CS100 Lecture 18

Smart Pointers

Contents

Ideas

Memory management is difficult!

For raw pointers obtained from `new` / `new[]` expressions, a manual `delete` / `delete[]` is required.

```
void runGame(const std::vector<Option> &options, const Settings &settings) {
  auto pWindow = new Window(settings.width, settings.height, settings.mode);
  auto pGame = new Game(options, settings, pWindow);
  // Run the game ...
  while (true) {
    auto key = getUserKeyAction();
    // ...
  }
  delete pGame;   // You must not forget this.
  delete pWindow; // You must not forget this.
}
```

Will you always remember to `delete`?

Will you always remember to `delete`?

```cpp
void runGame(const std::vector<Option> &options, const Settings &settings) {
  auto pWindow = new Window(settings.width, settings.height, settings.mode);
  auto pGame = new Game(options, settings, pWindow);
  if (/* condition1 */) {
    // ...
    return; // `pWindow` and `pGame` should also be `delete`d here!
  }
  // Run the game ...
  while (true) {
    auto key = getUserKeyAction();
    // ...
    if (/* condition2 */) {
      // ...
      return; // `pWindow` and `pGame` should also be `delete`d here!
    }
  }
  delete pGame;
  delete pWindow;
}
```

Idea: Make use of destructors.

```
struct WindowPtr { // A "smart pointer".
  Window *ptr;
  WindowPtr(Window *p) : ptr(p) {}
  ~WindowPtr() { delete ptr; } // The destructor will `delete` the object.
};
```

When the control reaches the end of the scope in which the `WindowPtr` lives, the destructor of `WindowPtr` will be called automatically.

```
void runGame(const std::vector<Option> &options, const Settings &settings) {
  WindowPtr pWindow(new Window(settings.width, settings.height, settings.mode));
  if (/* condition1 */) {
    // ...
    return; // `pWindow` is destroyed automatically, with its destructor called.
  }
  // ...
  // `pWindow` is destroyed automatically, with its destructor called.
}
```

What if `WindowPtr` is copied?

Now `WindowPtr` only has a compiler-generated copy constructor, which copies the value of `ptr`.

```cpp
{
  WindowPtr pWindow(new Window(settings.width, settings.height, settings.mode));
  auto copy = pWindow; // `copy.ptr` and `pWindow.ptr` point to the same object!
} // The object is deleted twice! Disaster!
```

What should be the behavior of `auto copy = pWindow;`? Possible designs are:

1. Copy the object, as if `WindowPtr copy(new Window(*pWindow.ptr));`.
2. Copy the pointer, as if `WindowPtr copy(pWindow.ptr);`.
   - To avoid disasters caused by multiple `delete`s, some special design is needed.
3. Disable it. If there is no unique reasonable design, disable that operation.

What if `WindowPtr` is copied?

What should be the behavior of `auto copy = pWindow;`? Possible designs are:

1. Copy the object, as if `WindowPtr copy(new Window(*pWindow.ptr));`.
   - **"Value semantics"**
   - Typical example: Standard library containers. When you copy a `std::string`, a new string is created, with the **contents** copied.
   - May be referred to as "deep copy" in some other languages.
2. Copy the pointer, as if `WindowPtr copy(pWindow.ptr);`.
   - To avoid disasters caused by multiple `delete`s, some special design is needed.
   - **"Pointer semantics"**, or **"Reference semantics"**
   - "shallow copy" in some other languages.
3. Disable it. If there is no unique reasonable design, disable that operation.
   - In this case, `pWindow` **exclusively owns** the `Window` object.

Overview of smart pointers

A "smart pointer" is a pointer that manages its resources.

Possible behaviors of copy of a smart pointer:

1. Copy the object. (Value semantics)
   - **Standard library containers.** e.g. `std::string`, `std::vector`, `std::set`, ...
2. Copy the pointer, but with some special design. (Pointer semantics)
   - **`std::shared_ptr<T>`**. Defined in standard library file `<memory>`.
3. Disable it. (Unique ownership)
   - **`std::unique_ptr<T>`**. Defined in standard library file `<memory>`.

The smart pointers `std::shared_ptr<T>`, `std::unique_ptr<T>` and `std::weak_ptr<T>` are **the C++'s answer to garbage collection**.

- `std::weak_ptr` is not covered in CS100.

Overview of smart pointers

The smart pointers `std::shared_ptr<T>`, `std::unique_ptr<T>` and `std::weak_ptr<T>` are **the C++'s answer to garbage collection**.

