# Polymorphism

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# Section Overview

Polymorphism and Inheritance

- What is Polymorphism?
- Using base class pointers
- Static vs. dynamic binding
- Virtual functions
- Virtual destructors
- The override and final specifiers
- Using base class references
- Pure virtual functions and abstract classes
- Abstract classes as interfaces

# What is Polymorphism?

# Polymorphism

## What is Polymorphism?

- Fundamental to Object-Oriented Programming

- Polymorphism
  - Compile-time / early binding / static binding
  - **Run-time / late binding / dynamic binding**

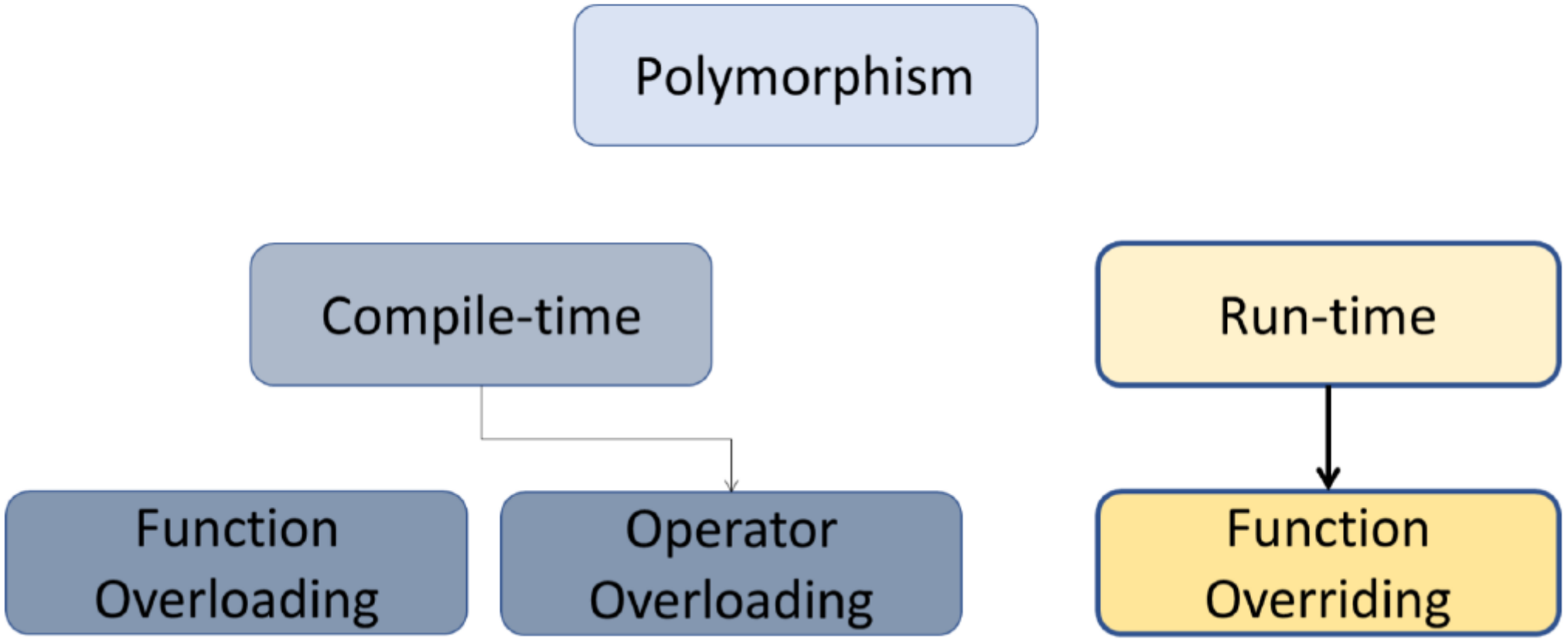
- Runtime polymorphism
  - Being able to assign different meanings to the same function at run-time

- Allows us to program more abstractly
  - Think general vs. specific
  - Let C++ figure out which function to call at run-time

- Not the default in C++, run-time polymorphism is achieved via
  - Inheritance
  - Base class pointers or references
  - virtual functions

# Polymorphism

Types of Polymorphism in C++?



