Class inheritance

Programação (L.EIC009)

José Proença (FCUP) & **João Bispo** (FEUP) – *slides by Eduardo R. B.*

Topics

- Class inheritance - fundamental notions:
  - base class and sub-class
  - inherited functionality from base class to derived class
  - `protected` access modifier
- Member function redefinition
  - redefinition and polymorphism
  - use of `virtual`, `override` and `final`
  - pure `virtual` functions puras and abstract classes
- Consolidating example
  - a class hierarchy for 2D geometric shapes

Code examples are available online at GitHub.

Declaring subclasses

Inheritance is normally declared as follows:

```
class SubClass : public BaseClass {
    ...
};
```

`SubClass` is called a **subclass** of the `BaseClass` **base class**. Other common designations: the base class is also called the **parent class** or **super-class**, the subclass is also called the **derived class** or **child class**.

`SubClass` inherits the functionality of `BaseClass`, and can define additional functionality on its own.

More advanced: `SubClass` may redefine the inherited functionality, and in some cases `BaseClass` may just define abstract functionality to be implemented by `SubClass`.

A first example

U.PORTO

```
class person {
public:
  person(int id, const string& name);
  person(const person& p);
  int id() const;
  const string& name() const;
  ...
private:
  int pid;
  string pname;
};
```

person will be used as a base class.

A first example (cont.)

```
class teacher : public person {
public:
  teacher(int id, const string& name,
          const string& dept);
  teacher(const teacher& t);
  const string& department() const;
  ...
private:
  string tdepartment;
};
```

`teacher` is a subclass of `person`. It inherits all the definitions of `person` but also defines new functionality, for instance the `department()` member function.

A class may have an arbitrary number of classes, and a class hierarchy can have several levels. We could have for instance:

```
class person { ... };

// Subclasses of person
class teacher : public person { ... };
class student : public person { ... };

// Subclasses of student
class erasmus_student : public student { ... };
class working_student : public student { ... };
```

We will see a concrete example later.

Inherited functionality

Over a `teacher` object we can invoke the `department()` member function. Since `teacher` is a subclass of `person` we can also invoke `id()` and `name()` member functions inherited from `person`.

```
person p(123, "Joana Doa");
std::cout << p.id() << ' '
          << p.name() << '\n';

teacher t(124, "John Doe", "Computer S
std::cout << t.id() << ' '
          << t.name() << ' '
          << t.department()
          << '\n';
```

Inherited functionality

U.PORTO

Over a `teacher` object we can invoke the `department()` member function. Since `teacher` is a subclass of `person` we can also invoke `id()` and `name()` member functions inherited from `person`.

```
person p(123, "Joana Doa");
std::cout << p.id() << ' '
          << p.name() << '\n';

teacher t(124, "John Doe", "Computer S
std::cout << t.id() << ' '
          << t.name() << ' '
          << t.department()
          << '\n';
```

Output:

```
123 Joana Doa
124 John Doe Computer Science
```

Inherited functionality (cont.)

```
int person::id() const { return pid; }
const std::string&
person::name() const { return pname; }
...
const std::string&
teacher::department() const { return tdepartment; }
```

`id()` and `name()` are only defined for `person`. The functionality is thus reused for `teacher`. The `teacher` subclass only needs to implement the new functionality it declares on its own such as `department()`.

Class inheritance vs. class composition

Inheritance should reflect an "**is a**" relationship between the abstract notions represented by classes, e.g., a teacher is a person.

A **common design** error is to use class inheritance to model a "**has a**" relationship, for which class composition is more appropriate. For example we could have the `polynomial` class of previous classes formulated as:

```
// BAD design
class polynomial : public std::vector<fraction> { ... };
```

instead of using a `vector<fraction>` field for the coefficients. A polynomial *is not* a vector of fractions, but it *has a* (it internally employs) vector of fractions.

Subclass constructors

```
person::person
(int id, const string& name)
  : pid(id), pname(name) {

}
...
teacher::teacher(int id,
 const string& name,
 const string& dept) :
   person(id, name), // base class constructor call
   tdepartment(department) {

}
```

A subclass constructor must call the base class constructor. This happens typically through a member initializer list that begins with a call to a constructor in the base class. If such a call is absent, a call to the default constructor of the base class is assumed.

Subclass constructors (const.)

```
person::person(const person &p) :
  pid(p.pid), pname(p.pname) { }
...
teacher::teacher(const teacher &t)
  : person(t), tdepartment(t.tdepartment) { }
```

Another subclass constructor example: the `teacher` copy constructor calls the `person` copy constructor.

