Exception Safety continued

CS 311 Data Structures and Algorithms
Lecture Slides
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Unit Overview
Handling Data & Sequences

Major Topics

- ✓ Data abstraction
- ✓ Introduction to Sequences
- Smart arrays
  - ✓ Array interface
  - ✓ Basic array implementation
  - (part) Exception safety
  - Allocation & efficiency
  - Generic containers
- Linked Lists
  - Node-based structures
  - More on Linked Lists
- Sequences in the C++ STL
- Stacks
- Queues

Review
Array Interface

Ctors & Dctor

- Default ctor
- Ctor given size
- Copy ctor
- Dctor

Member Operators

- Copy assignment
- Bracket

Global Operators

- *None*

Associated Global Functions

- *None*

Named Public Member Functions

- **`size`**
- **`empty`**
- **`begin`**
- **`end`**
- **`resize`**
- **`insert`**
- **`remove`**
- **`swap`**

Review
Basic Array Implementation

What data members should class **`SmArray`** have?

- Size of the array: **`size_type size_;`**
- Pointer to the array: **`value_type * data_;`**

What class invariants should it have?

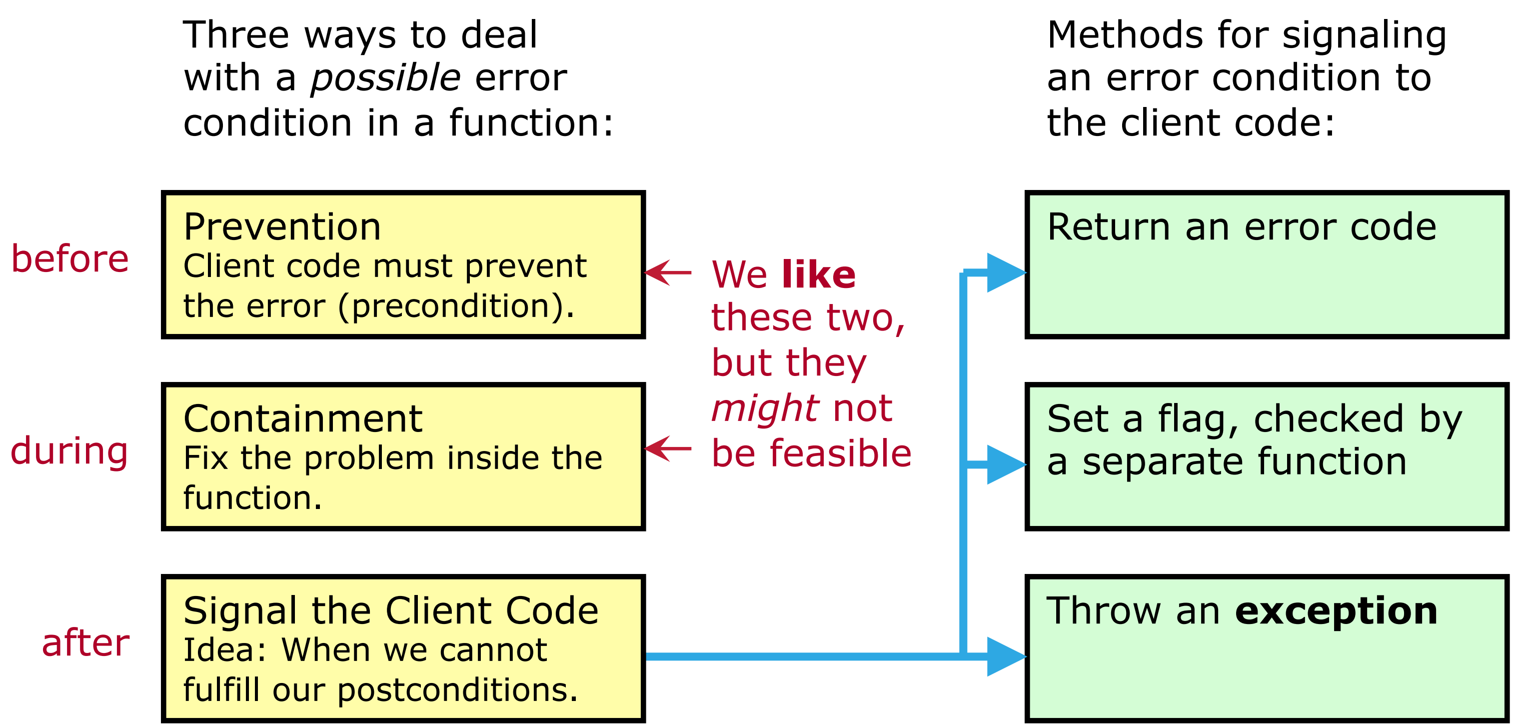
- Member "**`size_`**" should be nonnegative.
- Member "**`data_`**" should point to an **`int`** array, allocated with **`new []`**, owned by **`*this`**, holding **`size_`** **`int`**s.

