Allocation & Efficiency
Generic Containers
Notes on Assignment 5

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
  - ✓ Exception safety
  - Allocation & efficiency
  - Generic containers
- Linked Lists
  - Node-based structures
  - More on Linked Lists
- Sequences in the C++ STL
- Stacks
- Queues

Review
Exception Safety — 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**.

Review
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.
- Don’t say “Weak guarantee”

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

- 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.

Review
Exception Safety — Writing Exception-Safe Code [1/2]

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.

A bad design can force us to be unsafe.

- Thus, good design is part of of exception safety.
- An often helpful idea is that every module has exactly one well defined responsibility (the **Single Responsibility Principle**).
- In particular: A non-const member function should not return an object by value.

Review
Exception Safety — Writing Exception-Safe Code [2/2]

TO DO

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

*Done. See the latest versions of **`smarray.h`**, **`smarray.cpp`**, on the web page.*

- 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.*

Review
Exception Safety — Commit Functions [1/5]

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

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.

A good commit function is a non-throwing **swap** function.

Exception Safety — Commit Functions [2/5]

Swap member functions usually look like this:

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

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

If the data members are all built-in types (including pointers!), then we can usually just call **`std::swap`** on them.

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

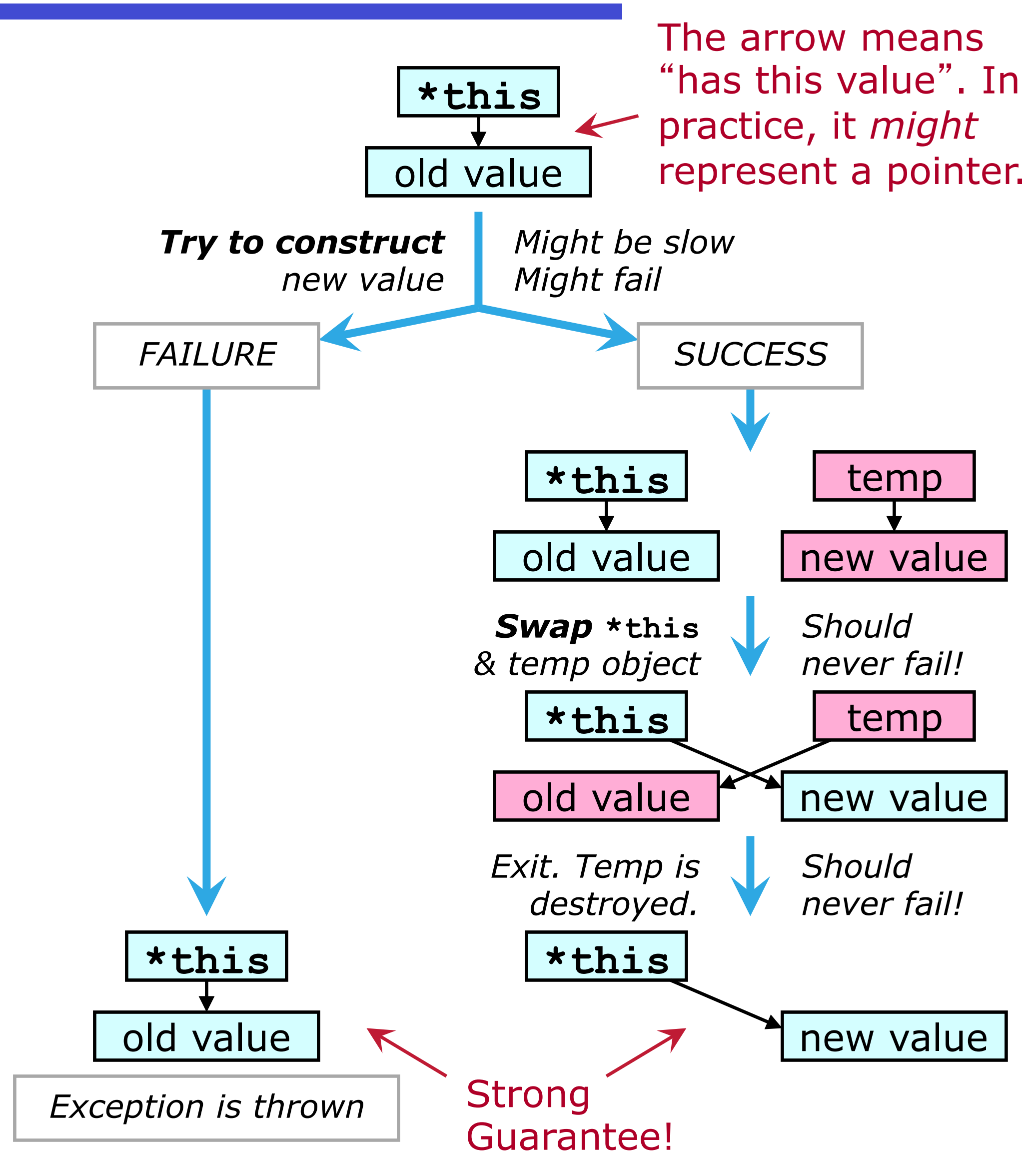
Review
Exception Safety — Commit Functions [3/5]

