Building Java Programs

Chapter 13
binary search and complexity

reading: 13.1-13.2
10/07/2018

DOGS SPOTTED THIS WEEKEND

CHUNK ON THE STREET

DAZZLING SMILE

WAITING PATIENTLY

LITTLE WEENIE, TOO FAR AWAY
## Road Map

### CS Concepts
- Client/Implementer
- Efficiency
- Recursion
- Regular Expressions
- Grammars
- Sorting
- Backtracking
- Hashing
- Huffman Compression

### Java Language
- Exceptions
- Interfaces
- References
- Comparable
- Generics
- Inheritance/Polymorphism
- Abstract Classes

### Data Structures
- Lists
- Stacks
- Queues
- Sets
- Maps
- Priority Queues

### Java Collections
- Arrays
- ArrayList
- LinkedList
- Stack
- TreeSet / TreeMap
- HashSet / HashMap
- PriorityQueue
Let’s write a method to calculate the sum from 1 to some n

```java
public static int sum1(int n) {
    int sum = 0;
    for (int i = 1; i <= n; i++) {
        sum += i;
    }
    return sum;
}
```

Gauss also has a way of solving this

```java
public static int sum2(int n) {
    return n * (n + 1) / 2;
}
```

Which one is more efficient?
Runtime Efficiency (13.2)

- **efficiency**: measure of computing resources used by code.
  - can be relative to speed (time), memory (space), etc.
  - most commonly refers to run time
- We want to be able to compare different algorithms to see which is more efficient
Efficiency Try 1

Let’s time the methods!

<table>
<thead>
<tr>
<th>n</th>
<th>sum1 took.ms</th>
<th>sum2 took.ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0ms</td>
<td>0ms</td>
</tr>
<tr>
<td>5</td>
<td>0ms</td>
<td>0ms</td>
</tr>
<tr>
<td>10</td>
<td>0ms</td>
<td>0ms</td>
</tr>
<tr>
<td>100</td>
<td>0ms</td>
<td>0ms</td>
</tr>
<tr>
<td>1,000</td>
<td>0ms</td>
<td>0ms</td>
</tr>
<tr>
<td>10,000,000</td>
<td>10ms</td>
<td>0ms</td>
</tr>
<tr>
<td>100,000,000</td>
<td>43ms</td>
<td>0ms</td>
</tr>
<tr>
<td>2,147,483,647</td>
<td>804ms</td>
<td>0ms</td>
</tr>
</tbody>
</table>

Downsides

- Different computers give different run times
- The same computer gives different results!!! D:<
Efficiency – Try 2

• Count number of “simple steps” our algorithm takes to run
• Assume the following:
  • Any single Java statement takes same amount of time to run.
    • `int x = 5;`
    • `boolean b = (5 + 1 * 2) < 15 + 3;`
    • `System.out.println("Hello");`
  • A loop's runtime, if the loop repeats N times, is N times the runtime of the statements in its body.
  • A method call's runtime is measured by the total runtime of the statements inside the method's body.
public static void method1() {
    statement1;  
    statement2;  
    statement3;  
    for (int i = 1; i <= N; i++) {
        statement4;  
    }
    for (int i = 1; i <= N; i++) {
        statement5;  
        statement6;  
        statement7;  
    }
}
public static void method2() {
    for (int i = 1; i <= N; i++) {
        for (int j = 1; j <= N; j++) {
            statement1;
        }
    }
    for (int i = 1; i <= N; i++) {
        statement2;
        statement3;
        statement4;
        statement5;
    }
}

• How many statements will execute if N = 10? If N = 1000?
Let’s write a method to calculate the sum from 1 to some n

```java
public static int sum1(int n) {
    int sum = 0;
    for (int i = 1; i <= n; i++) {
        sum += i;
    }
    return sum;
}
```

Gauss also has a way of solving this

```java
public static int sum2(int n) {
    return n * (n + 1) / 2;
}
```

Which one is more efficient?
Visualizing Difference

Comparing sum1 and sum2.

Number of steps

n
Algorithm growth rates (13.2)

- We measure runtime in proportion to the input data size, N.
  - **growth rate**: Change in runtime as N changes.

- Say an algorithm runs $0.4N^3 + 25N^2 + 8N + 17$ statements.
  - Consider the runtime when N is *extremely large*.
  - We ignore constants like 25 because they are tiny next to N.
  - The highest-order term ($N^3$) dominates the overall runtime.

