EN.601.414/614 Computer Networks

Routing Algorithms

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Spring 2019 (MW 3:00-4:15pm in Shaffer 301)

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https://github.com/xinjin/course-net

Agenda

- **Recap: assignment 2**
- **Recap: least-cost path routing**
- **Link-state routing**
- **Distance-vector routing**
- **Tutorial: assignment 3**

Recap: Assignment 2

- **Primary goal: understand reliable transport**
  - ➢You do not FULLY understand it without implementing it by yourself
- **Secondary goal: it is a lesson for you to learn**
  - ➢Teamwork
    - You and you teammates are on the same boat!
    - Start early, and check progress regularly
  - ➢Software testing
    - You are responsible for the software you write
    - Make sure it passes basic test cases
    - Use the test script of assignment 1 as your start

Recap: Assignment 2

- **Feedback from midterm survey**
  - Content: useful and practical
    - Reliable transport is used everywhere, and is critical to many applications, e.g., messages, web, remote control, etc.
  - Difficulty
    - Some students find it too easy, while others find too difficult
    - Tedious things like handling input/output and multi-threading are an integral part of making it work in the real-world
      - Tons of lines of code at Google to make Page-Rank work and build a fast, scalable and reliable search engine
    - We use Python and provide some scaffolding code to abstract away most of the low-level tedious work
      - It is in C, and has no scaffolding code at other schools!

Recap: Assignment 2

- **That being said, changes to assignment 3…**
  - ➢ We provide more scaffolding code and the test script (which is the same used for grading)
  - ➢ But do try to write the code from scratch, and write your own test script if possible. It is a good learning experience for your own benefit.
    - You can also try other languages (C/C++/Java/Go) yourself and build your own test environments
  - ➢ Our goal is not to give you a hard time and make you feel bad. We hope you learn something useful besides getting A+ (😀) from this course.
  - ➢ Finish both distance-vector and link-state protocols to get bonus points

Recap: Least-cost path routing

- **Given: router graph & link costs**
- **Goal: find least-cost path**
  - From each source router to each destination router

- **Easy way to avoid loops**
  - No reasonable cost metric is minimized by traversing a loop

Recap: Dijkstra’s algorithm

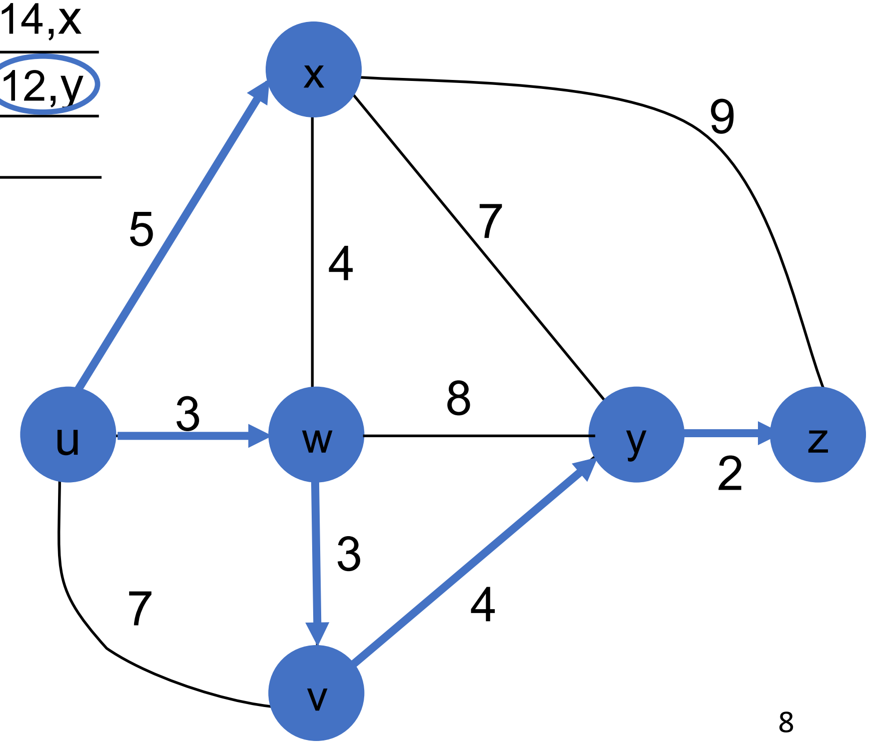
- **Network topology, link costs known to all nodes**
  - All nodes have same info
- **Each node (“src”) computes least-cost paths to all other nodes**
  - After k iterations, know least-cost path to k destinations

Recap: Dijkstra's algorithm: Example

Step	N'	D(v) p(v)	D(w) p(w)	D(x) p(x)	D(y) p(y)	D(z) p(z)
0	u	7,u	3,u	5,u	∞	∞
1	uw	6,w		5,u	11,w	∞
2	uwx	6,w			11,w	14,x
3	uwxv				10,v	14,x
4	uwxvy					12,y
5	uwxvyz					

Notes:

- Construct shortest path tree by tracing predecessor nodes
- Ties can exist (can be broken arbitrarily)



From routing algorithm to protocol

- **Dijkstra's is a local computation!**
  - Computed by a node given complete network graph
- **Possibilities:**
  - Option#1: a separate machine runs the algorithm
  - Option#2: every router runs the algorithm
- **The Internet currently uses Option#2**

