Smart Pointers in C++

Jonas R. Glesaaen
glesaaen@th.physik.uni-frankfurt.de

September 24th 2014

Literature

[1] Boost c++ library.
http://www.boost.org.

[2] C++ reference.
http://cppreference.com.

[3] E. Gamma, R. Helm, R. Johnson, and J. Vlissides.
Design Patterns: Elements of Reusable Object-Oriented Software.
Pearson Education, 1994.

[4] S. Meyers.
More Effective C++: 35 New Ways to Improve Your Programs and Designs.
Pearson Education, 1995.

[5] S. Meyers.
Effective C++: 55 Specific Ways to Improve Your Programs and Designs.
Pearson Education, 2005.

[6] H. Sutter.
Gotw #89 solution: Smart pointers.
http://herbsutter.com/2013/05/29/gotw-89-solution-smart-pointers/.

What are smart pointers?

Objects designed to act like pointers, but provide extended functionality. Example of the proxy pattern [3].

Standard pointer use example:

```
MyClass * ptr = new MyClass();
ptr->Function();
delete ptr;
```

Smart pointers can manipulate three aspects of pointer behaviour:

- Construction
- Dereferencing
- Destruction

Why use smart pointers?

Primarily to avoid memory leaks, which can come from a myriad of different sources;

Memory leak sources

```
MyClass * ptr = new MyClass();
//... (1)
ptr->Function(); //(2)
//...
delete ptr; //(3)
```

1. Might have multiple return paths
2. Might throw an exception
3. One might simply forget to free the resource

Why use smart pointers?

Primarily to avoid memory leaks, which can come from a myriad of different sources;

Memory leak sources

```
MyClass * ptr = new MyClass();
//... (1)
ptr->Function(); //(2)
//...
delete ptr; //(3)
```

1. Might have multiple return paths
2. Might throw an exception
3. One might simply forget to free the resource

Solution: Wrap the resource in a class which frees it on destruction.

Types of smart pointers

Smart pointers where one object singularly owns a resource

Smart pointers where the resource is shared by multiple objects.

Shared smart pointers utilising the *copy-on-write* technique.

Types of smart pointers

Smart pointers where one object singularly owns a resource

Smart pointers where the resource is shared by multiple objects.

Shared smart pointers utilising the *copy-on-write* technique.

The copy-on-write technique is an optimisation technique where if two objects are initialised to have the same value to begin with, they both "point to" the same resource (shared smart resource), but the moment one of them edits its own version, a copy is made before it is written to, and the two objects do not point to the same resource any more. `std::string` followed this principle up to C++03, but after the introduction of move semantics, they went away from that.

Smart pointer implementations

All following smart pointers do “garbage collection”, but they differ in how they are assigned:

Assignment

```
SmartPtr<MyClass> p(new MyClass());
SmartPtr<MyClass> q = p;
```

← What happens here?

std	boost	Qt
`std::unique_ptr`		
`std::shared_ptr`	`boost::shared_ptr`	`QSharedPointer`
`std::weak_ptr`	`boost::weak_ptr`	`QWeakPointer`
`std::auto_ptr`	`boost::scoped_ptr`	`QScopedPointer`

Smart pointer implementations

All following smart pointers do "garbage collection", but they differ in how they are assigned:

Assignment

```
SmartPtr<MyClass> p(new MyClass());
SmartPtr<MyClass> q = p;  ←— What happens here?
```

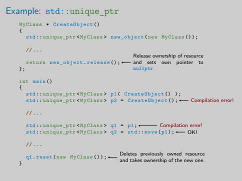
std	boost	Qt
std::unique_ptr		
std::shared_ptr	boost::shared_ptr	QSharedPointer
std::weak_ptr	boost::weak_ptr	QWeakPointer
std::auto_ptr	boost::scoped_ptr	QScopedPointer

Qt handles memory through the parent-child relationship of QObjects and the smart pointers are not as frequently used.

unique_ptr forbids copy assignment and copy construction, while shared_ptr keeps a reference count of how many objects point to a specific resource. A weak pointer has a non-owning reference to a shared_ptr, but one must "lock" the object before one can use the resource. First and foremost, auto_ptr's are deprecated and shouldn't be used. They handle copy assignment/construction by handing over the pointer, setting it's own pointer to null. It does therefore not have a const assignment operator / copy constructor.