- We say that this algorithm runs "on the order of" $N^3$.
- or $O(N^3)$ for short (*Big-Oh of N cubed*)
Suppose our list had the contents
public void method(int n) {
    int value = 0;
    for (int i = 0; i < 7; i++) {
        for (int j = 0; j < n; j++) {
            value += j;
        }
    }
    return value + n / 2;
}

What is the Big-O efficiency for this function?
- O(1)
- O(n)
- O(7n)
- O(7n + 4);
- O(n^2)
- O(n^3)
Complexity classes

- **complexity class**: A category of algorithm efficiency based on the algorithm's relationship to the input size N.

<table>
<thead>
<tr>
<th>Class</th>
<th>Big-Oh</th>
<th>If you double N, ...</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>constant</td>
<td>O(1)</td>
<td>unchanged</td>
<td>10ms</td>
</tr>
<tr>
<td>logarithmic</td>
<td>O(log₂ N)</td>
<td>increases slightly</td>
<td>175ms</td>
</tr>
<tr>
<td>linear</td>
<td>O(N)</td>
<td>doubles</td>
<td>3.2 sec</td>
</tr>
<tr>
<td>log-linear</td>
<td>O(N log₂ N)</td>
<td>slightly more than doubles</td>
<td>6 sec</td>
</tr>
<tr>
<td>quadratic</td>
<td>O(N²)</td>
<td>quadruples</td>
<td>1 min 42 sec</td>
</tr>
<tr>
<td>cubic</td>
<td>O(N³)</td>
<td>multiplies by 8</td>
<td>55 min</td>
</tr>
<tr>
<td>exponential</td>
<td>O(2^N)</td>
<td>multiplies drastically</td>
<td>5 * 10^{61} years</td>
</tr>
</tbody>
</table>
Complexity classes

Range algorithm

What complexity class is this algorithm? Can it be improved?

// returns the range of values in the given array;
// the difference between elements furthest apart
// example: range({17, 29, 11, 4, 20, 8}) is 25
public static int range(int[] numbers) {
    int maxDiff = 0; // look at each pair of values
    for (int i = 0; i < numbers.length; i++) {
        for (int j = 0; j < numbers.length; j++) {
            int diff = Math.abs(numbers[j] - numbers[i]);
            if (diff > maxDiff) {
                maxDiff = diff;
            }
        }
    }
    return diff;
}
Range algorithm

What complexity class is this algorithm? Can it be improved?

// returns the range of values in the given array;
// the difference between elements furthest apart
// example: range({17, 29, 11, 4, 20, 8}) is 25
public static int range(int[] numbers) {
    int maxDiff = 0;  // look at each pair of values
    for (int i = 0; i < numbers.length; i++) {
        for (int j = 0; j < numbers.length; j++) {
            int diff = Math.abs(numbers[j] - numbers[i]);
            if (diff > maxDiff) {
                maxDiff = diff;
            }
        }
    }
    return diff;
}
The last algorithm is $O(N^2)$. A slightly better version:

// returns the range of values in the given array;  
// the difference between elements furthest apart  
// example: range({17, 29, 11, 4, 20, 8}) is 25

public static int range(int[] numbers) {
    int maxDiff = 0;  // look at each pair of values
    for (int i = 0; i < numbers.length; i++) {
        for (int j = i + 1; j < numbers.length; j++) {
            int diff = Math.abs(numbers[j] - numbers[i]);
            if (diff > maxDiff) {
                maxDiff = diff;
            }
        }
    }
    return diff;
}
Range algorithm 3

This final version is $O(N)$. It runs MUCH faster:

```java
// returns the range of values in the given array;
// example: range({17, 29, 11, 4, 20, 8}) is 25
public static int range(int[] numbers) {
    int max = numbers[0]; // find max/min values
    int min = max;
    for (int i = 1; i < numbers.length; i++) {
        if (numbers[i] < min) {
            min = numbers[i];
        }
        if (numbers[i] > max) {
            max = numbers[i];
        }
    }
    return max - min;
}
```
Runtime of first 2 versions

- Version 1:

<table>
<thead>
<tr>
<th>N</th>
<th>Runtime (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>15</td>
</tr>
<tr>
<td>2000</td>
<td>47</td>
</tr>
<tr>
<td>4000</td>
<td>203</td>
</tr>
<tr>
<td>8000</td>
<td>781</td>
</tr>
<tr>
<td>16000</td>
<td>3110</td>
</tr>
<tr>
<td>32000</td>
<td>12563</td>
</tr>
<tr>
<td>64000</td>
<td>49937</td>
</tr>
</tbody>
</table>

