CSCE 463/612
Networks and Distributed Processing
Fall 2020

Network Layer IV

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Chapter 4: Roadmap

4.1 Introduction

4.2 Virtual circuit and datagram networks

4.3 What's inside a router

4.4 IP: Internet Protocol

4.5 Routing algorithms

- Link state
- Distance Vector
- Hierarchical routing

4.6 Routing in the Internet

4.7 Broadcast and multicast routing

Distance Vector Algorithm

- Two metrics known to each node x
  - Estimate $D_x(y)$ of least cost from x to y
  - Link cost $c(x,v)$ to reach x's immediate neighbors
- Each node maintains a distance vector:

$$\vec{D}_x = \{D_x(y) : y \in V\}$$

- Node x periodically asks its neighbors for their distance vectors
  - Thus, x has access to the following for each neighbor v

$$\vec{D}_v = \{D_v(y) : y \in V\}$$

Distance Vector Algorithm (cont'd)

Basic idea (Bellman-Ford):

- When a node x receives new DV estimate from neighbor v, it updates its own DV using the Bellman-Ford equation:

$$D_x(y) \leftarrow \min\{D_x(y), c(x,v) + D_v(y)\}, \forall\ y \in V$$

- Centralized Bellman Ford requires O(|V|·|E|) time
  - Dijkstra's algorithm was O(|V|·log|V|)
  - Convergence of decentralized version depends on topology, link weights, update delays, and timing of events
- Bellman Ford allows negative weights

Distance Vector Algorithm (cont'd)

Iterative, asynchronous

Each iteration 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

if DV to any dest has changed, *notify* neighbors

node x table

from \ cost to	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

node y table

from \ cost to	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

node z table

from \ cost to	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

from \ cost to	x	y	z
x	0	2	7
y	2	0	1
z	3	1	0

from \ cost to	x	y	z
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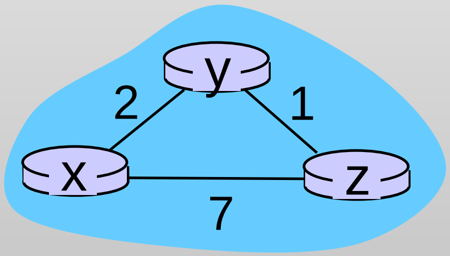
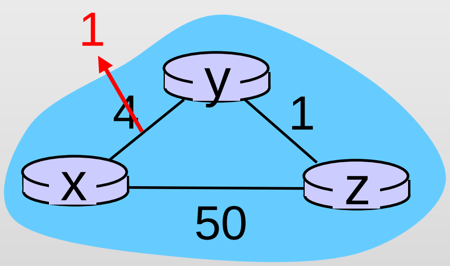
time



Distance Vector: Link Cost Changes

Link cost changes:

- Node detects local link cost change
- Recalculates distance vector, updates routing info if needed
- If DV changes, notifies neighbors



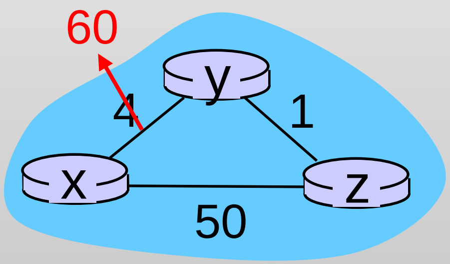
"good news travels fast"

- Node y detects link-cost change, updates its distance to x, and informs its neighbors
- Node z receives y's message and updates its table; computes a new least-cost to x and sends its DV to x and y
- Finally, node y receives z's vector and updates its distance table; y's least costs do not change and hence y does *not* send any messages after that

Distance Vector: Link Cost Changes

Link cost changes:

- Good news travels fast
- Bad news travels slow – “count to infinity” problem!
- 46 iterations before algorithm stabilizes



Poisoned reverse (“split horizon”):

- If z routes through y to get to x:
  - z tells y that its (z’s) distance to x is infinite (so y won’t route to x via z)
- Will this completely solve count to infinity problem?

