COMP322 - Introduction to C++

Lecture 09 - Inheritance continued

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Recall from last time

- Inheritance describes the creation of derived classes from base classes.
- Derived classes inherit all data and functions from their base classes, while certain functions such as constructors are handled specially.

Today:

- Polymorphism is a product of the combination of virtual functions and C++ assignment compatibility rules.
- We can create abstract types which contain “pure” functions that may have no implementation. We can’t actually create objects from these types, but we can create references or pointers to abstract types.
- A key goal of inheritance: allow us to link related data together. (e.g. Create an array of Shape*)

What is inheritance?

- We've looked at classes in C++, which allow us to create abstract types with separate public declarations and private implementations.
- *Inheritance* refers to our ability to create a hierarchy of classes, in which *derived* classes (subclass) automatically incorporate functionality from their *base* classes (superclass).
- A derived class inherits all of the data and methods from its base class.
- A derived class may *override* one or more of the inherited methods.
- Most of the utility of classes and objects comes from the creation of class hierarchies.

Inheritance syntax

```
class A {       // base class
private:
  int x;        // Visible only within 'A'
protected:
  int y;        // Visible to derived classes
public:
  int z;        // Visible globally
  A();          // Constructor
  ~A();         // Destructor
  void f();     // Example method
};

class B : public A { // B is derived from A
private:
  int w;        // Visible only within 'B'
public:
  B();          // Constructor
  ~B();         // Destructor
  void g() {
    w = z + y; // OK
    f();        // OK
    w = x + 1; // Error - 'x' is private to 'A'
  }
};
```

Overriding member functions

A derived class may *override* a function from its base class:

```
class A {
public:
  void f(int x) { cerr << "A::f(" << x << ")\n"; }
};

class B: public A {
public:
  void f(int x) { cerr << "B::f(" << x << ")\n"; }
};

int main() {
  A a;
  B b;
  a.f(1);
  b.f(2);
}
```

the `main()` program will print:

```
A::f(1)
B::f(2)
```

Basics of inheritance

- Inheritance is used to denote an *is-a* relationship.
- e.g. A square IS a shape.
- If we have a class Square inherit from Shape then all functions and properites of the Shape object are automatically added to the Square object.
- public Shape : public Square

Assignment compatibility

C++ considers objects of a derived class to be assignment compatible with objects of their base class. This just makes a copy, skipping members that aren't part of the base class.

```
class A {
protected:
  int x;
//...
};

class B: public A {
  int y;
//...
};

int main() {
  B b;
  A a;
  a = b;   // OK, but 'y' is not copied!
}
```

Assignment compatibility

However, we can’t to the reverse and assign an object from a base class to a derived class. This could leave derived class members in an undefined state.

```
class A {
protected:
  int x;
//...
};

class B: public A {
  int y;
//...
};

int main() {
  B b;
  A a;
  b = a;   // Not OK - undefined value for 'y'
}
```

Assignment compatibility with pointers

The same rules apply with pointers. We can assign the address of an object of a derived class to an pointer to the base class, but not the opposite.

```
class A {
  // ...
};
class B: public A {
  // ...
};

int main() {
  A a, *pa;
  B b, *pb;
  pa = &b; // OK
  pb = &a; // Error!
}
```

However, since we are assigning pointers, the objects in these assignments *are not modified*, as opposed to the case when objects are copied. They retain their full contents.

Polymorphism

The ability to use base class pointers to refer to any of several derived objects is a key part of *polymorphism*.

Exploiting polymorphism requires additional effort:

```
class A {
public:
  void f() { cerr << "A::f()" << endl; }
};
class B: public A {
public:
  void f() { cerr << "B::f()" << endl; }
};

int main() {
  B b;
  A *pa = &b; // OK

  pa->f();    // Which f() does this call?
}
```

This call invokes the base class, A::f()!

