

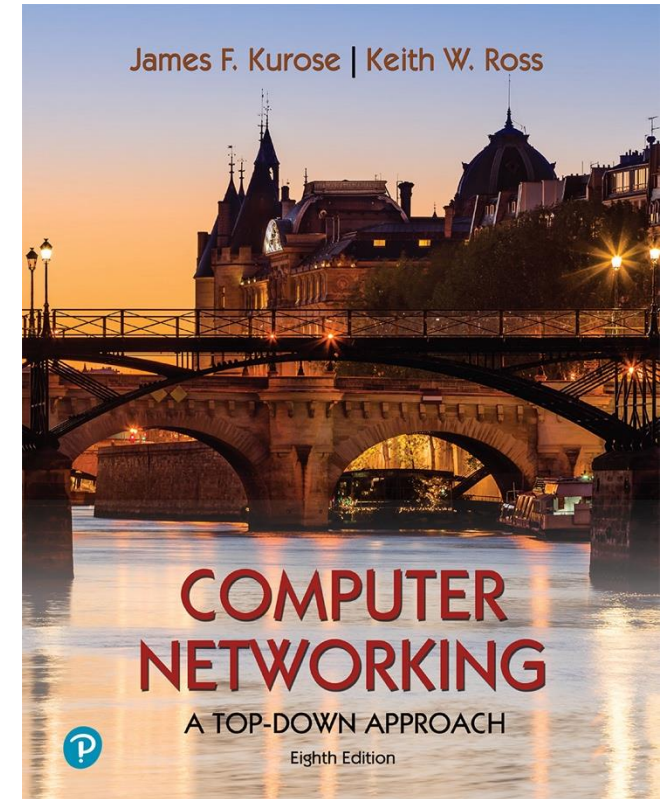
Chapter 5

Network Layer: Control Plane

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Adapted from the slides of the book's authors



*Computer Networking: A
Top-Down Approach*

8th edition

Jim Kurose, Keith Ross
Pearson, 2020

Network layer: “control plane” roadmap

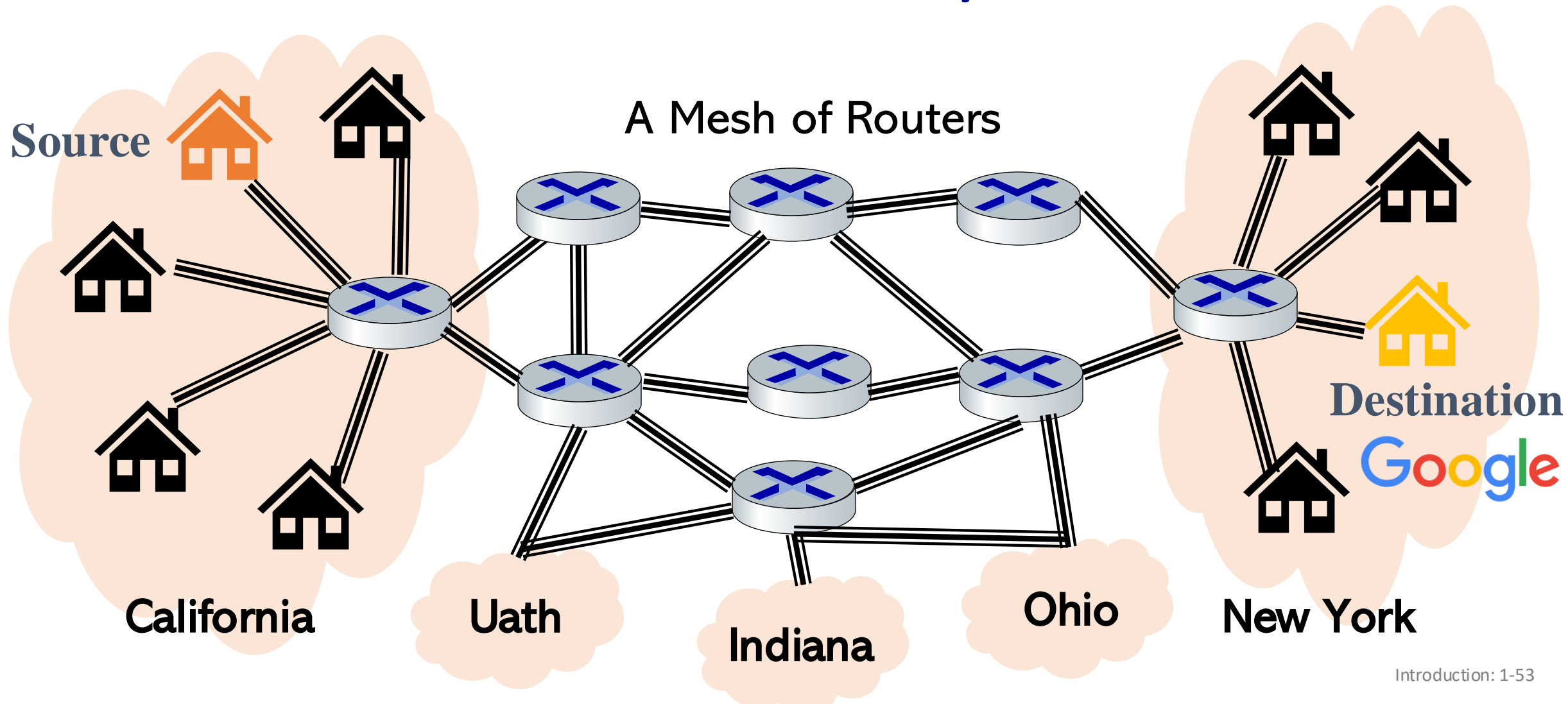
- introduction
- routing protocols
- **intra-ISP routing: OSPF**
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol



- network management, configuration
 - SNMP
 - NETCONF/YANG

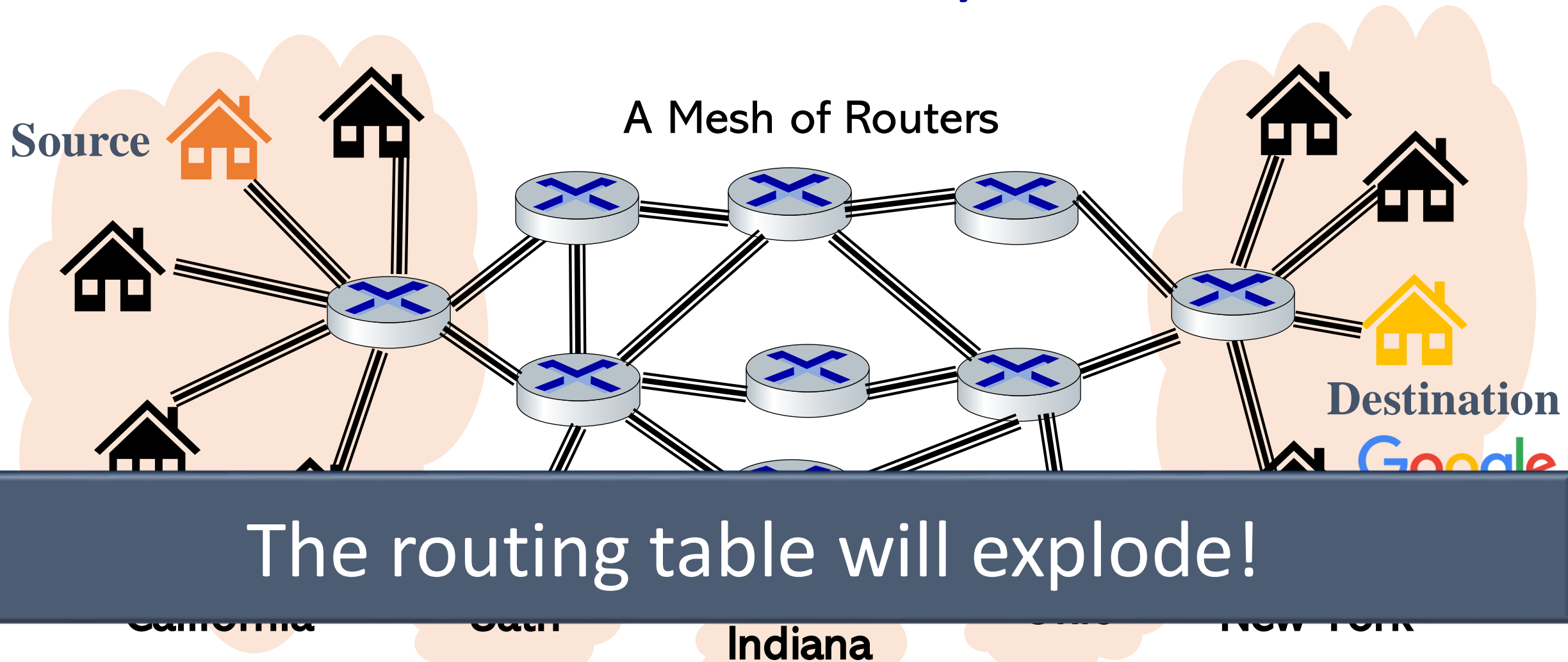
The scalability of routing

Strawman: remember every destination?



