



University of Pittsburgh

ECE 1150: Computer Networks

The Network Layer— Routing

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ECE Department

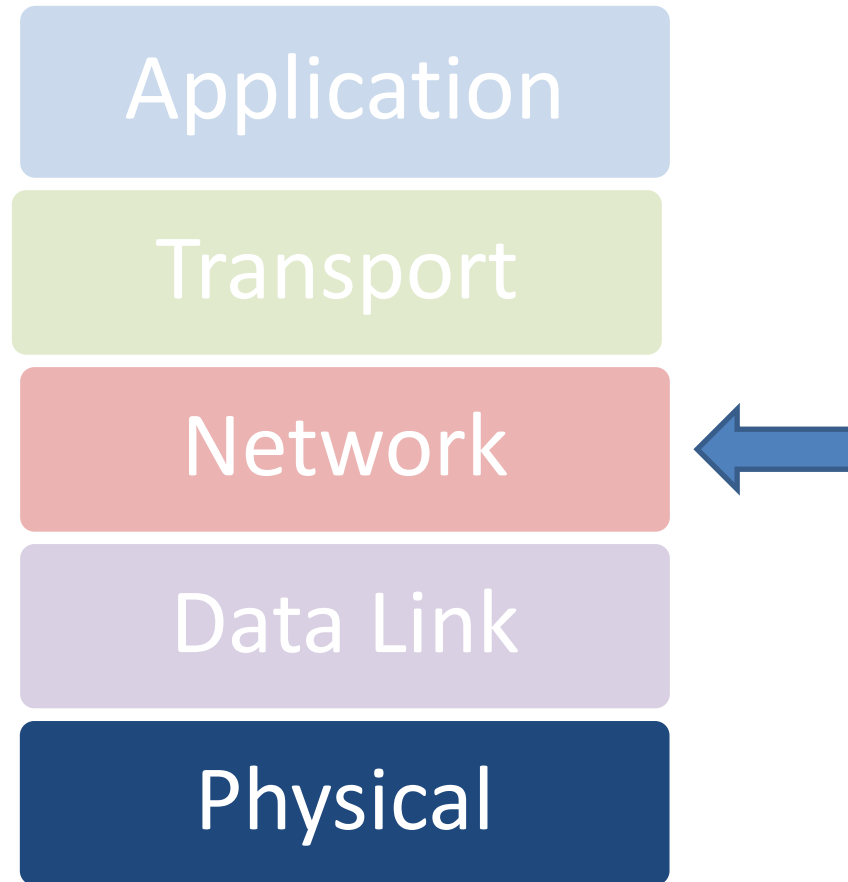
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Context

TCP/IP Protocol Stack



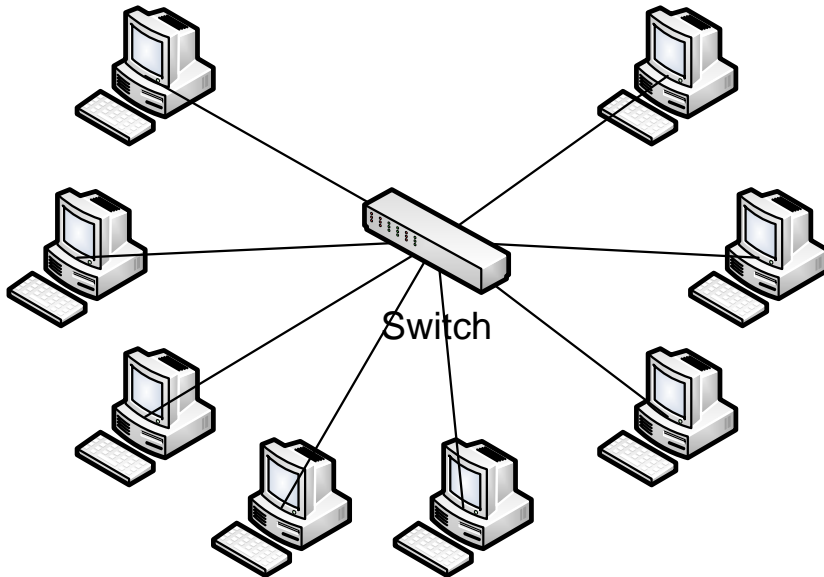
This Unit

- Routing

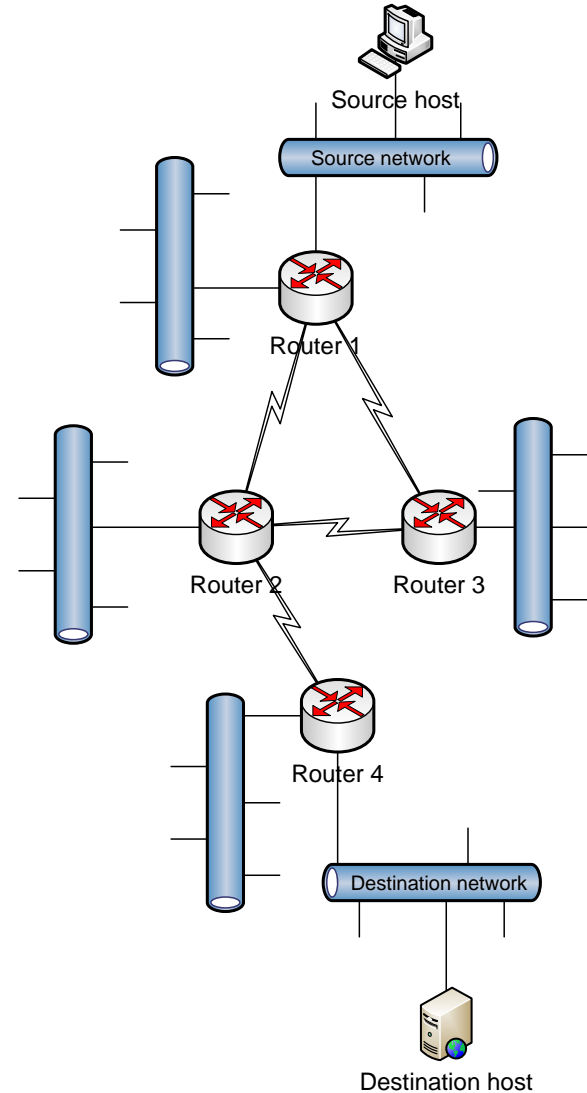
Routing

- Definition
 - **Moving information** across networks from the source network to the destination network
- Routing is done by devices called **Routers**
 - Typically, these are expensive devices at ISPs,
 - E.g. manufactured by CISCO, Juniper, Force10, etc.
 - Inside LAN, some inexpensive devices
 - E.g. Linksys/ Belkin home routers

