Smart Pointers

Problems:

- Forget to use delete - memory leak
- Use delete multiple times - double free
- Use the pointer after delete is also dangerous

The smart pointer template classes defines class object that acts like a pointer but has additional features. We can think of the pointer has a destructor defined, which frees the memory it controlled upon expiration of the pointer object. In C++ there are **std::unique_ptr**, **std::shared_ptr**, **std::weak_ptr** and **std::auto_ptr**. auto_ptr is deprecated in C++11. So it will not be covered in this document.

Each of these classes has an explicit constructor taking a pointer as an argument. Thus, there is no automatic type cast from a pointer to a smart pointer object:

```
std::shared_ptr<double> pd;
double *p_reg = new double;
pd = p_reg; // not allowed (implicit conversion)
pd = std::shared_ptr<double>(p_reg); // allowed (explicit conversion )
std::shared_ptr<double> pshared = p_reg; // not allowed (implicit conversion)
std::shared_ptr<double> pshared(p_reg); // allowed (explicit conversion)
```

The smart pointer template classes are defined so that in most respects a smart pointer object acts like a regular pointer. For example, given that ps is a smart pointer object, you can:

- Dereference it (`*ps`)
- Use it to access structure members (`ps->puffIndex`).

To use smart pointers, the `<memory>` header must be included.

Unique pointer

`std::unique_ptr<T>` is a **move-only** class that represents unique ownership over a dynamically allocated object.

```
struct foo
{
    foo()  { std::cout << "Constructor called." << std::endl;  }
    ~foo() { std::cout << "Destructor called." << std::endl; }
};
int useSmart() {
  std::unique_ptr<foo> f{new foo};
}
```

When the `std::unique_ptr` instance `f` goes out of scope, it will automatically call `delete` for us, making sure that we do not forget to free the previously-allocated memory.

The uniqueness of std::unique_ptr is implemented through deleting copy assignment operator and copy constructor.

```
int useSmart() {
  std::unique_ptr<foo> f{new foo};

  // Won't compile!
  // auto f2 = f;
```

```cpp
    // Need to convert f to rvalue reference
    auto f2 = std::move(f);
}
```

Unique pointer and functions

Examples of returning/accepting `std::unique_ptr` instances from/to functions.

```cpp
std::unique_ptr<foo> bar()
{
    std::unique_ptr<foo> f{new foo};
    return f;
}

void take_ownership(std::unique_ptr<foo> f)
{
    std::cout << "took ownership of `f`\n";
}

int main()
{
    auto f = bar();
    take_ownership(std::move(f)); // Need to use std::move, otherwise f is lvalue
}
```

Runtime overhead

std::unique_ptr can be thought as a zero-cost abstract. Refer to the following comparison of assembly codes: [Over Head of std::unique_ptr]

Exception-safety

There's no such guarantee in the evaluation order in C++ function parameters(until C++17). Consider the following codes:

```cpp
void foo(std::unique_ptr<int>, int);
int bar() { throw std::runtime_error{"whoops!"}; }
int main()
{
    foo(std::unique_ptr<int>{new int{5}}, bar());
}
```

The evaluation order for function parameters of foo() can be any of the following:

Order #0:

- Allocate memory for `new int{5}`
- Construct `unique_ptr`
- Invoke `bar()` and throw

Order #1:

- Invoke `bar()` and throw

- Allocate memory for `new int{5}`
- Construct `unique_ptr`

Order #2:

- Allocate memory for `new int{5}`
- Invoke `bar()` and throw
- Construct `unique_ptr`

We see that if order #2 take place, then we have memory leak. In C++14, std::make_unique is introduced to solve this issue.

```
// Template declaration of std::make_unique
template< class T, class... Args >
unique_ptr<T> make_unique( Args&&... args );

foo(std::make_unique<int>(5), bar());
```

