administrivia...
- assignment 5 due tonight at midnight

- assignment 6 is out
  - YOU WILL BE SWITCHING PARTNERS!

- analysis documents

- review midterm
assignment 2 scores

<table>
<thead>
<tr>
<th>Score Range</th>
<th>Number of Students</th>
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Assignment 3: Searching a List

Assignment 3 scores

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1. Who is your programming partner? Which of you submitted the source code of your program?

Jacob Osterloh was my partner and I submitted the source code.

2. What did you learn from your partner? What did your partner learn from you?

I taught my partner about testing for all cases, it’s important to test code every way possible so that it isn’t bugged. I also taught him a few tools to help test Arrays. I learned from him a lot about the comparator, he clarified the questions that I had about how to use it properly.

3. Evaluate your programming partner. Do you plan to work with this person again?

Jake and I have a good thing going and I plan to work with him as long as possible. He is very dedicated to learn and strives for excellence, which is nice because I have the same mentality as he does for this class.

4. Analyze the run-time performance of the areAnagrams method. What is the Big-O behavior and why? Be sure to define N. Plot the running time for various problem sizes (up to you to choose problem sizes that sufficiently analyze the problem). (NOTE: The provided AnagramTester.java contains a method for generating a random string of a certain length.) Does the growth rate of the plotted running times match the Big-O behavior you predicted?

The Big O behavior for the areAnagrams method is O(N^2). N is the size of the string. It is O(N^2) because it uses an Insertions sort. Here is a plot of the time it took to run our areAnagrams method:
review midterm
last time...
mergesort
divide and conquer

quicksort
another divide and conquer
mergesort

1) divide the array in half
2) sort the left half
3) sort the right half
4) merge the two halves together
mergesort

1) divide the array in half
2) sort the left half
3) sort the right half
4) merge the two halves together

2) take the left half, and go back to step 1
3) take the right half, and go back to step 1
mergesort

1) divide the array in half
2) sort the left half
3) sort the right half
4) merge the two halves together

2) take the left half, and go back to step 1  UNTIL???
3) take the right half, and go back to step 1  UNTIL???
mergesort

1) divide the array in half
2) sort the left half
3) sort the right half
4) merge the two halves together

2) take the left half, and go back to step 1 until??
3) take the right half, and go back to step 1 until??

WHAT DOES THIS LOOK LIKE?
watch a video online…
void mergesort(int[] arr, int left, int right)
{
    // arrays of size 1 are already sorted
    if(left >= right)
        return;

    int mid = (left + right) / 2;
    mergesort(arr, left, mid);
    mergesort(arr, mid+1, right);
    merge(arr, left, mid+1, right);
}
void merge(int[] arr, start, mid, end) {
    // create temp array for holding merged arr
    int[] temp = new int[end - start + 1];

    int i1 = 0, i2 = mid;
    while(i1 < mid && i2 < end) {
        put smaller of arr[i1], arr[i2] into temp;
    }

    copy anything left over from larger half to temp;
    copy temp over to arr;
}
notes on merging

-the major disadvantage of mergesort is that the merging of two arrays requires an extra, temporary array

-this means that mergesort requires 2x as much space as the array itself
  -can be an issue if space is limited!
  -an *in-place* mergesort exists, but is complicated and has worse performance

-to achieve the overall running time of $O(N \log N)$ it is critical that the running time of the merge phase be linear
quicksort

1) select an item in the array to be the **pivot**

2) **partition** the array so that all items less than the pivot are to the left of the pivot, and all the items greater than the pivot are to the right

3) sort the left half

4) sort the right half
quicksort

1) select an item in the array to be the *pivot*

2) *partition* the array so that all items less than the pivot are to the left of the pivot, and all the items greater than the pivot are to the right

3) take the left half, and go back to step 1

4) take the right half, and go back to step 1
quicksort

1) select an item in the array to be the pivot

2) partition the array so that all items less than the pivot are to the left of the pivot, and all the items greater than the pivot are to the right

3) take the left half, and go back to step 1 UNTIL???
4) take the right half, and go back to step 1 UNTIL???
quicksort

1) select an item in the array to be the *pivot*

2) *partition* the array so that all items less than the pivot are to the left of the pivot, and all the items greater than the pivot are to the right

3) sort the left half

3) take the left half, and go back to step 1 *UNTIL***?

