Chapter 15

Polymorphism and Virtual Functions

Learning Objectives

- Virtual Function Basics
  - Late binding
  - Implementing virtual functions
  - When to use a virtual function
  - Abstract classes and pure virtual functions
- Pointers and Virtual Functions
  - Extended type compatibility
  - Downcasting and upcasting
  - C++ "under the hood" with virtual functions

Virtual Function Basics

- Polymorphism
  - Associating many meanings to one function
  - Virtual functions provide this capability
  - Fundamental principle of object-oriented programming!
- Virtual
  - Existing in "essence" though not in fact
- Virtual Function
  - Can be "used" before it's "defined"

late binding or dynamic binding

C++ polymorphism means that a call to a member function will cause a different function to be executed depending on the type of object that invokes the function.

Figures Example

- Best explained by example:
- Classes for several kinds of figures
  - Rectangles, circles, ovals, etc.
  - Each figure might be an object of different class
    - Rectangle data: height, width, center point
    - Circle data: center point, radius
- All derive from one parent-class: Figure
- Require function: draw()
  - Different instructions for each figure

Figures Example 2

- Each class needs different *draw* function
- Can be called "draw" in each class, so:

  Rectangle r;
  Circle c;
  r.draw(); //Calls Rectangle class's draw
  c.draw(); //Calls Circle class's draw
- Nothing new here yet…

Figures Example: center()

- Parent class Figure contains functions that apply to "all" figures; consider:
  center(): moves a figure to center of screen
  1. Erases 1st,
  2. then re-draws
  - So Figure::center() would use function draw() to re-draw
  - Complications!
    - Which draw() function?
    - From which class?

Figures Example: New Figure

- Consider new kind of figure comes along:
  Triangle class
  derived from Figure class
- Function center() inherited from Figure
  - Will it work for triangles?
  - It uses draw(), which is different for each figure!
  - It will use Figure::draw() → won't work for triangles
- Want inherited function center() to use function Triangle::draw() NOT function Figure::draw()
  - But class Triangle wasn't even WRITTEN when Figure::center() was! Doesn't know "triangles"!

Figures Example: Virtual!

- Virtual functions are the answer
- Tells compiler:
  - "Don’t know how function is implemented"
  - "Wait until used in program"
  - "Then get implementation from object instance"
- Called late binding or dynamic binding
  - Virtual functions implement late binding

Virtual Functions: Another Example

- Record-keeping program for automotive parts store
  - Track sales
  - Don't know all sales yet
  - 1st only regular retail sales
  - Later: Discount sales, mail-order, etc.
    - Depend on other factors besides just price, tax

Virtual Functions: Auto Parts

- Program must:
  - Compute daily gross sales
  - Calculate largest/smallest sales of day
  - Perhaps average sale for day
- All come from individual bills
  - But many functions for computing bills will be added "later"!
    - When different types of sales added!
- So function for "computing a bill" will be virtual!

Class Sale Definition

- class Sale // for each part (item)

```
{
public:
    Sale();
    Sale(double thePrice);
    double getPrice() const;
    virtual double bill() const;
    double savings(const Sale& other) const;
private:
    double price;
};
```

Member Functions: savings and operator <

- ```
  double Sale::savings(const Sale& other) const
  {
      return (bill() – other.bill());
  }
  ```

- ```
  bool operator < (const Sale& first, const Sale& second)
  {
      return (first.bill() < second.bill());
  }
  ```

- Notice BOTH use member function bill()!

Class Sale

- Represents sales of single item with no added discounts or charges.
- Notice reserved word "virtual" in declaration of member function *bill*
  – Impact: Later, derived classes of Sale can define THEIR versions of function bill
  – Other member functions of Sale will use version based on object of derived class!
  – They won’t automatically use Sale’s version!