Switching vs. Routing



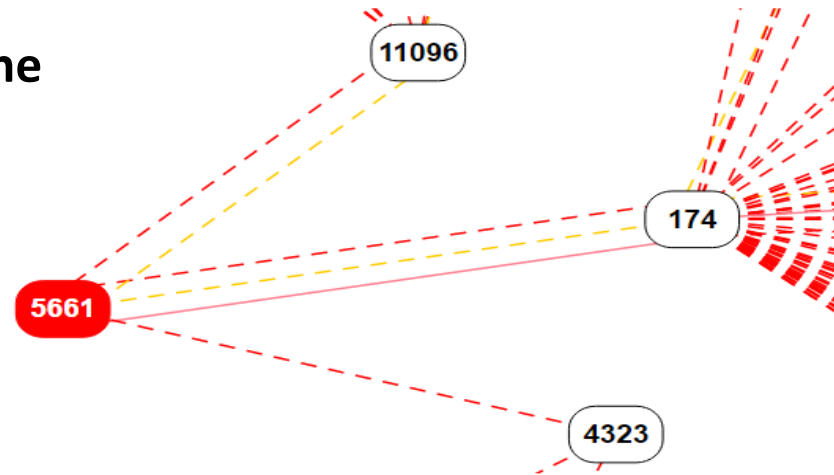
One path



Multiple possible paths

Autonomous Systems

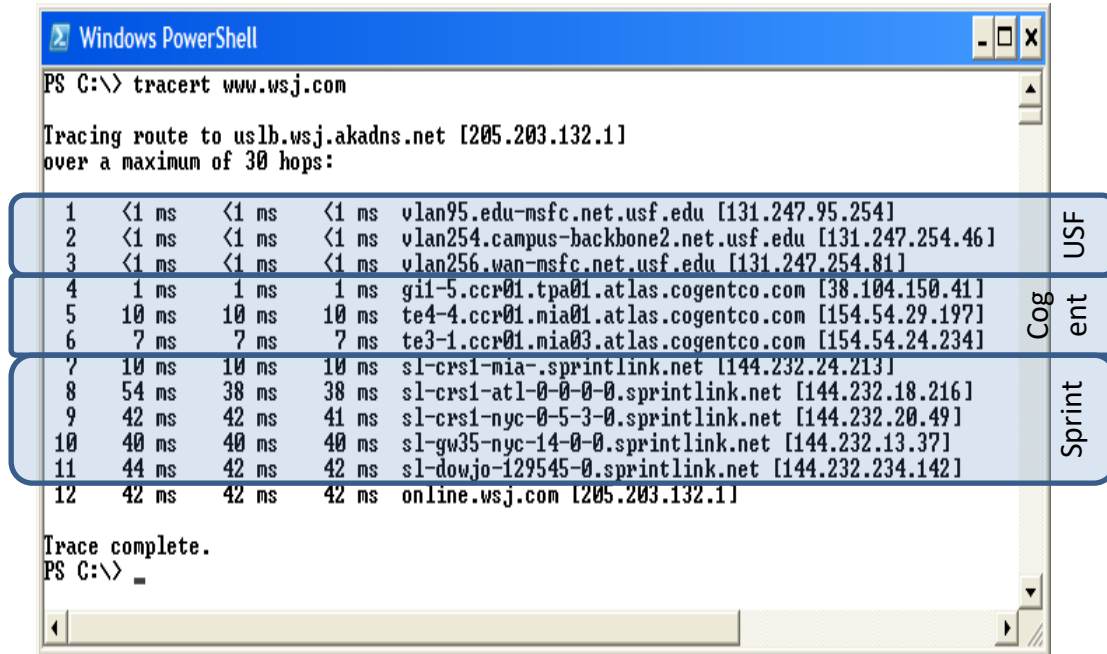
- Autonomous Systems (AS) are the **unit of Internet routing**
 - Routing sends data from the source AS to the destination AS
- AS is **collection of routers** that fall under **one administrative entity** – **each has a unique number**
 - Internet is made up of a large number of independent networks /“Autonomous Systems” **operates by different organizations**, (a company, university, or ISP).
- AS number to name mapping
<http://www.cidr-report.org/as2.0/autnums.html>



Search for University of Pittsburgh (UPITT-AS)

Viewing Routes

- Many utilities are available to see Internet routes
 - Easiest to use is `tracert`
 - In Windows, Start > Run > `cmd`
 - `tracert <domain>`
 - For MAC users: Use `traceroute`
 - `Traceroute my.pitt.edu`



```
Windows PowerShell
PS C:\> tracert www.wsj.com

Tracing route to uslb.wsj.akadns.net [205.203.132.1]
over a maximum of 30 hops:

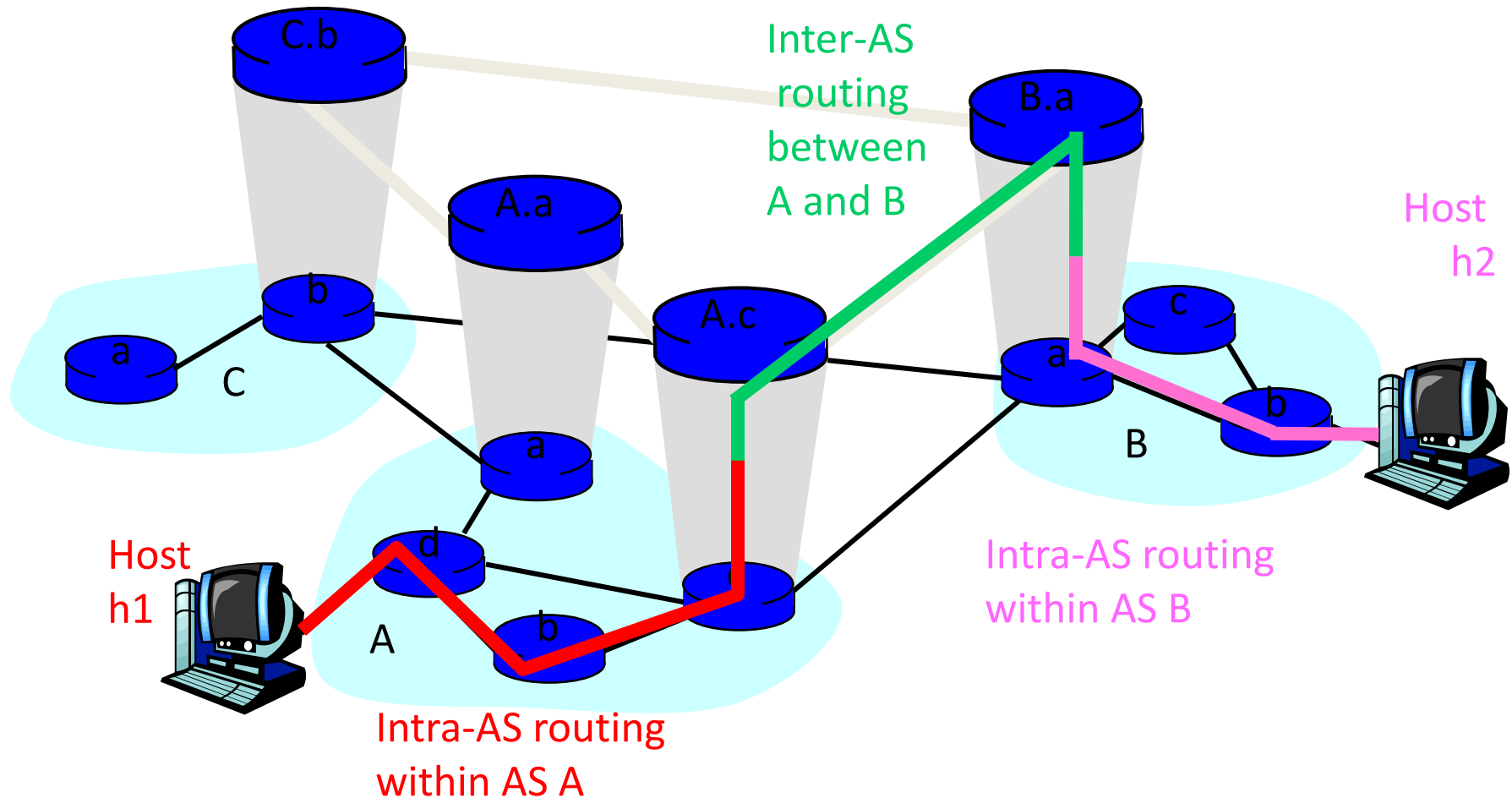
  1  <1 ms  <1 ms  <1 ms  vlan95.edu-msfc.net.usf.edu [131.247.95.254]
  2  <1 ms  <1 ms  <1 ms  vlan254.campus-backbone2.net.usf.edu [131.247.254.46]
  3  <1 ms  <1 ms  <1 ms  vlan256.wan-msfc.net.usf.edu [131.247.254.81]
  4  1 ms   1 ms   1 ms   gi1-5.ccr01.tpa01.atlas.cogentco.com [38.104.150.41]
  5  10 ms  10 ms  10 ms  te4-4.ccr01.mia01.atlas.cogentco.com [154.54.29.197]
  6  7 ms   7 ms   7 ms   te3-1.ccr01.mia03.atlas.cogentco.com [154.54.24.234]
  7  10 ms  10 ms  10 ms  sl-crs1-mia-.sprintlink.net [144.232.24.213]
  8  54 ms  38 ms  38 ms  sl-crs1-atl-0-0-0.sprintlink.net [144.232.18.216]
  9  42 ms  42 ms  41 ms  sl-crs1-nyc-0-5-3.sprintlink.net [144.232.20.49]
 10  40 ms  40 ms  40 ms  sl-gw35-nyc-14-0-0.sprintlink.net [144.232.13.37]
 11  44 ms  42 ms  42 ms  sl-dowjo-i29545-0.sprintlink.net [144.232.234.142]
 12  42 ms  42 ms  42 ms  online.wsj.com [205.203.132.1]

Trace complete.
PS C:\>
```