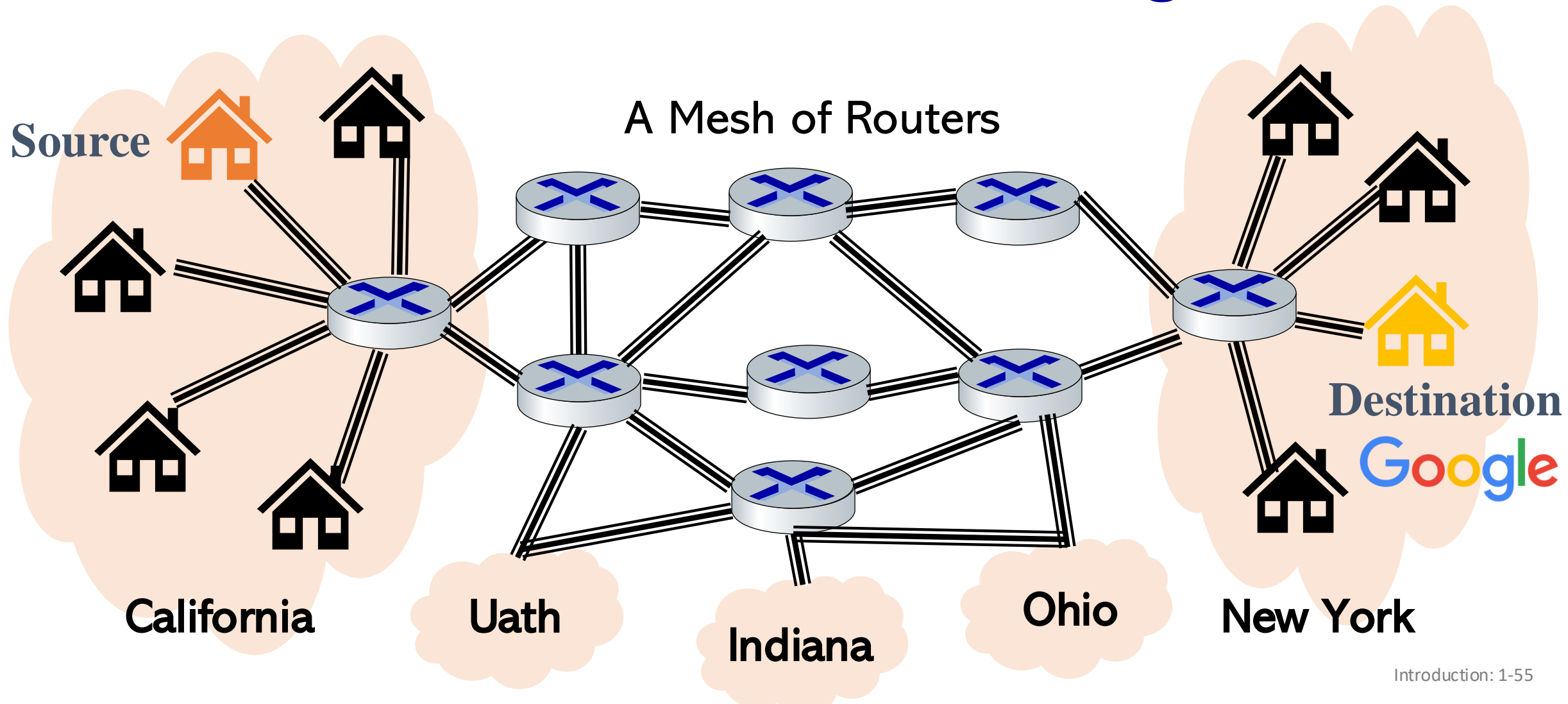
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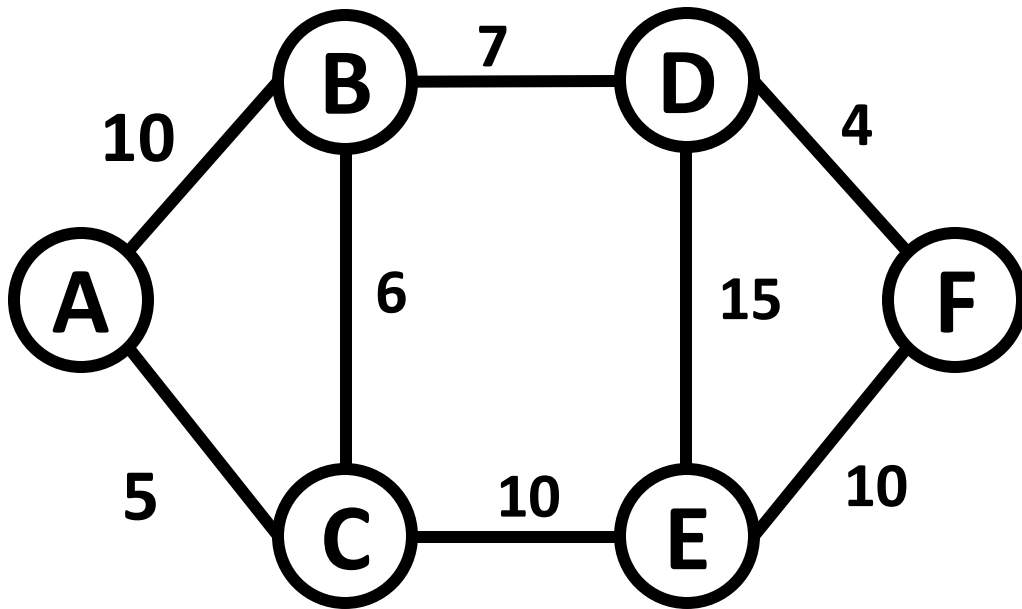


The scalability of routing

Strawman: all the router work together?



Two Routing Algorithm: link-state and distance vector



- **centralized**: network topology, link costs known to *all* nodes
 - accomplished via “link state broadcast”
 - all nodes have same info
- computes least cost paths from one node (“source”) to all other nodes
 - gives *forwarding table* for that node
- **iterative**: after k iterations, know least cost path to k destinations

Two Routing Algorithm: link-state and distance vector

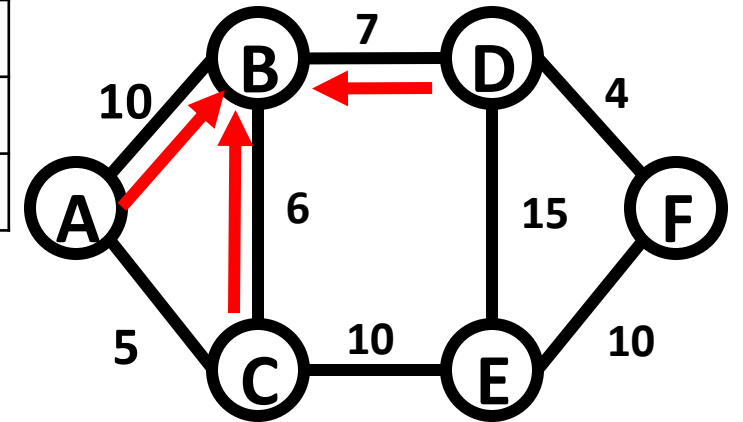
Router B has 4 distance vector tables

Link	Cost
A->B	10
A->C	5

Link	Cost
B->A	10
B->C	6
B->D	7

Link	Cost
C->A	5
C->B	6
C->E	10

Link	Cost
D->B	7
D->E	15
D->F	4



New paths

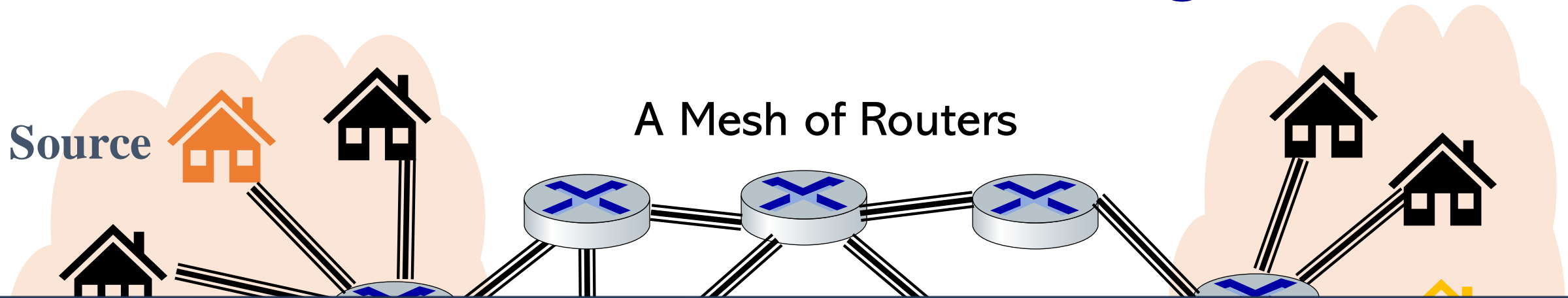
B->A->C 15 > B->C 6
B->C->E 16 New destination
B->C->A 11 > B->A 10
B->D->E 21 > B->C->E 16
B->D->F 11 New destination

