EECS 489
Computer Networks

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Agenda

- Link-state routing
- Distance-vector routing

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

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

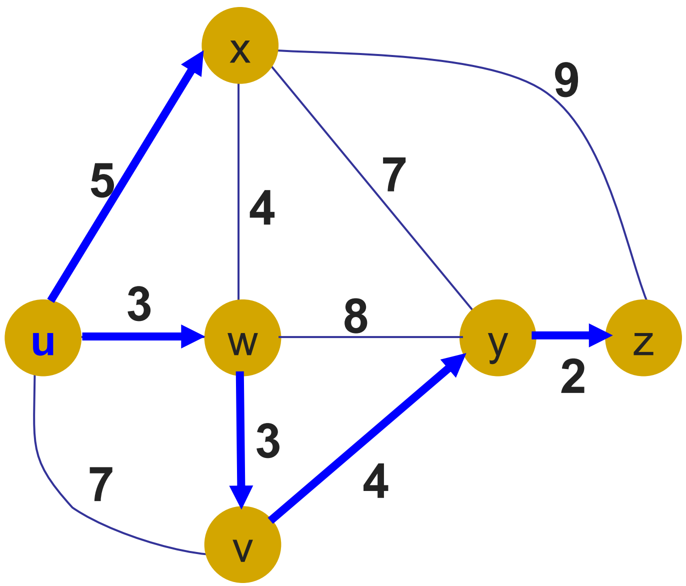
Convergence

- 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

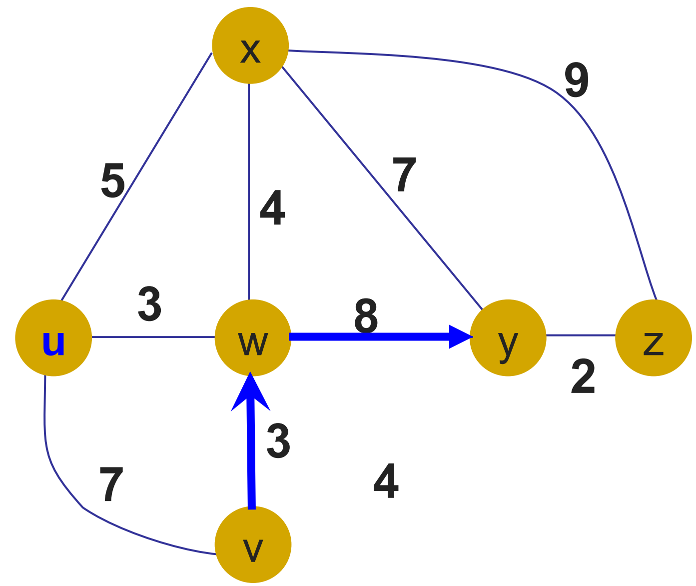
Convergence delay

- 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

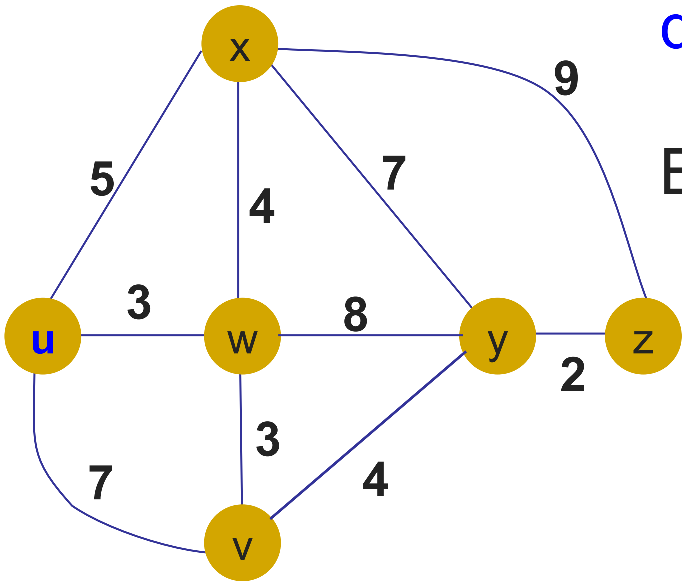
- Let
  - $d_x(y)$:= cost of least-cost path from x to y
- Then
  - $d_x(y) = \min_v \{c(x, v) + d_v(y)\}$

