Department I - C Plus Plus

# Modern and Lucid C++ Advanced for Professional Programmers

## Week 12 – Hourglass Interfaces

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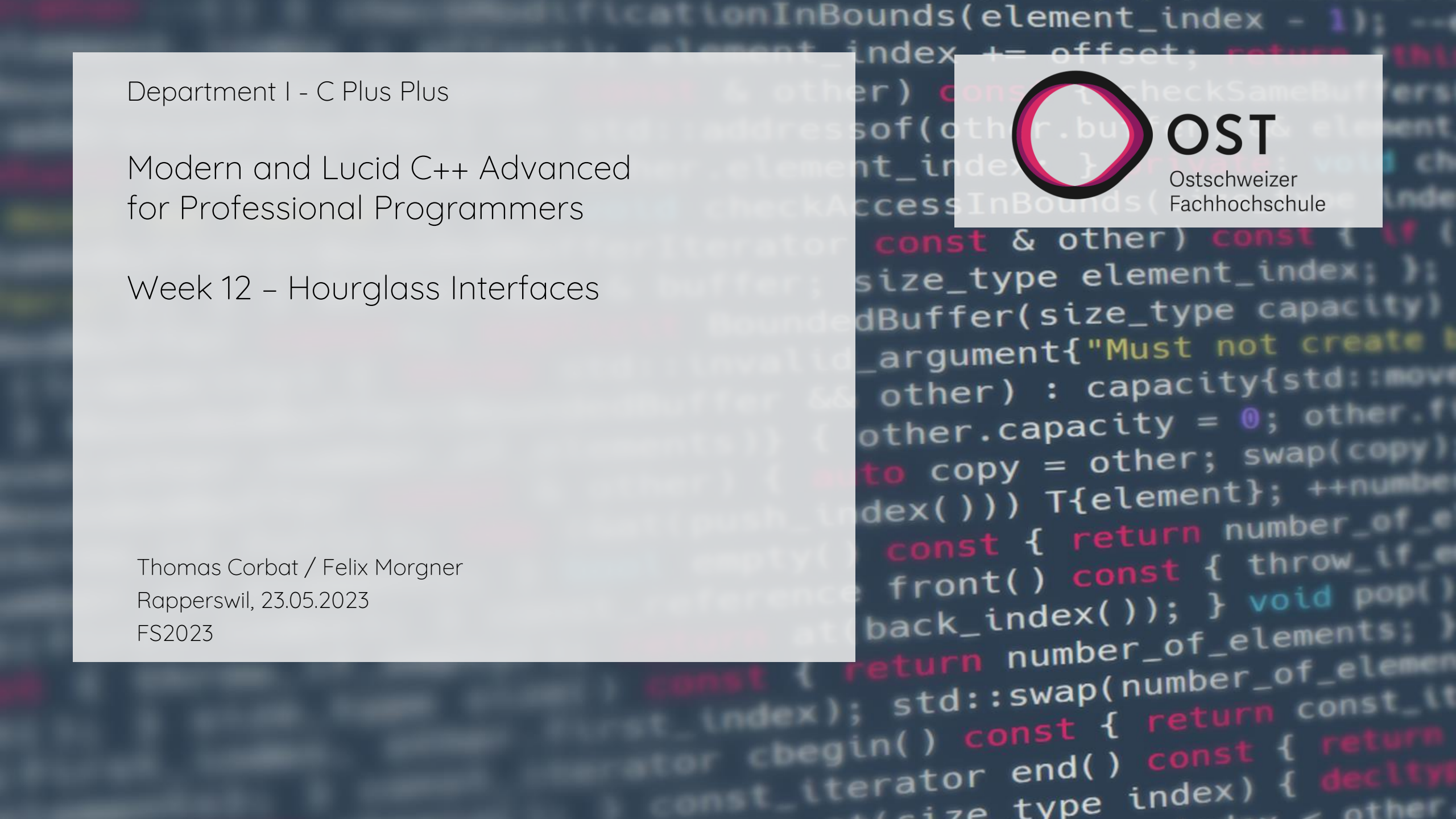

# Agenda



- **Recap Week 11**
- **Hourglass Interfaces**
- **Java Native Access (JNA)**

# Goals

- **Participants should ...**
  - know how to provide portable APIs for their libraries
  - be able to explain how hourglass interfaces work and why they are needed
  - be able to call C APIs from Java using JNA