- Version 2:

<table>
<thead>
<tr>
<th>N</th>
<th>Runtime (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>16</td>
</tr>
<tr>
<td>2000</td>
<td>16</td>
</tr>
<tr>
<td>4000</td>
<td>110</td>
</tr>
<tr>
<td>8000</td>
<td>406</td>
</tr>
<tr>
<td>16000</td>
<td>1578</td>
</tr>
<tr>
<td>32000</td>
<td>6265</td>
</tr>
<tr>
<td>64000</td>
<td>25031</td>
</tr>
</tbody>
</table>
Runtime of 3rd version

- Version 3:

<table>
<thead>
<tr>
<th>N</th>
<th>Runtime (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>0</td>
</tr>
<tr>
<td>4000</td>
<td>0</td>
</tr>
<tr>
<td>8000</td>
<td>0</td>
</tr>
<tr>
<td>16000</td>
<td>0</td>
</tr>
<tr>
<td>32000</td>
<td>0</td>
</tr>
<tr>
<td>64000</td>
<td>0</td>
</tr>
<tr>
<td>128000</td>
<td>0</td>
</tr>
<tr>
<td>256000</td>
<td>0</td>
</tr>
<tr>
<td>512000</td>
<td>0</td>
</tr>
<tr>
<td>1e6</td>
<td>0</td>
</tr>
<tr>
<td>2e6</td>
<td>16</td>
</tr>
<tr>
<td>4e6</td>
<td>31</td>
</tr>
<tr>
<td>8e6</td>
<td>47</td>
</tr>
<tr>
<td>1.67e7</td>
<td>94</td>
</tr>
<tr>
<td>3.3e7</td>
<td>188</td>
</tr>
<tr>
<td>6.5e7</td>
<td>453</td>
</tr>
<tr>
<td>1.3e8</td>
<td>797</td>
</tr>
<tr>
<td>2.6e8</td>
<td>1578</td>
</tr>
</tbody>
</table>
Searching methods

• Implement the following methods:
  - `indexOf` – returns first index of element, or -1 if not found
  - `contains` - returns true if the list contains the given int value

• Why do we need `isEmpty` and `contains` when we already have `indexOf` and `size`?
  - Adds convenience to the client of our class:

```java
// less elegant                   // more elegant
if (myList.size() == 0) {
    if (myList.isEmpty()) {
        if (myList.indexOf(42) >= 0) {
            if (myList.contains(42)) {
```
Sequential search

- **sequential search**: Locates a target value in an array / list by examining each element from start to finish. Used in `indexOf`.

  - How many elements will it need to examine?
  - Example: Searching the array below for the value 42:

| index | 0   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  | 15  | 16  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| value | -4  | 2   | 7   | 10  | 15  | 20  | 22  | 25  | 30  | 36  | 42  | 50  | 56  | 68  | 85  | 92  | 103 |

- The array is sorted. Could we take advantage of this?
Sequential search

- What is its complexity class?

```java
public int indexOf(int value) {
    for (int i = 0; i < size; i++) {
        if (elementData[i] == value) {
            return i;
        }
    }
    return -1; // not found
}
```

- On average, "only" N/2 elements are visited
  - 1/2 is a constant that can be ignored

<table>
<thead>
<tr>
<th>index</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>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>-4</td>
<td>2</td>
<td>7</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>22</td>
<td>25</td>
<td>30</td>
<td>36</td>
<td>42</td>
<td>50</td>
<td>56</td>
<td>68</td>
<td>85</td>
<td>92</td>
<td>103</td>
</tr>
</tbody>
</table>
Binary search (13.1)

- **binary search**: Locates a target value in a *sorted* array or list by successively eliminating half of the array from consideration.
  - How many elements will it need to examine?
  - Example: Searching the array below for the value **42**:

<table>
<thead>
<tr>
<th>index</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>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>-4</td>
<td>2</td>
<td>7</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>22</td>
<td>25</td>
<td>30</td>
<td>36</td>
<td>42</td>
<td>50</td>
<td>56</td>
<td>68</td>
<td>85</td>
<td>92</td>
<td>103</td>
</tr>
</tbody>
</table>

- **min**, **mid**, **max**
Arrays.binarySearch

// searches an entire sorted array for a given value
// returns its index if found; a negative number if not found
// Precondition: array is sorted
Arrays.binarySearch(array, value)