Routing Protocols

- Routing Protocols: mechanism used by **routers to exchange routing information**
 - Build and maintain routing tables.
- There are two kinds of routing protocols used on the Internet
 - **Interior routing protocols (Intra-AS routing)**
 - used within an autonomous system to reach internal networks
 - **Exterior routing protocols (Inter-AS routing)**
 - connect autonomous systems to each other
 - E.g. BGP (Border Gateway Protocol)

Intra-AS and Inter-AS Routing



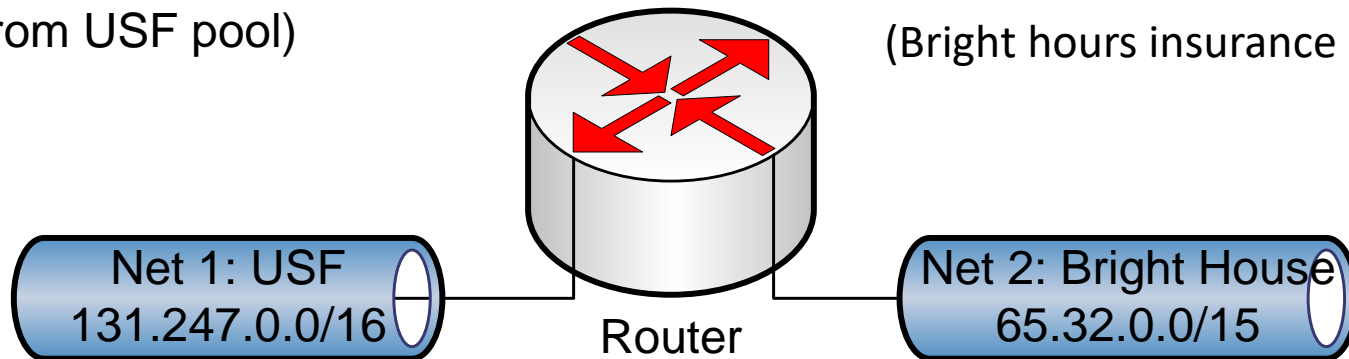
Interior Router Protocol (IRP) passes information between routers within an AS (Intra-AS)
Exterior Router Protocol (ERP) passes information between routers in different AS (Inter-AS)

Routers can have multiple addresses if it is in the interface between two networks

A router has multiple interfaces. Each interface gets IP address from the network it's connected to. That is, each interface has different IP address.

Router interface facing USF
IP address: **131.247.254.182**
(from USF pool)

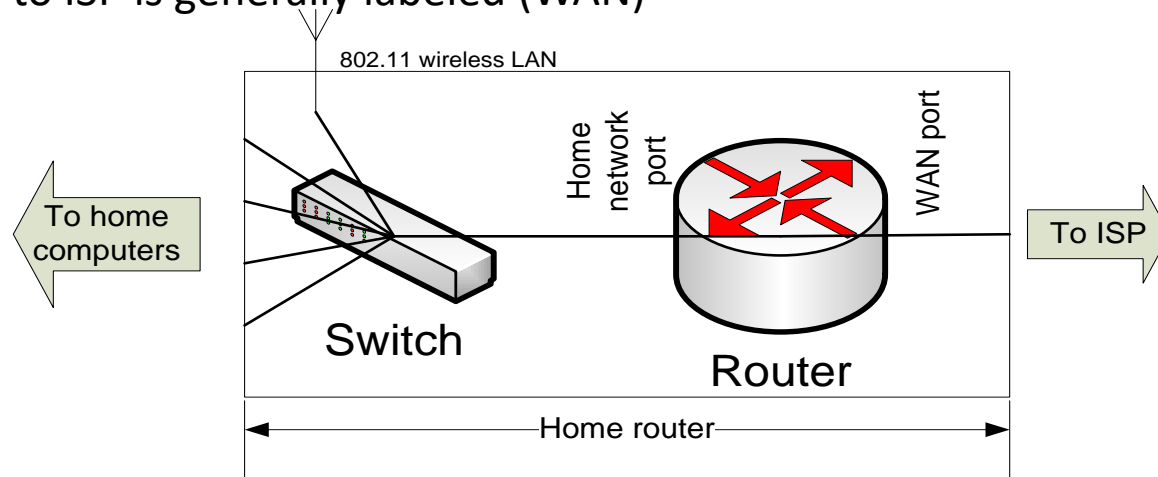
Router interface facing Bright House
IP address: **65.32.8.150**
(Bright hours insurance company)



