Administrative:

- Test #1 Tuesday night.
  - Sections 11-13 go to 10 Evans.
  - Sections 14-20 go to 155 Dwinelle.
  - Sections 21-26 go to 2050 VLSB.
  - Others(?) go to 155 Dwinelle.

CS61B Lecture #17

Topics

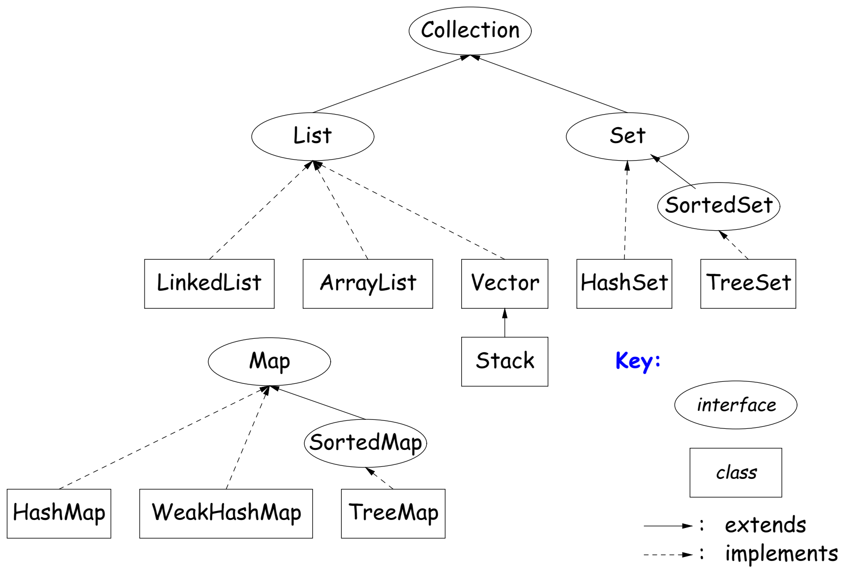
- Overview of standard Java Collections classes.
  - Iterators, ListIterators
  - Containers and maps in the abstract
- Amortized analysis of implementing lists with arrays:

Readings: *Data Structures,* Chapter 2, 3 (for today), and 4 (Friday).

Data Types in the Abstract

- Most of the time, should *not* worry about implementation of data structures, search, etc.
- What they do for us—their specification—is important.
- Java has several standard types (in `java.util`) to represent collections of objects
  - Six interfaces:
    - `Collection`: General collections of items.
    - `List`: Indexed sequences with duplication
    - `Set`, `SortedSet`: Collections without duplication
    - `Map`, `SortedMap`: Dictionaries (key $\mapsto$ value)
  - Concrete classes that provide actual instances: `LinkedList`, `ArrayList`, `HashSet`, `TreeSet`.
  - To make change easier, purists would use the concrete types only for **new**, interfaces for parameter types, local variables.

Collection Structures in java.util



The Collection Interface

- Collection interface. Main functions promised:
  - Membership tests: `contains` ($\in$), `containsAll` ($\subseteq$)
  - Other queries: `size`, `isEmpty`
  - Retrieval: `iterator`, `toArray`
  - *Optional* modifiers: `add`, `addAll`, `clear`, `remove`, `removeAll` (set difference), `retainAll` (intersect)

Side Trip about Library Design: Optional Operations

- Not all `Collections` need to be modifiable; often makes sense just to get things from them.
- So some operations are optional (`add`, `addAll`, `clear`, `remove`, `removeAll`, `retainAll`)
- The library developers decided to have *all* Collections implement these, but allowed implementations to throw an exception:

  `UnsupportedOperationException`
- An alternative design would have created separate interfaces:

```
interface Collection { contains, containsAll, size, iterator, ... }
interface Expandable extends Collection { add, addAll }
interface Shrinkable extends Collection { remove, removeAll, difference, ... }
interface ModifiableCollection
   extends Collection, Expandable, Shrinkable { }
```

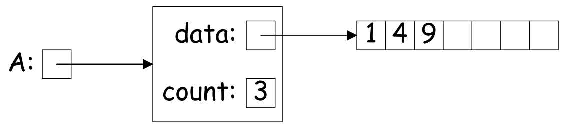
- You'd soon have lots of interfaces. Perhaps that's why they didn't do it that way.

