Programming in Modern C++

Module M40: Functors: Function Objects

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All url's in this module have been accessed in September, 2021 and found to be functional

Module Recap

- Discussed class templates as generic solution for data structure reuse
- Explained partial template instantiation and default template parameters
- Demonstrated templates on inheritance hierarchy
- Illustrated with examples

Module Objectives

- Understand the Function Objects or Functor
- Study the utility of functor in design, especially in STL

Module Outline

Callable Entities

Callable Entities in C / C++

- A Callable Entity is an object that
  - Can be called using the function call syntax
  - Supports *Function Call Operator*: `operator()`
- Such objects are often called
  - A *Function Object* or
  - A *Functor*

Functors

Some authors distinguish between *Callable Entities*, *Function Objects* and *Functors*, but we will treat these terminology equivalently depending on the context

Several Callable Entities C++

- *Function-like Macros*
- *C Functions* (Global or in Namespace)
- *Member Functions*
  - Static
  - Non-Static
- *Pointers to Functions*
  - C Functions
  - Member Functions (static / Non-Static)
- *References to functions*: Acts like const pointers to functions
- *Functors*: Objects that define `operator()`

Function Pointers

Function Pointers

- *Points to the address of a function*
  - Ordinary C functions
  - Static C++ member functions
  - Non-static C++ member functions
- *Points to a function with a specific signature*
  - List of Calling Parameter Types
  - Return-Type
  - Calling Convention

Function Pointers in C

- *Define a Function Pointer*

```
int (*pt2Function) (int, char, char);
```

- *Calling Convention*

```
int DoIt (int a, char b, char c); // __cdecl, __stdcall used in MSVC
int DoIt (int a, char b, char c) {
    printf ("DoIt\n");
    return a+b+c;
}
```

- *Assign Address to a Function Pointer*

```
pt2Function = &DoIt; // OR
pt2Function = DoIt;
```

- *Compare Function Pointers*

```
if (pt2Function == &DoIt) {
    printf ("pointer points to DoIt\n");
}
```

- *Call the Function pointed by the Function Pointer*

```
int result = (*pt2Function) (12, 'a', 'b');
```

Function Pointers in C

Direct Function Pointer

```
#include <stdio.h>

int (*pt2Function) (int, char, char);
int DoIt (int a, char b, char c);

int main() {
    pt2Function = DoIt; // &DoIt

    int result = (*pt2Function)(12, 'a', 'b');

    printf("%d", result);

    return 0;
}
int DoIt (int a, char b, char c) {
    printf ("DoIt\n");

    return a + b + c;
}
```

```
DoIt
207
```

Using `typedef`

```
#include <stdio.h>

typedef int (*pt2Function) (int, char, char);
int DoIt (int a, char b, char c);

int main() {
    pt2Function f = &DoIt; // DoIt

    int result = f(12, 'a', 'b');

    printf("%d", result);

    return 0;
}
int DoIt (int a, char b, char c) {
    printf ("DoIt\n");

    return a + b + c;
}
```

```
DoIt
207
```

Function Reference In C++

- *Define a Function Pointer*

```
int (A::*pt2Member)(float, char, char);
```

- *Calling Convention*

```
class A {
int DoIt (float a, char b, char c) {
    cout << "A::DoIt" << endl; return a+b+c; }
};
```

- *Assign Address to a Function Pointer*

```
pt2Member = &A::DoIt;
```

- *Compare Function Pointers*

```
if (pt2Member == &A::DoIt) {
    cout <<"pointer points to A::DoIt" << endl;
}
```

- *Call the Function pointed by the Function Pointer*

```
int result = (*this.*pt2Member)(12, 'a', 'b');
```

Function Pointer: Operations and Programming Techniques

- **Operations**
  - *Assign* an Address to a Function Pointer
  - *Compare* two Function Pointers
  - *Call* a Function using a Function Pointer
  - *Pass* a Function Pointer as an Argument
  - *Return* a Function Pointer
  - *Arrays* of Function Pointers
- **Programming Techniques**
  - *Replacing switch/if-statements*
  - *Realizing user-defined late-binding*, or
    - Functions in Dynamically Loaded Libraries
    - Virtual Functions
  - *Implementing callbacks*

