CSE 333

Lecture 15 - inheritance

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Administrivia

HW3 due a week from Thursday - how's it look?

Sections this week: debugging disk files in hex & other useful tools & information (+ C++ subclasses)

No new exercise for Wednesday. Next exercise out now but not due until Friday before class.

(we might not get to absolutely everything involved today, but we should get to most of it, and all topics are included in these slides and the *C++ Primer*)

HW3 tip

HW3 writes some pretty big index files

- Hundreds of thousands of write operations
- No problem for today's fast machines and disks!!

Except...

- If you're running on attu or a CSE lab linux workstation, every write to your personal directories goes to a network file server(!)
  - ∴ Lots of slow network packets vs full-speed disks — can take much longer to write an index to a server vs. a few sec. locally (!!)
  - Suggestion: write index files to /tmp/... . That's a local scratch disk and is very fast. But please clean up when you're done.

Today

C++ inheritance

- Review of basic idea (pretty much the same as 143)
- What's different in C++ (compared to Java)
    - *Static vs dynamic dispatch - virtual functions and vtables*
    - *Pure virtual functions, abstract classes, why no Java "interfaces"*
    - *Assignment slicing, using class hierarchies with STL*
- Casts in C++
- Reference: C++ Primer, ch. 15

Credits: Thanks to Marty Stepp for stock portfolio example

Let’s build a stock portfolio

A portfolio represents a person’s financial investments

- each asset has a cost (how much was paid for it) and a market value (how much it is worth)
  - the difference is the profit (or loss)
- different assets compute market value in different ways
  - **stock**: has a symbol (“GOOG”), a number of shares, share price paid, and current share price
  - **dividend stock**: is a stock that also has dividend payments
  - **cash:** money; never incurs profit or loss.   (hah!)

One possible design

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( )