Note: This design has a serious (but not obvious) problem, as we will see.

Review
Exception Safety — Refresher [1/3]

An **error condition** (or “error”) is a condition occurring during runtime that cannot be handled by the normal flow of execution.

- Not necessarily a bug or a user mistake.
- Example: Could not read file.



Review
Exception Safety — Refresher [2/3]

Exceptions are objects that are “**thrown**”, generally to signal error conditions.

We can catch **all** exceptions, using “`...`”.

- In this case, we do not get to look at the exception, since we do not know what type it is.

```
try {
    p = new Foo[mySize];  // May throw
}
catch (...) {
    fixThingsUp();
    throw;
}
```

- Inside any `catch` block, we can **re-throw the same exception** using `throw` with no parameters.

Review
Exception Safety — Refresher [3/3]

The following can throw in C++:

- "**`throw`**" throws.
- "**`new`**" may throw **`std::bad_alloc`** if it cannot allocate.
- A function that (1) calls a function that throws, and (2) does not catch the exception, will throw.
- Functions written by others may throw. See their doc's.

The following do *not* throw:

- Built-in operations on built-in types.
  - Including the built-in **`operator[]`**.
- Deallocation done by the built-in version of "**`delete`**".
  - Note: "**`delete`**" also calls destructors. These can throw.
- C++ Standard I/O Libraries (default behavior)

If a destructor is called between a throw and a catch, and that destructor throws, then the program terminates.

- Therefore, **destructors should not throw**.

Exception Safety continued
Introduction [1/2]

Issues: Does a function ever signal client code that an error has occurred, and if it does:

- Are the data left in a usable state?
- Do we know something about that state?
- Are resource leaks avoided?

These issues are collectively referred to as **safety**.

We consider these in the context of exceptions: **exception safety**.

However, **most of the ideas we will discuss apply to any kind of error signaling technique**.

Exception Safety
Introduction [2/2]

There are a number of commonly used safety levels.

- These are stated in the form of **guarantees** that a function makes.

In this class, we will adopt the convention that a function throws when it cannot satisfy its postconditions.

- When a function exits without satisfying its postconditions, we will say it has **failed**.

Thus, a function we write must do one of two things:

- Succeed (satisfy its postconditions), or
- Fail, throw an exception, and satisfy its safety guarantee.

Exception Safety
The Three Standard Guarantees

Basic Guarantee

- Data remain in a usable state, and resources are never leaked, even in the presence of exceptions.
- Some people say “Weak guarantee.” This is wrong. Catch me when I say it.

Strong Guarantee

- If the operation throws an exception, then it makes no changes that are visible to the client code.

No-Throw Guarantee

- The operation never throws an exception.

Notes

- First set out by Dave Abrahams in the mid-1990s.
  - Thus, they are sometimes called the “Abrahams Guarantees”.
- Written as part of the effort to standardize the C++ Standard Library.
  - However, they are applicable to more general contexts, not just C++.
- Each guarantee includes the previous one.
- The Basic Guarantee is the minimum standard for all code.
- The Strong Guarantee is the one we generally prefer.
- The No-Throw Guarantee is required in some special situations.

Exception Safety
The Three Standard Guarantees — Basic Guarantee

Data remain in a usable state, and resources are never leaked, even in the presence of exceptions.

- When a member function throws, an object may end up in an **unknown** state, but it must be a **valid** state, with invariants maintained.

This is minimum standard that we expect well-written code to meet.

- What happens if this standard is not met, and an exception is thrown?

Exception Safety
The Three Standard Guarantees — Strong Guarantee

If the operation throws an exception, then it makes no changes that are visible to the client code.

- Changes can be made, but the client must not see them.
- In practice, we exempt things like logging from these requirements.
- Generally, any work that has been done, must be undone.
- Thus, this is also called **commit or roll-back semantics**.

We like this level of safety, and we write code that meets it whenever it is reasonable to do so.

- But sometimes it is not reasonable, often due to efficiency concerns.

Exception Safety
The Three Standard Guarantees — No-Throw Guarantee

The operation never throws an exception.

