CSE 374 Programming Concepts and Tools

Lecture 21 - C++ Smart Pointers

This week

Today: C++ Smart Pointers

Monday: C++ Inheritance

Wednesday: Concurrency

Friday: Exam 3 (Covering all C/C++ concepts)

Today

Smart Pointer Basics

`unique_ptr`

`shared_ptr` and `weak_ptr`

- Reference counting

Review: C++ Standard Template Library

Containers store data using various underlying data structures

- The specifics of the data structures define properties and operations for the container

Iterators allow you to traverse container data

- Iterators form the common interface to containers
- Different flavors based on underlying data structure

Algorithms perform common, useful operations on containers

- Use the common interface of iterators, but different algorithms require different ‘complexities’ of iterators

Common C++ STL Containers (and Java equiv)

Sequence containers can be accessed sequentially

- **vector<Item>** uses a dynamically-sized contiguous array (like ArrayList)
- **list<Item>** uses a doubly-linked list (like LinkedList)

Associative containers use search trees and are sorted by keys

- **set<Key>** only stores keys (like TreeSet)
- **map<Key, Value>** stores key-value pair<>'s (like TreeMap)

Unordered associative containers are hashed

- **unordered_map<Key, Value>** (like HashMap)

Java vs C/C++ Memory Management

Java automatically removes data that has no pointers referring to it.

C/C++ does not have this feature, memory allocated on the heap must be manually deleted.

- **`C is unable to recognize whether a piece of memory is a pointer, number, char, or anything else, since there are no variable types after compilation`** 🥹🥹🫰

Benefit: C/C++ does not need a garbage collector, making it run faster and without an interpreter (Java Runtime).
C++ has ways to mimic's Java's automatic deletion system.

Smart Pointers 💔

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
  - By overloading `*`, `->`, `[]`, etc.
- These can help you manage memory
  - The smart pointer will try to delete the pointed-to object *at the right time*
    - When that is depends on what kind of smart pointer you use, each with tradeoffs
  - With correct use of smart pointers, memory will be easier to manage, although sometimes still tricky!

Intro and `toy_ptr`

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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
- What happens when a local stack variable leaves scope?

A smart pointer is just a Template object.

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_
```

Takes advantage of implicit calling of destructor to clean up for us

ToyPtr Example

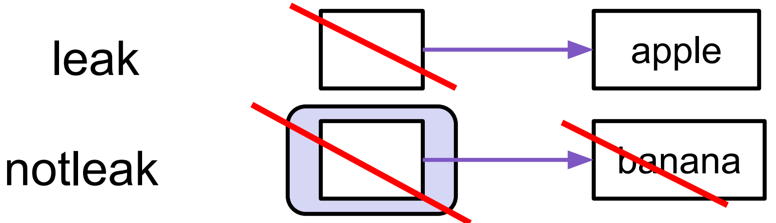
usetoy.cc

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

int main(int argc, char **argv) {
  // Create a dumb pointer
  std::string* leak = new std::string("apple");

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

  std::cout << "     *leak: " << *leak << std::endl;
  std::cout << "  *notleak: " << *notleak << std::endl;
  return 0;
}
```



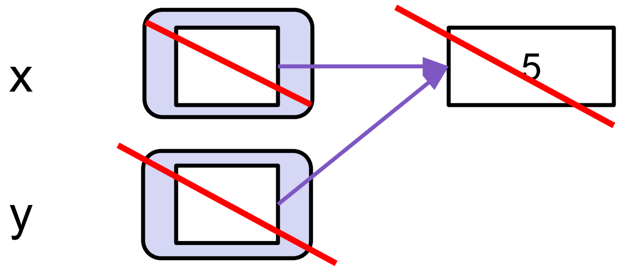
Demo: ToyPtr

ToyPtr Class Template Issues

toyuse.cc

```
#include "ToyPtr.h"

int main(int argc, char **argv) {
  // We want two pointers!
  ToyPtr<int> x(new int(5));
  ToyPtr<int> y = x;
  return 0;
}
```



!! Double `delete` !!

What Makes This a Toy?

Can't handle:

- Arrays
    - Needs to use `delete[]`
- Copying
- Reassignment
- Comparison
- … plus many other subtleties…

Luckily, others have built *non-toy* smart pointers for us!

`unique_ptr`

Fixes ToyPtr by taking sole ownership

`std::unique_ptr`

A `unique_ptr` is the ***sole owner*** 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)
- Once we give a vanilla pointer a `unique_ptr`, we should *stop using the original* (non-smart) pointer
- Its destructor invokes `delete` on the owned pointer
    - Invoked when `unique_ptr` object is `delete`’d or falls out of scope via the `unique_ptr` destructor
    - Also invoked when a C++ container is destroyed!

Guarantees uniqueness by disabling copy and assignment.

