

Outline

- Handling exceptional cases: `errno`, `assert`, `longjmp`
- Goals of exception handling
- Handlers and exceptions
- Standard exceptions
- Exception safe programming
- C++11 `noexcept`
- `Exception_ptr`, `nested_exceptions`

C Errno

```
#include <errno.h>
#include <stdio.h> /* fopen */
#include <string.h> /* strerror */

struct record { ... };
struct record rec;

extern int errno; /* preprocessor macro: thread-local since C11 */
int myerrno; /* my custom error code */

void f() {
    FILE *fp;
    if ( NULL == (fp = fopen( "fname", "r")) ) /* try to open the file */
    {
        fprintf( stderr, "can't open file %s\n", "fname");
        fprintf( stderr, "reason: %s\n", strerror(errno)); /* perror(NULL) */
        myerrno = 1;
    }
    else if ( ! fseek( fp, n*sizeof(rec), SEEK_SET) ) /* pos to record */
    {
        fprintf( stderr, "can't find record %d\n", n);
        myerrno = 2;
    }
    else if ( 1 != fread( &r, sizeof(r), 1, fp) ) /* try to read a record */
    {
        fprintf( stderr, "can't read record\n");
        myerrno = 3;
    }
    else /* everything was successful up to now */
    {
        /* ... */
    }
}
```

C++ Errno

```
#include <cerrno>
#include <cstdio> // std::fopen
#include <cstring> // std::strerror

struct record { ... };
struct record rec;

extern int errno; /* preprocessor macro: thread-local since C++11 */
int myerrno;      /* my custom error code */

void f() {
    std::FILE *fp;
    if ( NULL == (fp = std::fopen( "fname", "r")) ) /* try to open the file */
    {
        std::fprintf( stderr, "can't open file %s\n", "fname");
        std::fprintf( stderr, "reason: %s\n", std::strerror(errno)); /* perror(NULL) */
        myerrno = 1;
    }
    else if ( ! std::fseek( fp, n*sizeof(rec), SEEK_SET) ) /* pos to record */
    {
        std::fprintf( stderr, "can't find record %d\n", n);
        myerrno = 2;
    }
    else if ( 1 != std::fread( &r, sizeof(r), 1, fp) ) /* try to read a record */
    {
        std::fprintf( stderr, "can't read record\n");
        myerrno = 3;
    }
    else /* everything was successful up to now */
    {
        ...
    }
}
```

iostream error handling

```
void f()
{
    std::ifstream file("input.txt");

    if ( ! file )    /* before C++11: void*, since C++11: bool */
    {
        std::cerr << "file opening failed\n";
        return;
    }

    for( int n; file >> n; ) /* while ( ! cin.fail() ) */
    {
        std::cout << n << '\n';
    }

    if ( file.bad() )
    {
        std::cerr << "i/o error while reading\n";
    }
    else if ( file.eof() )
    {
        std::cerr << "eof reached\n";
    }
    else if ( file.fail() )
    {
        std::cerr << "non-integer\n";
    }
}
```

Assert

```
#include <cassert>    /* assert.h in C */  
  
void open_file(std::string fname)  
{  
    assert(fname.length() > 0);  
  
    std::ifstream f(fname.c_str());  
    . . .  
}
```

- Run-time error!

Static assert (C++11)

```
#include <type_traits>

template <typename T>
void swap(T &x, T &y)
{
    static_assert( std::is_nothrow_move_constructible<T>::value, &&
                  std::is_nothrow_move_assignable<T>::value, "Swap may throw" );

    auto tmp = x;
    x = y;
    y = tmp;
}

#if __STDC_HOSTED__ != 1
# error "Not a hosted implementation"
#endif

#if __cplusplus >= 202302L
# warning "Using #warning as a standard feature"
#endif
```

Goals of exception handling

- Type-safe transmission of arbitrary data from throw-point to handler
- Every exceptions should be caught by the appropriate handler
- No extra code/space/time penalty if not used
- Grouping of exceptions
- Work fine in multithreaded environment
- Cooperation with other languages (like C)

