EDAF50 – C++ Programming

8. Classes and polymorphism.

Sven Gestegård Robertz
Computer Science, LTH

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Outline

Polymorphism and dynamic binding

Polymorphism

Overloading	*Static binding*
Generic programming (templates)	*Static binding*
Virtual functions	*Dynamic binding*

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

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

Concrete and abstract types

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

- The *representation* is part of the *definition* [1]
- Can be placed on the stack, and in other objects
- can be directly refererred to
- Can be copied
- User code *must be recompiled* if the type is changed

An *Abstract type* *decouples the interface from the representation*:

- isolates the user from implementation details
- 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

[1] can be private, but is known

Concrete and abstract types
A concrete type: Vector

```
class Vector {
public:
    Vector(int l = 0) :elem{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:
    virtual int size() const;
    virtual int& operator[](int o);
};
```

Concrete and abstract types
Generalization: an abstract type, Container

```
class Container {
public:
    virtual int size() const  =0;
    virtual int& operator[](int o) =0;
    virtual ~Container() =default;
    // copy and move...
};
```

- *pure virtual* function
- Abstract class
- 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

Destructors must be `virtual`

Polymorph types are used through base class pointers:

```
Container* c = new Vector(10);

// use...

delete c;
```

- The destructor is called through a `Container*`.
- `~Container()` is called.
- If not virtual, `~Vector()` is never called $\Rightarrow$ memory leak.

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

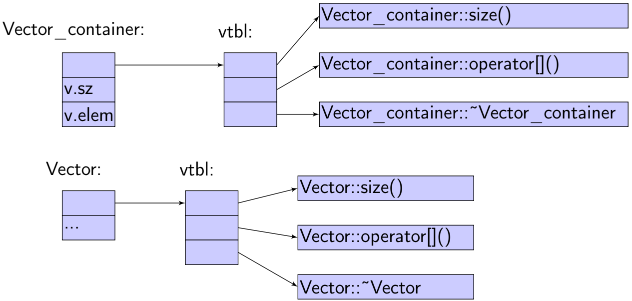
Instead of changing `Vector` we can use it in a new class:

```
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
Typical implementation

- virtual functions need run-time type info
- 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



Class templates
The Container classes

```
class Container {
public:
    virtual int size() const  =0;
    virtual int& operator[](int o) =0;
    virtual ~Container() =default;
    virtual void print() const =0;
};

class Vector :public Container {
public:
    explicit Vector(int l);
    ~Vector();
    int size() const override;
    int& operator[](int i) override;
    virtual void print() const override;
private:
    int *p;
    int sz;
};
```

- generalize on element type

Class templates
Generic Container and Vector

```
template <typename T>
class Container {
public:
    using value_type = T;
    virtual size_t size() const =0;
    virtual T& operator[](size_t o) =0;
    virtual ~Container() =default;
    virtual void print() const =0;
};

template <typename T>
class Vector :public Container<T> {
public:
    Vector(size_t l = 0) :p{new T[l]},sz{l} {}
    ~Vector() {delete[] p;}
    size_t size() const override {return sz;}
    T& operator[](size_t i) override {return p[i];}
    virtual void print() const override;
private:
    T *p;
    size_t sz;
};
```

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)

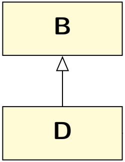
1. *The base class is initialized*: The base class ctor is called
2. *The derived class is initialized*: Data members (in the derived class) is initialized
3. The constructor body of the derived class is executed

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 b1;     // use of deleted function
                  // Derived::Derived()
  Derived d2(5); // no matching function for call to
                  // Derived::Derived(int)
}
```

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 {
    Derived(int i) :Base(i) {}
};

void test_ctors()
{
  Derived b1;     // use of deleted function
                  // Derived::Derived()
  Derived d2(5); // OK

}
```

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 d1;     //use of deleted function
                  //Derived::Derived()
  Derived d2(5); // OK!
  d2.print();
}
```

Constructors vid 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!
  d.print();
  Derived d2(5); // OK!
  d2.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
    $\Rightarrow$ *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 destructior is implicitly called.
- The synthesized default constructor or the copy control members 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 (typically) 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.

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 funcions 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;
}
```

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!
```

Pitfalls

- Type conversion
- Copying objects of polymorph types

Type conversion

- Be careful with type casts
  - In particular `(Derived*) base_class_pointer`
  - No safety net, no `ClassCastException`
- Use **`dynamic_cast`** (returns `nullptr` or throws if not OK)

```
void example(Container* c)
{
        if(dynamic_cast<Vector*>(c)) {
            cout << " *c instanceof Vector\n";
        }
```

- **`typeid`** corresponds to `.getClass()` 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;
};
Point& assign(Point& l, const Point& r) {
  return l = r;
}
void test_slicing() {
    Point3d q1{1,2,3};
    Point3d q2{3,4,5};

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

solution: virtual operator=

Object slicing
Solution with virtual operator=

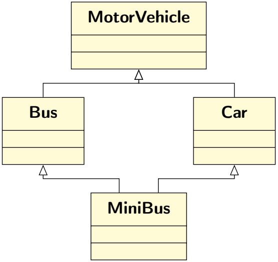
```
struct Point {
  ...
  virtual Point& operator=(const Point& p) =default;
};

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

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

Multiple inheritance

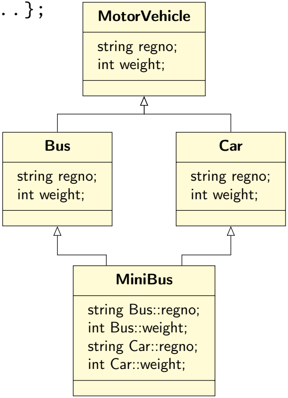
- A class can inherit from multiple base classes
- cf. implementing multiple `interfaces` in Java
  - Like in Java if at most one of the base classes have member variables
  - Can be tricky otherwise
- *The diamond problem*
  - How many `MotorVehicle` are there in a `MiniBus`?



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 {...};
```

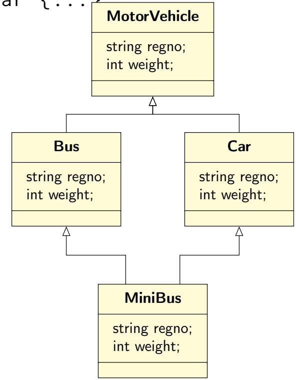


Multiple inheritance
The diamond problem

- 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

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 {...};
```



The *most derived class* (`Minibus`) must call *the constructor of the grandparent* (`MotorVehicle`).

Next lecture

Standard library containers. More about inheritance.

References to sections in Lippman

Sequential containers 9.1 – 9.3

Container Adapters 9.6

Associative containers chapter 11

Tuples 17.1

Swap 13.3

Moving objects 13.6

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