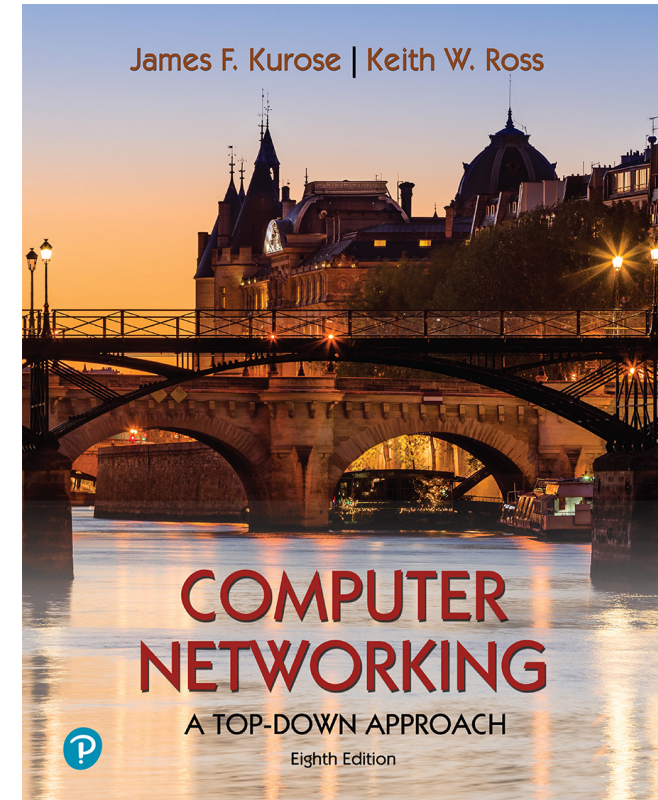# Chapter 5
Network Layer: Control Plane

Computer Networking: A Top-Down Approach

8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Acknowledgement: Based on the textbook's website:
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
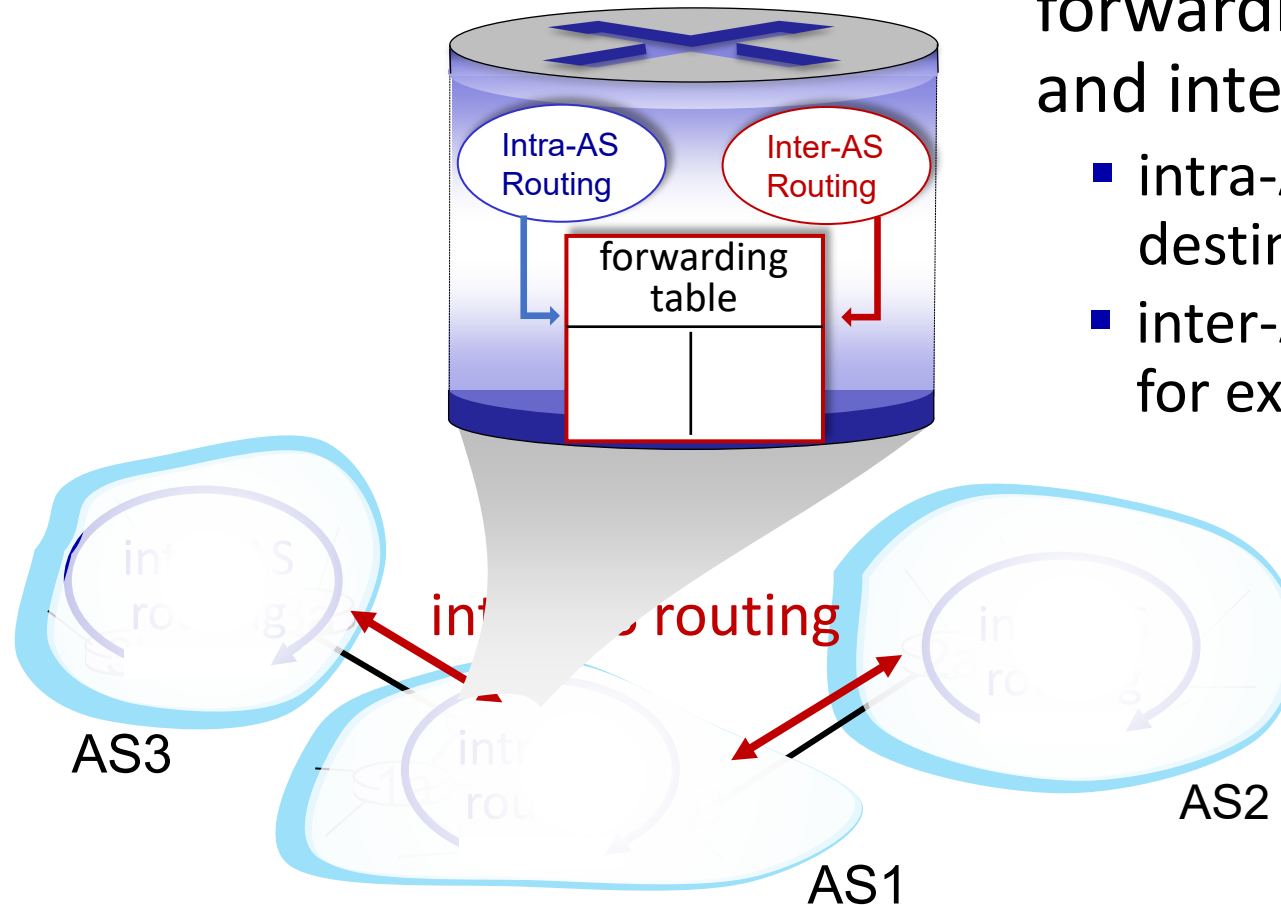
forwarding table configured by intra- and inter-AS routing algorithms