Smart pointers support the similar operations as raw pointers:

- `*sp` returns reference to the pointed-to object.
- `sp->mem` is equivalent to `(*sp).mem`.
- `sp` is *contextually convertible* to `bool`: It can be treated as a "condition".
  - It can be placed at the "condition" part of `if`, `for`, `while`, `do` statements.
  - It can be used as operands of `&&`, `||`, `!` or the first operand of `?:`.
  - In all cases, the conversion result is `true` **iff** `sp` holds an object (not "null").

[Best practice] <u>In modern C++, prefer smart pointers to raw pointers.</u>

`std::unique_ptr`

Design: Unique ownership of the object

```
class WindowPtr {
  Window *ptr;
public:
  WindowPtr(Window *p = nullptr) : ptr(p) {}
  ~WindowPtr() { delete ptr; }




};
```

A "unique-pointer" saves a raw pointer internally, pointing to the object it owns.

When the unique-pointer is destroyed, it disposes of the object it owns.

Design: Unique ownership of the object

```
class WindowPtr {
  Window *ptr;
public:
  WindowPtr(Window *p = nullptr) : ptr(p) {}
  ~WindowPtr() { delete ptr; }
  WindowPtr(const WindowPtr &) = delete;
  WindowPtr &operator=(const WindowPtr &) = delete;


};
```

The unique-pointer **exclusively** owns the object. Copying a unique-pointer is not allowed.

Design: Unique ownership of the object

```
class WindowPtr {
  Window *ptr;
public:
  WindowPtr(Window *p = nullptr) : ptr(p) {}
  ~WindowPtr() { delete ptr; }
  WindowPtr(const WindowPtr &) = delete;
  WindowPtr &operator=(const WindowPtr &) = delete;
  WindowPtr(WindowPtr &&other) noexcept : ptr(other.ptr) { other.ptr = nullptr; }
  WindowPtr &operator=(WindowPtr &&other) noexcept {
    if (&other != this) {
      delete ptr; ptr = other.ptr; other.ptr = nullptr;
    }
    return *this;
  }
};
```

Move of a unique-pointer: **transfer of ownership**.

- **Move-only type**

`std::unique_ptr`

Like `std::vector`, `std::unique_ptr` is also a class template. It is not a type itself.

- `std::unique_ptr<PointeeType>` is the complete type name, where `PointeeType` is the type of the object that it points to.
- For `T` $\neq$ `U`, `std::unique_ptr<T>` and `std::unique_ptr<U>` are **two different and independent types**.

Same for `std::shared_ptr`, which we will talk about later.

Creating a `std::unique_ptr`: Two common ways

- Pass a pointer created by `new` to the constructor:

  ```
  std::unique_ptr<Student> p(new Student("Bob", 2020123123));
  ```

  - Here `<Student>` can be omitted. The compiler is able to deduce it.

- Use `std::make_unique<T>`, and pass the initializers to it.

  ```
  std::unique_ptr<Student> p1 = std::make_unique<Student>("Bob", 2020123123);
  auto p2 = std::make_unique<Student>("Alice", 2020321321);
  ```

  - `std::make_unique<T>(args...)` *perfectly forwards* the arguments `args...` to the constructor of `T`, as if the object were created by `new T(args...)`.
  - `std::make_unique<T>` returns a `std::unique_ptr<T>` to the created object.

Default initialization of a `std::unique_ptr`

```
std::unique_ptr<T> up;
```

The default constructor of `std::unique_ptr<T>` initializes `up` to be a "null pointer".

`up` is in the state that does not own any object.

- This is a defined and deterministic behavior! It is **not** holding some indeterminate value.
  - The standard library hates indeterminate values, just as we do.

`std::unique_ptr`: Automatic memory management

```cpp
void foo() {
  auto pAlice = std::make_unique<Student>("Alice", 2020321321);
  // Do something...
  if (some_condition()) {
    auto pBob = std::make_unique<Student>("Bob", 2020123123);
    // ...
  } // `Student::~Student()` is called for Bob,
    // because the lifetime of `pBob` ends.
} // `Student::~Student()` is called for Alice,
  // because the lifetime of `pAlice` ends.
```

A `std::unique_ptr` automatically calls the destructor once it gets destroyed.

- No manual `delete` needed!

