

# Unit 3. Inheritance & Polymorphism

## 3.1 Building Polymorphism

Sam loves the idea of using class relations to solve programming problems. However, he can't see how it can work. Worse! He is afraid that it will incur a huge performance penalty. The only way he can trust a new programming technique is to know how it works. While digging around the internet to get to the bottom of this mystery, he remembers reading about V-Tables earlier in the semester. This should make "is-a" relations quite easy...

### Objectives

By the end of this chapter, you will be able to:

- Describe how "is-a" relations can be accomplished with V-Table assignments
- Appreciate how efficient "is-a" can be

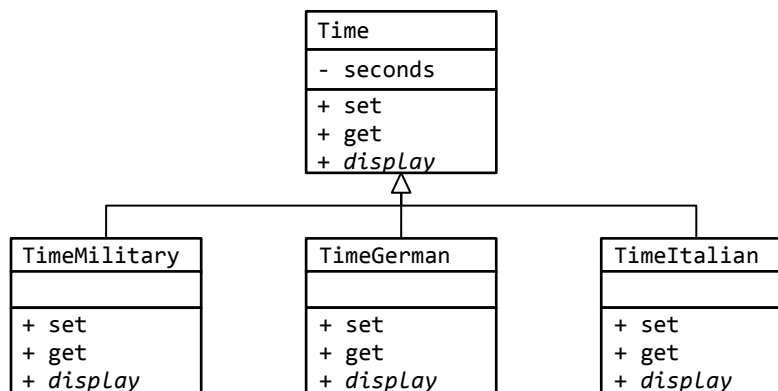
### Prerequisites

Before reading this chapter, please make sure you are able to:

- How to define a pointer to a function (Chapter 1.5)
- How to build a class out of a structure and function pointers (Chapter 2.1)
- Create a UML class diagram describing "is-a" relations (Chapter 3.0)

## What is polymorphism and why you should care

**Polymorphism** is the process of one class having more than one variation. Each variation honors the same contract (called "interface") though the behavior details (called "implementation") may be different. Consider, for example, a `Time` class. An object of this class is able to display a time in the traditional US format "3:28pm." We also wish to have variations of this class that use a different time format. We might have the military time format "15:28" as well as the German format "15.28" and the Italian format of "03:28 PM." If we were to have an array of `Time` objects, some of which were traditional, some are military, some German, and some Italian, then polymorphism would be at work. Though each member of the array is of type `Time`, four different flavors are represented in the array.



The purpose of this chapter is to illustrate how the compiler is able to implement polymorphism. This is important for understanding the performance and space implications of making a class polymorphic. Additionally, polymorphism in C++ has a few quirks that are difficult to understand unless you can see the underlying mechanisms. By seeing how the compiler implements polymorphism, these quirks make a lot more sense and polymorphism becomes much easier to use.

# Binding

**Binding** is the process of connecting the name of a function or variable with the location in memory where the code or data resides. If, for example, you instantiate an integer called `count` (`int count;`), the compiler sets aside four bytes of memory for the integer and binds the memory to the name `count`. The same happens with functions. When a function is defined, the instructions corresponding to the function are placed into memory and the compiler binds the name with that memory address. If the programmer attempts to call a function that is not defined, then the compiler (actually the linker) reports the binding error and compilation is halted.

There are two flavors of binding that occur in a program: early binding and late binding.

## Early binding

Early binding is the flavor of binding that the compiler performs. In a traditional program, the function name is “connected” with the code of the function at compile time. In other words, when a function is referenced in some caller code, the compiler knows exactly where the code for the function is. This process is called “early binding” because the binding between the name of the function and the code of the function occurs before the program is executed. Errors in early binding are displayed as a compiler error.

## Late binding

Late binding is the flavor of binding that occurs while the program is executing or running. Consider an array of ten integers. If the program initializes one of the members of the array with `array[index] = 0;`, then it is impossible for the compiler to tell which location in memory is being changed. The reason is that the value of `index` is not known at compile time; it is resolved at run-time. If the programmer attempts to access an item in an array with an index that is out of bounds (such as `index == -1`), the compiler cannot catch the programmer’s error. Instead we will get a run-time error such as a crash or a segmentation fault.

