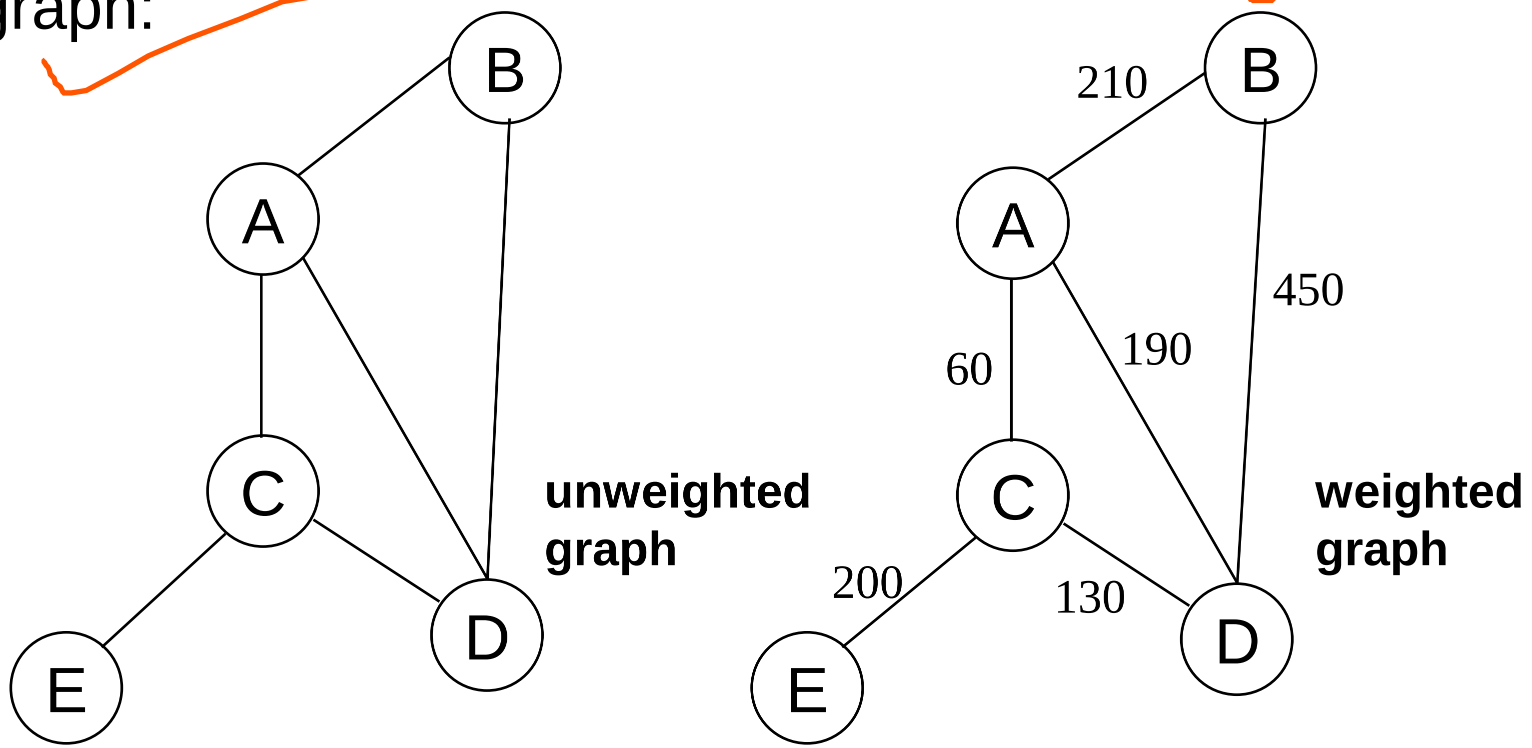
CSE 2202
Design and Analysis of Algorithms – I

Single Source Shortest Path (Dijkstra and Bellman Ford)

SINGLE SOURCE SHORTEST PATH(DIJKSTRA'S ALGORITHM)

Shortest Path Problems

- **What is shortest path ?**
  - shortest length between two vertices for an unweighted graph:
  - smallest cost between two vertices *for* a weighted graph:



Shortest Path Problems

- How can we find the shortest route between two points on a map?
- Model the problem as a graph problem:
  - Road map is a weighted graph:

    vertices = cities

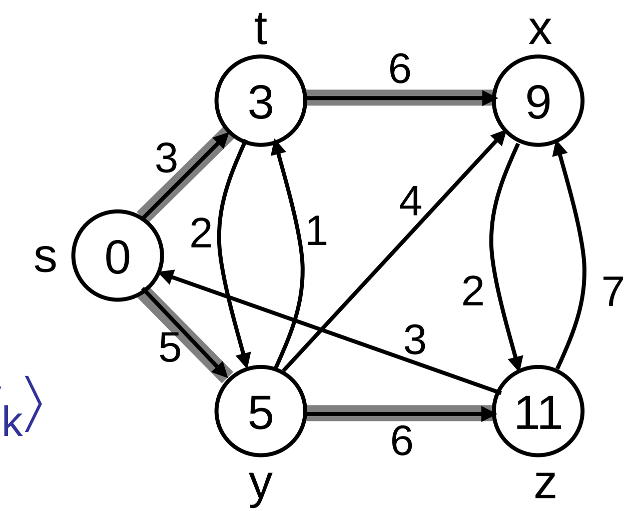
    edges = road segments between cities

    edge weights = road distances
  - Goal: find a shortest path between two vertices (cities)

Shortest Path Problems

- **Input:**
  - Directed graph $G = (V, E)$
  - Weight function $w : E \to \mathbf{R}$
- **Weight of path** $p = \langle v_0, v_1, \ldots, v_k \rangle$

$$w(p) = \sum_{i=1}^{k} w(v_{i-1}, v_i)$$



- **Shortest-path weight** from u to v:

$$\delta(u, v) = \begin{cases} \min\{w(p) : u \overset{p}{\rightsquigarrow} v\} & \text{if there exists a path from u to v} \\ \infty & \text{otherwise} \end{cases}$$

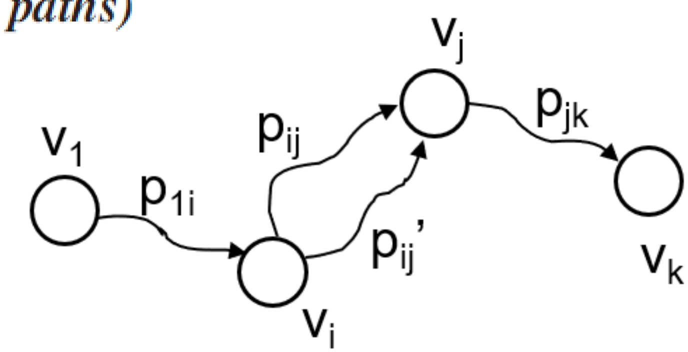
- Shortest path u to v is any path p such that $w(p) = \delta(u, v)$

