More on Linked Lists continued
Sequences in the C++ STL

CS 311 Data Structures and Algorithms

Lecture Slides

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Review

Where Are We? — The Big Challenge

Our problem for most of the rest of the semester:

- Store: A collection of data items, all of the same type.
- Operations:
  - Access items [single item: retrieve/find, all items: traverse].
  - Add new item [insert].
  - Eliminate existing item [delete].
- Time & space efficiency are desirable.

A solution to this problem is a **container**.

In a **generic container**, client code can specify the value type.

Unit Overview
Data Handling & Sequences

Major Topics

- ✓ Data abstraction
- ✓ Introduction to Sequences
- ✓ Interface for a smart array
- ✓ Basic array implementation
- ✓ Exception safety
- ✓ Allocation & efficiency
- ✓ Generic containers

Smart Arrays

- ✓ Node-based structures
- (part) More on Linked Lists

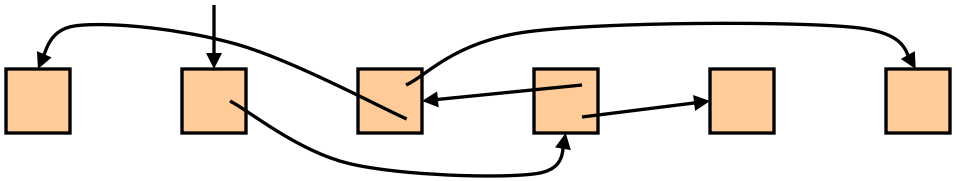
Linked Lists

- Sequences in the C++ STL
- Stacks
- Queues

Review
Node-Based Structures — Introduction

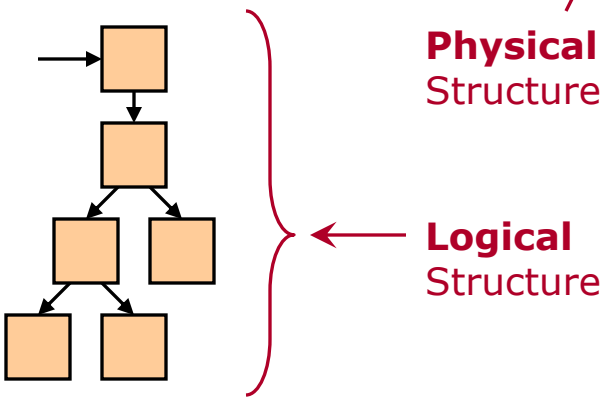
Many data structures are built out of *nodes*.

- A **node** is usually a small block of memory that is referenced via a pointer, and which may reference other nodes via pointers.



- To find a node, follow a chain of pointers. Look-up can be slow.
- Operations that require rearrangement *might* be very fast.

Our pictures are usually prettier than the actual arrangement of nodes in memory.



Node-Based Structures — Smart Pointers [1/4]

The C++ Standard Library includes RAII class templates called **smart pointers**, which automatically handle ownership of dynamic objects.

`std::unique_ptr<T>` (`<memory>`)

- One-owner-at-a-time ownership of a dynamic object of type `T`.
- The destructor of an owning `unique_ptr` destroys the object pointed to.
- Movable but not copyable. Moving transfers ownership.

`std::shared_ptr<T>` (`<memory>`)

- Allows shared ownership of a dynamic object of type `T`.
- Uses a **reference count**. Destroys object when the count hits `0`.
  - "The last one to leave turns out the lights."
- Copyable. Copying grants shared ownership.

Node-Based Structures — Smart Pointers [2/4]

Create using `make_unique`/`make_shared`. Then we do neither the `new` nor the `delete` directly.

```
auto unp = make_unique<Foo>(5, "xy", 3.2);
```

Dereference just like a pointer.

```
Foo x = *unp;
unp->bar();
```

To obtain a regular pointer to the referenced object, call member function `get`.

```
Foo * p = unp.get()
```

Node-Based Structures — Smart Pointers [3/4]

An **empty** smart pointer is one that does not point to anything. Check for this by treating a smart pointer like a `bool`.

```
if (unp)  // Nonempty?
    unp->bar();
```

Relinquish ownership *early* using member function `reset`.

```
unp.reset();
```

With a `unique_ptr`, transfer ownership by passing/returning a `unique_ptr` by value (`std::move` may be required). Otherwise, pass a `unique_ptr` by reference or reference-to-const.

