Department I - C Plus Plus

Modern and Lucid C++ Advanced for Professional Programmers

Week 12 – Advanced Library Design

Prof. Peter Sommerlad / Thomas Corbat

Rapperswil, 09.05.2019

FS2019

HSR
HOCHSCHULE FÜR TECHNIK
RAPPERSWIL
FHO Fachhochschule Ostschweiz

IFS
INSTITUTE FOR
SOFTWARE

Recap Week 11

HSR
HOCHSCHULE FÜR TECHNIK
RAPPERSWIL
FHO Fachhochschule Ostschweiz

IFS
INSTITUTE FOR
SOFTWARE

```
struct ConcurrentCounter {
  void increment() {
    std::scoped_lock lock{m};
    ++value;
  }

  int current() const {
    std::scoped_lock lock{m};
    return value;
  }

private:
  mutable std::mutex m{};
  int value{};
};
```

```
template <typename T, typename MUTEX = std::mutex>
struct ThreadsafeQueue {
  using guard = std::lock_guard<MUTEX>;
  using lock = std::unique_lock<MUTEX>;
  void push(T const & t) {
    guard lk{mx};
    q.push(t);
    notEmpty.notify_one();
  }
  T pop() {
    lock lk{mx};
    notEmpty.wait(lk, [this] { return !q.empty(); });
    T t = q.front();
    q.pop();
    return t;
  }
private:
  mutable MUTEX mx{};
  std::condition_variable notEmpty{};
  std::queue<T> q{};
};
```

- **Can everything be used as template argument for `std::atomic<T>`?**
  - `T` must be trivially copyable
- **Member Operations (all atomic)**

`void` **`store`**`(T)` set the new value	`T` **`load`**`()` get the current value	`T` **`exchange`**`(T)` set a new value and get the previous
`bool` **`compare_exchange_weak`**`(T & expected, T desired)` compare `expected` with current value, if equal replace the current value with `desired`, otherwise replace `expected` with current value. May spuriously fail (even when current value == `expected`). **`compare_exchange_strong`** cannot fail spuriously, but might be slower		

- **Specializations like `std::atomic<int>` also provide atomic operators like ++, --, +=, etc.**

- **In this lecture you should learn...**
  - ... to distinguish between the different exception safety levels
  - ... to decide when a function can be noexcept
  - ... how to hide implementations with the pimpl idiom

Exception Safety

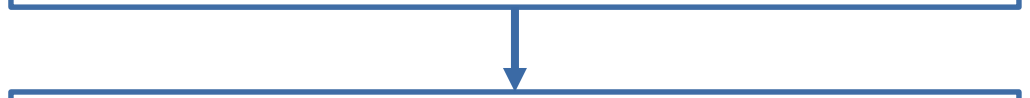
Cevelop
Your C++ deserves it

HSR
HOCHSCHULE FÜR TECHNIK
RAPPERSWIL
FHO Fachhochschule Ostschweiz

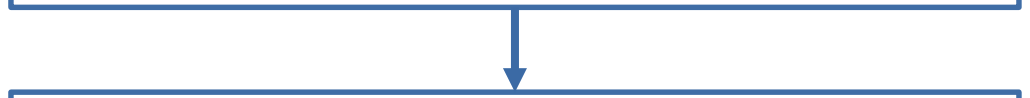
IFS
INSTITUTE FOR
SOFTWARE

- **There is code that handles exceptions**
  - Does it handle all possible exceptions?
- **There is code that throws exceptions**
- **There is exception neutral code**
  - Does not throw exceptoins
  - Does not catch exceptions
  - It just forwards exceptions thrown in called code
- **Exception neutral code is probably the most common kind you will deal with**
  - Can you neglect exceptions in exception neutral code?

```
void code_that_catches() {
  try {
    //...
  } catch(...) {
    //...
  }
}
```



```
void code_that_is_exception_neutral() {
  //...
}
```



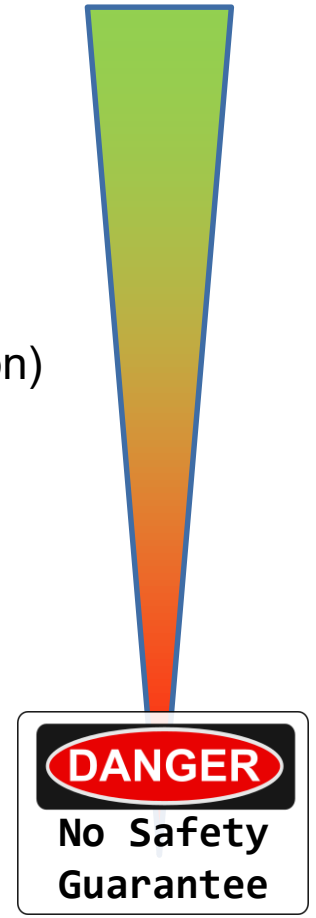
```
void code_that_throws() {
  //...
  throw std::some_exception{"what"};
}
```

Why Is Exception Safety Important?

- **In generic code that manages resources or data structures**
  - It might call user-defined operations from template arguments explicitly or implicitly
  - It must not garble its data structures
  - It must not leak resources (esp. memory!) – RAII helps
- **Generic code must also be usable to not make user-provided code suffer**
  - Responsibility goes in both directions
- **Deterministic lifetime model of C++ requires it**
  - When an exception is thrown, “stack unwinding” ends the lifetime of temporary and local objects
  - Throwing an exception while another exception is “in flight” in the same thread causes the program to `std::terminate()`
  - Better do not throw on stack unwinding from an exception

Exception Safety Levels of an Operation/Function

- **`noexcept` aka no-throw**
  - Will never-ever throw an exception (and the operation is successful!)
- **Strong exception safety**
  - Operation succeeds and doesn't throw, or nothing happens but an exception is thrown (transaction)
- **Basic exception safety**
  - Does not leak resources or garble internal data structures in case of an exception but might be incomplete
- **No guarantee**
  - You do not want to go there, undefined behavior and garbled data lurking
- **A function can only be as exception-safe as the weakest sub-function it calls!**



Dave Abrahams: http://www.boost.org/community/exception_safety.html

No Guarantee

- **You do not want to go there**
- **Invalid or corrupted data when an exception is thrown**
  - better never catch and let main terminate
  - often unintentional, but happens
  - undefined behavior is lurking
- **Very easy to achieve!**

```
BoundedBuffer & operator=(BoundedBuffer const & other) {
  if (m_container != other.m_container) {
    m_capacity = other.m_capacity;
    // what if this allocation throws?
    m_container = new char[sizeof(T) * m_capacity];
    m_position = 0;
    m_size = 0;

    for (auto const & element : other){
      this->push(element); // what if a copy throws?
    }
  }
  return *this;
}
```

- **No resource leaks**
- **No garbled internal data structure (invariants hold)**
- **But**
  - Operation request could be only half-done

```
template<typename...TYPE>
static BoundedBuffer<value_type> make_buffer(const int size, TYPE&&...param) {
  int const number_of_arguments = sizeof...(TYPE);
  if (number_of_arguments > size)
    throw std::invalid_argument{"Invalid argument"};
  BoundedBuffer<value_type> buffer{size};
  buffer.push_many(std::forward<TYPE>(param)...);
  return buffer;
}
```

Is push_many() safe?