Setjmp/longjmp

```
#include <setjmp.h>
#include <stdio.h>

jmp_buf x;

int main()
{
    int i = 0;

    if ( (i = setjmp(x)) == 0 ) // try
    {
        f();
    }
    else // catch
    {
        switch( i )
        {
            case 1: handler1(); break;
            case 2: handler2(); break;
            default: fprintf( stdout, "error code = %d\n", i); break;
        }
    }
    return 0;
}
```

// perhaps in another source file

```
#include <setjmp.h>
extern jmp_buf x;

void f()
{
    // ...
    g();
}

void g()
{
    if ( something_wrong() )
    {
        longjmp(x, 2); // throw
    }
}
```

Setjmp/longjmp

```
#include <setjmp.h>
#include <stdio.h>
```

```
jmp_buf x;
```

```
int main()
{
    int i = 0;

    if ( (i = setjmp(x)) == 0 ) // try
    {
        f();
    }
    else // catch
    {
        switch( i )
        {
            case 1: handler1(); break;
            case 2: handler2(); break;
            default: fprintf( stdout, "error code = %d\n", i); break;
        }
    }
    return 0;
}
```

```
// perhaps in another source file
```

```
#include <setjmp.h>
extern jmp_buf x;
```

```
void f()
```

```
{
    // ...
    g();
}
```

```
void g()
```

```
{
    if ( something_wrong() )
    {
        longjmp(x, 2); // throw
    }
}
```

Exceptions in C++

- ```
try // dangerous area
{
 f(); // someth
}
catch (T1 e1) { /* handler for T1 */ }
catch (T2 e2) { /* handler for T2 */ }
catch (T3 e3) { /* handler for T3 */ }

void f()
{
 //...
 T e;
 throw e; /* throws exception of type T */

 // or:
 throw T(); /* throws default value of T */
}
```

# Which handler?

**A handler of type H catches the exception of type E if**

- H and E is the same type
- H is unambiguous base type of E
- H and E are pointers or references and some of the above stands

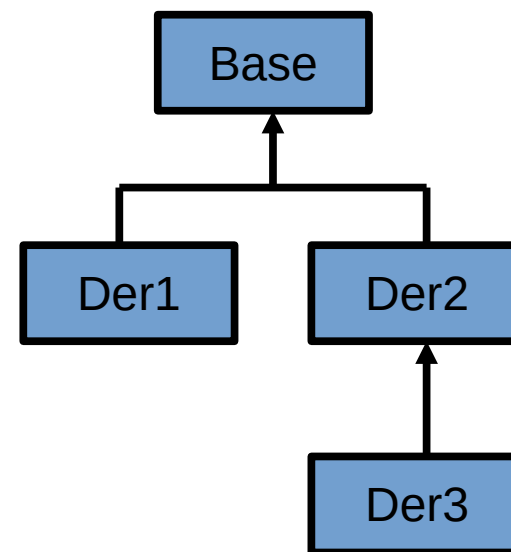
# Exception hierarchies

- Resolved run-time
- Not overloading!

```
class Base { ... };
class Der1 : public Base { ... };
class Der2 : public Base { ... };
class Der3 : public Der2 { ... };
```

```
try
{
 f();
 // ...
}
catch (Der3 &e1) { /* handler for Der3 */ } /* the most derived handler first */
catch (Der2 &e2) { /* handler for Der2 */ }
catch (Der1 &e3) { /* handler for Der1 */ }
catch (Base &e3) { /* handler for Base */ } /* the base handler last */

void f()
{
 if (...)
 throw Der3(); /* throw the most derived type */
}
```



# Exception hierarchies 2

- Multiple inheritance is possible
- And sometimes even useful

```
class net_error { ... };
class file_error { ... };

class nfs_error : public net_error, public file_error { ... };

void f()
{
 try
 {
 ...
 }
 catch(nfs_error nfs) { ... }
 catch(file_error fe) { ... }
 catch(net_error ne) { ... }
}
```

# Re-throw

- Re-throw works only inside a catch block
- Re-throws the original object, not the (possible sliced) one

```
class Base { ... };
class Der1 : public Base { ... };

void g()
{
 throw Der1; // throw derived exception Der1
}

void f()
try // function block itself can be try block
{
 g();
}
catch (Base b) // catch Base by value: copied, since C++11 can be moved
{
 must_do_at_exception(b);
 throw; // re-throw original exception Der1
}
catch (...) // catch all
{
 must_do_at_exception();
 throw; // re-throw original exception
}
```

