



## Outline

- 1 Polymorphism and inheritance
  - Concrete and abstract types
  - Virtual functions
  - Constructors and destructors
  - Accessibility
  - Inheritance without polymorphism
  - Pitfalls
- 2 Multiple inheritance
- 3 More about polymorphic types

## Polymorphism and dynamic binding

### Polymorphism

Overloading	<i>Static binding</i>
Generic programming (templates)	<i>Static binding</i>
Virtual functions	<i>Dynamic binding</i>

*Static binding:* The meaning of a construct is decided *at compile-time*

*Dynamic binding:* The meaning of a construct is decided *at run-time*

## Polymorphism

### Static

```
void foo(int);
void foo(double);

int x;
foo(x);

std::vector<int> v;
std::sort(begin(v), end(v));
```

### Dynamic

```
struct Animal{
    virtual void speak();
};

struct Dog :public Animal{
    void speak();
};

struct Cat :public Animal{
    void speak();
};

void use(Animal& a)
{
    a.speak();
}
```

## Concrete and abstract types

A *concrete type* behaves “just like built-in-types”:

- ▶ The *representation* is part of the *definition*<sup>1</sup>
- ▶ Can be placed on the stack, and in other objects
- ▶ can be directly referred to
- ▶ Can be copied
- ▶ User code *must be recompiled* if the type is changed

An *Abstract types* isolates the user from implementation details

- ▶ Decouples the interface from the representation:
- ▶ The representation of objects (*incl. the size!*) is not known
- ▶ Can only be accessed through pointers or references
- ▶ Cannot be instantiated (*only concrete subclasses*)
- ▶ Code using the abstract type *does not need to be recompiled* if the concrete subclasses are changed

<sup>1</sup>can be private, but is known

## Concrete and abstract types

A concrete type: Vector

```
class Vector {
public:
    Vector(int l = 0) :p(new int[l]),sz{l} {}
    ~Vector() {delete[] elem;}
    int size() const {return sz;}
    int& operator[](int i) {return elem[i];}
private:
    int *elem;
    int sz;
};
```

### Generalize: *extract interface*

```
class Container {
public:
    int size() const;
    int& operator[](int o);
};
```

## Concrete and abstract types

### Generalization: an abstract type, Container

```
class Container {
public:
    virtual int size() const =0;           ▶ pure virtual function
    virtual int& operator[](int o) =0;    ▶ Abstract class
    virtual ~Container() {}              ▶ or interface in Java
};

class Vector :public Container {
public:
    Vector(int l = 0) :p{new int[l]},sz{l} {}
    ~Vector() {delete[] elem;}
    int size() const override {return sz;}
    int& operator[](int i) override {return elem[i];}
private:
    int *elem;
    int sz;
};
```

- ▶ extends (or implements) Container in Java
- ▶ **override** ⇔ @Override in Java (C++11)
- ▶ A polymorph type needs a virtual destructor

## Concrete and abstract types

### Use of an abstract class

```
void fill(Container& c, int v)
{
    for(int i=0; i!=c.size(); ++i){
        c[i] = v;
    }
}

void print(Container& c)
{
    for(int i=0; i!=c.size(); ++i){
        cout << c[i] << " ";
    }
    cout << endl;
}

void test_container()
{
    Vector v(10);

    print(v);
    fill(v,3);
    print(v);
}
```

## Concrete and abstract types

### Use of an abstract class

Assume that we have two other subclasses to Container

```
class MyArray : public Container { ...};
class List : public Container { ...};
```

```
void test_container()
{
    Vector v(10);
    print(v);
    fill(v,7);
    print(v);

    MyArray a(5);
    fill(a,0);
    print(a);

    List l{1,2,3,4,5,6,7};
    print(l);
}
```

- ▶ Dynamic binding of Container::size() and Container::operator[]()

## Concrete and abstract types

### Variant, without changing Vector

Instead of changing Vector we can use it in a new class:

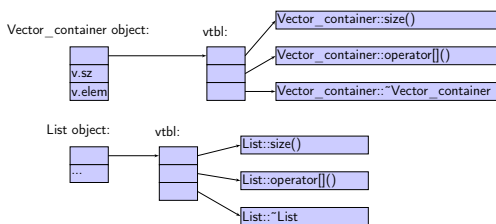
```
class Vector_container :public Container {
public:
    Vector_container(int l = 0) :v{l} {}
    ~Vector_container() =default;
    int size() const override {return v.size();}
    int& operator[](int i) override {return v[i];}
private:
    Vector v;
};
```

- ▶ Vector is a concrete class
- ▶ Note that v is a Vector object, not a reference
  - ▶ Different from Java
- ▶ The destructor of a member variable (here, v) is implicitly called by the default destructor

## Dynamic binding

- ▶ virtual function table (vtbl)
  - ▶ contains pointers to the virtual functions of the object
  - ▶ each class with virtual member function(s) has a vtbl
  - ▶ each object of such a class has a pointer to the vtbl of the class
  - ▶ calling a virtual function (typically) < 25% more expensive

```
int example(Container& c)
{
    return c.size();
}
```



## Constructors and inheritance

### Rules for the base class constructor

- ▶ The default constructor of the base class is implicitly called
  - ▶ if it exists!
- ▶ Arguments to the base class constructor
  - ▶ are given in the member initializer list in the derived class constructor.
  - ▶ the name of the base class must be used. (super() like in Java does not exist due to multiple inheritance.)

