SEARCHING, SORTING, AND ASYMPTOTIC COMPLEXITY

Lecture 11
CS2110 – Spring 2016

Time spent on A2

<table>
<thead>
<tr>
<th>Histogram: [inclusive:exclusive)</th>
<th>Gave time: 543</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0:1): 0</td>
<td>No time: 34</td>
</tr>
<tr>
<td>[1:2): 24  *****</td>
<td>Average: 4.3</td>
</tr>
<tr>
<td>[2:3): 84  ********************</td>
<td>Median: 4</td>
</tr>
<tr>
<td>[3:4): 123  ********************</td>
<td></td>
</tr>
<tr>
<td>[4:5): 125  ********************</td>
<td></td>
</tr>
<tr>
<td>[5:6): 80  ********************</td>
<td>3 people took</td>
</tr>
<tr>
<td>[6:7): 37  ********************</td>
<td>more than 11 hrs</td>
</tr>
<tr>
<td>[7:8): 25  *****</td>
<td></td>
</tr>
<tr>
<td>[8:9): 20  *****</td>
<td></td>
</tr>
<tr>
<td>[9:10): 5  *</td>
<td></td>
</tr>
</tbody>
</table>

A2 and Prelim

- Some time this morning, you should be able to see your feedback on “A3 test” (if you submitted it). We are again making A3 available.
  Deadline for A3: Wednesday night.
  Only one late day allowed (Thursday)
- Prelim: Next Tuesday.
  Remember to read about conflicts on the course website (under Exams) and to complete “assignment” P1 Conflict on the CMS.
  So far, 23 people filled it out.
  Deadline for completing it: Wednesday night.

Merge two adjacent sorted segments

```java
// Merge two adjacent sorted segments
// Sort b[h..k]. Precondition: b[h..t] and b[t+1..k] are sorted.
public static merge(int[] b, int h, int t, int k) {
    int[] c = new int[k - h];
    int i = 0, j = h - t;
    while (i < c.length && j < t - h)
        if (c[i] >= b[j]) c[i] = c[i] - b[j];
        else c[i] = b[j++];
    for (int u = j; u < t - h; u++) c[i++] = b[u];
    for (int v = 0; v < c.length; v++) b[h + v] = c[v];
}
```

We leave you to write this method. Just move values from c and b[t+1..k] into b in the right order, from smallest to largest.
Runs in time linear in size of b[h..k].
Mergesort

```java
/** Sort b[h..k] */
public static void mergesort(int[] b, int h, int k) {
    if (size b[h..k] < 2)
        return;
    int t = (h+k)/2;
    mergesort(b, h, t);
    mergesort(b, t+1, k);
    merge(b, h, t, k);
}
```

**Mergesort**

```java
/** Sort b[h..k] */
public static void mergesort(int[] b, int h, int k) {
    if (size b[h..k] < 2)
        return;
    int t = (h+k)/2;
    mergesort(b, h, t);
    mergesort(b, t+1, k);
    merge(b, h, t, k);
}
```

Merge: time proportional to n
Depth of recursion: log n
Can therefore show (later) that time taken is proportional to n log n
But space is also proportional to n!

QuickSort versus MergeSort

```java
/** Sort b[h..k] */
public static void QS(int[] b, int h, int k) {
    if (k – h < 1)
        return;
    int j = partition(b, h, k);
    QS(b, h, j-1);
    QS(b, j+1, k);
}
```

```java
/** Sort b[h..k] */
public static void MS(int[] b, int h, int k) {
    if (k – h < 1)
        return;
    MS(b, h, (h+k)/2);
    MS(b, (h+k)/2 + 1, k);
    merge(b, h, (h+k)/2, k);
}
```

One processes the array then recurses. One recurses then processes the array.

**QuickSort versus MergeSort**

```java
/** Sort b[h..k] */
public static void QS(int[] b, int h, int k) {
    if (k – h < 1)
        return;
    int j = partition(b, h, k);
    QS(b, h, j-1);
    QS(b, j+1, k);
}
```

```java
/** Sort b[h..k] */
public static void MS(int[] b, int h, int k) {
    if (k – h < 1)
        return;
    MS(b, h, (h+k)/2);
    MS(b, (h+k)/2 + 1, k);
    merge(b, h, (h+k)/2, k);
}
```

Readings, Homework

- Textbook: Chapter 4
- Homework:
  - Recall our discussion of linked lists and A2.
  - What is the worst case time for appending an item to a linked list? For testing to see if the list contains X? What would be the best case time for these operations?
  - If we were going to talk about time (speed) for operating on a list, which makes more sense: worst-case, average-case, or best-case time? Why?