# Exception hierarchies 3

```
#include <stdexcept>
struct matrixError // perhaps member in class Matrix
{
 matrixError(std::string r) : reason(r) { }
 std::string reason;
 virtual ~matrixError() { }
};
struct indexError : public matrixError, public std::out_of_range
{
 indexError(int i, const char *r="Bad index") : matrixError(r),out_of_range(r),index(i)
 {
 std::ostringstream os;
 os << index;
 reason += ", index = ";
 reason += os.str();
 }
 const char *what() const noexcept override
 {
 return reason.c_str();
 }
 virtual ~indexError() { }
 int index;
};
struct rowIndexError : public indexError
{
 rowIndexError(int i) : indexError(i, "Bad row index") { }
};
struct colIndexError : public indexError
{
 colIndexError(int i) : indexError(i, "Bad col index") { }
};
```

- Catch by:
  - std::logic\_error
  - indexError
  - Etc...

# std exception hierarchy

```
class exception {}; // in <exception>

class bad_exception : public exception {}; // calls unexpected()
class bad_weak_ptr : public exception {}; // C++11 weak_ptr -> shared_ptr
class bad_function_call : public exception {}; // C++11 function::operator()
class bad_typeid : public exception {}; // typeid(0)
class bad_cast : public exception {}; // dynamic_cast
 class bad_any_cast : public bad_cast {}; // C++17
class bad_variant_access : exception {}; // C++17
class bad_optional_access : exception {}; // C++17
class bad_alloc : public exception {}; // new <new>
 class bad_array_new_length : bad_alloc {}; // C++11, new T[-1]

class logic_error : public exception {};
 class domain_error : public logic_error {}; // domain error, std::sqrt(-1)
 class invalid_argument : public logic_error {}; // bitset char != 0 or 1
 class length_error : public logic_error {}; // length str.resize(-1)
 class out_of_range : public logic_error {}; // bad index in container or string
 class future_error : public logic_error {}; // C++11: promise abandons the shared state

class runtime_error : public exception {};
 class range_error : public runtime_error {}; // floating point ovf or unf
 class overflow_error : public runtime_error {}; // int overflow INT_MAX+1
 class underflow_error : public runtime_error {}; // int underflow INT_MIN-1
 class system_error : public runtime_error {}; // e.g. std::thread constr.
 class ios_base::failure : public system_error {}; // C++11
 class filesystem::filesystem_error : public system_error {}; // C++17
 class nonexistent_local_time : public system_error // C++20
 class ambiguous_local_time : public system_error // C++20
 class format_error : public system_error // C++20
```

# Exception specification before C++11

```
class E1;
class E2;

void f() throw(E1) // throws only E1 or subclasses
{
 ...
 throw E1(); // throws exception of type E1
 ...
 throw E2(); // calls unexpected() which calls terminate()
}

// same as:

void f()
try {
 ...
}
catch(E1) { throw; }
catch(...) { std::unexpected(); }
```

- Unexpected before C++17 != unexpected since C++23
- Deprecated since C++11, removed since C++17

# Exception specification before C++11

```
class E1;
class E2;

void f() throw(E1, std::bad_exception) // throws only E1 or subclasses
{
 ...
 throw E1(); // throws exception of type E1
 ...
 throw E2(); // calls unexpected() which throws bad_exception()
}
```

```
typedef void (*terminate_handler)();
terminate_handler set_terminate(terminate_handler);
terminate_handler get_terminate(); // C++11

// until C++17
typedef void (*unexpected_handler)();
unexpected_handler set_unexpected(unexpected_handler);
unexpected_handler get_unexpected(); // C++11
```

- `void f() throw()` // does not throw, can be optimized
- Deprecated since C++11, removed since C++17



# Noexcept specifier in C++11

- Since C++11
  - Part of function type since C++17
  - But not part of function signature (so no overload on noexcept)
- C++ functions are either non-throwing or potentially throwing
- C++ cannot execute full compile time check on possible exceptions
  - Partially due to possible call of non C++ functions
- Destructors, deallocation functions are non-throwing
- Implicitly declared or defaulted default-, copy- and move constructors, copy, move oper.
  - Unless base class or called operations throw
- Noexcept is important for optimizations and program safety

```
void f() noexcept(expr) { }
void f() noexcept(true) { }
void f() noexcept { } // noexcept(true)
```