# Polymorphism

## An non-polymorphic example – Static Binding

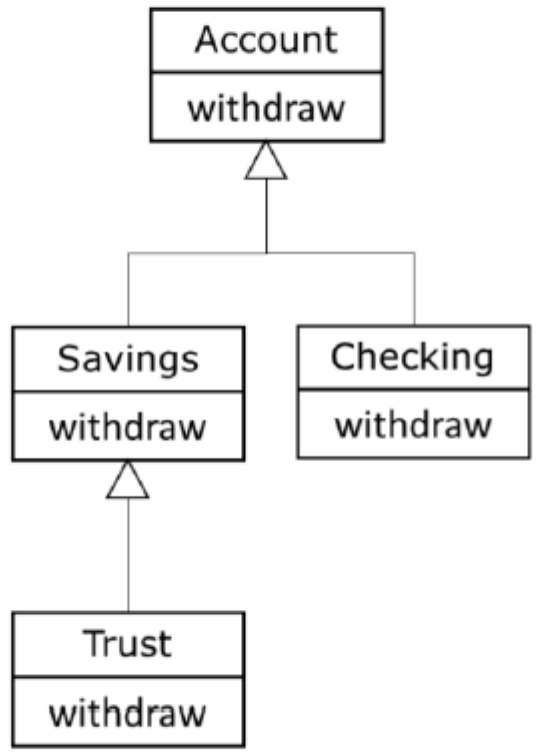
```
Account a;
a.withdraw(1000);    // Account::withdraw()

Savings b;
b.withdraw(1000);    // Savings::withdraw()

Checking c;
c.withdraw(1000);    // Checking::withdraw()

Trust d;
d.withdraw(1000);    // Trust::withdraw()


Account *p = new Trust();
P->withdraw(1000);   // Account::withdraw()
                     // should be
                     // Trust::withdraw()
```



# Polymorphism

## An non-polymorphic example – Static Binding

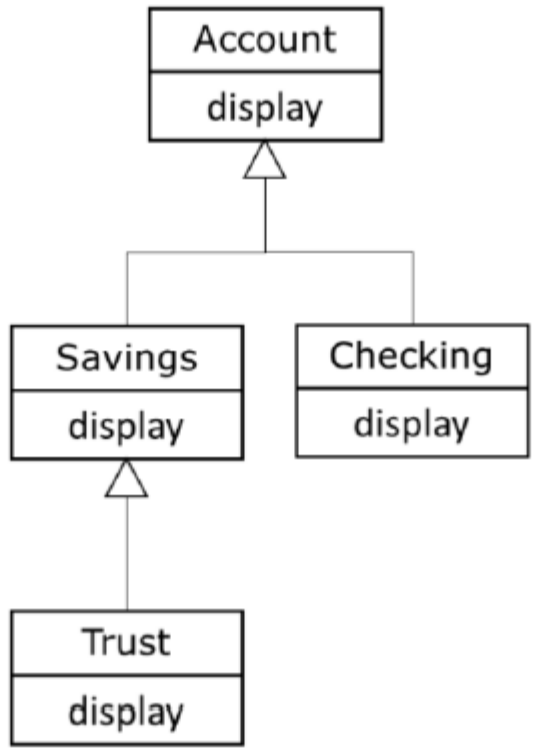
```
void display_account(const Account &acc)  {
   acc.display();
   // will always use Account::display
}

Account a;
display_account(a);

Savings b;
display_account(b);

Checking c;
display_account(c);

Trust d;
display_account(d);
```