What Makes a Good Algorithm?

Suppose you have two possible algorithms or ADT implementations that do the same thing; which is better?

What do we mean by better?
- Faster?
- Less space?
- Easier to code?
- Easier to maintain?
- Required for homework?

How do we measure time and space of an algorithm?

Basic Step: One “constant time” operation

- If-statement: number of basic steps on branch that is executed
- Loop: (number of basic steps in loop body) * (number of iterations) – also bookkeeping
- Method: number of basic steps in method body (include steps needed to prepare stack-frame)
### Counting basic steps in worst-case execution

**Linear Search**  
Let \( n = b.\text{length} \)

```java
/** return true iff \( v \) is in \( b \) */
static boolean find(int [] b, int v) {
  for (int i = 0; i < b.length; i++) {
    if (b[i] == v) return true;
  }
  return false;
}
```

We sometimes simplify counting by counting only important things. Here, it’s the number of array element comparisons \( b[i] == v \).
That’s the number of loop iterations: \( n \).

### Sample Problem: Searching

**Second solution:**  
**Binary Search**

```java
int bsearch(int [] b, int v) {
  int h= -1;
  int k= b.length;
  while (h+1 != k) {
    int e= (h+ k)/2;
    if (b[e] <= v)  h= e;
    else  k= e;
  }
  return h;
}
```

### What do we want from a definition of “runtime complexity”?

1. Distinguish among cases for large \( n \), not small \( n \)
2. Distinguish among important cases, like:
   - \( n^2 \) basic operations
   - \( n \) basic operations
   - \( \log n \) basic operations
   - 5 basic operations
3. Don’t distinguish among trivially different cases.
   - 5 or 50 operations
   - \( n, n^2, \) or 4n operations

### Prove that \( (n^2 + n) \) is \( O(n^2) \)

**Formal definition:**  
\( f(n) \) is \( O(g(n)) \) if there exist constants \( c > 0 \) and \( N \geq 0 \) such that for all \( n \geq N \), \( f(n) \leq c \cdot g(n) \)

**Example:**  
Prove that \( (n^2 + n) \) is \( O(n^2) \)

**Methodology:**
- Start with \( f(n) \) and slowly transform into \( c \cdot g(n) \):
  - Use \( = \) and \( \leq \) and \( < \) steps
  - At appropriate point, can choose \( N \) to help calculation
  - At appropriate point, can choose \( c \) to help calculation
Prove that \((n^2 + n)\) is \(O(n^2)\)

**Example:** Prove that \((n^2 + n)\) is \(O(n^2)\)

\[
\begin{align*}
 f(n) &= \text{<definition of } f(n)> \\
 &= n^2 + n \\
 &\leq \text{<for } n \geq 1, \quad n \leq n^2> \\
 &= 2^n \\
 &= \text{<choose } g(n) = n^2> \\
 &= 2 \times g(n)
\end{align*}
\]

Choose \(N = 1\) and \(c = 2\)

Formal definition: \(f(n)\) is \(O(g(n))\) if there exist constants \(c > 0\) and \(N \geq 0\) such that for all \(n \geq N\), \(f(n) \leq c \times g(n)\)

**Choose** \(N = 1\) and \(c = 101\)

Prove that \(100n + \log n\) is \(O(n)\)

\[
\begin{align*}
 f(n) &= \text{<put in what } f(n)\text{ is>} \\
 &= 100n + \log n \\
 &\leq \text{<We know } \log n \leq n \text{ for } n \geq 1> \\
 &= 100n + n \\
 &= 101n \\
 &= \text{<g(n) = n>} \\
 &= 101g(n)
\end{align*}
\]

Formal definition: \(f(n)\) is \(O(g(n))\) if there exist constants \(c\) and \(N\) such that for all \(n \geq N\), \(f(n) \leq c \times g(n)\)

Choose \(N = 1\) and \(c = 101\)

