

CS100 Lecture 20

Contents

- Inheritance
- Dynamic binding
- Abstract base class

Inheritance

Example: An item for sale

```
class Item {
    std::string m_name;
    double m_price = 0.0;
public:
    Item() = default;
    Item(const std::string &name, double price)
        : m_name(name), m_price(price) {}
    auto getName() const { return m_name; }
    auto netPrice(int cnt) const {
        return cnt * m_price;
    }
};
```

Defining a subclass

A discounted item is an item, and has more information:

- `std::size_t m_minQuantity;`
- `double m_discount;`

The net price for such an item is

$$\text{netPrice}(n) = \begin{cases} n \cdot \text{price}, & \text{if } n < \text{minQuantity}, \\ n \cdot \text{discount} \cdot \text{price}, & \text{otherwise.} \end{cases}$$

Defining a subclass

Use inheritance to model the "is-a" relationship:

- A discounted item is an item.

```
class DiscountedItem : public Item {  
    int m_minQuantity = 0;  
    double m_discount = 1.0;  
public:  
    // constructors  
    // netPrice  
};
```

protected members

A `protected` member is private, except that it is accessible in subclasses.

- `m_price` needs to be `protected`, of course.
- Should `m_name` be `protected` or `private`?
 - `private` is ok if the subclass does not modify it. It is accessible through the public `getName` interface.
 - `protected` is also reasonable.

protected members

```
class Item {  
    std::string m_name;  
protected:  
    double m_price = 0.0;  
public:  
    Item() = default;  
    Item(const std::string &name, double price)  
        : m_name(name), m_price(price) {}  
    auto getName() const { return m_name; }  
    auto netPrice(int cnt) const {  
        return cnt * m_price;  
    }  
};
```


Inheritance

By defining `DiscountedItem` to be a subclass of `Item`, every `DiscountedItem` object contains a subobject of type `Item`.

- Every data member and member function, except the ctors and dtors, is inherited, no matter what access level they have.

What can be inferred from this?

Inheritance

By defining `DiscountedItem` to be a subclass of `Item`, every `DiscountedItem` object contains a subobject of type `Item`.

- Every data member and member function, except the ctors and dtors, is inherited, **no matter what access level they have.**

What can be inferred from this?

- A constructor of `DiscountedItem` must first initialize the base class subobject by calling a constructor of `Item`'s.
- The destructor of `DiscountedItem` must call the destructor of `Item` after having destroyed its own members (`m_minQuantity` and `m_discount`).
- `sizeof(Derived) >= sizeof(Base)`

Inheritance

Key points of inheritance:

- Every object of the derived class (subclass) contains a base class subobject.
- Inheritance should not break the encapsulation of the base class.
 - e.g. To initialize the base class subobject, **we must call a constructor of the base class**. It is not allowed to initialize data members of the base class subobject directly.

Constructor of DiscountedItem

```
class DiscountedItem : public Item {  
    int m_minQuantity = 0;  
    double m_discount = 1.0;  
public:  
    DiscountedItem(const std::string &name, double price,  
                   int minQ, double disc)  
        : Item(name, price), m_minQuantity(minQ), m_discount(disc) {}  
};
```

It is not allowed to write this:

```
DiscountedItem(const std::string &name, double price,  
               int minQ, double disc)  
    : m_name(name), m_price(price), m_minQuantity(minQ), m_discount(disc) {}
```

Constructor of derived classes

Before the initialization of the derived class's own data members, the base class subobject **must** be initialized by having one of its ctors called.

- What if we don't call the base class's ctor explicitly?

```
DiscountedItem(...)
: /* ctor of Item is not called */ m_minQuantity(minQ), m_discount(d) {}
```

Constructor of derived classes

Before the initialization of the derived class's own data members, the base class subobject **must** be initialized by having one of its ctors called.

- What if we don't call the base class's ctor explicitly?
 - The default constructor of the base class is called.
 - If the base class is not default-constructible, an error.
- What does this constructor do?

```
DiscountedItem() = default;
```

Constructor of derived classes

Before the initialization of the derived class's own data members, the base class subobject **must** be initialized by having one of its ctors called.