Derived Class DiscountSale Defined

```
class DiscountSale   :  public Sale
{
public:
      DiscountSale();
      DiscountSale(double thePrice, double the Discount);
      double getDiscount() const;
      void setDiscount(double newDiscount);
      double bill() const;      // omit "virtual"
      // double savings(const Sale& other) const;
private:
      double discount;
};
```

DiscountSale’s Implementation of bill()

- double DiscountSale::**bill**() const
  {
  double fraction = discount/100;
  return (1 – fraction)*getPrice();
  }
- Qualifier "virtual" does not go in actual function definition
  - "Automatically" virtual in derived class
  - Declaration (in interface) not required to have "virtual" keyword either (but usually does)

DiscountSale’s Implementation of bill()

- Virtual function in base class:
  - "Automatically" virtual in derived class
- Derived class declaration (in interface)
  - Not required to have "virtual" keyword
  - But typically **<u>included</u>** anyway, for readability

Derived Class DiscountSale

- DiscountSale's member function bill() implemented differently than Sale's
  - Particular to "discounts"
- Member functions *savings* and "<"
  - Will use this definition of bill() for all objects of DiscountSale class!
  - Instead of "defaulting" to version defined in Sales class!

Virtual: Wow!

- Recall class Sale written long before derived class DiscountSale
  - Members savings and "<" compiled before even had ideas of a DiscountSale class
- Yet in a call like:
  DiscountSale **d1**, d2;
  d1.savings(d2);
  - Call in savings() to function bill() knows to use definition of ***bill() from DiscountSale*** class
- Powerful!

Virtual: How?

- To write C++ programs:
  - Assume it happens by "magic"!
- But explanation involves late binding
  - Virtual functions implement late binding
  - Tells compiler to "wait" until function is used in program
  - Decide which definition to use based on calling object
- Very important OOP principle!

Overriding

- Virtual function definition changed in a derived class
  - We say it's been "overridden"
- Similar to redefined
  - Recall: for standard functions
- So:
  - Virtual functions changed: ***overridden***
  - Non-virtual functions changed: ***redefined***

Virtual Functions: Why Not All?

- Clear advantages to virtual functions as we've seen
- One major *disadvantage*: overhead!
  - Uses **more storage**
  - Late binding is "on the fly", so programs run **slower**
- So if virtual functions not needed,

  should **not be used**

One More Example of “Virtual”

What are outputs?

One Sample Output

- Elf attacks for 37 points!
- Creature 2 has 13 hit points.
- Balrog attacks for 46 points!
- Creature 1 has 4 hit points.
- Elf attacks for 8 points!
- Creature 2 has 5 hit points.
- Balrog attacks for 9 points!
- Creature 1 has -5 hit points.

- Creature 2 wins!

Pure Virtual Functions

- Base class might not have "meaningful“ definition for some of it’s members!
  - It’s purpose solely for others to derive from
- Recall class Figure
  - All figures are objects of derived classes
    - Rectangles, circles, triangles, etc.
  - Class Figure has no idea how to draw!
- Make it a pure *virtual* function:

virtual void draw() = 0;

Abstract Base Classes

- Pure virtual functions require no definition
  - Forces all derived classes to define "their own" version
- Class with one or more pure virtual functions is: abstract base class
  - Can only be used as base class
  - No objects can ever be created from it
    - Since it doesn't have complete "**definitions**" of all it's members!
- If derived class fails to define all pure's:
  - It's an abstract base class too

Example of Abstract Class

```
class Base          //Abstract base class
{
 public:
 virtual void show() = 0;
//Pure Virtual Function
};

class Derived:public Base
{
 public:
 void show()
 {
     cout << "Implementation of Virtual Function in Derived class";
  }
};
```

