

15.082J & 6.855J & ESD.78J
September 30, 2010

The Label Correcting Algorithm

Overview of the Lecture

- ◆ A generic algorithm for solving shortest path problems
 - negative costs permitted
 - but no negative cost cycle (at least for now)
- ◆ The use of reduced costs
- ◆ All pair shortest path problem

- ◆ INPUT $G = (N, A)$ with costs c
- ◆ Node 1 is the source node
- ◆ There is no negative cost cycle
 - We will relax that assumption later

Optimality Conditions

Lemma. Let $d^*(j)$ be the shortest path length from node 1 to node j , for each j . Let $d(\cdot)$ be node labels with the following properties:

$$d(j) \leq d(i) + c_{ij} \text{ for } i \in N \text{ for } j \neq 1. \quad (1)$$

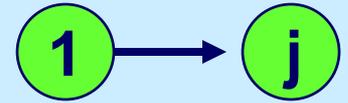
$$d(1) = 0. \quad (2)$$

Then $d(j) \leq d^*(j)$ for each j .

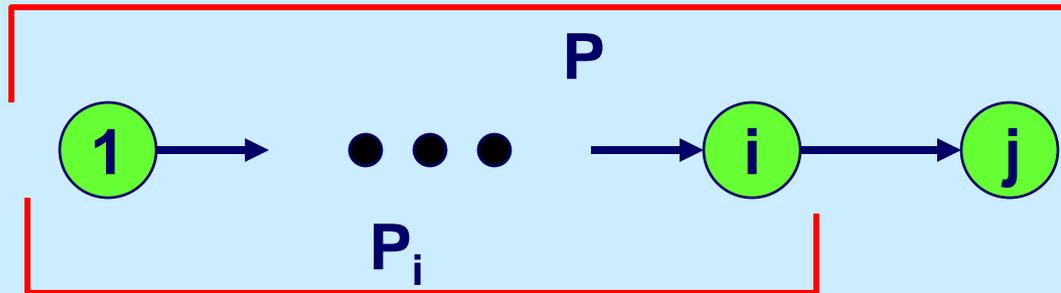
Proof. Let P be the shortest path from node 1 to node j .

Completion of the proof.

If $P = (1, j)$, then $d(j) \leq d(1) + c_{1j} = c_{1j} = d^*(j)$.



Suppose $|P| > 1$, and assume that the result is true for paths of length $|P| - 1$. Let i be the predecessor of node j on P , and let P_i be the subpath of P from 1 to i .



P_i is the shortest path from node 1 to node i . So, $d(i) \leq d^*(i) = c(P_i)$ by inductive hypothesis.

Then, $d(j) \leq d(i) + c_{ij} \leq c(P_i) + c_{ij} = c(P) = d^*(j)$.

Optimality Conditions

Theorem. Let $d(1), \dots, d(n)$ satisfy the following properties for a directed graph $G = (N, A)$:

1. $d(1) = 0$.
2. $d(i)$ is the length of some path from node 1 to node i .
3. $d(j) \leq d(i) + c_{ij}$ for all $(i, j) \in A$.

Then $d(j) = d^*(j)$.

Proof. $d(j) \leq d^*(j)$ by the previous lemma.

But, $d(j) \geq d^*(j)$ because $d(j)$ is the length of some path from node 1 to node j . Thus $d(j) = d^*(j)$.

A Generic Shortest Path Algorithm

Notation.

$d(j)$ = “temporary distance labels”.

- At each iteration, it is the length of a path (or walk) from 1 to j .
- At the end of the algorithm $d(j)$ is the minimum length of a path from node 1 to node j .

$\text{Pred}(j)$ = Predecessor of j in the path of length $d(j)$ from node 1 to node j .

c_{ij} = length of arc (i,j) .

A Generic Shortest Path Algorithm

Algorithm LABEL CORRECTING;

$d(1) := 0$ and $\text{Pred}(1) := \emptyset$;