# Polymorphism

## A polymorphic example – Dynamic Binding

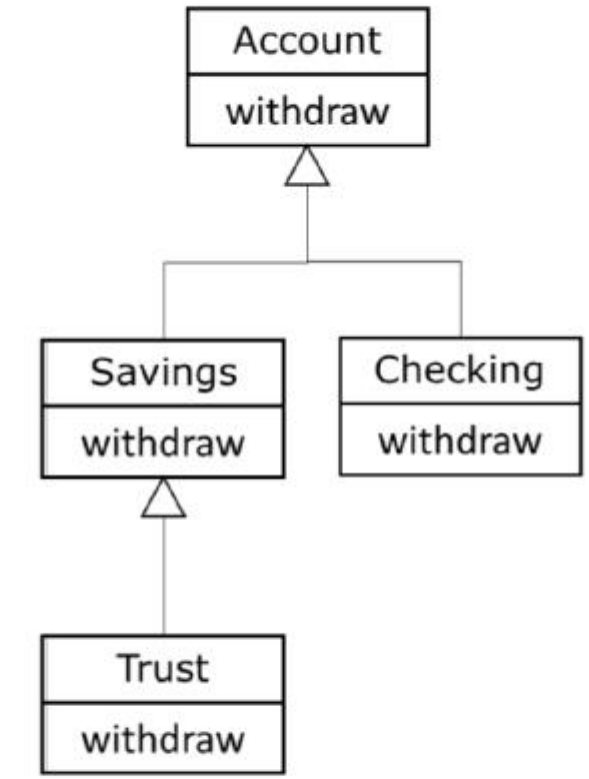
```
Account a;
a.withdraw(1000);    // Account::withdraw()

Savings b;
b.withdraw(1000);    // Savings::withdraw()

Checking c;
c.withdraw(1000);    // Checking::withdraw()

Trust d;
d.withdraw(1000);    // Trust::withdraw()


Account *p = new Trust();
P->withdraw(1000);   // Trust::withdraw()
```




`withdraw` method is virtual in Account

# Polymorphism

## A polymorphic example – Dynamic Binding

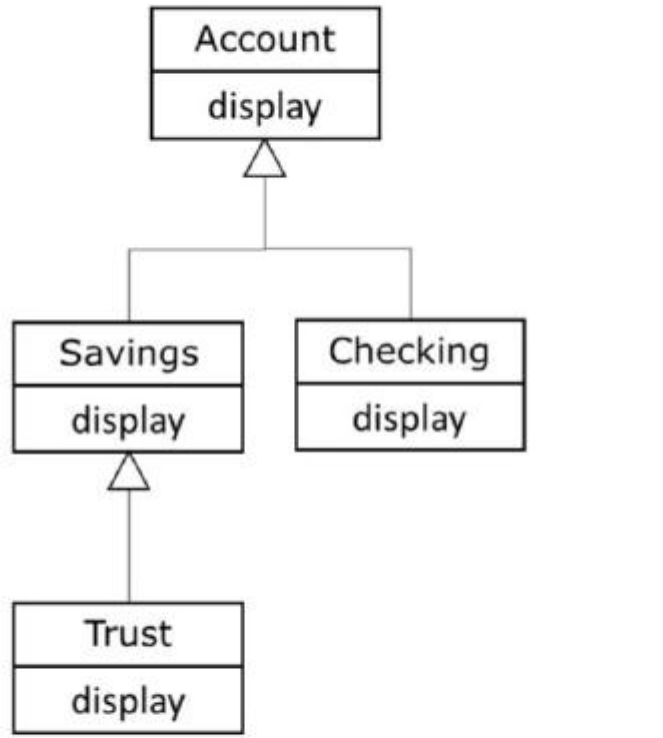
```
void display_account(const Account &acc)
{
   acc.display();
   // will always call the display method
   // depending on the object's type
   // at RUN-TIME!
}

Account a;
display_account(a);

Savings b;
display_account(b);

Checking c;
display_account(c);

Trust d;
display_account(d);
```




`display` method is virtual in Account

# Using Base Class Pointers

# Polymorphism

Using a Base class pointer

- For dynamic polymorphism we must have:
  - Inheritance
  - Base class pointer or Base class reference
  - virtual functions

