Chapter 5
Network Layer: The Control Plane

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12 May 2019

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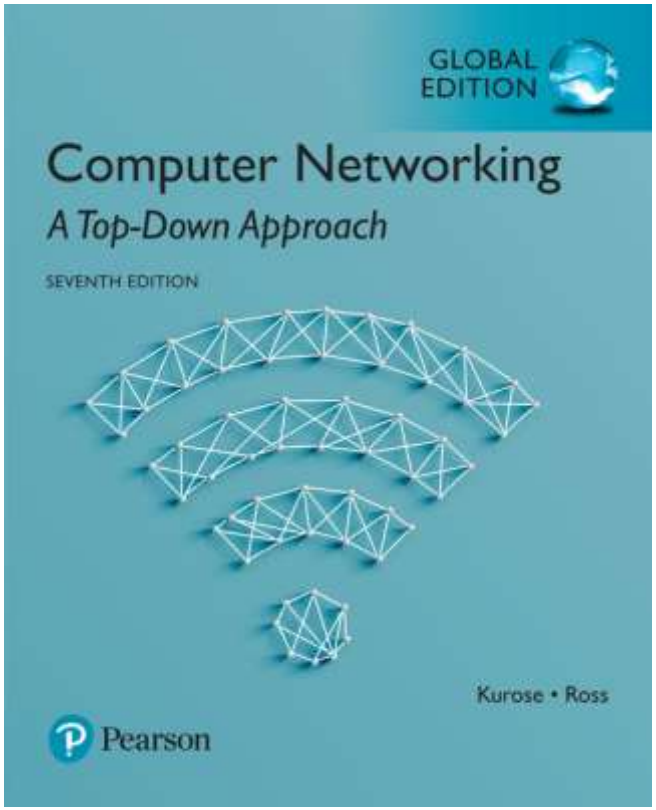


Computer Networking: A Top Down Approach

7th edition
Jim Kurose, Keith Ross
Pearson/Addison Wesley
April 2016

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

~~5.5 The SDN control plane~~

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Making routing scalable

our routing study thus far - idealized 'graph'

- all routers identical
- network "flat"

… *not* true in practice

scale: with billions of destinations:

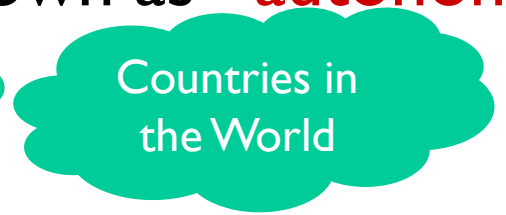
- can't store all destinations in routing tables!
- routing table exchange would swamp links!

administrative autonomy

- internet = 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")



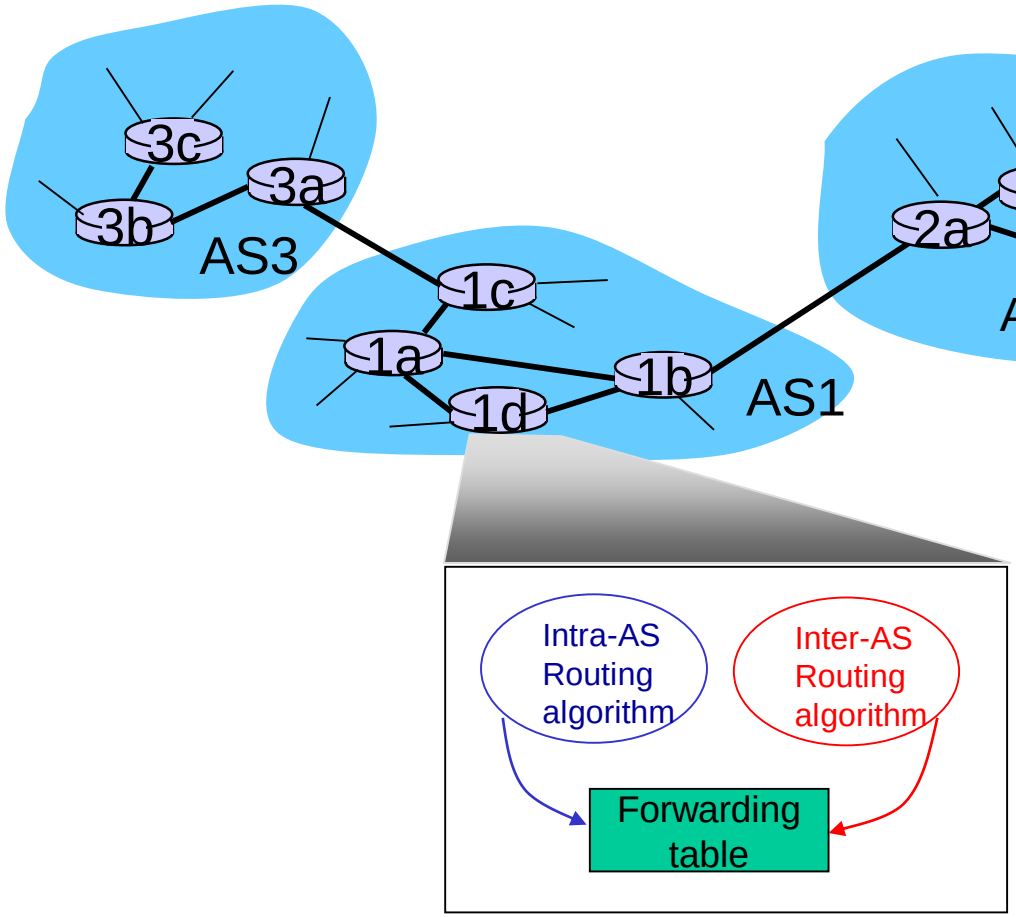
intra-AS routing

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

inter-AS routing

- routing among AS'es
- gateways perform inter-domain routing (as well as intra-domain routing)

Interconnected ASes



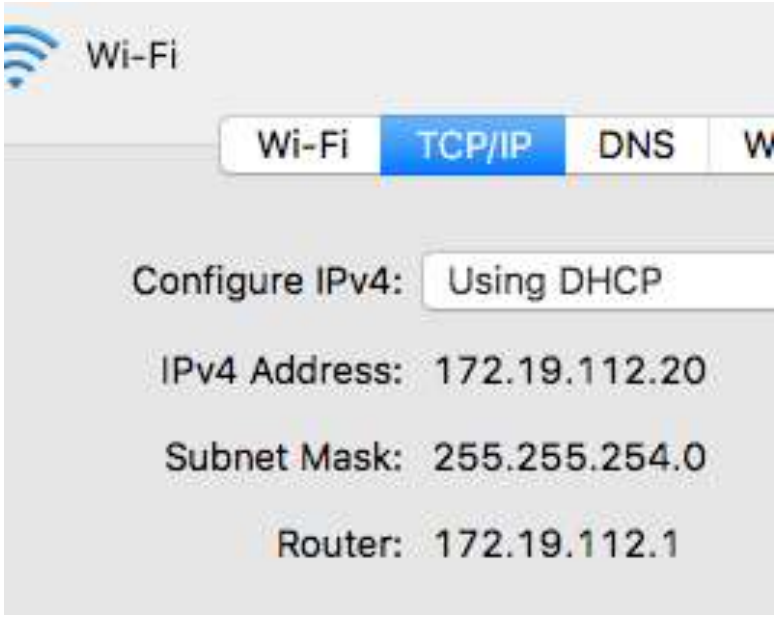
- forwarding table configured by both intra- and inter-AS routing algorithm
  - intra-AS routing determine entries for destinations within AS
  - inter-AS & intra-AS determine entries for external destinations

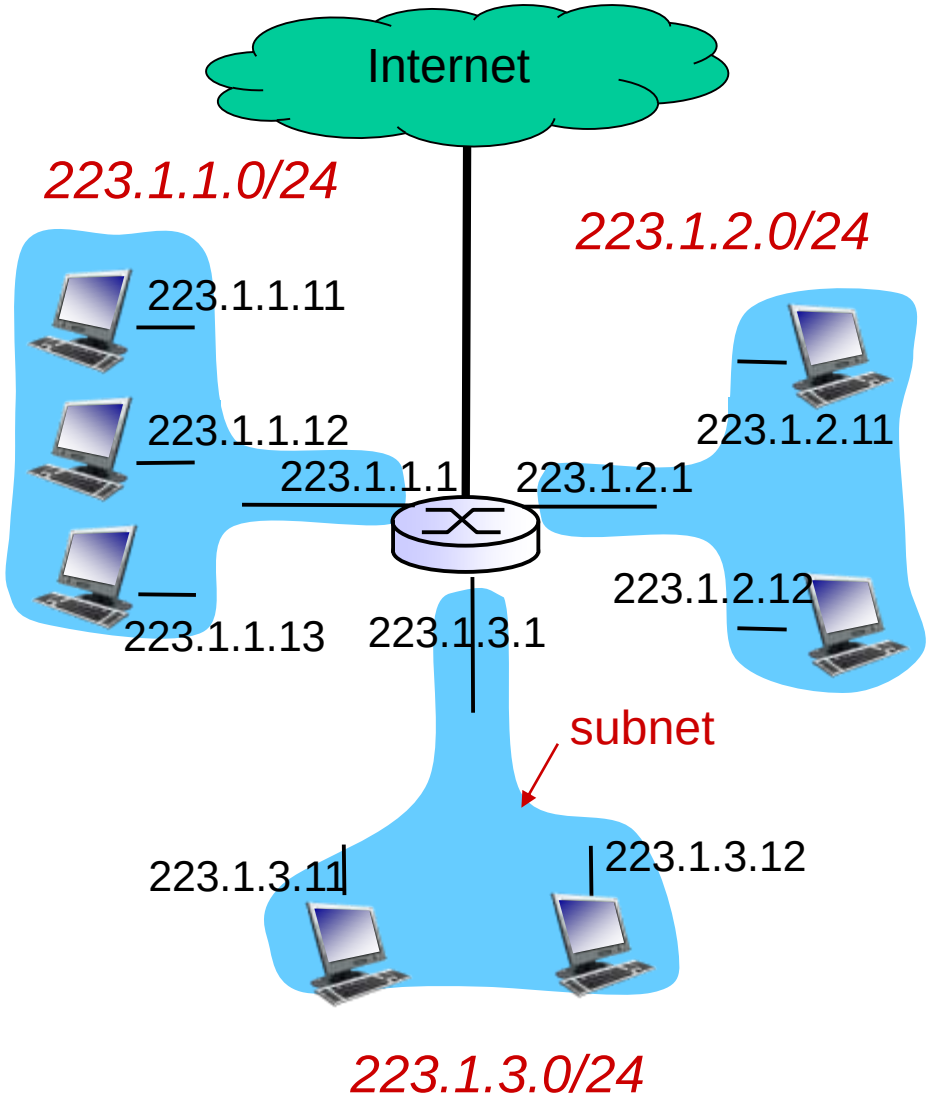
Intra-AS Routing

- Routing / Forwarding
  - Routing in a host
  - Routing and forwarding table
  - Routing aggregation and
  - Longest prefix matching
- Intra-AS Routing protocols
  - OSPF etc

