CS100 Lecture 24

Exception Handling and Exception Safety

Contents

Input failure

```
int num_of_people;
std::cin >> num_of_people;
```

What happens when the input is not an integer?

Input failure

```
int num_of_people;
std::cin >> num_of_people;
```

What happens when the input is not an integer?

```
if (!std::cin) {
  // handle input failure
}
```

strcpy

You are asked to write a strcpy function...

```
void strcpy(char *dest, const char *source) {
  while (*source)
    *dest++ = *source++;
  *dest = '\0';
}
```

strcpy

You are asked to write a `strcpy` function...

```
void strcpy(char *dest, const char *source) {
  while (*source)
    *dest++ = *source++;
  *dest = '\0';
}
```

In reality, things may go wrong: Null pointers?

Which is better?

1. Terminate the program and report the error on failure:

```
void strcpy(char *dest, const char *source) {
  if (!dest || !source) {
    std::cerr << "strcpy arguments invalid.\n";
    exit(1);
  }
  while (*source)
    *dest++ = *source++;
  *dest = '\0';
}
```

2. Return false on failure:

```
bool strcpy(char *dest, const char *source) {
  if (!dest || !source)
    return false;
  while (*source)
    *dest++ = *source++;
  *dest = '\0';
  return true;
}
```

Which is better?

3. Be silent to errors:

```
void strcpy(char *dest, const char *source) {
  if (dest && source) {
    while (*source)
      *dest++ = *source++;
    *dest = '\0';
  }
}
```

4. Use assertions:

```
void strcpy(char *dest, const char *source) {
  assert(dest != NULL);
  assert(source != NULL);
  while (*source)
    *dest++ = *source++;
  *dest = '\0';
}
```

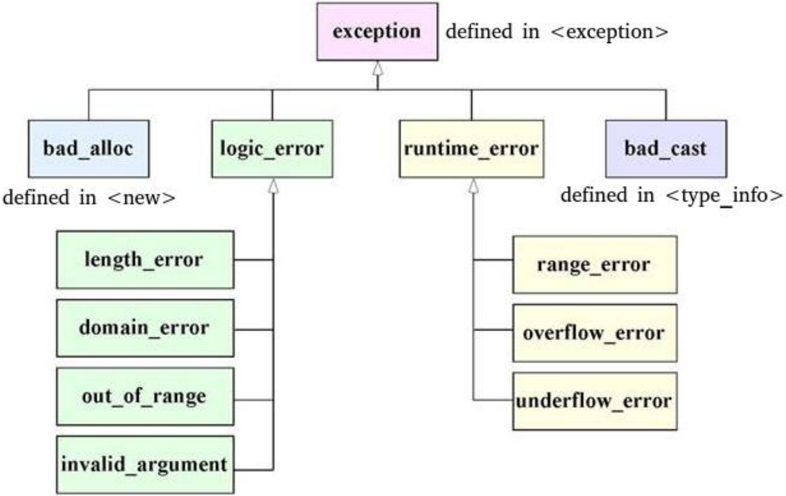
Contents

Throw an exception

```cpp
class Dynarray {
  std::size_t m_length;
  int *m_storage;

public:
  int &at(std::size_t n) {
    if (n >= m_length)
      throw std::out_of_range("Dynarray subscript out of range!");
    return m_storage[n];
  }
};
```

Standard exceptions



Standard exceptions

- The normal `new` and `new[]` operators throw `std::bad_alloc` when running out of memory.
- `dynamic_cast` for references throws `std::bad_cast` when the cast fails.
  - `dynamic_cast` for pointers does not throw. It returns `nullptr` on failure.
- `at(i)` for STL containers throws `std::out_of_range` when `i` exceeds the valid range.

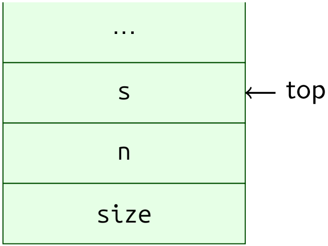
```
std::vector<int> v;
v.at(0) = 42; // Throws std::out_of_range.
v[0] = 42;    // Does not throw, but undefined behavior.
```

We will see that exceptions thrown could be catched and handled.