The arguments args are passed to the constructor of T, thus avoiding extra level of evaluation. Hence, `std::make_unique` above will not interleave an allocation with the call to `bar()`. However, in C++11 std::make_unique is not defined yet, therefore we need to make our own make_unique if our funtion contain more than one parameters other than make_unique and they can throw.

```
// Defining your own make_unique;
// Remember to put it into a namespace other than std!
template<typename T, typename... Args>
std::unique_ptr<T> make_unique(Args&&... args)
{
    return std::unique_ptr<T>(new T(std::forward<Args>(args)...));
}
```

Shared Pointer

`std::shared_ptr<T>` Manages the storage of a pointer, providing a limited garbage-collection facility, possibly sharing that management with other objects. It is a **copyable class** that represents shared ownership over a dynamically allocated object. It uses **"reference counting"** to keep track of how many alive owners are present and releases the memory when that count reaches zero.

- Copying a `std::shared_ptr` shares ownership: increase `use_count`.
- Moving a `std::shared_ptr` transfers ownership: does not increase `use_count`.

```
std::shared_ptr<int> sp = make_shared<int>(1);
auto sp1 = sp; // share ownership
auto sp2 = std::move(sp1); // transfer ownership
```

Constructing shared pointer

Prefer using std::make_shared instead of constructing std::shared_ptr using raw pointer.

It's legal to construct std::shared_ptr from raw pointer:

```
std::shared_ptr<int> s0{new int{5}};
```

However, it's more ideal to use std::make_shared to construct std::shared_ptr, for the following reason:

- Prevents memory leaks due to unspecified order of evaluation (just as explained in std::unique_ptr)
- Prevents an unnecessary additional allocation and improves cache locality.

```
auto s1 = std::make_shared<int>(5);
```

For the 2nd point, compared with `std::shared_ptr<int> s0{new int{5}};`, constructing std::shared_ptr using raw pointer forces the compiler to perform allocation twice.

- Once for the `int`
- Once for the `shared_ptr`'s control block

This is wasteful, as both allocations could be coalesced into one. `std::make_shared` allows implementations to only allocate once for both the shared object and the control block. Having one allocation has the additional benefit of cache locality. Plus, std::make_shared is available in C++11, unlike std::make_unique.

It's also possible to construct a std::shared_ptr by moving ownership from std::unique_ptr to std::shared_ptr. The std::unique_ptr being moved from manages no object after the call.

```
unique_ptr<Foo> u(new Foo);
shared_ptr<Foo> f = move(u);
```