- **`push()` could fail**
  - If in the middle of the pushs no memory is leaked, but the buffer only contains some of the pushed elements

```
void push_many() { }

template<typename FIRST, typename...REST>
void push_many(FIRST && first, REST&&...rest) {
  push(std::forward<FIRST>(first));
  push_many(std::forward<decltype(rest)>(rest)...);
}

void push(value_type const & elem) {
  if(full()) throw std::logic_error{"full"};
  auto pointer = reinterpret_cast<value_type*>(dynamic_container_) + tail_;
  new (pointer) value_type{elem}; // might throw due to copy
  tail_ = (tail_ + 1) % (capacity() + 1);
  elements_++;
}
```

- **Transaction semantic**
  - operation succeeds, or
  - operation fails with an exception and has no effects
- **Can be hard to achieve**
  - when multiple effects have to happen in sequence and something can go wrong in the middle
  - doable with 2 effects, when the second one can not throw an exception or when one can undo at least one of the effects

```
BoundedBuffer & operator=(BoundedBuffer const & other) {
  if (this != &other) {
    BoundedBuffer copy {other}; // might throw
    swap(copy); // mustn't throw
  }
  return *this;
}
```

Copy-Swap Idiom

- **A function will never throw an exception**
- **And it will be successful**
  - Any failure is handled internally and compensated for
  - Or no failures are possible
- **How?**
  - Very hard, up to impossible if resource requests are required, i.e., memory allocation
  - Even if it doesn't happen in practical cases, it might happen in theory and in the field
  - All possible argument values must be considered valid (wide contract)

```
bool std::vector<T>::empty() const noexcept;
size_type std::vector<T>::size() const noexcept;
size_type std::vector<T>::capacity() const noexcept;

T * std::vector<T>::data() noexcept;

// all iterator factories begin(), end()...
void std::vector<T>::clear() noexcept;


// but not:
void std::vector<T>::push_back(T const&);
void std::vector<T>::pop_back();
// as well as emplace, insert, resize, erase
void swap(vector&); //until C++17
```

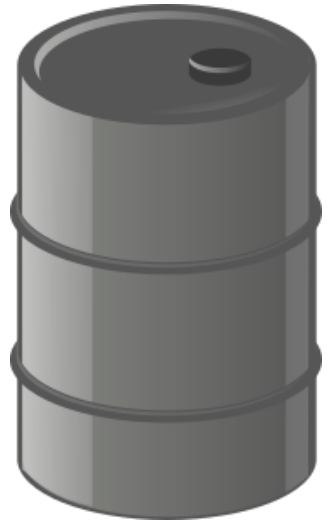
	Invariant OK	All or Nothing	Will Not Throw
No Guarantee	✗	✗	✗
Basic Guarantee	✓	✗	✗
Strong Guarantee	✓	✓	✗
No-Throw Guarantee	✓	✓	✓

- **noexcept belongs to the function signature**
  - Cannot overload on noexcept
- **noexcept is shorthand for noexcept(true)**
  - noexcept(false) is the default, when no exception specification is given for a function
- **noexcept(expression) can be used to determine the "noexceptiness" of an expression, without actually computing it**
  - noexcept(expression) is true if and only if expression consists only of operations that are noexcept(true)
  - You specify a conditional noexcept as
    - noexcept(noexcept(<expression>))

```
void function() noexcept {
  //...
}

template<typename T>
void function(T t) noexcept(<expression>) {
  //...
}
```

```
void main() {
  std::cout << "is function() noexcept? " <<
    noexcept(function()) << '\n';
}
```

```
template <unsigned ChanceToExplode>
struct Liquid;

using Nitroglycerin = Liquid<75>;
using JetFuel = Liquid<10>;
using Water = Liquid<0>;

template <typename Liquid>
struct Barrel {
  Barrel(Liquid && content)
    : content{std::move(content)} {
  }
  void poke() noexcept(noexcept(std::declval<Liquid>().shake())) {
    content.shake();
  }
private:
  Liquid content;
};
```



Member Functions That Should Not Throw

- **Destructors must not throw when used during stack unwinding**
- **Move construction and move assignment better not throw**
- **swap should not throw**
  - `std::swap` requires non-throwing move operations
- **Copying might throw, when memory needs to be allocated**

```
// g++ library std::vector:
void swap(vector & __x) _GLIBCXX_NOEXCEPT
```

- **It may be hard for a library type (container) to implement its move operations correctly if the element type does not support noexcept-move.**
  - What could we do instead?
- **`std::move_if_noexcept`**

```
template< class T>
constexpr typename std::conditional<
    !std::is_nothrow_move_constructible<T>::value && std::is_copy_constructible<T>::value,
    const T&,
    T&&
>::type move_if_noexcept(T& x);
```

`is_nothrow_constructible`	`is_nothrow_move_constructible`	`is_nothrow_move_assignable`
`is_nothrow_default_constructible`	`is_nothrow_assignable`	`is_nothrow_destructible`
`is_nothrow_copy_constructible`	`is_nothrow_copy_assignable`	`is_nothrow_swappable`

http://en.cppreference.com/w/cpp/utility/move_if_noexcept

noexcept Example

```
template<typename T>
class _box {
  T value;
public:
  explicit _box(T const &t) noexcept(noexcept(T(t))) :
      value(t) {
  }

  explicit _box(T && t) noexcept(noexcept(T(std::move_if_noexcept(t)))) :
      value(std::move_if_noexcept(t)) {
  }

T & get() noexcept {
    return value;
  }
};
```

- **A function that can handle all argument values of the given parameter types successfully has a "Wide Contract"**
  - It cannot fail
  - It should be specified as `noexcept(true)`
  - `this` is also a parameter
  - Globals and external resources also (heap)
- **A function that has preconditions on its parameters has a narrow contract**
  - I.e., `int` parameter must not be negative
  - I.e., pointer parameter must not be `nullptr`
  - Even if not checked and no exception thrown, those functions should not be `noexcept`
  - This allows later checking and throwing if U.B.