Example: std::unique_ptr

```
MyClass * CreateObject()
{
  std::unique_ptr<MyClass> new_object(new MyClass());

  //...

  return new_object.release(); ← Release ownership of resource and sets own pointer to nullptr
};

int main()
{
  std::unique_ptr<MyClass> p1( CreateObject() );
  std::unique_ptr<MyClass> p2 = CreateObject(); ← Compilation error!

  //...

  std::unique_ptr<MyClass> q1 = p1; ← Compilation error!
  std::unique_ptr<MyClass> q2 = std::move(p1); ← OK!

  //...

  q1.reset(new MyClass()); ← Deletes previously owned resource and takes ownership of the new one.
}
```



The `std::unique_ptr<T> ptr = new T()` can't compile as we would have to write a converter from a raw pointer to `std::unique_ptr` for it to work, something which could in general have unexpected consequences. As usual, do not provide a cast operator (or an implicit cast) unless there is a good reason for it. Smart pointers should never allow to be implicitly converted to or from raw pointers.

Example: std::shared_ptr and std::weak_ptr

```
std::shared_ptr<MyClass> p1(new MyClass());

std::shared_ptr<MyClass> p2 = p1;

{
  std::shared_ptr<MyClass> p3 = p2;

  std::weak_ptr<MyClass> wp = p2;

  if(auto p = wp.lock()) {
    // ...
  }
}

// ...
```

Example: std::shared_ptr and std::weak_ptr

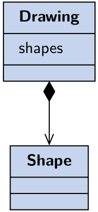
```
std::shared_ptr<MyClass> p1(new MyClass());    use count: 1

std::shared_ptr<MyClass> p2 = p1;              use count: 2

{
  std::shared_ptr<MyClass> p3 = p2;            use count: 3

  std::weak_ptr<MyClass> wp = p2;              use count: 3

  if(auto p = wp.lock()) {
    // ...                                     use count: 4
  }
}

// ...                                         use count: 2
```

Example: std::shared_ptr and std::weak_ptr

```
std::weak_ptr<MyClass> wp;

{
  std::shared_ptr<MyClass> sp =
        std::make_shared<MyClass>();

  wp = sp;

  if(auto wsp = wp.lock()) {
    // ...
  }

  // ...
}

if(wp.expired()) {
  // Managed resource has been deleted
}
```

Choosing the right smart pointer

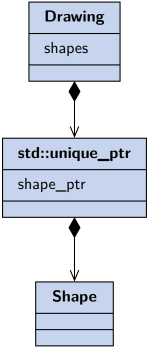
`std::unique_ptr` symbolises owning a resource.



The resource can be shared through references or raw pointers

Choosing the right smart pointer

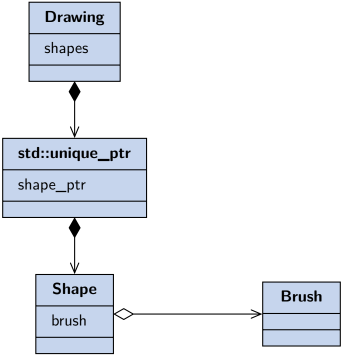
`std::unique_ptr` symbolises owning a resource.



The resource can be shared through references or raw pointers

Choosing the right smart pointer

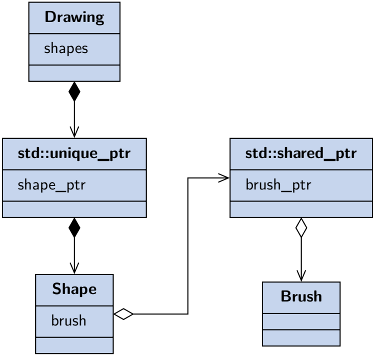
`std::shared_ptr` on the other hand symbolises sharing a resource with other objects.



The resource can still be shared through pointers and references, but also using the `std::shared_ptr` copy constructor and copy assignment operator.

Choosing the right smart pointer

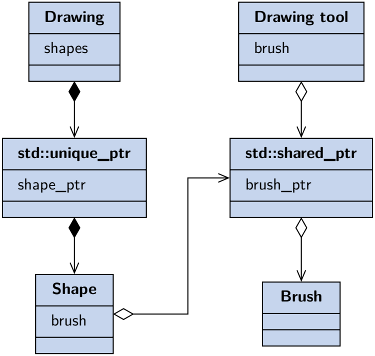
`std::shared_ptr` on the other hand symbolises sharing a resource with other objects.



