Where Are We?
Data Abstraction
Introduction to Sequences
Array Interface

CS 311 Data Structures and Algorithms

Lecture Slides

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Unit Overview
Algorithmic Efficiency & Sorting

Major Topics

- ✓ Introduction to Analysis of Algorithms
- ✓ Introduction to Sorting
- ✓ Comparison Sorts I
- ✓ More on Big-*O*
- ✓ The Limits of Sorting
- ✓ Divide-and-Conquer
- ✓ Comparison Sorts II
- ✓ Comparison Sorts III
- ✓ Radix Sort
- ✓ Sorting in the C++ STL

DONE

Where Are We?
From the First Day of Class: Course Overview — Goals

After taking this class, you should:

- Have experience writing and documenting high-quality code.
- Understand how to write robust code with proper error handling.
- Be able to perform basic analyses of algorithmic efficiency, including use of "big-O" notation.
- Be familiar with various standard algorithms, including those for searching and sorting.
- Understand what data abstraction is, and how it relates to software design.
- Be familiar with standard data structures, including their implementations and relevant trade-offs.

The rest of the semester

We will also discuss this in more detail

Where Are We?
From the First Day of Class: Course Overview — Topics

The following topics will be covered, *roughly* in order:

- Advanced C++
- Software Engineering Concepts
- Recursion
- Searching
- Algorithmic Efficiency
- Sorting
- **Data Abstraction**
- **Basic Abstract Data Types & Data Structures:**
  - **Smart Arrays & Strings**
  - **Linked Lists**
  - **Stacks & Queues**
  - **Trees (various types)**
  - **Priority Queues**
  - **Tables**
- Other, as time permits: graph algorithms, external methods.

DONE

Goal: Practical generic containers

A **container** is a data structure holding multiple items, usually all the same type.

A **generic** container is one that can hold objects of client-specified type.

Where Are We?
The Big Problem

For most of the rest of the semester, we will be addressing the following problem:

- We have a collection of data items, all of the same type, that we wish to store.
- We need to be able to access items [retrieve/find, traverse], add new items [insert] and eliminate items [delete].
- All this needs to be efficient in both time and space.

Solutions to this problem are called "**containers**".

- There are many good ones.
- Which one we use depends on many factors, including what priority we place on the various requirements above.

We are particularly interested in **generic containers**: containers in which client code can specify the type of data to be stored.

Unit Overview
Handling Data & Sequences

We now begin a unit on handling data and implementing Sequence data.

Major Topics

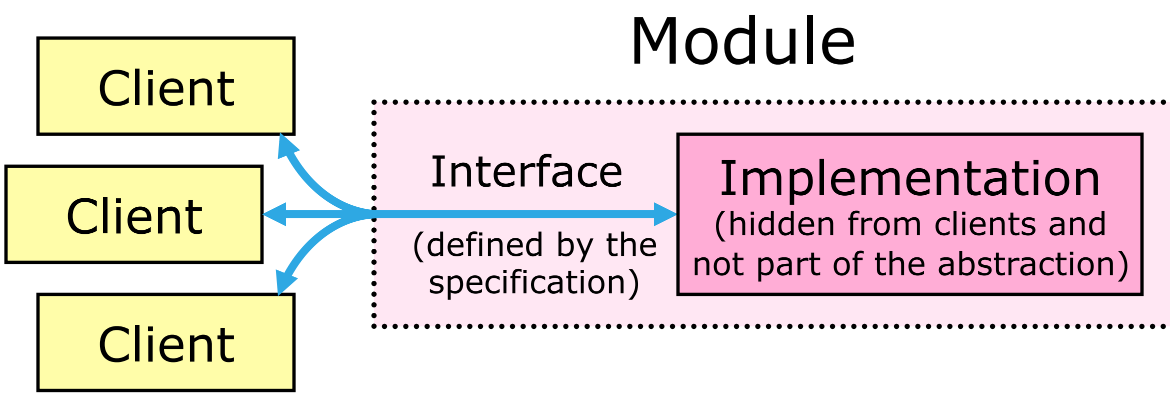
- Data abstraction
- Introduction to Sequences
- Smart arrays
  - Array interface
  - Basic array implementation
  - Exception safety
  - Allocation & efficiency
  - Generic containers
- Linked Lists
  - Node-based structures
  - More on Linked Lists
- Sequences in the C++ STL
- Stacks
- Queues

After this, we will look at trees.

