Modern C++ Design

1 Policy-Based Class Design

In brief, policy-based class design fosters assembling a class with complex behavior out of many little classes (called policies), each of which takes care of only one behavioral or structural aspect.
The generic SingletonHolder class **template** (Chapter 6) uses policies for managing lifetime and thread safety. SmartPtr (Chapter 7) is built almost entirely from policies. The **double-dispatch engine** in Chapter 11 uses policies for selecting various trade-offs. The generic **Abstract Factory** implementation in Chapter 9 uses a policy for choosing a creation method.

1.1 Failure of the Do-it-all Interface

Implementing everything under the umbrella of a do-it-all interface is not a good solution, for several reasons:

- Intellectual overhead, sheer size, and inefficiency.
- Loss of static type safety. A design should enforce most constraints at compile time. (No two singleton objects)

1.2 Multiple Inheritance to the Rescue?

For example, the user would build a multi-threaded, reference-counted smart pointer class by inheriting some `BaseSmartPtr` class and two classes: `MultiThreaded` and `RefCounted`. Any experienced class designer knows that such a naive design does not work.
The problems with assembling separate features by using multiple inheritance are as follows:

- **Mechanics**. There is no boilerplate code to assemble the inherited components in a controlled manner. **The language applies simple superposition in combining the base classes and establishes a set of simple rules for accessing their members.**
- **Type information**. The base classes do not have enough type information to carry out their tasks.
- **State manipulation**. Various behavioral aspects implemented with base classes must manipulate the same state. This means that they must use virtual inheritance to inherit a base class that holds the state. This complicates the design and makes it more rigid because the premise was that user classes inherit library classes, not vice versa.

1.3 Templates

Benefits:

- Class templates are customizable in ways not supported by regular classes.

- for class templates with multiple parameters, you can use partial template specialization.

As soon as you try to implement such designs, you stumble upon several problems that are not self-evident:

- You cannot specialize structure.
- Specialization of member functions does not scale: you cannot specialize individual member functions for templates with multiple template parameters.
- The library writer cannot provide multiple **default** values.

Multiple inheritance and templates foster complementary trade-offs:

- Multiple inheritance has scarce mechanics; templates have rich mechanics
- Multiple inheritance loses type information, which abounds in templates.
- Specialization of templates does not scale, but multiple inheritance scales quite nicely.
- You can provide only one default for a template member function, but you can write an unbounded number of base classes.

1.4 Policy Classes

A **policy** defines a class interface or a class template interface. The interface consists of one or all of the following: **inner type definitions, member functions, and member variables**. The implementations of a policy are called **policy classes**. Policy classes are not intended for stand-alone use; instead, they are inherited by, or contained within, other classes.

```
template <class T>
struct OpNewCreator{
  static T* Create(){
    return new T;
  }
};

template <class T>
struct MallocCreator{
  static T* Create(){
    void* buf = std::malloc(sizeof(T));
    if (!buf) return 0;
    return new(buf) T;
  }
};

template <class T>
struct PrototypeCreator{
  PrototypeCreator(T* pObj = 0):pPrototype_(pObj){}
  T* Create(){
```

```
    return pPrototype_ ? pPrototype_->Clone() : 0;
  }
  T* GetPrototype() { return pPrototype_; }
  void SetPrototype(T* pObj) { pPrototype_ = pObj; }
private:
  T* pPrototype_;
};
```

The classes that use one or more policies are called hosts or **host classes**.

```
template <class CreationPolicy>
class WidgetManager : public CreationPolicy{
  ...
};
typedef WidgetManager< OpNewCreator<Widget> > MyWidgetMgr;
```

It is the user of `WidgetManager` **who chooses the creation policy**. This is the gist of policy-based class design.

1.5 Implementing Policy Classes with Template Template Parameters

The policy's template argument is redundant. In this case, we can use **template template parameters** for specifying policies, as shown in the following:

```
template <template <class> class CreationPolicy = OpNewcreator>
class WidgetManager : public CreationPolicy<Widget>{
  ...
};
typedef WidgetManager<OpNewCreator> MyWidgetMgr;
```

Using template template parameters with policy classes is not simply a matter of convenience; sometimes, it is essential that the host class have access to the template so that the host can instantiate it with a different type. For example:

```
template <template <class> class CreationPolicy = OpNewcreator>
class WidgetManager : public CreationPolicy<Widget>{
  void DoSomething(){
    Gadget* pW = CreationPolicy<Gadget>().Create();
  }
};
```

Benefits of using policies:

- you can change policies from theoutside as easily as changing a template argument when you instantiate `WidgetManager`.
- you can provide your own policies that are specific to your concrete application.
- Policies allow you to generate designs by combining simple choices in a typesafe manner.
- the binding between a host class and its policies is done at compile time, the code is tight and efficient, comparable to its handcrafted equivalent.

1.6 Destructors of Policy Classes

The user can automatically convert a host class to a policy and later `delete` that pointer. Unless the policy class defines a virtual destructor, applying delete to a pointer to the policy class has undefined behavior.

Defining a virtual destructor for a policy, however, works against its static nature and hurts performance. The lightweight, effective solution that policies should use is to define a nonvirtual protected destructor:

```
template <class T>
struct OpNewCreator{
protected:
  ~OpNewCreator() {}
};
```

Because the destructor is protected, **only derived classes can destroy policy objects**, so it's impossible for outsiders to apply delete to a pointer to a policy class.

1.7 Enriched Policies

The `Creator` policy prescribes only one member function, `Create`. However, `PrototypeCreator` defines two more functions: `GetPrototype` and `SetPrototype`.

A user who uses a prototype-based Creator policy class can write the following code:

```
typedef WidgetManager<PrototypeCreator> MyWidgetManager;

Widget* pPrototype = ...;
MyWidgetManager mgr;
mgr.SetPrototype(pPrototype);
```

If the user later decides to use a creation policy that does not support prototypes, **the compiler pinpoints the spots where the prototype-specific interface was used.** This is exactly what should be expected from a sound design.

1.8 Optional Functionality Through Incomplete Instantiation

If a member function of a class template is never used, **it is not even instantiated—the compiler does not look at it at all**, except perhaps for syntax checking.

```
template <template <class> class CreationPolicy>
class WidgetManager : public CreationPolicy<Widget>{
  void SwitchPrototype(Widget* pNewPrototype){
    CreationPolicy<Widget>& myPolicy = *this;
    delete myPolicy.GetPrototype();
    myPolicy.SetPrototype(pNewPrototype);
  }
};
```

The resulting context is very interesting:

- If the user instantiates `WidgetManager` with a Creator policy class that does not support prototypes and tries to use `SwitchPrototype`, a compile-time error occurs.
- If the user instantiates `WidgetManager` with a Creator policy class that does not support prototypes and does not try to use `SwitchPrototype`, the program is valid.

This all means that `WidgetManager` can benefit from optional enriched interfaces but still work correctly with poorer interfaces.

1.9 Compatible and Incompatible Policies

Suppose you create two instantiations of `SmartPtr : FastWidgetPtr`, a pointer with out checking, and `SafeWidgetPtr`, a pointer with checking before dereference. It is natural to accept the conversion from `FastWidgetPtr` to `SafeWidgetPtr`, but freely converting `SafeWidgetPtr` objects to `FastWidgetPtr` objects is dangerous.

The best, most scalable way to implement conversions between policies is to initialize and copy `SmartPtr` objects policy by policy, as shown below:

```
template<class T,template <class> class CheckingPolicy>
class SmartPtr : public CheckingPolicy<T>{
  template<class T1,template <class> class CP1,>
  SmartPtr(const SmartPtr<T1, CP1>& other)
    : pointee_(other.pointee_), CheckingPolicy<T>(other){ ... }
};
```

When you initialize a `SmartPtr<Widget, EnforceNotNull>` with a `SmartPtr<ExtendedWidget, NoChecking>`. The compiler tries to match `SmartPtr<ExtendedWidget, NoChecking>` to `EnforceNotNull`'s constructors.

If `EnforceNotNull` implements a **constructor** that accepts a `NoChecking` object, then the compiler matches that constructor. If `NoChecking` implements a **conversion** operator to `EnforceNotNull`, that conversion is invoked. In any other case, the code fails to compile.

Although conversions from `NoChecking` to `EnforceNotNull` and even vice versa are quite sensible, some conversions don't make any sense at all. As soon as you try to confine a pointer to another ownership policy, you break the invariant that makes reference counting work.

In conclusion, conversions that change the ownership policy should not be allowed implicitly and should be treated with maximum care.

1.10 Decomposing a Class into Policies

Two policies that do not interact with each other are orthogonal. By this definition, the Array and the Destroy policies are not orthogonal.

Nonorthogonal policies are an imperfection you should strive to avoid. **They reduce compile-time type safety and complicate the design of both the host class and the policy classes.**

If you must use nonorthogonal policies, you can minimize dependencies by passing a policy class as an argument to another policy class's template function. However, this decreases encapsulation.

2 Techniques

2.1 Compile-Time Assertions

C++17 provides static_assert.

The simplest solution to compile-time assertions works in C as well as in C++, relies on the fact that a zero-length array is illegal.

```
#define STATIC_CHECK(expr) { char unnamed[(expr) ? 1 : 0]; }
template <class To, class From>
To safe_reinterpret_cast(From from){
  STATIC_CHECK(sizeof(From) <= sizeof(To));
  return reinterpret_cast<To>(from);
}
void* somePointer = ...;
char c = safe_reinterpret_cast<char>(somePointer);
```

The problem with this approach is that the error message you receive is not terribly informative. Error messages have no rules that they must obey; it's all up to the compiler.

A better solution is to rely on a template with an informative name; with luck, the compiler will mention the name of that template in the error message.

```
template<bool> struct CompileTimeError;
template<> struct CompileTimeError<true> {};
#define STATIC_CHECK(expr) \
(CompileTimeError<(expr) != 0>())
```

If you try to instantiate CompileTimeError<false>, the compiler utters a message such as "Undefined specialization CompileTimeError<false>." This message is a slightly better hint that the error is intentional and not a compiler or a program bug.

Actually, the name CompileTimeError is no longer suggestive in the new context. **The ellipsis means the constructor accepts anything.**

```
template<bool> struct CompileTimeChecker{
  CompileTimeChecker(...);
};
template<> struct CompileTimeChecker<false> { };
#define STATIC_CHECK(expr, msg) {\
  class ERROR_##msg {}; \
  (void)sizeof(CompileTimeChecker<(expr) != 0>((ERROR_##msg())));\
}

template <class To, class From>
To safe_reinterpret_cast(From from){
  STATIC_CHECK(sizeof(From) <= sizeof(To),Destination_Type_Too_Narrow);
  return reinterpret_cast<To>(from);
}
void* somePointer = ...;
char c = safe_reinterpret_cast<char>(somePointer);
```

After macro preprocessing, the code of safe_reinterpret_cast expands to the following:

```
template <class To, class From>
To safe_reinterpret_cast(From from){
  class ERROR_Destination_Type_Too_Narrow {};
  (void)sizeof(
    CompileTimeChecker<(sizeof(From) <= sizeof(To))>(
      ERROR_Destination_Type_Too_Narrow()));
  return reinterpret_cast<To>(from);
}
```

The CompileTimeChecker<true> specialization has a constructor that accept anything; it's an ellipsis function. If the comparison between sizes evaluates to false, a decent compiler outputs an error message such as "Error: Cannot convert ERROR_Destination_Type_Too_Narrow to CompileTimeChecker <false>.

2.2 Partial Template Specialization

```
template <class Window, class Controller>
class Widget{
  ... generic implementation ...
};

// Partial specialization of Widget
template <class Window>
class Widget<Window, MyController>{
  ... partially specialized implementation ...
};

template <class ButtonArg>
class Widget<Button<ButtonArg>, MyController>{
  ... further specialized implementation ...
};
```

Unfortunately, partial template specialization does not apply to functions—be they member or nonmember—which somewhat reduces the flexibility and the granularity of what you can do:

- Although you can **totally specialize** member functions of a class template, you cannot **partially specialize** member functions.
- You cannot partially specialize namespace-level (nonmember) template functions. The closest thing to partial specialization for namespace-level template functions is overloading (not for changing the return value or for internally used type).

```
template <class T, class U> T Fun(U obj); // primary template
template <class U> void Fun<void, U>(U obj); // illegal partial specialization
template <class T> T Fun (Window obj); // legal (overloading)
```

2.3 Local Classes

Local classes cannot define static member variables and cannot access nonstatic local variables. What makes local classes truly interesting is that you can use them in template functions. **Local classes defined inside template functions can use the template parameters of the enclosing function.**

```
class Interface{
public:
virtual void Fun() = 0;
};
template <class T, class P>
Interface* MakeAdapter(const T& obj, const P& arg){
  class Local : public Interface{
  public:
    Local(const T& obj, const P& arg): obj_(obj), arg_(arg) {}
    virtual void Fun(){
      obj_.Call(arg_);
    }
  private:
     T obj_;
     P arg_;
  };
  return new Local(obj, arg);
}
```

It can be easily proven that any idiom that uses a local class can be implemented using a template class outside the function. On the other hand, local classes can simplify implementations and improve locality of symbols.