The resource can still be shared through pointers and references, but also using the `std::shared_ptr` copy constructor and copy assignment operator.

Choosing the right smart pointer

`std::shared_ptr` on the other hand symbolises sharing a resource with other objects.



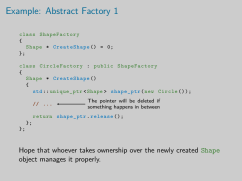
The resource can still be shared through pointers and references, but also using the `std::shared_ptr` copy constructor and copy assignment operator.

Example: Abstract Factory 1

```
class ShapeFactory
{
  Shape * CreateShape() = 0;
};

class CircleFactory : public ShapeFactory
{
  Shape * CreateShape()
  {
    std::unique_ptr<Shape> shape_ptr(new Circle());

    // ...

    return shape_ptr.release();
  };
};
```

The pointer will be deleted if something happens in between

Hope that whoever takes ownership over the newly created Shape object manages it properly.



Factory methods can also obviously return pointers with shared ownership. Unless the return type tells you whether it is shared or unique ownership, whoever calls the function has no way of knowing. Factory methods should return unique pointers unless the resource is shared by the factory itself.

Example: Abstract Factory 2

```
class ShapeFactory
{
  std::unique_ptr<Shape> CreateShape() = 0;
};

class CircleFactory : public ShapeFactory
{
  std::unique_ptr<Shape> CreateShape()
  {
    std::unique_ptr<Shape> shape_ptr(new Circle());

    // ...

    return shape_ptr;   <----- OK, because it is turned into an rvalue.
  };
};
```

The new owner of the `Shape` object is forced to manage its memory properly.

Example: Abstract Factory 2

```
class ShapeFactory
{
  std::unique_ptr<Shape> CreateShape() = 0;
};

class CircleFactory : public ShapeFactory
{
  std::unique_ptr<Shape> CreateShape()
  {
    std::unique_ptr<Shape> shape_ptr(new Circle());

    // ...

    return shape_ptr;
  };
};
```

OK, because it is turned into an rvalue.

The new owner of the Shape object is forced to manage its memory properly.

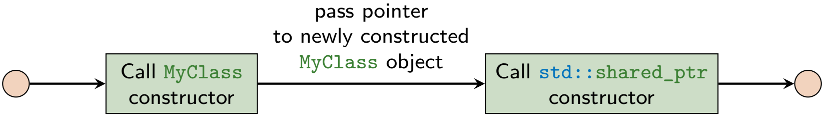
Apparently whether the return is turned into an rvalue is compiler dependent, but it should.

Problems with explicit new's: #1

Consider creating a std::shared_ptr with a new statement

Naïve construction

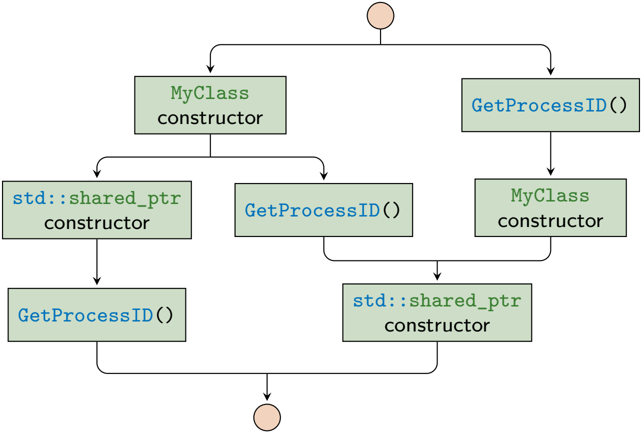
```
std::shared_ptr<MyClass> ptr(new MyClass());
```



The constructors are called separately and the compiler cannot optimise memory location.

