C++ Inheritance I
CSE 333 Spring 2023

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Relevant Course Information

- Exercise 9 released this afternoon
  - C++ smart pointers and inheritance
- Homework 3 is due next Thursday (5/18)
  - Get started early!
  - Videos for overview and demo and file debugging
- 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++ (bonus material in this week's section)

- 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()

data members ↑ / ↓ methods

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

must be of same type

- 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:

"higher" on heirarchy
subset of subclass

"lower" on herarchy
superset of superclass

Java	C++
Superclass	Base Class
Subclass	Derived Class

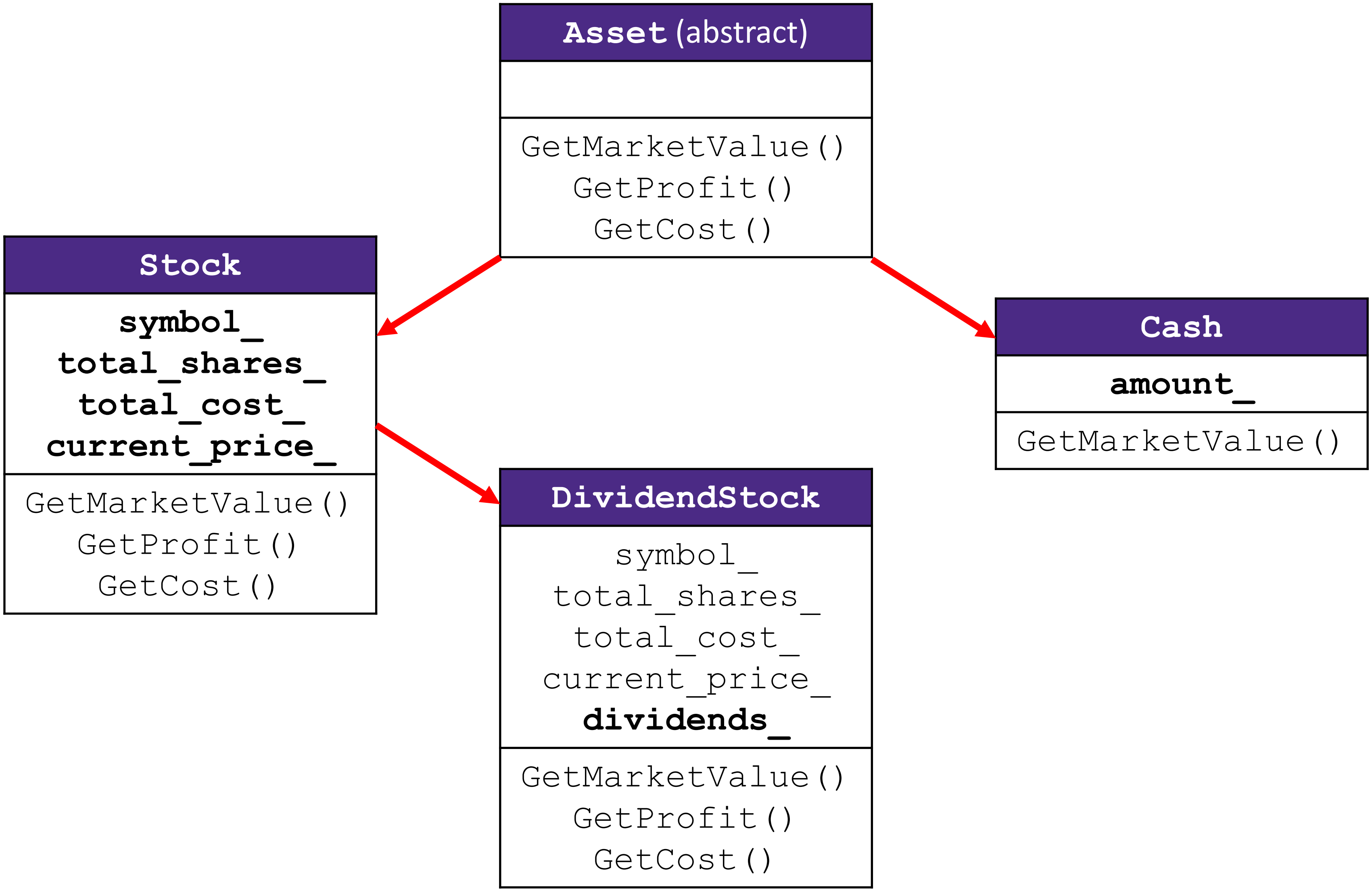
  - Mean the same things. You'll hear both.

