**Virtual Functions**

Object-oriented languages support selection of behavior across related types through polymorphism.  *Polymorphism* is the third principal concept that these languages implement (alongside encapsulation and inheritance).  Polymorphism refers to the multiplicity of meanings attached to a single identifier.  Polymorphic stands for 'of many forms'.  A polymorphic language selects an operation on an object based on the type associated with the object.

Virtual functions are an example of inclusion polymorphism.  Object-oriented languages implement inclusion polymorphism through member functions in a hierarchy.  The type of a polymorphic object can change throughout its lifetime to any type in the same inheritance hierarchy.  We distinguish between the static and dynamic type associated with a polymorphic object.  Its static type is the type of the object's hierarchy, its dynamic type is the object's actual type.

This chapter describes how C++ implements inclusion polymorphism.  The chapter describes the concept of types, the options for binding a function call to its definition and how polymorphic objects are implemented in C++.

Types

Raw memory stores information in the form of bit strings.  These bit strings represent variables, objects, addresses, instructions, constants, etc.  Without knowing *what* a bit string represents, the compiler cannot interpret the bit string.  By associating a type with a region of memory, we tell the compiler how to interpret the bit string in that region of memory.

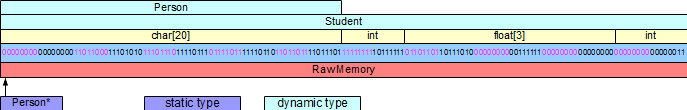
bit string in memory

For example, if we associate a region of memory with a Student and define the structure of a Student, the compiler knows that the first 4 bytes holds an int stored in equivalent binary form, the next 12 bytes holds an array of 3 floats and the remaining 4 bytes hold an int.

C++ Pointers

C++ implements a polymorphic object using pointer syntax.  The pointer type identifies the static type of the inheritance hierarchy to which the object belongs.  This static type is known at compile time.  The pointer holds the address of the polymorphic object.

To dereference the object's address, the compiler needs to know its dynamic type.  The dynamic type is the referenced type of the object.  Initially, we specify the dynamic type at object creation time through the constructor that we invoke.



In the following example, we instantiate a Person\* object by dynamically allocating memory once for a Person type and one for a Student type.

|  |
| --- |
| void show(const Person\*);  // Polymorphic Objects  Person jane("Jane");  float g[] = {54.6f, 67.7f, 89.6f};  Student john("John", 1234, g, 3);  Person\* pJane = &jane;  Person\* pJohn = &john;  // possibly different behaviors  show(pJohn);  show(pJane);  ... |

By implementing different behaviors for different types in the same hierarchy, we enable different execution paths in show() for different dynamic types.

Function Bindings

The compiler binds a function call to a function definition using an object's type.  The object's type determines the member function to call in the inheritance hierarchy.

The binding of a member function can take either of two forms:

* early binding - based on the object's static type
* dynamic dispatch - based on the object's dynamic type

Early Binding

Consider the following definition of our Student class from the chapter entitled [Functions in a Hierarchy](https://mwatler.github.io/sep200/Week4/FunctionsHierarchy.docx):

|  |
| --- |
| // Early Binding  // Student.h  #include <iostream>  const int NC = 30;  const int NG = 20;  class Person {  char name[NC+1];  public:  Person();  Person(const char\*);  void display(std::ostream&) const;  };  class Student : public Person {  int no;  float grade[NG];  int ng;  public:  Student();  Student(int);  Student(const char\*, int, const float\*, int);  void display(std::ostream&) const;  }; |

The implementation file is also the same as in the chapter entitled [Functions in a Hierarchy](https://mwatler.github.io/sep200/Week4/FunctionsHierarchy.docx):