$d(j) := \infty$ for each $j \in N - \{1\}$;

while some arc (i,j) satisfies $d(j) > d(i) + c_{ij}$ **do**

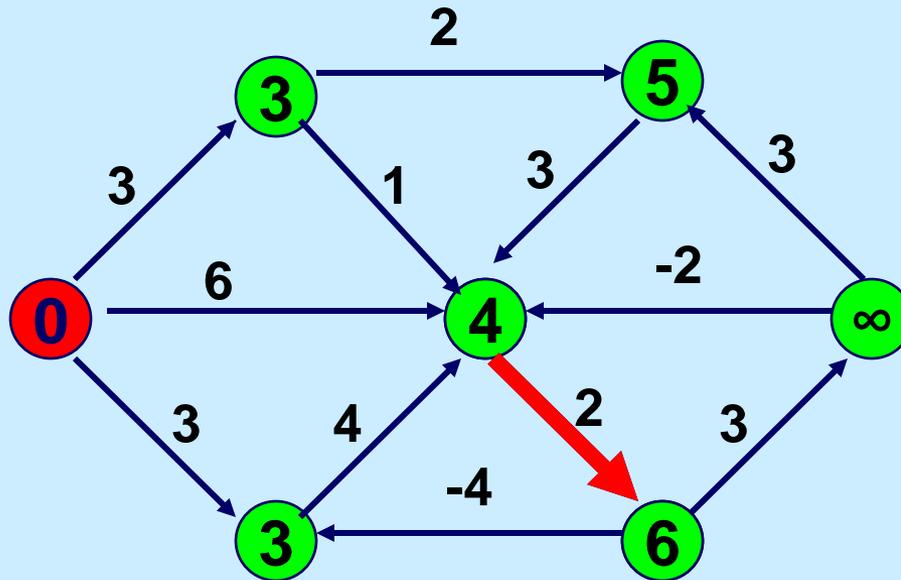
$d(j) := d(i) + c_{ij}$;

$\text{Pred}(j) := i$;

Label correcting animation.

Algorithm Invariant

At each iteration, if $d(j) < \infty$, then $d(j)$ is the length of some walk from node 1 to node j .



Theorem. Suppose all data are integral, and that there are no negative cost cycles in the network. Then the label correcting algorithm ends after a finite number of steps with the optimal solution.

Proof of correctness. The algorithm invariant ensures that $d(j)$ is the length of some walk from node 1 to node j . If the algorithm terminates, then the distances satisfy the optimality conditions.

Proof of Finiteness. Consider finite distance labels. At each iteration, $d(j)$ decreases by at least one for some j .

Also $nC \geq d(j) \geq d^*(j) > -nC$, where $C = \max (|c_{ij}| : (i,j) \in A)$.

So, the number of iterations is $O(n^2C)$.

More on Finiteness

What happens if data are not required to be integral?

The algorithm is still finite, but one needs to use a different proof.

What happens if there is a negative cost cycle?

The algorithm may no longer be finite.

Possibly, $d(j)$ keeps decreasing to $-\infty$.

But we can stop when $d(j) < -nC$ since this guarantees that there is a negative cost cycle.

On computational complexity

Proving finiteness is OK, but

Can we make the algorithm polynomial time?

If so, what is the best running time?

Can we implement it efficiently in practice?

A Polynomial Time Version of the Label Correcting Algorithm

We define a *pass* to consist of scanning all arcs in A , and updating distance labels when $d(j) > d(i) + c_{ij}$. (We permit the arcs to be scanned in any order).

Theorem. If there is no negative cost cycle, then the label correcting algorithm determines the shortest path distances after at most $n-1$ passes. The running time is $O(nm)$.

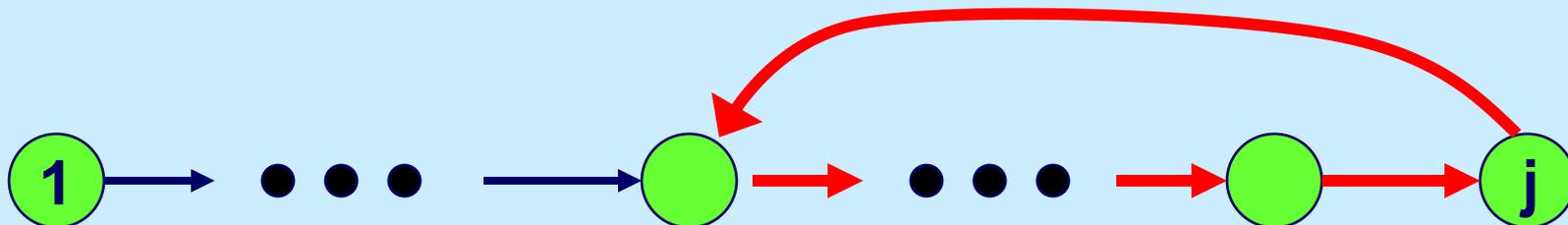
Proof follows from this lemma

Lemma. Let P_j be a shortest walk from node i to node j .
(If there are multiple shortest walks, choose one with the fewest number of arcs.)

