Smart Pointers

Computer Systems Programming, Spring 2024

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Logistics

- Project released
  - Due May 1st at midnight, please get started if you haven't already
- HW4
  - To be posted shortly after lecture
  - Should have everything you need after Today's Lecture
- Checkin to be released soon

Poll Everywhere

pollev.com/tqm

- Any questions?

Lecture Outline

- **Smart Pointers**
  - **Intro and `toy_ptr`**
  - `unique_ptr`
  - Reference Counting and `shared_ptr` vs `weak_ptr`
- `Concepts & Templates`

In Previous Lectures…

- Objects
- Templates
- Destructors
- Memory management

- All of these relate to “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 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

A smart pointer is just a Template object.

ToyPtr Class Template

ToyPtr.hpp

```
#ifndef _TOYPTR_HPP_
#define _TOYPTR_HPP_

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

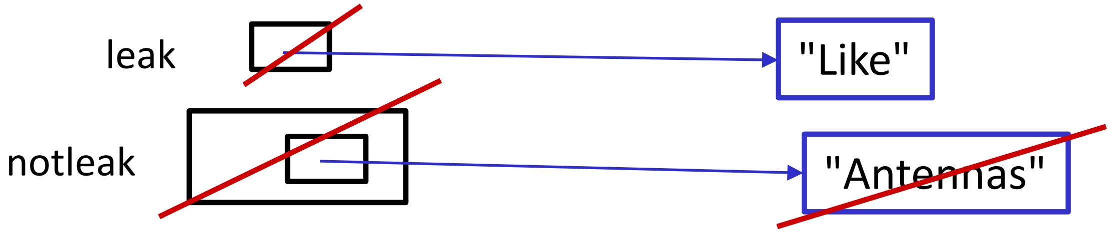
Takes advantage of implicit calling of destructor to clean up for us

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

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

#endif  // _TOYPTR_HPP_
```

ToyPtr Example

usetoy.cpp

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

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

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

  std::cout << "   *leak: " << *leak << std::endl;
  std::cout << "*notleak: " << *notleak << std::endl;

  return EXIT_SUCCESS;
}
```



Notleak cleans up for us, leak has a memory leak

What Makes This a Toy?

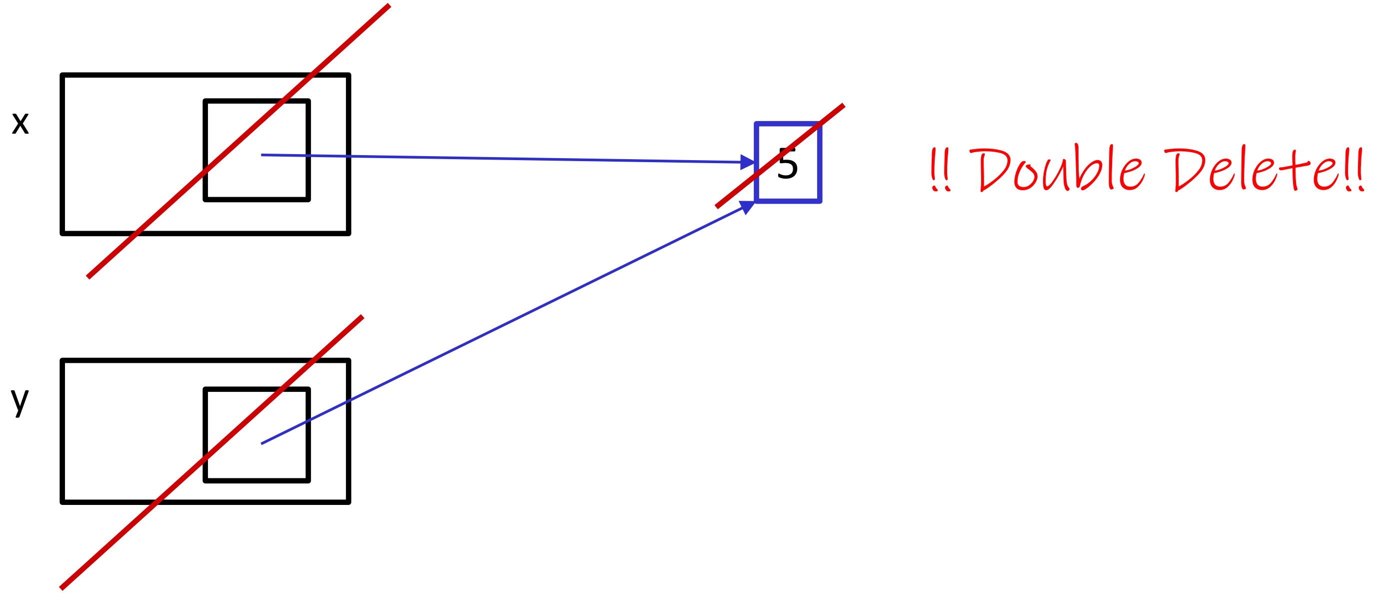
- Can't handle:
  - Arrays // needs to use delete[]
  - Copying
  - Reassignment
  - Comparison
  - … plus many other subtleties…

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

ToyPtr Class Template Issues

UseToyPtr.cpp

