Adventures in Perfect Forwarding

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Lvalues and Rvalues

Lvalues:

- Generally expressions you can take the address of.
  - E.g., named variables.
- Copy requests *copy* (i.e., don't change source expression).

Rvalues:

- Generally expressions that aren't lvalues.
  - E.g., temporary objects.
- C++98/03 copy requests often become *move* requests.

Examples:

```
std::shared_ptr<Widget> factory();     // return type is rvalue

auto p1 = factory();                   // move construction
                                       // from rvalue source

auto p2 = p1;                          // copy construction
                                       // from lvalue source
```

Rvalue References and Universal References

Rvalue references:

- Like "normal" ("lvalue") references, but bind only to rvalues.
- Syntax: *type*&& (e.g., int&&, std::string&&).

"&&" parameters in function templates:

- Mean "bind to anything" ⇒ *universal references*:

```
template<typename T>
void f(T&& param);
```

  - ➡ T's deduced type T& for lvalue args, T for rvalue args.
  - ➡ Function param type T& for lvalue args, T&& for rvalues.

```
int x;
f(x);                 // lvalue: T is int&
                      // instantiates f(int&)
f(factory());         // rvalue:
                      // T is std::shared_ptr<Widget>
                      // instantiates f(std::shared_ptr<Widget>&&)
```

Practically speaking, not an rvalue reference!

Perfect Forwarding

Given

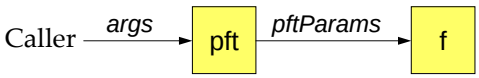
```
returnType f( fParams );
```

a perfect forwarding template for f

```
template< templateParms >
returnType pft( pftParams );
```

is (typically) designed so that

```
pft( args );
```

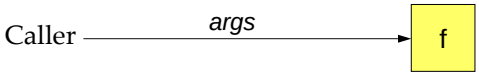


internally invokes

```
f( pftParams );
```

which behaves the same as

```
f( args );
```

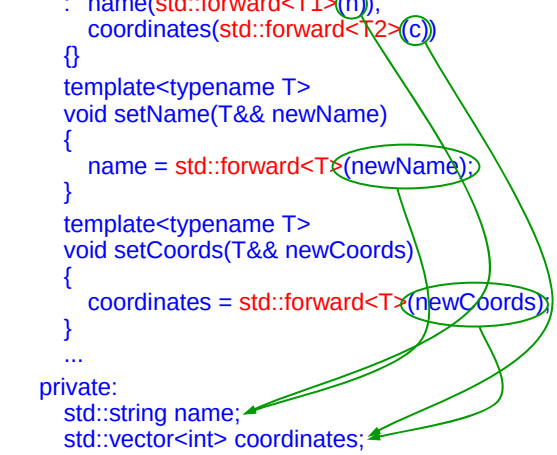


would have.

Use Cases for Perfect Forwarding

Constructors and setters:

```
class Widget {
public:
  template<typename T1, typename T2>                  // PF ctor
  Widget(T1&& n, T2&& c)
  : name(std::forward<T1>(n)),
    coordinates(std::forward<T2>(c))
  {}
  template<typename T>                                // PF setter
  void setName(T&& newName)
  {
    name = std::forward<T>(newName);
  }
  template<typename T>                                // PF setter
  void setCoords(T&& newCoords)
  {
    coordinates = std::forward<T>(newCoords);
  }
  ...
private:
  std::string name;
  std::vector<int> coordinates;
};
```



Use Cases for Perfect Forwarding

std::make_shared:

```
std::string s("PF Example");
auto pw = std::make_shared<Widget>(s,                          // lvalue
                                   std::vector<int>({1, 2, 3}));  // rvalue

template<typename T, typename... ParamTs>
shared_ptr<T> make_shared(ParamTs&&... params)
{                                                              // very
  void *memForSP =                                             // simplified!
    ::operator new(sizeof(T)+sizeof(RCBlock));
  auto sp =
    new (memForSP) shared_ptr<T>(make_shared_tag,
                                 std::forward<ParamTs>(params)...);
  return *sp;
}
```

g++ does it indirectly:

- make_shared→allocate_shared→shared_ptr ctor→...→T ctor

Perfect Forwarding is Imperfect

Several kinds of arguments can't be perfect-forwarded.

- 0 as null pointer constant
- Braced initializer lists
- Integral const static class members lacking a definition
- Template names (e.g., std::endl)
- Non-const lvalue bitfields

Further Information has details.

- Though imperfect, perfect forwarding is still quite good.

"Specializing" Forwarding Templates

Forwarding to f is easy,

```
template<typename T>
void fwd(T&& param)
{
  ...
  f(std::forward<T>(param));
  ...
}
```

but what if we want to treat some types differently?

