Object-Oriented Programming and Data Structures

COMP2012: Inheritance

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Example: University Admin Info

Let's implement a system for maintaining university administrative information.

- **Teacher** and **Student** are two completely separate classes.
- Their implementation uses separate code.
- However, some of their members and methods are implemented in the same way: name and department, and their handling member functions.
- Why do we implement the same function twice?
- That is not good re-use of software!

Example: U. Admin Info — Student Class

```
/* File: student1.h */
enum Department { CBME, CIVL, CSE, ECE, IELM, MAE };

class Student
{
  private:
    string name;
    Department dept;
    float GPA;
    Course *enrolled; int num_courses;
  public:
    Student(string n, Department d, float x) :
      name(n), dept(d), GPA(x), enrolled(NULL), num_courses(0) { };
    string get_name( ) const;
    Department get_department( ) const;
    string get_GPA( ) const;
    bool add_course(const Course &);
    bool drop_course(const Course &);
};
```

```
/* File: teacher1.h */
enum Department { CBME, CIVL, CSE, ECE, IELM, MAE };
enum Rank { PROFESSOR, DEAN, PRESIDENT };

class Teacher
{
  private:
    string name;
    Department dept;
    Rank rank;
    string research_area;
  public:
    Teacher(string n, Department d, Rank r, string a) :
                name(n), dept(d), rank(r), research_area(a) { };
    string get_name( ) const;
    Department get_department( ) const;
    Rank get_rank( ) const;
    string get_research_area( ) const;
};
```

Things to Consider

- We want a way to say that **Student** and **Teacher** both have the same members: name, dept, but yet require them to keep a separate copy of these members.
- We want to share the code for **get_name** etc. between **Student** and **Teacher** as well.
- However, objects have state, and it needs to remain consistent when these methods are called — so we cannot just write global functions to do it.

Solution#1: Re-use by Copying

Copy the code from one class to the other class, and change the class names.

- This is very error prone.
- It is also a maintenance nightmare.
  - What if we find a bug in the code in one class?
  - What if we want to improve the code? Perhaps we introduce a new member **address**.
- "Re-use by copying" is a bad idea!

Part I

What is Inheritance?

Solution#2: By Inheritance — UPerson Class

Idea: Find out the common data members and member functions of **Student** and **Teacher** and put them into a parent class, called **UPerson** here, and apply the inheritance mechanism.

```
#ifndef UPERSON_H                                   /* File: uperson.h */
#define UPERSON_H
enum Department { CBME, CIVL, CSE, ECE, IELM, MAE };
class UPerson
{
  private:
    string name;
    Department dept;

  public:
    UPerson(string n, Department d) : name(n), dept(d) { };
    string get_name( ) const { return name; }
    Department get_department( ) const { return dept; }
};
#endif
```

```
#ifndef STUDENT_H                                    /* File: student.h */
#define STUDENT_H
#include "uperson.h"
class Course { /* incomplete */ };
class Student : public UPerson                       // Public inheritance
{
  private:
    float GPA;
    Course *enrolled;
    int num_courses;

  public:
    Student(string n, Department d, float x) :
        UPerson(n, d), GPA(x), enrolled(NULL), num_courses(0) { }
    float get_GPA( ) const { return GPA; }
    bool enroll_course(const string &) { /* incomplete */ };
    bool drop_course(const Course &) { /* incomplete */ };
};
#endif
```

Solution#2: By Inheritance — Teacher Class

```
#ifndef TEACHER_H                                   /* File: teacher.h */
#define TEACHER_H
#include "uperson.h"

enum Rank { PROFESSOR, DEAN, PRESIDENT };

class Teacher : public UPerson                      // Public inheritance
{
  private:
    Rank rank;
    string research_area;

  public:
    Teacher(string n, Department d, Rank r, string a) :
        UPerson(n, d), rank(r), research_area(a) { };
    Rank get_rank( ) const { return rank; }
    string get_research_area( ) const { return research_area; }
};
#endif
```

- Inheritance is the ability to define a new class based on an existing class with a hierarchy.
- The derived class inherits the data members and member functions of the base class.
- New members and functions are added to the derived class.
- The new class only has to implement the behavior that is extra to the base class, and the code of the base class can be re-used in the derived class.
- In this example, **UPerson** is the base class, and **Student** and **Teacher** are the derived classes.
- **Student** and **Teacher** inherit all data members and functions from **UPerson**.
- E.g., The data members of **Student** are the data members of **UPerson** {name, dept}, plus the extra data members declared in **Student**'s definition {GPA, enrolled, num_courses}.
- Inheritance enables code re-use.

Example: Inherited Members and Functions

```
#include <iostream>                          /* File: inherited-fcn.cpp */
using namespace std;
#include "student.h"

void some_func(UPerson& uperson, Student& student) {
    cout << uperson.get_name( ) << endl;
    Department dept = uperson.get_department();
    // Error! Base class object can't call derived class's function
    uperson.enroll_course("COMP1001");

    // Derived class object may call base class's member function
    cout << student.get_name( ) << endl;
    // Derived class object call its own member functions
    cout << student.get_GPA( ) << endl;
    student.enroll_course("COMP2012");
}
int main( ) {
    UPerson abby("Abby", CBME);
    Student bob("Bob", CIVL, 3.0);
    some_func(abby, bob);
}
```

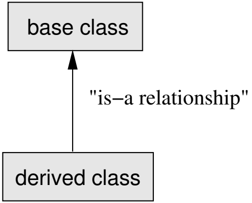
Polymorphic or Liskov Substitution Principle

Inheritance implements the is-a relationship.

- Since **Student** inherits from **UPerson**,
  - Every **Student** object can be used like a **UPerson** object.
  - All methods of **UPerson** can be called by a **Student** object.
- In other words, a **Student** object is a **UPerson** object.
- In general, an object of the derived class can be treated like an object of the base class under all circumstances.

If class **D** (a derived class) inherits from class **B** (the base class):

- Every **D** object is also a **B** object, but not vice-versa.
- **B** is a more general concept; **D** is a more special concept.
- Where a **B** object is needed, a **D** object can be used instead.



Polymorphic or Liskov Substitution Principle ..