Segmentation fault (core dumped)

All late binding mechanisms involve pointers, and all uses of pointers indicates late binding is at work. Therefore pointers to variables, arrays, and pointers-to-functions are indications of late binding.

In polymorphic scenarios, the compiler does not know which version of a function will get executed until run time. In this scenario, the function name is actually a pointer. When the object owning the pointer gets instantiated, then the pointer gets initialized. In other words, it is unknown which version of the function will get associated with (or assigned to) the pointer until the object is created. This process an example of late binding because the binding between the name of the function and the code of the function occurs after the program execution has begun.

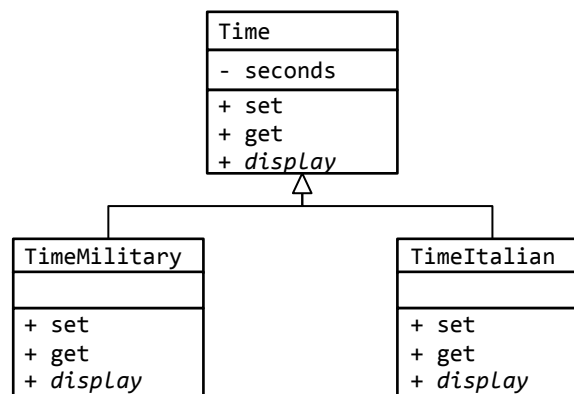
Polymorphism in C++ is accomplished by assigning the v-table to a class when an object is instantiated allowing the programmer to specify the flavor of a class at run-time.

# Virtual method tables and polymorphism

Recall from Chapter 2.1 how a class can be built from a structure and function pointers. This could be done by having one function pointer for each method or by creating a special structure called a virtual method table (v-table) containing all the function pointers.

```
struct VTableTime
{
    void (*display)(const Time * pThis);
    void (*set)(Time * pThis, int hour, int minute, int second);
    void (*get)(const Time &* pTime, int & hour, int & minute, int & second);
};
```

In most cases, all the objects from a given class use the same v-table. For example, if there are ten `Time` objects, each object will use the same `display()` function. What happens when you want to have many variations of the `Time` class: one displaying a date using the short format 3:28pm, another using the military version 15:28, and yet another using the Italian format 05:28 PM?



The only differences between these three classes is the different `display()` functions.

```
void displayTime(const Time * pThis);           // 3:28pm
void displayTimeMilitary(const Time * pThis);   // 15:28
void displayTimeItalian(const Time & pThis);    // 03.28 PM
```

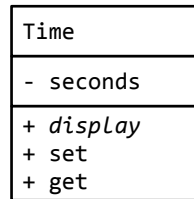
With these functions, we can initialize our three v-tables:

```
const VTableTime V_TABLE_TIME =                // for the Time variation
{
    &displayTime,                               // for Time::display() with 3:28pm
    &setTime,                                   // for Time::set()
    &getTime                                  // for Time::get()
};

const VTableTime V_TABLE_TIME_MILITARY =       // for the Military Time variation
{
    &displayTimeMilitary,                     // for Time::display() with 15:28
    &setTime,                                // for Time::set()
    &getTime                                  // for Time::get()
};

const VTableTime V_TABLE_TIME_ITALIAN =        // for the Italian Time variation
{
    &displayTimeItalian,                     // for Time::display() with 03:28 PM
    &setTime,                                // for Time::set()
    &getTime                                  // for Time::get()
};
```

In Chapter 2.1, we saw how to turn a UML class diagram into a structure:



The class implementation of `Time` using structures is:

```
struct Time // the class/structure tag Time
{
    int seconds; // the one member variable: seconds
    VTableTime * __vptr; // all the methods are in VTableTime
}; // using the standard name __vptr
```