- **`vector::size()` is noexcept as it has a wide contract and cannot fail**
- **Constructor of BoundedBuffer must not be declared noexcept**
  - Exception is thrown if capacity is 0 and allocate might throw

```
// wide contract
size_type size() const _GLIBCXX_NOEXCEPT
{
  return size_type(this->_M_impl._M_finish - this->_M_impl._M_start);
}

// narrow contract:
explicit BoundedBuffer(size_type capacity)
  : startIndex { 0 }, nOfElements { 0 }, capacity { capacity }, values { allocate(capacity) } {
  if (capacity == 0) {
    throw std::invalid_argument { "size must be > 0." };
  }
}
```

- **The compiler might optimize a call of a noexcept function better**
  - It is not required to provide the infrastructure of unwinding the stack properly for the non-existing exception case
- **However, the compiler will not provide an in-depth analysis whether your code adheres to your exception specification**
  - If you throw an exception from a `noexcept` function (directly or indirectly) `std::terminate()` will be called

```
struct Ball {};

void barrater() noexcept {
  throw Ball{};
}

int main() try {
    barrater();
  } catch(Ball const & b) {
    std::cout << "caught the ball!";
  }
}
```

```
This application has requested the Runtime to terminate it in an unusual way.
Please contact the application's support team for more information.
terminate called after throwing an instance of 'Ball'
```

- **A swap operation should be noexcept**
  - If it is you can rely on it to implement the move constructor

```
BoundedBuffer(BoundedBuffer && other) noexcept :
    startIndex {0},
    nOfElements {0},
    bufferCapacity {0},
    values_memory {nullptr} {
  swap(other);
}
```

```
void swap(BoundedBuffer & other) noexcept {
  std::swap(startIndex, other.startIndex);
  std::swap(nOfElements, other.nOfElements);
  std::swap(bufferCapacity, other.bufferCapacity);
  std::swap(values_memory, other.values_memory);
}
```

It Is Not Always That Easy: Piecewise Construction

- **See code for P0052R2 standard submission (Eric Niebler: “It is hard…”)**

```
unique_resource & operator=(unique_resource && that)
  noexcept(is_nowthrow_delete_v &&
           std::is_nothrow_move_assignable<R>::value &&
           std::is_nothrow_move_assignable<D>::value) {
  if(&that == this) return *this;
  reset();
  if (std::is_nothrow_move_assignable<detail::_box<R>>::value) {
    deleter = _move_assign_if_noexcept(that.deleter);
    resource = _move_assign_if_noexcept(that.resource);
  } else if (std::is_nothrow_move_assignable<detail::_box<D>>::value) {
    resource = _move_assign_if_noexcept(that.resource);
    deleter = _move_assign_if_noexcept(that.deleter);
  } else {
    resource = _as_const(that.resource);
    deleter = _as_const(that.deleter);
  }
  execute_on_destruction = std::exchange(that.execute_on_destruction, false);
  return *this;
}
```

- **Exception Safety is an important consideration**
  - Especially when designing generic code
  - Do it consciously
- **Make your Destructor and Move operations `noexcept(true)`**
- **Ensure invariants, even in case of exceptions (basic guarantee)**
- **If really pedantic, rely on `noexcept` expressions to "compute" the `noexcept` value of your functions, if there is a chance that they can be `noexcept(true)`**

PIMPL Idiom

Cevelop
Your C++ deserves it

HSR
HOCHSCHULE FÜR TECHNIK
RAPPERSWIL
FHO Fachhochschule Ostschweiz

IFS
INSTITUTE FOR
SOFTWARE

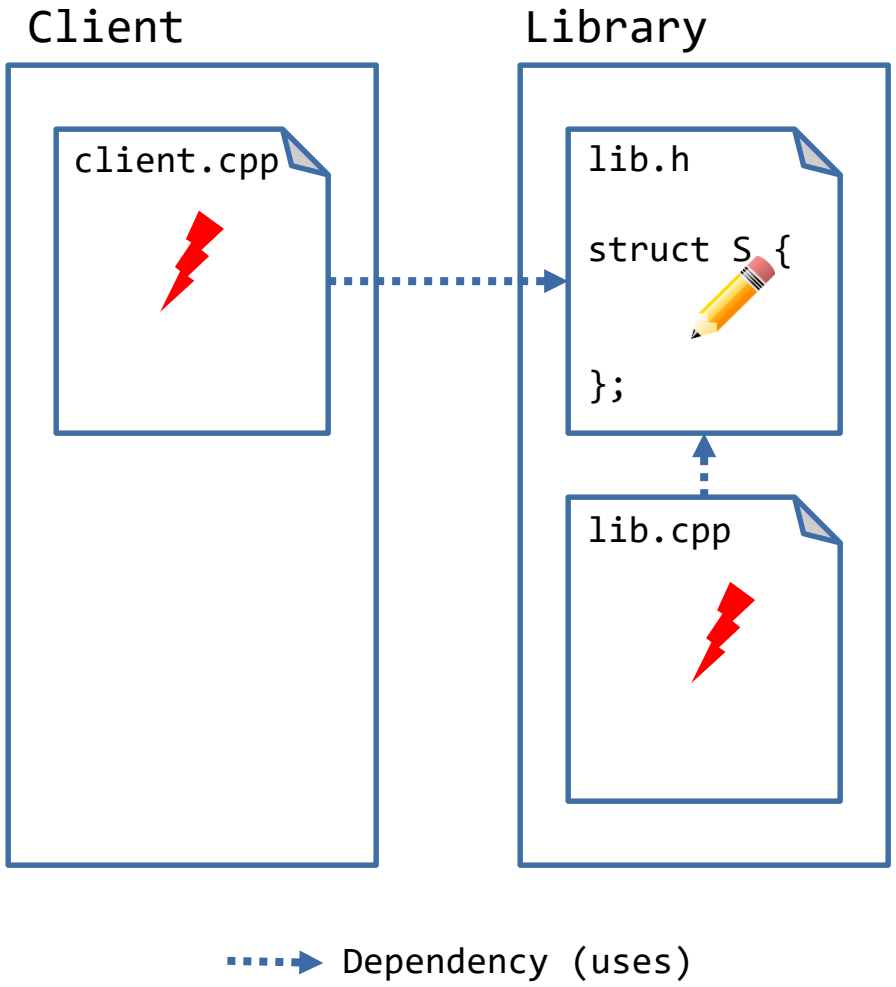
Opaque Types (Incomplete Types)