Stack unwinding

When an exception is thrown inside a function, *stack unwinding* destroys the function's local objects that are allocated on the stack (remove them from the stack).

```
void fun(int n) {
  std::string s;
  std::cin >> s;
  int *p = new int[n];
  // ...
}
int main() {
  int size = 100;
  fun(size);
  // ...
}
```



Suppose new[] encounters shortage of memory...

Stack unwinding

```
void fun(int n) {
  std::string s;
  std::cin >> s;
⚠ int *p = new int[n];
  // ...
}
int main() {
  int size = 100;
  fun(size);
  // ...
}
```

1. During the creation of `p`, `std::bad_alloc` is raised in `new[]`.

Stack unwinding

```
void fun(int n) {
  std::string s;
  std::cin >> s;
  int *p = new int[n];
  // ...
}
int main() {
  int size = 100;
  fun(size);
  // ...
}
```

1. During the creation of p, std::bad_alloc is raised in new[].
2. Control flow returns to func.

Stack unwinding

```
void fun(int n) {
  std::string s;
  std::cin >> s;
   int *p = new int[n];
  // ...
}
int main() {
  int size = 100;
  fun(size);
  // ...
}
```

1. During the creation of p, std::bad_alloc is raised in new[].
2. Control flow returns to func.
3. s is destroyed.

Stack unwinding

```
void fun(int n) {
  std::string s;
  std::cin >> s;
  int *p = new int[n];
  // ...
}
int main() {
  int size = 100;
  fun(size);
  // ...
}
```

1. During the creation of p, std::bad_alloc is raised in new[].
2. Control flow returns to func.
3. s is destroyed.
4. n is destroyed.

Stack unwinding

```
void fun(int n) {
  std::string s;
  std::cin >> s;
  int *p = new int[n];
  // ...
}
int main() {
  int size = 100;
  fun(size);
  // ...
}
```

1. During the creation of `p`, `std::bad_alloc` is raised in `new[]`.
2. Control flow returns to `func`.
3. `s` is destroyed.
4. `n` is destroyed.
5. Control flow returns to `main`.

Stack unwinding

```
void fun(int n) {
  std::string s;
  std::cin >> s;
   int *p = new int[n];
  // ...
}
int main() {
  int size = 100;
  fun(size);
  // ...
}
```

1. During the creation of p, std::bad_alloc is raised in new[].
2. Control flow returns to func.
3. s is destroyed.
4. n is destroyed.
5. Control flow returns to main.
6. size is destroyed.

Stack unwinding

```cpp
void fun(int n) {
  std::string s;
  std::cin >> s;
  int *p = new int[n];
  // ...
}
int main() {
  int size = 100;
  fun(size);
  // ...
}
```

1. During the creation of `p`, `std::bad_alloc` is raised in `new[]`.
2. Control flow returns to `func`.
3. `s` is destroyed.
4. `n` is destroyed.
5. Control flow returns to `main`.
6. `size` is destroyed.

Contents

Catch an exception

```
void fun(int n) {
  std::string s;
  std::cin >> s;
  int *p = new int[n];
  // ...
}
int main() {
  try {
   // A block of code that may throw an exception.
    int size = 100;
    fun(size);
  } catch (const std::bad_alloc &e) { // Specify the type of exception to be caught.
    // A block of code that handles the exception.
    // Deal with shortage of memory here.
  }
  // ...
}
```

what()

The error message could be obtained via the member function `what()`, which is `virtual`, `const` and `noexcept`.

```
void fun() {
  throw std::runtime_error("I love watermelons.");
}
int main() {
  try {
    fun();
  } catch (const std::runtime_error &re) { // 're' is initialized from the caught exception object.
    std::cout << re.what() << std::endl;
  }
}
```

Output:

```
I love watermelons.
```

Catch an exception

A `try` block can be followed by multiple `catch` blocks to catch and handle different types of exceptions.

```
void f(const std::vector<int> &v) {
  try {
    auto i = 42;
    auto copy = v;
    int x = copy.at(100);
    g(x);
  } catch (const std::bad_alloc &ba) {
    // Deal with shortage of memory
  } catch (const std::out_of_range &oor) {
    // Deal with illegal subscript '100'
  } catch (...) { // Use `...` to catch anything thrown.
    // What else may happen (probably in 'g(x)')? We are not sure.
    throw; // Throw the exception again.
  }
  std::cout << "returns.\n";
}
```