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

Inter-AS routing plays 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
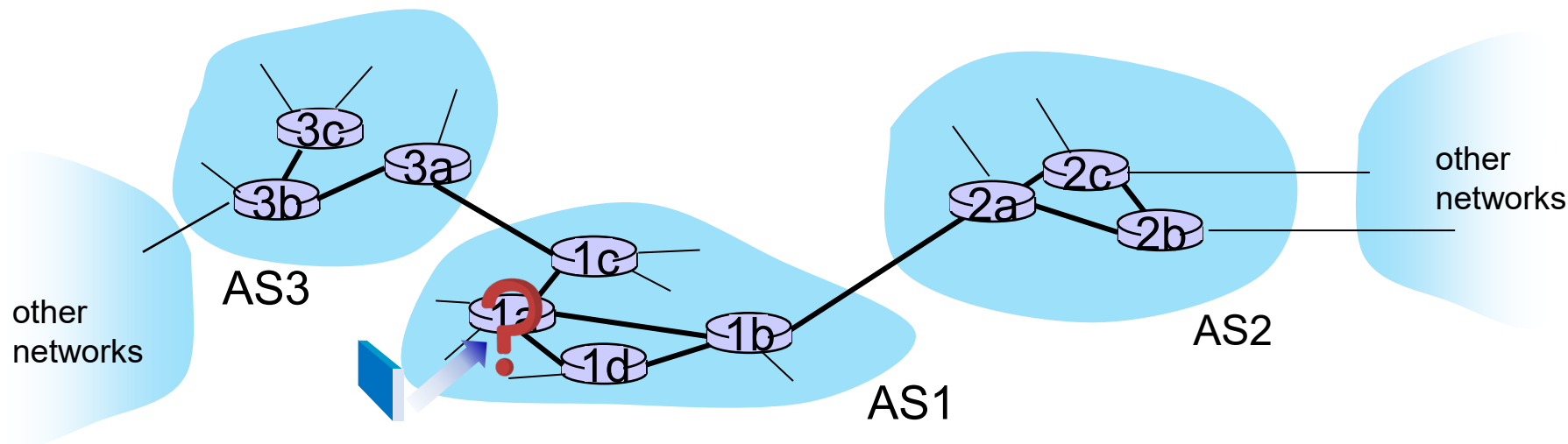
Intra-AS routing: routing within an AS

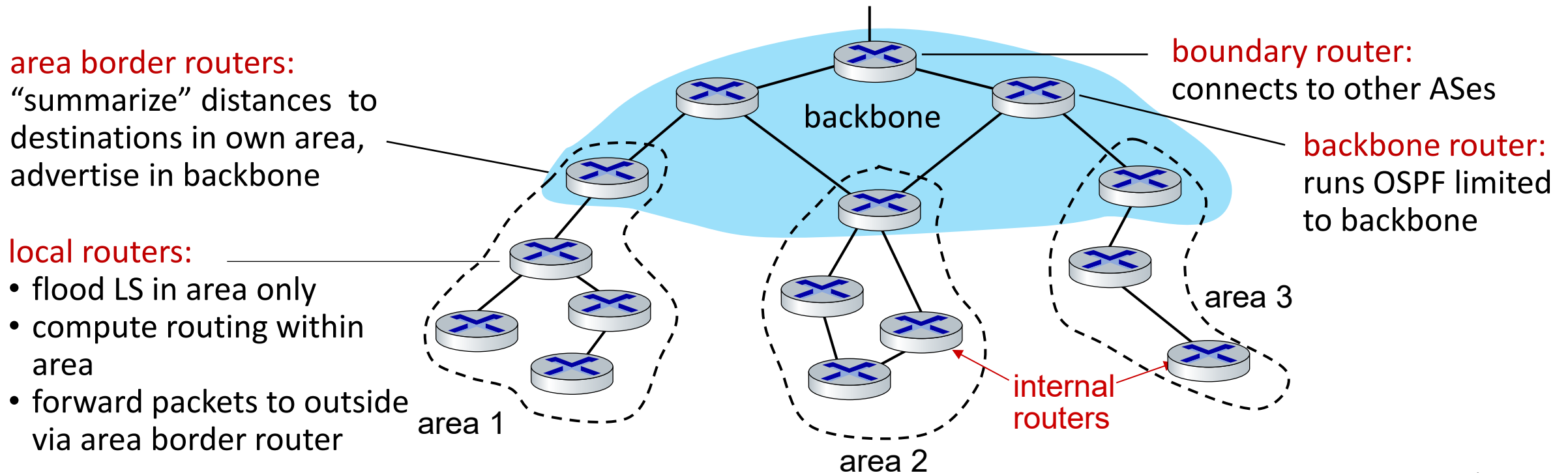most common intra-AS routing protocols:

- **RIP: Routing Information Protocol** [RFC 1723]
  - classic Distance Vector: 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

area border routers:
"summarize" distances to destinations in own area, advertise in backbone

local routers:
- flood LS in area only
- compute routing within area
- forward packets to outside via area border router

boundary router:
connects to other ASes

backbone router:
runs OSPF limited to backbone

backbone

area 1

area 2

area 3

internal routers

Network layer: "control plane" roadmap

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- **routing among ISPs: BGP**
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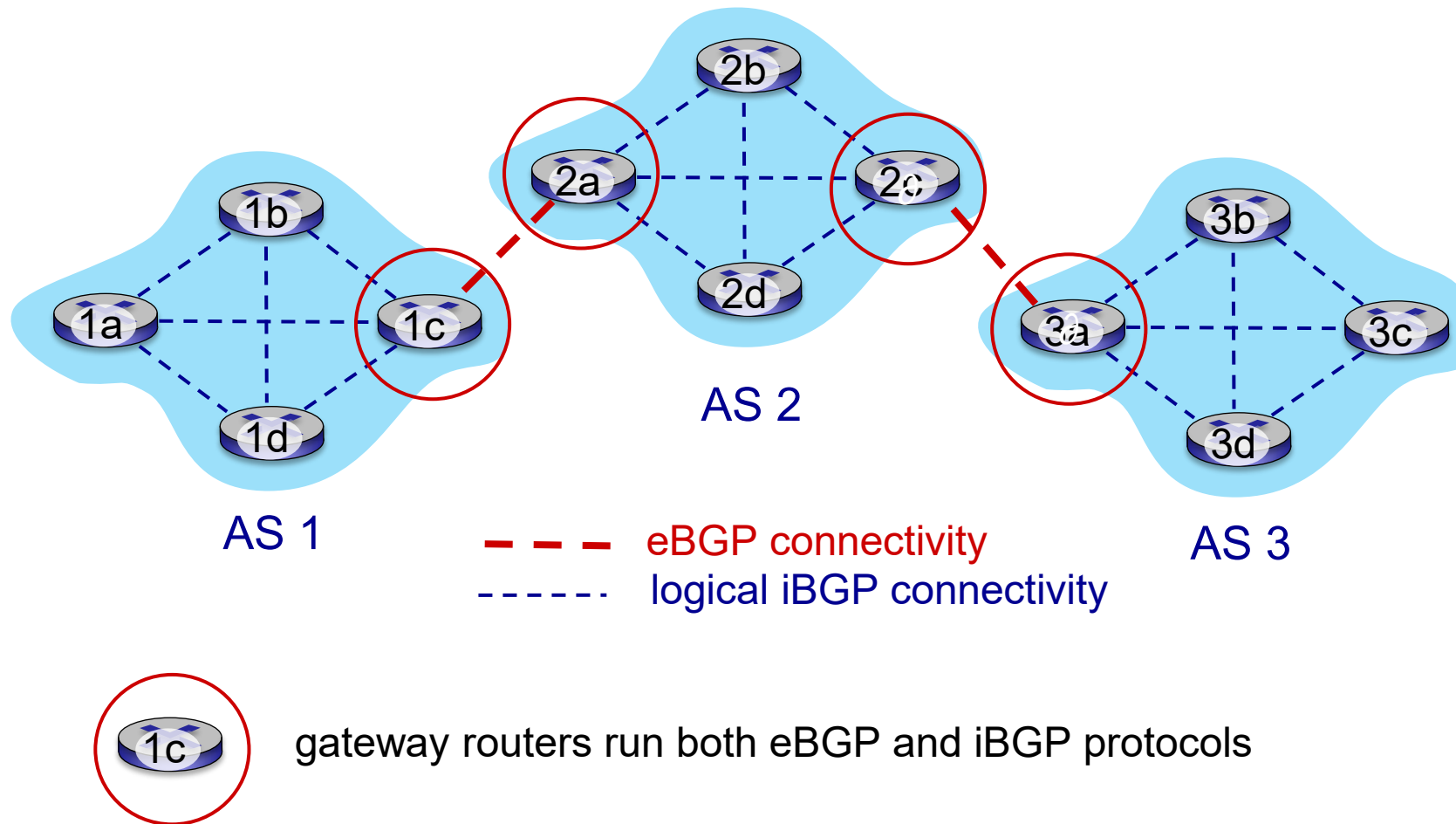 - SNMP
  - NETCONF/YANG