Route in a host

- IP addr: 223.1.1.11
- Subnet mask: 255.255.255.0
- Router: 223.1.1.1



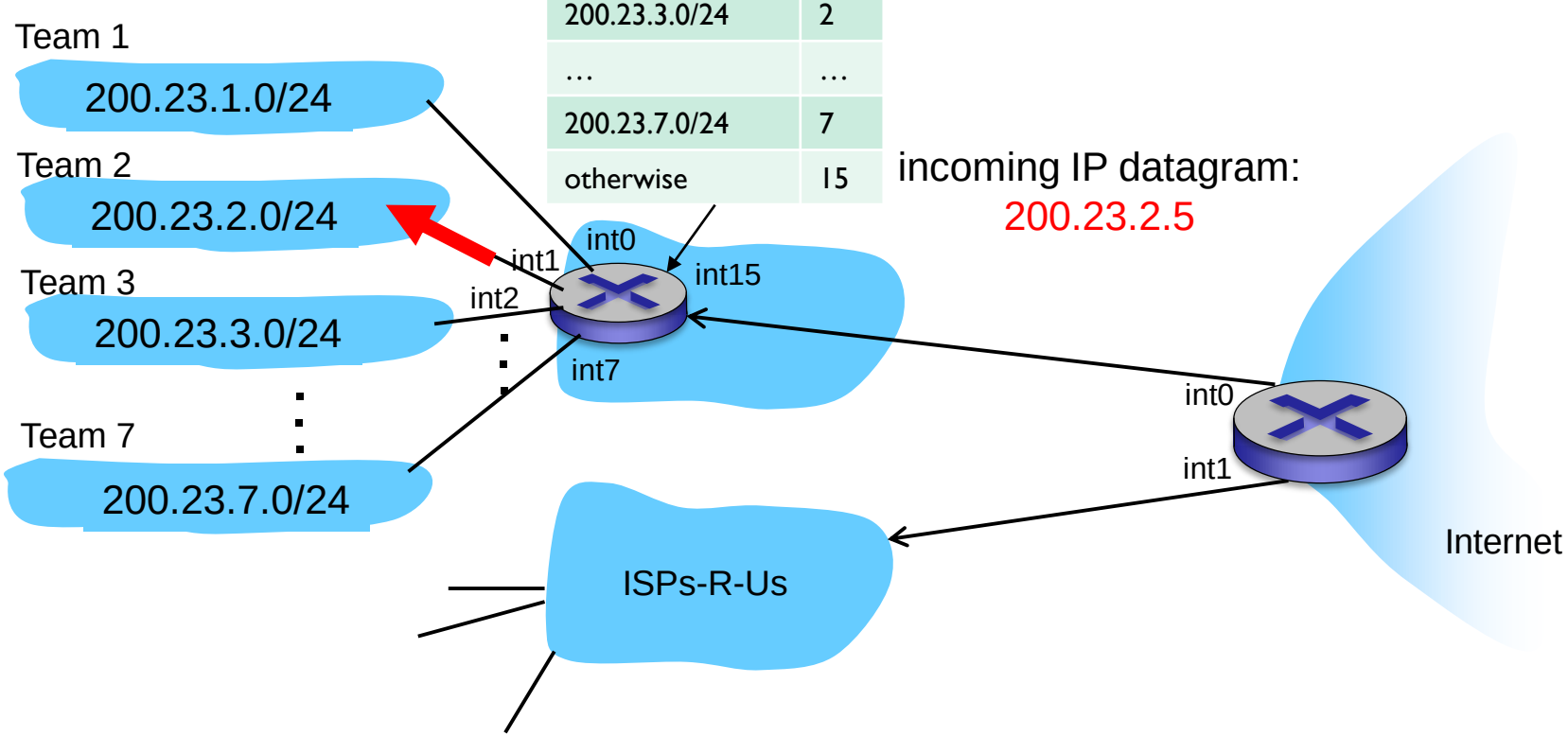


subnet mask: /24

IP Routing: routing table in a router

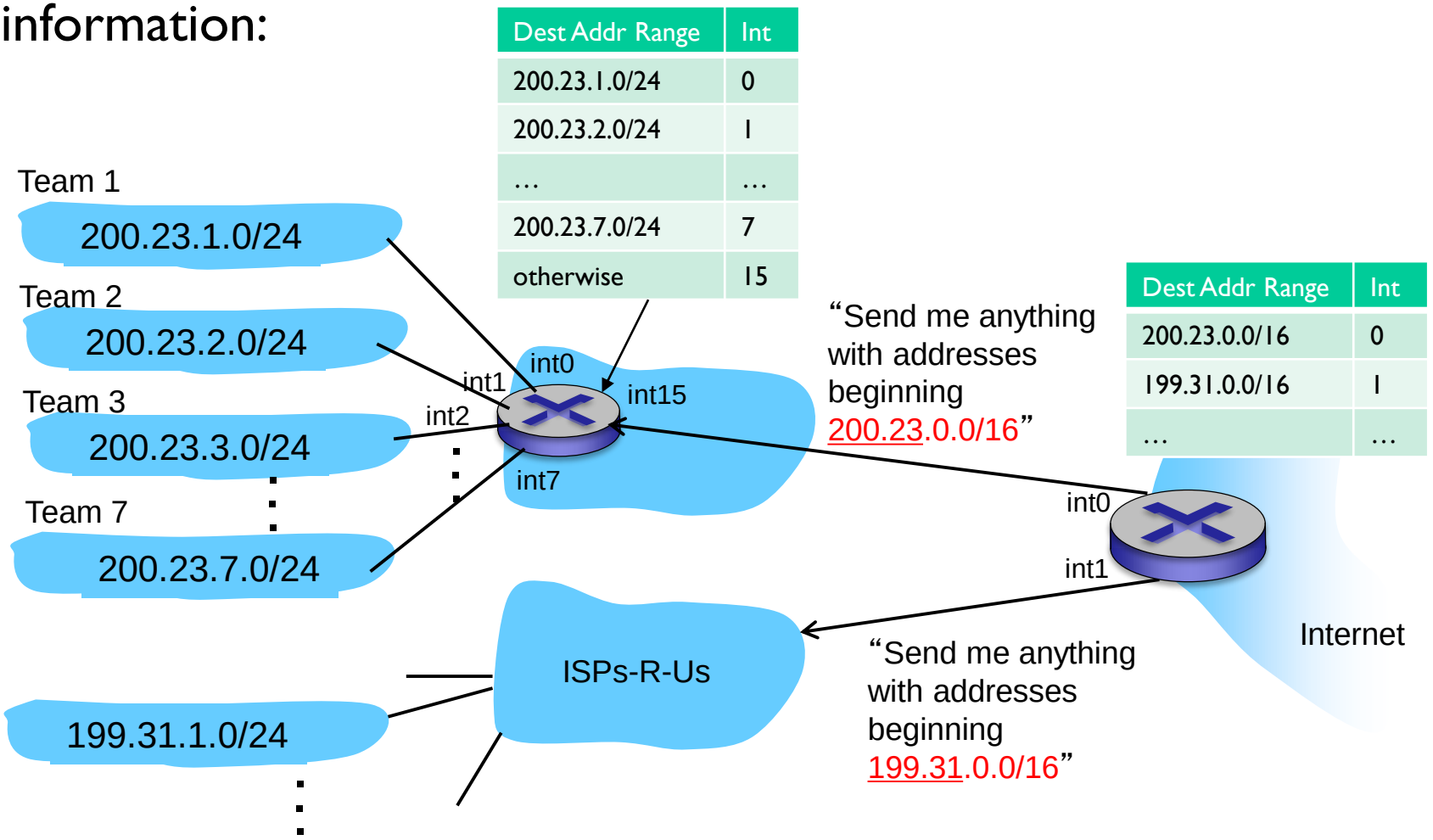
Routing Table: match IP network address to outgoing interface

Dest Addr Range	Int
200.23.1.0/24	0
200.23.2.0/24	1
200.23.3.0/24	2
…	…
200.23.7.0/24	7
otherwise	15