# Recap Week 11

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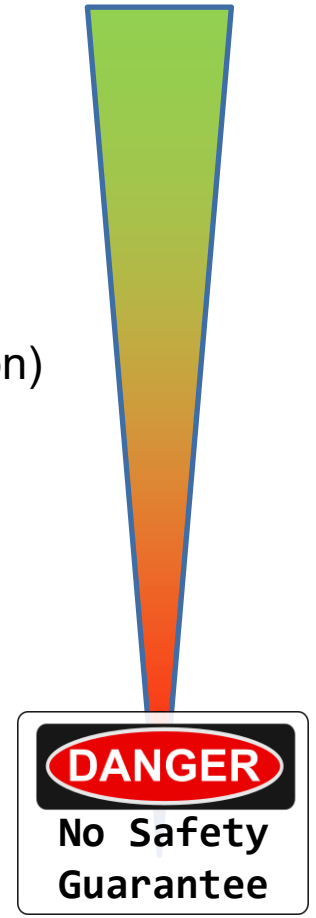
# Exception Safety Levels of an Operation/Function

- **`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

- **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>))

```
auto function() noexcept -> void {
  //...
}

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

```
auto main() -> int {
  std::cout << "is function() noexcept? " <<
    noexcept(function()) << '\n';
}
```

- **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.

# 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
auto foo(S & s) -> void {
  foo(s);
  //S s{}; //Invalid
}
struct S{}; //Definition
auto main() -> int {
  S s{};
  foo(s);
}
```


