Module 31: Programming in C++

Virtual Function Table

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Slides taken from NPTEL course on Programming in Modern C++

by **Prof. Partha Pratim Das**

Weekly Recap

- Understood type casting – implicit as well as explicit – for built-in types, unrelated types, and classes on a hierarchy
- Understood the notions of upcast and downcast
- Understood Static and Dynamic Binding for Polymorphic type
- Understood `virtual` destructors, Pure Virtual Functions, and Abstract Base Class
- Designed the solution for a staff salary processing problem using iterative refinement – starting with a simple C solution and repeatedly refining finally to an easy, efficient, and extensible C++ solution based on flexible polymorphic hierarchy

Module Objectives

- Introduce a new C solution with function pointers
- Understand Virtual Function Table for dynamic binding (polymorphic dispatch)

Module Outline

1. Weekly Recap
2. Staff Salary Processing: New C Solution
3. Staff Salary Processing: C++ Solution
4. C and C++ Solutions: A Comparison
5. Virtual Function Pointer Table
6. Module Summary

Staff Salary Processing: New C Solution

Staff Salary Processing: New C Solution

Staff Salary Processing: Problem Statement: RECAP (Module 29)

- An organization needs to develop a salary processing application for its staff
- At present it has an engineering division only where Engineers and Managers work. Every Engineer reports to some Manager. Every Manager can also work like an Engineer
- The logic for processing salary for Engineers and Managers are different as they have different salary heads
- In future, it may add Directors to the team. Then every Manager will report to some Director. Every Director could also work like a Manager
- The logic for processing salary for Directors will also be distinct
- Further, in future it may open other divisions, like Sales division, and expand the workforce
- **Make a suitable extensible design**

C Solution: Function Pointers
Engineer + Manager + Director: RECAP (Module 29)

- How to represent Engineers, Managers, and Directors?
  - Collection of `struct`s
- How to initialize objects?
  - Initialization functions
- How to have a collection of mixed objects?
  - Array of `union`
- How to model variations in salary processing algorithms?
  - `struct`-specific functions
- How to invoke the correct algorithm for a correct employee type?
  - Function switch
  - **Function pointers**

C Solution: Function Pointers: Engineer + Manager + Director

- In Module 29, we have developed a flat C Solution using *function switch*
- In Module 30, we refined the C Solution to develop two types of C++ Solution using
  - Non-polymorphic hierarchy - employing *function switch*
  - Polymorphic hierarchy - eomploying *virtual function*
- In Module 29, we had mentioned that in the flat C Solution it is not easy to use function pointers as the processing functions `void ProcessSalaryEngineer(Engineer *)`, `void ProcessSalaryManager(Manager *)`, and `void ProcessSalaryDirector(Director *)` all have different types of arguments and therefore a common function pointer type cannot be defined
- We can work around this by:
  - Passing the staff object as `void *`, instead of `Engineer *`, `Manager *`, or `Director *`
  - Cast it to respective object type in the respective function. That is, cast to `Engineer *` in `ProcessSalaryEngineer(Engineer *)` and so on
  - We can then use a function pointer type `void (*)(void *)`
- We illustrate in the Solution

C Solution: Function Pointers: Engineer + Manager + Director

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>
typedef enum E_TYPE { Er, Mgr, Dir } E_TYPE; // Staff tag type
typedef void (*psFuncPtr)(void *);          // Processing func. ptr. type, passing the object by void *
typedef struct Engineer { char *name_; } Engineer; // Engineer Type
Engineer *InitEngineer(const char *name) { Engineer *e = (Engineer *)malloc(sizeof(Engineer));
    e->name_ = strdup(name); return e;
}
void ProcessSalaryEngineer(void *v) { Engineer *e = (Engineer *)v; // Cast explicitly to the staff object
    printf("%s: Process Salary for Engineer\n", e->name_);
}
typedef struct Manager { char *name_; Engineer *reports_[10]; } Manager; // Manager Type
Manager *InitManager(const char *name) { Manager *m = (Manager *)malloc(sizeof(Manager));
    m->name_ = strdup(name); return m;
}
void ProcessSalaryManager(void *v) { Manager *m = (Manager *)v; // Cast explicitly to the staff object
    printf("%s: Process Salary for Manager\n", m->name_);
}
typedef struct Director { char *name_; Manager *reports_[10]; } Director; // Director Type
Director *InitDirector(const char *name) { Director *d = (Director *)malloc(sizeof(Director));
    d->name_ = strdup(name); return d;
}
void ProcessSalaryDirector(void *v) { Director *d = (Director *)v; // Cast explicitly to the staff object
    printf("%s: Process Salary for Director\n", d->name_);
}
```

C Solution: Function Pointers: Engineer + Manager + Director