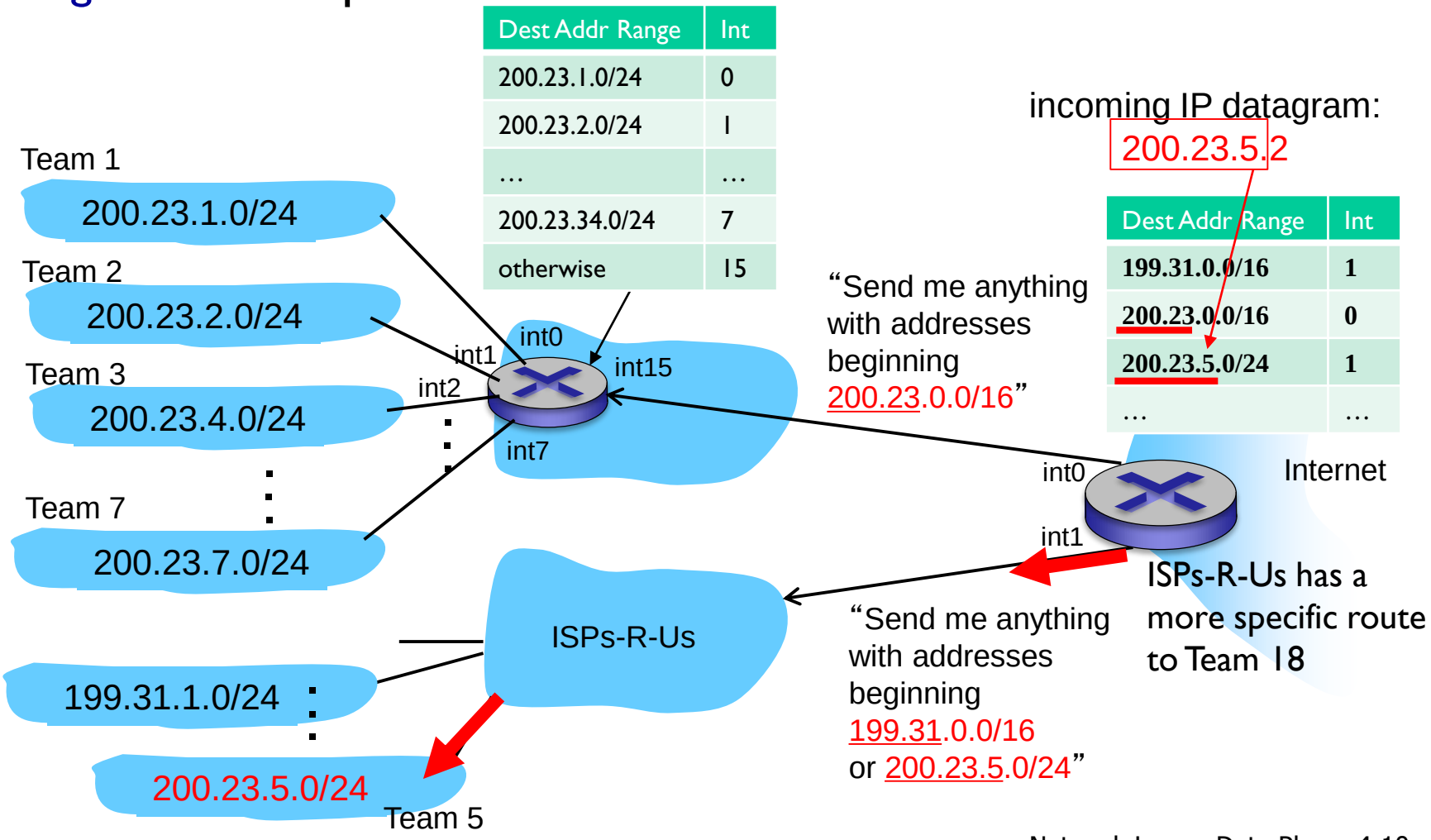
Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



Longest prefix matching

when looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.



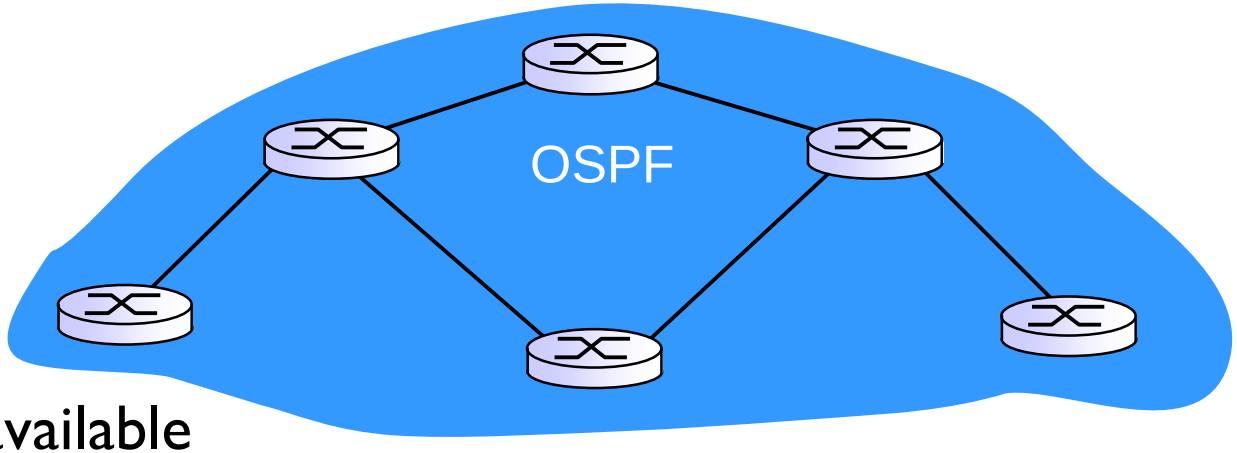
Intra-AS Routing Protocols

- also known as *interior gateway protocols (IGP)*
- most common intra-AS routing protocols:
  - RIP: Routing Information Protocol
  - IGRP: Interior Gateway Routing Protocol (Cisco proprietary for decades, until 2016)
  - OSPF: Open Shortest Path First
  - IS-IS protocol essentially same as OSPF

Distance Vector

Link State

OSPF (Open Shortest Path First)



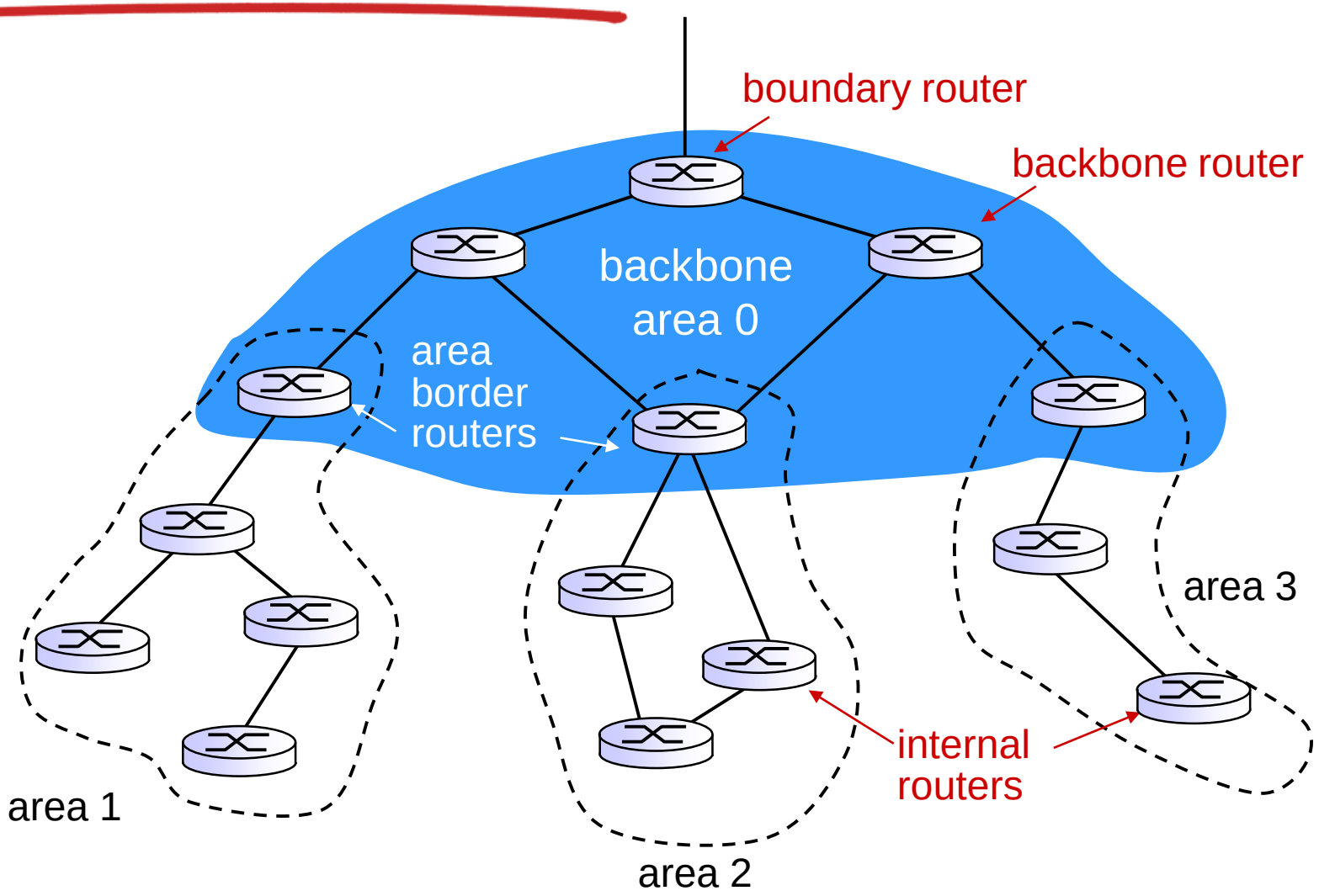
- "open": publicly available
- uses Link-state algorithm - Dijkstra
  - link state packet dissemination
  - topology map at each node
  - route computation using Dijkstra's algorithm
- router floods OSPF link-state advertisements to all other routers in *entire* AS
  - carried in OSPF messages directly over IP (rather than TCP or UDP
  - link state: for each attached link
- *IS-IS routing* protocol: nearly identical to OSPF