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:

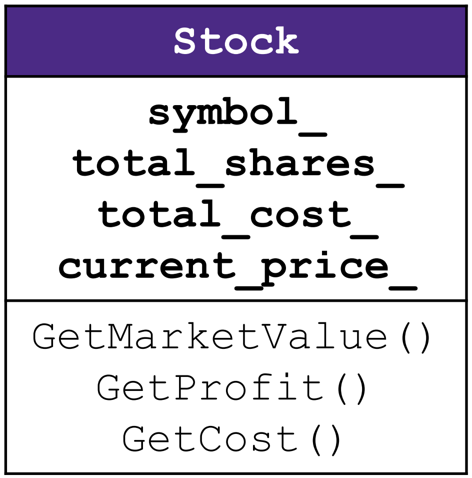
```
#include "BaseClass.h"

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

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

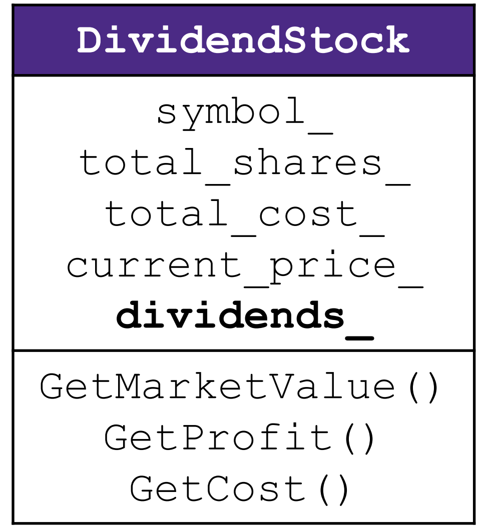
    : public Base1, public Base2 {

- 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

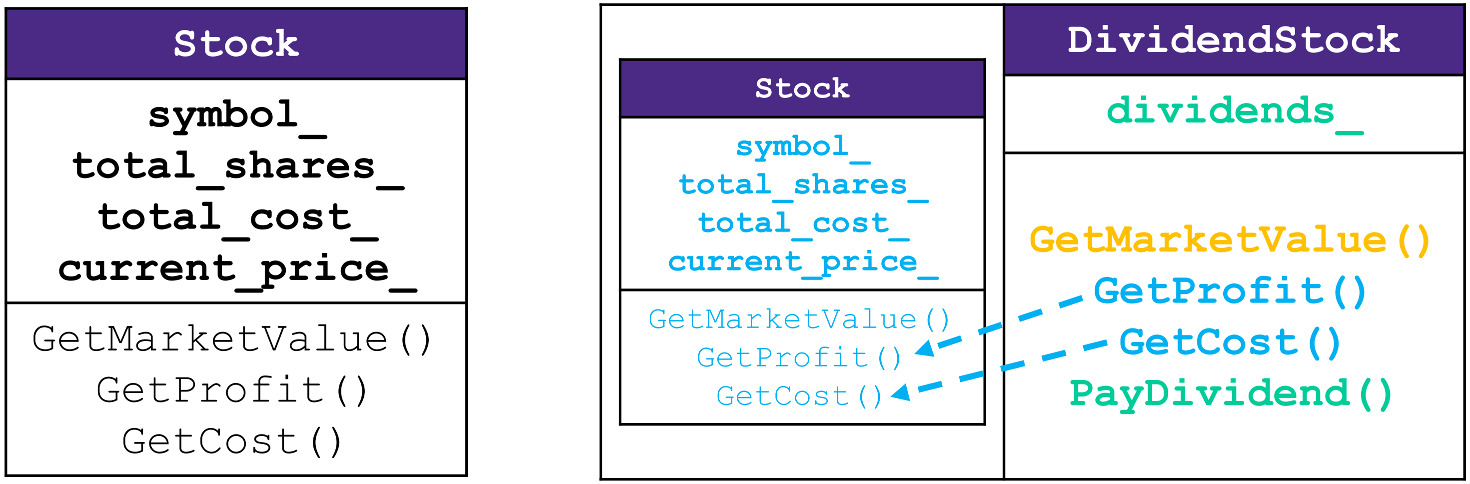


BASE



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:

  Stock?
  DividendStock?

  - `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

inherited from Stock

↑ should invoke DividendStock::GetMarketValue( )

```
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();
```

every part of Stock's interface is part of DividendStock's interface

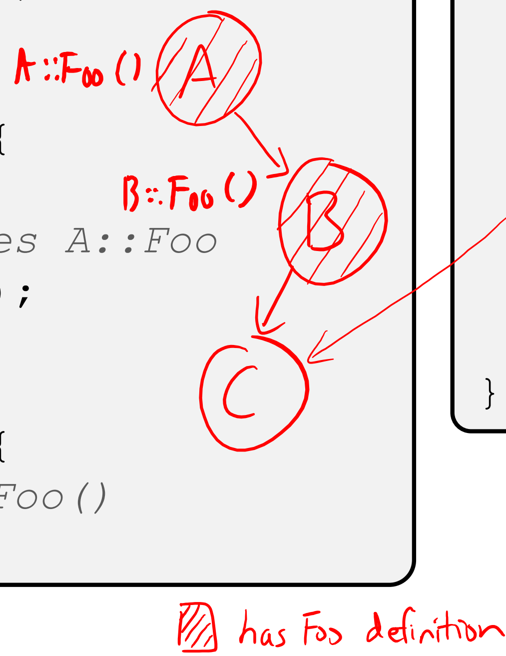
called on DividendStock object

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) similar to @override in Java
  - 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()
};
```

