C++ Inheritance I

CSE 333

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Lecture Outline

- C++ Inheritance
  - **Roadmap for Next Two Lectures**
  - Conceptual Review
  - Dynamic Dispatch
  - vtables and vptr

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

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 (i.e., dynamic dispatch) are optional
    - Pure virtual functions, abstract classes, why no Java "interfaces"
    - Assignment slicing, using class hierarchies with STL
- Casts in C++

- Reference: C++ Primer, ch. 15

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  - What's different in C++ (compared to Java)
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    - *Pure virtual functions, abstract classes, why no Java "interfaces"*
    - *Assignment slicing, using class hierarchies with STL*
- *Casts in C++*

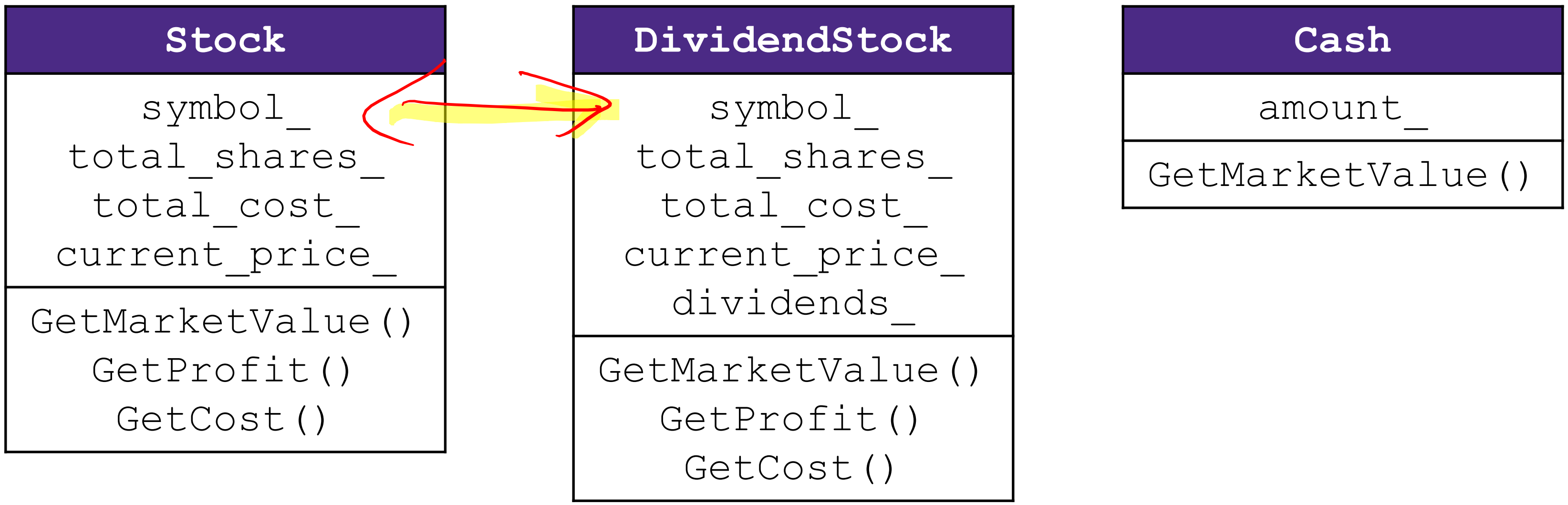
- Reference: C++ Primer, ch. 15
  - (read it! a lot of how C++ does this looks like Java, but details differ)

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

Design Without Inheritance

- One class per asset type:



