# Data Structures & Algorithms in C++

WEEK 02

# Object-Oriented Design

- Inheritance and Polymorphism
- Templates
- Exceptions

# Procedure-oriented vs. Object-oriented

- **Comparison between POD and OOD**

| Feature | Procedure-Oriented Design (POD) | Object-Oriented Design (OOD) |
|---|---|---|
| **Focus** | Functions or procedures | Objects |
| **Modularity** | Divides program into small functions | Organizes program into objects |
| **Data** | Data is secondary to functions | Data and behavior are encapsulated |
| **Approach** | Top-down approach | Bottom-up approach |
| **Examples** | Languages like C, Pascal, Fortran | Languages like Java, C++, Python |
| **Design Philosophy** | Emphasizes functions and action sequences | Emphasizes objects and interactions |
| **Data Handling** | Data is passed around between functions | Data and methods are within objects |
| **Reusability** | Functions can be reused | Objects and classes are highly reusable |
| **Maintenance** | Can be challenging to maintain as size grows | Easier to maintain due to encapsulation |

# OOD Goals

- **Objects**
  - Main “actors” in the object-oriented design paradigm
  - Instances of the class including data members and member functions
- **Goals**
  - **Robustness** : capability of handling unexpected inputs that are not explicitly defined for its application (more importantly in life-critical applications)
  - **Adaptability** : ability of software to run with minimal change on different H/W and OS platforms (Web browsers and Internet search engines)
  - **Reusability** : reusing of the same code can reduce the cost of developing high-quality software

# OOD Principles
# - ① Abstraction

- **Abstraction**
  - Simplifies a complicated system by focusing on its **fundamental parts**
  - Involves :
    - **Naming** system components
    - **Explaining their functionality** in simple, precise terms
- **Abstract Data Types (ADTs)**
  - A mathematical model of a data structure
  - Specifies :
    - **Data types** stored
    - **Supported operations** on the data
    - **Parameter types** for the operations
  - ADTs define **what the operations do**, not how they do it

# OOD Principles
# - ① Abstraction

- **Abstraction in C++**
  - Achieved through the **public interface** of a class :
    - **Signatures** : Names, return types, argument types of public member functions
    - The **only accessible part** of a class for its users
  - ADT is modeled in C++ by a class; classes specify **how the operations are performed** in the body of each function

# OOD Principles
# - ① Abstraction

➢ **Example**

```
class Shape {   // Abstract Base Class
public:
      virtual double getArea() const = 0;
};

class Circle : public Shape {    // Derived Class: Circle
private:
   double radius;
public:
   Circle(double r) : radius(r) {}
   double getArea() const override {
      return M_PI * radius * radius; // Area of a circle
   }
};
```

```
class Rectangle : public Shape {  // Derived Class: Rectangle
private:
   double width, height;
public:
   Rectangle(double w, double h) : width(w), height(h) {}
   double getArea() const override {
      return width * height; // Area of a rectangle
   }
};

int main() {
   // Create objects of Circle and Rectangle
   Shape* circle = new Circle(5.0);
   Shape* rectangle = new Rectangle(4.0, 6.0);
   return 0;
}
```

# OOD Principles
# - ② Encapsulation

- **Encapsulation**
  - Ensure that **internal details** of a component or system are **hidden**
  - Only necessary information is exposed through an **abstract interface**
- **Advantages**
  - Freedom to modify the internal implementation
  - Change to implementation are localized, reducing system-wise impacts
  - Protected from unintended interference
- **Constraints**
  - Maintain the **abstract interface** visible to outside components
  - Ensure **consistency** in interactions

# OOD Principles
# - ② Encapsulation

- **Example**

```
class EncapsulatedClass {
private:
    int hiddenData;  // Internal detail

public:
    // Abstract interface
    void setData(int value) {
        hiddenData = value;  // Controls access
    }

    int getData() const {
        return hiddenData; // Provides controlled access
    }
};
```

# OOD Principles
# - ③ Modularity

- **Modularity**
  - Divide a software system into separate, function units
  - Enhance clarity and maintainability by keeping components well-organized
- **Importance of Modularity**
  - Ensure that components in complex systems interact properly
  - Keep components logically divided, simplifying understanding and debugging
- **Benefits**
  - Improved maintainability
  - Code reusability
  - Scalability

