Programming Design

Polymorphism

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Outline

- **Motivation**
- Basic ideas and the first example
- Virtual functions

An RPG game

- In a typical Role-Playing Game (RPG), a player plays the role of a character, who keep beating enemies (monsters, bad guys, or other players' characters).
  – By beating enemies, one earns experience points to advance to higher levels and become stronger.
- In many RPGs, one can choose the **occupation** for her character(s). The occupation typically affects the **ability** of a character (e.g., a warrior and a wizard are quite different).
  – Characters with different occupations have different attributes and behave differently. However, **they are all characters**.
- Given a class **`Character`** that defines some general features of an RPG character, let's create two new classes **`Warrior`** and **`Wizard`**.

Class `Character`

- The class **`Character`** includes the name, current level, accumulated experience points, and three ability levels: power, knowledge, and luck.
  - When a character joins your team, she/he may be at any level.
  - For all characters in our game, the number of experience points required for level k is $100(k-1)^2$. The number 100 is stored as a static constant.
- There is a constructor:
  - To create a character, we must specify all its attributes except the experience point: A new character at level k always starts with $100(k-1)^2$ experience points.
- There is a public function **`print()`**:
  - It prints out the current status of a character.

Class `Character`

- There is a public function **`beatMonster(int exp)`**:
  - It is invoked when the character beats a monster.
  - **`exp`** is the number of experience points earns in this battle.
  - This function increments the accumulated experience points and checks whether there should be a level up. If so, a private member function **`levelUp()`** is invoked.
- There is a private function **`levelUp()`**:
  - The character's **`level`** will be incremented.
  - However, her abilities will remain the same because characters of different occupations should get different improvements.
  - This should be specified in **`Warrior`** and **`Wizard`**.

Class Character

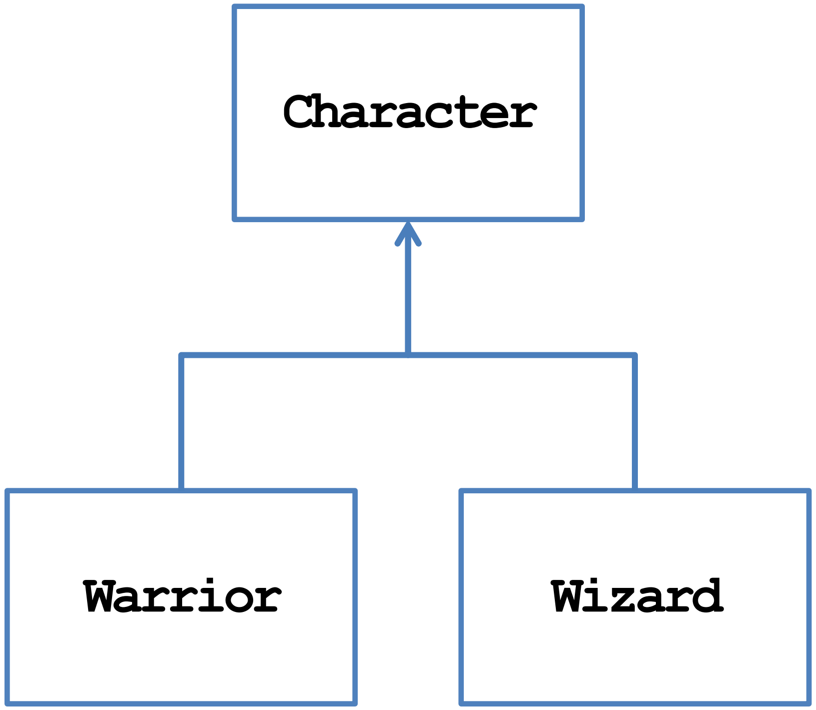
```
class Character
{
protected:
  string name;
  int level;
  int exp;
  int power;
  int knowledge;
  int luck;
  static const int expForLevel = 100;
  void levelUp(int pInc, int kInc, int lInc); // private member function
public:
  Character(string n, int lv, int po, int kn, int lu);
  void beatMonster(int exp);
  void print();
  string getName();
};
```