Local classes do have a unique feature, though: They are **final**. Outside users cannot derive from a class hidden in a function. Without local classes, you'd have to add an unnamed namespace in a separate translation unit.

2.4 Mapping Integral Constants to Types

```
template <int v>
struct Int2Type{
enum { value = v };
};
```

`Int2Type` generates a distinct type for each distinct constant integral value passed. You can use `Int2Type` whenever you need to "typify" an integral constant quickly. This way you can **select different functions, depending on the result of a compile-time calculation.** Effectively, you **achieve static dispatching on a constant integral value.**

For dispatching at runtime, you can use simple `if-else` statements or the `switch` statement. However, the `if-else` statement requires both branches to compile successfully, even when the condition tested by `if` is known at compile time.

```
template <typename T, bool isPolymorphic>
class NiftyContainer{
  void DoSomething(){
    T* pSomeObj = ...;
    if (isPolymorphic){
      T* pNewObj = pSomeObj->Clone();
      ... polymorphic algorithm ...
    }
    else{
      T* pNewObj = new T(*pSomeObj);
      ... nonpolymorphic algorithm ...
    }
  }
};
```

The polymorphic algorithm uses `pObj->Clone()`, `NiftyContainer::DoSomething` does not compile for any type that doesn't define a member function `Clone()`.

If `T` has disabled its copy constructor (by making it private), if `T` is a polymorphic type and the nonpolymorphic code branch attempts `new T(*pObj)`, the code might fail to compile.

```
template <typename T, bool isPolymorphic>
class NiftyContainer{
private:
  void DoSomething(T* pObj, Int2Type<true>){
    T* pNewObj = pObj->Clone();
    ... polymorphic algorithm ...
  }
  void DoSomething(T* pObj, Int2Type<false>){
    T* pNewObj = new T(*pObj);
    ... nonpolymorphic algorithm ...
  }
public:
  void DoSomething(T* pObj){
    DoSomething(pObj, Int2Type<isPolymorphic>());
  }
};
```

There is another solution, `if constexpr()`, the new feature provided by c++17.

2.5 Type-to-Type Mapping

```
template <class T, class U>
T* Create(const U& arg){
  return new T(arg);
}
```

If objects of type `Widget` are untouchable legacy code and must take two arguments upon construction, the second being a fixed value such as -1. How can you specialize Create so that it treats `Widget` differently from all other types with a uniform interface?

```
// Illegal code | don't try this at home
template <class U>
Widget* Create<Widget, U>(const U& arg){
  return new Widget(arg, -1);
}

// rely on overloading
template <class T, class U>
T* Create(const U& arg, T /* dummy */){
  return new T(arg);
}
template <class U>
Widget* Create(const U& arg, Widget /* dummy */){
  return new Widget(arg, -1);
}
```

Such a solution would incur the overhead of constructing an arbitrarily complex object that remains unused.

```
template <typename T>
struct Type2Type{
  typedef T OriginalType;
};
template <class T, class U>
T* Create(const U& arg, Type2Type<T>){
  return new T(arg);
}
template <class U>
Widget* Create(const U& arg, Type2Type<Widget>){
  return new Widget(arg, -1);
}
// Use Create()
String* pStr = Create("Hello", Type2Type<String>());
Widget* pW = Create(100, Type2Type<Widget>());
```

2.6 Type Selection

Sometimes generic code needs to select one type or another, depending on a Boolean constant. You might want to use an `std::vector` as your back-end storage. Obviously, you cannot store polymorphic types by value, so you must store pointers. On the other hand, you might want to store nonpolymorphic types by value, because this is more efficient.

```
template <typename T, bool isPolymorphic>
struct NiftyContainerValueTraits{
  typedef T* ValueType;
};
template <typename T>
```

```
struct NiftyContainerValueTraits<T, false>{
  typedef T ValueType;
};
template <typename T, bool isPolymorphic>
class NiftyContainer{
  typedef NiftyContainerValueTraits<T, isPolymorphic> Traits;
  typedef typename Traits::ValueType ValueType;
};
```

This way of doing things is unnecessarily clumsy. Moreover, it doesn't scale: For each type selection, you must define a new traits class template.

```
template <bool flag, typename T, typename U>
struct Select{
  typedef T Result;
};
template <typename T, typename U>
struct Select<false, T, U>{
  typedef U Result;
};

template <typename T, bool isPolymorphic>
class NiftyContainer{
  typedef typename Select<isPolymorphic, T*, T>::Result ValueType;
}
```

2.7 Detecting Convertibility and Inheritance at Compile Time

In a generic function, you can rely on an optimized algorithm if a class implements a certain interface. Discovering this at compile time means not having to use `dynamic_cast`, which is costly at runtime.

Detecting inheritance relies on a more general mechanism, that of detecting convertibility. The more general problem is, How can you detect whether an arbitrary type `T` supports automatic conversion to an arbitrary type `U`?

There is a surprising amount of power in `sizeof`: You can apply `sizeof` to any expression, no matter how complex, and `sizeof` **returns its size without actually evaluating that expression at runtime.**

The idea of conversion detection relies on using `sizeof` in conjunction with overloaded functions. We provide two overloads of a function: **One accepts the type to convert to (`U`), and the other accepts just about anything else.** If the function that accepts a `U` gets called, we know that `T` is convertible to `U`.

```
typedef char Small;
class Big { char dummy[2]; };
Small Test(U);
Big Test(...);
const bool convExists = sizeof(Test(T())) == sizeof(Small);
```

Passing a C++ object to a function with ellipses has undefined results, but this doesn't matter. Nothing actually calls the function. It's not even implemented. Recall that `sizeof` does not evaluate its argument.

There is one little problem. If `T` makes its default constructor private, the expression `T()` fails to compile. Fortunately, there is a simple solution, just use a strawman function returning a `T`. `MakeT` and `Test` not only don't do anything but don't even really exist at all.

```
template <class T, class U>
class Conversion{
  typedef char Small;
  class Big { char dummy[2]; };
  static Small Test(U);
  static Big Test(...);
  static T MakeT(); // not implemented
public:
  enum { exists = sizeof(Test(MakeT())) == sizeof(Small) };
};
cout << Conversion<size_t, vector<int> >::exists << ' ';
// return 0, because that constructor is explicit.
```

We can implement one more constant inside `Conversion::sameType`, which is true if `T` and `U` represent the same type:

```
template <class T, class U>
class Conversion{
  ... as above ...
  enum { sameType = false };
};
template <class T>
class Conversion<T, T>{
public:
  enum { exists = 1, sameType = 1 };
};
#define SUPERSUBCLASS(T, U) \
(Conversion<const U*, const T*>::exists && \
!Conversion<const T*, const void*>::sameType)
```

There are only three cases in which `const U*` converts implicitly to `const T*`:

1. `T` is the same type as `U`
2. `T` is an unambiguous public base of `U`
3. `T` is `void`.

Using `const` in `SUPERSUBCLASS`, we're always on the safe side, we don't want the conversion test to fail due to `const` issues.

Why use `SUPERSUBCLASS` and not the cuter `BASE_OF` or `INHERITS`? Think with `INHERITS(T, U)` it was a constant struggle to say which way the test worked.

2.8 A Wrapper Around type_info

tandard C++ provides the std::type_info class, which gives you the ability to investigate object types at runtime. You typically use type_info in conjunction with the typeid operator. The typeid operator returns a reference to a type_info object:

```
void Fun(Base* pObj){
  // Compare the two type_info objects corresponding to the type of *pObj and Derived
  if (typeid(*pObj) == typeid(Derived)){
    ... aha, pObj actually points to a Derived object ...
  }
}
```

In addition to supporting the comparison operators operator== and operator!=, type_info provides two more functions:

1. The name member function returns a textual representation of a type, in the form of const char*.
2. he before member function introduces an implementation's collation ordering relationship for type_info objects.
3. The type_info class disables the copy constructor and assignment operator, which makes storing type_info objects impossible.
4. The objects returned by typeid have static storage, so you don't have to worry about lifetime issues.

You do have to worry about pointer identity, the standard does not guarantee that each invocation returns a reference to the same type_info object. Consequently, you cannot compare pointers to type_info objects. What you should do is to store pointers to type_info objects and compare them by applying type_info::operator== to the dereferenced pointers.
If you want to use STL's ordered containers with type_info, you must write a little functor and deal with pointers. All this is clumsy enough to mandate a wrapper class around type_info that stores a pointer to a type_info object and provides:

1. All member functions of type_info
2. Value semantics (public copy constructor and assignment operator)
3. Seamless comparisons by defining operator< and operator==

```
class TypeInfo{
public:
  // Constructors/destructors
  TypeInfo(); // needed for containers
  TypeInfo(const std::type_info&);
  TypeInfo(const TypeInfo&);
  TypeInfo& operator=(const TypeInfo&);
  // Compatibility functions
```

```
  bool before(const TypeInfo&) const;
  const char* name() const;
private:
  const std::type_info* pInfo_;
};
// Comparison operators
bool operator==(const TypeInfo&, const TypeInfo&);
bool operator!=(const TypeInfo&, const TypeInfo&);
bool operator<(const TypeInfo&, const TypeInfo&);
bool operator<=(const TypeInfo&, const TypeInfo&);
bool operator>(const TypeInfo&, const TypeInfo&);
bool operator>=(const TypeInfo&, const TypeInfo&);

void Fun(Base* pObj){
  TypeInfo info = typeid(Derived);
  if (typeid(*pObj) == info){
    ... pBase actually points to a Derived object ...
  }
}
```

The cloning factory in Chapter 8 and one double-dispatch engine in Chapter 11 put `TypeInfo` to good use.

2.9 `NullType` and `EmptyType`

```
class NullType {};
struct EmptyType {};
```

You can use `NullType` for cases in which a type must be there syntactically but doesn't have a semantic sense. You can use `EmptyType` as a default ("don't care") type for a template.

2.10 Type Traits

Traits are a generic programming technique that allows compile-time decisions to be made based on types, much as you would make runtime decisions based on values.

2.10.1 Implementing Pointer Traits

```
template <typename T>
class TypeTraits{
private:
  template <class U>
  struct PointerTraits{
    enum { result = false };
    typedef NullType PointeeType;
  };
  template <class U>
```

```
  struct PointerTraits<U*>{
    enum { result = true };
    typedef U PointeeType;
  };
public:
  enum { isPointer = PointerTraits<T>::result };
  typedef PointerTraits<T>::PointeeType PointeeType;
};

const bool iterIsPtr = TypeTraits<vector<int>::iterator>::isPointer;
cout << "vector<int>::iterator is " << iterIsPtr ? "fast" : "smart" << '\n';
```

Similarly, TypeTraits implements an `isReference` constant and a `ReferencedType` type definition.

Detection of pointers to members is a bit different. The specialization needed is as follows:

```
template <typename T>
class TypeTraits{
private:
  template <class U>
  struct PToMTraits{
    enum { result = false };
  };
template <class U, class V>
  struct PToMTraits<U V::*>{
    enum { result = true };
  };
public:
  enum { isMemberPointer = PToMTraits<T>::result };
};
```

2.10.2 Detection of Fundamental Types

`TypeTraits<T>` implements an `isStdFundamental` compile-time constant that says whether or not `T` is a standard fundamental type.

In Section 3, we will know an `TypeList` and the expression

```
TL::IndexOf<T, TYPELIST_nn(comma-separated list of types)>::value
```

returns the zero-based position of `T` in the list, or –1 if `T` does not figure in the list.

```
template <typename T>
class TypeTraits
{
... as above ...
public:
  typedef TYPELIST_4(unsigned char, unsigned short int, unsigned int, unsigned long int) Uns
  typedef TYPELIST_4(signed char, short int, int, long int) SignedInts;
```

```
  typedef TYPELIST_3(bool, char, wchar_t) OtherInts;
  typedef TYPELIST_3(float, double, long double) Floats;
  enum { isStdUnsignedInt = TL::IndexOf<T, UnsignedInts>::value >= 0 };
  enum { isStdSignedInt = TL::IndexOf<T, SignedInts>::value >= 0 };
  enum { isStdIntegral = isStdUnsignedInt || isStdSignedInt || TL::IndexOf <T, OtherInts>::v
  enum { isStdFloat = TL::IndexOf<T, Floats>::value >= 0 };
  enum { isStdArith = isStdIntegral || isStdFloat };
  enum { isStdFundamental = isStdArith || isStdFloat || Conversion<T, void>::sameType };
  ...
};
```

2.10.3 Optimized Parameter Types

Given an arbitrary type `T`, what is the most efficient way of passing and accepting objects of type `T` as arguments to functions? In general, the most efficient way is to pass elaborate types by reference and scalar types by value.