Routers in Networks - Homes

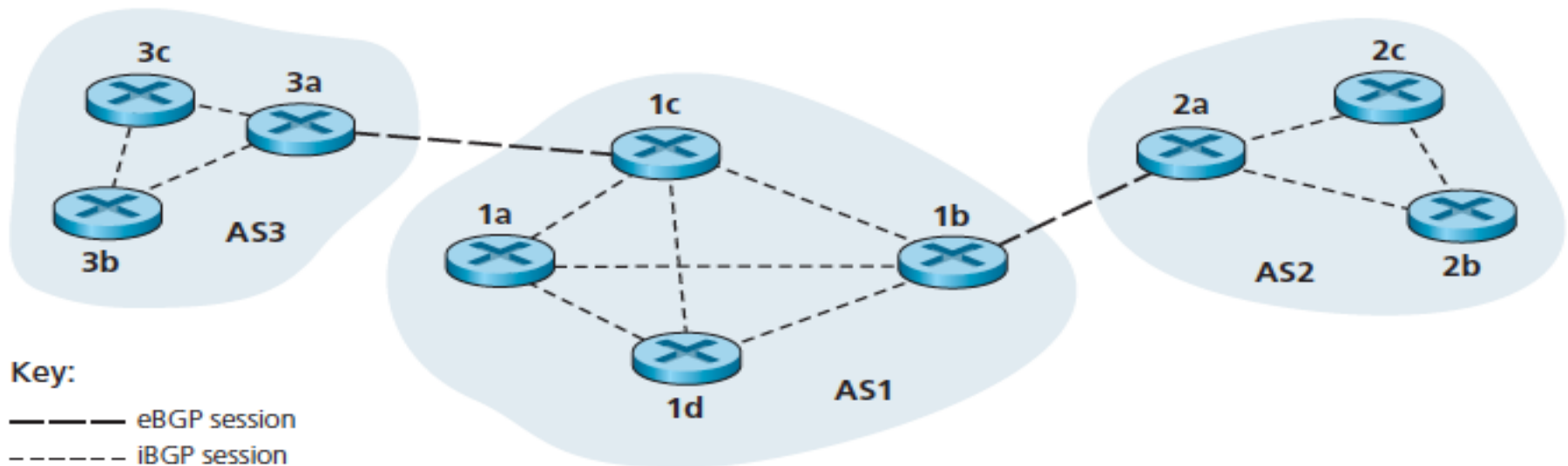
A router has multiple interfaces. Each interface gets IP address from the network it's connected to. That is, each interface has different IP address.

Router at home acts as interface between you home network and ISP. The port connected to ISP is generally labeled (WAN)



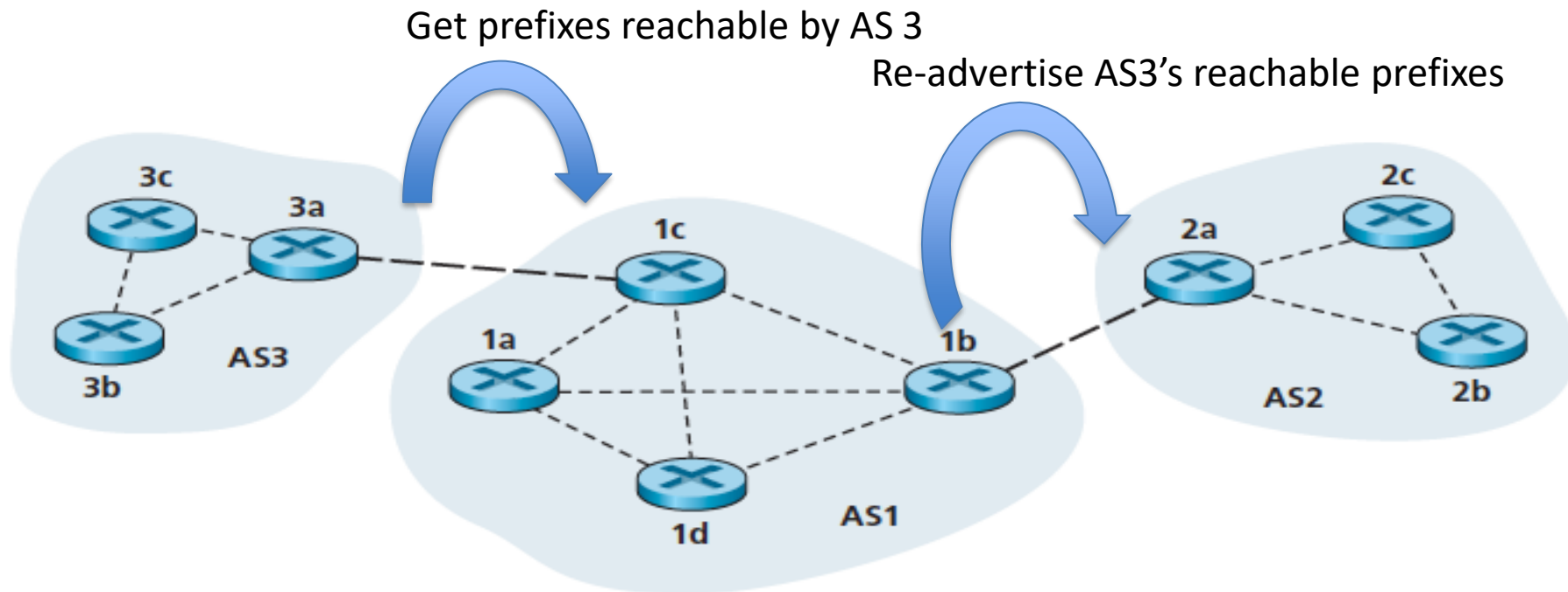
Inter-AS Routing: Border Gateway Protocol (BGP)

- Used to route between different AS
- Obtain **reachability information** from neighboring AS
- **Propagate information** to all routers within AS
- **Determine “good” routes**



Inter-AS Routing: Border Gateway Protocol (BGP)

- Each AS learns about reachable destinations via other AS using **CIDR prefixes**