Function Pointers: Replace Switch/ IF Statements

Solution Using switch

```
#include <iostream>
using namespace std ;
// The four arithmetic operations
float Plus(float a, float b) { return a+b ; }
float Minus(float a, float b) { return a-b ; }
float Multiply(float a, float b) { return a*b; }
float Divide(float a, float b) { return a/b ; }
void Switch(float a, float b, char opCode) {
    float result;
    switch (opCode) { // execute operation
      case '+': result = Plus(a, b); break;
      case '-': result = Minus(a, b); break;
      case '*': result = Multiply(a, b); break;
      case '/': result = Divide(a, b); break;
    }
    cout << "Result of = "<< result << endl;
}
int main() { float a = 10.5, b = 2.5 ;
    Switch(a, b, '+');
    Switch(a, b, '-');
    Switch(a, b, '*');
    Switch(a, b, '/');
    return 0;
}
```

Solution Using Function Pointer

```
#include <iostream>
using namespace std ;
// The four arithmetic operations
float Plus(float a, float b)
    { return a+b; }
float Minus(float a, float b)
    { return a-b; }
float Multiply(float a, float b)
    { return a*b; }
float Divide(float a, float b)
    { return a/b; }
// Solution with Function pointer
void Switch (float a, float b,
    float (*pt2Func)(float, float)) {
    float result = pt2Func(a, b);
    cout << "Result := " << result << endl;
}
int main() { float a = 10.5, b = 2.5 ;
    Switch(a, b, &Plus);
    Switch(a, b, &Minus);
    Switch(a, b, &Multiply);
    Switch(a, b, &Divide);
    return 0;
}
```

Function Pointers: Late Binding / Dynamically Loaded Library

- A C Feature in Shared Dynamically Loaded Libraries

Program Part-1

```
#include <dlfcn.h>
int main() {
    void* handle = dlopen("hello.so", RTLD_LAZY);
    typedef void (*hello_t)();

    hello_t myHello = 0;
    myHello = (hello_t)dlsym(handle, "hello");
    myHello();

    dlclose(handle);
}
```

Program Part-2

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

extern "C" void hello() {
   cout << "hello" << endl;
}
```

Function Pointers: Late Binding / Virtual Function

- A C++ Feature for Polymorphic Member Functions

Code Snippet Part-1

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

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

Code Snippet Part-2

```
int main() {
    A a;
    B b;
    A *p = &b;

    a.f();  // A::f()
    a.g();  // A::g()
    p->f(); // A::f()
    p->g(); // B::g()
}
```

Example: Callback, Function Pointers

- It is a Common C Feature

```
// Application
extern void (*func)();
void f() { }
int main() {
    func = &f;
    g();
}

// Library
void (*func)();
void g() {
    (*func)();
}
```

Function Pointers: Callback Illustration (Step 1)


```
// Application
extern void (*func)();
void f()
{


}

void main()
{
    func = &f;

    g();
}
```

```
// Library
void (*func)();

void g()
{

    (*func)();

}
```

Function Pointers: Callback Illustration (Step 2)

```
// Application
extern void (*func)();
void f()
{


}

void main()
{
    func = &f;

    g();
}
```

```
// Library
void (*func)();

void g()
{

    (*func)();

}
```

Function Pointers: Callback Illustration (Step 3)


```
// Application
extern void (*func)();
void f()
{


}

void main()
{
    func = &f;

    g();
}
```

```
// Library
void (*func)();

void g()
{

    (*func)();

}
```

Function Pointers: Callback Illustration (Step 4)


```
// Application
extern void (*func)();
void f()
{

}

void main()
{
    func = &f;

    g();
}
```

Callback

```
// Library
void (*func)();

void g()
{

    (*func)();

}
```

Function Pointers: Callback Illustration (Step-Final)