A detail that must be carefully handled is that C++ does not allow references to references. Thus, if `T` is already a reference, you should not add one more reference to it.

```
template <typename T>
class TypeTraits{
  ... as above ...
public:
  typedef Select<isStdArith || isPointer || isMemberPointer, T,ReferencedType&>::Result Para
};
```

2.10.4 Stripping Qualifiers

```
template <typename T>
class TypeTraits{
  ... as above ...
private:
  template <class U> struct UnConst{
    typedef U Result;
  };
  template <class U> struct UnConst<const U>{
    typedef U Result;
  };
public:
  typedef UnConst<T>::Result NonConstType;
};
```

2.10.5 Using `TypeTraits`

```
enum CopyAlgoSelector { Conservative, Fast };
// Conservative routine-works for any type
template <typename InIt, typename OutIt>
```

```
OutIt CopyImpl(InIt first, InIt last, OutIt result, Int2Type<Conservative>){
  for (; first != last; ++first, ++result)
  *result = *first;
  return result;
}
// Fast routine-works only for pointers to raw data
template <typename InIt, typename OutIt>
OutIt CopyImpl(InIt first, InIt last, OutIt result, Int2Type<Fast>){
  const size_t n = last-first;
  BitBlast(first, result, n * sizeof(*first));
  return result + n;
}
template <typename InIt, typename OutIt>
OutIt Copy(InIt first, InIt last, OutIt result){
  typedef TypeTraits<InIt>::PointeeType SrcPointee;
  typedef TypeTraits<OutIt>::PointeeType DestPointee;
  enum { copyAlgo =
         TypeTraits<InIt>::isPointer &&
         TypeTraits<OutIt>::isPointer &&
         TypeTraits<SrcPointee>::isStdFundamental &&
         TypeTraits<DestPointee>::isStdFundamental &&
         sizeof(SrcPointee) == sizeof(DestPointee) ? Fast : Conservative };
  return CopyImpl(first, last, result, Int2Type<copyAlgo>);
}
```

The drawback of Copy is that it doesn't accelerate everything that could be accelerated. For example, you might have a plain C-like struct containing nothing but primitive data—a so-called plain old data, or POD, structure.

```
template <typename T>
struct SupportsBitwiseCopy{
  enum { result = TypeTraits<T>::isStdFundamental };
};
template<>
struct SupportsBitwiseCopy<MyType>{
  enum { result = true };
};
template <typename InIt, typename OutIt>
OutIt Copy(InIt first, InIt last, OutIt result, Int2Type<true>){
  typedef TypeTraits<InIt>::PointeeType SrcPointee;
  typedef TypeTraits<OutIt>::PointeeType DestPointee;
  enum { useBitBlast =
         TypeTraits<InIt>::isPointer &&
         TypeTraits<OutIt>::isPointer &&
         SupportsBitwiseCopy<SrcPointee>::result &&
         SupportsBitwiseCopy<DestPointee>::result &&
         sizeof(SrcPointee) == sizeof(DestPointee) };
```

```
  return CopyImpl(first, last, Int2Type<useBitBlast>);
}
```

2.10.6 Summary

The most important point is that the compiler always find the best match of template specialization.

3 Typelists

3.1 The need for Typelists

If you want to generalize the concept of Abstract Factory and put it into a library, you have to make it possible for the user to create factories of arbitrary collections of types.

- . In the Abstract Factory case, although the abstract base class is quite simple, you can get a nasty amount of code duplication when implementing various concrete factories.
- You cannot easily manipulate the member functions of `WidgetFactory` **because virtual functions cannot be templates.**
- We wish it would be nice if we could create a `WidgetFactory` by passing a parameter list to an `AbstractFactory` template and we coul have a template-like invocation for various `CreateXxx` functions, such as `Create<Window>()`.

The definition and algorithm of `Typelist` is the same as `std::Tuple`

```
template <class T, class U>
struct Typelist{
  typedef T Head;
  typedef U Tail;
};
typedef Typelist<int, NullType> OneTypeOnly;
#define TYPELIST_1(T1) Typelist<T1, NullType>
#define TYPELIST_2(T1, T2) Typelist<T1, TYPELIST_1(T2) >
#define TYPELIST_3(T1, T2, T3) Typelist<T1, TYPELIST_2(T2, T3) >
...
```

There is a lot of utility algorithms of Typelist:

- Calculating length

  ```
  template <class TList> struct Length;
  template <> struct Length<NullType>{
    enum { value = 0 };
  };
  template <class T, class U>
  struct Length< Typelist<T, U> >{
    enum { value = 1 + Length<U>::value };
  };
  ```

- Indexed Access

```
template <class Head, class Tail>
struct TypeAt<Typelist<Head, Tail>, 0>{
  typedef Head Result;
};
template <class Head, class Tail, unsigned int i>
struct TypeAt<Typelist<Head, Tail>, i>{
  typedef typename TypeAt<Tail, i - 1>::Result Result;
};
```

- Searching Typelists

```
template <class T>
struct IndexOf<NullType, T>{
  enum { value = -1 };
};
template <class T, class Tail>
struct IndexOf<Typelist<T, Tail>, T>{
  enum { value = 0 };
};
template <class Head, class Tail, class T>
struct IndexOf<Typelist<Head, Tail>, T>{
private:
  enum { temp = IndexOf<Tail, T>::value };
public:
  enum { value = temp == -1 ? -1 : 1 + temp };
};
```

- Appending to Typelist

```
template <> struct Append<NullType, NullType>{
  typedef NullType Result;
};
template <class T> struct Append<NullType, T>{
  typedef TYPELIST_1(T) Result;
};
template <class Head, class Tail>
struct Append<NullType, Typelist<Head, Tail> >{
  typedef Typelist<Head, Tail> Result;
};
template <class Head, class Tail, class T>
struct Append<Typelist<Head, Tail>, T>{
  typedef Typelist<Head,typename Append<Tail, T>::Result> Result;
};
```

- Erasing a type from Typelist

```
template <class T>
struct Erase<NullType, T>{
  typedef NullType Result;
};
template <class T, class Tail>
struct Erase<Typelist<T, Tail>, T>{
  typedef Tail Result;
};
template <class Head, class Tail, class T>
struct Erase<Typelist<Head, Tail>, T>{
  typedef Typelist<Head,typename Erase<Tail, T>::Result> Result;
};
```

- Erasing Duplicates

```
template <> struct NoDuplicates<NullType>{
typedef NullType Result;
};
template <class Head, class Tail>
struct NoDuplicates< Typelist<Head, Tail> >{
private:
typedef typename NoDuplicates<Tail>::Result L1;
typedef typename Erase<L1, Head>::Result L2;
public:
typedef Typelist<Head, L2> Result;
};
```

- Replacing a type in a Typelist

```
template <class T, class U>
struct Replace<NullType, T, U>{
  typedef NullType Result;
};
template <class T, class Tail, class U>
struct Replace<Typelist<T, Tail>, T, U>{
  typedef Typelist<U, Tail> Result;
};
template <class Head, class Tail, class T, class U>
struct Replace<Typelist<Head, Tail>, T, U>{
  typedef Typelist<Head,typename Replace<Tail, T, U>::Result> Result;
};
```

- Partially Ordering Typelist

```
template <class T>
struct MostDerived<NullType, T>{
  typedef T Result;
```

```
};
template <class Head, class Tail, class T>
struct MostDerived<Typelist<Head, Tail>, T>{
private:
  typedef typename MostDerived<Tail, T>::Result Candidate;
public:
  typedef typename Select<SUPERSUBCLASS(Candidate, Head), Head, Candidate>::Result Resul
};
template <>
struct DerivedToFront<NullType>{
  typedef NullType Result;
};
template <class Head, class Tail>
struct DerivedToFront< Typelist<Head, Tail> >{
private:
  typedef typename MostDerived<Tail, Head>::Result TheMostDerived;
  typedef typename Replace<Tail, TheMostDerived, Head>::Result L;
public:
  typedef Typelist<TheMostDerived, L> Result;
};
```

3.2 Class Generation with Typelists

```
template <class TList, template <class> class Unit>
class GenScatterHierarchy;

template <class T1, class T2, template <class> class Unit>
class GenScatterHierarchy<Typelist<T1, T2>, Unit>
: public GenScatterHierarchy<T1, Unit>
, public GenScatterHierarchy<T2, Unit>{
public:
  typedef Typelist<T1, T2> TList;
  typedef GenScatterHierarchy<T1, Unit> LeftBase;
  typedef GenScatterHierarchy<T2, Unit> RightBase;
};

template <class AtomicType, template <class> class Unit>
class GenScatterHierarchy : public Unit<AtomicType>{
  typedef Unit<AtomicType> LeftBase;
};

template <template <class> class Unit>
class GenScatterHierarchy<NullType, Unit>{};

template <class T>
struct Holder{
```

```
  T value_;
};
typedef GenScatterHierarchy<TYPELIST_3(int, string, Widget), Holder> WidgetInfo;
WidgetInfo obj;
string name = (static_cast<Holder<string>&>(obj)).value_;
```

This cast is quite ugly.

```
template <class T, class H>
typename Private::FieldTraits<H>::Rebind<T>::Result& Field(H& obj){
  return obj;
}
```

If you call `Field<Widget>(obj)` , the compiler figures out that `Holder<Widget>` is a base class of `WidgetInfo` and simply returns a reference to that part of the compound object.

3.3 Generating Tuples

```
template <class T>
struct TupleUnit{
  T value_;
  operator T&() { return value_; }
  operator const T&() const { return value_; }
};
template <class TList>
struct Tuple : public GenScatterHierarchy<TList, TupleUnit>{};
```

4 Small-Object Allocation

4.1 Why we need smallObj allocation?

For various reasons, polymorphic behavior being the most important, these small objects cannot be stored on the stack and must live on the free store . C++ provides the operators `new` and `delete` as the primary means of using the free store. However, these operators are general purpose and perform badly for allocating small objects.

For occult reasons, the default allocator (`malloc, realloc, free`) is notoriously slow. In addition to being slow, the genericity of the default C++ allocator makes it very space inefficient for small objects. Usually, the bookkeeping memory amounts to a few extra bytes (4 to 32) for each block allocated with `new`, If you allocate 8-byte objects, the per-object overhead becomes 50% to 400%.

4.2 The workings of a memory allocator

```
struct MemControlBlock{
  std::size_t size_;
  bool available_;
};
```

For each allocation request, a linear search of memory blocks finds a suitable block for the requested size. Each deallocation incurs, again, a linear search for figuring out the memory block that precedes the block being deallocated, and an adjustment of its size.

```
struct MemControlBlock{
  bool available_ ;
  MemControlBlock* prev_;
  MemControlBlock* next_;
};
```

If you store pointers to the previous and next `MemControlBlock` in each `MemControlBlock`, you can achieve constant-time deallocation.

4.3 A Small-Object Allocator

The small-object allocator described in this chapter sports a four-layered structure:

1. `Chunk` contains and manages a chunk of memory consisting of an integral number of fixedsize blocks. `Chunk` contains logic that allows you to allocate and deallocate memory blocks
2. A `FixedAllocator` object uses `Chunk` as a building block. `FixedAllocator`'s primary purpose is to satisfy memory requests that go beyond a `Chunk`'s capacity. `FixedAllocator` does this by aggregating an array of `Chunk`s.
3. `SmallObjAllocator` provides general allocation and deallocation functions. A `SmallObjAllocator` holds several `FixedAllocator` objects, each specialized for allocating objects of one size.
4. Finally, `SmallObject` wraps `FixedAllocator` to offer encapsulated allocation services for C++ classes. SmallObject overloads operator `new` and operator `delete` and passes them to a `SmallObjAllocator` object.

4.4 Chunk

```
struct Chunk{
  void Init(std::size_t blockSize, unsigned char blocks);
  void* Allocate(std::size_t blockSize);
  void Deallocate(void* p, std::size_t blockSize);
  void Reset(std::size_t blockSize, unsigned char blocks);
  void Release();
  unsigned char* pData_;
  unsigned char firstAvailableBlock_, blocksAvailable_;
};
```

`firstAvailableBlock_` holds the index of the first block available in this chunk, `blocksAvailable_` holds the number of blocks available in this chunk.

`Chunk` does not define constructors, destructors, or assignment operator. Defining proper copy semantics at this level hurts efficiency at upper level. Allocating and deallocating a block inside a Chunk takes constant time.

Why we use `unsinged char` but not `unsigned short` (2 bytes on many machines):

1. We cannot allocate blocks smaller than `sizeof(unsigned short)`, which is awkward because we're building a small-object allocator.
2. Imagine you build an allocator for 5-byte blocks. In this case, casting a pointer that points to such a 5-byte block to unsigned int engenders undefined behavior.

4.5 FixedAllocator

```
class FixedAllocator{
private:
    // Internal functions
    void DoDeallocate(void* p);
    Chunk* VicinityFind(void* p);

    std::size_t blockSize_;
    unsigned char numBlocks_;
    typedef std::vector<Chunk> Chunks;
    Chunks chunks_;
    Chunk* allocChunk_;
    Chunk* deallocChunk_;

    // For ensuring proper copy semantics
    mutable const FixedAllocator* prev_;
    mutable const FixedAllocator* next_;
public:
    explicit FixedAllocator(std::size_t blockSize = 0);
    FixedAllocator(const FixedAllocator&);
    FixedAllocator& operator=(const FixedAllocator&);
    ~FixedAllocator();
```

```
    void Swap(FixedAllocator& rhs);

    // Allocate a memory block
    void* Allocate();
    void Deallocate(void* p);
    std::size_t BlockSize() const{ return blockSize_; }
};
```

allocChunk_ holds a pointer to the last chunk that was used for an allocation. Whenever an allocation request comes, FixedAllocator::Allocate first checks allocChunk_ for available space. If not, a linear search occurs.
deallocChunk_ points to the last Chunk object that was used for a deallocation. Whenever a deallocation occurs, deallocChunk_ is checked first. Then, if it's the wrong chunk, Deallocate performs a linear search:

1. during deallocation, a chunk is freed only when there are two empty chunks.
2. chunks_ is searched starting from deallocChunk_ and going up and down with two iterators.