Using `unique_ptr`

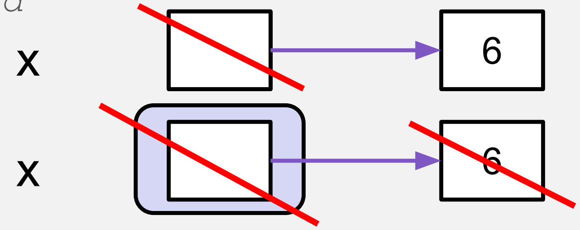
unique.cc

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

void Leaky() {
  int* x = new int(6);  // new = heap-allocated
  (*x)++;
  std::cout << *x << std::endl;
}  // never used delete, leak

void NotLeaky() {
  std::unique_ptr<int> x(new int(6));  // 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
- There's nothing a unique pointer can do that a normal pointer can't, but makes pointers easier to work with. (Can manually call free)

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

unique_ptrs 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));  // 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;
}
```

Transferring Ownership

Use **reset**() and **release**() to transfer ownership, possibly dangerous!

- **release** returns the pointer, sets wrapped pointer to `nullptr`
- **reset** `delete`'s the current pointer and stores a new one

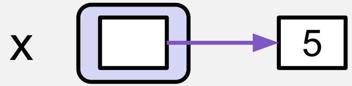
uniquepass.cc

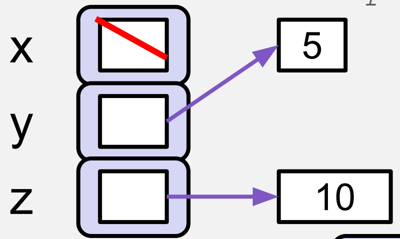
```
int main(int argc, char **argv) {
  unique_ptr<int> x(new int(5));
  cout << "x: " << x.get() << endl;

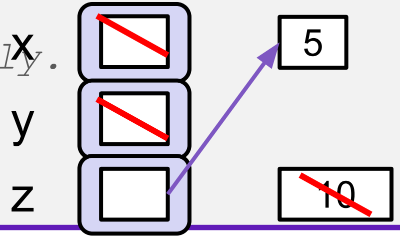
  unique_ptr<int> y(x.release());  // x abdicates ownership to y
  cout << "x: " << x.get() << endl;
  cout << "y: " << y.get() << endl;

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

  // y transfers ownership of its pointer to z.
  // z's old pointer was delete'd (freed) automatically.
  z.reset(y.release());
  return EXIT_SUCCESS;
}
```







unique_ptr and Arrays

unique_ptr can store arrays as well

- Will call delete[] on destruction

uniquearray.cc

```
#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;
}
```

Demo: `unique_ptr` and Array

shared_ptr
weak_ptr

Smart pointers using reference counting

What is Reference Counting?

Idea: associate a *reference count* with each object

- Reference count holds number of references (pointers) to the object
- Adjusted whenever pointers are changed:
  - *Increase by 1* each time we have a *new pointer* to an object
  - *Decrease by 1* each time a pointer to an *object is removed*
- When reference counter decreased to 0, no more pointers to the object, so delete it (automatically)

Used by C++ `shared_ptr`, *not used in general* for C++ memory management

Example

Suppose for the moment that we have a new C++ -like language that uses *reference counting* for heap data

As in C++, a struct is a type with public fields, so we can implement lists of integers using the following Node type

```
struct Node {
  int payload;   // node payload
  Node* next;    // next Node or nullptr
};
```

In this example, reference counts would be handled behind the scenes by the memory manager code – they are not accessible to the programmer

Example: “C++” With Reference Counting

Let’s execute the following code. Heap data is shown using rectangles; associated reference counts with ovals


```
Node* p = new Node();
Node* q = new Node();
Node* r = p;
q->next = new Node();
p = nullptr;
r = nullptr;
q = nullptr;
```

Example: "C++" With Reference Counting

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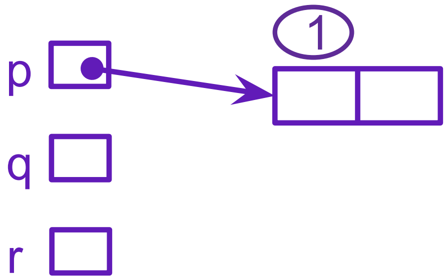


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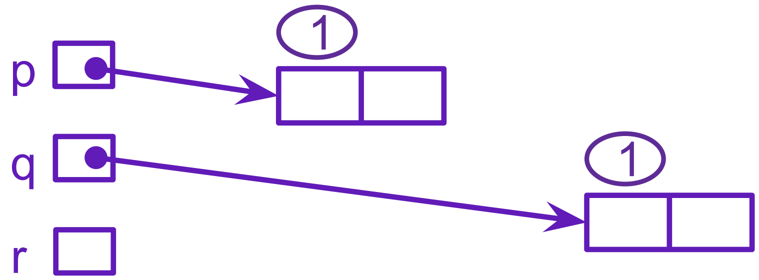


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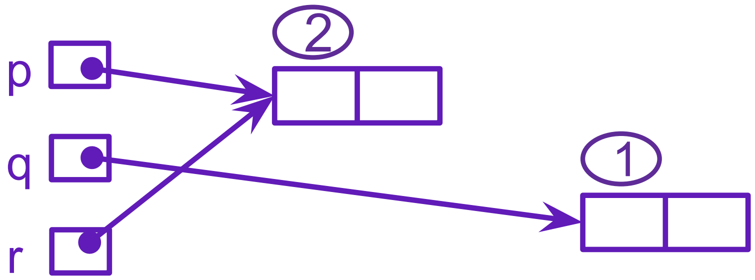


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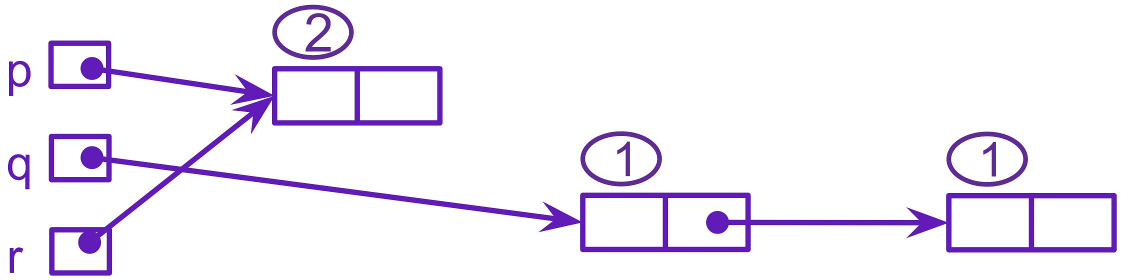