Variants of Shortest Paths

- **Single-source shortest path**
  - G = (V, E) $\Rightarrow$ find a shortest path from a given source vertex *s* to each vertex v $\in$ V
- **Single-destination shortest path**
  - Find a shortest path to a given destination vertex **t** from each vertex v
  - Reverse the direction of each edge $\Rightarrow$ single-source
- **Single-pair shortest path**
  - Find a shortest path from u to v for given vertices u and v
  - Solve the single-source problem
- **All-pairs shortest-paths**
  - Find a shortest path from u to v for every pair of vertices u and v

Optimal Substructure of Shortest Paths

Lemma 24.1 (Subpaths of shortest paths are shortest paths)



Given:

- A weighted, directed graph $G = (V, E)$
- A weight function $w: E \rightarrow \mathbf{R}$,
- A shortest path $p = \langle v_1, v_2, \ldots, v_k \rangle$ from v_1 to v_k
- A subpath of p: $p_{ij} = \langle v_i, v_{i+1}, \ldots, v_j \rangle$, with $1 \leq i \leq j \leq k$

Then: p_{ij} is a shortest path from v_i to v_j

Proof: $p = v_1 \overset{p_{1i}}{\leadsto} v_i \overset{p_{ij}}{\leadsto} v_j \overset{p_{jk}}{\leadsto} v_k$

$$w(p) = w(p_{1i}) + w(p_{ij}) + w(p_{jk})$$

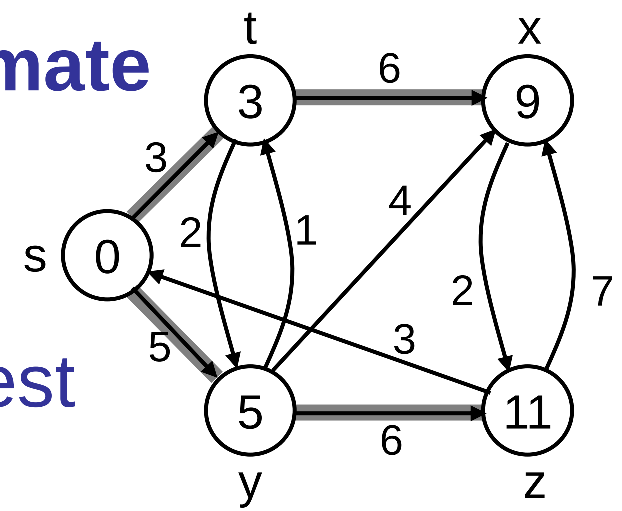
Assume $\exists\ p'_{ij}$ from v_i to v_j with $w(p'_{ij}) < w(p_{ij})$

$\Rightarrow w(p') = w(p_{1i}) + w(p_{ij}') + w(p_{jk}) < w(p)$ contradiction!

Shortest-Path Representation

For each vertex $v \in V$:

- $v.d = \delta(s, v)$: a **shortest-path estimate**
  - Initially, $d[v]=\infty$
  - Reduces as algorithms progress
- $v.\pi$ = **predecessor** of v on a shortest path from *s*
  - If no predecessor, $v.\pi$ = NIL
  - π induces a tree—**shortest-path tree**
- Shortest paths & shortest path trees are not unique



Initialization

INITIALIZE-SINGLE-SOURCE(G, s)

1 **for** each vertex $v \in G.V$
2 $\quad v.d = \infty$
3 $\quad v.\pi = \text{NIL}$
4 $s.d = 0$

- All the shortest-paths algorithms start with INITIALIZE-SINGLE-SOURCE

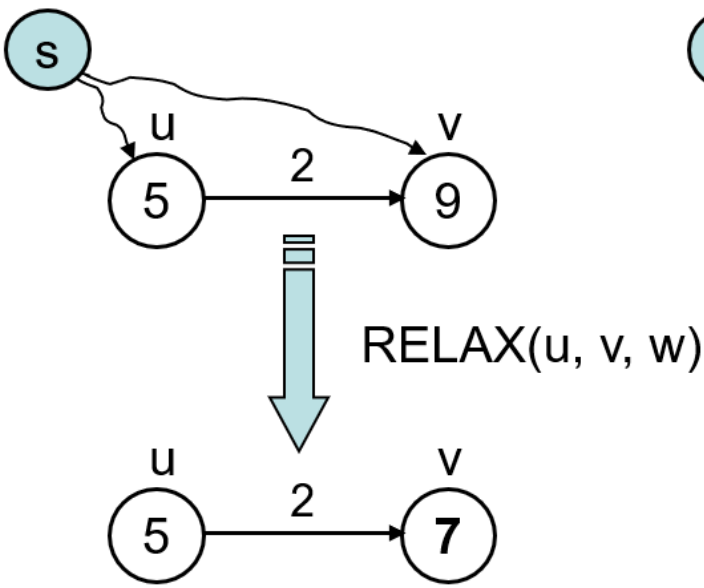
After initialization, we have $v.\pi = \text{NIL}$ for all $v \in V$, $s.d = 0$, and $v.d = \infty$ for $v \in V - \{s\}$.

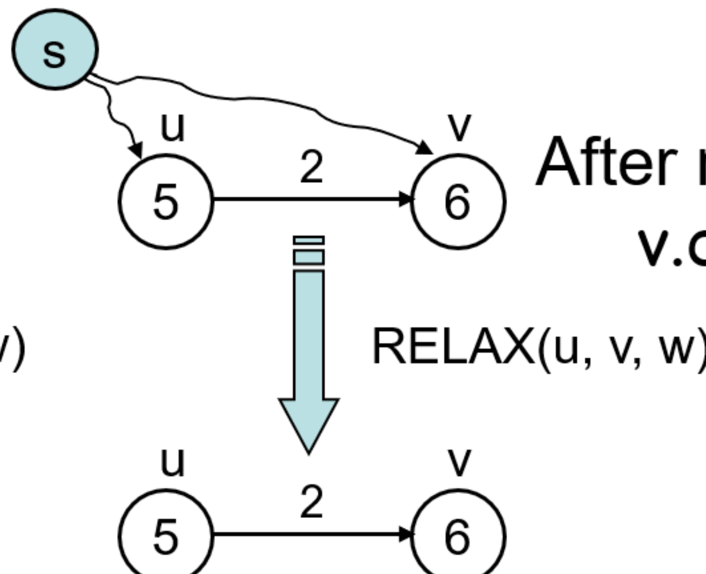
Relaxation

- **Relaxing** an edge (u, v) = testing whether we can improve the shortest path to v found so far by going through u

RELAX(u, v, w)

if $v.d > u.d + w(u, v)$
    $v.d = u.d + w(u, v)$
    $v.\pi = u$





After relaxation:
$v.d \le u.d + w(u, v)$

RELAX(u, v, w)