Link-state routing

- **Every router knows its local "link state"**
  - Router u: "(u,v) with cost=2; (u,x) with cost=1"
- **Each router floods its local link state to all other routers in the network**
  - Does so periodically or when its link state changes
- **Every router learns the entire network graph**
  - Each runs Dijkstra's Shortest-Path First (SPF) algorithm locally to compute forwarding table

Flooding link state

- **Flooding**
  - A node sends its link-state info out all of its links
  - The next node forwards the info on all of its links except the one the information arrived at
- **When to initiate flooding?**
  - Topology change (e.g., link/node failure/recovery)
  - Configuration change (e.g., link cost change)
  - Periodically
    - To refresh link-state information (soft states)
    - Typically (say) every 30 minutes

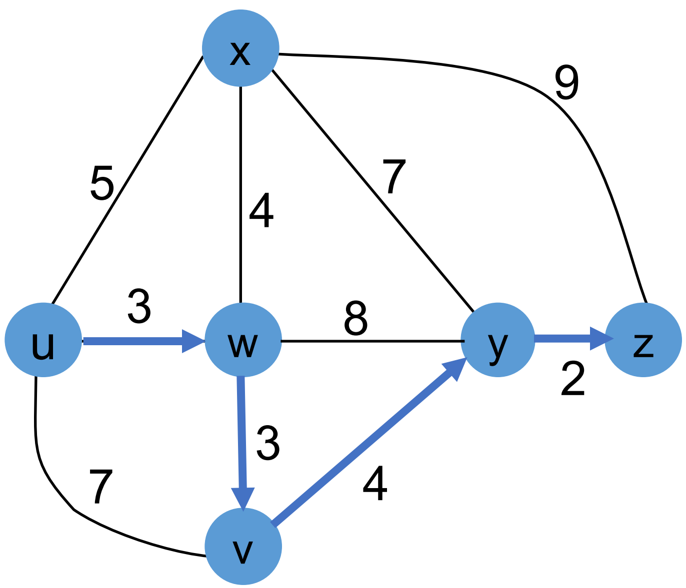
Convergence

- **Why flood?**
  - To get all the nodes in the network to converge to the new topology
- **Upon convergence, all nodes will have consistent routing information and can compute consistent forwarding:**
  - All nodes have the same link-state database
  - All nodes forward packets on shortest paths
  - The next router on the path forwards to the expected next hop

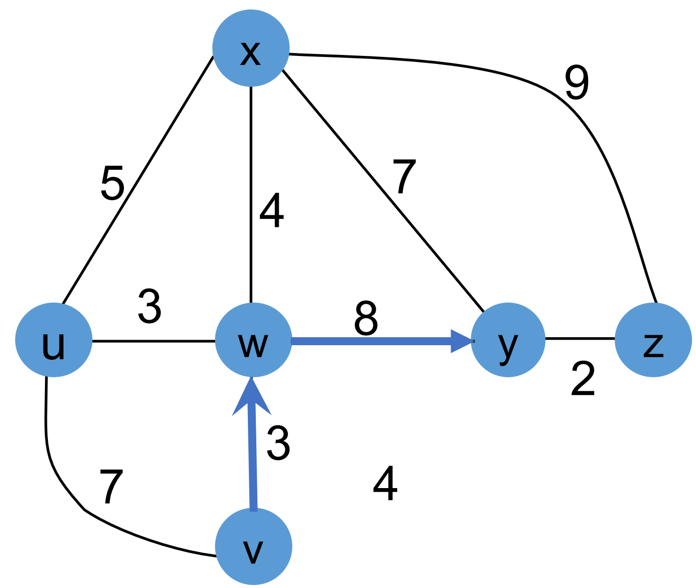
Convergence delay

- **Time to achieve convergence**
- **Sources of convergence delay**
  - Time to detect failure
  - Time to flood link-state information
  - Time to re-compute forwarding tables
- **What happens if it takes too long to converge?**

Loop from convergence delay



u and w think that the path to y goes through v



v thinks that the path to y goes through w

Performance during convergence period

- **Looping packets**
- **Lost packets due to black holes**
- **Out-of-order packets reaching the destination**

Link-state routing

- **Scalability?**
  - ➢O(NE) messages
  - ➢O(N^2) computation time
  - ➢O(Network diameter) convergence delay
  - ➢O(N) entries in forwarding table

Link-state routing protocols

- **OSPF: Open Shortest Path First**
- **IS-IS: Intermediate System to Intermediate System**
  - Similar to OSPF

OSPF:
Open Shortest-Path First

- **Open: publicly available**
- **Uses link-state algorithm**
  - ➢Link-state packet dissemination
  - ➢Topology map at each node
  - ➢Route computation using Dijkstra’s algorithm
- **Router floods OSPF link-state advertisements to all other routers in entire AS**
  - ➢Carried in OSPF messages directly over IP (rather than TCP or UDP)
    - Requires reliable transmission

Distance-vector protocol

- **Link-state routing protocol**
  - Each node broadcasts its local information

- **Distance-vector routing protocol**
  - The opposite (sort of)
  - Each node tells its neighbors about its global view