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

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

Wizard.hpp

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

WizardImpl.cpp (Wizard Members)

```
//Implementation of WizardImpl ...

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

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

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

Wizard.hpp

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

WizardImpl.cpp

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

//...

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

- **How should objects be copied?**

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

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

# Hourglass Interfaces

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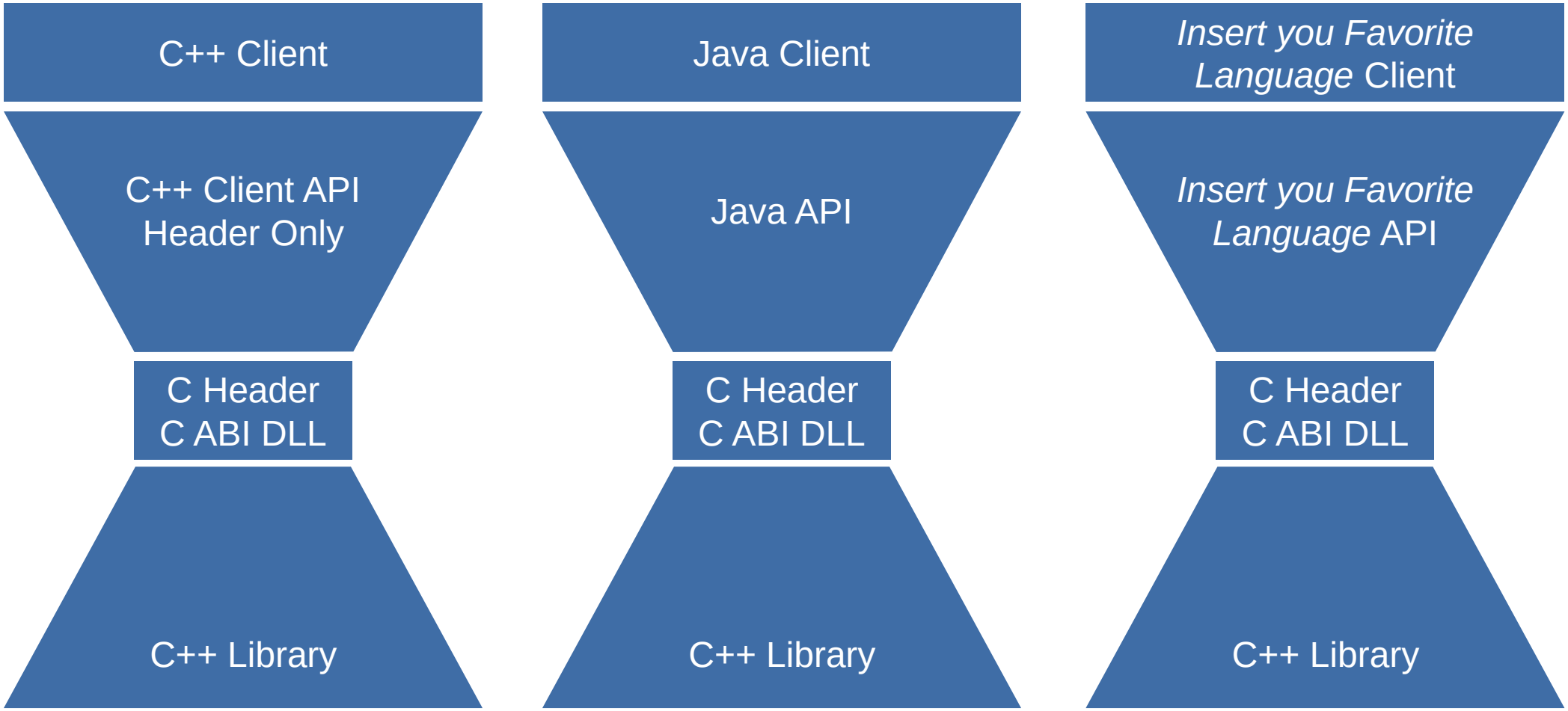
# Application Binary Interfaces (ABIs)

- **ABIs define how programs interact on a binary level**
  - Names of structures and functions
  - Calling conventions
  - Instruction sets
- **C++ does not define any specific ABI**
  - Because they are tightly coupled to the platform