4.6 SmallObjAllocator

```
class SmallObjAllocator{
public:
  SmallObjAllocator(std::size_t chunkSize,std::size_t maxObjectSize);
  void* Allocate(std::size_t numBytes);
  void Deallocate(void* p, std::size_t size);
private:
  std::vector<FixedAllocator> pool_;
  FixedAllocator* pLastAlloc_;
  FixedAllocator* pLastDealloc_;
  std::size_t chunkSize_;
  std::size_t maxObjectSize_;
};
```

The chunkSize parameter is the default chunk size (the length in bytes of each Chunk object), and maxObjectSize is the maximum size of objects that must be considered to be "small." SmallObjAllocator forwards requests for blocks larger than maxObjectSize directly to ::operator new.
We store FixedAllocators only for sizes that are requested at least once. This way pool_ can accommodate various object sizes without growing too much. To improve lookup speed, pool_ is kept sorted by block. size.
When an allocation request arrives, pLastAlloc_ is checked first. If it is not of the correct size, SmallObjAllocator::Allocate performs a binary search in pool_. Deal location requests are handled in a similar way.

4.7 Small Object

```
class SmallObject{
```

```
public:
  static void* operator new(std::size_t size);
  static void operator delete(void* p, std::size_t size);
  virtual ~SmallObject() {}
};
```

In standard C++ you can overload the default operator delete in two ways—either as

```
void operator delete(void* p);
```

or as

```
void operator delete(void* p, std::size_t size);
```

To avoid the overhead of storing the size of the actual object to which p points, the compiler does a hat trick: It generates code that figures out the size on the fly. Four possible techniques of achieving that are listed here:

1. Pass a Boolean flag to the destructor meaning "Call/don't call operator delete after destroying the object." Base's destructor is virtual, so, `delete p` will reach the right object, `Derived`. At that time, the size of the object is known statically—it's `sizeof(Derived)`, and the compiler simply passes this constant to operator `delete`.

2. You can arrange that each destructor, after destroying the object, returns `sizeof(Class)`.

3. Implement a hidden virtual member function that gets the size of an object, say `_Size()`.

4. Store the size directly somewhere in the virtual function table (vtable) of each class. This solution is both flexible and efficient, but less easy to implement.

We need a unique `SmallObjAllocator` object for the whole application. That `SmallObjAllocator` must be properly constructed and properly destroyed, which is a thorny issue on its own. we solve this problem thoroughly with its `SingletonHolder` template.

```
typedef Singleton<SmallObjAllocator> MyAlloc;
void* SmallObject::operator new(std::size_t size){
  return MyAlloc::Instance().Allocate(size);
}
void SmallObject::operator delete(void* p, std::size_t size){
  MyAlloc::Instance().Deallocate(p, size);
}
```

4.8 Multithreading issues

The unique `SmallObjAllocator` is shared by all instances of `SmallObject`. If these instances belong to different threads, we end up sharing the `SmallObjAllocator` between multiple threads.

```
template <template <class T> class ThreadingModel>
class SmallObject : public ThreadingModel<SmallObject>{
  ... as before ...
```

```
}

template <template <class T> class ThreadingModel>
void* SmallObject<ThreadingModel>::operator new(std::size_t size){
  Lock lock;
  return MyAlloc::Instance().Allocate(size);
}
template <template <class T> class ThreadingModel>
void SmallObject<ThreadingModel>::operator delete(void* p, std::size_t size){
  Lock lock;
  MyAlloc::Instance().Deallocate(p, size);
}
```

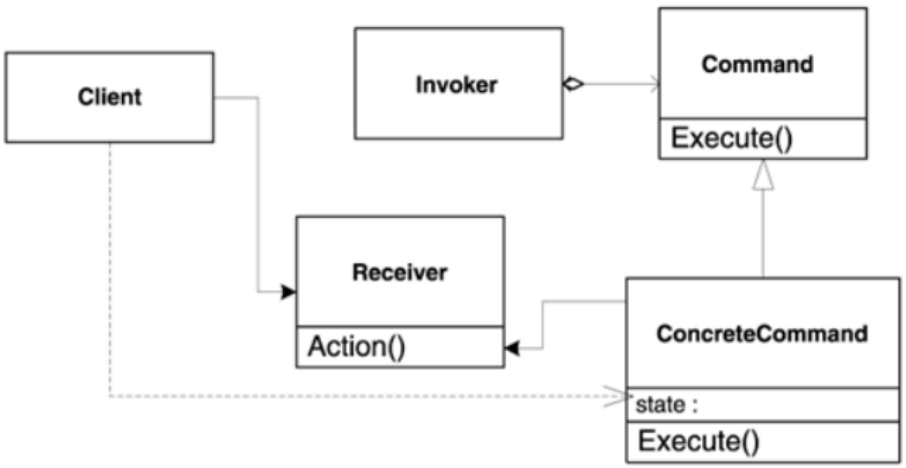
5 Generalized Functors

5.1 Why we need functors?

A generalized functor

- **Encapsulates** any processing invocation because it accepts pointers to simple functions, pointers to member functions, functors, and even other generalized functors—together with some or all of their respective arguments.
- Is **typesafe** because it never matches the wrong argument types to the wrong functions.
- Is an object with **value semantics** because it fully supports copying, assignment, and pass by value. A generalized functor can be copied freely and does not expose virtual member functions.

A typical sequence of actions is as follows:



1. The application (client) creates a `ConcreteCommand` object, passing it enough information to carry on a task.
2. The application passes the `Command` interface of the `ConcreteCommand` object to the invoker. The invoker stores this interface.
3. the invoker decides it's time to execute the action and fires `Command`'s Execute virtual member function. The virtual call mechanism dispatches the call to the `Concrete-Command` object, which takes care of the details. `ConcreteCommand` reaches the `Receiver` object (the one that is to do the job) and uses that object to perform the actual processing, such as calling its `Action` member function. Alternatively, the `ConcreteCommand` object might carry the processing all by itself. In this case, the receiver in Figure disappears.

There are two important aspects of the Command pattern:

- **Interface separation**. The invoker is isolated from the receiver.

- **Time separation**. Command stores a ready-to-go processing request that's to be started later.

From an implementation standpoint, two kinds of concrete `Command` classes can be identified:

1. All they do is call a member function for a `Receiver` object. We call them **forwarding commands**.
2. Others do tasks that are more complex. They might call member functions of other objects, but they also embed logic that's beyond simple forwarding. Let's call them active commands.

Because forwarding commands act much like pointers to functions and their C++ colleagues, functors, we call them **generalized functors**.

5.2 C++ Callable Entities

A forwarding command is a callback on steroids, a generalized callback. A callback is a pointer to a function that can be passed around and called at any time.

In addition to simple callbacks, C++ defines many more entities that support the function-call operator. Let's enumerate all the things that support `operator()` in C++:

- C-like functions
- C-like pointers to functions
- References to functions (which essentially act like const pointers to functions)
- Functors, that is, objects that define an `operator()`
- The result of applying `operator.*` or `operator->*` having a pointer to a member function

The objects that support `operator()` are known as **callable entities**.

5.3 `Functor` Class Template Skeleton

in C++ a bald pointer to a polymorphic type does not strictly have first-class semantics because of the ownership issue. To lift the burden of lifetime management from `Functor`'s clients, it's best to provide `Functor` with value semantics (well-defined copying and assignment). `Functor` does have a polymorphic implementation, but that's hidden inside it. We name the implementation base class `FunctorImpl`.

```
template <typename R, class TList>
class Functor{
public:
  Functor();
  Functor(const Functor&);
  Functor& operator=(const Functor&);
  explicit Functor(std::auto_ptr<Impl> spImpl);
private:
  // Handy type definition for the body type
```

```
  typedef FunctorImpl<R, TList> Impl;
  std::auto_ptr<Impl> spImpl_;
};
```

The purpose of `Clone` is the creation of a polymorphic copy of the `FunctorImpl` object. `FunctorImpl` defines a polymorphic interface that abstracts a function call.

```
template <typename R>
class FunctorImpl<R, NullType>{
public:
  virtual R operator()() = 0;
  virtual FunctorImpl* Clone() const = 0;
  virtual ~FunctorImpl() {}
};
template <typename R, typename P1>
class FunctorImpl<R, TYPELIST_1(P1)>{
public:
  virtual R operator()(P1) = 0;
  virtual FunctorImpl* Clone() const = 0;
  virtual ~FunctorImpl() {}
};
template <typename R, typename P1, typename P2>
class FunctorImpl<R, TYPELIST_2(P1, P2)>{
public:
  virtual R operator()(P1, P2) = 0;
  virtual FunctorImpl* Clone() const = 0;
  virtual ~FunctorImpl() {}
};
```

Constructing from `auto_ptr` is a clear statement to the outside world that `Functor` takes ownership of the `FunctorImpl` object. Users of `Functor` will actually have to type `auto_ptr` whenever they invoke this constructor; we assume that if they type `auto_ptr`, they know what `auto_ptr` is about.

5.4 Implementing the Forwarding `Functor::operator()`

```
template <typename R, class TList>
class Functor{
... as above ...
public:
  R operator()(){  return (*spImpl_)(); }
  R operator()(Parm1 p1){  return (*spImpl_)(p1); }
  R operator()(Parm1 p1, Parm2 p2){  return (*spImpl_)(p1, p2); }
};
```

The trick relies on the fact that **C++ does not instantiate member functions for templates until they are actually used**. If you try to call an overload of `operator()` that doesn't make sense, the compiler tries to generate the body of `operator()` and discovers the mismatch.

5.5 Handling Functors

```
template <class ParentFunctor, typename Fun>
class FunctorHandler: public FunctorImpl<
                        typename ParentFunctor::ResultType,
                        typename ParentFunctor::ParmList>{
public:
  typedef typename ParentFunctor::ResultType ResultType;
  FunctorHandler(const Fun& fun) : fun_(fun) {}
  FunctorHandler* Clone() const{
    return new FunctorHandler(*this);
  }
  ResultType operator()(){
    return fun_();
  }
  ResultType operator()(typename ParentFunctor::Parm1 p1){
    return fun_(p1);
  }
  ResultType operator()(typename ParentFunctor::Parm1 p1,typename ParentFunctor::Parm2 p2){
    return fun_(p1, p2);
  }
private:
  Fun fun_;
};
```

The functor is stored by value, not by pointer. This is because, in general, functors are meant to be this way—nonpolymorphic types with regular copy semantics.

Given `FunctorHandler`'s declaration, it's easy to write the templated constructor of `Functor` declared earlier in this section.

```
template <typename R, class TList>
template <typename Fun>
Functor<R, TList>::Functor(const Fun& fun) : spImpl_(new FunctorHandler<Functor, Fun>(fun)){
```

`FuncotHandler` **not only handles functor, function but also pointer and reference to functions.**

However, if the function is **overloaded**, the type of the function is no longer defined.

```
void TestFunction(int i, double d){ cout << "TestFunction << endl; }
void TestFunction(int);
```

There are two methods:

```
int main()
{
typedef void (*TpFun)(int, double);
// Method 1: use an initialization
TpFun pF = TestFunction;
Functor<void, TYPELIST_2(int, double)> cmd1(pF);
```

```
cmd1(4, 4.5);

// Method 2: use a cast
Functor<void, int, double> cmd2(static_cast<TpFun>(TestFunction));
cmd2(4, 4.5);
}
```

5.6 Argument and Return Type Conversions

In an ideal world, we would like conversions to work for `Functor` just as they work for regular function calls.

```
const char* TestFunction(double, double){
  static const char buffer[] = "Hello, world!";
// It's safe to return a pointer to a static buffer
  return buffer;
}
int main(){
  Functor<string, TYPELIST_2(int, int)> cmd(TestFunction);
  // Should print "world!"
  cout << cmd(10, 10).substr(7);
}
```

The function

```
string Functor<...>::operator()(int i, int j)
```

forwards to the virtual function

```
string FunctorHandler<...>::operator()(int i, int j)
```

whose implementation ultimately calls

```
return fun_(i, j);
```

where `fun_` has type `const char* (*)(double, double)` and evaluates to `TestFunction`. When the compiler encounters the call to `fun_`, it compiles it normally. The compiler then generates code to convert `i` and `j` to `double`, and the result to `std::string`.