Bellman-Ford equation

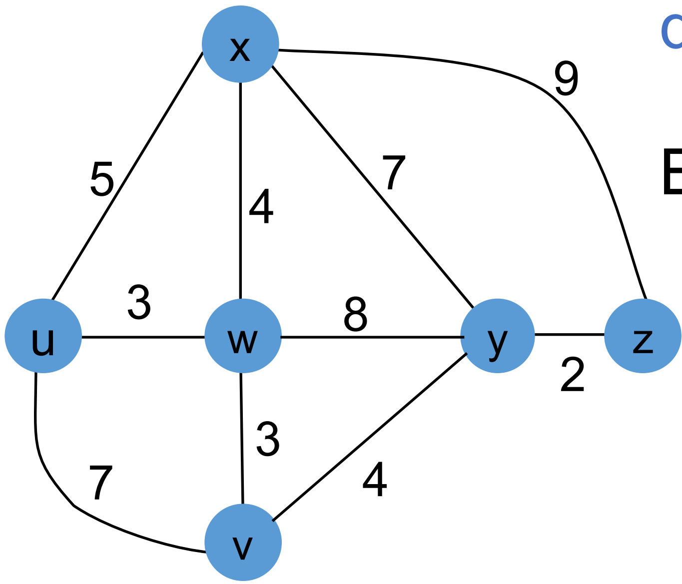
- **Let**
  - ➢ $d_x(y)$:= cost of least-cost path from x to y
- **Then**
  - ➢ $d_x(y) = \min_v \{c(x, v) + d_v(y)\}$

cost from neighbor v to destination y

cost to neighbor v

min taken over all neighbors v of x

Bellman-Ford example



$d_x(z) = 9$, $d_w(z) = 9$, $d_v(z) = 6$

B-F equation says:

$$
\begin{aligned}
d_u(z) = \min \{&c(u,x) + d_x(z), \\
&c(u,w) + d_w(z), \\
&c(u,v) + d_v(z) \} \\
= \min \{&5 + 9, \\
&3 + 9, \\
&7 + 6\} = 12
\end{aligned}
$$

Neighbor achieving the minimum (w) is next hop in shortest path, used in forwarding table

Distance vector algorithm

- **$D_x(y)$ is the estimate of least cost from x to y**
    - x maintains its own distance vector $\mathbf{D_x} = [D_x(y): y \in N]$
- **Node x:**
    - Knows cost to each neighbor v: $c(x,v)$
    - Maintains its neighbors' distance vectors
        - For each neighbor v, x has $\mathbf{D_v} = [D_v(y): y \in N]$

Distance vector algorithm

- **From time-to-time, each node sends its own distance vector estimate to neighbors**
- **When x receives new DV estimate from neighbor, it updates its own DV using B-F equation**
  - $D_x(y) \leftarrow \min_v\{c(x,v) + D_v(y)\}$ for each node $y \in N$
- **Eventually, the estimate $D_x(y)$ may converge to the actual least cost $d_x(y)$**

Distance vector algorithm

- **Iterative, asynchronous**
  - ➢ Local iterations caused by
    - Local link cost change
    - DV update message from neighbor
- **Distributed**
  - ➢ Each node notifies neighbors only when its DV changes
    - Neighbors then notify their neighbors if necessary

@each node:

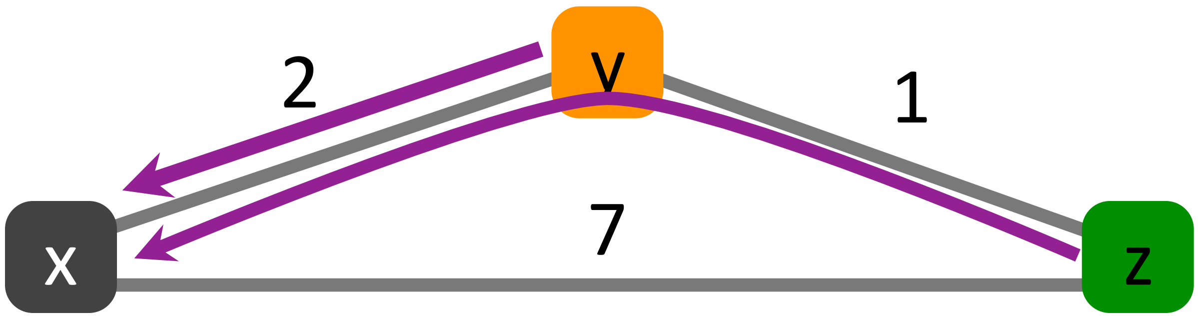
Wait for (change in local link cost OR msg from neighbor)

