Lecture 17: Shortest Paths III: Bellman-Ford

Lecture Overview

- Review: Notation
- Generic S.P. Algorithm
- Bellman-Ford Algorithm
  - Analysis
  - Correctness

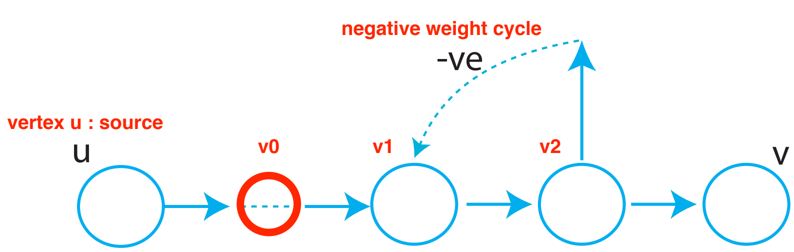
compute shortest paths in a graph with negative edges
& report the existence of a negative cycle

polynomial time algo.

Recall:

$$\begin{aligned} \text{path } p &= \; < v_0, v_1, \; \ldots, \; v_k > \\ & \quad (v_1, v_{i+1}) \; \in E \quad 0 \leq i < k \\ w(p) &= \sum_{i-0}^{k-1} w(v_i, v_{i+1}) \end{aligned}$$

Shortest path weight from u to v is $\delta(u, v)$. $\delta(u, v)$ is ∞ if v is unreachable from u, undefined if there is a negative cycle on some path from u to v.



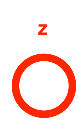


Figure 1: Negative Cycle.

가정 : negative weight edge(v2 -> v1)을 제외한 나머지 edge들은 positive weight를 갖는다

δ(u, v1) : undefined
δ(u, v2) : undefined
δ(u, v) : undefined
δ(u, v0) = 2
δ(u, z) = ∞

shortest path

Generic S.P. Algorithm

graph의 모든 vertex에 infinite path weight를 초기값으로 부여

Initialize: for $v \in V$: $d[v] \leftarrow \infty$
$\Pi[v] \leftarrow$ NIL predecessor를 NIL로 초기화

$d[S] \leftarrow 0$ source

Main: repeat

select edge (u, v) [somehow]

"Relax" edge (u, v):
- if $d[v] > d[u] + w(u, v)$:
  - $d[v] \leftarrow d[u] + w(u, v)$
  - $\pi[v] \leftarrow u$ predecessor update

until you can't relax any more edges or you're tired or . . .

<Generic S.P. Algorithm's problem>
problem1) complexity could be exp. time (even for the positive edge weights) (p.3의 graph) -> 다익스트라로 해결 가능
problem2) will not even terminate if there is a negative weight cycle reachable from the source -> Bellman-Ford로 해결 가능

Complexity:

Termination: Algorithm will continually relax edges when there are negative cycles present.

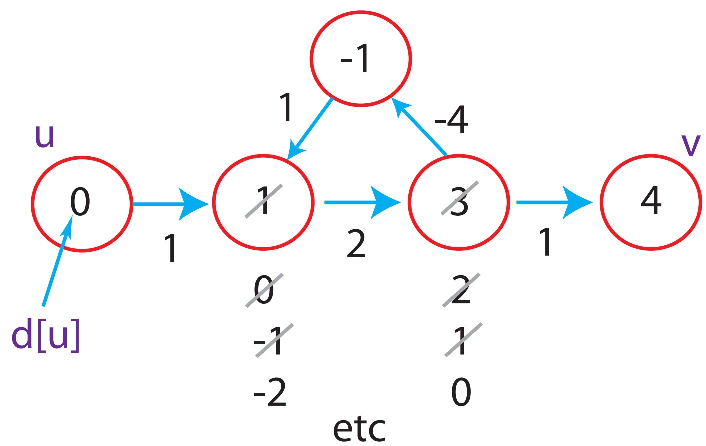


Figure 2: Algorithm may not terminate due to negative cycles.

Complexity could be exponential time with poor choice of edges.

