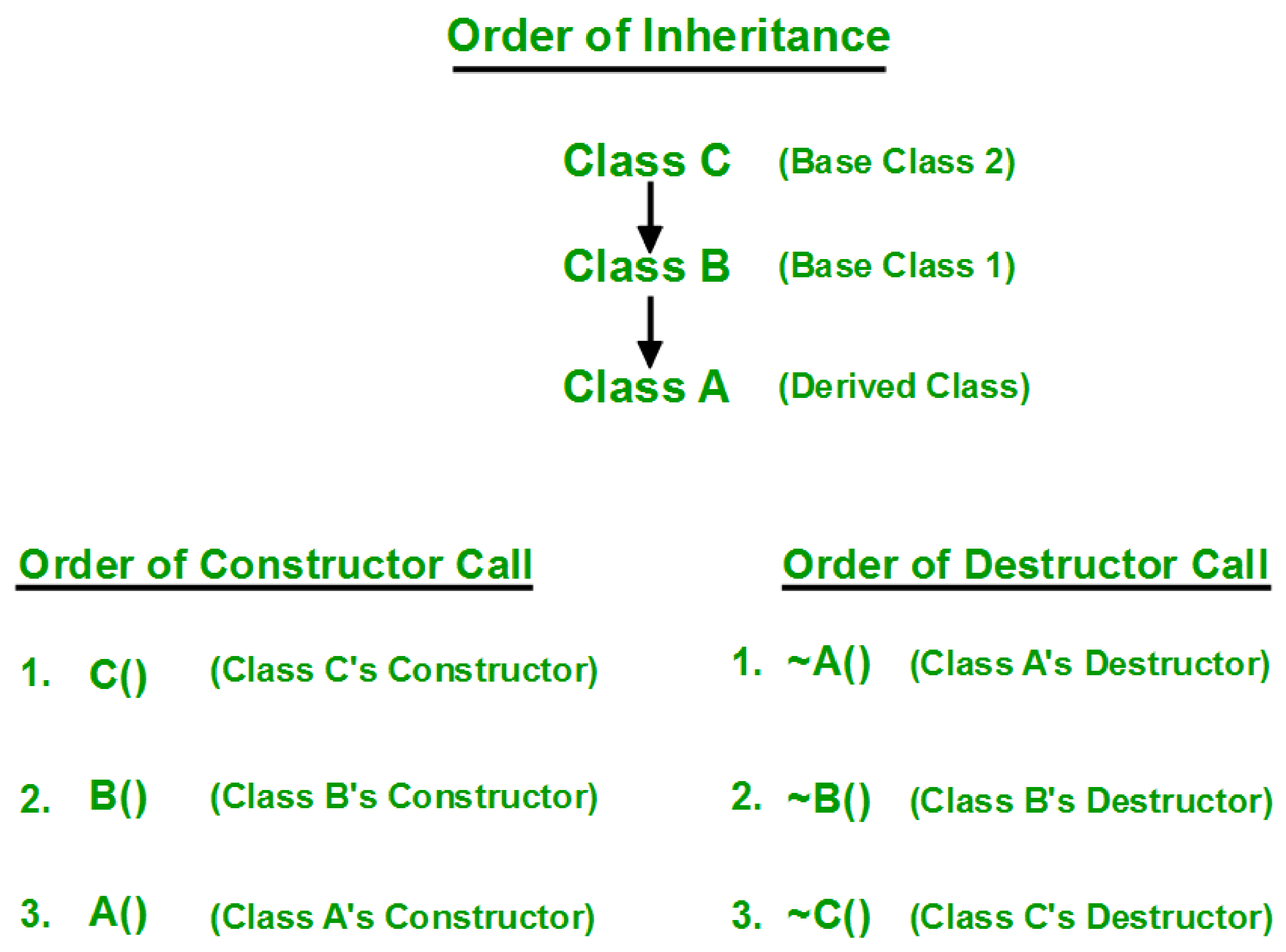
An example would be as follows. Which parts of the code does not compile? (Constructors and Destructors are omitted)

```cpp
class Base {

    friend void friendBase(Base* b);

/* A */
private:
    int priv;
    void privMethod(){
        priv = 0;
    }

/* B */
protected:
    int prot;
    void protMethod(){
        prot = 0;
    }

/* C */
public:
    int pub;
    void pubMethod(){
        pub = 0;
    }

};

class Derived : public Base {

    int derived;
    friend void friendDrived(Derived* d);

    /* D */
    void tryPrivDerived() {
        priv = 0;
        privMethod();
    }

    /* E */
    void tryProtDerived() {
        prot = 0;
        protMethod();
    }

    /* F */
    void tryPubDerived() {
        pub = 0;
        pubMethod();
    }

};

class PrivateDerived : Base {};
class Rederived : PrivateDerived {
    /* G */
    void tryPubRederived(){
        pub = 0;
        pubMethod();
    }
};