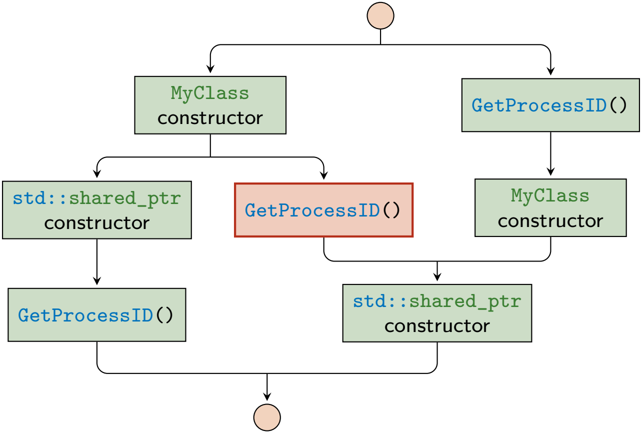
Problems with explicit new's: #2

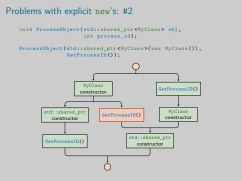
```
void ProcessObject(std::shared_ptr<MyClass> obj,
                   int process_id);

ProcessObject(std::shared_ptr<MyClass>(new MyClass()),
              GetProcessID());
```



Problems with explicit new's: #2

```
void ProcessObject(std::shared_ptr<MyClass> obj,
                   int process_id);

ProcessObject(std::shared_ptr<MyClass>(new MyClass()),
              GetProcessID());
```





We have no control over the order in which the compiler carries out the three processes (other than that calling `MyClass`'s creator has to happen before `std::shared_ptr`'s).

Create using `std::make_unique` and `std::make_shared`

Both these problems can be remedied by using `std::make_shared` and `std::make_unique` (*C++14*).

Replacing the constructor call

```
void ProcessObject(std::shared_ptr<MyClass> obj,
                   int process_id);

ProcessObject(std::make_shared<MyClass>(),
              GetProcessID());
```

Constructor calls cannot be intertwined with the `GetProcessID()` anymore.

Create using std::make_unique and std::make_shared

Both these problems can be remedied by using std::make_shared and std::make_unique (C++14).

Replacing the constructor call

```
void ProcessObject(std::shared_ptr<MyClass> obj,
                   int process_id);

ProcessObject(std::make_shared<MyClass>(),
              GetProcessID());
```

Constructor calls cannot be intertwined with the GetProcessID() anymore.

On top of fixing these types of issues, using make_shared and make_unique doesn't reveal the underlying pointer, and therefore one cannot misuse the raw pointer without actively calling .get() or .release(), in which case it is easy to spot ones mistakes.

Create using `std::make_unique` and `std::make_shared`

Guideline

> *Don't use explicit new, delete, and owning * pointers, except in rare cases encapsulated inside the implementation of a low-level data structure.*
>
> — Herb Sutter [6]

Match constructors with destructors

Smart pointers have a control block which also keeps track of an allocator and a deleter

std::shared_ptr constructor

```
template <class Type, class Deleter, class Alloc>
std::shared_ptr(Type * p, Deleter d, Alloc a);
```

Custom deleter

```
std::shared_ptr<int> ap(new int[10]);
```

Destructs using `delete`

```
std::shared_ptr<int> ap(new int[10],
  std::default_delete<int[]>());
```

Destructs using `delete[]`

```
std::shared_ptr<int[]> ap(new int[10]);
```

Destructs using `delete[]`

Very important that the deleter doesn't throw.

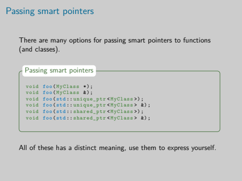
Passing smart pointers

There are many options for passing smart pointers to functions (and classes).

Passing smart pointers

```
void foo(MyClass *);
void foo(MyClass &);
void foo(std::unique_ptr<MyClass>);
void foo(std::unique_ptr<MyClass> &);
void foo(std::shared_ptr<MyClass>);
void foo(std::shared_ptr<MyClass> &);
```

All of these has a distinct meaning, use them to express yourself.



Pointer vs reference boils down to the usual "Is no-value a valid option?", and in classes pointers can be rebound, references not. Passing smart pointers by reference limits the function to only accept one type of smart pointers, while passing shared pointers by value has a cost (as the object needs to be constructed and destructed).

