Poll Everywhere

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About how long did Exercise 7 take you?

A. [0, 2) hours
B. [2, 4) hours
C. [4, 6) hours
D. [6, 8) hours
E. 8+ Hours
F. I didn’t submit / I prefer not to say

C++ Smart Pointers

CSE 333 Winter 2023

Instructor: Justin Hsia

Teaching Assistants:

Adina Tung
Danny Agustinus
Edward Zhang
James Froelich
Lahari Nidadavolu
Mitchell Levy
Noa Ferman
Patrick Ho
Paul Han
Saket Gollapudi
Sara Deutscher
Tim Mandzyuk
Timmy Yang
Wei Wu
Yiqing Wang
Zhuochun Liu

Relevant Course Information

- Exercise 8 released today and due next Wednesday
  - Practice using C++ STL containers, a little bit of templatizing
- Midterm starts tomorrow (2/9) and runs until end of Saturday (2/11)
  - **Topics:** everything from lecture, exercises, project, etc. up through hw2 and ex7
  - Written answers – short-answer questions and text file uploads
  - Gradescope quiz – can open, close, & submit as much as you want
  - Some discussion allowed if following the *Gilligan's Island Rule*

Lecture Outline

- **Introducing STL Smart Pointers**
  - `std::shared_ptr`
  - `std::unique_ptr`
- Smart Pointer Limitations
  - `std::weak_ptr`

Goals for Smart Pointers

- Should automatically handle dynamically-allocated memory to decrease programming overhead of managing memory
  - Don’t have to explicitly call `delete` or `delete[]`
  - Memory will deallocate when no longer in use – ties the lifetime of the data to the smart pointer object

- Should work similarly to using a normal/“raw” pointer
  - Expected/usual behavior using `->`, `*`, and `[]` operators
  - Only declaration/construction should be different

Refresher: ToyPtr Class Template

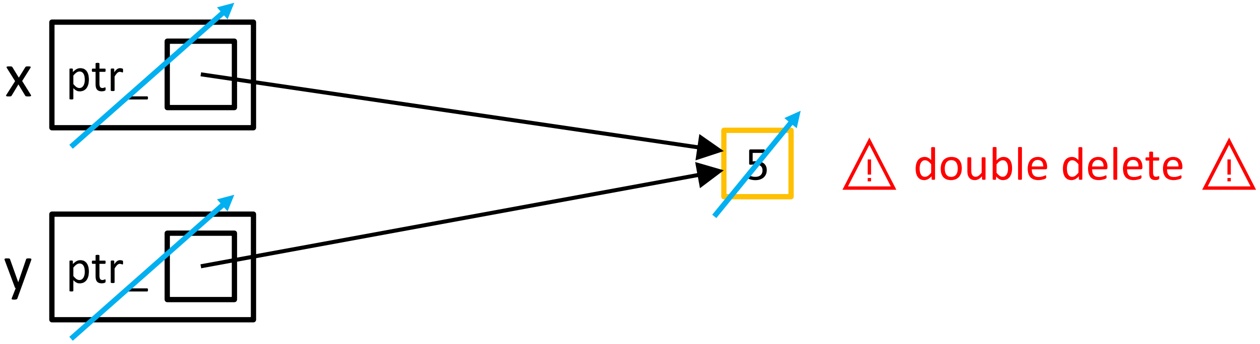
ToyPtr.h

```
#ifndef TOYPTR_H_
#define TOYPTR_H_

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


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

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

#endif  // TOYPTR_H_
```

ToyPtr Class Issue

toyuse.cc

```
#include "ToyPtr.h"

// We want two pointers!
int main(int argc, char** argv) {
  ToyPtr<int> x(new int(5));
  ToyPtr<int> y(x);
  return EXIT_SUCCESS;
}
```



⚠ double delete ⚠

Brainstorm ways to design around this. 🤔 💭

Smart Pointers Solutions

- Option 1: **Reference Counting**
  - `shared_ptr` (and `weak_ptr`)
  - Track the number of references to an “owned” piece of data and only deallocate when no smart pointers are managing that data

- Option 2: **Unique Ownership of Memory**
  - `unique_ptr`
  - Disable copying (cctor, op=) to prevent sharing