# Principles
# - ③ Modularity

- **Example**

```
// Module 1: Class for User Authentication
class AuthModule {
public:
    void authenticateUser() {
        cout << "User authenticated." << endl;
    }
};
// Module 2: Class for Database Operations
class DatabaseModule {
public:
    void fetchData() {
        cout << "Data fetched from the database." << endl;
    }
};
```

```
// Main Application
int main() {
    AuthModule auth;
    DatabaseModule db;

    auth.authenticateUser();
    db.fetchData();

    return 0;
}
```

# Principles
# - Hierarchical Organization

- **Hierarchical Organization**
  - A tree-like structure : base classes (parents), derived classes (children)
  - Derived classes inherit properties and behaviors from their base classes
- **Characteristics**
  - **Generalization** at higher levels

    : base classes define broad, generic behaviors and attributes
  - **Specialization** at lower levels

    : derived classes provide more specific implementations or extend functionality
- **Benefits**
  - Code reusability, Modularity, Ease of Maintenance, Extensibility

# Design Patterns in OOD

- Advantages of OOD
  - Reusable, robust, and adaptable software
- Desing Patterns
  - Describe a solution to a “typical” software design problem
  - Provide a general template for solutions in various situations
  - Elements
    - **Name** : identifies design pattern
    - **Context** : describes scenarios for pattern application
    - **Template** : describes how the pattern is applied
    - **Result** : describes and analyzes what the pattern produces

# Design Patterns in OOD

- Algorithm Design Patterns
  - Recursion
  - Amortization
  - Divide-and-conquer
  - Prune-and-search (decrease-and-conquer)
  - Brute force
  - The greedy method
  - Dynamic programming
- Software Engineering Patterns
  - Position
  - Adapter
  - Iterator
  - Template method
  - Composition
  - Comparator
  - Decorator

# Inheritance

- Object-Oriented Paradigm
  - Provides a modular and hierarchical organizing structure
- **Inheritance**
  - Specialized classes reuse the code from the generic class

(*derived class, child class, subclass*) (base class , *parent class, superclass*)

  - Specialized class inherits general functions from the base class, and only defines the specialized functions

```
class Person {                          // Person (base class)
private:
  string        name;                   // name
  string        idNum;                  // university ID number
public:
  // ...
  void print();                         // print information
  string getName();                     // retrieve name
};
```

```
class Student : public Person {         // Student (derived from Person)
private:
  string        major;                  // major subject
  int           gradYear;               // graduation year
public:
  // ...
  void print();                         // print information
  void changeMajor(const string& newMajor); // change major
};
```

# Inheritance

- **Public** Members
  - An object of derived class can access the public members of both base and derived classes. However, an object of base class cannot access members of the derived class

```
Person person("Mary", "12-345");     // declare a Person
Student student("Bob", "98-764", "Math", 2012); // declare a Student

cout << student.getName() << endl; // invokes Person::getName()
person.print();                    // invokes Person::print()
student.print();                   // invokes Student::print()
person.changeMajor("Physics");     // ERROR!
student.changeMajor("English");    // okay
```

- **Protected** Members
  - “public” to all classes derived from this base class, but “private” to all other functions

# Inheritance

- Illustrating Class Protection
  - **Protected** members : allow derived classes to access and modify certain members
  - **Private** members : used to encapsulate data and methods, not to accessed or modified directly from outside the class

```
class Base {
  private:    int priv;
  protected:  int prot;
  public:     int publ;
};

class Derived: public Base {
  void someMemberFunction() {
    cout << priv;          // ERROR: private member
    cout << prot;          // okay
    cout << publ;          // okay
  }
};
```

```
class Unrelated {
  Base X;

  void anotherMemberFunction() {
    cout << X.priv;        // ERROR: private member
    cout << X.prot;        // ERROR: protected member
    cout << X.publ;        // okay
  }
};
```

# Inheritance

- **Constructors and Destructors**
  - Bottom-up construction : base class first, then its members, then the derived class

```
Person::Person(const string& nm, const string& id)
  : name(nm),                          // initialize name
    idNum(id) { }                      // initialize ID number

Student::Student(const string& nm, const string& id,
                 const string& maj, int year)
  : Person(nm, id),                    // initialize Person members
  major(maj),                          // initialize major
  gradYear(year) { }                   // initialize graduation year
```

  - Destruction in the reverse order : the derived classes destroyed before base classes

    → the derived class destructor does not need to call the base class destructor

```
delete s;                              // calls ~Student() then ~Person()
```