|  |
| --- |
| // Student.cpp  #include <cstring>  #include "Student.h"  using namespace std;  Person::Person() {  name[0] = '\0';  }  Person::Person(const char\* nm) {  strncpy(name, nm, NC);  name[NC] = '\0';  }  void Person::display(ostream& os) const {  os << name << ' ';  }  Student::Student() {  no = 0;  ng = 0;  }  Student::Student(int n) {  float g[] = {0.0f};  \*this = Student("", n, g, 0);  }  Student::Student(const char\* nm, int sn, const float\* g, int ng\_) : Person(nm) {  bool valid = sn > 0 && g != nullptr && ng\_ >= 0;  if (valid)  for (int i = 0; i < ng\_ && valid; i++)  valid = g[i] >= 0.0f && g[i] <= 100.0f;  if (valid) {  // accept the client's data  no = sn;  ng = ng\_ < NG ? ng\_ : NG;  for (int i = 0; i < ng; i++)  grade[i] = g[i];  } else {  \*this = Student();  }  }  void Student::display(ostream& os) const {  if (no > 0) {  Person::display(os);  os << no << ":\n";  os.setf(ios::fixed);  os.precision(2);  for (int i = 0; i < ng; i++) {  os.width(6);  os << grade[i] << endl;  }  os.unsetf(ios::fixed);  os.precision(6);  } else {  os << "no data available" << endl;  }  } |

Note that this hierarchy has two distinct definitions of the member function named display().

The main() function listed below defines a global function named show().  This client code calls that global function twice, first for a Student object and second for a Person object.  The global function show() in turn calls the display member function on p.  The compiler binds the call to this member function to its Person version.  C++ applies this convention irrespective of the argument type in the call to show().  That is, the compiler uses the *parameter type* in definition of show() to determine the kind of binding to implement.  We call this binding an *early binding*.

The client program produces the output shown on the right:

|  |  |
| --- | --- |
| // Function Bindings  // functionBindings.cpp  #include <iostream>  #include "Student.h"  void show(const Person& p) {  p.display(std::cout);  std::cout << std::endl;  }  int main() {  Person jane("Jane Doe");  float gh[] = {89.4f, 67.8f, 45.5f};  Student harry("Harry", 1234, gh, 3);  harry.display(std::cout);  jane.display(std::cout);  std::cout << std::endl;  show(harry);  show(jane);  } | Harry 1234:  89.40  67.80  45.50  Jane Doe  Harry  Jane Doe |

Early binding occurs at compile time and is the most efficient binding of a member function call to that function's definition.  Early binding is the default in C++.

Note that shadowing does not occur inside the global function show().  show() has no way of knowing which version of display() to select aside from the type of its parameter p.  The statements harry.display() and jane.display() in the main() function demonstrate shadowing.  The call to display() on harry shadows the base version of display().

Dynamic Dispatch

The output in the above example omits the details for the Student part of harry.  To output these details, we need to postpone the binding of the call to display() until run-time when the executable code is aware of the dynamic type of object p.  We refer to this postponement as *dynamic dispatch*.

C++ provides the keyword virtual for dynamic dispatching.  If this keyword is present, the compiler inserts code that binds the call to most derived version of the member function based on the dynamic type.

For example, the keyword virtual in the following class definition instructs the compiler to postpone calling the display() member function definitions until run-time:

|  |
| --- |
| // Dynamic Dispatch  // Student.h  #include <iostream>  const int NC = 30;  const int NG = 20;  class Person {  char name[NC+1];  public:  Person();  Person(const char\*);  virtual void display(std::ostream&) const;  };  class Student : public Person {  int no;  float grade[NG];  int ng;  public:  Student();  Student(int);  Student(const char\*, int, const float\*, int);  void display(std::ostream&) const;  }; |

Note that the implementation file and the client program have not changed.  Because the keyword is present, the compiler overrides the early binding of display() so that the show() function will call the most derived version of display() for the type of the argument passed to it.  The following client code (identical to that above) then produces the output shown on the right:

|  |  |
| --- | --- |
| // Function Bindings  // functionBindings.cpp  #include <iostream>  #include "Student.h"  void show(const Person& p) {  p.display(std::cout);  std::cout << std::endl;  }  int main() {  Person jane("Jane Doe");  float gh[] = {89.4f, 67.8f, 45.5f};  Student harry("Harry", 1234, gh, 3);  harry.display(std::cout);  jane.display(std::cout);  std::cout << std::endl;  show(harry);  show(jane);  } | Harry 1234:  89.40  67.80  45.50  Jane Doe  Harry 1234:  89.40  67.80  45.50  Jane Doe |

Each call to show() passes a reference to an object of different dynamic type:

* show(harry) passes an unmodifiable reference to a Student
* show(jane) passes an unmodifiable reference to a Person

In each case, the executable code binds at run time the version of display() that is the most derived version for the dynamic type referenced by the parameter in show().