Let $d^k(j)$ be the value $d(j)$ after k passes.

Then $d^k(j) = d^*(j)$ if P_j has at most k arcs.

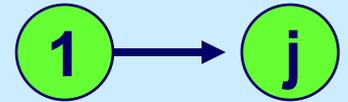
Note: if there are no negative cost cycles, then P_j will also be a path. If there is a negative cost cycle containing node j , then there is no shortest walk to node j .



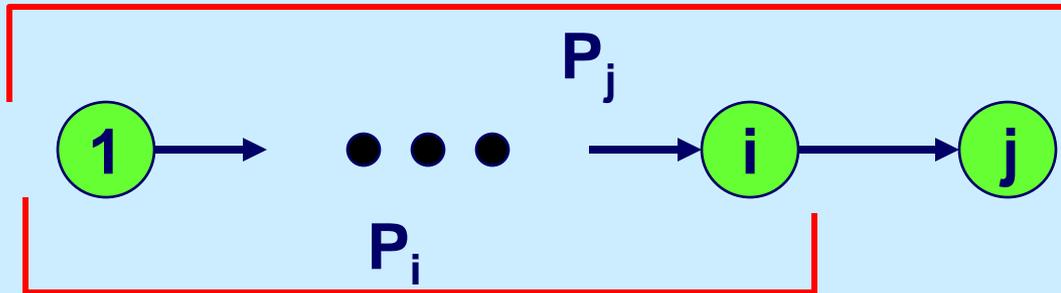
Proof of lemma

To show: $d^k(j) = d^*(j)$ whenever that shortest path from 1 to j has at most k arcs.

$d^1(j) \leq c_{1j}$. If $P_j = (1, j)$ the lemma is true.



Suppose $|P_j| > 1$, and assume that the result is true for paths of length $|P_j| - 1$. Let i be the predecessor of node j on P_j . Then the subpath from 1 to i is a shortest path to i .



After pass k , $d^k(j) \leq d^{k-1}(i) + c_{ij} = c(P_i) + c_{ij} = d^*(j)$.

What if there is a negative cost cycle?

If in the n -th pass, there is no update, then the algorithm has found the shortest path distances.

If in the n th pass, there is an update, then there must be a negative cost cycle.

Mental Break

In China, what is another (English) name for white tea?

Boiled water

Approximately how many Americans eat at McDonalds on a given day?

Around 20 million

In what year was Diet Coke invented?

1983

Mental Break

What nuts are the most cultivated and extensively used nuts in the world.

Almonds. They were also the first to be cultivated.

What is pomology?

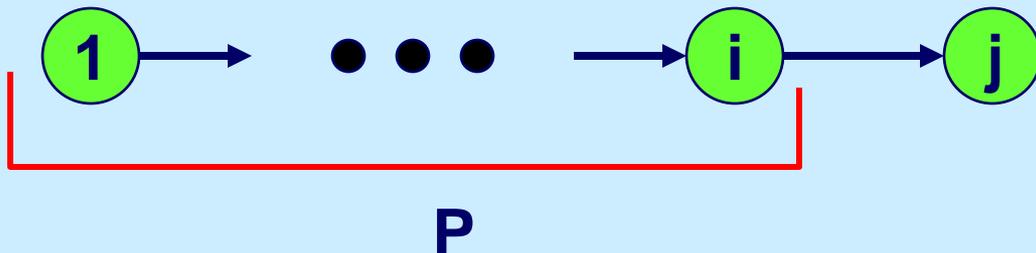
The study of fruits

How many M & Ms are sold every day in the U.S.

Approximately 200 million. M & Ms were named after their inventors, Forrest Mars and Bruce Murray. They were developed for the U.S. Army so that soldiers could eat candy without getting sticky hands.

Can we speed this up in practice?

Observation: if $d(i)$ is not decreased in one pass, then there is no need to scan arcs out of i at the next pass.



Create a LIST of nodes j that need to be scanned.

Whenever $d(j)$ is decreased, then add j to LIST

Major iteration: select a node i from LIST and

Procedure Update(i)

for each $(i, j) \in A(i)$ **do**

if $d(j) > d(i) + c_{ij}$ **then** $d(j) := d(i) + c_{ij}$ and
 $\text{pred}(j) := i$ and $\text{LIST} := \text{LIST} \cup \{j\}$.

