COMP6771 Week 5.1

Exceptions

Let's start with an example

- What does this produce?

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

int main() {
  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(print_index) << '\n';
    std::cout << "Enter an index: ";
  }
}
```

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  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(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: ";
  }
}
```

Exceptions: What & Why?

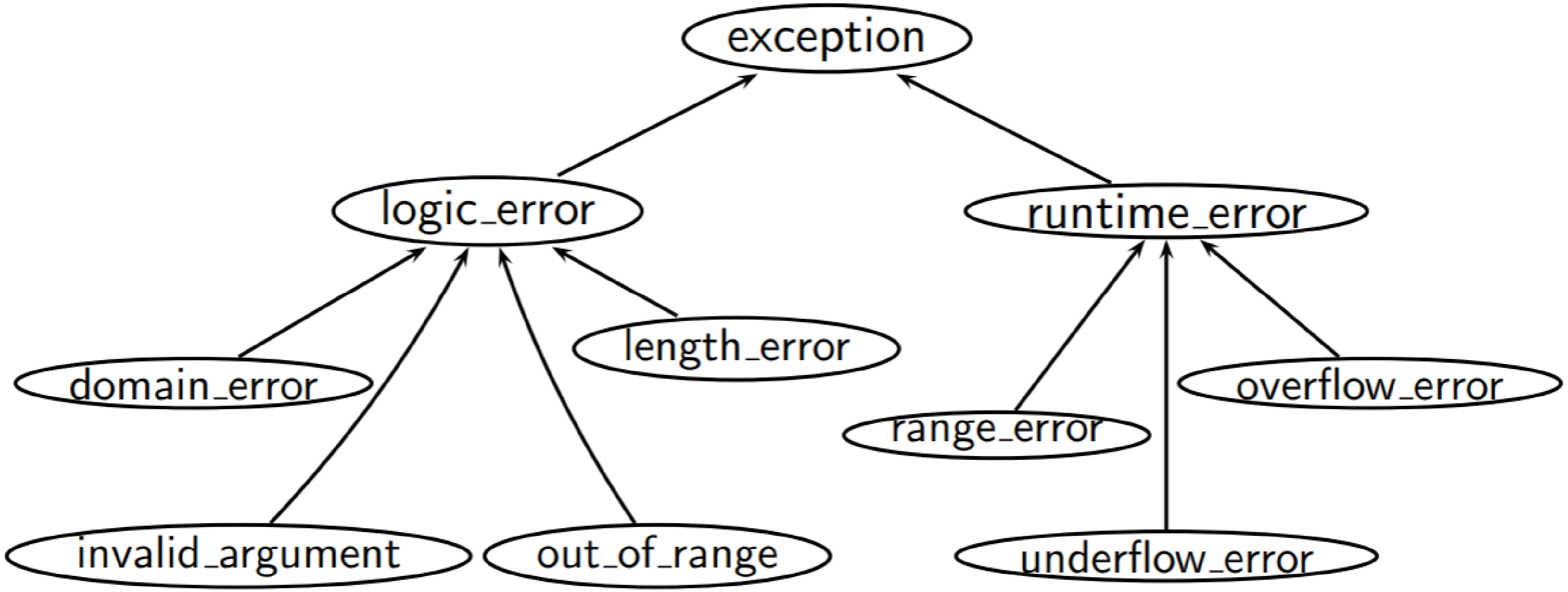
- **What:**
  - **Exceptions:** Are for exceptional circumstances
    - Happen during run-time anomalies (things not going to plan A!)
  - **Exception handling**:
    - Run-time mechanism
    - C++ detects a run-time error and raises an appropriate exception
    - Another unrelated part of code catches 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?