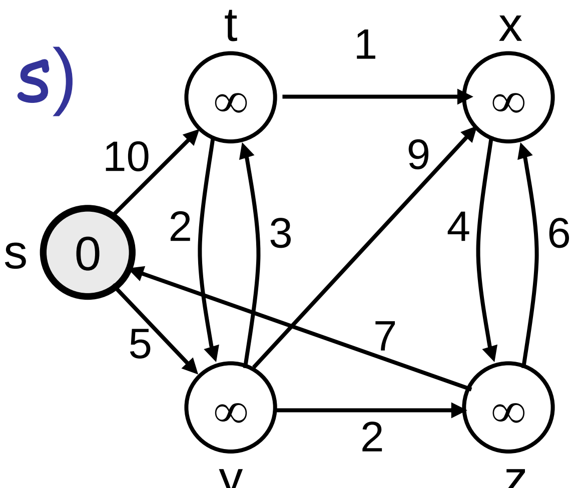
- All the single-source shortest-paths algorithms
  - start by calling INIT-SINGLE-SOURCE
  - then relax edges
- The algorithms differ in the order and how many times they relax each edge

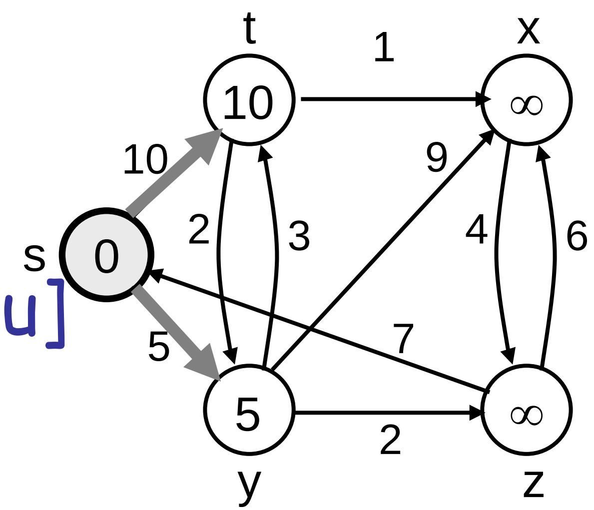
Dijkstra's Algorithm

- Single-source shortest path problem:
  - No negative-weight edges: $w(u, v) > 0 \ \forall \ (u, v) \in E$
- Maintains two sets of vertices:
  - S = vertices whose final shortest-path weights have already been determined
  - Q = vertices in V – S: min-priority queue
    - Keys in Q are estimates of shortest-path weights (v.d)
- Repeatedly select a vertex $u \in V - S$, with the minimum shortest-path estimate v.d

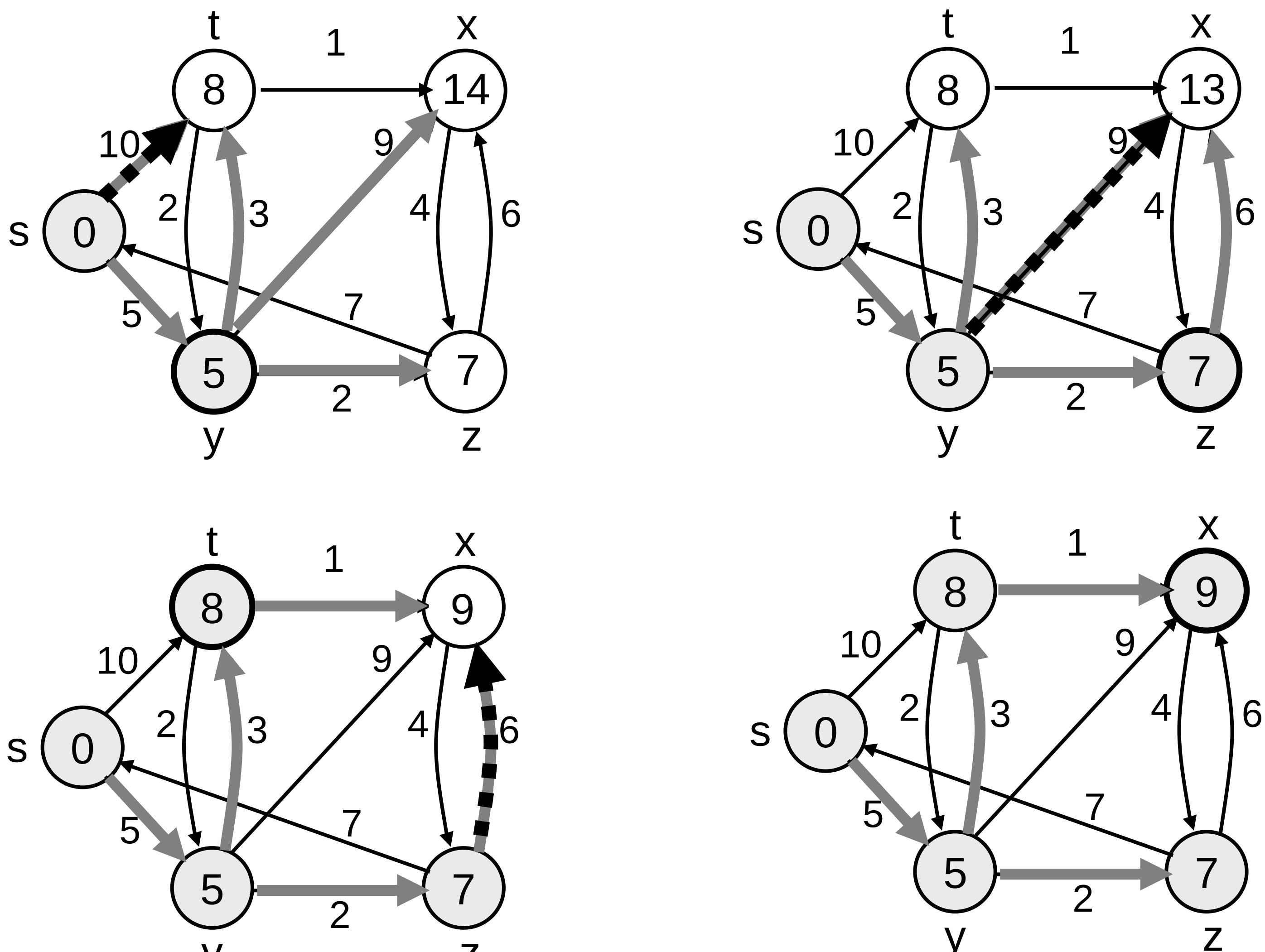
Dijkstra (G, w, s)

1. INITIALIZE-SINGLE-SOURCE(V, *s*)
2. S ← ∅
3. Q ← G. V
4. **while** Q ≠ ∅
5. **do** u ← EXTRACT-MIN(Q)
6. S ← S ∪ {u}
7. **for** each vertex v ∈ *G.Adj[u]*
8. **do** RELAX(u, v, w)