Modified Label Correcting Algorithm

Algorithm Modified Label Correcting;

$d(1) := 0$ and $\text{pred}(1) := \emptyset$;

$d(j) := \emptyset$ for each $j \in N - \{1\}$;

$\text{LIST} := \{1\}$;

while $\text{LIST} \neq \emptyset$ *do*

 delete an element i from LIST ;

 Update(i)

 for each j such that $d(j)$ decreases, add j to LIST

Modified Label Correcting Algorithm

FIFO Implementation

FIFO. Treat LIST as a Queue. Add nodes to the end of LIST and take nodes from the beginning.

LIFO. Treat LIST as a Stack. Add nodes to the “top” of LIST, and delete the top node of LIST as well. (Efficient in practice, but bad in the worst case.)

Theorem. *The FIFO modified label correcting algorithm finds the minimum length path from 1 to j for all j in N in $O(nm)$ steps, or else shows that there is a negative cost cycle.*

Proof. Similar to proof of previous algorithm.

Solving all pairs shortest problems

Note: Dijkstra's algorithm is much faster **in the worst case** than label correcting.

- $O(m + n \log nC)$ vs $O(mn)$
- ◆ To solve the all pairs shortest path problem we will solve it as
 - one shortest path problem using label correcting
 - $n-1$ shortest path problems using Dijkstra
 - Technique: create an equivalent optimization problem with nonnegative arc lengths.

Reduced Costs

Suppose that π is any vector of *node potentials*.

Let $c_{ij}^\pi = c_{ij} - \pi_i + \pi_j$ be the *reduced cost* of arc (i,j)

For a path P , let $c(P)$ denote the cost (or length) of P .

Let $c^\pi(P)$ denote the reduced cost (or length) of P

$$c(P) = \sum_{(i,j) \in P} c_{ij}; \quad c^\pi(P) = \sum_{(i,j) \in P} c_{ij}^\pi ;$$

Lemma. For any path P from node s to node t ,

$$c^\pi(P) = c(P) - \pi_s + \pi_t .$$

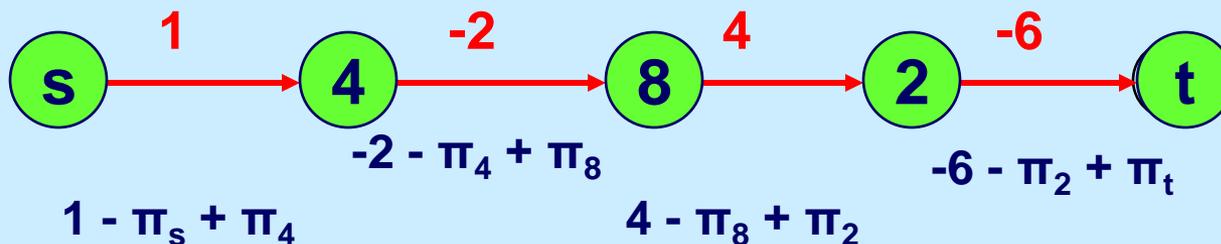
For any path P from node s to node t ,

$$c^\pi(P) = c(P) - \pi_s + \pi_t.$$

Proof. When written as a summation, the terms in $c^\pi(P)$ involving π_i for some i all cancel, except for the term $-\pi_s$ and the term π_t .

Note: for fixed vector π of multipliers and for any pair of nodes s and t , $c^\pi(P) - c(P)$ is a constant for every path P from s to t .

Corollary. A shortest path P from s to t with respect to c^π is also the shortest path with respect to c .

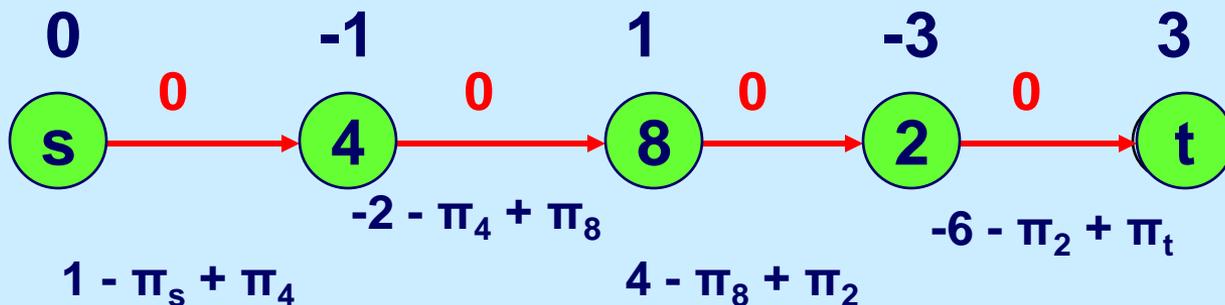


Using reduced costs

Lemma. Let $d(j)$ denote the shortest path from node s to node j . Let $\pi_j = -d(j)$ for all j .