One class per asset type

Problem: redundancy

Problem: cannot treat multiple investments the same way

e.g., cannot put them in a single array or Vector *see initial_design/*

Inheritance

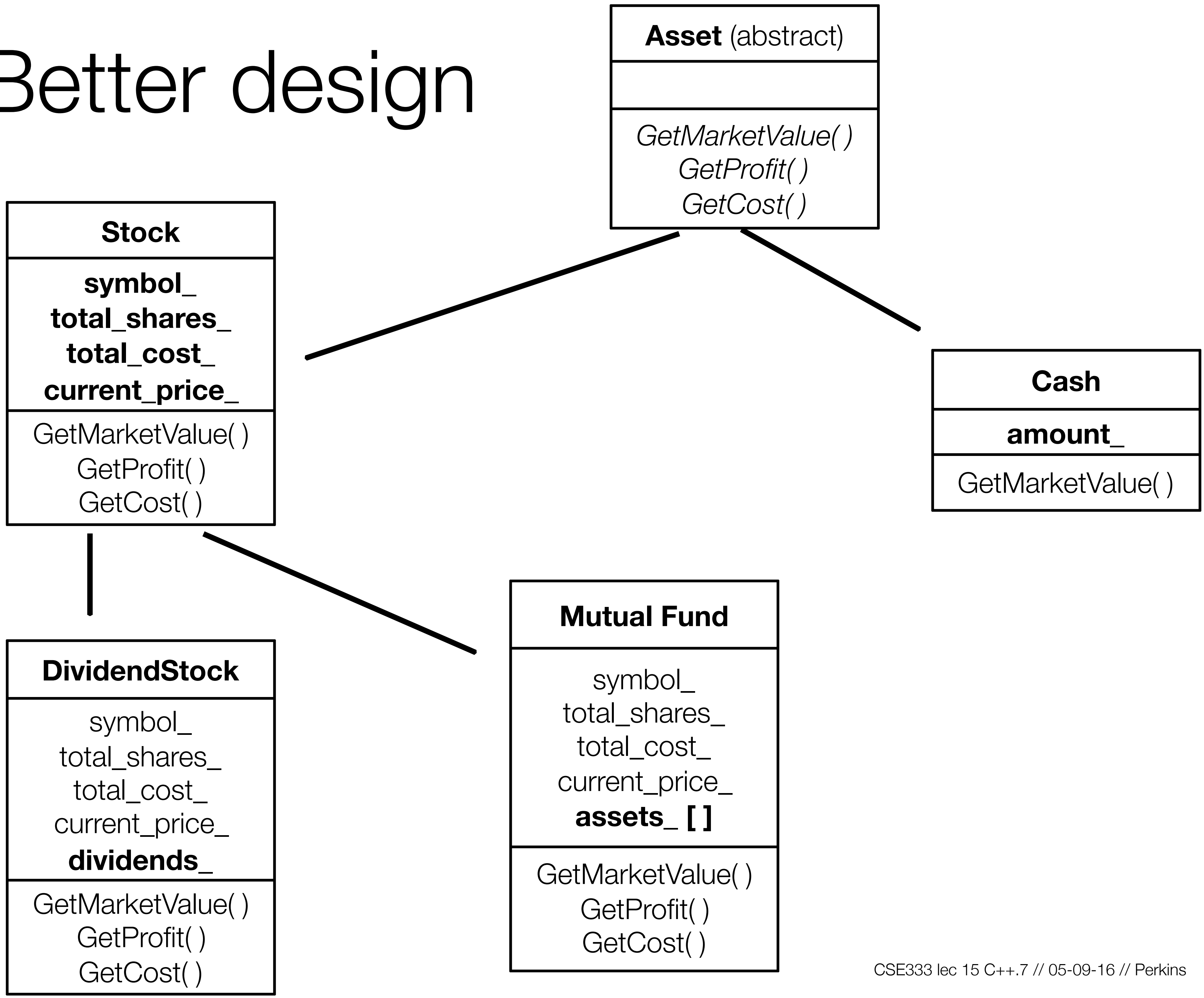
A parent-child “is-a” relationship between classes

- a child (**derived** class) extends a parent (**base** class)

Benefits:

- code reuse: subclasses inherit code from superclasses
- polymorphism
  - ability to redefine existing behavior but preserve the interface
  - children can override behavior of parent
  - others can make calls on objects without knowing which part of the inheritance tree it is in
- extensibility: children can add behavior

Better design



Like Java: Access specifiers

public: visible to all other classes

protected: visible to current class and its subclasses

private: visible only to the current class

declare members as **protected** if:

- you don't want random clients accessing them, but...
  - you want to be subclassed and let subclasses access them