```
typedef struct Staff {
    E_TYPE type_; // Staff tag type
    void *p;      // Pointer to staff object
} Staff;          // Staff object wrapper
int main() {
    // Array of function pointers
    psFuncPtr psArray[] = { ProcessSalaryEngineer,  ProcessSalaryManager, ProcessSalaryDirector };

    // Array of staffs
    Staff staff[] = { { Er, InitEngineer("Rohit") }, { Mgr, InitEngineer("Kamala") },
                      { Mgr, InitEngineer("Rajib") }, { Er, InitEngineer("Kavita") },
                      { Er, InitEngineer("Shambhu") }, { Dir, InitEngineer("Ranjana") } };

    for (int i = 0; i < sizeof(staff) / sizeof(Staff); ++i)
        psArray[staff[i].type_] // Pick the right processing function for the tag - staff type
            (staff[i].p);       // Pass the pointer to the object - implicitly cast to void*
}
```

```
Rohit: Process Salary for Engineer
Kamala: Process Salary for Manager
Rajib: Process Salary for Manager
Kavita: Process Salary for Engineer
Shambhu: Process Salary for Engineer
Ranjana: Process Salary for Director
```

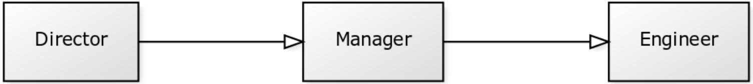
C Solution: Advantages and Disadvantages: RECAP (Module 26) Annotated for Function Pointers

- **Advantages**
  - Solution exists!
  - Code is well structured – has patterns
- **Disadvantages**
  - Employee data has scope for better organization
    - ▷ No encapsulation for data
    - ▷ Duplication of fields across types of employees – possible to mix up types for them (say, `char *` and `string`)
    - ▷ Employee objects are created and initialized dynamically through `Init...` functions. How to release the memory?
  - Types of objects are managed explicitly by `E_Type`:
    - ▷ Difficult to extend the design – addition of a new type needs to:
      - — Add new type code to `enum E_Type`
      - — Add a new pointer field in `struct Staff` for the new type
      - — Add a new case (`if-else` or `case`) based on the new type: **Removed using function pointer**
    - ▷ Error prone – developer has to decide to call the right processing function for every type (`ProcessSalaryManager` for `Mgr` etc.): **Removed using function pointer**
  - Unable to use Function Pointers as each processing function takes a parameter of different type - no common signature for dispatch
- **Recommendation**
  - Use classes for encapsulation on a hierarchy

Staff Salary Processing: C++ Solution

Staff Salary Processing: C++ Solution

C++ Solution: Polymorphic Hierarchy: RECAP Engineer + Manager + Director: (Module 30)



- How to represent Engineers, Managers, and Directors?
  - Polymorphic `class` hierarchy
- How to initialize objects?
  - Constructor / Destructor
- How to have a collection of mixed objects?
  - `array` of base class pointers
- How to model variations in salary processing algorithms?
  - Member functions
- How to invoke the correct algorithm for a correct employee type?
  - Virtual Functions

C++ Solution: Polymorphic Hierarchy: RECAP Engineer + Manager + Director: (Module 30)

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

class Engineer {
protected:
    string name_;
public:
    Engineer(const string& name) : name_(name) { }
    virtual ~Engineer() { }
    virtual void ProcessSalary() { cout << name_ << ": Process Salary for Engineer" << endl; }
};
class Manager : public Engineer {
    Engineer *reports_[10];
public:
    Manager(const string& name) : Engineer(name) { }
    void ProcessSalary() { cout << name_ << ": Process Salary for Manager" << endl; }
};
class Director : public Manager {
    Manager *reports_[10];
public:
    Director(const string& name) : Manager(name) { }
    void ProcessSalary() { cout << name_ << ": Process Salary for Director" << endl; }
};
```