Then $c_{ij}^\pi \geq 0$ for all $(i,j) \in A$.

Proof. $d(j) \leq d(i) + c_{ij} \quad \textcircled{R} \quad c_{ij} + d(i) - d(j) \geq 0 \quad \textcircled{R} \quad c_{ij}^\pi \geq 0$



Solving the all pair shortest path problem

Step 1. Find the shortest path from node 1 to all other nodes.
Let $d(j)$ denote the shortest path from 1 to j for all j .

Step 2. Let $\pi_j = -d(j)$ for all j .

Step 3. For $i = 2$ to n , compute the shortest path from node i to all other nodes with respect to arc lengths c^π .

Running time using Radix Heaps.**

$O(nm)$ for the first shortest path tree

$O(m + n \log C)$ for each other shortest path tree.

$O(nm + n^2 \log C)$ in total.

** One can choose a slightly faster approach.

Detecting Negative Cost Cycles

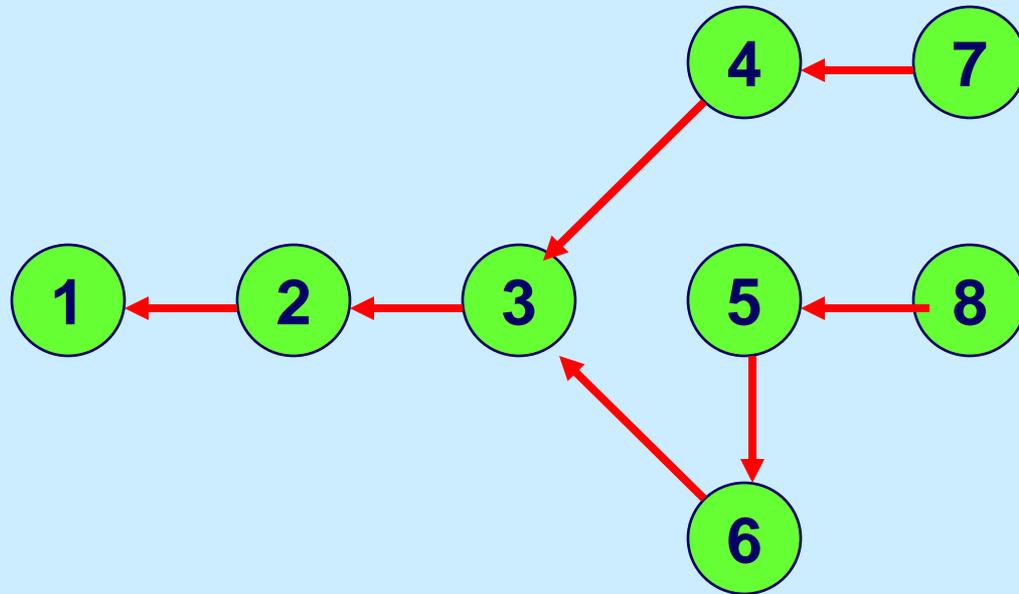
Approach 1. Stop if $d(j)$ is sufficiently small, say $d(j) \geq -nC$.

Approach 2. Run the FIFO modified label correcting algorithm, and stop after n passes.

Approach 3. Run the FIFO label correcting algorithm, and keep track of the number of arcs on the "path" from s to j . If the number of arcs exceeds $n-1$, then quit.

