Introduction to proposed std::expected<T, E>

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Relevant WG21 papers

Relevant WG21 papers

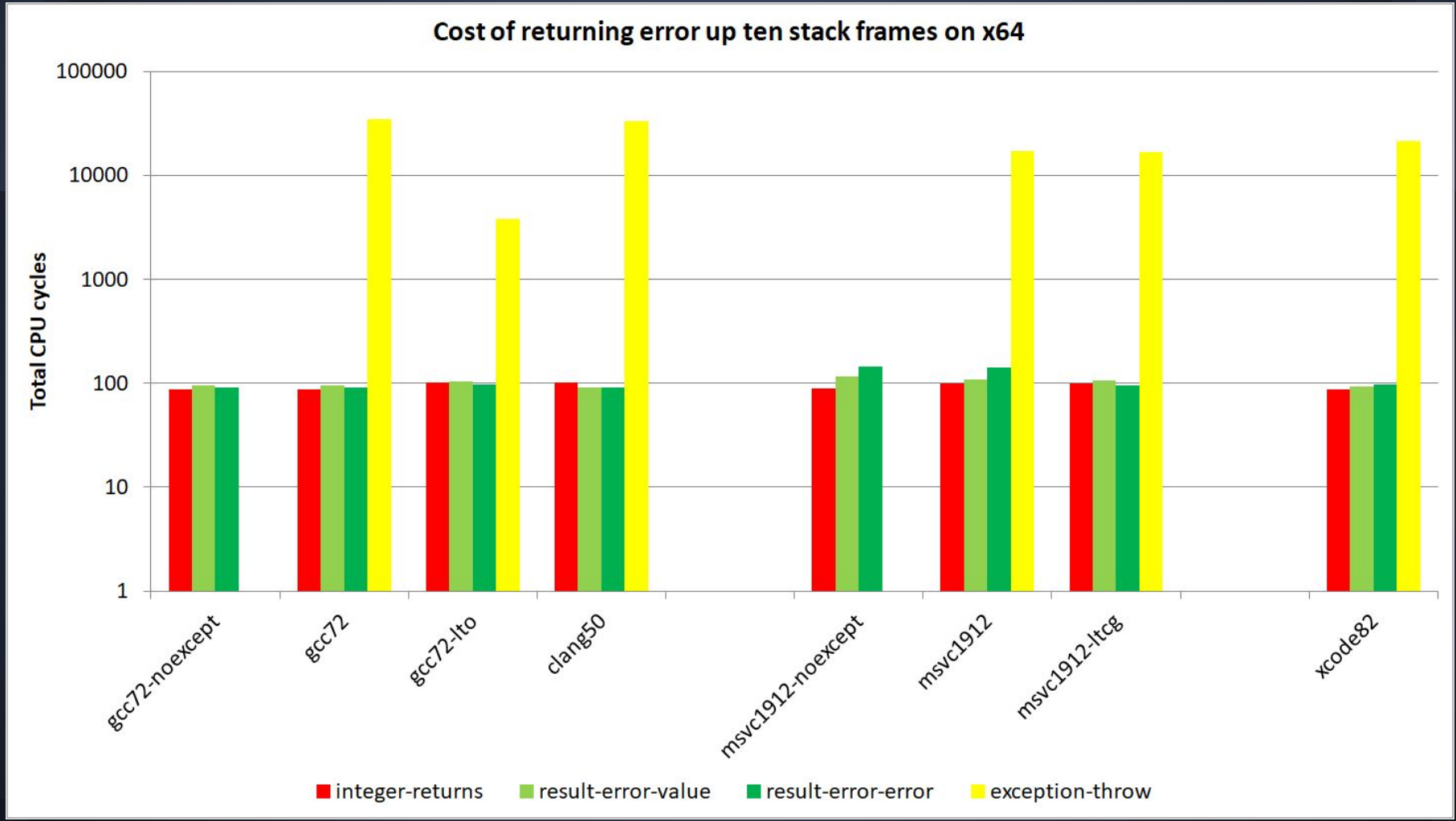
This talk is based on these specific papers:

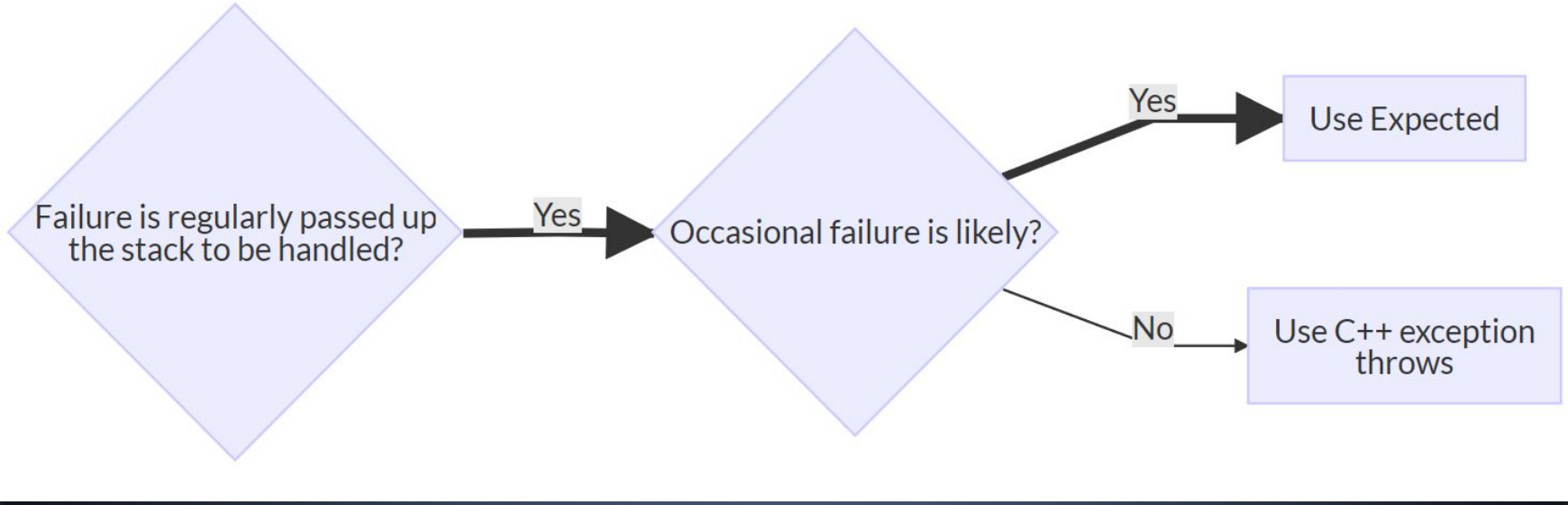
1. P0157R0 *Handling Disappointment in C++* (Lawrence Crowl, 2015)
2. P0323R3 *Utility class to represent expected object* (Vicente J. Botet Escriba, 2014-2017)
3. P0650R1 *C++ Monadic interface* (Vicente J. Botet Escriba, 2016-2017)