As you may recall, using this manual method of instantiating an object requires us to assign the v-table to the object in a separate step:

```
{
    Time time1; // no methods currently attached
    time1.__vptr = &V_TABLE_TIME; // this gets the standard display()
    time1.__vptr->set(&time1, 15, 28, 0);

    Time time2;
    time2.__vptr = &V_TABLE_MILITARY; // with the Military version of the
    time2.__vptr->set(&time2, 15, 28, 0); // v-table, this gets the
    // displayTimeMilitary() function

    Time time3;
    time3.__vptr = &V_TABLE_ITALIAN; // displayTimeItalian() here
    time3.__vptr->set(&time3, 15, 28, 0);

    // now display all three Times
    time1.__vptr->display(&time1); // 3:28pm
    time2.__vptr->display(&time2); // 15:28
    time3.__vptr->display(&time3); // 03:29 PM
}
```

There are a couple key take-aways from this:

- The cost of binding a v-table to an object is a single instruction. This is extremely fast.
- Once the appropriate v-table is binded to the object immediately after the object is instantiated, there is no run-time cost to polymorphism.
- Having one derived class off of `Time` and having a thousand derived classes cost the same. Therefore there is zero cost to adding a derived class to a base class.

### Example 3.1 – Date

Demo

This example will demonstrate how to create a simple polymorphic Date class using structures and function pointers instead of true C++ classes.

Problem

Write a program to represent three variations of dates: a long date in the form of “11th of November, 1888,” a short date in the form of “11/12/1888,” and an empty date displaying the empty string.

Solution

The first part of the solution is to make a v-table representing the methods of Date:

```
struct VTableDate
{
    bool (*set)(Date * pThis, int year, int month, int day);
    void (*display)(const Date * pThis);
};
```

Next the class definition will include the three member variables and the v-table:

```
struct Date
{
    VTableDate *__vtptr;
    int year;
    int month;
    int day;
};
```

Finally it is necessary to bind the appropriate v-table to the newly created Date object.

```
void bind(Date * pThis, DateType td)
{
    // these need to be static. If not, when the function is returned, these
    // variables will fall out of scope and be destroyed. That will cause
    // the program to crash...
    static VTableDate vTableDateShort = { &setDate, &displayShort };
    static VTableDate vTableDateLong = { &setDate, &displayLong };
    static VTableDate vTableDateNone = { &setDate, &displayNone };

    switch (td)
    {
        default:
            assert(false); // this should never happen!
            // fall through
        case NONE:
            pThis->__vtptr = &vTableDateNone;
            break;
        case SHORT:
            pThis->__vtptr = &vTableDateShort;
            break;
        case LONG:
            pThis->__vtptr = &vTableDateLong;
            break;
    }
}
```

See Also

The complete solution is available at [3-1-date.html](http://3-1-date.html) or:

```
/home/cs165/examples/3-1-date.cpp
```



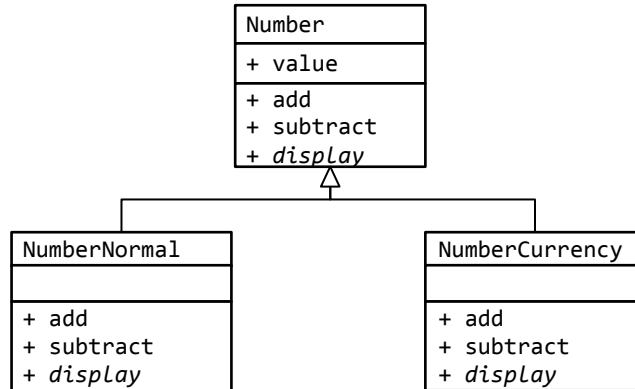
## Example 3.1 – Numbers

Demo

This example will demonstrate how to create a simple polymorphic `Number` class using structures and function pointers instead of true C++ classes.

Problem

Write a program to represent two variations of numbers: one displaying the value as an integer and the second as US dollars currency.



Solution

The first part of the solution is to make a v-table representing the methods of `Number`:

```

struct VTableNumber
{
    void (*add)(          Number * pThis, const Number & rhs);
    void (*subtract)(     Number * pThis, const Number & rhs);
    void (*display)(const Number * pThis);
};
    
```

The class definition is extremely simple:

```

struct Number
{
    double value;
    const VTableNumber * __vptr;
};
    
```

The binding occurs in `main()`:

```

int main()
{
    ... code removed for brevity ...
    num1.__vptr = &V_TABLE_NUMBER;           // default member functions
    num2.__vptr = &V_TABLE_NUMBER_CURRENCY;   // currency member functions
    ... code removed for brevity ...
    num1.__vptr->display(&num1);               // 42
    num2.__vptr->display(&num2);               // $41.99
};
    
```