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

- See sample code in `initial_design/`

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Inheritance

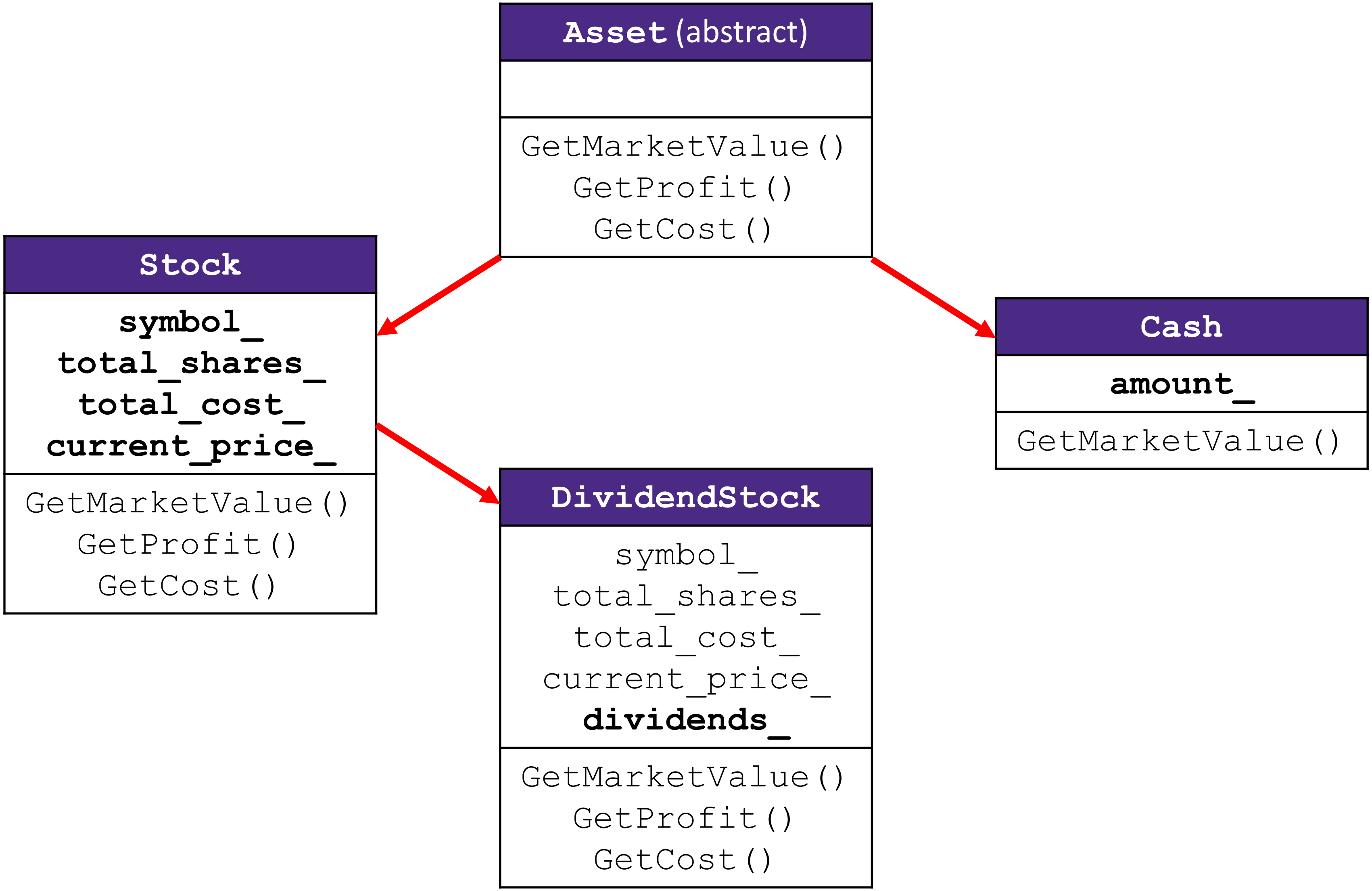
- A parent-child "is-a" relationship between classes
  - A child (derived class) extends a parent (base class)
- Benefits:
  - Code reuse
    - Children can automatically inherit code from parents
  - Polymorphism
    - Ability to redefine existing behavior but preserve the interface
    - Children can 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

Terminology

Java	C++
Superclass	Base Class
Subclass	Derived Class

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

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 subclasses
  - Subclasses must have access but clients should not be allowed
  - (recall that C++ style guide says all *data members* should be `private`; therefore your getters/setters must, minimally, be `protected`)

