C++ Inheritance I
CSE 333 Summer 2020

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Poll Everywhere

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About how long did Exercise 12 take?

A. 0-1 Hours
B. 1-2 Hours
C. 2-3 Hours
D. 3-4 Hours
E. 4+ Hours
F. I didn't submit / I prefer not to say

Side question:
how are you liking C++?

Administrivia

- Exercise 12a released today!
  - Next exercise is exercise 14. (We are temporarily skipping ex13)
- HW3 is due in two Thursdays (8/6)
  - Get started early! (Typically considered the hardest HW)
  - Debugging is hard, more in section!
- Mid Quarter Survey due Today!!! (7/27) @ 11:59 pm
  - Feedback will be used to try and better the rest of this quarter and future quarters!

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()

Data members

methods

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.tar`

Inheritance

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

- Terminology:

Subclass inherits from super class. (Superclass is "higher" in the hierarchy)

Java	C++
Superclass	Base Class
Subclass	Derived Class

Derived class inherits from base class. (base class is "higher" in the hierarchy)

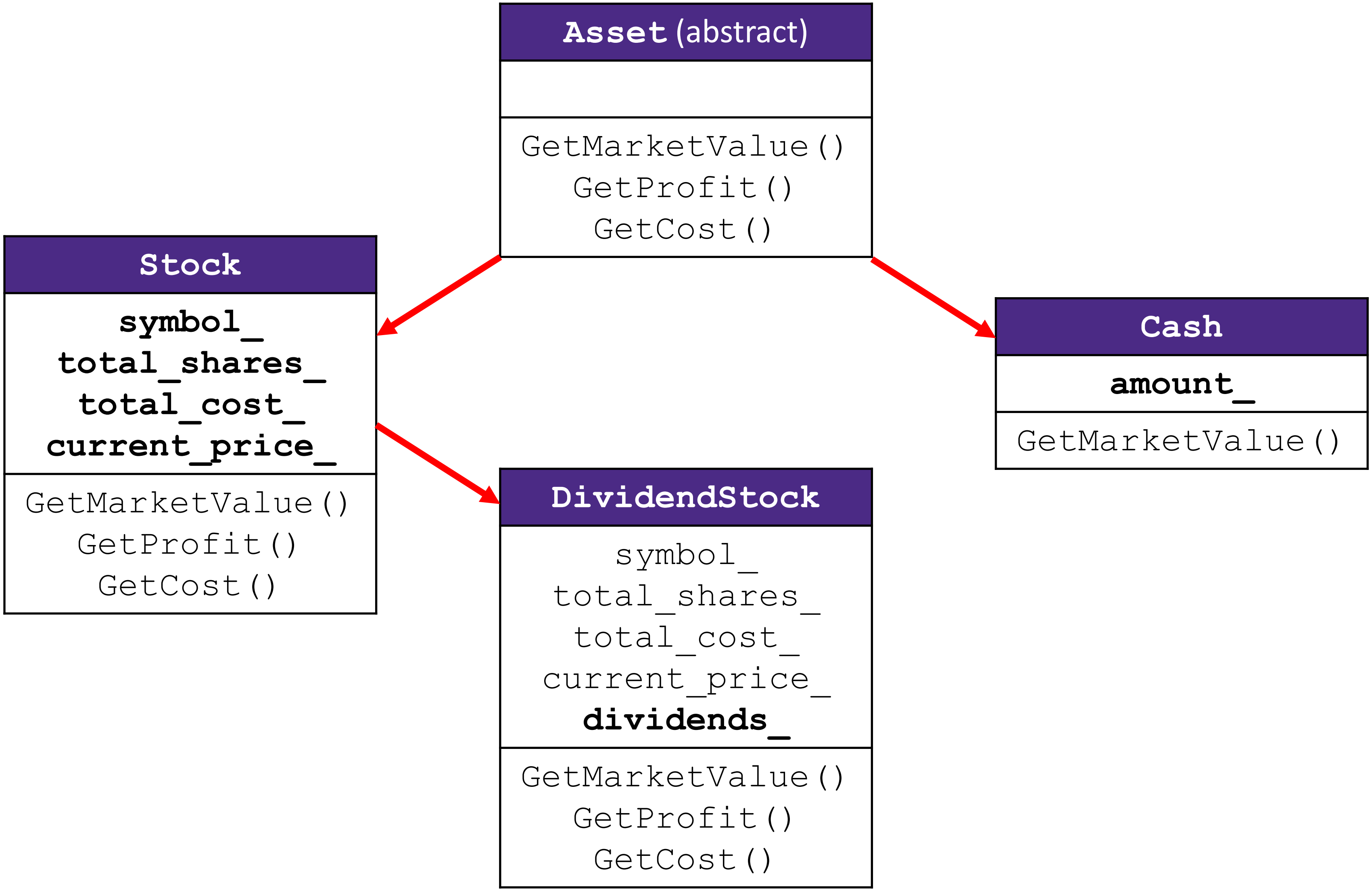
  - Mean the same things. You'll hear both.

