CS 455/555
Intro to Networks and Communications

The Network Layer: Routing in the Internet

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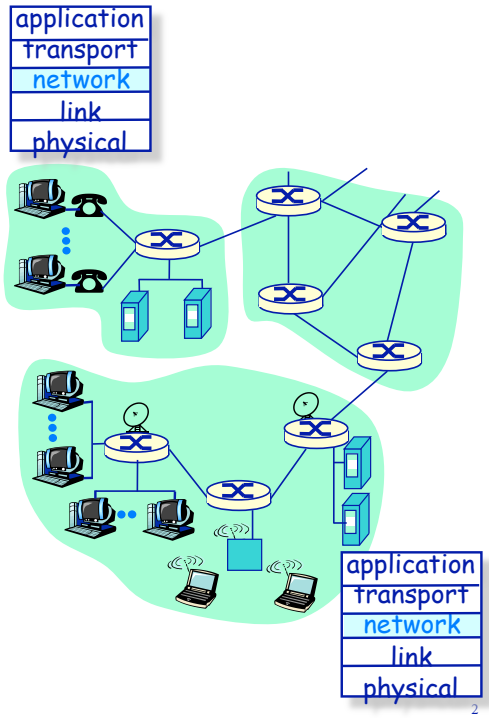
The Network Layer: Routing & Addressing
Outline

- Network layer functions
- Virtual circuits and datagram networks
- Router architecture
- IP Internet Protocol
  - » Addressing
- Routing algorithms
  - » Least cost path computation algorithms
- Hierarchical routing
  - » Connecting networks of networks
- Routing on the Internet
  - » Intra-domain routing
  - » Inter-domain routing



The Network Layer: Routing & Addressing

Hierarchical routing

- The theory of routing: relatively simple algorithms with manageable shortcomings
- Critical assumptions:
  - » All routers are identical
  - » The network is "flat"
- The reality: Routing is dominated by issues of scale
  - » The Internet has 100 million hosts!
    - ❖ Can't store all host destinations in routing tables!
    - ❖ Routing table exchange would swamp links!
  - » We must route to *networks,* not hosts
- Routing also dominated by issues of administrative autonomy
  - » The Internet is a network of networks — each network owner may want to control routing in its own network

Hierarchical Routing

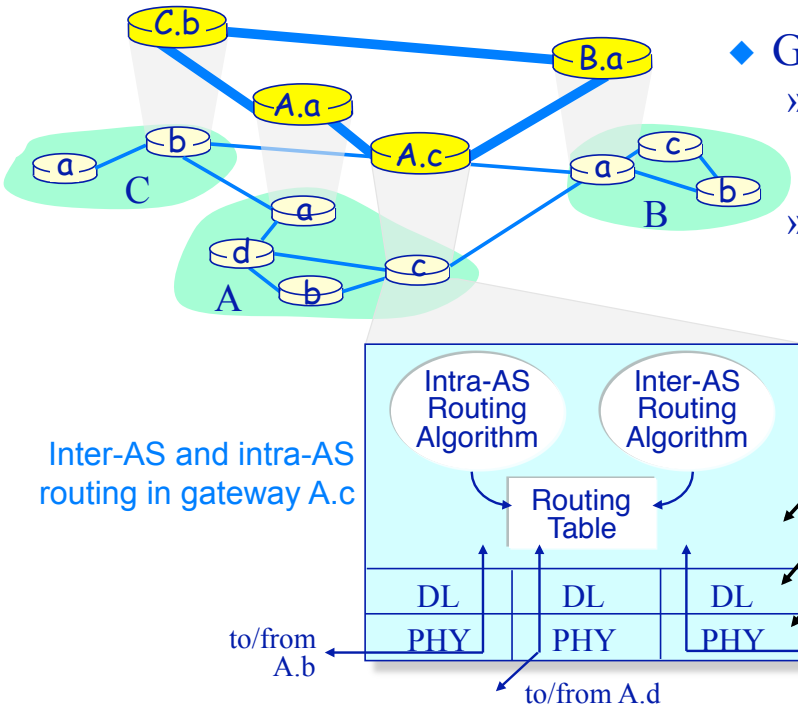
Gateway routers

- Aggregate routers into regions, "autonomous systems" (AS)
- All routers inside same AS run same routing protocol among themselves
  - » "*Intra-AS*" routing protocol
  - » Routers in different AS can run different *intra-AS* routing protocol