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

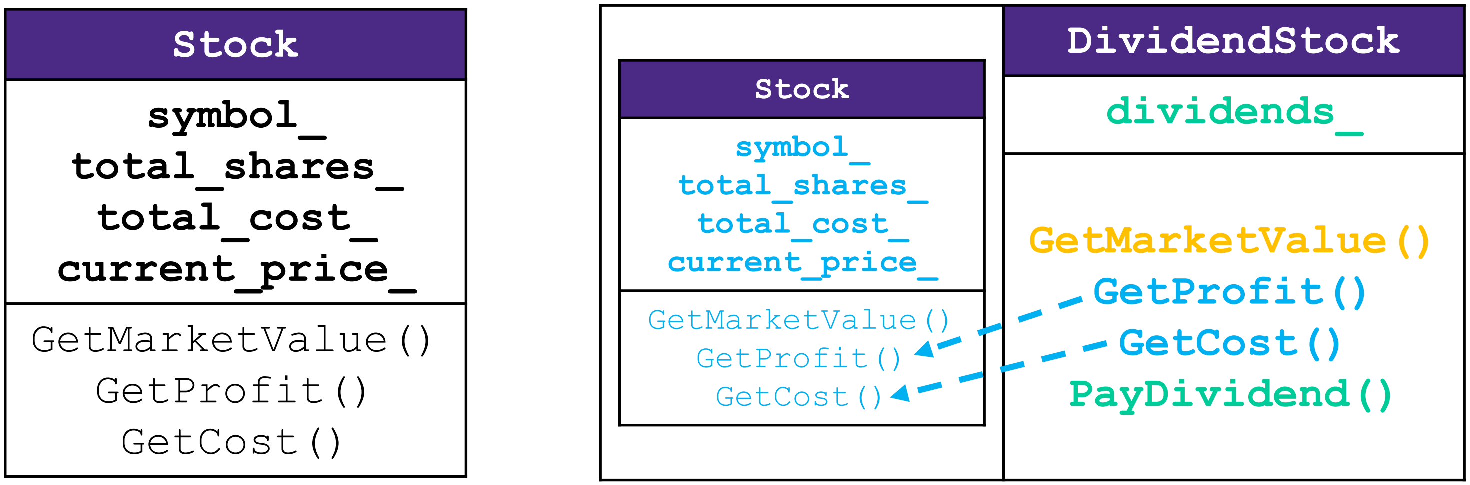
Stock
symbol_
total_shares_
total_cost_
current_price_
GetMarketValue()
GetProfit()
GetCost()

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.)

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Like Java: Dynamic Dispatch

- 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
  - This is similar to Java
- 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: PrintStock(Stock *s) { s->Print() }
  - Calls Print() function appropriate to Stock, DividendStock, etc. without knowing the exact class of *s, other than it is some sort of Stock
  - So the Stock (DividendStock, etc.) object *itself* has to carry some sort of information that can be used to decide which Print() to call
  - (see inherit-design/useassets.cc)

Requesting Dynamic Dispatch

- Prefix the member function declaration with the `virtual` keyword
  - Derived functions don't need to repeat `virtual`, since it's virtual in all subclasses, 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
  - A virtual function is virtual in all subclasses as well
  - Be consistent and follow local conventions

Static vs Dynamic Types

- Suppose we have a variable declared

  `T*  x`

  and a method call

  `x->f(`*params*`)`

- There are *two types* associated with `x`:
  - Static type: the declared type of `x`, which is `T` here
  - Dynamic type: the actual type of the object `*x`, which will either be `T` *or some subclass (subtype) of `T`*
    - And this *can change during execution* if `x` is changed to point to different objects with different (sub)types of `T`

Obtaining Dynamic Dispatch

- Static type (compile-type type) must differ from the dynamic type (actual runtime type of the object)
  - Therefore, need to have some form of indirection (eg, a pointer or reference)
- The member function in the static type must be declared `virtual`

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

DividendStock dividend;
DividendStock* dp = &dividend;
Stock stock;
Stock* sp = &dividend;

dp->GetMarketValue();
sp->GetMarketValue();

stock.GetMarketValue();
```

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();
}        // really Stock::GetProfit()
```

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();
```

Most-Derived

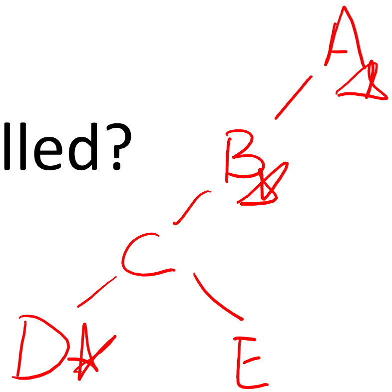
```
class A {
 public:
  // Foo will use dynamic dispatch
  virtual void Foo();
};

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();
}
```

Poll Everywhere

pollev.com/uwcse333

- 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 {
};
```

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How Can This Possibly Work?