```

```cpp
/* H */
void tryPrivOutside() {
    Derived d;
    d.priv = 0;
    d.privMethod();
}

/* I */
void tryProtOutside() {
    Derived d;
    d.prot = 0;
    d.protMethod();
}

/* J */
void tryPubOutside() {
    Derived d;
    d.pub = 0;
    d.pubMethod();
}

friend void friendBase(Base* b){
    /* K */
    b->priv = 0;
    b->privMethod();
}

friend void friendDrived(Derived* d){
    /* L */
    d->derived = 0;
    d->tryPubDerived();

    /* M */
    d->priv = 0;
    d->privMethod();
}
```

## Constructors and Destructors in Inheritance

What would be the order of constructor and destructor call in a inheritance system? A short answer to remember would be:



Order of Constructor Call

1. C() (Class C's Constructor)
2. B() (Class B's Constructor)
3. A() (Class A's Constructor)

Order of Destructor Call

1. ~A() (Class A's Destructor)
2. ~B() (Class B's Destructor)
3. ~C() (Class C's Destructor)

Consider the following example:

```cpp
class Parent {
public:
    Parent() { cout << "Parent::Constructor\n"; }
    virtual ~Parent() { cout << "Parent::Destructor\n"; }
};

class Child : public Parent {
public:
    Child() : Parent() { cout << "Child::Constructor\n"; }
    ~Child() override { cout << "Child::Destructor\n"; }
};

class GrandChild : public Child {
public:
    GrandChild() : Child() { cout << "GrandChild::Constructor\n"; }
    ~GrandChild() override { cout << "GrandChild::Destructor\n"; }
};

int main() {
    GrandChild gc;
}
```

Here’s what actually happens when derived is instantiated:

1. Memory for derived is set aside
    - Enough for both the Base and Derived portions, in fact
2. The appropriate Derived constructor is called
3. **The Base object is constructed first using the appropriate Base constructor**. If no base constructor is specified, the default constructor will be used.
4. The initialization list initializes variables
5. **The body of the constructor executes**
6. Control is returned to the caller

Thus the output would be:

```
Parent::Constructor
Child::Constructor
GrandChild::Constructor
GrandChild::Destructor
Child::Destructor
Parent::Destructor
```

See also the default keyword for good clang-tidy coding style.

## Inheritance & Subtyping

Inheritance is neither a sufficient nor a necessary condition of subtyping relation. Yet, it is the only subtyping method supported by C++ (without a hack) in runtime.

We can create a subtype simply by repeating everything.

```cpp
class A {
public:
    void quak(){}
};

class B {
public:
    void quak(){}
    void nop(){}
};
```

Private inheritance prevents B from being a subtype of A.

```cpp
class A {
    int priv;
};

class B : A {};
```

Yet, we will **assume public inheritance** in the rest of discussion.

## Pointer and Reference in Inheritance

From the language perspective, C++ simply trusts the programmer that every subclass is indeed a subtype. We have the following rules.

- Derived class pointer compatible to base class.
- Derived class instance compatible to base class (possibly `const`) reference.
- You can assign a derived class object to a base class object.

The reverse is generally false. E.g. assigning a base class pointer to derived class pointers needs special casting.

An example for the third rule is as follows. What would be the output?

```cpp
class Base {
    string str;
public:
    Base() { cout << "base::default\n"; }
    Base(const Base& other) { cout << "base::copy\n"; }
};

class Derived1 : public Base {};

class Derived2 : public Base {
public:
    Derived2() = default;
    Derived2(const Derived2& d2) : Base(d2) { cout << "derived::copy\n"; }
};

int main() {
    cout << "Derived 1: \n";
    Derived1 d1;
    Derived1 d1c(d1);

    cout << "Derived 2: \n";
    Derived2 d2;
    Derived2 d2c(d2);
}
```

The output would be:

```
Derived 1:
base::default
base::copy
Derived 2:
base::default
base::copy
derived::copy
```

A synthesized copy constructor will do things almost identical to synthesized default constructor.

- Copy construct the base class. See `Derived1`.
- Copy construct every member, if there is any.
- Call the copy constructor of the class.

The case of `Derived2` shows how we do this manually.

Without default constructor (see `Derived3`), since you already provided a constructor, compiler won't synthesize default constructor for you.

```cpp
class Derived3 : public Base {
public:
    Derived3(const Derived3& d3) : Base(d3) { cout << "derived3::copy\n"; }
};

int main() {
    cout << "Derived 3: \n";
    Derived3 d3; // error
    Derived3 d3c(d3);
}
```

This code leads to a compile error.

