CS/ECE 374 A ✧ Spring 2026

Homework 9

Due Tuesday, April 7, 2026 at 9pm Central Time

This is the last homework before Midterm 2.

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1. Suppose you are given a directed graph $G = (V, E)$ with n vertices and m edges. Each vertex $v \in V$ is assigned a number $c(v)$. You are also given four vertices $s, t, s', t' \in V$ and a positive integer $k \leqslant n$. You may assume $m \geqslant n$.

   Given two walks $W = \langle s, u_1, u_2, \ldots, u_{k-1}, t\rangle$ and $W' = \langle s', v_1, v_2, \ldots, v_{k-1}, t'\rangle$ of length k in G, we define their ***pair-by-pair discrepancy*** by the value $\sum_{i=1}^{k-1} |c(u_i) - c(v_i)|$. Describe an algorithm that either returns the minimum pair-by-pair discrepancy over all pairs of (s, t)- and (s', t')-walks of length k or returns ∞ if no such pair exists. State your running time in terms of k, m, and n.

2. Suppose you are given a directed graph $G = (V, E)$ with n vertices and $m \geqslant n$ edges. Each edge $e \in E$ has a length $\ell(e)$ along with an associated character $c(e) \in \{0, 1\}$ from the binary alphabet. Each walk $W = \langle e_1, e_2, \ldots, e_r \rangle$ in G encodes a string $c(W) = c(e_1)c(e_2)\ldots c(e_r)$.

   You are also given a DFA $M = (\{0, 1\}, Q, \delta, s, A)$. Concretely, the input DFA M is represented as follows:

   - $Q = \{1, 2, \ldots, k\}$ for some integer k.
   - The start state s is state 1.
   - Accepting states are represented by a Boolean array $Acc[1..k]$ where $Acc[q] = \textsc{True}$ if and only if $q \in A$.
   - The transition function δ is represented by an integer array $Delta[1..k, 0..1]$ where $Delta[q, a] = \delta(q, a)$.

   (Note that the representation of δ has changed slightly since Homework 7, because we are describing a **D**FA here as opposed to an NFA.)

   (a) Suppose the length $\ell(e)$ of each edge e can be positive, zero, or *negative*. Describe a graph G and DFA M where
   - G contains a negative length cycle,
   - M accepts an infinite set of strings, and
   - Every walk in G encoding a string accepted by M has positive length.

   (b) Now suppose the length $\ell(e)$ of each edge e is *positive*.

   Describe an algorithm to compute the length of the shortest *walk* W in G for which $c(W)$ is accepted by the DFA M. You may assume there exists at least one walk that encodes a string accepted by M.

For this problem, you do not need to start your solution to part (b) on a new page or include a separate list of source and collaborators for parts (a) and (b).

   (c) ***Practice only. Do not submit solutions.***

   Suppose instead that the lengths of edges can be negative after all. Describe an algorithm that *either* computes the length of the shortest *walk* W in G for which $c(W)$ is accepted by the DFA M or correctly reports that no shortest walk *of that type* exists.

3. ***Practice only. Do not submit solutions.***

After a grueling midterm at the See-Bull Center for Commuter Silence, you decide to take the bus home. Since you planned ahead, you have a schedule that lists the times and locations of every stop of every bus in Sham-Poobanana. Unfortunately, no single bus visits both the See-Bull Center and your home; you must change buses at least once. There are exactly b different buses. Each bus starts at 12:00:01AM, makes exactly n stops, and finally stops running at 11:59:59PM. Buses always run exactly on schedule, and you have an accurate watch. Finally, you are far too tired to walk between bus stops.

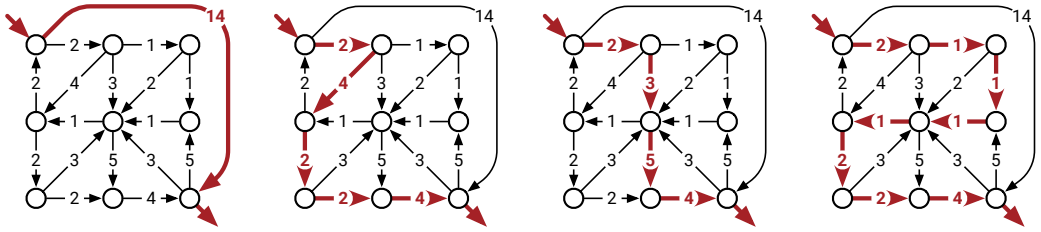
(a) Describe and analyze an algorithm to determine a sequence of bus rides that gets you home as early as possible. Your goal is to minimize your *arrival time*, not the time you spend traveling.

