CSE 421

Dynamic Programming

Longest Path in a DAG,

Yin Tat Lee

Longest Path in a DAG

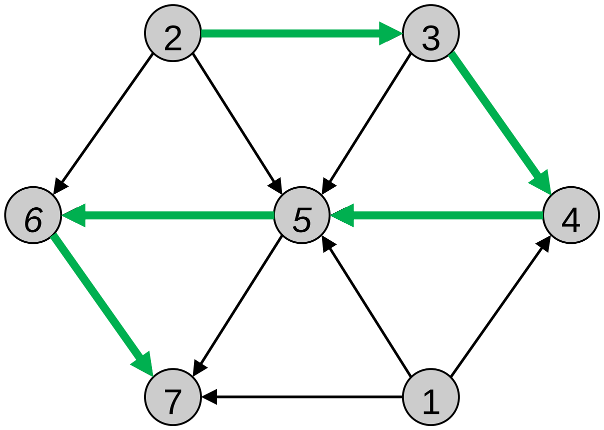
Longest Path in a DAG

Goal: Given a DAG G, find the longest path.

Recall: A directed graph G is a DAG if it has no cycle.

This problem is NP-hard for general directed graphs:

- It has the Hamiltonian Path as a special case



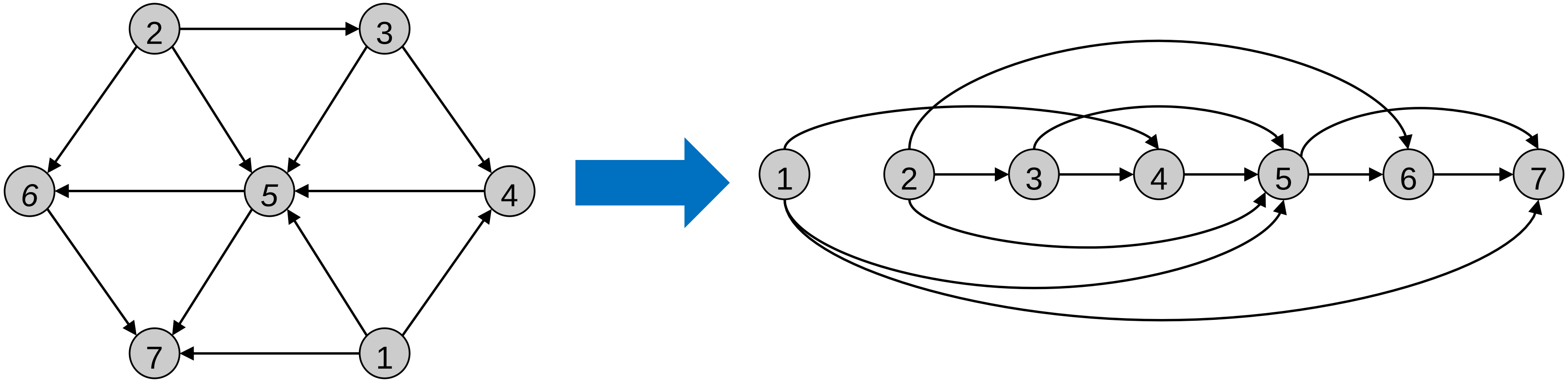
DP for Longest Path in a DAG

Q: What is the right ordering?

Remember, we have to use that G is a DAG, ideally in defining the ordering

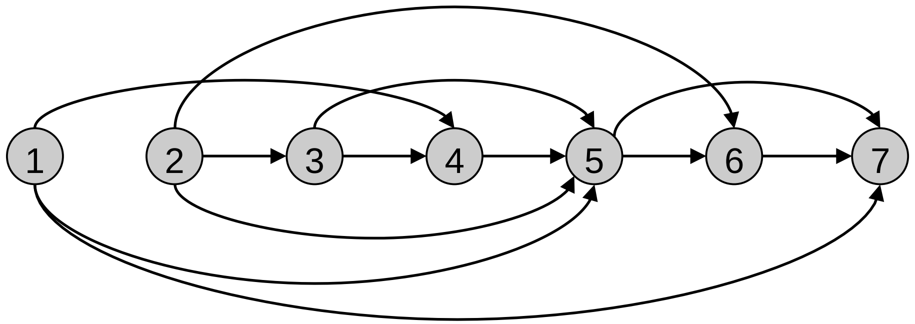
We saw that every DAG has a topological sorting

So, let's use that as an ordering.



DP for Longest Path in a DAG

Suppose we have labelled the vertices such that (i, j) is a directed edge only if $i < j$.



Let $OPT(j)$ = length of the longest path ending at j

Suppose OPT(j) is $(i_1, i_2), (i_2, i_3), \ldots, (i_{k-1}, i_k), (i_k, j)$, then

Obs 1: $i_1 \leq i_2 \leq \cdots \leq i_k \leq j$.

Obs 2: $(i_1, i_2), (i_2, i_3), \ldots, (i_{k-1}, i_k)$ is the longest path ending at i_k.

$$OPT(j) = 1 + OPT(i_k).$$

DP for Longest Path in a DAG

Suppose we have labelled the vertices such that (i, j) is a directed edge only if $i < j$.