Example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Dijkstra's Pseudo Code

- Graph *G*, weight function *w*, root *s*

```
DIJKSTRA(G, w, s)
for each v ∈ V
        do d[v] ← ∞
d[s] ← 0
S ← ∅     ▷ Set of discovered nodes
Q ← V
while Q ≠ ∅
        do u ← EXTRACT-MIN(Q)
           S ← S ∪ {u}
           for each v ∈ Adj[u]
               do if d[v] > d[u] + w(u, v)
                     then d[v] ← d[u] + w(u, v)
```

relaxing edges

Dijkstra (G, w, s)

1. INITIALIZE-SINGLE-SOURCE(G, s) $\longleftarrow$ $\Theta(V)$
2. $S \leftarrow \emptyset$ never inserts vertices into Q after line 3
3. $Q \leftarrow G.V$ $\longleftarrow$ O(V) build min-heap
4. **while** $Q \neq \emptyset$ $\longleftarrow$ Executed O(V) times
5. **do** $u \leftarrow$ EXTRACT-MIN(Q) $\longleftarrow$ O(lgV)
6. $S \leftarrow S \cup \{u\}$
7. **for** each vertex $v \in G.Adj[u]$
8. **do** RELAX(u, v, w) $\longleftarrow$ O(E) times; O(lgV)

Running time: $O(VlgV + ElgV) = O(ElgV)$

Dijkstra's Running Time

- Extract-Min executed $|V|$ time
- Decrease-Key executed $|E|$ time
- Time = $|V|\ T_{\text{Extract-Min}} + |E|\ T_{\text{Decrease-Key}}$
- T depends on different Q implementations

Q	T(Extract-Min)	T(Decrease-Key)	Total
array	$O(V)$	$O(1)$	$O(V^2)$
binary heap	$O(\lg V)$	$O(\lg V)$	$O(E \lg V)$
Fibonacci heap	$O(\lg V)$	$O(1)$ (amort.)	$O(V \lg V + E)$

Question

- Prove that, if there exists negative edge, dijkstra's shortest path algorithm may fail to find the shortest path
- Print the shortest path for dijkstra's algorithm
- Suppose you are given a graph where each edge represents the path cost and each vertex has also a cost which represents that, if you select a path using this node, the cost will be added with the path cost. How can it be solved using Dijkstra's algorithm?

Negative-Weight Edges

- $s \to a$: only one path

  $\delta(s, a) = w(s, a) = 3$

- $s \to b$: only one path

  $\delta(s, b) = w(s, a) + w(a, b) = -1$

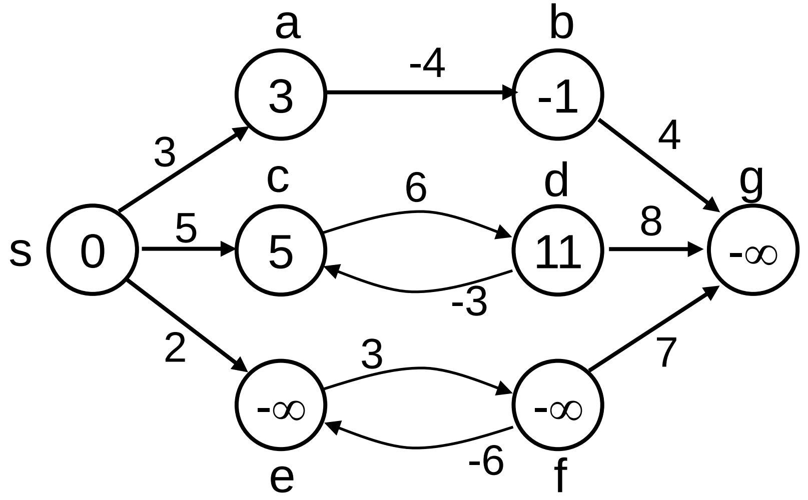
- $s \to c$: infinitely many paths

  $\langle s, c \rangle, \langle s, c, d, c \rangle, \langle s, c, d, c, d, c \rangle$

  cycle has positive weight (6 - 3 = 3)

  $\langle s, c \rangle$ is shortest path with weight $\delta(s, c) = w(s, c) = 5$

What if we have negative-weight edges?

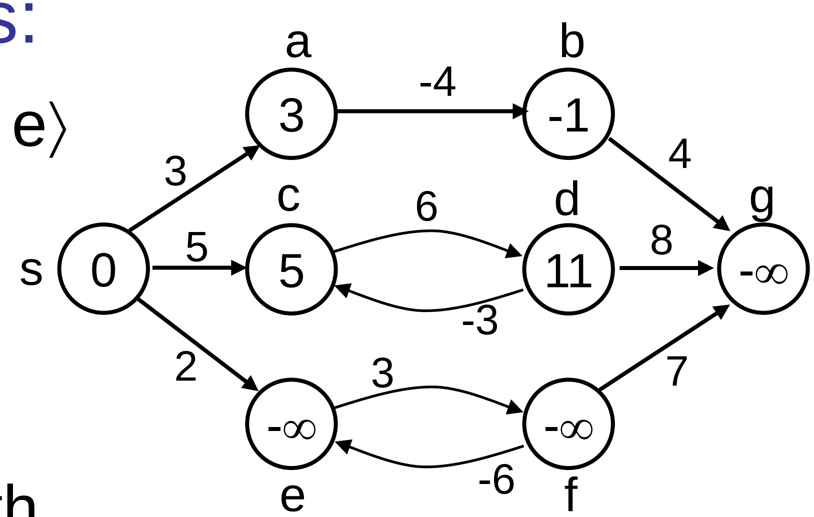


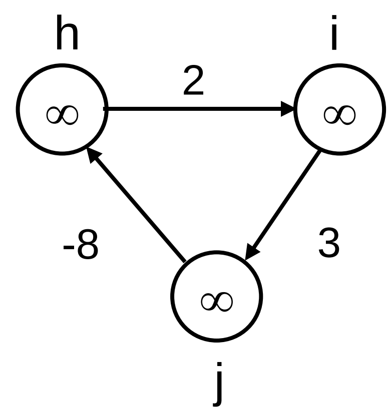
Negative-Weight Edges

- $s \rightarrow e$: infinitely many paths:
  - $\langle s, e\rangle, \langle s, e, f, e\rangle, \langle s, e, f, e, f, e\rangle$
  - cycle $\langle e, f, e\rangle$ has negative weight:

    $3 + (-6) = -3$
  - can find paths from s to e with arbitrarily large negative weights
  - $\delta(s, e) = -\infty \Rightarrow$ no shortest path exists between s and e
  - Similarly: $\delta(s, f) = -\infty$,