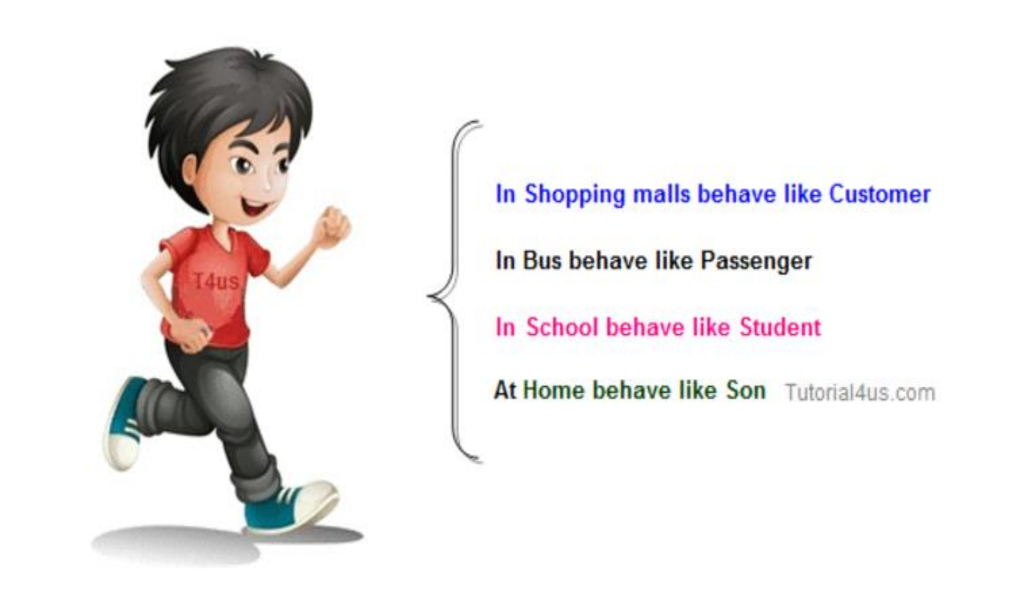
```
int main()
{
 Base obj;       //Compile Time Error
 Base *b;
 Derived d;
 b = &d;
 b->show();
}
```

Abstract classes cannot be used to instantiate objects and serves only as an interface

Real life example of polymorphism

- If you are in
  - Class room => behave like a student
  - Market => behave like a customer
  - Home => behave like a son or daughter

Here one person have different-different behaviors.



Types of polymorphism

- Compile time polymorphism
  – Method overloading
  – Method overriding (redefine)
- Run time polymorphism
  – achieve by using **virtual function**

Extended Type Compatibility

- Given:
  Derived is derived class of Base
  - Derived objects can be assigned to objects of type Base
  - But NOT the other way!
- Consider previous example:
  - A DiscountSale "is a" Sale, but reverse not true

Extended Type Compatibility Example

```
class Pet
{
  public:
     string name;
     virtual void print() const;
};
class Dog : public Pet
{
public:
     string breed;
     virtual void print() const;
};
```

Classes Pet and Dog

- Now given declarations:
  Dog vdog;
  Pet vpet;
- Notice member variables name and breed are public!
  - For example purposes only! Not typical!

Using Classes Pet and Dog

```
class Pet
{
  public:
      string name;
      virtual void print() const;
};
class Dog : public Pet
{
public:
      string breed;
      virtual void print() const;
};
```

- Anything that "is a" dog "is a" pet:
  - **vdog**.name = "Tiny";
    vdog.breed = "Great Dane";
    vpet = **vdog**;
  - These are allowable
- Can assign values to parent-types, but **not** reverse
  - A pet "is not a" dog (not necessarily)

Extended Type Compatibility Example II

```
class Polygon {
protected:
        int width, height;
public:
        Polygon() :width(0), height(0) {}
        void set_values(int a, int b)
        {
                width = a; height = b;
        }
};

class Rectangle : public Polygon {
public:
        int area()
        {
                return width*height;
        }
};

class Triangle : public Polygon {
public:
        int area()
        {
                return width*height / 2;
        }
};
```

```
int main() {
        Rectangle rect;
        Triangle trgl;
        Polygon  ppolyRect = rect;
        Polygon  ppolyTri = trgl;
        ppolyRect.set_values(4, 5);
        ppolyTri.set_values(4, 5);
        cout << rect.area() << '\n';
        cout << trgl.area() << '\n';
        return 0;
}
```

```
0
0
```

