CSE 333
Lecture 15 - inheritance

Hal Perkins
Department of Computer Science & Engineering
University of Washington
Midterm

Stats: mean 89.4, stdev 10.1

- Lots of very high scores - great!
- <insert “what does this do to my grade?” speech here>

Regrading

- We’ll fix anything that’s wrong, but first...
- Please wait (overnight?) and compare to solutions first
  ‣ (unless it’s trivial or clerical; that we’ll fix right away)
- Then probably best to write a note and attach it to front of exam and return to instructor
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 is to a network file server(!)
  
  ‣ : Lots of really slow network packets compared to relatively slow disk  
    — 4 min. to write enron index vs. 3-4 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++

• 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

<table>
<thead>
<tr>
<th>Stock</th>
<th>DividendStock</th>
<th>Cash</th>
</tr>
</thead>
<tbody>
<tr>
<td>symbol_</td>
<td>symbol_</td>
<td>amount_</td>
</tr>
<tr>
<td>total_shares_</td>
<td>total_shares_</td>
<td></td>
</tr>
<tr>
<td>total_cost_</td>
<td>total_cost_</td>
<td></td>
</tr>
<tr>
<td>current_price_</td>
<td>current_price_</td>
<td></td>
</tr>
<tr>
<td>GetMarketValue()</td>
<td>GetMarketValue()</td>
<td>GetMarketValue( )</td>
</tr>
<tr>
<td>GetProfit()</td>
<td>GetProfit()</td>
<td></td>
</tr>
<tr>
<td>GetCost()</td>
<td>GetCost()</td>
<td></td>
</tr>
<tr>
<td>dividends_</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Asset (abstract)

GetMarketValue()
GetProfit()
GetCost()

Cash

amount_
GetMarketValue()

Stock

symbol_
total_shares_
total_cost_
current_price_

GetMarketValue()
GetProfit()
GetCost()

DividendStock

symbol_
total_shares_
total_cost_
current_price_
dividends_

GetMarketValue()
GetProfit()
GetCost()

Mutual Fund

symbol_
total_shares_
total_cost_
current_price_

assets_ []

GetMarketValue()
GetProfit()
GetCost()
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 customers accessing them
    ▸ you want to be subclassed and let subclasses access them
Like Java: Public inheritance

- “public” inheritance
  - anything that is [public, protected] in the base is [public, protected] in the derived class - interface + 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

<table>
<thead>
<tr>
<th>C++, etc.</th>
<th>Java, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>base class</em></td>
<td><em>superclass</em></td>
</tr>
<tr>
<td><em>derived class</em></td>
<td><em>subclass</em></td>
</tr>
</tbody>
</table>

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 is good style to do so

( 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

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

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

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

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

```cpp
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()
};
```

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

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

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

A more extreme version

```cpp
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 {
};

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??!?

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

```cpp
double Stock::GetMarketValue() const {
    return get_shares() * get_share_price();
}
double Stock::GetProfit() const {
    return GetMarketValue() - GetCost();
}
```
vtables and the vptr

If a member function is virtual, the compiler emits:

- a “vtable”, or virtual function table, for the class
  - it contains a 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()

compiled code

Base :: fn1()
    mov (%eax),%eax
    add $0x18,%eax
...

Base :: fn2()
    add $0x1c,%eax
    sub $0x4,%esp
...

Dr1 :: fn1()
    add $0x1c,%eax
    mov (%eax),%eax
...

Dr2 :: fn2()
    sub $0x4,%esp
    mov (%eax),%eax
...

CSE333 lec 15 C++:7 // 07-31-13 // Perkins
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();
}

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

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

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

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

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

// 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;
};
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
Slicing -- C++’s revenge

C++ allows you to...
- assign to...
  ‣ an instance of a base class...
  ‣ the value of a derived class

```cpp
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! :(  

```cpp
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!

```cpp
#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

```c
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

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

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!

```cpp
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!
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

```cpp
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

```cpp
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 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

```cpp
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!