(b) Oh, no! The midterm was held barely a week after Easter and the Sham-Poobanana Moving Transports Department is unloading an excess supply of stale Peeps at the bus stops. Each bus stop has an attendant who will happily give away multiple Peeps to the same person over time, and your impeccable manners demand you never refuse one! Describe how to modify your algorithm from part (a) to minimize *the total time you spend waiting at bus stops*; you don't care how late you get home or how much time you spend on buses. (Assume you can wait inside the See-Bull Center until your first bus is just about to leave.)

For both questions, your input consists of the exact time when the midterm ends See-Bull and two arrays $Time[1..b, 1..n]$ and $Stop[1..b, 1..n]$, where $Time[i, j]$ is the scheduled time of the ith bus's jth stop, and $Stop[i, j]$ is the location of that stop. Report the running times of your algorithms as functions of the parameters n and b.

Solved Problems

4. Although we typically speak of "the" shortest path from one vertex to another, a single graph could contain several minimum-length paths with the same endpoints.



Four (of many) equal-length shortest paths.

Describe and analyze an algorithm to compute the *number* of shortest paths from a source vertex s to a target vertex t in an arbitrary directed graph G with weighted edges. Assume that all edge weights are positive and that any necessary arithmetic operations can be performed in $O(1)$ time each.

[Hint: Compute shortest path distances from s to every other vertex. Throw away all edges that cannot be part of a shortest path from s to another vertex. What's left?]

Solution: We start by computing shortest-path distances $dist(v)$ from s to v, for every vertex v, using Dijkstra's algorithm. Call an edge $u \to v$ ***tight*** if $dist(u) + w(u \to v) = dist(v)$. Every edge in a shortest path from s to t must be tight. Conversely, every path from s to t that uses only tight edges has total length $dist(t)$ and is therefore a shortest path!

Let H be the subgraph of all tight edges in G. We can easily construct H in $O(V + E)$ time. Because all edge weights are positive, H is a directed acyclic graph. It remains only to count the number of paths from s to t in H.

For any vertex v, let $NumPaths(v)$ denote the number of paths in H from v to t; we need to compute $NumPaths(s)$. This function satisfies the following simple recurrence:

$$NumPaths(v) = \begin{cases} 1 & \text{if } v = t \\ \displaystyle\sum_{v \to w} NumPaths(w) & \text{otherwise} \end{cases}$$

In particular, if v is a sink but $v \neq t$ (and thus there are no paths from v to t), this recurrence correctly gives us $NumPaths(v) = \sum \varnothing = 0$.

We can memoize this function into the graph itself, storing each value $NumPaths(v)$ at the corresponding vertex v. Since each subproblem depends only on its successors in H, we can compute $NumPaths(v)$ for all vertices v by considering the vertices in reverse topological order, or equivalently, by performing a depth-first search of H starting at s. The resulting algorithm runs in $O(V + E)$ time.

The overall running time of the algorithm is dominated by Dijkstra's algorithm in the preprocessing phase, which runs in $\boldsymbol{O(E \log V)}$ ***time***. ■

Rubric: 10 points = 5 points for reduction to counting paths in a dag (standard graph reduction rubric) + 5 points for the path-counting algorithm (standard dynamic programming rubric)

5. After moving to a new city, you decide to choose a walking route from your home to your new office. Your route must consist of an uphill path (for exercise) followed by a downhill path (to cool down), or just an uphill path, or just a downhill path. But you also want the *shortest* path that satisfies these conditions, so that you actually get to work on time.

   Your input consists of an undirected graph G, whose vertices represent intersections and whose edges represent road segments, along with a start vertex s and a target vertex t. Every vertex v has a value $h(v)$, which is the height of that intersection above sea level, and each edge uv has a value $\ell(uv)$, which is the length of that road segment.

   (a) Describe and analyze an algorithm to find the shortest uphill–downhill walk from s to t. Assume all vertex heights are distinct.

Solution: We define a new directed graph $G' = (V', E')$ as follows:

- $V' = \{v^\uparrow, v^\downarrow \mid V \in V\}$. Vertex $v^\uparrow$ indicates that we are at intersection v moving uphill, and vertex $v^\downarrow$ indicates that we are at intersection v moving downhill.
- E' is the union of three sets:
  - Uphill edges: $\{u^\uparrow \to v^\uparrow \mid uv \in E \text{ and } h(u) < h(v)\}$. Each uphill edge $u^\uparrow \to v^\uparrow$ has weight $\ell(uv)$.
  - Downhill edges: $\{u^\downarrow \to v^\downarrow \mid uv \in E \text{ and } h(u) > h(v)\}$. Each downhill edge $u^\downarrow \to v^\downarrow$ has weight $\ell(uv)$.
  - Switch edges: $\{v^\uparrow \to v^\downarrow \mid v \in V\}$; each switch edge has weight 0.