Catch an exception

```cpp
void f(const std::vector<int> &v) {
  try {
    auto i = 42;
    auto copy = v;
⚠   int x = copy.at(100);       Throw std::out_of_range
    g(x);
  } catch (const std::bad_alloc &ba) {
    // Deal with shortage of memory
  } catch (const std::out_of_range &oor) {
    // Deal with illegal subscript '100'
  } catch (...) { // Use `...` to catch anything thrown.
    // What else may happen (probably in 'g(x)')? We are not sure.
    throw; // Throw the exception again.
  }
  std::cout << "returns\n";
}
```

Catch an exception

```cpp
void f(const std::vector<int> &v) {
  try {
    auto i = 42;
    auto copy = v;  `copy' is destroyed
     int x = copy.at(100);
    g(x);
  } catch (const std::bad_alloc &ba) {
    // Deal with shortage of memory
  } catch (const std::out_of_range &oor) {
    // Deal with illegal subscript '100'
  } catch (...) { // Use `...` to catch anything thrown.
    // What else may happen (probably in 'g(x)')? We are not sure.
    throw; // Throw the exception again.
  }
  std::cout << "returns\n";
}
```

Catch an exception

```
void f(const std::vector<int> &v) {
  try {
    auto i = 42;        `i' is destroyed
    auto copy = v;
    int x = copy.at(100);
    g(x);
  } catch (const std::bad_alloc &ba) {
    // Deal with shortage of memory
  } catch (const std::out_of_range &oor) {
    // Deal with illegal subscript '100'
  } catch (...) { // Use `...` to catch anything thrown.
    // What else may happen (probably in 'g(x)')? We are not sure.
    throw; // Throw the exception again.
  }
  std::cout << "returns\n";
}
```

Catch an exception

```
void f(const std::vector<int> &v) {
  try {
    auto i = 42;
    auto copy = v;
    int x = copy.at(100);
    g(x);
  } catch (const std::bad_alloc &ba) {  Not matched
    // Deal with shortage of memory
  } catch (const std::out_of_range &oor) {
    // Deal with illegal subscript '100'
  } catch (...) { // Use `...` to catch anything thrown.
    // What else may happen (probably in 'g(x)')? We are not sure.
    throw; // Throw the exception again.
  }
  std::cout << "returns\n";
}
```

Catch an exception

```
void f(const std::vector<int> &v) {
  try {
    auto i = 42;
    auto copy = v;
    int x = copy.at(100);
    g(x);
  } catch (const std::bad_alloc &ba) {
    // Deal with shortage of memory
  } catch (const std::out_of_range &oor) {  Matched
    // Deal with illegal subscript '100'
  } catch (...) { // Use `...` to catch anything thrown.
    // What else may happen (probably in 'g(x)')? We are not sure.
    throw; // Throw the exception again.
  }
  std::cout << "returns\n";
}
```

Catch an exception

```
void f(const std::vector<int> &v) {
  try {
    auto i = 42;
    auto copy = v;
    int x = copy.at(100);
    g(x);
  } catch (const std::bad_alloc &ba) {
    // Deal with shortage of memory
  } catch (const std::out_of_range &oor) {
    // Deal with illegal subscript '100'
  } catch (...) { // Use `...` to catch anything thrown.
    // What else may happen (probably in 'g(x)')? We are not sure.
    throw; // Throw the exception again.
  }
  std::cout << "returns\n";
}
```

Catch an exception

```
void f(const std::vector<int> &v) {
  try {
    auto i = 42;
    auto copy = v;
    int x = copy.at(100);
    g(x);
  } catch (const std::bad_alloc &ba) {
    // Deal with shortage of memory
  } catch (const std::out_of_range &oor) {
    // Deal with illegal subscript '100'
  } catch (...) { // Use `...` to catch anything thrown.
    // What else may happen (probably in 'g(x)')? We are not sure.
    throw; // Throw the exception again.
  }
  std::cout << "returns\n";  Control flow continues here
}
```

Catch by base class

`new[]` raises `std::bad_alloc` when out of memory.

- But if the array length is obviously invalid, an instance of `std::bad_array_new_length` is raised.

```
new int[-1]; // negative size
new int[3]{2, 3, 4, 6, 8}; // too many initializers
new int[LONG_MAX][100]; // too large
```

Catch by base class

new[] raises std::bad_alloc when out of memory.

