COMP6771

Exceptions

Lecture 5.1

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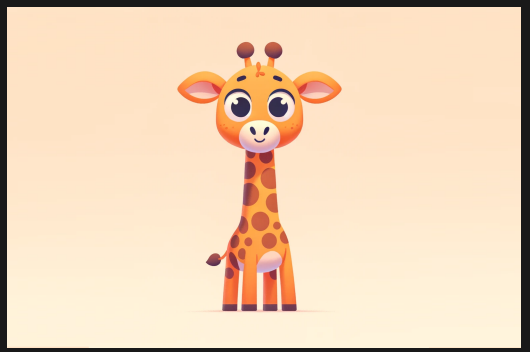

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In This Lecture

- **Why? 🤔**
  - Sometimes our programs need to deal with unexpected runtime errors and handle them gracefully

- **What? 📰**
  - Exception object
  - Throwing and catching exceptions
  - Rethrowing
  - noexcept

Explore An Example

What does this produce?

```cpp
#include <iostream>
#include <vector>

auto main() -> int
{
    std::cout << "Enter -1 to quit\n";
    std::vector<int> items { 97, 84, 72, 65 };
    std::cout << "Enter an index: ";
    for (int print_index; std::cin >> print_index;) {
        if (print_index == -1)
            break;
        std::cout << items.at(static_cast<unsigned int>(print_index)) << '\n';
        std::cout << "Enter an index: ";
    }
}
```

exception1.cpp

🚎 Explore An Example

Now we use exceptions instead

```cpp
#include <iostream>
#include <vector>

auto main() -> int
{
    std::cout << "Enter -1 to quit\n";
    std::vector<int> items { 97, 84, 72, 65 };
    std::cout << "Enter an index: ";
    for (int print_index; std::cin >> print_index;) {
        if (print_index == -1)
            break;
        try {
            std::cout << items.at(static_cast<unsigned int>(print_index)) << '\n';
            items.resize(items.size() + 10);
        } catch (const std::out_of_range& e) {
            std::cout << "Index out of bounds\n";
        } catch (...) {
            std::cout << "Something else happened";
        }
        std::cout << "Enter an index: ";
    }
}
```

exception2.cpp

Explore An Example

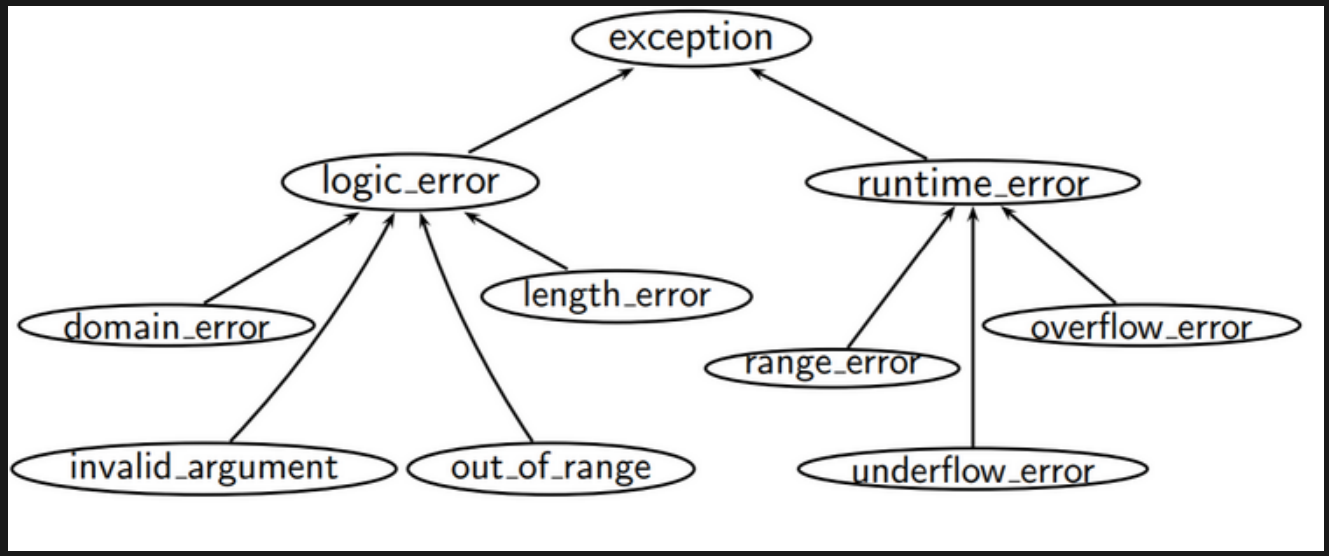
Let's take a step back and unpack what we just saw...

