Solutions to Third Examination

CS 430 Introduction to Algorithms
Spring, 2016

Wednesday, April 27, 2016
10am–11:15am & 11:25am–12:40pm, 111 Life Sciences

Exam Statistics

111 students took the exam. The range of scores was 0–95, with a mean of 45.85, a median of 46, and a standard deviation of 20.18.

Problem Solutions

1. Fibonacci Heaps

(a) Tall-Heap(1, b) clearly produces

\[
\begin{array}{c}
\bullet \\
\end{array}
\]

because line 1 creates an empty Fibonacci heap, after which line 2 inserts b. Tall-Heap(2, b) creates an empty Fibonacci heap T in line 5, after which lines 6–8 insert b − 1, b, and b + 1, respectively, all singleton nodes at the root level. The EXTRACT-MIN(T) deletes b − 1, but then the consolidation phase then combines the two remaining roots each have degree 0 into

\[
\begin{array}{c}
\bullet \\
\bullet \\
\end{array}
\]

That takes care of the base cases. Now assume that Tall-Heap(h, b) produces
Tall-Heap\((h + 1, b)\), for \(h + 1 > 2\) first calls Tall-Heap\((h, b + 1)\) producing the heap

\[
\begin{array}{c}
\circ b \\
\circ b + 1 \\
\circ b + 2 \\
\vdots \\
\circ b + h - 1 \\
\end{array}
\]

by induction. Inserting \(b - 0.5, b,\) and \(b + 0.5\) adds these three values as roots of degree 0. Extracting the minimum deletes \(b - 0.5,\) and the consolidation phase first merges degree 0 roots \(b,\) and \(b + 0.5\) into

\[
\begin{array}{c}
\circ b \\
\circ b + 0.5 \\
\end{array}
\]

and then combines the two roots of degree 1 to form
whereupon deleting $b + 0.5$ produces

as desired.

(b) Although generally both extracting the minimum or deleting an element require amortized time $O(\log n)$ in a Fibonacci heap of $n$ elements, here the consolidation phase takes only $O(1)$ worst-case time; making the heap initially and doing the insertions are all $O(1)$ worst-case time. Thus Tall-Heap($h + 1, b$) takes time $O(h)$.

(c) By part (a), Tall-Heap($n, 1$) produces
2. Depth First Search

function DFS-visit(u)
1: color[u] ← GRAY
2: d[u] ← time ← time + 1
3: for all v ∈ Adj[u] do
4: if color[v] = WHITE then
5: Tree edge
6: π[v] ← u
7: DFS-visit(v)
8: else if color[v] = GRAY then
9: Back edge
10: else if d[u] < d[v] then
11: Forward edge
12: else
13: Cross edge
14: end if
15: end for
16: color[u] ← BLACK
17: f[u] ← time ← time + 1

3. Shortest Paths

(a) Consider two paths: \( P_1 = (u, u_1, u_2, \ldots, v) \) and \( P_2 = (u, v_1, v_2, \ldots, v) \) of equal length, \( L = |P_1| = |P_2| \). Under the transformation, the path length telescopes:

\[
|P_1|' = \sum_{\text{edge } (a,b) \in P_1} \frac{w_V(a) + w_V(u_b)}{2} = |P_1| - \frac{w_V(u) + w_V(v)}{2} = L - \frac{w_V(u) + w_V(v)}{2}
\]

and

\[
|P_2|' = \sum_{\text{edge } (a,b) \in P_2} \frac{w_V(a) + w_V(u_b)}{2} = |P_2| - \frac{w_V(u) + w_V(v)}{2} = L - \frac{w_V(u) + w_V(v)}{2}
\]

Thus, equal paths in the vertex-weighted graph also have equal path lengths in the edge-weighted graph.

(b) Reasoning as in part (a), the newly weighted paths differ by:

\[
|P_2|' - |P_1|' = |P_2| - \frac{w_V(u) + w_V(v)}{2} - |P_1| + \frac{w_V(u) + w_V(v)}{2} = |P_2| - |P_1|
\]

So that if \( P_1 \) is shorter than \( P_2 \) in the vertex-weighted graph, it will also be shorter in the edge-weighted graph.
4. NP-Completeness

The EXAM3-SCHEDULING decision problem is “Given an $n \times n$ graph job compatibility matrix $C_{ij}$ and a constant $d$, can the $n$ jobs be scheduled in $d$ days?”

EXAM3-SCHEDULING is clearly in the class NP because given $C_{ij}$ and a proposed schedule using $d$ days, we can easily check in time $O(n^2)$ whether the schedule has two incompatible jobs scheduled for the same day.

To prove EXAM3-SCHEDULING is NP-hard, we reduce from GRAPH-COLORING (Problem 34-3 on page 1103 in CLRS; discussed at length in the lectures of April 11–13 and in HW 8). Given a graph $G = (V, E)$ and an integer $k > 0$, we can determine whether $G$ can be $k$-colored by using the $|V| \times |V|$ Boolean matrix which is the adjacency matrix for $G$ (see page 591 of CLRS or the lecture notes from March 28) as a compatibility matrix for $|V|$ jobs and $k$ as the number of days. If the jobs can be scheduled, assign a unique color to each of the $k$ days and color each job (vertex) with a color of the day on which it is scheduled. Similarly, if the graph can be colored with $k$ colors, the coloring gives a $k$-day schedule for the $|V|$ jobs.

5. Spanning Tree Approximation

(a) The following graph achieves the desired result for any $k > 0$:

![Diagram of a graph with vertices A, B, and C and edges AB, AC, and BC with costs 1, 2k, and 1 respectively.]

The minimum spanning tree MST has edges $AB$ and $BC$ with cost 2. But the stupid algorithm could construct the spanning tree ST consisting of $AC$ and $BC$ with cost $2k + 1$. Now

$$\frac{|ST|}{|MST|} = \frac{2k + 1}{2} > k.$$

(b) The new approximation bound is clearly 2 because any spanning tree has $|V| - 1$ edges, and hence the MST has cost at least $|V| - 1$. But no edge costs more than 2, so the stupid tree will have cost at most $2|V| - 2$. Thus

$$\frac{|ST|}{|MST|} \leq \frac{2}{1} = 2.$$