C++ Smart Pointers
CSE 333 Winter 2019

Instructor: Hal Perkins

Teaching Assistants:
Alexey Beall    Renshu Gu    Harshita Neti
David Porter    Forrest Timour    Soumya Vasisht
Yifan Xu        Sujie Zhou
Lecture Outline

- Smart Pointers
  - Intro and `toy_ptr`
  - `std::unique_ptr`
  - Reference counting
  - `std::shared_ptr` and `std::weak_ptr`
Last Time...

- We learned about STL

- We noticed that STL was doing an enormous amount of copying

- A solution: store pointers in containers instead of objects
  - But who’s responsible for deleting 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
  - By overloading *, ->, [], etc.

- These 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
  - With correct use of smart pointers, 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
ToyPtr Class Template

```cpp
#ifndef _TOYPTR_H_
#define _TOYPTR_H_

template <typename T> class ToyPtr {
   public:
      ToyPtr(T *ptr) : ptr_(ptr) { }  // constructor
      ~ToyPtr() { }  // destructor
         if (ptr_ != nullptr) {
            delete ptr_;  
            ptr_ = nullptr;
         }
   }

   T &operator*() { return *ptr_; }  // * operator
   T *operator->() { return ptr_; }  // -> operator

   private:
      T *ptr_;  // the pointer itself
};

#endif // _TOYPTR_H_
```

ToyPtr.cc
ToyPtr Example

```cpp
#include <iostream>
#include "ToyPtr.h"

// simply struct to use
typedef struct { int x = 1, y = 2; } Point;
std::ostream &operator<<(std::ostream &out, const Point &rhs) {
    return out << "(" << rhs.x << "," << rhs.y << ")";
}

int main(int argc, char **argv) {
    // Create a dumb pointer
    Point *leak = new Point;

    // Create a "smart" pointer (OK, it's still pretty dumb)
    ToyPtr<Point> notleak(new Point);

    std::cout << "     *leak: " << *leak << std::endl;
    std::cout << "   leak->x: " << leak->x << std::endl;
    std::cout << "   *notleak: " << *notleak << std::endl;
    std::cout << "  notleak->x: " << notleak->x << std::endl;

    return 0;
}
```
What Makes This a Toy?

- Can’t handle:
  - Arrays
  - Copying
  - Reassignment
  - Comparison
  - ... plus many other subtleties...

- Luckily, others have built non-toy smart pointers for us!
std::unique_ptr

- A `unique_ptr` takes ownership of a pointer
  - A template: template parameter is the type that the “owned” pointer references (i.e., the T in pointer type T*)
  - Part of C++'s standard library (C++11)
  - Its destructor invokes `delete` on the owned pointer
    - Invoked when `unique_ptr` object is `delete`'d or falls out of scope
#include <iostream>  // for std::cout, std::endl
#include <memory>    // for std::unique_ptr
#include <cstdlib>   // 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

```cpp
void NotLeaky() {
    std::unique_ptr<int> x(new int(5));
    ...
    // lots of code, including several returns
    // lots of code, including potential exception throws
    ...
}
```
#include <memory>    // for std::unique_ptr
#include <cstdlib>    // 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));

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

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

    // Deallocate current pointed-to object and store new pointer
    x.reset(new int(1));

    ptr = x.release(); // Release responsibility for freeing
    delete ptr;
    return EXIT_SUCCESS;
}
**unique_ptr**s Cannot Be Copied

- **std::unique_ptr** has disabled its copy constructor and assignment operator
  - You cannot copy a **unique_ptr**, helping maintain “uniqueness” or “ownership”

```cpp
#include <memory>  // for std::unique_ptr
#include <cstdlib> // for EXIT_SUCCESS

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

    std::unique_ptr<int> y(x);             // fail - no copy ctor

    std::unique_ptr<int> z;                // OK - z is nullptr

    z = x;                                 // fail - no assignment op

    return EXIT_SUCCESS;
}
```

uniquefail.cc
Transferring Ownership

- Use `reset()` and `release()` to transfer ownership
  - `release` returns the pointer, sets wrapped pointer to `nullptr`
  - `reset` delete's the current pointer and stores 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());  // x abdicates ownership to y
    cout << "x: " << x.get() << endl;
    cout << "y: " << y.get() << endl;

