CS 228: Introduction to Data Structures
Lecture 22

`DoublyLinkedList` (continued)

ListIterators

`add()` inserts a new item between `previous` and `next`.

```
    public void add(E item)
    {
      Node temp = new Node(item);
      link(cursor.previous, temp);
      ++index;
      ++size;
      direction = NONE;
    }
```

This method takes O(1) time.
`hasNext()`, **`hasPrevious()`**, **`nextIndex()`**, **and `previousIndex()`** do the obvious. They all take O(1) time.

```
public boolean hasNext()
{
  return index < size;
}

public boolean hasPrevious()
{
  return index > 0;
}

public int nextIndex()
{
  return index;
}

public int previousIndex()
{
  return index - 1;
}
```

`next()` and `previous()` not only move `cursor` forward or backward, but must also set the direction from which the cursor is coming, `BEHIND` or `AHEAD`.

```
public E next()
{
  if (!hasNext())
    throw new NoSuchElementException();

  E ret = cursor.data;
  cursor = cursor.next;
  ++index;
  direction = BEHIND;
  return ret;
}

public E previous()
{
  if (!hasPrevious())
    throw new NoSuchElementException();

  cursor = cursor.previous;
  --index;
  direction = AHEAD;
  return cursor.data;
}
```

Both `next()` and `previous()` take O(1) time.

`set()` and **`remove()`** need to know the direction we are coming from — `AHEAD`, `BEHIND`, or `NONE` — to determine which element to set/remove. `set()` can be called

multiple times, even if the cursor has not moved. Thus, it should leave `direction` unchanged.

```
    public void set(E item)
    {
      if (direction == NONE)
      {
        throw new IllegalStateException();
      }

      if (direction == AHEAD)
      {
        cursor.data = item;
      }
      else
      {
        cursor.previous.data = item;
      }
    }
```

This method takes O(1) time.

The `remove()` Method

The **`remove()`** method is like `set()`, except that after it has been called it changes `direction` to NONE, to disallow a subsequent `remove()`, unless there is another call to `next()` or `previous()`.

```
public void remove()
{
  if (direction == NONE)
  {
    throw new IllegalStateException();
  }
  else
  {
    if (direction == AHEAD)
    {
      // remove node at cursor and move
      // to next node
      Node n = cursor.next;
      unlink(cursor);
      cursor = n;
    }
    else
    {
      // remove node behind cursor and
      // adjust index
      unlink(cursor.previous);
      --index;
    }
  }
  --size;
  direction = NONE;
}
```

The worst-case running time of this method is O(1).

Array Implementation

The `ResizingArray2<E>` class, posted on Blackboard, implements the `List` interface using an array as the backing store. This is similar to what we did for `FirstCollection`, the array-based implementation of `Collection` that we saw some weeks ago. (Note that Java `ArrayLists` are array-based lists.)

The basic list `get()` and `set()` methods are O(1). An `add()` to the end of the list takes O(1) (amortized) time. Adding and removing elements at a specified index require shifting and are therefore O(n). List iterators must keep track of their current position and the direction they are coming from. The ideas are intuitive; we ask you to study the implementation on your own. We just note two things.

- `ResizingArray2<E>` implements the `List` interface *directly*, rather than through an intermediate, predefined, abstract class, as was the case for `DoublyLinkedList`. This means that `ResizingArray2` has to implement ***all*** the methods of the `List` interface.

- In addition to array *expansion* during `add()`, `ResizingArray2` also uses array ***contraction*** during `remove()` to avoid wasting too much space in unused array slots: When the occupancy rate (number of

elements in the list divided by the total number of slots in the backing array) drops below 1/4, the list is copied into an array of half the size.

