

Virtual Classes & Polymorphism

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Example (revisited)

- We want to implement a graphics system
- We plan to have lists of shape. Each shape should be able to draw itself, compute its size, etc.

Class Hierarchy

```
class Shape { public:  
    void draw() const {cout<<'h';}  
    double area() const;  
    void drawTwice() const {draw(); draw();}  
};
```

```
class Square: public Shape { public:  
    void draw() const {cout<<'q';}  
    double area() const;  
};
```

```
class Circle: public Shape { public:  
    void draw() const {cout<<'c';}  
    double area() const;  
};
```

Class Hierarchy

Now if we write

```
Shape myShapes[2];  
myShapes[0] = Circle();  
myShapes[1] = Square();  
for (...) myShapes[i].draw();
```

What will happen?

Class Hierarchy

Now if we write

```
Shape myShapes[2];  
myShapes[0] = Circle();  
myShapes[1] = Square();
```

What will happen?

-- The Circle and Square will be constructed and then sliced to fit inside the Shape objects.

“myShapes[0] = Circle()” copies from the circle, its hidden “Shape” field.

Class Hierarchy

Now if we write (like in Java):

```
Shape* myShapes[2];  
myShapes[0] = new Circle();  
myShapes[1] = new Square();
```

What will happen when we call

```
myShapes[0]->draw(); ?
```

Class Hierarchy

Now if we write (like in Java):

```
Shape* myShapes[2];  
myShapes[0] = new Circle();  
myShapes[1] = new Square();
```

What will happen when we call
`myShapes[0]->draw();` ?

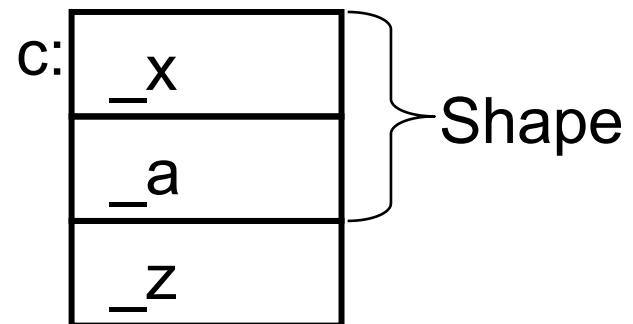
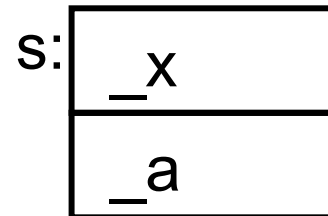
No slicing, but still, **h will be printed!**

Underneath the Hood: Static Resolution

```
class Shape
{
    double _x;
    int _a;
};
```

```
class Circle:
    public Shape
{
    double _z;
};
```

```
Shape s;
Circle c;
```



Pointing to an Inherited Class

```
Circle c;
```

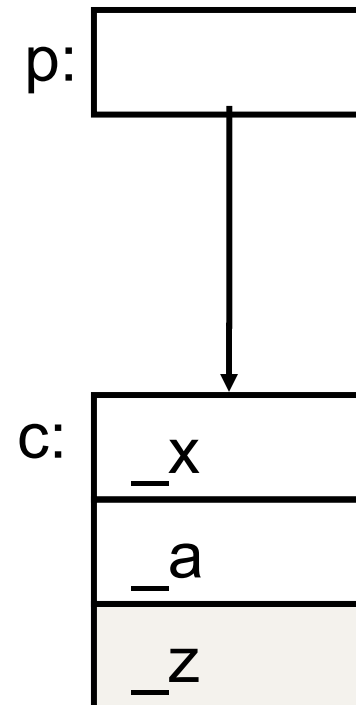
```
Shape* p = &c;
```

p points to the hidden

“Base” field inside d.

When using *p, we treat d
as though it was a Base
object.

The compiler cannot know if
*p is from a derived class
or not!



Dynamic Resolution

Static/early resolution

is clearly not what we want to in this example.

- Based on the type of the *variable*.
- Determined at compile time.