In C++, using our university administration example, where **Student** and **Teacher** are derived from **UPerson**, this means:

- Since a **Student**/**Teacher** object is also a **UPerson** object, we can define a function on **UPerson** objects but apply it on both **Student** and **Teacher** objects.

Function Expecting an Argument of Type	Will Also Accept
UPerson	**Student**
pointer to **UPerson**	pointer to **Student**
UPerson reference	**Student** reference

Example: Derived Objects Treated as Base Class Objects

```
#include <iostream>                                    /* File: print-label.cpp */
using namespace std;
#include "student.h"
#include "teacher.h"

void print_label(const UPerson& uperson)
{
    cout << "Name:   " << uperson.get_name( ) << endl;
    cout << "Dept:   " << uperson.get_department( ) << endl;
}

int main( )
{
    Student tom("Tom", CIVL, 3.9);
    print_label(tom);                          // Tom is also a UPerson

    Teacher brian("Brian", CSE, PROFESSOR, "AI");
    print_label(brian);                        // Brian is also a UPerson
}
```

```
#include <iostream>                               /* File: substitute.cpp */
using namespace std;
#include "student.h"

int main( ) {
    void dance(const UPerson &p);                   // Anyone can dance
    void study(const Student &s);                   // Only students study
    void dance(const UPerson *p);                   // Anyone can dance
    void study(const Student *s);                   // Only students study
    UPerson p("P", IELM); Student s("S", MAE, 3.3);

    // Which of the following statements can compile?
    dance(p);
    dance(s);
    dance(&p);
    dance(&s);
    study(s);
    study(p);
    study(&s);
    study(&p);
}
```

Extending Class Hierarchy

We can easily add classes to our existing class hierarchy of **UPerson**, **Student**, and **Teacher**.

- New classes can immediately benefit from all functions that are available to their base classes.
- e.g. void print_label(const UPerson& person)
  will work immediately for a new class type **Research_Scholar**, even though this type of object was unknown when **print_label( )** was designed and written.
- In fact, it is not even necessary to recompile the existing code: It is enough to link the new class with the object code for **UPerson** and **print_label( )**.
- Advanced use: Link in new objects while the code is running!

Direct and Indirect Inheritance

Let's add a new class **PG_Student** to the hierarchy.

- **PG_Student** is directly derived from **Student**.
- It is indirectly derived from **UPerson**.
- So a **PG_Student** object is also a **UPerson** object.
- **UPerson** is called an indirect base class of **PG_Student**.

```
#include "student.h"                    /* File: pg-student.h */
class PG_Student : public Student
{
  private:
    string research_topic;
  public:
    PG_Student(string n, Department d, float x) :
        Student(n, d, x), research_topic("") { }
    string get_topic( ) const { return research_topic; }
    void set_topic(const string& x) { research_topic = x; }
};
```

Example: Indirect Inheritance

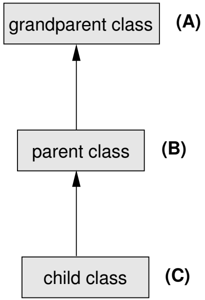
- Let's promote Tom to **PG_Student**.
- Can Tom still use the **print_label( )** function?

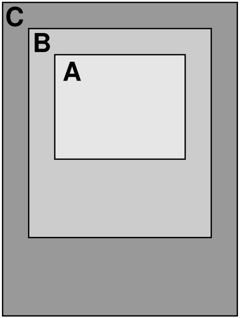
```
#include <iostream>                /* File: pg-print-label.cpp */
using namespace std;
#include "pg-student.h"            // Change student.h to pg-student.h

void print_label(const UPerson& uperson)
{
    cout << "Name:   " << uperson.get_name( ) << endl;
    cout << "Dept:   " << uperson.get_department( ) << endl;
}

int main( )
{
    PG_Student tom("Tom", CIVL, 3.9); // Tom is now a PG Student
    print_label(tom);                 // Tom is also a UPerson
}
```

Part II

Initialization of Classes in An Inheritance Hierarchy

Initialization of Base Class Objects





- If class C is derived from class B which is in turn derived from class A, then C will contain data members of both B and A.
- Class C's constructor can only call class B's constructor, and class B's constructor can only call class A's constructor.
- It is the responsibility of each derived class to initialize its direct base class correctly.

Initialization of Base Class Objects by Initializer

- Before a **Student** object can come into existence, we have to create its **UPerson** part.
- This has to be done using a constructor of **UPerson** through the member initialization list.

```
Student::Student(string n, Department d, float x) :
  UPerson(n,d), GPA(x), enrolled(NULL), num_courses(0) { }
```

- Similarly, **PG_Student** has to create its **Student** part before it can be created.
- But, it does not need to create its **UPerson** part directly by calling **UPerson**'s constructor.
- In fact, its **UPerson** part should have been created by **Student**.

```
PG_Student::PG_Student(string n, Department d, float x) :
    Student(n, d, x), research_topic("") { }
```

Order of Cons/Destruction: Student w/ an Address

```
#include <iostream>                              /* File: init-order.cpp */
using namespace std;

class Address { public:
    Address( ) { cout << "Address's constructor" << endl; }
    ~Address( ) { cout << "Address's destructor" << endl; }
};

class UPerson { public:
    UPerson( ) { cout << "UPerson's constructor" << endl; }
    ~UPerson( ) { cout << "UPerson's destructor" << endl; }
};

class Student : public UPerson { public:
    Student( ) { cout << "Student's constructor" << endl; }
    ~Student( ) { cout << "Student's destructor" << endl; }
  private: Address address;
};

int main( ) { Student x; }
```

Order of Cons/Destruction: Student w/ an Address ..

```
UPerson's constructor
Address's constructor
Student's constructor
Student's destructor
Address's destructor
UPerson's destructor
```

Order of Cons/Destruction: Move Address to UPerson

```
#include <iostream>                              /* File: init-order2.cpp */
using namespace std;

class Address { public:
    Address( ) { cout << "Address's constructor" << endl; }
    ~Address( ) { cout << "Address's destructor" << endl; }
};

class UPerson { public:
    UPerson( ) { cout << "UPerson's constructor" << endl; }
    ~UPerson( ) { cout << "UPerson's destructor" << endl; }
  private: Address address;
};

class Student : public UPerson { public:
    Student( ) { cout << "Student's constructor" << endl; }
    ~Student( ) { cout << "Student's destructor" << endl; }
};

int main( ) { Student x; }
```

Question: What is the output now?