Standard Exceptions

- #include <stdexcept>
- Your class can inherit from these types



- 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

```
try {
  // Code that may throw an exception
} catch (/* exception type */) {
  // Do something with the exception
} catch (...) { // any exception
  // Do something with the exception
}
```

- 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>

int main() {
  std::vector<int> items;
  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";
  }
}
```

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)

(Extra reading for those interested)

- https://blog.knatten.org/2010/04/02/always-catch-exceptions-by-reference/

Catch by value is inefficient

```cpp
#include <iostream>

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

void zebra() {
  throw Giraffe{};
}

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

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

Catch by value inefficiency

```cpp
#include <iostream>

class Giraffe {
 public:
  Giraffe() { std::cout << "Giraffe constructed" << '\n'; }
  Giraffe(const Giraffe &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) {
    std::cout << "caught in llama; rethrow" << '\n';
    throw;
  }
}

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

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?

```
try {
  try {
    try {
      throw T{};
    } catch (T& e1) {
      std::cout << "Caught\n";
      throw;
    }
  } catch (T& e2) {
    std::cout << "Caught too!\n";
    throw;
  }
} catch (...) {
  std::cout << "Caught too!!\n";
}
```

(Not-advisable) Rethrow, catch by value

```
#include <iostream>

class Cake {
 public:
  Cake() : pieces_{8} {}
  int getPieces() { return pieces_; }
  Cake& operator--() { --pieces_; }
 private:
  int pieces_;
};

int main() {
  try {
    try {
      try {
        throw Cake{};
      } catch (Cake& e1) {
        --e1;
        std::cout << "e1 Pieces: " << e1.getPieces() << " addr: " << &e1 << "\n";
        throw;
      }
    } catch (Cake e2) {
      --e2;
      std::cout << "e2 Pieces: " << e2.getPieces() << " addr: " << &e2 << "\n";
      throw;
    }
  } catch (Cake& e3) {
    --e3;
    std::cout << "e3 Pieces: " << e3.getPieces() << " addr: " << &e3 << "\n";
  }
}
```

Stack unwinding

- Stack unwinding is the process of exiting the stack frames until we find an exception handler for the function
- This calls any destructors on the way out
  - Any resources not managed by destructors won't get freed up
  - If an exception is thrown during stack unwinding, std::terminate is called

Not safe

```
void g() {
  throw std::runtime_error{""};
}

int main() {
  auto ptr = new int{5};
  g();
  // Never executed.
  delete ptr;
}
```

Safe

```
void g() {
  throw std::runtime_error{""};
}

int main() {
  auto ptr = std::make_unique<int>(5);
  g();
}
```

Exceptions & Destructors

- During stack unwinding, std::terminate() will be called if an exception leaves a destructor
- The resources may not be released properly if an exception leaves a destructor
- All exceptions that occur inside a destructor should be handled inside the destructor
- Destructors usually don't throw, and need to explicitly opt in to throwing
  - STL types don't do that

RAII

-
-
  - Acquire the resource in the constructor
  - Release the resource in the destructor
  -
-
  -
  -
  -

Partial construction

- What happens if an exception is thrown halfway through a constructor?
  - The C++ standard: "An object that is partially constructed or partially destroyed will have destructors executed for all of its fully constructed subobjects"
  - A destructor is not called for an object that was partially constructed
  - Except for an exception thrown in a constructor that delegates (why?)

Spot the bug

```
class UnsafeClass {
  UnsafeClass::UnsafeClass(int a, int b):
      a_{new int{a}}, b_{new int{b}} {}

  ~UnsafeClass() {
    delete a_;
    delete b_;
  }

  int* a_;
  int* b_;
}
```

Partial construction: Solution

- Option 1: Try / catch in the constructor
  - Very messy, but works (if you get it right...)
  - Doesn't work with initialiser lists (needs to be in the body)
- Option 2:
  - An object managing a resource should initialise the resource last
    - The resource is only initialised when the whole object is
    - Consequence: An object can only manage one resource
    - If you want to manage multiple resources, instead manage several wrappers , which each manage one resource