- What if we don't call the base class's ctor explicitly?
 - The default constructor of the base class is called.
 - If the base class is not default-constructible, an error.
- What does this constructor do?

```
DiscountedItem() = default;
```

- Calls `Item::Item()` to default-initialize the base class subobject before initializing `m_minQuantity` and `m_discount`.

Dynamic binding

Upcasting

If `D` is a subclass of `B`:

- A `B*` can point to a `D`, and
- A `B&` can be bound to a `D`.

```
DiscountedItem di = someValue();  
Item &ir = di; // correct  
Item *ip = &di; // correct
```

Reason: The **is-a** relationship! A `D` is a `B`.

But on such references or pointers, only the members of `B` can be accessed.

Upcasting: Example

```
void printItemName(const Item &item) {  
    std::cout << "Name: " << item.getName() << std::endl;  
}  
DiscountedItem di("A", 10, 2, 0.8);  
Item i("B", 15);  
printItemName(i); // "Name: B"  
printItemName(di); // "Name: A"
```

`const Item &item` can be bound to either an `Item` or a `DiscountedItem`.

Static type and dynamic type

- **static type** of an expression: The type known at compile-time.
- **dynamic type** of an expression: The real type of the object that the expression is representing. This is known at run-time.

```
void printItemName(const Item &item) {  
    std::cout << "Name: " << item.getName() << std::endl;  
}
```

The static type of `item` is `const Item &`, but its dynamic type is not known until run-time. (It may be `const Item` or `const DiscountedItem`.)

virtual functions

Item and DiscountedItem have different ways of computing the net price.

```
void printItemInfo(const Item &item) {  
    std::cout << "Name: " << item.getName()  
                << ", price: " << item.netPrice(1) << std::endl;  
}
```

- Which netPrice should be called?
- How do we define two different netPrice s?

virtual functions

```
class Item {
public:
    virtual double netPrice(int cnt) const {
        return m_price * cnt;
    }
    // other members
};

class DiscountedItem : public Item {
public:
    double netPrice(int cnt) const override {
        return cnt < m_minQuantity ? cnt * m_price : cnt * m_price * m_discount;
    }
    // other members
};
```

Note: `auto` cannot be used to deduce the return type of `virtual` functions.

Dynamic binding

```
void printItemInfo(const Item &item) {  
    std::cout << "Name: " << item.getName()  
                << ", price: " << item.netPrice(1) << std::endl;  
}
```

The dynamic type of `item` is determined at run-time.

Since `netPrice` is a `virtual` function, which version is called is also determined at run-time:

- If the dynamic type of `item` is `Item`, it calls `Item::netPrice`.
- If the dynamic type of `item` is `DiscountedItem`, it calls `DiscountedItem::netPrice`.

late binding, or dynamic binding

virtual - override

To **override** (覆盖/覆写) a `virtual` function,

- The function parameter list must be the same as that of the base class's version.
- The return type should be either **identical to** or **covariant with** that of the corresponding function in the base class.
 - We will talk about "covariant with" in later lectures or recitations.
- The `const` ness should be the same!

To make sure you are truly overriding the `virtual` function (instead of making a overloaded version), use the `override` keyword.

* Not to be confused with "overloading" (重载) .

virtual - override

An overriding function is also `virtual`, even if not explicitly declared.

```
class DiscountedItem : public Item {  
    virtual double netPrice(int cnt) const override; // correct, explicitly virtual  
};  
class DiscountedItem : public Item {  
    double netPrice(int cnt) const; // also correct, but not recommended  
};
```

To override a virtual function, both `virtual` and `override` can be omitted, **but the best practice is to always use the `override` keyword.**

The `override` keyword lets the compiler check and report if the function is not truly overriding.

virtual destructors

```
Item *ip = new DiscountedItem(...);  
delete ip;
```

Whose destructor should be called?

virtual destructors

```
Item *ip = new DiscountedItem(...);  
delete ip;
```

Whose destructor should be called? - It should be determined at run-time!