Gateway routers

- Special routers in AS
- Run *intra-AS* routing protocol with all other routers inside AS
- Responsible for routing to destinations outside AS
  - » Also run *inter-AS* routing protocol with gateway routers in adjacent AS

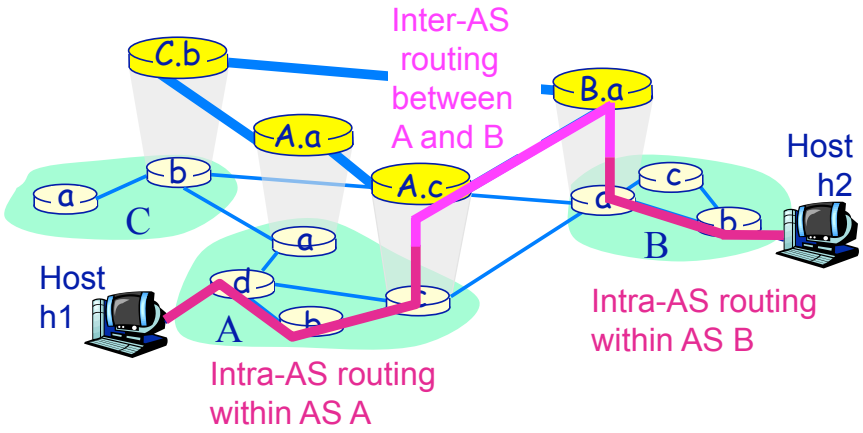
Hierarchical Routing
Intra-AS & Inter-AS Routing



Inter-AS and intra-AS routing in gateway A.c

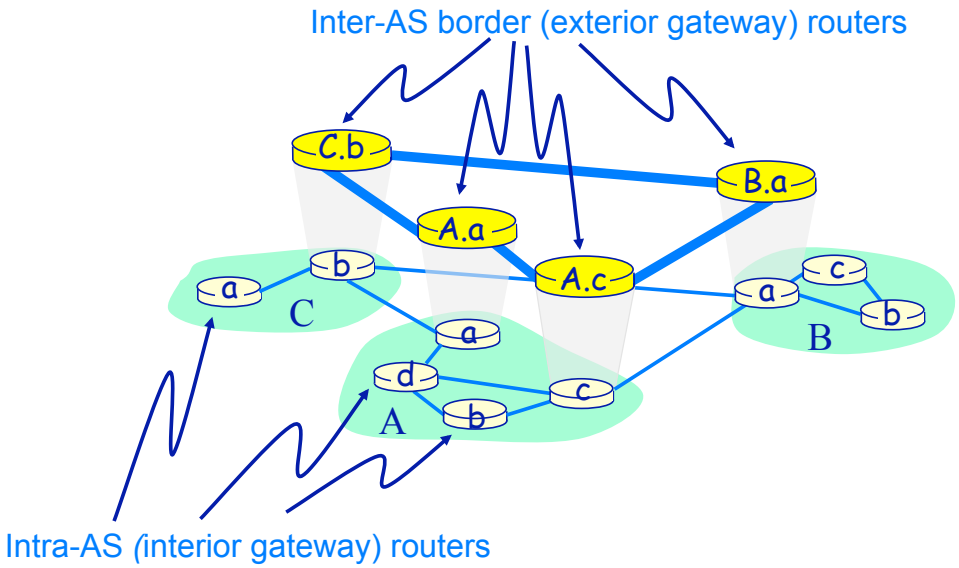
- Gateways:
  - » Perform *inter-AS* routing among themselves
  - » Perform *intra-AS* routing with other routers in their AS