🔥 Exceptions: What & Why?

- What:
  - Exceptions: Are for exceptional circumstances
    - Happen during run-time anomalies (things not going to plan A!)
  - Exception handling:
    - Run-time mechanism
    - C++ detects a run-time error and raises an appropriate exception
    - Another unrelated part of code catches the exception, handles it, and potentially rethrows it
  - Why:
    - Allows us to gracefully and programmatically deal with anomalies, as opposed to our program crashing.

 What Are "Exception Objects"

- Any type we derive from std::exception
  - `throw std::out_of_range("Exception!");`
  - `throw std::bad_alloc("Exception!");`
- Why std::exception? Why classes?
- `#include <exception>` for `std::exception` object
- `#include <stdexcept>` for objects that inherit `std::exception`



- https://en.cppreference.com/w/cpp/error/exception
- https://stackoverflow.com/questions/25163105/stdexcept-vs-exception-headers-in-c

Conceptual Structure

- Exceptions are treated like lvalues
- Limited type conversions exist (pay attention to them):
  - nonconst to const
  - other conversions we will not cover in the course

```
1 try {
2   // Code that may throw an exception
3 } catch (/* exception type */) {
4   // Do something with the exception
5 } catch (...) { // any exception
6   // Do something with the exception
7 }
```

- https://en.cppreference.com/w/cpp/language/try_catch

Multiple Catch Options

This does not mean multiple catches will happen, but rather that multiple options are possible for a single catch

```cpp
#include <iostream>
#include <vector>

auto main() -> int
{
    auto items = std::vector<int> {};
    try {
        items.resize(items.max_size() + 1);
    } catch (std::bad_alloc& e) {
        std::cout << "Out of bounds.\n";
    } catch (std::exception&) {
        std::cout << "General exception.\n";
    }
}
```

multiple.cpp

 Rethrow

- When an exception is caught, by default the catch will be the only part of the code to use/action the exception
- What if other catches (lower in the precedence order) want to do something with the thrown exception?

```
 1 try {
 2   try {
 3     try {
 4       throw T{};
 5     } catch (T& e1) {
 6       std::cout << "Caught\n";
 7       throw;
 8     }
 9   } catch (T& e2) {
10     std::cout << "Caught too!\n";
11     throw;
12   }
13 } catch (...) {
14   std::cout << "Caught too!!\n";
15 }
```

 Catching The Right Way

- **Throw by value, catch by const reference**
- Ways to catch exceptions:
  - By value (no!)
  - By pointer (no!)
  - By reference (yes)
- References are preferred because:
  - more efficient, less copying (exploring today)
  - no slicing problem (related to polymorphism, exploring later)