```
#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;
}
```



Lecture Outline

- **Smart Pointers**
  - Intro and `toy_ptr`
  - **`unique_ptr`**
  - Reference Counting and `shared_ptr` vs `weak_ptr`

Introducing: `unique_ptr`

- A `unique_ptr` is the *sole owner* of its pointee
  - It will call `delete` on the pointee when it falls out of scope

    Via the unique_ptr destructor
- Guarantees uniqueness by disabling copy and assignment

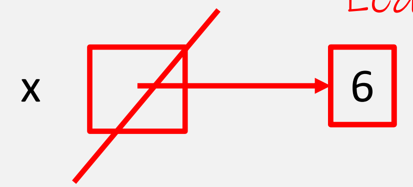
Using `unique_ptr`

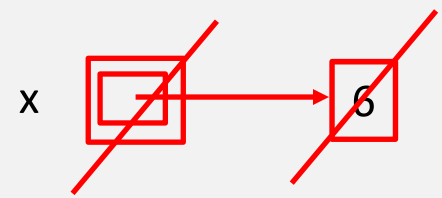
Must include <memory>

unique1.cpp

```
#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;
}
```

Memory Leak☹





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.cpp

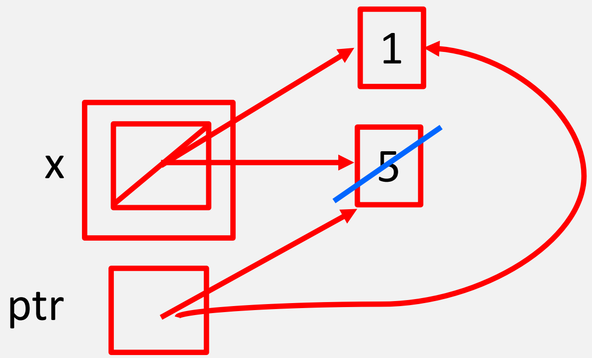
```
#include <memory>   // for std::unique_ptr
#include <cstdlib>  // for EXIT_SUCCESS

int main(int argc, char **argv) {
  std::unique_ptr<int> x(new int(5));  // ctor that takes a 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;
}
```

✓ yes Compiles ✗ no Doesn't compile

unique_ptr Operations

unique2.cpp

```
#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;
}
```

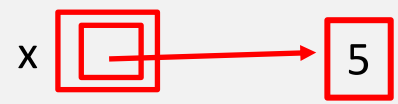


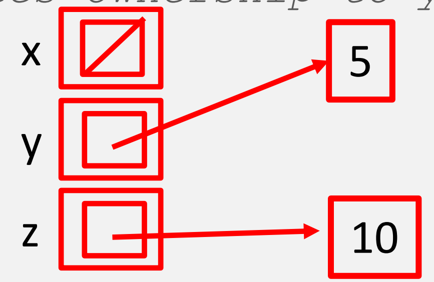
Transferring Ownership

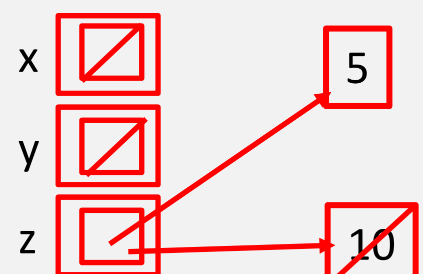
- Use **reset()** and **release()** to transfer ownership
  - **release** returns the pointer, sets wrapped pointer to `nullptr`
  - **reset** `delete`'s the current pointer and stores a new one

unique3.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;
}
```