Other Implementations

We have seen `Lists` and `ListIterators`, presented a doubly-linked list implementation with two dummy nodes, and sketched an alternative array implementation. Many other implementations are possible, for example:

- Null-terminated list with no dummy nodes or one dummy node
- Circular list with or without dummy node
- Singly-linked list, circular or null-terminated, with or without dummy nodes

While these implementations differ in specific details, they don't involve any major new ideas. Once you make the basic design decisions, writing the code is a matter of following your intuition: For each operation, draw a "before" picture of the list, then draw an "after" picture after

the operation. Now, look at how the links have to change, and write the code to make it so. Try this!

It is important to remember that, from the client's point of view, the *logical* behavior of all implementations of the `List` and `ListIterator` interfaces should be exactly the same, regardless of the underlying mechanics. Of course, the *running times* can be quite different.

Time Complexity

We now compare the running times of the various operations on linked lists and array lists. We first consider the `List` methods.

`get(i)`: *Getting an element at a given index*

- linked list: O(n)
  - Reason: We have to traverse the list to find the position
- array list: O(1)

`contains(item)`

- linked list: O(n)
- array list: O(n)

`size()`

- linked list: O(1)
- array list: O(1)

`add(item):` *Adding a new element at the end*

- linked list: O(1)
- array list: O(1) (*)

(*) This is not quite right, because during a sequence of such operations, we may have to resize the array several times. In practice we don't worry about this, because we can prove that adding n elements to an array list requires time O(n). That is, the ***amortized*** cost per add is O(1).

`add(i,item):` *Adding or removing at a given position*

- linked list: O(n)
  - Reason: We have to traverse the list to find the position
- array list: O(n)
  - Reason, we have to shift elements to add/remove in the middle of the array

`remove(item):` *Removing a given element*

- linked list: O(n)
  - Reason: Have to find the element
- array list: O(n)
  - Reason: Have to find the element, then shift elements to remove, but O(n) + O(n) = O(n)

Next, we consider the `ListIterator` methods.

`add(item)`, `remove()`: *Adding or removing an element during iteration*

- linked list: O(1)
  - Reason: Already have the node, so linking or unlinking is O(1)
- array list: O(n)
  - Reason: Have to shift elements to add/remove

Given a list of length n, iterate over the list and perform k adds or removes at arbitrary locations:

- linked list: O(n) + O(k) = O(n + k) or O(max(n, k))
- array list: O(nk)
  - Reason: each of the k operations is potentially O(n)

Note: The last item probably sums up the potential advantage of linked lists in terms of time complexity: In this application the linked list takes linear time, and the array list takes quadratic time.

Other considerations:

- **Space**. Array lists potentially waste some space because of the empty cells. (But remember, each empty cell is just an object reference – it takes up 4 bytes, not the space of the object itself!) For many short lists, linked lists may be more space-efficient. On the other hand, linked lists potentially waste space, because each element has to be wrapped in its own node object.

- **Practical performance.** In practice, array-based operations are very fast. Adding a new node to a linked list requires creation of the node object and several memory operations. Thus `ArrayLists` tend to be good for most purposes.

So, linked data structures are interesting for lists, and, as we'll soon see, they are also useful for queues and stacks. Later, we will see that they are absolutely indispensable for more complex structures like trees and graphs.

Stacks

A ***stack*** is an access-restricted list. You may manipulate only the item at the top of the stack: You may ***push*** a new item onto the top of the stack; you may ***pop*** the top item off the stack; you may examine (***peek*** at) the ***top*** item of the stack. Thus, the access policy for stacks is ***last-in first-out***. Formally, the following methods characterize a stack consisting of elements of type `E`:

`void push(E item):` Adds an element to the top of stack.

`E pop():` Removes and returns the top element of the stack. Throws `NoSuchElementException` if the stack is empty.