New table

Link	Cost
B->A	10
B->C	6
B->D	7
B->E	16
B->F	11

The scalability of routing

Strawman: all the router work together?



- Excessive number messages exchanged
- Takes forever to converge!

California

Oath

Indiana

Ohio

NEW YORK

Making routing scalable

our routing study thus far - idealized

- all routers identical
- network “flat”

... not true in practice

scale: billions of destinations:

- can't store all destinations in routing tables!
- routing table exchange would swamp links!

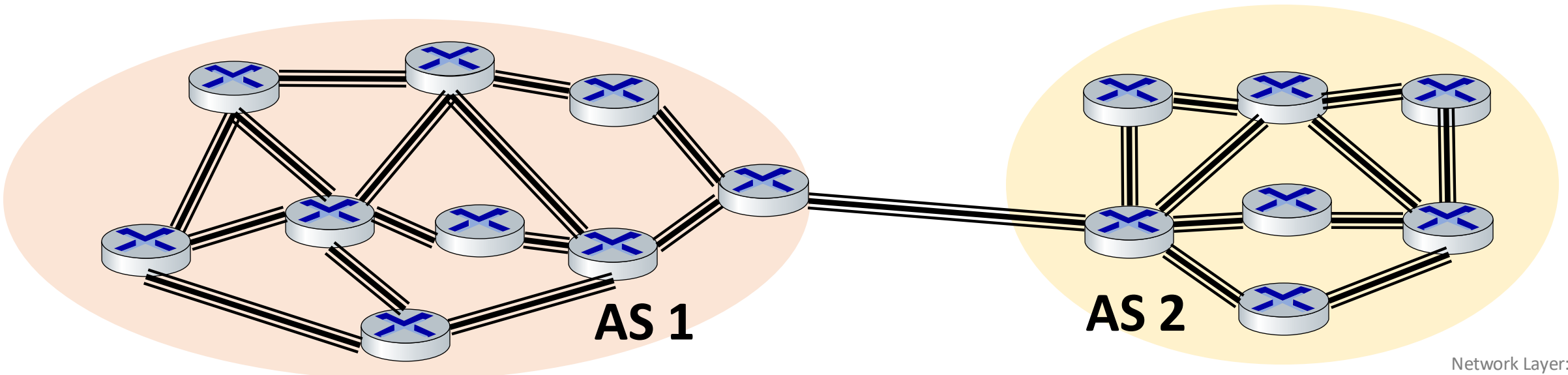
administrative autonomy:

- Internet: a network of networks
- each network admin may want to control routing in its own network

Internet approach to scalable routing

aggregate routers into regions known as “autonomous systems” (AS) (a.k.a. “domains”)

Definition: a collection of IP networks and routers under the control of a single organization that presents a common routing policy to the internet.

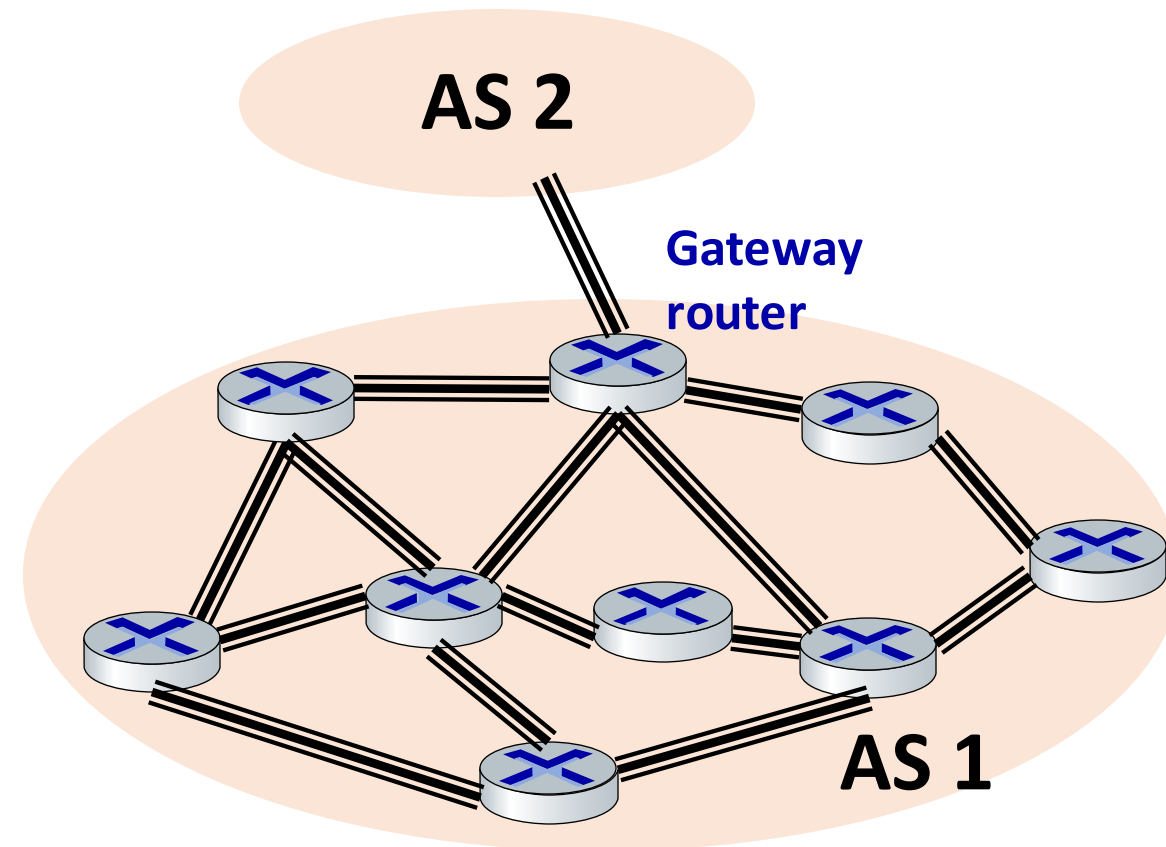


Internet approach to scalable routing

aggregate routers into regions known as “autonomous systems” (AS) (a.k.a. “domains”)

intra-AS (aka “intra-domain”):
routing among routers *within same AS (“network”)*

- all routers in AS must run same intra-domain protocol
- routers in different AS can run different intra-domain routing protocols
- **gateway router:** at “edge” of its own AS, has link(s) to router(s) in other AS'es