Like Java: Public inheritance

```
#include "BaseClass.h"

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

“public” inheritance

anything that is [*public, protected*] in the base is [*public, protected*] in the derived class - this is interface (specification) + implementation inheritance

derived class inherits **almost** all behavior from the base class

not constructors and destructors

not the assignment operator or copy constructor

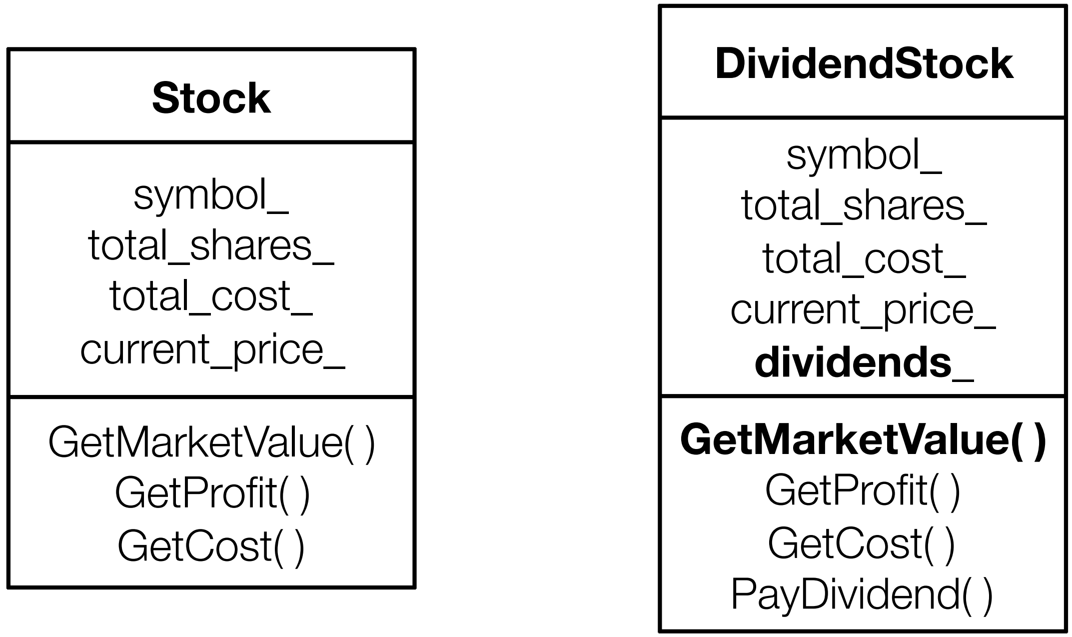
(Yes there is “private” inheritance — don’t ask and don’t use)

Terminology

C++, etc.	**Java, etc.**
base class	*superclass*
derived class	*subclass*

Means the same. You'll hear both.

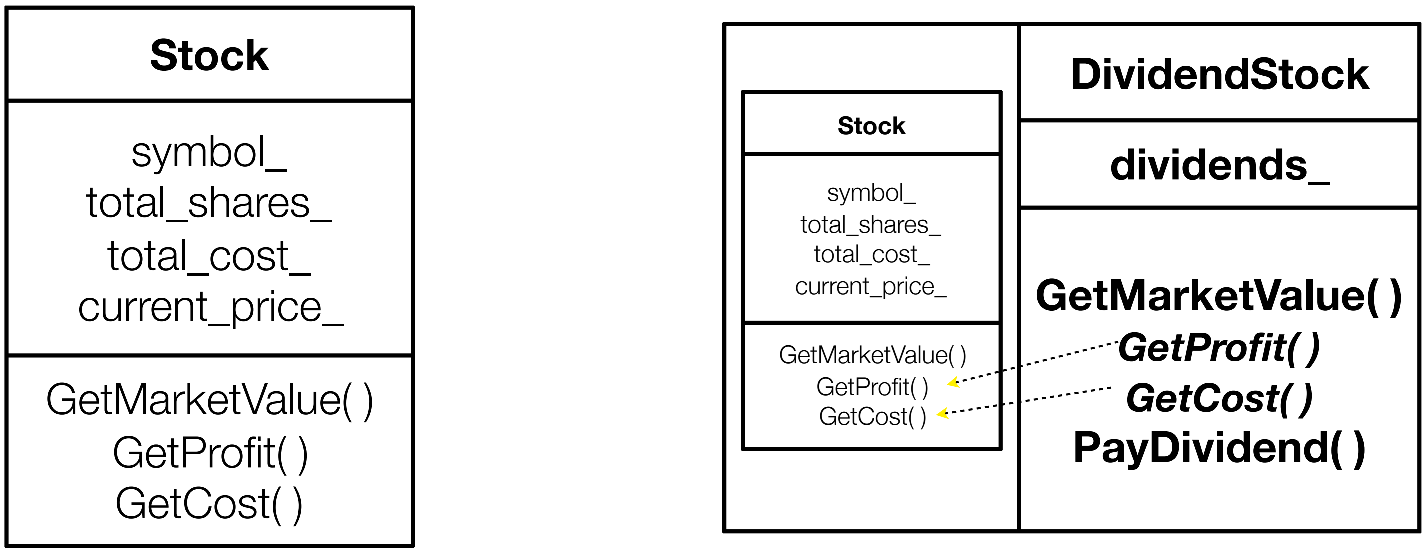
Revisiting the portfolio example



Without inheritance (separate class per type)

- lots of redundancy
- no type relationship between the classes

Revisiting the portfolio example



A derived class:

inherits the behavior and state of the base class

overrides some of the base class's member functions

extends the base class with new member functions, variables

(implement better_design/)

Like Java: Dynamic dispatch

Usually, when a derived function is available to an object, we want that derived function to be invoked by it

as we will see, this requires a runtime decision of what code to invoke

When a member function is invoked on an object...

the code that is invoked is decided at run time, and is the **most-derived function** accessible to the object's visible type

How to use dynamic dispatch

If you want a member function to use dynamic dispatch, prefix its declaration with the “virtual” keyword

- derived (child) functions don’t need to repeat the virtual keyword, but it traditionally has been good style to do so
  - “override” added in C++ 11 - always use if it’s available
    - “virtual” + “override”? Be consistent; follow local conventions
- This is how method calls work in Java (all normal methods are virtual; no “virtual” keyword needed)

(see even_better_design/)

Dynamic dispatch

When a member function is invoked on an object

- the code that is invoked is decided at run time, and is the **most-derived function** accessible to the object's visible type

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

double DividendStock::GetProfit() const {
  return DividendStock::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