- To use dynamic binding correctly, you almost always need a `virtual` destructor.
- The implicitly-defined (compiler-generated) destructor is **non-`virtual`**, but we can explicitly require a `virtual` one:

```
virtual ~Item() = default;
```

- If the dtor of the base class is `virtual`, the compiler-generated dtor for the derived class is also `virtual`.

(Almost) completed `Item` and `DiscountedItem`

```
class Item {
    std::string m_name;
protected:
    double m_price = 0.0;
public:
    Item() = default;
    Item(const std::string &name, double price) : m_name(name), m_price(price) {}
    auto getNname() const { return name; }
    virtual double net_price(int n) const {
        return n * price;
    }
    virtual ~Item() = default;
};
```

(Almost) completed `Item` and `DiscountedItem`

```
class DiscountedItem : public Item {
    int m_minQuantity = 0;
    double m_discount = 1.0;
public:
    DiscountedItem(const std::string &name, double price,
                   int minQ, double disc)
        : Item(name, price), m_minQuantity(minQ), m_discount(disc) {}
    double netPrice(int cnt) const override {
        return cnt < m_minQuantity ? cnt * m_price : cnt * m_price * m_discount;
    }
};
```

Usage with smart pointers

Smart pointers are implemented by wrapping the raw pointers, so they can also be used for dynamic binding.

```
std::vector<std::shared_ptr<Item>> myItems;  
for (auto i = 0; i != n; ++i) {  
    if (someCondition) {  
        myItems.push_back(std::make_shared<Item>(someParams));  
    } else {  
        myItems.push_back(std::make_shared<DiscountedItem>(someParams));  
    }  
}
```

`std::unique_ptr<Base>` can accept a `std::unique_ptr<Derived>` .

`std::shared_ptr<Base>` can accept a `std::shared_ptr<Derived>` .

Copy-control

Remember to copy/move the base subobject! One possible way:

```
class Derived : public Base {
public:
    Derived(const Derived &other)
        : Base(other), /* Derived's own members */ { /* ... */ }
    Derived &operator=(const Derived &other) {
        Base::operator=(other); // call Base's operator= explicitly
        // copy Derived's own members
        return *this;
    }
    // ...
};
```

Why `Base(other)` and `Base::operator=(other)` work?

- The parameter type is `const Base &`, which can be bound to a `Derived` object.

Synthesized copy-control members

Guess!

- What are the behaviors of the compiler-generated copy-control members?
- In what cases will they be `deleted`?

Synthesized copy-control members

Remember that the base class's subobject is always handled first.

These rules should be natural.

- What are the behaviors of the compiler-generated copy-control members?
 - First, calls the base class's corresponding copy-control member.
 - Then, performs the corresponding operation on the derived class's own data members.
- In what cases will they be `deleted`?
 - If the base class's corresponding copy-control member is not accessible (e.g. non-existent, or `private`),
 - or if any of the data members' corresponding copy-control member is not accessible.

Slicing

Dynamic binding only happens on references or pointers to base class.

```
DiscountedItem di("A", 10, 2, 0.8);  
Item i = di; // What happens?  
auto x = i.netPrice(3); // Which netPrice?
```

Slicing

Dynamic binding only happens on references or pointers to base class.

```
DiscountedItem di("A", 10, 2, 0.8);  
Item i = di; // What happens?  
auto x = i.netPrice(3); // Which netPrice?
```

`Item i = di;` calls the **copy ctor** of `Item`

- but `Item`'s copy ctor handles only the base part.
- So `DiscountedItem`'s own members are **ignored**, or "sliced down".
- `i.netPrice(3)` calls `Item::netPrice`.

Downcasting

```
Base *bp = new Derived{};
```

If we only have a `Base` pointer, but we are quite sure that it points to a `Derived` object

- Accessing the members of `Derived` through `bp` is not allowed.
- How can we perform a "downcasting"?