4) sort the right half

4) take the right half, and go back to step 1 *UNTIL***?

WHAT DOES THIS LOOK LIKE?

watch a video online…
void quicksort(int[] arr, int left, int right) {
    // arrays of size 1 are already sorted
    if(left >= right)
        return;

    int pivot_index = partition(arr, left, right);
    quicksort(arr, left, pivot_index-1);
    quicksort(arr, pivot_index+1, right);
}
void quicksort(int[] arr, int left, int right)
{
    // arrays of size 1 are already sorted
    if(left >= right)
        return;

    int pivot_index = partition(arr, left, right);
    quicksort(arr, left, pivot_index-1);
    quicksort(arr, pivot_index+1, right);
}

WHAT IS THE DIVIDE STEP?
void quicksort(int[] arr, int left, int right)
{
    // arrays of size 1 are already sorted
    if(left >= right)
        return;

    int pivot_index = partition(arr, left, right);
    quicksort(arr, left, pivot_index-1);
    quicksort(arr, pivot_index+1, right);
}

WHAT IS THE DIVIDE STEP?
WHAT IS THE CONQUER STEP?
in-place partitioning

1) select an item in the array to be the \textit{pivot}

2) swap the pivot with the last item in the array \textit{(just get it out of the way)}

3) step from left to right until we find an item $> \text{pivot}$
   - \textit{this item needs to be on the right of the partition}

4) step from right to left until we find an item $< \text{pivot}$
   - \textit{this item needs to be on the left of the partition}

5) swap items

6) continue until left and right stepping cross

7) swap pivot with left stepping item
choosing a pivot

- the median of all array items is the best possible choice… why?
  - is time-consuming to compute
  - finding true median is \( O(N) \)

- it is important that we avoid the worst case
  - what IS the worst case(s)?

- middle array item is a safe choice… why?

- median-of-three: pick a few random items and take median
  - why not the first, middle, and last items?

- random pivot: faster than median-of-three, but lower quality
quicksort vs mergesort
- both are $O(N \log N)$ in the average case

- mergesort is also $O(N \log N)$ in the worst case
  - so, why not always use mergesort?

- mergesort requires $2N$ space
  - and, copying everything from the merged array back to the original takes time

- quicksort requires no extra space
  - thus, no copying overhead!
  - but, in $O(N^2)$ worst case <wha wha>
base cases

recursive calls

[A]
mergesort

Every node gets sorted by $\text{merge}()$ but this consumes more memory.
mergesort

Every node gets sorted by \textit{merge()} but this consumes more memory.

quicksort

Pivots determine effectiveness of the \textit{partition()} split.
- both are divide and conquer algorithms (recursive)

- mergesort sorts “on the way up”
  - after the base case is reached, the calls return and `merge()` does the sorting

- quicksort sorts “on the way down”
  - once the base case is reached, that part of the array is already sorted

- though quicksort is more popular, it is not always the right choice!
today…
- memory allocation

- linked structures

- linked lists

- insertion & deletion

- implementation details

- doubly linked lists

- LinkedList vs ArrayList
memory primer

-all data in your program resides in memory at some point during its life

-think of memory as giant blocks of bytes:

```plaintext
0 1 0 0 0 1 1 0
```

- each byte has its own memory address (a number)

-byte n is next to byte n-1 and n+1

-ie. memory is ordered
memory in Java
-what actually happens when you use the `new` keyword?

-`new` instructs the system to find a contiguous block of bytes big enough to hold whatever you are creating
  - `int arr[] = new int[10];`
  - *finds a block of memory big enough to hold 10 ints - how many bytes for an int?*
  - `arr[0]` is right next to `arr[1]` in memory
  - *the addresses of these two numbers are contiguous!*
-arrays are a **random access** data structure
  - any item in the array can be accessed instantly

-**EXAMPLE**
  - to access item 23 in an array, simply take the address of the beginning of the array and add 23 times the size of each item
    - address of `arr[23]` is address of `arr[0] + (23 * 4)`

-no matter the size of the array, accessing item `i` can be done in **O(c)**
  - ie. one addition and one multiplication
-each time you call new, the allocated block can be anywhere in memory

Circle c1 = new Circle();
Circle c2 = new Circle();

-\( c1 \) may be at location 2048, and \( c2 \) may be at location 640

-you have no control over this!
linked structures
**linked structures** are data storage in which individual items have *links* (references) to other items.