# Inheritance

- **Static Binding**
  - C++'s default action is to consider an object's declared type, not its actual type

```
Person* pp[100];
pp[0] = new Person(...);
pp[1] = new Student(...);
```

```
cout << pp[1]->getName() << '\n'; // okay
pp[0]->print();                   // calls Person::print()
pp[1]->print();                   // also calls Person::print() (!)
pp[1]->changeMajor("English");    // ERROR!
```

- **Dynamic binding and Virtual Functions**
  - To use dynamic binding, the keyword "virtual" is added to the function's declaration

```
class Person {
  virtual void print() { ... }
  // ...
};
class Student : public Person {
  virtual void print() { ... }
  // ...
};
```

```
Person* pp[100];                  // array of 100 Person pointers
pp[0] = new Person(...);          // add a Person (details omitted)
pp[1] = new Student(...);         // add a Student (details omitted)
pp[0]->print();                   // calls Person::print()
pp[1]->print();                   // calls Student::print()
```

※ Virtual destructor

# Polymorphism

- **Polymorphism**
  - Allows a variable to take on different types
  - Typically applied using pointer variables
- **Dynamic binding**
  - Both S and T define a virtual member function a
  - Invocation p->a() uses dynamic binding : T::a or S::a ( p : pointer of the object)
  - Caller of p->a() doesn't need to know if p refers to T or S

  * Software reuse support : inheritance, polymorphism, function overloading
- **Specialization** : override for specialized functions
- **Extension** : add new functions

# Polymorphism

| Aspect | Overriding | Overloading |
|---|---|---|
| **Method Name** | Same name, same parameters | Same name, different parameter lists |
| **Inheritance** | Requires inheritance | Does not require inheritance |
| **Purpose** | Changes behavior of inherited method | Provides multiple ways to call a method |
| **Resolution Time** | Resolved at **runtime** | Resolved at **compile time** |

# Examples of Inheritance

firstValue(): Reset the progression to the first value and return it.
nextValue(): Step the progression to the next value and return it.
printProgression($n$): Reset the progression and print its first $n$ values.

```
class Progression {                          // a generic progression
public:
  Progression(long f = 0)                    // constructor
    : first(f), cur(f) { }
  virtual ~Progression() { };                // destructor
  void printProgression(int n);              // print the first n values
protected:
  virtual long firstValue();                 // reset
  virtual long nextValue();                  // advance
protected:
  long first;                                // first value
  long cur;                                  // current value
};
```

```
void Progression::printProgression(int n) {      // print n values
  cout << firstValue();                          // print the first
  for (int i = 2; i <= n; i++)                   // print 2 through n
    cout << ' ' << nextValue();
  cout << endl;
}


long Progression::firstValue() {                 // reset
  cur = first;
  return cur;
}
long Progression::nextValue() {                  // advance
  return ++cur;
}
```

# Examples of Inheritance

```
class ArithProgression : public Progression {  // arithmetic progression
public:
  ArithProgression(long i = 1);                // constructor
protected:
  virtual long nextValue();                    // advance
protected:
  long inc;                                    // increment
};
```

```
class GeomProgression : public Progression {  // geometric progression
public:
  GeomProgression(long b = 2);                // constructor
protected:
  virtual long nextValue();                   // advance
protected:
  long base;                                  // base value
};
```

```
ArithProgression::ArithProgression(long i)     // constructor
  : Progression(), inc(i) { }

long ArithProgression::nextValue() {           // advance by adding
  cur += inc;
  return cur;
}
```

```
GeomProgression::GeomProgression(long b)     // constructor
  : Progression(1), base(b) { }

long GeomProgression::nextValue() {          // advance by multiplying
  cur *= base;
  return cur;
}
```

# Examples of Inheritance

```
/** Test program for the progression classes */
int main() {
  Progression* prog;
                                    // test ArithProgression
  cout << "Arithmetic progression with default increment:\n";
  prog = new ArithProgression();
  prog->printProgression(10);
  cout << "Arithmetic progression with increment 5:\n";
  prog = new ArithProgression(5);
  prog->printProgression(10);
                                    // test GeomProgression
  cout << "Geometric progression with default base:\n";
  prog = new GeomProgression();
  prog->printProgression(10);
  cout << "Geometric progression with base 3:\n";
  prog = new GeomProgression(3);
  prog->printProgression(10);
```

```
Arithmetic progression with default increment:
0 1 2 3 4 5 6 7 8 9
Arithmetic progression with increment 5:
0 5 10 15 20 25 30 35 40 45
Geometric progression with default base:
1 2 4 8 16 32 64 128 256 512
Geometric progression with base 3:
1 3 9 27 81 243 729 2187 6561 19683
```