OSPF "advanced" features

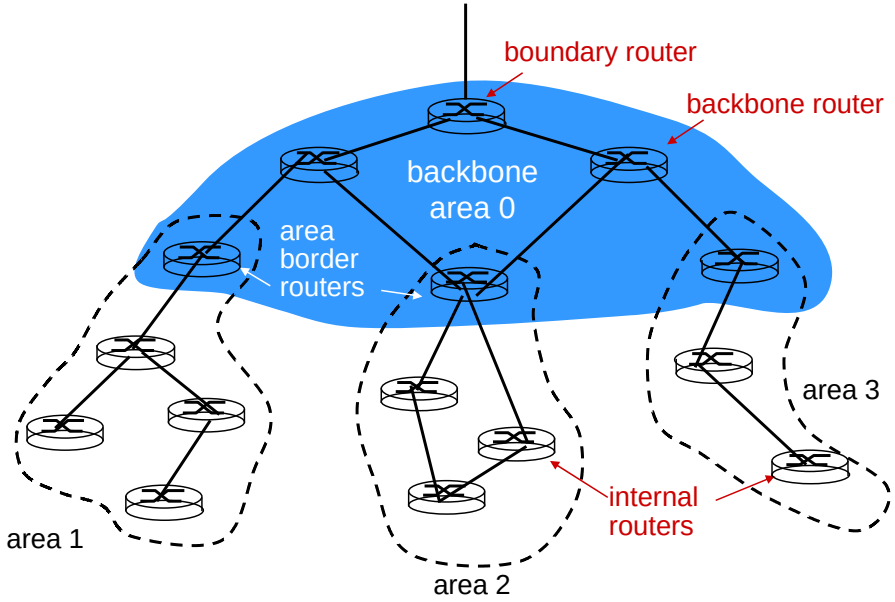
- *security:* all OSPF messages authenticated (to prevent malicious intrusion)
- multiple same-cost paths allowed (only one path in RIP)
- for each link, multiple cost metrics for different TOS (e.g., satellite link cost set low for best effort ToS; high for real-time ToS)
- integrated uni- and multi-cast support:
  - Multicast OSPF (MOSPF) uses same topology data base as OSPF
- hierarchical OSPF in large domains.

Optional – not tested

Hierarchical OSPF



Hierarchical OSPF



- *two-level hierarchy:* local area, backbone.
  - link-state advertisements only in each area
  - each nodes has detailed area topology;
  - Each area runs an independent link state routing.
- *backbone routers:* Backbone area '0'
  - core to all other areas.
- *area border routers:* "aggregate" networks in own area,
  - advertise to Area 0, through to other Areas.
- *boundary routers:* connect to other AS' es.

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5.5 The SDN control plane

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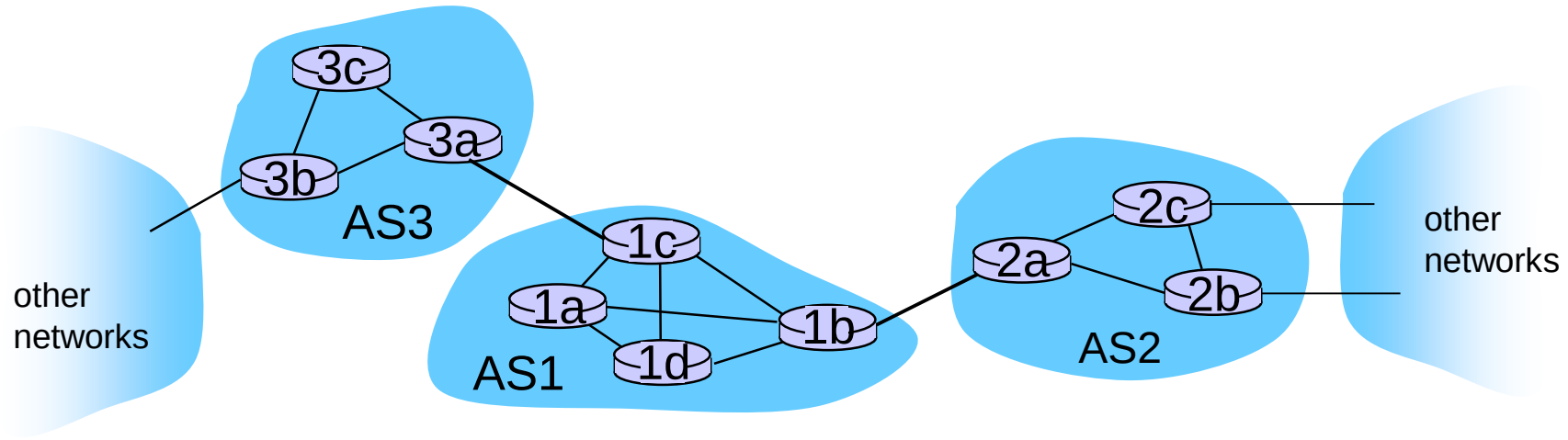
Inter-AS tasks

- suppose router in AS1 receives datagram destined outside of AS1:
  - router should forward packet to gateway router, but which one?

AS1 must:

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

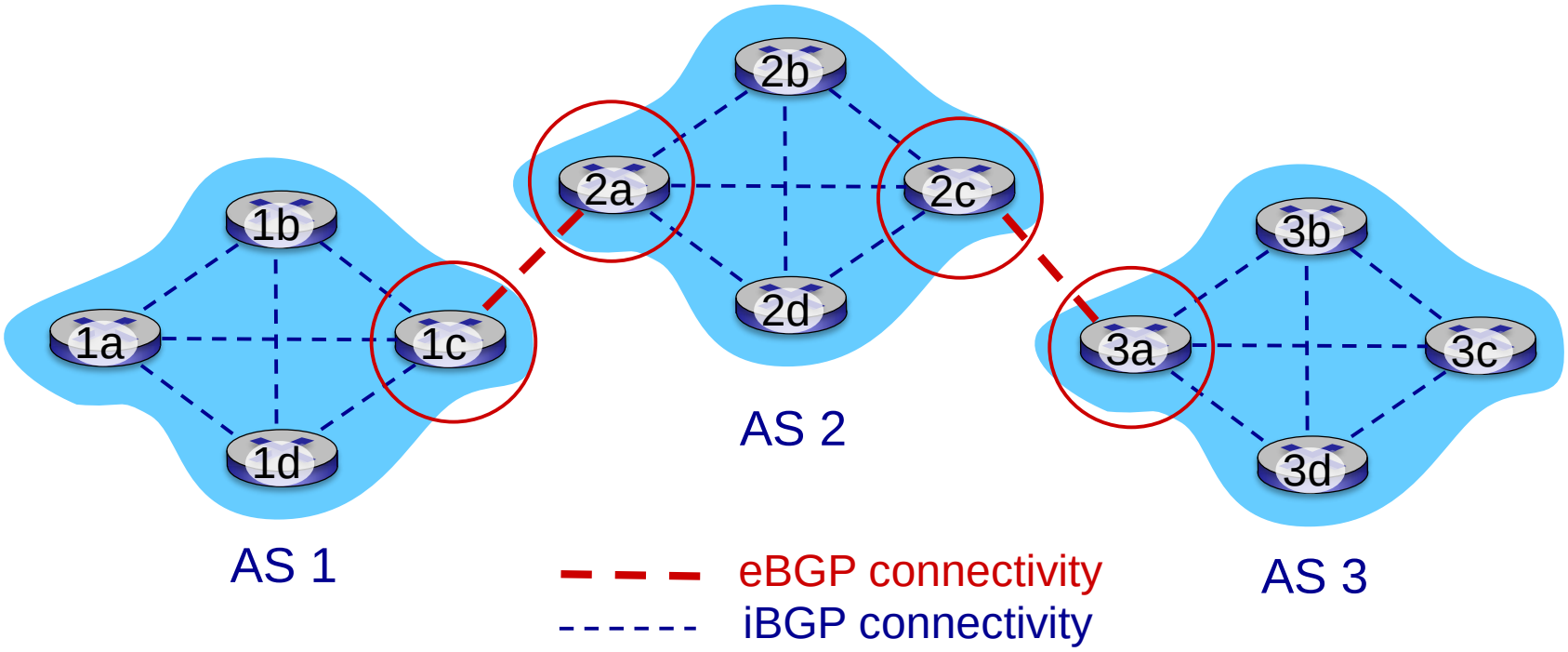
job of inter-AS routing!