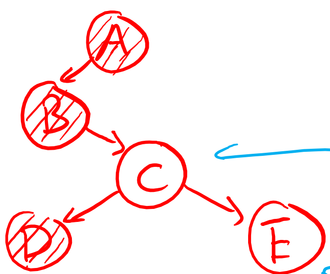



```
void Bar() {
  A* a_ptr;
  C c;

  a_ptr = &c;

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

Poll Everywhere

pollev.com/cse333sp

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();
}
```

B::Foo()
B::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;
```

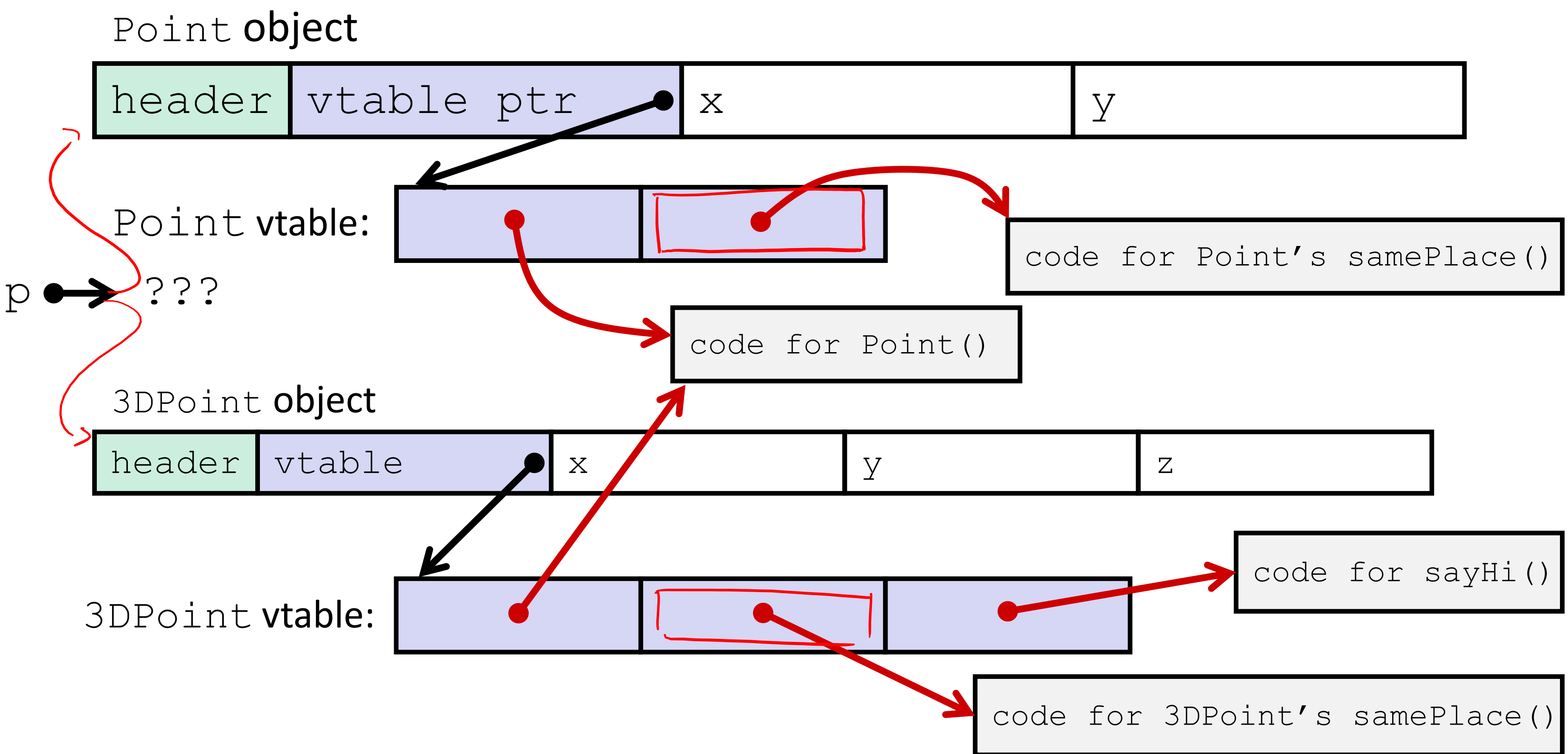
```
double Stock::GetMarketValue() const {
  return get_shares() * get_share_price();
}