- This is also know as the “No-Fail Guarantee”.

This is the **highest** level of exception safety, but it is not necessarily the **best** level.

- Exceptions are not “bad”. They are a tool that can help us deal with problematic situations. If we make the No-Throw Guarantee, then we have prohibited ourselves from using this tool.
- The No-Throw Guarantee does not say “errors do not occur”; rather, it says that if an error condition occurs, then we are not allowed to signal the client; we must fix it ourselves.

Sometimes it is important to make the No-Throw Guarantee, often in situations in which we are “finishing something”.

- One such situation: destructors.
- Another situation (“commit functions”) will be covered shortly.

Exception Safety
Writing Exception-Safe Code — Ideas

To make sure code is exception-safe:

- Look at **every** place an exception might be thrown.
- For each, make sure that, if an exception is thrown, either
  - we terminate normally and meet our postconditions, or
  - we throw and meet our guarantees.

That can be a lot of work. However, **modularity** helps.

- Once we can certify a function as exception-safe, we can use it as such without re-examining it.

A bad design can force us to be unsafe.

- Thus, good design is part of of exception safety.
- In particular, an often helpful idea is that every module has exactly one well defined responsibility (the **Single Responsibility Principle**). Code that follows this principle is **cohesive**.
  - Suppose that a function has two things to do, and the second thing produces an error.
  - Suppose that the second thing, above, is when the function returns a value.
  - Thus, the rule: A non-const member function should not return an object by value.

Exception Safety
Writing Exception-Safe Code — Write It

TO DO

- Figure out and comment the exception-safety guarantees made by all functions implemented so far in class **`SmArray`**.
- Can/should any of these be improved?

Exception Safety
Writing Exception-Safe Code — Write It

TO DO

- Figure out and comment the exception-safety guarantees made by all functions implemented so far in class **`SmArray`**.

- Can/should any of these be improved?
  - *No. All the constructors offer the Strong Guarantee, which cannot be improved, since they do dynamic allocation, and so might fail. All other functions written so far offer the No-Throw Guarantee.*

Exception Safety
Commit Functions — The Need

Often it is tricky to offer the Strong Guarantee when modifying multiple parts of a large object.

- If we make several changes, and then we get an error, it can be difficult to undo the changes.
- In fact, it may be impossible, if the undo operation itself may result in an error.

Solution

- Create an entirely new object with the new value.
- If there is an error, destroy the new object. The old object has not changed, so there is nothing to roll back.
- If there is no error, **commit** to our changes using a non-throwing operation.

For many purposes, a good commit function is a non-throwing **swap** function.

Exception Safety
Commit Functions — Swap [1/3]

Swap member functions usually look like this:

```
void MyClass::swap(MyClass & other);
```

This should exchange the values of **`*this`** and **`other`**.

Swap functions can *usually* be written very easily.

- Just swap the data members.
  - If they have swap methods, use them. Otherwise, use std::swap.
- Ownership issues are easy to handle properly (right?).

In fact, it is usually easy to write a swap function that is:

- Non-throwing.
- *Very* fast.

Exception Safety
Commit Functions — Swap [2/3]

```
class MyClass {
private:
    int x;
    double y;
public:
    void swap(MyClass & other);  // Does not throw
```

We can implement **`MyClass::swap`** like this:

```
void MyClass::swap(MyClass & other)  // Does not throw
{
    int tempi = x;
    x = other.x;
    other.x = tempi;

    double tempd = y;
    y = other.y;
    other.y = tempd;
}
```

Exception Safety
Commit Functions — Swap [3/3]

Alternatively, we can use **`std::swap`**, in **`<algorithm>`**:

```
void MyClass::swap(MyClass & other)
{
    std::swap(x, other.x);
    std::swap(y, other.y);
}
```

If we need to swap members that are **objects**, we might want to avoid **`std::swap`**.

- Algorithm **`std::swap`** uses the copy ctor and copy assignment. These might throw.
- If the objects have their own non-throwing swap member function, we can use that:

```
void MyClass::swap(MyClass & other)
{
    …
    z.swap(other.z);  // z is a member
                      //  of class type
}
```

Note: if **`Foo`** is a class, then **`Foo`** is not a built-in type; it is an object. However, **`(Foo *)`** is a pointer, which **is** a built-in type.

- Many C++ Standard Library classes have such a member function.