Class Character

```
Character::Character(string n, int lv, int po, int kn, int lu)
  : name(n), level(lv), exp(pow(lv - 1, 2) * expForLevel), power(po), knowledge(kn), luck(lu) {}
void Character::beatMonster(int exp) {
  this->exp += exp;
  while(this->exp >= pow(this->level, 2) * expForLevel)
    this->levelUp(0, 0, 0); // No improvement when advancing to the next level
}
void Character::print() {
  cout << this->name
       << ": Level " << this->level << " (" << this->exp << "/" << pow(this->level, 2) * expForLevel
       << "), " << this->power << "-" << this->knowledge << "-" << this->luck << "\n";
}
void Character::levelUp(int pInc, int kInc, int lInc) {
  this->level++; this->power += pInc; this->knowledge += kInc; this->luck += lInc;
}
string Character::getName() {
  return this->name;
}
```

Character, Warrior, and Wizard

- **Character** should **not** be used to create an object.
  - No improvement when advancing to the next level.
  - Personal attributes for improvements per level are not defined.
- We define two derived classes **Warrior** and **Wizard**:
  - **Character** is an **abstract class**.
  - **Warrior** and **Wizard** are **concrete classes**.



Classes Warrior and Wizard

```
class Warrior : public Character
{
private:
  static const int powerPerLevel = 10;
  static const int knowledgePerLevel = 5;
  static const int luckPerLevel = 5;
public:
  Warrior(string n) : Character(n, 1, powerPerLevel, knowledgePerLevel, luckPerLevel) {}
  Warrior(string n, int lv)
    : Character(n, lv, lv * powerPerLevel, lv * knowledgePerLevel, lv * luckPerLevel) {}
  void print() { cout << "Warrior "; Character::print(); }
  void beatMonster(int exp) // function overriding
  {
    this->exp += exp;
    while(this->exp >= pow(this->level, 2) * expForLevel)
      this->levelUp(powerPerLevel, knowledgePerLevel, luckPerLevel);
  }
};
```

Classes `Warrior` and `Wizard`

```
class Wizard : public Character
{
private:
  static const int powerPerLevel = 4;
  static const int knowledgePerLevel = 9;
  static const int luckPerLevel = 7;
public:
  Wizard(string n) : Character(n, 1, powerPerLevel, knowledgePerLevel, luckPerLevel) {}
  Wizard(string n, int lv)
    : Character(n, lv, lv * powerPerLevel, lv * knowledgePerLevel, lv * luckPerLevel) {}
  void print() { cout << "Wizard "; Character::print(); }
  void beatMonster(int exp) // function overriding
  {
    this->exp += exp;
    while(this->exp >= pow(this->level, 2) * expForLevel)
      this->levelUp(powerPerLevel, knowledgePerLevel, luckPerLevel);
  }
};
```

Some questions

- We may create **`Warrior`** and **`Wizard`** objects in our program.
  - May we **prevent** one from creating a **`Character`** object?
- A "team" has at most ten members.
  - We create two arrays, one for warriors and one for wizards. Each of them has a length of 10.
  - Why **wasting spaces**?

```
class Team
{
private:
  int warriorCount;
  int wizardCount;
  Warrior* warrior[10];
  Wizard* wizard[10];
public:
  Team();
  ~Team();
  // some other functions
};
```

Some questions

- We may need to add a warrior/wizard, let a warrior/wizard beat a monster, and print the current status of a warrior/wizard.
  - Characters' names are all different.
- Either we write two functions for a task, or write just one.
  - Two: **tedious** and **inconsistent**.
  - One: **Inefficient**.

```
class Team
{
private:
  int warriorCount;
  int wizardCount;
  Warrior* warrior[10];
  Wizard* wizard[10];
public:
  Team();
  ~Team();
  void addWar(string name, int lv);
  void addWiz(string name, int lv);
  void warBeatMonster(string name, int exp);
  void wizBeatMonster(string name, int exp);
  void printWar(string name);
  void printWiz(string name);
};
```

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Polymorphism

- The key flaw is to create two arrays, one for warriors and one for wizards.
  - May we use **only one array** to store the ten members?
  - But **`Warrior`** and **`Wizard`** are different classes.
- While they are different classes, they have **the same base class**.
  - They are all **`Character`**s!
  - May we declare a **`Character`** array to store **`Warrior`** and **`Wizard`** objects?
- We can. This is called **polymorphism**.
  - In C++, the way we implement polymorphism is to

    "***Use a variable of a parent type to store a value of a child type***."