# Noexcept operator in C++11

- **bool noexcept(expr);**
- Can be used inside function template noexcept specifier
- Compile-time check: does not evaluate *expr* (like **sizeof**)
- False if
  - Expr throws
  - Expr has `dynamic_cast` or `typeid`
  - Has function which is not `noexcept(true)` and not `constexpr`
- Otherwise **true**

```
template <typename T>
void f() noexcept (noexcept(T::g()))
{
 T::g();
}
```

# Destructors

## Destructors must not throw!

- Exception thrown during exception triggers **std::terminate()**
- Since C++11 every destructor is implicit **noexcept**
- It is possible to declare the destructor as **noexcept(false)**
- If exception is thrown during stack unwinding: **std::terminate** is called instead
- But the real situation is more complex:

<https://akrzemi1.wordpress.com/2011/09/21/destructors-that-throw/>

# Exception safety

```
class T1 { ... };
class T2 { ... };

template <typename T1, typename T2>
void f(T1*, T2*);

void g()
{
 f(new T1(), new T2());
 // ...
}
```

## Scenario1 (before C++17)

Allocates memory for T1  
Allocates memory for T2  
Constructs T1  
Constructs T2  
Calls f

## Scenario2

Allocates memory for T1  
Constructs T1  
Allocates memory for T2  
Constructs T2  
Calls f

# Exception safety

- Usually solved by rearranging the source and use sequence points
- Since C++17, parameter evaluation order changed

undefined -> unspecified

```
class T1 { ... };
class T2 { ... };
```

```
template <typename T1, typename T2>
void f(std::unique_ptr<T1>, std::unique_ptr<T2>);
```

```
void g()
{
 std::unique_ptr<T1> ptr1{new T1()};
 std::unique_ptr<T2> ptr2{new T2()};

 f(ptr1, ptr2);
 // ...
}
```

# Exception safety in STL

- **Basic guarantee:** no memory leak or other resource issue
- **Strong guarantee:** the operation is atomic:  
it either succeeds or has no effect  
e.g. `push_back()` for vector, `insert()` for assoc. cont.
- **Nothrow guarantee:** the operation does not throw  
e.g. `pop_back()` for vector, `erase()` for assoc. cont., `swap()`

# Strong guarantee

```
template <class T>
class Vec
{
 // ...
private:
 size_t cap;
 size_t sz;
 T *v;
};

Vec<T>& Vec<T>::operator=(const Vec& rhs)
{
 if (this != &rhs)
 {
 delete[] v;
 cap = sz = rhs.sz;
 v = new T[cap];
 for (size_t i = 0; i < cap; ++i)
 v[i] = rhs.v[i];
 }
 return *this;
}
```

# Strong guarantee

```
template <class T>
class Vec
{
 // ...
private:
 size_t cap;
 size_t sz;
 T *v;
};

Vec<T>& Vec<T>::operator=(const Vec& rhs)
{
 if (this != &rhs)
 {
 delete[] v;
 cap = sz = rhs.sz;
 v = new T[cap];
 for (size_t i = 0; i < cap; ++i)
 v[i] = rhs.v[i];
 }
 return *this;
}

Vec<T>& Vec<T>::operator=(const Vec& rhs)
{
 if (this != &rhs)
 {
 Vec tmp(rhs);
 cap = sz = tmp.sz;
 std::swap(v, tmp.v);
 }
 // tmp deleted here with the old buffer
 return *this;
}
```

# Exception safety in STL

|               | <b>vector</b> | <b>deque</b>  | <b>list</b>   | <b>map</b>     |
|---------------|---------------|---------------|---------------|----------------|
| clear()       | nothrow(copy) | nothrow(copy) | nothrow       | nothrow        |
| erase()       | nothrow(copy) | nothrow(copy) | nothrow       | nothrow        |
| insert() one  | strong(copy)  | strong(copy)  | strong        | strong         |
| insert() more | strong(copy)  | strong(copy)  | strong        | strong         |
| merge()       |               |               | nothrow(comp) |                |
| push_back()   | strong        | strong        | strong        |                |
| push_front()  |               | strong        | strong        |                |
| pop_back()    | nothrow       | nothrow       | nothrow       |                |
| pop_front()   |               | nothrow       | nothrow       |                |
| remove()      |               |               | nothrow(comp) |                |
| remove_if()   |               |               | nothrow(pred) |                |
| reverse()     |               |               | nothrow       |                |
| splice()      |               |               | nothrow       |                |
| swap()        | nothrow       | nothrow       | nothrow       | nothrow(cp,co) |
| unique()      |               |               | nothrow(comp) |                |