 Exploring Catch By Value

```cpp
#include <iostream>

class Giraffe {
public:
    Giraffe() { std::cout << "Giraffe constructed" << '\n'; }
    Giraffe(const Giraffe& g) { (void) g; std::cout << "Giraffe copy-constructed" << '\n'; }
    ~Giraffe() { std::cout << "Giraffe destructed" << '\n'; }
};

void zebra()
{
    throw Giraffe {};
}

void llama()
{
    try {
        zebra();
    } catch (Giraffe g) {
        (void) g;
        std::cout << "caught in llama; rethrow" << '\n';
        throw;
    }
}

int main()
{
    try {
        llama();
    } catch (Giraffe g) {
        (void) g;
        std::cout << "caught in main" << '\n';
    }
}
```

by-value.cpp

 Exploring Catch By Value

```cpp
#include <iostream>

class Giraffe {
public:
    Giraffe() { std::cout << "Giraffe constructed" << '\n'; }
    Giraffe(const Giraffe& g) { (void) g; std::cout << "Giraffe copy-constructed" << '\n'; }
    ~Giraffe() { std::cout << "Giraffe destructed" << '\n'; }
};

void zebra()
{
    throw Giraffe {};
}

void llama()
{
    try {
        zebra();
    } catch (Giraffe g) {
        (void) g;
        std::cout << "caught in llama; rethrow" << '\n';
        throw;
    }
}

int main()
{
    try {
        llama();
    } catch (Giraffe g) {
        (void) g;
        std::cout << "caught in main" << '\n';
    }
}
```

by-value.cpp

 Exploring Catch By Reference

```cpp
#include <iostream>

class Giraffe {
public:
    Giraffe() { std::cout << "Giraffe constructed" << '\n'; }
    Giraffe(const Giraffe& g) { (void) g; std::cout << "Giraffe copy-constructed" << '\n'; }
    ~Giraffe() { std::cout << "Giraffe destructed" << '\n'; }
};

void zebra()
{
    throw Giraffe {};
}

void llama()
{
    try {
        zebra();
    } catch (const Giraffe& g) {
        (void) g;
        std::cout << "caught in llama; rethrow" << '\n';
        throw;
    }
}

int main()
{
    try {
        llama();
    } catch (const Giraffe& g) {
        (void) g;
        std::cout << "caught in main" << '\n';
    }
}
```

by-ref.cpp

 Exploring Catch By Reference

```cpp
#include <iostream>

class Giraffe {
public:
    Giraffe() { std::cout << "Giraffe constructed" << '\n'; }
    Giraffe(const Giraffe& g) { (void) g; std::cout << "Giraffe copy-constructed" << '\n'; }
    ~Giraffe() { std::cout << "Giraffe destructed" << '\n'; }
};

void zebra()
{
    throw Giraffe {};
}

void llama()
{
    try {
        zebra();
    } catch (const Giraffe& g) {
        (void) g;
        std::cout << "caught in llama; rethrow" << '\n';
        throw;
    }
}

int main()
{
    try {
        llama();
    } catch (const Giraffe& g) {
        (void) g;
        std::cout << "caught in main" << '\n';
    }
}
```

by-ref.cpp

Exception Safety Levels

- This part is not specific to C++
- Operations performed have various levels of safety
  - No-throw (failure transparency)
  - Strong exception safety (commit-or-rollback)
  - Weak exception safety (no-leak)
  - No exception safety

 No-Throw Guarantee

- Also known as failure transparency
- Operations are guaranteed to succeed, even in exceptional circumstances
  - Exceptions may occur, but are handled internally
- No exceptions are visible to the client
- This is the same, for all intents and purposes, as noexcept in C++
- Examples:
  - Closing a file
  - Freeing memory
  - Anything done in constructors or moves (usually)
  - Creating a trivial object on the stack (made up of only ints)

No-Throw Guarantee

The noexcept specifier

- Specifies whether a function could potentially throw
- **It doesn't not actually prevent a function from throwing an exception**
- https://en.cppreference.com/w/cpp/language/noexcept_spec
- STL functions can operate more efficiently on noexcept functions

