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About how long did the Midterm take you?

A. [0, 2) hours
B. [2, 4) hours
C. [4, 6) hours
D. [6, 8) hours
E. [8, 10) hours
F. 10+ Hours
G. I didn't submit / I prefer not to say

C++ Inheritance I

CSE 333 Winter 2023

Instructor: Justin Hsia

Teaching Assistants:

Adina Tung
Danny Agustinus
Edward Zhang
James Froelich
Lahari Nidadavolu
Mitchell Levy
Noa Ferman
Patrick Ho
Paul Han
Saket Gollapudi
Sara Deutscher
Tim Mandzyuk
Timmy Yang
Wei Wu
Yiqing Wang
Zhuochun Liu

Relevant Course Information

- Mid-quarter survey open now on Canvas and due on Wednesday (2/15)
- Exercise 8 due Wednesday
- Exercise 9 released on Wednesday
  - C++ smart pointers and inheritance
- Homework 3 is due next Thursday (2/23)
  - Get started early!
  - Videos for overview and demo and file debugging
  - Partner sign-ups close at end of Thursday (2/16)
- Midterm grading will take a while
  - Lots of acceptable answers for reflection questions

Overview of Next Two Lectures

- **C++ inheritance**
  - **Review of basic idea** (pretty much the same as in Java)
  - What's different in C++ (compared to Java)
    - **Static vs. dynamic dispatch – virtual functions and vtables** (optional)
    - Pure virtual functions, abstract classes, why no Java "interfaces"
    - Assignment slicing, using class hierarchies with STL
  - Casts in C++

- Reference: *C++ Primer*, Chapter 15

Lecture Outline

- **Inheritance motivation & C++ Syntax**
- Polymorphism & Dynamic Dispatch
- Virtual Tables & Virtual Table Pointers

Stock Portfolio Example

- A portfolio represents a person's financial investments
  - Each *asset* has a cost (*i.e.*, how much was paid for it) and a market value (*i.e.*, how much it is worth)
    - The difference between the cost and market value is the *profit* (or loss)
  - Different assets compute market value in different ways
    - A **stock** that you own has a ticker symbol (*e.g.*, "GOOG"), a number of shares, share price paid, and current share price
    - A **dividend stock** is a stock that also has dividend payments
    - **Cash** is an asset that never incurs a profit or loss

(Credit: thanks to Marty Stepp for this example)

Design Without Inheritance

- One class per asset type:

Stock
symbol_ total_shares_ total_cost_ current_price_
GetMarketValue() GetProfit() GetCost()

DividendStock
symbol_ total_shares_ total_cost_ current_price_ dividends_
GetMarketValue() GetProfit() GetCost()

Cash
amount_
GetMarketValue()

  - Redundant!
  - Cannot treat multiple investments together
    - *e.g.*, can't have an array or `vector` of different assets

- See sample code in `initial/` directory

Inheritance

- A parent-child "is-a" relationship between classes
  - A child (derived class) extends a parent (base class)

- Terminology:

Java	C++
Superclass	Base Class
Subclass	Derived Class

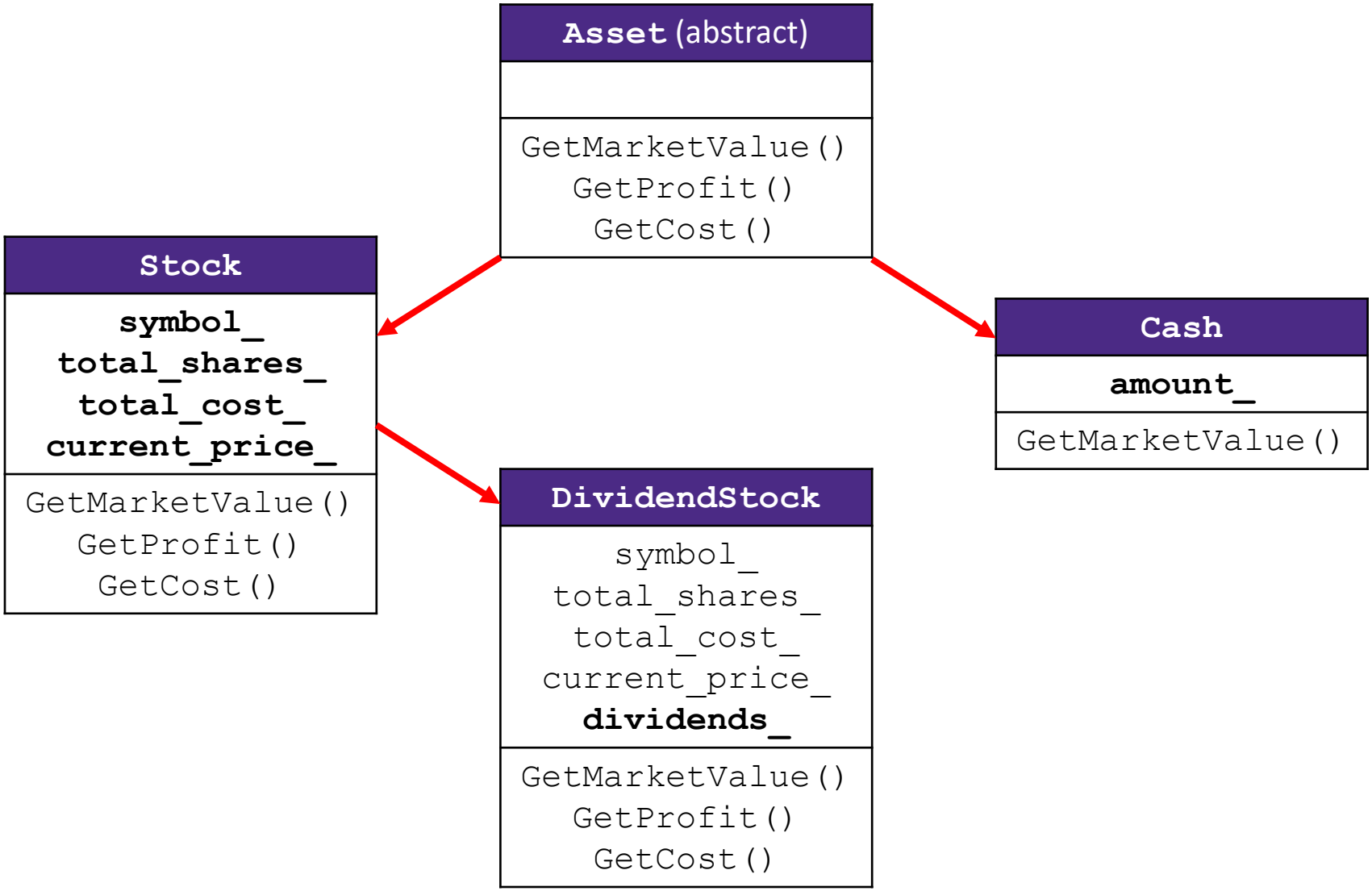
  - Mean the same things. You'll hear both.

Inheritance

- A parent-child "is-a" relationship between classes
  - A child (derived class) extends a parent (base class)

- Benefits:
  - Code reuse
    - Children can automatically inherit code from parents
  - Polymorphism
    - Ability to redefine existing behavior but preserve the interface
    - Children can override the behavior of the parent
    - Others can make calls on objects without knowing which part of the inheritance tree it is in
  - Extensibility
    - Children can add behavior

Design With Inheritance



Like Java: Access Modifiers

- `public`: visible to all other classes
- `protected`: visible to current class and its *derived* classes
- `private`: visible only to the current class

- Use `protected` for class members only when
  - Class is designed to be extended by derived classes
  - Derived classes must have access but clients should not be allowed

Class Derivation List

- Comma-separated list of classes to inherit from:

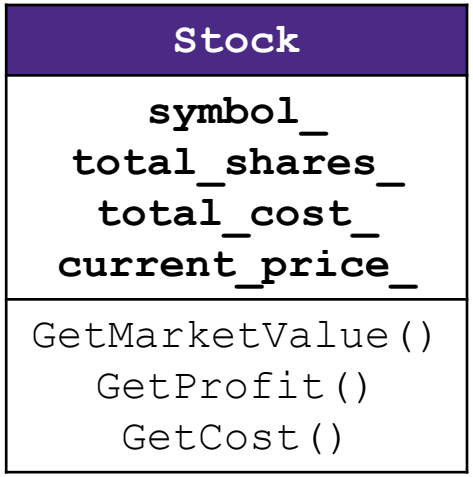
```
#include "BaseClass.h"

class Name : public BaseClass {
  ...
};
```