# Some new features in C++11

- **class exception\_ptr** smart pointer type, default constructible, copyable, == if null or points to the same
- **make\_exception\_ptr(E e)** creates an exception\_ptr pointing to the exception object **e**.
- **current\_exception()** null ptr if called outside of exception handling or it returns an exception\_ptr pointing to the current exception
- **rethrow\_exception(std::exception\_ptr p)** rethrow exception **p**
- **class nested\_exception** polymorphic mixin class capture and store current exception  
has **rethrow\_nested() const** member function
- **throw\_with\_nested(T&& t)**  
**throw\_if\_nested(const E& e)**

# exception\_ptr

```
#include <iostream>
#include <string>
#include <exception>
#include <stdexcept>

void handle_eptr(std::exception_ptr eptr) // passing by value is ok
{
 try
 {
 if (eptr != std::exception_ptr())
 {
 std::rethrow_exception(eptr);
 }
 }
 catch(const std::exception& e)
 {
 std::cout << "Caught exception \"" << e.what() << "\"\n";
 }
}

int main()
{
 std::exception_ptr eptr;
 try
 {
 std::string().at(1); // this generates an std::out_of_range
 }
 catch(...)
 {
 eptr = std::current_exception(); // capture
 }
 handle_eptr(eptr);
} // destructor for std::out_of_range called here, when the eptr is destructed

// output: Caught exception "basic_string::at"
```

# Nesting exceptions

```
#include <iostream>
#include <stdexcept>
#include <exception>
#include <string>
#include <fstream>

void print_exception(const std::exception& e, int level = 0) // prints the string of an exception.
{
 I // if nested, recurses
 std::cerr << std::string(level, ' ') << "exception: " << e.what() << '\n';
 try {
 std::rethrow_if_nested(e);
 } catch(const std::exception& e) {
 print_exception(e, level+1);
 } catch(...) {}
}

void open_file(const std::string& s) // catches an exception and wraps it in a nested exception
{
 try {
 std::ifstream file(s);
 file.exceptions(std::ios_base::failbit);
 } catch(...) {
 std::throw_with_nested(std::runtime_error("Couldn't open " + s));
 }
}

void run() // sample function that catches an exception and wraps it in a nested exception
{
 try {
 open_file("nonexistent.file");
 } catch(...) {
 std::throw_with_nested(std::runtime_error("run() failed"));
 }
}

int main() // runs the sample function above and prints the caught exception
try {
 run(); // exception: run() failed
} catch(const std::exception& e) { // exception: Couldn't open nonexistent file
 print_exception(e); // exception: basic_ios::clear
}

}
```

# Optional (C++17)

- Maybe monad implementation
- Replaces return types like `std::pair<T,bool>`
- Optional contains value
  - Initialized/assigned with value of T
  - Initialized/assigned with `optional<T>` which contains value
- Optional does not contain value
  - Default initialized or initialized with value of `std::nullopt_t`
  - Initialized/assigned with `optional<T>` which does not contain value
- If `optional<T>` contains a value, than it is allocated as T
  - Not a pointer based heap storage
- Convertible to `bool`: true if contains value
- No optional reference

# std::optional

```
std::optional<int> convert(const std::string& s)
try
{
 return std::stoi(s); // C++11
}
catch (std::invalid_argument e) // s is not an integer
{
 return {}; // std::optional<int>{std::nullopt}
}
catch (std::out_of_range e) // result cannot be represented in int
{
 return {}; // std::optional<int>{std::nullopt};
}

int main()
{
 int i = convert("42").value_or(-1);
}
```