Recompute estimates

Notify neighbors if DV to any dest has changed

Example

	x	y	z
y	2	0	1
z	3	1	0

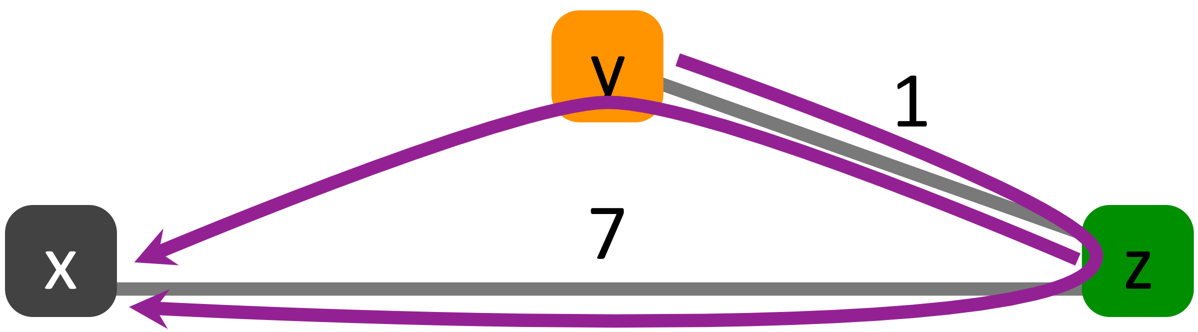


	x	y	z
y	2	0	1
z	3	1	0

Example

	x	y	z
y	4	0	1
z	3	1	0

routing loop!

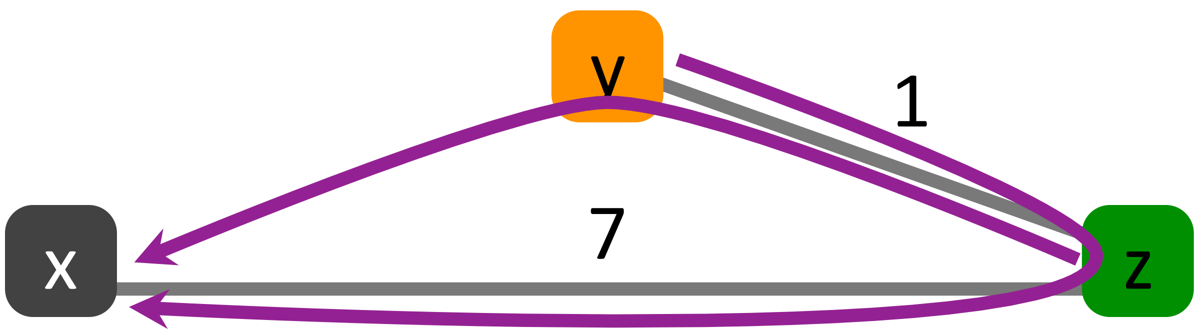


	x	y	z
y	2	0	1
z	3	1	0

Example

	x	y	z
y	4	0	1
z	3	1	0

routing loop!



	x	y	z
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z	3	1	0

Example

	x	y	z
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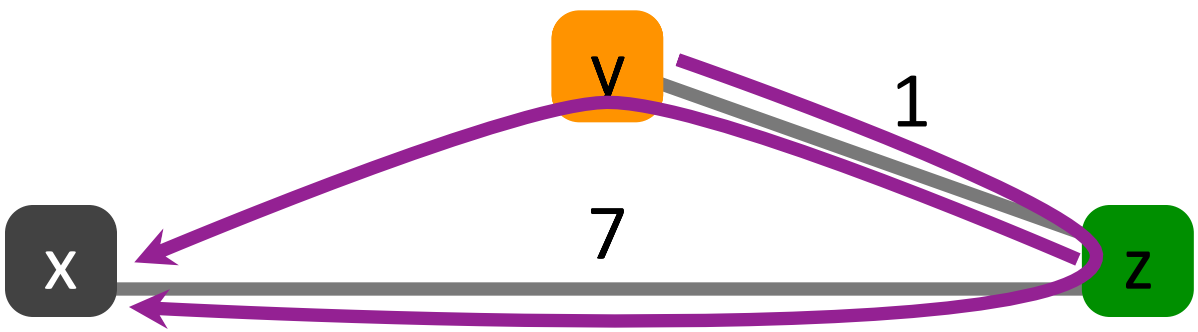
routing loop!

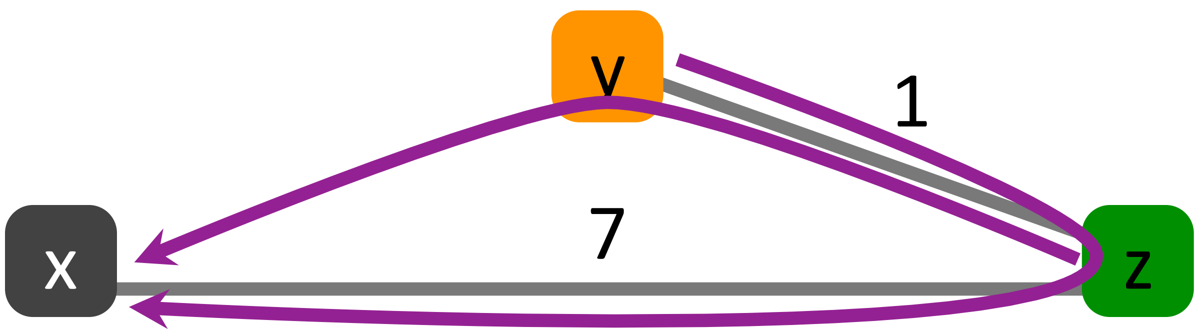


	x	y	z
y	4	0	1
z	5	1	0

Example

	x	y	z
y	4	0	1
z	5	1	0

routing loop!