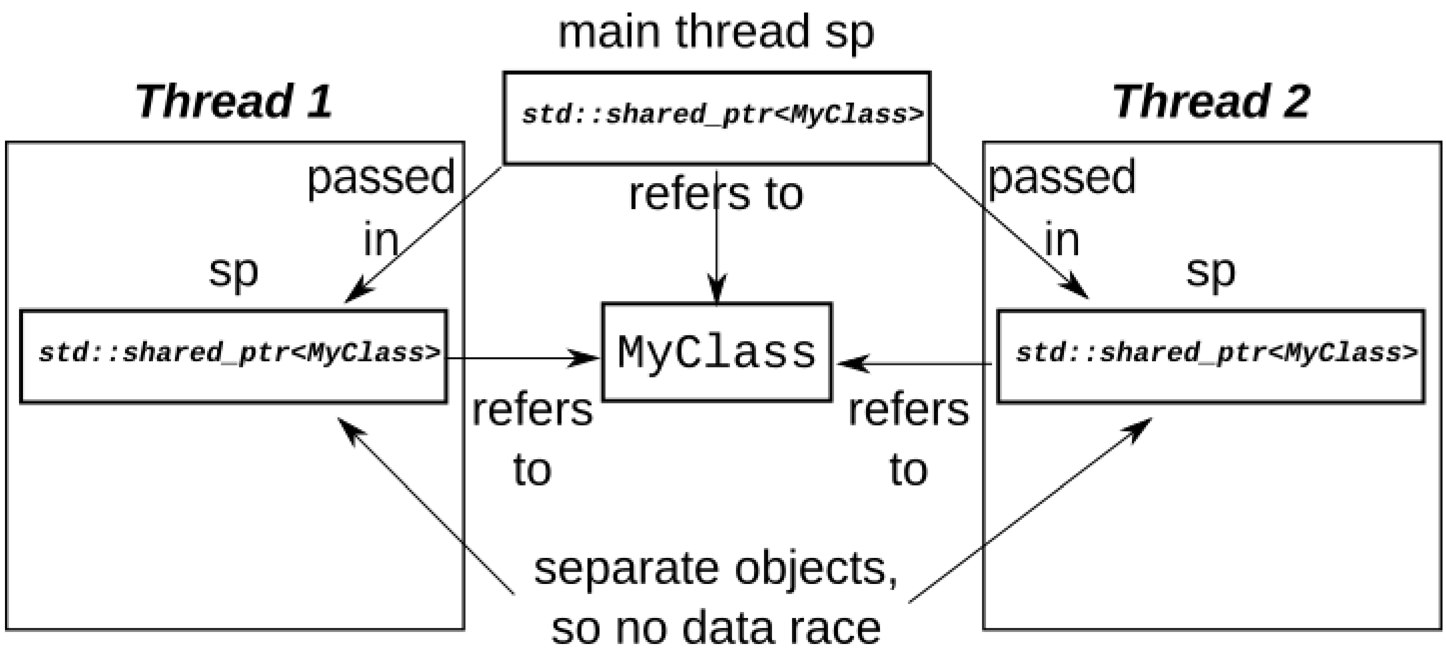
Runtime overhead

Check out the comparison of compiled codes here: [Link].
`std::shared_ptr` has time overhead in constructor (to create the reference counter), in destructor (to decrement the reference counter and possibly destroy the object) and in assignment operator (to increment the reference counter). Due to thread-safety guarantees of std::shared_ptr, these increments/decrements are atomic, thus adding some more overhead.

More on thread safety

std::shared_ptr can work in multiple threads, provided each thread has **its own copy or copies**. In this case, the changes to the reference count are indeed synchronized(but it's our responsibility that make sure what we do with the shared data is correctly synchronized).

- Standard guarantees reference counting is handled thread safe and it's platform independent
- Standard guarantees that only one thread (holding last reference) will call delete on shared object
- shared_ptr does not guarantee any thread safety for object stored in it



But if multiple threads of execution access the same shared_ptr instance without synchronization and any of those accesses uses a non-const member function of shared_ptr then a data race will occur; the shared_ptr overloads of atomic functions can be used to prevent the data race.

Weak Pointer

std::weak_ptr can be thought of as an **observer** to an object that is managed by std::shared_ptr. It must be converted to std::shared_ptr in order to access the referenced object.

- `std::weak_ptr` can only be constructed from instances of `std::shared_ptr` or other weak pointers.
- `std::weak_ptr::lock` must be called to in order to access the referenced object: it return a new std::shared_ptr that shares ownership of the managed object.

```
#include <iostream>
#include <cassert>
#include <memory>

// `std::weak_ptr` can only be constructed from
// instances of `std::shared_ptr` or other weak
// pointers.

// http://en.cppreference.com/w/cpp/memory/weak_ptr

// Weak pointers can be used to check whether or
// not an object managed by `shared_ptr` is alive:
void checking_existence()
{
    std::weak_ptr<int> wp;

    assert(wp.use_count() == 0);
    assert(wp.expired());

    {
        auto sp = std::make_shared<int>(42);
        wp = sp;

        assert(wp.use_count() == 1);
        assert(!wp.expired());
```

```
        auto sp2 = sp;

        assert(wp.use_count() == 2);
        assert(!wp.expired());
    }

    assert(wp.use_count() == 0);
    assert(wp.expired());
}

// Accessing an object through an `std::weak_ptr`
// requires a conversion to `std::shared_ptr`
// first:
void accessing_objects()
{
    // http://en.cppreference.com/w/cpp/memory/weak_ptr/lock

    std::weak_ptr<int> wp;
    assert(wp.lock() == nullptr);

    auto sp = std::make_shared<int>(42);
    wp = sp;
    assert(* wp.lock() == 42);
}

int main()
{
    checking_existence();
    accessing_objects();
}
```