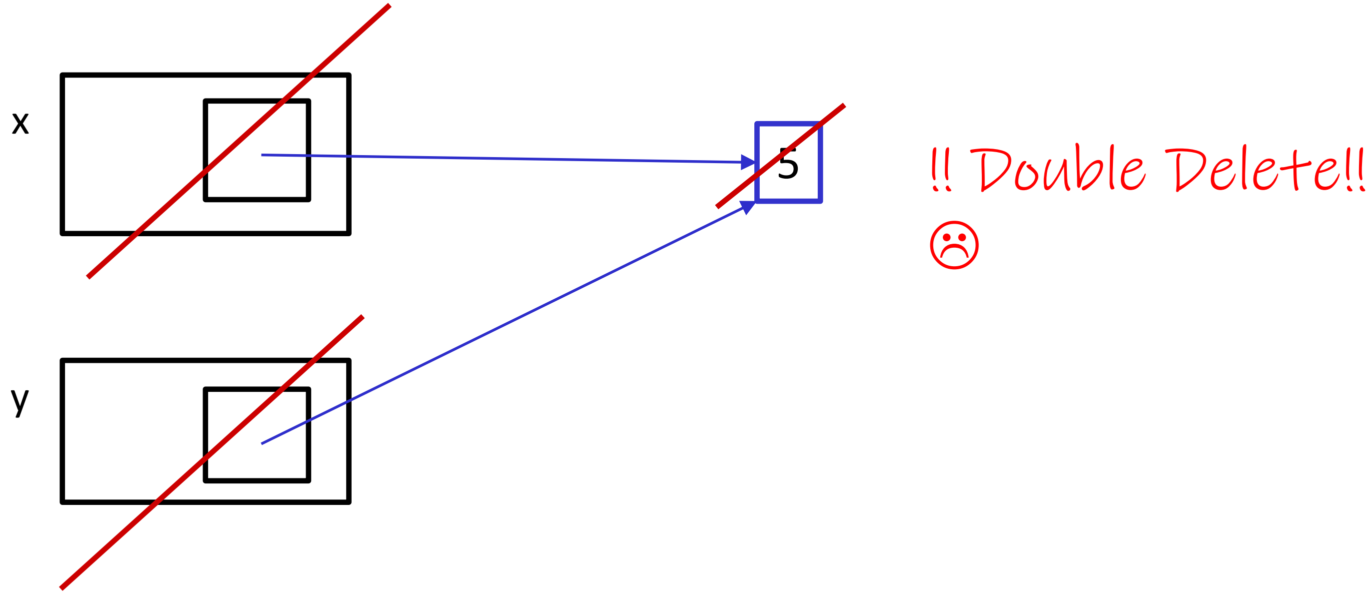




Caution with get() !!

UniqueGetFail.cpp

```
#include <memory>

// Trying to get two pointers to the same thing
int main(int argc, char **argv) {
  unique_ptr<int> x(new int(5));
  unique_ptr<int> y(x.get());
  return EXIT_SUCCESS;
}
```



`unique_ptr` and STL

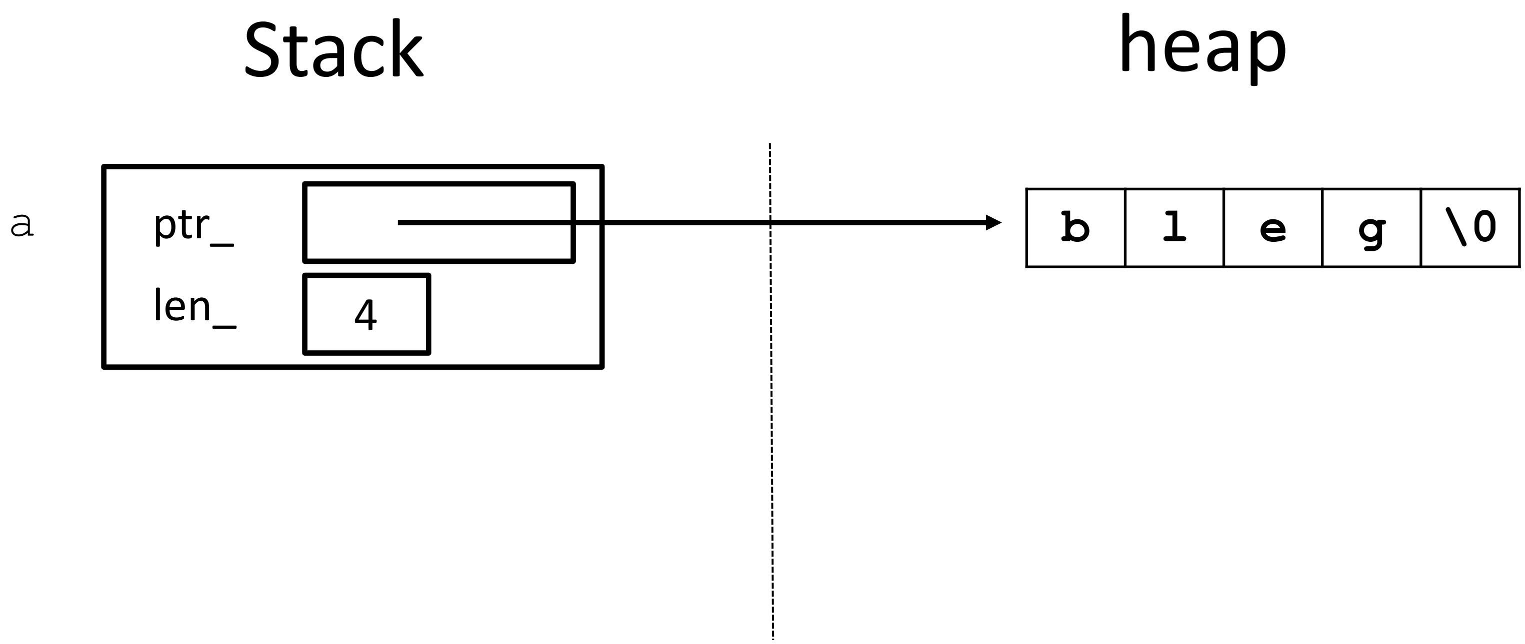
- `unique_ptr`s *can* be stored in STL containers
  - Wait, what? STL containers like to make lots of copies of stored objects and `unique_ptr`s cannot be copied…
- Move semantics to the rescue!
  - When supported, STL containers will *move* rather than *copy*
    - `unique_ptr`s support move semantics