The List Interface

- Extends `Collection`
- Intended to represent *indexed sequences* (generalized arrays)
- Adds new methods to those of `Collection`:
  - Membership tests: `indexOf`, `lastIndexOf`.
  - Retrieval: `get`(i), `listIterator()`, `sublist`(B, E).
  - Modifiers: `add` and `addAll` with additional index to say *where* to add. Likewise for removal operations. `set` operation to go with `get`.
- Type `ListIterator<Item>` extends `Iterator<Item>`:
  - Adds `previous` and `hasPrevious`.
  - `add`, `remove`, and `set` allow one to iterate through a list, inserting, removing, or changing as you go.
  - **Important Question:** What advantage is there to saying `List L` rather than `LinkedList L` or `ArrayList L`?

Implementing Lists (I): ArrayLists

- The main concrete types in Java library for interface `List` are `ArrayList` and `LinkedList`:
- As you might expect, an `ArrayList`, `A`, uses an array to hold data. For example, a list containing the three items 1, 4, and 9 might be represented like this:



- After adding four more items to `A`, its `data` array will be full, and the value of `data` will have to be replaced with a pointer to a new, bigger array that starts with a copy of its previous values.
- Question: For best performance, how big should this new array be?
- If we increase the size by 1 each time it gets full (or by any constant value), the cost of N additions will scale as $\Theta(N^2)$, which makes `ArrayList` look much worse than `LinkedList` (which uses an `IntList`-like implementation.)

Amortization: Expanding Vectors

- When using array for expanding sequence, best to *double* the size of array to grow it. Here's why.
- If array is size s, doubling its size and moving s elements to the new array takes time proportional to $2s$.
- In all cases, there is an additional $\Theta(1)$ cost for each addtion to account for actually assigning the new value into the array.
- When you add up these costs for inserting a sequence of N items, the *total* cost turns out to proportional to N, as if each addition took constant time, even though some of the additions actually take time proporational to N all by themselves!

Amortization: Expanding Vectors (II)

To Insert Item #	**Resizing Cost**	**Cumulative Cost**	**Resizing Cost per Item**	**Array Size After Insertions**
0	0	0	0	1
1	2	2	1	2
2	4	6	2	4
3	0	6	1.5	4
4	8	14	2.8	8
5	0	14	2.33	8
⋮	⋮	⋮	⋮	⋮
7	0	14	1.75	8
8	16	30	3.33	16
⋮	⋮	⋮	⋮	⋮
15	0	30	1.88	16
⋮	⋮	⋮	⋮	⋮
$2^m + 1$ to $2^{m+1} - 1$	0	$2^{m+2} - 2$	≈ 2	2^{m+1}
2^{m+1}	2^{m+2}	$2^{m+3} - 2$	≈ 4	2^{m+2}

- If we spread out (*amortize*) the cost of resizing, we average at most about 4 time units on each item: "amortized insertion time is 4 units." Time to add N elements is $\Theta(N)$, *not* $\Theta(N^2)$.

Demonstrating Amortized Time: Potential Method

- To formalize the argument, associate a *potential*, $\Phi_i \geq 0$, to the i^{th} operation that keeps track of "saved up" time from cheap operations that we can "spend" on later expensive ones. Start with $\Phi_0 = 0$.
- Now define the *amortized cost* of the i^{th} operation as

$$a_i = c_i + \Phi_{i+1} - \Phi_i,$$

  where c_i is the real cost of the operation.
- On cheap operations, we artificially set $a_i > c_i$ and increase Φ ($\Phi_{i+1} > \Phi_i$).
- On expensive ones, we typically have $a_i \ll c_i$ and greatly decrease Φ (but don't let it go negative—may not be "overdrawn").
- We try to do all this so that a_i remains as we desired (e.g., $O(1)$ for expanding array), without allowing $\Phi_i < 0$.
- Requires that we choose a_i so that Φ_i always stays ahead of c_i.

Application to Expanding Arrays

- When adding to our array, the cost, c_i, of adding element #i when the array already has space for it is 1 unit.
- The array does not initially have space when adding items 1, 2, 4, 8, 16,...—in other words at item 2^n for all $n \geq 0$. So,
  - $c_i = 1$ if $i \geq 0$ and is not a power of 2; and
  - $c_i = 2i + 1$ when i is a power of 2 (copy i items, clear another i items, and then add item #i).
- So on each operation #2^n we're going to need to have saved up at least $2{\cdot}2^n = 2^{n+1}$ units of potential to cover the expense of expanding the array, and we have this operation and the preceding $2^{n-1} - 1$ operations in which to save up this much potential (everything since the preceding doubling operation).
- To do so, just choose $a_i = 5$ (actually, could let $a_0 = 1$).
- Here's what happens:

i	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
c_i	1	3	5	1	9	1	1	1	17	1	1	1	1	1	1	1	33	1
a_i	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Φ_i	0	4	6	6	10	6	10	14	18	6	10	14	18	22	26	30	34	6