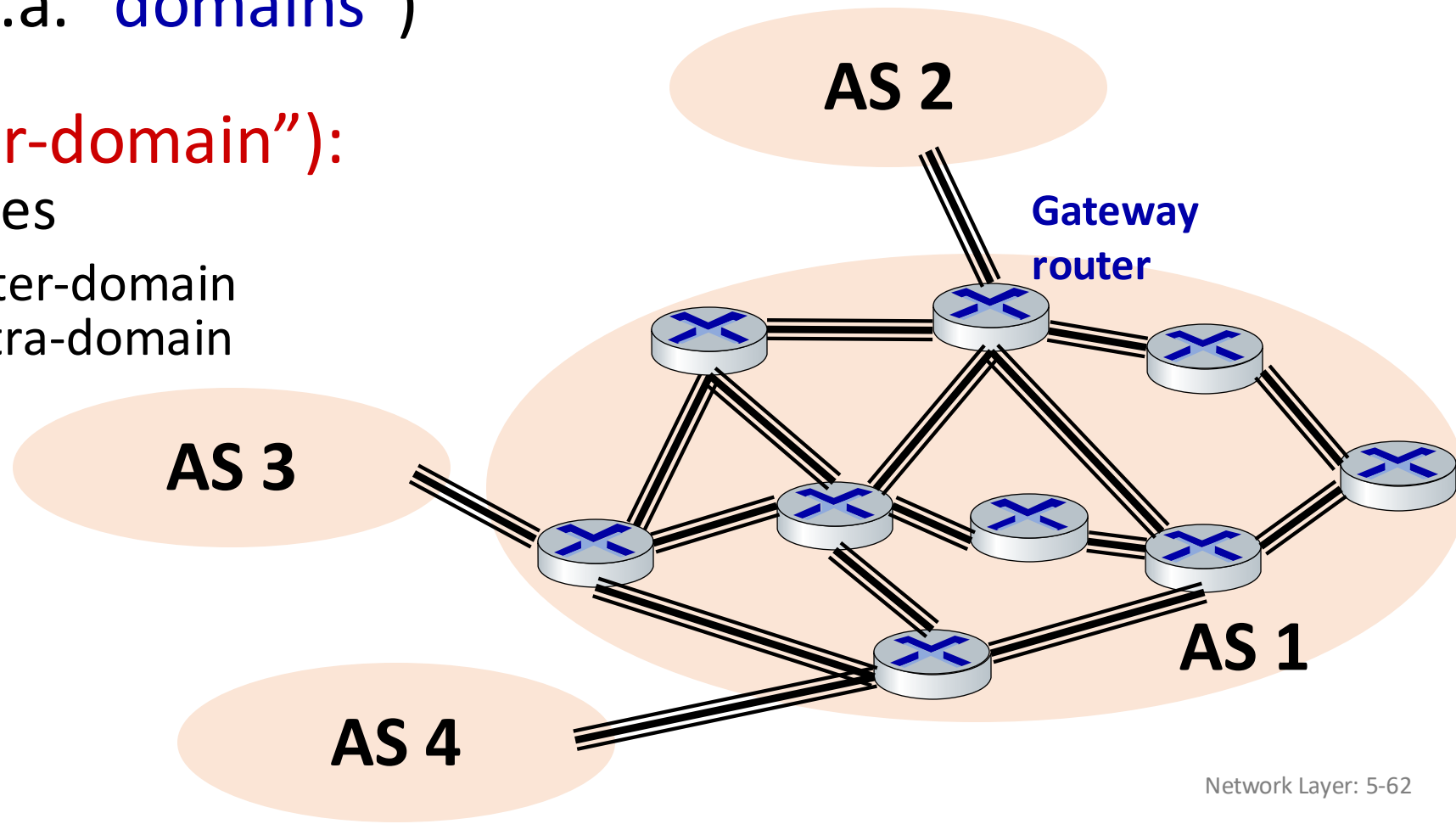
Internet approach to scalable routing

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inter-AS (aka “inter-domain”):

routing *among* AS'es

- gateways perform inter-domain routing (as well as intra-domain routing)



Internet approach to scalable routing

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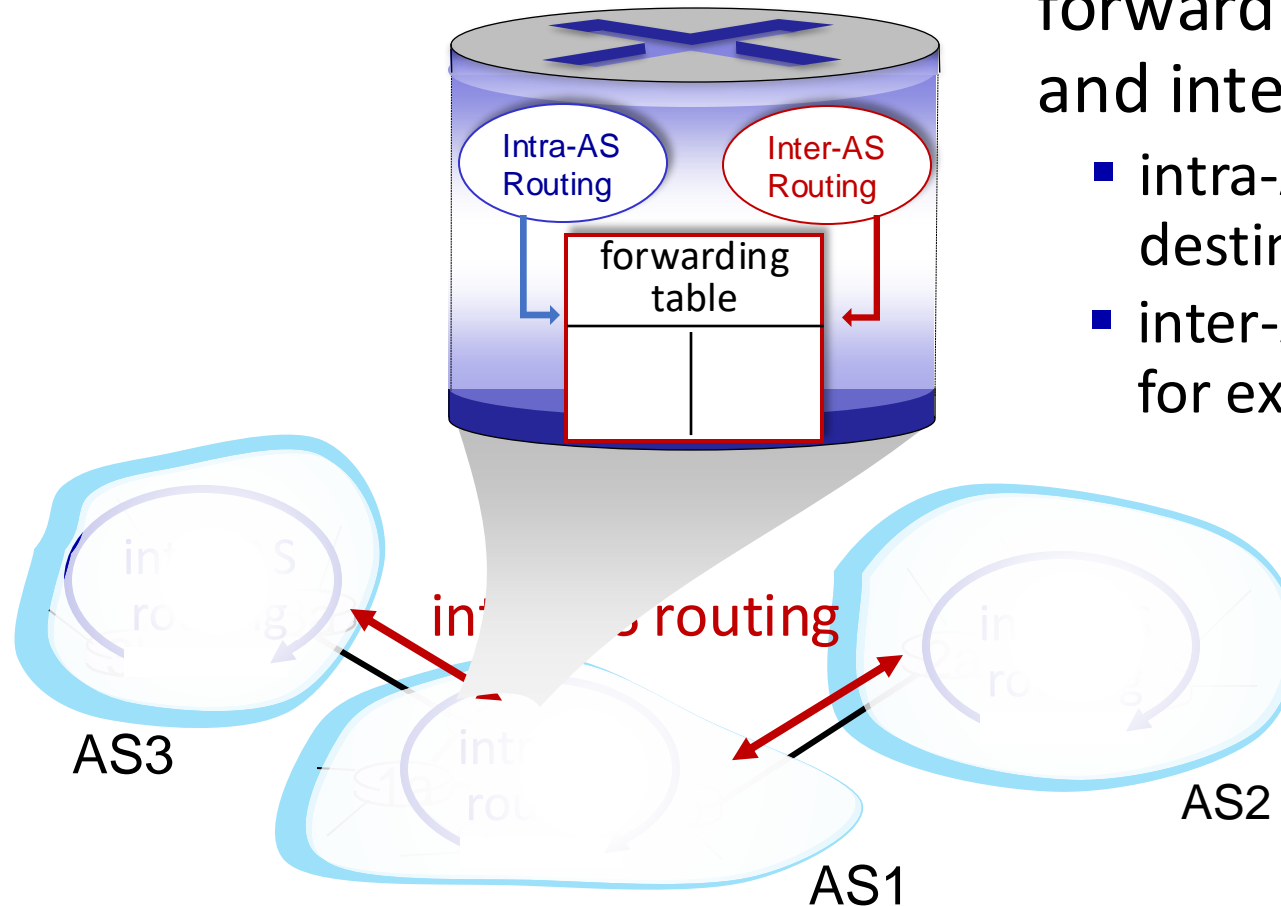
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routing *among* AS'es

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Interconnected ASes



forwarding table configured by intra- and inter-AS routing algorithms

- intra-AS routing determine entries for destinations within AS
- inter-AS & intra-AS determine entries for external destinations

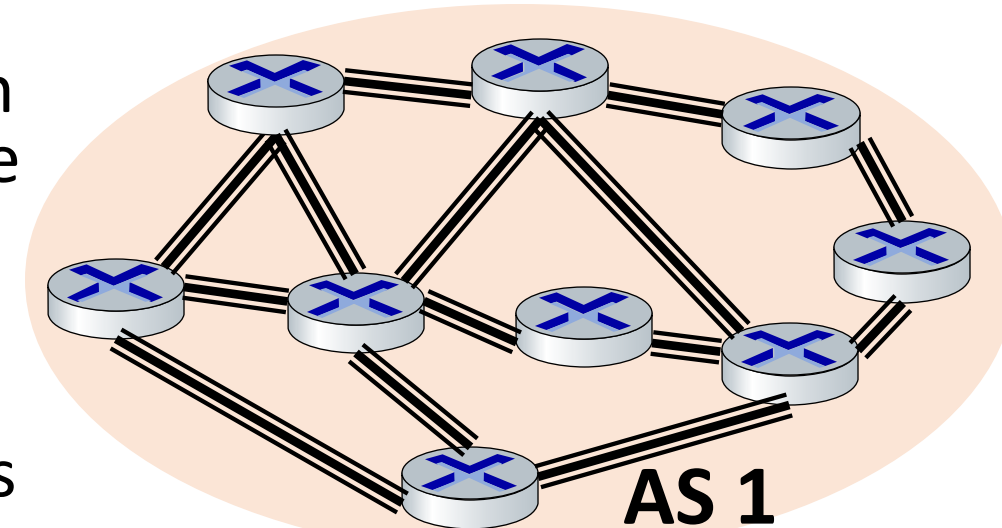
Intra-AS routing: routing within an AS

most common intra-AS routing protocols:

- **RIP: Routing Information Protocol** [RFC 1723]
 - classic DV: DVs exchanged every 30 secs
 - no longer widely used
- **EIGRP: Enhanced Interior Gateway Routing Protocol**
 - DV based
 - formerly Cisco-proprietary for decades (became open in 2013 [RFC 7868])
- **OSPF: Open Shortest Path First** [RFC 2328]
 - link-state routing
 - IS-IS protocol (ISO standard, not RFC standard) essentially same as OSPF

OSPF (Open Shortest Path First) routing

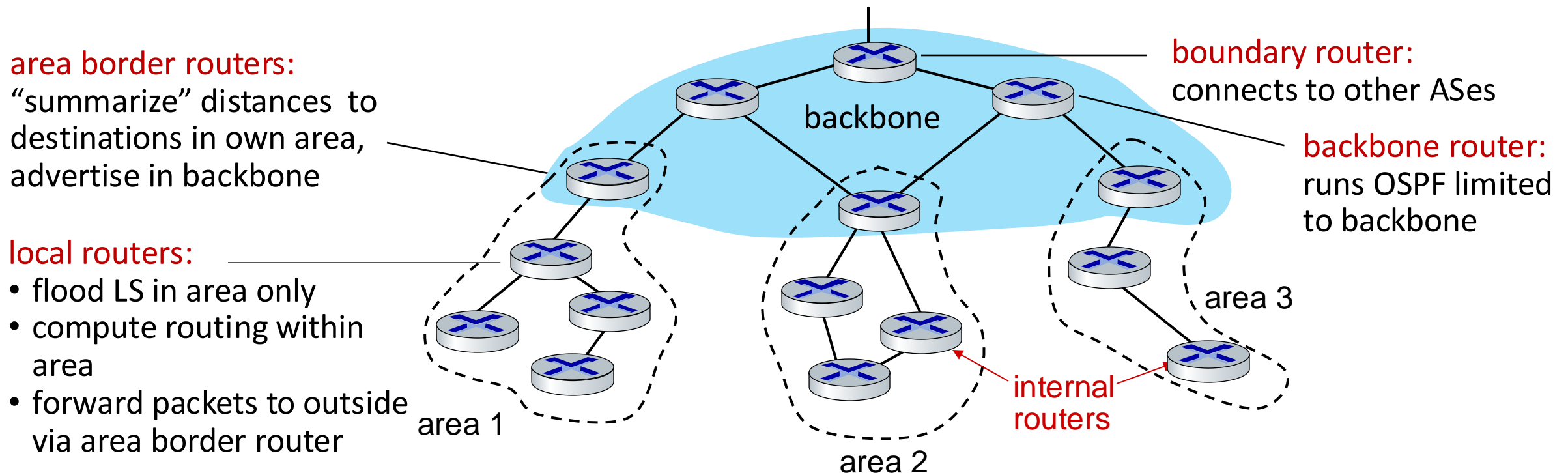
- “open”: publicly available
- classic link-state
 - each router floods OSPF link-state advertisements (directly over IP rather than using TCP/UDP) to all other routers in entire AS
 - multiple link costs metrics possible: bandwidth, delay
 - each router has full topology, uses Dijkstra's



What if the AS itself becomes extremely large?

Hierarchical OSPF

- **two-level hierarchy:** local area, backbone.
 - link-state advertisements flooded only in area, or backbone
 - each node has detailed area topology; only knows direction to reach other destinations