```
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Node* q = new Node();
Node* r = p;
q->next = new Node();
p = nullptr;
r = nullptr;
q = nullptr;
```

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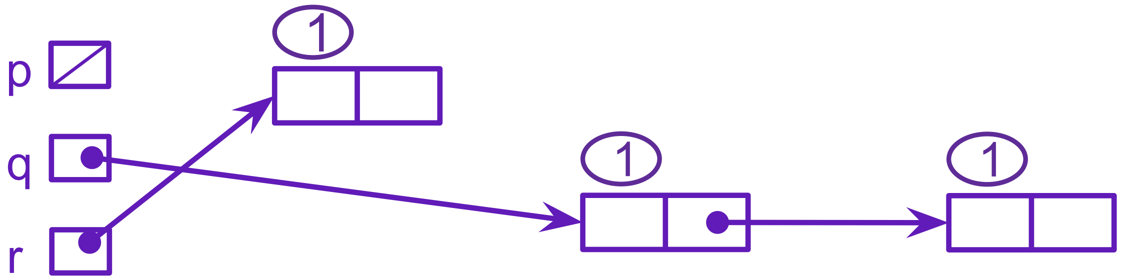


```
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Node* q = new Node();
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p = nullptr;
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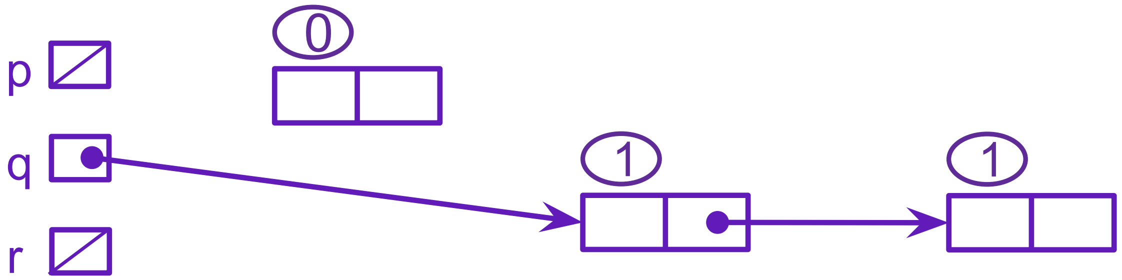


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```

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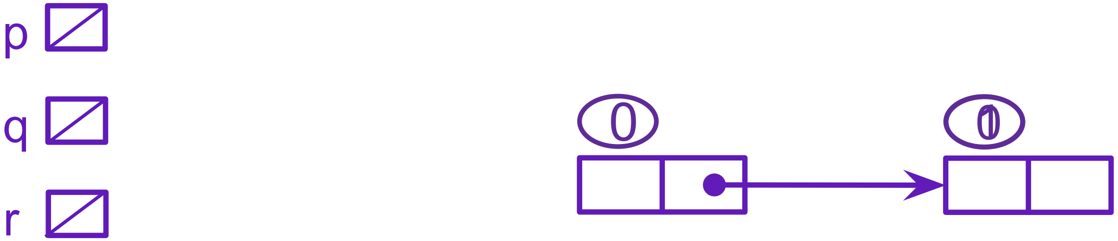



```
Node* p = new Node();
Node* q = new Node();
Node* r = p;
q->next = new Node();
p = nullptr;
r = nullptr;
q = nullptr;
```

