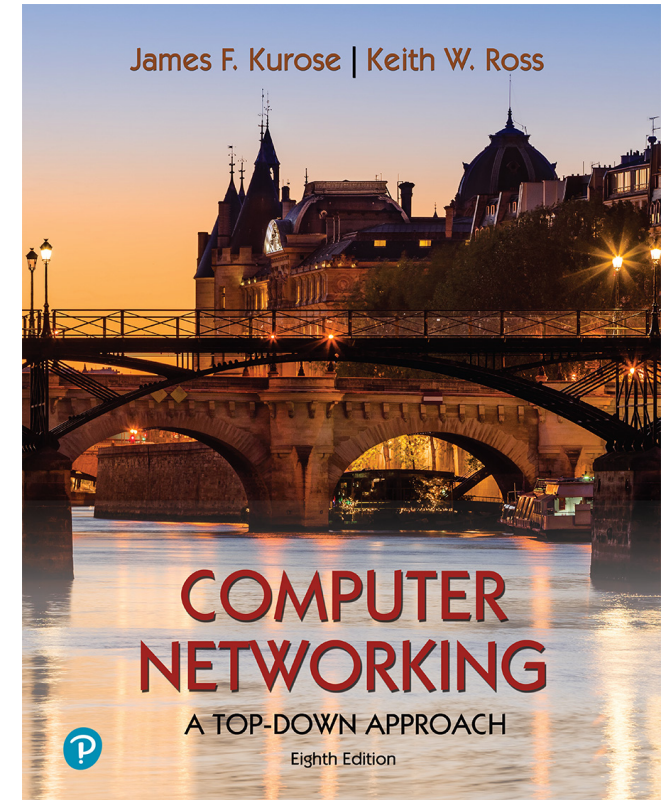


# Chapter 5

## Network Layer: Control Plane



### *Computer Networking: A Top-Down Approach*

8<sup>th</sup> edition

Jim Kurose, Keith Ross  
Pearson, 2020

Acknowledgement: Based on the textbook's website:  
[https://gaia.cs.umass.edu/kurose\\_ross/index.php](https://gaia.cs.umass.edu/kurose_ross/index.php)

# 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

# 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”)

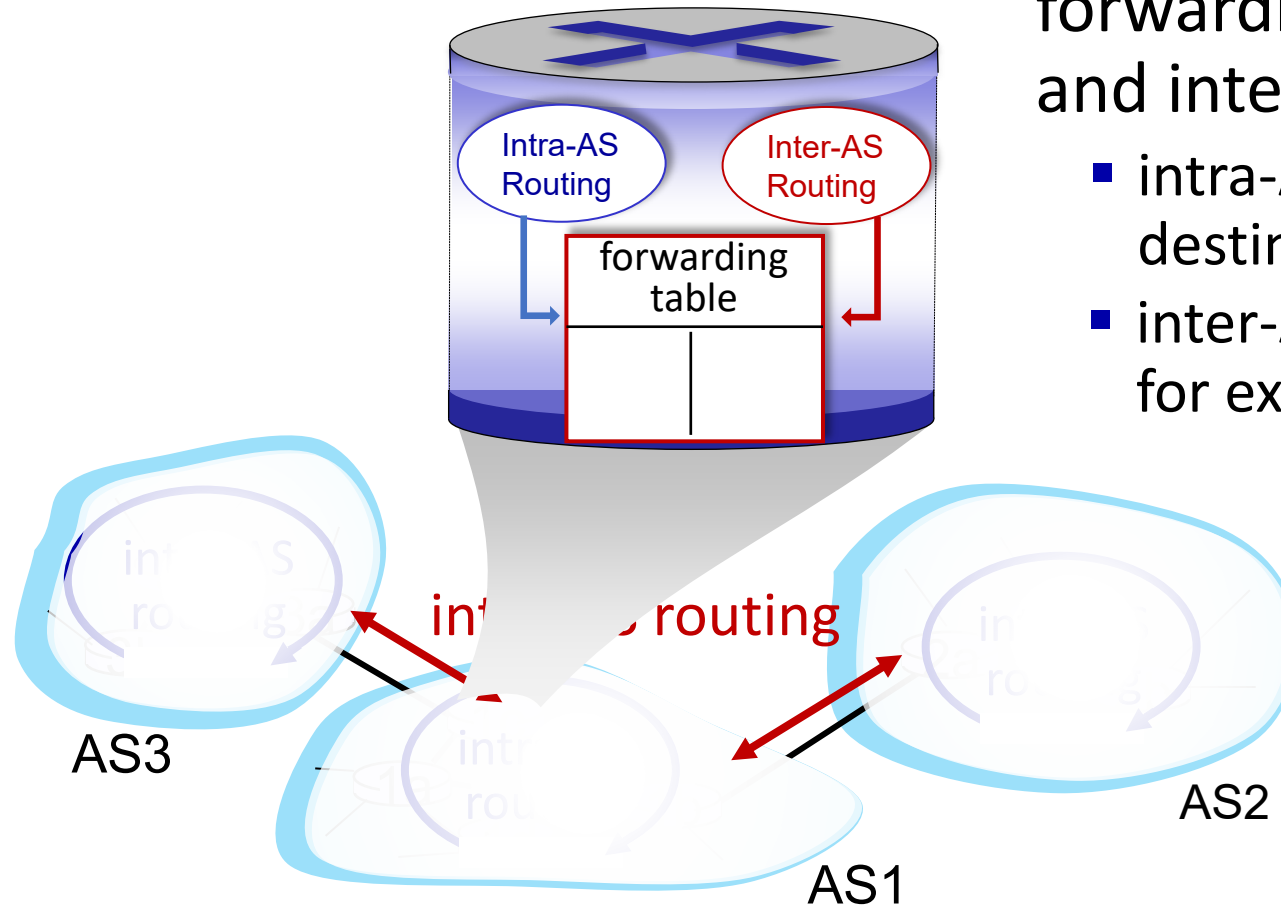
**intra-AS (aka “intra-domain”):**  
routing among routers *within same AS (“network”)*