Dynamic/late resolution:

is more desirable here:

- Based on the type of the *object*
- Determined at run time

[Java Like]

dynamic resolution

The `virtual` keyword states that the method can be overridden in a dynamic manner.

```
class Shape
{
public:
    virtual void draw() const
        {cout<<'h';}
    virtual double area() const;
};
```

```
class Square: public Shape
{
public:
    virtual void draw() const
        {cout<<'q';}
    virtual double area() const;
};
```

```
class Circle: public Shape
{
public:
    void draw() const
        {cout<<'c';}
    double area() const;
};
```

dynamic resolution

Returning to the shapes example, using virtual methods gives the desired result:

```
Shape* s=new Circle;  
s->draw();
```

Will print 'c'

Virtual Methods

Class Base defines a *virtual method* `foo()`

The resolution of `foo()` is dynamic in **all** subclasses of Base.

- If the subclass Derived overrides `foo()`, then `Derived::foo()` is called
- If not, `Base::foo()` is called

With references

```
struct Base
{
    virtual void f()
    {
        cout << "B" << endl;
    }
};

struct Derived: public Base
{
    virtual void f()
    {
        cout << "D" << endl;
    }
};
```

```
int main()
{
    Derived d;

    Base b = d;
    b.f(); //B

    Base& bref= d;
    bref.f(); //D

    Base b1;
    // Derived d1 = b1;
    // won't compile
}
```

Base function that calls virtual function

```
struct Base {  
    virtual void f() { cout<< "Base f()" <<endl; }  
    void g() { f(); }  
};
```

```
struct Derived : public Base {  
    void f() { cout<< "Derived f()" <<endl; }  
};
```

```
int main(){  
    Derived d;  
    d.g()
```

will print "Derived f()". Why??

Base function that calls virtual function

```
struct Base {  
    virtual void f() { cout<< "Base f()" <<endl; }  
    void g(Base* this) {this->f(); }  
};
```

```
struct Derived : public Base {  
    void f() { cout<< "Derived f()" <<endl; }  
};
```

```
int main(){  
    Derived d;  
    Base::g(&d)  
}
```

will print "Derived f()". Why??

Calling virtual function from a constructor

```
struct Base {  
    Base() { f(); }  
    virtual void f(){ cout<<"Base"<<endl;}  
};  
struct Derived: public Base {  
    virtual void f(){ cout<<"Derived"<<endl;}  
};  
int main(){  
    Derived d; // would print "Base"  
}
```

Why? Because when Base() is called, Derived is not constructed yet!

<https://stackoverflow.com/q/962132/827927s>

Calling virtual function from a destructor

```
struct Base {  
    ~Base() { f(); }  
    virtual void f() { cout<<"Base"<<endl;}  
};  
struct Derived: public Base {  
    virtual void f() { cout<<"Derived"<<endl;}  
};  
int main(){  
    Derived d; // would print "Base"  
}
```

Why? Because when ~Base() is called, Derived is already destructed!

<https://stackoverflow.com/q/962132/827927>

Polymorphism rules:

When calling a method, polymorphism will take place if:

- We call a method through pointer or reference to a base class that actually points to a derived object.
- The method must be virtual.
- We are not in ctor / dtor
- The derived class must override the base method with exactly the same signature (C++11 put **override** between () and { } to check that the method really overrides in compile time)

Implementation of Virtual Methods (under the hood)

Implementation of Virtual Methods

Possible approach:

- If `foo()` is a virtual method, then each object has a pointer to the implementation of `foo()` that it uses
- Can be implemented by using array of pointers to functions

Cost:

- Each virtual method requires a pointer
 - Large number of virtual methods
 - ↙ waste of memory

Implementation of Virtual Methods

Alternative solution:

- Each object has a **single** pointer to an array of function pointers
- This array points to the appropriate functions