We will discuss move semantics briefly, not enough time to talk about deeply

Copy Semantics: close up look

- Internally a string manages a heap allocated C string and looks something like:

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


}
```



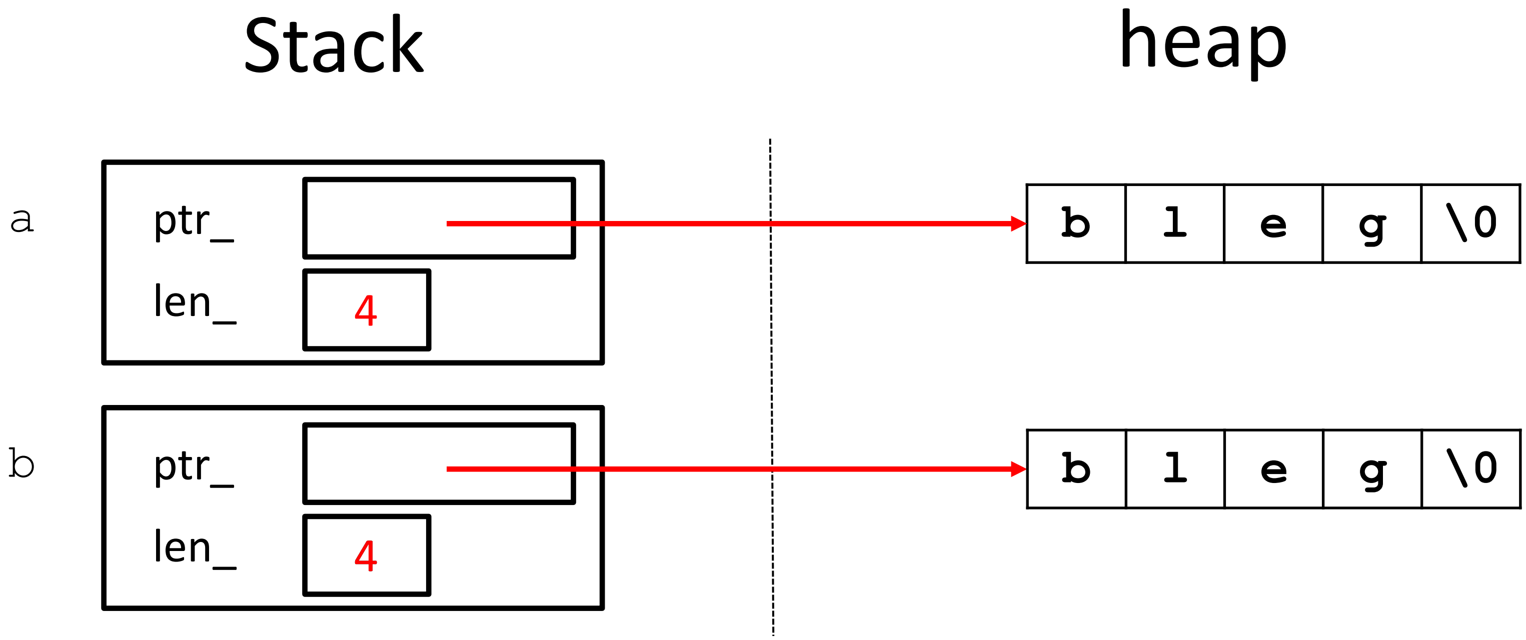
Copy Semantics: close up look

- When we copy construct string **b**

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

  std::string b{a};
}
```

we could get something like:

This is another memory allocation, and we need to copy over the characters of the string



Move Semantics (C++11)

- "Move semantics" move values from one object to another without copying ("stealing")
  - A complex topic that uses things called "*rvalue references*"
    - Mostly beyond the scope of this class

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

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

  return EXIT_SUCCESS;
}
```

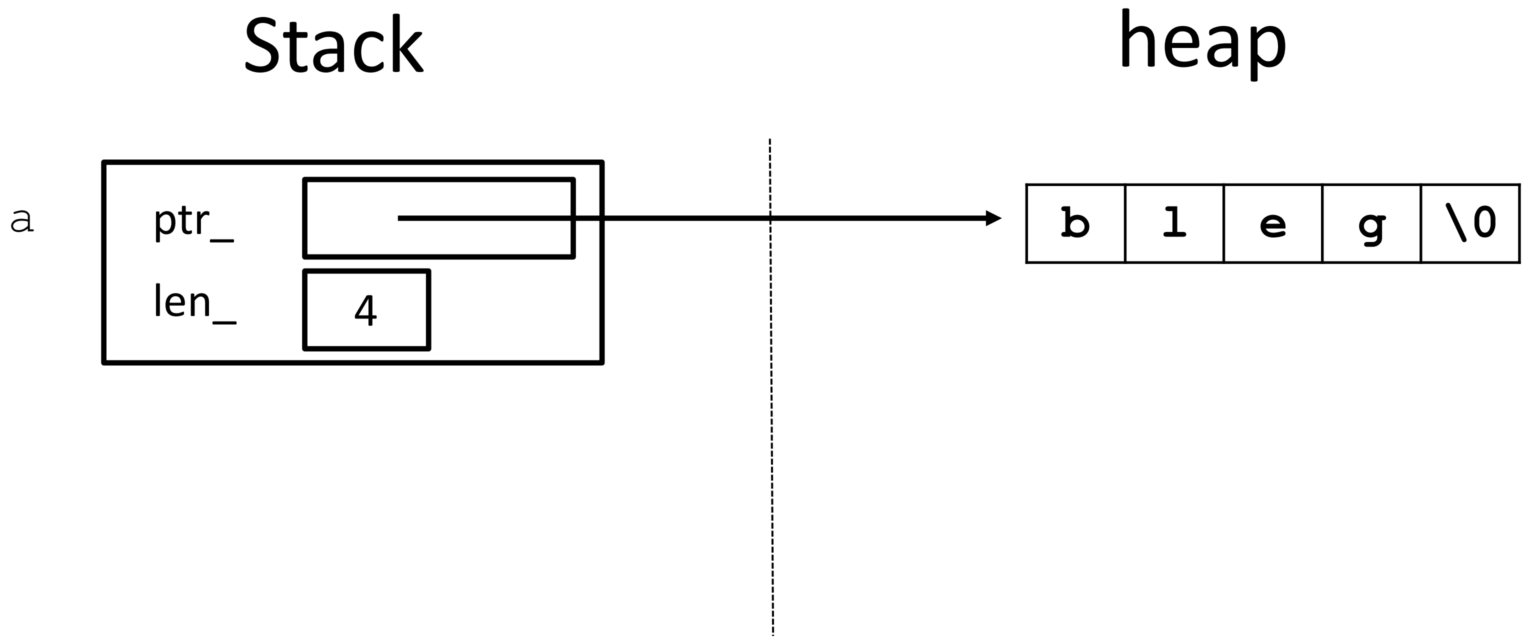
a: ""
b: "bleg"

Note: we should NOT access 'a' after we move it. It is undefined to do so, it just so happens it is set to the empty string

Move Semantics: close up look

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

}
```

- Internally a string manages a heap allocated C string and looks something like:

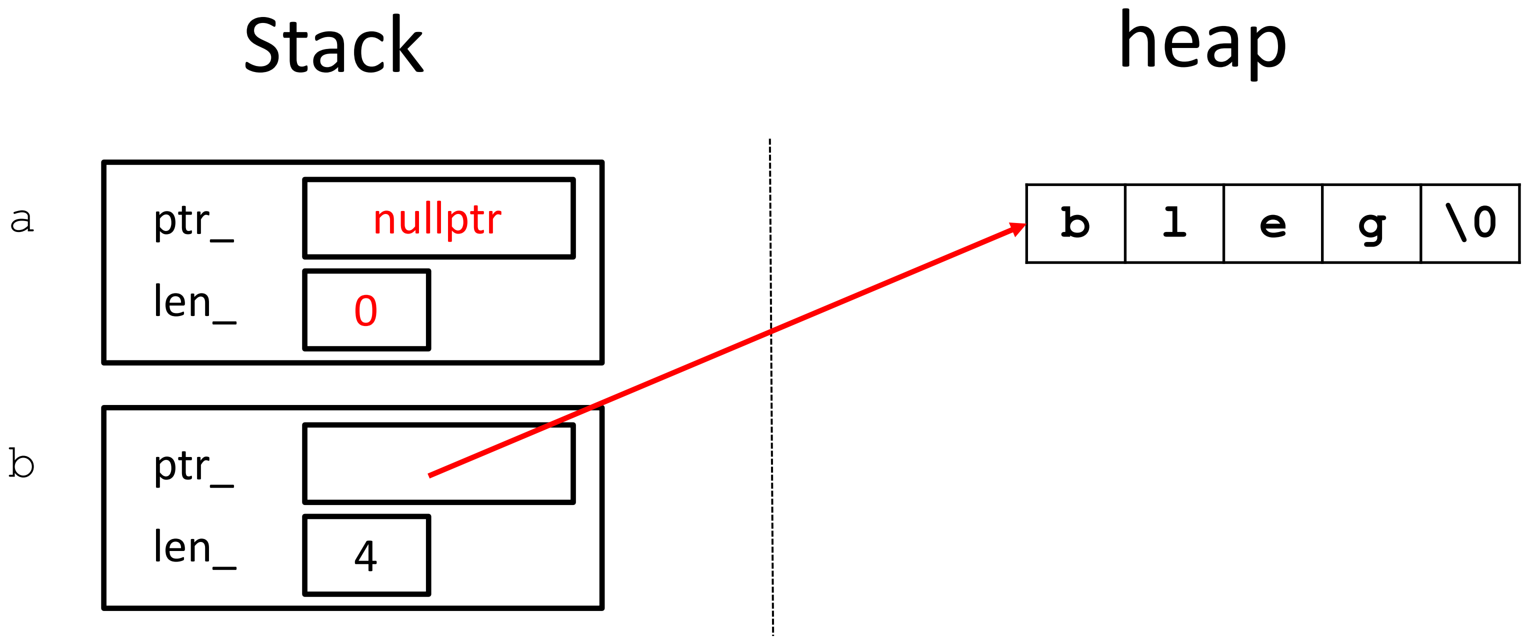


Move Semantics: close up look

- When we use move to construct string **b**

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

  std::string b{std::move(a)};
}
```

we could get something like:



Move Semantics: Use Cases

- Useful for optimizing away temporary copies
- Preferred in cases where copying may be expensive
  - Consider we had a vector of strings… we could transfer ownership of memory to avoid copying the vector and each string inside of it.
- Can be used to help enforce uniqueness

- Rust is a systems programming language that is gaining popularity and by default it will move variables instead of copy them.

Move Semantics: Details

- Implement a "Move Constructor" with something like:

```
Point::Point(Point&& other) {
  // ...
}
```

- Implement a "Move assignment" with something like:

```
Point& Point::operator=(Point&& rhs) {
  // ...
}
```

Move Semantics: Details

- "Move Constructor" example for a fake **`String`** class:

```
String::String(String&& other) {
  this->len_ = other.len_;
  this->ptr_ = other.ptr_;

  other.len_ = 0;
  other.ptr_ = nullptr;
}
```

std::move

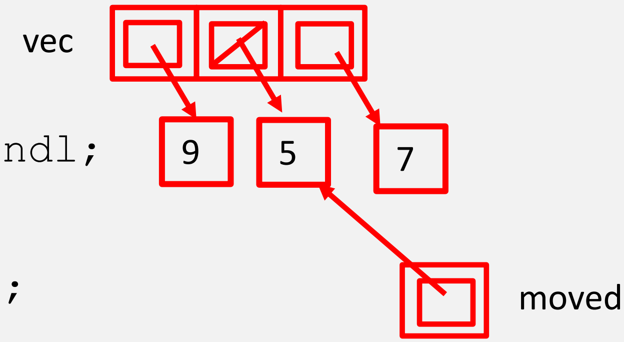
- Use `std::move` to indicate that you want to move something and not copy it