- 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

**inter-AS (aka “inter-domain”):**  
routing *among* AS'es

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

# 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

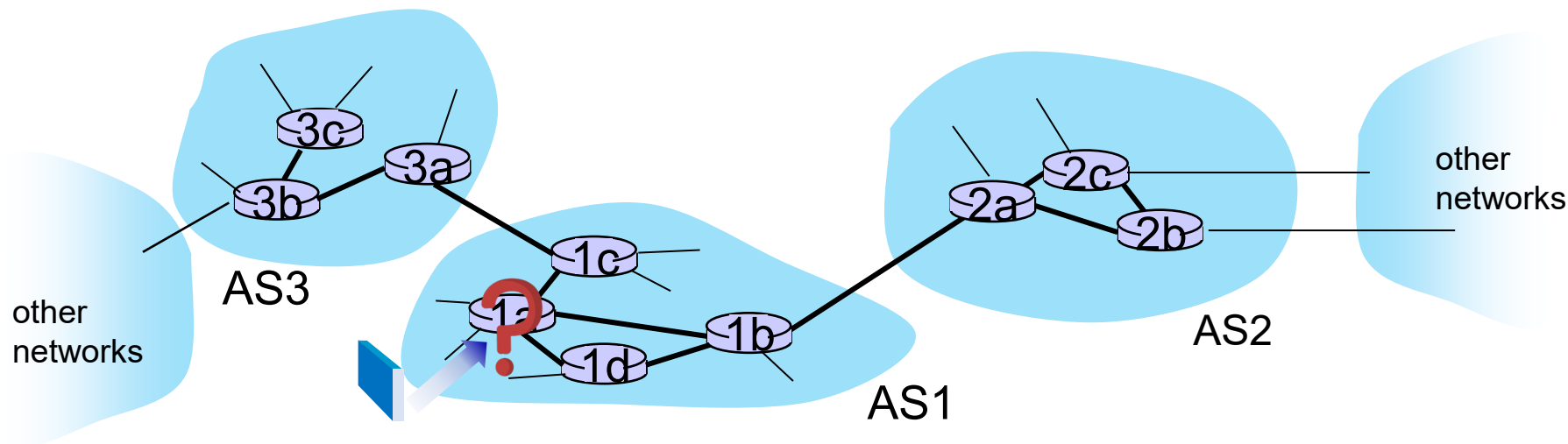
# Inter-AS routing: a role in intradomain forwarding

- suppose router in AS1 receives datagram destined outside of AS1:

? • router should forward packet to gateway router in AS1, but which one?

## AS1 inter-domain routing must:

1. learn which destinations reachable through AS2, which through AS3
2. propagate this reachability info to all routers in AS1