    $\delta(s, g) = -\infty$



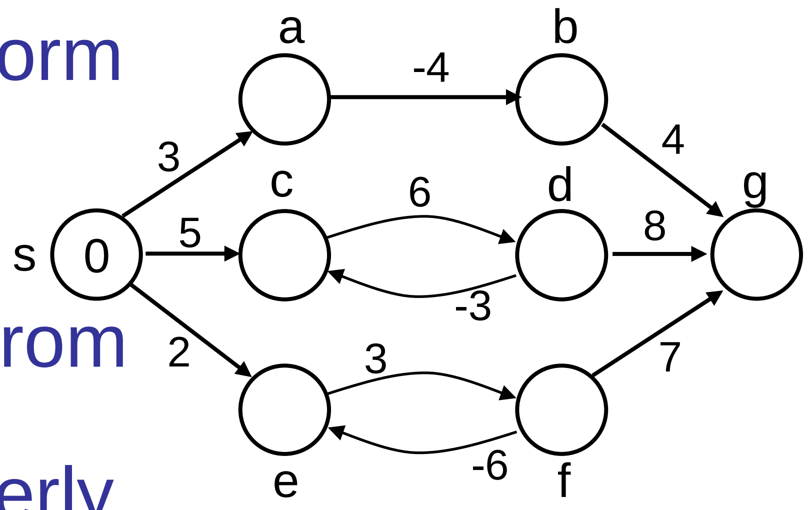


h, i, j not reachable from s

$\delta(s, h) = \delta(s, i) = \delta(s, j) = \infty$

Negative-Weight Edges

- Negative-weight edges may form negative-weight cycles
- If such cycles are reachable from the source: $\delta(s, v)$ is not properly defined
  - Keep going around the cycle, and get $w(s, v) = -\infty$ for all v on the cycle



Cycles

- Can shortest paths contain cycles?
- Negative-weight cycles No!
- Positive-weight cycles: No!
  - By removing the cycle we can get a shorter path
- We will assume that when we are finding shortest paths, the paths will have no cycles

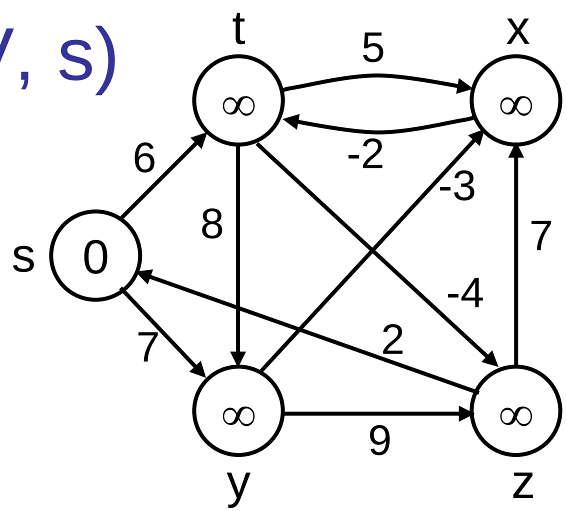
BELLMAN FORD

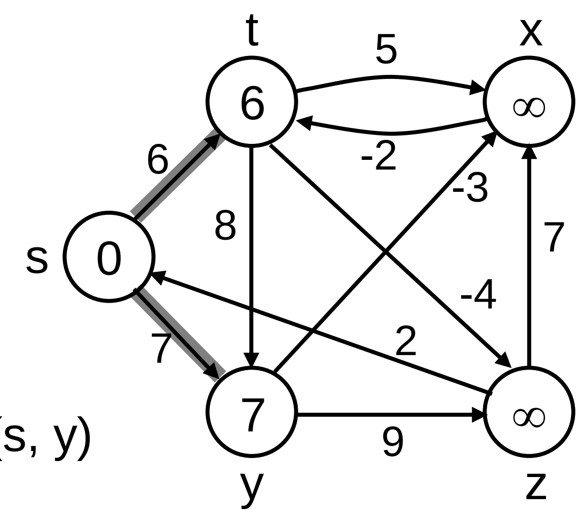
Bellman-Ford Algorithm

- Single-source shortest paths problem
  - Computes v.d and v.πv for all v $\in$ V
- Allows negative edge weights
- Returns:
  - TRUE if no negative-weight cycles are reachable from the source s
  - FALSE otherwise $\Rightarrow$ no solution exists
- Idea:
  - Traverse all the edges **|V – 1| times**, every time performing a relaxation step of each edge
  - This is because, in the **worst-case scenario**, any vertex's path length can be changed N times to an even shorter path length.

BELLMAN-FORD(V, E, w, s)

```
INITIALIZE-SINGLE-SOURCE(V, s)
for i ← 1 to |V| - 1
    do for each edge (u, v) ∈ E
        do RELAX(u, v, w)
for each edge (u, v) ∈ E
    do if d[v] > d[u] + w(u, v)
        then return FALSE
return TRUE
```

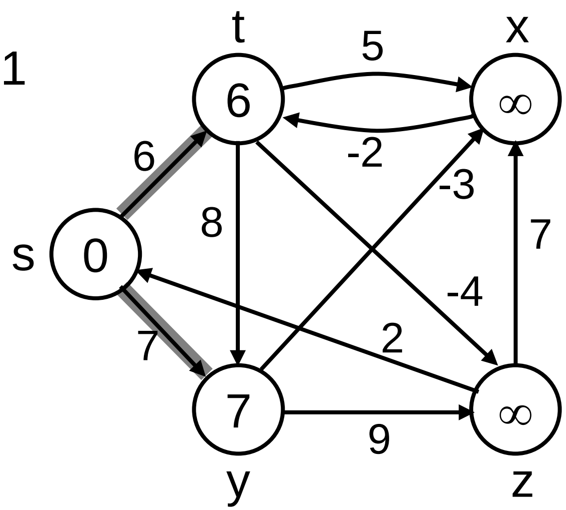




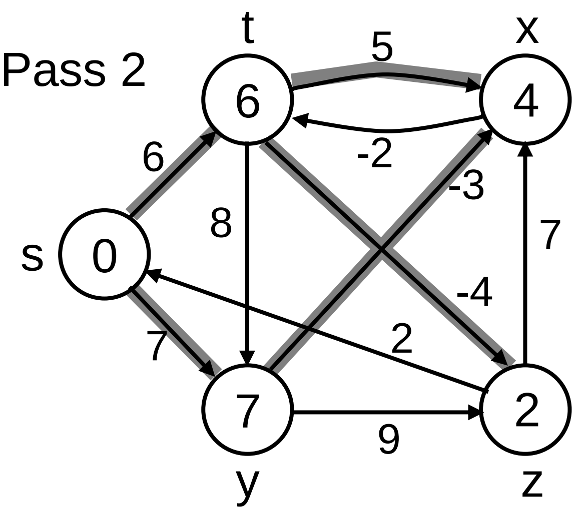
E: (t, x), (t, y), (t, z), (x, t), (y, x), (y, z), (z, x), (z, s), (s, t), (s, y)