5.7 Handling Pointers to Member Functions

```
class Parrot{
public:
void Eat(){ cout << "Tsk, knick, tsk...\n"; }
void Speak(){ cout << "Oh Captain, my Captain!\n"; }
};
int main(){
  typedef void (Parrot::* TpMemFun)();
  TpMemFun pActivity = &Parrot::eat;
```

```
  Parrot geronimo;
  Parrot* pGeronimo = &geronimo;
  (geronimo.*pActivity)();
  (pGeronimo->*pActivity)();
  pActivity = &Parrot::Speak;
  (geronimo.*pActivity)();
}
```

There is no C++ type for the result of `geronimo.*p-Activity` and `pGeronimo->*pActivity`. Both are binary operations all right, and they return something to which you can apply the function-call operator immediately, but that "something" does not have a type. You cannot store the result of `operator.*` or `operator->*` in any way.

Here's the implementation of `MemFunHandler`.

```
template <class ParentFunctor, typename PointerToObj, typename PointerToMemFn>
class MemFunHandler : public FunctorImpl<
                        typename ParentFunctor::ResultType,
                        typename ParentFunctor::ParmList>{
public:
  typedef typename ParentFunctor::ResultType ResultType;

  MemFunHandler(const PointerToObj& pObj, PointerToMemFn pMemFn) : pObj_(pObj), pMemFn_(pMem
  MemFunHandler* Clone() const{
    return new MemFunHandler(*this);
  }

  ResultType operator()(){
    return ((*pObj_).*pMemFn_)();
  }
  ResultType operator()(typename ParentFunctor::Parm1 p1){
    return ((*pObj_).*pMemFn_)(p1);
  }
ResultType operator()(typename ParentFunctor::Parm1 p1, typename ParentFunctor::Parm2 p2){
    return ((*pObj_).*pMemFn_)(p1, p2);
  }
private:
  PointerToObj pObj_;
  PointerToMemFn pMemFn_;
};
```

Why is `MemFunHandler` parameterized with the type of the pointer (`PointerToObj`) and not with the type of the object itself? i.e.

```
template <class ParentFunctor, typename Obj,
typename PointerToMemFn>
class MemFunHandler : public FunctorImpl<
                        typename ParentFunctor::ResultType,
                        typename ParentFunctor::ParmList>{
```

```
private:
  Obj* pObj_;
  PointerToMemFn pMemFn_;
public:
MemFunHandler(Obj* pObj, PointerToMemFn pMemFn) : pObj_(pObj), pMemFn_(pMemFn) {}
};
```

The first implementation can store any type that acts as a pointer to an object **but** the second is hardwired to store and use only simple pointers, if you want to use smart pointers, there will be wrong.

Moreover, the second version does not work for pointers to `const`. Such is the negative effect of hardwiring type.

```
int main(){
  Parrot geronimo;
  Functor<> cmd1(&geronimo, &Parrot::Eat), cmd2(&geronimo, &Parrot::Speak);
  cmd1();
  cmd2();
}
```

5.8 Binding

As soon as `Functor` is ready, new ideas come to mind. For instance, we'd like to be able to convert from a type of `Functor` to another. Think of a `Functor` as a computation, and of its arguments as the **environment** necessary to perform that computation, binding allows `Functor` to store part of the **environment** together with the computation and to reduce progressively the environment necessary at invocation time.

```
template <class Incoming>
class BinderFirst : public FunctorImpl<typename Incoming::ResultType,
                    typename Incoming::Arguments::Tail>{
  typedef Functor<typename Incoming::ResultType,Incoming::Arguments::Tail> Outgoing;
  typedef typename Incoming::Parm1 Bound;
  typedef typename Incoming::ResultType ResultType;
public:
  BinderFirst(const Incoming& fun, Bound bound): fun_(fun), bound_(bound){}
  BinderFirst* Clone() const{ return new BinderFirst(*this); }
  ResultType operator()(){ return fun_(bound_); }
  ResultType operator()(typename Outgoing::Parm1 p1){
    return fun_(bound_, p1);
  }
  ResultType operator()(typename Outgoing::Parm1 p1,typename Outgoing::Parm2 p2){
    return fun_(bound_, p1, p2);
  }
private:
  Incoming fun_;
  Bound bound_;
```

```
};

template <class Fctor>
typename Private::BinderFirstTraits<Fctor>::BoundFunctorType
BindFirst(const Fctor& fun,typename Fctor::Parm1 bound){
  typedef typename private::BinderFirstTraits<Fctor>::BoundFunctorType Outgoing;
  return Outgoing(std::auto_ptr<typename Outgoing::Impl>(
                    new BinderFirst<Fctr>(fun, bound)));
}
```

5.9 Chaining Request

MacroCommand class, a command that holds a linear collection (such as a list or a vector) of Commands. When a MacroCommand is executed, it executes in sequence each of the commands that it holds.

5.10 Functor Quick Facts

- You can initialize a Functor with a function, a functor, another Functor, or a pointer to an object and a pointer to a method.
- You also can initialize Functor with a std::auto_ptr< FunctorImpl<R,TList> >.
- Functor supports automatic conversions for arguments and return values.
- Manual disambiguation is needed in the presence of overloading.
- Functor fully supports first-class semantics: copying, assigning to, and passing by value.
- Functor is not polymorphic and is not intended to be derived from. If you want to extend Functor, derive from FunctorImpl.
- A call to BindFirst binds the first argument to a fixed value.
- Multiple Functors can be chained in a single Functor object by using the Chain function.
- FunctorImpl uses the small-object allocator.

6 Singleton

A singleton is an improved global variable. The improvement that Singleton brings is that you cannot create a secondary object of the singleton's type.

6.1 Static Data + Static Functions != Singleton

There is another pattern, the **Monostate pattern**:

```
class Font { ... };
class PrinterPort { ... };
class PrintJob { ... };

class MyOnlyPrinter{
public:
  static void AddPrintJob(PrintJob& newJob){
    if (printQueue_.empty() && printingPort_.available()){
      printingPort_.send(newJob.Data());
    }else{
      printQueue_.push(newJob);
    }
  }
private:
  // All data is static
  static std::queue<PrintJob> printQueue_;
  static PrinterPort printingPort_;
  static Font defaultFont_;
};
```

The main problem is that static functions cannot be virtual, which makes it difficult to change behavior without opening `MyOnlyPrinter`'s code.

6.2 The Basic C++ Idioms Supporting Singletons

Most often, singletons are implemented in C++ by using some variation of the following idiom:

```
class Singleton{
public:
  static Singleton* Instance(){
    if (!pInstance_)
      pInstance_ = new Singleton;
    return pInstance_;
  }
... operations ...
private:
  Singleton(); // Prevent clients from creating a new Singleton
  Singleton(const Singleton&); // Prevent clients from creating
  static Singleton* pInstance_; // The one and only instance
```

```
};
// Implementation file Singleton.cpp
Singleton* Singleton::pInstance_ = 0;
```

If it's never used (no call to `Instance` occurs), the `Singleton` object is not created. The advantage of the build-on-first-request solution becomes significant if `Singleton` is expensive to create and seldom used.

An ill-fated temptation is to simplify things by replacing the pointer `pInstance_` in the previous example with a full Singleton object.

```
class Singleton{
public:
  static Singleton* Instance() // Unique point of access{
    return &instance_;
  }
private:
  static Singleton instance_;
};
// Implementation file Singleton.cpp
Singleton Singleton::instance_;
```

`instance_` is initialized dynamically (by calling `Singleton`'s constructor at runtime), whereas `pInstance_` benefits from static initialization (it is a type without a constructor initialized with a compile-time constant).

```
#include "Singleton.h"
int global = Singleton::Instance()->DoSomething();
```

Depending on the order of initialization that the compiler chooses for `instance_` and `global`, the call to `Singleton::Instance` may return an object that has not been constructed yet.

6.3 Enforcing the Singleton's Uniqueness

The default constructor and the copy constructor, the assignment operator are private.

The problem with having Instance return a pointer is that callers might be tempted to `delete` it. To minimize the chances of that happening, it's safer to return a reference:

```
// inside class Singleton
static Singleton& Instance();
```

After the enumerated measures are added, Singleton's interface looks like the following.

```
class Singleton{
public:
  Singleton& Instance();
  ... operations ...
private:
  Singleton();
  Singleton(const Singleton&);
  Singleton& operator=(const Singleton&);
  ~Singleton();
};
```

6.4 Destroying the Singleton

If `Singleton` is not deleted, that's not a memory leak. **Memory leaks appear when you allocate accumulating dataand lose all references to it.**

However, **there is a leak, and a more insidious one: a resource leak.** Singleton's constructor may acquire an unbound set of resources: network connections, handles to OS-wide mutexes and other interprocess communication means and so on. The only correct way to avoid resource leaks is to delete the Singleton object during the application's shutdown.

The simplest solution for destroying the singleton is to **rely on language mechanisms**:

```
Singleton& Singleton::Instance(){
  static Singleton obj;
  return obj;
}
```

This `Meyers singleton` relies on some compiler magic. When the initializer is not a compile-time constant, or the static variable is an object with a constructor, **the variable is initialized at runtime during the first pass through its definition.**

In addition, the compiler generates code so that after initialization, the pseudo-C++ representation of the generated code may look like the following code:

```
Singleton& Singleton::Instance(){
  // Functions generated by the compiler
  extern void __ConstructSingleton(void* memory);
  extern void __DestroySingleton();
  // Variables generated by the compiler
  static bool __initialized = false;
  // Buffer that holds the singleton
  // (We assume it is properly aligned)
  static char __buffer[sizeof(Singleton)];
  if (!__initialized){
    // First call, construct object
    // Will invoke Singleton::Singleton
    // In the __buffer memory
    __ConstructSingleton(__buffer);
    // register destruction
    atexit(__DestroySingleton);
    __initialized = true;
  }
  return *reinterpret_cast<Singleton *>(__buffer);
}
```

The core is the call to the `atexit` function, which allows you to register functions to be automatically called during a program's exit, in a last in, first out (LIFO) order. Each call to atexit pushes its parameter on a private stack maintained by the C runtime library.

6.5 The Dead Reference Problem

Assuming we implement `Keyboard`, `Display`, `Log` with three singletons as Meyers singletons. Assume that after `Keyboard` is constructed successfully, `Display` fails to initialize. `Display`'s constructor creates `Log`, the error is logged.

At exit time, `Log` is destroyed before `Keyboard`. If for some reason `Keyboard` fails to shut down and tries to report an error to `Log`, `Log::Instance` unwittingly returns a reference to the "shell" of a destroyed `Log` object. So **a reasonable singleton should at least perform dead-reference *detection.***

```
class Singleton{
public:
  Singleton& Instance(){
    if (!pInstance_){
      if (destroyed_){
        OnDeadReference();
      }else{
        Create();
      }
    }
    return *pInstance_;
  }
private:
  static void Create(){
    static Singleton theInstance;
    pInstance_ = &theInstance;
  }
  static void OnDeadReference(){
    throw std::runtime_error("Dead Reference Detected");
  }
  virtual ~Singleton(){
    pInstance_ = 0;
    destroyed_ = true;
  }

  Singleton *pInstance_;
  bool destroyed_;
  ... disabled 'tors/operator= ...
};

// Singleton.cpp
Singleton* Singleton::pInstance_ = 0;
bool Singleton::destroyed_ = false;
```

6.6 Addressing the Dead Reference Problem (I): The Phoenix Singleton

The implementation of the Phoenix Singleton with a static variable is simple. When we detect the dead reference, we create a new `Singleton` object in the shell of the old one. (C++ guarantees this is possible. Static objects' memory lasts for the duration of the program.)

```
class Singleton{
  ... as before ...
  void KillPhoenixSingleton(); // Added
};
void Singleton::OnDeadReference(){
  Create();
  // Now pInstance_ points to the "ashes" of the singleton
  // - the raw memory that the singleton was seated in.
  // Create a new singleton at that address
  new(pInstance_) Singleton;
  // Queue this new object's destruction
  atexit(KillPhoenixSingleton);
  // Reset destroyed_ because we're back in business
  destroyed_ = false;
}
void Singleton::KillPhoenixSingleton(){
  pInstance_->~Singleton();
}
```

The `new` operator that `OnDeadReference` uses is called the placement `new` operator. The placement `new` operator does not allocate memory; it only constructs a new object at the address passed—in our case, `pInstance_`.

```
#ifdef ATEXIT_FIXED
atexit(KillPhoenixSingleton);
#endif
```

This measure has to do with an unfortunate omission in the C++ standard. The standard fails to describe what happens when you register functions with atexit during a call made as the effect of another `atexit` registration. To illustrate this problem, let's write a short test program:

```
#include <cstdlib>
void Bar(){ ... }
void Foo(){ std::atexit(Bar); }
int main(){
  std::atexit(Foo);
}
```

They say that `Bar` will be called before `Foo` because `Bar` was registered last, but at the time it's registered, it's too late for `Bar` to be first because `Foo` is already being called.

6.7 Addressing the Dead Reference Problem (II): Singletons with Longevity

The Phoenix singleton breaks the normal lifetime cycle of a singleton, which may confuse some clients.