- **Name known (declared) but not the content (structure)**
  - Introduced by a forward declaration
- **Can be used for pointers and references**
  - but not dereference values without definition (access members)
- **C only uses pointers**
  - `void *` is the universally opaque pointer in C
- **`void *` can be cast to any other pointer type**
- **Validity and avoidance of undefined behavior is left to the programmer**
- **Sometimes `std::byte *` is used for memory of a given size (see BoundedBuffer)**

```
struct S; //Forward Declaration
void foo(S & s) {
  foo(s);
  //S s{}; //Invalid
}
struct S{}; //Definition
int main() {
  S s{};
  foo(s);
}
```


```
template<typename T>
void *makeOpaque(T *ptr) {
  return ptr;
}
template<typename T>
T *ptrCast(void *p) {
  return static_cast<T*>(p);
}
int main() {
  int i { 42 };
  void * const pi {makeOpaque(&i)};
  cout << *ptrCast<int>(pi) << endl;
}
```

- **Problem: even minor/internal changes in a class' definition require clients to re-compile**
  - E.g. changing a type of a private member variable
- **Compilation "Firewall"**
  - Allow changes to implementation without the need to re-compile users
- **It can be used to shield client code from implementation changes, e.g., when you want to provide a binary library as a DLL/shared library for clients and want to be able to update the library without having the client code to be re-compiled**
  - ⊡ You must not change header files your client relies upon
- **Put in the "exported" header file a class consisting of a "Pointer to IMPLementation" plus all public member functions to be used**
- **Read self-study material! (http://herbsutter.com/gotw/_100/)**



- **All internals and details are exposed to those interacting with class Wizard**
- **Makes changes hard and will require recompile**

Should not be shown to "no-majs"

```
class Wizard { // all magic details visible
  std::string name;
  MagicWand wand;
  std::vector<Spell> books;
  std::vector<Potion> potions;
  std::string searchForSpell(std::string const & wish);
  Potion mixPotion(std::string const & recipe);
  void castSpell(Spell spell);
  void applyPotion(Potion phial);
public:
  Wizard(std::string name = "Rincewind") :
    name { name }, wand{} {
  }
  std::string doMagic(std::string const & wish);
  //...
};
```

- **Minimal header (`Wizard.h`)**
- **All details hidden in implementation (see next slide)**
- **Delegation to Impl (see `Wizard::doMagic`)**

Wizard.h

```
class Wizard {
  std::shared_ptr<class WizardImpl> pImpl;
public:
  Wizard(std::string name);
  std::string doMagic(std::string wish);
};
```

WizardImpl.cpp (Wizard Members)

```
//Implementation of WizardImpl

//Implementation of Wizard
Wizard::Wizard(std::string name):
  pImpl{std::make_shared<WizardImpl>(name)} {
}

std::string Wizard::doMagic(std::string wish) {
  return pImpl->doMagic(wish);
}
```

- **WizardImpl class declaration (in `WizardImpl.cpp`)**

WizardImpl.cpp

```
#include "../Wizard.h"
#include "WizardIngredients.h"
#include <vector>
#include <algorithm>

class WizardImpl {
  std::string name;
  MagicWand wand;
  std::vector<Spell> books;
  std::vector<Potion> potions;
  std::string searchForSpell(std::string const & wish);
  Potion mixPotion(std::string const & recipe);
  void castSpell(Spell spell);
  void applyPotion(Potion phial);
public:
  WizardImpl(std::string name="Rincewind") : name{name}, wand{}{}
  std::string doMagic(std::string const &wish);
  //...
};
```

- **WizardImpl implementation**
  - in `WizardImpl.cpp`
  - Example member function `WizardImpl::doMagic`

`WizardImpl.cpp`

```
std::string WizardImpl::doMagic(std::string const &wish) {
  auto spell = searchForSpell(wish);
  if (!spell.empty()) {
    castSpell(spell);
    return "wootsh";
  }
  auto potion=mixPotion(wish);
  if (!potion.empty()) {
    applyPotion(potion);
    return "zapp";
  }
  throw std::logic_error{"magic failed"};
}
```

- **Expected required change?**

Wizard.h

```
class Wizard {
  std::shared_ptr<class WizardImpl> pImpl;
public:
  Wizard(std::string name);
  std::string doMagic(std::string wish);
};
```

Wizard.h

```
class Wizard {
  std::unique_ptr<class WizardImpl> pImpl;
public:
  Wizard(std::string name);
  std::string doMagic(std::string wish);
};
```

WizardImpl.cpp

```
//Implementation of Wizard
Wizard::Wizard(std::string name):
  pImpl{std::make_shared<WizardImpl>(name)} {
}
```