We can pass a `shared_ptr` by value arbitrarily, sharing ownership.

Node-Based Structures — Smart Pointers [4/4]

Programmers have found that shared ownership is rarely needed.

It is true that, whenever you might use `unique_ptr`, it will also work to use `shared_ptr`. On the other hand, using `unique_ptr` helps the compiler find bugs for you (and it is more efficient!).

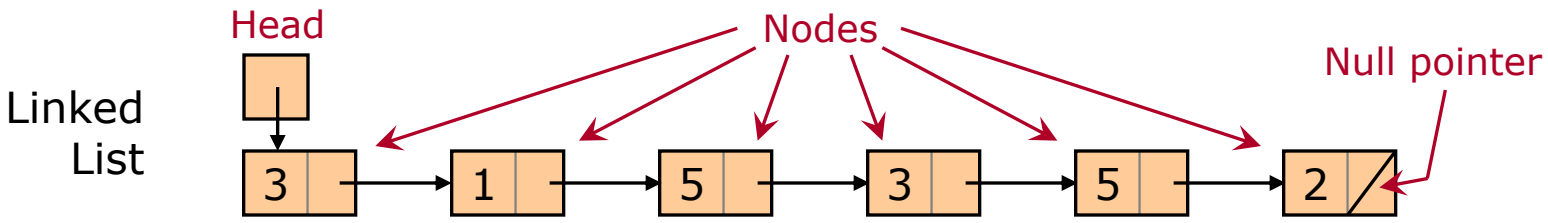
Suggestions

- When you want a smart pointer, start by using `unique_ptr` and `make_unique`.
- Pass a smart pointer by reference or reference-to-const when you do not want to transfer/share ownership.
- If code does not compile because it tries to copy a `unique_ptr`:
  - If you want to transfer ownership, then you might simply need to wrap the `unique_ptr` in `std::move`.
  - If you do not want to transfer ownership, then you can call `get` to obtain a non-owning regular pointer and use that instead.
  - If it turns out that you really need shared ownership, then do a global search/replace: `unique` → `shared`

More on Linked Lists [1/5]

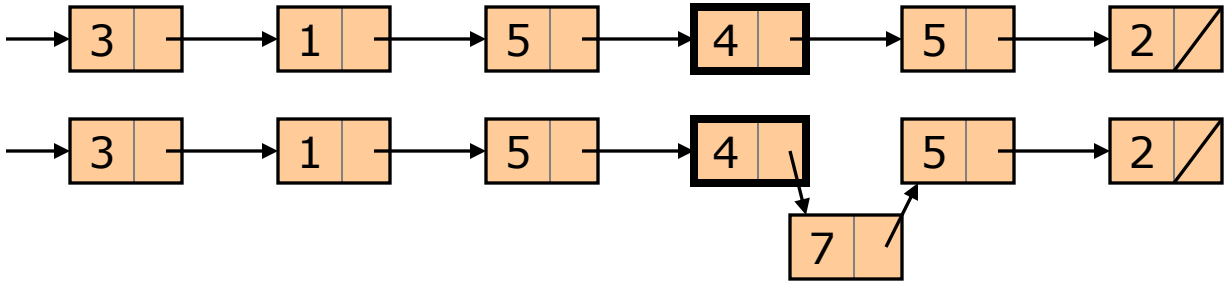
Our first node-based data structure is the (**Singly**) **Linked List**.

- A Linked List is composed of nodes. Each has a single data item and a pointer to the next node.



- These pointers are the only way to find the next data item.

Once we have found a position (think *iterator*) within a Linked List, we can insert or remove an item in constant time.



We can also **splice** in constant time.