```
// Application
extern void (*func)();
void f()
{


}

void main()
{
    func = &f;

    g();
}
```

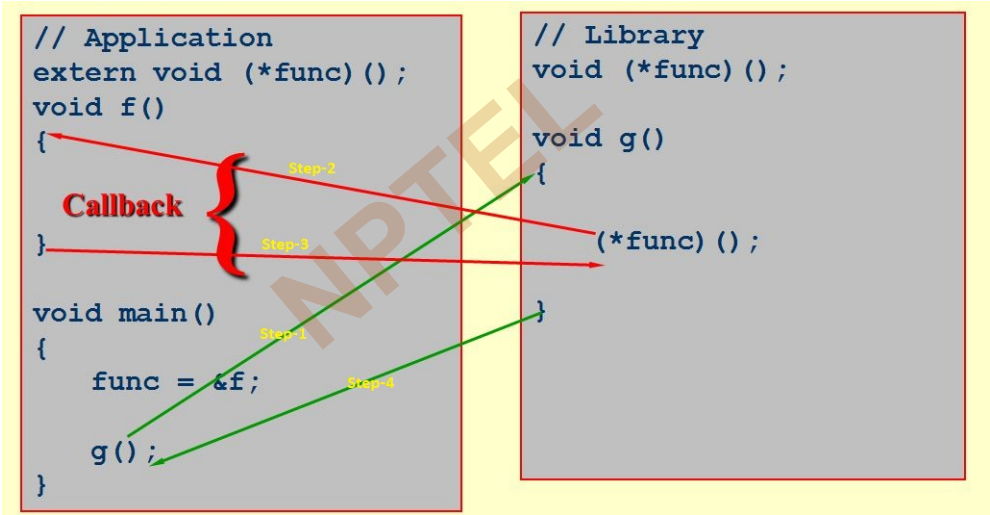
```
// Library
void (*func)();

void g()
{

    (*func)();

}
```

Function Pointers: Callback Illustration: Whole Process



Function Pointers: Callback: qsort to Quick Sort


```
void qsort(void *base,    // Pointer to the first element of the array to be sorted
           size_t nitems, // Number of elements in the array pointed by base
           size_t size,   // Size in bytes of each element in the array
           int (*compar)(const void *, const void*)); // Function that compares two elements

int CmpFunc(const void* a, const void* b) { // Compare function for int
    int ret = (*(const int*)a > *(const int*) b)? 1:
                  (*(const int*)a == *(const int*) b)? 0: -1;
    return ret;
}

int main() {
    int field[10];

    for(int c = 10; c>0; c--)
        field[10-c] = c;

    qsort((void*) field, 10, sizeof(field[0]), CmpFunc);
}
```

Function Pointers: Issues

- No value semantics
- Weak type checking
- Two function pointers having identical signature are necessarily indistinguishable
- No encapsulation for parameters

Functors in C++

Functors or Function Objects

- Smart Functions
  - Functors are *functions with a state*
  - Functors *encapsulate C / C++ function pointers*
    - Uses templates and
    - Engages polymorphism
- Has its own *Type*
  - A class with zero or more private members to store the state and an overloaded `operator()` to execute the function
- Usually *faster* than ordinary Functions
- Can be used to implement *callbacks*
- Provides the basis for *Command Design Pattern*

Basic Functor

- Any class that overloads the function call operator:
  - `void operator()();`
  - `int operator()(int, int);`
  - `double operator()(int, double);`
  - `...`

Functors: Simple Example

- Consider the code below

```
int AdderFunction(int a, int b) { // A function
    return a + b;
}

class AdderFunctor {
public:
    int operator()(int a, int b) { // A functor
        return a + b;
    }
};

int main() {
    int x = 5;
    int y = 7;
    int z = AdderFunction(x, y);  // Function invocation

    AdderFunctor aF;
    int w = aF(x, y);             // aF.operator()(x, y); -- Functor invocation
}
```

Functors: Examples from STL: Function Pointer for Functor

- **Fill a vector with random numbers**
  - **generate** algorithm

