

# C++ Smart Pointers

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# Administrivia

- ❖ New exercise Wednesday: ex13 on smart pointers
  - Due Friday morning
- ❖ hw3 deadline is now May 21 (a week from Thursday)
  - How's progress? Any questions, observations?
- ❖ If you are using the zoom app, you should check versions and update if you haven't recently (but not until after class!). Zoom app < 5.0 won't be able to access UW meetings after the end of May.

# 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???

# 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

# ToyPtr Class Template

ToyPtr.cc

```
#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 Example

usetoy.cc

```
#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

# Using `unique_ptr`

`unique1.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(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*

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

# unique\_ptr Operations

unique2.cc

```
#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

```
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;
}
```

unique3.cc

# unique\_ptr 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;
}
```

# 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



# 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

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

copysemantics.cc

```
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;  
}
```

# Move Semantics (added in 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

movesemantics.cc

```
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

```
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;  
}
```

unique4.cc

# 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 gets a copy of int value pointed to by vec[1]
    int z = *vec[1];
    std::cout << "z is: " << z << std::endl;

    // won't compile! Cannot copy unique_ptr
    std::unique_ptr<int> copied = vec[1];    // hmmm...

    // Works! vec[1] now wraps a 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 “<”

- ❖ 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

# 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;
}
```

# 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 3<sup>rd</sup> 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

```
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

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;
}
```

# `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;
    }                                     // 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`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\_ptr

strongcycle.cc

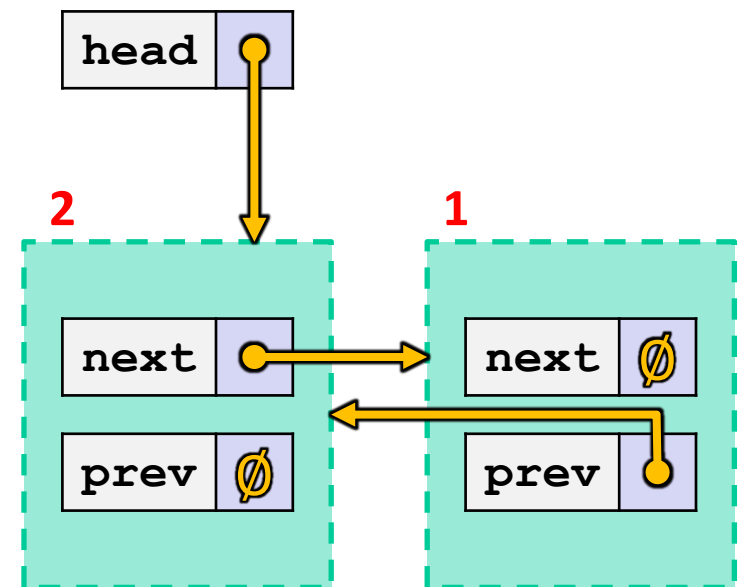
```
#include <cstdlib>
#include <memory>

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?

# Cycle of `shared_ptr`s

strongcycle.cc

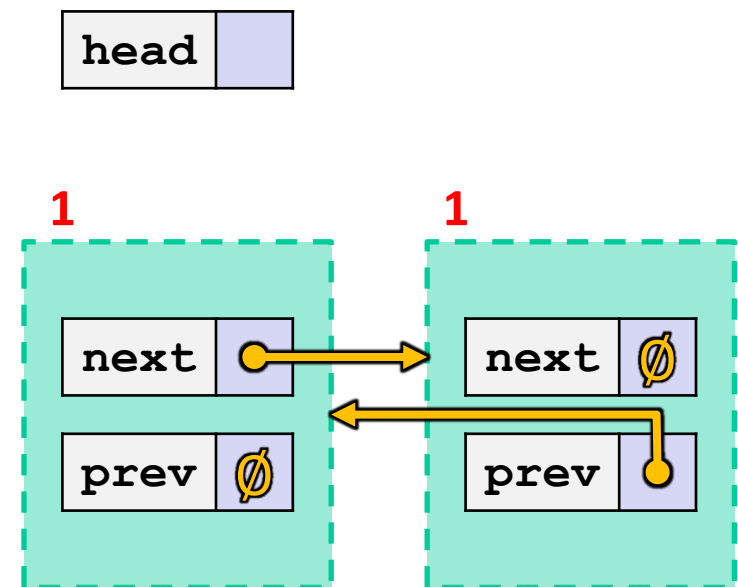
```
#include <cstdlib>
#include <memory>