Let $OPT(j)$ = length of the longest path ending at j

$$OPT(j) = \begin{cases} 0 & \text{If } j \text{ is a source} \\ 1 + \max_{i:(i,j) \text{ an edge}} OPT(i) & \text{o.w.} \end{cases}$$

Outputting the Longest Path

```
Let G be a DAG given with a topological sorting: For all edges
(i,j) we have i<j.
Initialize Parent[j]=-1 for all j.
Compute-OPT(j){
   if (in-degree(j)==0)
     return 0
   if (M[j]==empty)
     M[j]=0;
     for all edges (i,j)
       if (M[j] < 1+Compute-OPT(i))
         M[j]=1+Compute-OPT(i)
         Parent[j]=i
   return M[j]
}
Let M[k] be the maximum of M[1],…,M[n]
While (Parent[k]!=-1)
   Print k
   k=Parent[k]
```

Record the entry that
we used to compute OPT(j)

Exercise:
Longest Increasing Subsequence

Longest Increasing Subsequence

Given a sequence of numbers

Find the longest increasing subsequence in $O(n^2)$ time

41, 22, 9, 15, 23, 39, 21, 56, 24, 34, 59, 23, 60, 39, 87, 23, 90

41, 22, **9**, **15**, **23**, 39, 21, 56, **24**, **34**, **59**, 23, **60**, 39, **87**, 23, **90**

DP for LIS

Let OPT(j) be the longest increasing subsequence ending at j.

Observation: Suppose the OPT(j) is the sequence

$$x_{i_1}, x_{i_2}, \dots, x_{i_k}, x_j$$

Then, $x_{i_1}, x_{i_2}, \dots, x_{i_k}$ is the longest increasing subsequence ending at x_{i_k}, i.e., $OPT(j) = 1 + OPT(i_k)$

$$OPT(j) = \begin{cases} 1 & \text{If } x_j > x_i \text{ for all } i < j \\ 1 + \max_{i: x_i < x_j} OPT(i) & \text{o.w.} \end{cases}$$

Alternative Soln: This is a special case of Longest path in a DAG: Construct a graph 1,…n where (i, j) is an edge if $i < j$ and $x_i < x_j$.

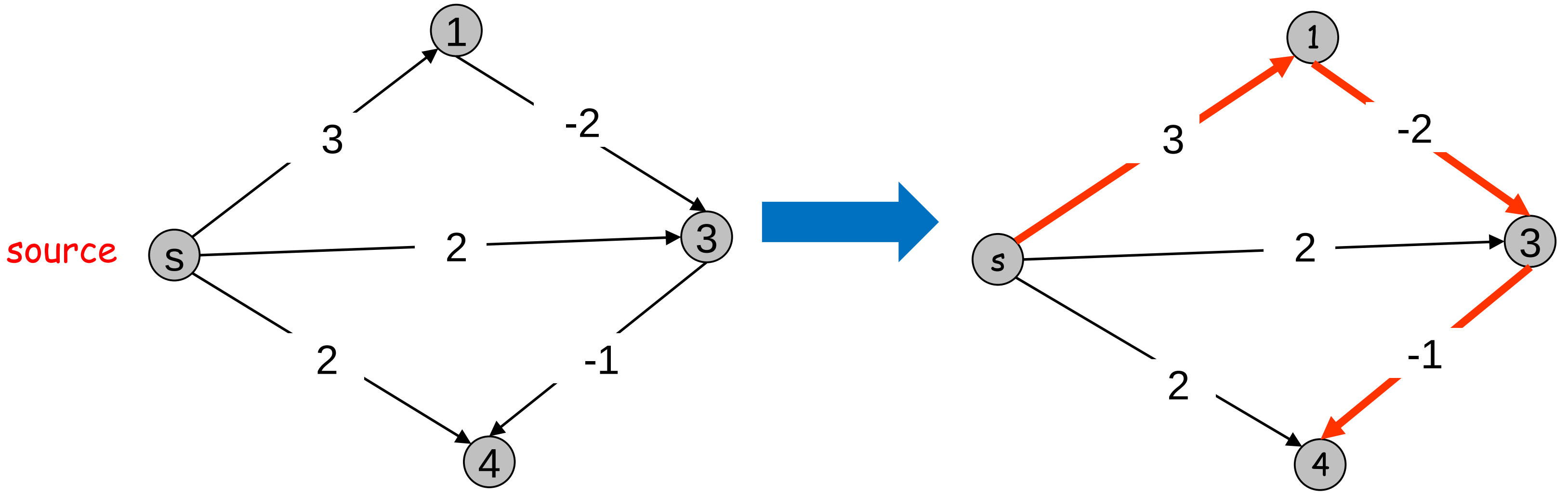
Shortest Paths with Negative Edge Weights

Shortest Paths with Neg Edge Weights

Given a weighted directed graph $G = (V, E)$ and a source vertex s, where the weight of edge (u,v) is $c_{u,v}$ **(that can be negative)**

Goal: Find the shortest path from s to all vertices of G.