WizardImpl.cpp

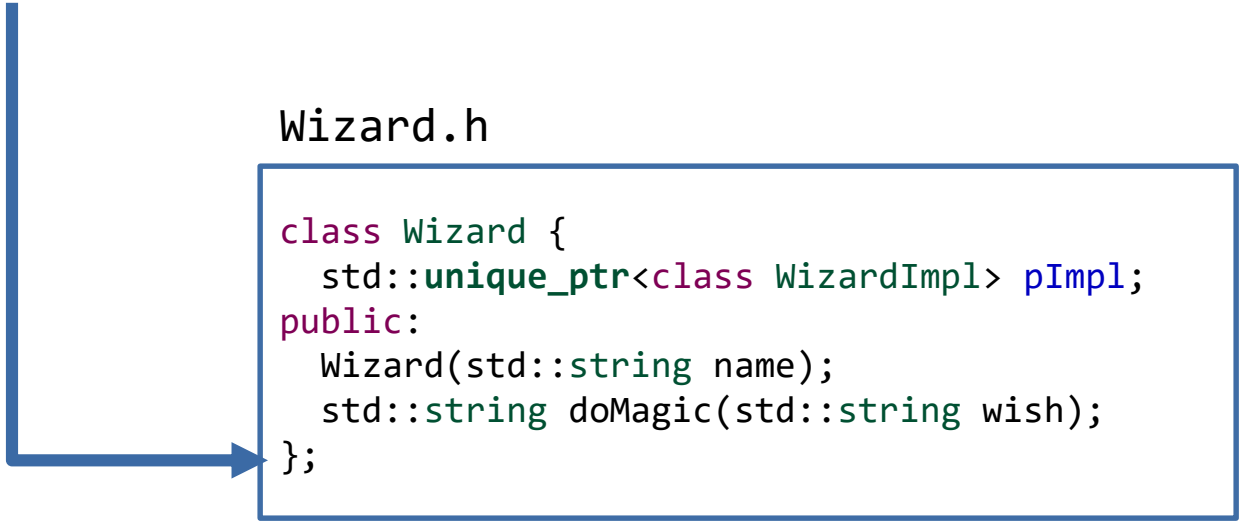
```
//Implementation of Wizard
Wizard::Wizard(std::string name):
  pImpl{std::make_unique<WizardImpl>(name)} {
}
```

- **Won't compile!**

```
.../unique_ptr.h: In instantiation of 'void std::default_delete<_Tp>::operator()(_Tp*) const [with _Tp = WizardImpl]':
.../unique_ptr.h:239:17:   required from 'std::unique_ptr<_Tp, _Dp>::~unique_ptr() [with _Tp = WizardImpl; _Dp =
std::default_delete<WizardImpl>]'
.../Wizard.h:6:7:   required from here
.../unique_ptr.h:74:22: error: invalid application of 'sizeof' to incomplete type 'WizardImpl'
  static_assert(sizeof(_Tp)>0,
```

- **`std::unique_ptr` has 2 template parameters:**
  - pointee type
  - deleter for pointee type
- **The default deleter cannot delete an incomplete type**

- **Definition of implicitly declared Destructor**
  - [special]/1 states: ... An implicitly-declared special member function is declared at the closing } of the class-specifier.



Wizard.h

```
class Wizard {
  std::unique_ptr<class WizardImpl> pImpl;
public:
  Wizard(std::string name);
  std::string doMagic(std::string wish);
};
```

- **At this point WizardImpl is incomplete**
- **What can we do?**

- **Define the destructor of Wizard after the definition of WizardImpl**

Wizard.h

```
class Wizard {
  std::unique_ptr<class WizardImpl> pImpl;
public:
  Wizard(std::string name);
  ~Wizard();
  std::string doMagic(std::string wish);
};
```

WizardImpl.cpp

```
class WizardImpl {
  //...
};

//...

Wizard::~Wizard() = default;
```

- **How should objects be copied?**

No Copying – Only Moving	`std::unique_ptr<class Impl>` • Declare destructor & `=default` • Declare move operations & `=default`
Shallow Copying (Sharing the implementation)	`std::shared_ptr<class Impl>`
Deep Copying (Default for C++)	`std::unique_ptr<class Impl>` • with DIY copy constructor (use copy constructor of Impl

- **Can pImpl == nullptr?**
  - IMHO: never!
- **Can you inherit from PIMPL class?**
  - Better don't

- **Write code that is as exception-safe as possible**
- **Lower limit is the basic guarantee, unless it is code you have absolute control of and only you can call it**
- **The Pimpl idiom can be applied to hide implementation details and reduce static dependencies**

What Else?