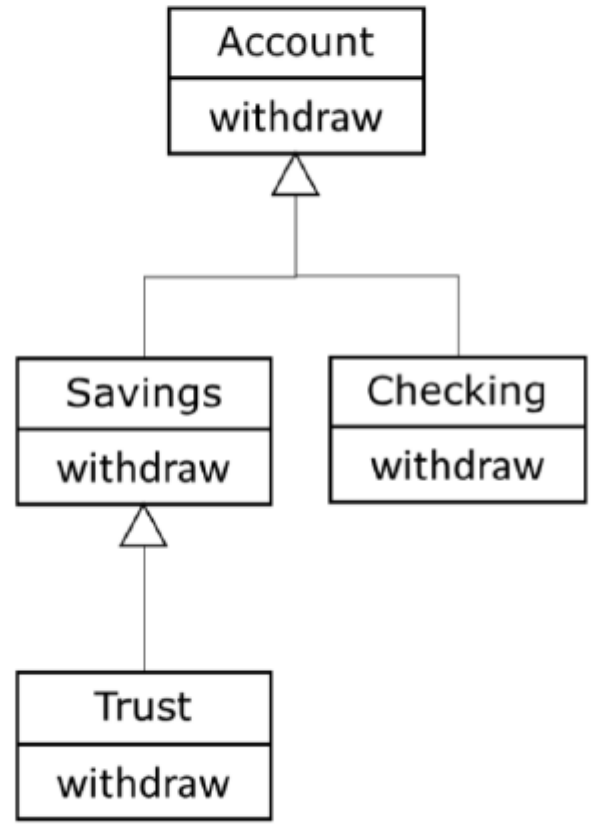
# Polymorphism

## Using a Base class pointer

```
Account *p1 = new Account();
Account *p2 = new Savings();
Account *p3 = new Checking();
Account *p4 = new Trust();

p1->withdraw(1000);       //Account::withdraw
p2->withdraw(1000);       //Savings::withdraw
p3->withdraw(1000);       //Checking::withdraw
p4->withdraw(1000);       //Trust::withdraw

// delete the pointers
```



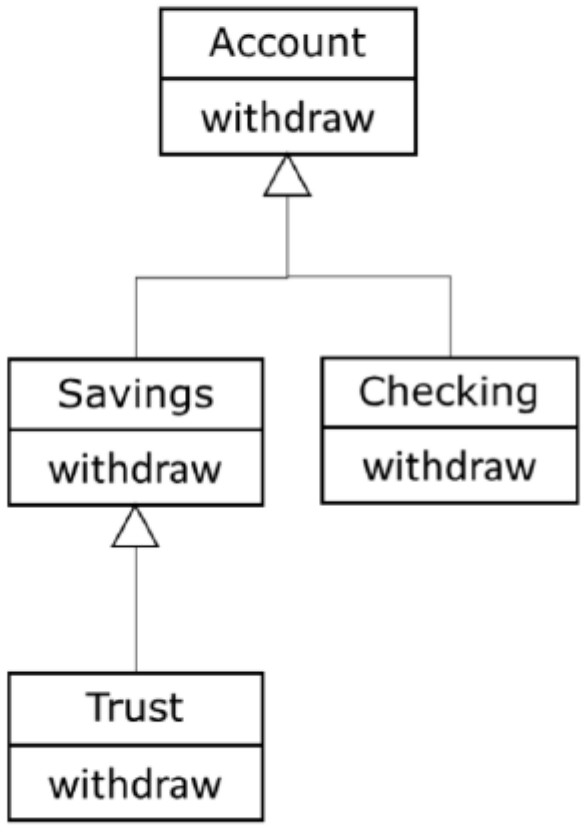
# Polymorphism

Using a Base class pointer

```
Account *p1 = new Account();
Account *p2 = new Savings();
Account *p3 = new Checking();
Account *p4 = new Trust();

Account *array [] = {p1,p2,p3,p4};

for (auto i=0; i<4; ++i)
    array[i]->withdraw(1000);
```



# Polymorphism

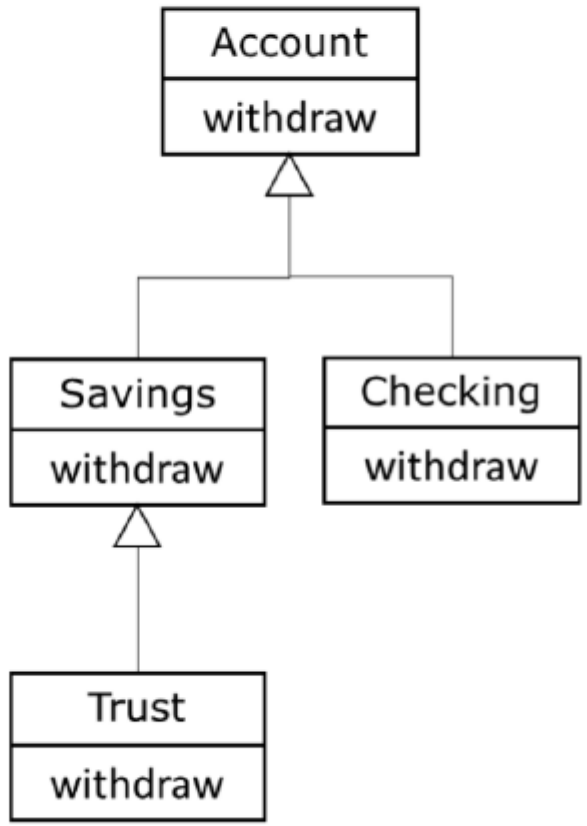
## Using a Base class pointer

```
Account *p1 = new Account();
Account *p2 = new Savings();
Account *p3 = new Checking();
Account *p4 = new Trust();

vector<Account *> accounts
        {p1, p2, p3, p4 };

for (auto acc_ptr: accounts)
    acc_ptr->withdraw(1000);

// delete the pointers
```