Hierarchical Routing
Intra-AS & Inter-AS Routing



Hierarchical Routing

The Internet AS hierarchy



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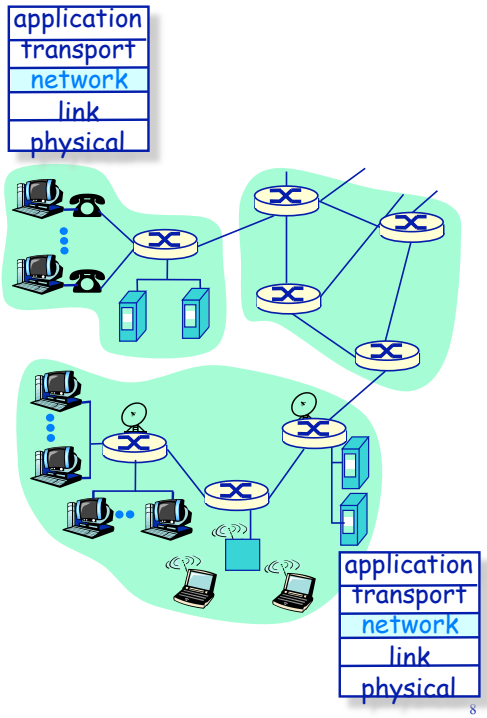
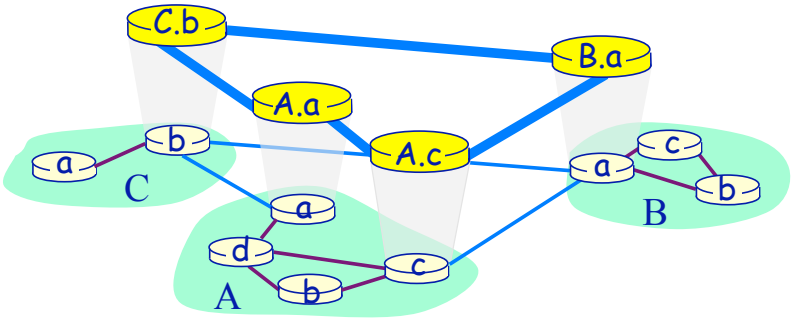


The Internet AS Hierarchy

Intra-AS routing



- Also known as "Interior Gateway Protocols" (IGPs)
- Most common IGPs:
  - » RIP: Routing Information Protocol
  - » OSPF: Open Shortest Path First

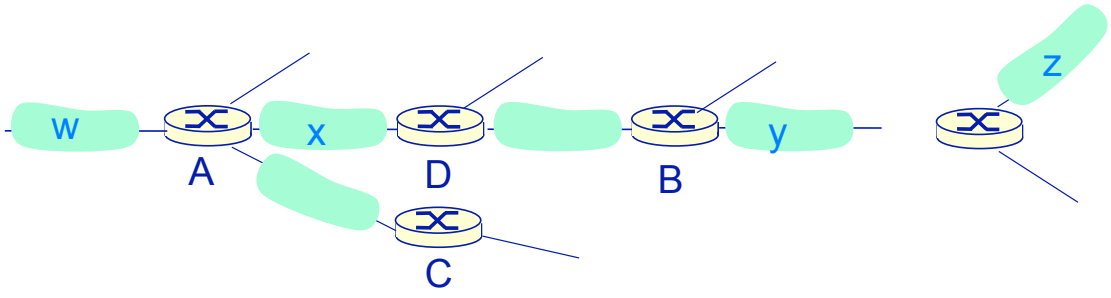
Intra-AS Routing

Routing Information Protocol (RIP)