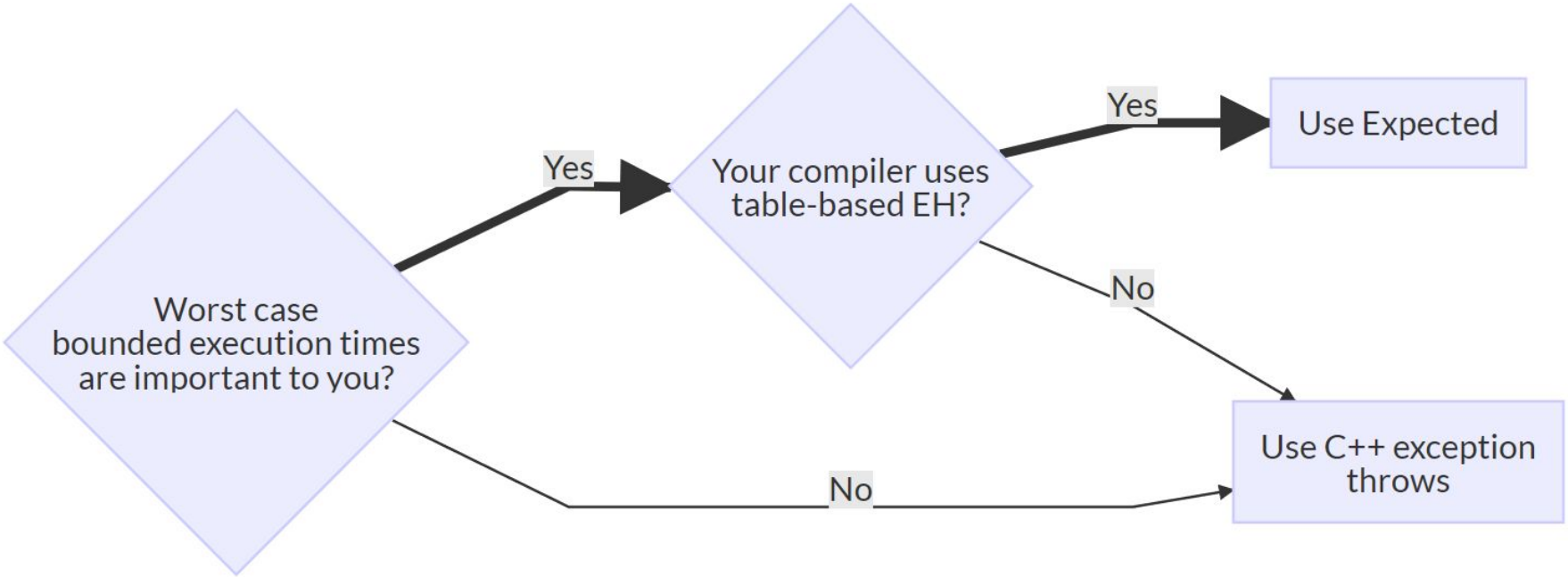
Relevant WG21 papers

4. P0762R0 *Concerns about expected<T, E> from the Boost.Outcome peer review* (Niall Douglas [me!], 2017)
5. P0779R0 *Proposing operator try() (with added native C++ macro functions!)* (Niall Douglas [me!], 2017)
6. P0786R0 *ValuedOrError and ValuedOrNone types* (Vicente J. Botet Escriba, 2017)

Why might you need Expected?


Cost of returning error up ten stack frames on x64
Total CPU cycles
100000
10000
1000
100
10
1
gcc72-noexcept
gcc72
gcc72-lto
clang50
msvc1912-noexcept
msvc1912
msvc1912-ltcg
xcode82
integer-returns
result-error-value
result-error-error
exception-throw


Failure is regularly passed up the stack to be handled?
Yes
Occasional failure is likely?
Yes
Use Expected
No
Use C++ exception throws


Worst case bounded execution times are important to you?
Yes
Your compiler uses table-based EH?
Yes
Use Expected
No
No
Use C++ exception throws

And if you answer yes to any of these questions:

- Failure handling logic is as important or more important than success handling logic?
- The cost of fully testing your code for exception safety isn't worth it to your organisation?
- Code peer review checks correctness of failure handling first?

And if you answer yes to any of these questions:

- You compile with C++ exceptions globally disabled?
- You wish to start adding exception throwing code into an older codebase not written to be exception safe?
  - For example, introducing snazzy new classes from the C++ 17 STL into a mature Qt codebase

Questions?

What is the current proposed Expected?

P0323R3 *Utility class to represent expected object*
(Vicente J. Botet Escriba, 2014-2017)

`expected<T, E>`

Design-wise the proposed `expected<T, E>` sits in between C++ 17's `std::optional<T>` and `std::variant<...>`

- Like a variant, stores either a `T` or an `E`, but with strong "never empty" guarantees
- But has the API of an optional with a `T` state being an "expected" thing and an `E` state being an "unexpected" thing

```
template<class T, class E>
requires(is_nothrow_move_constructible_v<E> && !is_void_v<E>)
class expected {
public:
  // all the same member functions from optional<T>
  using value_type = T;
  constexpr expected(...);  // implicit usual ways of
constructing a T, usual assignment, swap, etc
  constexpr T* operator ->();
  constexpr T& operator *();
  constexpr explicit operator bool() const noexcept;
  constexpr bool has_value() const noexcept;
```

```
  constexpr T& value();
  template <class U> constexpr T value_or(U&&);

  // with these additions
  using error_type = E;
  constexpr expected(unexpected_type<E>);  // type sugar for
constructing an E
  constexpr E& error();
};

// C++17 template deduced unexpected type sugar
template<class E>
class unexpected { ...
```

Questions?