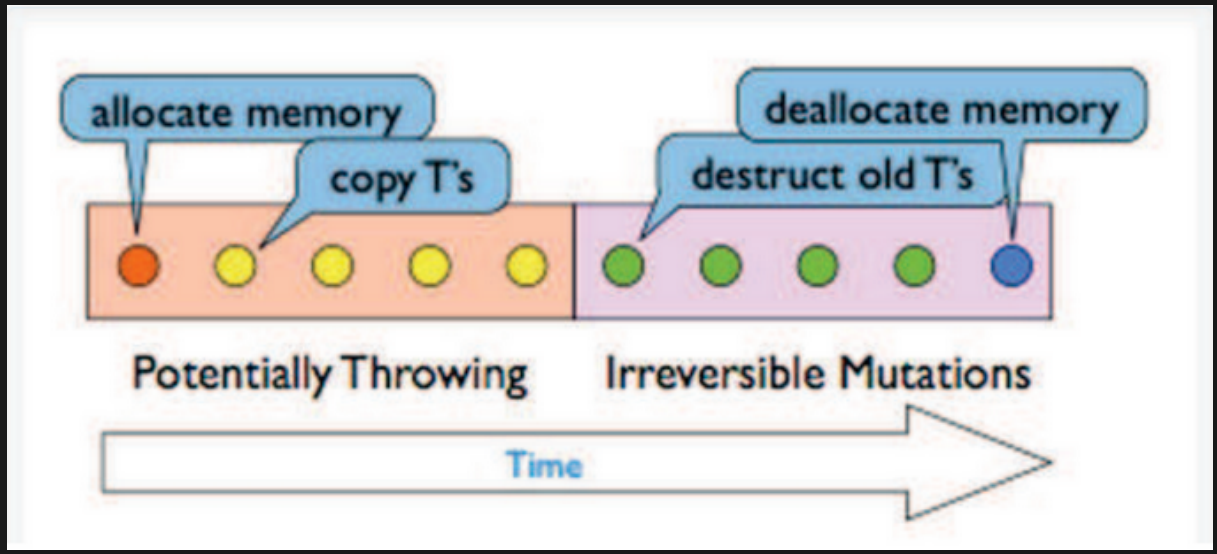
```
1 class S {
2  public:
3   int foo() const; // may throw
4 }
5
6 class S {
7  public:
8   int foo() const noexcept; // does not throw
9 }
```

 Strong Exception Safety

- Also known as "commit or rollback" semantics
- Operations can fail, but failed operations are guaranteed to have no visible effects
- Probably the most common level of exception safety for types in C++
- All your copy-constructors should generally follow these semantics
- Similar for copy-assignment
  - Copy-and-swap idiom (usually) follows these semantics (why?)
  - Can be difficult when manually writing copy-assignment

 Strong Exception Safety

- To achieve strong exception safety, you need to:
  - First perform any operations that may throw, but don't do anything irreversible
  - Then perform any operations that are irreversible, but don't throw



 Basic Exception Safety

- This is known as the no-leak guarantee
- Partial execution of failed operations can cause side effects, but:
  - All invariants must be preserved
  - No resources are leaked
- Any stored data will contain valid values, even if it was different now from before the exception
  - Does this sound familiar? A "valid, but unspecified state"
  - Move constructors that are not noexcept follow these semantics

 No Exception Safety

- No guarantees
- Don't write C++ with no exception safety
  - Very hard to debug when things go wrong
  - Very easy to fix - wrap your resources and attach lifetimes
    - This gives you basic exception safety for free

Exceptions And Catch2

`CHECK_NOTHROW(expr);`	Checks expr doesn't throw an exception.
`CHECK_THROWS(expr);`	Checks expr throws an exception.
`CHECK_THROWS_AS(expr, type);`	Checks expr throws an exception.

`namespace Matchers = Catch::Matchers;`
`CHECK_THROWS_WITH(`
`  expr,`
`  Matchers::Message("message"));`
	Checks expr throws an exception with a message.

`CHECK_THROWS_MATCHES(`
`  expr,`
`  type,`
`  Matchers::Message("message"));`
	`CHECK_THROWS_AS` and
	`CHECK_THROWS_WITH` in a single check.

🦻 Feedback

Or go to the form here.