Comparison of LS and DV Algorithms

Message complexity

- LS: with n nodes, E links, $O(nE)$ msgs sent
- DV: exchange between neighbors only
  - Depends on convergence time

Time to Convergence

- LS: $O(n \log n)$ algorithm + delay to send $O(nE)$ msgs
  - Oscillations (cost = congestion)
- DV: convergence time varies
  - May have routing loops
  - Count-to-infinity problem

Robustness: what happens if router malfunctions?

LS:

- Node can advertise incorrect *link* cost
- Affects only a small portion of the graph

DV:

- DV node can advertise incorrect *path* cost
- Each node's table used by others
- Errors propagate thru network

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Hierarchical Routing

Problems in practice:

- Memory: can’t store paths to all destinations in a routing table (several billion links)
- CPU time: can’t overload routers with such huge computational expense
- Message overhead: routing table exchanges would overload links
- Competitiveness: ISPs not willing to share their topology with others

Solution: administrative autonomy

- Internet = network of networks
- Network admins control routing in their own networks, export reachable subnets to outside world

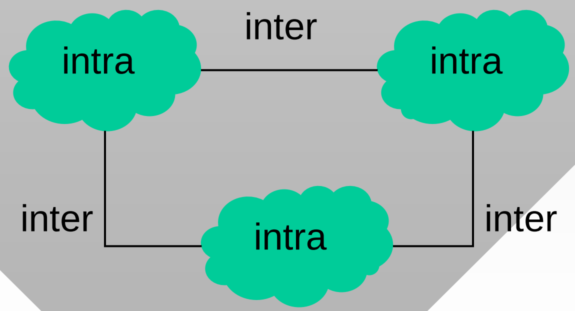
Hierarchical Routing

Texas A&M owns AS3794 with two subnets: 128.194/16 and 165.91/16

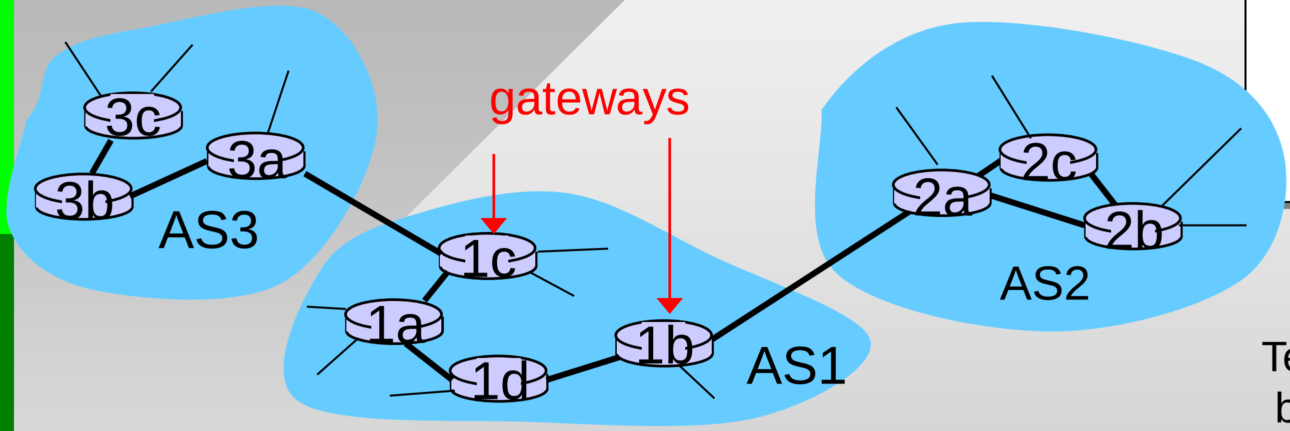
- Aggregate routers into regions called AS (Autonomous Systems)
- Routers in the same AS run the same algorithm
  - Accomlished via intra-AS routing protocols
- ISPs gain flexibility
  - Routers in different ASes can run different intra-AS protocols that cannot directly speak to each other, which is OK

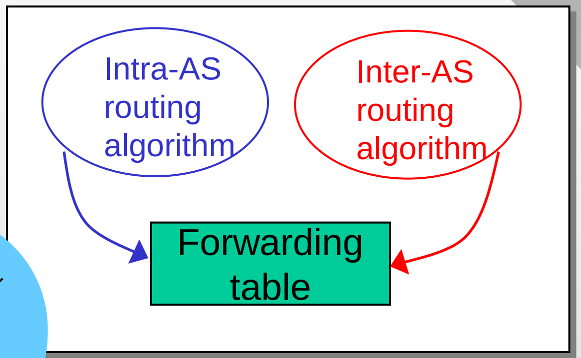
Gateway routers

- Direct links to routers in other ASes
- Exchange routing view of each AS using an inter-AS protocol
  - Summary of subnets to which this AS is willing to route