# 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

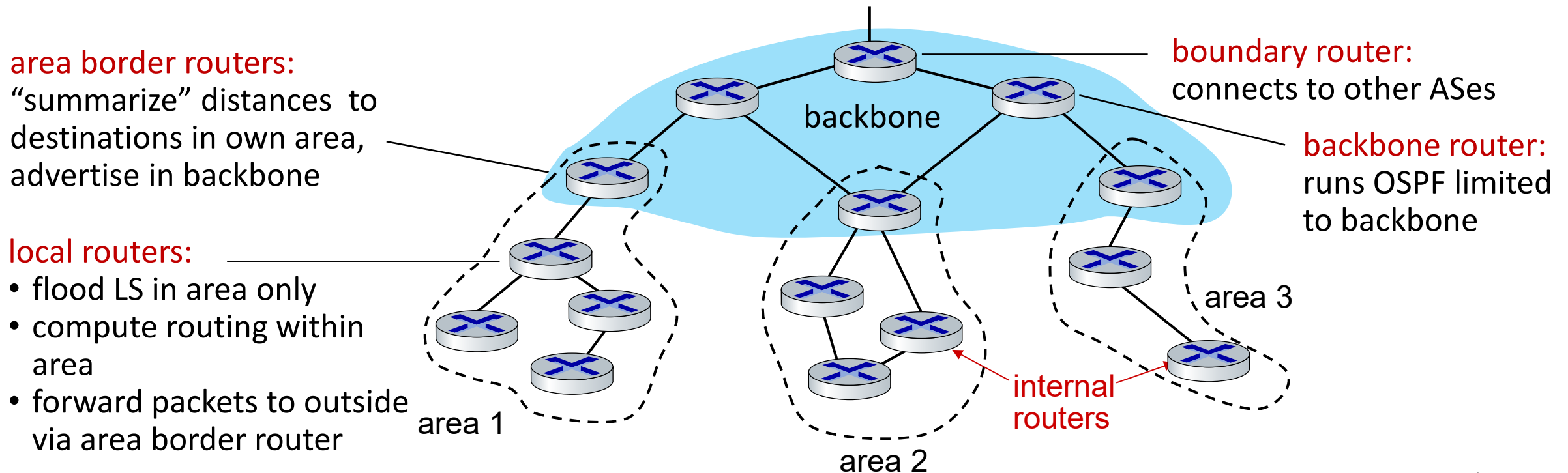
# OSPF (Open Shortest Path First) routing

- “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 algorithm to compute forwarding table
- *security*: all OSPF messages authenticated (to prevent malicious intrusion)



# 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



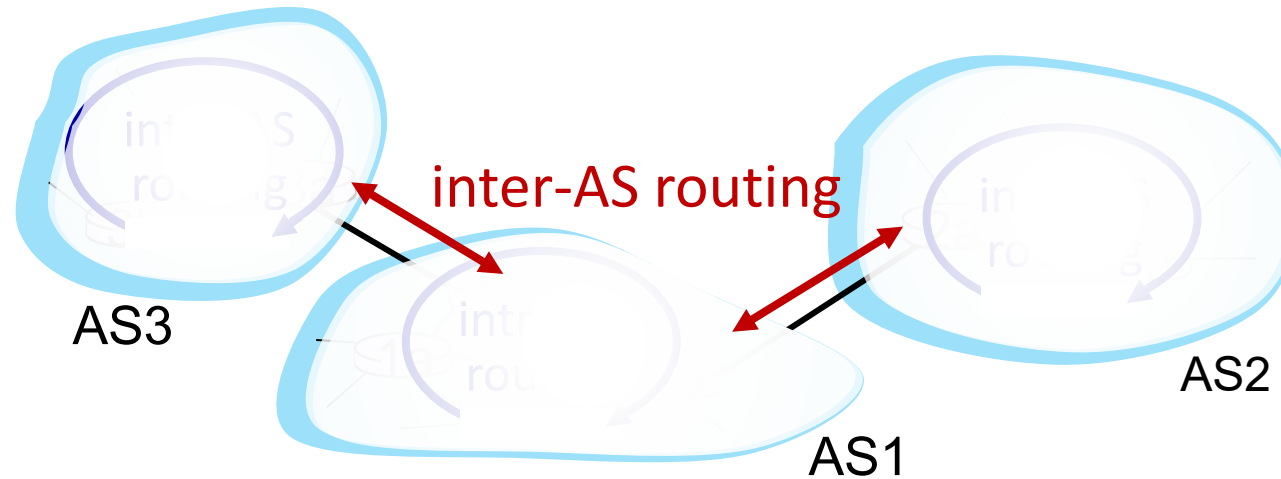
# Network layer: “control plane” roadmap