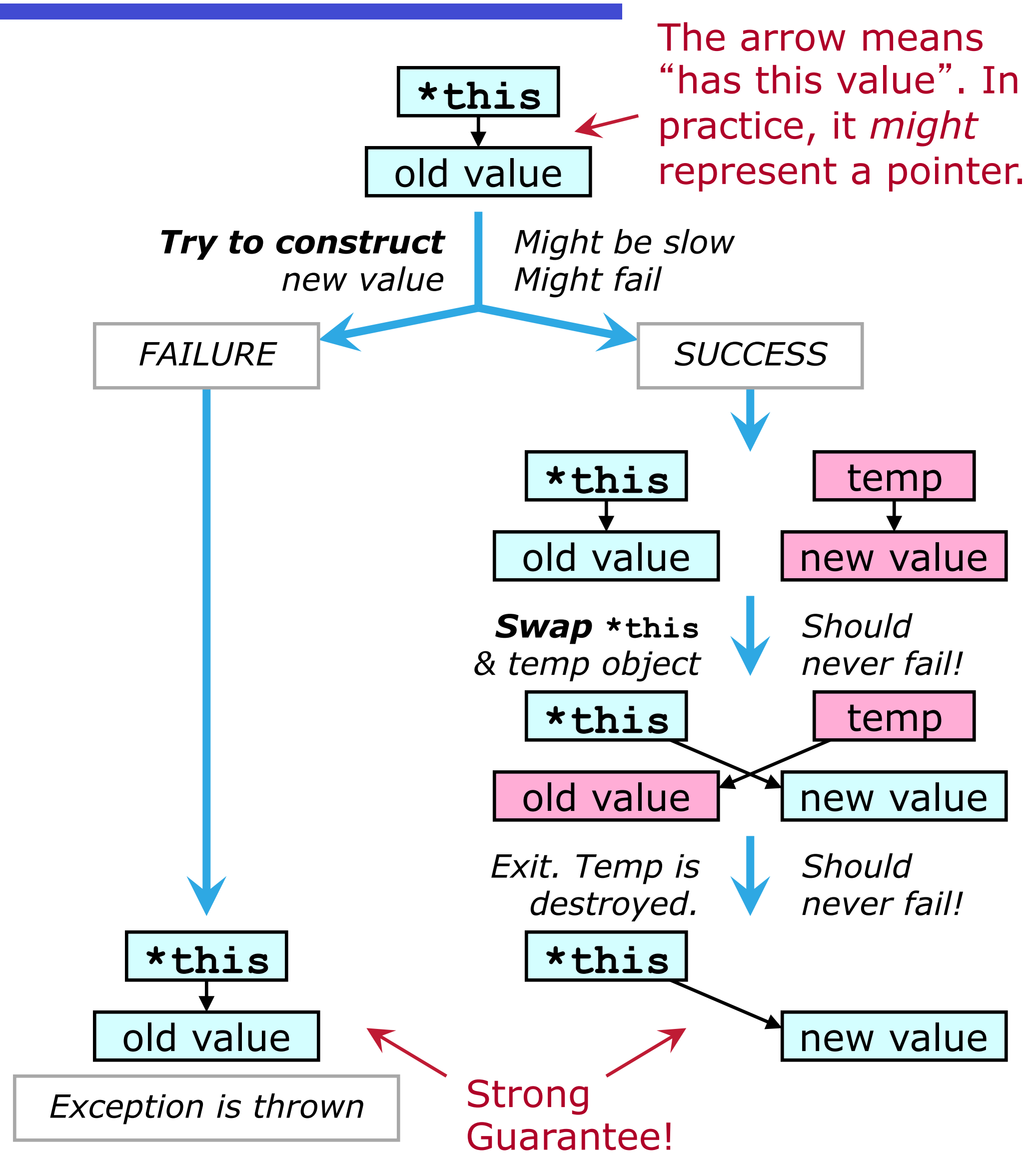
Exception Safety
Commit Functions — Usage [1/3]

We can use a non-throwing swap function to get the Strong Guarantee.

To give our object a new value:

- First, **try to construct** a temporary object holding this new value.
- If this fails, exit. No change.
  - Exiting is automatic, if the failing operation throws.
- If the construction succeeds, then **swap** our object with the temporary object holding the new value.
- Exit. The destructor of the temporary object cleans up the old value of our object.
  - Destruction is automatic.
  - And it should never fail.

Note: boldface = code we write.



Exception Safety
Commit Functions — Usage [2/3]

Thus, we can set an object to a new value, while offering the Strong Guarantee, as long as we have a way to construct the new value that offers the Strong Guarantee, along with a dctor and a swap function that offer the No-Throw Guarantee.