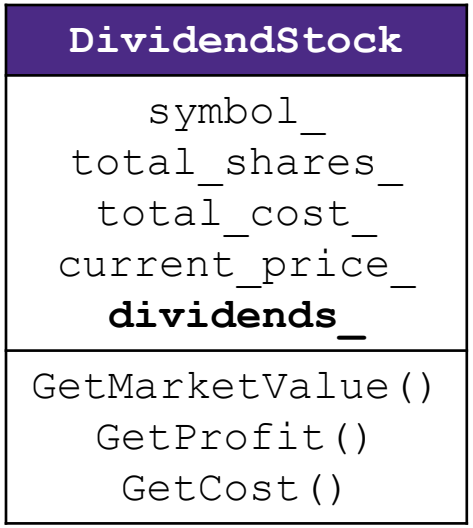
  - Focus on single inheritance, but *multiple inheritance* possible

- Almost always you will want public inheritance
  - Acts like `extends` does in Java
  - Any member that is non-private in the base class is the same in the derived class; both *interface and implementation inheritance*
    - Except that constructors, destructors, copy constructor, and assignment operator are *never* inherited

Back to Stocks

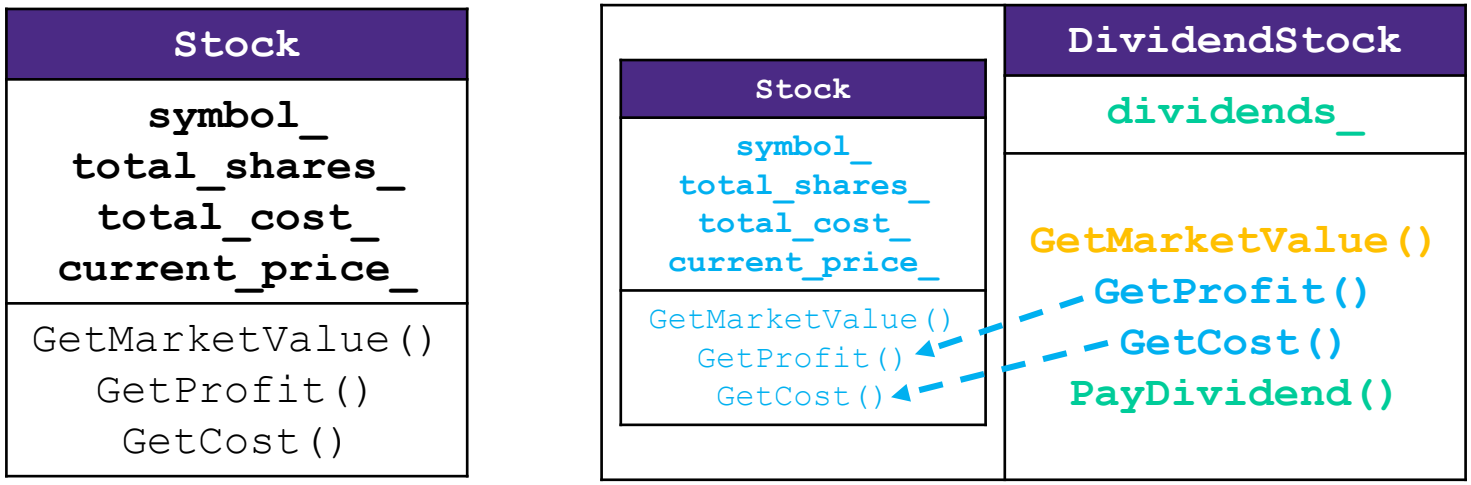


BASE



DERIVED

Back to Stocks



- A derived class:
  - **Inherits** the behavior and state (specification) of the base class
  - **Overrides** some of the base class' member functions (opt.)
  - **Extends** the base class with new member functions, variables (opt.)

Lecture Outline

- Inheritance motivation & C++ Syntax
- **Polymorphism & Dynamic Dispatch**
- Virtual Tables & Virtual Table Pointers

Polymorphism in C++

- In Java: `PromisedType var = new ActualType();`
  - `var` is a reference (different term than C++ reference) to an object of `ActualType` on the Heap
  - `ActualType` must be the same class or a subclass of `PromisedType`
- In C++: `PromisedType* var_p = new ActualType();`
  - `var_p` is a *pointer* to an object of `ActualType` on the Heap
  - `ActualType` must be the same or a derived class of `PromisedType`
  - (also works with references)
  - `PromisedType` defines the *interface* (*i.e.*, what can be called on `var_p`), but `ActualType` may determine which *version* gets invoked

Dynamic Dispatch (like Java)

- Usually, when a derived function is available for an object, we want the derived function to be invoked
  - This requires a *run time* decision of what code to invoke