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# Interconnected ASes

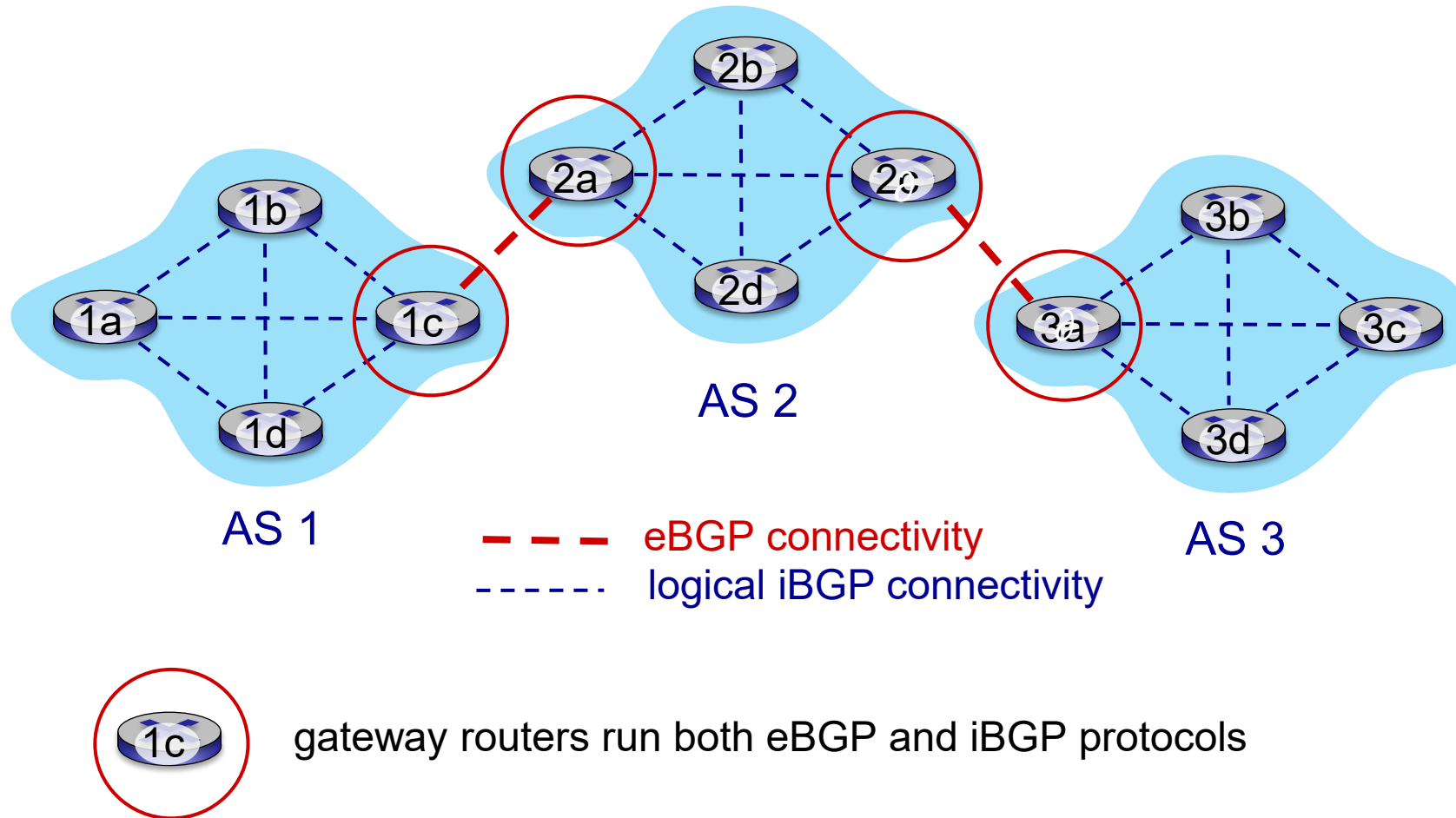


- ✓ **intra-AS (aka “intra-domain”)**: routing among routers *within same* AS (“*network*”)
- ➡ **inter-AS (aka “inter-domain”)**: routing *among* AS'es

# Internet inter-AS routing: BGP

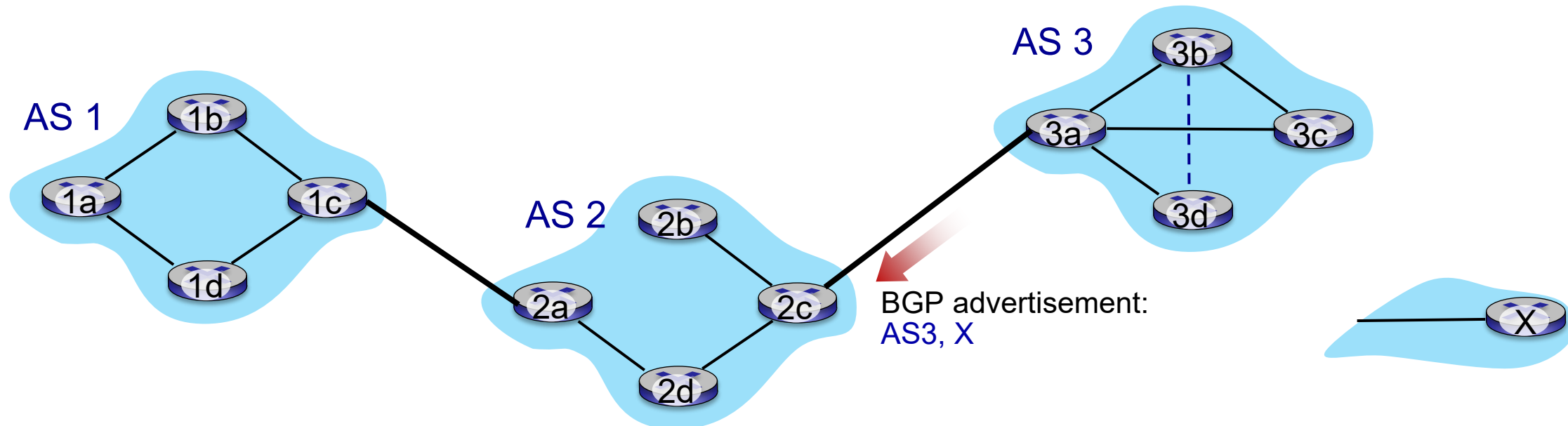
- **BGP (Border Gateway Protocol)**: *the* de facto inter-domain routing protocol
  - “glue that holds the Internet together”
- allows subnet to advertise its existence, and the destinations it can reach, to rest of Internet: *“I am here, here is who I can reach, and how”*
- BGP provides each AS a means 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