C++ Solution: Polymorphic Hierarchy: RECAP Engineer + Manager + Director: (Module 30)

```
int main() {
    Engineer e1("Rohit"), e2("Kavita"), e3("Shambhu");
    Manager m1("Kamala"), m2("Rajib");
    Director d("Ranjana");
    Engineer *staff[] = { &e1, &m1, &m2, &e2, &e3, &d };

    for (int i = 0; i < sizeof(staff) / sizeof(Engineer*); ++i)
        staff[i]->ProcessSalary();
}
```

```
Rohit: Process Salary for Engineer
Kamala: Process Salary for Manager
Rajib: Process Salary for Manager
Kavita: Process Salary for Engineer
Shambhu: Process Salary for Engineer
Ranjana: Process Salary for Director
```

C and C++ Solutions: A Comparison

C and C++ Solutions: A Comparison

C Solution

- How to represent Engineers, Managers, and Directors?
  - `structs`
- How to initialize objects?
  - Initialization functions
- How to have a collection of mixed objects?
  - array of `union` wrappers
- How to model variations in salary processing algorithms?
  - functions for `structs`
- How to invoke the correct algorithm for a correct employee type?
  - Function pointers

C++ Solution

- How to represent Engineers, Managers, and Directors?
  - Polymorphic hierarchy
- How to initialize objects?
  - Ctor / Dtor
- How to have a collection of mixed objects?
  - `array` of base class pointers
- How to model variations in salary processing algorithms?
  - `class` member functions
- How to invoke the correct algorithm for a correct employee type?
  - Virtual Functions

C and C++ Solutions: A Comparison

C Solution (Function Pointer)

```
typedef enum E_TYPE { Er, Mgr, Dir } E_TYPE;
typedef void (*psFuncPtr)(void *);
typedef struct { E_TYPE type_; void *p; } Staff;
typedef struct { char *name_; } Engineer;
Engineer *InitEngineer(const char *name);
void ProcessSalaryEngineer(void *v);
typedef struct { char *name_; } Manager;
Manager *InitManager(const char *name);
void ProcessSalaryManager(void *v);
typedef struct { char *name_; } Director;
Director *InitDirector(const char *name);
void ProcessSalaryDirector(void *v);
int main() { psFuncPtr psArray[] = {
    ProcessSalaryEngineer,    // Function
    ProcessSalaryManager,     // pointer
    ProcessSalaryDirector };  // array
    Staff staff[] = {
    { Er, InitEngineer("Rohit") },
    { Mgr, InitEngineer("Kamala") },
    { Dir, InitEngineer("Ranjana") } };
    for (int i = 0; i <
        sizeof(staff)/sizeof(Staff); ++i)
        psArray[staff[i].type_](staff[i].p);
}
```

C++ Solution (Virtual Function)

```
class Engineer { protected: string name_;
public: Engineer(const string& name);
     virtual void ProcessSalary(); };
     virtual ˜Engineer(); };
class Manager : public Engineer {
public: Manager(const string& name);
    void ProcessSalary(); };
class Director : public Manager {
public: Director(const string& name);
    void ProcessSalary(); };
int main() {
    // Function pointer array is subsumed in
    // virtual function tables of classes

    Engineer e1("Rohit");
    Manager m1("Kamala");
    Director d("Ranjana");
    Engineer *staff[] = { &e1, &m1, &d };
    for(int i = 0; i <
        sizeof(staff)/sizeof(Engineer*); ++i)
        staff[i]->ProcessSalary();
}
```

Virtual Function Pointer Table

Virtual Function Pointer Table

How do virtual functions work?