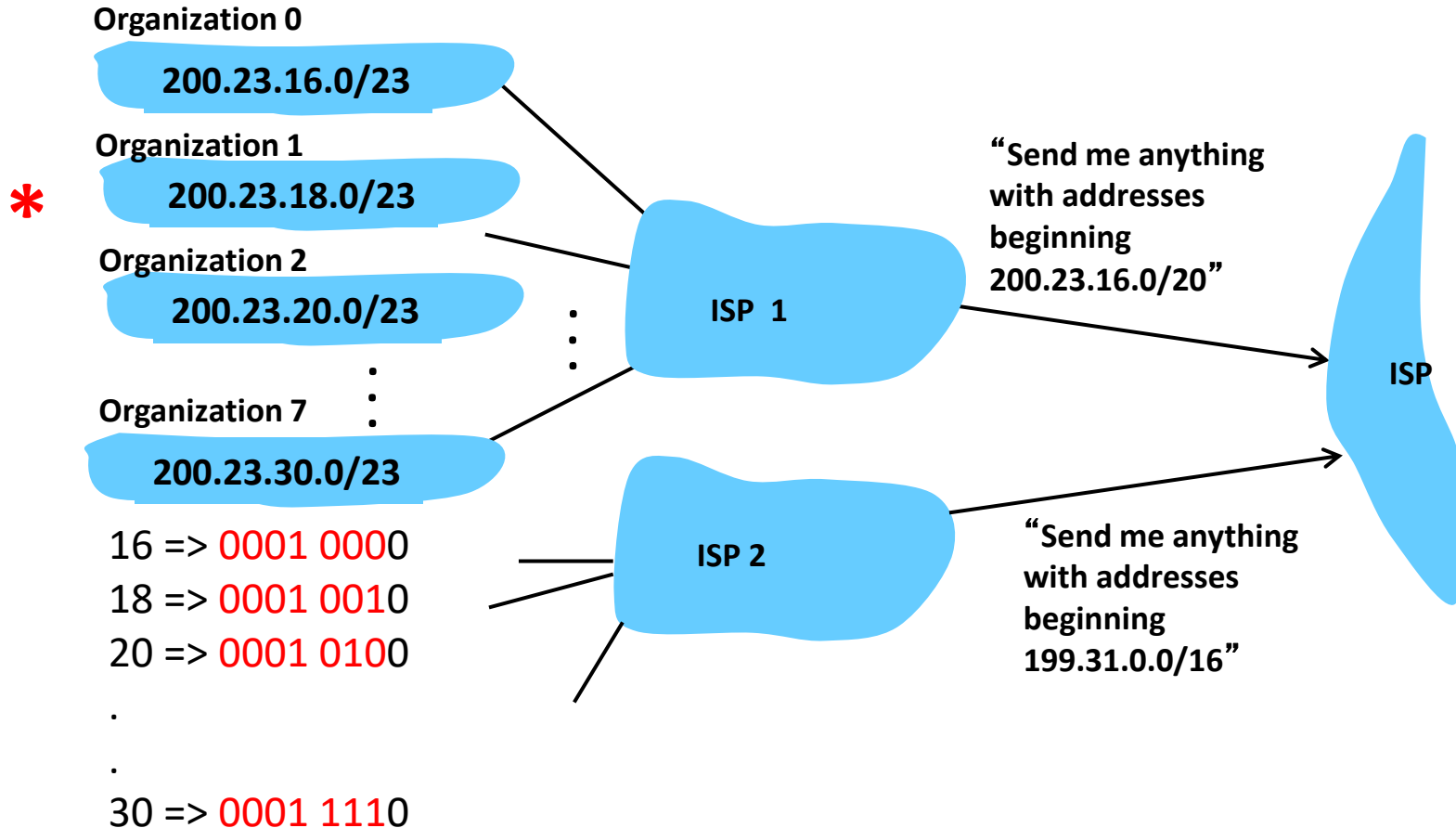
Simplifying Routing Tables

- As more and more organizations join the Internet, **routing tables keep getting larger** to accommodate the newer routes
- **Route aggregation** is used to **simplify routing tables**