Not covered in the lecture

Cevelop
Your C++ deserves it

Hourglass Interfaces

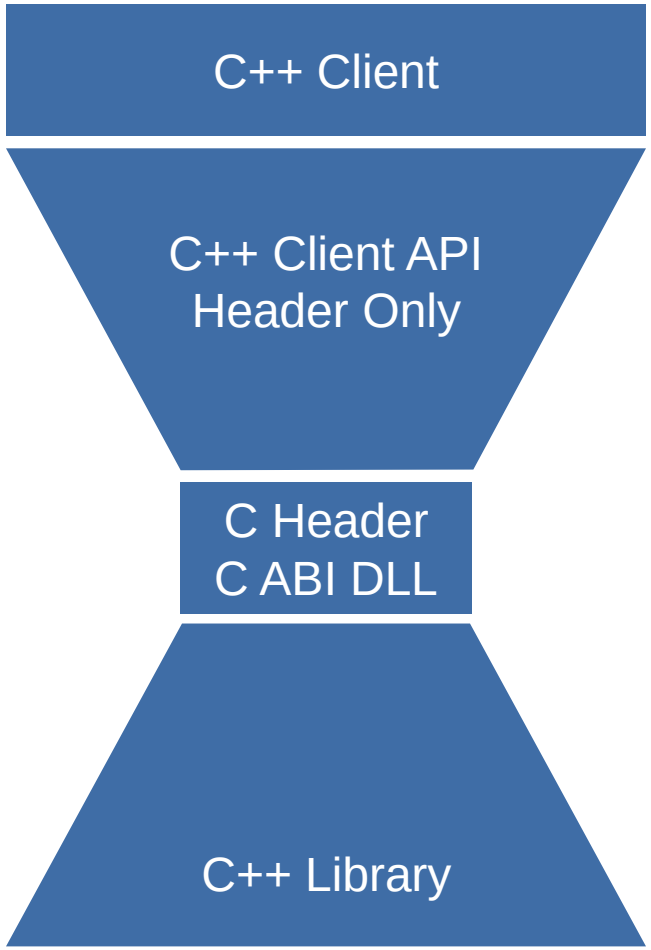
Cevelop
Your C++ deserves it

HSR
HOCHSCHULE FÜR TECHNIK
RAPPERSWIL
FHO Fachhochschule Ostschweiz

IFS
INSTITUTE FOR
SOFTWARE

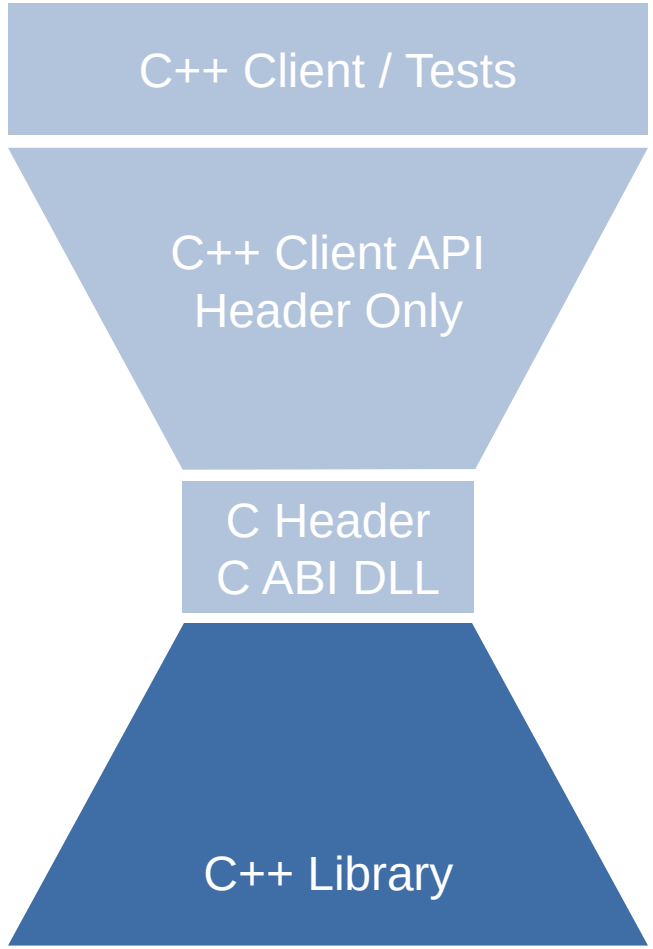
- **DLL APIs work best (and corss platform compatible) with C only**
  - We ignore the Windows burdon of providing DLL-export and DLL-import syntax
- **C++ can provide C-compatible function interfaces using `extern "C"` in front of a declaration**
- **C-APIs are error-prone and can be tedious to use**
- **C++ exceptions do not pass nicely across a C-API**
- **Foreign language bindings (e.g. for Python etc) often expect C-APIs**
- **API - Application Programming Interface**
  - If stable, you do not need to change your code, if something changes
- **ABI - Application Binary Interface**
  - If stable, you can use and share DLLs/shared libraries without recompilation
- **Not universally applicable, but very common**

- **Shape of an hourglass**

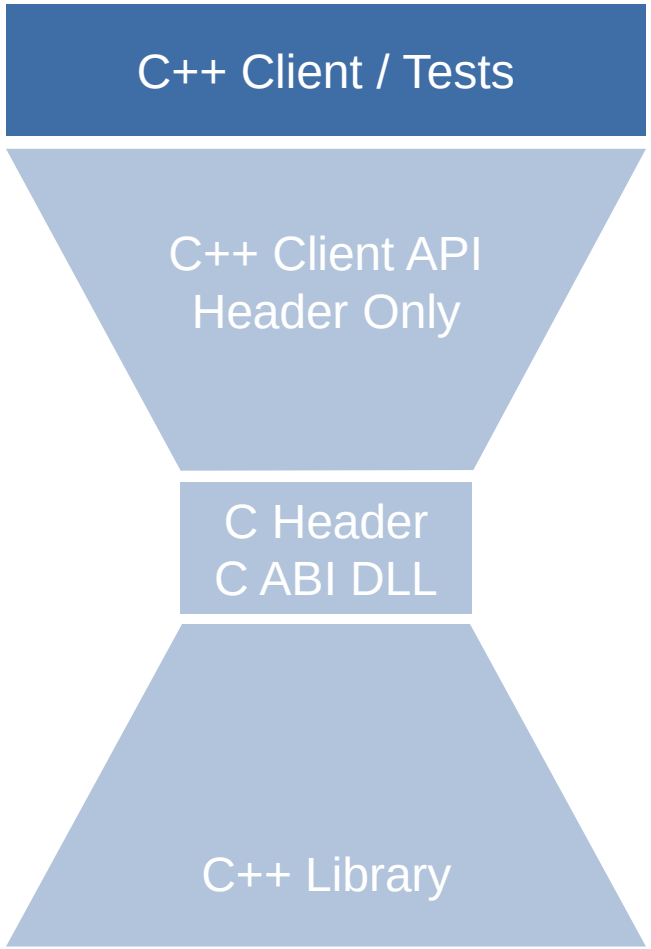


- **Let's add some functionality to our Wizard**
  - `doMagic()` – still casts a spell ("wootsh") or uses a potion ("zapp")
  - `learnSpell()` – learns a new spell (by name)
  - `maxAndStorePotion()` – creates a potion and puts it to the inventory
  - `getName()` – function to make Java programmers happy, otherwise there wouldn't be a "getX" function

```
struct Wizard {
  Wizard(std::string name = "Rincewind")
    : name{name}, wand{} {
  }
  char const * doMagic(std::string const & wish);
  void learnSpell(std::string const & newspell);
  void mixAndStorePotion(std::string const & potion);
  char const * getName() const {
    return name.c_str();
  }
};
```