Data Abstraction
Abstraction Again

Abstraction: Separate the purpose of a module from its implementation.

Recall: Function, class, or other unit of code. Generally smaller than a *package*.



We have been doing **functional abstraction**.

Now we look at **data abstraction**.

Data Abstraction
What is It?

In **data abstraction**, we separate the various aspects of dealing with data, from the implementation of the data:

- The conceptual form of the data.
- The **operations** available on the data.
- The method used to access the data.

Important concepts

- **Abstract data type** (ADT).
- **Interface**.

Data Abstraction
ADTs, Data Structures, Classes

Abstract data type (ADT):

- a **collection of data**, along with
- a **set of operations** on that data.

ADTs are independent of implementation, and even of programming language.

Data structure: a construct within a programming language that stores a collection of data.

C++ and some other programming languages include **classes**, which facilitate object-oriented programming.

- An important use of classes is the implementation of data structures, each of which is often conceptually based on some ADT.
- However, one can implement data structures without using classes.

Data Abstraction
ADT Example

Suppose we want to specify an ADT that holds exactly three pieces of information.

- We might call this ADT “Triple”.
- These are not assumed to be numeric or have any arithmetic properties at all. Rather, they are simply three pieces of data. Think of this as a list that always has size three.

What operations might such an ADT have?

We *might* store the data for a Triple in an obvious data structure: three variables.

And we *might* implement all this using a class with three data members, and member functions implementing the various Triple operations.

Data Abstraction
ADT Example

Suppose we want to specify an ADT that holds exactly three pieces of information.

- We might call this ADT “Triple”.
- These are not assumed to be numeric or have any arithmetic properties at all. Rather, they are simply three pieces of data. Think of this as a list that always has size three.

What operations might such an ADT have?

- *Get/set*
- *Compare (if comparable)*
- *Copy*
- *Create/Destroy*
- *Reorder*
- *Sort (if comparable)*
- *Output (if each piece can be output)*

We *might* store the data for a Triple in an obvious data structure: three variables.

And we *might* implement all this using a class with three data members, and member functions implementing the various Triple operations.

Data Abstraction
Good Interfaces

When we implement a data structure, the idea of abstraction requires that we have a well defined **interface**.

Designing a good interface can be difficult. Here are some characteristics of a good interface.

An interface should be **complete**.

- All required operations should be *possible*.

We often strive for interfaces that are **minimal**.

- Avoid unnecessary functionality.

An interface should be **convenient**.

- Avoid making the interface a pain to use.

These two often pull in opposite directions.

We want to **facilitate efficiency**.

- Allow the data to be dealt with efficiently.

We often want our interface to be **generic**.

- Avoid restricting possible implementations and internal data types.

These two *can* pull in opposite directions.

Introduction to Sequences
What is a Sequence?

A **Sequence** is a collection of items that are in some order.

- We will restrict our attention to **finite** Sequences in which all items have the **same type**.
- It may help to think of an array here. However, there are other ways to store Sequences.

5	3	4	2	2	8	7	4	7	5	1	2

Questions

- What operations do we perform on Sequences?
- How can we implement a Sequence?
- How do we decide which implementation best fits any given circumstance?

Introduction to Sequences
ADT Sequence — Definition

ADT **Sequence**

- Data
  - An ordered sequence of values, all same type, indexed by 0, …, size-1.
- Operations
  - CreateEmpty
    - Creates empty Sequence (with size 0, i.e., no data).
  - CreateSized
    - Given a size, create a Sequence with that size.
  - Destroy
    - Destroys a Sequence.
  - Copy
    - Make a copy of a given Sequence.
  - LookUpByIndex
    - Given a valid index, returns Sequence item in modifiable form.
  - Size
    - Returns size of Sequence.
  - Empty
    - Returns whether the Sequence is empty, that is, has size zero.
  - Sort
    - Sort a Sequence, using some given comparison function.
  - Resize
    - Changes size of Sequence. Data for indices 0, …, min(old size, new size)–1 remains identical.
  - InsertByIter
    - Given an iterator (or pointer?) and an item, insert the item at the specified position.
  - RemoveByIter
    - Given an iterator, remove the item at that position.
  - InsertBeg
    - Given an item, insert it at the beginning.
  - RemoveBeg
    - Remove the first item.
  - InsertEnd
    - Like insertBeg, but at the end.
  - RemoveEnd
    - Like removeBeg, but at the end.
  - Splice
    - Move a contiguous subsequence from one Sequence to another.
  - Traverse
    - Performs some operation on every item in the Sequence, in order.
  - Swap
    - Exchange the values of two given Sequences.