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? Nodes unreachable but not deleted because ref counts > 0

# `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

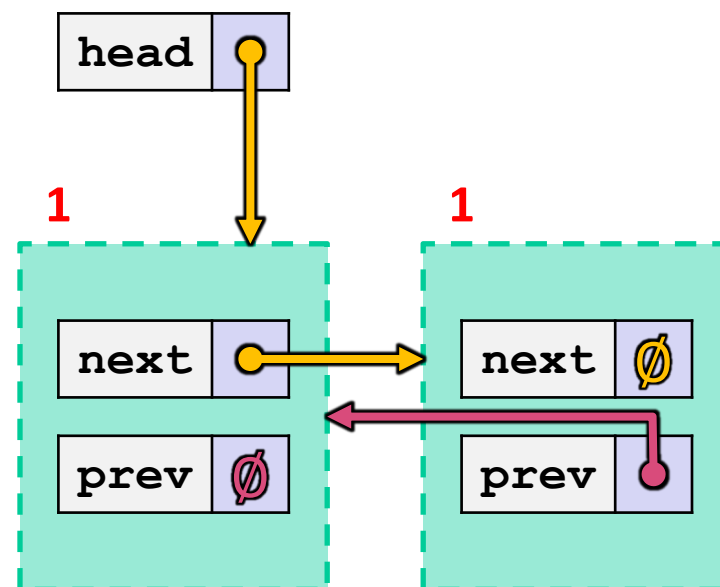
```
#include <cstdlib>
#include <memory>

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

weakcycle.cc

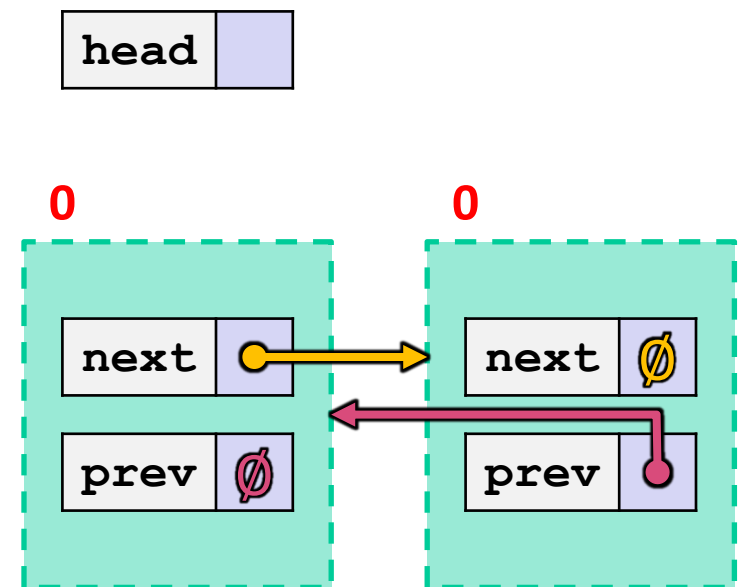
```
#include <cstdlib>
#include <memory>

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? 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
        std::shared_ptr<int> x;
        { // temporary inner-inner scope
            std::shared_ptr<int> y(new int(10));
            w = y;           // weak ref; ref count for "10" node is same
            x = w.lock();    // get "promoted" shared_ptr, ref cnt = 2
            std::cout << *x << std::endl;
        }
        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;
}
```

# Reference Counting Perspective

- ❖ **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
  - Not general enough for automatic memory management (need automatic garbage collection as in Java), but when it's appropriate it's a clean solution for resource management and cleanup

# 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*
  - `deletes` 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