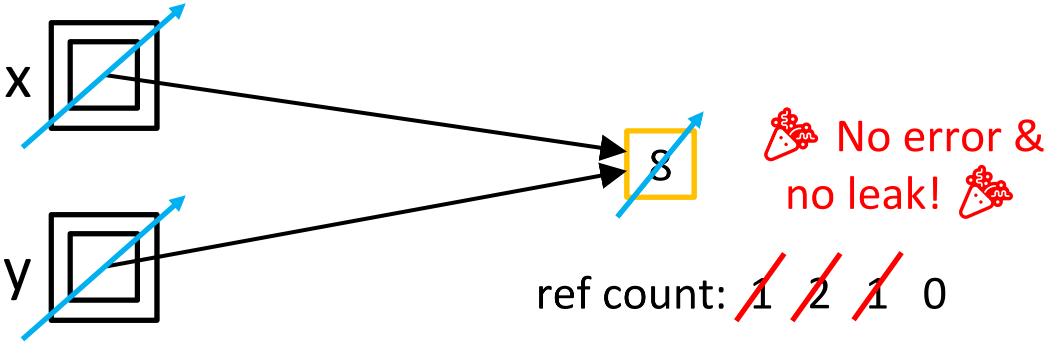
Option 1: Reference Counting

- `shared_ptr` implements **reference counting**
  - https://cplusplus.com/reference/memory/shared_ptr/
  - Counts the number of references to a piece of heap-allocated data and only deallocates it when the reference count reaches 0
    - This means that it is no longer being used and its lifetime has come to an end
  - Managed abstractly through sharing a *resource counter*:
    - Constructors will **create** the counter
    - Copy constructor and operator= will **increment** the counter
    - Destructor will **decrement** the counter

Now using `shared_ptr`

shareduse.cc

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

// We want two pointers!
int main(int argc, char** argv) {
  std::shared_ptr<int> x(new int(5));  // creates ref count
  *x += 3;                             // usage is the same
  std::shared_ptr<int> y(x);           // increments ref count
  return EXIT_SUCCESS;
}
```



No error & no leak!

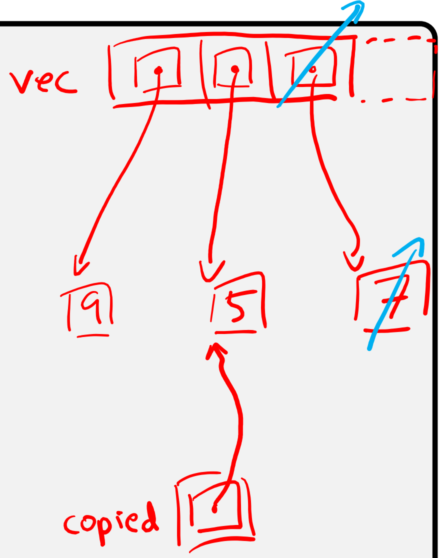
ref count: ~~1~~ ~~2~~ ~~1~~ 0

`shared_ptr`s and STL Containers

- Use `shared_ptr`s inside STL Containers
  - Avoid extra object copies
  - Safe to do, since copy/assign maintain a shared reference count
    - Copying increments ref count, then original is destructed

sharedvec.cc

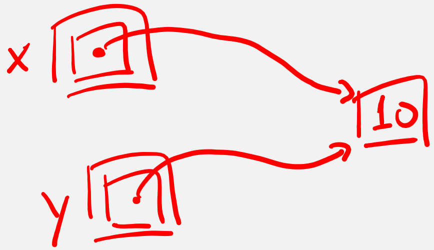
```
vector<std::shared_ptr<int> > vec;

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;

vec.pop_back(); // removes smart ptr & deallocates 7!
```



Practice with Reference Counts

- What is the expected output of this program?
  - **`use_count`**`()` – returns reference count
  - **`unique`**`()` – returns ref count == 1 (`bool`)

sharedrefcount.cc



```
... // the necessary includes are here

int main(int argc, char** argv) {
  std::shared_ptr<int> x(new int(10));
  std::cout << x.use_count() << std::endl; // 1

  // temporary inner scope (!)
  {
    std::shared_ptr<int> y(x);
    std::cout << y.use_count() << std::endl;  //2
  }  // y is destructed here!
  std::cout << x.use_count() << std::endl;  // 1
  std::cout << x.unique() << std::endl;  // true

  return EXIT_SUCCESS;  // x is destructed here (10 is cleaned up)
}
```

Option 2: Unique Ownership

- A `unique_ptr` is the *sole owner* of a pointer to memory
  - https://cplusplus.com/reference/memory/unique_ptr/
  - Enforces uniqueness by disabling copy and assignment (compiler error if these methods are used)
    - Will therefore *always* call `delete` on the managed pointer when destructed
  - As the sole owner, a `unique_ptr` can choose to *transfer* or *release* ownership of a pointer

`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"

uniquefail.cc