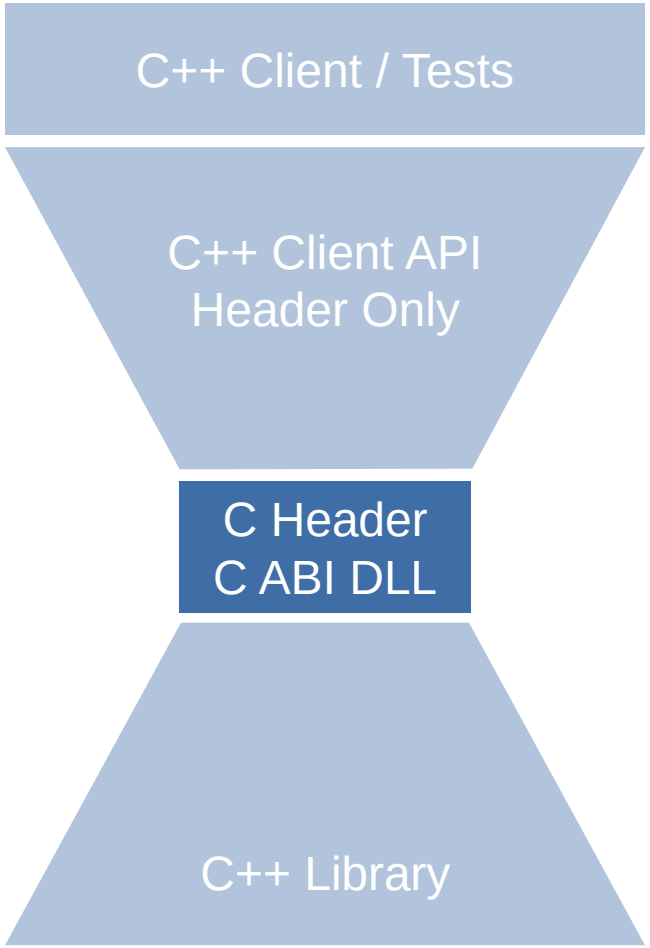


- **Testing a wizard provides the same view a client has**




```
using wizard_client::Wizard;

void canCreateDefaultWizard() {
  Wizard const magician{};
  ASSERT_EQUAL("Rincewind",magician.getName());
}

void canCreateWizardWithName() {
  Wizard const magician{ "Petrosilius Zwackelmann" };
  ASSERT_EQUAL("Petrosilius Zwackelmann", magician.getName());
}

void wizardLearnsSpellAndCanRecall() {
  Wizard magician{};
  magician.learnSpell("Expelliarmus");
  ASSERT_EQUAL("wootsh", magician.doMagic("Expelliarmus"));
}

void wizardMixesPotionAndCanApply() {
  Wizard magician{};
  magician.mixAndStorePotion("Polyjuice Potion");
  ASSERT_EQUAL("zapp", magician.doMagic("Polyjuice Potion"));
}
void uknownMagicFails() {
  Wizard magician{};
  ASSERT_THROWS(magician.doMagic("Expecto Patronum!"), std::runtime_error);
}
```

- **Abstract data types can be represented by pointers**
  - Ultimate abstract pointer `void *`
- **Member functions map to functions taking the abstract data type pointer as first argument**
- **Requires Factory and Disposal functions to manage object lifetime**
- **Strings can only be represented by `char *`**
  - Need to know who will be responsible for memory
  - Make sure not to return pointers to temporary objects!
- **Exceptions do not work across a C API**



- **A Wizard can only be accessed thorugh a pointer (const and non-const)**
  - Construction and destruction through functions
- **An error pointer stores messages of exceptions**
  - Functions that may fail need an error pointer parameter for reporting exceptions
  - Errors need to be cleaned up when not used anymore
- **Member functions take a Wizard (pointer) as first parameter**

Wizard.h

```
typedef struct Wizard * wizard;
typedef struct Wizard const * cwizard;
wizard createWizard(char const * name,
                    error_t * out_error);
void disposeWizard(wizard toDispose);


typedef struct Error * error_t;
char const * error_message(error_t error);
void error_dispose(error_t error);


char const *doMagic(wizard w,
                    char const * wish,
                    error_t *out_error);
void learnSpell(wizard w,
                char const * spell);
void mixAndStorePotion(wizard w,
                       char const * potion);
char const *wizardName(cwizard w);
```

What Parts of C++ Can Be Used in an `extern "C"` Interface?

- **Functions, but not templates or variadic**
  - No overloading in C!
- **C primitive types (`char`, `int`, `double`, `void`)**
- **Pointers, including function pointers**
- **Forward-declared structs**
  - Pointers to those are opaque types!
  - Are used for abstract data types
- **Enums (unscoped - without class or base type!)**
- **If using from C must embrace it with `extern "C"` when compiling it with C++**
  - Otherwise names do not match, because of mangling

Wizard.h

```
#ifdef __cplusplus
extern "C" {
#endif

typedef struct Wizard * wizard;
typedef struct Wizard const * cwizard;
wizard createWizard(char const * name,
                    error_t * out_error);
void disposeWizard(wizard toDispose);

// ...
// Comments are ok too, as the preprocessor
// eliminates them anyway

#ifdef __cplusplus
}
#endif
```

- **Wizard class must be implemented**
- **To allow full C++ including templates, we need to use a "trampolin" class**
  - It wraps the actual Wizard implementation

Wizard.cpp

```
extern "C" {
struct Wizard { // C linkage trampolin
  Wizard(char const * name)
    : wiz{name} {
  }
  unseen::Wizard wiz;
};
```

WizardHidden.h

```
namespace unseen {
struct Wizard {
  // ...
  Wizard(std::string name = "Rincewind")
    : name{name}, wand{} {
  }
  char const * doMagic(std::string const & wish);
  void learnSpell(std::string const & newspell);
  void mixAndStorePotion(std::string const & potion);
  char const * getName() const {
    return name.c_str();
  }
};
}
```

Note: The Hairpoll example of Stefanus Du Toit has non-standard code in the trampolin

- **Remember the 5 ways to deal with errors!**
- **You can't use references in C API, must use pointers to pointers**
- **In case of an error, allocate error value on the heap**
  - You must provide a disposal function to clean up
- **You can use C++ types internally (`std::string`)**
- **It is safe to return the `char const *`**
  - because caller owns the object providing the memory

Wizard.h

```
typedef struct Error * error_t;
char const * error_message(error_t error);
void error_dispose(error_t error);

wizard createWizard(char const * name,
                    error_t * out_error);
```

Wizard.cpp

```
extern "C" {
struct Error {
  std::string message;
};

const char * error_message(error_t error) {
  return error->message.c_str();
}

void error_dispose(error_t error) {
  delete error;
}
}
```

- **Call the function body and catch exceptions**
- **Map them to an Error object**
- **Set the pointer pointed to by `out_error`**
  - Use pointer to pointer as reference to pointer
  - Passed `out_error` must not be `nullptr`!