Procedure

- **Try to construct** a temporary object holding the new value.
- **Swap** with this temporary object.

Example: "clear" by swapping with a default-constructed temporary object.

```
void MyClass::clear()  // Strong Guarantee
{
    MyClass temp;
    swap(temp);
}
```

If there is a problem creating **`temp`**, then an exception is thrown, and "nothing" happens (Strong Guarantee).

Otherwise, the values are swapped. **`*this`** gets its new value. The old value of **`*this`** is cleaned up by **`temp`**'s destructor.

Exception Safety
Commit Functions — Usage [3/3]

This idea lets us write a copy assignment operator that makes the Strong Guarantee. We need:

- A copy ctor that offers the Strong Guarantee (this is usually not too difficult).
- A swap member function that makes the No-Throw Guarantee (usually easy).
- A dctor that makes the No-Throw Guarantee (of course).

Code:

```
MyClass & MyClass::operator=(const MyClass & rhs)  // Strong Guarantee
{
    MyClass temp(rhs);
    swap(temp);
    return *this;
}
```

Do the actual assignment:
1. **Try to construct** a temporary copy of `rhs`.
2. **Swap** with the temporary copy.

The old value is cleaned up by the destructor of `temp` (which does not throw).

Always end an assignment operator this way.

Admittedly this is a bit mind-twisting. However, assuming the requirements are met, it is easy to write, and it always works.

operator=
Alternate version

Even better, we can pass by value (!):

```
MyClass & MyClass::operator=(MyClass rhs)  // Strong Guarantee
{
   swap(rhs);
   return *this;
}
```

This will occasionally be more efficient because of copy elision. (Essentially, the compiler may optimize away some copies if they are unnecessary.)

This is the canonical version of operator=. Short, efficient, exception safe (Strong Guarantee), and correct!

Allocation & Efficiency
Write It?

TO DO

- Consider how to write **`SmArray::resize`**.

Ideas

Allocation & Efficiency
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Ideas

- *If we are resizing smaller than (or equal to) the current size, just change the* **`size_`** *member to the new value.*
- *If we are resizing larger than the current size, then reallocate a large-enough chunk of memory for the array, copy the data there, and increase* **`size_`** *to the new value ("reallocate-and-copy").*

Allocation & Efficiency
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- Consider how to write **`SmArray::resize`**.

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- *If we are resizing smaller than (or equal to) the current size, just change the* **`size_`** *member to the new value.*
- *If we are resizing larger than the current size, then reallocate a large-enough chunk of memory for the array, copy the data there, and increase* **`size_`** *to the new value ("reallocate-and-copy").*
- *But the above method has a problem. For example, suppose we are using a Sequence object to implement a Stack. Pushing a new item on the end always requires a reallocate-and-copy, which will be very inefficient.*

Allocation & Efficiency
Amortized Constant Time [1/2]

For a smart array, insert-at-end is linear time.

- It is constant time if space is available (already allocated).
- It is linear time in general, due to reallocate-and-copy.

We can speed this up much of the time if we reallocate very rarely.

- Idea: When we reallocate, get more memory than we need. Say twice as much. Then do not reallocate again until we fill this up.

Now, using this idea, suppose we do **many** insert-at-end operations. How much time is required by k insert-at-end operations?

- Answer: $O(k)$.
  - If, when we reallocate-and-copy, we increase the reserved memory by some constant factor.
- Even though a single operation is not $O(1)$.

If k consecutive operations require $O(k)$ time, we say the operation is **amortized constant time**.

- Amortized constant time means constant time on average over a large number of consecutive operations.
- It does **not** mean constant time on average over all possible inputs.
- This is our last efficiency-related terminology.

Allocation & Efficiency
Amortized Constant Time [2/2]

Recall our time-efficiency categories.

Using Big-*O*	**In Words**
$O(1)$	Constant time
$O(\log n)$	Logarithmic time
$O(n)$	Linear time
$O(n \log n)$	Log-linear time
$O(n^2)$	Quadratic time
$O(b^n)$, for some $b > 1$	Exponential time

Q: Where does “amortized constant time” fit in the above list?

Allocation & Efficiency
Amortized Constant Time [2/2]

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Q: Where does "amortized constant time" fit in the above list?

A: It doesn't!

- The above are talking about the time taken by a single operation. "Amortized …" is not.
- Insert-at-end for a well written smart array is amortized constant time. It is also still linear time.