We need to compute three shortest paths in this graph:

- The shortest path from $s^\uparrow$ to $t^\downarrow$ gives us the best uphill-then-downhill route.
- The shortest path from $s^\uparrow$ to $t^\uparrow$ gives us the best uphill-only route.
- The shortest path from $s^\downarrow$ to $t^\downarrow$ gives us the best downhill-only route.

G' is a directed ***acyclic*** graph; we can get a topological ordering by listing the up vertices $v^\uparrow$, sorted by increasing height, followed by the down vertices $v^\downarrow$, sorted by decreasing height. Thus, we can compute the shortest path in G' from any vertex to any other in $O(V' + E') = O(V + E)$ time by dynamic programming. (The algorithm is the same as the longest-path algorithm in the notes, except we use "min" instead of "max" in the recurrence, and define $\min \varnothing = \infty$.)

Our overall algorithm runs in $\boldsymbol{O(V + E)}$ ***time***. ■

Rubric: 5 points = 1 for vertices + 1 for edges + 1 for arguing G' is a dag + 1 for algorithm + 1 for running time. This is not the only correct solution. Max 4 points for a correct reduction to Dijkstra's algorithm that runs in $O(E \log V)$ time.

(b) Suppose you discover that there is no path from s to t with the structure you want. Describe an algorithm to find a path from s to t that alternates between "uphill" and "downhill" subpaths as few times as possible, and has minimum length among all such paths. (There may be even shorter paths with more alternations, but you don't care about them.) Again, assume all vertex heights are distinct.

Solution (Dijkstra, 5/5): Let $L = 1 + \sum_{u \to v} \ell(u \to v)$. Define a new graph $G' = (V', E')$ as follows:

- $V' = \{v^\uparrow, v^\downarrow \mid V \in V\} \cup \{s, t\}$. Vertex $v^\uparrow$ indicates that we are at intersection v moving uphill, and vertex $v^\downarrow$ indicates that we are at intersection v moving downhill.
- E' contains four types of edges:
  - Uphill edges: $\{u^\uparrow \to v^\uparrow \mid uv \in E \text{ and } h(u) < h(v)\}$. Each uphill edge $u^\uparrow \to v^\uparrow$ has weight $\ell(uv)$.
  - Downhill edges: $\{u^\downarrow \to v^\downarrow \mid uv \in E \text{ and } h(u) > h(v)\}$. Each downhill edge $u^\downarrow \to v^\downarrow$ has weight $\ell(uv)$.
  - Switch edges: $\{v^\uparrow \to v^\downarrow \mid v \in V\} \cup \{v^\downarrow \to v^\uparrow \mid v \in V\}$. Each switch edge has weight L.
  - Start and end edges $s \to s^\uparrow$, $s \to s^\downarrow$, $t^\uparrow \to t$, and $t^\downarrow \to t$, each with weight 0,

We need to compute the shortest path from s to t in G'; the large weight L on the switch edges guarantees that this path with have the minimum number of switches, and the minimum length among all paths with that number of switches. Dijkstra's algorithm finds this shortest path in $O(E' \log V') = \boldsymbol{O(E \log V)}$ ***time***.

(Because G' includes switch edges in both directions, G' is not a dag, so we can't use dynamic programming directly.) ■

Rubric: 5 points, standard graph-reduction rubric. This is not the only correct solution with running time $O(E \log V)$.

Solution (clever, extra credit): Our algorithm works in two phases: First we determine the minimum number of switches required to reach every vertex, and then we compute the shortest path from s to t with the minimum number of switches. The first phase is can be solved in $O(V + E)$ time by a modification of breadth-first search; the second by computing shortest paths in a dag.

For the first phase, we define a new graph $G' = (V', E')$ as follows:

- $V' = \{v^\uparrow, v^\downarrow \mid V \in V\} \cup \{s, t\}$. Vertex $v^\uparrow$ indicates that we are at intersection v moving uphill, and vertex $v^\downarrow$ indicates that we are at intersection v moving downhill.
- E' contains four types of edges:
  - Uphill edges: $\{u^\uparrow \to v^\uparrow \mid uv \in E \text{ and } h(u) < h(v)\}$. Each uphill edge has weight 0.
  - Downhill edges: $\{u^\downarrow \to v^\downarrow \mid uv \in E \text{ and } h(u) > h(v)\}$. Each downhill

edge has weight 0.