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:

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

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)

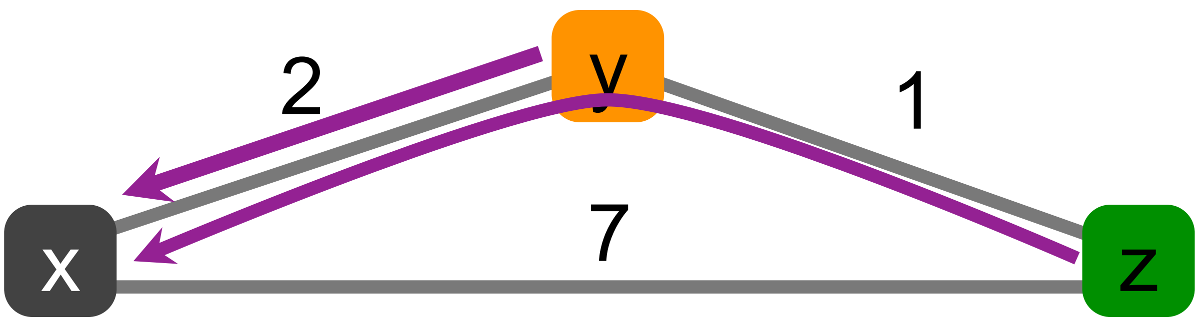
Recompute estimates

Notify neighbors if DV to any dest has changed

5-MINUTE BREAK!

Example

	x	y	z
y	2	0	1
z	3	1	0

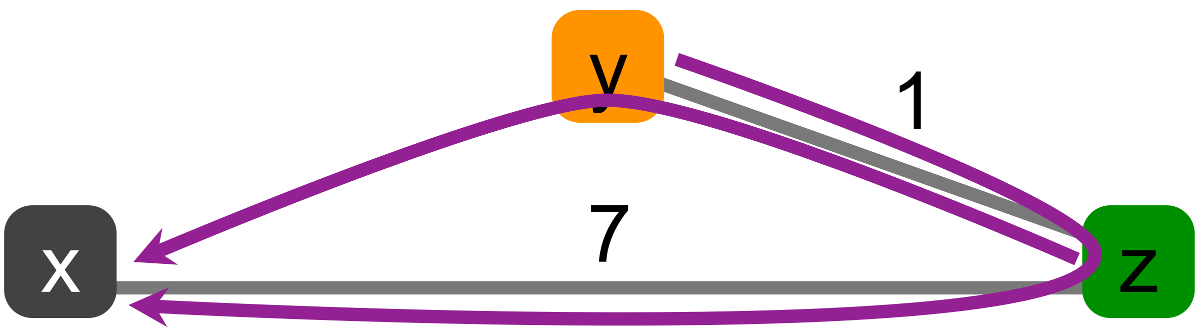


	x	y	z
y	2	0	1
z	3	1	0

Example

	x	y	z
y	4	0	1
z	3	1	0

routing loop!



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y	2	0	1
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Example

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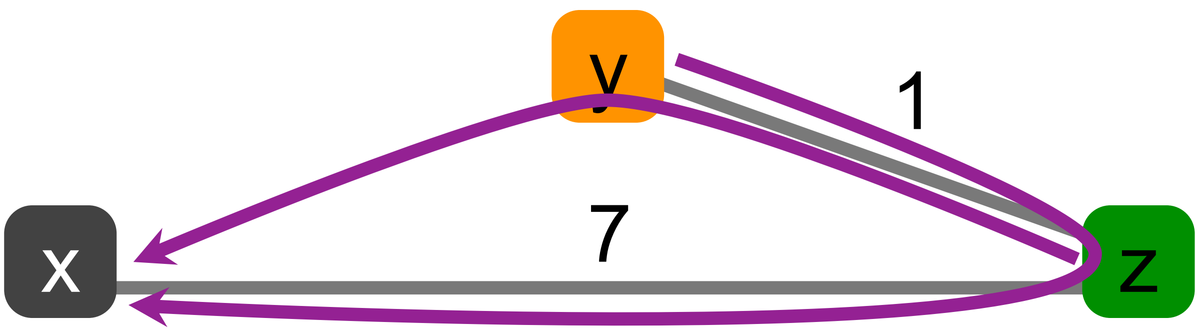