Hierarchical Addressing and Route Aggregation

Use largest matching prefix to advertisement of address for routing information

Prefix is the network ID portion of IP address

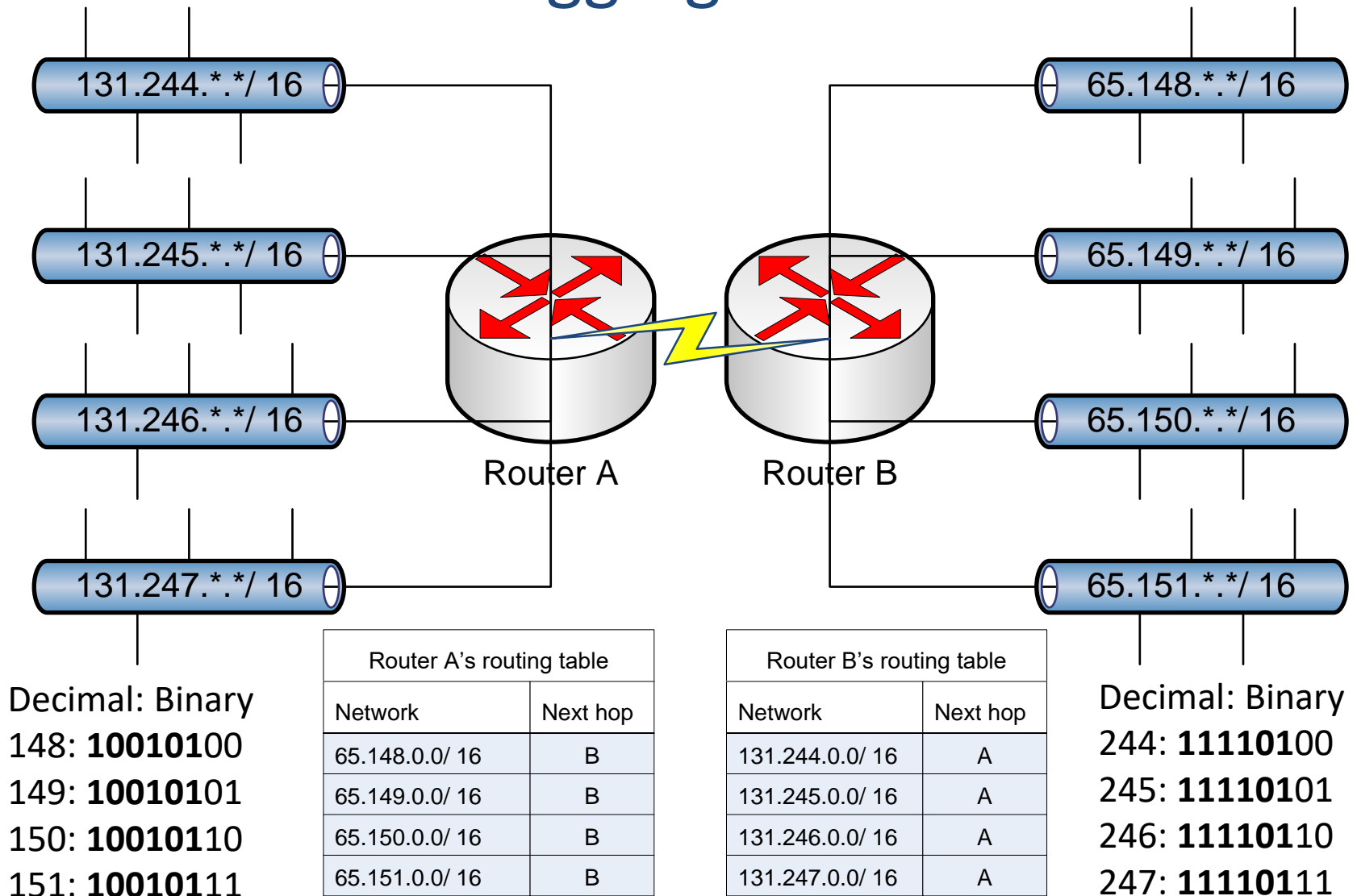


Comment on Previous Example

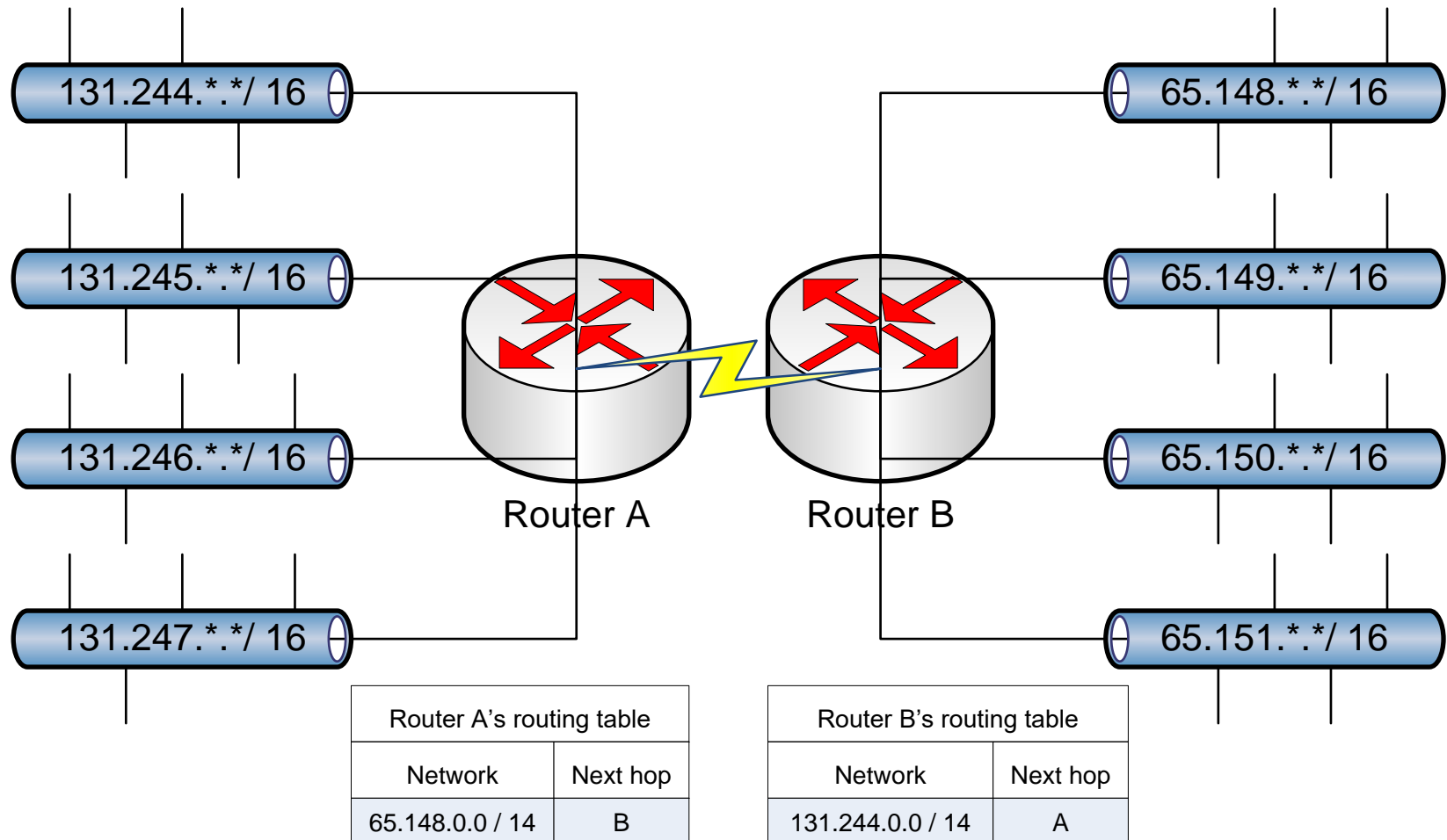
ISP's block	200.23.16.0/20	<u>11001000 00010111 00010000</u> 00000000
Organization 0	200.23.16.0/23	<u>11001000 00010111 00010000</u> 00000000
Organization 1	200.23.18.0/23	<u>11001000 00010111 00010010</u> 00000000
Organization 2	200.23.20.0/23	<u>11001000 00010111 00010100</u> 00000000
...
Organization 7	200.23.30.0/23	<u>11001000 00010111 00011110</u> 00000000

Largest matching prefix is 20 bits.