Setting longevity control applies not only to singletons but also to global objects in general. The concept emerging here is that of longevity control and is independent of the concept of a singleton: **The greater longevity an object has, the later it will be destroyed.**

```
class SomeSingleton { ... };
class SomeClass { ... };
SomeClass* pGlobalObject(new SomeClass);
int main(){
  SetLongevity(&SomeSingleton().Instance(), 5);
  SetLongevity(pGlobalObject, 6);
}
```

The function `SetLongevity` takes a reference to an object of any type and an integral value (the longevity).

You cannot apply SetLongevity to objects whose lifetimes are controlled by the compiler, such as regular global objects, static objects, and automatic objects. The compiler already generates code for destroying them.

```
class SomeClass { ... };
int main(){
  SomeClass* pObj1 = new SomeClass;
  SetLongevity(pObj1, 5);
  static SomeClass obj2;
  SomeClass* pObj3 = new SomeClass;
  SetLongevity(pObj3, 6);
}
```

A careful constraints analysis leads to the following design decisions:

1. Each call to `SetLongevity` issues a call to `atexit`.
2. Destruction of objects with lesser longevity takes place before destruction of objects with greater longevity.
3. Destruction of objects with the same longevity follows the C++ rule: last built, first destroyed.

In the example program, the rules lead to the following guaranteed order of destruction: `*pObj1, obj2, *pObj3`.

6.8 Implementing Singletons with Longevity

`SetLongevity` maintains a hidden `priority queue`, separate from the inaccessible `atexit` stack. The core is the priority queue data structure. We cannot use the standard `std::priority_queue` class because **it does not guarantee the ordering of the elements having the same priority.**

The elements that the data structure holds are pointers to the type `LifetimeTracker`.

```
class LifetimeTracker{
public:
  LifetimeTracker(unsigned int x) : longevity_(x) {}
  virtual ~LifetimeTracker() = 0;
  friend inline bool Compare(unsigned int longevity, const LifetimeTracker* p){
  return p->longevity_ > longevity;
  }
private:
  unsigned int longevity_;
};
// Definition required
inline LifetimeTracker::~LifetimeTracker() {}

typedef LifetimeTracker** TrackerArray;
extern TrackerArray pTrackerArray;
extern unsigned int elements;
```

There is only one instance of the `Tracker` type. Consequently, `pTrackerArray` is exposed to all the Singleton problems just discussed, `SetLongevity` must be available at any time. To deal with this problem, `SetLongevity` carefully manipulates `pTrackerArray` with the low-level functions `realloc`. if you call it with a zero size, it behaves like `std::free`.

```
//Helper destroyer function
template <typename T>
struct Deleter{
  static void Delete(T* pObj){ delete pObj; }
};
// Concrete lifetime tracker for objects of type T
template <typename T, typename Destroyer>
class ConcreteLifetimeTracker : public LifetimeTracker{
public:
  ConcreteLifetimeTracker(T* p, unsigned int longevity, Destroyer d) : LifetimeTracker(longe
  ~ConcreteLifetimeTracker(){ destroyer_(pTracked_); }
private:
  T* pTracked_;
  Destroyer destroyer_;
};

void AtExitFn(); // Declaration needed below

template <typename T, typename Destroyer>
void SetLongevity(T* pDynObject, unsigned int longevity,Destroyer d = Private::Deleter<T>::D
  TrackerArray pNewArray = static_cast<TrackerArray>(
  std::realloc(pTrackerArray, sizeof(T) * (elements + 1)));
  if (!pNewArray) throw std::bad_alloc();
  pTrackerArray = pNewArray;
  LifetimeTracker* p = new ConcreteLifetimeTracker<T, Destroyer>(pDynObject, longevity, d);
```

```
  TrackerArray pos = std::upper_bound(pTrackerArray, pTrackerArray + elements, longevity, Co
  std::copy_backward(pos, pTrackerArray + elements,pTrackerArray + elements + 1);
  *pos = p;
  ++elements;
  std::atexit(AtExitFn);
}
```

The `AtExitFn` function pops the object with the smallest longevity and deletes it. Deleting the pointer to `LifetimeTracker` invokes `ConcreteLifetimeTracker`'s destructor, which in turn deletes the tracked object.

```
static void AtExitFn(){
  assert(elements > 0 && pTrackerArray != 0);
  LifetimeTracker* pTop = pTrackerArray[elements - 1];
  pTrackerArray = static_cast<TrackerArray>(std::realloc(pTrackerArray, sizeof(T) * --elemen
  delete pTop;
}
```

6.9 Putting It All Together

6.9.1 Decomposing `SingletonHolde` into Policies

The three corresponding polices therefore are as follows:

- **Creation**. You can create a singleton in various ways.
- **Lifetime**. We identified the following lifetime policies:
  1. Following C++ rules—last created, first destroyed
  2. Recurring (Phoenix singleton)
  3. User controlled (singleton with longevity)
  4. Infinite (the "leaking" singleton, an object that's never destroyed)
- **ThreadingModel**. Whether singleton is single threaded, is standard multithreaded or uses a nonportable threading model.

6.9.2 Defining Requirements for `SingletonHolder`'s Policies

The Creation policy must create and destroy objects, so it must expose two corresponding functions. `Creator<T>` must support the following calls:

```
T* pObj = Creator<T>::Create();
Creator<T>::Destroy(pObj);
```

Lifetime decides the action to be taken if the application violates the lifetime rules of the Singleton object. Hence:

- If you need the singleton to be destroyed according to C++ rules, then Lifetime uses a mechanism similar to `atexit`.

- For the Phoenix singleton, Lifetime still uses an `atexit`-like mechanism but accepts the recreation of the Singleton object.
- For a singleton with longevity, Lifetime issues a call to `SetLongevity`.
- For infinite lifetime, Lifetime does not take any action.

If `Lifetime<T>` is a class that implements the Lifetime policy, the following expressions make sense:

```
void (*pDestructionFunction)();
Lifetime<T>::ScheduleDestruction(pDestructionFunction);
Lifetime<T>::OnDeadReference();
```

6.9.3 Assembling `SingletonHolder`

```
template<class T,
  template <class> class CreationPolicy = CreateUsingNew,
  template <class> class LifetimePolicy = DefaultLifetime,
  template <class> class ThreadingModel = SingleThreaded>
class SingletonHolder{
public:
  static T& Instance();
private:
  static void DestroySingleton();
  SingletonHolder();

  typedef ThreadingModel<T>::VolatileType InstanceType;
  static InstanceType* pInstance_;
  static bool destroyed_;
};

template <...>
T& SingletonHolder<...>::Instance(){
  if (!pInstance_){
    typename ThreadingModel<T>::Lock guard;
    if (!pInstance_){
      if (destroyed_){
        LifetimePolicy<T>::OnDeadReference();
        destroyed_ = false;
      }
    pInstance_ = CreationPolicy<T>::Create();
    LifetimePolicy<T>::ScheduleCall(&DestroySingleton);
    }
  }
  return *pInstance_;
}
```

```
template <...>
void SingletonHolder<...>::DestroySingleton(){
  assert(!destroyed_);
  CreationPolicy<T>::Destroy(pInstance_);
  pInstance_ = 0;
  destroyed_ = true;
}
```

7 Smart Pointer

A smart pointer is a C++ class that mimics a regular pointer in syntax and some semantics, but it does more.

```
template <class T>
class SmartPtr{
public:
  explicit SmartPtr(T* pointee) : pointee_(pointee);
  SmartPtr& operator=(const SmartPtr& other);
  ~SmartPtr();
  T& operator*() const{
    ...
    return *pointee_;
  }
  T* operator->() const{
    ...
    return pointee_;
  }
private:
  T* pointee_;
  ...
};
```

`SmartPtr<T>` aggregates a pointer to `T` in its member variable `pointee_`. That's what most smart pointers do. In some cases, a smart pointer might aggregate some handles to data and compute the pointer on the fly.

7.1 The Deal with Smart Pointer

Smart pointers have value semantics, whereas some simple pointers do not, which means you can *copy* and *assign to*.

```
Widget* p = new Widget;
```

the variable p not only points to, but also owns, the memory allocated for the `Widget` object, because later you must issue delete p to ensure that the Widget object is destroyed and its memory is released. Furthermore, when you copy p into another variable, all you get is two raw pointers pointing to the same object, and you have to track them even more carefully because double deletions are even more catastrophic than no deletion.

Smart pointers can be of great help in this area. Most smart pointers offer **ownership management** in addition to pointer-like behavior. Smart pointers can figure out how ownership evolves, and their destructors can release the memory according to a well-defined strategy:

- Some smart pointers transfer ownership automatically: after you copy a smart pointer to an object, the source smart pointer becomes null. This is the behavior implemented by the standard-provided `std::auto_ptr`.

- Other smart pointers implement reference counting: They track the total count of smart pointers that point to the same object, and when this count goes down to zero, they delete the pointed-to object.

However, you will find that adding seemingly worthwhile features might expose the clients to costly risks.

7.2 Storage (Policy) of Smart Pointers

There are two generalizations of smart pointers:
Firstly, When you apply `operator->` to a type that's not a built-in pointer, the compiler does an interesting thing. After looking up and applying the user-defined `operator->` to that type, it applies `operator->` again to the result. So **a smart pointer's `operator->` does not have to return a pointer.**
Secondly, in rare cases, smart pointers could drop the pointer syntax. An object that does not define `operator->` and `operator*` violates the definition of a smart pointer, but there are objects that **do deserve smart pointer–like treatment**, although they are not, strictly speaking, smart pointers.
For example, in real-world APIs and applications, many operating systems foster handles as accessors to certain internal resources. Handles are intentionally obfuscated pointers, one of their purposes is to prevent their users from manipulating critical operating system resources directly. Most of the time, handles are integral values that are indices in a hidden table of pointers. The table provides the additional level of indirection that protects the inner system from the application programmers. Although they don't provide an `operator->`, handles resemble pointers in semantics and in the way they are managed.
To generalize the type universe of smart pointers, we distinguish three potentially distinct types in a smart pointer:

1. **The storage type**. This is the type of `pointee_`. By "default"—in regular smart pointers—it is a raw pointer.
2. **The pointer type**. This is the type returned by `operator->`. It can be different from the storage type if you want to return a proxy object instead of just a pointer. (You will find an example of using proxy objects later in this chapter.)
3. **The reference type**. This is the type returned by `operator*`

There three types are called Storage policy.

7.3 Smart Pointer Member Functions

Many existing smart pointer implementations allow operations through member functions, such as `Get` for accessing the `pointee` object, `Set` for changing it, and `Release` for taking over ownership.
However, the interaction between member function calls for the smart pointer for the pointed-to object can be extremely confusing.

```
SmartPtr<Printer> spRes = ...;
spRes->Acquire(); // acquire the printer
spRes->Release(); // release the printer
spRes.Release(); // release the pointer to the printer
```

Both sp.Release() and sp->Release() compile flag-free but do very different things. The cure is simple: **A smart pointer should not use member functions.** SmartPtr use only nonmember functions. These functions become friends of the smart pointer class.

The only functions that necessarily remain members of SmartPtr are the constructors, the destructor, operator=, operator->, and unary operator*. All other operations of SmartPtr are provided through named nonmember functions.

```
template <class T> T* GetImpl(SmartPtr<T>& sp);
template <class T> T*& GetImplRef(SmartPtr<T>& sp);
template <class T> void Reset(SmartPtr<T>& sp, T* source);
template <class T> void Release(SmartPtr<T>& sp, T*& destination);
```

- GetImpl returns the pointer object stored by SmartPtr.
- GetImplRef returns a reference to the pointer object stored by SmartPtr. GetImplRef allows you to change the underlying pointer, so it requires extreme care in use.
- Reset resets the underlying pointer to another value, releasing the previous one.
- Release releases ownership of the smart pointer, giving its user the responsibility of managing the pointee object's lifetime.

7.4 Ownership (Policy) Strategies

A smart pointer is a first-class value that takes care of deleting the pointed-to object under the covers. For implementing self-ownership, smart pointers must carefully track the pointee object, especially during copying, assignment, and destruction.

7.4.1 Deep Copy

The simplest strategy applicable is to copy the pointee object whenever you copy the smart pointer. If you ensure this, **there is only one smart pointer for each pointee object.** But why would you make the effort of using a smart pointer, when simple pass by value of the pointee object works just as well?

The answer is **support for polymorphism.** Smart pointers are vehicles for transporting polymorphic objects safely. When you copy the smart pointer, you want to copy its polymorphic behavior, too.

However, the following naive implementation of the copy constructor is wrong:

```
template <class T>
class SmartPtr{
public:
  SmartPtr(const SmartPtr& other): pointee_(new T(*other.pointee_)){}
};
```

The copy constructor above copies only the Widget part of the ExtendedWidget object. This phenomenon is known as **slicing**.

Chapter 8 discusses cloning in depth. As shown there, the classic way of obtaining a polymorphic clone for a hierarchy is to define a virtual Clone function and implement it as follows:

```
class AbstractBase{
  virtual Base* Clone() = 0;
};
class Concrete : public AbstractBase{
  virtual Base* Clone(){ return new Concrete(*this); }
};
```

A generic smart pointer cannot count on knowing the exact name of the cloning member function—maybe it's `clone`, or maybe `MakeCopy`. Therefore, the most flexible approach is to parameterize `SmartPtr` with a policy that addresses cloning.