- I.e., want to "specialize" fwd for pointers.

"Specializing" Forwarding Templates

Function templates can't be specialized, only overloaded.

- But the form of forwarding templates is constrained.
  - ➡ The only parameter type that works is T&&!
    - ◆ "Works" ≡ handles all combos of const/non-const + lvalue/rvalue

```
template<typename T>
void fwd(T&& param);          // fine, handles all combos

template<typename T>
void fwd(T*&& param);         // handles rvalues only
                              // (param type is rref-to-pointer)
```


"Specializing" Forwarding Templates

```
template<typename T>          // #1: "normal" forwarding
void fwd(T&& param)           // template
{
  f(std::forward<T>(param));
}

template<typename T>          // #2: attempted "specialized"
void fwd(T*&& param)          // forwarding template
{
  f(std::forward<T*>(param));
}

std::string* ps;
const std::string *pcs;

fwd(ps);                      // calls #1
fwd(pcs);                     // calls #1
fwd((std::string*&&)ps);      // calls #2
```

Using std::enable_if

One solution: overload via std::enable_if:

```
template<typename T>
typename std::enable_if<
   !std::is_pointer<                                  // template for
      typename std::remove_reference<T>::type         // non-pointer types
   >::value
>::type
fwd(T&& param)
{
   f(std::forward<T>(param));
}

template<typename T>
typename std::enable_if<
   std::is_pointer<                                   // template for
      typename std::remove_reference<T>::type         // pointer types
   >::value
>::type
fwd(T&& param)
{
   f(std::forward<T>(param));
}
```


Using std::enable_if

Drawbacks:

- No ordering among templates with satisfied enable_ifs.
  - ➧More/less "specialized" requires manual implementation.
- New "specialization" ⇒ existing ones may have to be modified.

Consider a new "specialization" for forwarding const char*s.

- Next slide.

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Using std::enable_if

```
template<typename T>                                    // general version
typename std::enable_if<
   !std::is_pointer<typename std::remove_reference<T>::type>::value
>::type
fwd(T&& param)
{ f(std::forward<T>(param)); }

template<typename T>                                    // general T* version
typename std::enable_if<
   std::is_pointer<typename std::remove_reference<T>::type>::value
   && !std::is_same<typename std::remove_reference<T>::type,
                    const char*>::value
>::type
fwd(T&& param)
{ f(std::forward<T>(param)); }

template<typename T>                                    // const char* version
typename std::enable_if<
   std::is_same< typename std::remove_reference<T>::type,
                 const char*>::value
>::type
fwd(T&& param)
{ f(std::forward<T>(param)); }
```


Dispatching Through a Class Template

Enables use of class template partial specialization:

```
template<typename T>                                  // General template
class fwd_impl {
public:
   template<typename U>                               // Standard forwarding function
   static void call(U&& param)
   {
      f(std::forward<U>(param));
   }
};

template<typename T>                                  // Partial specialization
class fwd_impl<T*> {
public:
   template<typename U>
   static void call(U&& param)
   {
      f(std::forward<U>(param));
   }
};

template<typename T>                                  // Standard declaration
void fwd(T&& param)
{
  return fwd_impl<typename std::remove_reference<T>::type>::call(std::forward<T>(param));
}
```

Turn e.g., T*& into T*

Standard forwarding call

Dispatching Through a Class Template

Adding a new specialization now easy:

```
template<>
class fwd_impl<const char*> {
public:
  template<typename U>
  static void call(U&& param)
  {
    f(std::forward<U>(param));
  }
};
```

- Existing specializations not affected.
- Compiler automatically chooses most specialized version.

Meanwhile, Back on Earth...

Specializing for pointers unrealistic.

- Rarely useful to distinguish pointer lvalues and rvalues.

Specializing for UDTS very realistic.

- Often useful to distinguish lvalues and rvalues
- std::shared_ptr is such a UDT.
  - ➡ Moving cheaper than copying.

New goal: "specialize" fwd for std::shared_ptrs.

"Specializing" for std::shared_ptrs

Easy:

```
template<typename T>
class fwd_impl<std::shared_ptr<T>> {
public:
  template<typename U>
  static void call(U&& param)
  {
    f(std::forward<U>(param));
  }
};
```

But doesn't catch const std::shared_ptrs:

```
std::shared_ptr<Widget> spw;
...
fwd(spw);                          // calls above specialization
const std::shared_ptr<Widget> cspw;
...
fwd(cspw);                         // calls general fwd_impl
                                   // template
```


"Specializing" for std::shared_ptrs

To catch both, you can add another partial specialization:

```
template<typename T>
class fwd_impl<const std::shared_ptr<T>> {
public:
  template<typename U>
  static void call(U&& param)
  {
    f(std::forward<U>(param));
  }
};
```

But this won't handle volatile-qualified std::shared_ptrs, sigh.