- The C Solution with function pointers gives us the lead to implement virtual functions. Here
  - ○ We have used an array of function pointers (`psFuncPtr psArray[]`) to keep the processing functions (`void ProcessSalaryEngineer(Engineer *)`, `void ProcessSalaryManager(Manager *)`, and `void ProcessSalaryDirector(Director *)`) indexed by the type tag (`enum E_TYPE { Er, Mgr, Dir }`)
  - ○ In C++, every class is a separate type - so the tag can be removed if we bind this table (**Virtual Function Table** or VFT) with the class
  - ○ Every class can have a VFT with its appropriate processing function pointer put there
  - ○ By override, all these functions can have the same signature (`void ProcessSalary()`) and can be called through the same expression (`(Engineer *)->ProcessSalary()`)
- We now illustrate Virtual Function Table through simple examples to show how does it work for inherited, overridden and overloaded member functions

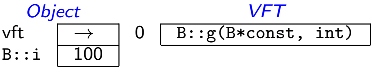
Virtual Function Pointer Table

Base Class

```
class B {
    int i;
public:
    B(int i_): i(i_) { }
        void f(int); // B::f(B*const, int)
virtual void g(int); // B::g(B*const, int)
};

B b(100);
B *p = &b;
```

b Object Layout



	Object		*VFT*
vft	→	0	B::g(B*const, int)
B::i	100		

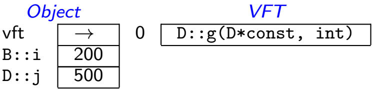
Source Expression	Compiled Expression
`b.f(15);`	`B::f(&b, 15);`
`p->f(25);`	`B::f(p, 25);`
`b.g(35);`	`B::g(&b, 35);`
`p->g(45);`	`p->vft[0](p, 45);`

Derived Class

```
class D: public B {
    int j;
public:
    D(int i_, int j_): B(i_), j(j_) { }
        void f(int); // D::f(D*const, int)
        void g(int); // D::g(D*const, int)
};

D d(200, 500);
B *p = &d;
```

d Object Layout



	Object		*VFT*
vft	→	0	D::g(D*const, int)
B::i	200		
D::j	500		

Source Expression	Compiled Expression
`d.f(15);`	`D::f(&d, 15);`
`p->f(25);`	`B::f(p, 25);`
`d.g(35);`	`D::g(&d, 35);`
`p->g(45);`	`p->vft[0](p, 45);`

Virtual Function Pointer Table

- Whenever a class defines a `virtual` function a hidden member variable is added to the class which points to an array of pointers to (`virtual`) functions called the **Virtual Function Table** (VFT)
- VFT pointers are used at run-time to invoke the appropriate function implementations, because at compile time it may not yet be known if the base function is to be called or a derived one implemented by a class that inherits from the base class
- VFT is class-specific – all instances of the class has the same VFT
- VFT carries the **Run-Time Type Information** (RTTI) of objects

Virtual Function Pointer Table

```
class A { public:
    virtual void f(int) { }
    virtual void g(double) { }
    int h(A *) { }
};
class B: public A { public:
    void f(int) { }
    virtual int h(B *) { }
};
class C: public B { public:
    void g(double) { }
    int h(B *) { }
};
A a; B b; C c;
A *pA; B *pB;
```

Source Expression	Compiled Expression
`pA->f(2);`	`pA->vft[0](pA, 2);`
`pA->g(3.2);`	`pA->vft[1](pA, 3.2);`
`pA->h(&a);`	`A::h(pA, &a);`
`pA->h(&b);`	`A::h(pA, &b);`
`pB->f(2);`	`pB->vft[0](pB, 2);`
`pB->g(3.2);`	`pB->vft[1](pB, 3.2);`
`pB->h(&a);`	`pB->vft[2](pB, &a);`
`pB->h(&b);`	`pB->vft[2](pB, &b);`

a Object Layout

Object		*VFT*	
vft →	0	A::f(A*const, int)	Defined
	1	A::g(A*const, double)	Defined

b Object Layout

Object		*VFT*	
vft →	0	B::f(B*const, int)	Overridden
	1	A::g(A*const, double)	Inherited
	2	B::h(B*const, B*)	Overloaded

c Object Layout

Object		*VFT*	
vft →	0	B::f(B*const, int)	Inherited
	1	C::g(C*const, double)	Overridden
	2	C::h(C*const, B*)	Overridden

Module Summary

- Leveraging an innovative solution to the Salary Processing Application in C using function pointers, we compare C and C++ solutions to the problem
- The new C solution with function pointers is used to explain the mechanism for dynamic binding (polymorphic dispatch) based on `virtual` function tables