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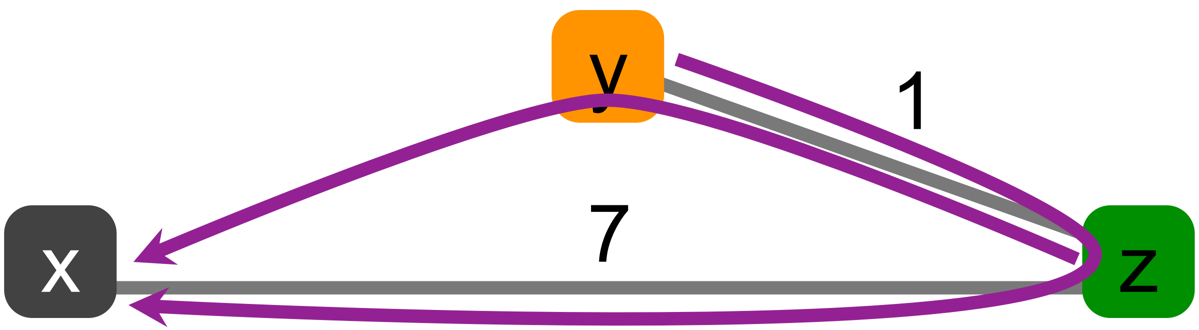
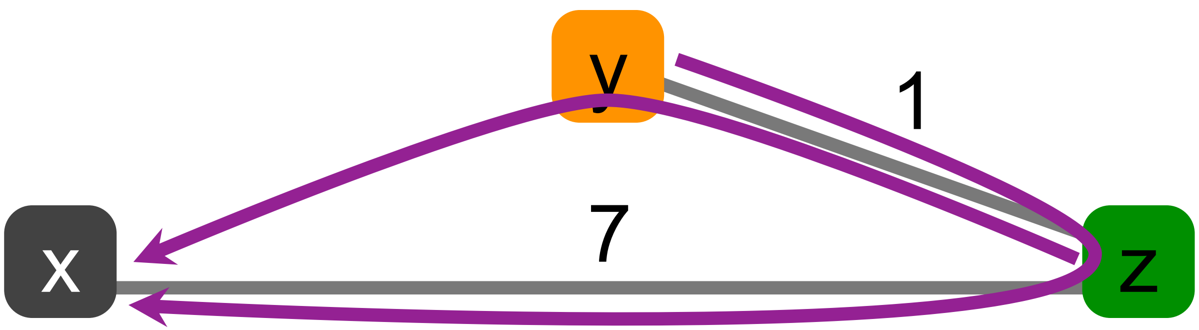


	x	y	z
y	4	0	1
z	5	1	0

Example

	x	y	z
y	4	0	1
z	5	1	0

routing loop!

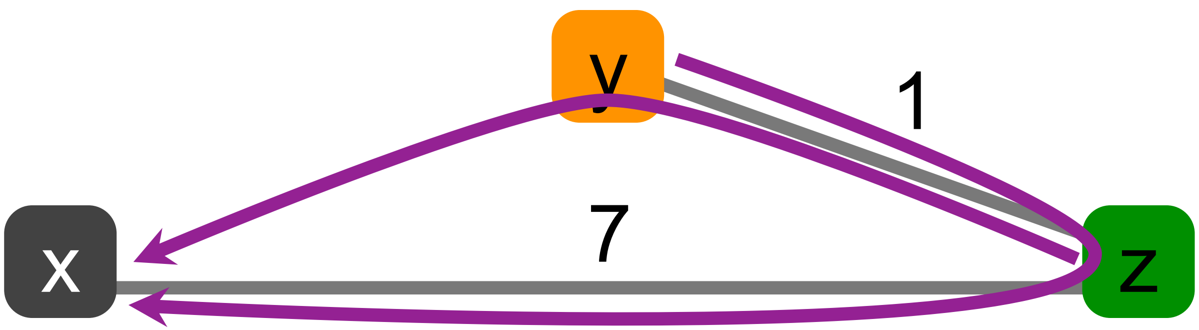


	x	y	z
y	4	0	1
z	5	1	0

Example

	x	y	z
y	6	0	1
z	5	1	0

routing loop!