// searches given portion of a sorted array for a given value
// examines minIndex (inclusive) through maxIndex (exclusive)
// returns its index if found; a negative number if not found
// Precondition: array is sorted
Arrays.binarySearch(array, minIndex, maxIndex, value)

- The `binarySearch` method in the `Arrays` class searches an array very efficiently if the array is sorted.
  - You can search the entire array, or just a range of indexes (useful for "unfilled" arrays such as the one in `ArrayIntList`)
Using `binarySearch`

```java
// index          0  1  2  3  4  5  6  7  8  9  10  11  12  13  14  15
int[] a = {-4, 2, 7, 9, 15, 19, 25, 28, 30, 36, 42, 50, 56, 68, 85, 92};

int index  = Arrays.binarySearch(a, 0, 16, 42);  // index1 is 10
int index2 = Arrays.binarySearch(a, 0, 16, 21);  // index2 is -7
```

- `binarySearch` returns the index where the value is found
- If the value is `not` found, `binarySearch` returns:
  
  ```java
  -(insertionPoint + 1)
  ```

  - Where `insertionPoint` is the index where the element `would`
    have been, if it had been in the array in sorted order.
  - To insert the value into the array, negate `insertionPoint + 1`

  ```java
  int indexToInsert21 = -(index2 + 1);  // 6
  ```
Binary search

- **binary search** successively eliminates half of the elements.

  - **Algorithm:** Examine the middle element of the array.
    - If it is too big, eliminate the right half of the array and repeat.
    - If it is too small, eliminate the left half of the array and repeat.
    - Else it is the value we're searching for, so stop.

- Which indexes does the algorithm examine to find value 42?
- What is the runtime complexity class of binary search?

<table>
<thead>
<tr>
<th>index</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>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>-4</td>
<td>2</td>
<td>7</td>
<td>10</td>
<td>15</td>
<td>20</td>
<td>22</td>
<td>25</td>
<td>30</td>
<td>36</td>
<td>42</td>
<td>50</td>
<td>56</td>
<td>68</td>
<td>85</td>
<td>92</td>
<td>103</td>
</tr>
</tbody>
</table>

• min
• mid
• max
Binary search runtime

- For an array of size $N$, it eliminates $\frac{1}{2}$ until 1 element remains.
  
  $N, \frac{N}{2}, \frac{N}{4}, \frac{N}{8}, \ldots, 4, 2, 1$

- How many divisions does it take?

- Think of it from the other direction:
  
  - How many times do I have to multiply by 2 to reach $N$?
    
    $1, 2, 4, 8, \ldots, \frac{N}{4}, \frac{N}{2}, N$
  
  - Call this number of multiplications "$x$".

  \[ 2^x = N \]

  \[ x = \log_2 N \]

- Binary search is in the \textit{logarithmic} complexity class.
### Collection efficiency

- Efficiency of our Java's **ArrayList** and **LinkedList** methods:

<table>
<thead>
<tr>
<th>Method</th>
<th>ArrayList</th>
<th>LinkedList</th>
</tr>
</thead>
<tbody>
<tr>
<td>add</td>
<td>O(1)*</td>
<td>O(1)</td>
</tr>
<tr>
<td>add(index, value)</td>
<td>O(N)</td>
<td>O(N)</td>
</tr>
<tr>
<td>indexOf</td>
<td>O(N)</td>
<td>O(N)</td>
</tr>
<tr>
<td>get</td>
<td>O(1)</td>
<td>O(N)</td>
</tr>
<tr>
<td>remove</td>
<td>O(N)</td>
<td>O(N)</td>
</tr>
<tr>
<td>set</td>
<td>O(1)</td>
<td>O(N)</td>
</tr>
<tr>
<td>size</td>
<td>O(1)</td>
<td>O(1)</td>
</tr>
</tbody>
</table>

* Most of the time!
Recall two weeks ago when we counted the number of unique words in a file. Our first attempt

```java
public static int uniqueWords(Scanner input) {
    List<String> words = new LinkedList<String>();
    while (input.hasNext()) {
        String word = input.next();
        if (!words.contains(word)) {
            words.add(word);
        }
    }
    return words.size();
}
```
Throw Back: Unique words

- Recall two weeks ago when we counted the number of unique words in a file. Our second attempt
- We saw briefly that operations on HashSet are $O(1)$

```java
public static int uniqueWords(Scanner input) {
    Set<String> words = new HashSet<String>();
    while (input.hasNext()) {
        String word = input.next();
        words.add(word);
    }
    return words.size();
}
```
Max subsequence sum

- Write a method `maxSum` to find the largest sum of any contiguous subsequence in an array of integers.
  - Easy for all positives: include the whole array.
  - What if there are negatives?