# Virtual Functions

# Polymorphism

Virtual functions

- Redefined functions are bound statically
- Overridden functions are bound dynamically
- Virtual functions are overridden
- Allow us to treat all objects generally as objects of the Base class

# Polymorphism

Declaring virtual functions

- Declare the function you want to override as virtual in the Base class
- Virtual functions  are virtual all the way down the hierarchy from this point
- Dynamic polymorphism only via Account class pointer or reference

```
class Account {
public:
    virtual void withdraw(double amount);
  . . .
};
```

# Polymorphism

Declaring virtual functions

- Override the function in the Derived classes
- Function signature and return type must match EXACTLY
- Virtual keyword not required but is best practice
- If you don't provide an overridden version it is inherited from it's base class

```
class Checking : public Account {
public:
    virtual void withdraw(double amount);
  . . .
};
```

# Virtual Destructors

# Polymorphism

Virtual Destructors

- Problems can happen when we destroy  polymorphic objects
- If a derived class is destroyed by deleting its storage via the base class pointer and the class a non-virtual destructor. Then the behavior is undefined in the C++ standard.
- Derived objects must be destroyed in the correct order starting at the correct destructor

# Polymorphism

Virtual Destructors

- Solution/Rule:
  - If a class has virtual functions
  - ALWAYS provide a public virtual destructor
  - If base class destructor is virtual then all derived class destructors are also virtual

```
class Account {
public:
    virtual void withdraw(double amount);
    virtual ~Account();
  . . .
};
```

# The Override and Final Specifiers

# Polymorphism

The override specifier

- We can override Base class virtual functions
- The function signature and return must be EXACTLY the same
- If they are different then we have redefinition NOT overriding
- Redefinition is statically bound
- Overriding is dynamically bound
- C++11 provides an override specifier to have the compiler ensure overriding

# Polymorphism

## The override specifier

```
class Base {
public:
    virtual void say_hello() const {
        std::cout << "Hello - I'm a Base class object" << std::endl;
    }
    virtual ~Base() {}
};

class Derived: public Base {
public:
    virtual void say_hello()    {    // Notice I forgot the const - NOT OVERRIDING
        std::cout << "Hello - I'm a Derived class object" << std::endl;
    }
    virtual ~Derived() {}
};
```

# Polymorphism

The override specifier

Base:

```
virtual void say_hello() const;
```

Derived:

```
virtual void say_hello();
```

# Polymorphism

The override specifier

```
Base *p1 = new Base();
p1->say_hello();      // "Hello - I'm a Base class object"

Base *p2 = new Derived();
p2->say_hello();      // "Hello - I'm a Base class object"
```

- Not what we expected
- say_hello method signatures are different
- So Derived **redefines** say_hello instead of overriding it!

# Polymorphism

## The override specifier

```
class Base {
public:
    virtual void say_hello() const {
        std::cout << "Hello - I'm a Base class object" << std::endl;
    }
    virtual ~Base() {}
};

class Derived: public Base {
public:
    virtual void say_hello() override  {    // Produces compiler error
                                            // Error: marked override but does not override
        std::cout << "Hello - I'm a Derived class object" << std::endl;
    }
    virtual ~Derived() {}
};
```

# Virtual Inheritance vs. Virtual Functions and override

# virtual

- ‘virtual’ has different meanings depending on where it's used in C++.
- virtual in the context of inheritance (virtual inheritance) and virtual functions with the override specifier are quite different.