`protected` access modifier

```cpp
class person {
protected:
  // directly accessible
  // in subclasses
  int pid;
  std::string pname;
...
};

class teacher : public person {
...
};
```

Like `public` and `private`, `protected` is an access modifier. **A `protected` declaration is accessible inside the declaring class but also any of its subclasses**. Code outside the class or subclasses cannot access `protected` declarations (like in the case of `private`)

In the above variant of `person`, code in the `teacher` subclass may directly access member fields `pid` and `pname` in `person`.

If we have ...

```
class person {
protected:
  // directly accessible
  // in subclasses
  int pid;
  std::string pname;
...
};
```

then access to pid and pname would be valid in code such as the following:

```
teacher::teacher(const teacher &t)
  : person(t),
  tdepartment(t.tdepartment) {
    // direct access
    pid = pid + 1000;
    pname = "Prof. " + pname;
  }
```

Usually inheritance is declared with a `public` access modifier, as in our example:

```
class teacher : public person ...
```

We will always use `public` in the course. But technically, it is also possible to have ...

```
class teacher : protected person ...
```

or ...

```
class teacher : private person ...
```

- `public`: preserves the accessibility of inherited definitions;
- `protected`: `public` declarations in the base class are changed to `protected`;
- `private`: `public` and `protected` declarations in the base class are changed to `private` in the subclass.

Inheritance and access modifiers (cont.)

For example, suppose we have:

```
class teacher : protected person { ... };
```

Then the following code is not valid, if defined outside class `teacher`:

```
teacher t(123, "John Doe", "Computer Science");
cout << t.id(); // NOT VALID!
```

```
'int person::id() const' is inaccessible within this context
```

`id()` has `protected` access for `teacher` objects, even if it remains `public` for `person`-only objects

```
person p(123,"John Doe");
cout << p.id(); // VALID!
```

```
teacher t(...);
person& r = t;
person* p = &t;
```

Since `teacher` is a subclass of `person`, we can have `person` references or pointers to `teacher` objects, since the `teacher` type is a subtype of the `person` type.

The ability to use base class pointers or references to refer to objects of subclasses can be quite useful, as we will see.

On the other hand, a `person` reference or pointer does not necessarily refer to a `teacher` object. Pointer or reference assignment requires a **cast**, for example as in

```
person* p = ...;
teacher* t = (person*) p; // cast
```

The above cast is **ok** if `p` really points to a `teacher` object. Otherwise the behavior is undefined … bad things tend to happen …

Excluding pointers or references, a cast cannot be used for a direct conversion from base class to subclass (we get a compilation error):

```
person p (...);
teacher t = (teacher) p;
```

```
no matching conversion for C-style cast from 'person' to 'teacher'
```

U.PORTO

What happens when we use a derived class object to construct or assign a base class object? For example, as in:

```
teacher t(124, "john doe", "Computer Science");
person p = t;
```

Only the base class "part" of the subclass object is considered. This is known as **object slicing**.

In the example, a "slice" is taken only for the `person` part of `t`: `t` is treated just as a `person` object for the construction of `p`.

Redefinition of member functions

Both `person` and `teacher` declare the `print()` member function. The member function declaration is the same in both classes:

```
class person {
   ...
   void print(std::ostream& out) const;
};
class teacher : public person {
   ...
   void print(std::ostream& out) const;
};
```

`teacher::print()` is in this case called a **redefinition** of `person::print()`.

Redefinition of member functions (cont.)

U.PORTO

`teacher::print()` may internally call `person::print()` ....

```
void person::print(std::ostream &out) const {
    // Print id and name
    out << "ID: " << pid << std::endl
        << "Name: " << pname << std::endl;
}
void teacher::print(std::ostream &out) const {
    // Call person::print
    person::print(out);
    // Print department info
    out << "Department: " << tdepartment << std::endl;
}
```

In line with the previous code of `teacher::print` then

```
teacher t(124, "John Doe", "Computer Science");
t.print(std::cout);
```

will print

```
ID: 124
Name: John Doe
Department: Computer Science
```

Redefinition of member functions (cont.)

Since we can have base class pointers or references what will we get in the following case?

```
teacher t(124, "John Doe", "Computer Science");
person* pt = &t;
pt->print(std::cout);
```

`pt` points to an object of type `teacher` but is declared as a pointer to `person`. Which member function is called: `person::print` or `teacher::print`?