Internet inter-AS routing: BGP

- BGP (Border Gateway Protocol): *the* de facto inter-domain routing protocol
  - "glue that holds the Internet together"
  - Based on Distance Vector Routing Algorithm
- BGP provides each AS a means to:
  - eBGP: obtain subnet reachability information from neighboring ASes
  - iBGP: propagate reachability information to all AS-internal routers.
  - determine "good" routes to other networks based on reachability information and *policy*
- allows subnet to advertise its existence to rest of Internet: *"I am here"*

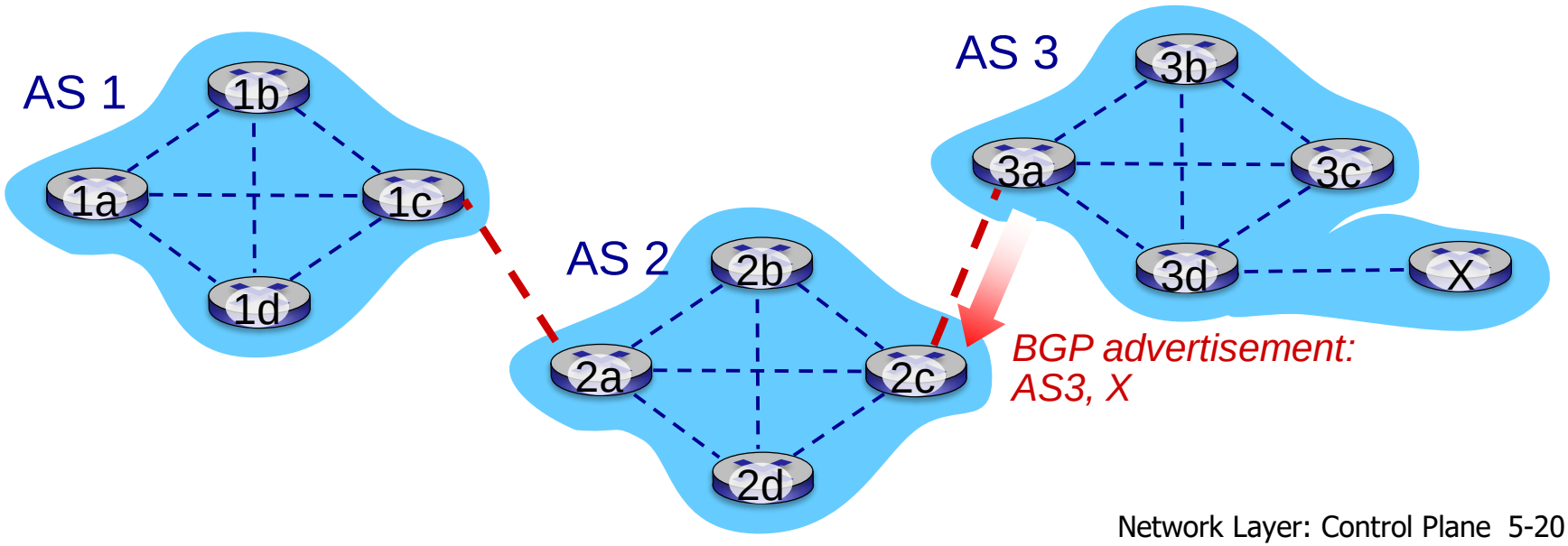
eBGP, iBGP connections



gateway routers run both eBGP and iBGP protocols

BGP basics

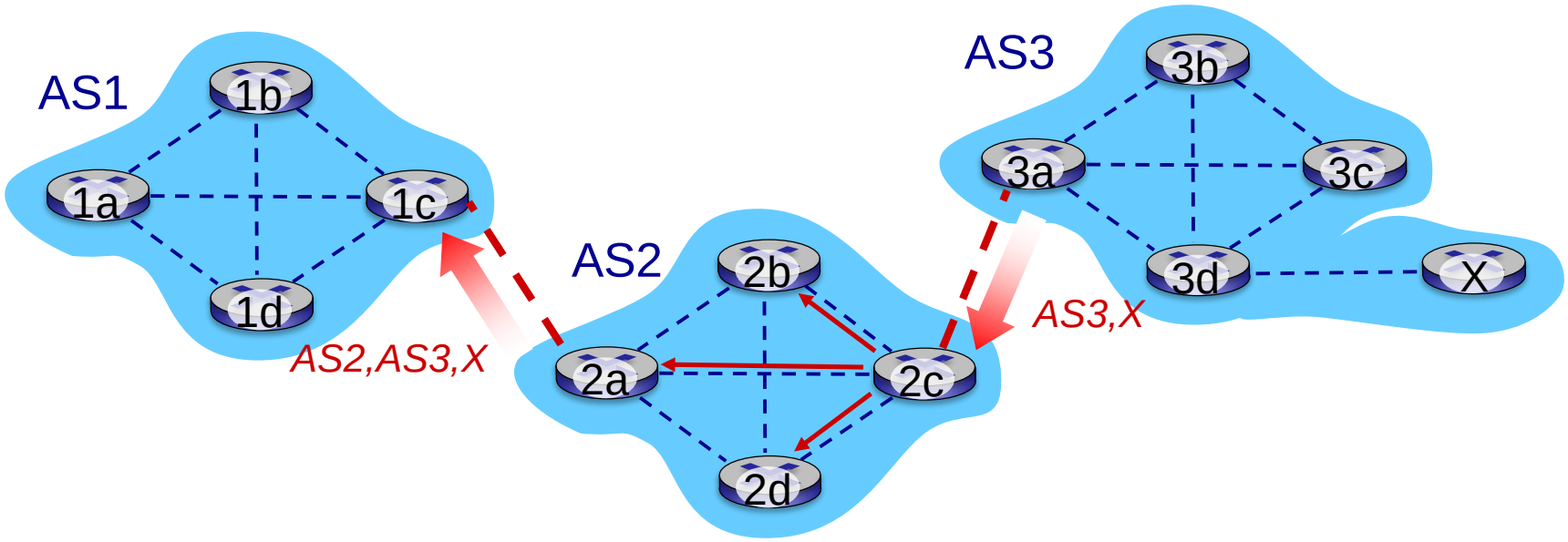
- BGP session: two BGP routers ("peers") exchange BGP messages over semi-permanent TCP connection:
  - advertising *paths* to different destination network prefixes (BGP is a "path vector" protocol)
- when AS3 gateway router 3a advertises path AS3,X to AS2 gateway router 2c:
  - AS3 *promises* to AS2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



Path attributes and BGP routes

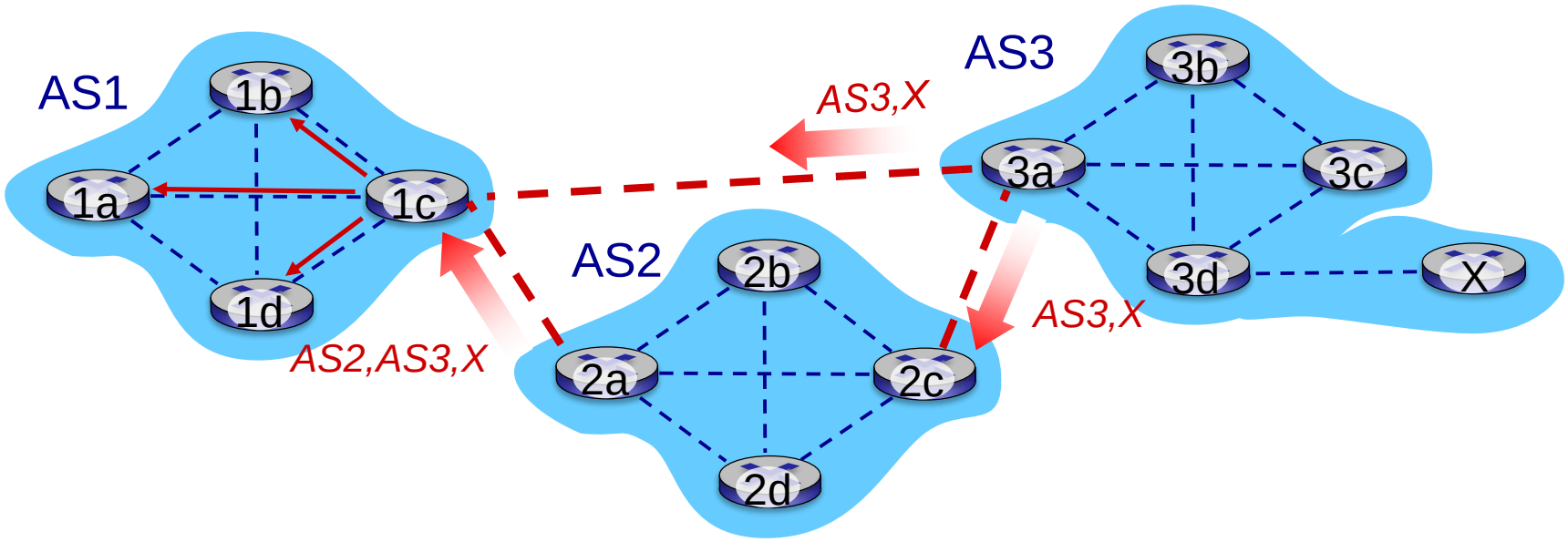
- advertised prefix includes BGP attributes
  - prefix + attributes = "route"
- two important attributes:
  - AS-PATH: list of ASes through which prefix advertisement has passed
  - NEXT-HOP: indicates specific internal-AS router to next-hop AS
- *Policy-based routing:*
  - gateway receiving route advertisement 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



gateway router may learn about multiple paths to destination:

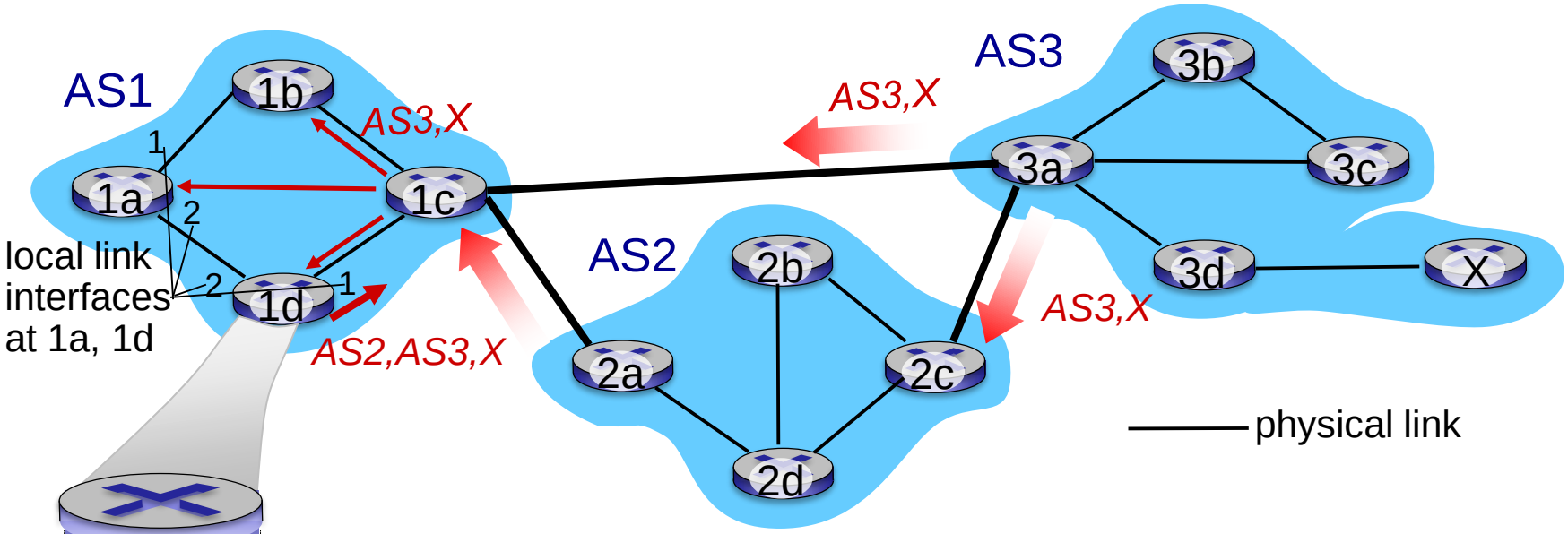
- AS1 gateway router 1c learns path *AS2,AS3,X* from 2a
- AS1 gateway router 1c learns path *AS3,X* from 3a
- Based on policy, AS1 gateway router 1c chooses path *AS3,X, and advertises path within AS1 via iBGP*

BGP messages

- BGP messages exchanged between peers over TCP connection
- BGP messages:
  - 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

BGP, OSPF, forwarding table entries

Q: how does router set forwarding table entry to distant prefix?

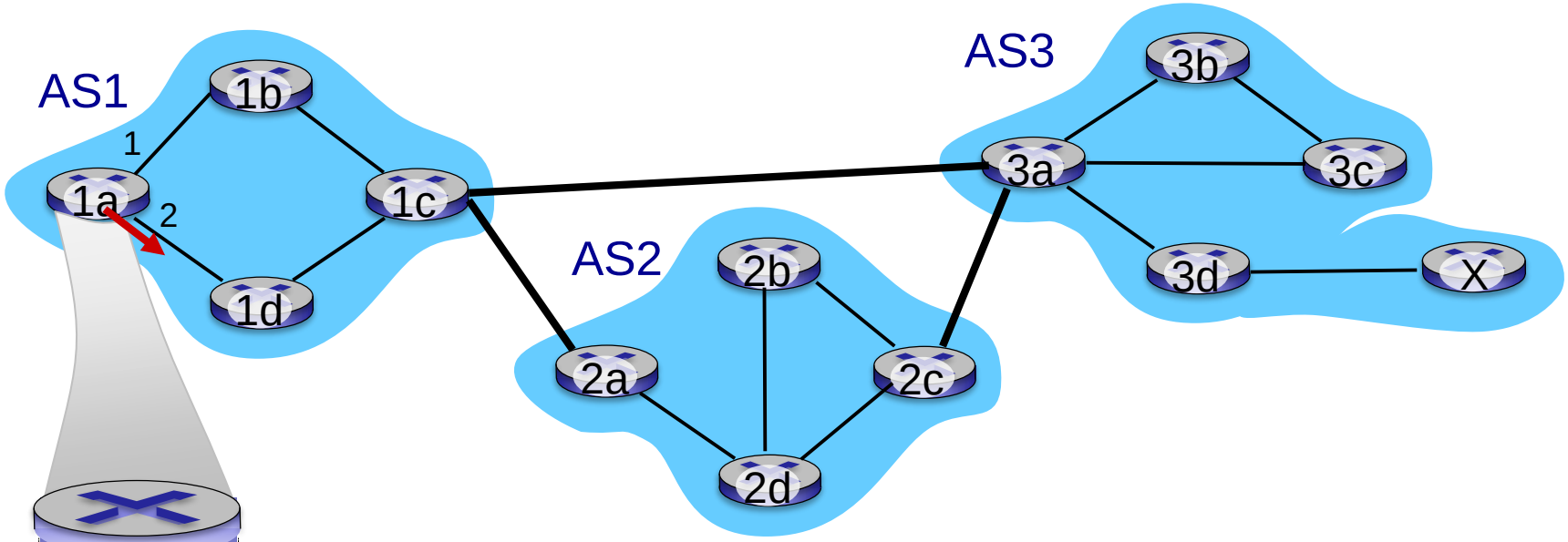


dest	interface
…	…
X	1
…	…

- recall: 1a, 1b, 1d learn about dest X via iBGP from 1c: "path to X goes through 1c"
- 1d: OSPF intra-domain routing: to get to 1c, forward over outgoing local interface 1

BGP, OSPF, forwarding table entries

Q: how does router set forwarding table entry to distant prefix?



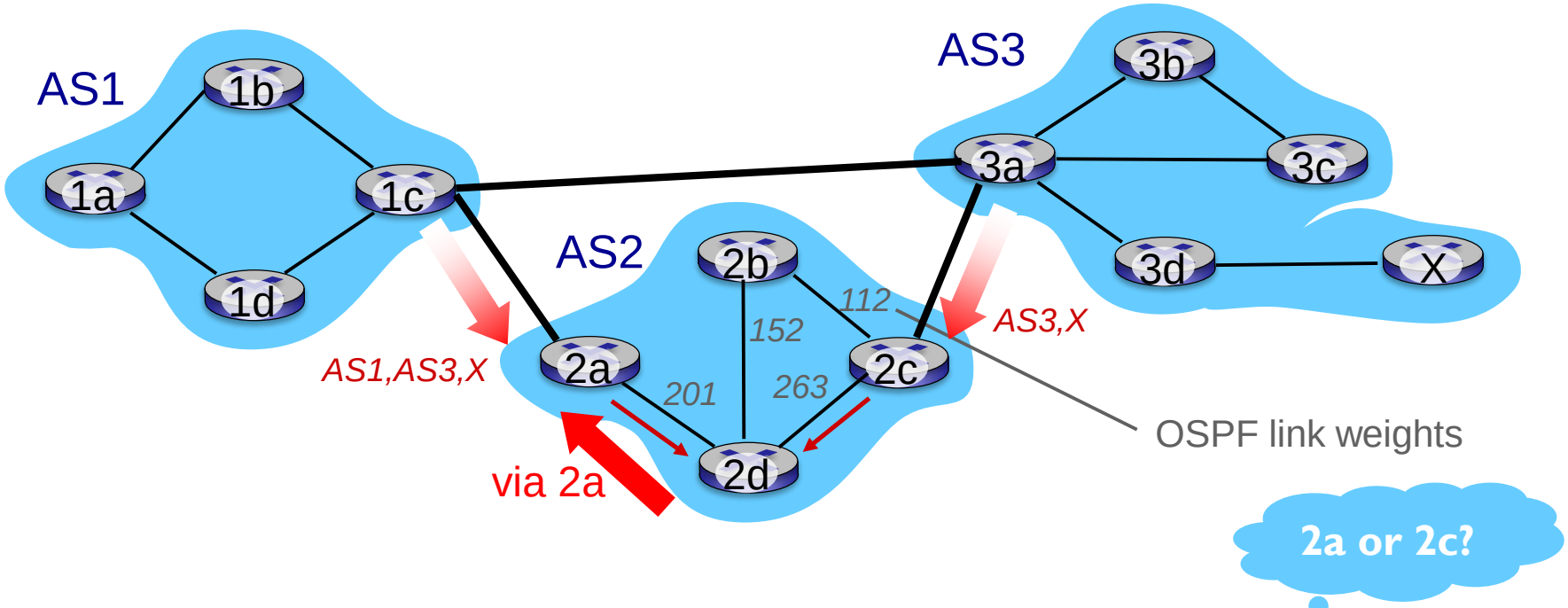
dest	interface
…	…
X	2
…	…

- recall: 1a, 1b, 1c learn about dest X via iBGP from 1c: "path to X goes through 1c"
- 1d: OSPF intra-domain routing: to get to 1c, forward over outgoing local interface 1
- 1a: OSPF intra-domain routing: to get to 1c, forward over outgoing local interface 2

BGP route selection

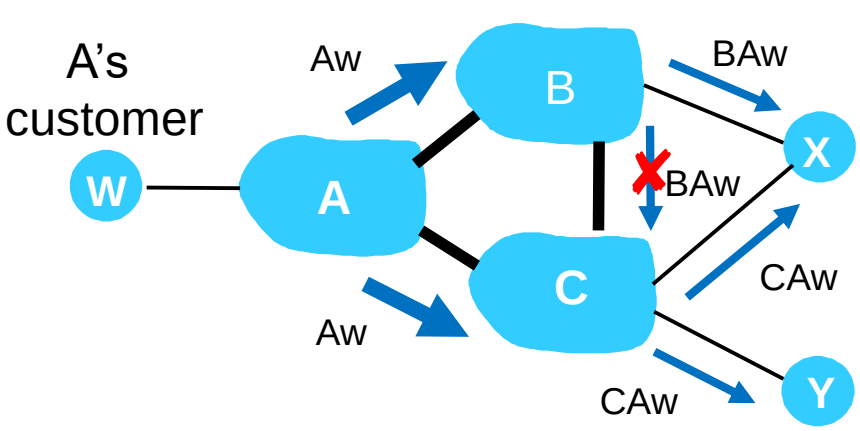
- router may learn about more than one route to destination AS, selects route based on:
  1. local preference value attribute: policy decision
  2. shortest AS-PATH
  3. closest NEXT-HOP router: hot potato routing
  4. additional criteria