7.4.2 Copy on Write

Copy on write is an optimization technique that avoids unnecessary object copying. The idea that underlies COW is to **clone the pointee object at the first attempt of modification; until then, several pointers can share the same object.**

Smart pointers, however, are not the best place to implement COW, because smart pointers cannot differentiate between calls to const and non-const member functions of the pointee object. (*pointer to non-const object can also call const member function*).

7.4.3 Reference Counting

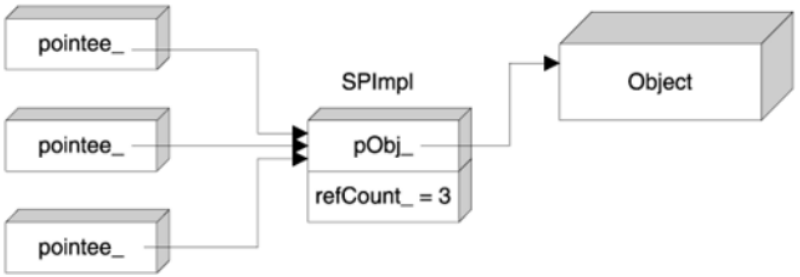
Reference counting tracks the number of smart pointers that point to the same object. When that number goes to zero, the pointee object is deleted. This strategy works very well if you don't break certain rules—**you should not keep dumb pointers and smart pointers to the same object.**

There are three structures:

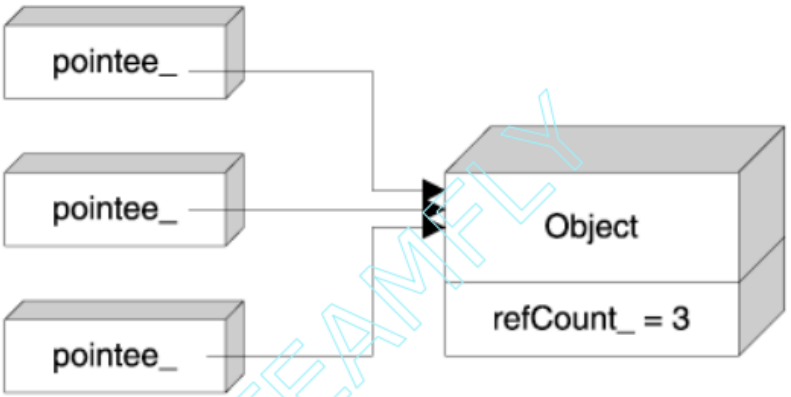
- Each smart pointer holds **a pointer to the reference counter** in addition to the pointer to the object itself. This usually **doubles the size of the smart pointer**, which may or may not be an acceptable amount of overhead, depending on your needs and constraints.

  There is another, subtler overhead issue. Reference-counted smart pointers must store the reference counter on the free store. **The problem is that in many implementations, the default C++ free store allocator is remarkably slow and wasteful of space when it comes to allocating small objects.**

- The relative size overhead can be partially mitigated by holding the pointer and the reference count together, the structure in the following figure reduces the size of the smart pointer to that of a pointer, but at the expense of access speed.

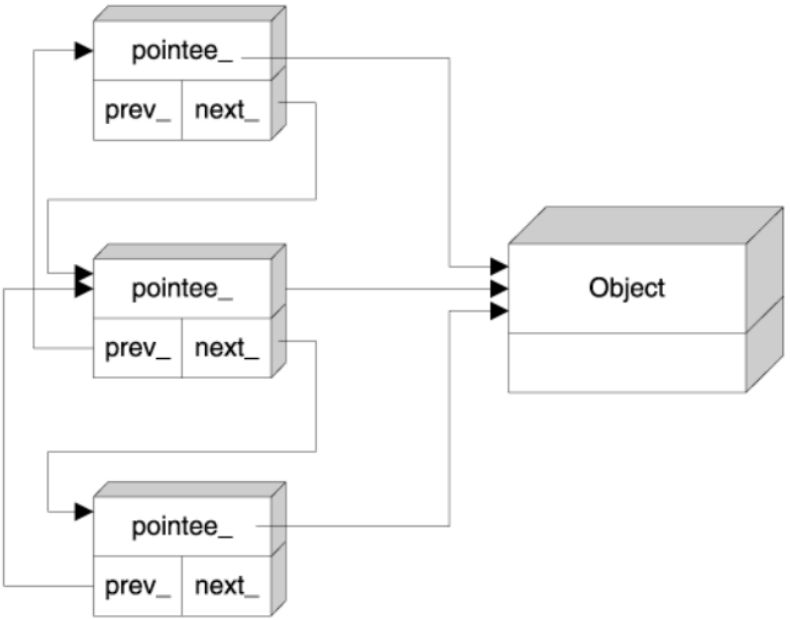


- The most efficient solution is to hold the reference counter in the pointee object itself, as shown in the following figure.



However, you must design up front or modify the pointee class to support reference counting. For implementing nonintrusive reference counting, the small-object allocator presented in Chapter 4 can help a great deal.

7.4.4 Reference Linking



When you create a new `SmartPtr` from an existing `SmartPtr`, the new object is appended to the list; `SmartPtr`'s destructor takes care of removing the destroyed object from the list.

You cannot use a singly linked list or vector because removals from such a list take linear time.

The advantage of reference linking over reference counting is that the former does not use extra free store, which makes it more reliable: Creating a reference-linked smart pointer cannot fail.

The disadvantage is that reference linking needs more memory for its bookkeeping and reference counting should be a bit speedier. You should use reference linking only when the free store is scarce.

There is a significant disadvantage of reference management—be it counting or linking—is **a victim of the resource leak known as cyclic reference**. Imagine an object `A` holds a smart pointer to an object `B`. Also, object `B` holds a smart pointer to `A`. The reference management strategy cannot detect such cyclic references, and the two objects remain allocated forever.

7.4.5 Destructive Copy

Destructive copy does exactly what you think it does: During copying, it destroys the object being copied. Smart pointers may use destructive copy to ensure that at any time there is only one smart pointer pointing to a given object.

```
template <class T>
class SmartPtr{
public:
  SmartPtr(SmartPtr& src){
    pointee_ = src.pointee_;
    src.pointee_ = 0;
  }
  SmartPtr& operator=(SmartPtr& src){
    if (this != &src){
      delete pointee_;
      pointee_ = src.pointee_;
      src.pointee_ = 0;
    }
    return *this;
  }
};
```

C++ etiquette calls for the right-hand side of the copy constructor and the assignment operator to be a reference to a `const` object. Classes that foster destructive copy break this convention for obvious reasons.

Because they do not support value semantics, smart pointers with destructive copy cannot be stored in containers and in general must be handled with almost as much care as raw pointers.

On the bright side, smart pointers with destructive copy have significant advantages:

- **They incur almost no overhead.**
- **They are good at enforcing ownership transfer semantics.** In this case, you use the "maelstrom effect" described earlier to your advantage: You make it clear that your function takes over the passed-in pointer.
- **They are good as return values from functions.** If the smart pointer implementation uses a certain trick, you can return smart pointers with destructive copy from functions.

This way, you can be sure that the pointee object gets destroyed if the caller doesn't use the return value.

- They are excellent as stack variables in functions that have multiple return paths. You don't have to remember to delete the pointee object manually—the smart pointer takes care of this for you.

The destructive copy strategy is used by the standard-provided `std::auto_ptr`.

7.5 Implicit Conversion to Raw Pointer Types

```
template <class T>
class SmartPtr{
public:
  operator T*() // user-defined conversion to T*{
    return pointee_;
  }
  ...
};
```

However, they might become dangerous especially when they expose handles to internal data, which is precisely the case with the operator T* in the previous code. Passing the raw pointer around defeats the inner workings of the smart pointer. Once unleashed from the confines of its wrapper, the raw pointer can easily become a threat to program sanity again, just as it was before smart pointers were introduced.

Another danger is that user-defined conversions pop up unexpectedly, even when you don't need them.

```
SmartPtr<Something> sp;
// However, it goes undetected at compile time
delete sp;
```

There are quite a few ways to prevent the delete call from compiling.

```
template <class T>
class SmartPtr{
public:
  operator T*(){ return pointee_; }
  operator void*(){ return pointee_; }
};
```

A call to delete against such a smart pointer object is ambiguous. But don't forget that disabling the delete operator was only a part of the issue.

However, forbidding implicit conversion does not necessarily eliminate all access to the raw pointer. Therefore, all smart pointers do provide explicit access to their wrapped pointer via a call to a function:

```
void Fun(Something* p);
SmartPtr<Something> sp;
Fun(GetImpl(sp));
```

SmartPtr provides this implicit conversion as a choice. The default is on the safe side—no implicit conversions. Explicit access is always available through the GetImpl function.

7.6 Equality and Inequality

Sometimes we expect the following tests to compile and run as they do for a raw pointer:

```
SmartPtr<Something> sp1, sp2;
Something* p;
if (sp1) // Test 1: direct test for non-null pointer
if (!sp1) // Test 2: direct test for null pointer
if (sp1 == 0) // Test 3: explicit test for null pointer
if (sp1 == sp2) // Test 4: comparison of two smart pointers
if (sp1 == p) // Test 5: comparison with a raw pointer
```

There is an unfortunate interference between the solution to the previous issue (preventing delete from compiling) and a possible solution to this issue. With one user-defined conversion to the pointee type, you can accidentally call the delete operator against the smart pointer. With two user-defined conversions (intentional ambiguity), you detect wrongful delete calls.

An additional user-defined conversion to bool helps, but you allow SmartPtr to act as a bool in many more situations than you actually wanted.

A true, complete, rock-solid solution to this dilemma is to go all the way and overload each and every operator separately.

```
template <class T>
class SmartPtr{
public:
  bool operator!() const{ return pointee_ == 0; }
  inline friend bool operator==(const SmartPtr& lhs,const T* rhs){
    return lhs.pointee_ == rhs;
  }
  inline friend bool operator==(const T* lhs,const SmartPtr& rhs){
    return lhs == rhs.pointee_;
  }
  inline friend bool operator!=(const SmartPtr& lhs,const T* rhs){
    return lhs.pointee_ != rhs;
  }
  inline friend bool operator!=(const T* lhs,const SmartPtr& rhs){
    return lhs != rhs.pointee_;
  }
};
```

We still haven't solved the problem completely. If you provide an automatic conversion to the pointee type, there still is the risk of ambiguities.

```
SmartPtr<Base> sp;
Derived* p;
if (sp == p) {}
```

We can add templated versions of them:

```
template <class T>
class SmartPtr{
public:
  ... as above ...
  template <class U>
  inline friend bool operator==(const SmartPtr& lhs,const U* rhs){
    return lhs.pointee_ == rhs;
  }
  template <class U>
  inline friend bool operator==(const U* lhs,const SmartPtr& rhs){
    return lhs == rhs.pointee_;
  }
... similarly defined operator!= ...
};
```

we need both the nontemplated and the templated comparison operators. For example, in the test `if(sp==0)`.

If we compare two SmartPtrs instantiated with different types, the compiler chokes on the comparison because of an ambiguity: Each of the two `SmartPtr` instantiations defines an `operator==`, and the compiler does not know which one to choose. So

```
template <class T>
class SmartPtr{
public:
  template <class U>
  bool operator==(const SmartPtr<U>& rhs) const{
    return pointee_ == rhs.pointee_;
  }
  // Similarly for operator!=
};
```

If you want to provide automatic conversions to the pointee type (see previous section), then you have two choices: Either you risk unattended calls to `operator` delete, or you forgo the `if (sp)` test.

If you don't want to provide automatic conversions to the pointee type, there is an interesting trick you can use to make `if (sp)` possible:

```
template <class T>
class SmartPtr{
  class Tester{
    void operator delete(void*);
  };
public:
  operator Tester*() const{
    if (!pointee_) return 0;
    static Tester test;
```

```
    return &test;
  }
};
```

Now if you write `if (sp)`, `operator Tester*` enters into action. This operator returns a null value if and only if `pointee_` is null. Tester itself disables operator delete, so if somebody calls `delete sp`, a compile-time error occurs.

7.7 Ordering Comparisions

Ordering comparisons for pointers is defined only when the pointers belong to the same contiguous memory.

If `SmartPtr`'s client chooses to allow implicit conversion, the following code compiles:

```
SmartPtr<Something> sp1, sp2;
if (sp1 < sp2){}
```

This means that if we want to disable ordering comparisons, we must be proactive, disabling them explicitly.

```
template <class T>
class SmartPtr{ ... };
template <class T, class U>
bool operator<(const SmartPtr<T>&, const U&); // Not defined
template <class T, class U>
bool operator<(const T&, const SmartPtr<U>&); // Not defined
```

However, it is wiser to define all other operators in terms of `operator<`, as opposed to leaving them undefined.