Variables vs. values

- Let’s differentiate a **variable’s type** and a **value’s type**.
- A variable can store values and must have a type.
  - E.g., a `double` variable is a **container** which “should” store a `double` value.
- A value is the thing that is stored in a variable.
  - E.g., `12.5` or `7`.
- A value has its own type, which may be **different** from the variable’s type.
- In C++, a **parent variable** can store a **child object**.
  - A `Character` variable can store a `Warrior` or a `Wizard` object.
  - Because a warrior/wizard is a character!

Examples of polymorphism

- For example, we may do this:

```
int main
{
  Warrior w("Alice", 10);
  Character c = w; // copy constructor
  cout << c.getName() << endl; // Alice
  return 0;
}
```

- Or we may do this with pointers:

```
int main
{
  Warrior w("Alice", 10);
  Character* c = &w;
  cout << c->getName() << endl; // Alice
  return 0;
}
```

Why a parent variable for a child value?

- What happens to the following program?

```
int main
{
  P p1(1, 2);
  C c1(3, 4, 5);
  P p2 = c1; // OK: 5 will be discarded
  // C c2 = p1; // Not OK: v3 has no value
  return 0;
}
```

```
class P
{
protected:
  int x;
  int y;
public:
  P(int a, int b) : x(a), y(b) {}
  // other functions
};
class P : public C
{
protected:
  int z;
public:
  C(int a, int b, int c) : P(x, y) { z = c; }
  // other functions
};
```

Polymorphism with arrays

- Polymorphism is useful typically with **functions** or **arrays**:

```
int main
{
  Character* c[3];
  c[0] = new Warrior("Alice", 10);
  c[1] = new Wizard("Sophie", 8);
  c[2] = new Warrior("Amy", 12);
  for(int i = 0; i < 3; i++)
    c[i]->print();
  for(int i = 0; i < 3; i++)
    delete c[i];
  // do not delete [] c;
  return 0;
}
```

```
int main
{
  Character c[3]; // error! Why?
  Warrior w1("Alice", 10);
  Wizard w2("Sophie", 8);
  Warrior w3("Amy", 12);
  c[0] = w1;
  c[1] = w2;
  c[2] = w3;
  for(int i = 0; i < 3; i++)
    c[i].print();
  return 0;
}
```

Class Team with Polymorphism

- With polymorphism, we may redefine the class **Team**:

```
class Team
{
private:
  int warriorCount;
  int wizardCount;
  Warrior* warrior[10];
  Wizard* wizard[10];
public:
  Team();
  ~Team();
  void addWarrior(string name, int lv);
  void addWizard(string name, int lv);
  void warriorBeatMonster(string name, int exp);
  void wizardBeatMonster(string name, int exp);
  void printWarrior(string name);
  void printWizard(string name);
};
```

```
class Team
{
private:
  int memberCount;
  Character* member[10];
public:
  Team();
  ~Team();
  void addMember
    (string name, int lv, char occupation);
  void memberBeatMonster(string name, int exp);
  void printMember(string name);
};
```

Class Team with Polymorphism

- With polymorphism, we may redefine the class **Team**:

```
Team::Team()
{
  this->memberCount = 0;
  for(int i = 0; i < 10; i++)
    member[i] = NULL;
}
Team::~Team()
{
  for(int i = 0;
      i < this->memberCount;
      i++)
    delete this->member[i];
}
```

```
void Team::addMember
  (string name, int lv, char occupation)
{
  if(this->memberCount < 10)
  {
    if(occupation == 'R')
      this->member[this->memberCount] = new Warrior(name, lv);
    else if(occupation == 'D')
      this->member[this->memberCount] = new Wizard(name, lv);
    this->memberCount++;
  }
}
```