```
DividendStock dividend();

DividendStock *ds = &dividend;
Stock *s = &dividend;

// invokes Stock::GetProfit(), since that function is
// inherited (i.e, not overridden).  Stock::GetProfit()
// invokes Dividend::GetMarketValue(), since that is
// the most-derived accessible function.
ds->GetProfit();

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

// invokes DividendStock::GetMarketValue()
s->GetMarketValue();
```

Dynamic dispatch

Here's what "most derived" means:

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

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

  // Why is this OK?
  a_ptr = &c;

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

Dynamic dispatch

```
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 {
};
```

A more extreme version

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

  // Whose Foo() is called?
  a_ptr = &c;
  a_ptr->Foo();

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

But how can this possibly work??

The compiler produces Stock.o from Stock.cc

- while doing this, it can't know that DividendStock exists
  - so, how does the code emitted for Stock::GetProfit( ) know to invoke Stock::GetMarketValue( ) some of the time, and DividendStock::GetMarketValue( ) other times???!?

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

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

Stock.h

```
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 member function is virtual, the compiler emits:

- a “vtable”, or virtual function table, **for the class**
  - it contains an function pointer for each virtual function in the class
  - the pointer points to the most-derived function for that class
- a “vptr”, or virtual table pointer, **for each object instance**
  - the vptr is a pointer to a virtual table, and it is essentially a hidden member variable inserted by the compiler
  - when the object’s constructor is invoked, the vptr is initialized to point to the virtual table for the object’s class
  - thus, the vptr “remembers” what class the object is

vtable/vptr example

```
class Base {
 public:
  virtual void fn1() {};
  virtual void fn2() {};
};

class Dr1: public Base {
 public:
  virtual void fn1() {};
};

class Dr2: public Base {
 public:
  virtual void fn2() {};
};
```

```
// what needs to work

Base b;
Dr1  d1;
Dr2  d2;

Base *bptr = &b;
Base *d1ptr = &d1;
Base *d2ptr = &d2;

bptr->fn1();    // Base::fn1()
bptr->fn2();    // Base::fn2()

d1ptr->fn1();   // Dr1::fn1();
d1ptr->fn2();   // Base::fn2();

d2.fn1();       // Base::fn1();
d2ptr->fn1();   // Base::fn1();
d2ptr->fn2();   // Dr2::fn2();
```