Without copy constructing the base (see `Derived4`), the compiler will treat it as if the copy constructor is a usual constructor, defaulting constructing the base and all members.

```cpp
class Derived4 : public Base {
public:
    Derived4() = default;
    Derived4(const Derived4& d4) { cout << "derived4::copy\n"; }
};

int main() {
    cout << "Derived 4: \n";
    Derived4 d4;
    Derived4 d4c(d4);
}
```

The output would be:

```
Derived 4:
base::default
base::default
derived4::copy
```

## `friend` Keyword

We may want to access private member of class instances. You could provide an accessing operator for each of the member, but often it is not a good idea. One workaround is specifically grant access to the protected members. This can be done by using the `friend` keyword:

```cpp
class Bar {
    friend void foo (const MyClass &mc);
}
```

It doesn't matter where this is marked public or private.

`friend` can also grant access to classes:

```cpp
class Bar {
    friend class Baz;
}
```

Pay attention that friend is not mutual. If Class A declares Class B as friend. Class B can access Class A's private member, but the other way around doesn't work.

### ~~Inheritance and Memory Map~~

~~Skipped. SeeMemory Layout of C++ Object in Different Scenarios.~~

### ~~Multiple Inheritance & The Diamond Problem~~

~~Skipped. See Multiple Inheritance.~~

## Virtuousness and Polymorphism

### Problem: Static Binding

Consider the following example.

```cpp
class IntSet {
public:
    void insert(int i) { cout << "IntSet\n"; }
};

class SortedIntSet : public IntSet {
public:
    void insert(int i) { cout << "SortedIntSet\n"; }
};

void insert100(IntSet& set) { set.insert(100); }

int main() {
    SortedIntSet set;
    set.insert(10);
    insert100(set);
}
```

Now in `insert100()`, the method `insert()` is called on object set. set is an instance of `IntSet`. In this case, the compiler will choose the function `IntSet::Insert()`. Remember that the compiler have no idea what is actually referenced by set. When it compiles `insert100`, all it knows is that set refer to an object of `IntSet`. It doesn't care if this object is part of a larger object. In fact, up till this point, when you make a function call in the code, the actual function being called is always know at compile time. The process of binding a function call to the actual definition is static.

The output is thus

```
SortedIntSet
IntSet
```

Consider the apparent type and actual type:

- Apparent Type: Apparent type is the type annotated by the type system. It is the static type information. It is the you remarked to the compiler.
- Actual Type: It is the data type of the actual instance. It is the data type that describes what exactly is in the memory.

In our previous example, in function `insert100()`, the apparent type of the variable set is `IntSet`, while what's in the memory is actually a `SortedIntSet` (The actual type).

## Dynamic Polymorphism

### `virtual` keyword

What we want is dynamic function binding, the ability to bind a function call based on an object's actual type, instead of the apparent type. This is done through the virtual keyword. Using the previous example:

```cpp
class IntSet {
public:
    virtual void insert(int i) {
        //...
    }
};
```

The above syntax marks insert as a `virtual` function.

The syntax marks insert as a virtual function (method).

Virtual methods are methods replaceable by subclasses. When a method call is made, if the method you are calling is a virtual function (based on the apparent type), the language bind the call according to the actual type. In this way, the function `insert100` achieves dynamic polymorphism, the ability to change its behavior based on the actual type of the argument.

### `override` keyword

The act of replacing a function is called overriding a base class method. The syntax is as follows.

```cpp
void insert(int i) override {
    //...
}
```

`override` cause the compiler to verify if a function is indeed overriding a base class method. If the base class method is not a virtual function, compiler will complain. The keyword is introduced in C++11. It is considered a best practice always mark override whenever possible.

Now, consider the adapted previous example:

```cpp
class IntSet {
public:
    virtual void insert(int i) { cout << "IntSet\n"; }
};

class SortedIntSet : public IntSet {
public:
    virtual void insert(int i) override { cout << "SortedIntSet\n"; }
    // Note: It's good coding style to add `virtual` here.
};

void insert100(IntSet& set) { set.insert(100); }

int main() {
    SortedIntSet set;
    set.insert(10);
    insert100(set);
}
```

The output is now:

```
SortedIntSet
SortedIntSet
```

### ~~`final` keyword~~

~~Skipped. See final specifier (since C++11).~~

## ~~Virtual Table~~

~~Skipped.~~

~~Virtual function comes with cost in performance.~~

- ~~The cost of one extra layer of indirectness. There exists one more pointer dereference to find the target function. That's one more memory access.~~
- ~~Cost of unknown call target. Modern processors will "prefetch", or guess the future instructions and execute them in advance. Since the function call target is unknown, this will not be possible for virtual functions~~
- ~~Cost of unable to inline methods. For simple methods, compiler will try to inline them. Since the binding happens at runtime for virtual methods, this is no longer possible.~~