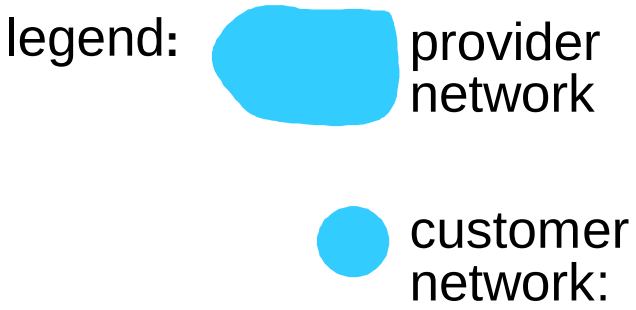
Hot Potato Routing



- 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

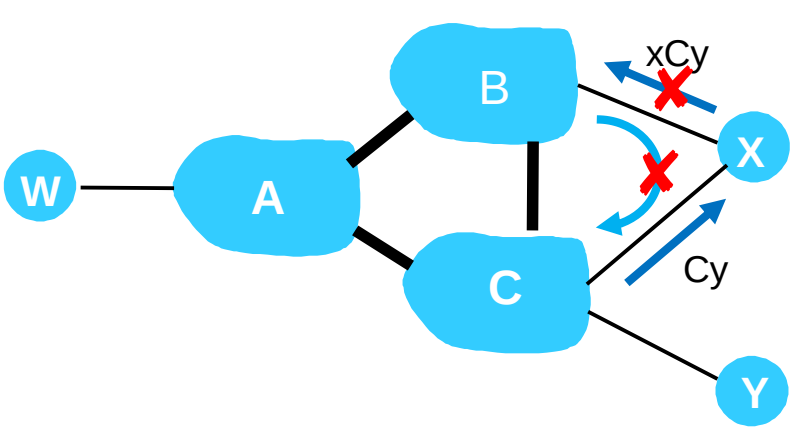


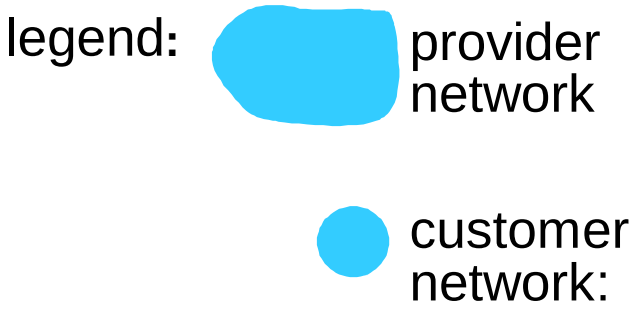


Suppose an ISP only wants to route traffic to/from its customer networks (does not want to carry transit traffic between other ISPs)

- A advertises path Aw to B and to C
  - B, C advertise to their customers x, y
- B *chooses not to advertise* BAw to C:
  - w, y are NOT 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





Suppose an ISP only wants to route traffic to/from its customer networks (does not want to carry transit traffic between other ISPs)

- x is *dual-homed:* attached to two networks
  - if x advertise C to B
  - B→C→y traffic could go through x.
- *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
  - …so x will not carry BCy traffic

Why different Intra-, Inter-AS routing ?

policy:

- intra-AS: single admin, so no policy decisions needed
- inter-AS: admin wants control (using policy) over how its traffic routed, who routes through its net.

performance:

- intra-AS: can focus on performance
- inter-AS: policy may dominate over performance

scale:

- hierarchical routing saves table size, reduced update traffic

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ICMP: internet control message protocol

- used by hosts & routers to communicate network-level information
  - error reporting: unreachable host, network, port, protocol
  - echo request/reply (used by ping)
- network-layer "above" IP:
  - ICMP msgs carried in IP datagrams
- ICMP message: type, code plus first 8 bytes of IP datagram causing error

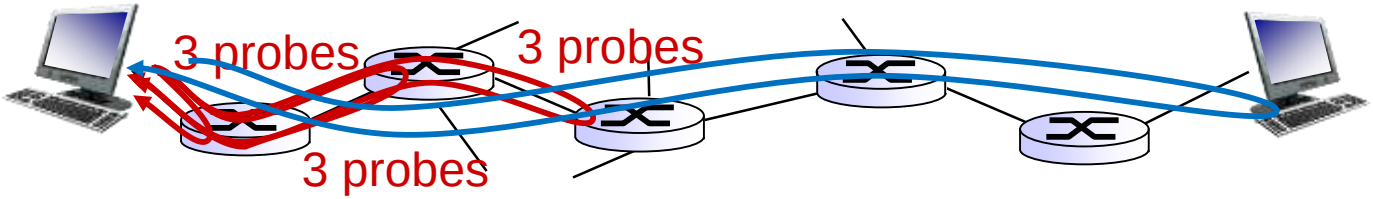
Type	Code	description
0	0	echo reply (ping)
3	0	dest. network unreachable
3	1	dest host unreachable
3	2	dest protocol unreachable
3	3	dest port unreachable
3	6	dest network unknown
3	7	dest host unknown
4	0	source quench (congestion control - not used)
8	0	echo request (ping)
9	0	route advertisement
10	0	router discovery
11	0	TTL expired
12	0	bad IP header

Traceroute and ICMP

- source sends series of UDP segments to destination
  - first set has TTL =1
  - second set has TTL=2, etc.
  - unlikely port number
- when datagram in *n*th set arrives to nth router:
  - router discards datagram and sends source ICMP message *TTL expired* (type 11, code 0)
  - ICMP message include name of router & IP address
- when ICMP message arrives, source records RTTs

stopping criteria:

- UDP segment eventually arrives at destination host
- destination returns ICMP "*port unreachable*" message (type 3, code 3)
- source stops



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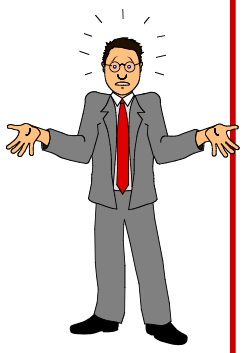
What is network management?

- autonomous systems (aka "network"): 1000s of interacting hardware/software components
- other complex systems requiring monitoring, control:
  - jet airplane
  - nuclear power plant
  - others?



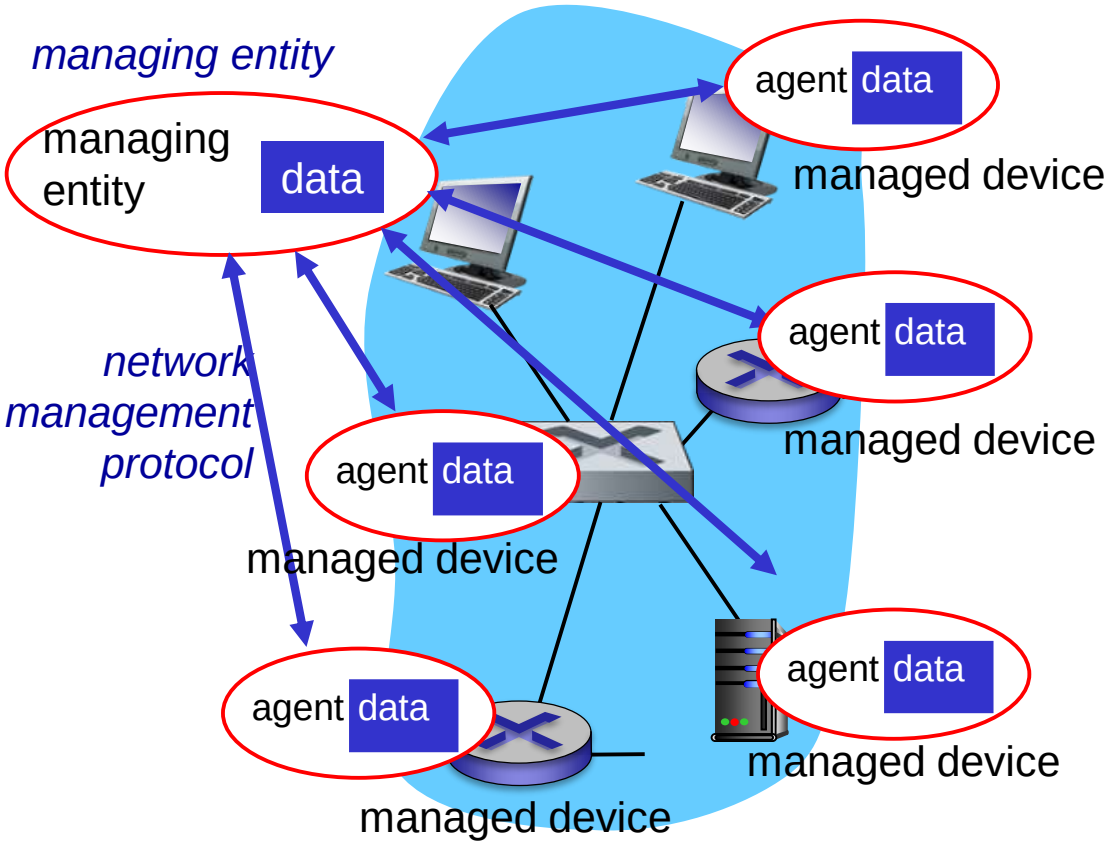
"Network management includes the deployment, integration and coordination of the hardware, software, and human elements to monitor, test, poll, configure, analyze, evaluate, and control the network and element resources to meet the real-time, operational performance, and Quality of Service requirements at a reasonable cost."