- The compiler produces `Stock.o` from *just* `Stock.cc`
  - It doesn't know that `DividendStock` exists during this process

Stock.h

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

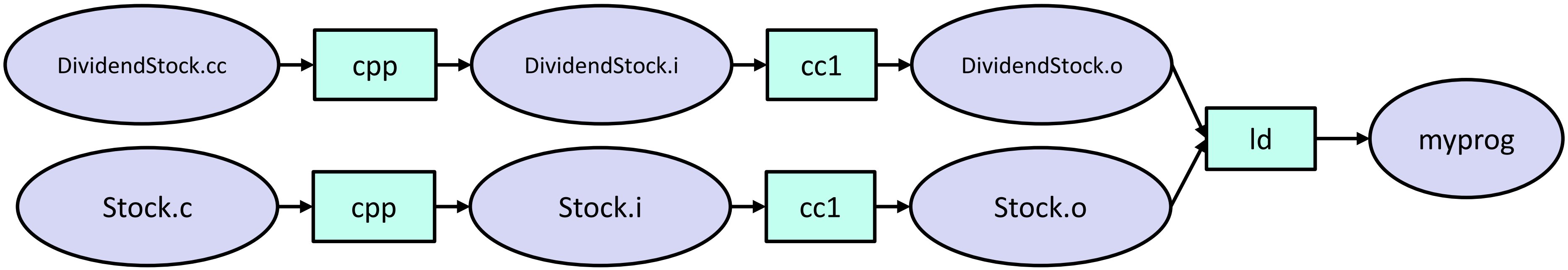
```
double Stock::GetMarketValue() const {
  return get_shares() * get_share_price();
}

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

Stock.cc

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()` vs. `DividendStock::GetMarketValue()`

    vs. something else that might not exist yet?



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  - So then how does the emitted code know to call `Stock::GetMarketValue()` vs. `DividendStock::GetMarketValue()`

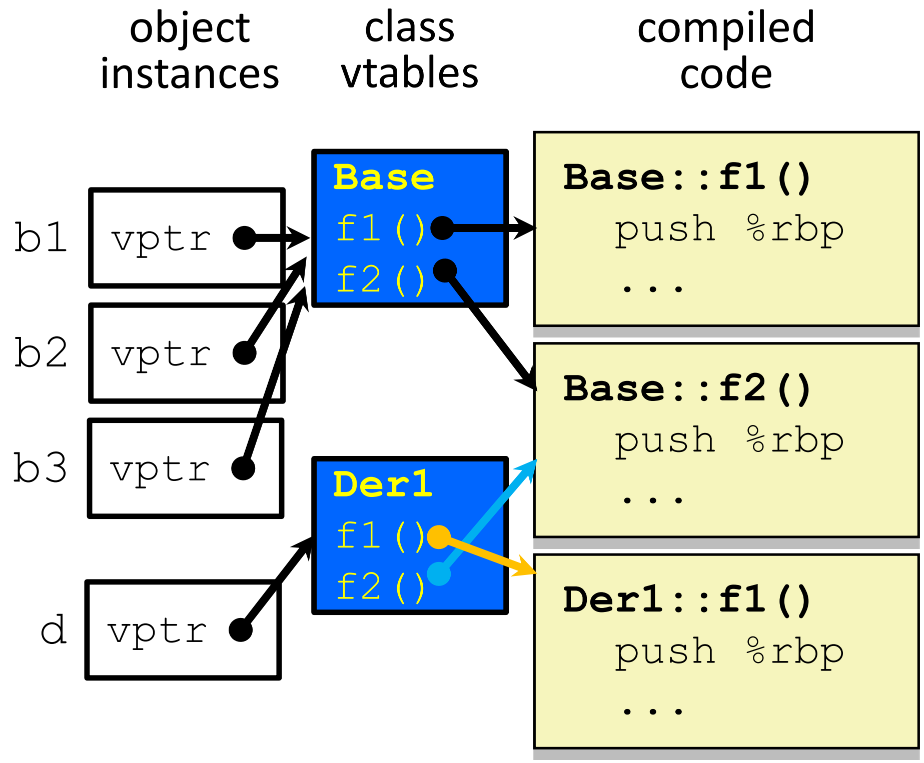
    vs. something else that might not exist yet?
  - ***Function pointers!***

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 newly constructed object's class
    - Thus, the vptr "remembers" what class the object is

vtable/vptr Example

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

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

Base b1, b2, b3;
Der1 d;
Base * bp = &d;
```