- A member function invoked on an object should be the *most-derived function* accessible to the object's visible type
  - Can determine what to invoke from the *object* itself

- Example:
  - `void PrintStock(Stock* s) { s->Print(); }`
  - Calls the appropriate `Print()` without knowing the actual type of `*s`, other than it is some sort of `Stock`

Dynamic Dispatch Example

- When a member function is invoked on an object:
  - The *most-derived function* accessible to the object's visible type is invoked (decided at run time based on actual type of the object)

```
double DividendStock::GetMarketValue() const {
  return get_shares() * get_share_price() + dividends_;
}

double "DividendStock"::GetProfit() const {  // inherited
  return GetMarketValue() - GetCost();
}
```

DividendStock.cc

```
double Stock::GetMarketValue() const {
  return get_shares() * get_share_price();
}

double Stock::GetProfit() const {
  return GetMarketValue() - GetCost();
}
```

Stock.cc

Dynamic Dispatch Example

```
#include "Stock.h"
#include "DividendStock.h"

DividendStock dividend();
DividendStock* ds = &dividend;
Stock* s = &dividend;   // why is this allowed?

// Invokes DividendStock::GetMarketValue()
ds->GetMarketValue();

// Invokes DividendStock::GetMarketValue()
s->GetMarketValue();

// invokes Stock::GetProfit(), since that method is inherited.
// Stock::GetProfit() invokes DividendStock::GetMarketValue(),
// since that is the most-derived accessible function.
s->GetProfit();
```

Requesting Dynamic Dispatch (C++)

- Prefix the member function declaration with the `virtual` keyword
  - Derived/child functions don't need to repeat `virtual`, but was traditionally good style to do so
  - This is how method calls work in Java (no virtual keyword needed)
  - You almost always want functions to be virtual
- `override` keyword (C++11)
  - Tells compiler this method should be overriding an inherited virtual function – *always* use if available
  - Prevents overloading vs. overriding bugs
- Both of these are technically *optional* in derived classes
  - Be consistent and follow local conventions (Google Style Guide says no `virtual` if `override`)

Most-Derived

```
class A {
 public:
  // Foo will use dynamic dispatch
  virtual void Foo();
};

class B : public A {
 public:
  // B::Foo overrides A::Foo
  virtual void Foo();
};

class C : public B {
  // C inherits B::Foo()
};
```

```
void Bar() {
  A* a_ptr;
  C c;

  a_ptr = &c;

  // Whose Foo() is called?
  a_ptr->Foo();
}
```

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Whose `Foo()` is called?

	Q1	Q2
A.	A	B
B.	A	D
C.	B	B
D.	B	D
E.	We're lost…	

```
void Bar() {
  A* a_ptr;
  C c;
  E e;

  // Q1:
  a_ptr = &c;
  a_ptr->Foo();

  // Q2:
  a_ptr = &e;
  a_ptr->Foo();
}
```

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

class B : public A {
 public:
  virtual void Foo();
};

class C : public B {
};

class D : public C {
 public:
  virtual void Foo();
};

class E : public C {
};
```

Lecture Outline

- Inheritance motivation & C++ Syntax
- Polymorphism & Dynamic Dispatch
- **Virtual Tables & Virtual Table Pointers**

How Can This Possibly Work?

- The compiler produces `Stock.o` from *just* `Stock.cc`
  - It doesn't know that `DividendStock` exists during this process
  - So then how does the emitted code know to call `Stock::GetMarketValue()` or `DividendStock::GetMarketValue()` or something else that might not exist yet?
    - ***Function pointers!!!***

Stock.h

