CSE 333
Lecture 14 -- smart pointers

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

Midterm Friday
- Review in sections this week
- Closed book; topic list & old exams on the web

Assignments
- HW3 out by end of week, due a couple of weeks later (see calendar)
- New exercise on smart pointers out this week, due before class next Wednesday(!) [UW closed next Monday for President’s day]

Upcoming topics
- finishing up C++ this week and early next week
- remainder of quarter
  ‣ networking, tools, coding style, additional systems topics
Last time

We learned about STL

- noticed that STL was doing an enormous amount of copying
- we were tempted to use pointers instead of objects
  - but tricky to know who is responsible for delete’ing and when
A **smart pointer** is an **object** that stores a pointer to a heap allocated object

- a smart pointer looks and behaves like a regular C++ pointer
  
  ‣ how? by overloading *, ->, [], etc.

- a smart pointer can help you manage memory

  ‣ the smart pointer will delete the pointed-to object **at the right time**, including invoking the object’s destructor

  • **when** that is depends on what kind of smart pointer you use

  ‣ so, if you use a smart pointer correctly, you no longer have to remember when to delete new’d memory
A toy smart pointer

We can implement a simple one with:

- a constructor that accepts a pointer
- a destructor that frees the pointer
- overloaded * and -> operators that access the pointer

see toyptr/
What makes it a toy?

Can’t handle:

- arrays
- copying
- reassignment
- comparison
- ...plus many other subtleties...

Luckily, others have built non-toy smart pointers for us!
C++11’s std::unique_ptr

The unique_ptr template is part of C++’s standard library

- available in the new C++11 standard

A unique_ptr takes ownership of a pointer

- when the unique_ptr object is delete’ed or falls out of scope, its destructor is invoked, just like any C++ object
- this destructor invokes delete on the owned pointer
Using a unique_ptr

```cpp
#include <iostream> // for std::cout, std::endl
#include <memory>    // for std::unique_ptr
#include <stdlib.h>  // ... never used delete, but no leak

void Leaky() {
    int *x = new int(5);  // heap allocated
    (*x)++;
    std::cout << *x << std::endl;
}  // never used delete, therefore leak

void NotLeaky() {
    std::unique_ptr<int> x(new int(5));  // wrapped, heap-allocated
    (*x)++;
    std::cout << *x << std::endl;
}  // never used delete, but no leak

int main(int argc, char **argv) {
    Leaky();
    NotLeaky();
    return EXIT_SUCCESS;
}
```

Why are unique_ptrs useful?

If you have many potential exits out of a function, it’s easy to forget to call `delete` on all of them

- unique_ptr will delete its pointer when it falls out of scope
- thus, a unique_ptr also helps with exception safety

```cpp
int NotLeaky() {
  std::unique_ptr<int> x(new int(5));

  lots of code, including several returns
  lots of code, including a potential exception throw
  lots of code

  return 1;
}
```
unique_ptr operations

```cpp
#include <memory>    // for std::unique_ptr
#include <stdlib.h>  // for EXIT_SUCCESS
using namespace std;
typedef struct { int a, b; } IntPair;

int main(int argc, char **argv) {
  unique_ptr<int> x(new int(5));

  // Return a pointer to the pointed-to object
  int *ptr = x.get();

  // Return a reference to the pointed-to object
  int val = *x;

  // Access a field or function of a pointed-to object
  unique_ptr<IntPair> ip(new IntPair);
  ip->a = 100;

  // Deallocate the pointed-to object and reset the unique_ptr with
  // a new heap-allocated object.
  x.reset(new int(1));

  // Release responsibility for freeing the pointed-to object.
  ptr = x.release();
  delete ptr;
  return EXIT_SUCCESS;
}
```
unique_ptrs cannot be copied

std::unique_ptr disallows the use of its copy constructor and assignment operator

- therefore, you cannot copy a unique_ptr
- this is what it means for it to be “unique”

```cpp
#include <memory>
#include <stdlib.h>

int main(int argc, char **argv) {
  std::unique_ptr<int> x(new int(5));

  // fail, no copy constructor
  std::unique_ptr<int> y(x);

  // succeed, z starts with NULL pointer
  std::unique_ptr<int> z;

  // fail, no assignment operator
  z = x;

  return EXIT_SUCCESS;
}
```

uniquefail.cc
Transferring ownership

You can use reset() and release()