Recall that Dikjstra's Algorithm fails when weights are negative

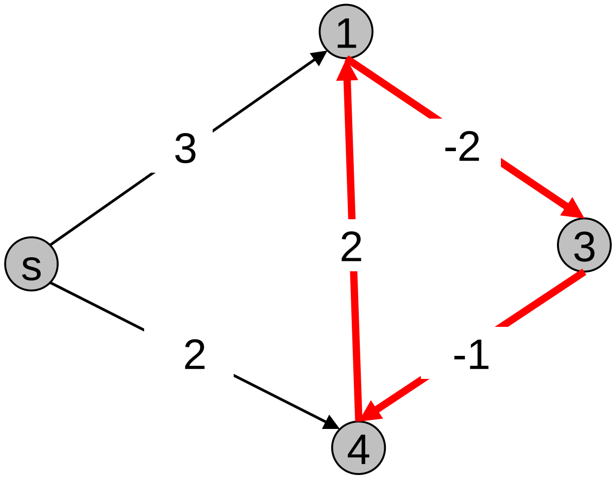


Impossibility on Graphs with Neg Cycles

Observation: No solution exists if G has a negative cycle.

This is because we can minimize the length by going over the cycle again and again.

So, suppose G does not have a negative cycle.



DP for Shortest Path (First Attempt)

Def: Let $OPT(v)$ be the length of the shortest s - v path

$$OPT(v) = \begin{cases} 0 & \text{if } v = s \\ \min\limits_{u:(u,v) \text{ an edge}} OPT(u) + c_{u,v} & \end{cases}$$

The formula is correct. But it is not clear how to compute it.

DP for Shortest Path

Def: Let $OPT(v, i)$ be the length of the shortest s - v path with at most i edges.

Let us characterize $OPT(v, i)$.

Case 1: $OPT(v, i)$ path has less than i edges.

- Then, $OPT(v, i) = OPT(v, i - 1)$.

Case 2: $OPT(v, i)$ path has exactly i edges.

- Let $s, v_1, v_2, \dots, v_{i-1}, v$ be the $OPT(v, i)$ path with i edges.
- Then, $s, v_1, \dots, v_{i-1}$ must be the shortest s - v_{i-1} path with at most $i - 1$ edges. So,

$$OPT(v, i) = OPT(v_{i-1}, i - 1) + c_{v_{i-1}, v}$$

DP for Shortest Path

Def: Let $OPT(v, i)$ be the length of the shortest s - v path with at most i edges.

$$OPT(v,i) = \begin{cases} 0 & \text{if } v = s \\ \infty & \text{if } v \neq s, i = 0 \\ \min\left(OPT(v, i-1), \min\limits_{u:(u,v) \text{ an edge}} OPT(u, i-1) + c_{u,v}\right) \end{cases}$$

So, for every v, $OPT(v, ?)$ is the shortest path from s to v.

But how long do we have to run?

Since G has no negative cycle, it has at most $n - 1$ edges. So, $OPT(v, n-1)$ is the answer.

Bellman Ford Algorithm

```
for v=1 to n
   if v ≠ s then
      M[v,0]=∞
M[s,0]=0.

for i=1 to n-1
   for v=1 to n
      M[v,i]=M[v,i-1]
      for every edge (u,v)
         M[v,i]=min(M[v,i], M[u,i-1]+c_{u,v})
```

	Complexity	Author
	$O(n^4)$	Shimbel (1955) [30]
	$O(Wn^2m)$	Ford (1956) [14]
*	$O(nm)$	Bellman (1958) [1], Moore (1959) [25]
	$O(n^{\frac{3}{4}}m \log W)$	Gabow (1983) [9]
	$O(\sqrt{n}m \log(nW))$	Gabow and Tarjan (1989) [10]
*	$O(\sqrt{n}m \log(W))$	Goldberg (1993) [12]
*	$\tilde{O}(Wn^{\omega})$	Sankowski (2005) [27] Yuster and Zwick (2005) [35]
*	$\tilde{O}(m^{10/7} \log W)$	Cohen, Madry, Sankowski, Vladu (2016)

Table 1: The complexity results for the SSSP problem with negative weights (* indicates asymptotically the best bound for some range of parameters).

Running Time: $O(nm)$
Can we test if G has negative cycles?
Yes, run for i=1…3n and see if the M[v,n-1] is different from M[v,3n]

DP Techniques Summary

Recipe:

- Follow the natural induction proof.
- Find out additional assumptions/variables/subproblems that you need to do the induction
- Strengthen the hypothesis and define w.r.t. new subproblems

Dynamic programming techniques.

- Whenever a problem is a special case of an NP-hard problem an ordering is important:
- Adding a new variable: knapsack.
- Dynamic programming over intervals: RNA secondary structure.

Top-down vs. bottom-up:

- Different people have different intuitions
- Bottom-up is useful to optimize the memory