## Constructors and inheritance

### Order of initialization in a constructor (for a derived class)

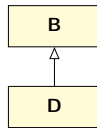
- 1 *The base class is initialized:* The base class ctor is called
- 2 *The derived class is initialized:* Data members (in the derived class) is initialized
- 3 The constructor body of the derived class is executed

Explicit call of base class constructor in the member initializer list

```
D::D(param...) :B(param...), ... {...}
```

Note:

- ▶ Constructors are not inherited
- ▶ *Do not call virtual functions in a constructor:*  
In the base class B, **this** is of type B\*.



## Constructors and inheritance

### Constructors are not inherited

```
class Base{
public:
    Base(int i) :x{i} {}
    virtual void print() {cout << "Base: " << x << endl;}
private:
    int x;
};

class Derived :public Base {
};

void test_ctors()
{
    Derived b(5); //no matching function for call to
                //Derived::Derived(int)
    Derived b2; //use of deleted function Derived::Derived()
}
```

## Constructors and inheritance

### using: make the base class constructor visible (C++11)

```
class Base{
public:
    Base(int i) :x{i} {}
    virtual void print() {cout << "Base: " << x << endl;}
private:
    int x;
};

class Derived :public Base {
    using Base::Base;
};

void test_ctors()
{
    Derived b(5); // OK!
    Derived b2; //use of deleted function Derived::Derived()
    b.print();
}
```

## Constructors and inheritance

### Now with a default constructor

```
class Base{
public:
    Base(int i=0) :x{i} {}
    virtual void print() {cout << "Base: " << x << endl;}
private:
    int x;
};

class Derived :public Base {
    using Base::Base;
};

void test_ctors()
{
    Derived b; // OK!
    b.print();
    Derived b2(5); // OK!
    b2.print();
}
```

## Inherited constructors rules

- ▶ **using** makes all base class constructors inherited, except
  - ▶ those hidden by the derived class (with the same parameters)
  - ▶ default, copy, and move constructors  
⇒ *if not defined, synthesized as usual*
- ▶ default arguments in the super class gives multiple inherited constructors

## Copying and inheritance

- ▶ The copy constructor shall copy *the entire object*
  - ▶ typically: call the base class copy-constructor
- ▶ The same applies to **operator=**
- ▶ Different from the destructor
  - ▶ A destructor shall only deallocate what has been allocated in the class itself. The base class destructor is implicitly called.
- ▶ The synthesized special member functions are *deleted in a derived class* if the corresponding function is *deleted in the base class*. (i.e., **private** or **=delete**)
  - ▶ default constructor,
  - ▶ copy constructor,
  - ▶ copy assignment operator
  - ▶ (destructor, but avoid classes without a destructor)
- ▶ Base classes should define these **=default**

## Destructors and inheritance

Destruction is done in reverse order:

### Execution order in a destructor

- 1 The function body of the derived class destructor is executed
- 2 The members of the derived class are destroyed
- 3 The base class destructor is called

*The base class destructor must be virtual*

## Accessibility

### The different levels of accessibility

```
class C {
public:
    // Members accessible from any function
protected:
    // Members accessible from member functions
    // in the class or a derived class
private:
    // Members accessible only from member functions
    // in the class
};
```

## Accessibility

### Accessibility and inheritance

```
class D1 : public B { // Public inheritance
    // ...
};

class D2 : protected B { // Protected inheritance
    // ...
};

class D3 : private B { // Private inheritance
    // ...
};
```

## Accessibility

### Accessibility and inheritance

	Accessibility in B	Accessibility through D
Public inheritance	public protected private	public protected private
Protected inheritance	public protected private	protected protected private
Private inheritance	public protected private	private private private

The accessibility inside D is *not* affected by the type of inheritance

## Function overloading and inheritance

### Function overloading does not work as usual between levels in a class hierarchy

```
class C1 {
public:
    void f(int) {cout << "C1::f(int)\n";}
};

class C2 : public C1 {
public:
    void f(); {cout << "C2::f(void)\n";}
};

C1 a;
C2 b;
a.f(5); // Ok, calls C1::f(int)
b.f(); // Ok, calls C2::f(void)
b.f(2) // Error! C1::f is hidden!
b.C1::f(10); // Ok
```