Part III

Some Problems of Inheritance

Problem #1: Slicing

- An assignment from a derived class object to a base class object results in "slicing".
- This is rarely desirable.
- Once slicing has happened, there is no trace of the fact that we started with a derived class.

```
/* File: slice.cpp */
Student student("Snoopy", CSE, 3.5);
UPerson* pp = &student;
UPerson* pp2 = new Student("Mickey", ECE, 3.4);

UPerson uperson;
uperson = student;              // What does "uperson" have?
```

Problem #2: Name Conflicts

```
#include <iostream>                          /* File: name-conflict.cpp */
using namespace std;

void print_xy(int x, int y) { cout << x << " , " << y << '\n'; }

class B
{
  private: int x, y;
  public:
    B(int p=1, int q=2) : x(p), y(q)
      { cout << "Base class constructor:  "; print_xy(x, y); }
    void f( ) const { cout << "Base class:  "; print_xy(x, y); }
};

class D : public B
{
  private: float x, y;
  public:
    D( ) : x(10.0), y(20.0) { cout << "Derived class constructor\n"; }
    void f( ) const { cout << "Derived class:  "; print_xy(x, y); B::f( ); }
};
```

Problem #2: Name Conflicts ..

```
void smart(const B* z) { cout << "Inside smart( ):  "; z->f( ); }

int main( )
{
    B base(5, 6); cout << endl;
    D derive; cout << endl;

    B* b = &base;
    D* d = &derive;

    b->f( ); cout << endl;
    d->f( ); cout << endl;

    b = &derive; b->f( ); cout << endl;

    smart(b); cout << endl;
    smart(d); cout << endl;

}
```

Problem #2: Name Conflicts Output

```
Base class constructor: 5 , 6

Base class constructor: 1 , 2
Derived class constructor

Base class: 5 , 6

Derived class: 10 , 20
Base class: 1 , 2

Base class: 1 , 2

Inside smart( ): Base class: 1 , 2

Inside smart( ): Base class: 1 , 2
```

Problem #3: Bad Design

- Let's design a Bird class.

```
class Bird                                    /* File: bird.h */
{
    ...
  public:
    void hatch_eggs( );                       // Birds lay eggs
    void lay_egg(int n);
    void spread_wings( );                     // Birds have wings
    void fly( );                              // Birds can fly
    int altitude( ) const;                    // Return current altitude
};
```

- We can re-use **Bird** to implement some special cases:

```
class Swallow : public Bird { ... };
class Eagle : public Bird { public: void hunt(Bird *prey); };
```

Example: Derive a Penguin from a Bird

Now we need a penguin object, and we would like to re-use all the code we have for hatching and laying eggs, spreading wings, etc.

```
class Penguin : public Bird                /* File: penguin1.h */
{
    ...
  public:
    ...
    void swim( );
    void catch_fish( );
};
```

Oops! Penguins cannot fly!
What can we do?

Example: Derive a Penguin from a Bird ..

```
void Penguin::fly( )                          /* File: penguin1.cpp */
{
    cerr << "Penguins cannot fly!" << endl;
    exit(999);
}
```

- Some people try to solve the problem like above.
- But this doesn't really say "Penguins cannot fly".
  It says: "Penguins can fly, but they are forbidden!"

- Some people try to solve the problem like this:
  Penguins can fly, but the altitude is zero.

```
class Penguin : public Bird                    /* File: penguin2.h */
{
    ...
  public:
    ...
    void swim( );
    void catch_fish( );
    void fly( ) { }    // Penguin can't fly
    int altitude() const { return 0; }    // Always zero
};
```

Penguin Example: What's Wrong?

```
void find_food(Bird *b)                 /* File: penguin-wrong.cpp */
{
    b->fly( );                  // Visibility decreases with altitude
    double visibility = 10.0 / b->altitude( );
    ...
}
```

- Declaring **Penguin** as a derived class of **Bird** violates the substitution principle.
- It is not possible to use a **Penguin** in some functions that work for **Bird** objects:
- The only solution is: REDESIGN!

Summary

- Behavior and structure of the base class is inherited by the derived class.
- However, constructors and destructor are an exception. They are never inherited.
- There is a kind of contract between base class and derived class:
  - The base class provides functionality and structure (methods and data members).
  - The derived class guarantees that the base class is initialized in a consistent state by calling an appropriate constructor.
- A base class is constructed before the derived class.
- A base class is destructed after the derived class.

Part IV

Access Control: public, protected, private

Example: Add **print( )** to UPerson/Student Class

```
#include "uperson.h"                                    /* File: print1.cpp */
#include "student.h"

class UPerson { public: void print( ) const; ... };
class Student: public UPerson { public: void print( ) const; ... };

void UPerson::print( ) const {
    cout << "--- UPerson details ---" << endl;
    cout << "Name:   " << name << endl << "\nDept:   " << dept << endl;
}

void Student::print( ) const {
    cout << "--- Student details ---" << endl
         << "Name:   " << name << endl << "\nDept:   " << dept << endl
         << "Enrolled in:" << endl;
    for (int i = 0; i < num_courses; i++)
        enrolled[i].print( );                  // Assume a Course print function
}
```

Example: Add **print( )** to UPerson/Student Class — Doesn't Compile!

- The implementation of **Student::print( )** given before doesn't work. It will raise an error during compilation:

  Student::print( ): **name** and **dept** are declared private.

- **name** is a private data member of the base class **UPerson**.
- Public inheritance does not change the access control of the data members of the base class.
- Private members are still only available to base class' own member functions (methods), and not to any other classes including derived classes (except friends) or global functions.