Review
More on Linked Lists [2/5]

	Smart Array	Linked List
Look-up by index	***O*(1)**	***O*(*n*)**
Search sorted	***O*(log *n*)**	***O*(*n*)**
Search unsorted	*O*(*n*)	*O*(*n*)
Sort	*O*(*n* log *n*)	*O*(*n* log *n*)
Insert @ given pos	***O*(*n*)**	***O*(1)***
Remove @ given pos	***O*(*n*)**	***O*(1)***
Splice	***O*(*n*)**	***O*(1)**
Insert @ beginning	***O*(*n*)**	***O*(1)**
Remove @ beginning	***O*(*n*)**	***O*(1)**
Insert @ end	*O*(*n*)** amortized const	*O*(1) or *O*(*n*)***
Remove @ end	*O*(1)	*O*(1) or *O*(*n*)***
Traverse	*O*(*n*)	*O*(*n*)

*For Singly Linked Lists, insert/remove just *after* the given position.
- Doubly Linked Lists can help.

**$O(1)$ if no reallocate-and-copy.
- Pre-allocate to ensure this.

***For $O(1)$, need a pointer to end of list. Otherwise, $O(n)$.
- This can be tricky.
- And, for remove @ end, it is mostly impossible.
- Doubly Linked Lists can help.

Find faster with an array

Rearrange faster with a Linked List

More on Linked Lists [3/5]

Arrays store consecutive items in *nearby memory locations*.

Modern processors **prefetch** memory locations near those accessed, storing them in a fast on-chip **cache**.

An algorithm has **locality of reference** if, when it accesses a data item, the following accesses are likely to be nearby items.

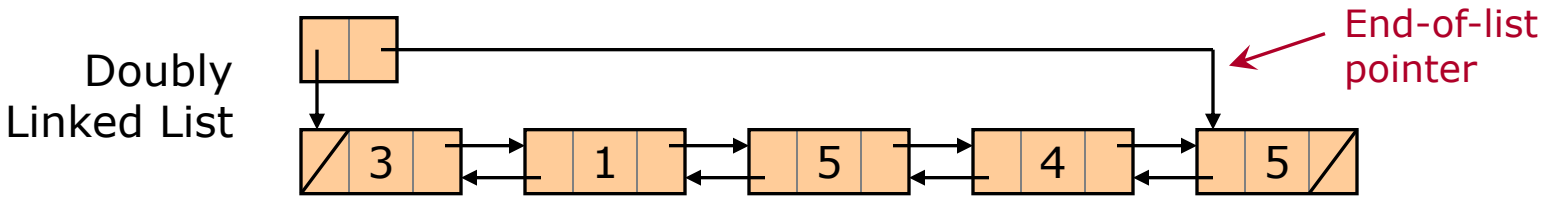
Therefore:

Array + Algorithm with good locality of reference
→ significant speed advantage over a Linked List

More on Linked Lists [4/5]

In a **Doubly Linked List**, each node has a data item & **two pointers**:

- A pointer to the next node (null at the end).
- A pointer to the previous node (null at the beginning).



Doubly Linked Lists often have an end-of-list pointer. This can be efficiently maintained, resulting in constant-time insert and remove at the end of the list.

Review
More on Linked Lists [5/5]

	Smart Array	**Doubly** Linked List
Look-up by index	***O*(1)**	***O*(*n*)**
Search sorted	***O*(log *n*)**	***O*(*n*)**
Search unsorted	*O*(*n*)	*O*(*n*)
Sort	*O*(*n* log *n*)	*O*(*n* log *n*)
Insert @ given pos	***O*(*n*)**	***O*(1)**
Remove @ given pos	***O*(*n*)**	***O*(1)**
Splice	***O*(*n*)**	***O*(1)**
Insert @ beginning	***O*(*n*)**	***O*(1)**
Remove @ beginning	***O*(*n*)**	***O*(1)**
Insert @ end	*O*(*n*)* amortized const	*O*(1)
Remove @ end	*O*(1)	*O*(1)
Traverse	*O*(*n*)	*O*(*n*)

Find faster with an array

Rearrange faster with a Linked List

With Doubly Linked Lists, we can eliminate asterisks.