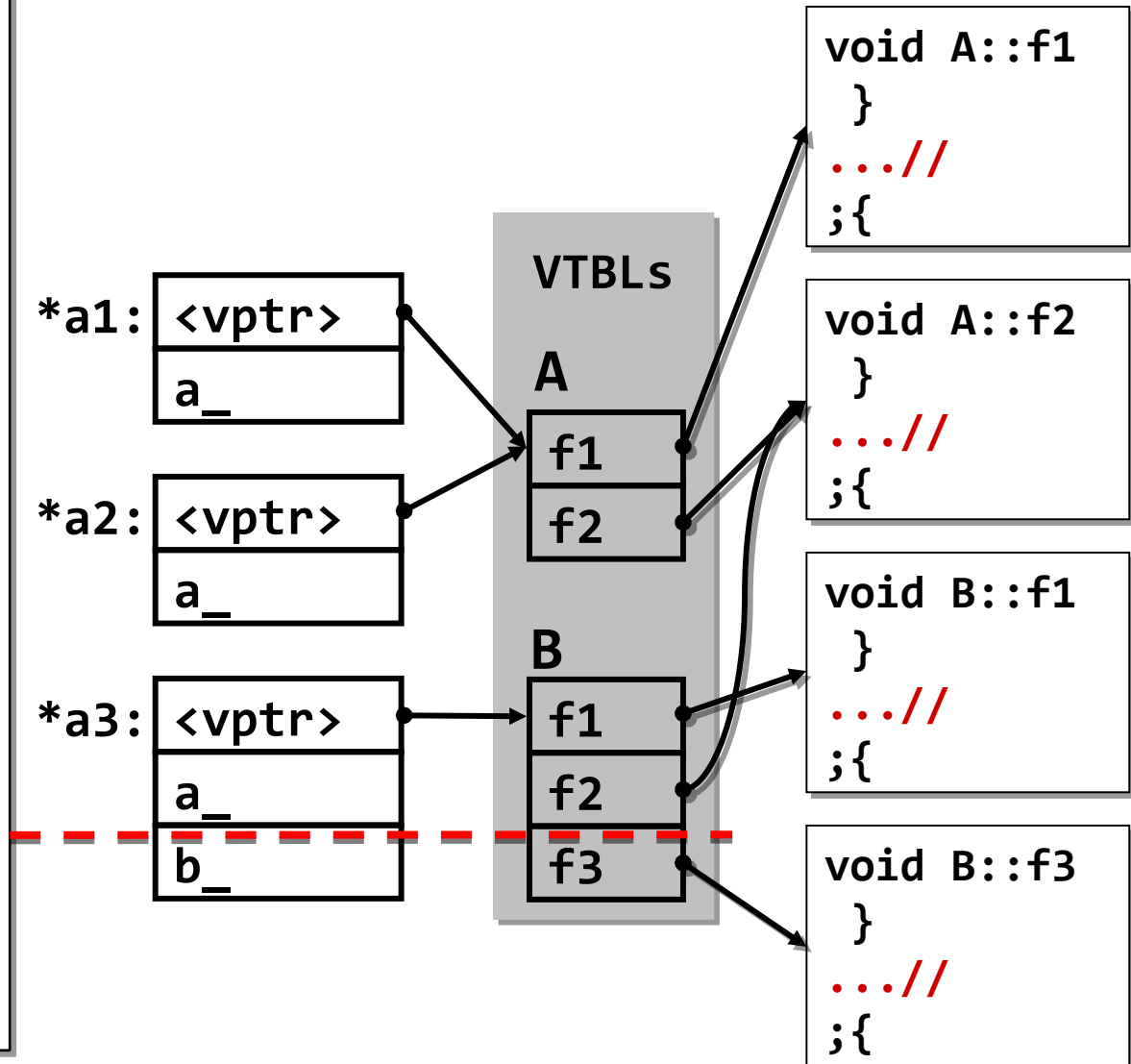
Cost:

- For each class, we store one table
- Each object contains one field that points to the right table

```
class A
{ public:
    virtual void f1();
    virtual void f2();
    int _a;
};
```

```
class B: public A
{ public:
    void f1();
    virtual void f3();
    void f4();
    int _b;
};
```