One Solution: Protected Data Members

```
class UPerson                                    /* File: protected-uperson.h */
{
  protected:
    string name;
    Department dept;
  public:
    UPerson(string n, Department d) : name(n), dept(d) { };
    void print( ) const;
    ...
};
```

- By making **name** and **dept** protected, they are accessible to methods in the base class as well as methods in the derived classes.
- They should not be public though! (principle of information hiding)

Member Access Control: public, protected, private

There are 3 levels of member (data or methods) access control:

1. public: accessible to
   - member functions of the class (from class developer)
   - any member functions of other classes (application programmers)
   - any global functions (application programmers)
2. protected: accessible to
   - member functions and friends of the class
   - member functions and friends of its derived classes (subclasses)

   $\Rightarrow$ class developer restricts what subclasses may directly use
3. private: accessible only to
   - member functions and friends of the class

   $\Rightarrow$ class developer enforces information hiding

Without inheritance, private and protected have exactly the same meaning.

So why not always use protected instead of private?

- Because protected means that we have less data encapsulation: Remember that all derived classes can access protected data members of the base class.
- Assume that later you decided to change the implementation of the base class having the protected data members.
- For example, we might want to represent dept of **UPerson** by a new class called **class Department** instead of **enum Department**. If the **dept** data member is private, we can easily make this change. The update on the **UPerson** class documentation is small.
- However, if it is protected, we have to go through not only the **UPerson** class, but also all its derived classes and change them. We also need to update the documentation of many classes.

- In general, it is preferable to have private members instead of protected members.
- Use protected only where it is really necessary. private is the only category ensuring full data encapsulation.
- This is particularly true for data members, but it is less harmful to have protected member functions. Why?

In our example, there is no reason at all to make **name**, and **dept** protected, as we can access the name and address through appropriate public member functions.

Write Student::print( ), Teacher::print( ) with UPerson's Public Member Functions Only

```
void Student::print( ) const                /* correct-student-print.cpp */
{
    cout << "--- Student details ---" << endl
         << "Name:   " << get_name( ) << endl
         << "Dept:   " << get_dept( ) << endl
         << "Enrolled in:" << endl;
    for (int i = 0; i < num_courses; i++)
        enrolled[i].print( );
}

void Teacher::print( ) const                /* correct-teacher-print.cpp */
{
    cout << "--- Teacher details ---" << endl
         << "Name:   " << get_name( ) << endl
         << "Dept:   " << get_dept( ) << endl
         << "Rank:   " << get_rank( ) << endl;
}
```

Write Student::print( ), Teacher::print( ) with UPerson's Public Member Functions Only ..

Let's use the new **print( )** functions now.

```
/* File: print-example.cpp (incomplete) */
UPerson mouse("Mickey", CIVL);
Teacher einstein("Einstein", CSE, DEAN);
Student plato("Plato", ECE, 2.5);
plato.enroll_course("COMP2012");

mouse.print( );
einstein.print( );
plato.print( );
```

Write Student::print( ), Teacher::print( ) with UPerson's Public Member Functions Only — Expected Output

```
--- UPerson details ---
Name: Mickey
Dept: 1

--- Teacher details ---
Name: Einstein
Dept: 2
Rank: 0

--- Student details ---
Name: Plato
Dept: 3
Enrolled in:
COMP2012
```

Part V

Public Inheritance
Protected Inheritance
Private Inheritance

Different Types of Inheritance

- So far, we have been dealing with only public inheritance.

  `class` Student: `public` UPerson { . . . }

- There are two other kinds of inheritance: protected and private inheritance.
- They control how the inherited members of Student are accessed by Student's derived classes (*not* UPerson's derived classes).

UPerson Class Again

```
#ifndef UPERSON_H                                    /* File: uperson.h */
#define UPERSON_H
enum Department { CBME, CIVL, CSE, ECE, IELM, MAE };
class UPerson
{
  private:
    string name;
    Department dept;

  protected:
    void set_name(const char* s) { name = s };
    void set_department(Department d) { dept = d; };

  public:
    UPerson(string n, Department d) : name(n), dept(d) { };
    string get_name( ) const { return name; }
    Department get_department( ) const { return dept; }
};
#endif
```

Student Class Again

```
#ifndef STUDENT_H                                    /* File: student.h */
#define STUDENT_H
#include "uperson.h"
class Course {                                            incomplete */ };
class Student : ??? UPerson          // ??? = public/protected/private
{
  private:
    float GPA;
    Course *enrolled;
    int num_courses;

  public:
    Student(string n, Department d, float x) :
        UPerson(n, d), GPA(x), enrolled(NULL), num_courses(0) { }
    float get_GPA( ) const { return GPA; }
    bool enroll_course(const string &) {                  incomplete */ };
    bool drop_course(const Course &) {                    incomplete */ };
};
#endif
```

Example: Public Inheritance

`class` Student: `public` UPerson { ... }

public	protected	private
get_name( )	set_name( )	name
get_department( )	set_department( )	dept
enroll_course( )		enrolled
drop_course( )		num_courses

Example: Protected Inheritance

`class Student: protected UPerson { ... }`

public	protected	private
enroll_course( )	set_name( )	name
drop_course( )	set_department( )	dept
	get_name( )	enrolled
	get_department( )	num_courses

Example: Private Inheritance

`class Student: private UPerson { ... }`

public	protected	private
enroll_course( )		name
drop_course( )		dept
		enrolled
		num_courses
		set_name( )
		set_department( )
		get_name( )
		get_department( )

Summary

1. Public inheritance preserves the original accessibility of inherited members:

$$\begin{array}{rcl} \text{public} & \Rightarrow & \text{public} \\ \text{protected} & \Rightarrow & \text{protected} \\ \text{private} & \Rightarrow & \text{private} \end{array}$$

2. Protected inheritance affects only public members and renders them protected.

$$\begin{array}{rcl} \text{public} & \Rightarrow & \text{protected} \\ \text{protected} & \Rightarrow & \text{protected} \\ \text{private} & \Rightarrow & \text{private} \end{array}$$

3. Private inheritance renders all inherited members private.

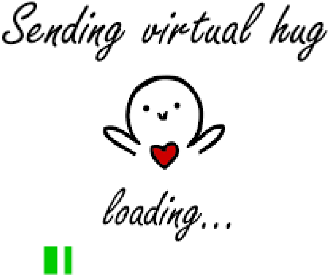
$$\begin{array}{rcl} \text{public} & \Rightarrow & \text{private} \\ \text{protected} & \Rightarrow & \text{private} \\ \text{private} & \Rightarrow & \text{private} \end{array}$$

Summary ..