**O(\ldots) Examples**

Let \(f(n) = 3n^2 + 6n - 7\)

- \(f(n)\) is \(O(n^2)\)
- \(f(n)\) is \(O(n^2)\)
- \(f(n)\) is \(O(n^2)\)
- \(\ldots\)
- \(p(n) = 4n \log n + 34 n - 89\)
  - \(p(n)\) is \(O(n \log n)\)
  - \(p(n)\) is \(O(n^2)\)
  - \(h(n) = 20 \cdot 2^x + 40n\)
  - \(h(n)\) is \(O(2^n)\)
- \(a(n) = 34\)
- \(a(n)\) is \(O(1)\)

Only the leading term (the term that grows most rapidly) matters.

If it’s \(O(n^2)\), it’s also \(O(n^3)\), etc! However, we always use the smallest one.

**Commonly Seen Time Bounds**

| \(O(1)\) | constant | excellent |
| \(O(\log n)\) | logarithmic | excellent |
| \(O(n)\) | linear | good |
| \(O(n \log n)\) | quadratic | OK |
| \(O(n^2)\) | cubic | maybe OK |
| \(O(2^n)\) | exponential | too slow |

**Problem-size examples**

Suppose a computer can execute 1000 operations per second; how large a problem can we solve?

<table>
<thead>
<tr>
<th>algo</th>
<th>1 second</th>
<th>1 minute</th>
<th>1 hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>(O(n))</td>
<td>1000</td>
<td>60,000</td>
<td>3,600,000</td>
</tr>
<tr>
<td>(O(n \log n))</td>
<td>140</td>
<td>4893</td>
<td>200,000</td>
</tr>
<tr>
<td>(O(n^2))</td>
<td>31</td>
<td>244</td>
<td>1897</td>
</tr>
<tr>
<td>(3n^2)</td>
<td>18</td>
<td>144</td>
<td>1096</td>
</tr>
<tr>
<td>(O(n^3))</td>
<td>10</td>
<td>39</td>
<td>153</td>
</tr>
<tr>
<td>(O(2^n))</td>
<td>9</td>
<td>15</td>
<td>21</td>
</tr>
</tbody>
</table>

**Why bother with runtime analysis?**

Computers so fast that we can do whatever we want using simple algorithms and data structures, right?

Not really — data-structure/algorithm improvements can be a very big win.

Problem of size \(n=10^4\)

- \(A: 10^4\) sec \(\approx 17\) minutes
- \(A': 10^4\) sec \(\approx 1.7\) minutes
- \(B: 10^5\) sec \(\approx 17\) minutes

Problem of size \(n=10^6\)

- \(A: 10^6\) sec \(\approx 30\) years
- \(A': 10^6\) sec \(\approx 3\) years
- \(B: 2 \times 10^7\) sec \(\approx 2\) days

1 day \(\approx 86,400\) sec \(\approx 10^5\) sec
1,000 days \(\approx 3\) years
Human genome
= 3.5 billion nucleotides
~ 1 Gb

@1 base-pair
instruction/µsec

\[ n^2 \rightarrow 388445 \text{ years} \]
\[ n \log n \rightarrow 30.824 \text{ hours} \]
\[ n \rightarrow 1 \text{ hour} \]

Worst-Case/Expected-Case Bounds

May be difficult to determine time bounds for all imaginable inputs of size \( n \)

- **Worst-case**
  - Determine how much time is needed for the worst possible input of size \( n \)

- **Expected-case**
  - Determine how much time is needed on average for all inputs of size \( n \)

Simplifying Assumptions

- Use the size of the input rather than the input itself – \( n \)
- Count the number of "basic steps" rather than computing exact time
- Ignore multiplicative constants and small inputs (order-of, big-O)
- Determine number of steps for either
  - worst-case
  - expected-case

These assumptions allow us to analyze algorithms effectively

Worst-Case Analysis of Searching

- **Linear Search**

```java
static boolean find(int[] b, int v) {
    for (int x : b) {
        if (x == v)
            return true;
    }
    return false;
}
```

- **Binary Search**

```java
int h = -1;
int t = b.length;
while (h != t-1) {
    int e = (h + t) / 2;
    if (b[e] <= v)  h = e;
    else
        t = e;
}
```