- But if the array length is obviously invalid, an instance of std::bad_array_new_length is raised.

```
new int[-1]; // negative size
new int[3]{2, 3, 4, 6, 8}; // too many initializers
new int[LONG_MAX][100]; // too large
```

- catch (const std::bad_alloc &) also catches it, because of **inheritance**:

Catch by base class

```cpp
try {
  do_something();
} catch (const std::runtime_error &re) {
  // Deal with runtime_error
} catch (const std::exception &e) {
  // Deal with other types of exceptions
} catch (...) {
  // Deal with other things
}
```

Catch by base class

```
try {
  do_something();
} catch (const std::runtime_error &re) {
  // Deal with runtime_error
} catch (const std::exception &e) {
  // Deal with other types of exceptions
} catch (...) {
  // Deal with other things
}
```

Note: Other things (e.g., a string) can also be thrown.

```
throw "I don\'t want to talk to you.";
throw 42;
```

In this case, these things are caught by `catch (...)`.

Catch by base class

To find the matching `catch` block for a thrown exception, `catch` blocks are examined from top to bottom.

```
try {
  do_something();
} catch (const std::exception &e) {
  std::cout << "exception\n";
} catch (const std::runtime_error &re) {
  std::cout << "runtime_error\n";
} catch (...) {
  // Deal with other things
}
```

If an instance of `std::runtime_error` is thrown, it will be caught by "`catch (const std::exception &)`" instead of "`catch (const std::runtime_error &)`" in this case.

Stack unwinding

```cpp
void fun() {
  int i = 42;
  std::vector<int> v;
⚠v.at(i) = 10;    Throw std::out_of_range
}
int main() {
  try {
    std::string str("Hello");
    fun();
  } catch (...) {}
}
```

Stack unwinding

```
void fun() {
  int i = 42;
  std::vector<int> v;  `v' is destroyed
   v.at(i) = 10;
}
int main() {
  try {
    std::string str("Hello");
    fun();
  } catch (...) {}
}
```

Stack unwinding

```cpp
void fun() {
  int i = 42;     `i' is destroyed
  std::vector<int> v;
   v.at(i) = 10;
}
int main() {
  try {
    std::string str("Hello");
    fun();
  } catch (...) {}
}
```

Stack unwinding

```
void fun() {
  int i = 42;
  std::vector<int> v;
   v.at(i) = 10;
}
int main() {
  try {
    std::string str("Hello");
    fun();     Control flow returns here
  } catch (...) {}
}
```

Stack unwinding

```
void fun() {
  int i = 42;
  std::vector<int> v;
   v.at(i) = 10;
}
int main() {
  try {
    std::string str("Hello");  `str' is destroyed
    fun();
  } catch (...) {}
}
```

Stack unwinding

```
void fun() {
  int i = 42;
  std::vector<int> v;
   v.at(i) = 10;
}
int main() {
  try {
    std::string str("Hello");
    fun();
  } catch (...) {}  The exception is caught.
}
```

Notes

- The `try` block and `catch` blocks are independent scopes. Objects declared in the `try` block cannot be used in `catch` blocks.
- When an exception occurs, local objects in the `try` block are destroyed before the exception is caught.
- Stack unwinding is only guaranteed to happen for **caught** exceptions. If an exception is not caught, if stack unwinding happens is **implementation-defined**.
- If an exception is thrown and not caught, `std::terminate` (defined in `<exception>`) will be called to terminate the program.

Contents

Exception safety guarantees

Exception safety: the code can work correctly even when exceptions occur.
Exception-safe functions must offer one of the following three guarantees (in descending order of safety):

- **Nothrow guarantee**: Promise never to throw exceptions.
- **Strong guarantee**: Promise that if an exception is thrown, the state of the program is **unchanged**, as if the function had not been called ("roll back").
- **Weak guarantee** (basic guarantee): Promise that if an exception is thrown, everything in the program remains in a valid state (though possibly changed).
  - No objects or data structures become corrupted.
  - All class invariants are satisfied. For example, for a `Dynarray` object, `m_length` should represent the length of the array in the memory block that `m_storage` points to. For a `std::vector<int>` object, `size() <= capacity()`.

Effective C++ Item 29: Strive for exception-safe code.