ADT SortedSequence — Introduction

It is common to keep Sequence data sorted.

However, this changes the operations available.

- Operations that mess up the ordering are now disallowed.
- New operations, that make use of the ordering, become possible.

Therefore, we define another ADT, SortedSequence.

- Essentially, a SortedSequence is a Sequence in which the items are always kept sorted according to some comparison function.

Introduction to Sequences
ADT SortedSequence — Draft

ADT **SortedSequence** (draft)

- Data
  - An ordered list of values, all same type, indexed by 0, …, size-1, **in ascending order**.
- Operations
  - CreateEmpty
    - Creates empty SortedSequence (with size 0, i.e., no data).
  - CreateSized
    - Given a size, create a SortedSequence with that size.
  - Destroy
    - Destroys a SortedSequence.
  - Copy
    - Make a copy of a given SortedSequence.
  - LookUpByIndex
    - Given a valid index, returns SortedSequence item in modifiable form.
  - Size
    - Returns size of SortedSequence.
  - Empty
    - Returns whether the SortedSequence is empty, that is, has size zero.
  - Sort
    - Sort a SortedSequence, using some given comparison function.

Iffy …

Problems

Pointless or problematic

- Resize
  - Changes size of SortedSequence. Data for indices 0, …, min(old size, new size)−1 remains identical.
- InsertByIter
  - Given an iterator (or pointer?) and an item, insert the item at the specified position.
- RemoveByIter
  - Given an iterator, remove the item at that position.
- InsertBeg
  - Given an item, insert it at the beginning.
- RemoveBeg
  - Remove the first item.
- InsertEnd
  - Like insertBeg, but at the end.
- RemoveEnd
  - Like removeBeg, but at the end.
- Splice
  - Move a contiguous subsequence from one Sequence to another.
- Traverse
  - Performs some operation on every item in the SortedSequence, in order.
- Swap
  - Exchange the values of two given SortedSequences.

But if we get rid of the “problems”, how can we add new items?

Introduction to Sequences
ADT SortedSequence — Improved

ADT **SortedSequence** (final)

- Data
  - An ordered list of values, all same type, indexed by 0, …, size-1, in ascending order, by some given comparison function.
- Operations
  - CreateEmpty
    - Creates empty SortedSequence (with size 0, that is, no data).
  - Destroy
    - Destroys a SortedSequence.
  - Copy
    - Make a copy of a given SortedSequence.
  - LookUpByIndex
    - Given a valid index, returns SortedSequence item in **non-modifiable** form.
  - Size
    - Returns size of SortedSequence.
  - Empty
    - Returns whether the SortedSequence is empty, that is, has size zero.
  - **InsertByValue**
    - Given an item, insert it.
  - **RemoveByValue**
    - Given a value, remove it.
  - RemoveByIter
    - Given an iterator, remove item at that position.
  - Traverse
    - Performs some operation on every item in the SortedSequence, in order.
  - Swap
    - Exchange the values of two given SortedSequences.
  - **Find**
    - Given value, find item(s) with equivalent value, if any exist.

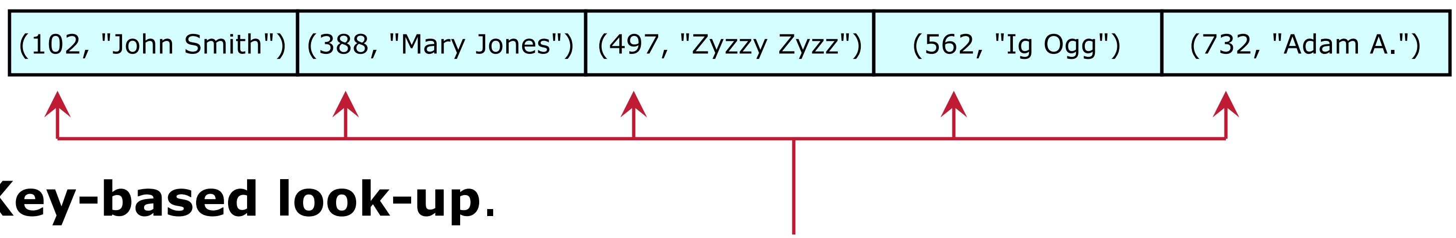
Introduction to Sequences
ADT SortedSequence — What is it For?