```cpp
class SafeClass {
  SafeClass::SafeClass(int a, int b):
      a_{std::make_unique<int>(a)},
      b_{std::make_unique<int>(b)} {}

  std::unique_ptr<int> a_;
  std::unique_ptr<int> b_;
}
```

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 exception safety

No-throw guarantee

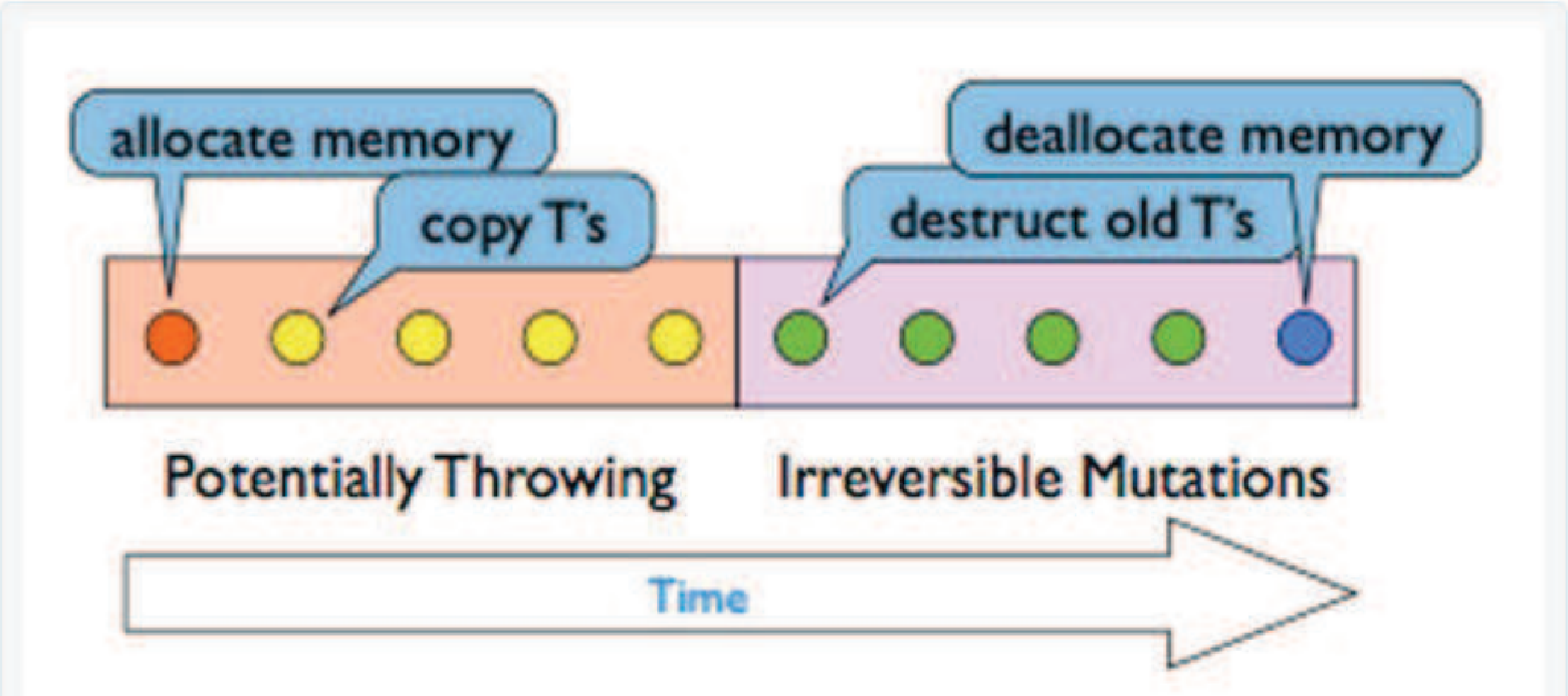
- Also known as failure transparency
- Operations are guaranteed to succeed, even in exceptional circumstances
  - Exceptions may occur, but are handled internally
- No exceptions are visible to the client
- This is the same, for all intents and purposes, as noexcept in C++
- Examples:
  - Closing a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

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

Exception safety: example

- Consider meallocating for a std::vector<MyClass> (required upon push_back)
- Assume copy constructor for MyClass has a strong guarantee
  - We can assume this because a copy-constructor takes a const ref
  - Can't perform any irreversible mutations, because const
-
  - Move constructor: no-throw or weak guarantee