Creative Software Design

9 – Polymorphism 1

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Today's Topics

- What is Polymorphism?
- Pointers & References with Inheritance
- Polymorphism in C++
- Virtual Function
- Virtual Destructor
- Caution: Object Slicing

What is Polymorphism?

- From Greek words: “poly” means "many, much" and “morphism” means "form, shape“
- The ability to create a variable, a function, or an object **that has more than one form**. [wikipedia] - 다형성 (多形性).
- In other words,
  - Ability of an object of type A **to appear as and be used like another type B**
  - Ability to provide **access to entities of different types through the same interface**
- One of the fundamental OOP principles

Real-world Examples

- Steering wheel + accelerator + brake in trucks or cars.

  the same interface for *entities of different types*

- Volume + channel control in TV or DVD player remotes.

  the same interface for *entities of different types*

- Shutter button for film or digital cameras.

  the same interface for *entities of different types*

Types of Polymorphism

- **Subtype polymorphism (today's topic)**
  - Ability to **access a derived class object** through **its base class interface**
  - Often simply referred to as just "polymorphism".

- Ad hoc polymorphism
  - Allows functions with the same name to work differently for each type
  - Overloading in C++

- Parametric polymorphism
  - Allows a function or a data type to be written generically
  - Templates in C++

- Coercion polymorphism
  - (Implicit or explicit) casting in C++

An Example of Subtype Polymorphism

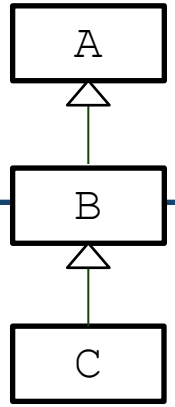
```
class Animal
{
public:
    virtual string talk() = 0;
};

class Cat : public Animal
{
public:
    virtual string talk()
    { return "Meow!"; }
};

class Dog : public Animal
{
public:
    virtual string talk()
    { return "Woof!"; }
};

void letsHear(Animal& animal)
{ cout << animal.talk() << endl; }

int main()
{
    Cat cat;
    Dog dog;
    letsHear(cat);
    letsHear(dog);
    return 0;
}
```

Pointers & References with Inheritance

- To use polymorphism in C++, you first have to understand **how to use pointers and references with inheritance**

- Recall that inheritance implies “is-a” relationship
  - A car is a vehicle.
    A truck is a vehicle.
    A cart is a vehicle.
    ...

Pointers with Inheritance



- A class (`B`) pointer can store
  - the address of its own class (`B`) object
  - the address of its derived class (`C`) object
  - CANNOT store the address of its base (`A`) class object

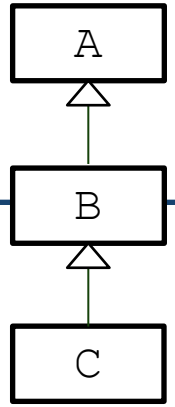
```cpp
#include <iostream>
using namespace std;

class Person
{
public:
    void talk()
    {
        cout << "talk" << endl;
    }
};

class Student : public Person
{
public:
    void study()
    {
        cout << "study" << endl;
    }
};

class CSStudent : public Student
{
public:
    void writeCode()
    {
        cout << "writeCode" << endl;
    }
};
```

```cpp
int main()
{
    Student* s1 = new Person; // error
// A Person CANNOT be regarded as a Student.

    Student* s2 = new Student;
    // A Student is regarded as a Student

    Student* s3 = new CSStudent;
    // A CSStudent is regarded as a Student

    Person* p1 = new Person;
    Person* p2 = new Student;
    Person* p3 = new CSStudent;

    delete p1;
    delete p2;
    delete p3;

    delete s1;
    delete s2;
    delete s3;

    return 0;
}
```

```cpp
#include <iostream>
using namespace std;

class Person
{
public:
    void talk()
    {
        cout << "talk" << endl;
    }
};

class Student : public Person
{
public:
    void study()
    {
        cout << "study" << endl;
    }
};

class CSStudent : public Student
{
public:
    void writeCode()
    {
        cout << "writeCode" << endl;
    }
};
```

```cpp
int main()
{
    Student st;

    Person* person_st = &st; // ok
    // A Student is regarded as a Person.

    Student* student_st = &st; // ok
    // A Student is regarded as a Student.

    CSStudent* csstudent_st = &st; //error!
// A Student CANNOT be regarded as a CSStudent.


    CSStudent csst;

    Person* person_csst = &csst; // ok
    Student* student_csst = &csst; // ok
    CSStudent* csstudent_csst = &csst; //ok

    return 0;
}
```