```
#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));  // 1-arg ctor (pointer)              ✓

  std::unique_ptr<int> y(x);           // cctor disabled; compiler error ✗

  std::unique_ptr<int> z;              // default ctor, holds nullptr       ✓

  z = x;                               // op= disabled; compiler error    ✗

  return EXIT_SUCCESS;
}
```

`unique_ptr`s and STL

- `unique_ptr`s *can* also be stored in STL containers!
  - Contradiction? STL containers make copies of stored objects and `unique_ptr`s cannot be copied…

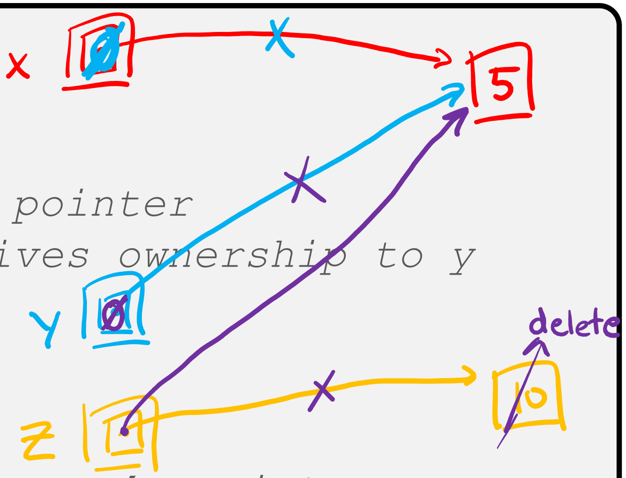
- Recall: *why* do container operations/methods create extra copies?
  - Generally to **move** things around in memory/the data structure
  - The end result is still one copy of each element – this doesn't break the sole ownership notion!

Passing Ownership

- As the “owner” of a pointer, `unique_ptr`s should be able to remove or transfer its ownership
  - **`release`**`()` and **`reset`**`()` free ownership

uniquepass.cc

```
int main(int argc, char** argv) {
① unique_ptr<int> x(new int(5));
  cout << "x: " << *x << endl;

  // Releases ownership and returns a raw pointer
② unique_ptr<int> y(x.release());   // x gives ownership to y
  cout << ”y: " << *y << endl;

③ unique_ptr<int> z(new int(10));
  // y gives ownership to z
  // z’s reset() deallocates "10" and stores y’s pointer
④z.reset(y.release());
  return EXIT_SUCCESS;
}
```



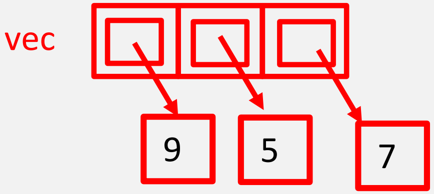
`unique_ptr` and STL Example

- STL's supports transfer ownership of `unique_ptr`s using **move** semantics

uniquevec.cc

```
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)));

  // z holds 5
  int z = *vec[1];
  std::cout << "z is: " << z << std::endl;

  // compiler error!
  std::unique_ptr<int> copied(vec[1]);

  return EXIT_SUCCESS;
}
```

moves instead of copying when capacity is increased

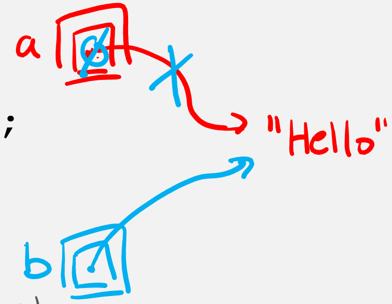


`unique_ptr` and Move Semantics

- "Move semantics" (as compared to "Copy semantics") move values from one object to another without copying
  - https://cplusplus.com/doc/tutorial/classes2/#move
  - Useful for optimizing away temporary copies
  - STL's use move semantics to transfer ownership of `unique_ptr`s instead of copying

uniquemove.cc

```
... (includes and other examples)
int main(int argc, char** argv) {
  std::unique_ptr<string> a(new string("Hello"));