**O*(1) if no reallocate-and-copy.*

- Pre-allocate to ensure this.

More on Linked Lists

continued

More on Linked Lists
Implementation — Two Approaches

Two Approaches to Implementing a Linked List

- A Linked List package to be used by others.
- An internal-use Linked List: part of a larger package, and not exposed to client code.

I bring this up because you will probably never need to write the former, except perhaps as homework. But you may have occasion to write the latter.

Q. How would these be different? In particular, what classes might we define in each case?

A1. In the first case, many classes: container, node, iterator.

A2. In the second case, a node class, but possibly nothing else.

More on Linked Lists
Implementation — CODE

We have already written an internal-use-style Singly Linked List, back in *A Little About Linked Lists.* But now we can improve it, by using smart pointers.

TO DO

- Update our Linked List to include the following. Follow the suggestions in the *Node-Based Structures/Smart Pointers* subtopics.
  - An owning smart pointer.
  - An insert-at-beginning operation.
  - A remove-at-beginning operation.
  - Exception-safety information.

Done. See `llnode2.h`*.*
See `use_list2.cpp` *for a program that uses this Linked List.*

More on Linked Lists
Implementation — Problem

Twice now, we have written a Linked List in which the node destructor recursively destroys the rest of the list.

For a list that may be arbitrarily long, this is a bad idea!

Why? The recursive node destructor has **linear recursion depth**. Stack overflow awaits.

The phrase
"linear recursion depth"
should strike terror into
your heart.

More on Linked Lists
Implementation — More CODE

TO DO

- Rewrite our Linked List so that it no longer has a recursive destructor.

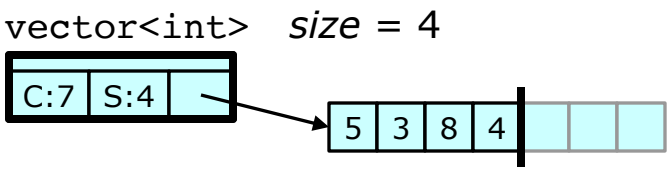
Done. See `llnode2.h`*.*
See `use_list2.cpp` *for a program that uses this Linked List.*

Sequences in the C++ STL

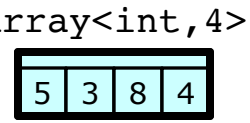
Sequences in the C++ STL
Generic Sequence Containers

The C++ STL includes six generic Sequence containers.

- `std::vector`
  - Smart array.



- `std::basic_string`
  - Much like `std::vector`, but aimed at character string operations.
  - `string` is `basic_string<char>`; other string-ish types are defined.
- `std::array`
  - Kinda-smart array. Not resizable. Size is part of the type.
  - *Not* the same as a C++ built-in array.
  - Data items are stored in the object.
  - A little faster than `vector`.



- `std::forward_list`
  - Singly Linked List.

We will not say much more about `std::array` & `std::forward_list`.

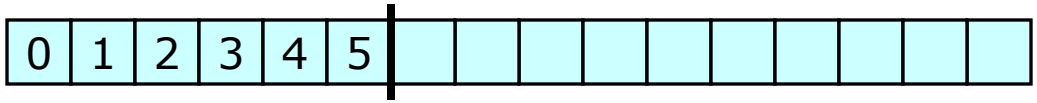
- `std::list`
  - Doubly Linked List.
- `std::deque` (stands for Double-Ended QUEue; say "deck")
  - Somewhat like `vector`, but slower. Fast insert/remove at both ends.

Sequences in the C++ STL
std::deque [1/3]

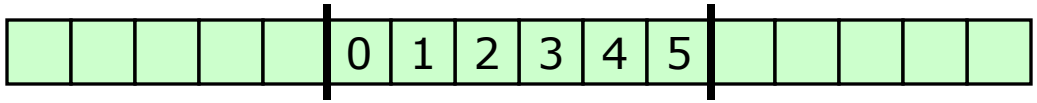
We are familiar with arrays and Linked Lists. How is `std::deque` implemented? There are two big ideas behind it.