- Items don’t reside in a single contiguous block of memory.

- Items can be *dynamically* added or removed from the structure, simply by creating or destroying links.
- **linked structures** are data storage in which individual items have *links* (references) to other items.

- Items don’t reside in a single contiguous block of memory.

- Items can be *dynamically* added or removed from the structure, simply by creating or destroying links.

**How is this different than an array?**
-linked structures have a reference to another instance of the structure

-looks a bit like a recursive class definition

```java
class ListNode {
    // each node stores some data
    int ID;
    String name;

    ListNode next; // and one of itself!
}
```
-nodes could also have multiple links
-think of a family tree, or airports

class LinkedNode {
    // each node stores some data
    int ID;
    String name;

    ArrayList<LinkedNode> neighbors;
}
linked lists
we’ve seen a list implemented with an array in ArrayList<>.

a linked list is another way to implement a list.

each node, or item in the list, has a link to the next item in the list.

-a single node consists of some data and a reference to another node.
nodes may not be contiguous in memory!
-with an array, we have a single variable that can access any item with \[\]

-with a linked list, how do we access individual elements?
  -HINT: we need somewhere to start
-with an array, we have a single variable that can access any item with \[ \]

-with a linked list, how do we access individual elements?
   -HINT: we need somewhere to start

-always keep track of the first node
   -called the head
-with an array, we have a single variable that can access any item with \[\]

-with a linked list, how do we access individual elements?
  -HINT: we need somewhere to start

-always keep track of the first node
  -called the **head**

-from the head node we can access any other node by following the links
LinkedNode head = new LinkedNode();
head.ID = 5;
head.name = "head node";

head.next = new LinkedNode();

LinkedNode temp = head.next;
temp.ID = 12;
temp.name = "next node";
linked list vs array

cost of accessing a random item at location $i$?
cost of removeFirst()?
cost of addFirst()?

A) $c$
B) $\log N$
C) $N$
D) $N \log N$
E) $N^2$
F) $N^3$
insertion & deletion
inserting into an array:

\[ 5 \ 9 \ 12 \ 17 \ 25 \]

inserting into a linked list:

\[ 5 \ 8 \ 9 \ 12 \ 17 \ 25 \]
inserting into an array:

\[
\begin{array}{cccccc}
5 & 9 & 12 & 17 & 25 & \text{8}
\end{array}
\]

\[
\begin{array}{cccccc}
5 & 8 & 9 & 12 & 17 & 25
\end{array}
\]

inserting into a linked list:

**WHAT IS THE COST OF INSERTION?**

A) \( c \)
B) \( \log N \)
C) \( N \)
D) \( N \log N \)
E) \( N^2 \)
F) \( N^3 \)
inserting into an array:

5 9 12 17 25

8

5 8 9 12 17 25

WHAT IS THE COST OF INSERTION?
A) c  
B) \log N  
C) N  
D) N \log N  
E) N^2  
F) N^3

inserting into a linked list:

5 → 9 → 12 → 17 → 25

8
inserting into an array:

```
5  9  12  17  25
```

8

```
5  8  9  12  17  25
```

**WHAT IS THE COST OF INSERTION?**

A) $c$
B) $\log N$
C) $N$
D) $N \log N$
E) $N^2$
F) $N^3$

inserting into a linked list:

```
5  9  12  17  25
```

8

```
5  9  12  17  25
```

8
deletion from a linked list:
deletion from a linked list:
deletion from a linked list:

\[ \begin{array}{cccccc}
5 & \rightarrow & 9 & \rightarrow & 12 & \rightarrow & 17 & \rightarrow & 25 \\
\end{array} \]

9 IS NOW STRANDED – GARBAGE COLLECTOR WILL CLEAN IT UP
implementation details
linked lists have some methods, a size, etc.
   -but, it doesn’t make sense for every node to store the size!

out class LinkedList keeps track of the size, head node, and defines all methods

Node should be a simple, inner class (private)
   -with a data field, and one or more Nodes (links)
non-generic implementation (only stores ints):

class LinkedList {
    private Node head;
    private int size;

    private class Node {
        private int data;
        private Node next;
        ...
    }
    ...
}
things to consider...