- release() returns the pointer, sets wrapper’s pointer to NULL
- reset() delete’s the current pointer, acquires a new one

```cpp
int main(int argc, char **argv) {
  unique_ptr<int> x(new int(5));
  cout << "x: " << x.get() << endl;

  unique_ptr<int> y(x.release());  // y takes ownership, x abdicates it
  cout << "x: " << x.get() << endl;
  cout << "y: " << y.get() << endl;

  unique_ptr<int> z(new int(10));

  // z delete's its old pointer and takes ownership of y's pointer.
  // y abdicates its ownership.
  z.reset(y.release());

  return EXIT_SUCCESS;
}
```
Copy semantics

Assigning values typically means making a copy

- sometimes this is what you want
  - assigning the value of one string to another makes a copy
- sometimes this is wasteful
  - returning a string and assigning it makes a copy, even though the returned string is ephemeral

```cpp
#include <iostream>
#include <string>

std::string ReturnFoo(void) {
  std::string x("foo");
  // this return might copy
  return x;
}

int main(int argc, char **argv) {
  std::string a("hello");
  // copy a into b
  std::string b(a);
  // copy return value into b.
  b = ReturnFoo();
  return EXIT_SUCCESS;
}
```

copysemantics.cc
Move semantics

C++11 introduces “move semantics”
- moves values from one object to another without copying (“steal”)
- useful for optimizing away temporary copies
- complex topic
  ‣ “rvalue references”
  ‣ beyond scope of 333 (this qtr anyway)

```cpp
#include <iostream>
#include <string>

std::string ReturnFoo(void) {
    std::string x("foo");
    // this return might make a copy
    return x;
}

int main(int argc, char **argv) {
    std::string a("hello");

    // moves a to b
    std::string b = std::move(a);
    std::cout << "a: " << a << std::endl;
    std::cout << "b: " << b << std::endl;

    // moves the returned value into b.
    b = std::move(ReturnFoo());
    std::cout << "b: " << b << std::endl;

    return EXIT_SUCCESS;
}
```

movesemantics.cc
Move semantics and unique_ptr

unique_ptr supports move semantics

- can “move” ownership from one unique_ptr to another

- old owner:
  ‣ post-move, its wrapped pointer is set to NULL

- new owner:
  ‣ pre-move, its wrapped pointer is delete’d
  ‣ post-move, its wrapped pointer is the moved pointer
Transferring ownership

Using move semantics

```cpp
int main(int argc, char **argv) {
    unique_ptr<int> x(new int(5));
    cout << "x: " << x.get() << endl;
    
    unique_ptr<int> y = std::move(x); // y takes ownership, x abdicates it
    cout << "x: " << x.get() << endl;
    cout << "y: " << y.get() << endl;
    
    unique_ptr<int> z(new int(10));
    // z delete's its old pointer and takes ownership of y's pointer.
    // y abdicates its ownership.
    z = std::move(y);
    
    return EXIT_SUCCESS;
}
```

unique4.cc
unique_ptr and STL

unique_ptrs can be stored in STL containers!!

- but, remember that STL containers like to make lots copies of stored objects
  ⇣ and, remember that unique_ptrs cannot be copied
  ⇣ how can this work??

Move semantics to the rescue

- when supported, STL containers will move rather than copy
  ⇣ luckily, unique_ptrs support move semantics
unique_ptr and STL

see uniquevec.cc
unique_ptr and "<"

A unique_ptr implements some comparison operators.
- e.g., a unique_ptr implements the "<" operator
  ▸ but, it doesn’t invoke "<" on the pointed-to objects
  ▸ instead, it just promises a stable, strict ordering (probably based on the pointer address, not the pointed-to value)
- so, to use sort on vectors, you want to provide sort with a comparison function
unique_ptr and sorting with STL

see uniquevecsort.cc
unique_ptr, “<“ and maps

Similarly, you can use unique_ptrs as keys in a map

- good news: a map internally stores keys in sorted order
  ‣ so iterating through the map iterates through the keys in order
  ‣ under the covers, by default, “<“ is used to enforce ordering