Polymorphic class

A class is said to be **polymorphic** if it has (declares or inherits) at least one virtual function.

- Either a `virtual` normal member function or a `virtual` dtor is ok.

If a class is polymorphic, all classes derived from it are polymorphic.

- There is no way to "refuse" to inherit any member functions, so `virtual` member functions must be inherited.
- The dtor must be `virtual` if the dtor of the base class is `virtual`.

Downcasting: For polymorphic class only

```
dynamic_cast<Target>(expr) .
```

```
Base *bp = new Derived{};  
Derived *dp = dynamic_cast<Derived *>(bp);  
Derived &dr = dynamic_cast<Derived &>(*bp);
```

- `Target` must be a **reference** or a **pointer** type.
- `dynamic_cast` will perform **runtime type identification (RTTI)** to check the dynamic type of the expression.
 - If the dynamic type is `Derived`, or a derived class (direct or indirect) of `Derived`, the downcasting succeeds.
 - Otherwise, the downcasting fails. If `Target` is a pointer, returns a null pointer. If `Target` is a reference, throws an exception `std::bad_cast`.

`dynamic_cast` can be very slow

`dynamic_cast` performs a runtime **check** to see whether the downcasting should succeed, which uses runtime type information.

This is **much slower** than other types of casting, e.g. `const_cast`, or arithmetic conversions.

Guaranteed successful downcasting: Use `static_cast`.

If the downcasting is guaranteed to be successful, you may use `static_cast`

```
auto dp = static_cast<Derived*>(bp); // quicker than dynamic_cast,  
// but performs no checks. If the dynamic type is not Derived, UB.
```

Avoiding `dynamic_cast`

Typical abuse of `dynamic_cast` :

```
struct A {  
    virtual ~A() {}  
};  
struct B : A {};  
struct C : A {};
```

```
std::string getType(const A *ap) {  
    if (dynamic_cast<const B *>(ap))  
        return "B";  
    else if (dynamic_cast<const C *>(ap))  
        return "C";  
    else  
        return "A";  
}
```

Click here to see how large and slow the generated code is:

<https://godbolt.org/z/3367efGd7>

Avoiding `dynamic_cast`

Use a group of `virtual` functions!

```
struct A {  
    virtual ~A() {}  
    virtual std::string name() const {  
        return "A";  
    }  
};  
struct B : A {  
    std::string name()const override{  
        return "B";  
    }  
};  
struct C : A {  
    std::string name()const override{  
        return "C";  
    }  
};
```

```
auto getType(const A *ap) {  
    return ap->name();  
}
```

- This time:

<https://godbolt.org/z/KosbcaGnT>

The generated code is much simpler!

Abstract base class

Shapes

Define different shapes: Rectangle, Triangle, Circle, ...

Suppose we want to draw things like this:

```
void drawThings(ScreenHandle &screen,  
                const std::vector<std::shared_ptr<Shape>> &shapes) {  
    for (const auto &shape : shapes)  
        shape->draw(screen);  
}
```

and print information:

```
void printShapeInfo(const Shape &shape) {  
    std::cout << "Area: " << shape.area()  
               << "Perimeter: " << shape.perimeter() << std::endl;  
}
```

Shapes

Define a base class `Shape` and let other shapes inherit it.