Class `Team` with Polymorphism

- With polymorphism, we may redefine the class **`Team`**:

```
void Team::memberBeatMonster(string name, int exp)
{
  for(int i = 0; i < this->memberCount; i++)
  {
    if(this->member[i]->getName() == name)
    {
      this->member[i]->beatMonster(exp);
      break;
    }
  }
}
```

```
void Team::printMember(string name)
{
  for(int i = 0; i < this->memberCount; i++)
  {
    if(this->member[i]->getName() == name)
    {
      this->member[i]->print();
      break;
    }
  }
}
```

Remaining questions

- We still cannot prevent one from creating a **`Character`** object.
- What happens to the following program:
  - No "Warrior " and "Wizard " printed out.
  - No experience point accumulated.
- Why?

```
int main()
{
  Character* c[3];
  for(int i = 0; i < 3; i++)
    c[i]->print();
  c[0] = new Warrior("Alice", 10);
  c[1] = new Wizard("Sophie", 8);
  c[2] = new Warrior("Amy", 12);
  c[0]->beatMonster(10000);
  for(int i = 0; i < 3; i++)
    c[i]->print();
  for(int i = 0; i < 3; i++)
    delete c[i];
  return 0;
}
```

Invoking an overridden function

- Suppose a parent variable stores a child value (or a parent pointer pointing to a child object).
- If we use the parent variable (pointer) to invoke an overridden function, which implementation will be invoked?
- The default setting is to invoke the parent's implementation.
- To invoke the child's one, we need **virtual functions**.

```
class A
{
public:
  void a() { cout << "a\n"; }
  void f() { cout << "af\n"; }
};

class B : public A
{
public:
  void b() { cout << "b\n"; }
  void f() { cout << "bf\n"; }
};
```

```
int main()
{
  B b;
  A a = b;
  a.a();
  a.f();
  // a.b();
  return 0;
}
```

```
int main()
{
  B b;
  A* a = &b;
  a->a();
  a->f();
  // a->b();
  return 0;
}
```

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- **Virtual functions**

Early binding vs. late binding

- When we do **`A a = b`** or **`A* a = &b`**, we are using polymorphism.
- For **`A a = b`**, the system does **early binding**:
  - **`a`** occupies only four bytes for storing **`i`**.
  - **`a`** does not have a space for storing **`j`**.
  - Its type is determined to be **`A`** at **compilation**.
- For **`A* a = &b`**, the system does **late binding**:
  - **`a`** is just a pointer.
  - It can point to an **`A`** object or a **`B`** object.
  - Its "type" can be determined at the **run time**.

```
class A
{
protected:
  int i;
public:
  void a() { cout << "a\n"; }
  void f() { cout << "af\n"; }
};

class B : public A
{
private:
  int j;
public:
  void b() { cout << "b\n"; }
  void f() { cout << "bf\n"; }
};
```

Early binding may discard values

- Why **`p2.print()`** must be the parent class' **`print()`**?

```
int main
{
  P p1(1, 2);
  C c1(3, 4, 5);
  P p2 = c1; // OK: 5 will be discarded
  p2.print(); // must be the P::print()
  return 0;
}
```

```
class P
{
protected:
  int x;
  int y;
public:
  P(int a, int b) : x(a), y(b) {}
  void print() { cout << x << " " << y; }
};
class P : public C
{
protected:
  int z;
public:
  C(int a, int b, int c) : P(a, b) { z = c; }
  void print() { cout << z; }
};
```

Late binding does not discard values

- Is it "possible" for **`p2->print()`** to be the child class' **`print()`**?

```
int main
{
  P p1(1, 2);
  C c1(3, 4, 5);
  P* p2 = &c1; // 5 can be accessed by p2
  p2->print(); // P::print()? C::print()?
  return 0;
}
```

```
class P
{
protected:
  int x;
  int y;
public:
  P(int a, int b) : x(a), y(b) {}
  void print() { cout << x << " " << y; }
};
class P : public C
{
protected:
  int z;
public:
  C(int a, int b, int c) : P(a, b) { z = c; }
  void print() { cout << z; }
};
```

Early binding vs. late binding

- But we still see the parent's implementation being invoked. Why?

```
int main()
{
  A a;
  B b;
  A* who = &a;
  who->f(); // af
  who = &b;
  who->f(); // af

  return 0;
}
```

- To ask the system to invoke the child's implementation, we need to declare **virtual functions**.