## Virtual Inheritance:

1. In the context of inheritance, virtual is used to implement what is called "virtual inheritance."
2. This is particularly relevant in scenarios involving multiple inheritance where a class can be derived from more than one base class.
3. The virtual keyword is used to ensure that only a single instance of the common base class is shared among the derived classes.
4. In the given example, virtual is used to perform virtual inheritance to avoid the "diamond problem."

```
class A {
    //...
};

class B : virtual public A {
    //...
};

class C : virtual public A {
    //...
};

class D : public B, public C {
    //...
};
```

# virtual

## Virtual Functions and override:

1. In the context of member functions, virtual is used to declare a function as virtual. A virtual function is a member function that can be overridden in a derived class.
2. In the example, virtual is used to declare that *foo* is a virtual function in the Base class.
3. The override specifier is used in the Derived class to explicitly indicate that the function is intended to override a virtual function from a base class.
4. This helps catch errors at compile-time if the function doesn't actually override a base class function.

```
class Base {
public:
    virtual void foo() {
        std::cout << "Base::foo\n";
    }
};

class Derived : public Base {
public:
    void foo() override {
        std::cout << "Derived::foo\n";
    }
};
```

# Using the Final Specifier

# Polymorphism

The `final` specifier

- C++11 provides the final specifier
  - When used at the class level
  - Prevents a class from being derived from

  - When used at the method level
  - Prevents virtual method from being overridden in derived classes

# Polymorphism

- In C++, the final specifier is used in the context of classes to indicate that a virtual function cannot be overridden by any further derived class. Additionally, it can be applied to a class to prevent it from being inherited by other classes.

## Final Class:

In this case, the Base class is marked as final, indicating that it cannot be used as a base class for any other class. Attempting to derive a class from Base will result in a compilation error.

```
class Base final {
    // ...
};

// Error: Cannot inherit from final class
// class Derived : public Base {
//     // ...
// };
```

# Polymorphism

`final` class

```
class My_class final {
    . . .
};

class Derived final: public Base {
    . . .
};
```

# Polymorphism

## Final Virtual Function:

- In this example, foo() is declared as a virtual function in the Base class and marked as final. This means that no further derived class can override this function. If a derived class attempts to override it, it will result in a compilation error..

```
class Base {
public:
    virtual void foo() final {
        // ...
    }
};

class Derived : public Base {
public:
    // Error: Cannot override final function
    // void foo() override {
    //     // ...
    // }
};
```

# Polymorphism

`final` method

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

class B: public A {
   virtual void do_something() final;    // prevent futher overriding
};

class C: public B {
   virtual void do_something();          // COMPILER ERROR - Can't override
};
```

# Polymorphism

`final` method

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

class B: public A {
   virtual void do_something() final;    // prevent futher overriding
};

class C: public B {
   virtual void do_something();          // COMPILER ERROR - Can't override
};
```

# Function Hiding

# Polymorphism

- In this case, since the withdraw function in the derived classes (Checking, Savings, and Trust) does not have the const qualifier, the compiler will treat these functions as separate from the withdraw function in the base class (Account). This is known as function hiding.
- When you have a non-const member function in the derived class that has the same name as a const member function in the base class, the compiler considers them to be different functions. As a result, there won't be an override, and it will be static binding.

```
Account* ptr = new Checking();
ptr->withdraw(100); // Calls Account::withdraw, not Checking::withdraw
```

```
class Account {
public:
    virtual void withdraw(double amount) const {
        std::cout << "In Account::withdraw" << std::endl;
    }
};

class Checking : public Account  {
public:
    virtual void withdraw(double amount) {
        std::cout << "In Checking::withdraw" << std::endl;
    }
};

class Savings : public Account  {
public:
    virtual void withdraw(double amount) {
        std::cout << "In Savings::withdraw" << std::endl;
    }
};

class Trust : public Account  {
public:
    virtual void withdraw(double amount) {
        std::cout << "In Trust::withdraw" << std::endl;
    }
};
```

# Using Base Class References

# Polymorphism

## Using Base class references

- We can also use Base class references with dynamic polymorphism
- Useful when we pass objects to functions that expect a Base class reference

# Polymorphism

Using Base class references

```
Account a;
Account &ref = a;
ref.withdraw(1000); // Account::withdraw

Trust t;
Account &ref1 = t;
ref1.withdraw(1000);// Trust::withdraw
```

# Polymorphism

Using Base class references

```
void do_withdraw(Account &account, double amount) {
    account.withdraw(amount);
}

Account a;
do_withdraw(a, 1000);   // Account::withdraw

Trust t;
do_withdraw(t, 1000);   // Trust::withdraw
```