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

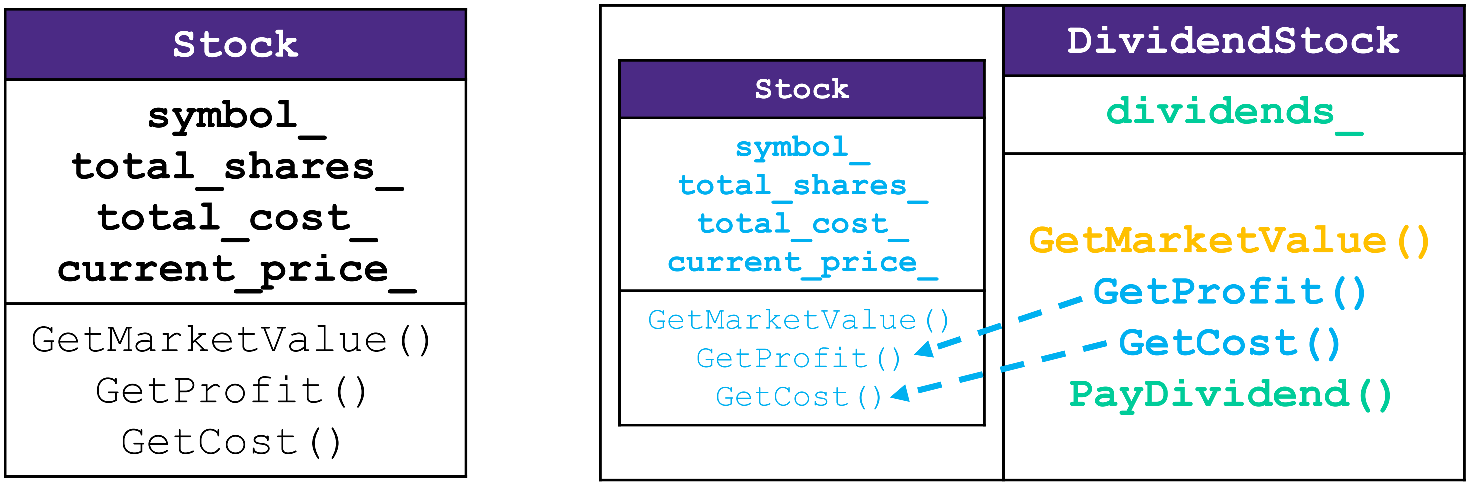
Stock
symbol_ **total_shares_** **total_cost_** **current_price_**
GetMarketValue() GetProfit() GetCost()

BASE

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

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(); }`

    Is this a Stock or a DividendStock?
  - Calls the appropriate `Print()` without knowing the actual type of `*s`, other than it is some sort of `Stock`

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`)

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();
}
```

Inherited from stock

Should call DividendStock::GetMarketValue()

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();
```

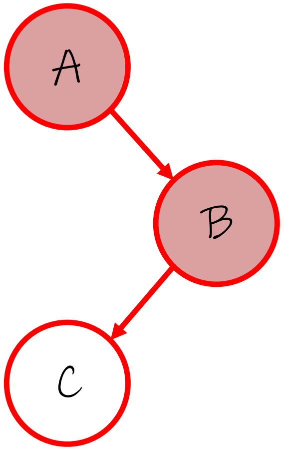
A DividendStock "is-a" Stock, and has every part of Stock's interface

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
}
```

Has Foo definition



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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 {
};
```

Poll Everywhere

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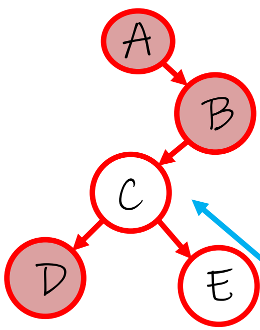
- Whose `Foo()` is called?