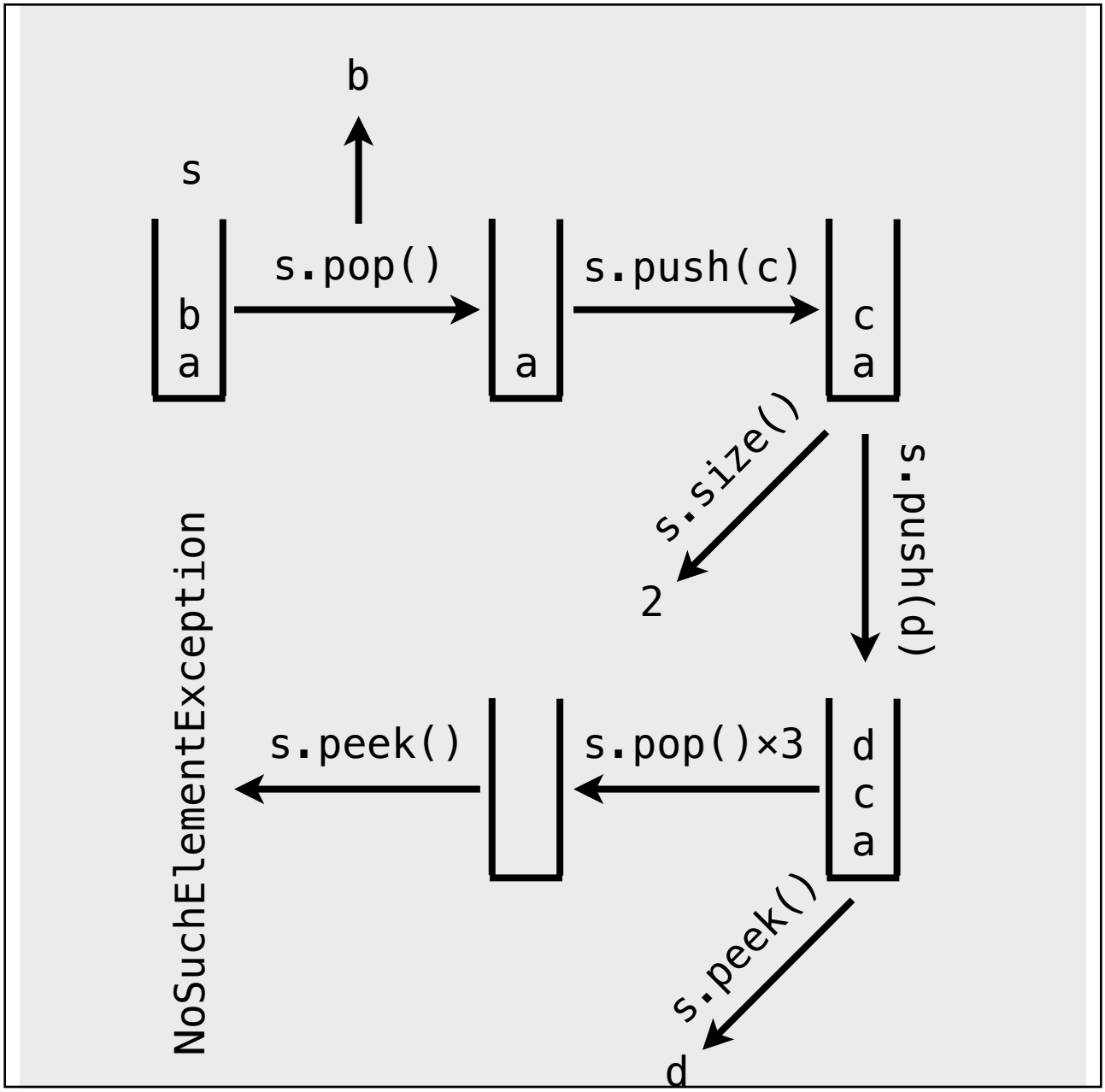
`E peek():` Returns the top element of the stack without removing it. Throws `NoSuchElementException` if the stack is empty.

`boolean isEmpty():` Return `true` if the stack is empty, `false` otherwise.

`int size():` Returns the number of elements in the stack.