# Multiple Inheritance and Class Casting

- Multiple Inheritance
  - C++ allows deriving a class from multiple base classes
  - Useful for defining interfaces, but introduces complexities
  - Single inheritance is used almost exclusively to avoid these complications

```
class Car {  // Base class: Car
public:
   void drive() {…}
   void park() {…}
};

class Boat {        // Base class: Boat
public:
   void sail() {…}
   void anchor() {…}
};
```

```
class HybridVehicle : public Car, public  Boat { // Derived class :
public:
   void hybridMode() {…}
};

int main() {
   HybridVehicle hybrid;
   hybrid.drive();  hybrid.park();
   hybrid.sail();     hybrid.anchor();
   hybrid.hybridMode();
   return 0;
}
```

# Multiple Inheritance and Class Casting

- Strong Typing
  - Enforces that all variables be typed and operations declare the types they expect
  - Helps prevent bugs by ensuring correct usage and function behavior
- Type Casting
  - Sometimes necessary to explicitly change a variable from one type to another
  - If an illegal pointer cast is attempted, then the result is a null pointer

```
Person* pp[100];
pp[0] = new Person(...);
pp[1] = new Student(...);
```

```
for (int i = 0; i < 100; i++) {
  Student *sp = dynamic_cast<Student*>(pp[i]);
  if (sp != NULL)                          // cast succeeded?
    sp->changeMajor("Undecided");          // change major
}
```

# Interfaces and Abstract Classes

- **Abstract Class**
  - Used only as a base class for inheritance; cannot be instantiated directly
  - Useful for defining generic base classes for related subclasses
- **Pure Virtual Function**
  - Declared by giving " = 0" in place of its body
  - Base class cannot be instantiated if it has pure virtual functions
- **Interfaces** and Abstract Base Classes
  - C++ does not provide a direct mechanism for defining interface for ADTs
    (cf. Java's interface : a collection of function declarations with no data and no bodies)
  - Use abstract base classes with all functions as pure virtual

# Interfaces and Abstract Classes

```
class Stack {                              // stack interface as an abstract class
public:
  virtual bool isEmpty() const = 0;        // is the stack empty?
  virtual void push(int x) = 0;            // push x onto the stack
  virtual int pop() = 0;                   // pop the stack and return result
};

class ConcreteStack : public Stack {       // implements Stack
public:
  virtual bool isEmpty() { ... }           // implementation of members
  virtual void push(int x) { ... }         // ... (details omitted)
  virtual int pop() { ... }
private:
  // ...                                   // member data for the implementation
};
```

# Templates
# - Function Templates

- **Function Template**
  - Automatic mechanism in C++ for generic functions
  - A well-defined pattern; allows instantiation of a concrete function for a specified type
  - Compiler checks the argument types at function call
- **Advantages** of Function Template
  - Reduce redundancy
  - Simplify the codebase
  - Easy to scale for multiple data types

# Templates
# - Function Templates

- Example

```
int integerMin(int a, int b)                    // returns the minimum of a and b
  { return (a < b ? a : b); }

template <typename T>
T genericMin(T a, T b) {                        // returns the minimum of a and b
  return (a < b ? a : b);
}

cout << genericMin(3, 4) << ' '     // = genericMin<int>(3,4)
  << genericMin(1.1, 3.1) << ' '    // = genericMin<double>(1.1, 3.1)
  << genericMin('t', 'g') << endl;  // = genericMin<char>('t','g')
```

# Templates
# - Class Templates

- **Class Template**
  - Allows templating of C++ classes to work with various data types
  - Provides a single declaration for multiple types
  - Extensively used in the STL (Standard Template Library)
- **Benefits** of Class Template
  - Code Reusability : define once, apply to various types
  - Simplified Syntax : reduces redundancy
  - Extensibility : easily adapt to new data types
- Usages in STL
  - std::vector<T>
  - std::map<Key, Value>

# Templates
# - Class Templates

- **Example**

```
template <typename T>
class BasicVector {
public:
  BasicVector(int capac = 10);
  T& operator[](int i)
    { return a[i]; }
  // ... other public members omitted
private:
  T* a;
  int capacity;
};
```

```
template <typename T>                    // constructor
BasicVector<T>::BasicVector(int capac) {
  capacity = capac;
  a = new T[capacity];                   // allocate array storage
}

BasicVector<int>     iv(5);              // vector of 5 integers
BasicVector<double>  dv(20);             // vector of 20 doubles
BasicVector<string>  sv(10);             // vector of 10 strings
```