## Function overloading and inheritance

Make base class names visible with `using`

### Function overloading between levels of a class hierarchy

```
class C1 {
public:
    void f(int); {cout << "C1::f(int)\n";}
};

class C2 : public C1 {
public:
    using C1::f;
    void f(); {cout << "C2::f(void)\n";}
};

// ...
C1 a;
C2 b;
a.f(5); // Ok, calls C1::f(int)
b.f(); // Ok, calls C2::f(void)
b.f(2) // Ok, calls C1::f(int)
```

## Inheritance and scope

- ▶ The *scope* of a derived class is *nested* inside the base class
  - ▶ Names in the base class are visible in derived classes
    - ▶ *if not hidden* by the same name in the derived class
- ▶ Use the *scope operator* `::` to access hidden names
- ▶ Name lookup happens at compile-time
  - ▶ *static type* of a pointer or reference determines which names are visible (like in Java)
  - ▶ Virtual functions must have the same parameter types in derived classes.
  - ▶ Use **override** to get help from the compiler with finding mistakes.

## Inheritance without virtual functions

In C++ member functions are *not virtual unless declared so*. (Difference from Java)

- ▶ It is possible to inherit from a class and *hide* functions.
- ▶ Base class functions can be called explicitly
- ▶ can be used to "extend" a function. (Add things before and after the function.)

## Inheritance without virtual functions Example

```
struct Clock{
    Clock(int h, int m, int s) :seconds{60*(60*h+m) + s} {}
    Clock& tick(); // NB! Not virtual
    int get_ticks() {return seconds;}
private:
    int seconds;
};
struct AlarmClock : public Clock {
    using Clock::Clock;
    void setAlarm(int h, int m, int s);
    AlarmClock& tick(); // hides Clock::tick()
    void soundAlarm();
private:
    int alarmTime;
};
AlarmClock& AlarmClock::tick()
{
    Clock::tick(); // explicit call of base class function
    if(get_ticks() == alarmTime) soundAlarm();
    return *this;
}
```

## Pitfalls

- ▶ Type conversion
- ▶ Copying objects of polymorph types

## Type conversion and run-time type info

- ▶ Be careful with type casts
  - ▶ In particular (Derived\*) base\_class\_pointer
  - ▶ and `static_cast<Derived*>(base_class_pointer)`
  - ▶ No safety net, no `ClassCastException`
- ▶ Use `dynamic_cast` (returns nullptr or throws if not OK)

```
Vector v;
Container* c = &v;
if(dynamic_cast<Vector*>(c)) {
    cout << " *c instanceof Vector\n";
}
```
- ▶ `typeid` corresponds to `.getClass()` comparison in Java

```
if(typeid(*c) == typeid(Vector)) {
    cout << " *c is a Vector\n";
}
```

## Object slicing Example

```
class Point {...};
class Point3d : public Point {...};
```

```
Point3d b;
Point a = b;
```

Not dangerous, but a only contains the Point part of b

```
Point3d b1;
Point3d b2;
```

```
Point& point_ref = b2;
point_ref = b1;
```

Wrong! b2 now contains the Point part of b1 and the Point3d part of its old value.

## Object slicing

### Example

```

struct Point{
    Point(int xi, int yi) :x{xi}, y{yi} {}
    virtual void print() const; // prints Point(x,y)
    int x;
    int y;
};

struct Point3d :public Point{
    Point3d(int xi, int yi, int zi) :Point(xi,yi), z{zi} {}
    virtual void print() const; // prints Point3d(x,y,z)
    int z;
};

void test_slicing() {
    Point3d q1{1,2,3};
    Point3d q2{3,4,5};

    q2.print();           Point3d(3,4,5)
    Point& pr = q2;
    pr = q1;
    q2.print();           Point3d(1,2,5)
}
    
```

solution: virtual operator=

## Object slicing

### Solution with virtual operator=

```

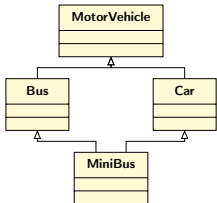
struct Point {
    ...
    virtual Point& operator=(const Point& p) =default;
};

struct Point3d :public Point{
    ...
    virtual Point3d& operator=(const Point& p);
};

Point3d& Point3d::operator=(const Point& p)
{
    Point::operator=(p);
    auto p3d = dynamic_cast<const Point3d*>(&p);
    if(p3d){
        z = p3d->z;
    } else {
        z = 0;
    }
    return *this;
}
    
```

## Multiple inheritance

- ▶ A class can inherit from multiple base classes
- ▶ cf. implementing multiple interfaces in Java
  - ▶ Like in Java if at most one of the base classes have member variables
  - ▶ Can be tricky otherwise
- ▶ *The diamond problem*
  - ▶ How many MotorVehicle are there in a MiniBus?