Virtual functions

The solution is to declare functions `virtual`. This causes the compiler to call the “right” function when a call is made through a base class pointer:

```
class A {
public:
  virtual void f() { cerr << "A::f()" << endl; }
};
class B: public A {
public:
  void f() { cerr << "B::f()" << endl; }
};

int main() {
  B b;
  A *pa = &b; // OK

  pa->f();    // Now this will call B::f()!
}
```

Virtual functions

A virtual function in the derived class will override the base class only if the type signatures match.

```
class A {
public:
  virtual void f() { cerr << "A::f()" << endl; }
};
class B: public A {
public:
  void f(int x) { cerr << "B::f()" << endl; }
};

int main() {
  B b;
  A *pa = &b; // OK

  pa->f();    // Now this will call A::f()!
}
```

As with overloading, changing only the return type introduces an ambiguity and will trigger a compile-time error.

Virtual function details

- You do not need to use the `virtual` keyword in the derived classes, but it is legal.
- If you explicitly use the scope operator, you can override the natural choice of function.

```
class A {
public: virtual void f() { cerr << "A::f()\n"; }
};

class B : public A {
public: virtual void f() { cerr << "B::f()\n"; }
};

int main() {
  A *pa = new B();

  pa->A::f();    // Explicity invokes the base class
  pa->f();       // Invokes B::f()
}
```

Virtual constructors or destructors

- You *cannot* declare a constructor virtual.
- You can, and often *should*, declare a destructor virtual:

```
class A {
public:
  virtual ~A() {};
};

class B : public A {
private:
  int *mem;
public:
  B(int n=10) { mem = new int[n]; }
  ~B() { cerr << "~B()\n"; delete [] mem; }
};

int main() {
  A *pa = new B(100);

  delete pa;
}
```

Abstract classes

- In C++ , an *abstract* type or class is related to the Java "interface" construct.
- An abstract class explicitly leaves one or more virtual member functions unimplemented or *pure*.
- You can't create an object based on an abstract class, but you can use it to define derived classes.
- You *can* create pointers and references to an abstract class.

Abstract class syntax

```
class A {
public:
 virtual int f() = 0; // ``Pure'' (i.e. not implemented)
 virtual int g() = 0;
};

class B : public A {
public:
  int f() { return 1; } // Overrides f()
}

class C : public B {
public:
  int g() { return 2; } // Overrides A::g()
}
```

Both A and B are abstract classes, and we cannot create objects of either type. Only C is a concrete class that can be created.

Of course, you can't call a pure virtual function. Any attempt to do so will usually generate a linker error.

Static dispatch

If a member function is not `virtual`, the choice of function to call is made at *compile* time:

```
class A {
  int f();
};

class B : public A {
  int f();
};

int main() {
  B b;
  A *pa = &b;
  pa->f();  // Calls A::f() because pa is of type 'A *'
}
```

This is called either “static dispatch” or “static binding”, and it is the default behavior in C++.

Dynamic dispatch

If a member function is `virtual`, the choice of function to call is made at *run* time:

```
class A {
  virtual int f();
};

class B : public A {
  int f();
};

int main() {
  B b;
  A *pa = &b;
  pa->f();  // Calls B::f() because pa points to a 'B *'
}
```

Called either “dynamic dispatch” or “run-time binding”, this is both more useful and less efficient than static dispatch.

Dynamic dispatch internals

- Dynamic dispatch is implemented by adding a layer of indirection to a function call.
- Any object with dynamic dispatch contains an automatically-generated pointer to a *vtable*.
- Objects of a given class generally share a vtable.
- The vtable contains the addresses of the virtual functions.
- At runtime, the call to the function is performed by indirecting through the vtable pointer.

Virtual functions and constructors/destructors

Calls to virtual functions in the context of the constructor or destructor always use *static* dispatch.

This is different from the behavior of Java, for example.

```
class A {
public:
  A() { cerr << "A()\n"; f(); }  // Always calls A::f()!
  ~A() { cerr << "~A()\n"; g(); } // Always calls A::g()!
  virtual void f() { cerr << "A::f()\n"; g(); } // Depends on context
  virtual void g() { cerr << "A::g()\n"; }
};

class B : public A {
public:
  virtual void g() { cerr << "B::g()\n"; }
};

int main() {
  B b;
  A *pa = &b;
  pa->f(); // Calls A::f(), then B::g()!
}
```

Dynamic dispatch from base classes

The prior example hints at an important point: A base class can invoke virtual functions in a derived class, with no knowledge of the derived classes.

```
class base {
public:
  virtual bool vf1(int x) = 0; // Pure virtual
  void f1(int x) {             // Some generic method
    if (vf1(x)) {
      // ...
    }
  }
};

class derived : public base {
public:
  bool vf1(int x) {
    // do something with 'x'...
    return 1;
  }
};
```

Implementing pure virtual functions

A pure virtual function can provide an implementation which could be used by derived classes.

```
class A {
public:
  virtual void f() = 0;
};

void A::g() {
  // ...
}

class B : public A {
public:
  void f();
};

void B::f() {
  A::g(); // call the base class
  // do more...
}
```

The compiler will still refuse to create an object of class A!