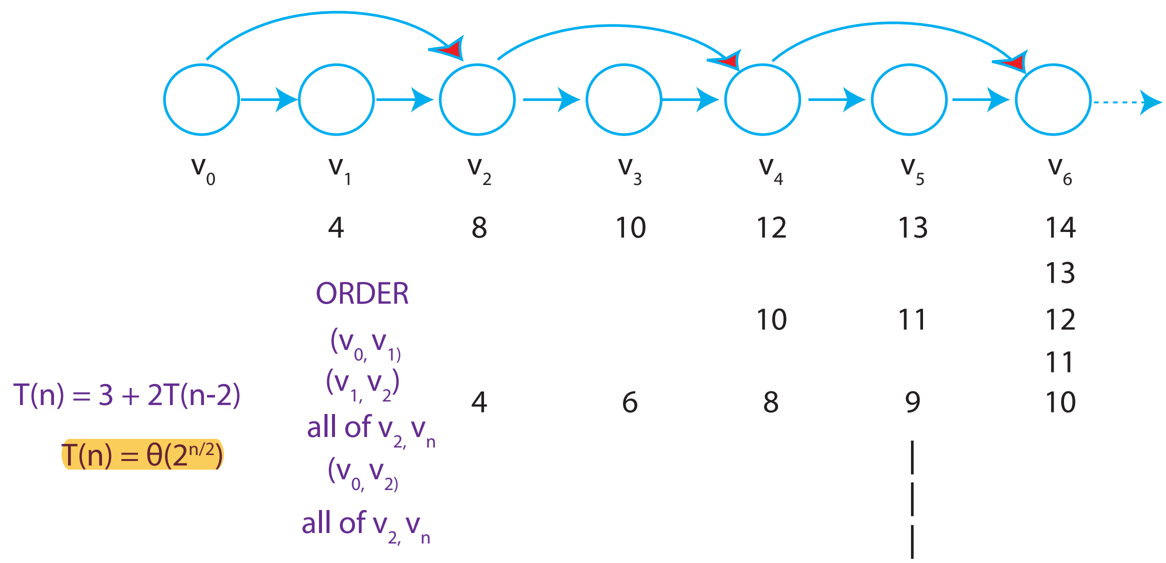


Figure 3: Algorithm could take exponential time. The outgoing edges from v_0 and v_1 have weight 4, the outgoing edges from v_2 and v_3 have weight 2, the outgoing edges from v_4 and v_5 have weight 1.

5-Minute 6.006

Figure 4 is what I want you to remember from 6.006 five years after you graduate!

Graph

Bellman-Ford(G,W,s)

Initialize ()
for $i = 1$ to $|V| - 1$
    for each edge $(u, v) \in E$:
        Relax(u, v)
for each edge $(u, v) \in E$
    do if $d[v] > d[u] + w(u, v)$
        then report a negative-weight cycle exists

At the end, $d[v] = \delta(s, v)$, if no negative-weight cycles.

Theorem:
If $G = (V, E)$ contains no negative weight cycles, then after Bellman-Ford executes $d[v] = \delta(s, v)$ for all $v \in V$.

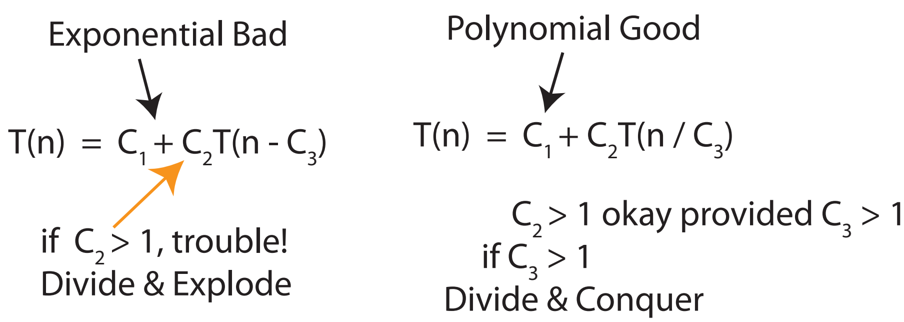


Figure 4: Exponential vs. Polynomial.

Proof:

Let $v \in V$ be any vertex. Consider path $p = \langle v_0, v_1, \ldots, v_k \rangle$ from $v_0 = s$ to $v_k = v$ path p that is a shortest path with minimum number of edges. No negative weight cycles $\Longrightarrow$ p is simple $\Longrightarrow$ $k \leq |V| - 1$.

3개의 edge를 갖는 path와 4개의 edge를 갖는 path가 동일한 weight를 갖는 경우,
3개의 edge를 갖는 path를 선택함
(shortest path가 unique하다고 장담할 수는 없지만, 그냥 그 중 하나를 선택)

Consider Figure 6. Initially $d[v_0] = 0 = \delta(s, v_0)$ and is unchanged since no negative cycles.

After 1 pass through E, we have $d[v_1] = \delta(s, v_1)$, because we will relax the edge (v_0, v_1) in the pass, and we can't find a shorter path than this shortest path. (Note that we are invoking optimal substructure and the safeness lemma from Lecture 16 here.)

After 2 passes through E, we have $d[v_2] = \delta(s, v_2)$, because in the second pass we will relax the edge (v_1, v_2).

After i passes through E, we have $d[v_i] = \delta(s, v_i)$.

After $k \leq |V| - 1$ passes through E, we have $d[v_k] = d[v] = \delta(s, v)$. $\square$

Corollary

If a value $d[v]$ fails to converge after $|V| - 1$ passes, there exists a negative-weight cycle reachable from s.