Always \( (\log \#b + 1) \) iterations.
Worst-case and expected times: \( O(\log \#b) \)

Analysis of Matrix Multiplication

Multiply \( n \times n \) matrices \( A \) and \( B \):

- Input size is really \( 2n^2 \), not \( n \)
- Worst-case time: \( O(n^3) \)
- Expected-case time: \( O(n^2) \)

```java
for (i = 0; i < n; i++)
    for (j = 0; j < n; j++) {
        c[i][j] = 0;
        for (k = 0; k < n; k++)
            c[i][j] += a[i][k]*b[k][j];
    }
```

Convention, matrix problems measured in terms of \( n \), the number of rows, columns

- Input size is really \( 2n^2 \), not \( n \)
- Worst-case time: \( O(n^3) \)
- Expected-case time: \( O(n^2) \)
Remarks

Once you get the hang of this, you can quickly zero in on what is relevant for determining asymptotic complexity.

- Example: you can usually ignore everything that is not in the innermost loop. Why?

One difficulty:
- Determining runtime for recursive programs
  Depends on the depth of recursion

Limitations of Runtime Analysis

Big-O can hide a very large constant.
- Example: selection
- Example: small problems

The specific problem you want to solve may not be the worst case.
- Example: Simplex method for linear programming

Your program may not run often enough to make analysis worthwhile.
- Example: one-shot vs. every day
- You may be analyzing and improving the wrong part of the program
- Very common situation
- Should use profiling tools

What you need to know / be able to do

- Know the definition of \( f(n) = O(g(n)) \)
- Be able to prove that some function \( f(n) = O(g(n)) \). The simplest way is as done on two slides above.
- Know worst-case and average (expected) case \( O(\ldots) \) of basic searching/sorting algorithms: linear/binary search, partition alg of quicksort, insertion sort, selection sort, quicksort, merge sort.
- Be able to look at an algorithm and figure out its worst case \( O(\ldots) \) based on counting basic steps or things like array-element swaps

Lower Bound for Comparison Sorting

Goal: Determine minimum time required to sort \( n \) items

Note: we want worst-case, not best-case time

- Best-case doesn’t tell us much. E.g. Insertion Sort takes \( O(n) \) time on already-sorted input
- Want to know worst-case time for best possible algorithm

How can we prove anything about the best possible algorithm?
- Want to find characteristics that are common to all sorting algorithms
- Limit attention to comparison-based algorithms and try to count number of comparisons

Comparison Trees

- Comparison-based algorithms make decisions based on comparison of data elements
- Gives a comparison tree
- If algorithm fails to terminate for some input, comparison tree is infinite
- Height of comparison tree represents worst-case number of comparisons for that algorithm
- Can show: Any correct comparison-based algorithm must make at least \( n \log n \) comparisons in the worst case

Lower Bound for Comparison Sorting

- Say we have a correct comparison-based algorithm
- Suppose we want to sort the elements in an array \( b[] \)
- Assume the elements of \( b[] \) are distinct
- Any permutation of the elements is initially possible
- When done, \( b[] \) is sorted
- But the algorithm could not have taken the same path in the comparison tree on different input permutations
Lower Bound for Comparison Sorting

How many input permutations are possible? \( n! - 2^{n \log n} \)

For a comparison-based sorting algorithm to be correct, it must have at least that many leaves in its comparison tree.

To have at least \( n! - 2^{n \log n} \) leaves, it must have height at least \( n \log n \) (since it is only binary branching, the number of nodes at most doubles at every depth).

Therefore its longest path must be of length at least \( n \log n \), and that is its worst-case running time.

Mergesort

```java
/** Sort b[h..k] */
public static mergesort(int[] b, int h, int k) {
  if (size b[h..k] < 2)
    return;
  int t = (h+k)/2;
  mergesort(b, h, t);
  mergesort(b, t+1, k);
  merge(b, h, t, k);
}
```

Runtime recurrence
\[
T(n): \text{ time to sort array of size } n
T(1) = 1
T(n) = 2T(n/2) + O(n)
\]

Can show by induction that \( T(n) \) is \( O(n \log n) \).

Alternatively, can see that \( T(n) \) is \( O(n \log n) \) by looking at tree of recursive calls.