Exception safety guarantees

Effective C++ Item 29:

> *A software system is* ***either exception-safe or it's not****. There's no such thing as a partially exception-safe system. If a system has* ***even a single function*** *that's not exception-safe, the system as a whole is not exception-safe.*
>
> *A function can usually offer a guarantee no stronger than the* ***weakest*** *guarantee of the functions it calls.*

Which exception safety guarantee?

```cpp
class Dynarray {
  int *m_storage;
  std::size_t m_length;

public:
  Dynarray &operator=(const Dynarray &other) {
    if (this != &other) {
      delete[] m_storage;
      m_storage = new int[other.m_length]; // May throw std::bad_alloc
      std::copy(other.m_storage, other.m_storage + other.m_length, m_storage);
      m_length = other.m_length;
    }
    return *this;
  }
};
```

Which exception safety guarantee?

```
class Dynarray {
  int *m_storage;
  std::size_t m_length;

public:
  Dynarray &operator=(const Dynarray &other) {
    if (this != &other) {
      delete[] m_storage;
      m_storage = new int[other.m_length]; // May throw std::bad_alloc
      std::copy(other.m_storage, other.m_storage + other.m_length, m_storage);
      m_length = other.m_length;
    }
    return *this;
  }
};
```

No guarantee at all! The data pointed to by `m_storage` has already been destroyed before the exception happens.

Which exception safety guarantee?

```cpp
class Dynarray {
public:
  Dynarray &operator=(const Dynarray &other) {
    auto new_data = new int[other.m_length];
    std::copy(other.m_storage, other.m_storage + other.m_length, new_data);
    delete[] m_storage;
    m_storage = new_data;
    m_length = other.m_length;
    return *this;
  }
};
```

Which exception safety guarantee?

```cpp
class Dynarray {
public:
  Dynarray &operator=(const Dynarray &other) {
    auto new_data = new int[other.m_length];
    std::copy(other.m_storage, other.m_storage + other.m_length, new_data);
    delete[] m_storage;
    m_storage = new_data;
    m_length = other.m_length;
    return *this;
  }
};
```

Strong guarantee. Nothing has been changed before `new[]` on the first line throws an exception.

Which exception safety guarantee?

```
class Dynarray {
public:
  Dynarray &operator=(const Dynarray &other) {
    m_length = other.m_length;
    auto new_data = new int[m_length];
    std::copy(other.m_storage, other.m_storage + m_length, new_data);
    delete[] m_storage;
    m_storage = new_data;
    return *this;
  }
};
```

Which exception safety guarantee?

```
class Dynarray {
public:
  Dynarray &operator=(const Dynarray &other) {
    m_length = other.m_length;
    auto new_data = new int[m_length];
    std::copy(other.m_storage, other.m_storage + m_length, new_data);
    delete[] m_storage;
    m_storage = new_data;
    return *this;
  }
};
```

No guarantee. `m_length` is changed too early. If `new[]` throws, `m_length` is not equal to the length of the array in the memory block that `m_storage` points to.

Which exception safety guarantee?

The "copy-and-swap" idiom.

```
class Dynarray {
public:
  void swap(Dynarray &other) noexcept {
    using std::swap;
    swap(m_length, other.m_length);
    swap(m_storage, other.m_storage);
  }
  Dynarray &operator=(const Dynarray &other) {
    Dynarray(other).swap(*this);
    return *this;
  }
};
```

Which exception safety guarantee?

The “copy-and-swap” idiom.

```
class Dynarray {
public:
  void swap(Dynarray &other) noexcept {
    using std::swap;
    swap(m_length, other.m_length);
    swap(m_storage, other.m_storage);
  }
  Dynarray &operator=(const Dynarray &other) {
    Dynarray(other).swap(*this);
    return *this;
  }
};
```

Strong guarantee. The only thing that may throw an exception is `Dynarray(other)` (which uses `new[]`), and it doesn't change the state of `other`.

Contents

noexcept vs. throw()

Before C++11, a function may declare in advance **what** exceptions it may throw.

```
void *operator new(std::size_t size) throw(std::bad_alloc); // May throw std::bad_alloc.
```

noexcept vs. throw()

Before C++11, a function may declare in advance **what** exceptions it may throw.

```
void *operator new(std::size_t size) throw(std::bad_alloc); // May throw std::bad_alloc.
```

For a function that offers nothrow guarantee, use `throw()`:

```
int add(int a, int b) throw() {
  return a + b;
}
```

noexcept vs. throw()

People came to realize that it is **whether the function throws exceptions or not** that really matters.
Since C++11, declare noexcept for non-throwing functions.

```
class Dynarray {
public:
  void swap(Dynarray &other) noexcept {
    std::swap(m_storage, other.m_storage);
    std::swap(m_length, other.m_length);
  }
};
```

The throw() specifiers have been deprecated and removed in modern C++.