<table>
<thead>
<tr>
<th>index</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>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>2</td>
<td>1</td>
<td>-4</td>
<td>10</td>
<td>15</td>
<td>-2</td>
<td>22</td>
<td>-8</td>
<td>5</td>
</tr>
</tbody>
</table>

Largest sum: $10 + 15 + -2 + 22 = 45$

- (Let's define the max to be 0 if the array is entirely negative.)

- Ideas for algorithms?
Algorithm 1 pseudocode

maxSum(a):

max = 0.
for each starting index i:
    for each ending index j:
        sum = add the elements from a[i] to a[j].
        if sum > max,
           max = sum.

return max.

<table>
<thead>
<tr>
<th>index</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>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>2</td>
<td>1</td>
<td>-4</td>
<td>10</td>
<td>15</td>
<td>-2</td>
<td>22</td>
<td>-8</td>
<td>5</td>
</tr>
</tbody>
</table>
What complexity class is this algorithm?

- $O(N^3)$. Takes a few seconds to process 2000 elements.

```java
public static int maxSum1(int[] a) {
    int max = 0;
    for (int i = 0; i < a.length; i++) {
        for (int j = i; j < a.length; j++) {
            // sum = add the elements from a[i] to a[j].
            int sum = 0;
            for (int k = i; k <= j; k++) {
                sum += a[k];
            }
            if (sum > max) {
                max = sum;
            }
        }
    }
    return max;
}
```
Flaws in algorithm 1

- Observation: We are redundantly re-computing sums.
  - For example, we compute the sum between indexes 2 and 5: \(a[2] + a[3] + a[4] + a[5]\)
  - We already had computed the sum of 2-5, but we compute it again as part of the 2-6 computation.
- Let's write an improved version that avoids this flaw.

<table>
<thead>
<tr>
<th>index</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>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>2</td>
<td>1</td>
<td>-4</td>
<td>10</td>
<td>15</td>
<td>-2</td>
<td>22</td>
<td>-8</td>
<td>5</td>
</tr>
</tbody>
</table>
Algorithm 2 code

- What complexity class is this algorithm?
  - $O(N^2)$. Can process tens of thousands of elements per second.

```java
public static int maxSum2(int[] a) {
    int max = 0;
    for (int i = 0; i < a.length; i++) {
        int sum = 0;
        for (int j = i; j < a.length; j++) {
            sum += a[j];
            if (sum > max) {
                max = sum;
            }
        }
    }
    return max;
}
```

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<td>5</td>
</tr>
</tbody>
</table>
A clever solution

- **Claim 1**: A max range cannot start with a negative-sum range.

  
  \[
  \begin{array}{cccccc}
  i & \ldots & j & j+1 & \ldots & k \\
  \hline
  < 0 & \text{sum}(j+1, k) \\
  \text{sum}(i, k) & < & \text{sum}(j+1, k)
  \end{array}
  \]

- **Claim 2**: If \(\text{sum}(i, j-1) \geq 0\) and \(\text{sum}(i, j) < 0\), any max range that ends at \(j+1\) or higher cannot start at any of \(i\) through \(j\).

  
  \[
  \begin{array}{cccccc}
  i & \ldots & j-1 & j & j+1 & \ldots & k \\
  \hline
  \geq 0 & < 0 & \text{sum}(j+1, k) \\
  < 0 & \text{sum}(j+1, k) \\
  \text{sum}(?, k) & < & \text{sum}(j+1, k)
  \end{array}
  \]

- Together, these observations lead to a very clever algorithm...
Algorithm 3 code

- What complexity class is this algorithm?
  - $O(N)$. Handles many millions of elements per second!

```java
public static int maxSum3(int[] a) {
    int max = 0;
    int sum = 0;
    int i = 0;
    for (int j = 0; j < a.length; j++) {
        if (sum < 0) {
            // if sum becomes negative, max range
            i = j;  // cannot start with any of i - j-1
            sum = 0;  // (Claim 2)
        }
        sum += a[j];
        if (sum > max) {
            max = sum;
        }
    }
    return max;
}
```