`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* 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 incremented by **1**
- When a `shared_ptr` is destroyed, the reference count is *decremented*
  - When the reference count hits **0**, we `delete` the pointed-to object!
- Allows us to create complex linked structures (doubly-linked lists, graphs, etc.) at the cost of maintaining reference counts

shared_ptr Example

```
#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> a(new int(374));


  {
    std::shared_ptr<int> b(a);
  }

  std::shared_ptr<int> c = a;

  return EXIT_SUCCESS;
}
```

shared_ptr Example

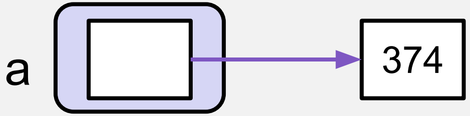
```
#include <cstdlib>   // for EXIT_SUCCESS
#include <iostream>  // for std::cout, std::endl
#include <memory>    // for std::shared_ptr

int main(int argc, char **argv) {
  std::shared_ptr<int> a(new int(374));  // ref count: 1


  {
    std::shared_ptr<int> b(a);
  }

  std::shared_ptr<int> c = a;

  return EXIT_SUCCESS;
}
```



shared_ptr Example

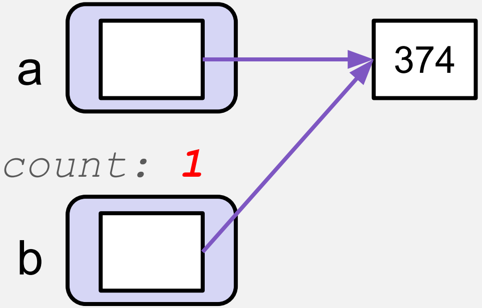
```
#include <cstdlib>    // for EXIT_SUCCESS
#include <iostream>   // for std::cout, std::endl
#include <memory>     // for std::shared_ptr

int main(int argc, char **argv) {
  std::shared_ptr<int> a(new int(374));  // ref count: 1

  // temporary inner scope with local b (!)
  {
    std::shared_ptr<int> b(a);           // ref count: 2
  }

  std::shared_ptr<int> c = a;

  return EXIT_SUCCESS;
}
```



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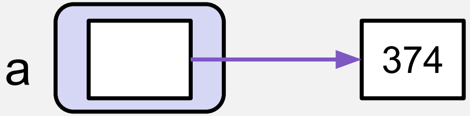
#include <memory>     // for std::shared_ptr

int main(int argc, char **argv) {
  std::shared_ptr<int> a(new int(374));  // ref count: 1

  // temporary inner scope with local y (!)
  {
    std::shared_ptr<int> b(a);           // ref count: 2
  }                                      // exit scope, b deleted

  std::shared_ptr<int> c = a;

  return EXIT_SUCCESS;
}
```



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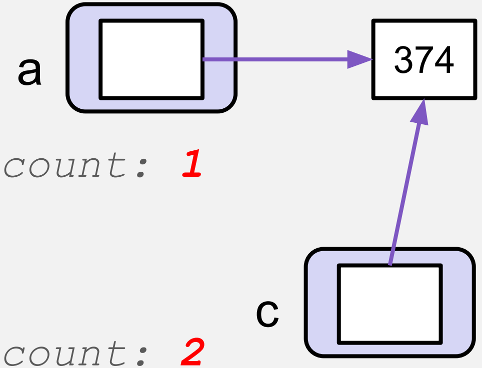
  std::shared_ptr<int> a(new int(374));  // ref count: 1

  // temporary inner scope with local y (!)
  {
    std::shared_ptr<int> b(a);           // ref count: 2
  }                                      // exit scope, b deleted
                                          // ref count: 1
  std::shared_ptr<int> c = a;            // ref count: 2

  return EXIT_SUCCESS;
}
```



shared_ptr Example

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  // temporary inner scope with local y (!)
  {
    std::shared_ptr<int> b(a);           // ref count: 2
  }                                      // exit scope, b deleted

  std::shared_ptr<int> c = a;            // ref count: 2

  return EXIT_SUCCESS;
}                                        // ref count: 0
                                          // deleted one at a time
```

Polling Time!

`use_count()` – returns reference count

`unique()` – returns `ref count == 1 (bool; true/false)`

Please answer in the [LP21 assignment on Gradescope]!
What is the output for each of the specified lines in this program?

shared.cc

```
#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));
  std::cout << x.use_count() << std::endl;    // Line 1

  // temporary inner scope with local y (!)
  {
    std::shared_ptr<int> y = x;
    std::cout << y.use_count() << std::endl;  // Line 2
  }

  std::cout << x.use_count() << std::endl;    // Line 3
  std::cout << x.unique()    << std::endl;    // Line 4

  return EXIT_SUCCESS;
}
```

Polling Question Explained

`use_count()` – returns reference count

`unique()` – returns `ref count == 1 (bool)`

What is the output for each of the specified lines of this program?

shared.cc

```
#include <cstdlib>    // for EXIT_SUCCESS
#include <iostream>   // for std::cout, std::endl
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int main(int argc, char **argv) {
  std::shared_ptr<int> x(new int(10));
  std::cout << x.use_count() << std::endl;

  // temporary inner scope with local y (!)
  {
    std::shared_ptr<int> y = x;
    std::cout << y.use_count() << std::endl;
  }

  std::cout << x.use_count() << std::endl;
  std::cout << x.unique()    << std::endl;