```
virtual double Stock::GetMarketValue() const;
virtual double Stock::GetProfit() const;
```

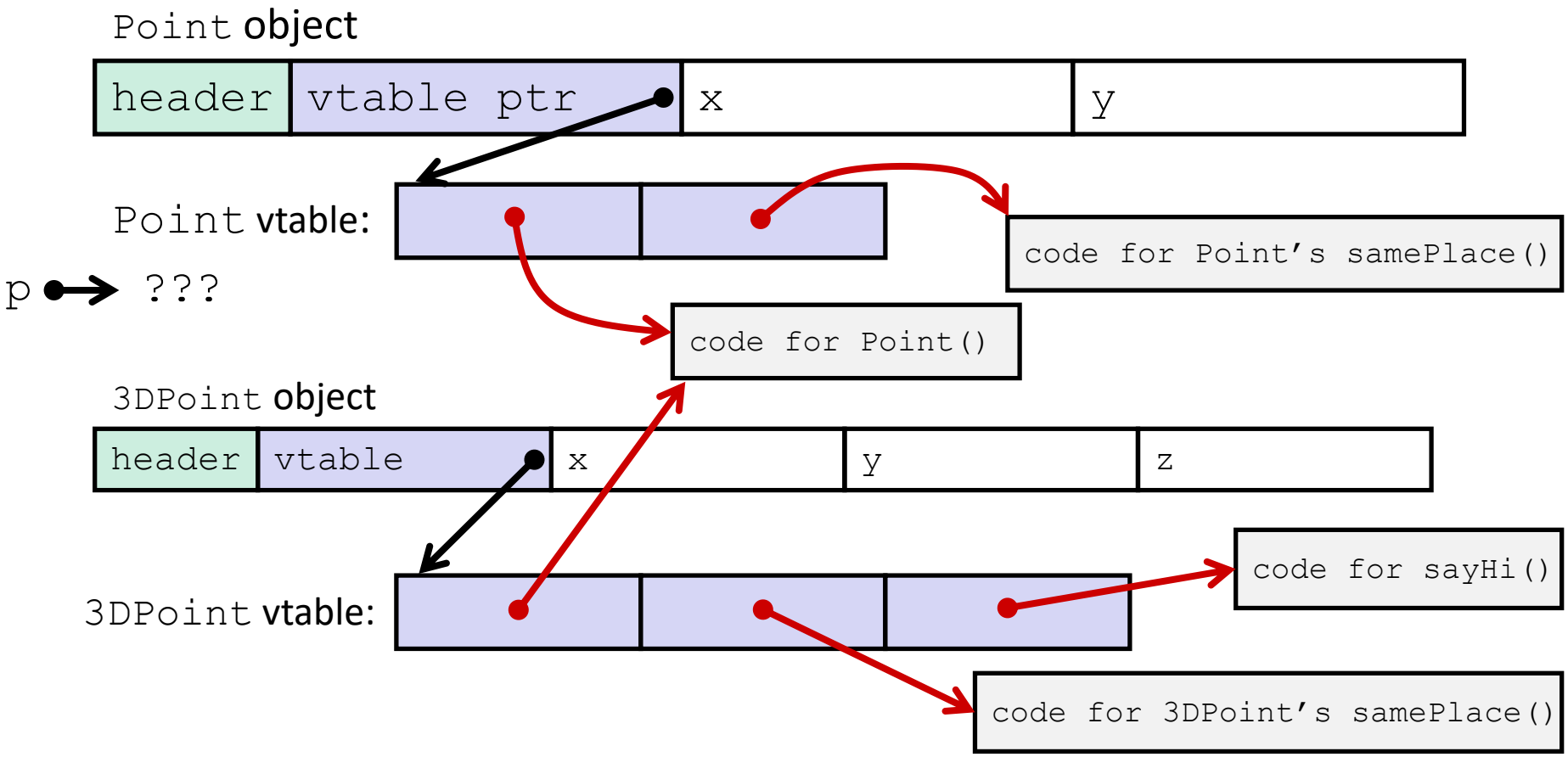
```
double Stock::GetMarketValue() const {
  return get_shares() * get_share_price();
}

double Stock::GetProfit() const {
  return GetMarketValue() - GetCost();
}
```

Stock.cc

vtables and the vptr

- If a class contains *any* virtual methods, the compiler emits:
  - A (single) virtual function table (vtable) for *the class*
    - Contains a function pointer for each virtual method in the class
    - The pointers in the vtable point to the most-derived function for that class
  - A virtual table pointer (vptr) for *each object instance*
    - A pointer to a virtual table as a "hidden" member variable
    - When the object's constructor is invoked, the vptr is initialized to point to the vtable for the object's class
    - Thus, the vptr "remembers" what class the object is

351 Throwback: Dynamic Dispatch



Java:

```
Point p = ???;
return p.samePlace(q);
```

C pseudo-translation:

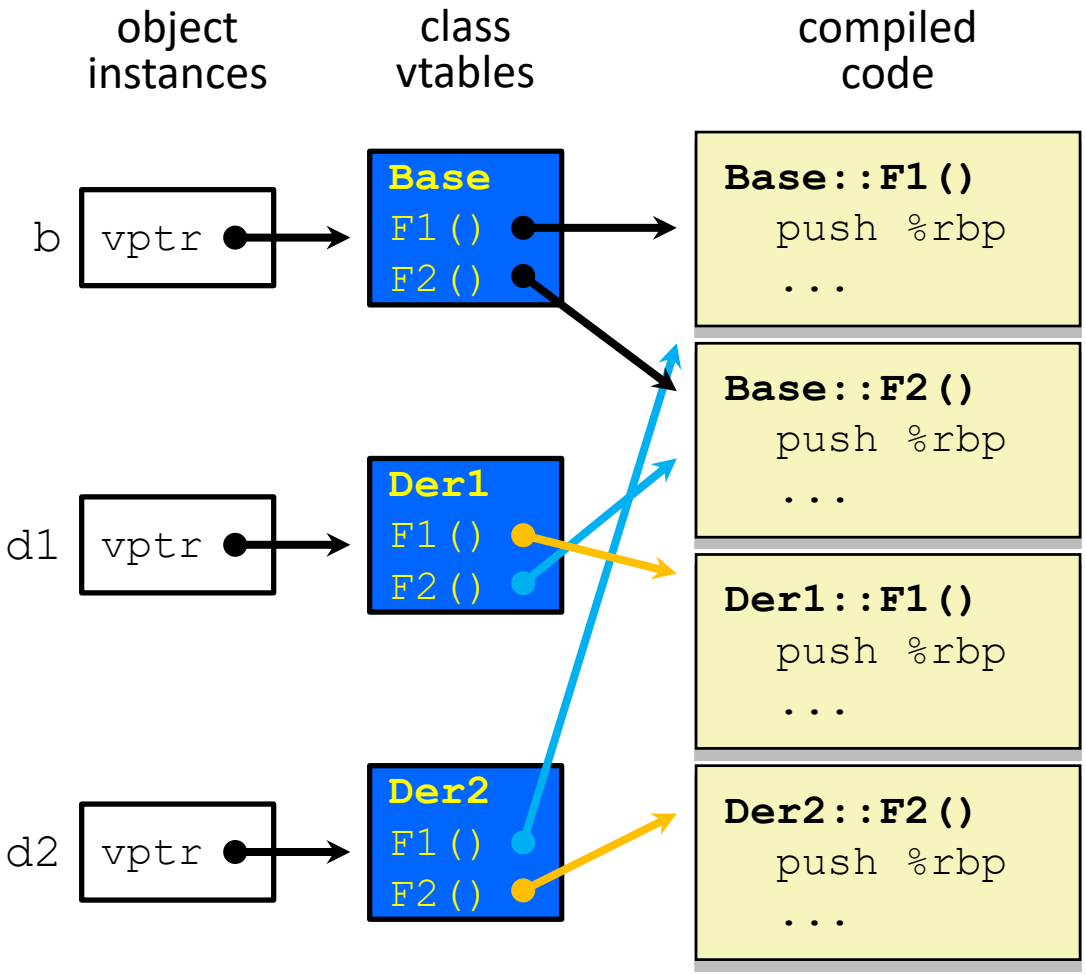
```
// works regardless of what p is
return p->vtable[1](p, q);
```

vtable/vptr Example

```
class Base {
 public:
  virtual void F1();
  virtual void F2();
};

class Der1 : public Base {
 public:
  virtual void F1();
};

class Der2 : public Base {
 public:
  virtual void F2();
};
```

```
Base b;
Der1 d1;
Der2 d2;

Base* b0ptr = &b;
Base* b1ptr = &d1;
Base* b2ptr = &d2;

b0ptr->F1();   //
b0ptr->F2();   //

b1ptr->F1();   //
b1ptr->F2();   //

b2ptr->F1();   //
b2ptr->F2();   //

d2.F1();       //
```

vtable/vptr Example




```
Base b;
Der1 d1;
Der2 d2;

Base* b2ptr = &d2;

b2ptr->F1();
// b2ptr -->
// d2.vptr -->
// Der2.vtable.F1 -->
// Base::F1()

d2.F1();
// d2.vptr -->
// Der2.vtable.F1 -->
// Base::F1()
```

Let's Look at Some Actual Code

- Let's examine the following code using `objdump`
  - `g++ -Wall -g -std=c++17 -o vtable vtable.cc`
  - `objdump -CDS vtable > vtable.d`

vtable.cc

```
class Base {
 public:
  virtual void f1();
  virtual void f2();
};

class Der1 : public Base {
 public:
  virtual void f1();
};

int main(int argc, char** argv) {
  Der1 d1;
  Base* bptr = &d1;
  bptr->f1();
  d1.f1();
}
```