Example of use

```
enum class arithmetic_errc {
  divide_by_zero,            // 9 / 0 == ?
  not_integer_division,      // 5 / 2 == 2.5 (which is not an integer)
  integer_divide_overflows, // INT_MIN / -1
};

expected<int, arithmetic_errc> safe_divide(int i, int j) {
  if (j == 0)
    return unexpected(arithmetic_errc::divide_by_zero);
  if (i == INT_MIN && j == -1)
    return unexpected(arithmetic_errc::integer_divide_overflows);
  if (i % j != 0)
    return unexpected(arithmetic_errc::not_integer_division);
  return i / j;
}
```

```
expected<double, arithmetic_errc>
  f1(double i, int j, int k)
{
  auto q = safe_divide(j, k);
  // propagate any error
  if (!q)
    return unexpected(q.error());

  // otherwise act on value
  return i + *q;
}
```

Littering your code with these kinda sucks!

Two solutions in the works (both would ship well after Expected):

1. `operator try` (P0779R0)
2. C++ Monadic interface (P0650R1)

Use in functional programming

P0650R1 *C++ Monadic interface*

(Vicente J. Botet Escriba, 2016-2017)

```
functor::transform          : [T] x (T->U) -> [U]
functor::map                : (T->U) x [T] -> [U]

applicative::ap             : [T] x [(T->U)] -> [U]
applicative::pure<A>        : T -> [T]

monad::unit<A>              : T -> [T]
monad::bind                 : [T] x (T->[U]) -> [U]  // mbind
monad::unwrap               : [[T]] -> [T]           // unwrap
monad::compose              : (B->[C]) x (A->[B])-> (A->[C])

monad_error::catch_error    : [T] x (E->[T]) -> [T]
```

```
expected<int, arithmetic_errc> f(int i, int j, int k)
{



  return monad::bind(safe_divide(i, k), [=](int q1) {
    return monad::bind(safe_divide(j,k), [q1](int q2) {
      return q1 + q2;
    });
  });
}
```

Questions?

Proposed Expected operations

P0786R0 *ValuedOrError and ValuedOrNone types*

(Vicente J. Botet Escriba, 2017)

Expected Concepts

P0786R0 proposes two *Concepts*:

1. **`ValueOrError`**
   - Accepts *any* type which provides **`.has_value()`**, **`.value()`** and **`.error()`** e.g. **`expected<T, E>`**

2. **`ValueOrNone`**
   - Accepts *any* type which provides **`.has_value()`** and **`.value()`** e.g. **`optional<T>`**

Expected operators

You then get these standard operations:

- `operator try` --OR-- `operator ?`
- `value_or`
- `value_or_throw`
- `error_or`
- `check_error`

These let you save typing boilerplate ...

try/?

```
expected<T, E> e1 = expr1(...);
if(!e1.has_value())
  return e1.error();
T v1 = std::move(e1.value());
```

```
// If operator try proposal:
T v1 = try expr1(...);
// If operator ? proposal then like Swift:
T v1 = expr1?(...);
```

value_or

```
template <ValueOrNone X, class T>
auto value_or(X&& x, T&& v) {
  return x.has_value() ? x.value() : v;
}
```

```
expected<T, E> e1 = expr1(...);
T v0 = ...;
T v1 = value_or(e1, v0);
```

value_or_throw

```
template <class E, ValueOrNone X>
auto value_or_throw(X&& x) {
  return x.has_value() ? x.value() : throw E{};
}
template <class E, ValueOrError X>
auto value_or_throw(X&& x) {
  return x.has_value() ? x.value() : throw E{x.error()};
}
```

```
expected<T, std::error_code> e1 = expr1(...);
T v1 = value_or_throw<system_error>(e1);
```

value_or

```
template <ValueOrError X, class T>
auto error_or(X&& x, T&& v) {
  return !x.has_value() ? x.error() : v;
}
```

```
expected<T, E> e1 = expr1(...);
E v0 = ...;
E v1 = error_or(e1, v0);
```

check_error

```
template <ValueOrError X, class E>
bool check_error(X&& x, E&& err) {
  if(x.has_value())
    return false;
  return x.error() == err;
}
```

```
expected<T, E> e1 = expr1(...);
E v0 = ...;
if(check_error(e1, v0))
  ...
```

Questions?