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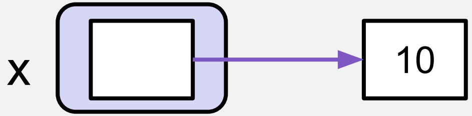
int main(int argc, char **argv) {
  std::shared_ptr<int> x(new int(10));       // ref count: 1
  std::cout << x.use_count() << std::endl;

  // temporary inner scope with local y (!)
  {
    std::shared_ptr<int> y = x;
    std::cout << y.use_count() << std::endl;
  }

  std::cout << x.use_count() << std::endl;
  std::cout << x.unique()    << std::endl;

  return EXIT_SUCCESS;
}
```



Polling Question Explained

use_count() – returns reference count

unique() – returns `ref count == 1 (bool)`

What is the output for each of the specified lines of this program?

shared.cc

```
#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
  std::cout << x.use_count() << std::endl;    // 1

  // temporary inner scope with local y (!)
  {
    std::shared_ptr<int> y = x;
    std::cout << y.use_count() << std::endl;
  }

  std::cout << x.use_count() << std::endl;
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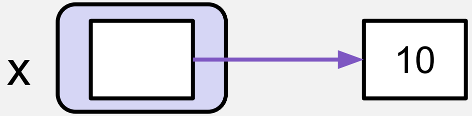

Polling Question Explained

`use_count``()` – returns reference count

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What is the output for each of the specified lines of this program?

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```
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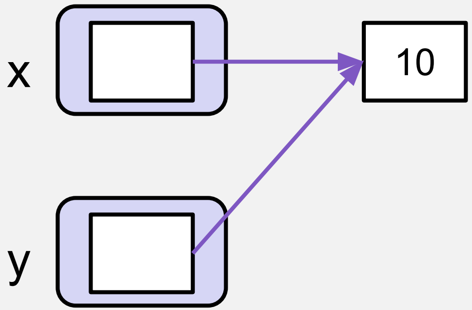
#include <iostream>   // for std::cout, std::endl
#include <memory>     // for std::shared_ptr

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

  // temporary inner scope with local y (!)
  {
    std::shared_ptr<int> y = x;               // ref count: 2
    std::cout << y.use_count() << std::endl;
  }

  std::cout << x.use_count() << std::endl;
  std::cout << x.unique()    << std::endl;

  return EXIT_SUCCESS;
}
```



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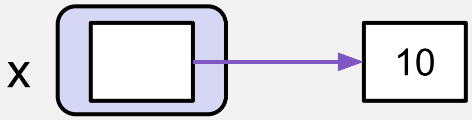
int main(int argc, char **argv) {
  std::shared_ptr<int> x(new int(10));     // ref count: 1
  std::cout << x.use_count() << std::endl;  // 1

  // temporary inner scope with local y (!)
  {
    std::shared_ptr<int> y = x;              // ref count: 2
    std::cout << y.use_count() << std::endl;  // 2
  }  // exit scope, y deleted. ref count: 1

  std::cout << x.use_count() << std::endl;
  std::cout << x.unique()    << std::endl;

  return EXIT_SUCCESS;
}
```



Polling Question Explained

`use_count()` – returns reference count

`unique()` – returns `ref count == 1 (bool)`

What is the output for each of the specified lines of this program?

shared.cc

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

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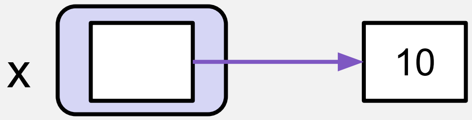
  return EXIT_SUCCESS;
}
```



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  std::cout << x.unique()    << std::endl;     // true

  return EXIT_SUCCESS;
}
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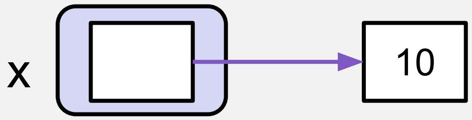

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    std::cout << y.use_count() << std::endl;  // 2
  }  // exit scope, y deleted. ref count: 1

  std::cout << x.use_count() << std::endl;    // 1
  std::cout << x.unique()    << std::endl;    // true

  return EXIT_SUCCESS;
}  // x is destructed here. ref count: 0
```

`shared_ptr`s and STL Containers

Safe to store `shared_ptr`s in containers, containers will call constructors and destructors of the smart pointers.

sharedvec.cc

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

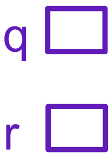
vec.push_back(std::shared_ptr<int>(new int(9)));
vec.push_back(std::shared_ptr<int>(new int(5)));
vec.push_back(std::shared_ptr<int>(new int(7)));

int& z = *vec[1];
std::cout << "z is: " << z << std::endl;
cout << " with ref count: " << vec[1].use_count() << std::endl;
std::shared_ptr<int> copied = vec[1];  // works!
std::cout << "*copied: " << *copied << std::endl;
cout << " with ref count: " << vec[1].use_count() << std::endl;
vec.pop_back();  // removes smart ptr & deallocate 7
```

Demo: `shared_ptr` and STL

Example 2

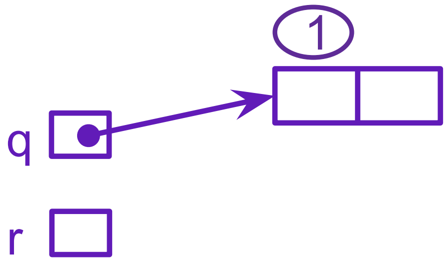
Similar to the previous code, but slightly different