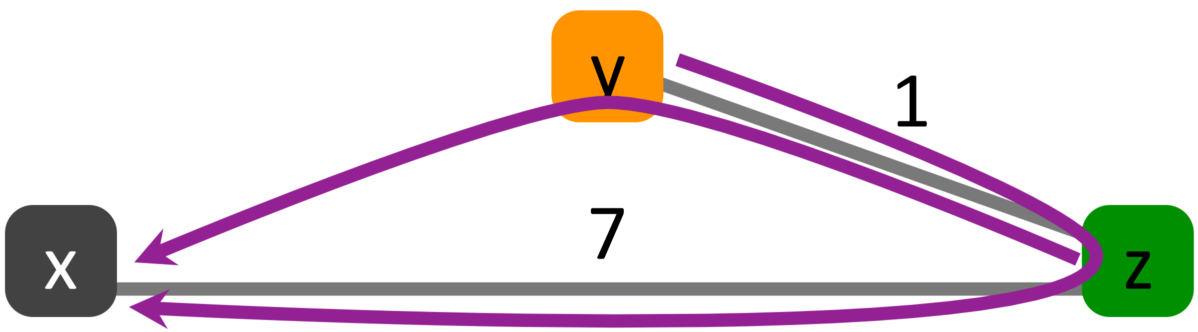


	x	y	z
y	4	0	1
z	5	1	0

Example

	x	y	z
y	6	0	1
z	5	1	0

routing loop!

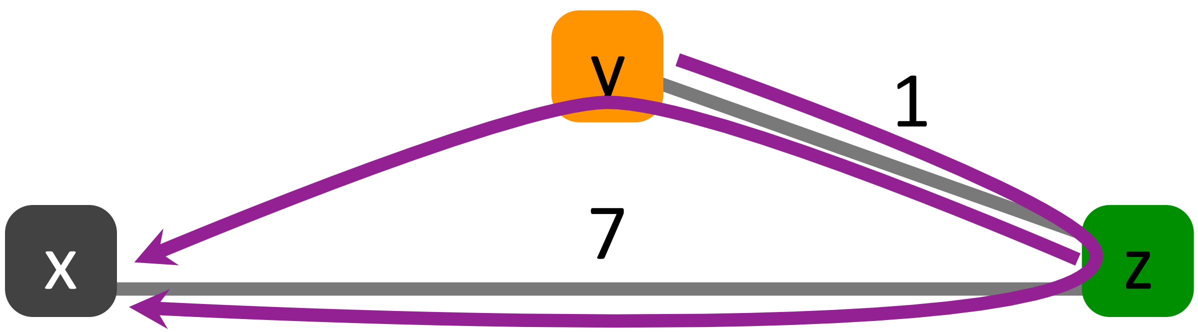


	x	y	z
y	4	0	1
z	5	1	0

Example

	x	y	z
y	6	0	1
z	5	1	0

routing loop!

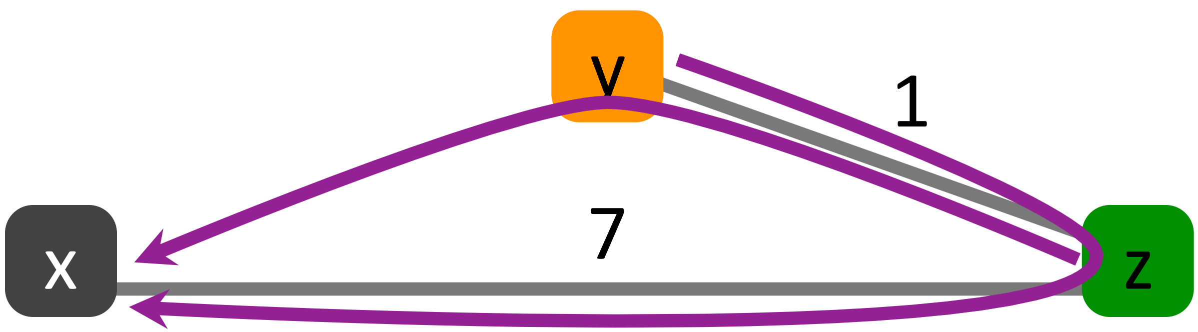


	x	y	z
y	6	0	1
z	5	1	0

Example

	x	y	z
y	6	0	1
z	5	1	0

routing loop!

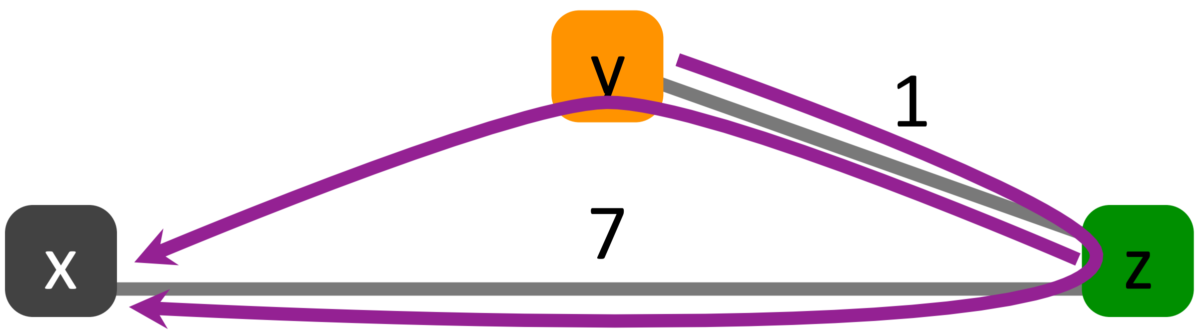


	x	y	z
y	6	0	1
z	7	1	0

Example

	x	y	z
y	6	0	1
z	7	1	0

routing loop!