Implementing object construction with Expected

100% Expected based constructors

- I get asked about this *a lot* … so here is one of many possible solutions
  - Developed during implementation of my proposed File I/O TS hopefully going before WG21 in 2018
- Prerequisites:
  - Your type must be movable
  - Moves must be cheap
  - You don’t mind a little bit of metaprogramming
  - You don’t mind typing more characters

100% Expected based constructors

Steps:

1. Break construction into two phases:
   a. An all-constexpr phase which places the object into a valid, legally destructible state
   b. All operations which aren't constexpr and/or could fail go into the second, Expected-returning, phase
2. Tell the metaprogramming how to construct your object
3. End users now do `construct<Foo>{Args...}()`

Phase 1: All-constexpr constructor

```
class file_handle {
  int _fd{-1};  // file descriptor
  struct stat _stat {
    0
  };  // stat of the fd at open

  // Phase 1 private constexpr constructor
  constexpr file_handle() {}

  // Phase 2 static member constructor function, which cannot throw
  static inline expected<file_handle, std::error_code> file(path_type path, mode
mode = mode::read) noexcept;
};
```

Phase 2: Expected returning stage

```
// Phase 2 static member constructor function, which cannot throw
inline expected<file_handle, std::error_code>
file_handle::file(file_handle::path_type path, file_handle::mode mode) noexcept
{
  // Perform phase 1 of object construction
  file_handle ret;
  ...
  // Perform phase 2 of object construction
  ret._fd = ::open(path.u8string().c_str(), flags);
  if(-1 == ret._fd)
    return unexpected(error_code{errno, std::system_category()});
  ...
  return {std::move(ret)};
}
```

Defining construct<T>

```
template <class T> struct construct {
  void operator()() const noexcept {
    static_assert(!std::is_same<T, T>::value, "construct<T>() was not
specialised for the type T supplied");
  }
};
template <> struct construct<file_handle> {
  file_handle::path_type _path;
  file_handle::mode _mode{file_handle::mode::read};
  // Any other args, “default initialised” if necessary, follow here ...

  expected<file_handle, std::error_code> operator()() const noexcept { return
file_handle::file(std::move(_path), _mode); }
};
```

Why this design?

Usage is thus: `construct<file_handle>{"hello"}();`

Why this choice of design?

- Passing around empty-callable objects is very useful for metaprogramming
- Nothing wrong with `{}(Args&&...)` of course ...
- But free functions are inferior to type specialisation
  - Free functions cannot be partially specialised, so tag dispatch is needed for those
  - Which is more typing, and much slower to compile

Questions?

Problems with Expected

P0762R0 *Concerns about expected<T, E> from the Boost.Outcome peer review*

(Niall Douglas [me!], 2017)

Expected problems (in my opinion):

1. It takes too much typing to use! Too verbose!
2. It alone doesn't solve alone the dual-`error_code`-API problem
3. The fact it can throw exceptions adds no value and adds significant costs to developers
    - Forces exception awareness onto devs

Expected problems (in my opinion):

4. Lack of stable ABI guarantees precludes usage in public interfaces for big iron C++ users
   - Specifically, no C compatibility
5. Underspecified on what happens at ABI boundaries where library A's custom Expecteds meet library B's?