- The various types of inheritance control the highest accessibility of the inherited member data and functions.
- Public inheritance implements the "is-a" relationship.
- Private inheritance is similar to "has-a" relationship.
- Public inheritance is the most common form of inheritance.

Part VI

Polymorphism: Dynamic Binding & Virtual Function



Global print( ) for UPerson and its Derived Objects

```
#include <iostream>                                    /* File: print-label.cpp */
using namespace std;
#include "student.h"
#include "teacher.h"

void print_label_pbv(UPerson uperson) { uperson.print(); }
void print_label_pbr(const UPerson& uperson) { uperson.print(); }
void print_label_pbp(const UPerson* uperson) { uperson->print(); }

int main( ) {
    UPerson uperson("Charlie Brown", CBME);
    Student student("Edison", ECE, 3.5);
    Teacher teacher("Alan Turing", CSE, PROFESSOR, "CS Theory");
    student.add_course("COMP2012"); student.add_course("MATH1003");

    cout << "\n##### PASS BY VALUE #####\n";
    print_label_pbv(uperson); print_label_pbv(student); print_label_pbv(teacher);

    cout << "\n##### PASS BY REFERENCE #####\n";
    print_label_pbr(uperson); print_label_pbr(student); print_label_pbr(teacher);

    cout << "\n##### PASS BY POINTER #####\n";
    print_label_pbp(&uperson); print_label_pbp(&student); print_label_pbp(&teacher);
}
```

Are These Outputs What You Want?

```
##### PASS BY VALUE  #####
--- UPerson Details ---
Name: Charlie Brown
Dept: 0
--- UPerson Details ---
Name: Edison
Dept: 3
--- UPerson Details ---
Name: Alan Turing
Dept: 2

##### PASS BY REFERENCE  #####
--- UPerson Details ---
Name: Charlie Brown
Dept: 0
--- UPerson Details ---
Name: Edison
Dept: 3
--- UPerson Details ---
Name: Alan Turing
Dept: 2
```

```
##### PASS BY POINTER  #####
--- UPerson Details ---
Name: Charlie Brown
Dept: 0
--- UPerson Details ---
Name: Edison
Dept: 3
--- UPerson Details ---
Name: Alan Turing
Dept: 2
```

You Probably Want This

```
#####  PASS BY VALUE  #####
--- UPerson Details ---
Name: Charlie Brown
Dept: 0
--- UPerson Details ---
Name: Edison
Dept: 3
--- UPerson Details ---
Name: Alan Turing
Dept: 2

#####  PASS BY REFERENCE  #####
--- UPerson Details ---
Name: Charlie Brown
Dept: 0
--- Student Details ---
Name: Edison
Dept: 3
2 Enrolled courses: COMP2012 MATH1003
--- Teacher Details ---
Name: Alan Turing
Dept: 2
Rank: 0
Research area: CS Theory
```

```
#####  PASS BY POINTER  #####
--- UPerson Details ---
Name: Charlie Brown
Dept: 0
--- Student Details ---
Name: Edison
Dept: 3
2 Enrolled courses: COMP2012 MATH1003
--- Teacher Details ---
Name: Alan Turing
Dept: 2
Rank: 0
Research area: CS Theory
```

Static (or Early) Binding

- Because of the polymorphic substitution principle, a function accepting a base class object also accepts its derived objects.
- In our current case, the following 3 global print functions:

```
void print_label_pbv(UPerson uperson) { uperson.print(); }
void print_label_pbr(const UPerson& uperson) { uperson.print(); }
void print_label_pbp(const UPerson* uperson) { uperson->print(); }
```

  will accept objects of **UPerson**/**Student**/**Teacher** classes, and objects derived from them directly or indirectly.
- However, when these function codes are compiled, the compiler only looks at the static type of **uperson** which is **UPerson**, **const UPerson&**, or **const UPerson***, and the method **UPerson::print( )** is called.
- Static binding: the binding (association) of a function name (here **print( )**) to the appropriate method is done by a static analysis of the code at compile time based on the static (or declared) type of the object (here, **uperson**) making the call.

Static Binding: Who May call Whose **print( )**

```
#include <iostream>                                    /* File: static-example.cpp */
using namespace std;
#include "teacher.h"

int main( )
{
    UPerson uperson("Charlie Brown", CBME);
    Teacher teacher("Alan Turing", CSE, PROFESSOR, "CS Theory");
    UPerson* u; Teacher* t;

    cout << "\nUPerson object pointed by UPerson pointer:\n";
    u = &uperson; u->print( );

    cout << "\nTeacher object pointed by Teacher pointer:\n";
    t = &teacher; t->print( );

    cout << "\nTeacher object pointed by UPerson pointer:\n";
    u = &teacher; u->print( );

    cout << "\nUPerson object pointed by Teacher pointer:\n";
    t = &uperson; t->print( );      // Error: convert base-class ptr to derived-class
    t = static_cast<Teacher*>(&uperson); t->print( );          // Ok, but ...
}
```

Dynamic (or Late) Binding

- By default, C++ uses static binding. (Same as C, Pascal, and FORTRAN.)
- In static binding, what a pointer really points to, or what a reference actually refers to is not considered.
- But C++ also allows dynamic binding which is supported through virtual functions.
- When dynamic binding is used, the actual method to be called is selected using the actual type of the object in the call, but only if the object is passed by reference or pointer. i.e. **print_label_pbr(**a **UPerson** object reference**)** would call **UPerson::print( )**; **print_label_pbr(**a **Teacher** object reference**)** would call **Teacher::print( )**; **print_label_pbr(**a **Student** object reference**)** would call **Student::print( )**.
- Note that the possible object types do not need to be known at the time when the function definition is being compiled!

Virtual Functions

- A virtual function is declared using the keyword virtual in the class definition, and not in the method implementation, if it is defined outside the class.
- Once a method is declared virtual in the base class, it is automatically virtual in all directly or indirectly derived classes.
- Even though it is not necessary to use the virtual keyword in the derived classes, it is a good style to do so because it improves the readability of header files.
- Calls to virtual functions are a little bit slower than normal function calls. The difference is extremely small and it is not worth worrying about, unless you write very speed-critical code.