- Distance vector-*like* algorithm
  - » Commonly used in the early Internet
- Distance metric: Number of hops
  - » Maximum value = 15 hops ($\infty = 16$)
- Routing tables (including costs) are exchanged with adjacent nodes every 30 seconds via a Response Message (also called a "route advertisement")
  - » *Receiver* determines if adjacent node has found a new minimum cost to a destination
- Each advertisement consists of the minimum cost route for up to 25 destination networks

RIP

Example



Routing Table in D

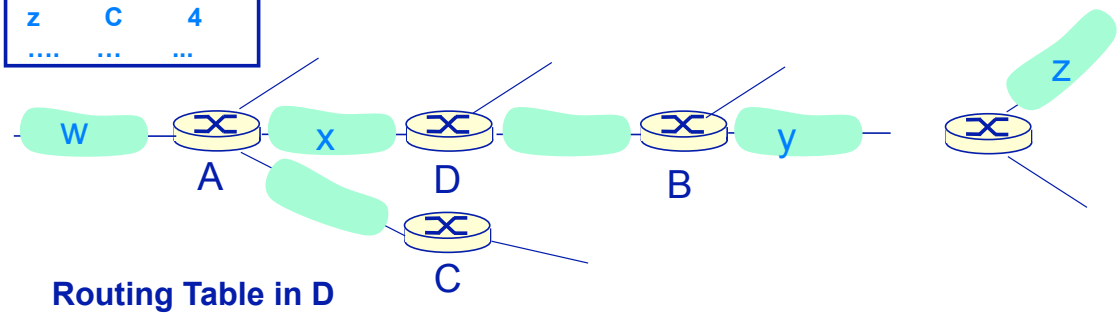
Destination Network	Next Router	Num. of hops to dest.
w	A	2
y	B	2
z	B	7
x	--	1
....	....	....

RIP

Example

Dest	Next	Hops
w	-	1
x	-	1
z	C	4
....	...	...

Advertisement from A to D



Routing Table in D

Destination Network	Next Router	Num. of hops to dest.
w	A	2
y	B	2
z	~~B~~ A	~~7~~ 5
x	--	1
....	....	....

RIP

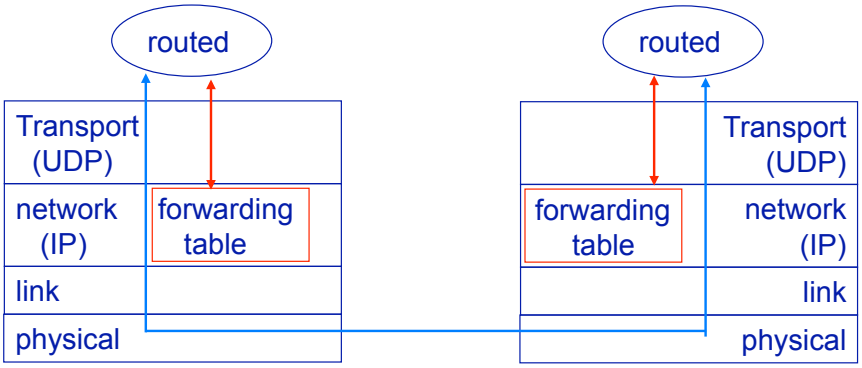
Link failure and recovery

- If no advertisement heard after 180 seconds, adjacent node/link declared "failed"
  - » Routes via that adjacent node invalidated
  - » New advertisements sent to other adjacent nodes
  - » Advertisement receivers in turn send out new advertisements (if their tables changed)
  - » Link failure information quickly propagates to entire net
  - » Poisoned reverse used to prevent ping-pong loops
    - ❖ "infinity" = 16

RIP

Table processing

- RIP routing tables managed by application-level process called route-d (daemon)
- Advertisements sent in UDP packets (port 520), periodically repeated



Intra-AS routing

Open Shortest Path First (OSPF)