"Specializing" for std::shared_ptrs

If std::shared_ptr is all you care about, strip cv qualifiers inside fwd:

```
template<typename T>
void fwd(T&& param)
{
  return fwd_impl<
    typename std::remove_cv<
      typename std::remove_reference<T>::type
      >::type
    >::call(std::forward<T>(param));
}

                std::shared_ptr<Widget> spw;
const           std::shared_ptr<Widget> cspw;
volatile        std::shared_ptr<Widget> vspw;
const volatile  std::shared_ptr<Widget> cvspw;

fwd(spw);                          // all invoke fwd_impl for
fwd(cspw);                         // std::shared_ptr
fwd(vspw);
fwd(cvspw);
```


Gratuitous Animal Photo: Atlas Moth

Source: http://lafinjack.net/images/random/

Forwarding and the pImpl Idiom

A class with a forwarding constructor and a setter:

```
class Widget {
public:
  template<typename T>
  Widget(T&& param)                          // forwarding ctor
  : name(std::forward<T>(param))
  {}

   template<typename T>
   void setName(T&& newName)                 // forwarding setter
   {
     name = std::forward<T>(newName);
  }
  ...
private:
  std::string name;
};
```


Forwarding and the pImpl Idiom

Pimplization is straightforward:

```
// File Widget.h
class WidgetImpl;                            // declaration only

class Widget {
public:
  template<typename T>
  Widget(T&& param);                         // declaration only

   template<typename T>
   void setName(T&& newName);                // declaration only
  ...
private:
  std::shared_ptr<WidgetImpl> p;             // pImpl.  (std::unique_ptr
};                                           // might be preferable.)
```

Widget clients compile with this.

Forwarding and the pImpl Idiom

Simple implementation equally straightforward:

```
// File WidgetImpl.cpp
struct WidgetImpl {                              // simplest thing that
  std::string name;                              // could possibly work
};

template<typename T>
Widget::Widget(T&& param)                        // forwarding ctor
: p(new WidgetImpl)
{
  p->name = std::forward<T>(param);
}

template<typename T>
void Widget::setName(T&& newName)                // forwarding setter
{
  p->name = std::forward<T>(newName);
}
```

Widget clients link against a compiled version of this.

Forwarding and the pImpl Idiom

Prospective client code:

```
#include "Widget.h"

int main()
{
  Widget w("This is a test");                          // lvalue
                                                       // const char[15]

  w.setName(std::string("This is another test"));      // rvalue std::string

  std::string s("Still testing...");
  w.setName(s);                                        // lvalue std::string
}
```

Compiles without fuss.

Forwarding and the pImpl Idiom

Linking a different story:

- g++ 4.7:

```
...:pimpl.cpp:(.text.startup+0x26): undefined reference to `Widget::Widget<char const (&) [15]>(char const (&) [15])'
...:pimpl.cpp:(.text.startup+0x4c): undefined reference to `void Widget::setName<string>(string &&)'
...:pimpl.cpp:(.text.startup+0x79): undefined reference to `void Widget::setName<string &>(string &)'
```

- VC11:

```
pimpl.obj : error LNK2019: unresolved external symbol "public: __thiscall Widget::Widget<char const (&)[15]>(char const
(&)[15])" (??$?0AAY0P@$$CBD@Widget@@QAE@AAY0P@$$CBD@Z) referenced in function _main

pimpl.obj : error LNK2019: unresolved external symbol "public: void __thiscall Widget::setName<class
std::basic_string<char,struct std::char_traits<char>,class std::allocator<char> > >(class std::basic_string<char,struct
std::char_traits<char>,class std::allocator<char> > &&)"
(??$setName@V?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@@Widget@@QAEX$$QAV?$
basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@@Z) referenced in function _main

pimpl.obj : error LNK2019: unresolved external symbol "public: void __thiscall Widget::setName<class
std::basic_string<char,struct std::char_traits<char>,class std::allocator<char> > &>(class std::basic_string<char,struct
std::char_traits<char>,class std::allocator<char> > &)"
(??$setName@AAV?$basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@@Widget@@QAEXAAV?$
basic_string@DU?$char_traits@D@std@@V?$allocator@D@2@@std@@@Z) referenced in function _main
```


Forwarding and the pImpl Idiom

The usual template instantiation problem:

- Compilers need template source for instantation.
- VC11 and g++ 4.7 (on Windows) want it during compilation.

Pimpl precludes that.

Possible solutions:

- Abandon pImpl, i.e., admit defeat (!).
- Use different build chain.
  - ➧Some use link-time instantation.
- Perform explicit instantation.