```
Node* q = new Node();
Node* r = new Node();
q->next = r;
r->next = q;
r = nullptr;
q = nullptr;
```

Example 2

Similar to the previous code, but slightly different

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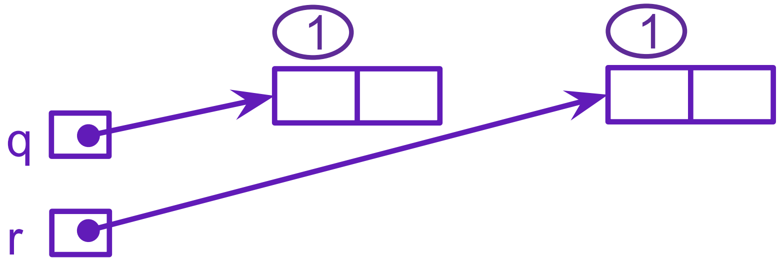


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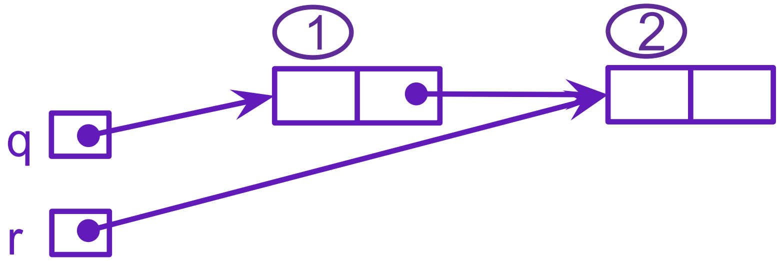


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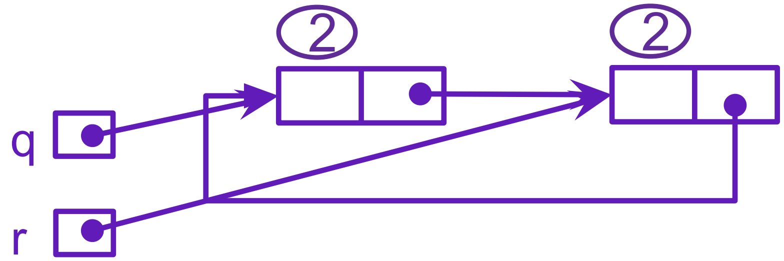


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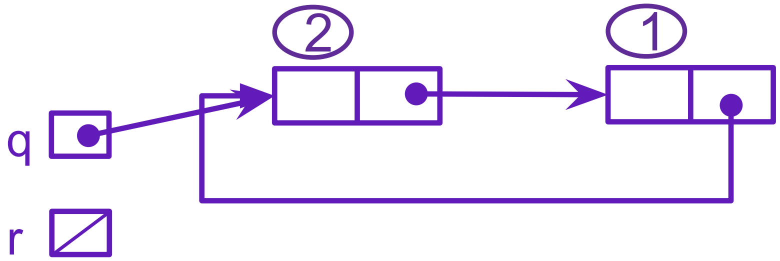


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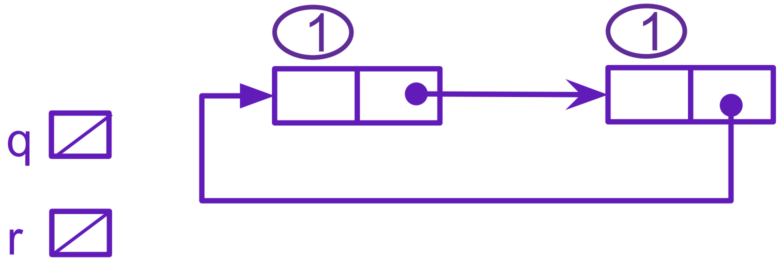


Memory leak!