See Also

The complete solution is available at [3-1-numbers.html](http://3-1-numbers.html) or:

`/home/cs165/examples/3-1-numbers.cpp`



## Problem 1

Write the UML class diagram for the following class:

```
class Date
{
public:
    void set(int year, int month = 1, int day = 1);
    void display() const;
    bool operator == (const Date & rhs) const;
    bool operator != (const Date & rhs) const;
    const Date & operator = (const Date & rhs);
private:
    bool isLeapYear() const;
    int daysSince1753;
};
```

*Please see page 110 for a hint.*

## Problem 2

Write the UML class diagram for the following class:

```
class Assignment
{
public:
    const Assignment & operator = (const Date & rhs );
    const Assignment & operator = (const string & rhs);
    void setScore( int score);
    void setPoints(int points);
    void display() const;
    const string & getName() const;
    const Date & getDate() const;
    int getScore() const;
    int getPoints() const;
private:
    bool isValid(int score, int points);
    Date date;
    string name;
    int score;
    int points;
};
```

*Please see page 205 for a hint.*

### Problem 3

Write the UML class diagram for the following class:

```
class GradeBook
{
public:
    const GradeBook & operator += (const Assignment & rhs);
    const Assignment & operator [] (int index);
    void display() const;
private:
    vector <Assignment> grades;
};
```

*Please see page 205 for a hint.*

### Problem 4

Write the UML class diagram for the following class:

```
class Date
{
public:
    void set(int year, int month = 1, int day = 1);
    void (*display)(const Date *pThis);
    void setLanguage(int code);
    int getYear() const;
    int getMonth() const;
    int getDay() const;
private:
    bool isLeapYear() const;
    int daysSince1753;
};

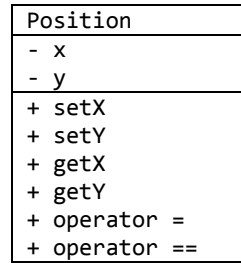
void displayEnglish(const Date *pThis);
void displayGerman( const Date *pThis);
void displayFrench( const Date *pThis);
```

*Please see page 206 for a hint.*



### Problem 5

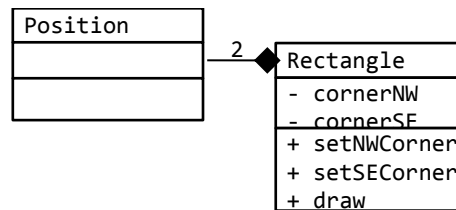
Write the class definition to match the following UML class diagram:



Please see page 127 for a hint.

### Problem 6

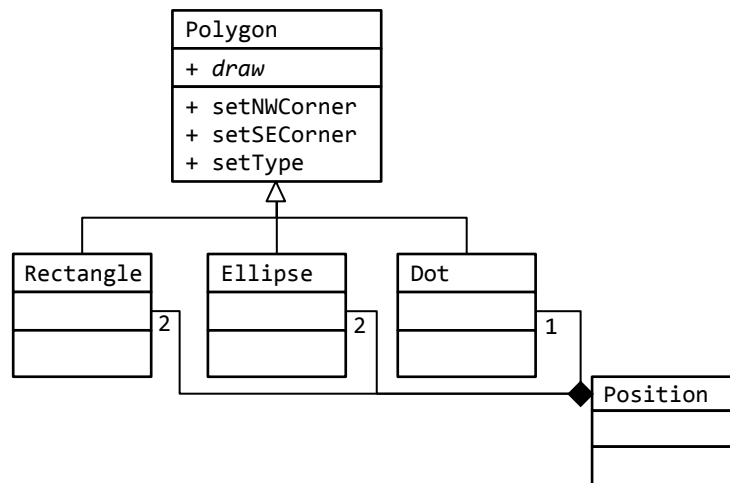
Write the class definition for Rectangle to match the following UML class diagram:



Please see page 127 for a hint.

### Problem 7

Write the class definition for Polygon to match the following UML class diagram:



Please see page 216 for a hint.