- what should `next` be for the last item in the list?

- don’t let a call to `new ListNode()` cause an infinite loop
  - ie. creating a new `ListNode`, which creates a new `ListNode`, and so on...

- constructor should set `next` to `null`
traversing a linked list:

```java
boolean contains(int item) {
    Node temp = head;

    while (temp != null) {
        if (temp.data == item)
            return true;
        temp = temp.next;
    }

    return false;
}
```
exercise ...

-what is the implementation of `get()`?

```java
int get(int i) { ... }
```

-NOTES
- throws `NoSuchElementException` if `i` is out of range
- move to the next node with the `.next` reference

-what is the equivalent method for an `ArrayList`?

-what is the worst case of `get()`?
doubly-linked lists
-nodes have a link to next and previous node

-allows for traversal in either forward or reverse order

-maintains a tail node as well as a head node
  -why?

-how can we use a doubly-linked list to optimize get(i)?
-special cases (empty or single-item lists) are more tricky due to managing tail as well as head

-what are the values of head and tail for any empty list?

-what about for a single-item list?
doubly-linked list insertion:
doubly-linked list insertion:

```java
newNode = new Node<Character>();
newNode.data = 'n';
```
doubly-linked list insertion:

```java
doubly-linked list insertion:
newNode = new Node<Character>();
newNode.data = 'n';
newNode.prev = current;
```

![Diagram of doubly-linked list insertion](image)
doubly-linked list insertion:

```java
newNode = new Node<Character>();
newNode.data = 'n';

newNode.prev = current;
newNode.next = current.next;
```
doubly-linked list insertion:

```java
newNode = new Node<Character>();
newNode.data = 'n';

newNode.prev = current;
newNode.next = current.next;
newNode.prev.next = newNode;
```
doubly-linked list insertion:

```java
doubly-linked list insertion:
newNode = new Node<Character>();
newNode.data = 'n';

newNode.prev = current;
newNode.next = current.next;
newNode.prev.next = newNode;
newNode.next.prev = newNode;
```
doubly-linked list deletion:

current.prev.next = current.next;
current.next.prev = current.prev;
doubly-linked list deletion:

current.prev.next = current.next;
current.next.prev = current.prev;

WHAT IS THE COST OF DELETION?

A) c 
B) log N 
C) N 
D) N log N 
E) N^2 
F) N^3
doubly-linked list deletion:

current.prev.next = current.next;
current.next.prev = current.prev;

WHAT IS THE COST OF DELETION?

A) c
B) $\log N$
C) N
D) $N \log N$
E) $N^2$
F) $N^3$

head

a

current

k

n

o

tail

y
doubly-linked list deletion:

```java
current.prev.next = current.next;
current.next.prev = current.prev;
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**WHAT IS THE COST OF DELETION?**

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doubly-linked list deletion:

current.prev.next = current.next;
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WHAT IS THE COST OF DELETION?

A) \( c \)
B) \( \log N \)
C) \( N \)
D) \( N \log N \)
E) \( N^2 \)
F) \( N^3 \)
generic implementation:

```java
class DoublyLinkedList<E> {
    private Node head;
    private Node tail;
    private int size;

    private class Node {
        private E data;
        private Node next;
        private Node prev;
        ...
    }
    ...
}
```
things to consider...

- adding to the front or end of a linked list is a little different than adding somewhere in the middle
  - why?

- removing from a list with 1 node
  - what happens to head/tail?

- adding to an empty list
  - what is the current value of head/tail?
LinkedList vs ArrayList
**LinkedList vs ArrayList**

- **insertion & deletion:**
  - O(c) (assuming position is known)
  - O(N)

- **accessing a random item:**
  - O(N)
  - O(c)

- Choose the structure based on the expected use.
- What is the common case?
- What if insertion / deletion is always from the front / end?
next time...
-reading
  - chapter 16: stacks & queues
  - chapter 2: array-based lists
    - http://opendatastructures.org/ods-java/

-homework
  - assignment 5 due tonight
  - assignment 6 is out