Redefinition of member functions (cont.)

```
teacher t(124, "John Doe", "Computer Science");
person* pt = &t;
pt->print(std::cout);
```

The above fragment invokes `person::print()`

```
ID: 124
Name: John Doe
```

because the declared type of `pt` refers to `person`, not `teacher`.

We can however get a different behavior if `print()` is declared to be a **virtual function** in `person`.

Virtual functions

U.PORTO

We can declare `print()` as a **virtual function** in `person` using the `virtual` keyword:

```
class person {
    ...
    virtual void print(std::ostream& out) const;
};
class teacher : public person {
    ...
    void print(std::ostream& out) const;
};
```

In this case, `teacher::print` is called a **virtual function override**.

But what changes in practice?

If `person::print` is declared as `virtual`, then a call to `print()` through a `person` reference or pointer will use **dynamic binding**, i.e., take into account the actual **type of the object at runtime** rather than the declared type of the variable ...

Hence

```
teacher t(124, "John Doe", "Computer Science");
person* pt = &t;
pt->print(std::cout);
```

will call `teacher::print` ...

```
ID: 124
Name: John Doe
Department: Computer Science
```

Good practice: although optional, it is recommended that a virtual function override is annotated with the `override` keyword.

```
class person {
    ...
    virtual void print(std::ostream& out) const;
};
class teacher : public person {
    ...
    void print(std::ostream& out) const override; // use of override
};
```

The `override` annotation explicitly signals that a function is a virtual function override. The compiler validates that the override is valid.

Use of the `override` modifier (const.)

Example of invalid override (different ‘constness’):

```
class person {
  ...
  virtual void print(
    std::ostream& out) const;
};
class teacher : public person {
  ...
  // Missing const! The function is
  // not a valid override of person::print().
  void print(std::ostream& out) override;
};
```

Use of the `override` modifier (const.)

The compiler infers that the override is invalid:

```
error: non-virtual member function marked
'override' hides virtual member function

note: hidden overloaded virtual function 'Base::print'
 declared here: different qualifiers ('const' vs unqualified)
```

If the `override` annotation was missing, this would warrant at most a warning. The code would compile!

Use of `final`

A virtual function may be declared as `final` to disallow overrides.

For `person::print` declared final

```
class person {
  ...
  virtual void print(std::ostream& out) const final;
};
class teacher : public person {
  ...
  // Not allowed!
  void print(std::ostream& out) const override;
};
```

Use of `final` (cont.)

We get a compilation error for the `teacher::print` override

```
error: declaration of 'print' overrides a 'final' function
```

`final` can also be declared for a class to disallow any subclasses ...

```
class person final { ... };
// Subclasses not allowed
class teacher : public person { ... };
```

```
error: base 'person' is marked 'final'
```

Pure virtual functions and abstract classes

A **pure virtual function**, sometimes also called an abstract function, is declared as `virtual ... func(...) = 0`, e.g.,

```
class person {
  ...
  virtual void print(std::ostream& out) const = 0;
};
```

A class with one or more pure virtual functions is called **abstract**. An abstract class cannot be directly instantiated. **An override of the function must be defined by (concrete) sub-classes**. The function **typically also has no implementation at the base class level**.

Pure virtual functions and abstract classes (cont.)

U.PORTO

For

```
class person {
  ...
  virtual void print(std::ostream& out) const = 0;
};
```

we cannot have variables of type `person` ...

```
person p(123, "Joana Doa");
```

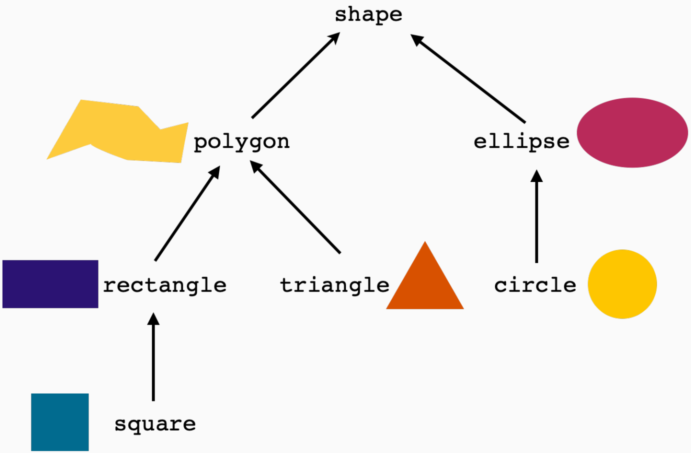
```
error: variable type 'person' is an abstract class
```

However, as `teacher` extends `person`, we can still have

```
teacher t(124, "John Doe", "Computer Science");
```

Consolidating example

A hierarchy of classes for 2D geometrical shapes:



`shape` abstract class

```
class shape {
public:
    virtual double area() const = 0;
    virtual coord2d center() const = 0;
    virtual void move(const coord2d& direction) = 0;
    virtual ~shape();
};
```

Since `shape` is abstract (it declares pure virtual functions), we cannot instantiate it directly.

