Problem Set 9

MIT students: This problem set is due in lecture on *Wednesday, November 21*.

SMA students: This problem set is due after recitation on *Friday, November 23*.

Reading: Chapters 22 and 24.

Both exercises and problems should be solved, but *only the problems* should be turned in. Exercises are intended to help you master the course material. Even though you should not turn in the exercise solutions, you are responsible for material covered by the exercises.

Mark the top of each sheet with your name, the course number, the problem number, your recitation instructor and time, the date, and the names of any students with whom you collaborated.

MIT students: Each problem should be done on a separate sheet (or sheets) of three-hole punched paper.

SMA students: Each problem should be done on a separate sheet (or sheets) of two-hole punched paper.

You will often be called upon to "give an algorithm" to solve a certain problem. Your write-up should take the form of a short essay. A topic paragraph should summarize the problem you are solving and what your results are. The body of your essay should provide the following:

1. A description of the algorithm in English and, if helpful, pseudocode.
2. At least one worked example or diagram to show more precisely how your algorithm works.
3. A proof (or indication) of the correctness of the algorithm.
4. An analysis of the running time of the algorithm.

Remember, your goal is to communicate. Graders will be instructed to take off points for convoluted and obtuse descriptions.

Exercise 9-1. Do exercise 22.2-7 on page 539 of CLRS.

Exercise 9-2. Do exercise 22.3-12 on page 549 of CLRS.

Exercise 9-3. Do exercise 22.4-3 on page 552 of CLRS.

Exercise 9-4. Do exercise 24.1-4 on page 591 of CLRS.

Exercise 9-5. Do exercise 24.3-6 on page 600 of CLRS.

Exercise 9-6. Do exercise 24.5-7 on page 614 of CLRS.

Problem 9-1. Running in Boston

To get in shape, you have decided to start running to work. You want a route that goes entirely uphill and then entirely downhill so that you can work up a sweat going uphill and then get a nice breeze at the end of your run as you run faster downhill. Your run will start at home and end at work and you have a map detailing the roads with m road segments (any existing road between two intersections) and n intersections. Each road segment has a positive length, and each intersection has a distinct elevation.

(a) Assuming that every road segment is either uphill or downhill, give an efficient algorithm to find the shortest route that meets your specifications.

(b) Give an efficient algorithm to solve the problem if some roads may be level (i.e., both intersections at the end of the road segments are at the same elevation) and therefore can be taken at any point.

Problem 9-2. Karp's minimum mean-weight cycle algorithm

Let $G = (V, E)$ be a directed graph with weight function $w : E \to \mathbb{R}$, and let $n = |V|$. We define the ***mean weight*** of a cycle $c = \langle e_1, e_2, \ldots, e_k \rangle$ of edges in E to be

$$\mu(c) = \frac{1}{k} \sum_{i=1}^{k} w(e_i) .$$

Let $\mu^* = \min_c \mu(c)$, where c ranges over all directed cycles in G. A cycle c for which $\mu(c) = \mu^*$ is called a ***minimum mean-weight cycle***. This problem investigates an efficient algorithm for computing μ^*.

Assume without loss of generality that every vertex $v \in V$ is reachable from a source vertex $s \in V$. Let $\delta(s, v)$ be the weight of a shortest path from s to v, and let $\delta_k(s, v)$ be the weight of a shortest path from s to v consisting of *exactly* k edges. If there is no path from s to v with exactly k edges, then $\delta_k(s, v) = \infty$.

(a) Show that if $\mu^* = 0$, then G contains no negative-weight cycles and $\delta(s, v) = \min_{0 \le k \le n-1} \delta_k(s, v)$ for all vertices $v \in V$.

(b) Show that if $\mu^* = 0$, then

$$\max_{0 \le k \le n-1} \frac{\delta_n(s, v) - \delta_k(s, v)}{n - k} \ge 0$$

for all vertices $v \in V$. (*Hint:* Use both properties from part (a).)

(c) Let c be a 0-weight cycle, and let u and v be any two vertices on c. Suppose that the weight of the path from u to v along the cycle is x. Prove that $\delta(s, v) = \delta(s, u) + x$. (*Hint:* The weight of the path from v to u along the cycle is $-x$.)

(d) Show that if $\mu^* = 0$, then there exists a vertex v on the minimum mean-weight cycle such that

$$\max_{0 \le k \le n-1} \frac{\delta_n(s, v) - \delta_k(s, v)}{n - k} = 0 .$$

(*Hint:* Show that a shortest path to any vertex on the minimum mean-weight cycle can be extended along the cycle to make a shortest path to the next vertex on the cycle.)

(e) Show that if $\mu^* = 0$, then

$$\min_{v \in V} \max_{0 \le k \le n-1} \frac{\delta_n(s, v) - \delta_k(s, v)}{n - k} = 0 .$$

(f) Show that if we add a constant t to the weight of each edge of G, then μ^* is increased by t. Use this to show that

$$\mu^* = \min_{v \in V} \max_{0 \le k \le n-1} \frac{\delta_n(s, v) - \delta_k(s, v)}{n - k} .$$

(g) Give an $O(VE)$-time algorithm to compute μ^*.