# BGP protocol messages

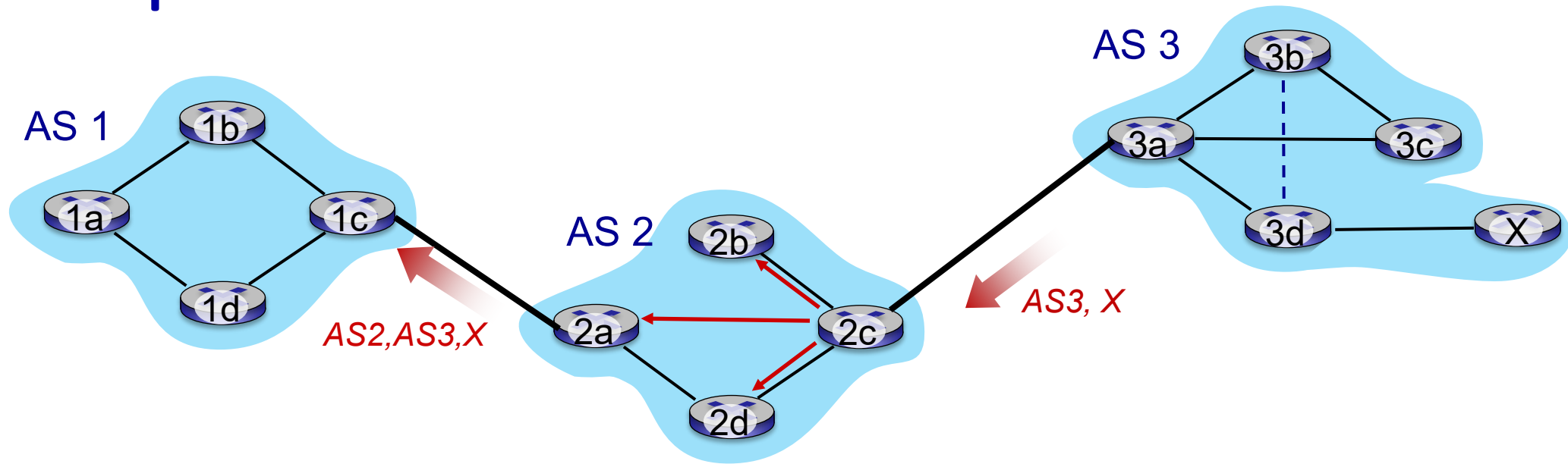
- BGP messages exchanged between peers over TCP connection
- BGP messages [RFC 4371]:
  - **OPEN**: opens TCP connection to remote BGP peer and authenticates sending BGP peer
  - **UPDATE**: advertises new path (or withdraws old)
  - **KEEPALIVE**: keeps connection alive in absence of UPDATES; also ACKs OPEN request
  - **NOTIFICATION**: reports errors in previous msg; also used to close connection