- **ABIs change between OSes, compiler versions, library versions, etc.**
- **Case in point:**
  - GCC changed its ABI from:
    - Version 2.95 to 3.0
    - 3.0 to 3.1
    - 3.1 to 3.2
    - 3.3 to 3.4
    - 5.0 to 5.1
    - …
  - Different standard library implementations are usually incompatible

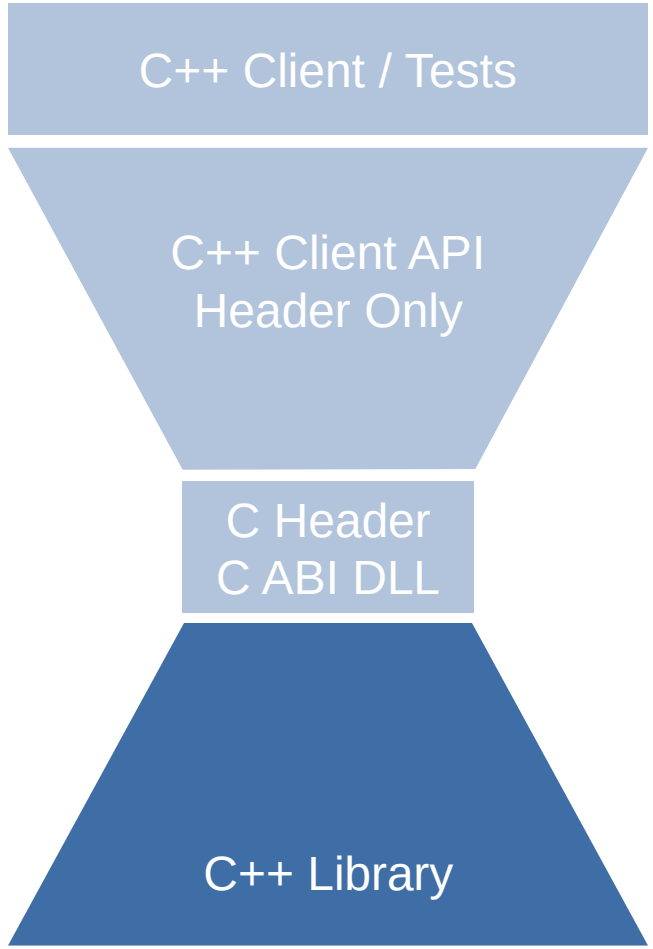
- **Use C (89) as an “intermediate” layer**
  - Think of it as a C frontend for our C++ code
- **While C also does not define, it has an extremely stable ABI**
  - No namespaces
  - No name mangling
- **However, C also has no …**
  - member functions
  - exceptions
  - templates

# Hourglass Interface

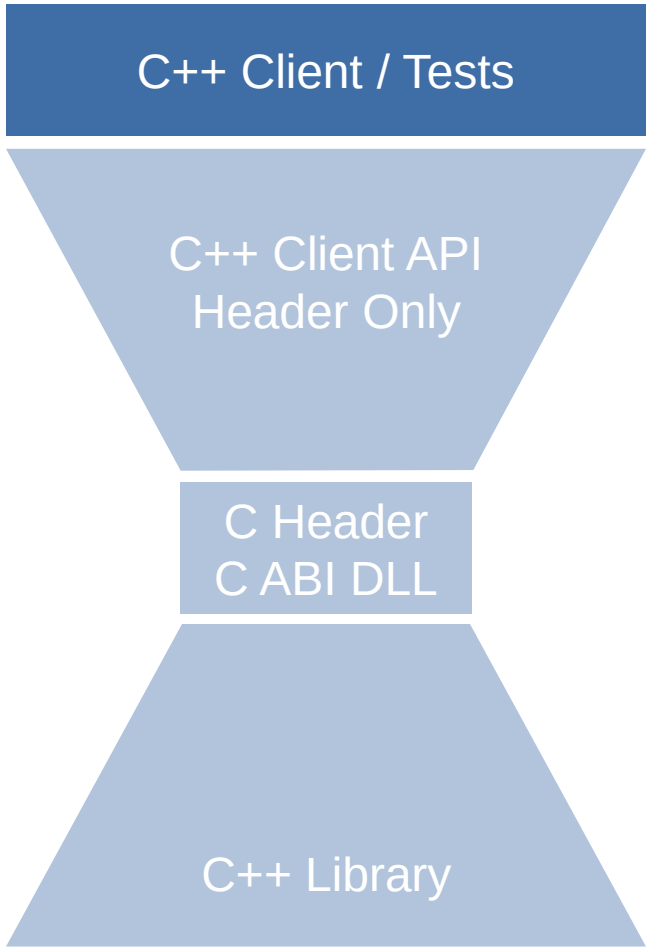


- **Back to our Wizard again**
  - `doMagic()` – still casts a spell ("wootsh") or uses a potion ("zapp")
  - `learnSpell()` – learns a new spell (by name)
  - `mixAndStorePotion()` – creates a potion and puts it to the inventory
  - `getName()` – function to make Java programmers happy, otherwise there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

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

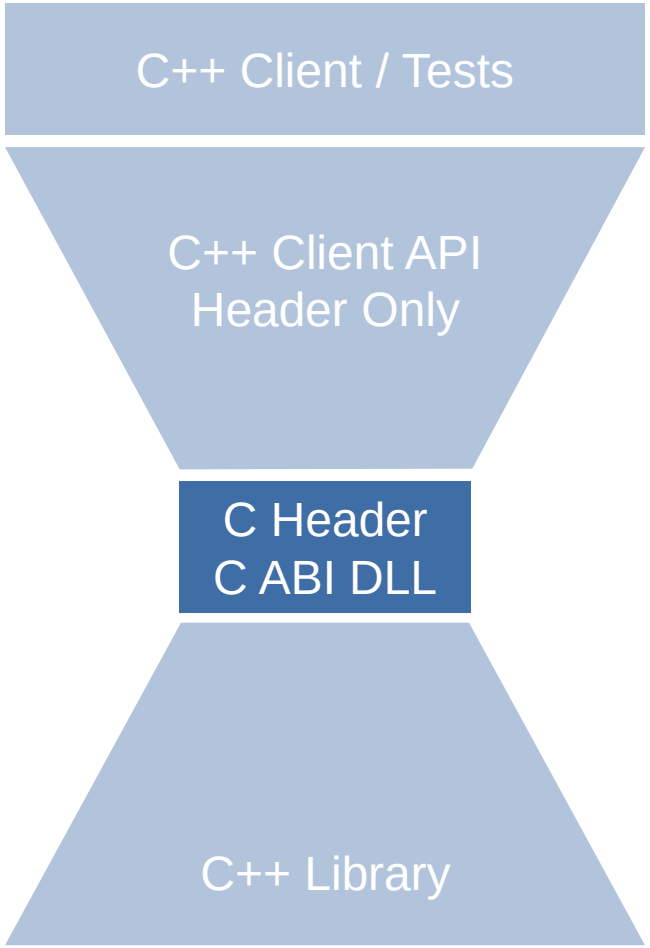


- **Testing a wizard provides the same view a client has**