Multiple inheritance

Java includes the “interface” construct, which allows one to generically specify a group of functions which must be implemented by a derived class.

C++ accomplishes the same thing through abstract classes and *multiple inheritance*.

Multiple inheritance allows a class to be derived from two *or more* base classes. The derived class inherits all of the data and functions of each base class, which clearly raises the possibility of naming conflicts.

Java interfaces are similar to a C++ abstract class with no data or function implementations. Both provide only the prototypes for functions which must be implemented by the derived class.

Multiple inheritance syntax

The syntax of multiple inheritance is straightforward. Each base class can use private, public, or protected inheritance:

```
class A {     // base class 1
  int x;
public:
  void f();
};

class B {     // base class 2
  int y;
public:
  void g();
};

class C : public A, public B { // C inherits from A & B
  int z;      // Visible only within 'C'
public:
  // ..
};
```

Class C will contain both functions and three variables.

Assignment compatibility

A derived class is assignment compatible with *any* base class.

```
class A {      // base class 1
// ...
};

class B {      // base class 2
// ...
};

class C : public A, public B { // C inherits from A & B
// ...
};

int main() {
  A a;
  B b;
  C c;
  a = c; // OK
  b = c; // OK
  c = a; // Error
  return 0;
}
```

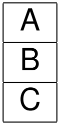
Assignment compatibility with pointers

Assignment compatibility with pointers is maintained similarly. However, the conversion to different base classes may return *different* values.

```
class A {     // base class 1
//...
};

class B {     // base class 2
//...
};

class C : public A, public B { // C is derived from A, B
//...
};

int main() {
  C c;
  A *pa = &c;
  B *pb = &c;
  // In general, (int)pa != (int)pb
  //...
}
```

Assignment compatibility with pointers

Why is this? Consider how the compiler arranges memory for an object of class C. The data for of A, B, and C are concatenated:



When we take the address of such an object, the compiler examines the type of the expression, and returns a pointer to the beginning of the appropriate part of the structure.

Sources of ambiguity

Multiple inheritance can introduce ambiguities and conflicts:

```
class A {
public:
  void f();
};

class B {
public:
  void f();
};

class C : public A, public B {
public:
  void g() { f(); } // Which f() do I invoke?
};
```

This can be resolved by qualifying the call to `f()` as `A::f()`, for example.

Diamond inheritance

An difficult situation arises when one class inherits from two others, both of which share a base class:

```
class person {
  string name;
public:
  void getName();
};

class student : public person {
  int year; // U0, U1, U2, etc..
public:
  void getYear();
};

class employee : public person {
   int year; // years of seniority
public:
   void getYear();
};

class studentemployee : public student, public employee {
};
```

The diamond inheritance problem

The problem is even worse than we might imagine at first glance. Our `getYear()` method is clearly ambiguous.

So is the `getName()` method! Our `student` and `employee` classes both inherited from `person`. Internally, C++ represents derived class as a concatenation of the base and derived classes, so our `studentemployee` class contains two copies of `person`:

person
student
person
employee
studentemployee

The diamond inheritance problem

If we use `getName()` in our `studentemployee` class, it could refer to either `person`. This can be overcome with scope resolution:

```
class studentemployee : public student, public employee {
public:
  void f() {
    string s = employee::getName();
  }
};
```

Assignment compatibility is now broken:

```
int main() {
  person p1;
  studentemployee se1;
  p1 = se1;  // Which person does the compiler use??
}
```

Again, there is a workaround:

```
  p1 = (employee) se1;
```

There are two solutions for diamond inheritance

- Avoid this situation at all costs!
- Use virtual inheritance:

```
class person {
  string name;
public:
  void getName();
};

class student : virtual public person {
  int year; // U0, U1, U2, etc..
public:
  void getYearOfStudy();
};

class employee : virtual public person {
   int year; // years of seniority
public:
   void getYearsOfService(); // avoid function name conflict
};

class studentemployee : public student, public employee {
};
```

What is virtual inheritance?