Interconnected ASes
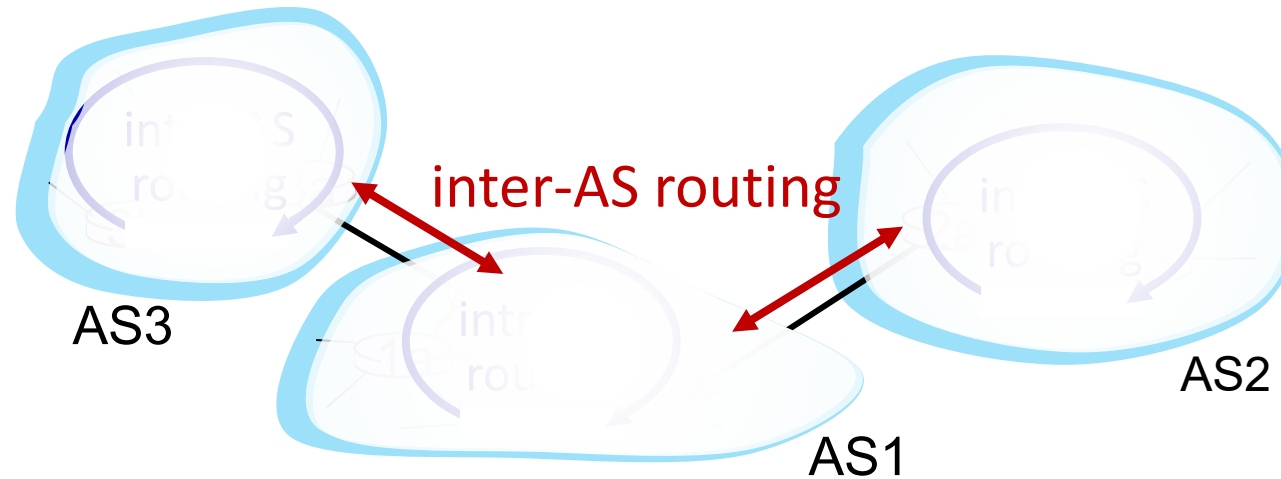
✅ **intra-AS** (aka "intra-domain"): routing among routers *within same AS ("network")*

➡ **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
  - Neither Distance Vector nor Link-State. It is a "Path-Vector" protocol
- allows AS 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

AS 2

AS 1

— — — eBGP connectivity

- - - - - logical iBGP connectivity

AS 3

gateway routers run both eBGP and iBGP protocols

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 advertisement:
AS3, X
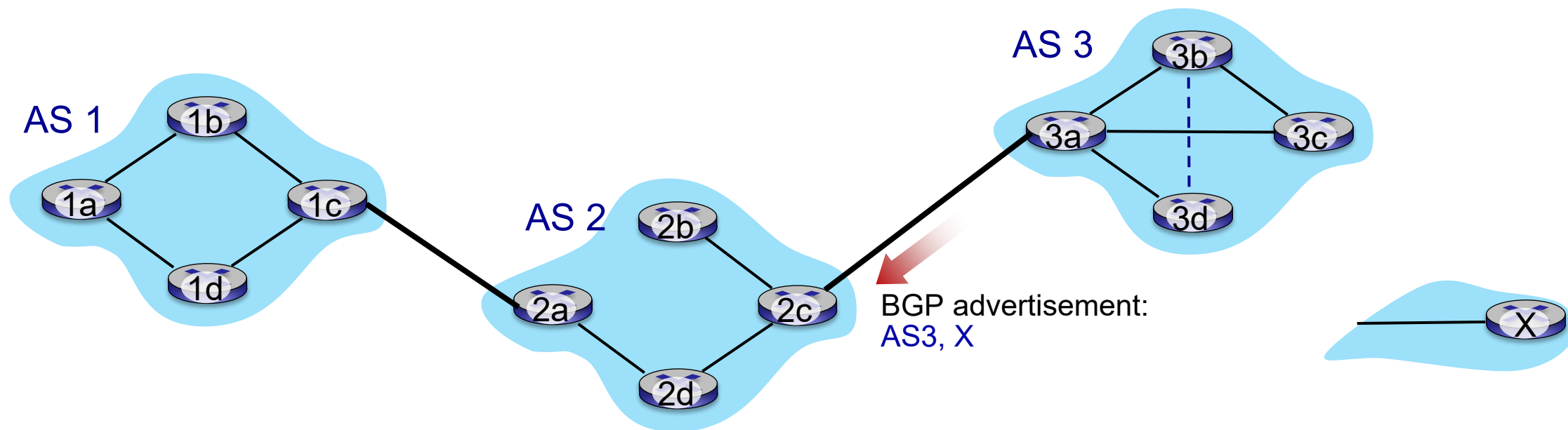
Path attributes and BGP routes