Move operations are often noexcept

Recall that `std::vector<T>` will allocate a larger block of memory when the current memory capacity is not enough.

```
template <typename T>
class vector {
  T *m_storage;
  T *m_end_of_elem, *m_end_of_storage; // Possible implementation.
public:
  void push_back(const T &x) {
    if (size() == capacity())
      reallocate(capacity() == 0 ? 1 : capacity() * 2);
    construct_object_at(m_end_of_elem, x);
    ++m_end_of_elem;
  }
private:
  void reallocate(std::size_t new_capacity);
};
```

Move operations are often `noexcept`

Before C++11, the elements are **copied** to the new memory block.

- Note: `std::vector<T>` does not use `new[]`, because it needs to separate **object creation** from **memory allocation**. The following code uses `allocate_memory`, `construt_object_at` and `destroy_and_deallocate` for demonstration only.

```
template <typename T>
class vector {
  void reallocate(std::size_t new_capacity) {
    auto new_storage = allocate_memory(new_capacity), p = new_storage;
    for (auto old_data = m_storage; old_data != m_end_of_elem; ++old_data)
      construct_object_at(p++, *old_data); // Copy initialization.
    destroy_and_deallocate(m_storage);
    m_storage = new_storage;
    m_end_of_elem = p;
    m_end_of_storage = m_storage + new_capacity;
  }
};
```

Move operations are often `noexcept`

To offer **strong exception safety guarantee**, `reallocate` needs to "recall" the operations once an exception is encountered.

```
template <typename T>
class vector {
  void reallocate(std::size_t new_capacity) {
    auto new_storage = allocate_memory(new_capacity), p = new_storage;
    try {
      for (auto old_data = m_storage; old_data != m_end_of_elem; ++old_data)
        construct_object_at(p++, *old_data); // Copy initialization.
    } catch (...) {
      while (p != new_storage) destroy(--p);
      deallocate(new_storage); throw;
    }
    destroy_and_deallocate(m_storage);
    m_storage = new_storage; m_end_of_elem = p; m_end_of_storage = m_storage + new_capacity;
  }
};
```

Move operations are often noexcept

Since C++11, a reasonable optimization is to **move** elements, instead of copying them.

```
template <typename T>
class vector {
  void reallocate(std::size_t new_capacity) {
    auto new_storage = allocate_memory(new_capacity), p = new_storage;
    try {
      for (auto old_data = m_storage; old_data != m_end_of_elem; ++old_data)
        construct_object_at(p++, std::move(*old_data)); // Move initialization.
    } catch (...) {
      // Wait ... The elements are moved! How can we recover them?
    }
    // ...
  }
};
```

Move operations are often `noexcept`

Since C++11, a reasonable optimization is to **move** elements, instead of copying them. Unlike copy, **move** of an element is a modifying operation.

- The old elements are modified during this procedure.
- If a move throws an exception, there is no way of rolling back!

Due to this consideration, `std::vector<T>` uses the move operation of `T` **only when it is** `noexcept`.

```
for (auto old_data = m_storage; old_data != m_end_of_elem; ++old_data)
  construct_object_at(p++, std::move_if_noexcept(*old_data));
```

`noexcept` is only a **logical guarantee**. A `noexcept` function may still

- call functions that are not `noexcept`, or
- throw exceptions under certain circumstances.

If a `noexcept` function *does* throw, `std::terminate` will be called to terminate the program.

Summary

- `throw` an exception
- `try`-`catch`: catch and handle exceptions
- Standard exceptions: `std::exception`, `std::bad_alloc`, `std::logic_error`, `std::runtime_error`, `std::bad_cast`, ...
- Stack unwinding: destroy local objects in reverse order of initialization.

Summary

- Exception safety guarantees:
  - Nothrow guarantee
  - Strong guarantee: "roll back"
  - Weak guarantee: promise that everything is in a valid state.
- `noexcept`: specify that a function offers nothrow guarantee.
- Move operations are often `noexcept`, because unlike copy, move is a modifying operation.