# 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

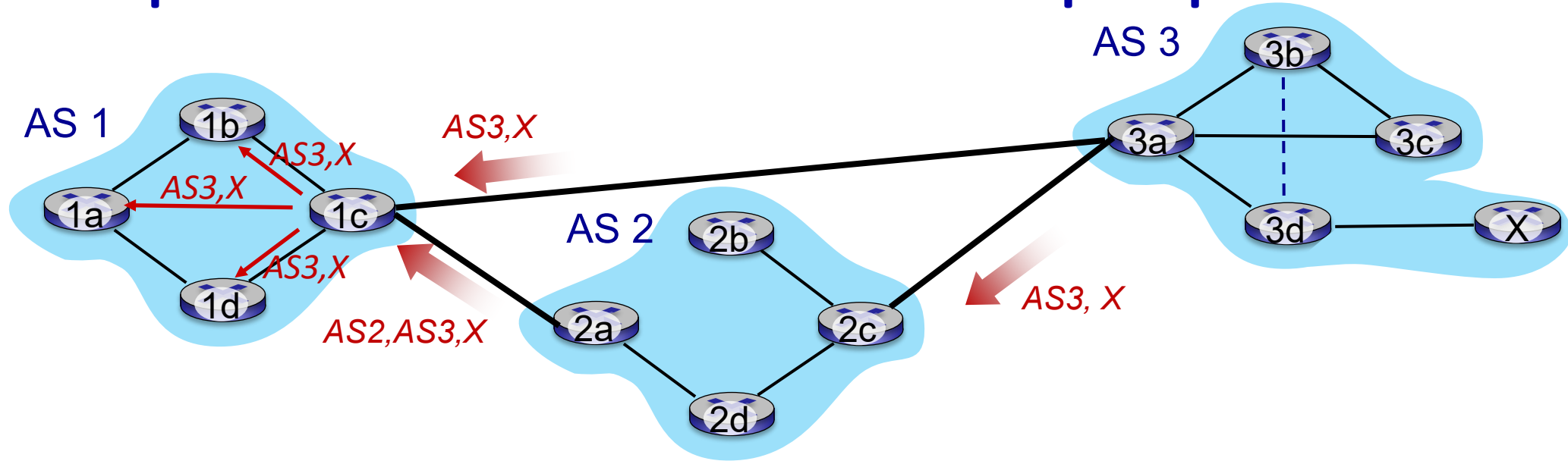


# BGP path advertisement



- 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

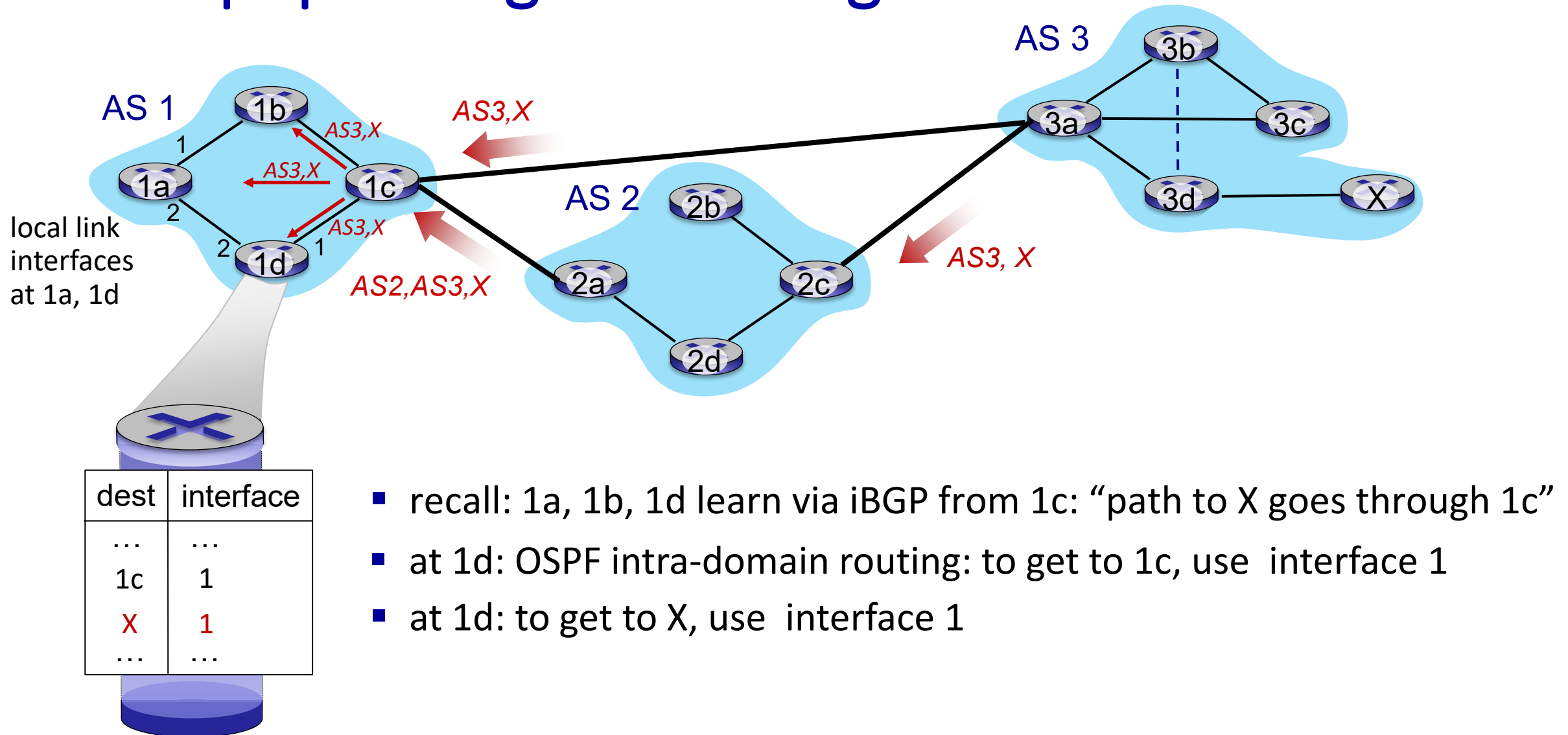
# BGP path advertisement: multiple paths