`std::unique_ptr`: Move-only

```
auto p = std::make_unique<std::string>(5, 'c');
std::cout << *p << std::endl;                          // Prints "ccccc".
auto q = p;                                            // Error. Copy is not allowed.
auto r = std::move(p);                                 // Correct.
// Now the ownership of this string has been transferred to `r`.
std::cout << *r << std::endl; // Prints "ccccc".
if (!p) // true
  std::cout << "p is \"null\" now." << std::endl;
```

`std::unique_ptr` is not copyable, but only movable.

- Remember, only one `std::unique_ptr` can point to the managed object.
- Move of a `std::unique_ptr` is the transfer of ownership of the managed object.

`std::unique_ptr`: Move-only

```cpp
auto p = std::make_unique<std::string>(5, 'c');
std::cout << *p << std::endl;                  // Prints "ccccc".
auto q = p;                                    // Error. Copy is not allowed.
auto r = std::move(p);                         // Correct.
// Now the ownership of this string has been transferred to `r`.
std::cout << *r << std::endl; // Prints "ccccc".
if (!p) // true
  std::cout << "p is \"null\" now." << std::endl;
```

After `auto up2 = std::move(up1);`, `up1` becomes "null". The object that `up1` used to manage now belongs to `up2`.

The assignment `up2 = std::move(up1)` destroys the object that `up2` used to manage, and lets `up2` take over the object managed by `up1`. After that, `up1` becomes "null".

Express your intent precisely.

You may accidentally write the following code:

```cpp
// Given that `pWindow` is a `std::unique_ptr<Window>`.
auto p = pWindow; // Oops, attempting to copy a `std::unique_ptr`.
```

The compiler gives an error, complaining about the use of deleted copy constructor.

What are you going to do?

A. Change it to `auto p = std::move(pWindow);`.
B. Give up on smart pointers, and switch back to raw pointers.
C. Copy-and-paste the compiler output and ask ChatGPT.

Express your intent precisely.

You may accidentally write the following code:

```cpp
// Given that `pWindow` is a `std::unique_ptr<Window>`.
auto p = pWindow; // Oops, attempting to copy a `std::unique_ptr`.
```

The compiler gives an error, complaining about the use of deleted copy constructor.

1. Syntactically, a `std::unique_ptr` is not copyable, but you are copying it. **(Direct cause of the error)**
2. Logically, a `std::unique_ptr` must exclusively manage the pointed-to object. Why would you copy a `std::unique_ptr`?
   - The **root cause of the error** is related to your intent: What are you going to do with `p`?

Express your intent precisely.

```cpp
// Given that `pWindow` is a `std::unique_ptr<Window>`.
auto p = pWindow; // Oops, attempting to copy a `std::unique_ptr`.
```

What are you going to do with `p`?

- If you want to copy the pointed-to object, change it to `auto p = std::make_unique<Window>(*pWindow);`.
- If you want `p` to be just an ***observer***, write `auto p = pWindow.get();`.
  - `pWindow.get()` returns a **raw pointer** to the object, which is of type `Window *`.
  - Be careful! As an observer, `p` should never interfere in the lifetime of the object. A simple `delete p;` will cause disaster.

Express your intent precisely.

```
// Given that `pWindow` is a `std::unique_ptr<Window>`.
auto p = pWindow; // Oops, attempting to copy a `std::unique_ptr`.
```

What are you going to do with `p`?

- If you want `p` to take over the object managed by `pWindow`, change it to `auto p = std::move(pWindow);`.
  - Be careful! `pWindow` will no longer own that object.
- If you want to `p` to be another smart pointer that ***shares*** the ownership with `pWindow`, `std::unique_ptr` is not suitable here. ⇒ See `std::shared_ptr` later.

Returning a `std::unique_ptr`

```cpp
struct Window {
  // A typical "factory" function.
  static std::unique_ptr<Window> create(const Settings &settings) {
    auto pW = std::make_unique<Window>(/* some arguments */);
    logWindowCreation(pW);
    // ...
    return pW;
  }
};
auto state = Window::create(my_settings);
```

A temporary is move-constructed from `pW`, and then is used to move-construct `state`.

- These two moves can be optimized out by NRVO.

Other operations on `std::unique_ptr`

`up.reset()`, `up.release()`, `up1.swap(up2)`, `up1 == up2`, etc.

Full list of operations supported on a `std::unique_ptr`.

`std::unique_ptr` for array type

By default, the destructor of `std::unique_ptr<T>` uses a `delete` expression to destroy the object it holds.

What happens if `std::unique_ptr<T> up(new T[n]);`?