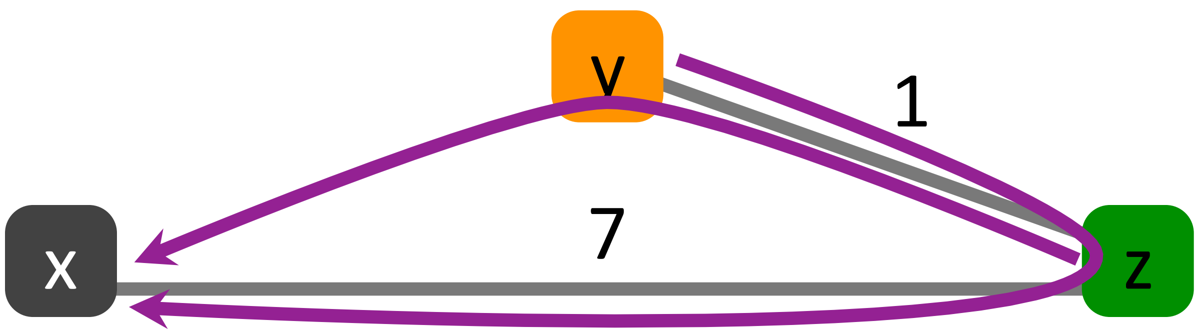


	x	y	z
y	6	0	1
z	7	1	0

Example

	x	y	z
y	8	0	1
z	7	1	0

routing loop!

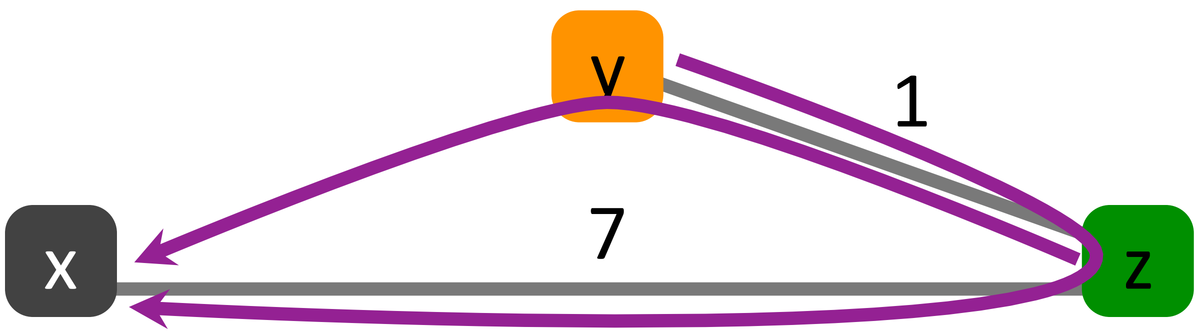


	x	y	z
y	6	0	1
z	7	1	0

Example

	x	y	z
y	8	0	1
z	7	1	0

routing loop!



	x	y	z
y	8	0	1
z	7	1	0

Example

	x	y	z
y	8	0	1
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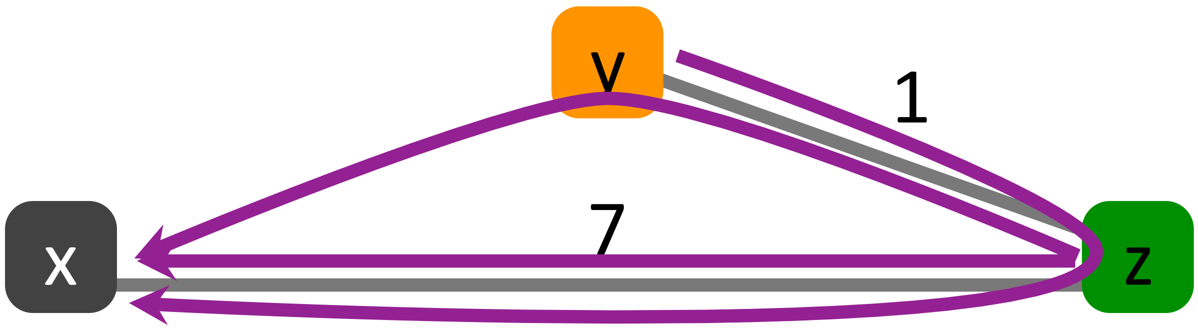
routing loop!