```
Point p {3, 2};         // constructor
Point a {p};            // copy constructor

Point b {std::move(p)}; // move constructor
```

unique_ptr and STL Example

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];

  // moved points to 5, vec[1] is nullptr
  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 Arrays

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

unique5.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;
}
```

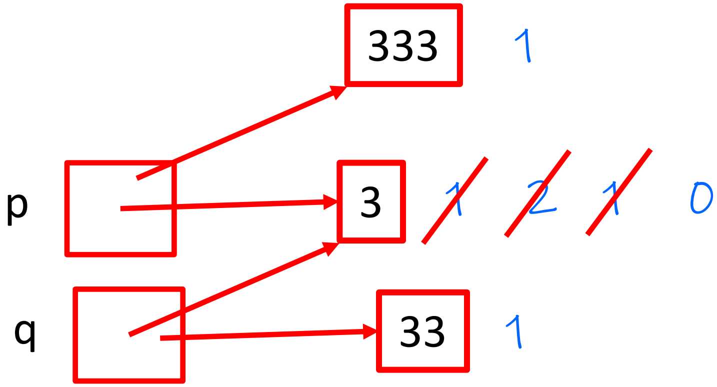
Lecture Outline

- **Smart Pointers**
  - Intro and `toy_ptr`
  - `unique_ptr`
  - **Reference Counting and `shared_ptr` vs `weak_ptr`**

Reference Counting

- Reference counting is a technique for managing resources by counting and storing the number of references (*i.e.* pointers that hold the address) to an object

```
int *p = new int(3);
int *q = p;
q = new int(33);
p = new int(333);
```



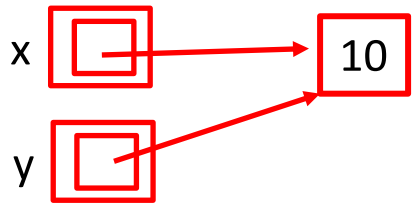
`std::shared_ptr`

- `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!

shared_ptr Example

sharedexample.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

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

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

  return EXIT_SUCCESS;
}                                       // ref count: 0
```



`shared_ptr`s and STL Containers

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

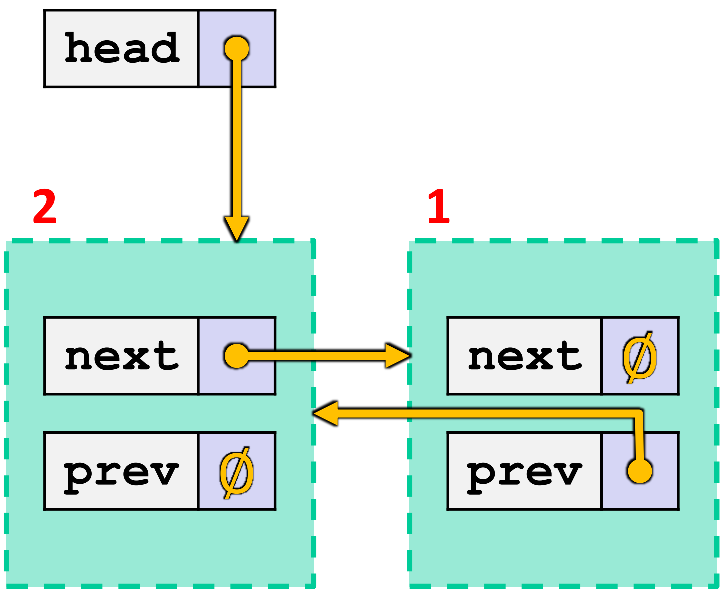
sharedvec.cc

```
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;