Virtual Function: UPerson Class

```
#ifndef V_UPERSON_H                                    /* File: v-uperson.h */
#define V_UPERSON_H

enum Department { CBME, CIVL, CSE, ECE, IELM, MAE };
class UPerson
{
  private:
    string name;
    Department dept;

  public:
    UPerson(string n, Department d) : name(n), dept(d) { };
    string get_name( ) const { return name; }
    Department get_department( ) const { return dept; }
    virtual void print( ) const
    {
        cout << "--- UPerson Details --- \n"
             << "Name:   " << name << "\nDept:   " << dept << "\n";
    }
};
#endif
```

Virtual Function: Course Class

```
#ifndef COURSE_H                                        /* File: course.h */
#define COURSE_H

class Course
{
  private:
    string code;

  public:
    Course(const string& s) : code(s) { }
    ~Course( ) { cout << "destruct course:  " << code << endl; }
    void print( ) const { cout << code; }
};
#endif
```

```
#ifndef V_STUDENT_H                                    /* File: v-student.h */
#define V_STUDENT_H
#include "course.h"
#include "v-uperson.h"

class Student : public UPerson {                       // Public inheritance
  private:
    float GPA; Course* enrolled[50]; int num_courses;
  public:
    Student(string n, Department d, float x) :
        UPerson(n, d), GPA(x), num_courses(0) { }
    ~Student( ) { for (int j = 0; j < num_courses; ++j) delete enrolled[j]; }
    float get_GPA( ) const { return GPA; }
    bool add_course(const string& s)
        { enrolled[num_courses++] = new Course(s); return true; };
    virtual void print( ) const
    {
        cout << "--- Student Details --- \n"
             << "Name:   " << get_name( ) << "\nDept:   " << get_department( )
             << "\n" << num_courses << " Enrolled courses:  ";
        for (int j = 0; j < num_courses; ++j)
           { enrolled[j]->print( ); cout << ' '; } cout << "\n";
    }
};
#endif
```

Virtual Function: Teacher Class

```
#ifndef V_TEACHER_H                              /* File: v-teacher.h */
#define V_TEACHER_H
#include "v-uperson.h"

enum Rank { PROFESSOR, DEAN, PRESIDENT };
class Teacher : public UPerson                   // Public inheritance
{
  private:
    Rank rank;
    string research_area;
  public:
    Teacher(string n, Department d, Rank r, string a) :
        UPerson(n, d), rank(r), research_area(a) { };
    Rank get_rank( ) const { return rank; }
    string get_research_area( ) const { return research_area; }
    virtual void print( ) const
    {
        cout << "--- Teacher Details --- \n"
             << "Name:  " << get_name( )
             << "\nDept:  " << get_department( )
             << "\nRank:  " << rank
             << "\nResearch area:  " << research_area << "\n";
    }
};
#endif
```

Polymorphism

poly = multiple   *morphos* = shape

- Polymorphism in C++ means that we can work with objects without knowing their precise type at compile time.
- In: `void print_label_pbp(const UPerson* uperson) { uperson->print(); }`

  the type of the object pointed to by **uperson** is not known to the programmer writing this code, nor to the compiler.
- We say that **uperson** exhibits polymorphism, because the object can take on multiple "shapes" (Student, Teacher, PG_Student, etc.).
- Polymorphism allows us to write programs that behave correctly even when used with objects of derived classes.
- Again a pointer or reference must be used to have polymorphism.

Question: Why won't polymorphism work if pass-by-value is used?

Example: Polymorphism using Virtual Function

```
#include <iostream>                                    /* File: v-example.cpp */
using namespace std;
#include "v-student.h"
#include "v-teacher.h"

int main( )
{
    UPerson* uperson[3] = { };
    char person_type; string name;

    for (int j = 0; j < sizeof(uperson)/sizeof(UPerson*); ++j)
    {
        cout << "Input the uperson type (u/s/t) and his name :  ";
        cin >> person_type >> name;
        switch (person_type)
        {
            case 'u': uperson[j] = new UPerson(name, MAE); break;
            case 's': uperson[j] = new Student(name, CIVL, 4.0); break;
            case 't': uperson[j] = new Teacher(name, CSE, DEAN, "AI"); break;
        }
    }

    for (int j = 0; j < sizeof(uperson)/sizeof(UPerson*); ++j)
        uperson[j]->print( );
} // The example does't destruct the dynamically allocated objects
```

Run-Time Type Information (RTTI)

- RTTI is a runtime facility that keeps track of dynamic types and thus allows a program to determine an object's type at execution time.
- The function **typeid(<expression>)** returns an object of the type **type_info**. It has a member function **name( )** that returns the type name of the expression.
- Different compilers may print out the type name differently.
- **static_cast( )** may be used to perform type conversions,
  - including conversions between pointers to classes in an inheritance hierarchy;
  - it doesn't consult RTTI to ensure the conversion is safe;
  - thus, it runs faster.
- **dynamic_cast( )**, on the other hand,
  - only works on pointers and references of polymorphic class (with virtual functions) types;
  - consults RTTI to make sure the conversion result is a pointer to a valid complete object of the target type; otherwise, it returns a null pointer.

Example: RTTI **typeid( )**

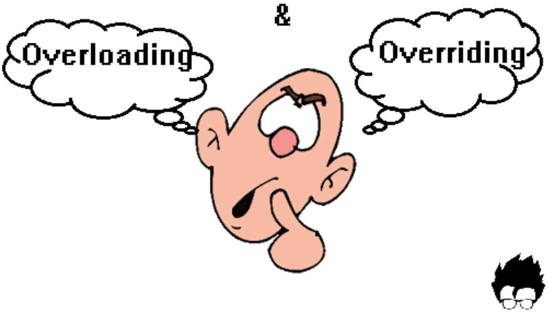
```
#include <iostream>                                          /* File: rtti.cpp */
using namespace std;
#include "v-student.h"
#include "v-teacher.h"

int main( )
{
    UPerson* uperson[3] = { };
    char person_type; string name;

    for (int j = 0; j < sizeof(uperson)/sizeof(UPerson*); ++j)
    {
        cout << "Input the uperson type (s/t) and his name :  ";
        cin >> person_type >> name;

        if (person_type == 's')
            uperson[j] = new Student(name, CIVL, 4.0);
        else if (person_type == 't')
            uperson[j] = new Teacher(name, CSE, DEAN, "AI");
    }

    for (int j = 0; j < sizeof(uperson)/sizeof(UPerson*); ++j)
        cout << "The uperson #" << j << " is a "
             << typeid(*uperson[j]).name( ) << endl;                  // RTTI
}
```