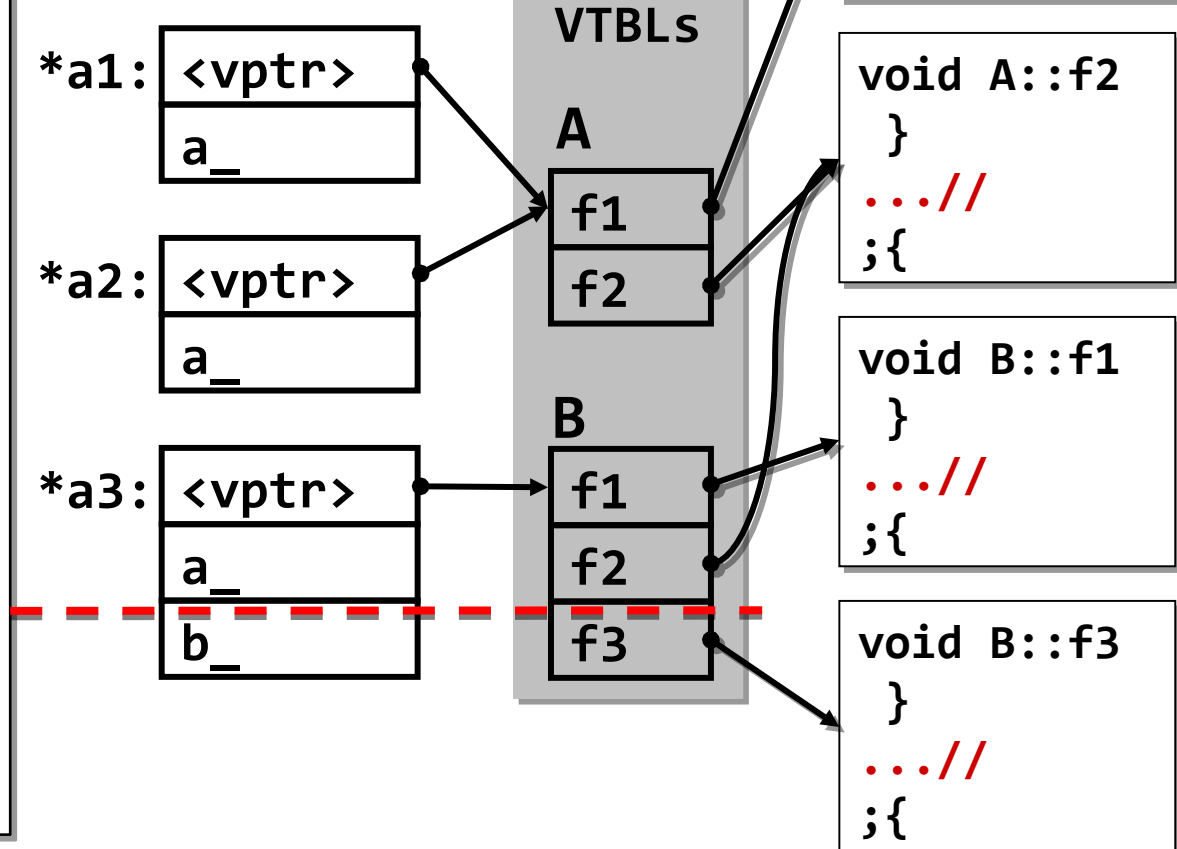
```
A* a1= new A;
A* a2= new A;
A* a3= new B;
a1→f1();
a3→f1(); // same code
```



Through `*a3` everything below the red dashed line will be hidden (you can downcast to a different name, later)

```
class B: public A
{ public:
  virtual void f1();
  virtual void f3();
  void f4();
  int _b;
};
```

```
A* a1= new A;
A* a2= new A;
A* a3= new B;
a3->f3(); // comp.err.
a3->f4(); // comp.err.
```



Virtual Functions - demo

Either view folder 2

Or put the following code in
<https://godbolt.org/>

```
class Base {  
    public:  
        int x, y;  
        int f() { return 111; }  
        virtual int g() { return 222; }  
        virtual int h() { return 333; }  
};  
  
class Derived: public Base {  
    int g() { return 444; }  
};  
  
int main() {  
    Base* p = new Derived;  
    p->f();  
    p->g();  
    p->h();  
    return 0;
```

Calling virtual function from a ctor/dtor explained

- When the code to the ctor/dtor is generated, it is generated to its class and not for a different class.
- Thus, the vptr will be to the vtable of the same class.