Extended Type Compatibility Example II

```
class Polygon {
protected:
    int width, height;
public:
    Polygon() :width(0), height(0) {}
    void set_values(int a, int b)
    {
        width = a; height = b;
    }
};

class Rectangle : public Polygon {
public:
    int area()
    {
        return width*height;
    }
};

class Triangle : public Polygon {
public:
    int area()
    {
        return width*height / 2;
    }
};
```

```
int main() {
    Rectangle rect;
    Triangle trgl;
    Polygon * ppoly1 = &rect;
    Polygon * ppoly2 = &trgl;
    ppoly1->set_values(4, 5);
    ppoly2->set_values(4, 5);
    cout << rect.area() << '\n';
    cout << trgl.area() << '\n';
    return 0;
}
```

20
10

Extended Type Compatibility Example III

```
class Polygon {
  protected:
    int width, height;
  public:
    void set_values (int a, int b)
      { width=a; height=b; }
    virtual int area ()
      { return 0; }
};

class Rectangle: public Polygon {
  public:
    int area ()
      { return width * height; }
};

class Triangle: public Polygon {
  public:
    int area ()
      { return (width * height / 2); }
};
```

```
int main () {
  Rectangle rect;
  Triangle trgl;
  Polygon poly;
  Polygon * ppolyRect = &rect;
  Polygon * ppolyTri = &trgl;
  Polygon * ppolyPly = &poly;
  ppolyRect->set_values (4,5);
  ppolyTri->set_values (4,5);
  ppolyPly->set_values (4,5);
  cout << ppolyRect->area() << '\n';
  cout << ppolyTri->area() << '\n';
  cout << ppolyPly->area() << '\n';
  return 0;
}
```

```
20
10
0
```

Slicing Problem

- Notice value assigned to vpet "loses" it's breed field!

  cout << vpet.breed; // Produces ERROR msg!

  – Called slicing problem
- Might seem appropriate
  – Dog was moved to Pet variable, so it should be treated like a Pet
    - And therefore not have "dog" properties

  – Makes for interesting ***philosphical debate***

Slicing Problem Fix

- In C++, slicing problem is nuisance
  - It still "is a" Great Dane named Tiny
  - We'd like to refer to it's breed even if it's been treated as a Pet
- Can do so with pointers to dynamic variables

Slicing Problem Example

- Pet *ppet;
  Dog *pdog;
  pdog = new Dog;
  pdog->name = "Tiny";
  pdog->breed = "Great Dane";
  ppet = pdog;
- Cannot access breed field of object pointed to by ppet:
  cout << ppet->breed;   //ILLEGAL!

Slicing Problem Example (Contd.)

- Must use **virtual** member function:
  ppet->print();
  - Calls print member function in Dog class!
    - Because it's virtual
  - C++ "waits" to see what object pointer ppet is actually pointing to before "binding" call

if we upcast (Upcasting and downcasting) to an object instead of a **pointer** or **reference**, the object is sliced.

Slicing Problem Example

```
class BaseCls {
 public:
   BaseCls(const string& s) : name(s) {}
   virtual void Show() const    {
     cout << "Base: " << name << " Show()" << endl;
   }
private:
   string name;
};
class DerivedCls : public BaseCls  {
 private:
   string name;
   string habitat;
 public:
   DerivedCls(const string& sp, const string &s, const string &h)  : BaseCls(sp), name(s), habitat(h) {};
   virtual void Show() const    {
      cout << "DerivedCls: " << name << " Show() in " << habitat << endl;
  }
};
void Fun1(BaseCls a) {  a.Show(); }
void Fun (const BaseCls &a) {  a.Show (); }
```

```
int main()
{
 BaseCls ocBase("Base");
 DerivedCls ocDerived("Test","Test1",
                      "Test1 & Test2");
 cout << "pass-by-value" << endl;
 Fun1(ocBase);
 Fun1(ocDerived);
 cout << "\npass-by-reference" << endl;
 Fun(ocBase);
 Fun(ocDerived);
return 0;
}
```

```
pass-by-value
Base: Base Show()
Base: Test Show()
pass-by-reference
Base: Base ()
DerivedCls: Test1 Show() in Test1 & Test2
```

```
int main()
{
 BaseCls ocBase("Base");
 DerivedCls ocDerived("Test","Test1",
                                         "Test1 & Test2");
 cout << "pass-by-value" << endl;
 Fun1(ocBase);
 Fun1(ocDerived);
 cout << "\npass-by-reference" << endl;
 Fun(ocBase);
 Fun(ocDerived);
return 0;
}
```

Pass-by-value

```
pass-by-value
Base: Base Show()
Base: Test Show()
pass-by-reference
Base: Base ()
DerivedCls: Test1 Show() in Test1 & Test2
```

Pass-by-value

The compiler knows the precise type of the object

- the derived object has been forced to become a base object.