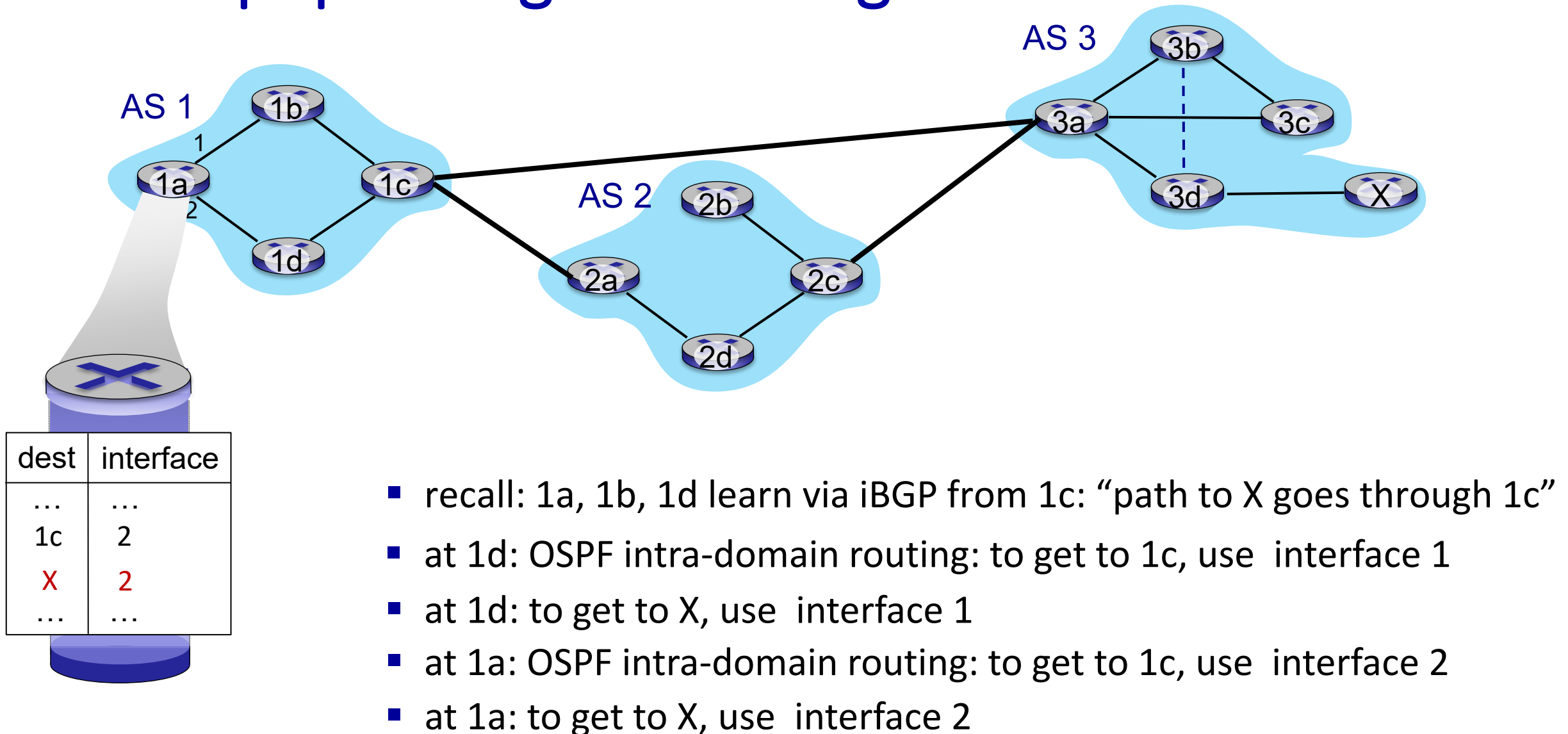
gateway router may learn about **multiple** paths to destination:

- 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

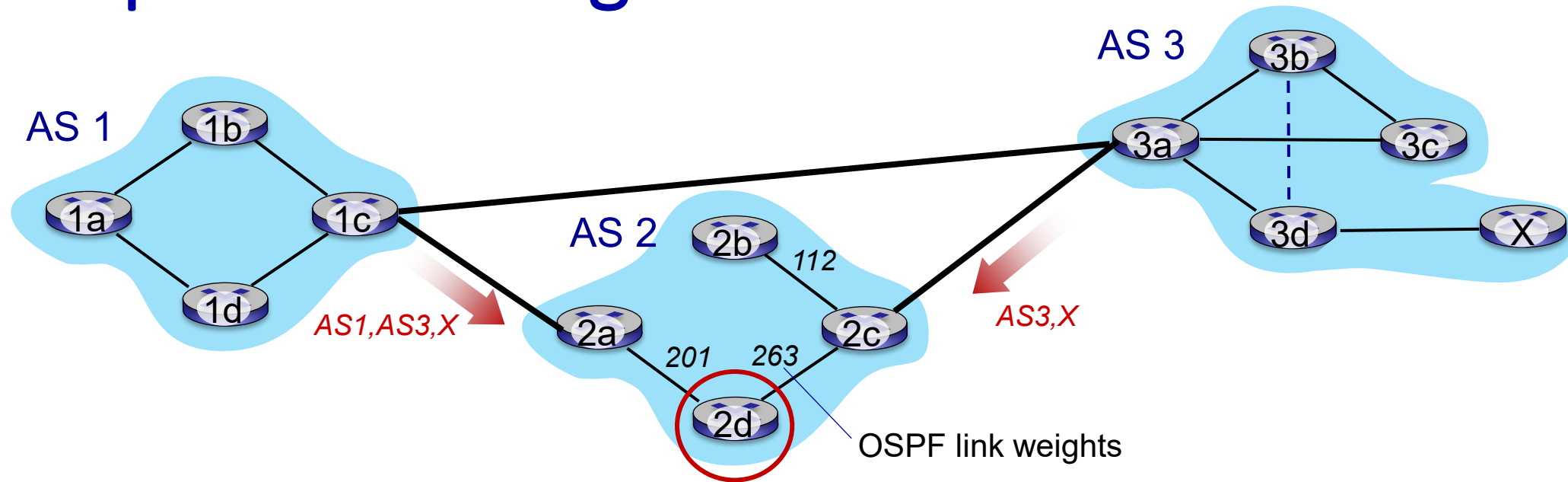
# BGP: populating forwarding tables



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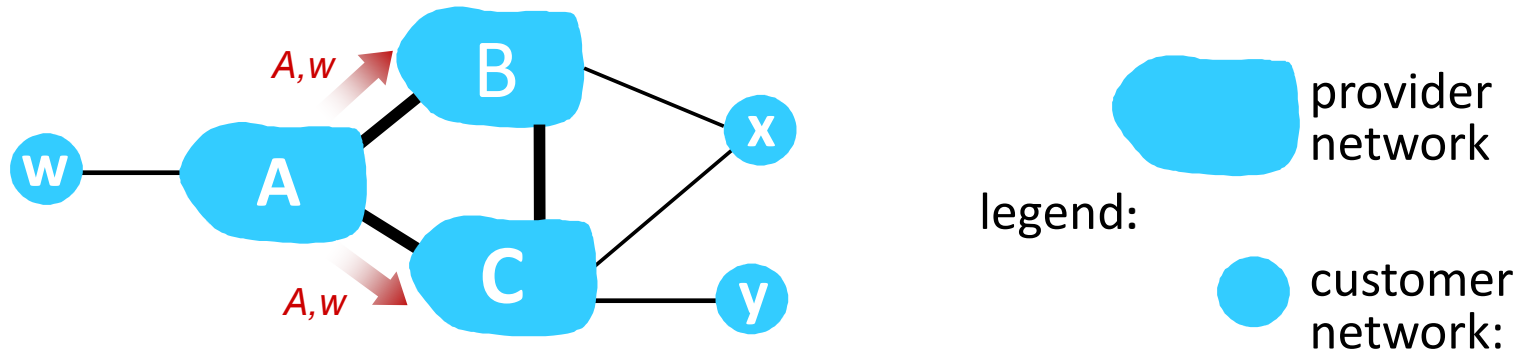


# Hot potato routing



- 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!

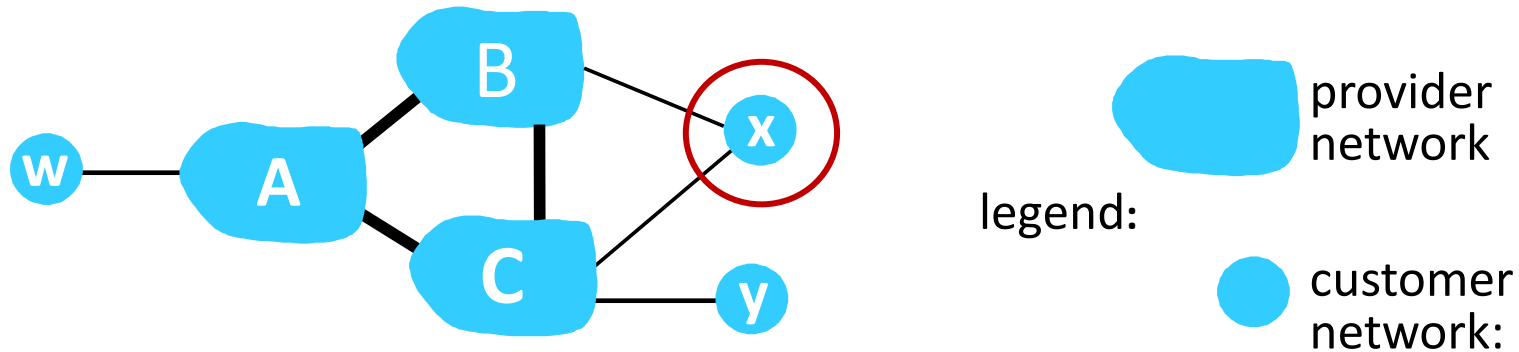
# BGP: achieving policy via advertisements



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* BA<sub>w</sub> to C!
  - B gets no “revenue” for routing CBA<sub>w</sub>, since none of C, A, w are B’s customers
  - C does *not* learn about CBA<sub>w</sub> path
- C will route CA<sub>w</sub> (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