This way, if `SmartPtr`'s users think it's best to introduce smart pointer ordering, they need only define `operator<`.

```
template <class T, class U>
bool operator<(const SmartPtr<T>& lhs, const SmartPtr<U>& rhs){
  return lhs < GetImpl(rhs);
}
// All other operators
template <class T, class U>
bool operator>(SmartPtr<T>& lhs, const U* rhs){
  return rhs < lhs;
}
... similarly for the other operators ...
```

Now if some library user thinks that `SmartPtr<Widget>` should be ordered, the following code is the ticket:

```
inline bool operator<(const SmartPtr<Widget>& lhs,const Widget* rhs){
  return GetImpl(lhs) < rhs;
}
```

```
inline bool operator<(const Widget* lhs,const SmartPtr<Widget>& rhs){
  return lhs < GetImpl(rhs);
}
```

It's a pity that the user must define two operators instead of one, but it's so much better than defining eight.

Sometimes it is very useful to have an ordering of arbitrarily located objects, not just objects belonging to the same array. For example, you might need to store supplementary per-object information, and you need to access that information quickly. A map ordered by the address of objects is very effective for such a task.

the standard guarantees that `std::less` yields meaningful results for any two pointers of the same type. `SmartPtr` should support this idiom, too :

```
namespace std{
  template <class T>
  struct less<SmartPtr<T> > : public binary_function<SmartPtr<T>, SmartPtr<T>, bool>{
    bool operator()(const SmartPtr<T>& lhs, const SmartPtr<T>& rhs) const{
      return less<T*>()(GetImpl(lhs), GetImpl(rhs));
    }
  };
}
```

7.8 Checking and Error Reporting

We can divide checking issues with smart pointers into two categories: initialization checking and checking before dereference.

```
template <class T>
class SmartPtr{
public:
  SmartPtr(T* p) : pointee_(p){
    if (!p) throw NullPointerException();
  }
...
};
```

`SmartPtr` migrates checking to a dedicated Checking policy. This policy implements checking functions (which can optionally provide lazy initialization) and the error reporting strategy.

7.9 Smart Pointers to const and const Smart Pointers

```
// Smart pointer to const object
SmartPtr<const Something> spc(new Something);
// const smart pointer
const SmartPtr<Something> scp(new Something);
// const smart pointer to const object
const SmartPtr<const Something> scpc(new Something);
```

7.10 Putting It All Together

Let's recap the previous sections by enumerating the variation points of `SmartPtr`. Each variation point translates into a policy.

- **Storage policy** (Section 7.3). By default, the stored type is `T*` (`T` is the first template parameter of `SmartPtr`), the pointer type is again `T*`, and the reference type is `T&`. The means of destroying the pointee object is the delete operator.
- **Ownership policy** (Section 7.5). Popular implementations are deep copy, reference counting, reference linking, and destructive copy. Note that Ownership is not concerned with the mechanics of destruction itself; this is Storage's task. Ownership controls the moment of destruction.
- **Conversion policy** (Section 7.7). Some applications need automatic conversion to the underlying raw pointer type; others do not.
- **Checking policy** (Section 7.10). This policy controls whether an initializer for `SmartPtr` is valid and whether a `SmartPtr` is valid for dereferencing.

8 Factory

1 什么是对象工厂

面向对象程序通过**继承**和**虚函数**获得了强大的抽象性和多态能力。我们在拥有指向多态对象的基类指针或者引用时，我们可以利用**虚函数**的特性，在调用成员函数时完全确定对象的动态类型从而调用正确的成员函数。例如：

```
class Base
{
public:
    virtual void fa() = 0;
};

class Derived: public Base
{
public:
    void fa(){...}
    void fb(){...}
};

Base *p = new Derived();
```

此时，我们调用 `p->fa()` 所真正调用的是继承类 `Derived` 中的 `fa()` 函数，而调用 `p->fb()` 则是未定义的行为。这说明，在基类接口的限制下，我们能够在执行期动态的调用多态类型的成员函数，这件事情在已经有了一个指向某一个多态对象的基类指针的情况下是显然的。但我们现在要思考一个问题，程序总要在某个地方去创建这么一个多态对象并把它绑定到基类指针上去，而通常多态对象是通过 `new` 来生成的，例如前面的 `Base *p = new Derived();` 但这里出现了 `Derived` 这一确定的类型名称，也就是说，我们必须在编译期就把它确定下来，把它真正的写在我们的程序里。所以，仅仅是利用虚函数的特性我们还是只能在调用成员函数的时候更加的方便，但对于**动态的去产生多态对象**是没有帮助的。

对象工厂就是为了解决这一问题，它的目标就是把所要产生对象的类型真正推迟到执行期再确定。其最基本的功能就是：**在不需要对程序进行任何的修改和重新编译的情况下，根据用户在执行期的不同输入来构造用户想要的不同**

多态对象，并返回其基类指针。工厂模式的作用就是隔离类对象的使用者和具体类型之间的耦合关系。

2 对象工厂的实现

假设我们正在编写一个绘图程序，我们定义了如下的基类：

```
class Shape
{
public:
    virtual void draw() const = 0;
    virtual void rotate(double angle) = 0;
};
```

我们还有一些继承类：

```
class Circle : public Shape
{
public:
    void draw(){...}
    void rotate(double angle){...}
};

class Line : public Shape
{
public:
    void draw(){...}
    void rotate(double angle){...}
};
...
```

对于每个继承类来说，我们都可以定义类似于下面这样的函数：

```
std::unique_ptr<Shape> createCircle()
{
    return std::make_unique<Circle>();
```

```
}
```

这个对象生成函数负责生成一个指向 Circle 对象的智能指针。有了对象生成函数之后，最简单粗暴的方法就是写一个函数，它接受一个身份识别 (ID)，这个 ID 标识着我想要生成哪种多态对象，在函数内部通过 switch 等类似的语句来选则调用哪个对象生成函数。这种方式可以实现我们想要的效果，但是最大的一个缺点就是：如果我又从 Shape 这个基类继承出了一个新的类型，比如 rectangle，那我们就必须找到这个函数在哪定义的，之后在 switch 里面加上一项，这种代码的可拓展性是很差的，我们没有办法在程序中随时随地的修改它。

下面我们来介绍对象工厂是怎么实现我们的目标的。我们所想要的其实就是从继承类的 **ID** 到**对象生成函数**间的一个一一对应关系，我们很自然的可以想到 **std::map** 这个工具。我们可以从一个空的 std::map 开始，每有一个新的继承类，我们就向其中添加一对键和值（即 ID 和对应的对象生成函数），这样我们就可以通过 ID 来得到对应的对象生成函数并用于生成对象。现在我们可以设计出如下的对象工厂：

```
class ShapeFactory
{
public:
    using CreateShapeCallback = std::unique_ptr<Shape> (*)();

private:
    using CallbackMap = std::map<std::string, CreateShapeCallback>;

public:
    //the only way to create a ShapeFactory object
    static ShapeFactory& createFactory()
    {
        static ShapeFactory object;
        return object;
    }

    //return true if registration was successful
    bool registerShape(std::string shapeId, CreateShapeCallback createFn)
```

```
    {
        return callbacks_.insert(CallbackMap::value_type(shapeId, createFn)).
            second;
    }

    //return true if the shapeId was registered before
    bool unregisterShape(std::string shapeId)
    {
        return callbacks_.erase(shapeId) == 1;
    }

    std::unique_ptr<Shape> createShape(std::string shapeId)
    {
        auto it = callbacks_.find(shapeId);
        if (it == callbacks_.end())
        {
            throw std::runtime_error("Unknown Shape ID. ");
        }
        return (it->second)();
    }

private:
    CallbackMap callbacks_;

    struct Object_Creater{
        Object_Creater()
        {
            ShapeFactory::createFactory();
        }
    };

    static Object_Creater obj_crt;


    ShapeFactory() = default;
    ShapeFactory(const ShapeFactory&) = default;
    ShapeFactory& operator=(const ShapeFactory&) = default;
    ~ShapeFactory() = default;
```

```
};

ShapeFactory::Object_Creater ShapeFactory::obj_crt;
```

这是一个**可伸缩对象工厂**的基本设计，每次添加一个新的继承类时，不必修改对象工厂的代码，只需要在程序的任意位置指定好 ID 和对象生成函数并调用 registerShape 注册一下就可以了。当你想要生成一个对象时，你只需要告诉工厂对应的 ID，调用 createShape 就会返回一个指向你想要的对象的基类指针。当你不想让工厂再生产某个多态对象时，只需要在程序的任意位置调用 unregisterShape 删除键值为对应 ID 的映射就可以了。

这个设计里面还加入了 singleton pattern，即全局范围内只能存在一个工厂对象，其他所有的工厂都只能是这个工厂的引用。这一设计是通过把工厂类的构造函数、拷贝构造函数、赋值构造函数都设为 private 的，并且定义一个 public 的 static 成员函数，也就是上例中的 createFactory()，它是能够获取一个工厂对象引用的唯一方式。可以看到这个函数内部定义了一个 static 的工厂对象，这就意味着这个函数只有在第一次调用时会产生这一对象，之后的调用都会直接返回这一对象，所以全局只会存在一个工厂对象。

下面的 Object_Creater 这个结构是用来帮助生成唯一的工厂对象的，可以看到工厂类内部有一个 static 成员变量 obj_crt，在它被定义的时候，就会自动的调用一次 createFactory()，即工厂类在定义完成的时候就已经生成了一个工厂对象，并且这个对象是全局唯一的。

3 泛型工厂

上一节的内容已经能针对 Shape 这个基类很好的实现我们的目标。但从它的实现我们可以看出，如果我有另一种基类和它的继承类，那我们就需要重新写一个对象工厂，但它们其实本质上是没什么区别的。这就是为什么需要泛型工厂。

在上一节里我们可以看到对象工厂具有下面的几个关键要素：

i. 具体产品：即生成的具体对象;

ii. 抽象产品：即返回的基类指针，不带有对象的具体类型;

iii. 产品 ID：用来标识产品的类型;

iv. 产品生产者：生产代表不同具体产品的抽象产品。

泛型工厂就是用来协调这些要素，利用**模板**来给出一个能够用于不同基类的通用对象工厂。在上面的四个要素中，我们实际上只需要确定三个，具体产品的类型是包含在具体的产品生产者中的，所以我们需要的就是一个具有三个模板参数的泛型工厂类。如果假设这里的产品生产者和上一节一样，都采用对象生成函数的话，那它的类型就是返回抽象产品类型指针的函数，也就是说第三个模板参数是可以给一个缺省值的。

我们还需要考虑一个问题，并不是每个基类的构造函数都是不需要参数的，那么考虑上一节中对象工厂的形式，我们没有办法对对象进行带参数构造。如果我们仍然想说我们的泛型工厂能够适用于所有基类，那就要解决这一问题，但不同的基类构造函数需要的参数个数又不一样。这里就需要一种手段叫作**可变长模板**，正如之后代码中 `creatProduct` 函数中展示的，这种手段可以把任意长度的参数完美转发给另一个函数，也就是我们的对象生成函数。下面我们来看泛型工厂的具体实现：

```
template <class AbstractProduct, typename IdType, typename ProductCreator = std
    ::unique_ptr<AbstractProduct> (*)()>
class GenericFactory
{
private:
    using CallbackMap = std::map<IdType, ProductCreator>;

public:
    static GenericFactory& createFactory()
    {
        static GenericFactory object;
        return object;
    }

    //return true if registration was successful
    bool registerProduct(IdType Id, ProductCreator createFn)
    {
```

```
        return callbacks_.insert(typename CallbackMap::value_type(Id, createFn))
            .second;
    }

    //return true if the Id was registered before
    bool unregisterProduct(IdType Id)
    {
        return callbacks_.erase(Id) == 1;
    }

    //support construction
    template<class ...TS>
    std::unique_ptr<AbstractProduct> createProduct(IdType Id, TS && ...args)
    {
        auto it = callbacks_.find(Id);
        if (it == callbacks_.end())
        {
            throw std::runtime_error("Unknown product ID. ");
        }
        return (it->second)(std::forward<TS>(args)...);
    }

private:
    CallbackMap callbacks_;

    struct Object_Creater{
        Object_Creater()
        {
            GenericFactory::createFactory();
        }
    };

    static Object_Creater obj_crt;

    GenericFactory() = default;
    GenericFactory(const GenericFactory&) = default;
    GenericFactory& operator=(const GenericFactory&) = default;
    ~GenericFactory() = default;
```

```
};

template<class AbstractProduct, typename IdType, typename ProductCreator>
typename GenericFactory<AbstractProduct, IdType, ProductCreator>::
    Object_Creater GenericFactory<AbstractProduct, IdType, ProductCreator>::
    obj_crt;
```

我们在使用泛型工厂的时候,只需要实例化为我们想要的对象工厂。比如说现在我们现在有一个基类 Shape_int,它的构造函数需要接受一个整数,那我们就把 AbstractProduct 实例化为 Shape_int,把 IdType 实例化为 std::string,把 ProductCreator 实例化为 std::unique_ptr<Shape_int> (*)(int)。之后在进行对象生成时, 调用:

```
GenericFactory<Shape_int, std::string, std::unique_ptr<Shape_int> (*)(int)>
    shapeFactory;
...
std::unique_ptr<Shape_int> p = shapeFactory.createProduct("Circle"/*Shape name
    */, 1/*integer*/);
```

就可以实现我们想要的对象工厂。