Explicit Instantiation

The templates again:

```
template<typename T>
Widget::Widget(T&& param) ...                    // forwarding ctor

template<typename T>
void Widget::setName(T&& newName) ...            // forwarding setter
```

The uses again:

```
Widget w("This is a test");                      // lvalue
                                                 // const char[15]

w.setName(std::string("This is another test")); // rvalue std::string

w.setName(s);                                    // lvalue std::string
```

Instantiations we need:

- Widget ctor with T = const char (&)[15]
- setName with T = std::string and also T = std::string&

Explicit Instantiation

This is *exactly* what g++ reported:

```
...:pimpl.cpp:(.text.startup+0x26): undefined reference to `Widget::Widget<char const (&) [15]>(char const (&) [15])'
...:pimpl.cpp:(.text.startup+0x4c): undefined reference to `void Widget::setName<string>(string &&)'
...:pimpl.cpp:(.text.startup+0x79): undefined reference to `void Widget::setName<string &>(string &)'
```

Explicit Instantiation

Piece of cake:

```
// In WidgetImpl.cpp (or a file that can see it)
template Widget::Widget<char const(&)[15]>(char const(&)[15]);
template void Widget::setName<std::string>(std::string&&);
template void Widget::setName<std::string&>(std::string&);
```

- For rvalues, deduced and parameter types not the same.
  - ➡ E.g., T = std::string, but parameter type is std::string&&.
- g++'s linker tells you what you need.

```
...:pimpl.cpp:(.text.startup+0x26): undefined reference to `Widget::Widget<char const (&) [15]>(char const (&) [15])'
...:pimpl.cpp:(.text.startup+0x4c): undefined reference to `void Widget::setName<string>(string &&)'
...:pimpl.cpp:(.text.startup+0x79): undefined reference to `void Widget::setName<string &>(string &)'
```

With code above, g++ 4.7 compiles/links/runs.

Explicit Instantiation

VC11 compiler rejects these explicit instantiation requests:

```
widgetimpl.cpp(24) : error C2143: syntax error : missing ';' before '<'
```

MS has confirmed two (!) compiler bugs. Plus a workaround :-)

- Explicitly force implicit instantiation:

```
// In WidgetImpl.cpp (or a file that can see it)
namespace {
  void forceInstantiations()        // never called
  {
    Widget w("This is a test");     // const char(&)[15]
    w.setName(std::string());       // rvalue std::string

    std::string s;
    w.setName(s);                   // lvalue std::string
  }
}
```

This works with g++, too (⇒ probably portable).

Explicit Instantiation and Arrays

Unpleasant and impractical:

```
...
template Widget::Widget<char const(&)[15]>(char const(&)[15]);
template Widget::Widget<char const(&)[16]>(char const(&)[16]);
template Widget::Widget<char const(&)[17]>(char const(&)[17]);
...
```

Would be nice to "partially specialize" the forwarding templates.

- T[n] arguments could be cast to T* before forwarding.
- Exercise for the attendee :-)

Summary

- Perfect forwarding fails for some kinds of arguments.
- To "specialize" forwarding templates, use helper class templates or std::enable_if.
- Templates + pImpl ⇒ explicitly force instantiations.

Further Information

Topics discussed here:

- "Perfect Forwarding Failure Cases," comp.std.c++ discussion initiated 16 January 2010.
- "Specializing Perfect Forwarding Templates?," comp.lang.c++ discussion initiated 15 March 2011.
- "Onward, Forward!," Dave Abrahams, *C++Next*, 7 Dec. 2009.
- "Universal References in C++11," *C++ and Beyond 2012*, August 2012.

Further Information

Topics related to topics discussed here:

- "Initial Thoughts on *Effective C++11*," *C++ and Beyond 2012*, August 2012.
- "unordered_map::emplace in C++0x," comp.lang.c++ discussion initiated 28 April 2011.
  - ➡ Forwarding multiple parameters as one object (forward_as_tuple):

Further Information

Nuances of std::forward specification/implementation.

- Focus on subtle "safely forward an X as a Y" cases.
  - ➧ E.g., in converting move constructors/operator=s.
- "forward," Howard E. Hinnant, WG21 Document N2951, 27 September 2009.
  - ➧ Abrahams' "Onward, Forward!" contains relevant comments.
- "Proposed wording for US 90," Howard Hinnant and Daniel Krügler, WG21 Document N3143, 15 October 2010.

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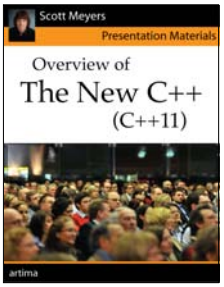

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