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;
```

Cycle of `shared_ptrs`

strongcycle.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`?

`std::weak_ptr`

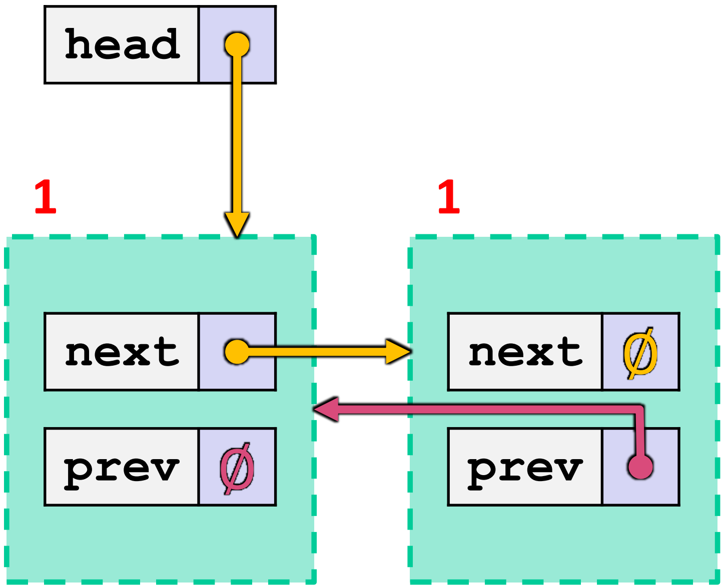
- `weak_ptr` is similar to a `shared_ptr` but doesn't affect the reference count
  - Can *only* "point to" an object that is managed by a `shared_ptr`
  - Not *really* a pointer – can't actually dereference unless you "get" its associated `shared_ptr`
  - Because it doesn't influence the reference count, `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;
}
```

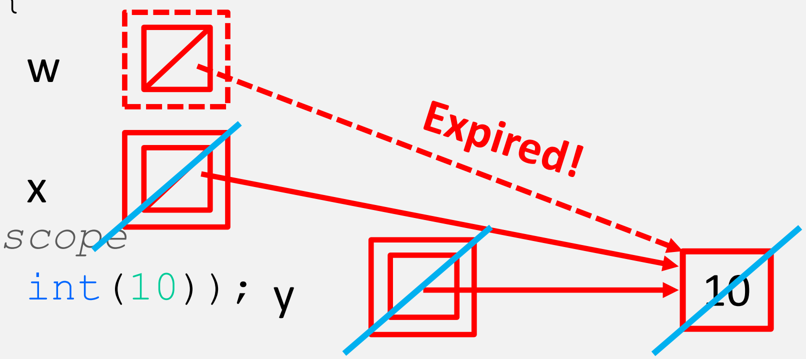


- Now what happens when we `delete head`?

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
    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;
}
```



"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.

Using a non-heap pointer

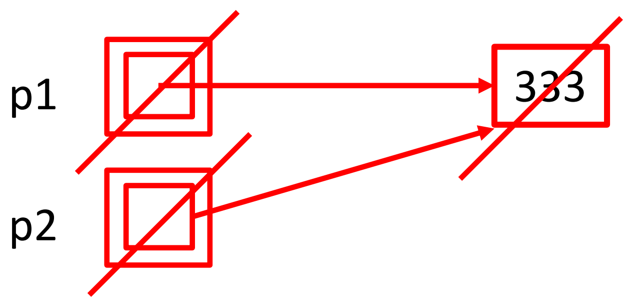
```
#include <cstdlib>
#include <memory>

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

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

  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(333);

  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.

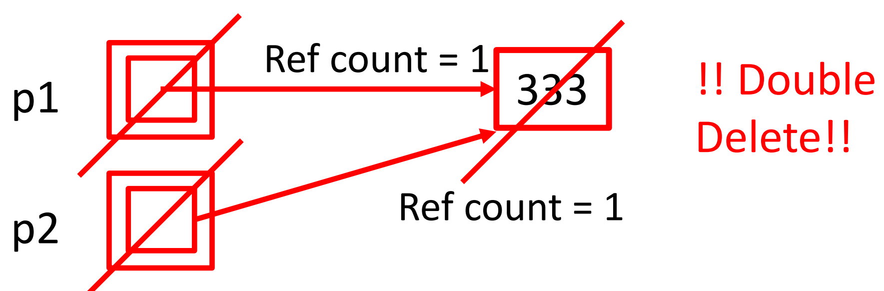


!! Double Delete!!

Re-using a raw pointer

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

using std::shared_ptr;


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

  shared_ptr<int> p1(x);  // ref count:

  shared_ptr<int> p2(x);  // ref count:

  return EXIT_SUCCESS;
}
```

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



Re-using a raw pointer: Fixed Code

```
#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); // ref count:

  return EXIT_SUCCESS;
}
```

- Smart pointers can't tell if you are re-using a raw pointer.
  - Takeaway: be careful!!!!
  - Safer to use cctor
  - To be extra safe, don't have a raw pointer variable!

Lecture 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()` `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 Methods

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

- `std::unique_ptr 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 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 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)