Pointers with Inheritance



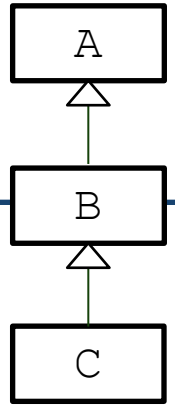
- A class (`B`) pointer can access
  - the members of its base class (`A`)
  - the members of its own class (`B`)
  - CANNOT access the members of its derived class (`C`)

```
#include <iostream>
using namespace std;

class Person
{
public:
    void talk()
    {
        cout << "talk" << endl;
    }
};

class Student : public Person
{
public:
    void study()
    {
        cout << "study" << endl;
    }
};

class CSStudent : public Student
{
public:
    void writeCode()
    {
        cout << "writeCode" << endl;
    }
};
```

```
int main()
{
    Student st;
    Person* person_st = &st;
    // A Student is regarded as a Person.

    person_st->talk();
    person_st->study(); // error!
    person_st->writeCode(); // error!
    // You cannot call them because not
all Persons are Students or CSStudents.

    return 0;
}
```

```
int main()
{
    Student st;
    Student* student_st = &st;

    student_st->talk();
    student_st->study();
    student_st->writeCode(); // error!

    return 0;
}
```

References with Inheritance



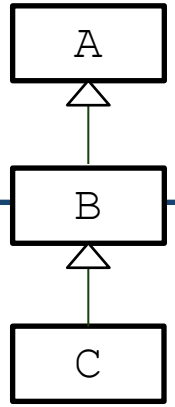
- A class (`B`) reference can refer to
  - its own class (`B`) object
  - its derived class (`C`) object
  - CANNOT refer to its base class (`A`) object

- Exactly the same as the pointers!

```cpp
#include <iostream>
using namespace std;

class Person
{
public:
    void talk()
    {
        cout << "talk" << endl;
    }
};

class Student : public Person
{
public:
    void study()
    {
        cout << "study" << endl;
    }
};

class CSStudent : public Student
{
public:
    void writeCode()
    {
        cout << "writeCode" << endl;
    }
};
```

```cpp
int main()
{
    Student st;

    Person& person_st = st; // ok
    Student& student_st = st; // ok
    CSStudent& csstudent_st = st; //error!

    CSStudent csst;

    Person& person_csst = csst; // ok
    Student& student_csst = csst; // ok
    CSStudent& csstudent_csst = csst; //ok

    return 0;
}
```

References with Inheritance



- A class (`B`) reference can access
  - the members of its base class (`A`)
  - the members of its own class (`B`)
  - CANNOT access the members of its derived class (`C`)

- Exactly the same as the pointers!

```cpp
#include <iostream>
using namespace std;

class Person
{
public:
    void talk()
    {
        cout << "talk" << endl;
    }
};

class Student : public Person
{
public:
    void study()
    {
        cout << "study" << endl;
    }
};

class CSStudent : public Student
{
public:
    void writeCode()
    {
        cout << "writeCode" << endl;
    }
};
```

```cpp
int main()
{
    Student st;
    Person& person_st = st;

    person_st.talk();
    person_st.study(); // error!
    person_st.writeCode(); // error!

    return 0;
}
```

```cpp
int main()
{
    Student st;
    Student& student_st = st;

    student_st.talk();
    student_st.study();
    student_st.writeCode(); // error!

    return 0;
}
```

Polymorphism in C++

- Subtype polymorphism *(will be referred to as just "polymorphism" in this lecture)* in C++ requires **references** or **pointers**
  - In C++, polymorphic behavior is **only possible when an object is referenced by a reference or a pointer**

- **A derived class object is treated as if it were its base class type** by accessing through a pointer or reference!