Big Idea #1

- `vector` uses an array with data stored at the beginning. This gives linear-time insert/remove at beginning, constant-time remove at end, and, if we are careful, amortized constant-time insert at end.



- What if we store data in the middle? When we reallocate-and-copy, we move our data to the middle of the new array.

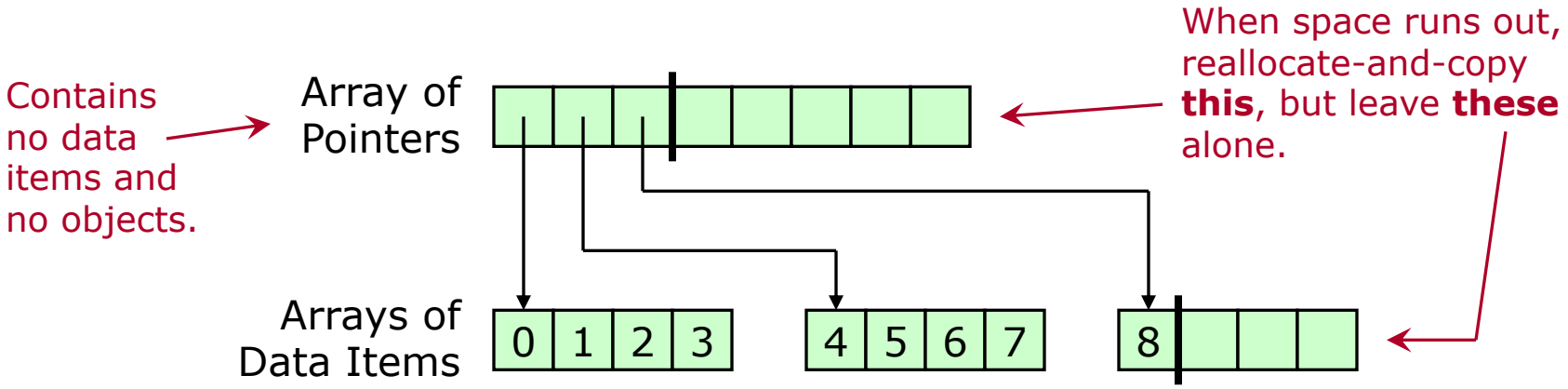


- Result: amortized Θ(1) insert and Θ(1) remove at beginning & end.

Sequences in the C++ STL
std::deque [2/3]

Big Idea #2

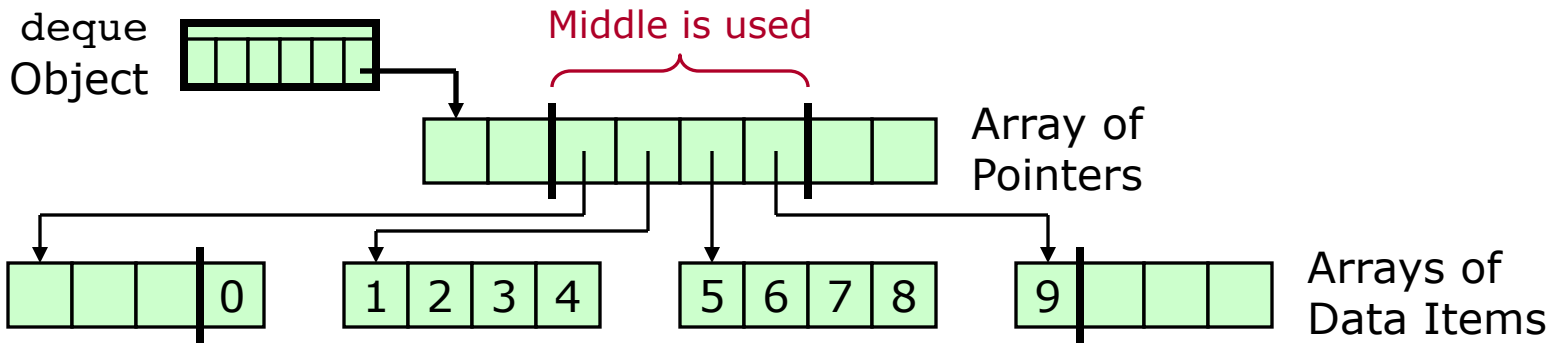
- Doing reallocate-and-copy for a `vector` requires a copy/move call for every data item. For large, complex data items, this can be time-consuming.
- Instead, use an array of pointers to arrays. Only the secondary arrays hold data items. Reallocate-and-copy only deals with the array of pointers.
  - We still get most of the locality-of-reference advantages of an array.
  - We can do the *copy* portion of reallocate-and-copy using a raw-memory copy—no copy/move ctor calls.