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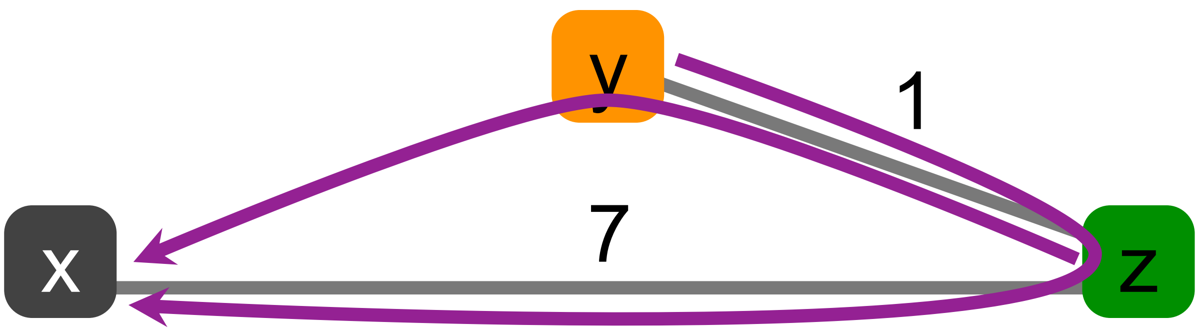

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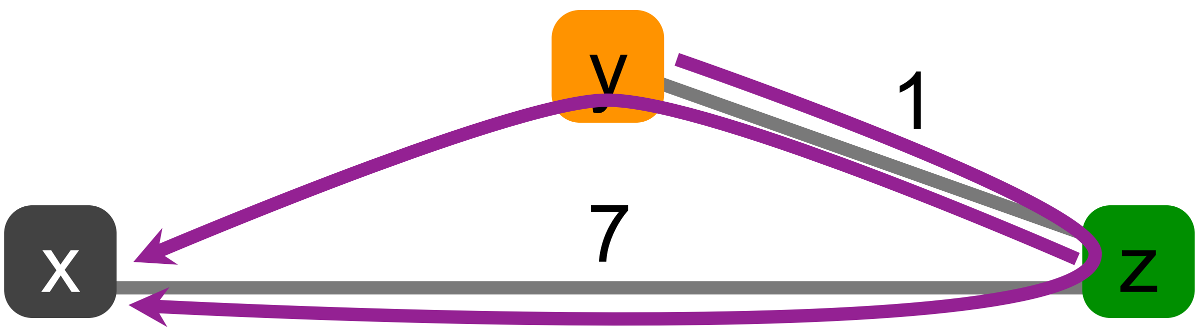
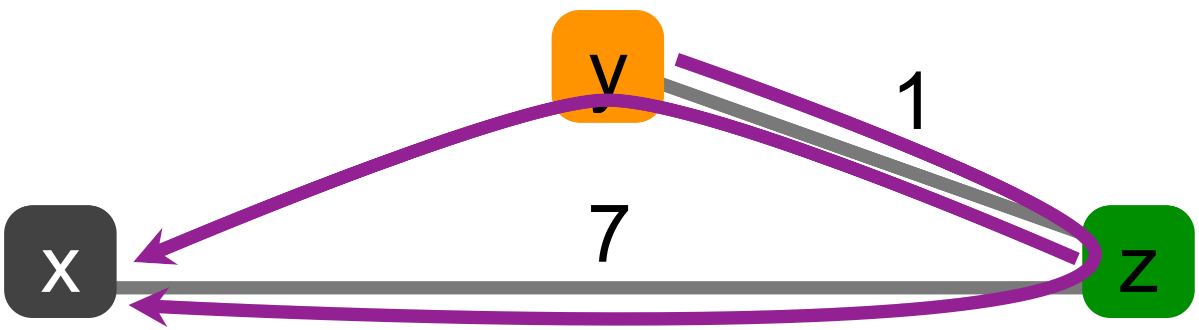


	x	y	z
y	6	0	1
z	7	1	0

Example

	x	y	z
y	6	0	1
z	7	1	0

routing loop!