Example: RTTI **typeid( )** Output

```
Input the uperson type (s/t) and his name : s Abby
Input the uperson type (s/t) and his name : t Brian
Input the uperson type (s/t) and his name : s Chris
The uperson #0 is a 7Student
The uperson #1 is a 7Teacher
The uperson #2 is a 7Student
```

Part VII

Virtual Functions



Overriding and Virtual Functions

- When a derived class defines a method with the same name as a base class method, it overrides the base class method. e.g.

  Student::print( ) overrides **UPerson::print( )**

- This is necessary if the behaviour of the base class method is not good enough for derived classes.
- All derived classes should respond to the same request (**print**!), but their response varies depending on the object.
- The designer of the base class (**UPerson**) must realize that this will be necessary, and declare its **print( )** a virtual function.
- Overriding is not possible if the method is not virtual.

Virtual Functions vs. Non-Virtual Functions

- The designer of the base class must distinguish carefully between two kinds of methods:
  - If the method works exactly the same for all derived classes, it should not be a virtual function.
  - If the precise behaviour of the method depends on the object, it should be a virtual function.
- However, derived classes have to be careful in implementing this method because of the substitution principle. The "effect" (meaning) of calling the derived class method must be the "same" as for the base class method.

Virtual Functions vs. Non-Virtual Functions ..

- Overriding is for specializing a behaviour, not changing the semantics.
- For example, **print( )** should not be a method that does something completely different.
- **fly( )** must do what it promises, and therefore we could not implement **Penguin** as a derived class of **Bird**.
- The compiler can only check that overriding is done syntactically correct, not whether the semantics of the method are preserved.

Overriding vs. Overloading

Overloading

Allows programmers to use functions with the same name, but different arguments for similar purposes.

- The decision on which function to use — overload resolution — is done by the compiler when the program is compiled.
- There is no dynamic binding.

Overriding

Allows a derived class to provide a different implementation for a function declared in the base class.

- Overriding is only possible with inheritance and dynamic binding — without inheritance there is no overriding.
- The decision of which method to use is done at the moment that the method is called.
- It only applies to member methods, not global functions.

Example: Destruction with No Substitution

```
#include <iostream>                 /* File: concrete-destructors.cpp */
using namespace std;
#include "v-student.h"

int main( )
{
    UPerson *p = new UPerson("Adam", ECE);
    delete p;

    Student *s = new Student("Simpson", CSE, 3.8);
    s->add_course("COMP1021");
    s->add_course("COMP2012");
    delete s;
}
```

- **delete p** will call **UPerson**'s destructor, and **delete s** will call **Student**'s destructor respectively.
- So it works fine.

Example: Destruction with Substitution

```
#include <iostream>                          /* File: require-v-destructors.cpp */
using namespace std;
#include "v-student.h"

int main( )
{
    Student *s = new Student("Simpson", CSE, 3.8);
    s->add_course("COMP1021"); s->add_course("COMP2012");

    UPerson *p = s;
    delete p;        // Error: how about the courses owned by Student?
}
```

- Here **p** actually points to a **Student** object.
- **delete p** calls the **UPerson**'s destructor, and not **Student**'s destructor.
- The **Student** object itself is removed from the heap, but the resources it owns — courses — are not deleted.
- Therefore there is a memory leak in this code.

- The solution is again to switch on dynamic binding, and make the destructors virtual.

```
class UPerson                                   /* File: v-uperson2.h */
{
  public: virtual ~UPerson( ) { };
  ...
};

class Student : public UPerson                  /* File: v-student2.h */
{
  public: virtual ~Student( )
    { for (int j = 0; j < num_courses; ++j) delete enrolled[j]; }
  ...
};
```

```
#include <iostream>                       /* File: v-destructors.cpp */
using namespace std;
#include "v-student2.h"                   // With virtual destructor

int main( )
{
    Student *s = new Student("Simpson", CSE, 3.8);
    s->add_course("COMP1021"); s->add_course("COMP2012");

    UPerson *p = s;
    delete p;               // Actually will call Student's destructor
}
```

- Now, **delete p** correctly calls the **Student**'s destructor if **p** points to a **Student** object.
- When a class does not have a virtual destructor, this is a strong hint that the class is not designed to be used as a base class.

Example: Order of Constructions

```
#include <iostream>                    /* File: construction-order.cpp */
using namespace std;

class Base
{
  public: Base( ) { cout << "Base's constructor\n"; }
};

class Derived : public Base
{
  public: Derived( ) { cout << "Derived's constructor\n"; }
};

int main( ) { Base *p = new Derived; }
```

Question: What is the output?

Example: Calling Virtual Functions in Constructors

```
#include <iostream>                              /* File: construct-vf.cpp */
using namespace std;

class Base {
  public:
    Base( ) { cout << "Base's constructor\n"; this->f( ); }
    virtual void f( ) { cout << "Base::f( )" << endl; }
};

class Derived : public Base {
  public:
    Derived( ) { cout << "Derived's constructor\n"; }
    virtual void f( ) { cout << "Derived::f( )" << endl; }
};

int main( ) {
    Base *p = new Derived;
    cout << "Derived-class object created" << endl;
    p->f( );
}
```

The output is:

```
Base's constructor
Base::f( )
Derived's constructor
Derived-class object created
Derived::f( )
```

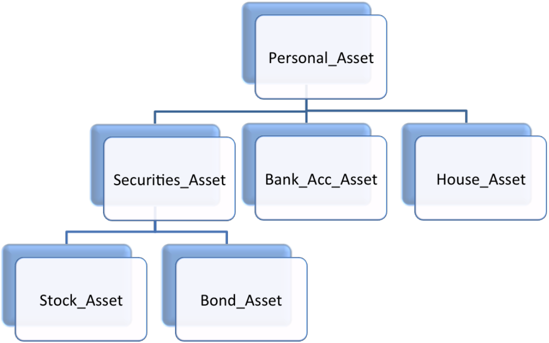
- Do not rely on the virtual function mechanism during the execution of a constructor.
- This is not a bug, but necessary — how can the derived object provide services if it has not been constructed yet?
- Similarly, if a virtual function is called inside the base class destructor, it represents base class' virtual function: when a derived class is being deleted, the derived-specific portion has already been deleted before the base class destructor is called!