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* (1 per 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* (1 per object)
    - 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



Could be Point or 3DPoint

Java:

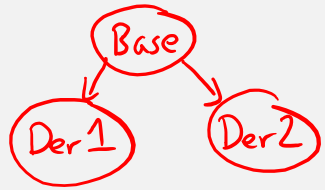
```
Point p = ???;
return p.samePlace(q);
```

C pseudo-translation:

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

vtable/vptr Example

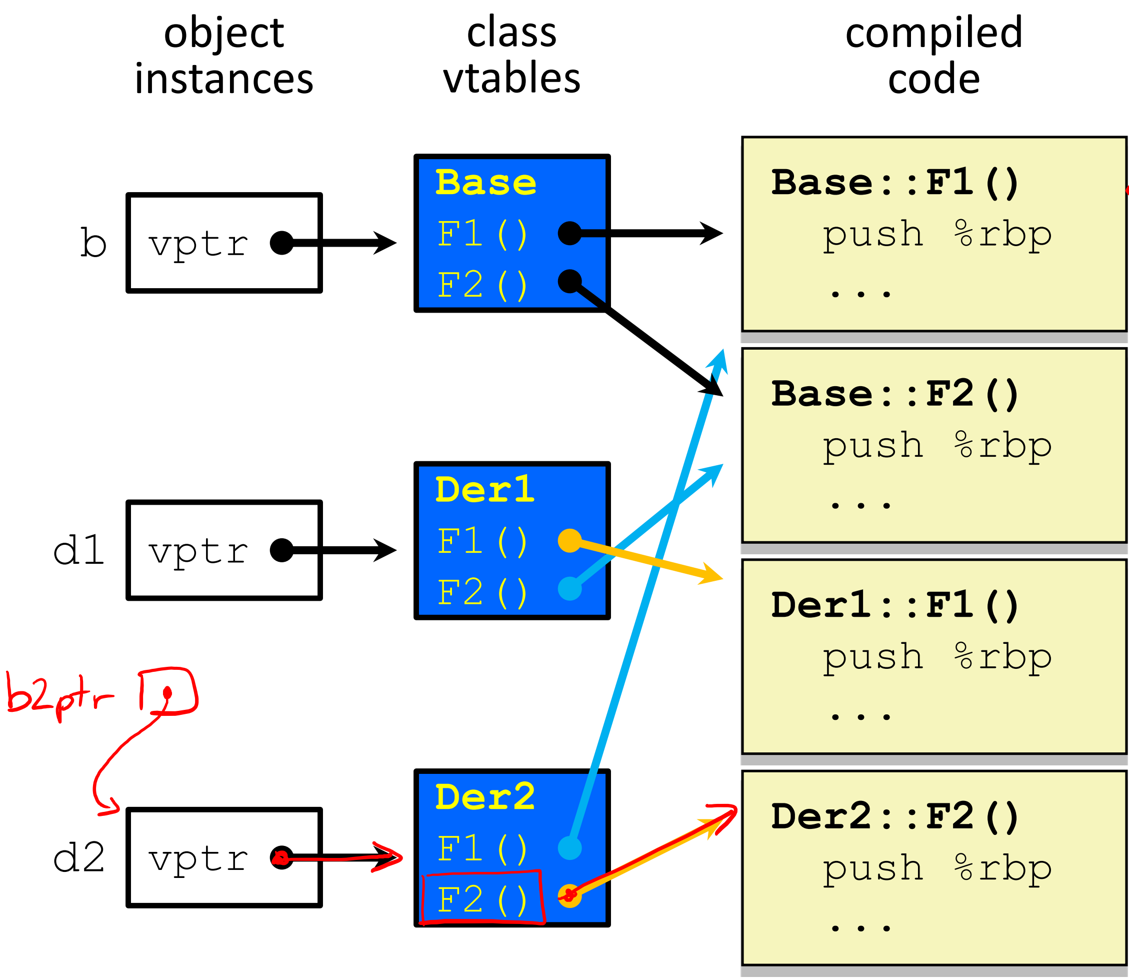
```cpp
class Base {
 public:
  virtual void F1();
  virtual void F2();
};

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

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




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

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

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

b1ptr->F1();   // Der1::F1()
b1ptr->F2();   // Base::F2()

b2ptr->F1();   // Base::F1()
b2ptr->F2();   // Der2::F2()

d2.F1();       // Base::F1()
```

difference?

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()
```

no ambiguity

can optimize out!

hard-code call to

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(); // done via indirect jump on vtable entry
  d1.f1();    // done via hard-coded callq
}
```