Example: Routing Table Without Aggregation

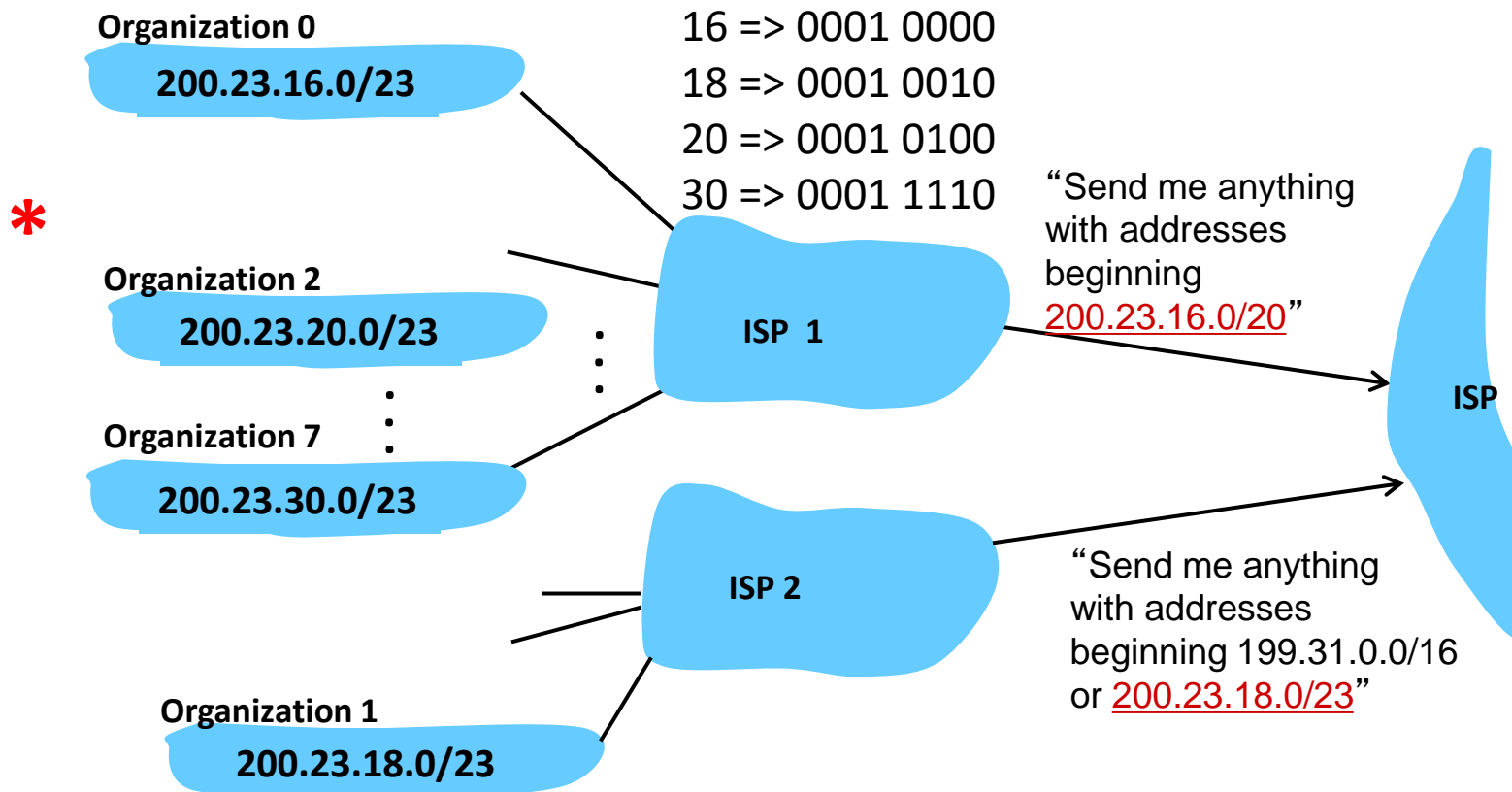


Example: Routing Table with Aggregation

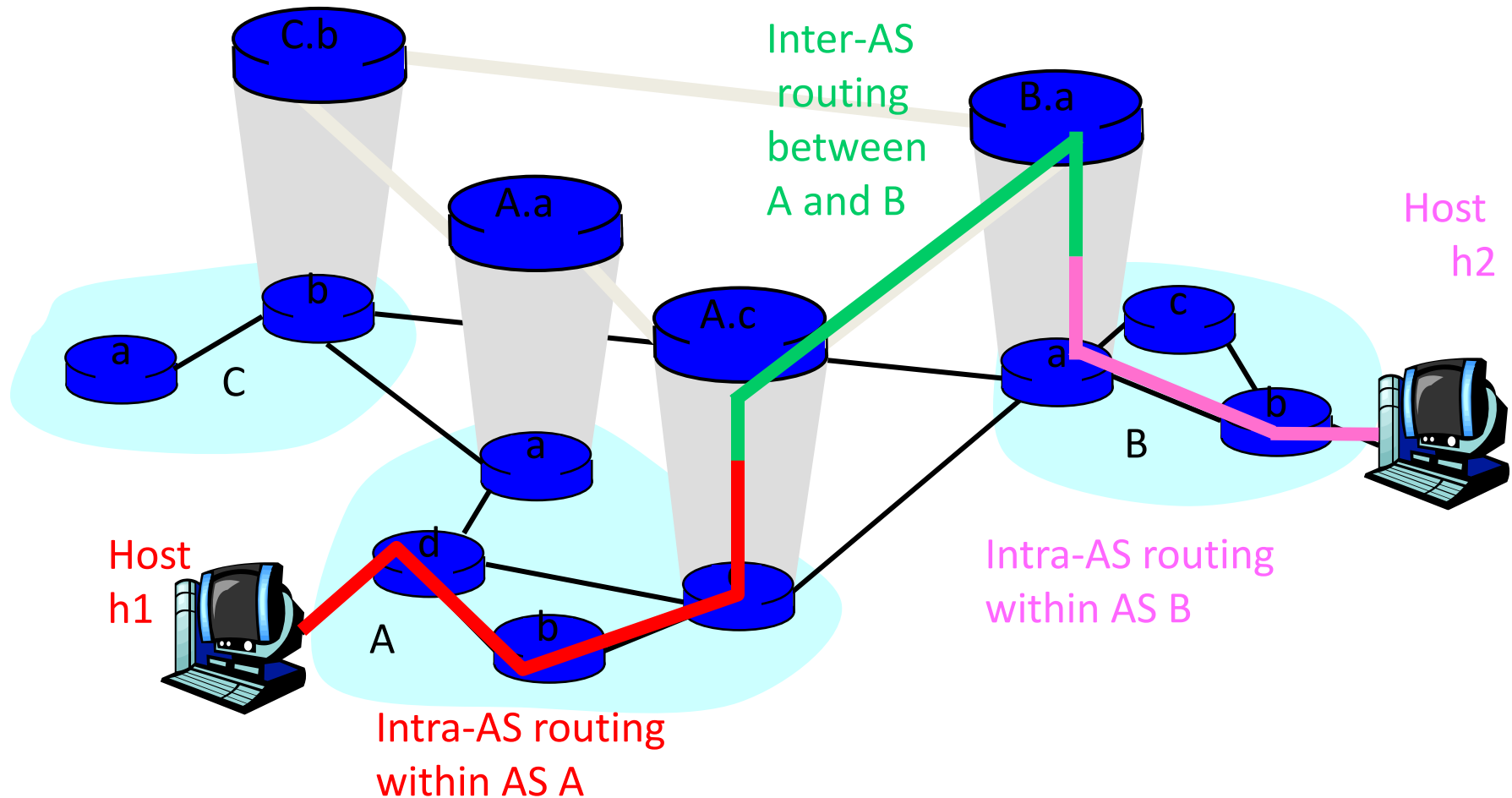


Hierarchical Addressing: more specific routes

What if Organization 1 now is connected to ISP2 & kept its IP address?
route aggregation still is advertised, but more details about
addressing are sent by ISP 2... **Other routers use largest common
prefix for routing**



Recall: Intra-AS and Inter-AS Routing

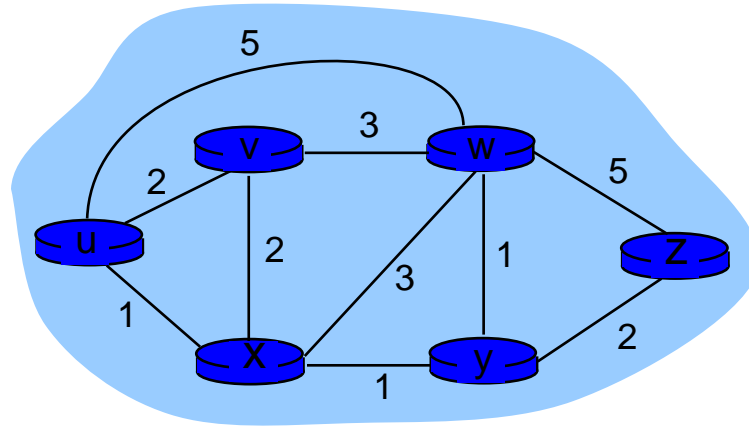


Interior Router Protocol (IRP) passes information between routers within an AS (Intra-AS)
Exterior Router Protocol (ERP) passes information between routers in different AS (Inter-AS)