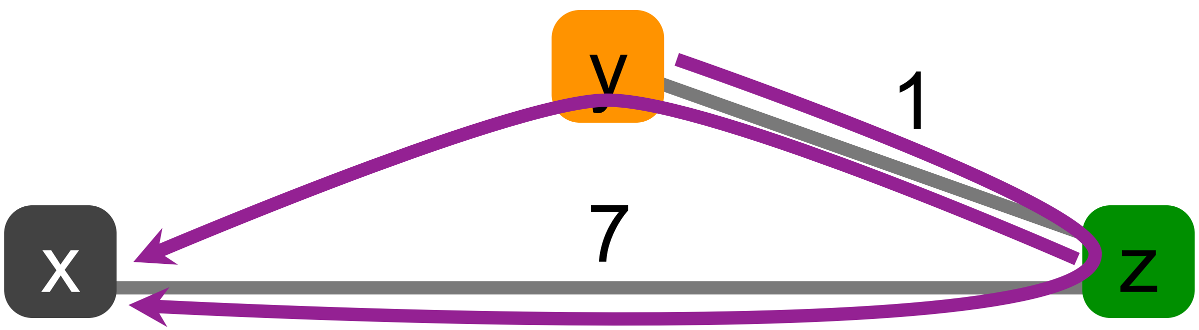


	x	y	z
y	6	0	1
z	7	1	0

Example

	x	y	z
y	8	0	1
z	7	1	0

routing loop!

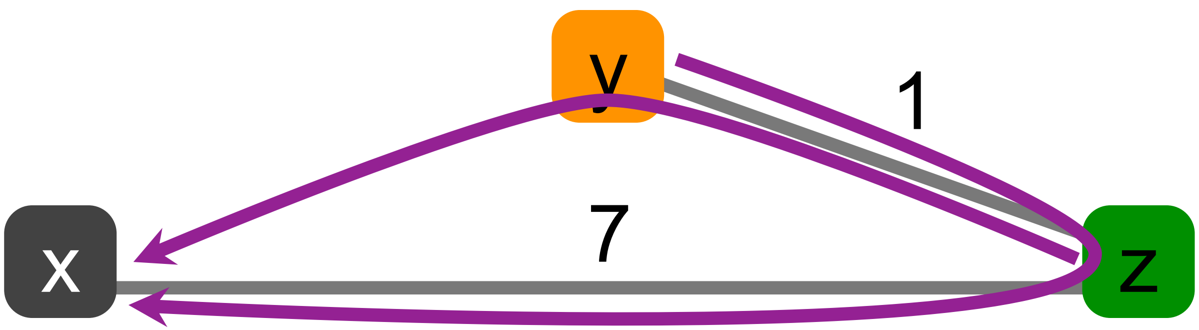


	x	y	z
y	6	0	1
z	7	1	0

Example

	x	y	z
y	8	0	1
z	7	1	0

routing loop!



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Example

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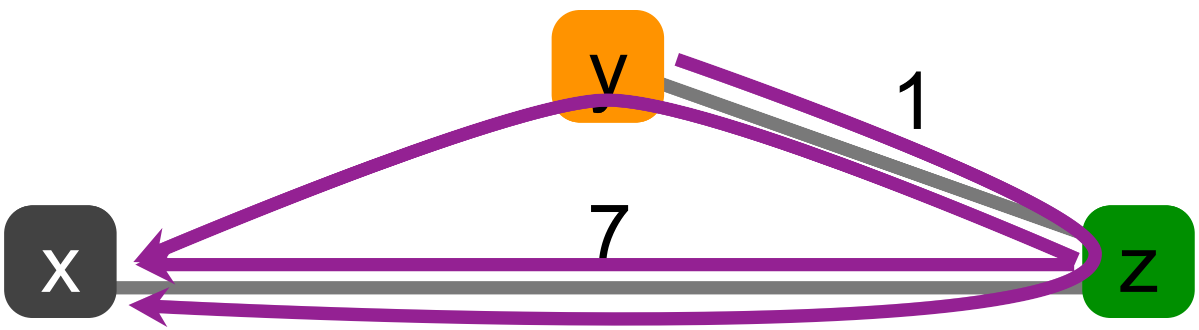
routing loop!