- 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 other neighboring ASes

BGP path advertisement
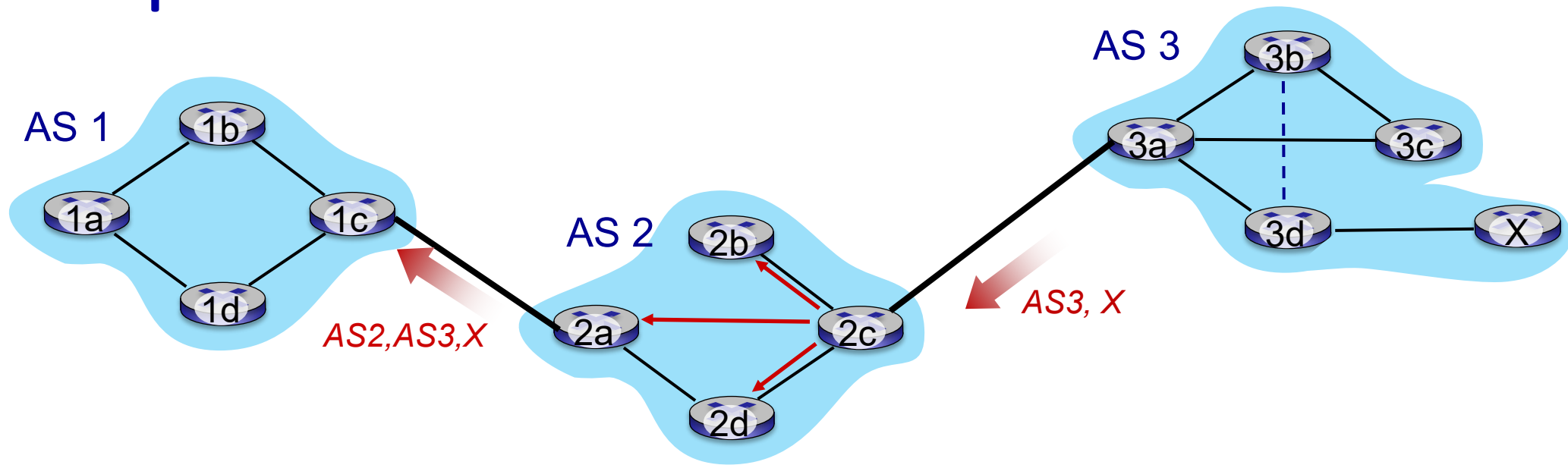
- AS2 router 2c receives path advertisement AS3,X (via eBGP) from AS3 router 3a

- based on AS2 policy, AS2 router 2c accepts path AS3,X, propagates (via iBGP) to all AS2 routers