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.



Review
Exception Safety — Commit Functions [4/5]

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);
}
```

Exception Safety — Commit Functions [5/5]

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

Do the actual assignment:
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.

Allocation & Efficiency
Write It?

TO DO

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

Ideas

Allocation & Efficiency
Write It?

TO DO

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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
Write It?

TO DO

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

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").*
- *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]

Recall our time-efficiency categories.

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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.

Allocation & Efficiency
Write It Again

How can we redesign class **`SmArray`** internally, so that we can write an amortized constant-time insert-at-end?

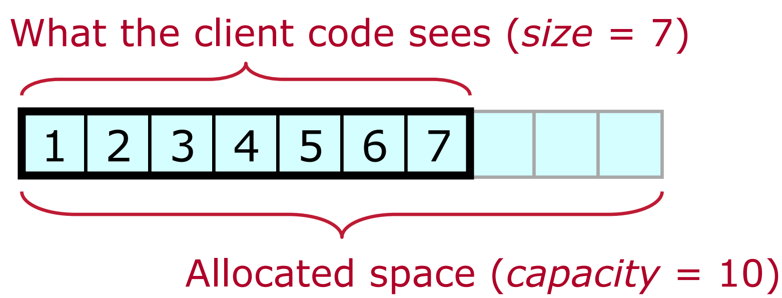
TO DO

- Finish the details of this new design. How does it work?
- Rewrite (most of) the existing member functions and invariants in **`SmArray`** to use the new design.

Allocation & Efficiency
Write It Again

How can we redesign class **`SmArray`** internally, so that we can write an amortized constant-time insert-at-end?

- A third data member can hold the amount of memory allocated. This is called the **capacity**.



TO DO

- Finish the details of this new design. How does it work?
- Rewrite (most of) the existing member functions and invariants in **`SmArray`** to use the new design.

Generic Containers
Introduction

A **generic container** is a container that can hold a client-specified data type.

Examples

- Arrays
- STL containers, including **`std::vector`**.

In C++, we usually implement a generic container using a **class template**.

Generic Containers
Class Templates — Recall …

The C++ Standard does **not** require compilers to be able to do separate compilation of templates.

- Thus, you should define all member functions of a class template and all associated global function templates in your header file.
- With templates, you probably will not have a source (`.cpp`) file.

When people write code that uses your template, they need to know what types it is usable with.

- In this class, when writing a template, include comments indicating **requirements on the types** it takes as template parameters.
  - Typically: must have certain member functions and/or operators.
- It is assumed that member functions must all offer at least the Basic Guarantee. You do not need to mention this.
  - If you need some member function to offer a stronger guarantee (e.g., swap must not throw), then you *do* need to mention this.

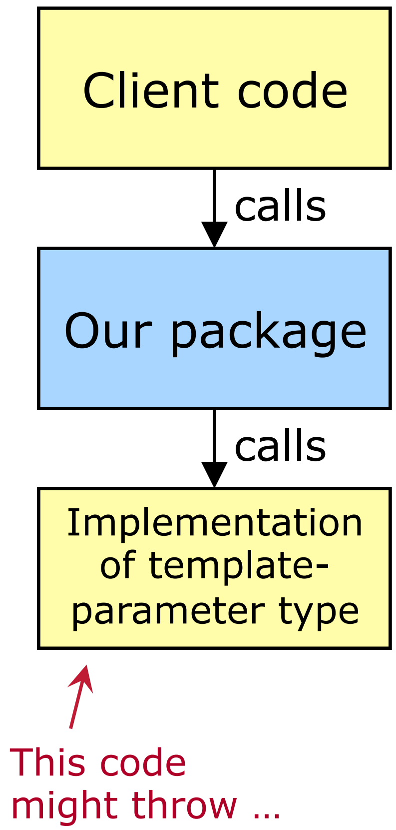
Generic Containers
Exception Safety [1/3]

When we write a template, we deal with the type given to us using its own member functions. These client-provided functions **may throw**.

- Unless we require that they do not (in our “requirements on types”).

Exception safety gets trickier.

- The same procedures apply, but now we have many more places that might generate exceptions.



Generic Containers
Exception Safety [2/3]

Since **every** member function of a template parameter type, that is not specifically prohibited from throwing, may throw, we need to check **every** use of such a member function, to make sure that we deal with them correctly.

Do not forget:

- Silently called functions (default ctor & copy ctor).
- Operators (in particular: assignment).
- STL algorithms. Those that modify a data set (**`std::copy`**, **`std::swap`**, **`std::rotate`**, etc.) generally do so using the assignment operator. If the assignment operator can throw, then these STL algorithms can throw.

Do *not* worry about these when they are called on built-in types.