- bad news: as before you can’t count on any meaningful sorted order using “<“ of unique_ptrs
  ‣ instead, you specify a comparator when constructing the map
unique_ptr, "<" and maps

see uniquemap.cc
unique_ptr and arrays

unique_ptr can store arrays as well
- will call delete[] on destruction

```cpp
#include <memory> // for std::unique_ptr
#include <stdlib.h> // for EXIT_SUCCESS

using namespace std;

int main(int argc, char **argv) {
  // x is a unique_ptr storing an array of 5 ints
  unique_ptr<int[]> x(new int[5]);

  x[0] = 1;
  x[2] = 2;

  return EXIT_SUCCESS;
}
```

unique5.cc
C++11 has more smart ptrs

**shared_ptr**
- copyable, reference counted ownership of objects / arrays
- multiple owners have pointers to a shared object

**weak_ptr**
- similar to shared_ptr, but doesn’t count towards refcount
shared_ptr

A std::shared_ptr is similar to a std::unique_ptr

- but, the copy / assign operators increment a reference count rather than transferring ownership

  ‣ after copy / assign, the two shared_ptr objects point to the same pointed-to object, and the (shared) reference count is 2

- when a shared_ptr is destroyed, the reference count is decremented

  ‣ when the reference count hits zero, the pointed-to object is deleted
```cpp
#include <cstdlib>
#include <iostream>
#include <memory>

int main(int argc, char **argv) {
  // x contains a pointer to an int and has reference count 1.
  std::shared_ptr<int> x(new int(10));

  {
    // x and y now share the same pointer to an int, and they
    // share the reference count; the count is 2.
    std::shared_ptr<int> y = x;
    std::cout << *y << std::endl;
  }

  // y fell out of scope and was destroyed. Therefore, the
  // reference count, which was previously seen by both x and y,
  // but now is seen only by x, is decremented to 1.
  std::cout << *x << std::endl;

  return EXIT_SUCCESS;
}
```

shared_ptrs and STL containers

Even simpler than unique_ptrs

- safe to store shared_ptrs in containers, since copy/assign maintain a shared reference count and pointer

see sharedvec.cc
weak_ptr

If you used shared_ptr and have a cycle in the sharing graph, the reference count will never hit zero

- a weak_ptr is just like a shared_ptr, but it doesn’t count towards the reference count
- a weak_ptr breaks the cycle
  ▷ but, a weak_ptr can become dangling
cycle of shared_ptr's

```cpp
#include <memory>
using std::shared_ptr;

class A {
public:
    shared_ptr<A> next;
    shared_ptr<A> prev;
};

int main(int argc, char **argv) {
    shared_ptr<A> head(new A());
    head->next = shared_ptr<A>(new A());
    head->next->prev = head;
    return 0;
}
```

strongcycle.cc
breaking the cycle with weak_ptr

```cpp
#include <memory>
using std::shared_ptr;
using std::weak_ptr;

class A {
  public:
    shared_ptr<A> next;
    weak_ptr<A> prev;
};

int main(int argc, char **argv) {
  shared_ptr<A> head(new A());
  head->next = shared_ptr<A>(new A());
  head->next->prev = head;

  return 0;
}
```

weakcycle.cc
using a weak_ptr

```cpp
#include <iostream>
#include <memory>
using std::shared_ptr;
using std::weak_ptr;

int main(int argc, char **argv) {
    weak_ptr<int> w;
    {
        shared_ptr<int> x;
        {
            shared_ptr<int> y(new int(10));
            w = y;
            x = w.lock();
            std::cout << *x << std::endl;
        }
        std::cout << *x << std::endl;
    }
    shared_ptr<int> a = w.lock();
    std::cout << a << std::endl;
    return 0;
}
```
Exercise 1

Write a C++ program that:

- has a Base class called “Query” that contains a list of strings
- has a Derived class called “PhrasedQuery” that adds a list of phrases (a phrase is a set of strings within quotation marks)
- uses a shared_ptr to create a list of Queries
- populates the list with a mixture of Query and PhrasedQuery objects
- prints all of the queries in the list
Exercise 2

Implement Triple, a templated class that contains three “things.” In other words, it should behave like std::pair, but it should hold three objects instead of two.

- instantiate several Triple that contains shared_ptr<int>’s
- insert the Triples into a vector
- reverse the vector
See you on Wednesday!