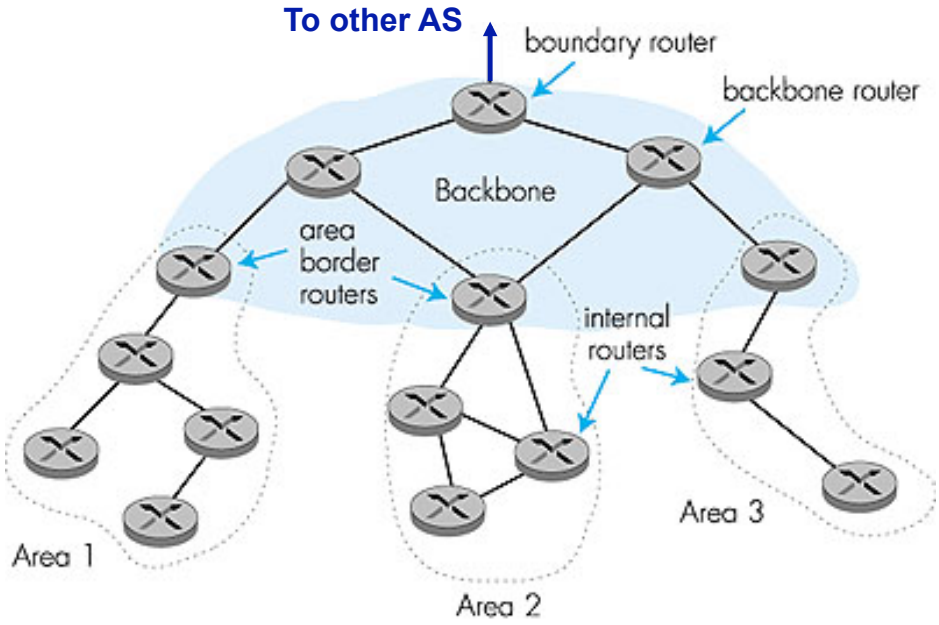
- "Open": publicly available
- Uses the Link State minimum cost path computation algorithm
  - » LS update flooding
  - » Topology map at each node
  - » Route computation using Dijkstra's algorithm
- OSPF advertisement carries one entry per adjacent node
- Advertisements disseminated to an entire AS (via flooding)

OSPF

"Advanced" features (not in RIP)

- Security: all OSPF messages can be authenticated to prevent malicious intrusion
  - » TCP connections used in flooding
- Multiple same-cost paths can be used (only one path in RIP)
  - » packets in a connection may travel different paths even if routing tables don't change
- For each link, multiple cost metrics for different network-layer "services"
  - » (e.g., satellite link cost set "low" for best effort; high for real time)
- Hierarchical OSPF used in large networks

OSPF
Hierarchical OSPF

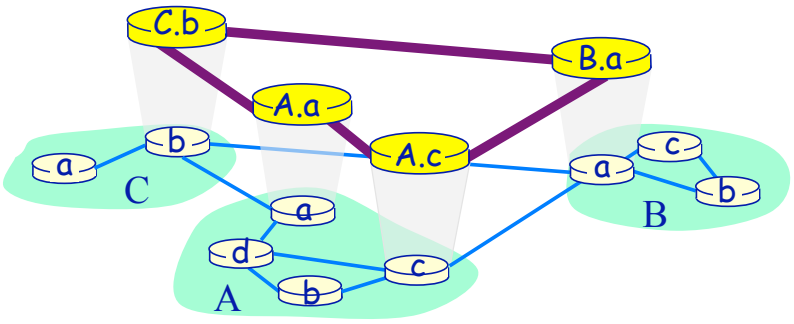


OSPF
Hierarchical OSPF

- Two-level hierarchy: local area, backbone
  - » Link-state advertisements only in area
  - » Each area node has detailed area topology; only knows shortest path to networks in other areas
- Area Border Routers: “summarize” distances to nets in own area and advertise to other Area Border routers
- Backbone Routers: run OSPF routing limited to backbone
- Boundary Routers: connect to other AS

The Internet AS Hierarchy

Inter-AS Routing



- Border Gateway Protocol (BGP) is the *de facto* standard
- BGP allows each subnet to advertise its existence to the rest of the Internet ("I'm here!")