Proof:

After $|V| - 1$ passes, if we find an edge that can be relaxed, it means that the current shortest path from s to some vertex is not simple and vertices are repeated. Since this cyclic path has less weight than any simple path the cycle has to be a negative-weight cycle. $\square$

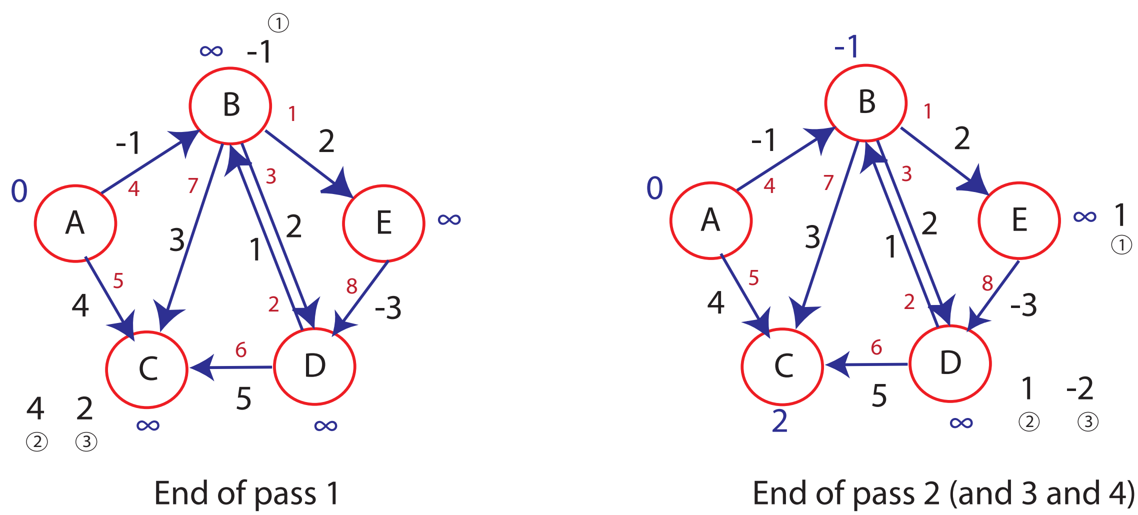
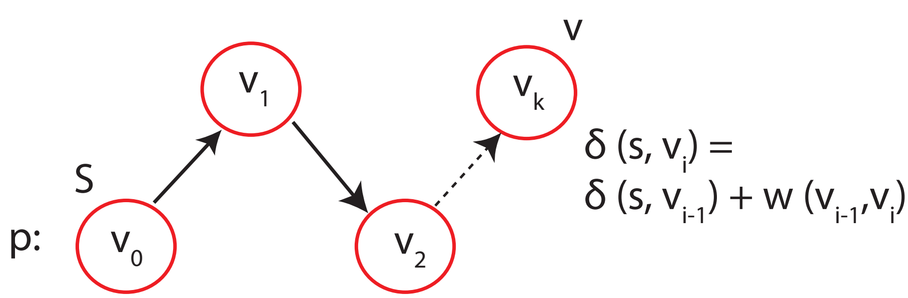


Figure 5: The numbers in circles indicate the order in which the δ values are computed.



path p : v0, v1, ... , vk
(만약 k가 |V| - 1보다 크면 cycle이 생겨서 simple path가 아니게 됨 -> 따라서 k <= |V| - 1이어야 하고, 이를 위배하면 cycle이 존재)

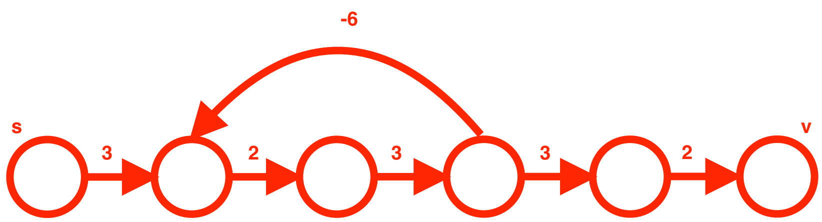
Figure 6: Illustration for proof.

Longest Simple Path and Shortest Simple Path

Finding the longest simple path in a graph with non-negative edge weights is an NP-hard problem, for which no known polynomial-time algorithm exists. Suppose one simply negates each of the edge weights and runs Bellman-Ford to compute shortest paths. Bellman-Ford will not necessarily compute the longest paths in the original graph, since there might be a negative-weight cycle reachable from the source, and the algorithm will abort.

Similarly, if we have a graph with negative cycles, and we wish to find the longest *simple* path from the source s to a vertex v, we cannot use Bellman-Ford. The shortest simple path problem is also NP-hard.

< Shortest path problem = Longest path problem >



Bellman-Ford는 negative cycle이 존재하지 않는 경우에만 shortest simple path를 알려줌
따라서 위의 그래프에 대해서 Bellman-Ford는 shortest simple path를 구해주지 못하며, 대신 negative cycle의 존재를 알려줌

위의 그래프에서의 shortest simple path의 값은 13(3+2+3+3+2)이며,
이와 같이 negative weight cycle을 갖는 graph에서 shortest simple path를 찾는 것은 NP-hard 문제

negative weight cycle 발견 시 abort하도록 하는 기존 Bellman-Ford algo.은 O(VE)이지만,
negative weight cycle이 있어도 어떠한 방식으로 처리해서 shortest simple path를 찾는 문제는 exp. 시간복잡도를 갖는 NP-hard 문제