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.
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

Collection

List
- LinkedList
- ArrayList
- Vector

Set
- HashSet
- TreeSet
- SortedSet

Map
- HashMap
- WeakHashMap
- TreeMap
- SortedMap

Key:
- interface
- class
- : extends
- : implements
The Collection Interface

- **Collection interface. Main functions promised:**
  - **Membership tests:** `contains (∈)`, `containsAll (⊆)`
  - **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:

  ![Diagram of an ArrayList](image)

- 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 addition 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 proportional to $N$ all by themselves!
### Amortization: Expanding Vectors (II)

<table>
<thead>
<tr>
<th>To Insert Item #</th>
<th>Resizing Cost</th>
<th>Cumulative Cost</th>
<th>Resizing Cost per Item</th>
<th>Array Size After Insertions</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>6</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>6</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>14</td>
<td>2.8</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>14</td>
<td>2.33</td>
<td>8</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>14</td>
<td>1.75</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>30</td>
<td>3.33</td>
<td>16</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>30</td>
<td>1.88</td>
<td>16</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>$2^m + 1$ to $2^{m+1} - 1$</td>
<td>$2^m + 2$</td>
<td>$2^{m+2} - 2$</td>
<td>$\approx 2$</td>
<td>$2^{m+1}$</td>
</tr>
<tr>
<td>$2^{m+1}$</td>
<td></td>
<td>$2^{m+2}$</td>
<td>$\approx 4$</td>
<td>$2^{m+2}$</td>
</tr>
</tbody>
</table>

- 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 $\Phi$ ($\Phi_{i+1} > \Phi_i$).

- On expensive ones, we typically have $a_i \ll c_i$ and greatly decrease $\Phi$ (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 $\Phi_i$ 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:

<table>
<thead>
<tr>
<th>(i)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
</tr>
</thead>
<tbody>
<tr>
<td>(c_i)</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>1</td>
<td>9</td>
<td>1</td>
<td>1</td>
<td>17</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>33</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>(a_i)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>(\Phi_i)</td>
<td>0</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>10</td>
<td>10</td>
<td>14</td>
<td>18</td>
<td>16</td>
<td>10</td>
<td>14</td>
<td>18</td>
<td>22</td>
<td>26</td>
<td>30</td>
<td>34</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>