Example (t, x), (t, y), (t, z), (x, t), (y, x), (y, z), (z, x), (z, s), (s, t), (s, y)

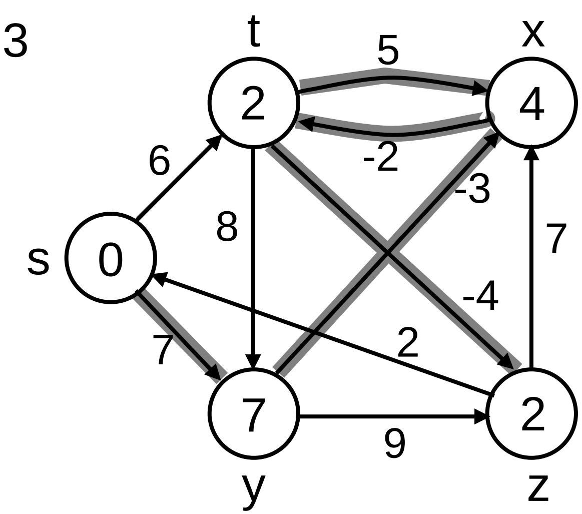
Pass 1



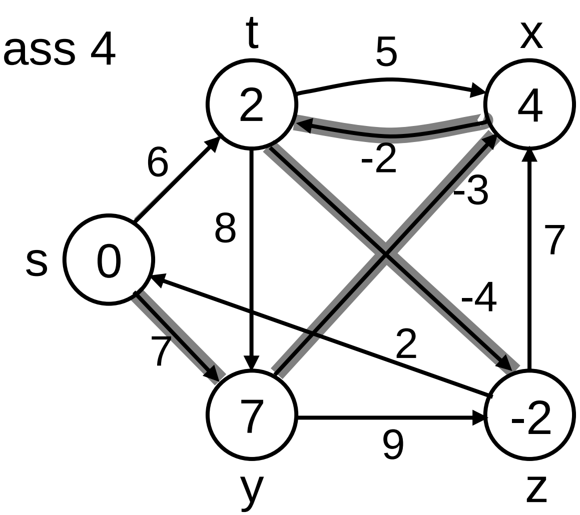
Pass 2



Pass 3

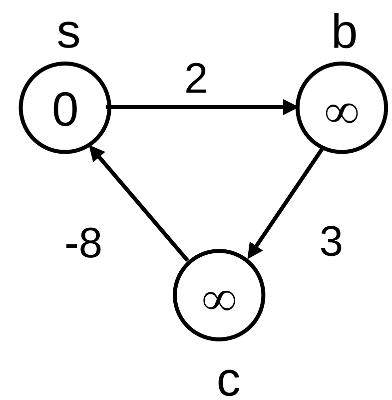


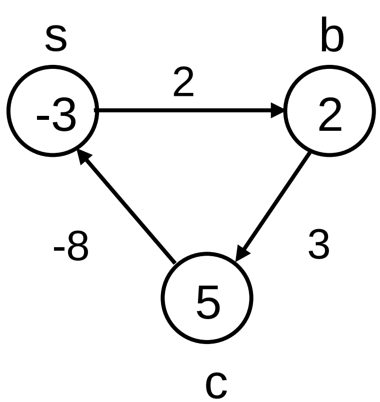
Pass 4

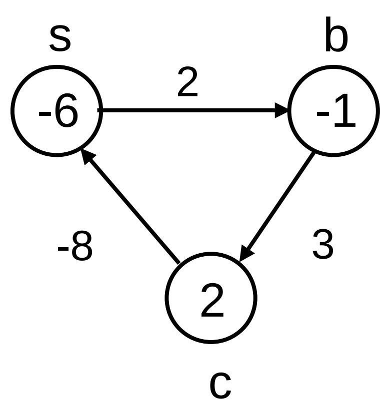


Detecting Negative Cycles

- **for** each edge (u, v) $\in$ E
- **do if** v.d > u.d + w(u, v)
- **then return** FALSE
- **return** TRUE







Look at edge (s, b):

b.d = -1

s.d + w(s, b) = -4

$\Rightarrow$ b.d > s.d + w(s, b)

BELLMAN-FORD(*V*, *E*, *w*, *s*)

1. INITIALIZE-SINGLE-SOURCE(V, s) ⟵ Θ(V)
2. **for** i ← 1 to |G.V| - 1 ⟵ O(V)
3. **do for** each edge (u, v) ∈ G.E ⟵ O(E)
4. **do** RELAX(u, v, w)
5. **for** each edge (u, v) ∈ G.E ⟵ O(E)
6. **do if** v.d > u.d + w(u, v)
7. **then return** FALSE
8. **return** TRUE

O(VE)

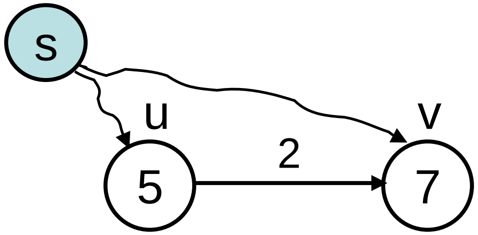
Running time: O(VE)

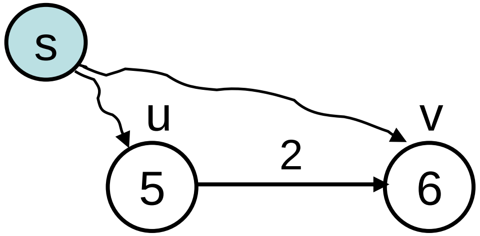
Shortest Path Properties

- **Triangle inequality**

  For all $(u, v) \in E$, we have:

  $$\delta(s, v) \leq \delta(s, u) + w(u, v)$$





- If u is on the shortest path to v we have the equality sign

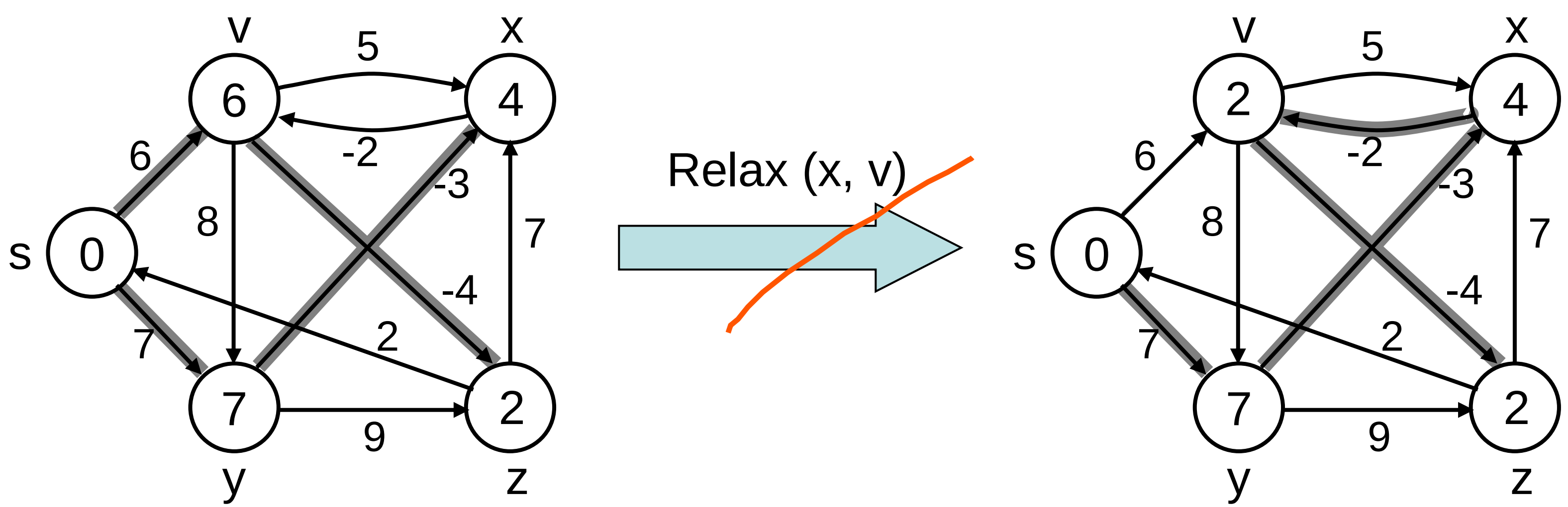
Shortest Path Properties

- **Upper-bound property**

  We always have v.d ≥ δ(s, v) for all v.

  Once v.d = δ(s, v), it never changes.

  – The estimate never goes up – relaxation only lowers the estimate

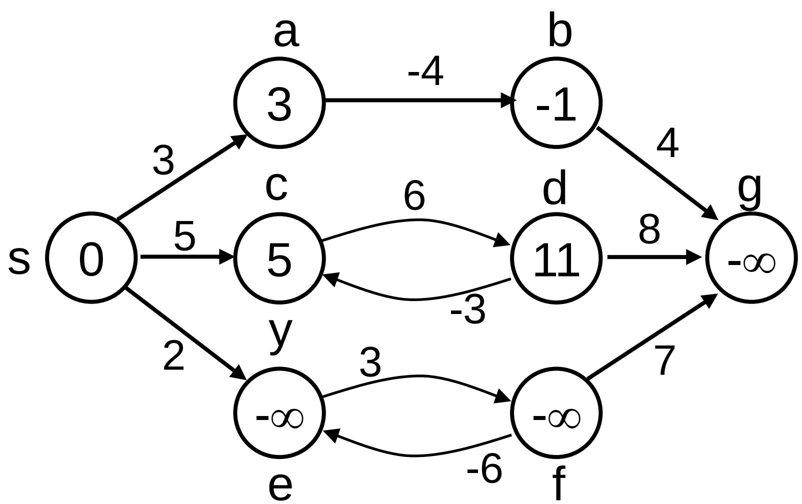


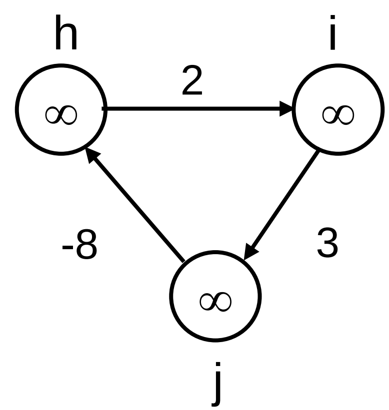
Shortest Path Properties

- **No-path property**

  If there is no path from *s* to v then v.d = ∞ always.

  – $\delta(s, h) = \infty$ and $h.d \geq \delta(s, h) \Rightarrow h.d = \infty$





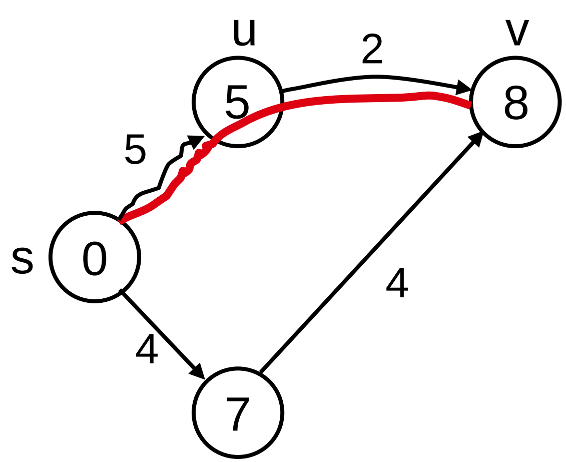
h, i, j not reachable from s

$\delta(s, h) = \delta(s, i) = \delta(s, j) = \infty$

Shortest Path Properties

- **Convergence property**

  If $s \leadsto u \rightarrow v$ is a shortest path, and if $u.d = \delta(s, u)$ at any time prior to relaxing edge (u, v), then $v.d = \delta(s, v)$ at all times afterward.



- If $v.d > \delta(s, v) \Rightarrow$ after relaxation:

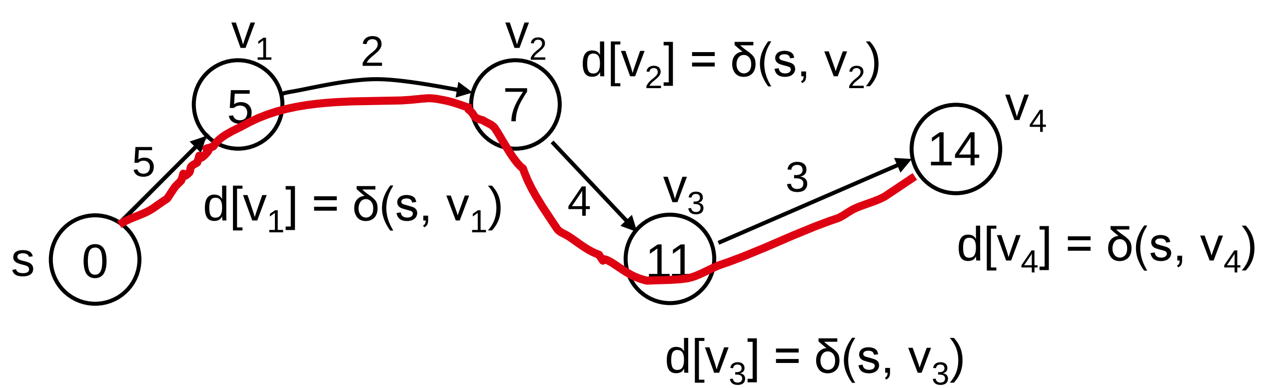
  $v.d = u.d + w(u, v)$

  $v.d = 5 + 2 = 7$
- Otherwise, the value remains unchanged, because it must have been the shortest path value