1. The verbosity

```
struct handle;      // Abstract base class for some handle implementation
class handle_ref;   // Some sort of smart pointer managing a handle *
// Returns the expected opened handle on success, or an
// unexpected cause of failure
extern std::expected<handle_ref, std::error_code> openfile(
        const char *path) noexcept {
  int fd = open(path, O_RDONLY);
  if(fd == -1) {
    return std::unexpected(std::error_code(errno, std::system_category()));
  }
  std::error_code ec;
  auto *p = new(std::nothrow)
    some_derived_handle_implementation(fd, ec);
```

```
  if(p == nullptr) {
    close(fd);
    // C++ 11 lets you convert generic portable error_condition's
    // into a platform specific error_code like this
    return std::unexpected(std::make_error_code(std::errc::not_enough_memory));
  }
  // The some_derived_handle_implementation constructor failed
  if(ec) {
    delete p;
    return std::unexpected(std::move(ec));
  }
  return handle_ref(p);  // expected<> takes implicit conversion
                         // to type T
}
```

```
std::expected<handle_ref, std::error_code> fh_ = openfile("foo");
// C++ 11 lets you compare some platform specific error code to a
// generic portable error_condition
if(!fh_ && fh_.error() != std::errc::no_such_file_or_directory) {
  if(fh_.error() == std::errc::not_enough_memory) {
    throw std::bad_alloc();
  }
  ... more ...
  // If unhandled, abort by throwing a system_error wrapping the code
  throw std::system_error(std::move(fh_.error()));
}
if(fh_) {
  handle_ref fh = std::move(fh_.value());
  fh->read(... etc
}
```

2. The dual error code API problem

```
namespace filesystem {
  /*! Copies the file at path `from` to path `to`.
  \returns True if file was successfully copied.
  \throws On failure throws `filesystem_error(ec.message(), from, to, ec)`
  with `ec` being the error code reported by the operating system.
  */
  bool copy_file(const path &from, const path &to);

  /*! Copies the file at path `from` to path `to`.
  \returns True if file was successfully copied. If false, `ec` is written
  with the error code reported by the operating system.
  \throws Never throws.
  */
  bool copy_file(const path &from, const path &to, std::error_code &ec)
noexcept;
}
```

3. The forced exception awareness problem

Expected's throwableness

1. **`.error()`**, **`operator->`** and **`operator*`** are *narrow* observers
   - Loss of program correctness (i.e. hard UB)
2. **`.value()`** alone is a *wide* observer
   - Can throw **`bad_expected_access<E>`**

What value does a throwing .value() add?

If the user really wants that, it is ***trivial*** to add on top

4. Lack of stable ABI guarantees

Big iron C++ interface requirements

1. Components are ABI stable over many years
   - Avoids needing to recompile components
   - Often enforced by automated tooling
   - Prevents ripples of change affecting other teams
2. Interface files have near-zero compile time impact and don't **`#include`** much else
   - Really matters with millions of compilands
   - Reduces header dependency management

Consequences

- Use of the STL is usually banned in public APIs
- Public APIs usually cannot throw exceptions
  - Indeed, are often C-compatible
- Examples:
  - Microsoft COM (no STL, C compatible)
  - Qt (no STL, no non-fatal C++ exception throws)
  - Google C++ style guide (bans much of the STL, most of Boost, bans C++ exception throws)

Will Expected be allowed into public APIs? **No!**

5. ABI interop underspecified

```
namespace lib_A {
  // Error code + paths related to a failure.
  struct failure_info {
    std::error_code ec;
    path path1, path2;
  };
  expected<void, failure_info>
write_file(std::string_view data) noexcept;
}
```

```
namespace lib_B {
  enum class status_code {  // HTTP status codes
    bad_request = 400,
    ...
  };
  struct failure {
    status_code status{status_code::success};
    std::string url{};  // The failing URL
  };
  // Performs a HTTP GET on the url, calling
  // completion(std::expected<std::string,failure>)
  // with results.
  template<class F>
  expected<void, failure> get(std::string url, F&& completion);
}
```

```
namespace some_app {
  lib_B::get("http://meetingcpp.com/",
    [](expected<std::string, lib_B::failure> contents)
      -> expected<void, lib_B::failure> {
        if(!contents)
          return unexpected(contents.error());
        expected<void, lib_A::failure_info> r =
          lib_A::write_file(*contents);
        if(r)
          return {};  // success
        ??? // How do I return failure to write the file?
    });
}
```

Thank you

And let the questions begin!