Interconnected ASes





Terminology: exit router = border router = gateway

- Intra-AS sets entries for all internal dests
  - E.g., 1a plots shortest path to 1b using link-state alg
- Inter-AS accepts external dests from neighbor ASes
  - E.g., 1b learns 128.194/16 is reachable via AS2
- Inter-AS broadcasts pairs (subnet, exit router)
  - E.g., 1b notifies all routers in AS1 that it can reach 128.194/16

Example: Choosing Among Multiple ASes

- Now suppose AS1 learns from the inter-AS protocol that 128.194/16 is reachable from AS3 *and* from AS2
  - To configure forwarding table, routers in AS1 must determine towards which exit (1c or 1b) they must forward packets
- This is also the job of inter-AS routing protocol!
  - Usually based on ISP policy, SLAs, prior traffic engineering
- Hot potato routing: send packet towards closest of two exit points (other options discussed later)

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- OSPF
- BGP

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Intra-AS Routing

- Common intra-AS routing protocols:
  - RIP: Routing Information Protocol (DV)
  - OSPF: Open Shortest Path First (LS)
  - IGRP: Interior Gateway Routing Protocol (Cisco proprietary, DV, now obsolete); EIGRP (Extended IGRP, still DV, open sourced in 2013)
  - IS-IS (Intermediate System to Intermediate System, LS)
- For Inter-AS, there is now just one option
  - BGP (Border Gateway Protocol)
  - All ISPs must support it

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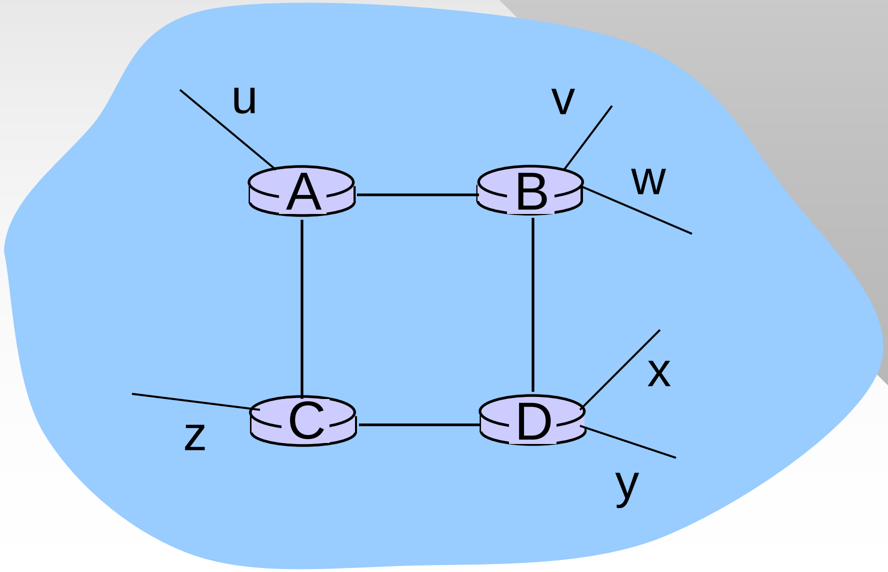
RIP (Routing Information Protocol)

- Included in BSD-UNIX distribution in 1982
  - Distance vector (DV) algorithm
- Distance metric: # of hops (max = 15)
  - Distance vectors: exchanged among neighbors every 30 sec using advertisement messages
  - Each message: lists of up to 25 destination nets within AS