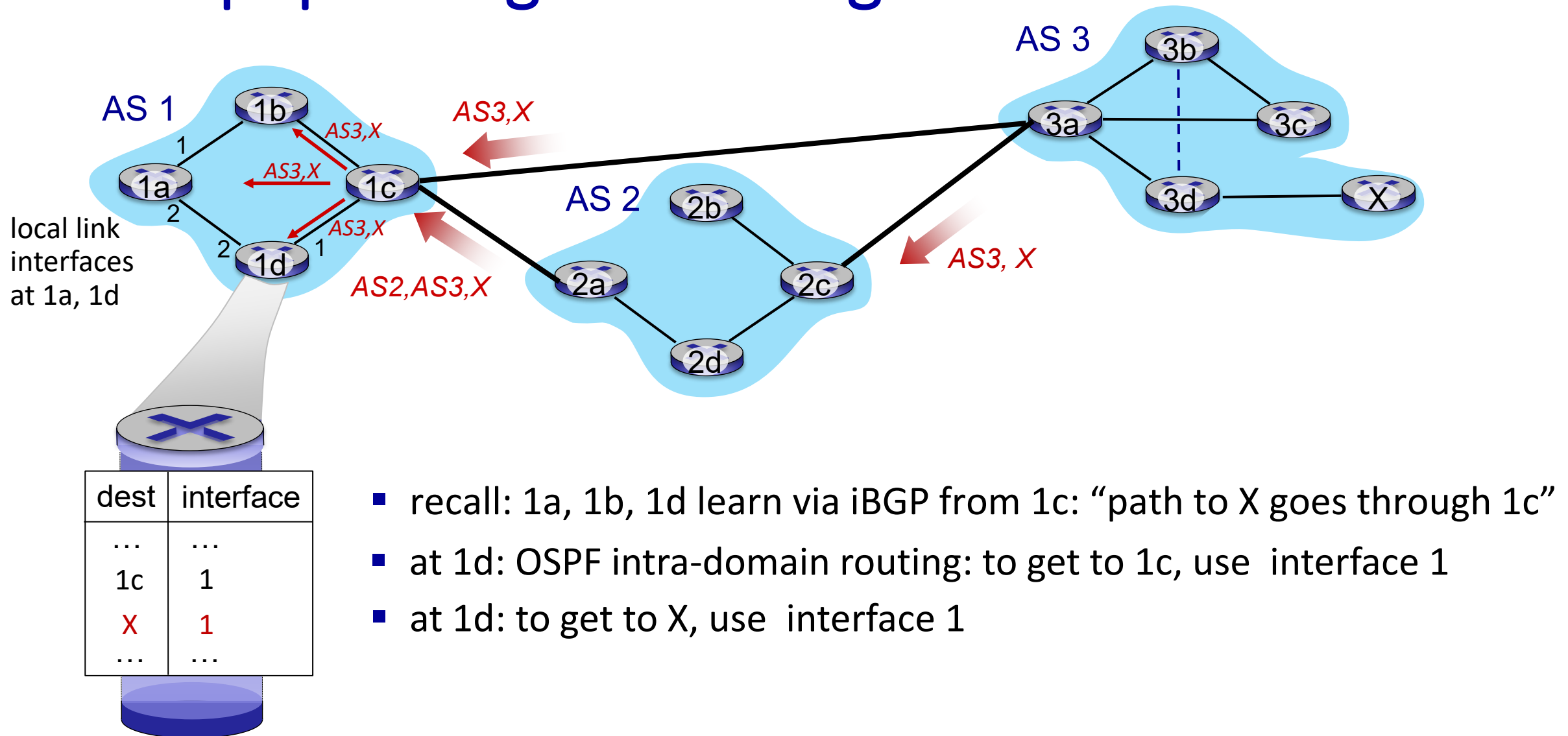- based on AS2 policy, AS2 router 2a advertises (via eBGP) path AS2, AS3, X   to AS1 router 1c