```
using wizard_client::Wizard;

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

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

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

TEST(wizardMixesPotionAndCanApply) {
  Wizard magician{};
  magician.mixAndStorePotion("Polyjuice Potion");
  ASSERT_EQUAL("zapp", magician.doMagic("Polyjuice Potion"));
}
TEST(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.hpp

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

- **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 create_wizard(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`!

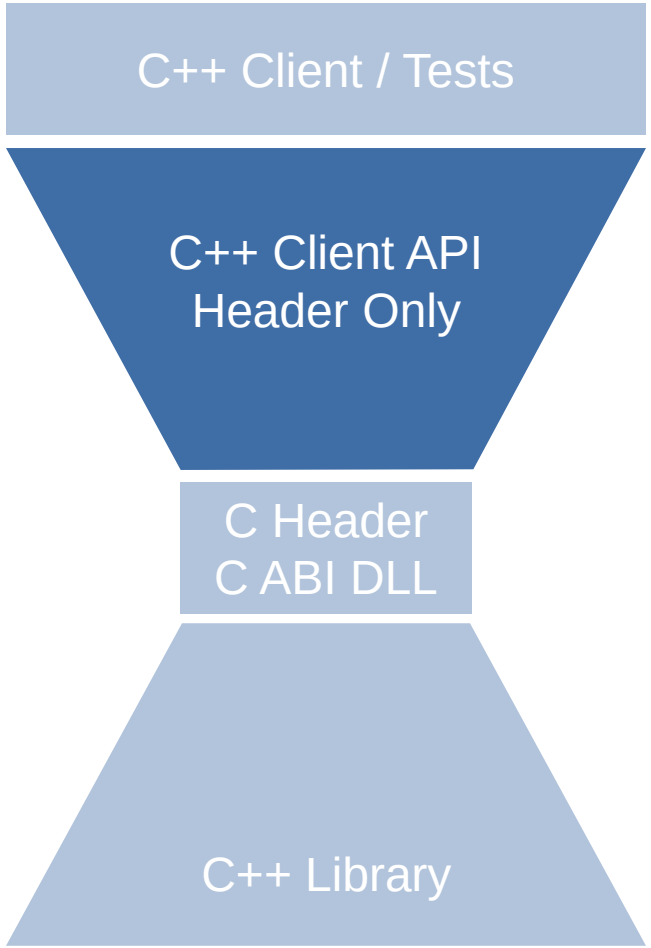
Wizard.cpp

```
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 create_wizard(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.hpp

```
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};
};
```




WizardClient.hpp

```
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 {create_wizard(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.hpp

```
struct Wizard {
  Wizard(std::string const & who = "Rincewind")
    : wiz {createWizard(who.c_str(), ThrowOnError{})} {
  }
  ~Wizard() {
    dispose_wizard(wiz);
  }
  auto doMagic(std::string const &wish) -> std::string {
    return ::do_magic(wiz, wish.c_str(), ThrowOnError{});
  }
  auto learnSpell(std::string const &spell) -> void {
    ::learn_spell(wiz, spell.c_str());
  }
  auto mixAndStorePotion(std::string const & potion) -> void{
    ::mix_and_store_potion(wiz, potion.c_str());
  }
  auto getName() const -> char const * {
    return wizard_name(wiz);
  }
private:
  Wizard(Wizard const &) = delete;
  Wizard & operator=(Wizard const &) = delete;
  wizard wiz;
};
```

# Really Hiding DLL Content (Compiler-Dependent)

- **With the GCC and Clang**
  - `-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 [[gnu::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 create_wizard(char const * name,
                     error_t *out_error);
WIZARD_EXPORT_DLL
void dispose_wizard(wizard toDispose);

WIZARD_EXPORT_DLL
char const * do_magic(wizard w,
                      char const * wish,
                      error_t *out_error);
WIZARD_EXPORT_DLL
void learn_spell(wizard w, char const *spell);
WIZARD_EXPORT_DLL
void mix_and_store_potion(wizard w, char const *potion);
WIZARD_EXPORT_DLL
char const * wizard_name(cwizard w);
```

# Java Native Access (JNA)

- **JNA provides a simple interface to C libraries**
  - Community Library (not part of the JDK/JRE)
  - Based on standard JNI
  - Generates “interfaces” at runtime
  - https://github.com/java-native-access/jna
- **Single JAR file**
- **Cross-platform**
  - Windows
  - Linux
  - macOS

| Native Type | Java Type |
|---|---|
| char | byte |
| short | short |
| wchar_t | char |
| int | int |
| bool (int) | boolean |
| long | NativeLong |
| long long (64-bit) | long |
| float | float |
| double | double |
| char * | String |
| some_type * | Pointer |
| struct xyz | Structure |