destination subnet	hops from A
u	1
v	2
w	2
x	3
y	3
z	2

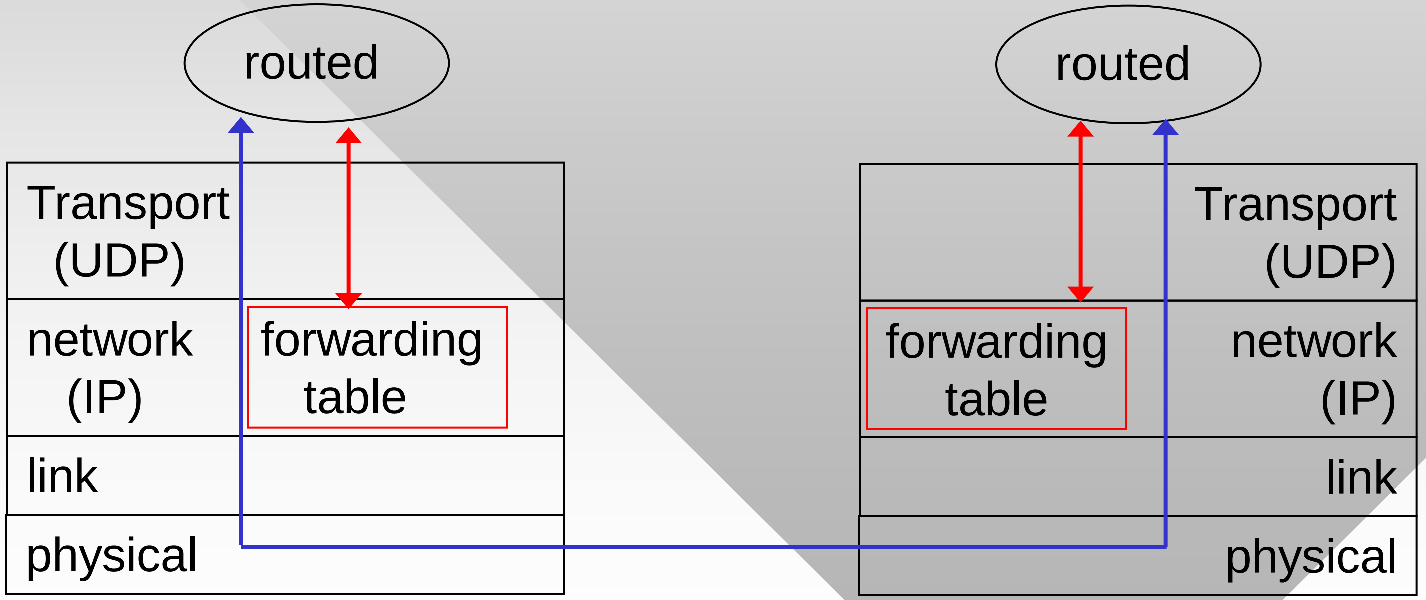
RIP: Link Failure and Recovery

- If no advertisement heard after 180 sec → neighbor/link declared dead
  - Routes via neighbor invalidated
  - New advertisements sent to neighbors
  - Neighbors in turn send out new advertisements (if tables changed)
  - Link-failure info propagates to entire network
- That’s why it is important to assign high priority to packets from routing protocols at ISP routers
  - Shows that QoS can work in a limited context
- RIP uses poisoned reverse to prevent loops (infinite distance = 16 hops)

RIP Table Processing

Note: named, smtpd, etc. are Unix deamons (services)

- RIP routing tables managed by an application-level process called *routed* (daemon)
- Advertisements sent in UDP packets (port 520)