Polymorphism in C++

- In this example,
- Derived class objects (`Student st, CSStudent csst`)
- are treated as if they were their base class type (`Person`)
- by accessing through references (`person_st, person_csst`)

```
int main()
{
    Student st;
    CSStudent csst;

    Person& person_st = st;
    Person& person_csst = csst;

    person_st.talk();
    person_csst.talk();
    ...
}
```

Quiz #1

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that you must submit all quiz answers **in this format** to be counted as attendance.

Recall: Overriding Member Function

- You can override a member function to provide a custom functionality of the derived class.

```
// Vehicle class.

class Vehicle {
 public:
  Vehicle() {}
  void Accelerate();
  void Decelerate();

  LatLng GetLocation() const;
  double GetSpeed() const;
  double GetWeight() const;

 private:
  LatLng location_;
  double speed_;
  double weight_;
};
```

```
// Car class.
class Car : public Vehicle {
 public:
  Car() : Vehicle() {}

  int GetCapacity() const;

  // Override the parent's GetWeight().
  double GetWeight() const {
    return Vehicle::GetWeight()+passenger_weight_;
  }
 private:
  int capacity_;
  double passenger_weight_;
};
```

Overriding in CSStudent Example

```
#include <iostream>
using namespace std;

class Person
{
public:
    void talk()
    {
        cout << "I'm a person" << endl;
    }
};

class Student : public Person
{
public:
    void talk()
    {
        cout << "I'm a student" << endl;
    }
    void study()
    {
        cout << "study" << endl;
    }
};
```

```
class CSStudent : public Student
{
public:
    void talk()
    {
        cout << "I'm a CS student" <<
endl;
    }
    void writeCode()
    {
        cout << "writeCode" << endl;
    }
};

int main()
{
    CSStudent csst;
    csst.talk();
    // Output: "I'm a CS student"

    Person& person_csst = csst;
    person_csst.talk();
    // Output: "I'm a person" ??

    return 0;
}
```

Why is `Person::talk()` called instead of `CSStudent::talk()`?

- By default, C++ compiler generates code that matches a function call with the correct function definition ***at compile time*** based on ***declared type*** (called ***static binding***).

- The ***actual type*** of the object referenced / pointed by the base class reference / pointer is **unknown *at compile time***.

- Only the ***declared type*** (base class reference / pointer type) is **known *at compile time***.

More Examples

```
int main()
{
    Person p;
    Student st;
    CSStudent csst;

    Person& person_p = p;
    Person& person_st = st;
    Person& person_csst = csst;

    person_p.talk();    // Person::talk()
    person_st.talk();    // Person::talk()
    person_csst.talk();    // Person::talk()

    Student& student_st = st;
    Student& student_csst = csst;

    student_st.talk();    // Student::talk()
    student_csst.talk();    // Student::talk()

    return 0;
}
```

How to get polymorphic behavior?

- But this is not what we want!

- We often want to customize the behavior of the same member function in each derived class
  - so that we get different behaviors through the same interface → **Polymorphism!**

Like this:

```
Person& person_p = p;
Person& person_st = st;
Person& person_csst = csst;

person_p.talk();     // Person::talk()
person_st.talk();     // Student::talk()
person_csst.talk();     // CSStudent::talk()
```

Virtual Functions

- By declaring the member function **`virtual`**, you can do this!

```
virtual void talk();
```

- Calling a virtual functions means:
- C++ compiler generates code that matches a function call with the correct function definition ***at runtime*** based on ***actual type*** (called ***dynamic binding***).

Virtual Functions

- Virtual functions are keys to implement polymorphism in C++.
  - declare polymorphic member functions to be 'virtual',
  - and use the base class pointer / reference to refer an instance of the derived class,
  - then the function call from a base class pointer / reference will execute the function overridden in the derived class.

- Where to specify ‘virtual’?
  - Actually, ‘virtual’ keyword is *not necessary* for the overridden virtual member function in the *derived class*.
  - But specifying ‘virtual’ for all virtual functions in descendant classes is recommended.