```
public interface CplaLib extends Library {
    CplaLib INSTANCE = (CplaLib) Native.load("cpla", CplaLib.class);
}
```

- **Calling the loaded library handle INSTANCE is only by convention**
- **The loader searches for a suitable library (lib<name>.so, <libname>.dylib, <libname>.dll)**
  - First in the path specified by `jna.library.path`
  - Otherwise in the system default library search path
  - Fallback into the classpath

```
extern "C" {
void printInt(int number);
}
```

```
public interface CplaLib extends Library {
    CplaLib INSTANCE = (CplaLib) Native.load("cpla", CplaLib.class);

    void printInt(int number);
}
```

- **Function names and parameter types must match**
  - However: The types are not validated! Even at runtime! (They are not part of the signature in C!)
- **Parameter names don't matter**

```
extern "C" {

struct Point {
    int x;
    int y;
};

void printPoint(Point point);
}
```

```
public interface CplaLib extends Library {
    CplaLib INSTANCE = (CplaLib) Native.load("cpla", CplaLib.class);

    public static class Point extends Structure implements Structure.ByValue {
        public int x, y;

        Point(int x, int y) {
            this.x = x;
            this.y = y;
        }

        @Override
        protected List<String> getFieldOrder() {
            return List.of("x", "y");
        }
    }

    void printPoint(Point point);
}
```

```
CplaLib.Point p = new CplaLib.Point(12, 90);
CplaLib.INSTANCE.printPoint(p);
```

- **Plain (non-opaque) struct types must inherit from `Structure`**
  - You must override `getFieldOrder()`
  - Can use the tag-interface `Structure.ByValue`
- **You can a pointers to such types using getPointer()**
  - However: Remember the GC!

```
extern "C" {

typedef struct Unicorn * unicorn;

unicorn createUnicorn(char * name);

void disposeUnicorn(unicorn instance);

void printUnicorn(unicorn unicorn);

}
```

```
public interface CplaLib extends Library {
    CplaLib INSTANCE = (CplaLib) Native.load("cpla", CplaLib.class);

    public static class Unicorn extends Pointer {
        Unicorn(String name) {
            super(Pointer.nativeValue(INSTANCE.createUnicorn(name)));
        }

        void dispose() {
            INSTANCE.disposeUnicorn(this);
        }
    }

    Pointer createUnicorn(String name);

    void disposeUnicorn(Unicorn instance);

    void printUnicorn(Unicorn unicorn);
}
```

```
CplaLib.Unicorn u = new CplaLib.Unicorn("freddy");
CplaLib.INSTANCE.printUnicorn(u);
u.dispose();
```

- **Opaque struct types should inherit from `Pointer`**
  - Provide a constructor using the `create…()` function
- **Managing lifetime is not trivial**
  - Using `dispose…()` API functions in finalizers is not recommended
  - Either provide a dispose method on you Java type
  - Or implement `AutoClosable` and use you objects with try-with-resources

```
extern "C" {

char * getData(int * size);

void freeData(char * data);

}
```

```
public interface CplaLib extends Library {
    CplaLib INSTANCE = (CplaLib) Native.load("cpla", CplaLib.class);

    Pointer getData(IntByReference size);
    void freeData(Pointer data);
}
```

```
IntByReference size = new IntByReference();
Pointer data = CplaLib.INSTANCE.getData(size);
byte[] javaData = data.getByteArray(0, size.getValue());
CplaLib.INSTANCE.freeData(data);

for(byte b : javaData) {
    System.out.println(b);
}
```

- **Use `IntByReference` to retrieve the size of the buffer**
  - Requires that the API supports it!
- **`getByteArray()` copies the data from the buffer**
- **Make sure to free the buffer**
  - Either using an API `free…()` functions
  - Or `Native.free()`
    - Tends to crash on Windows for some reason

- **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
- **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
- **JNA provides a convenient mechanism to work with native code from Java**