- Virtual inheritance ensures that a single copy of the common base class is maintained in all derived classes.
- As with virtual functions and dynamic dispatch, the compiler adds a layer of indirection to accesses to the virtual base class.
- Virtual inheritance must be anticipated and applied *above* the point where any two classes with a common base class are joined.

```
class A {};
class B: virtual public A {};
class C: virtual public A {};
class D: public B, public C {};
```

- Rules for virtual inheritance are more complex than we can cover here.

Advanced type casting

The complexity of C++ inheritance has inspired a number of additional type conversion operators.

`dynamic_cast<type>(`*expression*`)` - safely converts pointers and references among polymorphic types, with runtime checks.

```
class A { /* ... */ };
class B { /* ... */ };
class C: public A, public B { /* ... */ };

int main() {
  A *pa1 = new A;
  A *pa2 = new C;
  B *pb;
  C *pc;

  pc = dynamic_cast<C *>(pa1); // Returns NULL
  pc = dynamic_cast<C *>(pa2); // OK
  pb = dynamic_cast<B *>(pa2); // OK
}
```

Advanced type casting

`static_cast<type>(`*expression*`)` - converts among related classes with static checks. Unlike dynamic cast, it cannot consider the runtime type, it only considers the compile time type.

```
int main() {
  A *pa1 = new A;
  A *pa2 = new C;
  B *pb;
  C *pc;

  pc = static_cast<C *>(pa1); // OK, but dangerous
  pc = static_cast<C *>(pa2); // OK
  pb = static_cast<B *>(pc);  // OK
  pb = static_cast<B *>(pa2); // Compiler error
}
```

Advanced type casting

`reinterpret_cast<type>(`*expression*`)` - converts among any pointer types, with no checks or adjustments. This can lead to extremely dangerous situations, as we can convert among completely unrelated types!

```
int main() {
  A *pa1 = new A;
  B *pb;
  C *pc;

  pc = reinterpret_cast<C *>(pa1); // Legal but dangerous
  pb = reinterpret_cast<B *>(pa1); // Legal but dangerous
}
```

A few non-original comments

When designing class ’C’, given class ’B’, consider which of the following relationships applies:

- ’C’ **is a** ’B’ - if it makes sense to think of class ’C’ as a specialization of ’B’, then ’C’ can be implemented as a derived class of ’B’.
  - In a course system, a ’Student’ or ’Professor’ is a specialization of ’Person’
- ’C’ **has a** ’B’ - on the other hand, ’C’ may naturally contain a ’B’, but they aren’t the same kind of thing.
  - A ’Person’ probably has a ’Address’.
- ’C’ **is implemented as** ’B’ - ’C’ relies on the services of ’B’ in an inessential way. This is one case where private inheritance makes sense.
  - A stack ’C’ may be implemented as a linked list ’B’.

Using algorithm.h

Many of the functions in algorithm.h expect as input HOW to perform the task. For example sort takes as input 3 things: start iterator, end iterator and a FUNCTION specifying HOW to sort:

```
vector<int> foo;
......
sort(foo.begin(), foo.end(), compareNumbers);
```

You need to define in compareNumbers what “less than” means:

```
bool compareNumbers(int one, int two)
{
    return one % 2 < two % 2
}
```

Passing more arguments

Sometimes, you may want your function to require more arguments. In this case, you can not do it the same way. You must define a CLASS that defines the operator () . It will look something like: (see example on course webpage)

```
class ModComparer
{
private :
  int numberToModulus;
public :
  ModComparer(int number) {
    numberToModulus = number;
  }

  bool operator()(const int& one, const int& two )
  {
    //code here has access to private properties
    return one % numberToModulus < two % numberToModulus;
  }
};
...
vector<int> foo;
 ModComparer x(3);
 sort(foo.begin(), foo.end(),  x);
```