~~Using the `final` keyword will help. If the compiler is able to determine the actual type, it may choose to preform de-virtualization. Those costs could be quite huge if the method is used frequently. In old time the cost is often not durable. Modern computers are more powerful, things get better.~~

## ~~Casting: `dynamic_cast` & `const_cast`~~

~~Skipped.~~

~~See Type erasure for the boarder idea.~~

~~See dynamic_cast and const_cast for usage.~~

# Interfaces and Invariant

## Classes as Interfaces

Recall the two main advantages of an ADT:

1. Information hiding: we don't need to know the details of how the object is represented, nor do we need to know how the operations on those objects are implemented.
2. Encapsulation: the objects and their operations are defined in the same place; the ADT combines both data and operation in one entity.

To the caller, an ADT is only an interface, which is the contract for using things of this type.

The class mechanism failed to be a perfect interface. It mixes details of the implementation with the definition of the interface.

The method implementations can be written separately from the class definition and are usually in two separate files. Unfortunately, the data members still must be part of the class definition. Since any programmer using your class see that definition, those programmers know something about the implementation.

What we prefer is to create an "interface-only" class as a base class, from which an implementation can be derived. Such a base class is called an *Abstract Base Class*, or sometimes a *Virtual Base Class*.

- Note: classes must contain their data members, so this class cannot have an real implementation.

## Pure Virtual

It is possible that we do not supply a implementation when defining a base class. ~~In this case, the corresponding entry in the VTable would simply be left unfilled:~~

```
/* IntSet */ virtual void insert(int i) = 0;
```

In this case we say the method is pure virtual.

If a class contains one or more pure virtual methods, we say the class is a pure virtual class. You only need to have one pure virtual function for a class to be “purely virtual”. Pure virtual class are also called abstract base classes, or interfaces. It is often that the name abstract base classes starts with a case letter `I` for interface.

Note that **you can’t instantiate a pure virtual class.** This is one way to prevent users from instantiate your class (The other way is to make the constructor protected). However, you can always define references and pointers to an abstract class.

*Abstract Base Classes* are often used to model abstract concepts. E.g. we would like to say things like Matrices are subclass of summable object. We would like to increase code reuse. Consider the following class:

```cpp
class ISummable {
public:
    /* Add item x to itself */
    virtual void add(ISummable& x) = 0;
};
```

This class models the objects that are summable. Based on this modeling, we could write the following very general function:

```cpp
void sum(ISummable elem[],size_t size, ISummable& rst) {
    for (int i = 0; i < size; ++i)
        rst.add(elem[i]);
}
```

This will work for anything that is Summable object. When a class derives from an interface and provides an implementation, we say it implements the interface.

## Summary

Here is an comprehensive exercise. What would be the output?

```cpp
struct Foo {
    void f() { cout << "a"; };
    virtual void g() = 0;
    virtual void c() const = 0;
};

struct Bar : public Foo {
    void f() { cout << "b"; };
    void g() { cout << "c"; };
    void c() const { cout << "d"; };
    void h() { cout << "e"; };
};

struct Baz : public Bar {
    void f() { cout << "f"; };
    void g() { cout << "g"; };
    void c() { cout << "h"; };
    virtual void h() { cout << "i"; };
};

struct Qux : public Baz {
    void f() { cout << "j"; };
    void h() { cout << "k"; };
};

int main() {
    Bar bar; bar.g();
    Qux qux; qux.g();
    Baz baz; baz.h();
    Foo& f1 = qux; f1.f(); f1.g();
    Bar& b1 = qux; b1.h();
    Baz& b2 = qux; b2.h();
    Bar* b3 = &qux; b3->h();
    Baz* b4 = &qux; b4->h();
    const Foo& f2 = *b3; f2.c();
    Baz& b5 = *b4; b5.c();
}
```

Answer would be `cgiagekekdh`.

## Invariant

An invariant is a set of conditions that must always evaluate to true at certain well-defined points; otherwise, the program is incorrect. For ADT, there is so called representation invariant.

It describes the conditions that must hold on those members for the representation to correctly implement the abstraction. It must hold immediately before exiting each method of that implementation, including the constructor. Each method in the class can assume that the invariant is true on entry if the following 2 conditions hold:

- The representation invariant holds immediately before exiting each method (including the constructor);
- Each data element is truly private.

Writing some private `bool checker()` functions for *defensive programming* to check whether all invariants are true (before exiting, or after entering, each method):

Next, add assertions like `assert(checker());` right before returning from any function that modifies any of the representation.