vtable/vptr example

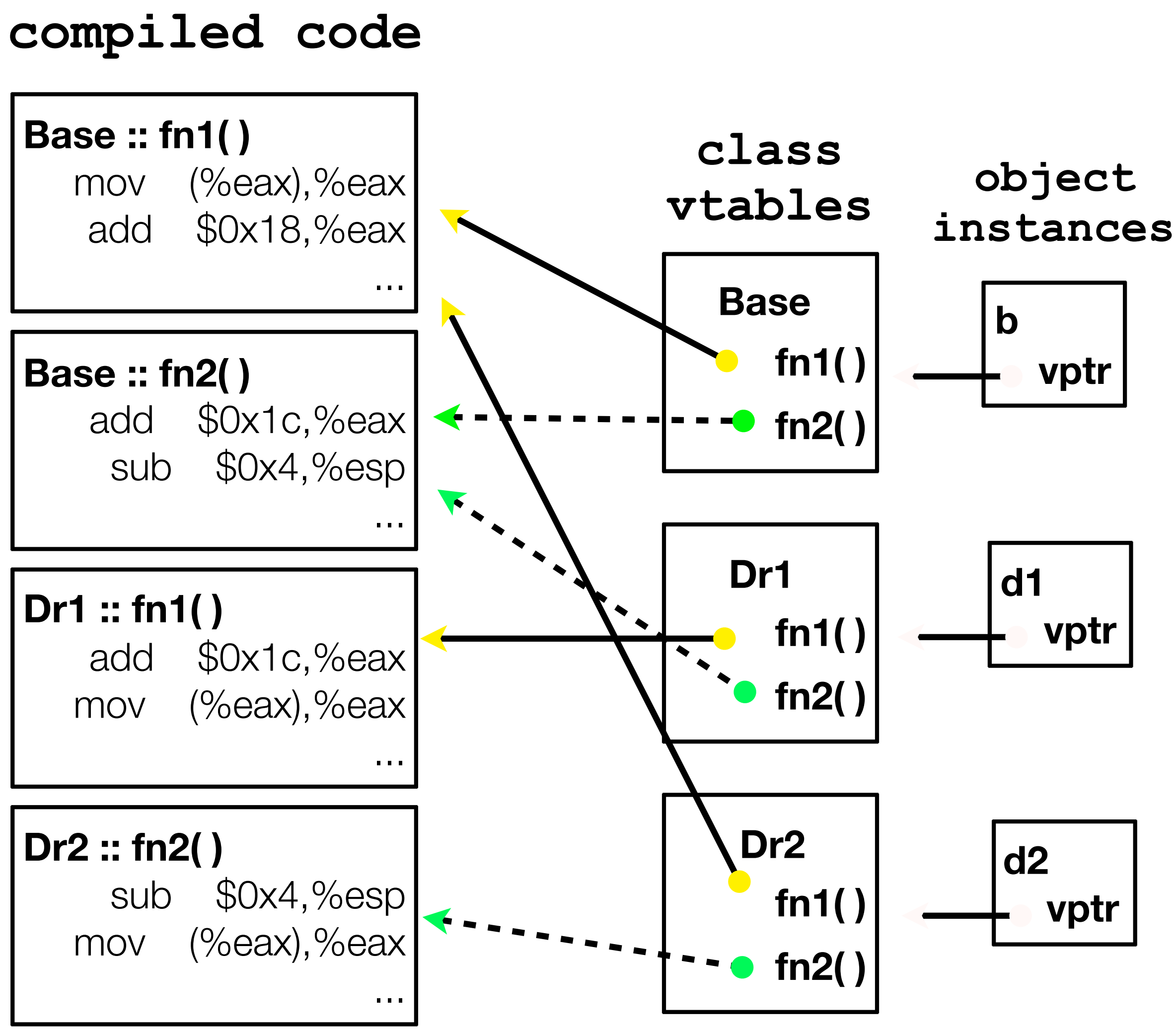
```
// what happens

Base b;
Dr1  d1;
Dr2  d2;

Base *d2ptr = &d2;

d2.fn1();
// d2.vptr -->
// Dr2.vtable.fn1 -->
// Base::fn1()


d2ptr->fn2();
// d2ptr -->
// d2.vptr -->
// Dr2.vtable.fn2 ->
// Dr2::fn2()
```