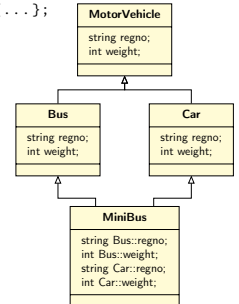


## Multiple inheritance

### How many MotorVehicle are there in a MiniBus?

```

class MotorVehicle {...};
class Bus : public MotorVehicle {...};
class Car : public MotorVehicle {...};
class MiniBus : public Bus, public Car {...};
    
```



## Multiple inheritance

### The diamond problem

- ▶ A common base class is included multiple times
  - ▶ Multiple copies of member variables
  - ▶ Members must be accessed as Base::name to avoid ambiguity
- ▶ if *virtual inheritance* is not used

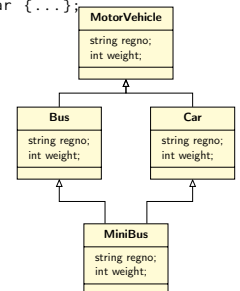
## Multiple inheritance

### Virtual inheritance

*Virtual inheritance* : Derived classes share the base class instance. (The base class is only included once)

```

class MotorVehicle {...};
class Bus : public virtual MotorVehicle {...};
class Car : public virtual MotorVehicle {...};
class MiniBus : public Bus, public Car {...};
    
```



## Example: A class hierarchy

```
class Animal{
public:
    void speak() const { cout << get_sound() << endl;}
    virtual string get_sound() const =0;
    virtual ~Animal() =default;
};

class Dog :public Animal{
public:
    string get_sound() const override {return "Woof!";}
};
class Cat :public Animal{
public:
    string get_sound() const override {return "Meow!";}
};
class Bird :public Animal{
public:
    string get_sound() const override {return "Tweet!";}
};
class Cow :public Animal{
public:
    string get_sound() const override {return "Moo!";}
};
```

## Example Use (not polymorphic)

```
int main()
{
    Dog d;
    Cat c;
    Bird b;
    Cow w;

    d.speak();    Woof!
    c.speak();    Meow!
    b.speak();    Tweet!
    w.speak();    Moo!
}
```

## Example Call by reference

```
void test_polymorph(const Animal& a)
{
    a.speak();
}

int main()
{
    Dog d;
    Cat c;
    Bird b;
    Cow w;

    test_polymorph(d);    Woof!
    test_polymorph(c);    Meow!
    test_polymorph(b);    Tweet!
    test_polymorph(w);    Moo!
}
```

## Example Container with polymorph objects

```
int main()
{
    Dog d;
    Cat c;
    Bird b;
    Cow w;

    vector<Animal> zoo{d,c,b,w};

    for(auto x : zoo){
        x.speak();
    }

    error: cannot allocate an object of abstract type 'Animal'
```

## Example Must use container of pointers

```
int main()
{
    Dog d;
    Cat c;
    Bird b;
    Cow w;

    vector<Animal*> zoo{&d,&c,&b,&w};

    for(auto x : zoo){
        x->speak();    Woof!
    };                Meow!
                    Tweet!
                    Moo!
}
```

## Example A class hierarchy

```
struct Foo{
    virtual void print() const {cout << "Foo" << endl;}
};

struct Bar :Foo{
    void print() const override {cout << "Bar" << endl;}
};

struct Qux :Bar{
    void print() const override {cout << "Qux" << endl;}
};
```

## Polymorph class example, *object slicing*

What is printed?

```
void print1(const Foo* f)
{
    f->print();
}
void print2(const Foo& f)
{
    f.print();
}
void print3(Foo f)
{
    f.print();
}

void test()
{
    Foo* a = new Bar;
    Bar& b = *new Qux;
    Bar c = *new Qux;

    print1(a); Bar
    print1(&b); Qux
    print1(&c); Bar
    std::cout << std::endl;
    print2(*a); Bar
    print2(b); Qux
    print2(c); Bar
    std::cout << std::endl;
    print3(*a); Foo
    print3(b); Foo
    print3(c); Foo
}
```

## Next lecture Generic programming

References to sections in Lippman

[Function templates](#) 16.1.1

[Class templates](#) 16.1.2

[Template arguments and deduction](#) 16.2–16.2.2

[Trailing return type](#) 16.2.3

[Templates and overloading](#) 16.3

## Suggested reading

References to sections in Lippman

[Dynamic polymorphism and inheritance](#) chapter 15 – 15.4

[Accessibility and scope](#) 15.5 – 15.6

[Type conversions and polymorphism](#) 15.2.3

[Inheritance and resource management](#) 15.7

[Polymorph types and containers](#) 15.8

[Multiple inheritance](#) 18.3

[Virtual base classes](#) 18.3.4 – 18.3.5