  // moves a to b
  std::unique_ptr<string> b = std::move(a);
  // a is now nullptr (default ctor of unique_ptr)
  std::cout << "b: " << *b << std::endl; // "Hello"

  return EXIT_SUCCESS;
}
```



Aside: Smart Pointers and Arrays

- Smart pointers can store arrays as well and will call `delete[]` on destruction

uniquearray.cc

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

using std::unique_ptr;

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

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

  return EXIT_SUCCESS;
}
```

Choosing Between Smart Pointers

- `unique_ptr`s make ownership very clear
  - Generally the default choice due to reduced complexity – the owner is responsible for cleaning up the resource
    - Example: would make sense in HW1 & HW2, where we specifically documented who takes ownership of a resource
  - Less overhead: small and efficient

- `shared_ptr`s allow for multiple simultaneous owners
  - Reference counting allows for "smarter" deallocation but consumes more space and logic and is trickier to get right
  - Common when using more "well-connected" data structures

Lecture Outline

- Introducing STL Smart Pointers
    - `std::shared_ptr`
    - `std::unique_ptr`
- **Smart Pointer Limitations**
    - `std::weak_ptr`

Limitations with Smart Pointers

- Smart pointers are only as "smart" as the behaviors that have been built into their class methods and non-member functions!

- Limitations we will look at now:
  - Can't tell if pointer is to the heap or not
  - Circumventing ownership rules
  - Still possible to leak memory!
  - Sorting smart pointers *[Bonus slides]*

Using a Non-Heap Pointer

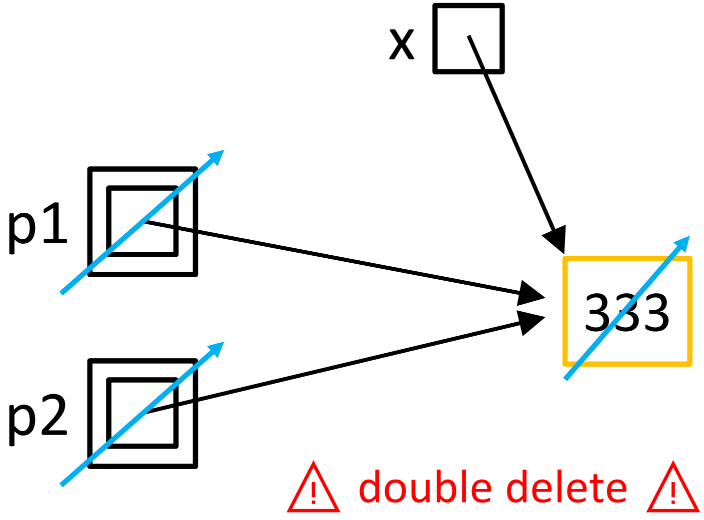
- Smart pointers will still call `delete` when destructed

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

using std::shared_ptr;

int main(int argc, char** argv) {
  int x = 333;

  shared_ptr<int> p1(&x);

  return EXIT_SUCCESS;
} // invalid delete on destruction!
```

Re-using a Raw Pointer (`unique_ptr`)

- Smart pointers can't tell if you are re-using a raw pointer

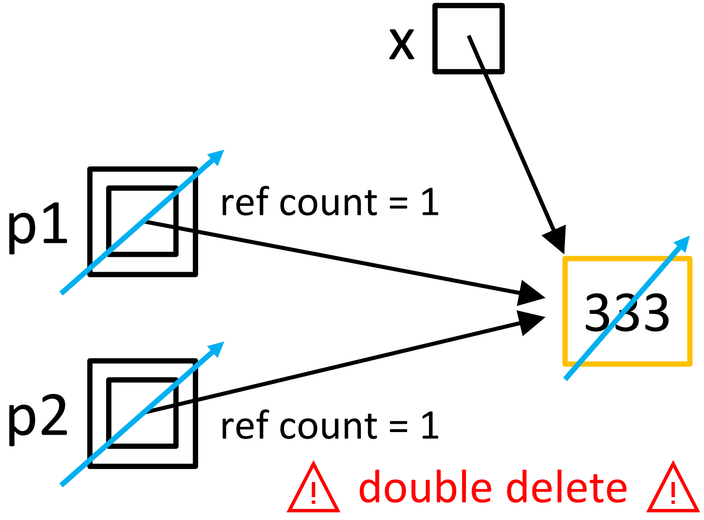
```
#include <cstdlib>
#include <memory>

using std::unique_ptr;

int main(int argc, char** argv) {
  int* x = new int(333);

  unique_ptr<int> p1(x);

  unique_ptr<int> p2(x);

  return EXIT_SUCCESS;
}
```



Re-using a Raw Pointer (`shared_ptr`)

- Smart pointers can't tell if you are re-using a raw pointer

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

using std::shared_ptr;

int main(int argc, char** argv) {
  int* x = new int(333);

  shared_ptr<int> p1(x);

  shared_ptr<int> p2(x);

  return EXIT_SUCCESS;
}
```