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

    // y transfers ownership of its pointer to z.
    // z's old pointer was delete'd in the process.
    z.reset(y.release());

    return EXIT_SUCCESS;
}
```
**unique_ptr and STL**

- *unique_ptr* can be stored in STL containers
  - Wait, what? STL containers like to make lots of copies of stored objects and *unique_ptr* cannot be copied...

- Move semantics to the rescue!
  - When supported, STL containers will move rather than copy
    - *unique_ptr* support move semantics
Aside: Copy Semantics

- Assigning values typically means making a copy
  - Sometimes this is what you want
    - e.g. assigning a string to another makes a copy of its value
  - Sometimes this is wasteful
    - e.g. assigning a returned string goes through a temporary copy

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

int main(int argc, char **argv) {
  std::string a("hello");
  std::string b(a); // copy a into b
  b = ReturnFoo(); // copy return value into b
  return EXIT_SUCCESS;
}```
Aside: Move Semantics (C++11)

- **"Move semantics"** move values from one object to another without copying ("stealing")
  - Useful for optimizing away temporary copies
  - A complex topic that uses things called "rvalue references"
    - Mostly beyond the scope of 333 this quarter

```cpp
std::string ReturnFoo(void) {
    std::string x("foo");
    // this return might 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;
}
```
Transferring Ownership via Move

- `unique_ptr` supports move semantics
  - Can “move” ownership from one `unique_ptr` to another
    - Behavior is equivalent to the “release-and-reset” combination

```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); // x abdicates ownership to y
    cout << "x: " << x.get() << endl;
    cout << "y: " << y.get() << endl;

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

    // y transfers ownership of its pointer to z.
    // z's old pointer was delete'd in the process.
    z = std::move(y);

    return EXIT_SUCCESS;
}
```
**unique_ptr and STL Example**

```cpp
int main(int argc, char **argv) {
    std::vector<std::unique_ptr<int>> vec;

    vec.push_back(std::unique_ptr<int>(new int(9)));
    vec.push_back(std::unique_ptr<int>(new int(5)));
    vec.push_back(std::unique_ptr<int>(new int(7)));

    //
    int z = *vec[1];
    std::cout << "z is: " << z << std::endl;

    //
    std::unique_ptr<int> copied = vec[1];

    //
    std::unique_ptr<int> moved = std::move(vec[1]);
    std::cout << "*moved: " << *moved << std::endl;
    std::cout << "vec[1].get(): " << vec[1].get() << std::endl;

    return EXIT_SUCCESS;
}
```
unique_ptr and "<"

- A unique_ptr implements some comparison operators, including operator<
  - However, it doesn’t invoke operator< 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 it with a comparison function
using namespace std;

bool sortfunction(const unique_ptr<int> &x, const unique_ptr<int> &y) { return *x < *y; }
void printfunction(unique_ptr<int> &x) { cout << *x << endl; }

int main(int argc, char **argv) {
    vector<unique_ptr<int>> vec;
    vec.push_back(unique_ptr<int>(new int(9)));
    vec.push_back(unique_ptr<int>(new int(5)));
    vec.push_back(unique_ptr<int>(new int(7)));

    // buggy: sorts based on the values of the ptrs
    sort(vec.begin(), vec.end());
    cout << "Sorted:" << endl;
    for_each(vec.begin(), vec.end(), &printfunction);

    // better: sorts based on the pointed-to values
    sort(vec.begin(), vec.end(), &sortfunction);
    cout << "Sorted:" << endl;
    for_each(vec.begin(), vec.end(), &printfunction);

    return EXIT_SUCCESS;
}
unique_ptr, "<", and maps

- Similarly, you can use unique_ptr as keys in a map
  - Reminder: a map internally stores keys in sorted order
    - Iterating through the map iterates through the keys in order
  - By default, "<" is used to enforce ordering
    - You must specify a comparator when constructing the map to get a meaningful sorted order using "<" of unique_ptr

- Compare (the 3rd template) parameter:
  - "A binary predicate that takes two element keys as arguments and returns a bool. This can be a function pointer or a function object."
    - bool fptr(T1& lhs, T1& rhs); OR member function
      bool operator() (const T1& lhs, const T1& rhs);
unique\_ptr and map Example

```cpp
struct MapComp {
    bool operator()(const unique\_ptr<int> &lhs,
                    const unique\_ptr<int> &rhs) const { return *lhs < *rhs; }
};

int main(int argc, char **argv) {
    map<unique\_ptr<int>, int, MapComp> a_map;  // Create the map

    unique\_ptr<int> a(new int(5));  // unique\_ptr for key
    unique\_ptr<int> b(new int(9));
    unique\_ptr<int> c(new int(7));

    a_map[std::move(a)] = 25;  // move semantics to get ownership
    a_map[std::move(b)] = 81;  // of unique\_ptrs into the map.
    a_map[std::move(c)] = 49;  // a, b, c hold NULL after this.

    map<unique\_ptr<int>, int>::iterator it;
    for (it = a_map.begin(); it != a_map.end(); it++) {
        std::cout << "key: " << *(it->first);
        std::cout << " value: " << it->second << std::endl;
    }
    return EXIT\_SUCCESS;
}
```
unique_ptr and Arrays

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