When passing by value, the copy-constructor for a BaseCls object is used

- which initializes the vptr (virtual table pointer) to the Base vtbl (virtual table) and copies only the BaseCls parts of the object.

The DerivedCls object lost all the things that make it Derived-like, and it becomes an BaseCls during slicing.

Virtual Destructors

- Recall: destructors needed to de-allocate dynamically allocated data
- Consider:
  Base *pBase = new Derived;
  …
  delete pBase;
  - Would **call** *base class destructor* even though pointing to Derived class object!
  - *Making destructor **virtual** fixes this!*
- Good policy for all destructors to be virtual

Virtual Destructor

```
class Base {
public:
    virtual ~Base()    {       cout << "Calling ~Base()" << endl;    }
};

class Derived: public Base {
private:
    int* m_pnArray;
 public:
    Derived(int nLength)    {        m_pnArray = new int[nLength];     }
     virtual ~Derived()
    {
        cout << "Calling ~Derived()" << endl;
        delete[] m_pnArray;
    }
};

int main() {
    Derived *pDerived = new Derived(5);
    Base *pBase = pDerived;
    delete pBase;

    return 0;
}
```

this program produces the following result:

1. Calling ~Derived()
2. Calling ~Base()

Pure Virtual Destructors

```
class Base
{
 public:
 virtual ~Base() = 0;     //Pure Virtual Destructor
};

//Definition of Pure Virtual Destructor
Base::~Base() { cout << "Base Destructor"; }

class Derived: public Base
{
 public:
 ~Derived() { cout<< "Derived Destructor"; }
};
```

Pure Virtual Destructors

- Also, pure virtual Destructors must be defined
  - Which is against the pure virtual behaviour.
- The only difference between Virtual and Pure Virtual Destructor
  - pure virtual destructor will make its Base class Abstract
    - Hence cannot create object of that class
- There is no requirement of implementing pure virtual destructors in the derived classes.

Casting

- Consider:
  Pet vpet;
  Dog vdog;
  …
  vdog = static_cast<Dog>(vpet); //**ILLEGAL**!
- Can’t cast a pet to be a dog, but:
  vpet = vdog;   // **Legal**!
  vpet = static_cast<Pet>(vdog); //Also **legal**!
- ***Upcasting*** is OK
  – From descendant type to ancestor type

Downcasting

- Downcasting dangerous!
  - Casting from ancestor type to descended type
  - Assumes information is "added"
  - Can be done with dynamic_cast:

    ```
    Pet *ppet;
    ppet = new Dog;
    Dog *pdog = dynamic_cast<Dog*>(ppet);
    ```

    - Legal, but dangerous!
- Downcasting rarely done due to pitfalls
  - Must track all information to be added
  - All member functions must be virtual

Inner Workings of Virtual Functions

- Don't need to know how to use it!
  - Principle of information hiding
- Virtual function table
  - Compiler creates it
  - Has pointers for each virtual member function
  - Points to location of correct code for that function
- Objects of such classes also have pointer
  - Points to ***virtual function table***

Summary 1

- Late binding delays decision of which member function is called until runtime
  - In C++, virtual functions use late binding
- Pure virtual functions have no definition
  - Classes with at least one are abstract
  - No objects can be created from abstract class
  - Used strictly as base for others to derive

Summary 2

- Derived class objects can be assigned to base class objects
  - Base class members are lost; slicing problem
- Pointer assignments and dynamic objects
  - Allow "fix" to slicing problem
- Make all destructors virtual
  - Good programming practice
  - Ensures memory correctly de-allocated