In practice, the ordering of a SortedSequence is often of little importance. Rather, are interested in items being **easy to find**.

What can we do with this?

- First, we can store **Set data**. In a Set, we only care *whether* an item is in the container, not *where* it is.

Now suppose we have a SortedSequence whose items are pairs, and a comparison function that compares only the *first parts* of each pair. What is this good for?



- **Key-based look-up**.
  - The first part of each pair is the **key**.
- “Arrays” (kind of), where the thing between the brackets does not have to be a nonnegative integer.
- That is, **Tables** (a.k.a. “dictionaries”, “associative arrays”, “maps”).

Introduction to Sequences
ADT SortedSequence — P.O. vs. V.O.

We conclude that, despite the similarities of Sequence and SortedSequence, there is a fundamental difference.

- Sequence handles an item according to its **position** (index) in the container.
- SortedSequence handles an item primarily according to its **value**.

Two Types of ADTs

- Sequence is a **position-oriented** ADT.
- SortedSequence is a **value-oriented** ADT.

SortedSequence is a bit inadequate as a value-oriented ADT.

- We often do not care about SortedSequence being a Sequence.
- Rather, we want to use it to store Set or Table data.
- Maybe we should break it away from its Sequence origins?

Important Questions (to be examined later)

- What do we really want from a value-oriented ADT?
- How does one implement these in efficient ways?

Array Interface
Start

We wish to implement a Sequence using a “smart” array.

- It should know its size, be able to copy itself, etc.
  - Just like in Assignment 2.
- It should also be able to *change* its size.
  - Recall that the ADT has resize and various insert/remove operations.

Basic Ideas

- Use a C++ class. An object of the class implements a single Sequence.
- Many (most? all?) of the ADT Sequence operations should be implemented using class member functions.
- Use iterators, operators, ctors, and the dctor in the usual ways.
- *Every* function in the interface should exist in order to implement, or somehow make possible, an ADT operation.

Array Interface
By ADT Operation

Use iterators to handle positions, traversing.

ADT Operations

- CreateEmpty
- CreateSized
- Destroy
- Copy
- LookUpByIndex
- Size
- Empty
- Sort
- Resize
- InsertByIter, InsertBeg, InsertEnd
- RemoveByIter, RemoveBeg, RemoveEnd.
- Splice
- Traverse
- Swap

Array Interface
By ADT Operation

Use iterators to handle positions, traversing.

ADT Operations

- CreateEmpty
  - Default ctor.
- CreateSized
  - Ctor given size.
- Destroy
  - Dctor.
- Copy
  - Copy ctor & copy assignment.
- LookUpByIndex
  - Bracket operator.
- Size
  - Member function "**`size`**".
- Empty
  - Member function "**`empty`**".
- Sort
  - Handle externally, using iterators. Use iterator-returning member functions "**`begin`**" and "**`end`**".
- Resize
  - Member function "**`resize`**".
- InsertByIter, InsertBeg, InsertEnd
  - Member function "**`insert`**" does InsertByIter.
  - Use in conjunction with iterator-returning functions to do InsertBeg, InsertEnd.
- RemoveByIter, RemoveBeg, RemoveEnd.
  - As above, using "**`remove`**".
- Splice
  - Call **`resize`**, then copy using **`op[]`**.
- Traverse
  - Use iterator-returning member functions "**`begin`**" and "**`end`**".
- Swap
  - Member function "**`swap`**".

Array Interface Summary

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`**

Array Interface Details

For most of the member functions in our class, it is pretty obvious what the function prototype should look like.

However, three of them are a little tricky:

- **`insert`**
  - Takes an iterator and an item.
  - Inserts the item just *before* the position referenced by the iterator.
  - Return value is an iterator to the inserted item.
- **`remove`**
  - Takes an iterator.
  - Removes the item referenced by the iterator.
  - Return value is an iterator to the item following the one removed.
- **`swap`**
  - Takes another Sequence, by reference.
  - Exchanges the values of this Sequence and the given one.
  - No return value.