Smart pointers and polymorphic classes

Using smart pointers and polymorphic classes as template arguments works as expected because one of the smart pointer constructors read:

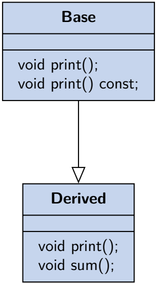
The `std::shared_ptr` constructor

```
template<class T, class U>
std::shared_ptr<T>(const std::shared_ptr<U> &)
```

This costructor can be used to convert between `std::shared_ptr`'s if `T*` is implicitly convertible to `U*`.

Smart pointers and polymorphic classes

Assume we have a class hierarchy:



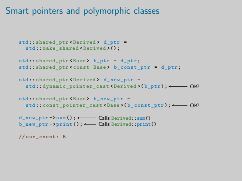
Where `Derived` overloads the `print()` function but not the `const` variant.

Smart pointers and polymorphic classes

```
std::shared_ptr<Derived> d_ptr =
  std::make_shared<Derived>();

std::shared_ptr<Base> b_ptr = d_ptr;
std::shared_ptr<const Base> b_const_ptr = d_ptr;

std::shared_ptr<Derived> d_err_ptr = b_ptr;          // Compilation error
std::shared_ptr<Base> b_err_ptr = b_const_ptr;       // Compilation error

b_ptr->print();          // Calls Derived::print()
b_const_ptr->print();    // Calls Base::print()const

//use_count: 3
```

Smart pointers and polymorphic classes

```
std::shared_ptr<Derived> d_ptr =
  std::make_shared<Derived>();

std::shared_ptr<Base> b_ptr = d_ptr;
std::shared_ptr<const Base> b_const_ptr = d_ptr;

std::shared_ptr<Derived> d_new_ptr =
  std::dynamic_pointer_cast<Derived>(b_ptr);        OK!

std::shared_ptr<Base> b_new_ptr =
  std::const_pointer_cast<Base>(b_const_ptr);       OK!

d_new_ptr->sum();        Calls Derived::sum()
b_new_ptr->print();      Calls Derived::print()

//use_count: 5
```



This is a more error safe way of working with pointer casts as one never has to access the underlying raw pointer and explicitly own raw pointers as one would have to do with `.get()` together with standard C++ casts. It would also not be possible to re-own the result of the standard cast as one has extraced it out of the reference counting object. This is inteded to use with `std::shared_ptr`'s, and doesn't work with `std::unique_ptr`.

Smart pointers and the STL

- Smart pointers can be stored in the STL containers.
- However, not all algorithms work with the resulting containers.
  - E.g. `std::unique_ptr` is MoveConstructible and MoveAssignable
  - But not CopyConstructable or CopyAssignable

Thus if an algorithm requires CopyConstructability and a `std::unique_ptr` is given, it should fail to compile.

`std::auto_ptr` on the other hand is a bit more unreliable.

Smart pointers and the STL

- Smart pointers can be stored in the STL containers.
- However, not all algorithms work with the resulting containers.
  - E.g. std::unique_ptr is MoveConstructible and MoveAssignable
  - But not CopyConstructable or CopyAssignable

Thus if an algorithm requires CopyConstructability and a std::unique_ptr is given, it should fail to compile.

std::auto_ptr on the other hand is a bit more unreliable.

`std::auto_ptr` is technically not CopyConstructable and CopyAssignable as the copied object is changed, but this won't always result in a compilation error (or even a compilation warning) as it should. It depends on your compiler, but is not a risk one should take regardless. Before the introduction of move semantics for example, an iterator needed to be CopyConstructable and assignable for it to be used with the sort-algorithm. auto_ptr's would therefore not be usable in this case, but not all compilers would warn you of that.

The boost pointer container library

Library inteded to provide a STL-like library for single ownership pointers.

Advantages

- Simplifies the container-of-pointer syntax.
- Notational convenience
  - Dereferencing an iterator returns a dereferenced pointer
- Introduces “Clonability” to do deep copies.
- Faster and has a small memory overhead.

Disadvantages

- Not very compatible with the algorithm library
- Not as flexible as a container of smart pointers

Summary

- Use smart pointers to manage dynamic resources so that they are freed when they aren't used anymore.
  - Use `std::unique_ptr` to signal singular ownership
  - Use `std::shared_ptr` to signal shared ownership
  - Use `std::weak_ptr` to signal uncommitted shared ownership
- Avoid using explicit `new` and `delete` statements, and explicit ownership of raw pointers.