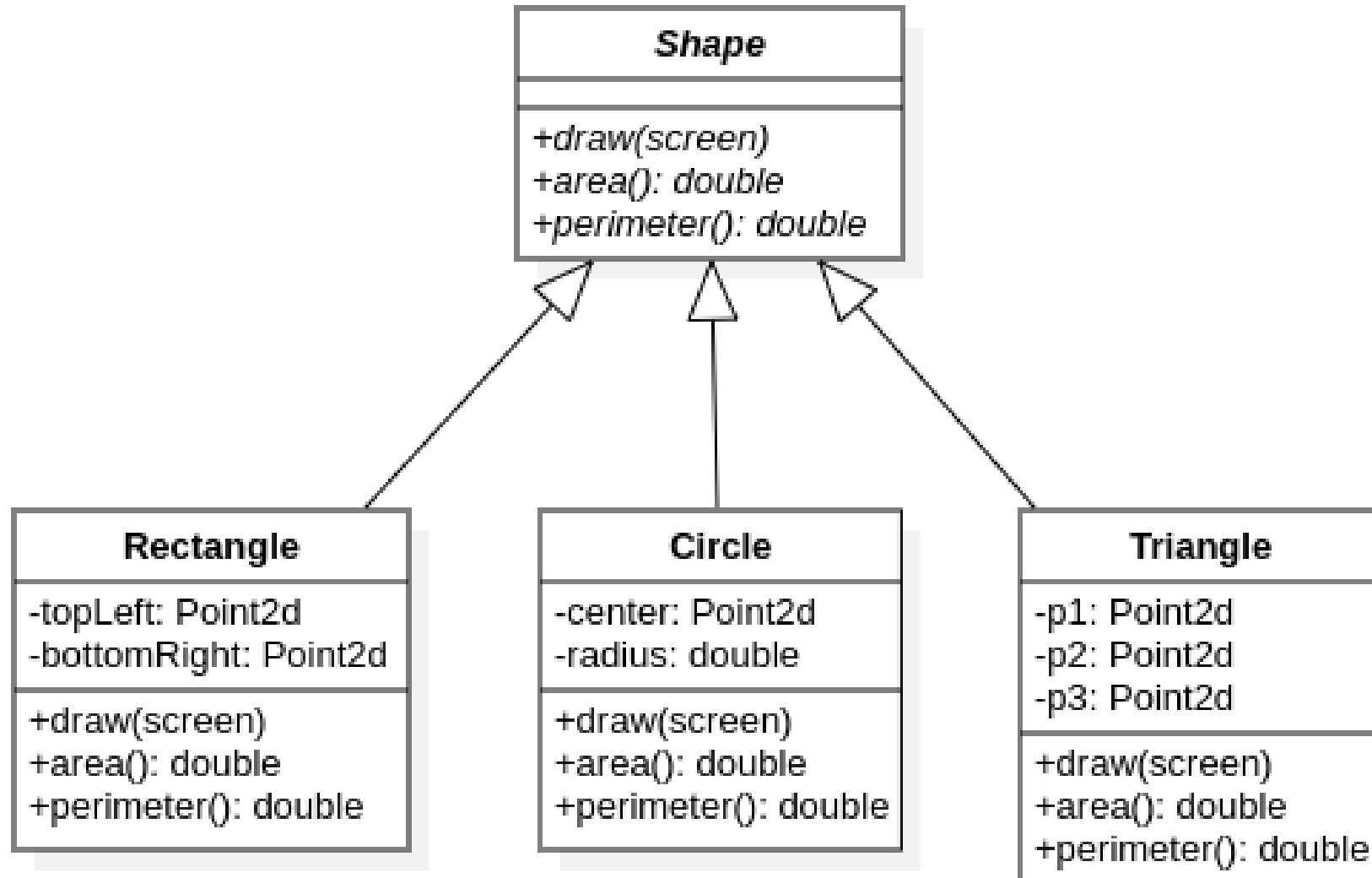
```
class Shape {  
    public:  
        Shape() = default;  
        virtual void draw(ScreenHandle &screen) const;  
        virtual double area() const;  
        virtual double perimeter() const;  
        virtual ~Shape() = default;  
};
```

Different shapes define their own `draw`, `area` and `perimeter`, so these functions should be `virtual`.

Shapes

```
class Rectangle : public Shape {
    Point2d m_topLeft, m_bottomRight;
public:
    Rectangle(const Point2d &tl, const Point2d &br)
        : m_topLeft(tl), m_bottomRight(br) {} // Base is default-initialized
    void draw(ScreenHandle &screen) const override { /* ... */ }
    double area() const override {
        return (m_bottomRight.x - m_topLeft.x) * (m_bottomRight.y - m_topLeft.y);
    }
    double perimeter() const override {
        return 2 * (m_bottomRight.x - m_topLeft.x + m_bottomRight.y - m_topLeft.y);
    }
};
```

Shapes



Pure **virtual** functions

How should we define `Shape::draw`, `Shape::area` and `Shape::perimeter`?