Note that if we pass the argument to the show() function by value instead of by reference, the show() function would still call the most derived version of display(), but that most derived version would be for the Person version, since the copied object would be a Person in all cases.

Overriding Dynamic Dispatch

To override dynamic dispatch with early binding, we resolve the scope explicitly:

|  |
| --- |
| void show(const Person& p) {  p.Person::display(std::cout);  } |

Documentation

Some programmers include the qualifier virtual in derived class declarations as a form of documentation.  This improves readability but has no syntactic effect.

We can identify a member function as virtual even if no derived class exists.  This clarifies the intent of the original developer for subsequent developers of the hierarchy

Polymorphic Objects

A polymorphic object is an object that can change its dynamic type throughout its lifetime.  Its static type identifies the hierarchy of types to which the object belongs.  Its dynamic type identifies the rule for interpreting the bit string in the region of memory currently allocated for the object.

We specify the static type of a polymorphic object through

* a pointer declaration
* a receive-by-address parameter
* a receive-by-reference parameter

For example, the highlighted code specifies the static type pointed to by person:

|  |
| --- |
| // Polymorphic Objects - Static Type  #include <iostream>  #include "Student.h"  void show(const Person\* p) {  // ...  }  void show(const Person& p) {  // ...  }  int main() {  Person\* p = nullptr;  // ...  } |

We specify the dynamic type of a polymorphic object by allocating memory dynamically using the appropriate constructor from the inheritance hierarchy.

The highlighted code in the example below identifies the dynamic type.  The results produced by this code are listed on the right:

|  |  |
| --- | --- |
| // Polymorphic Objects - Dynamic Type  // dyanmicType.cpp  #include <iostream>  #include "Student.h"  void show(const Person& p) {  p.display(std::cout);  std::cout << std::endl;  }  int main() {  Person\* p = nullptr;  p = new Person("Jane Doe");  show(\*p);  delete p;  float g[] = {89.4f, 67.8f, 45.5f};  p = new Student("Harry", 1234, g, 3);  show(\*p);  delete p;  } | Jane Doe  Harry 1234:  89.40  67.80  45.50 |

In the main() function:

* p initially points to nothing (holds the null address).  The object's dynamic type is undefined.
* after the first allocation, p points to a Student type (dynamic type).
* after the second allocation, p points to a Person type (the new dynamic type).

The static and dynamic types are related to one another through the hierarchy.

Note that we only need one show() function to display both dynamic types.

p holds the address a polymorphic object throughout its lifetime.  That address may change with deallocations and fresh allocations of memory.  The dynamic type may be of any type in the Person hierarchy.

show() is a polymorphic function.  Its parameter receives an unmodifiable reference to any type in the Person hierarchy.

Good Design

It is good programming practice to dynamically dispatch the destruction of any object in an inheritance hierarchy as virtual.  If an object of a derived class acquires a resource, typically the destructor of that class releases the resource.  To ensure that any object in the hierarchy calls the destructor of its most derived class at destruction time, we declare the base class destructor virtual.  Since the destructor of any derived class automatically calls the destructor of its immediate base class, all destructors in the object's hierarchy will be called in turn.

Good design codes the destructor in a base class as virtual, even if no class is currently derived from that base class.  The presence of a virtual base class destructor ensures that the most derived destructor will be called if and when a class is derived from the base class without requiring an upgrade to the definition of the base class.

Reusability and Flexibility

Implementing inclusion polymorphism improves reusability and flexibility of code.

Virtual functions reduce code size considerably.  Our show() function works on references of any type within the Person hierarchy.  We only define member functions (display()) for those classes that require specialized processing.

Consider a client application that uses our hierarchy.  During the life cycle of the hierarchy, we may add several classes.  Our original client code, without any alteration, will selects the most derived version of the member function for each upgrade of the hierarchy.  We will only need to add client code to create objects of new derived classes.

Summary

* polymorphism refers to the multiplicity of logic associated with the same name.
* static type is the type of the object's hierarchy and is available at compile-time
* dynamic type is the type of the object referenced and may change with different calls to the same function
* early binding of a call to a member function's definition occurs at compile-time
* the keyword virtual on a member function's declaration specifies dynamic dispatch
* a polymorphic object's pointer type identifies the object's static type
* a polymorphic object's constructor identifies the object's dynamic type
* declare a base class destructor virtual even if there are no derived classes