```
void size(std::size_t theSize) const;
```

Passed by value. Copy ctor call? But **`std::size_t`** is a built-in type; this will not throw.

Generic Containers
Exception Safety [3/3]

One tricky situation is copying the data in a dynamic array. Copy assignment of a class type can throw, often requiring deallocation.

```
arr = new MyType[size];
std::copy(a, a+size, arr);  // Memory leak, if MyType
                            //  copy assignment throws
```

We will come back to this example shortly.

Generic Containers
Exception Neutrality

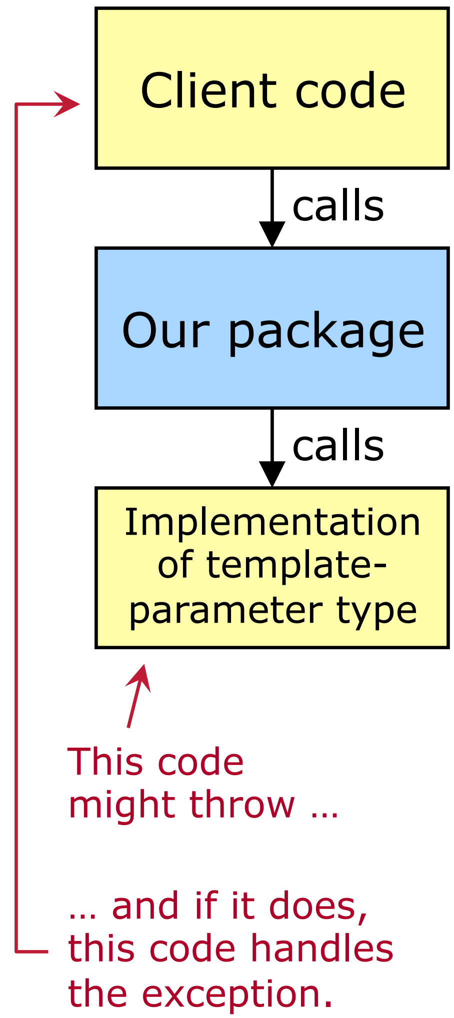
When we call client-provided functions, the client code generally handles any exceptions thrown.

Exception-neutral code allows exceptions thrown by client-provided code to propagate unchanged.

When such code calls a client-provided function that may throw, it must do one of two things:

- Call the function outside a try block, so that any exceptions terminate our code immediately.
- Or, call the function inside a try block, catch all exceptions, do necessary clean-up, and re-throw:

```
try {
    x.func();   // May throw
}
catch (...) {   // Exception not handled here
    [Do our own clean-up here]
    throw;      // Re-throw same exception
}
```



Generic Containers
Exception Safety & Neutrality Together

Putting it all together, we can use catch-all, clean-up, re-throw to get both exception safety and exception neutrality.

```
arr = new MyType[size];
try
{
    std::copy(a, a+size, arr);
}
catch (...)
{
    delete [] arr;
    throw;
}
```

Called outside any `try` block. If this fails, we exit immediately, throwing an exception.

Called inside a `try` block. If this fails, we need to deallocate the array before exiting.

This helps us meet the Basic Guarantee (also the Strong Guarantee if this function does nothing else).

This makes our code exception-neutral.

Notes on Assignment 5
Overview of Ideas

This ends the material that Assignment 5 covers.

Next, we will look at node-based structures. You do *not* need to worry about these on Assignment 5.

You *do* need to be concerned with:

- Invariants, Templates
  - Document everything properly.
- Exception Safety
  - Are your member functions offering the proper guarantee?
    - All functions must offer *at least* the Basic Guarantee.
    - Constructors generally need to offer a high level of exception safety.
    - Destructors and commit functions (**`swap`**) offer an even higher level.
    - Functions that do large-scale modifications (**`resize`**, **`insert`**, **`remove`**) will probably not offer a high level, for the sake of efficiency.
  - Are your member functions *satisfying* their guarantees?
    - Have you checked *every* place that might throw.
    - For a template, this includes things like **`std::copy`**, **`std::rotate`**.
- Allocation & Efficiency
  - Are functions that might need to do a reallocate-and-copy (**`resize`**, **`insert`**) written to handle this efficiently?

Notes on Assignment 5
Individual Functions [1/2]

Thoughts on making some Assignment 5 member functions exception-safe and exception-neutral.

- Function **`swap`**
  - Use **`std::swap`** on all data members. *Example is on earlier slide.*
- Copy ctor
  - Allocate *outside* **`try`** block. Copy *inside* a **`try`** block. Catch-all, clean-up, re-throw. *Same idea as the code two slides back.*
- Copy assignment
  - Write as discussed earlier, using the copy ctor and **`swap`** (the member, *not* **`std::swap`**!). *Example is on an earlier slide.*
- Function **`resize`**
  - If resizing to ≤ capacity: just set **`size`**.
  - If resizing to > capacity: create temp with the right size & capacity, **`std::copy`**, delete old & set members to new values.
    - The temp *could* be a separate object, and then you could use the swap trick. But if you do this, then make sure the temp's capacity and size are set correctly!
    - Alternatively, do not create a separate object. Have 3 variables that hold new values for the data members: **`newSize`**, **`newCapacity`**, **`newData`**. If this works, then delete the old data, and set all 3 data members to the new values.

Notes on Assignment 5
Individual Functions [2/2]

Thoughts (cont'd)

- Function **`remove`**
  - You need to resize the array. Function **`resize`** does this. Use it!
  - Suggestion: Do a **`std::rotate`**, and then call **`resize`**.
- Function **`insert`**
  - Again, call **`resize`** to do the resizing of the array. Do not duplicate code!
  - Suggestion: Call **`resize`**, put the new item in, and then **`std::rotate`**.
  - At the end, you need to return an iterator to the inserted item. This *would* be the same as the parameter, except that **`resize`** might have done a reallocate-and-copy. So: *Before* calling resize, save the *index* of the spot to insert, and then afterwards recreate the iterator from this index, and return it.