Wizard.cpp

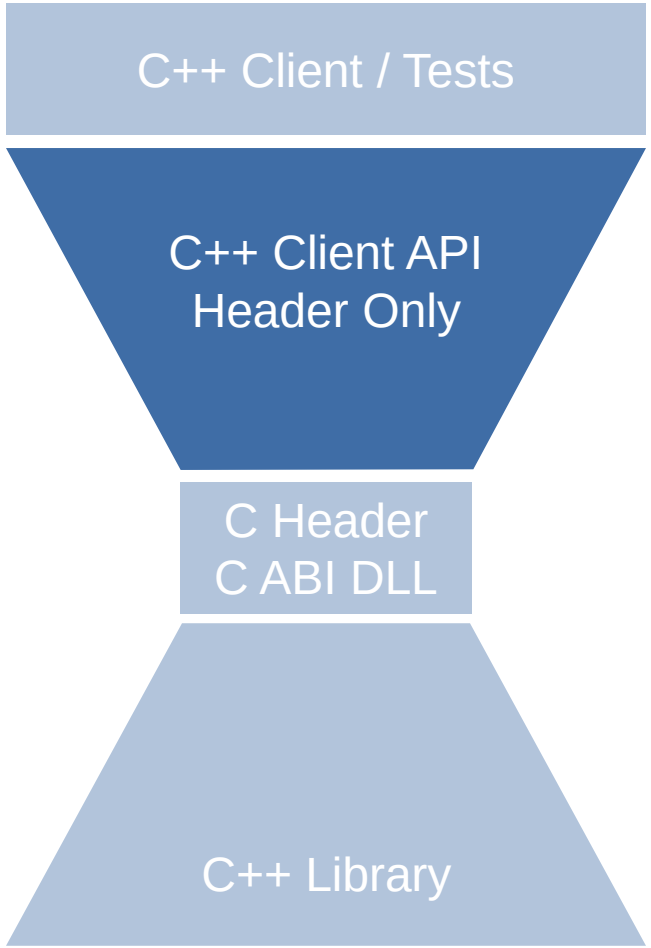
```
template<typename Fn>
bool translateExceptions(error_t * out_error, Fn && fn)
try {
  fn();
  return true;
} catch (const std::exception& e) {
  *out_error = new Error{e.what()};
  return false;
} catch (...) {
  *out_error = new Error{"Unknown internal error"};
  return false;
}

wizard createWizard(const char * name,
                    error_t * out_error) {
  wizard result = nullptr;
  translateExceptions(out_error,[&] {
    result = new Wizard{name};
  });
  return result;
}
```

- **Client-side C++ usage requires mapping error codes back to exceptions**
  - Unfortunately exception type doesn't map through
  - But can use a generic standard exception
    - `std::runtime_error`, keep the message
  - Dedicated RAII class for disposal
- **Temporary object with throwing destructor**
  - Strange but possible
  - Automatic type conversion passes the address of its guts (opaque)
  - Tricky, take care you don't leak when creating the object!

WizardClient.h

```
struct ErrorRAII {
  ErrorRAII(error_t error) : opaque {error} {}
  ~ErrorRAII() {
    if (opaque) {
      error_dispose(opaque);
    }
  }
  error_t opaque;
};

struct ThrowOnError {
  ThrowOnError() = default;
  ~ThrowOnError() noexcept(false) {
    if (error.opaque) {
      throw std::runtime_error{error_message(error.opaque)};
    }
  }
  operator error_t*() {
    return &error.opaque;
  }
private:
  ErrorRAII error{nullptr};
};
```

Using ThrowOnError in Client API



WizardClient.h

```
struct ThrowOnError {
  ThrowOnError() = default;
  ~ThrowOnError() noexcept(false) {
    if (error.opaque) {
      throw std::runtime_error{error_message(error.opaque)};
    }
  }
  operator error_t*() {
    return &error.opaque;
  }
private:
  ErrorRAII error{nullptr};
};

struct Wizard {
  Wizard(std::string const & who = "Rincewind")
      : wiz {createWizard(who.c_str(), ThrowOnError{})} {
  }
  // C linkage trampolin
};
```

- **Here the complete view of the client side Wizard class**
- **Calls "C" functions from global namespace**
  - Namespace prefix needed for synonyms to member functions
- **Header-only**
  - Inline functions delegating
- **Need to take care of passed and returned Pointers, esp. `char *`**
  - Do not pass/return dangling pointers!

WizardClient.h

```
struct Wizard {
  Wizard(std::string const & who = "Rincewind")
    : wiz {createWizard(who.c_str(), ThrowOnError{})} {
  }
  ~Wizard() {
    disposeWizard(wiz);
  }
  std::string doMagic(std::string const &wish) {
    return ::doMagic(wiz, wish.c_str(), ThrowOnError{});
  }
  void learnSpell(std::string const &spell) {
    ::learnSpell(wiz, spell.c_str());
  }
  void mixAndStorePotion(std::string const & potion) {
    ::mixAndStorePotion(wiz, potion.c_str());
  }
  char const * getName() const {
    return wizardName(wiz);
  }
private:
  Wizard(Wizard const &) = delete;
  Wizard & operator=(Wizard const &) = delete;
  wizard wiz;
};
```

- **With the Gnu compiler (and clang I presume)**
  - `-fvisibility=hidden`
    - Can be added to suppress exporting symbols
    - Must mark exported ABI functions with default visibility
- **Visibility refers to dynamic library/object file export of symbols**
  - Windows: `__declspec(dllexport)`
  - See also hairpoll demo project https://youtu.be/PVYdHDm0q6Y
  - For more on gcc visibility (expert-level knowledge): see https://gcc.gnu.org/wiki/Visibility

WizardClient.h

```
#define WIZARD_EXPORT_DLL
                __attribute__ ((visibility ("default")))

WIZARD_EXPORT_DLL
char const * error_message(error_t error);
WIZARD_EXPORT_DLL
void error_dispose(error_t error);

WIZARD_EXPORT_DLL
wizard createWizard(char const * name,
                    error_t *out_error);
WIZARD_EXPORT_DLL
void disposeWizard(wizard toDispose);

WIZARD_EXPORT_DLL
char const * doMagic(wizard w,
                     char const * wish,
                     error_t *out_error);
WIZARD_EXPORT_DLL
void learnSpell(wizard w, char const *spell);
WIZARD_EXPORT_DLL
void mixAndStorePotion(wizard w, char const *potion);
WIZARD_EXPORT_DLL
char const * wizardName(cwizard w);
```

- **Library API and ABI design can be tricky for third party users**
  - Only really a problem if not in-house or all open source
  - Even with open source libraries, re-compiles can be a burden
    - There are just too many compiler options
    - Plus DLL versioning
- **API stability can be important**
  - PIMPL idiom helps with avoiding client re-compiles
  - Not easily applicable with heavily templated code -> that often is header-only
- **ABI stability is even more important when delivering DLLs/shared libraries**
  - Only relevant when not header only
  - “C” linkage safe, but crippling - Hourglass-Interfaces allow shielding C++ clients from the crippled ABI
    - Still easy to make mistakes (which we always tried to avoid)