Count-to-infinity scenario

	x	y	z
y	8	0	1
z	7	1	0

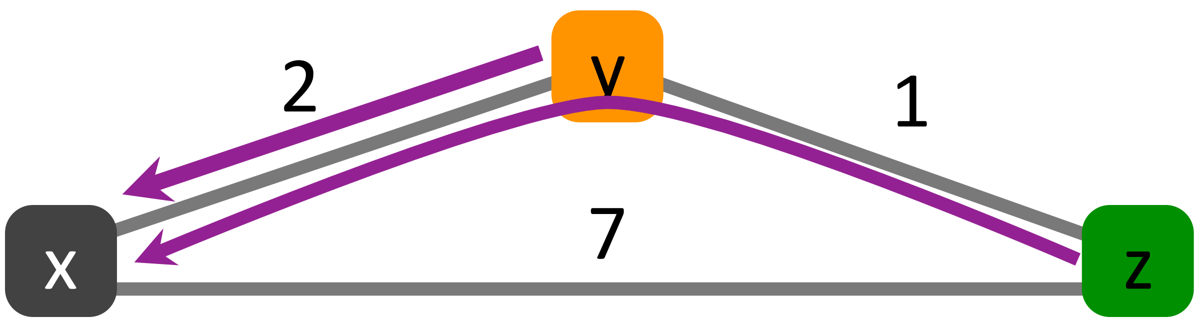
Problems with Bellman-Ford

- **Routing loops**
  - z routes through y, y routes through x
  - y loses connectivity to x
  - y decides to route through z
- **Can take a very long time to resolve**
  - Count-to-infinity scenario

Poisoned reverse

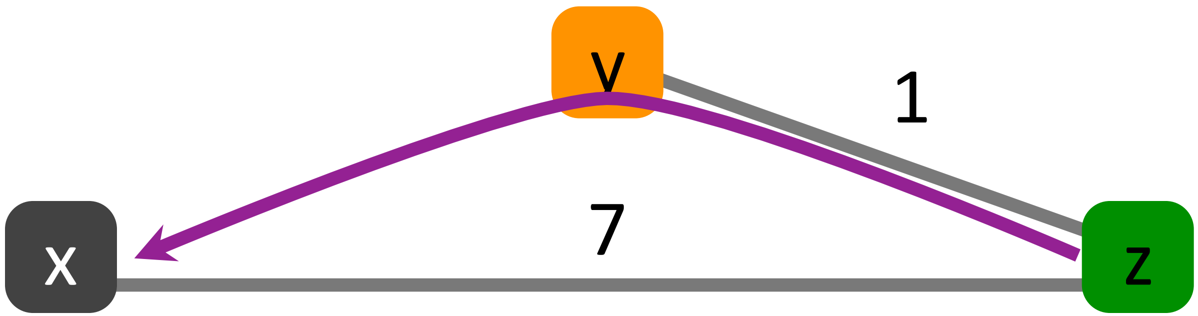
- **One heuristic to avoid count-to-infinity**
  - ➢ If z routes to x through y,
    - z advertises to y that its cost to x is infinite
  - ➢ y never decides to route to x through z