BGP path advertisement: multiple paths
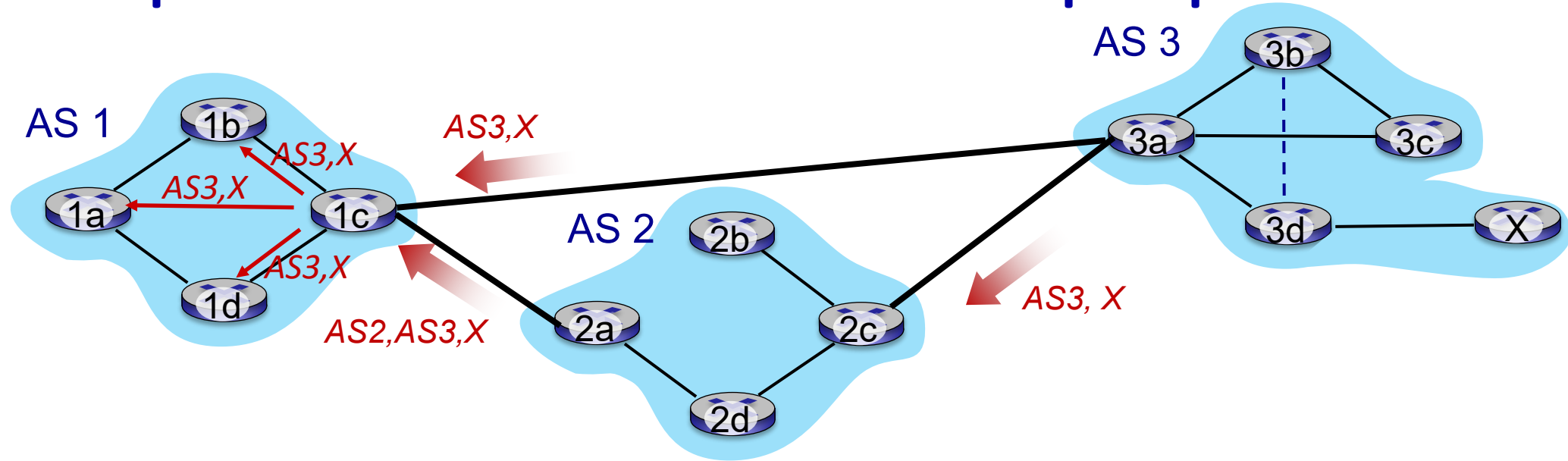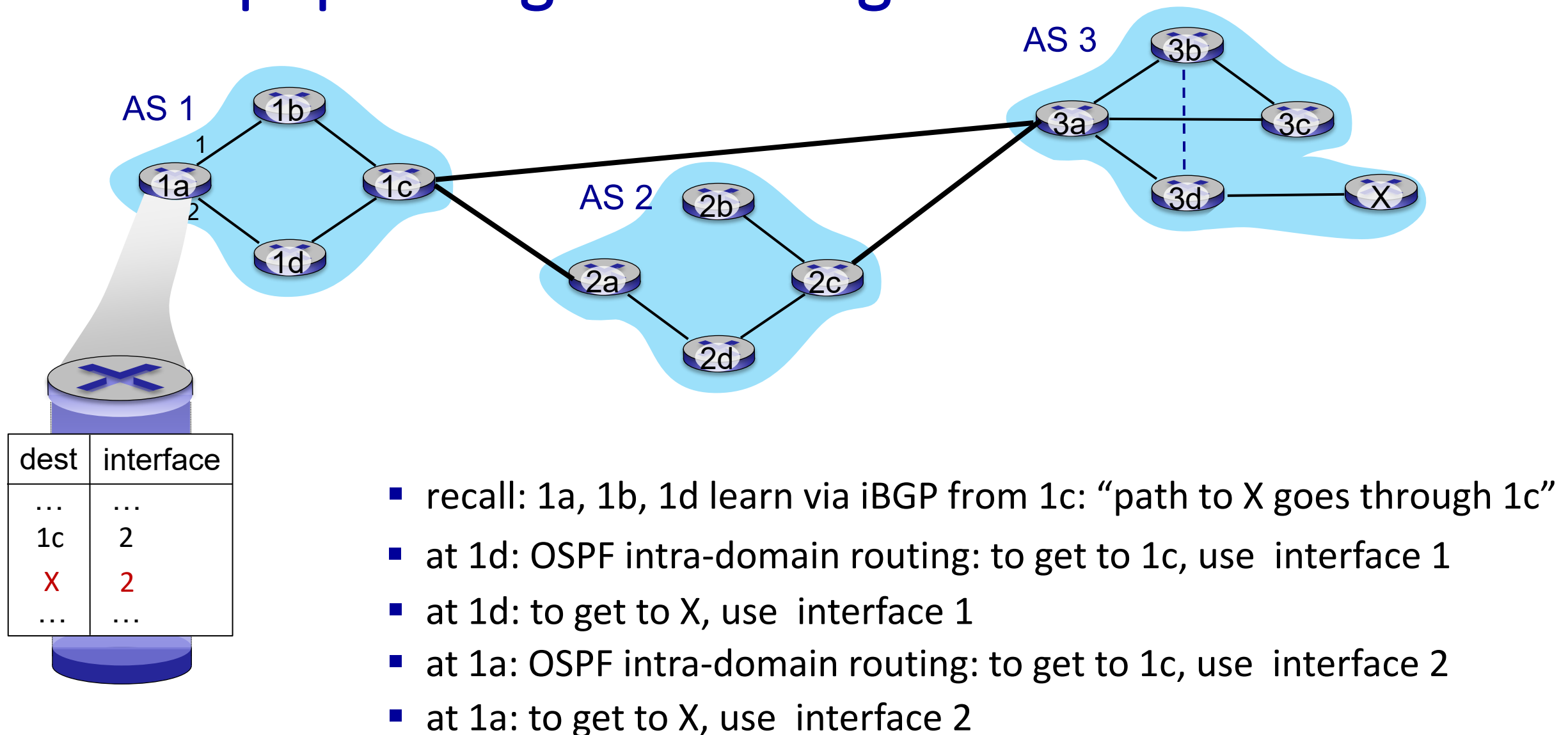

gateway router may learn about multiple paths to destination:

- 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

AS 3

AS 1

AS3,X

AS3,X

AS3,X

AS3,X

AS 2

AS3, X

AS2,AS3,X

local link
interfaces
at 1a, 1d

dest	interface
...	...
1c	1
X	1
...	...

- recall: 1a, 1b, 1d learn via iBGP from 1c: "path to X goes through 1c"
- at 1d: OSPF intra-domain routing: to get to 1c, use interface 1
- at 1d: to get to X, use interface 1

BGP: populating forwarding tables

AS 3

AS 1

AS 2

dest	interface
...	...
1c	2
X	2
...	...