Sequences in the C++ STL
std::deque [3/3]

A `std::deque` implementation typically uses both ideas.

- 2 levels: array of pointers to arrays. Or maybe 3 levels.
- Reallocate-and-copy relocates to the middle of the new space.



Result: `std::deque` is an array-ish container.

- Iterators are random-access.
- Look-up by index is constant time—but slower than `vector`.
- Locality-of-reference advantages are *almost* as good as `vector`.
- Reallocate-and-copy is likely to be faster than `vector`.
- Insert/remove is fast at both beginning and end.
- Large, difficult-to-copy data items are handled more efficiently.

Sequences in the C++ STL
Common Features

`vector`, `basic_string`, `deque`, `list`:

- `iterator`, `const_iterator`
  - `list` has bidirectional iterators.
  - Others are random-access.
- *iterator* `begin()`, *iterator* `end()`
- *reference* `front()`, *reference* `back()`
  - Return reference to first/last item.
- *iterator* `insert(`*iterator*`,` *item*`)`
  - Insert before. Return iterator to new item.
- *iterator* `erase(`*iterator*`)`
  - Remove this item. Return iterator to following item—or end.
- `push_back(`*item*`)`, `pop_back()`
  - Insert/remove at end.
- `clear()`
  - Remove all items.
- `resize(`*newSize*`)`
  - Set size.

Additionally:

`deque`, `list`:

- `push_front(`*item*`)`, `pop_front()`
  - Insert/remove at beginning.

`vector`, `basic_string`, `deque`:

- *reference* `operator[](`*index*`)`
  - Look-up by index.

`vector`, `basic_string`:

- `reserve(`*newCapacity*`)`
  - Set capacity to *at least* this.
  - Not the same as `resize`. Does not change the size.

And others …

Sequences in the C++ STL
Efficiency [1/2]

Now we compare the efficiency characteristics of STL generic Sequence containers.

In the model of computation used in the official description of C++ STL, the basic operations are value-type operations *only*. Things like pointer operations are not counted.

- So "constant time" in the Standard means that at most a constant number of *value-type* operations are performed.
- An algorithm that the Standard calls "constant time" may still perform a large number of pointer operations.

Our analyses will be based on the same model of computation that we have been using. When the efficiency characteristics specified in the C++ Standard appear to be different, we will note this.

Sequences in the C++ STL
Efficiency [2/2]

	`vector`, `basic_string`	`deque`	`list`
Look-up by index	Constant	Constant	Linear
Search sorted	Logarithmic	Logarithmic	Linear
Insert @ given pos	Linear	Linear	Constant
Remove @ given pos	Linear	Linear	Constant
Insert @ end	Linear/ Amortized constant*	Linear/ Amortized constant**	Constant
Remove @ end	Constant	Constant	Constant
Insert @ beginning	Linear	Linear/ Amortized constant**	Constant
Remove @ beginning	Linear	Constant	Constant

The way `vector` acts at the end is the way `deque` acts at beginning *and* end.

*Θ(1) if sufficient memory has already been allocated. We can pre-allocate.

**Only a constant number of value-type operations are required. The C++ Standard says these are constant-time.

All four have Θ(*n*) traverse & search-unsorted and Θ(*n* log *n*) sort.

This completes our discussion of Sequences *in full generality*.

Next, we look at two *restricted* versions of Sequences, that is, ADTs that are much like Sequence, but with fewer operations:

- Stack.
- Queue.

For each of these, we look at:

- What it is.
- Implementation.
- Availability in the C++ STL.
- Applications.