`std::unique_ptr` for array type

By default, the destructor of `std::unique_ptr<T>` uses a `delete` expression to destroy the object it holds.

What happens if `std::unique_ptr<T> up(new T[n]);`?

- The memory is obtained using `new[]`, but deallocated by `delete`! **Undefined behavior.**

`std::unique_ptr` for array type

A *template specialization*: `std::unique_ptr<T[]>`.

- Specially designed to represent pointers that point to a "dynamic array" of objects.
- It has some array-specific operators, e.g. `operator[]`. In contrast, it does not support `operator*` and `operator->`.
- It uses `delete[]` instead of `delete` to destroy the objects.

```
auto up = std::make_unique<int[]>(n);
std::unique_ptr<int[]> up2(new int[n]{}); // equivalent
for (auto i = 0; i != n; ++i)
  std::cout << up[i] << ' ';
```

~~`std::unique_ptr` for array type~~

~~A *template specialization*: `std::unique_ptr<T[]>`.~~

~~- Specially designed to represent pointers that point to a "dynamic array" of objects.~~
~~- It has some array-specific operators, e.g. `operator[]`. In contrast, it does not support `operator*` and `operator->`.~~
~~- It uses `delete[]` instead of `delete` to destroy the objects.~~

Use standard library containers instead!

They almost always do a better job. `std::unique_ptr<T[]>` is seldom needed.

`std::unique_ptr` is zero-overhead.

`std::unique_ptr` stores nothing more than a raw pointer. [1]

It does nothing more than better copy / move control and automatic object destruction.

Zero-overhead: Using a `std::unique_ptr` does not cost more time or space than using raw pointers.

[Best practice] Use `std::unique_ptr` for exclusive-ownership resource management.

`std::shared_ptr`

Motivation

A `std::unique_ptr` exclusively owns an object, but sometimes this is not convenient.

```
struct WindowManager {
  void addWindow(const std::unique_ptr<Window> &pW) {
    mWindows.push_back(pW); // Error. Attempts to copy a `std::unique_ptr`.
  }
private:
  std::vector<std::unique_ptr<Window>> mWindows;
};

struct Window {
  static std::unique_ptr<Window> create(const Settings &settings) {
    auto pW = std::make_unique<Window>(/* some arguments */);
    logWindowCreation(pW);
    settings.getWindowManager().addWindow(pW);
    return pW;
  }
};
```

Motivation

Design a "shared-pointer" that allows the object it manages to be ***shared***.

When should the object be destroyed?

- A `std::unique_ptr` destroys the object it manages when the pointer itself is destroyed.
- If we allow many shared-pointers to point to the same object, how can we know when to destroy that object?

Idea: Reference counting

Set a **counter** that counts how many `WindowPtr` s are pointing to it:

```
struct WindowWithCounter {
  Window theWindow;
  int refCount = 1;
};
```

When a new object is created by a `WindowPtr`, set the `refCount` to `1`.

Idea: Reference counting

When a `WindowPtr` is copied, let it point to the same object, and increment the counter.

```
class WindowPtr {
  WindowWithCounter *ptr;
public:
  WindowPtr(const WindowPtr &other) : ptr(other.ptr) { ++ptr->refCount; }









};
```

Idea: Reference counting

For copy assignment: the counter of the old object should be decremented.

- If it reaches zero, destroy that object!

```cpp
class WindowPtr {
  WindowWithCounter *ptr;
public:
  WindowPtr(const WindowPtr &other) : ptr(other.ptr) { ++ptr->refCount; }
  WindowPtr &operator=(const WindowPtr &other) {
    if (--ptr->refCount == 0)
      delete ptr;
    ptr = other.ptr;
    ++ptr->refCount;
    return *this;
  }
};
```

*** Is this correct?**

Idea: Reference counting

Self-assignment safe!!!

```cpp
class WindowPtr {
  WindowWithCounter *ptr;
public:
  WindowPtr(const WindowPtr &other) : ptr(other.ptr) { ++ptr->refCount; }
  WindowPtr &operator=(const WindowPtr &other) {
    ++other.ptr->refCount;
    if (--ptr->refCount == 0)
      delete ptr;
    ptr = other.ptr;
    return *this;
  }
};
```