# Exceptions

- **Exceptions**
  - Unexpected events during program execution
  - The result of an error condition or simply an unanticipated input
- "**Thrown**" by
  - The code itself when encountering a problem
  - C++ runtime environment (e.g., out of memory)
- Why use Exceptions
  - Cleaner, more efficient error management
  - Improves code readability and maintainability

# Exceptions

- **Example**

```
class MathException {
public:
  MathException(const string& err)
    : errMsg(err) { }
  string getError() { return errMsg; }
private:
  string errMsg;
};
```

```
class ZeroDivide : public MathException {
public:
  ZeroDivide(const string& err)                    // divide by zero
  : MathException(err) { }
};

class NegativeRoot : public MathException {
public:
  NegativeRoot(const string& err)                  // negative square root
  : MathException(err) { }
};
```

# Exceptions

- **Try-Catch Block**
  - Try block contains code that may throw exceptions
  - Catch blocks handle specific exception types
- **Benefits of Exception Handling**
  - Cleaner error management compared to special return values
  - Provides flexibility and reusability through catch blocks
  - Enables robust application development

# Exceptions

- Example

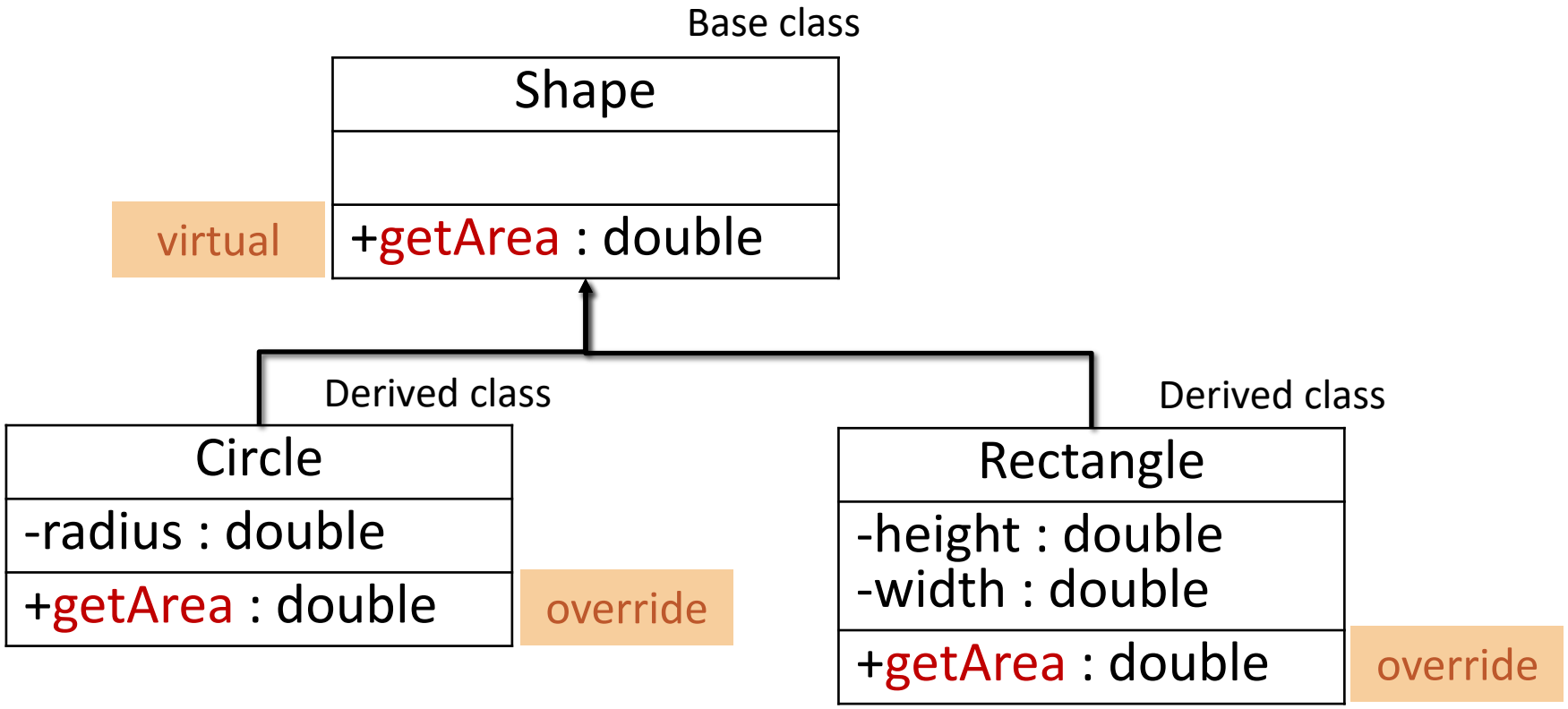
```
class MathException {
public :
  MathException(const string& err)
    : errMsg(err) {}
  string getError() { return errMsg; }
private :
  string errMsg;
};

class ZeroDivide : public MathException {
public :
  ZeroDivide(const string& err)
    : MathException(err) {}
};
```