Virtual – cost

- **Time:** Calling a virtual method is more expensive than standard calls
 - Two pointers are “chased” to get to the address of the function
 - No inlining
- **Memory:** objects with virtual methods have an additional fields (about 8 bytes).
- **Conclusion:** Declare a function “virtual” only if you need polymorphism.

Destructors & Inheritance

```
class Base
{ public:
    ~Base();
};

class Derived : public Base
{ public:
    ~Derived();
};

Base *p = new Derived;
delete p;
```

Which destructor is called?

Destructors & Inheritance

```
class Base
{ public:
    ~Base();
};

class Derived : public Base
{ public:
    ~Derived();
};

Base *p = new Derived;
delete p;
```

Which destructor is called? **Base::~~Base()!**

Virtual Destructor

- Destructor is like any other method
- The example uses static resolution, and hence the wrong destructor is called
- To fix that, we need to declare virtual destructor **at the base class!**

Once you declare virtual destructor, derived class must declare a destructor

Destructors & Inheritance

```
class Base
{ public:
    virtual ~Base();
};
class Derived : public Base
{ public:
    ~Derived();
};
Base *p = new Derived;
delete p;
```

Which destructor is called? `Derived::~~Derived()`!

Abstract classes

Revisiting our example, we write:

```
class Shape
{
public:
    virtual ~Shape();
    virtual void draw() const;
    virtual double area() const;
};
```

How do we implement Shape::draw() ?

Inheritance & Interfaces

- In this example, we never want to deal with objects of type Shape
 - Shape serves the role of an interface
- All shapes need to be specific shapes instances of derived classes of Shape.
- How do we enforce this?

Pure Virtual

We can specify that Shape::draw() must be implemented in derived class

```
class Shape {  
public:  
    virtual ~Shape() {};  
    // pure virtuals  
    virtual void draw() const = 0;  
    virtual double area() const = 0;  
    virtual setName() = 0;  
};
```

Pure Virtual

We cannot create objects of a Pure Virtual class – that is an object that contains at least one Pure Virtual method

```
Shape* p; // legal
```

```
Shape s; // illegal
```

```
p = new Shape; // illegal
```

```
Circle c; // legal
```

```
p = &c; // legal
```

```
p = new Circle; // legal
```

Private Pure Virtual

Legal and often used, derived objects must implement but cannot use:

```
class Shape { private:  
    virtual void drawImpl()= 0;  
    static int g_numDraws;  
public:  
    void draw() const {  
        ++g_numDraws;  
        drawImpl();  
    }  
    static int numDraws() const { return g_numDraws; }
```

Virtual Methods - Tips

- 1. If you have virtual methods in a class, always declare its destructor virtual**
- 2. Never call virtual methods during construction and destruction**
- 3. Use pure virtual classes without any fields to define interfaces**
- 4. Use inheritance with polymorphism with care: Be sure that this is the appropriate solution ("is a" relation)**

Interfaces

- To create an equivalent to java interface – declare a base class with all methods pure virtual and no fields.
- Inheritance can be used to hide implementation. But, you will need a factory, and with templates also pimpl pattern (like in C's List).

C++ pimpl

In List.h file:

```
class List {  
public:  
    virtual void Add()=0;  
    virtual ~List(){};  
    static List* make();  
};
```

In main.cpp:

```
List* L = List::make();  
L->Add();
```

In List.cpp file:

```
class ListImpl: public List {  
    int* theInts;  
    int numInts;  
public:  
    ListImpl(): theInts  
        (new int[...]) {...}  
    void Add() { ... }  
};  
List* List::make() {  
    return new ListImpl;  
}
```