Infrastructure for network management

NOC
Network Operations Centre

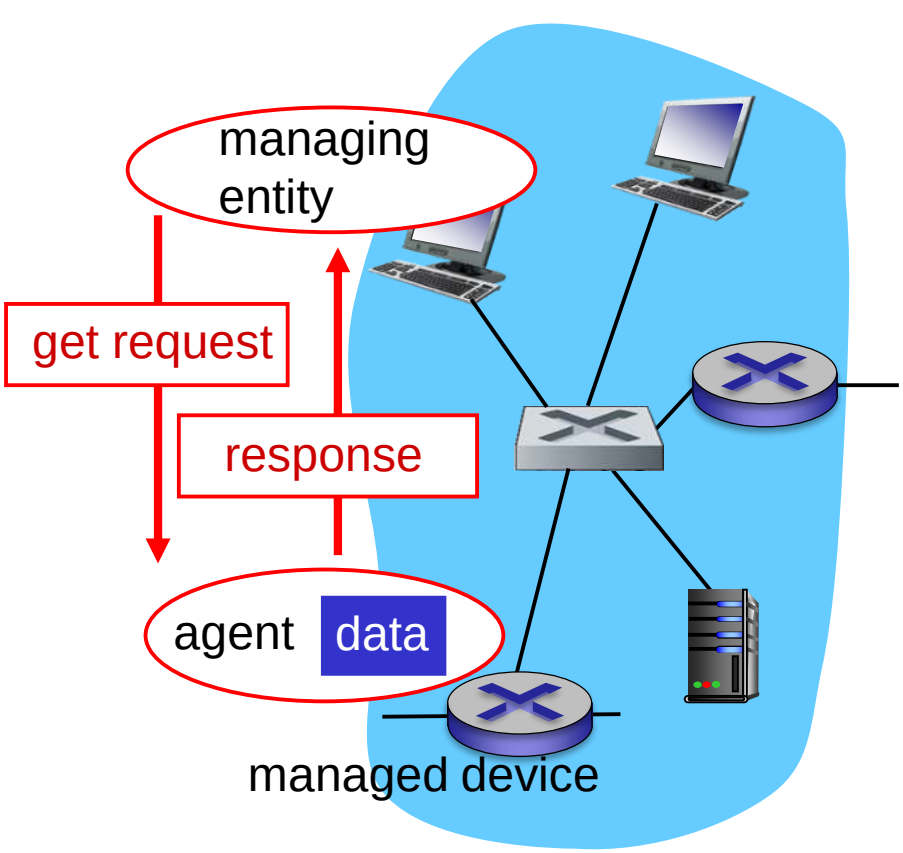
managed devices contain *managed objects* whose data is gathered into a *Management Information Base (MIB)*

definitions:

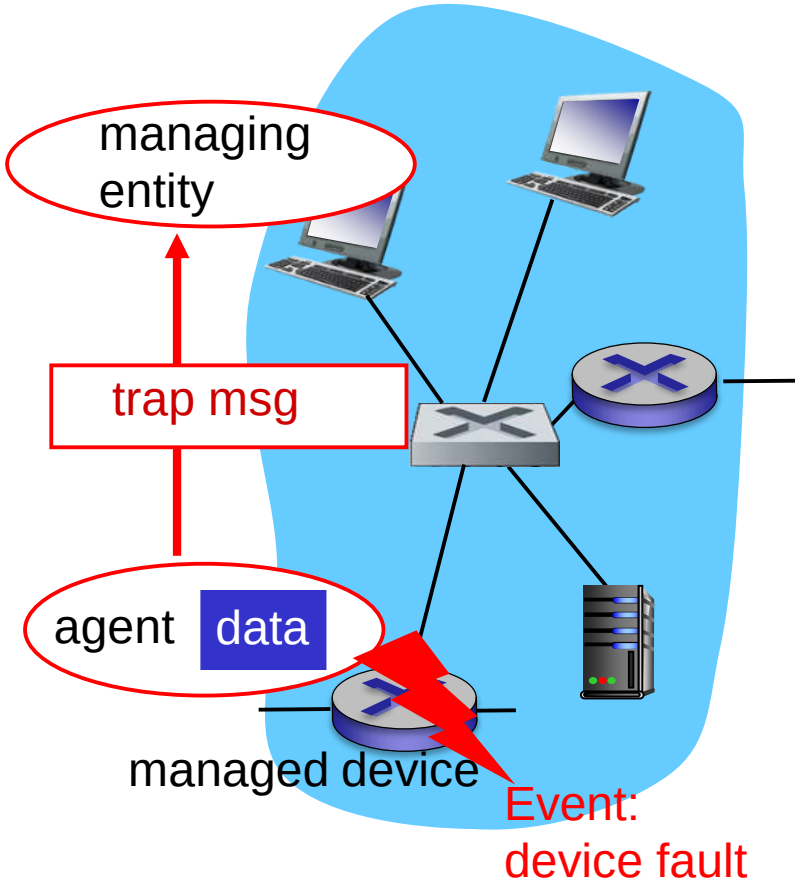


SNMP protocol

Two ways to convey MIB info, commands:



request/response mode

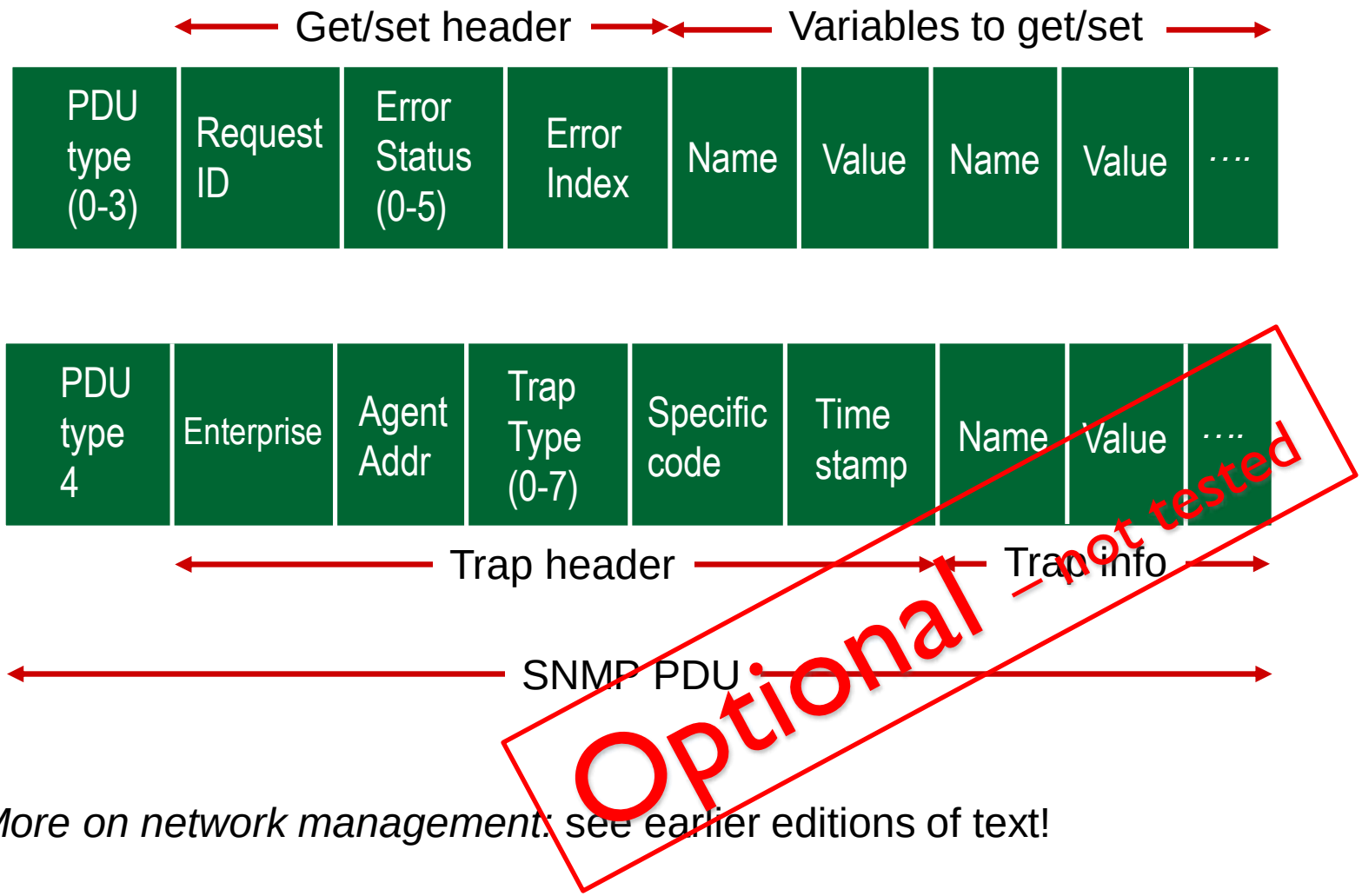


trap mode

SNMP protocol: message types

Message type	Function
GetRequest GetNextRequest GetBulkRequest	manager-to-agent: "get me data" (data instance, next data in list, block of data)
InformRequest	manager-to-manager: here's MIB value
SetRequest	manager-to-agent: set MIB value
Response	Agent-to-manager: value, response to Request
Trap	Agent-to-manager: inform manager of exceptional event

SNMP protocol: message formats



More on network management: see earlier editions of text!

Chapter 5: summary

we've learned a lot!

- approaches to network control plane
  - per-router control (traditional)
  - ~~logically centralized control (software defined networking)~~
- traditional routing algorithms
  - implementation in Internet: OSPF, BGP
- ~~SDN controllers~~
  - ~~implementation in practice: ODL, ONOS~~
- Internet Control Message Protocol
- network management

next stop: link layer!