CSE 333
Lecture 14 -- smart pointers

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

YAE (Yet Another Exercise) - due before class Friday

HW3 out since Mon. - due next Thur.(!), don’t wait!

Sections tomorrow: bytes, file systems, HW3

Upcoming topics

- finishing up C++ this week and next (subclasses in particular)

- remainder of quarter: networking, tools, more systems topics, other good stuff
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
C++ smart pointers

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 starting with the C++11 standard

A unique_ptr takes ownership of a pointer when the unique_ptr object is delete’d or falls out of scope, its destructor is invoked, just like any C++ object this destructor invokes delete on the owned pointer
#include <iostream>  // for std::cout, std::endl
#include <memory>     // for std::unique_ptr
#include <stdlib.h>   // for EXIT_SUCCESS

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_ptr`s 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.

```c++
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”

mostly 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;
}
```

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;
}
```

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. For example, 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
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
shared_ptr example

```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
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
#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;
}
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;
}
```

usingweak.cc
Exercise 1

Write a C++ program that:

- has a Base class called “Query” that contains a list of strings
  
  (Feel free to wait until after we’ve talked about C++ subclasses)

- 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 Friday!