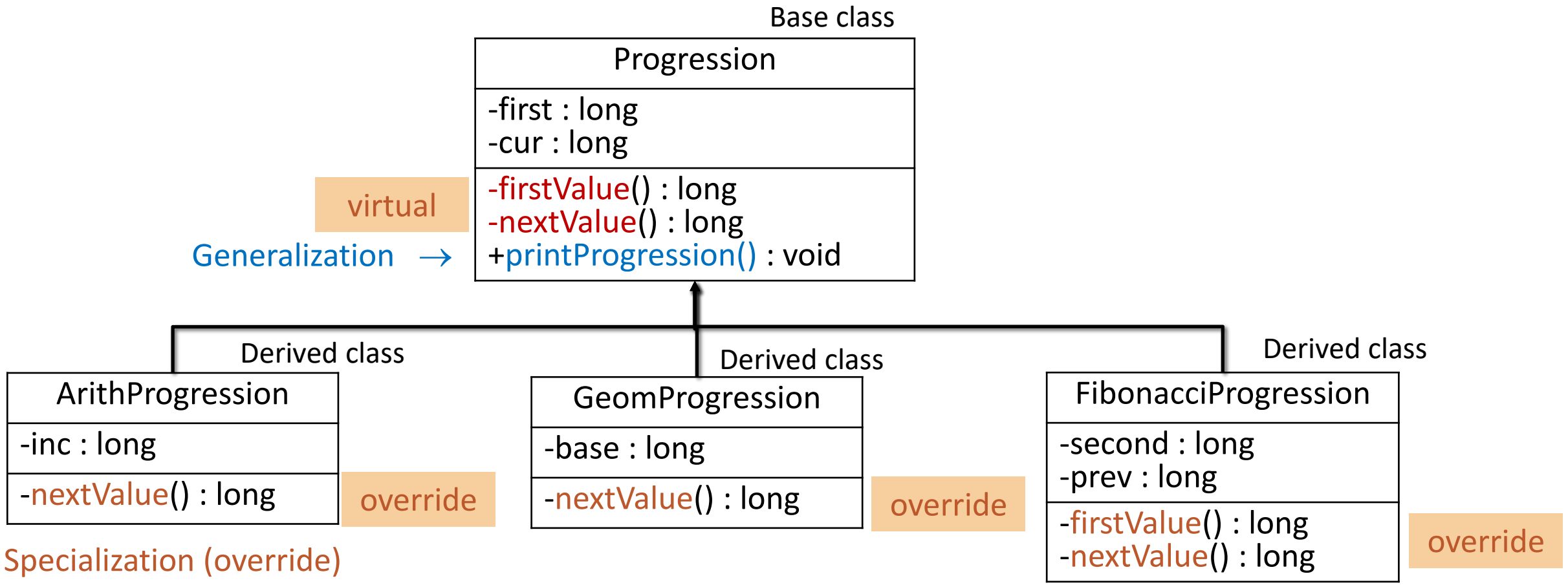
```
cout << "Enter two numbers : ";
cin >> num >> denom;

try {
  if ( denom == 0 )
    throw ZeroDivide("Division by Zero in main routine");
    result = num / denom;
    cout << "Division result = " << result << endl;
} catch (ZeroDivide &e) {
    cerr << "Exception caught : " << e.getError() << endl;
} catch (...) {
    cerr << "Unknown exception error " << endl;
}
```

# [Appendix] OOD Concepts
# - Inheritance and Polymorphism



# [Appendix] OOD Concepts - Inheritance and Polymorphism



# [Appendix] OOD Concepts
# - Inheritance and Polymorphism