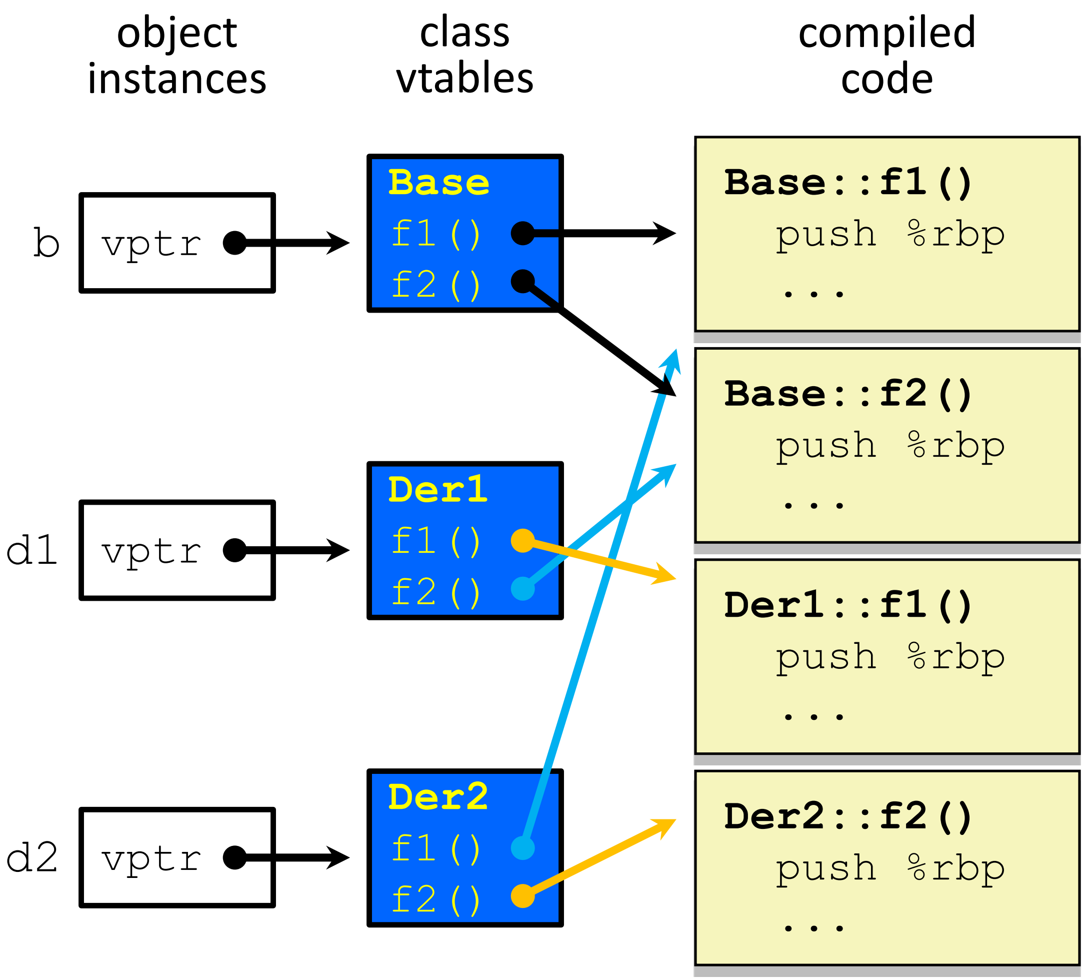
vtable/vptr Example

```
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()
```

No mismatch between static and dynamic type!

vtable/vptr Example




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

Base* bptr = &d1;

bptr->f1();
// bptr -->
//   d1.vptr -->
//   Der1.vtable.f1 -->
//   Der1::f1()

bptr = &d2;

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

Let's Look at Some Actual Code

- Let's examine the following code using `objdump`
  - `g++ -g -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();
}
```

More to Come…

Next time…