Part VIII

As Simple as ABC: Abstract Base Class

ABC Example: Assets

- Let's design a system for maintaining our assets: stocks, bank accounts, real estate, cars, yachts, etc.
- Each asset has a net worth (monetary value), and we would like to be able to make listings and compute the total net worth.
- There are different kinds of assets, and they are all derived from **Personal_Asset**.



ABC Example: Personal_Asset & Bank_Acc_Asset Classes

```
class Personal_Asset                              /* File: personal-asset.h */
{
  public:
    Personal_Asset(const string& date) : purchase_date(date) { }
    void set_purchase_date(const string& d);
    virtual double compute_net_worth( ) const;       // Current net worth
    virtual bool is_insurable( ) const;          // Can this asset be insured?

  private:
    string purchase_date;
};

class Bank_Acc_Asset : public Personal_Asset    // File: bank-acc-asset.h */
{
  public:
  Bank_Acc_Asset(const string& d, double m, double r = 0.0)
      : Personal_Asset(d), balance(m), interest_rate(r) { }
    virtual double compute_net_worth( ) const { return balance; }
  private:
    double balance;
    double interest_rate;
};
```

ABC Example: compute-assets.cpp

- There can be other classes of assets such as **Car_Asset**, **Securities_Asset**, **House_Asset**, etc.
- One may compute the total asset value for an array of different kinds of assets as follows:

```
double compute_total_worth(              /* File: compute-assets.cpp */
    const Personal_Asset* asset[ ], int num_assets)
{
    double total_worth = 0.0;
    for (int i = 0; i < num_assets; i++)
        total_worth += assets[i]->compute_net_worth();

    return total_worth;
}
```

- Now we have to implement the member functions of the base class **Personal_Asset**.
- How to implement **Personal_Asset::compute_net_worth( )**?
- It depends completely on the actual type of asset. There is no "standard way" of doing it!

```
/* File: personal-asset.cpp */
Personal_Asset::Personal_Asset(const string& date)
    : purchase_date(date) { }

void Personal_Asset::set_purchase_date(const string& date)
    { purchase_date = date; }

double Personal_Asset::compute_net_worth( ) const
    { return /* What? */ }
```

ABC Example: How to Implement compute_net_worth( ) ?

- The truth is: It makes no sense to have objects of type **Personal_Asset**.
- Such an object has only a purchase date, but otherwise no meaning. It is not a bank account, not a car, not a house — it is too general to be used.
- We cannot implement the **compute_net_worth( )** method in the base class **Personal_Asset** as the information needed to implement it is missing.
- However, we don't want to remove the method because that would make a polymorphic function like **compute_total_worth( )** impossible.

Solution: Abstract Base Class (ABC)

The solution is to make **Personal_Asset** an abstract base class (ABC), and **compute_net_worth( )** now becomes a pure virtual function.

```
class Personal_Asset                         /* File: personal-asset-abc.h */
{
  public:
    Personal_Asset(const string& date) : purchase_date(date) { }
    void set_purchase_date(const string& d);
    virtual bool is_insurable() const; // Can this asset be insured?

    // A pur virtual function to compute the current net worth
    virtual double compute_net_worth() const = 0;

  private:
    string purchase_date;
};
```

Abstract Base Class (ABC)

```
Personal_Asset p_asset("1997/07/01");              // Error
Bank_Acc_Asset b_asset("2000/01/01", 100.0);       // Ok
```

- An ABC has two properties:
  1. No objects of ABC can be created.
  2. Its derived classes must implement the pure virtual functions, otherwise they will also be ABC's.
- If a derived class, e.g., **Securities_Asset**, does not implement the pure virtual functions, then
  - the derived class is also an ABC, and
  - there cannot be objects of that type,
  - but it can be used as a base class itself, for instance for **Stocks_Asset**, **Bonds_Asset**, etc.

Interface Re-use

ABC as an Interface

An abstract base class provides a uniform interface to deal with a number of different derived classes.

- A base class contains what is common about several classes.
- If the only thing that is common is the interface, then the base class is a "pure interface," called ABC in C++.
- We discussed before that code re-use is an advantage of inheritance.
- For ABC's we do not re-use code, but create an interface that can be re-used by its derived classes.
- Interfaces are the soul of object-oriented programming. They are the most effective way of separating the use and implementation of objects.
- The user (of **compute_total_worth( )**) only knows about the abstract interface, objects from different derived classes of the ABC may implement the interface in different ways.

Final Remarks on ABC

- A pure virtual function is inherited as a pure virtual function by a derived class unless it implements the function.
- An abstract base class cannot be used
  - as an argument type that is passed by value
  - as a function return type that is returned by value
  - as the type of an explicit conversion
- However, pointers and references to an ABC can be declared.
- Calling a pure virtual function from the constructor of an ABC is undefined — don't do that.

ABC Example: Do and Don't

```
#include <string>                                        /* File: can-and-cant.cpp */
using namespace std;

#include "personal-asset-abc.h"
#include "bank-acc-asset.h"

Personal_Asset x("20010/01/01");     // Error: can't create objects of ABC
Personal_Asset f1(int x) { /* ... */ }    // Error: Can't return ABC objects
int f2(Personal_Asset x) { /* */ }   // Error: Can't CBV with ABC objects

Bank_Acc_Asset b("01/01/2000", 0.0);                                  // OK!
Personal_Asset* p_asset_ptr = &b;                                     // OK!
Personal_Asset& p_asset_ref = b;                                      // OK!

Personal_Asset* f3(const Personal_Asset& x) { /* incomplete */ }   // OK!
```