Solution: Don't Use Raw Pointer Variables

- Smart pointers replace your raw pointers; passing `new` and then using the copy constructor is safer:

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

using std::shared_ptr;


int main(int argc, char** argv) {
  ~~int* x = new int(333);~~

  shared_ptr<int> p1(new int(333));

  shared_ptr<int> p2(p1);

  return EXIT_SUCCESS;
}
```

Caution Using `get`()

- Smart pointers still have functions to return the raw pointer without losing its ownership
  - `get`() can circumvent ownership rules!

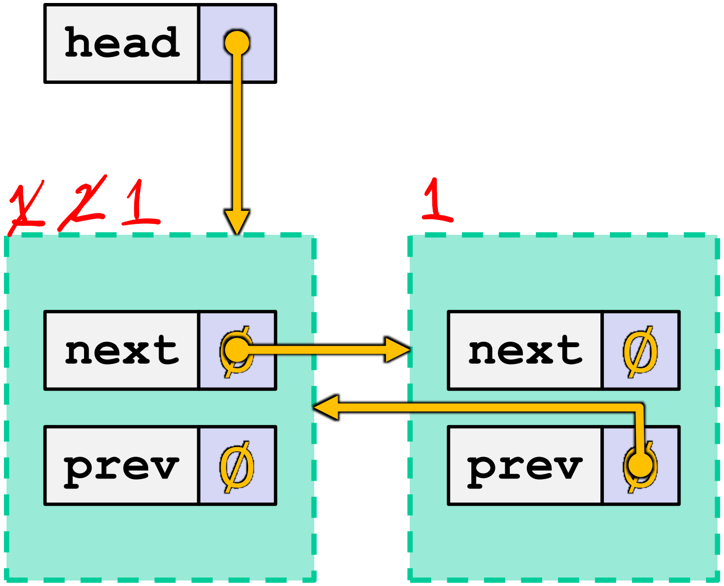
```
#include <cstdlib>
#include <memory>

// Same as re-using a raw pointer
int main(int argc, char** argv) {

  unique_ptr<int> p1(new int(5));

  unique_ptr<int> p2(p1.get());

  return EXIT_SUCCESS;
}
```

Cycle of `shared_ptr`s

- What happens when `main` returns?

memory leak!
nodes not deallocated

```
#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;
}
```



sharedcycle.cc

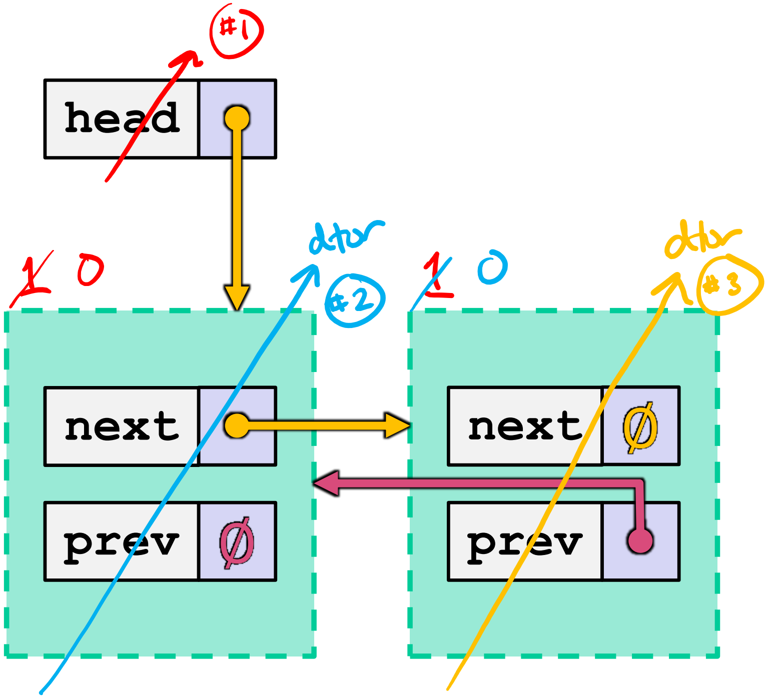
Solution: `weak_ptr`s

- `weak_ptr` is similar to a `shared_ptr` but *doesn't affect* the reference count
    - https://cplusplus.com/reference/memory/weak_ptr/
    - Not really a pointer as it **cannot be dereferenced** (!) – would break our notion of shared ownership
        - To deference, you first use the **`lock`** method to get an associated `shared_ptr`

Breaking the Cycle with `weak_ptr`

- Now what happens when `main` returns? No memory leak!