- Switch edges: $\{v^{\uparrow}\to v^{\downarrow} \mid v \in V\} \cup \{v^{\downarrow}\to v^{\uparrow} \mid v \in V\}$. Each switch edge has weight 1.
- Start and end edges $s\to s^{\uparrow}$, $s\to s^{\downarrow}$, $t^{\uparrow}\to t$, and $t^{\downarrow}\to t$, each with weight 0.

Now we compute the shortest path distance from s to every other vertex in G'. We could use Dijkstra's algorithm in $O(E \log V)$ time, but the structure of the graph supports a faster algorithm.

Intuitively, we break the shortest-path computation into phases, where in the kth phase, we mark all vertices at distance k from the source vertex s. During the kth phase, we may also discover vertices at distance $k+1$, but no further. So instead of using a binary heap for the priority queue, it suffices to use two bags: one for vertices at distance k, and one for vertices at distance $k+1$.

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ZeroOneDijkstra(G, ℓ, s):
  s.dist ← 0
  for all vertices v ≠ s
      v.dist ← ∞
  curr ← new empty bag
  add s to curr
  for k ← 0 to V
      next ← new empty bag
      while curr is not empty
          take v from curr            ⟪v.dist = k⟫
          for all edges v→w
              if w.dist > v.dist + ℓ(v→w)
                  w.dist ← v.dist + ℓ(v→w)
                  if ℓ(v→w) = 0
                      add w to curr
                  else ⟪if ℓ(v→w) = 1⟫
                      add w to next
      curr ← next
```

This phase of the algorithm runs in $O(V' + E') = O(V + E)$ time.

Once we have computed distances in G', we construct a second graph $G'' = (V', E'')$ with the same vertices as G', but only a subset of the edges:

$$E'' = \{u'\to v' \in E' \mid u'.dist + \ell(u'\to v') = v'.dist\}$$

Equivalently, an edge $u'\to v'$ belongs to E'' if and only if that edge is part of at least one shortest path in G' from s to another vertex. It follows (by induction, of course), that every path in G'' from s to another vertex v' is a shortest path in G', and therefore a minimum-switch path in G.

We also reassign the edge weights in G''. Specifically, we assign each uphill edge $u^{\uparrow}\to v^{\uparrow}$ and downhill edge $u^{\downarrow}\to v^{\downarrow}$ in G'' weight $\ell(uv)$, and we assign every switch edge, start edge, and end edge weight 0. **Now we need to compute the shortest path from s to t in G'', with respect to these new edge weights.**

We can expand the definition of E'' in terms of the original input graph as follows:

$$\begin{aligned} E'' = &\left\{u^{\uparrow} \to v^{\uparrow} \;\middle|\; uv \in E \text{ and } h(u) < h(v) \text{ and } u^{\uparrow}.dist = v^{\uparrow}.dist\right\} \\ &\cup \left\{u^{\downarrow} \to v^{\downarrow} \;\middle|\; uv \in E \text{ and } h(u) > h(v) \text{ and } u^{\downarrow}.dist = v^{\downarrow}.dist\right\} \\ &\cup \left\{v^{\uparrow} \to v^{\downarrow} \;\middle|\; v \in V \text{ and } v^{\uparrow}.dist < v^{\downarrow}.dist\right\} \\ &\cup \left\{v^{\downarrow} \to v^{\uparrow} \;\middle|\; v \in V \text{ and } v^{\downarrow}.dist < v^{\uparrow}.dist\right\} \end{aligned}$$

We can topologically sort G'' by first sorting the vertices by increasing $v'.dist$, and then within each subset of vertices with equal $v'.dist$, listing the up-vertices by increasing height, followed by the down vertices by decreasing height. It follows that G'' is a dag! Thus, we can compute shortest paths in G'' in $O(V'' + E'') = O(V + E)$ time, using the same dynamic programming algorithm that we used in part (a).

The overall algorithm runs in $\boldsymbol{O(V+E)}$ ***time***. ■

Rubric: max 10 points =

- 5 for computing minimum-switch paths = 1 for vertices + 1 for edges (including weights) + 2 for 0/1 shortest path algorithm + 1 for running time.
- 5 for computing shortest minimum-switch paths = 1 for vertices + 1 for edges (including weights) + 1 for proving dag + 1 for dynamic programming algorithm + 1 for running time