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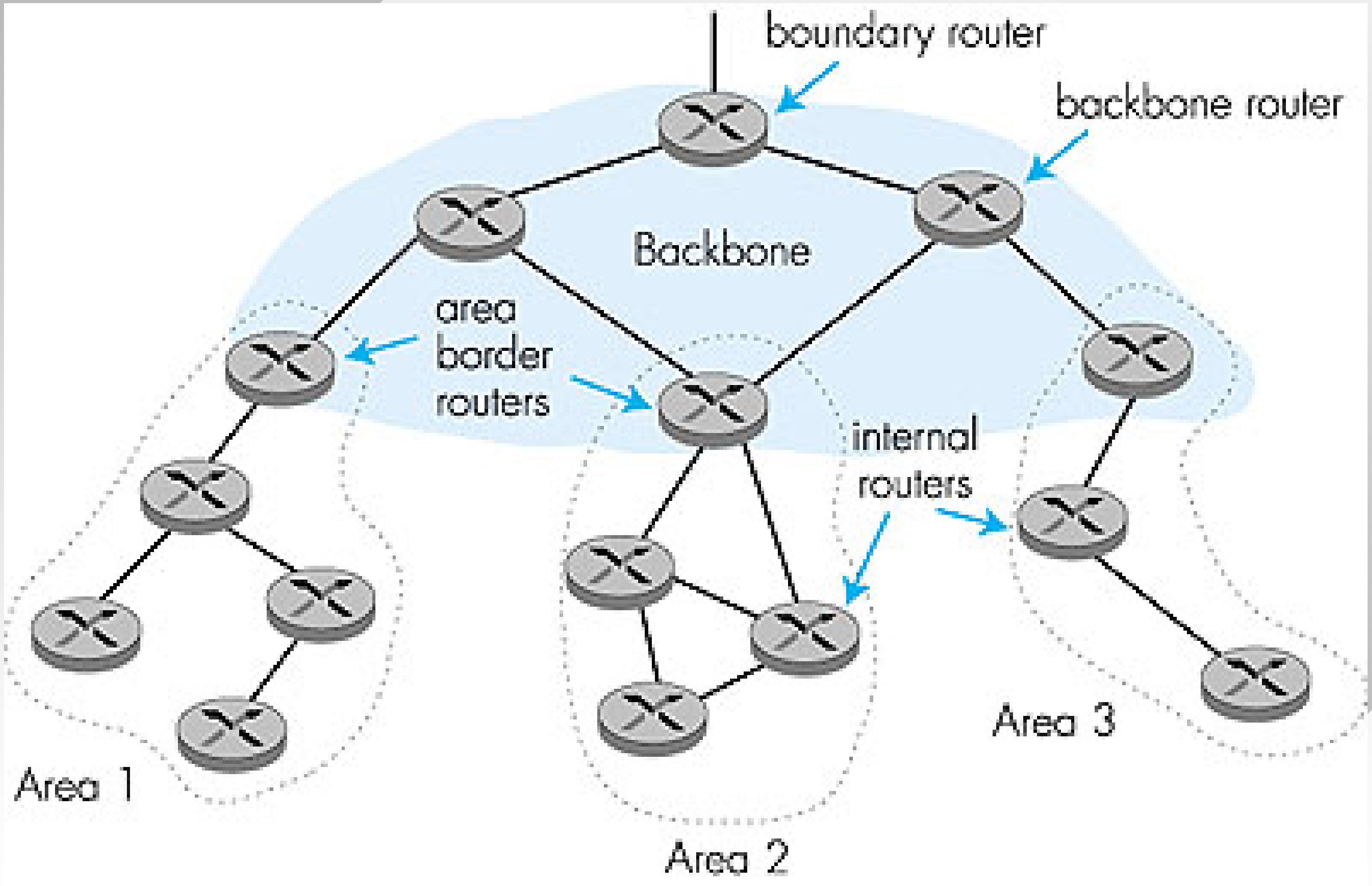
OSPF (Open Shortest Path First)

- “Open”: protocol specifications publicly available
  - v1 (1989), v2 (1998), and v3 (2008)
- Uses Link State (LS) algorithm
  - LS packet dissemination
  - Topology map at each node
  - Route computation using Dijkstra’s algorithm
- Advertisements disseminated to entire AS (via flooding)
  - Carried in OSPF messages directly over IP (rather than TCP or UDP) using protocol number 89
  - Layer 3.5 similar to ICMP
  - Handles own error detection/correction

OSPF "Advanced" Features (Not in RIP)

- Security: all OSPF messages authenticated to prevent malicious intrusion
- Multiple same-cost paths allowed (only one path in RIP)
- Integrated uni- and multicast support:
  - Multicast OSPF (MOSPF) uses same topology database as OSPF
- Hierarchical OSPF in large domains

Hierarchical OSPF



Hierarchical OSPF

- Two-level hierarchy: local area, backbone
  - Link-state advertisements only in area
  - Each node has a detailed topology for the area it belongs to and shortest paths to all destinations therein
- Area border routers: “summarize” distances to networks in their own area, advertise to other area border routers
- Backbone routers: run OSPF routing limited to the backbone
- Boundary routers: connect to other AS’s