	x	y	z
y	2	0	1
z	∞	1	0



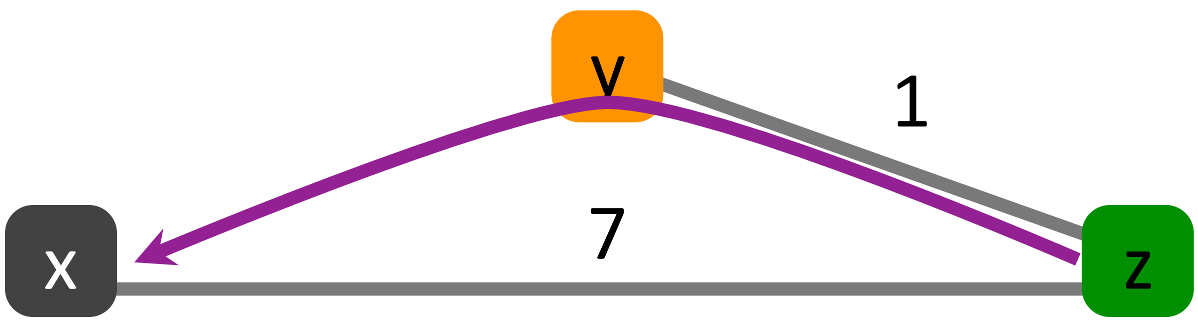
	x	y	z
y	2	0	1
z	3	1	0

	x	y	z
y	∞	0	1
z	∞	1	0



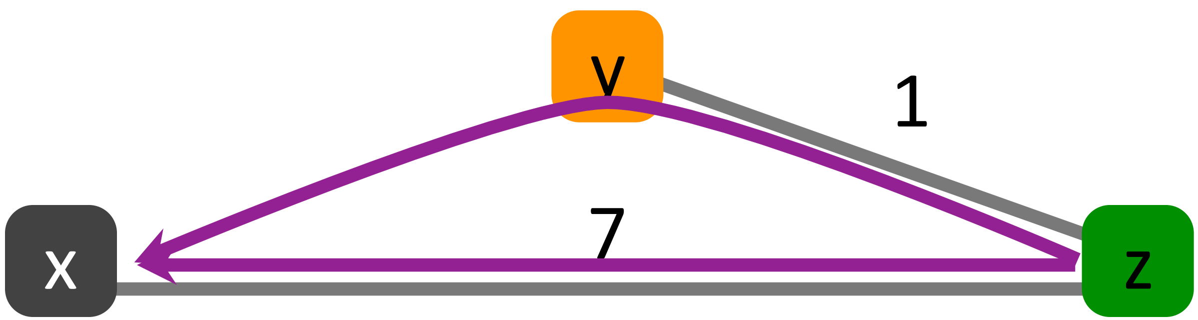
	x	y	z
y	2	0	1
z	3	1	0

	x	y	z
y	∞	0	1
z	∞	1	0



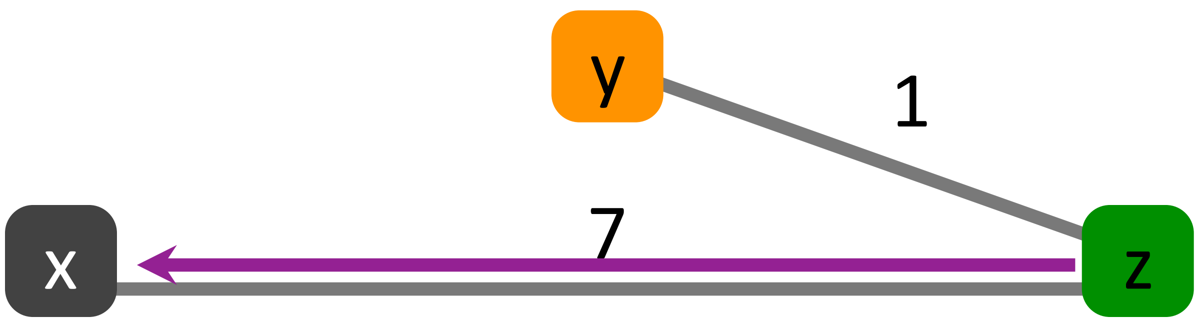
	x	y	z
y	∞	0	1
z	3	1	0

	x	y	z
y	∞	0	1
z	∞	1	0



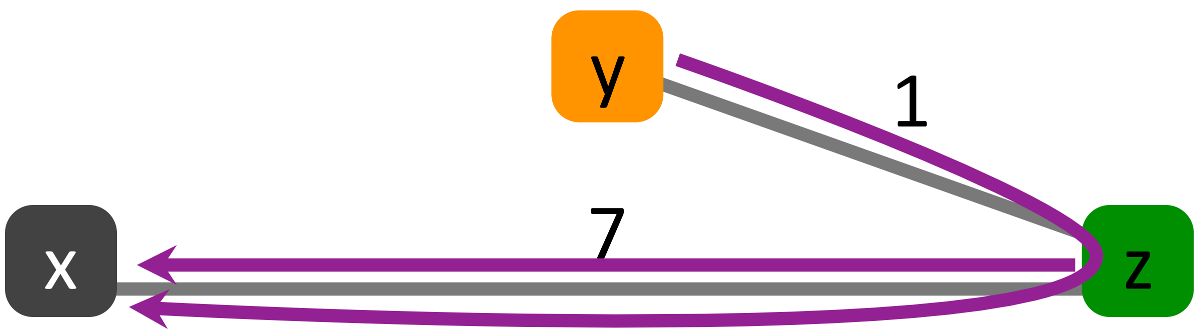
	x	y	z
y	∞	0	1
z	7	1	0

	x	y	z
y	∞	0	1
z	7	1	0



	x	y	z
y	∞	0	1
z	7	1	0

	x	y	z
y	8	0	1
z	7	1	0



	x	y	z
y	∞	0	1
z	7	1	0

Poisoned reverse

- **One heuristic to avoid count-to-infinity**
  - ➢If z routes to x through y,
    - z advertises to y that its cost to x is infinite
  - ➢y never decides to route to x through z
- **Not guaranteed (why?)**
- **Loop-free routing examples include**
  - ➢Path vector
  - ➢Source tracing

Distance-vector routing

- **Scalability?**
  - Requires fewer messages than Link-State
  - O(N) update time on arrival of a new DV from neighbor
  - O(network diameter) convergence time
  - O(N) entries in forwarding table

- **RIP is a protocol that implements DV (IETF RFC 2080)**

Comparison of LS and DV routing

Messaging complexity

- **LS: with N nodes, E links, O(NE) messages sent**
- **DV: exchange between neighbors only**

Speed of convergence

- **LS: relatively fast**
- **DV: convergence time varies**
  - Count-to-infinity problem

Robustness: what happens if router malfunctions?

- **LS:**
  - Node can advertise incorrect link cost
  - Each node computes its *own* table
- **DV:**
  - Node can advertise incorrect path cost
  - Each node's table used by others (error propagates)

Similarities between LS and DV routing

- **Both are shortest-path based routing**
  - ➢ Minimizing cost metric (link weights) a common optimization goal
    - Routers share a common view as to what makes a path “good” and how to measure the “goodness” of a path
- **Due to shared goal, commonly used inside an organization**
  - ➢ RIP and OSPF are mostly used for intra-domain routing

Tutorial: Assignment 3

- **Intra-domain routing algorithms**
  - Design and implement simple versions of link state and distance vector protocols by yourself
  - Hands-on experiences on routing protocols: real-world protocols in Cisco routers are just more complicated than the ones you designed and implemented!
  - Use NetworkX to compute shortest path if you do not want to implement it yourself
- **Implement either link-state or distance-vector**
  - Implementing both gives you a bonus of 2 points

Summary

- **Intra-AS routing**
  - Link-state routing
  - Distance-vector routing

- **Next class: Midterm re-cap**
- **Next Monday: Inter-AS routing**

Thanks!
Q&A