As an observer, std::weak_ptr does not increase the `use_count` of the std::shared_ptr it observes. The property makes it possible to use std::weak_ptr to break circular references of std::shared_ptr.

Circular references of shared pointer

We saw how std::shared_ptr allowed us to have multiple smart pointers co-owning the same resource. However, in certain cases, this can become problematic. Consider the following case, where the shared pointers in two separate objects each point at the other object.

```
#include <iostream>
#include <memory> // for std::shared_ptr
#include <string>

class Person
{
    std::string m_name;
    std::shared_ptr<Person> m_partner; // initially created empty

public:

    Person(const std::string &name): m_name(name)
    {
        std::cout << m_name << " created\n";
    }
    ~Person()
    {
        std::cout << m_name << " destroyed\n";
```

```
    }

    friend bool partnerUp(std::shared_ptr<Person> &p1, std::shared_ptr<Person> &p2)
    {
        if (!p1 || !p2)
            return false;

        p1->m_partner = p2;
        p2->m_partner = p1;

        std::cout << p1->m_name << " is now partnered with " << p2->m_name << "\n";

        return true;
    }
};

int main()
{
    auto lucy = std::make_shared<Person>("Lucy"); // create a Person named "Lucy"
    auto ricky = std::make_shared<Person>("Ricky"); // create a Person named "Ricky"

    partnerUp(lucy, ricky); // Make "Lucy" point to "Ricky" and vice-versa

    return 0;
}
```

Try running the codes above and we see that `lucy` and `ricky` is never destructed. To break the circular dependency, use `std::weak_ptr<Person>` for `Person`'s member `m_partner`. The rest of the codes are not changed. This time we will see that both `lucy` and `ricky` are destructed when the shared pointer for them expires.

```
class Person
{
    ...
    std::weak_ptr<Person> m_partner; // note: This is now a std::weak_ptr
  ...
};
```

Discussions Of Using Smart pointers

Dynamic allocation has cost

- Objects on the stack are generally easier to reason about and more "predictable"
- Allocations are not free, they can reduce locality, and compiler is often not able to aggressively optimize
- If allocation is necessary, use smart pointers over new/delete

std::unique_ptr as first choice

- Zero-cost abstraction over new/delete
- Simple to reason about

std::shared_ptr should be used sparingly

- Not a zero-cost abstraction over new/delete
- Harder to reason about

Always use std::make_xxx to create smart pointers

- Prevent potential memory leaks
- Better readability
- Improve performance for std::shared_ptr

Pointers used in function arguments

```
#include <memory>

// Observing/mutating an object: pass by reference.
void f0(int&);
void f1(const int&);

// Observing/mutating a smart pointer: pass by reference.
// For example, may be we want to reset a std::unique_ptr;
// or check whether a std::unique_ptr has been expired
void f2(std::unique_ptr<int>&);
void f3(const std::unique_ptr<int>&);
void f4(std::shared_ptr<int>&);
void f5(const std::shared_ptr<int>&);
void f6(std::weak_ptr<int>&);
void f7(const std::weak_ptr<int>&);

// Transferring ownership: pass by value.
// This makes it clear that we don't want to observe or mutate a unique_ptr
void f8(std::unique_ptr<int>);

// Sharing ownership: pass by value.
// Gives caller a chance to decide between Transferring/sharing ownership
void f9(std::shared_ptr<int>);

// Observing/mutating an optional object: pass by raw pointer.
void f10(int*);
void f11(const int*);
```