```cpp
#include <memory>  // for std::unique_ptr
#include <cstdlib> // for EXIT_SUCCESS

using namespace std;

int main(int argc, char **argv) {
    unique_ptr<int[]> x(new int[5]);
    x[0] = 1;
    x[2] = 2;
    return EXIT_SUCCESS;
}
```

Reference Counting

- Reference counting is a technique for managing resources by counting and storing number of references to an object (i.e., # of pointers that hold the address of the object)
  - Increment or decrement count as pointers are changed
  - Delete the object when reference count decremented to 0

- Works great! But...
  - Bunch of extra overhead on every pointer operation
  - Cannot reclaim linked objects with circular references (more later)
**std::shared_ptr**

- **shared_ptr** is similar to **unique_ptr** but we allow shared objects to have multiple owners
  - The copy/assign operators are not disabled and *increment* or *decrement* reference counts as needed
    - After a 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 0, we **delete** the pointed-to object!
#include <cstdlib>  // for EXIT_SUCCESS
#include <iostream>  // for std::cout, std::endl
#include <memory>    // for std::shared_ptr

int main(int argc, char **argv) {
    std::shared_ptr<int> x(new int(10));  // ref count: 1

    // temporary inner scope (!)
    {
        std::shared_ptr<int> y = x;         // ref count: 2
        std::cout << *y << std::endl;
    }                                        // exit scope, y deleted

    std::cout << *x << std::endl;            // ref count: 1

    return EXIT_SUCCESS;                    // ref count: 0
}
shared_ptr and STL Containers

- Even simpler than unique_ptr
  - Safe to store shared_ptr in containers, since copy/assign maintain a shared reference count

```cpp
vector<std::shared_ptr<int>> vec;
vec.push_back(std::shared_ptr<int>(new int(9)));
vec.push_back(std::shared_ptr<int>(new int(5)));
vec.push_back(std::shared_ptr<int>(new int(7)));

int &z = *vec[1];
std::cout << "z is: " << z << std::endl;

std::shared_ptr<int> copied = vec[1];  // works!
std::cout << "*copied: " << *copied << std::endl;

std::shared_ptr<int> moved = std::move(vec[1]);  // works!
std::cout << "*moved: " << *moved << std::endl;
std::cout << "vec[1].get(): " << vec[1].get() << std::endl;
```

sharedvec.cc
Cycle of shared_ptr

What happens when we delete head?

#include <cstdlib>
#include <memory>

using std::shared_ptr;

struct A {
    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 EXIT_SUCCESS;
}
**std::weak_ptr**

- `weak_ptr` is similar to a `shared_ptr` but doesn’t affect the reference count
  - Can only “point to” an object that is managed by a `shared_ptr`
  - Not really a pointer – can’t actually dereference unless you “get” its associated `shared_ptr`
  - Because it doesn’t influence the reference count, `weak_ptrs` can become “dangling”
    - Object referenced may have been `delete`d
    - But you can check to see if the object still exists

- Can be used to break our cycle problem!
Breaking the Cycle with `weak_ptr`

```cpp
#include <cstdlib>
#include <memory>

using std::shared_ptr;
using std::weak_ptr;

struct A {
    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 EXIT_SUCCESS;
}
```

- Now what happens when we `delete head`?
Using a `weak_ptr`

```cpp
#include <cstdlib>  // for EXIT_SUCCESS
#include <iostream> // for std::cout, std::endl
#include <memory>   // for std::shared_ptr, std::weak_ptr

int main(int argc, char **argv) {
    std::weak_ptr<int> w;

    {  // temporary inner scope
        std::shared_ptr<int> x;
        {  // temporary inner-inner scope
            std::shared_ptr<int> y(new int(10));
            w = y;
            x = w.lock();  // returns "promoted" shared_ptr
            std::cout << *x << std::endl;
        }
        std::cout << *x << std::endl;
    }
    std::shared_ptr<int> a = w.lock();
    std::cout << a << std::endl;

    return EXIT_SUCCESS;
}
```
Summary

- A `unique_ptr` **takes ownership** of a pointer
  - Cannot be copied, but can be moved
  - `get()` returns a copy of the pointer, but is dangerous to use; better to use `release()` instead
  - `reset()` deletes old pointer value and stores a new one
- A `shared_ptr` allows shared objects to have multiple owners by doing **reference counting**
  - `delete` an object once its reference count reaches zero
- A `weak_ptr` works with a shared object but doesn’t affect the reference count
  - Can’t actually be dereferenced, but can check if the object still exists and can get a `shared_ptr` from the `weak_ptr` if it does