# Pure Virtual Functions and Abstract Classes

# Polymorphism

Pure virtual functions and abstract classes

- Abstract class
  - Cannot instantiate objects
  - These classes are used as base classes in inheritance hierarchies
  - Often referred to as Abstract Base Classes
- Concrete class
  - Used to instantiate objects from
  - All their member functions are defined
    - `Checking Account, Savings Account`
    - `Faculty, Staff`
    - `Enemy, Level Boss`

# Polymorphism

Pure virtual functions and abstract classes

- Abstract base class
  - Too generic to create objects from
    - `Shape, Employee, Account, Player`
  - Serves as parent to Derived classes that may have objects
  - Contains at least one pure virtual function

# Polymorphism

Pure virtual functions and abstract classes

- Pure virtual function
  - Used to make a class abstract
  - Specified with "=0" in its declaration

```
virtual void function() = 0; // pure virtual function
```

  - Typically do not provide implementations

# Polymorphism

Pure virtual functions and abstract classes

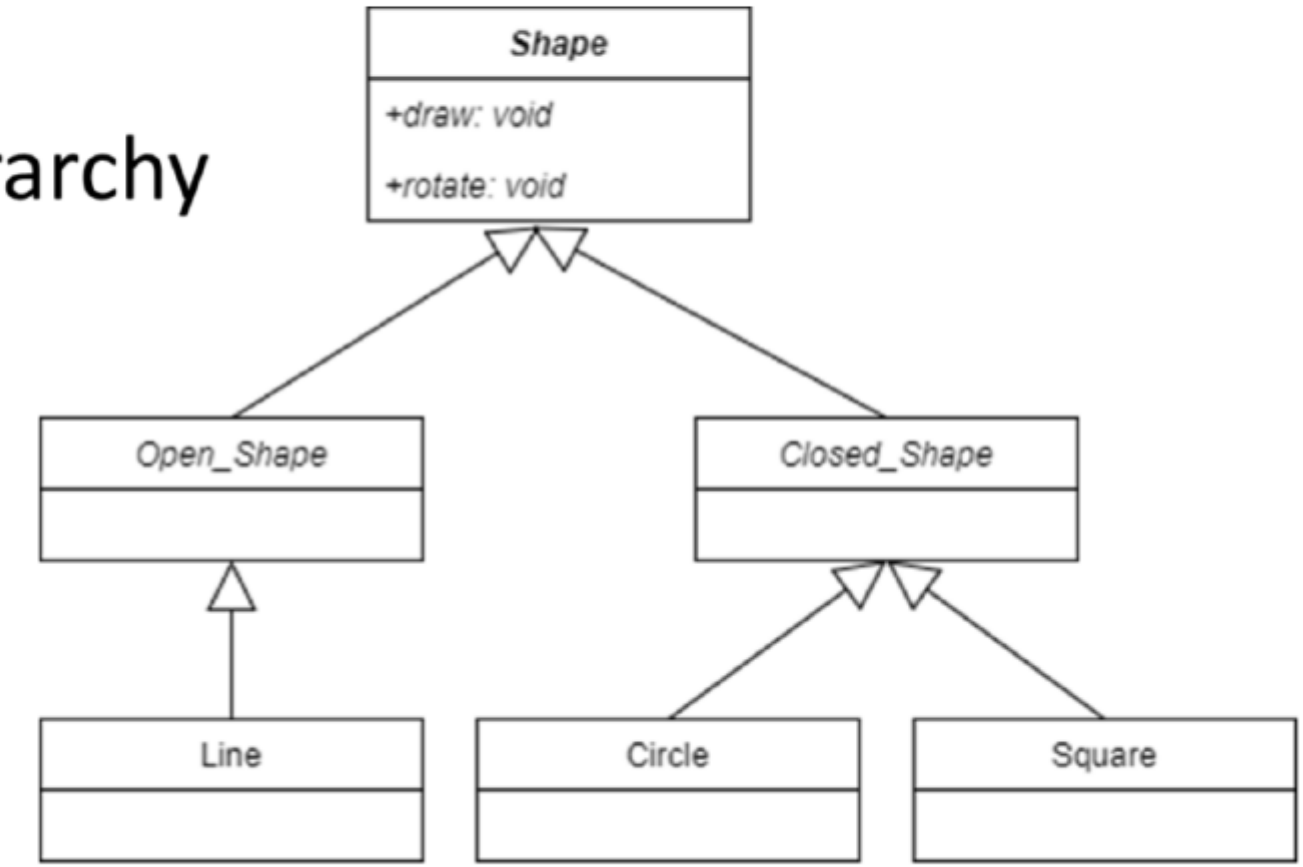
- Pure virtual function
  - Derived classes MUST override the base class
  - If the Derived class does not override then the Derived class is also abstract
  - Used when it doesn't make sense for a base class to have an implementation
    - But concrete classes must implement it

```
virtual void draw() = 0;    // Shape
virtual void defend() = 0;    // Player
```