actual code

```
class Base {
 public:
  virtual void fn1() {};
  virtual void fn2() {};
};

class Dr1: public Base {
 public:
  virtual void fn1() {};
};

main() {
 Dr1   d1;
 d1.fn1();
 Base *ptr = &d1;
 ptr->fn1();
}
```

vtable.cc

Let's compile this and use objdump to see what g++ emits!

- g++ -g vtable.cc
- objdump -CDSRTtx a.out | less

Static dispatch - What if we omit “virtual”?

When a member function is invoked on an object...

the code that is invoked is decided at compile time, based on the compile-time visible type of the callee

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

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

DividendStock.cc

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

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

Stock.cc

Static dispatch

```
DividendStock dividend();

DividendStock *ds = &dividend;
Stock *s = &dividend;

// invokes Stock::GetProfit(), since that function is
// inherited (i.e, not overridden).  Stock::GetProfit()
// invokes Stock::GetMarketValue(), since C++ uses
// static dispatch by default.
ds->GetProfit();

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

// invokes Stock::GetMarketValue()
s->GetMarketValue();
```

Why not always use “virtual”?

Two (fairly uncommon) reasons:

- Efficiency:
  - non-virtual function calls are a tiny bit faster (no indirect lookup)
  - if the class has no virtual functions, objects will not have a vptr field
- Control: If `f()` calls `g()` in class `X` and `g` is not virtual, we’re guaranteed to call `X::g()` and not `g()` in some subclass
  - Particularly useful for framework design

In Java, all functions (methods) are virtual (exception: static class methods, but these aren’t associated with objects — no “this” ptr)

In C++ and C# you can pick what you want

- But omitting “virtual” often causes obscure bugs

Virtual is "sticky"

If `X::f()` is declared virtual, then a vtable will be created for class `X` and for all of its subclasses. The vtables will include function pointers for (the correct version of) `f`.

`f()` will be called using dynamic dispatch even if overridden but not explicitly specified as `virtual` in a subclass

- But it's good style to help the reader by using override (and, particularly in older code, virtual) in subclasses

Pure virtual fcns, abstract classes

Sometimes we want to include a function in a class but only implement it in subclasses. In Java we would use an abstract method. In C++ we use a "pure virtual" function.

Example: `virtual string noise() = 0;` // see zoo.cc

A class that contains a pure virtual method is abstract

- Can't create instances of an abstract class (like Java)
- Extend abstract classes and override methods to use them (like Java)

A class containing *only* pure virtual methods is the same as a Java interface (∴ no separate "interface" thingys in C++)

- Pure type specification without implementations

Inheritance and constructors

A derived class **does not inherit** the base class's constructor

- the derived class ***must*** have its own constructor
  - if you don't provide one, C++ synthesizes a default constructor for you
    - it initializes derived class's non-POD member variables to zero-equivalents and invokes the default constructor of the base class
    - if the base class has no default constructor, a compiler error
- a constructor of the base class is invoked before the constructor of the derived class
  - you can specify which base class constructor in the initialization list of the derived class, or C++ will invoke default constructor of base class

Examples

```
// Base has no default constructor
class Base {
 public:
  Base(int x) : y(x) { }
  int y;
};

// Compiler error when you try
// to instantiate a D1, as D1's
// synthesized default constructor
// needs to invoke Base's default
// constructor.
class D1 : public Base {
 public:
  int z;
};

// Works.
class D2 : public Base {
 public:
  D2(int z) : Base(z+1) {
   this->z = z;
  }
  int z;
};
```

badcons.cc

```
// Base has a default constructor.
class Base {
 public:
  int y;
};

// Works.
class D1 : public Base {
 public:
  int z;
};

// Works.
class D2 : public Base {
 public:
  D2(int z) {
   this->z = z;
  }
  int z;
};
```

goodcons.cc

Destructors

When the destructor of a derived class is invoked...

