CSE 333
Lecture 15 - inheritance

Hal Perkins
Department of Computer Science & Engineering
University of Washington
HW3 due a week from tomorrow(!!)

- <panic>if not started yet</panic>

No new exercise for Friday. Next exercise out now but not due until Monday 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 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

- 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

**Stock**
- `symbol_`
- `total_shares_`
- `total_cost_`
- `current_price_`

  - GetMarketValue()
  - GetProfit()
  - GetCost()

**DividendStock**
- `symbol_`
- `total_shares_`
- `total_cost_`
- `current_price_`
- `dividends`

  - GetMarketValue()
  - GetProfit()
  - GetCost()

**Asset (abstract)**
- GetMarketValue()
- GetProfit()
- GetCost()

**Cash**
- `amount_`

  - GetMarketValue()

**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 clients accessing them, but...
  - 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 - 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

<table>
<thead>
<tr>
<th><strong>C++, etc.</strong></th>
<th><strong>Java, etc.</strong></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

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

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
- 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

```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();
}
```

DividendStock.cc

Stock.cc
Dynamic dispatch

```cpp
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

```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??!!?
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
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()
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
// Stock.cc
double Stock::GetMarketValue() const {
    return get_shares() * get_share_price();
}

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

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

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

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

\texttt{f()} will be called using dynamic dispatch even if overridden but not explicitly specified as \texttt{virtual} in a subclass.

- But it’s good style to help reader by using \texttt{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;
    }

// 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

```cpp
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

```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;
    li.push_back(s);  // OK
    li.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(); // waaaaaaah!!
}
```
Explicit casting in C

C’s *explicit typecasting* syntax is simple

\[
\text{lhs} = (\text{new type}) \text{ rhs};
\]

- 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)`

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

```cpp
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;
}
```
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

```cpp
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!

```c++
const_cast.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

```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 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

```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 Monday!