# Polymorphism

Pure virtual functions and abstract classes

## Shape Class Hierarchy



# Polymorphism

Pure virtual functions and abstract classes

```
class Shape {                    // Abstract
private:
       // attributes common to all shapes
public:
      virtual void draw() = 0;       // pure virtual function
      virtual void rotate() = 0;     // pure virtual function
      virtual ~Shape();
      . . .
};
```

# Polymorphism

Pure virtual functions and abstract classes

```
class Circle: public Shape {                    // Concrete
private:
      // attributes for a circle
public:
      virtual void draw() override {
          // code to draw a circle
       }
       virtual void rotate() override {
          // code to rotate a circle
       }
       virtual ~Circle();
       . . .
};
```

# Polymorphism

Pure virtual functions and abstract classes

Abstract Base class

- Cannot be instantiated

```
Shape shape;        // Error
Shape *ptr = new Shape();   // Error
```

- We can use pointers and references to dynamically refer to concrete classes derived from them

```
Shape *ptr = new Circle();
ptr->draw();
ptr->rotate();
```

# Abstract Classes and Interfaces

# Polymorphism

What is using a class as an interface?

- An abstract class that has only pure virtual functions
- These functions provide a general set of services to the user of the class
- Provided as public
- Each subclass is free to implement these services as needed
- Every service (method) must be implemented
- The service type information is strictly enforced

# Polymorphism

A Printable example

- C++ does not provide true interfaces
- We use abstract classes and pure virtual functions to achieve it
- Suppose we want to be able to provide `Printable` support for any object we wish without knowing it's implementation at compile time

```
std::cout << any_object << std::endl;
```

  - `any_object` must conform to the `Printable` interface

# Polymorphism

## An Printable example

```
class Printable {
   friend ostream &operator<<(ostream &, const Printable &obj);
public:
   virtual void print(ostream &os) const = 0;
   virtual ~Printable() {};
   . . .
};

ostream &operator<<(ostream &os, const Printable &obj) {
   obj.print(os);
   return os;
}
```

# Polymorphism

An Printable example

```
class Any_Class : public Printable {
public:
   // must override Printable::print()
   virtual void print(ostream &os) override {
      os << "Hi from Any_Class" ;
   }
   . . .
};
```

# Polymorphism

## An Printable example

```
Any_Class *ptr= new Any_Class();
cout << *ptr << endl;

void function1 (Any_Class &obj) {
   cout << obj << endl;
}

void function2 (Printable &obj) {
   cout << obj << endl;
}
function1(*ptr);          // "Hi from Any_Class"
function2(*ptr);          // "Hi from Any_Class"
```

# Polymorphism

A Shapes example

```
class Shape {
public:
    virtual void draw() = 0;
    virtual void rotate() = 0;
    virtual ~Shape() {};
    . . .
};
```

# Polymorphism

A Shapes example

```
class Circle : public Shape {
public:
    virtual void draw() override { /* code */ };
    virtual void rotate() override { /* code */ };
    virtual ~Circle() {};
    . . .
};
```

# Polymorphism

A Shapes example

```
class I_Shape {
public:
    virtual void draw() = 0;
    virtual void rotate() = 0;
    virtual ~I_Shape() {};
    . . .
};
```

# Polymorphism

A Shapes example

```
class Circle : public I_Shape {
public:
    virtual void draw() override   { /* code */ };
    virtual void rotate() override { /* code */ };
    virtual ~Circle() {};
    . . .
};
```

- Line and Square classes would be similar

# Polymorphism

A Shapes example

```
vector< I_Shape *> shapes;

I_Shape *p1 = new Circle();
I_Shape *p2 = new Line();
I_Shape *p3 = new Square();

for (auto const &shape: shapes) {
   shape->rotate();
   shape->draw();
}
// delete the pointers
```

# Good Luck!