```
Node* q = new Node();
Node* r = new Node();
q->next = r;
r->next = q;
r = nullptr;
q = nullptr;
```

Cycle of `shared_ptrs`

sharedcycle.cc

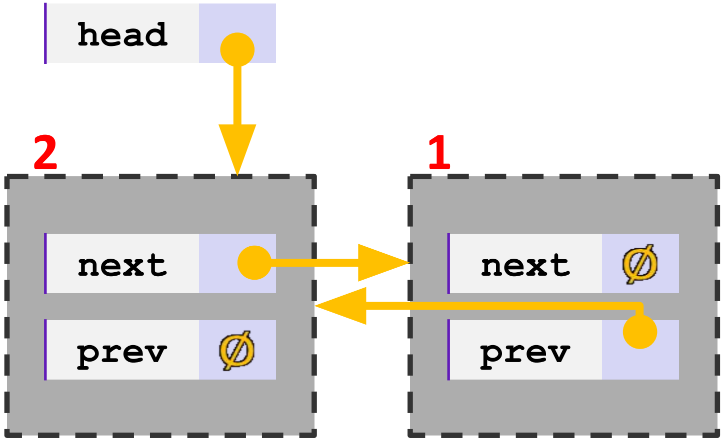
```
#include <cstdlib>
#include <memory>

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;
}
```



What happens when we `delete head`?

Cycle of `shared_ptrs`

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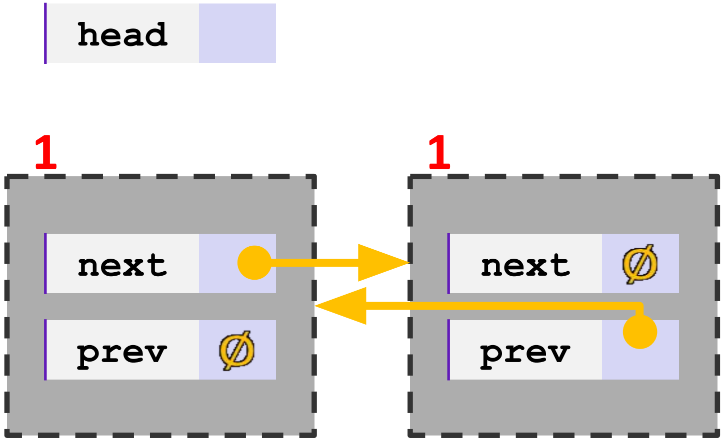


What happens when we `delete head`? Nodes unreachable but not deleted because ref counts > 0

Solution: `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_ptr`s 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`

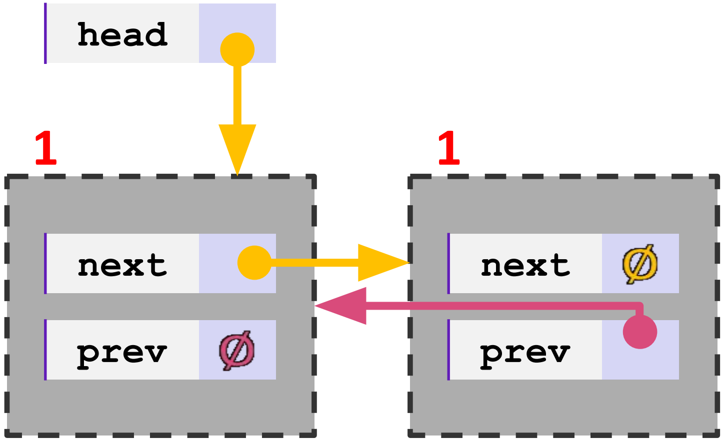
weakcycle.cc

```
#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`?

Breaking the Cycle with `weak_ptr`

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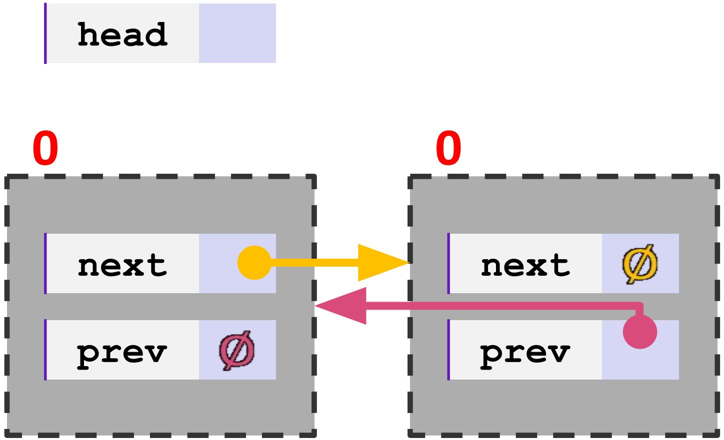
  return EXIT_SUCCESS;
}
```

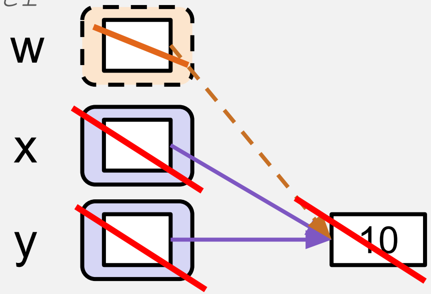


Now what happens when we `delete head`? Ref counts go to 0 and nodes deleted!

Using a `weak_ptr`

usingweak.cc