Count-to-infinity scenario

	x	y	z
y	8	0	1
z	7	1	0

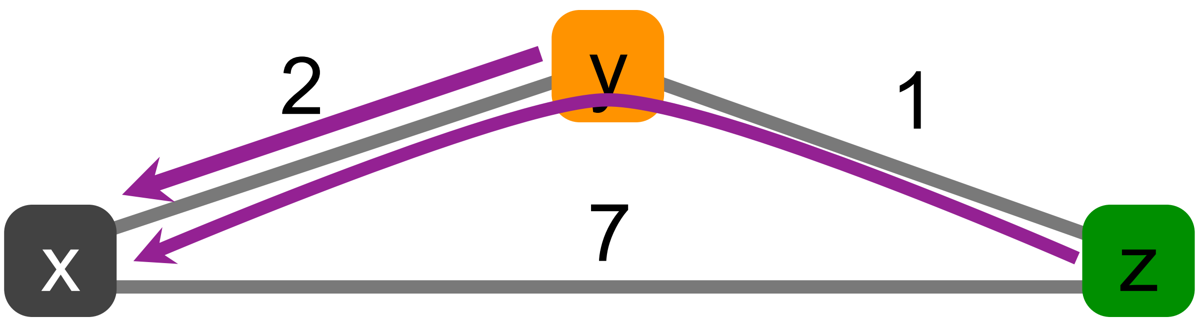
Problems with Bellman-Ford

- 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

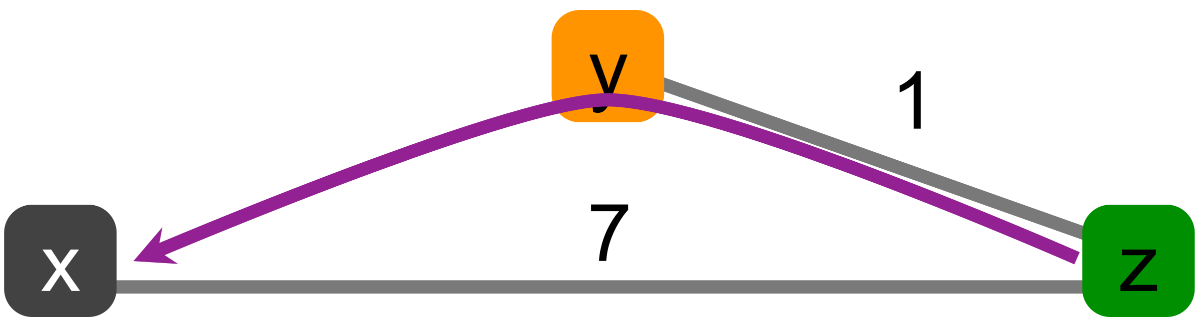
- One heuristic to avoid count-to-infinity
  - If z routes to x through y,
    - z advertises to y that its cost to x is infinite
  - y never decides to route to x through z