```
#include <algorithm>
template <class ForwardIterator, class Generator>
    void generate(ForwardIterator first, ForwardIterator last, Generator gen) {
        while (first != last) {
            *first = gen();
            ++first;
        }
    }
```

    - ▷ **first, last**: Iterators are defined for a range in the sequence. "[" or "]" means include the element and "(" or ")" means exclude the element. `ForwardIterator` has a range `[first,last)` spanning from `first` element to the element before the `last`
    - ▷ **gen**: Generator function that is called with no arguments and returns some value of a type convertible to those pointed by the iterators
    - ▷ This can either be a function pointer or a function object
  - Function Pointer **rand** as Function Object

```
#include <cstdlib>

// int rand (void);

vector<int> V(100);
generate(V.begin(), V.end(), rand);
```

Functors: Examples from STL: Functor without a state

- **Sort a vector of double by magnitude**
  - **sort** algorithm

```
#include <algorithm>
template <class RandomAccessIterator, class Compare>
    void sort (RandomAccessIterator first, // Simple interface
               RandomAccessIterator last,  // Difficult to use incorrectly
               Compare comp); // Compare Functor
```

    - ▷ **first, last**: RandomAccessIterator has a range [first,last)
    - ▷ RandomAccessIterator shall point to a type for which swap is properly defined and which is both move-constructible and move-assignable (C++11)
    - ▷ **comp**: Binary function that accepts two elements in the range as arguments, and returns a value convertible to bool. The value returned indicates whether the element passed as first argument is considered to go before the second in the specific strict weak ordering it defines.
    - ▷ The function shall not modify any of its arguments
    - ▷ This can either be a function pointer or a function object

Functors: Examples from STL: Functor without a state

- **Sort a vector of double by magnitude**

Using `qsort` in C with User-defined **Function** `less_mag`

```
#include <stdlib.h>
// Compare Function pointer
void qsort(void *base,
     size_t nitems,
     size_t size,
     int (*compar)(const void *, const void*))
// Complicated interface. Difficult to use correctly

// Type-unsafe comparison function
// Intricate and error-prone with void*
int less_mag(const void* a, const void* b) {
    return (fabs(*(const double*)a) <
            fabs(*(const double*)b) ? 1: 0;
}

double V[100]; // Capacity = 100
// 10 elements are filled - needs to be tracked

// Difficult to call
qsort((void*) V, 10, sizeof(V[0]), less_mag);
```

Using `sort` in C++ with User-defined **Functor** `less_mag`

```
#include <algorithm>
// Compare Functor
template <class RandomAccessIterator, class Compare>
    void sort (RandomAccessIterator first,
               RandomAccessIterator last,
               Compare comp);
// Simple interface. Difficult to use incorrectly

// Type-safe comparison functor
struct less_mag: public
    binary_function<double, double, bool> {
        bool operator()(double x, double y)
        { return fabs(x) < fabs(y); }
};

vector<double> V(100);
// 10 elements are filled tracked automatically

// Easy to call
sort(V.begin(), V.end(), less_mag());
```

Functors: Examples from STL: Functor with a state

- **Compute the sum of elements in a vector**
  - **for_each** algorithm

```
#include <algorithm>
template<class InputIterator, class Function>
    Function for_each(InputIterator first, InputIterator last, Function fn) {
        while (first!=last) {
            fn (*first);
            ++first;
        }
        return fn;      // or, since C++11: return move(fn);
    }
```

    - ▷ **first, last**: InputIterator has a range [first,last)
    - ▷ **fn**: Unary function that accepts an element in the range as argument
    - ▷ This can either be a function pointer or a move constructible function object (C++11)
    - ▷ Its return value, if any, is ignored.
  - User-defined Functor **adder** with local state

```
struct adder: public unary_function<double, void> { adder() : sum(0) { }
    double sum; // Local state
    void operator()(double x) { sum += x; }
};
vector<double> V;
...
adder result = for_each(V.begin(), V.end(), adder());
cout << "The sum is " << result.sum << endl;
```

Module Summary

- Introduced Function Objects or Functors
- Illustrated functors with several simple examples and examples from STL