Virtual functions

- If we declare a parent's member function to be **virtual**, its invocation priority will be lower than a child's (if we use late binding).
  - To do so, simply add **the modifier `virtual`** into the function header:
  - The child's implementation is invoked!
- No need to do that at the child's side.
  - A parent can declare its function as a virtual function.
  - A child cannot declare a parent's function as virtual (it is of no use).
- In summary, we need:
  - Late binding + virtual functions.

```
class A
{
private:
  int i;
public:
  void a() { cout << "a\n"; }
  virtual void f() { cout << "af\n"; }
};
```

Virtual functions

- For our **`Character`** class, simply declare **`beatMonster()`** and **`print()`** as virtual.

```
class Character
{
protected:
  // ...
public:
  Character(string n, int lv, int po, int kn, int lu);
  virtual void beatMonster(int exp);
  virtual void print();
  string getName();
};
```

- **`Warrior`** and **`Wizard`** override the two functions. Now their implementations get invoked.

```
int main
{
  Character* c[3];
  for(int i = 0; i < 3; i++)
    c[i]->print();
  c[0] = new Warrior("Alice", 10);
  c[1] = new Wizard("Sophie", 8);
  c[2] = new Warrior("Amy", 12);
  c[0]->beatMonstor(10000);
  for(int i = 0; i < 3; i++)
    c[i]->print();
  for(int i = 0; i < 3; i++)
    delete c[i];
  return 0;
}
```

Abstract classes

- The two virtual functions are different in their natures:
  - **`print()`** is invoked in the children's implementations.
  - **`beatMonster()`** should not be invoked by any one.
- We may set **`beatMonster()`** to be a **pure virtual function**:

```
class Character
{
  // ...
  virtual void beatMonster(int exp) = 0;
};
```

  - Now we do not need to implement it.
  - Moreover, we **cannot** create **`Character`** objects!

Late binding is required

- Even if we declare virtual functions, they do not work in the following program:

```
int main
{
  Character c[3]; // Suppose we add a default constructor
  Warrior w1("Alice", 10);
  Wizard w2("Sophie", 8);
  Warrior w3("Amy", 12);
  c[0] = w1;
  c[1] = w2;
  c[2] = w3;
  for(int i = 0; i < 3; i++)
    c[i].print();
  return 0;
}
```

- Late binding (by using pointers) is required.

Polymorphism is everywhere

- Recall **`MyVector`**, its overloaded operator **`==`**, and its child **`MyVector2D`**.

```
class MyVector
{
  // ...
private:
  int n;
  double* m;
public:
  // ...
  bool operator==(const MyVector& v) const;
};
```

```
int main()
{
  double d[3] = {1, 2, 3};
  MyVector v1(3, d);
  MyVector2D v2(4, 5);
  cout << v1 == v2 << endl; // allowed?
  return 0;
}
```

- Why can the program run?
- In fact, we may also compare **`MyVector2D`** with **`MyVector`**, **`MyVector2D`** with **`MyVector2D`**, **`NNVector`** with **`MyVector`**, **`NNVector`** with **`MyVector2D`**, etc.

Summary

- Polymorphism is a technique to make our program clearer, more flexible and more powerful.
  - It is based on **inheritance**.
  - It is tightly related to **function overriding**, **late binding**, and **virtual functions**.
- The key action is to "use a parent pointer to point to a child object".
- To implement late binding, you need to
  - Declare and override virtual functions.
  - Do late binding by using parent pointers to point to child objects.