Virtual destructor

```
class shape {
public:
    ...
    virtual ~shape();
}
```

Important: Base classes should define a virtual destrutor so that subclass destructors are properly invoked when using base class pointers, e.g.

```
shape* s =  new polygon ( ...);
...
// guarantees that destructor
// of polygon is called
delete s;
```

Example subclass of `shape`

```
class ellipse : public shape {
private:
    coord2d ecenter; double erx; double ery;
public:
    ellipse(const coord2d& c, double rx, double ry)  :
            ecenter(c), erx(rx), ery(ry) { }
    double radius_x() const { return erx; }
    double radius_y() const { return ery; }
    double area() const override final { return  M_PI * erx * ery; }
    coord2d center() const override final { return ecenter; }
    void move(const coord2d& movement) override final
      {  ecenter += movement; }
};
```

Example subclass of `shape` (cont.)

```
class ellipse : public shape {
public:
    double area() const override final  {
      { return  M_PI * erx * ery; }
    coord2d center() const override final
      { return ecenter; }
    void move(const coord2d& movement) override final
      {  ecenter += movement; }
};
```

`ellipse` defines overrides for the pure virtual functions declared in `shape`: `area()`, `center()`, and `move()`. In turn, these functions are marked `final` disallowing their override in subclasses of `ellipse` (`circle` discussed next).

One more level in the hierarchy ...

U.PORTO

```
class circle final : public ellipse {
public:
    circle(const coord2d& c, double r)
      : ellipse(c, r, r) { }
};
```

`circle` is a subclass of `ellipse`. It cannot override any member functions of `ellipse`, as all of them are marked `final`.

On the other hand, `circle` cannot have subclasses as it is is marked `final`.

The other classes in the `shape` hierarchy ….

(see code online)

```
class polygon : public shape { ... }
class triangle final : public polygon { ... };
class rectangle : public polygon { ... };
class square final : public rectangle { ... };
```

The drawing class

A drawing object can group several shapes:

```
class drawing final {
private:
    std::vector<shape*> shapes;
public:
    drawing() { }
    ~drawing() { ... }
    void add_shape(shape* s) { ... }
    void move_all(const coord2d& movement) { ... }
    std::vector<shape*>& get_shapes() { ... }
};
```

```
class drawing final {
private:
    std::vector<shape*> shapes;
public:
    ...
    void add_shape(shape* s) {
        shapes.push_back(s);
    }
};
```

To store the component shapes, `drawing` uses a vector of `shape*` pointers. We can not have the `vector<shape>` since `shape` is abstract. Even if `shape` was not abstract, we could not use `vector<shape>` to store objects that are subclasses of `shape` (they would be “sliced”).

The `drawing` class (cont.)

Example use of `drawing`:

```
drawing d;
d.add_shape(new rectangle({3, 5}, 2, 5));
d.add_shape(new circle({1, 1}, 1));
d.add_shape(new triangle({1, 1}, {1, 2}, {2, 1}));

d.move_all({3,-1}); // move all shapes

// Iterate shapes in the drawing
for (shape *s : d.get_shapes())
    std::cout << s->center() << ' '
              << s->area() << std::endl;
}
```

The `drawing` class (cont.)

```
class drawing final {
private:
    std::vector<shape*> shapes;
public:
    ...
    void move_all(const coord2d& movement) {
        for (shape* s : shapes) {
            s -> move(movement);
        }
    }
};
```

The abstract functionality of `shape` lets us manipulate all (possible types of) shapes using the same interface.

The `drawing` class (cont.)

`drawing` assumes that each contained shapes is dynamically allocated using `new`. Accordingly, the memory of each shape is released by the class destructor.

```
class drawing final {
private:
    std::vector<shape*> shapes;
public:
    ...
    ~drawing() {
        for (shape* s : shapes) {
            delete s;
        }
    }
};
```