- the destructor of the base class is invoked after the destructor of the derived class finishes

Note that static dispatch of destructors is almost always a mistake!

- good habit to always define a destructor as virtual
  - empty if you have no work to do

baddestruct.cc

```
class Base {
 public:
  Base() { x = new int; }
  ~Base() { delete x; }
  int *x;
};

class D1 : public Base {
 public:
  D1() { y = new int; }
  ~D1() { delete y; }
  int *y;
};

Base *b = new Base;
Base *dptr = (Base *) new D1;

delete b;    // ok
delete dptr; // leaks D1::y
```

Slicing -- C++'s revenge

C++ allows you to...

- assign to...
  - an instance of a base class...
  - ...the value of a derived class

slicing.cc

```
class Base {
 public:
  Base(int x) : x_(x) { }
  int x_;
};

class Dr : public Base {
 public:
  Dr(int y) : Base(16), y_(y) { }
  int y_;
};

main() {
  Base b(1);
  Dr d(2);
  b = d;     // what happens to y_?
  // d = b; // compiler error
}
```

Given this, STL containers?? :(

STL stores **copies of values** in containers, not pointers to object instances

- so, what if you have a class hierarchy, and want to store mixes of object types in a single container?
  - e.g., Stock and DividendStock in the same list
- you get sliced! :(

```
class Stock {
   ...
};

class DivStock : public Stock {
   ...
};

main() {
  Stock         s;
  DivStock     ds;
  list<Stock> li;

  l.push_back(s);    // OK
  l.push_back(ds);   // OUCH!
}
```

STL + inheritance: use pointers?

Store pointers to heap-allocated objects in STL containers

no slicing :)

you have to remember to delete your objects before destroying the container :(

sort( ) does the wrong thing :(:(

Use smart pointers!

```
#include <list>
using namespace std;

class Integer {
 public:
  Integer(int x) : x_(x) { }
 private:
  int x_;
};

main() {
  list<Integer *> li;
  Integer *i1 = new Integer(2);
  Integer *i2 = new Integer(3);

  li.push_back(i1);
  li.push_back(i2);
  li.sort();  // waaaaaah!!
}
```

Explicit casting in C

C's *explicit typecasting* syntax is simple

```
lhs = (new_type) rhs;
```

C's explicit casting is used to...

convert between pointers of arbitrary type

forcibly convert a primitive type to another

e.g., an integer to a float, so that you can do integer division

```
int x = 5;
int y = 2;
printf("%d\n", x / y);              // prints 2
printf("%f\n", ((float) x) / y);    // prints 2.5
```

C++

You can use C-style casting in C++, but C++ provides an alternative style that is more informative

static_cast<to_type>(expression)

dynamic_cast<to_type>(expression)

const_cast<to_type>(expression)

reinterpret_cast<to_type>(expression)

Always use these in C++ code - helps document intent

static_cast

C++'s static_cast can convert:

- pointers to classes **of related type**
  - get a compiler error if you attempt to static_cast between pointers to non-related classes
  - dangerous to cast a pointer to a base class into a pointer to a derived class
- non-pointer conversion
  - float to int, etc.

static_cast is checked at compile time

staticcast.cc

```
class Foo {
 public:
  int x_;
};

class Bar {
 public:
  float x_;
};

class Wow : public Bar {
 public:
  char x_;
};

int main(int argc, char **argv) {
  Foo a, *aptr;
  Bar b, *bptr;
  Wow c, *cptr;

  // compiler error
  aptr = static_cast<Foo *>(&b);

  // OK
  bptr = static_cast<Bar *>(&c);

  // compiles, but dangerous
  cptr = static_cast<Wow *>(&b);
  return 0;
}
```

dynamic_cast

C++'s dynamic_cast can convert:

- pointers to classes of related type
- references to classes of related type

dynamic_cast is checked at both compile time and run time

- casts between unrelated classes fail at compile time
- casts from base to derived fail at run-time if the pointed-to object is not a full derived object
  - result is nullptr if cast fails

dynamiccast.cc

```
class Base {
 public:
  virtual int foo() { return 1; }
  float x_;
};

class Deriv : public Base {
 public:
  char x_;
};

int main(int argc, char **argv) {
  Base b, *bptr = &b;
  Deriv d, *dptr = &d;

  // OK (run-time check passes).
  bptr = dynamic_cast<Base *>(&d);
  assert(bptr != NULL);

  // OK (run-time check passes).
  dptr = dynamic_cast<Deriv *>(bptr);
  assert(dptr != NULL);

  // Run-time check fails, so the
  // cast returns NULL.
  bptr = &b;
  dptr = dynamic_cast<Deriv *>(bptr);
  assert(dptr != NULL);

  return 0;
}
```

const_cast

Is used to strip or add const-ness

dangerous!

constcast.cc

```
void foo(int *x) {
  *x++;
}

void bar(const int *x) {
  foo(x);  // compiler error
  foo(const_cast<int *>(x));  // succeeds
}

main() {
  int x = 7;
  bar(&x);
}
```

reinterpret_cast

casts between incompatible types

- storing a pointer in an int, or vice-versa
  - works as long as the integral type is "wide" enough
- converting between incompatible pointers
  - dangerous!
    - But used (carefully) in HW3!!

Implicit conversion

The compiler tries to infer some kinds of conversions

when you don't specify an explicit cast, and types are not equal, the compiler looks for an acceptable implicit conversion

```
void bar(std::string x);

void foo() {
  int x = 5.7;    // implicit conversion float -> int
  bar("hi");      // implicit conversion, (const char *) -> string
  char c = x;     // implicit conversion, int -> char
}
```

Sneaky implicit conversions

How did the (const char *) --> string conversion work??

- if a class has a constructor with a single parameter, the compiler will exploit it to perform implicit conversions

- at most one user-defined implicit conversion will happen

  - can do int --> Foo

  - can't do int --> Foo --> Baz

implicit.cc

```
class Foo {
 public:
  Foo(int x) : x_(x) { }
  int x_;
};

int Bar(Foo f) {
  return f.x_;
}

int main(int argc, char **argv) {
  // The compiler uses Foo's
  // (int x) constructor to make
  // an implicit conversion from
  // the int 5 to a Foo.


  // equiv to return Bar(Foo(5));
  // !!!
  return Bar(5);
}
```

Avoiding sneaky implicits

Declare one-argument constructors as "explicit" if you want to disable them from being used as an implicit conversion path

- usually a good idea

explicit.cc

```
class Foo {
 public:
  explicit Foo(int x) : x_(x) { }
  int x_;
};

int Bar(Foo f) {
  return f.x_;
}

int main(int argc, char **argv) {

  // compiler error
  return Bar(5);
}
```

Exercise 1

Design a class hierarchy to represent shapes:

- examples of shapes: Circle, Triangle, Square

Implement methods that:

- construct shapes
- move a shape (i.e., add (x, y) to the shape position)
- returns the centroid of the shape
- returns the area of the shape
- Print( ), which prints out the details of a shape

Exercise 2

Implement a program that:

- uses your exercise 1
    - constructs a vector of shapes
    - sorts the vector according to the area of the shape
    - prints out each member of the vector
- notes:
    - to avoid slicing, you'll have to store pointers in the vector
    - to be able to sort, you'll have to implement a wrapper for the pointers, and you'll have to override the "<" operator

See you on Friday!