```
#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 with local x
    std::shared_ptr<int> x;
    {  // temporary inner-inner scope with local y
      std::shared_ptr<int> y(new int(10));
      w = y;           // weak ref; ref count for "10" node is same
      x = w.lock();    // get shared_ptr version of w, ref cnt = 2
      std::cout << *x << std::endl;
    } // y deleted; ref count now 1
    std::cout << *x << std::endl;
  }                    // x deleted; ref count now 0; mem freed
  std::shared_ptr<int> a = w.lock();   // nullptr
  std::cout << a << std::endl;         // output is 0 (null)
  return EXIT_SUCCESS;
}
```



Demo: `weak_ptr` fixed code

Polling Time!

Please answer in the [LP21 assignment on Gradescope]!

Which of the following statements about `shared_ptr` and `weak_ptr` in C++ is correct? Select *all* that apply.

- ❑ Both `shared_ptr` and `weak_ptr` share ownership of the managed object.
- ❑ `weak_ptr` increases the reference count when created from a `shared_ptr`.
- ❑ `shared_ptr` can detect if it is the unique owner of the managed object.
- ❑ `shared_ptr` and `weak_ptr` can be used interchangeably since they both provide direct access to the managed object.

Polling Time!

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Lecture Summary

Smart pointers try to imitate the convenience of languages with more memory management.

A `unique_ptr` ***takes ownership*** of a pointer

- Cannot be copied, but can be moved
- Use **`release`**`()` to release ownership and stop managing the pointer for you
- **`reset`**`()` `delete`s old pointer value and stores a new one

A `shared_ptr` allows shared objects to have multiple owners by doing *reference counting*

- `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

Some Important Smart Pointer Functions

std::unique_ptr u;

u.get()	Returns the raw pointer **u** is managing (⚠️**Dangerous!**)
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 s;

make_shared<T>(args)	Returns a shared_ptr pointer of a heap-allocated object shared_ptr<int> p3 = make_shared<int>(42);
s.use_count()	Returns the reference count
s.unique()	Returns true iff s.use_count() == 1

std::weak_ptr 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)

Caution

Smart pointers are smart… ?🧐

“Smart” Pointers

Smart pointers still don’t know everything, you must be careful with what pointers you give it to manage.

- Smart pointers can’t tell if a pointer is on the heap or not.
- Still uses `delete` on default.
- Smart pointers can’t tell if you are re-using a raw pointer.
- Don’t point smart pointers at the stack.
  - They should only point to things on the heap!

Using a non-heap pointer

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

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

int main(int argc, char **argv) {
    int x = 374;
    shared_ptr<int> p1(&x);
    return EXIT_SUCCESS;
}
```

Smart pointers can't tell if the pointer you gave points to the heap!

- Will still call delete on the pointer when destructed.

Re-using a raw pointer

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

using std::unique_ptr;

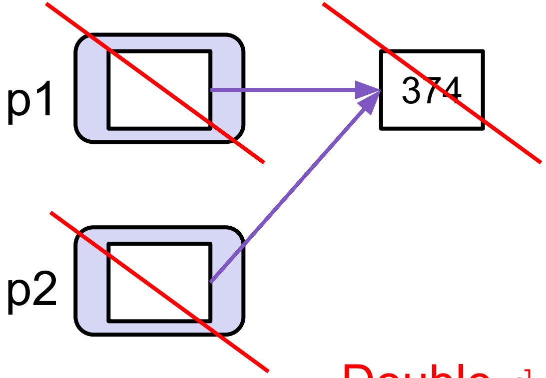
int main(int argc, char **argv) {
    int* x = new int(374);

    unique_ptr<int> p1(x);

    unique_ptr<int> p2(x);

    return EXIT_SUCCESS;
}
```

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



Double `delete`!

Re-using a raw pointer

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

using std::shared_ptr;

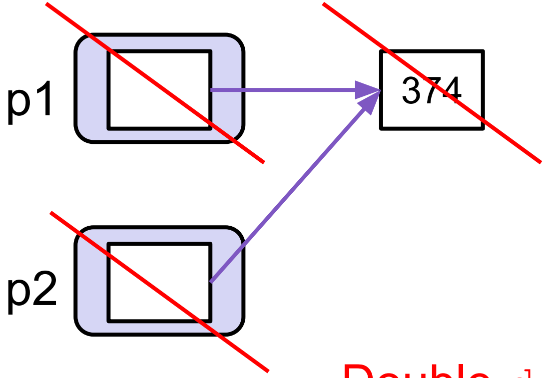
int main(int argc, char **argv) {
    int* x = new int(374);

    shared_ptr<int> p1(x);

    shared_ptr<int> p2(x);

    return EXIT_SUCCESS;
}
```

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



Double `delete`!

Automatic memory management

Different paradigms

	Tracing (mark & sweep)	Reference counting
Method	Mark all variables reachable from root objects, then sweep remaining ones	Automatically frees memory when `ref_count == 0`
Language	Java	C++ w/ Smart Pointers
Perf cost	Running the garbage collector can pause the entire program	Added overhead to every allocation/deallocation and assignment
Possible issues	Dangling references, GC behavior might be unpredictable	Cycles, overhead

Assignment Reminders

EX19 due Monday 8/17 **@10:49am**

HW5: Implementing Wiki Traversal **due next Wednesday 8/19 @11:59pm**

Make sure to submit LP21 before the next class as well.

All of these assignments can be found on our course's Gradescope page.