Virtual Function Example

```
// Vehicle classes.

class Vehicle {
 public:
  virtual void Accelerate() {
    cout << "Vehicle.Accelerate";
  }
};

class Car : public Vehicle {
 public:
  virtual void Accelerate() {
    cout << "Car.Accelerate";
  }
};

class Truck : public Vehicle {
 public:
  virtual void Accelerate();
    cout << "Truck.Accelerate";
  }
};
```

```
// Main routine.

int main() {
  Car car;
  Truck truck;
  Vehicle* pv = &car;
  pv->Accelerate();
  // Outputs Car.Accelerate.

  pv = &truck;
  pv->Accelerate();
  // Outputs Truck.Accelerate.

  Vehicle vehicle;
  pv = &vehicle;
  pv->Accelerate();
  // Outputs Vehicle.Accelerate.
  return 0;
}
```

Virtual Function Example (w/o virtual)

```
// Vehicle classes.

class Vehicle {
 public:
  void Accelerate() {
    cout << "Vehicle.Accelerate";
  }
};

class Car : public Vehicle {
 public:
  void Accelerate() {
    cout << "Car.Accelerate";
  }
};

class Truck : public Vehicle {
 public:
  void Accelerate();
    cout << "Truck.Accelerate";
  }
};
```

```
// Main routine.

int main() {
  Car car;
  Truck truck;
  Vehicle* pv = &car;
  pv->Accelerate();
  // Outputs Vehicle.Accelerate.
  car.Accelerate();
  // Outputs Car.Accelerate.

  pv = &truck;
  pv->Accelerate();
  // Outputs Vehicle.Accelerate.
  truck.Accelerate();
  // Outputs Truck.Accelerate.

  Vehicle vehicle;
  pv = &vehicle;
  pv->Accelerate();
  // Outputs Vehicle.Accelerate.
  return 0;
}
```

Virtual Functions in CSStudent Example

```
#include <iostream>
using namespace std;

class Person
{
public:
    virtual void talk()
    {
        cout << "I'm a person" << endl;
    }
};

class Student : public Person
{
public:
    virtual void talk()
    {
        cout << "I'm a student" << endl;
    }
    void study()
    {
        cout << "study" << endl;
    }
};
```

```
class CSStudent : public Student
{
public:
    virtual void talk()
    {
        cout << "I'm a CS student" <<
endl;
    }
    void writeCode()
    {
        cout << "writeCode" << endl;
    }
};

int main()
{
    CSStudent csst;
    csst.talk();
    // Output: "I'm a CS student"

    Person& person_csst = csst;
    person_csst.talk();
    // Output: "I'm a CS student"

    return 0;
}
```

Another Example

```
void makePersonTalk(Person* person)
{
    person->talk();
}

int main()
{
    vector<Person*> people;
    people.push_back(new Person);
    people.push_back(new Person);
    people.push_back(new Student);
    people.push_back(new Student);
    people.push_back(new Person);
    people.push_back(new Student);
    people.push_back(new CSStudent);
    people.push_back(new CSStudent);

    for(int i=0; i<people.size(); ++i)
        makePersonTalk(people[i]);

    for(int i=0; i<people.size(); ++i)
        delete people[i];

    return 0;
}
```

Quiz #2

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

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Destructor and Virtual

```
class A {
public:
  A() { cout << " A” << endl; }
  ~A() { cout << " ~A” << endl; }
};

class AA : public A {
public:
  AA() { cout << " AA” << endl; }
  ~AA() { cout << " ~AA” << endl; }
};

int main() {
  AA* pa = new AA;  // OK: prints ' A AA'.
  delete pa;        // prints ' ~AA ~A'.
  return 0;
}
```

Destructor and Virtual

- What happens if a derived class object is **'deleted' by its base class pointer?**

```
class A {
public:
  A() { cout << " A"; }
  ~A() { cout << " ~A"; }
};

class AA : public A {
public:
  AA() { cout << " AA"; }
  ~AA() { cout << " ~AA"; }
};

int main() {
  A* pa = new AA;  // OK: prints ' A AA'.
  delete pa;       // Hmm..: prints only ' ~A'.
  return 0;
}
```

Virtual Destructor

- What happens if a derived class object is **'deleted' by its base class pointer?**

- If the base class destructor **is not `virtual`**,
  - only the base class destructor is called
  - the derived class destructor is **not** called

- **This may cause memory leak**
  - Think about this case: A derived class destructor has the code that `delete` its member variables which are assigned by `new` in its constructor

```
#include <iostream>
using namespace std;

class Shape
{
public:
    Shape() {}
    ~Shape() {}
};

class Rectangle : public Shape
{
private:
    int* width;
    int* height;
public:
    Rectangle()
    {
        width = new int;
        height = new int;
        cout << "Rectangle()" << endl;
    }
    ~Rectangle()
    {
        delete width;
        delete height;
        cout << "~Rectangle()" << endl;
    }
};
```