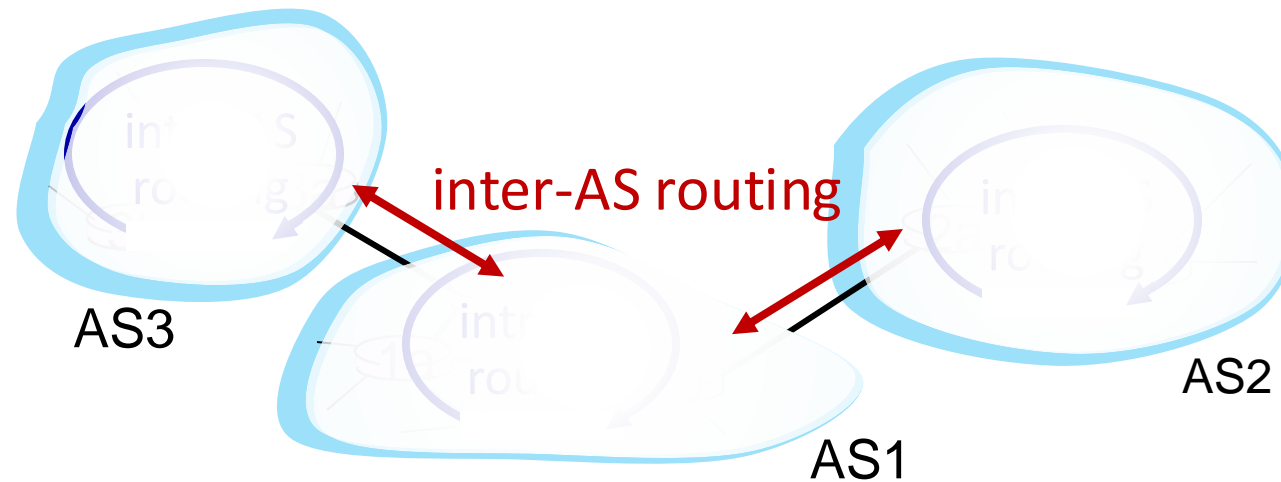
Network layer: “control plane” roadmap

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Interconnected ASes

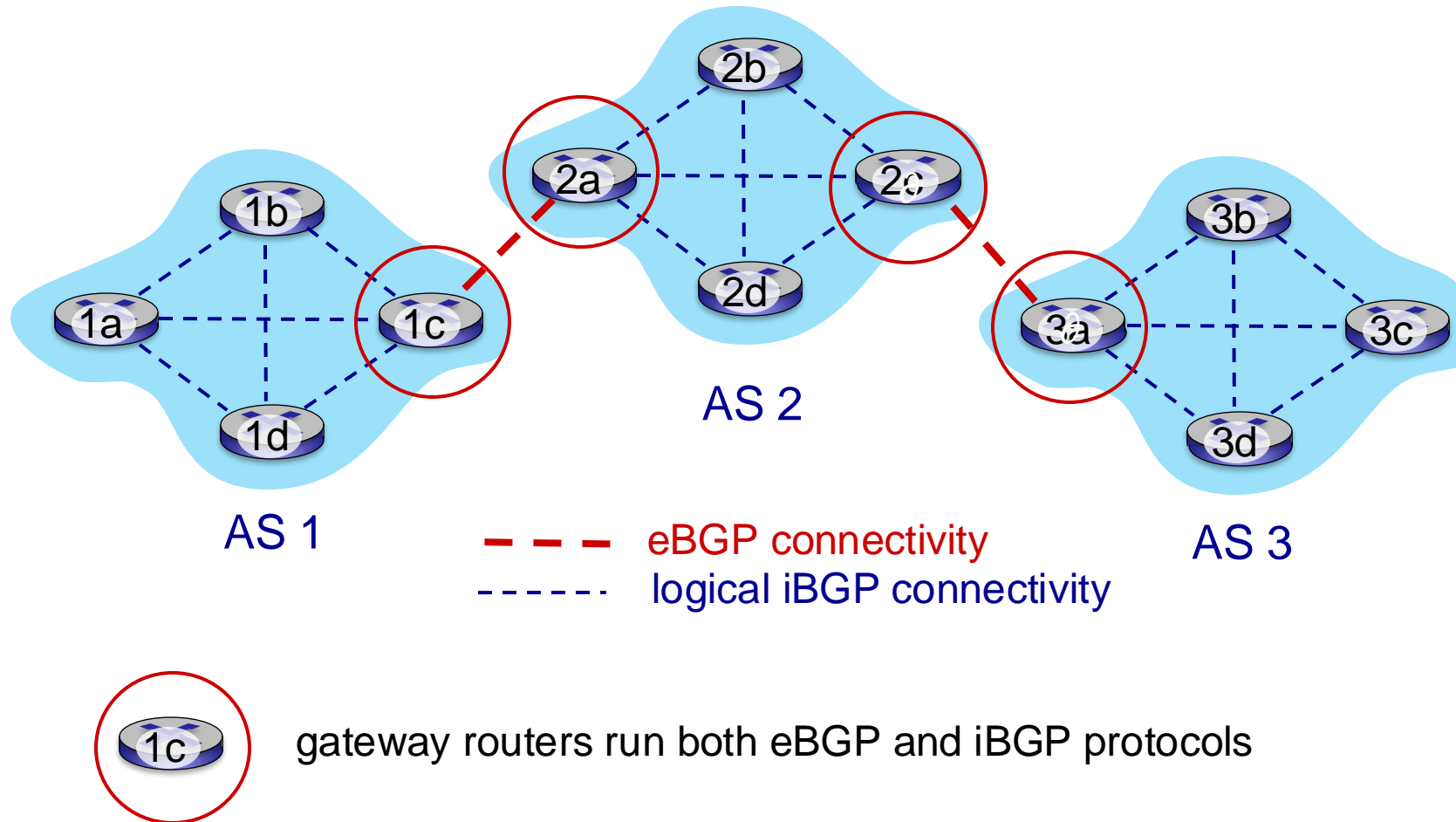


- ✓ **intra-AS (aka “intra-domain”)**: routing among routers *within same* AS (“*network*”)
- ➡ **inter-AS (aka “inter-domain”)**: routing *among* AS'es

Internet inter-AS routing: BGP

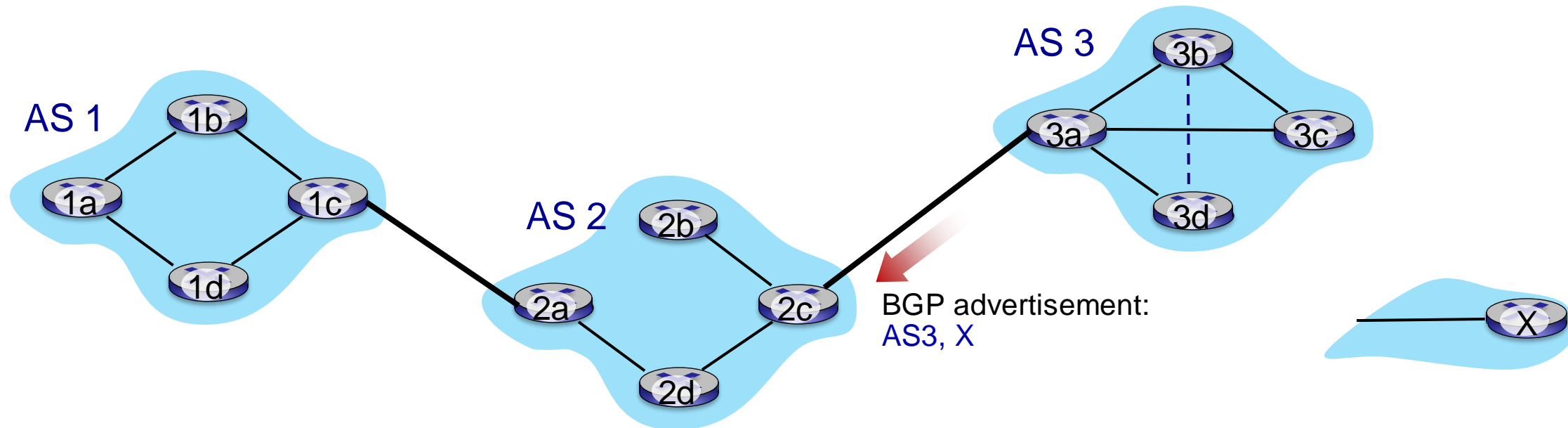
- **BGP (Border Gateway Protocol):** *the* de facto inter-domain routing protocol
 - “glue that holds the Internet together”
- allows subnet to advertise its existence, and the destinations it can reach, to rest of Internet: *“I am here, here is who I can reach, and how”*
- BGP provides each AS a means to:
 - obtain destination network reachability info from neighboring ASes (**eBGP**)
 - determine routes to other networks based on reachability information and *policy*
 - propagate reachability information to all AS-internal routers (**iBGP**)
 - **advertise** (to neighboring networks) destination reachability info

eBGP, iBGP connections



BGP basics

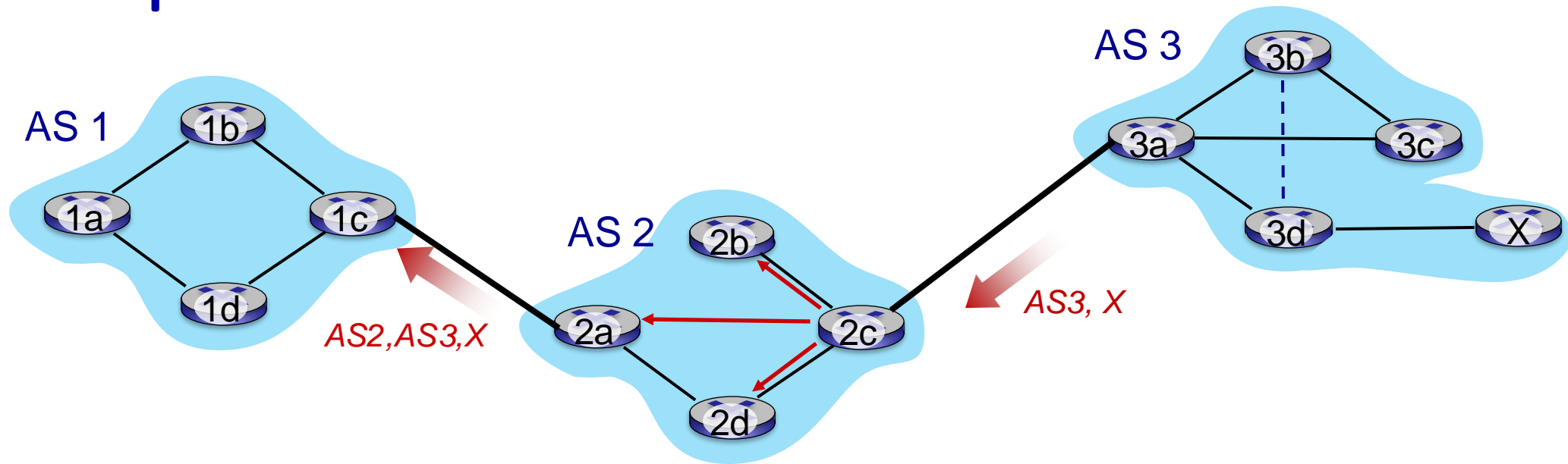
- **BGP session:** two BGP routers (“peers”) exchange BGP messages over semi-permanent TCP connection:
 - advertising *paths* to different destination network prefixes (BGP is a “path vector” protocol)
- when AS3 gateway 3a advertises *path AS3,X* to AS2 gateway 2c:
 - AS3 *promises* to AS2 it will forward datagrams towards X



Path attributes and BGP routes

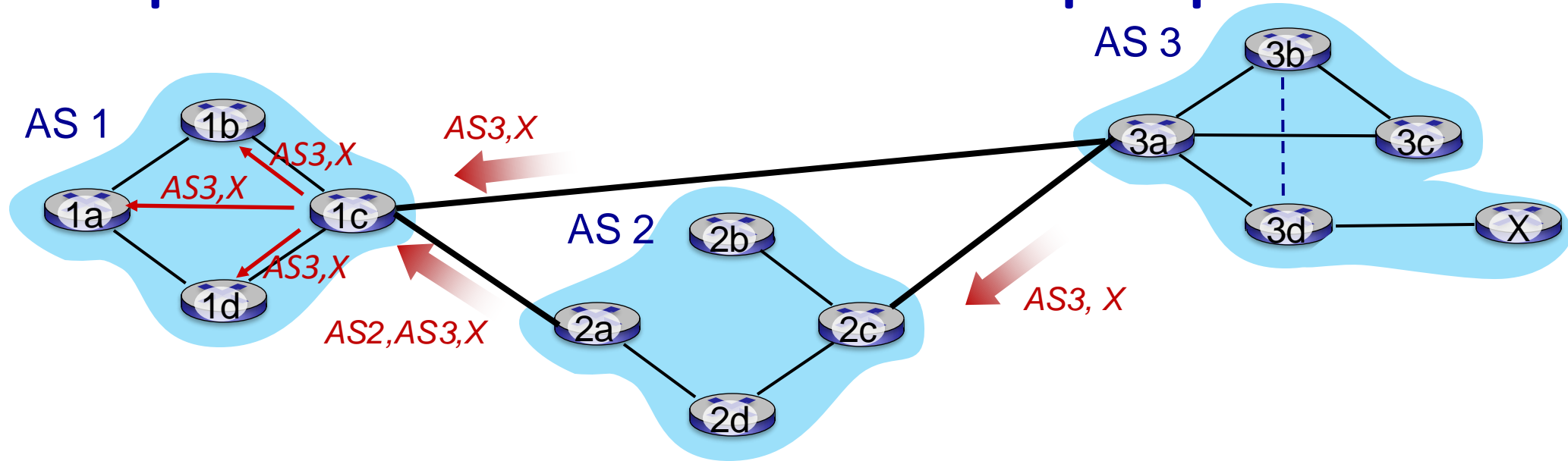
- BGP advertised route: prefix + attributes
 - prefix: destination being advertised
 - two important attributes:
 - **AS-PATH**: list of ASes through which prefix advertisement has passed
 - **NEXT-HOP**: indicates specific internal-AS router to next-hop AS
- **policy-based routing**:
 - gateway receiving route advertisement uses *import policy* to accept/decline path (e.g., never route through AS Y).
 - AS policy also determines whether to *advertise* path to other neighboring ASes