Idea: Reference counting

Destructor: decrement the counter, and destroy the object if the counter reaches zero.

```cpp
class WindowPtr {
  WindowWithCounter *ptr;
public:
  WindowPtr(const WindowPtr &other) : ptr(other.ptr) { ++ptr->refCount; }
  WindowPtr &operator=(const WindowPtr &other) {
    ++other.ptr->refCount;
    if (--ptr->refCount == 0)
      delete ptr;
    ptr = other.ptr;
    return *this;
  }
  ~WindowPtr() {
    if (--ptr->refCount == 0)
      delete ptr;
  }
};
```

Idea: Reference counting

Move: Just "steal" the object. It is also the transfer of ownership.

```
class WindowPtr {
  WindowWithCounter *ptr;
public:
  WindowPtr(WindowPtr &&other) noexcept : ptr(other.ptr) { other.ptr = nullptr; }
  WindowPtr &operator=(WindowPtr &&other) noexcept {
    if (this != &other) {
      if (--ptr->refCount == 0)
        delete ptr;
      ptr = other.ptr; other.ptr = nullptr;
    }
    return *this;
  }
};
```

Reference counting

By maintaining a variable that counts how many shared-pointers are pointing to the object, we can know when to destroy the object.

This strategy is adopted by Python.

It can prevent memory leak in many cases, but not all cases! $\Rightarrow$ See the question in the end of this lecture's slides.

`std::shared_ptr`

A smart pointer that uses **reference counting** to manage shared objects.

Create a `shared_ptr`:

```
std::shared_ptr<Type> sp2(new Type(args));
auto sp = std::make_shared<Type>(args); // equivalent, but better
```

For example:

```
// sp points to a string "cccccccccc".
auto sp = std::make_shared<std::string>(10, 'c');

auto pWindow = std::make_shared<Window>(80, 24, my_settings.mode);
```

Create a `shared_ptr`

Note: For `std::unique_ptr`, both of the following ways are ok (since C++17):

```
auto up = std::make_unique<Type>(args);
std::unique_ptr<Type> up2(new Type(args));
```

For `std::shared_ptr`, **`std::make_shared` is preferable to directly using `new`**.

```
auto sp = std::make_shared<Type>(args);    // preferred
std::shared_ptr<Type> sp2(new Type(args)); // ok, but less preferred
```

Read *Effective Modern C++* Item 21. (Note that this book is based on C++14.)

[Best practice] Prefer `std::make_shared` to directly using `new` when creating a `std::shared_ptr`.

Operations

`*` and `->` can be used as if it is a raw pointer:

```cpp
auto sp = std::make_shared<std::string>(10, 'c');
std::cout << *sp << std::endl;        // "cccccccccc"
std::cout << sp->size() << std::endl; // "10"
```

`sp.use_count()`: The value of the reference counter.

```cpp
auto sp = std::make_shared<std::string>(10, 'c');
{
  auto sp2 = sp;
  std::cout << sp.use_count() << std::endl; // 2
} // `sp2` is destroyed, but the managed object is not destroyed.
std::cout << sp.use_count() << std::endl;   // 1
```

Operations

Full list of supported operations on `std::shared_ptr`.

`std::shared_ptr` is relatively easy to use, since you are free to create many `std::shared_ptr`s pointing to one object.

However, `std::shared_ptr` **has time and space overhead**. Copy of a `std::shared_ptr` requires maintenance of reference counter.

Summary

`std::unique_ptr`

- Exclusive-ownership.
- Move-only. Move is the transfer of ownership.
- Zero-overhead.

`std::shared_ptr`

- Shared-ownership.
- Uses reference counting.
  - Copy increments the reference counter.
  - When the counter is decremented to zero, the object is destroyed.

Question

Does `std::shared_ptr` prevent memory leak in all cases? Think about what happens in the following code.

```
struct Node {
  int value;
  std::shared_ptr<Node> next;
  Node(int x, std::shared_ptr<Node> p) : value{x}, next{std::move(p)} {}
};
void foo() {
  auto p = std::make_shared<Node>(1, nullptr);
  p->next = std::make_shared<Node>(2, p);
  p.reset();
}
```

Notes

[1] The **deleter** that a `std::unique_ptr` uses is customizable, which also has to be stored in a `std::unique_ptr`. By default, `std::default_delete` is used that performs `delete ptr;` to destroy the object and release the memory. `std::unique_ptr` often uses some space-saving tricks to store the deleter. If the deleter is "stateless" (e.g. an object with no non-`static` data members), it may be stored with no unique address so that no extra space is required. `std::default_delete` belongs to this kind. Therefore, `sizeof(std::unique_ptr<T>)` is often reasonably equal to `sizeof(T *)`.