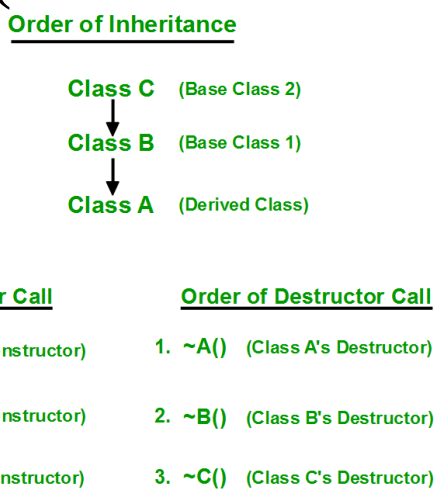
```
int main()
{
    Shape* shape1 = new Rectangle;
    delete shape1;

    return 0;
}
```

Virtual Destructor

- What happens if a derived class object is **'deleted' by its base class pointer?**

- If the base class destructor **is `virtual`**,
  - **the derived class destructor is called**
  - and then base class destructors is called (reverse order of constructor calls)



```cpp
#include <iostream>
using namespace std;

class Shape
{
public:
    Shape() {}
    virtual ~Shape() {}
};

class Rectangle : public Shape
{
private:
    int* width;
    int* height;
public:
    Rectangle()
    {
        width = new int;
        height = new int;
        cout << "Rectangle()" << endl;
    }
    virtual ~Rectangle()
    {
        delete width;
        delete height;
        cout << "~Rectangle()" << endl;
    }
};
```

```cpp
int main()
{
    Shape* shape1 = new Rectangle;
    delete shape1;

    return 0;
}
```

When do we need a virtual destructor?

- A destructor of a base class **should be** `virtual` if
  - its descendant class instance can be **deleted by the base class pointer.**
  - in other words, any of member function is **virtual** (which means it's a polymorphic base class).

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

class AA : public A {
public:
  AA() { cout << " AA"; }
  virtual ~AA() { cout << " ~AA"; }
};

int main() {
  A* pa = new AA;  // OK: prints ' A AA'.
  delete pa;       // OK: prints ' ~AA ~A'.
  return 0;
}
```

Virtual Destructor

- Note that constructors cannot be `virtual`
  - "virtual" allows us to call a function knowing only an interfaces and not the exact type of the object.
  - But to create an object, you need to know the exact type of what you want to create.
  - Bjarne Stroustrup's C++ Style and Technique FAQ: Why don't we have virtual constructors?

Quiz #3

- Go to https://www.slido.com/
- Join #**csd-ys**
- Click "Polls"

- Submit your answer in the following format:
  - **Student ID: Your answer**
  - **e.g. 2017123456: 4)**

- Note that you must submit all quiz answers **in this format** to be counted as attendance.

CAUTION: Copying a derived class object to a base class object

```
#include <iostream>
using namespace std;
class Animal{
public:
    virtual void makeSound() {cout << "(none)" << endl;}
};
class Dog : public Animal{
public:
    virtual void makeSound() {cout << "bark" << endl;}
};
int main()
{
    Animal animal;
    animal.makeSound(); // "(none)"

    Dog dog;
    dog.makeSound();  // "bark"

    // A typical way for polymorphism
    Animal& goodDog = dog;
    goodDog.makeSound(); // "bark"

    // ???
    Animal badDog = dog;
    badDog.makeSound(); // "(none)"
}
```

CAUTION: Avoid Object Slicing

- In C++, **object slicing** occurs when a derived class object is copied to a base class object.
  - Additional attributes of a derived class object are "sliced off"

```
class Base { int x, y; };

class Derived : public Base { int z, w; };

int main()
{
    Derived d;
    Base b = d; // Object Slicing,  z and w of d are sliced off
}
```

- Note that **C++ polymorphism** works only with references or pointers, **not with objects.**

Next Time

- Labs for this lecture:
  - Lab1 (next Tue): Assignment 9-1
  - Lab2 (next Thur): Assignment 9-2

- Next lecture:
  - 10 - Polymorphism 2