BGP path advertisement



- AS2 router 2c receives path advertisement **AS3,X** (via eBGP) from AS3 router 3a
- based on AS2 policy, AS2 router 2c accepts path AS3,X, propagates (via iBGP) to all AS2 routers
- based on AS2 policy, AS2 router 2a advertises (via eBGP) path **AS2, AS3, X** to AS1 router 1c

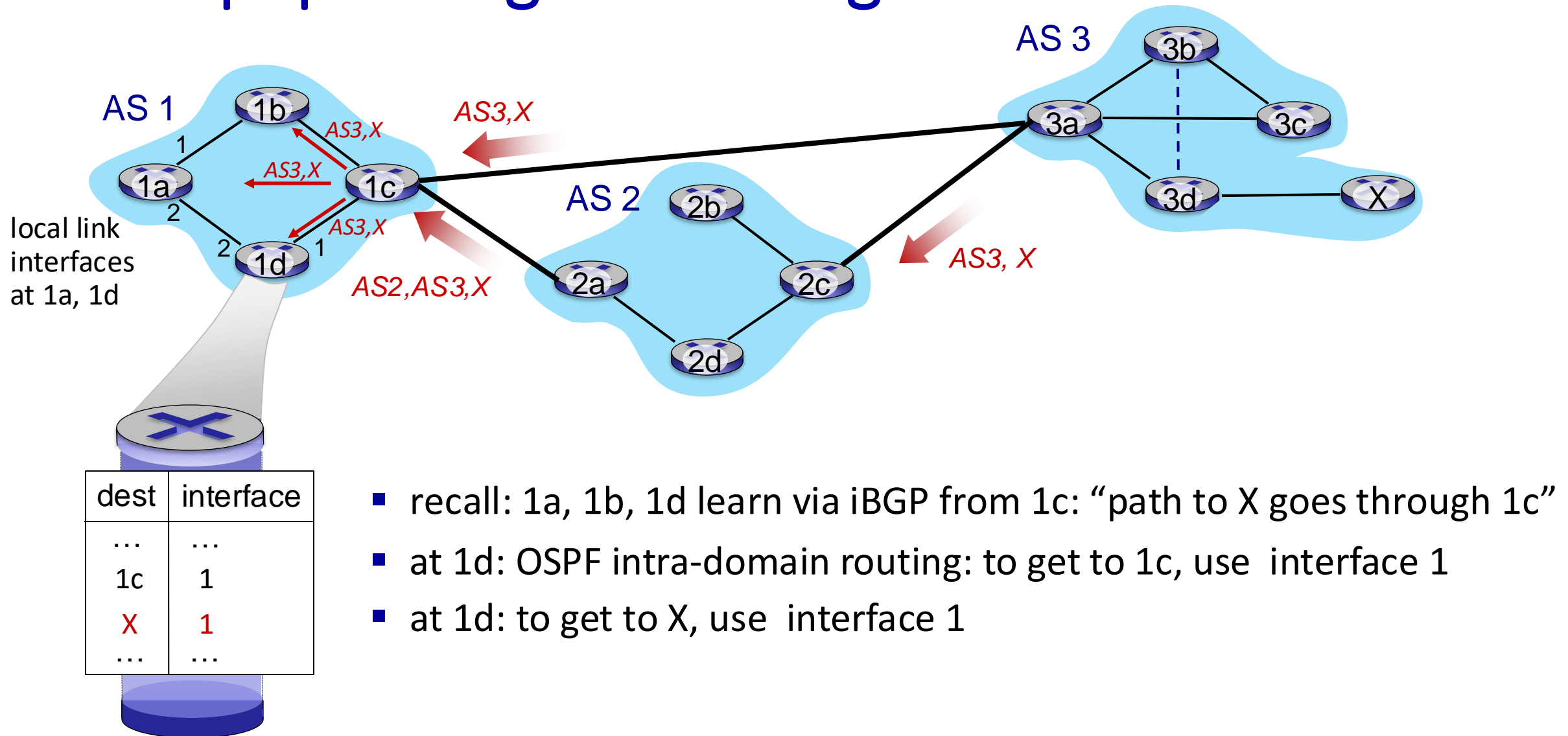
BGP path advertisement: multiple paths



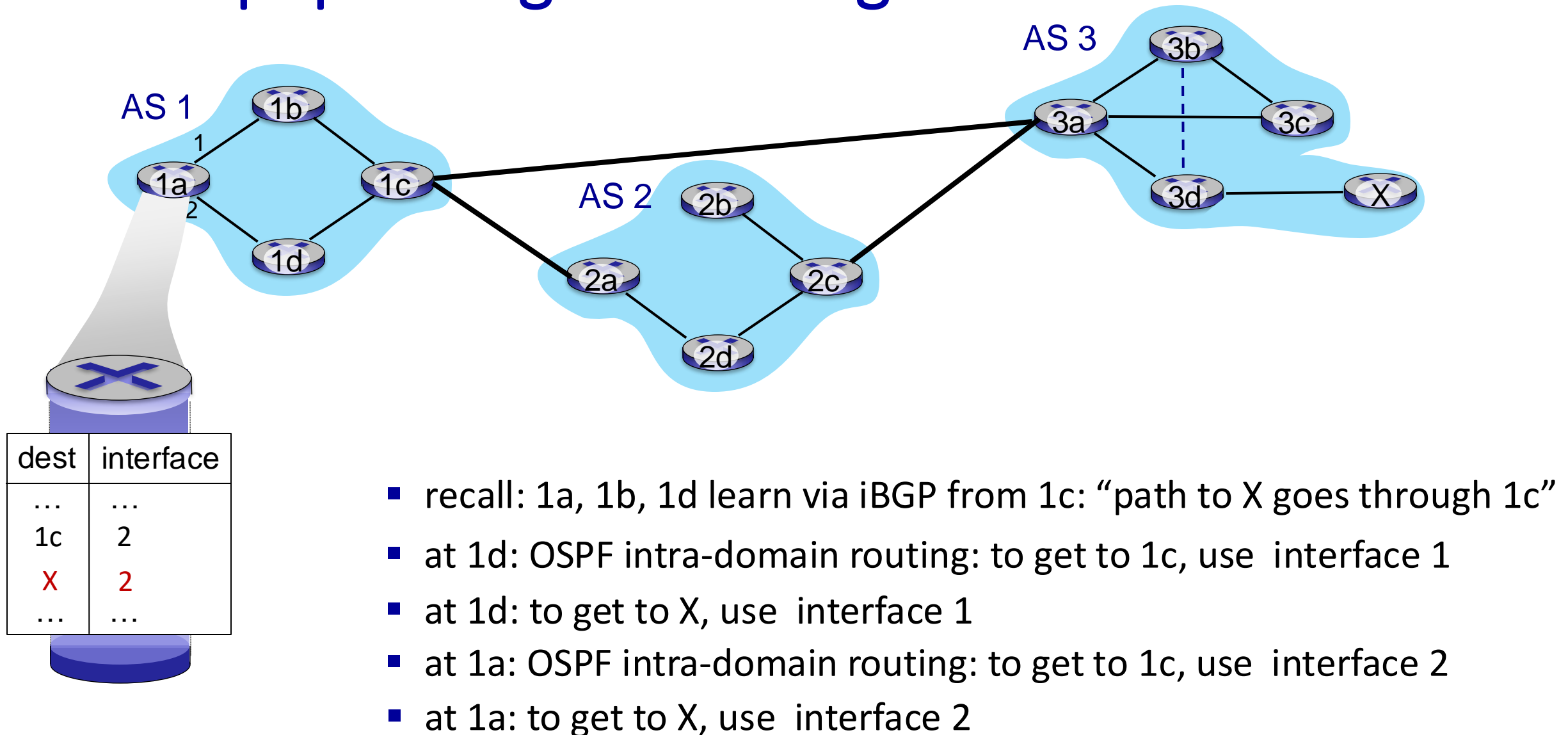
gateway router may learn about **multiple** paths to destination:

- AS1 gateway router 1c learns path **AS2,AS3,X** from 2a
- AS1 gateway router 1c learns path **AS3,X** from 3a
- based on **policy**, AS1 gateway router 1c chooses path **AS3,X** and advertises path within AS1 via iBGP

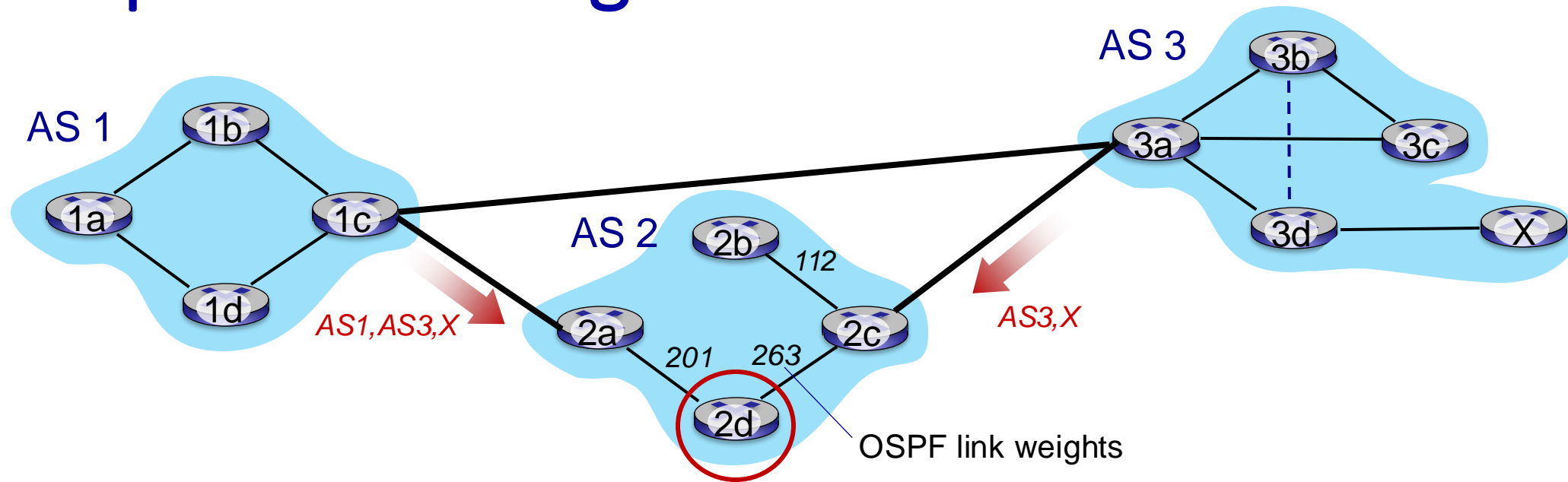
BGP: populating forwarding tables



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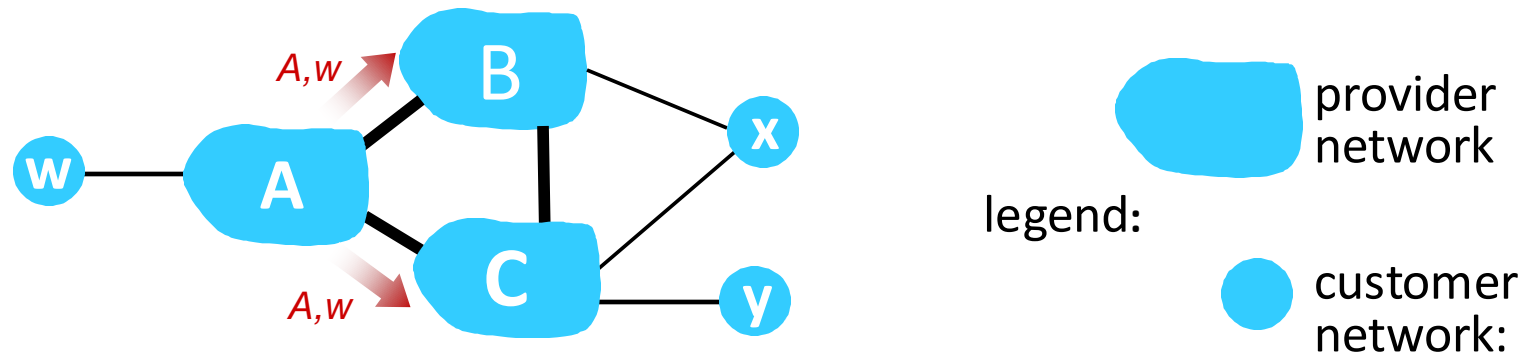


Hot potato routing



- 2d learns (via iBGP) it can route to X via 2a or 2c
- **hot potato routing**: choose local gateway that has least *intra-domain* cost (e.g., 2d chooses 2a, even though more AS hops to X): don't worry about inter-domain cost!

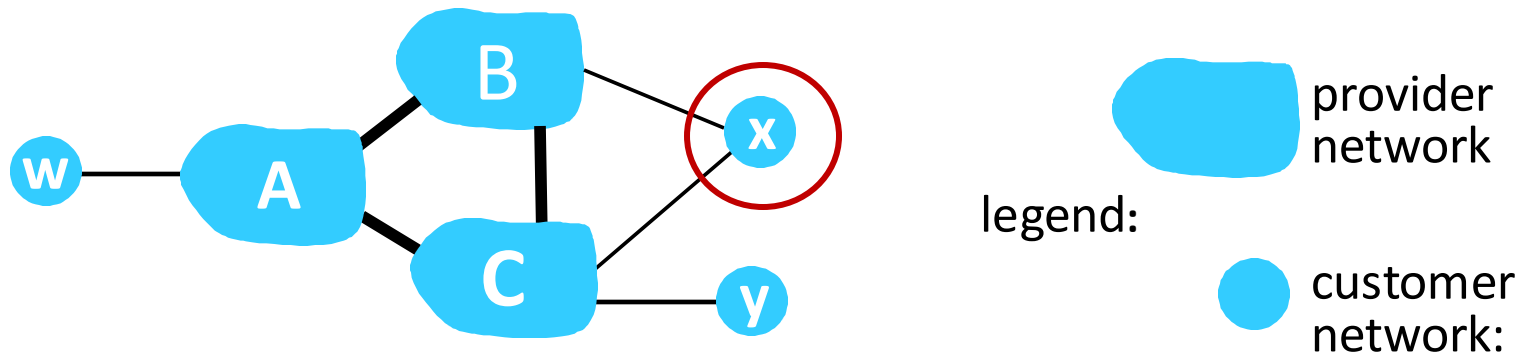
BGP: achieving policy via advertisements



ISP only wants to route traffic to/from its customer networks (does not want to carry transit traffic between other ISPs – a typical “real world” policy)

- A advertises path Aw to B and to C
- B *chooses not to advertise* BAw to C!
 - B gets no “revenue” for routing CBAw, since none of C, A, w are B’s customers
 - C does *not* learn about CBAw path
- C will route CAw (not using B) to get to w

BGP: achieving policy via advertisements (more)



ISP only wants to route traffic to/from its customer networks (does not want to carry transit traffic between other ISPs – a typical “real world” policy)

- A,B,C are **provider networks**
- x,w,y are **customer** (of provider networks)
- x is **dual-homed**: attached to two networks
- **policy to enforce**: x does not want to route from B to C via x
 - .. so x will not advertise to B a route to C

BGP route selection

- router may learn about more than one route to destination AS, selects route based on:
 1. local preference value attribute: policy decision
 2. shortest AS-PATH
 3. closest NEXT-HOP router: hot potato routing
 4. additional criteria

Why different Intra-, Inter-AS routing ?

policy:

- inter-AS: admin wants control over how its traffic routed, who routes through its network
- intra-AS: single admin, so policy less of an issue

scale:

- hierarchical routing saves table size, reduced update traffic

performance:

- intra-AS: can focus on performance
- inter-AS: policy dominates over performance