We don't *need* iterators, although there are cases where they can be useful. In principle, but not in practice, a stack can grow arbitrarily large.

Example.

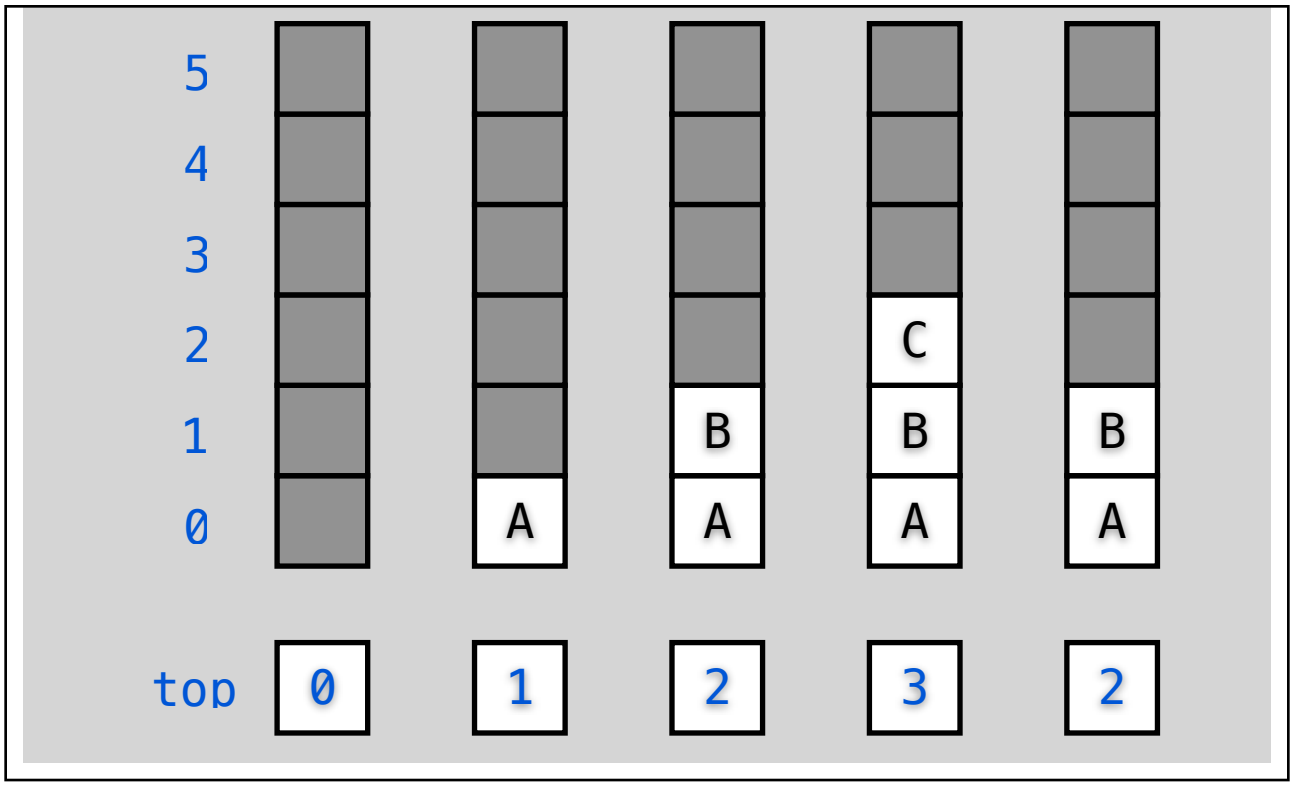


Remark. Why study stacks when we already have lists? One reason is to be able to carry on discussions with other programmers. If somebody tells you that an algorithm uses a stack, this can give you a good hint about how the algorithm works. In fact, stacks are central to Java: The Java Virtual Machine, which executes Java bytecode, is stack-based.