Shortest Path Properties

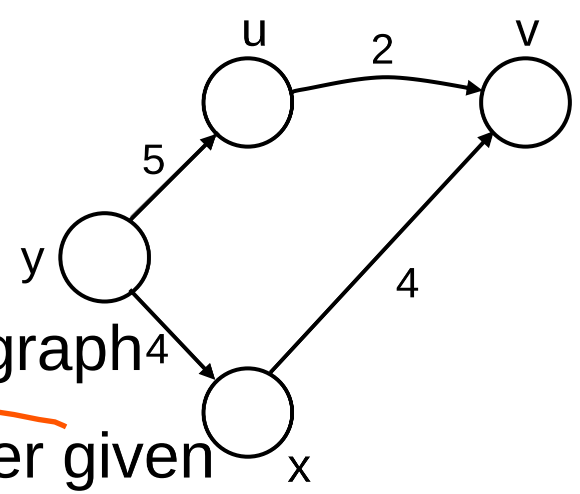
- **Path relaxation property**

  Let $p = \langle v_0, v_1, \ldots, v_k \rangle$ be a shortest path from $s = v_0$ to v_k. If we relax, in order, (v_0, v_1), (v_1, v_2), . . . , (v_{k-1}, v_k), even intermixed with other relaxations, then $d[v_k] = \delta(s, v_k)$.



SINGLE-SOURCE SHORTEST PATHS IN DAGS

Single-Source Shortest Paths in DAGs



- Given a weighted DAG: G = (V, E)
  – solve the shortest path problem
- Idea:
  – Topologically sort the vertices of the graph
  – Relax the edges according to the order given by the topological sort
    - for each vertex, we relax each edge that starts from that vertex
- Are shortest-paths well defined in a DAG?
  – Yes, (negative-weight) cycles cannot exist

In such setting, we can compute shortest paths from a single source in time:

$$\Theta(V + E)$$

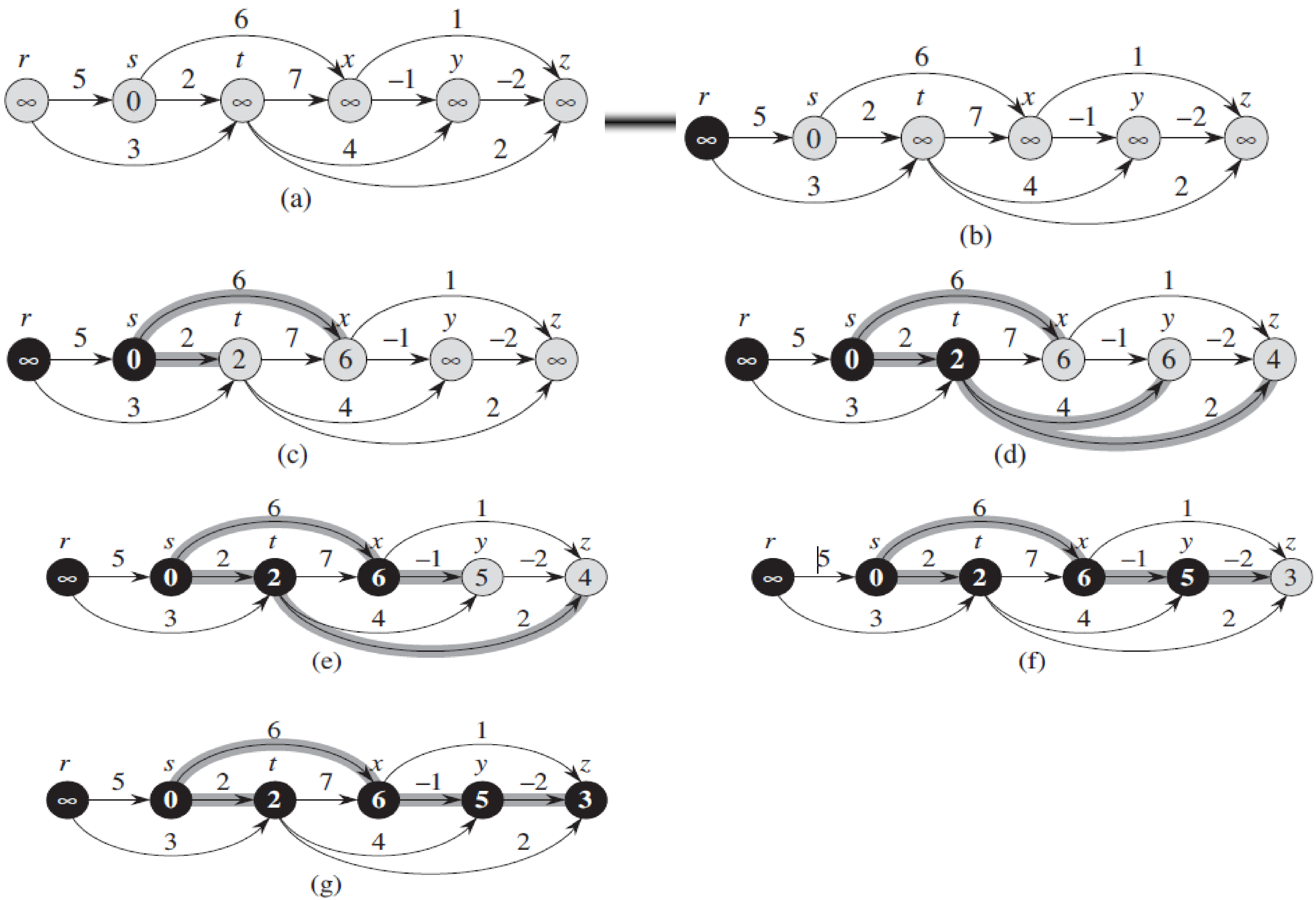
DAG-SHORTEST-PATHS(G, w, s)

1. topologically sort the vertices of G ← $\Theta(V+E)$
2. INITIALIZE-SINGLE-SOURCE(V, s) ← $\Theta(V)$
3. **for** each vertex u, taken in topologically sorted order $\Theta(V)$
4. **do for** each vertex $v \in G.Adj[u]$
5. **do** RELAX(u, v, w)

$\left.\begin{array}{l} \\ \\ \\ \end{array}\right\} \Theta(E)$

Running time: $\Theta(V+E)$

We have used an aggregate analysis here



The newly blackened vertex in each iteration was used as u in that iteration.

Readings

- Chapter 24
- Exercise
  - 24.1-6 – Find negative cycle
  - 24.2-4 – Total Number of paths in a DAG
- Difficult Problems (Solve these if you want):
  - 24.3-6 modify dijkstra
  - 24-2 – nesting boxes
  - 24-3 - Arbitrage
  - 24.6 – Bitonic Shortest path