- recall: 1a, 1b, 1d learn via iBGP from 1c: "path to X goes through 1c"
- at 1d: OSPF intra-domain routing: to get to 1c, use interface 1
- at 1d: to get to X, use interface 1
- at 1a: OSPF intra-domain routing: to get to 1c, use interface 2
- at 1a: to get to X, use interface 2

Hot potato routing

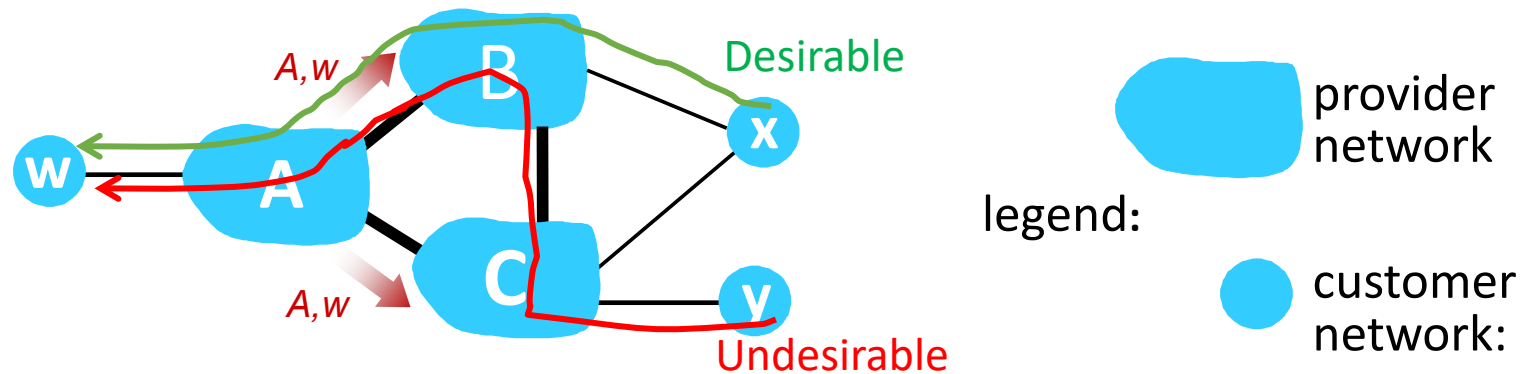AS 1

AS 2

AS 3

AS1,AS3,X

AS3,X

112

201   *263*

OSPF link weights

- 2d learns (via iBGP) it can route to X via 2a or 2c

- hot potato routing: OSPF chooses local gateway that has least *intra-domain* cost (e.g., 2d chooses 2a, even though more AS hops to *X*): intra-domain routing unaware of inter-domain cost

BGP: achieving policy via advertisements

A,w

B

Desirable

x

w

A

legend:

provider
network

A,w

C

y

Undesirable

customer
network:

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 their customers

- x is B's customer; y is C's customer. B wants to route traffic from x but not from y.

- A advertises path Aw to B and to C

- B *chooses not to advertise* BAw to C!

  - B gets no "revenue" for routing CBAw (red path), since none of C, A, w are B's customers

- C does *not* learn about CBAw path, so C will route CAw (not using B) to get to w

BGP: achieving policy via advertisements (more)
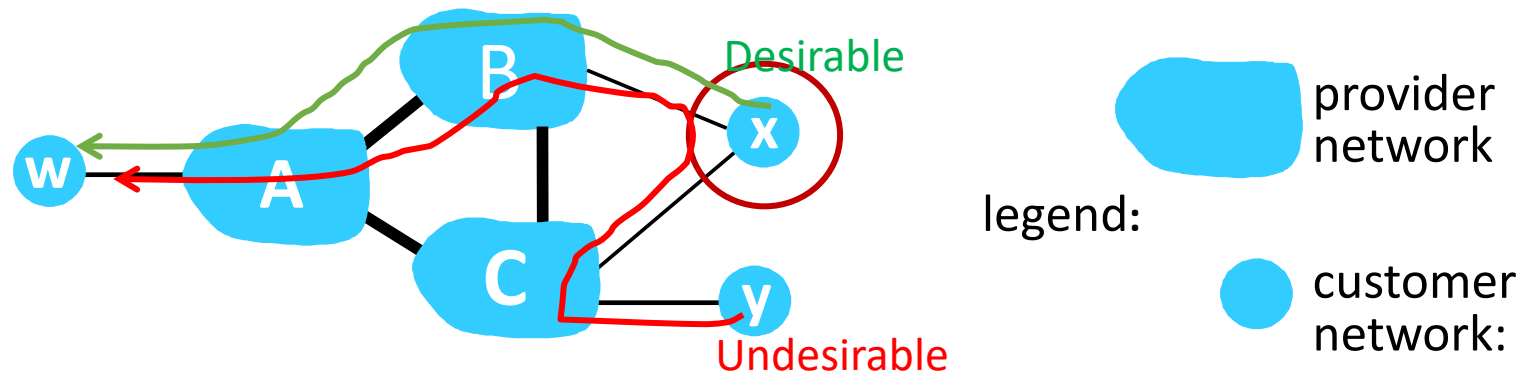
legend:

provider network

customer network:

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)

- x is dual-homed: attached to two networks
- *policy to enforce:* x does not want to route from B to C via x (red path) since it gets no "revenue" for this route
  - .. 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