Direct Implementations of Stacks

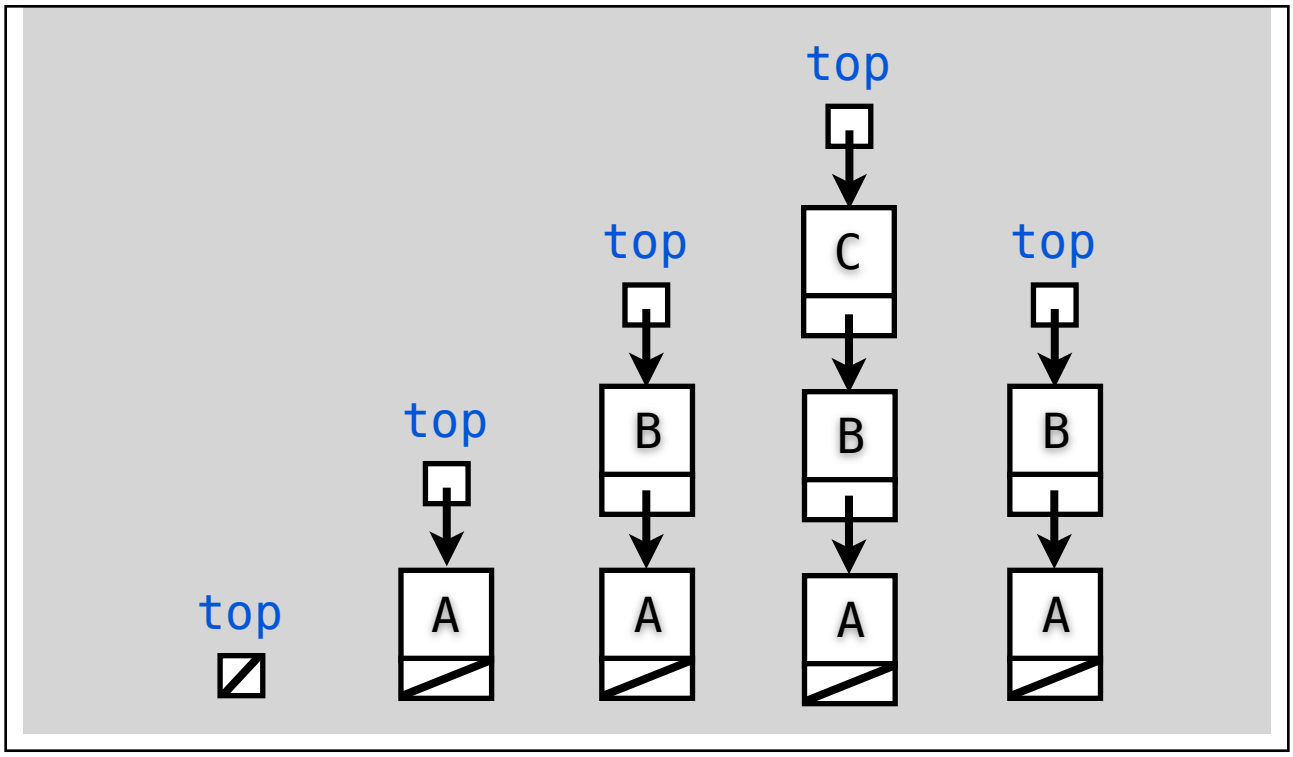
It is easy to implement stacks using arrays or linked lists. We sketch both approaches next.

Array implementation. We use a `data` array, and an index `top` into `data`. Entries `data[0]`, ... , `data[top-1]` contain the elements of the stack. A sequence of pushes and pops, starting from an empty stack might look like this.



When there is no more space in the `data` array for another `push`, just double the size of the array. All operations take O(1) time (amortized, in the case of `push`).

Linked list implementation. Singly-linked lists work well for stacks, since we only need access to the top. Simply use a sequence of linked nodes, with a pointer `top` to the first node, which is viewed as the top of the stack. This is illustrated next.



All operations take O(1) time.