```
#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;
}
```

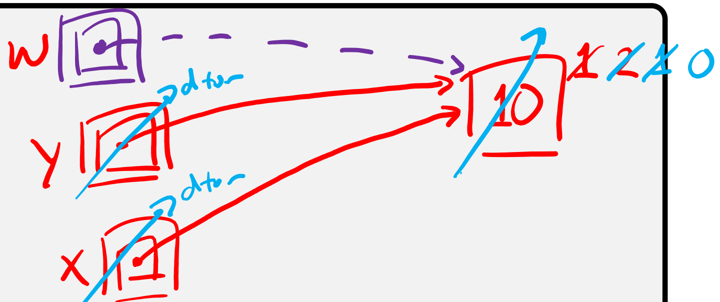


weakcycle.cc

Dangling `weak_ptr`s

- `weak_ptr`s don't change reference count and can become "*dangling*"
  - Data referenced may have been `delete`'d

weakrefcount.cc



```
... (includes and other examples)
int main(int argc, char** argv) {
  std::weak_ptr<int> w;

  {  // temporary inner scope
    std::shared_ptr<int> y(new int(10));
    w = y; // assignment operator of weak_ptr takes a shared_ptr
    std::shared_ptr<int> x = w.lock();  // "promoted" shared_ptr
              10                 false
    std::cout << *x << " " << w.expired() << std::endl;
  }  // x and y fall out of scope
  std::cout << w.expired() << std::endl;
                  true
  w.lock();  // returns a nullptr

  return EXIT_SUCCESS;
}
```

Summary of Smart Pointers

- A `shared_ptr` utilizes *reference counting* for multiple owners of an object in memory
  - `delete`s 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
- A `unique_ptr` ***takes ownership*** of a pointer
  - Cannot be copied, but can be moved

Some Important Smart Pointer Methods

Visit http://www.cplusplus.com/ for more information on these!

- `std::unique_ptr<T> U;`

`U.get()`	Returns the raw pointer U is managing
`U.release()`	U stops managing its raw pointer and returns the raw pointer
`U.reset(q)`	U cleans up its raw pointer and takes ownership of q

- `std::shared_ptr<T> S;`

`S.get()`	Returns the raw pointer S is managing
`S.use_count()`	Returns the reference count
`S.unique()`	Returns true iff S.use_count() == 1

- `std::weak_ptr<T> W;`

`W.lock()`	Constructs a shared pointer based off of W and returns it
`W.use_count()`	Returns the reference count
`W.expired()`	Returns true iff W is expired (W.use_count() == 0)

BONUS SLIDES

Some details about sorting the owned data within a container of smart pointers.

These slides expand on material covered today but won’t be needed for CSE333; however, they are relevant for general C++ smart pointer usage in STL containers.

Smart Pointers and "<"

- Smart pointers implement 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)

- To use the **`sort`**`()` algorithm on a container like `vector`, you need to provide a comparison function

- To use a smart pointer in a sorted container like `map`, you need to provide a comparison function when you *declare* the container

unique_ptr and STL Sorting

uniquevecsort.cc

```
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;
}
```

compare pointed-to values

swapping for sort done via move semantics

`unique_ptr`, "<", and `maps`

- Similarly, you can use `unique_ptr`s 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`s

- 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);`

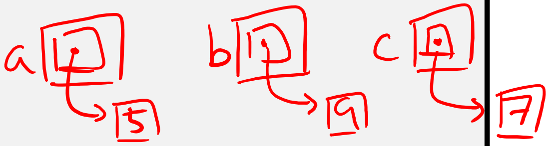
unique_ptr and map Example

uniquemap.cc

still compares pointed-to values

```
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;
}
```

// function object



move