Intra-AS routing

- Many Algorithms
 - Distance vector routing (know neighbors)
 - RIP: Routing Information Protocol is special case (know neighbors, link cost =1)
 - OSPF: Open Shortest Path First (know full topology)
 - IGRP: Interior Gateway Routing Protocol (Cisco proprietary)

Graph abstraction

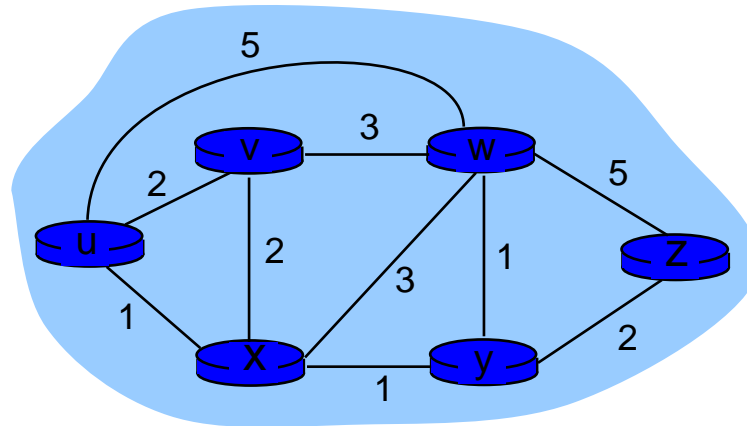


graph: $G = (N, E)$, nodes N and edges E

N = set of routers = $\{ u, v, w, x, y, z \}$

E = set of links = $\{ (u, v), (u, x), (v, x), (v, w), (x, w), (x, y), (w, y), (w, z), (y, z) \}$

Link and path costs



Every physical **link** $\{x, y\}$ is associated with a **cost** c ($c(x,y)$)

- The cost might be a function of its length, the cost of building it, bandwidth etc.

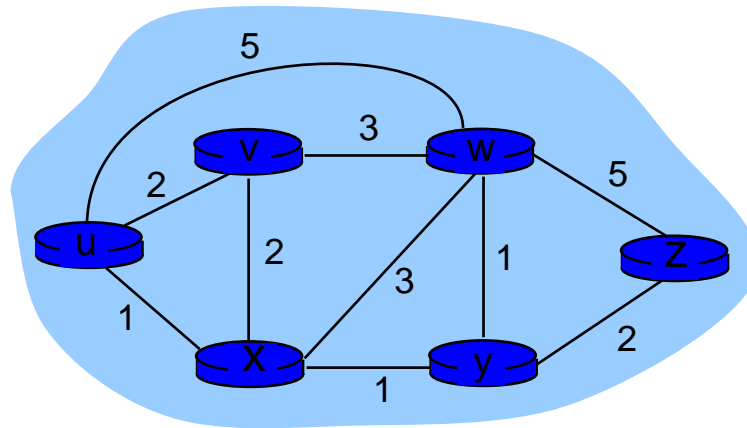
Route/Path cost is an extension of the link cost

- A path is a series of links traversed from the source to the destination

E.g., (u, v, w, z) is a path from router u to router z

$$c(u, v, w, z) = c(u,v) + c(v,w) + c(w,z)$$

key question: what is the least-cost path between u and z ?
routing algorithm: algorithm that finds that least cost path



Distance vector routing algorithm

Bellman-Ford equation

Cost: distance, bandwidth, delay, average traffic

let

$d_x(y) :=$ cost of least-cost path from x to y

then

$$d_x(y) = \min_v \{ c(x,v) + d_v(y) \}$$

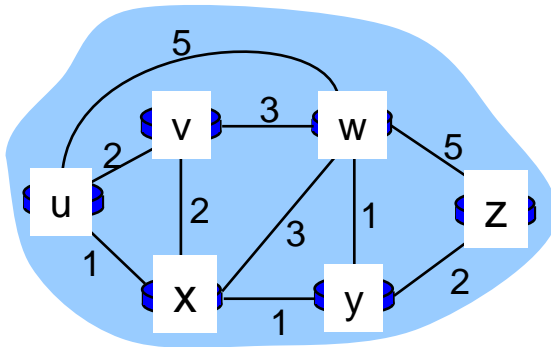
Distance from node x to
node y

cost from neighbor v to destination y
cost to neighbor v

\min taken over all neighbors v of x

Distance vector routing algorithm

Find distance from node u to node z



1) Neighbors of u are v, x, w (all have direct links)

2) Min distance from each of the neighbors to z
 $d_v(z) = 5$, **$d_x(z) = 3$** , $d_w(z) = 3$

Distance from node u to node z

$$\begin{aligned} 3) d_u(z) &= \min \{ c(u,v) + d_v(z), \\ &\quad c(u,x) + d_x(z), \\ &\quad c(u,w) + d_w(z) \} \\ &= \min \{ 2 + 5, \\ &\quad 1 + 3, \\ &\quad 5 + 3 \} = 4 \end{aligned}$$

Distance vector routing algorithm

key idea:

- 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:**

$$D_x(y) \leftarrow \min_v \{c(x,v) + D_v(y)\} \text{ for each node } y \in N$$

- ❖ under minor, natural conditions, the estimate $D_x(y)$ **converge** to the actual least cost $d_x(y)$

$$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\}$$

$$= \min\{2+0, 7+1\} = 2$$

$$D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\}$$

$$= \min\{2+1, 7+0\} = 3$$

node x
table

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

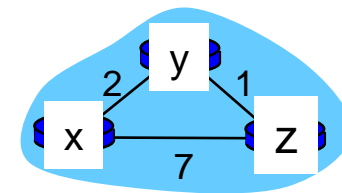
node y
table

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

node z
table

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

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



time →

First, each node knows
cost to immediate
neighbors

Then, routers exchange
information about their
reachable destinations

$$D_x(y) = \min\{c(x,y) + D_y(y), c(x,z) + D_z(y)\}$$

$$= \min\{2+0, 7+1\} = 2$$

$$D_x(z) = \min\{c(x,y) + D_y(z), c(x,z) + D_z(z)\}$$

$$= \min\{2+1, 7+0\} = 3$$

node x
table

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

node y
table

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

node z
table

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

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

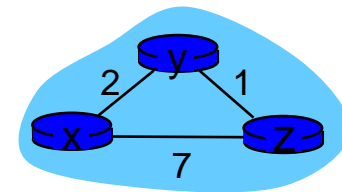
		cost to		
		x	y	z
from	x	0	2	7
	y	2	0	1
	z	7	1	0

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

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

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

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



Z checks: go through x directly (cost 7), or go through a neighbor y (cost = cost to y [1] + cost from y to x [2])

Tophat question



Q_Routing

What if each link in a network has a cost that is equal to 1, and we used distance vector routing algorithm to find best route between routers A and B?

- | | |
|---|---|
| A | Then, the best path will be the path with minimum delay |
| B | Then the best path will be the path with minimum number of hops |
| C | None of the above |

Summary

- Autonomous System (AS)
- Differentiate between Intra-AS and Inter-AS routing
- Examine route address aggregation
 - helps in simplifying routing tables
- Create routing tables using distance vector routing