- For the general concept "Shape", there is no way to determine the behaviors of these functions.

Pure **virtual** functions

How should we define `Shape::draw`, `Shape::area` and `Shape::perimeter`?

- For the general concept "Shape", there is no way to determine the behaviors of these functions.
- Direct call to `Shape::draw`, `Shape::area` and `Shape::perimeter` should be forbidden.
- We shouldn't even allow an object of type `Shape` to be instantiated! The class `Shape` is only used to **define the concept "Shape" and required interfaces**.

Pure `virtual` functions

If a `virtual` function does not have a reasonable definition in the base class, it should be declared as **pure `virtual`** by writing `=0`.

```
class Shape {  
    public:  
        virtual void draw(ScreenHandle &) const = 0;  
        virtual double area() const = 0;  
        virtual double perimeter() const = 0;  
        virtual ~Shape() = default;  
};
```

Any class that has a **pure `virtual` function** is an **abstract class**. Pure `virtual` functions (usually) cannot be called, and abstract classes cannot be instantiated.

Pure **virtual** functions and abstract classes

Any class that has a **pure virtual** function is an **abstract class**. Pure **virtual** functions (usually) cannot be called, and abstract classes cannot be instantiated.

```
Shape shape; // Error.  
Shape *p = new Shape; // Error.  
auto sp = std::make_shared<Shape>(); // Error.  
std::shared_ptr<Shape> sp2 = std::make_shared<Rectangle>(p1, p2); // OK.
```

We can define pointer or reference to an abstract class, but never an object of that type!

Pure `virtual` functions and abstract classes

A non-pure `virtual` function **must be defined**. Otherwise, the compiler will fail to generate necessary runtime information (the virtual table), which leads to an error.

```
class X {  
    virtual void foo(); // Declaration, without a definition  
    // Even if `foo` is not used, this will lead to an error.  
};
```

Linkage error:

```
/usr/bin/ld: /tmp/ccV9TNfM.o: in function `main':  
a.cpp:(.text+0x1e): undefined reference to `vtable for X'
```

Make the interface robust, not error-prone.

Is this good?

```
class Shape {  
    public:  
        virtual double area() const {  
            return 0;  
        }  
};
```

What about this?

```
class Shape {  
    public:  
        virtual double area() const {  
            throw std::logic_error{"area() called on Shape!"};  
        }  
};
```

Make the interface robust, not error-prone.

```
class Shape {  
    public:  
        virtual double area() const {  
            return 0;  
        }  
};
```

If `Shape::area` is called accidentally, the error will happen *silently*!

Make the interface robust, not error-prone.

```
class Shape {  
    public:  
        virtual double area() const {  
            throw std::logic_error{"area() called on Shape!"};  
        }  
};
```

If `Shape::area` is called accidentally, an exception will be raised.

However, a good design should make errors fail to compile.

If an error can be caught in compile-time, don't leave it until run-time.

Polymorphism (多态)

Polymorphism: The provision of a single interface to entities of different types, or the use of a single symbol to represent multiple different types.

- Run-time polymorphism: Achieved via **dynamic binding**.
- Compile-time polymorphism: Achieved via **function overloading, templates, concepts (since C++20), etc.**

Run-time polymorphism:

```
struct Shape {  
    virtual void draw() const = 0;  
};  
void drawStuff(const Shape &s) {  
    s.draw();  
}
```

Compile-time polymorphism:

```
template <typename T>  
concept Shape = requires(const T x) {  
    x.draw();  
};  
void drawStuff(Shape const auto &s) {  
    s.draw();  
}
```

Reading materials

Effective C++ Item 32: Make sure public inheritance models "is-a".

Effective C++ Item 34: Differentiate between inheritance of interface and inheritance of implementation.