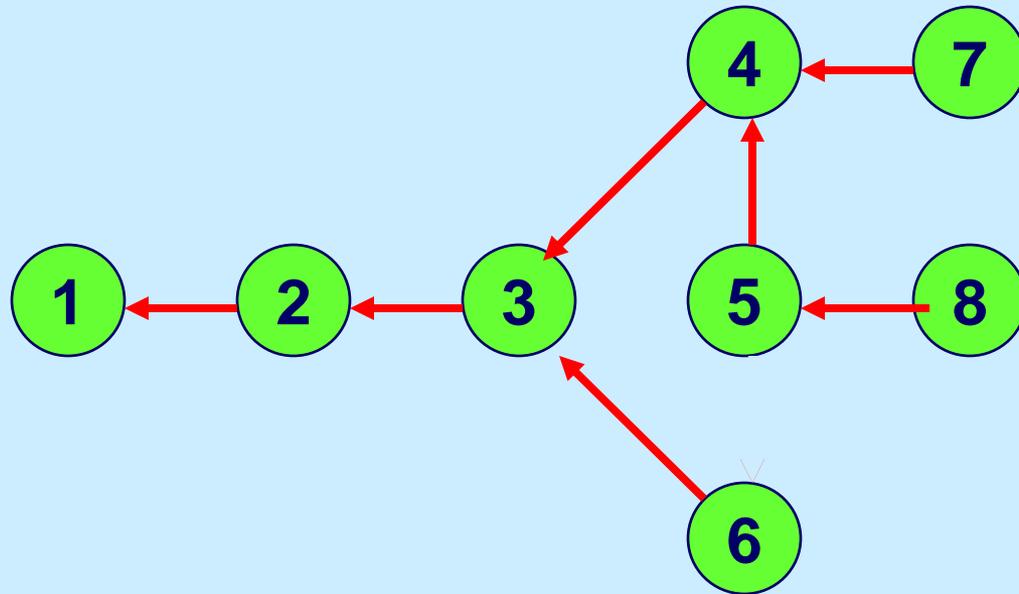
Approach 4. At each iteration of the algorithm, each node j (except for the root) has a temporary label $d(j)$ and a predecessor $\text{pred}(j)$. The *predecessor subgraph* consists of the $n-1$ arcs $\{(\text{pred}(j), j) : j \neq s\}$. It should be a tree. If it has a cycle, then the cost of the cycle will be negative, and the algorithm can terminate.

A Predecessor Graph



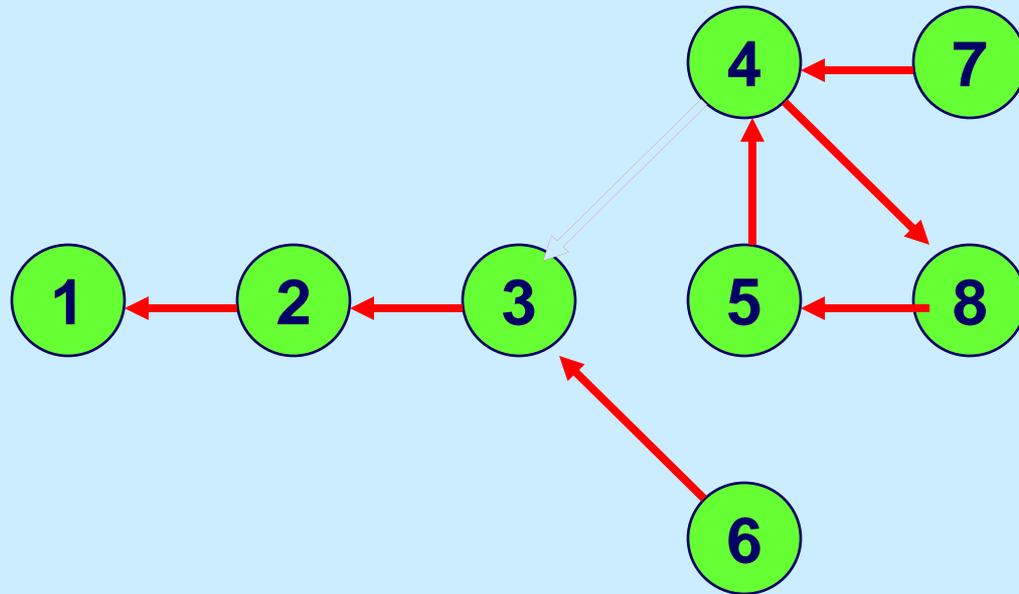
Each node except for node 1 has one predecessor. The graph either is an in-tree or it has a directed cycle.

A Predecessor Graph



Suppose we
Update(4), and
 $\text{pred}(5) := 4$.

A Predecessor Graph



Suppose we Update(8)
and $\text{pred}(4) := 8$.

Then 4-8-5-4 has
negative cost.

Prior to Update(8),
the following is true:

$$d(5) = d(4) + c_{45}$$

$$d(8) = d(5) + c_{58}$$

$$d(4) > d(8) + c_{84}$$

To find negative cost cycles, periodically check the predecessor subgraph to see if it contains a cycle.

Summary of Lecture

1. **Optimality conditions for the shortest path algorithm.**
2. **The label correcting algorithm. Excellent in practice.**
 $O(nm)$ in theory, using a FIFO implementation of LIST.
3. **All pairs shortest path problem**
4. **Detecting negative cost cycles.**

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