BGP

Basics

- Pairs of routers (*BGP peers*) exchange routing information over TCP connections on port 179
  - » semi-permanent connection
  - » one connection per link that connects two gateway routers in different ASs (external BGP - eBGP)
  - » one connection per link that connects two gateway routers in same AS (internal BGP - iBGP)
- Allows each AS to learn which destinations are reachable via neighbors
  - » destinations are CIDR network prefixes

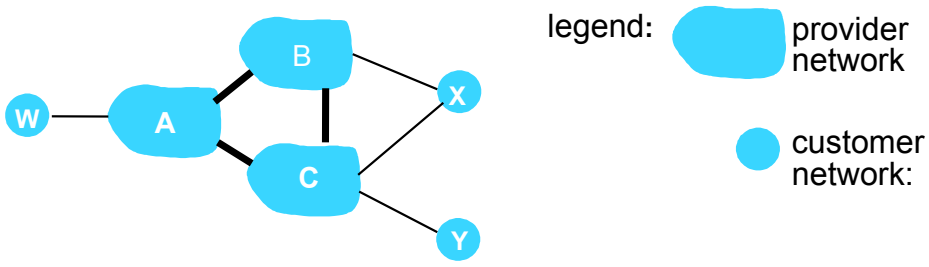
BGP
Path Attributes and BGP Routes

- Peers advertise entire routes
  - » AS-PATH
    - ASs through which the advertisement for the prefix has passed
    - when receiving an advertisement, each AS adds its ASN to the path list before sending its own advertisement
  - » NEXT-HOP
    - router interface that begins the AS-PATH

- Suppose gateway X sends a path to peer gateway W
  - » W may or may not select the path advertised by X
    - Cost, policy ("don't route via competitor X's network"), or loop prevention reasons
  - » If W selects the path advertised by X to Z, then:

$$path\ (W,Z) = W + path\ (X,Z)$$

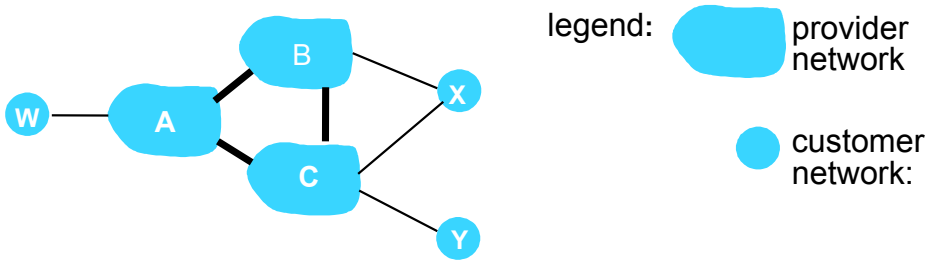
BGP
Routing Policy



- A,B,C are *provider networks*
- X,W,Y are customer (of provider networks)
- X is *dual-homed*: attached to two networks
  - » X does not want to route from B via X to C
  - » .. so X will not advertise to B a route to C

BGP

Routing Policy



- A advertises path AW to B
- B advertises path BAW to X
- Should B advertise path BAW to C?
  - » No way! B gets no "revenue" for routing CBAW since neither W nor C are B's customers
  - » B wants to force C to route to w via A
  - » B wants to route *only* to/from its customers!

The Internet AS Hierarchy

Why different intra- and inter-AS routing?

- Policy:
  - » Inter-AS: administration wants control over how its traffic routed and who routes through its network
  - » Intra-AS: single administration, so no "policy" decisions needed
- Scale:
  - » Hierarchical routing saves table size, reduced update traffic
- Performance:
  - » Intra-AS: can focus on performance
  - » Inter-AS: policy may dominate over performance

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