# Use of optional

```
void f(bool b1)
{
 std::optional<int> opt1; // default constr: std::nullopt
 std::cout << opt1.value_or(-1) << '\n'; // -1
 try
 {
 std::cout << opt1.value() << '\n'; // throw std::bad_optional_access
 }
 catch(std::bad_optional_access& e)
 {
 std::cerr << e.what() << '\n';
 }
 opt1 = b1 ? std::optional<int>(42) : std::nullopt; // 42

 std::cout << opt1.value_or(-1) << '\n'; // 42
 if (opt1) // true
 {
 std::cout << opt1.value() << '\n'; // 42
 *opt1 = 2; // access contained data, also -> exists
 int i = opt1.value();
 std::cout << i << '\n'; // 2
 }
}
```

-1

bad optional access

42

42

2

# Use of pointers

```
void f(bool b1)
{
 std::optional<std::string> opt2; // std::nullopt
 *opt2 = "Hello"; // undefined behavior if std::nullopt

 std::cout << *opt2 << '\n';
 std::cout << std::boolalpha << opt2.has_value() << '\n'; // false

 std::cout << opt2.value_or("no value") << '\n'; // "no value"
 std::string s = *std::move(opt2);

 std::cout << s << ", " << opt2->size() << '\n';
}
```

```
Hello
false
no value
Hello, 0
```

# Expected (C++23)

- Represents a value or an error code
- Type-safe error handling
- Much less overhead than exceptions
- Easier to integrated to existing code base
- Monadic operations to chaining expected

<https://www.open-std.org/jtc1/sc22/wg21/docs/papers/2022/p0323r12.html>

<https://youtu.be/PH4WBUe1BHI> (Andrei Alexandrescu CppCon 2018)

# Expected (C++23)

```
#include <expected> // since C++23

template <class T, class E> // T can be void, but T must not be unexpected<>
class expected {
 // types
 using value_type = T;
 using error_type = E;
 using unexpected_type = std::unexpected<E>;
 template <class U> using rebind = expected<U, error_type>;

 // accessors
 bool has_value()
 operator bool()
 operator void() // if T == void
 T* operator->() // undefined behavior if not expected
 T& operator*() // undefined behavior if not expected
 void operator*() // if T == void, undefined behavior if not expected

 T& value() // may throw std::bad_expected_value<E>
 E& error() // undefined behavior if expected
 T value_or(U def) // returned default value if error

 // monadic operations
 auto and_then(F&& f) // if has_value() calls f, returns T, otherwise E
 auto or_else(F&& f) // if ! has_value() calls f, returns E, otherwise T
 auto transform(F&& f) // if has_value() calls f, returns expected{T}, ...
 auto transform_error(F&& f) // if ! has_value() calls f, returns expected{E},...
};
```

# Expected (C++23)

```
#include <iostream>
#include <expected>
#include <string>

// https://johnfarrier.com/the-definitive-guide-to-std-expected-in-c/
std::expected<int, std::string> safe_divide(int numerator, int denominator) {
 if (denominator == 0) {
 return std::unexpected("Error: Division by zero");
 }
 return numerator / denominator;
}

// Function that adds 5 to a number
std::expected<int, std::string> add_five(int value) {
 return value + 5;
}

// Function that squares a number
std::expected<int, std::string> square(int value) {
 return value * value;
}

int main() {
 // Example: Chaining with and_then
 auto result = safe_divide(20, 2).and_then(add_five).and_then(square);

 // Check
 if (result.has_value()) {
 std::cout << "Final Result: " << result.value() << '\n';
 } else {
 std::cout << result.error() << '\n';
 }
}
```

# Expected (C++23)

```
#include <iostream>
#include <expected>
#include <string>

// Function that performs division and uses std::expected to handle errors
std::expected<int, std::string> safe_divide(int numerator, int denominator) {
 if (denominator == 0) {
 return std::unexpected("Error: Division by zero");
 }
 return numerator / denominator;
}

int main() {
 // Example: Using transform and transform_error
 auto result = safe_divide(10, 2)
 .transform([](int value) { return value + 5; }) // add_five
 .transform([](int value) { return value * value; }); // square

 // Check
 if (result.has_value()) {
 std::cout << "Transformed Result: " << result.value() << '\n';
 } else {
 std::cout << result.error() << '\n';
 }
}
```