	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();
                B::Foo()

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

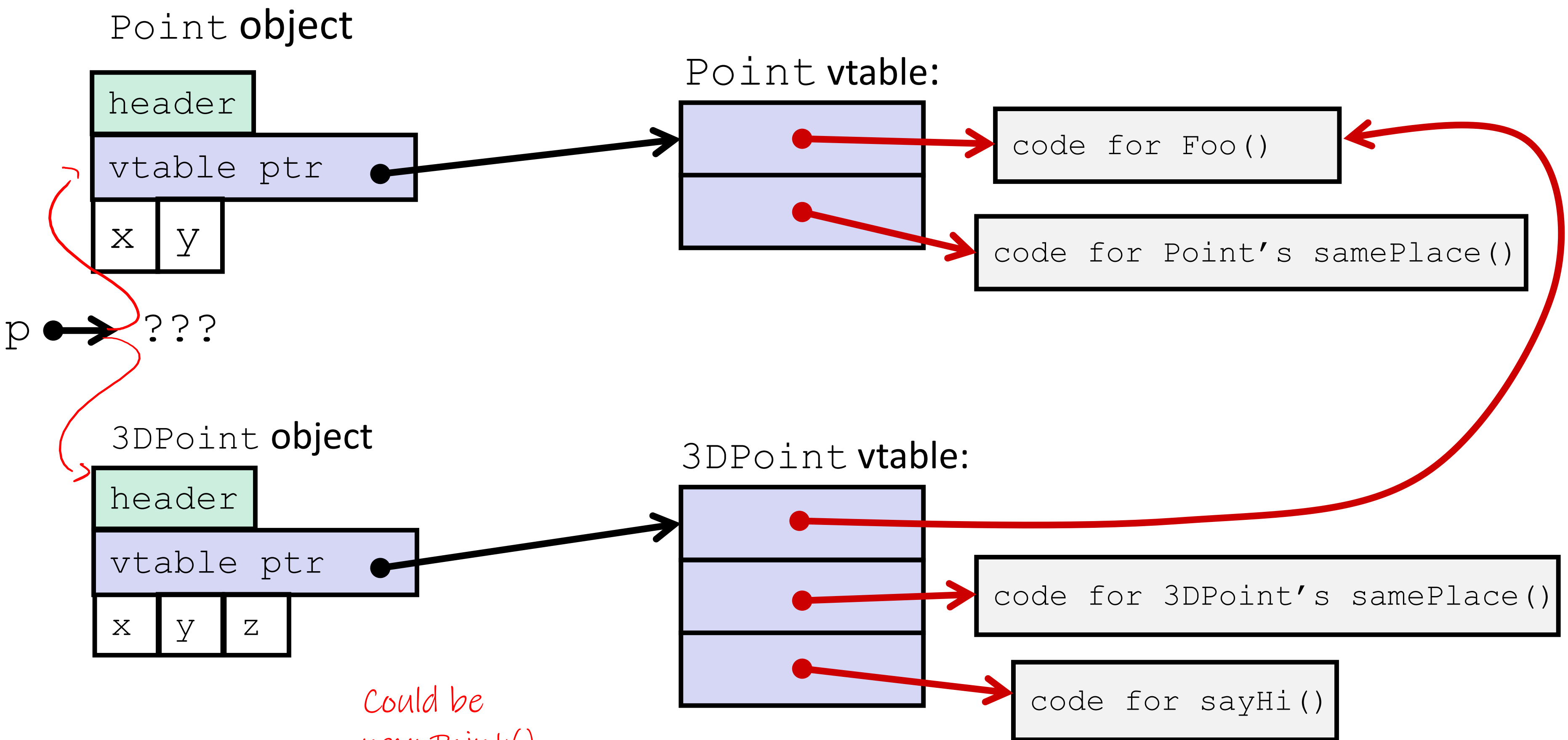
Could be called on a DividendStock
Since DividendStock inherits
Stock::GetProfit()

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 (NOT 1 per instance)
    - 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 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



Could be
new Point()
or
new 3DPoint()

Java:

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

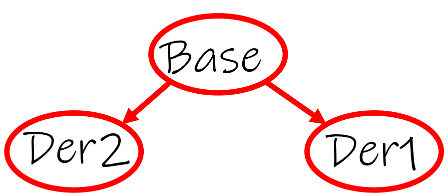
C pseudo-translation:

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

vtable/vptr Example

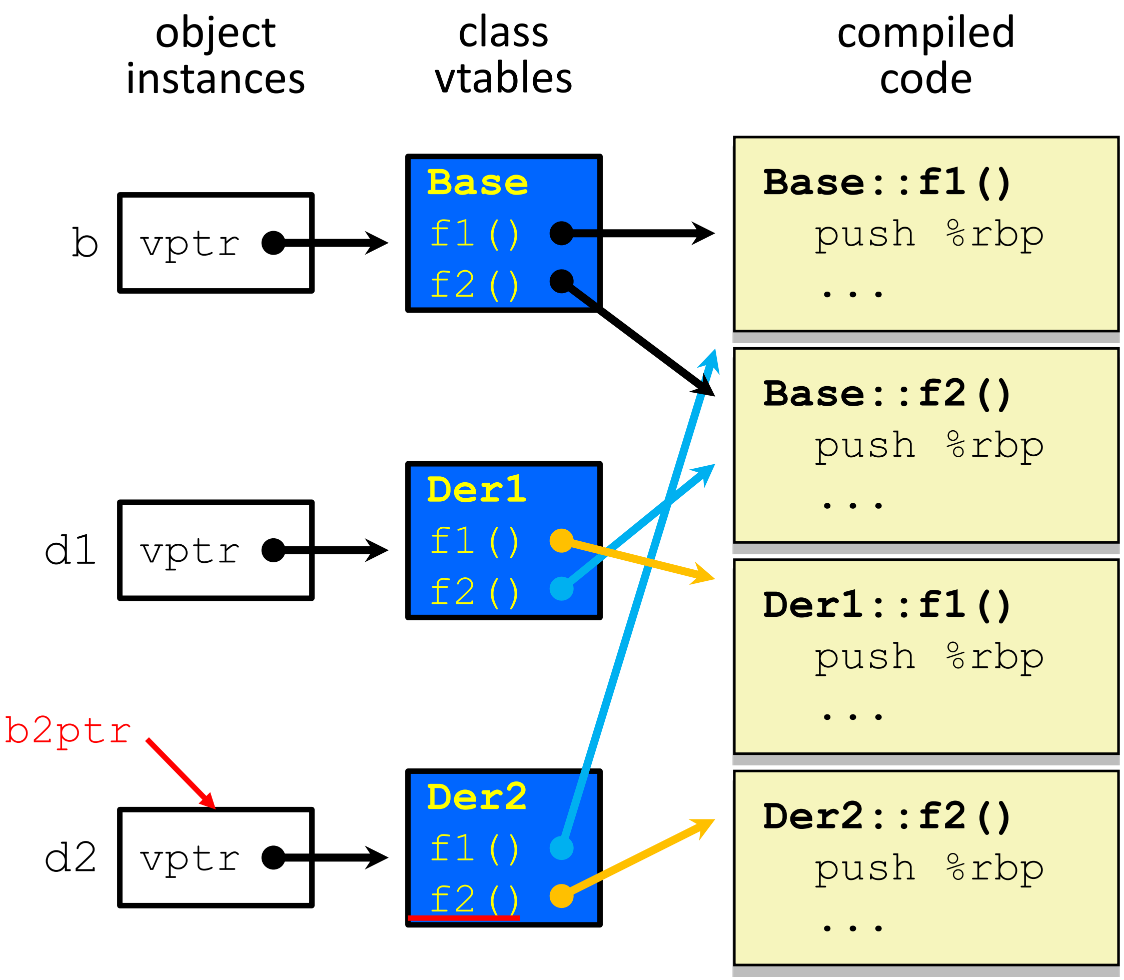
```
class Base {
 public:
  virtual void f1();
  virtual void f2();
};

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();   //Base::f1
b0ptr->f2();   //Base::f2

b1ptr->f1();   // Der1::f1
b1ptr->f2();   // Base::f2

d2.f1();       // Base::f1
b2ptr->f1();   // Base::f1
b2ptr->f2();   // Der2::f2
```



Difference Between these?

vtable/vptr Example




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

Base* b2ptr = &d2;

d2.f1();
// d2.vptr -->
// Der2.vtable.f1 -->
// Base::f1()

b2ptr->f1();
// b2ptr -->
// d2.vptr -->
// Der2.vtable.f1 -->
// Base::f1()
```

No ambiguity

Can optimize out

Hard coded call

Let’s Look at Some Actual Code

- Let’s examine the following code using `objdump`
  - `g++ -Wall -g -std=c++11 -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;
  d1.f1();
  Base* bptr = &d1;
  bptr->f1();
}
```

Done via hard-coded calla

Done with indirect jump on vtable entry

More to Come Next Time!

- Any lingering questions?