	x	y	z
y	2	0	1
z	∞	1	0



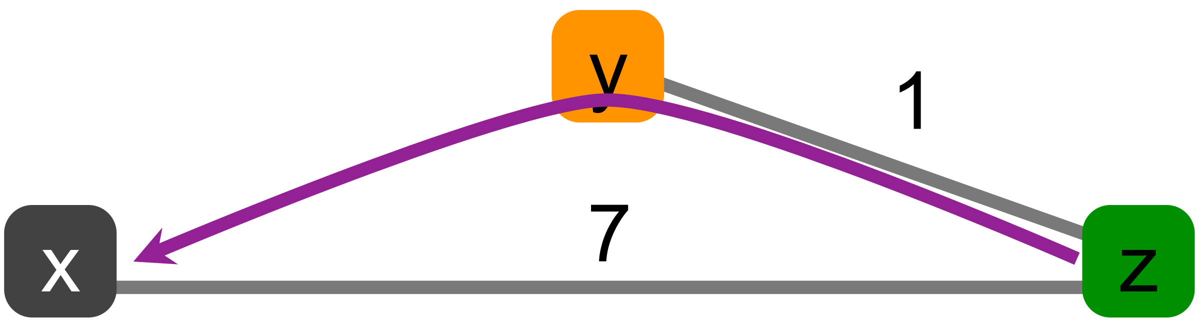
	x	y	z
y	2	0	1
z	3	1	0

	x	y	z
y	∞	0	1
z	∞	1	0



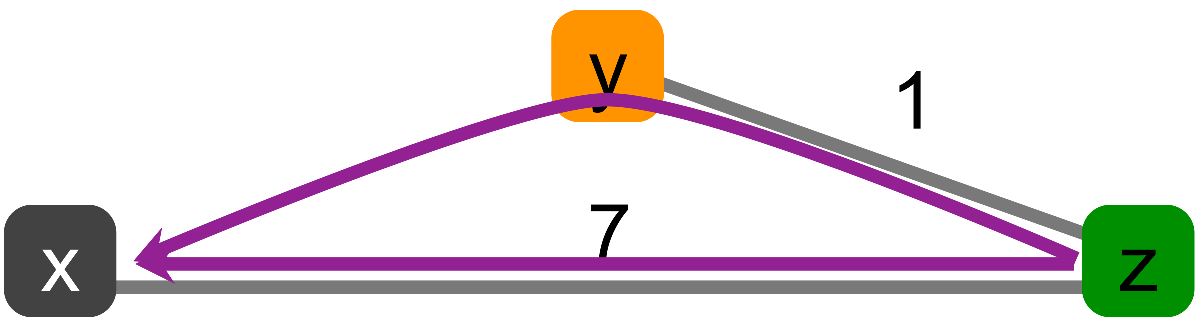
	x	y	z
y	2	0	1
z	3	1	0

	x	y	z
y	∞	0	1
z	∞	1	0



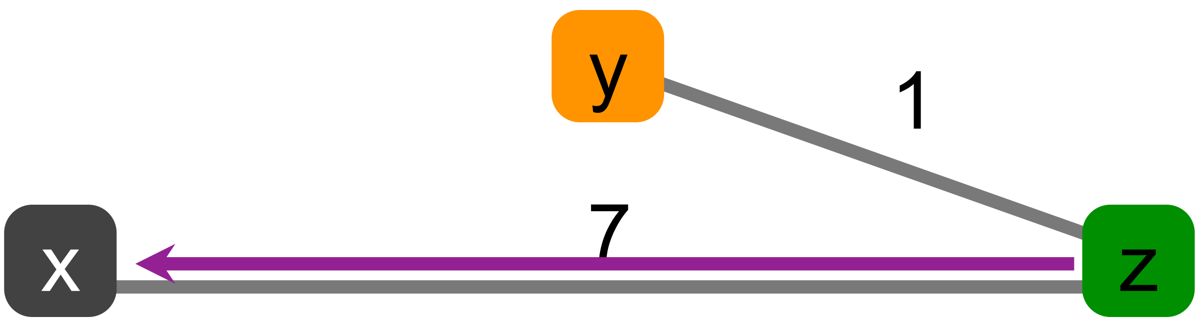
	x	y	z
y	∞	0	1
z	3	1	0

	x	y	z
y	∞	0	1
z	∞	1	0



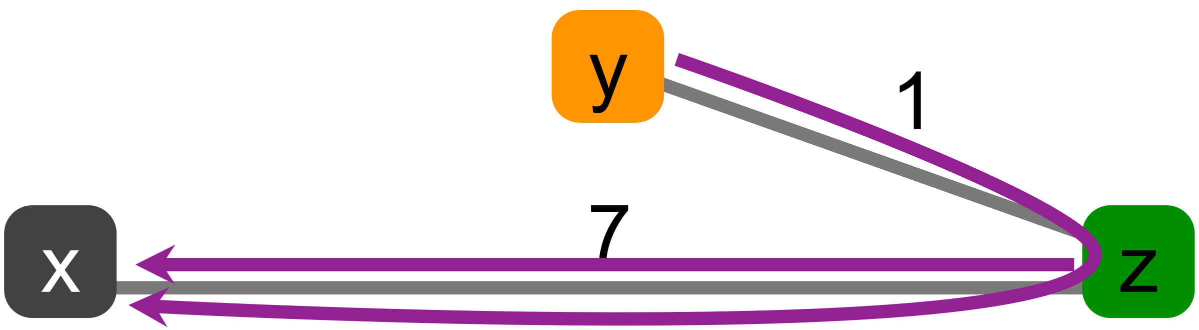
	x	y	z
y	∞	0	1
z	7	1	0

	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
- 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

Summary

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