

Chapter 5(Review) Network Layer: The Control Plane

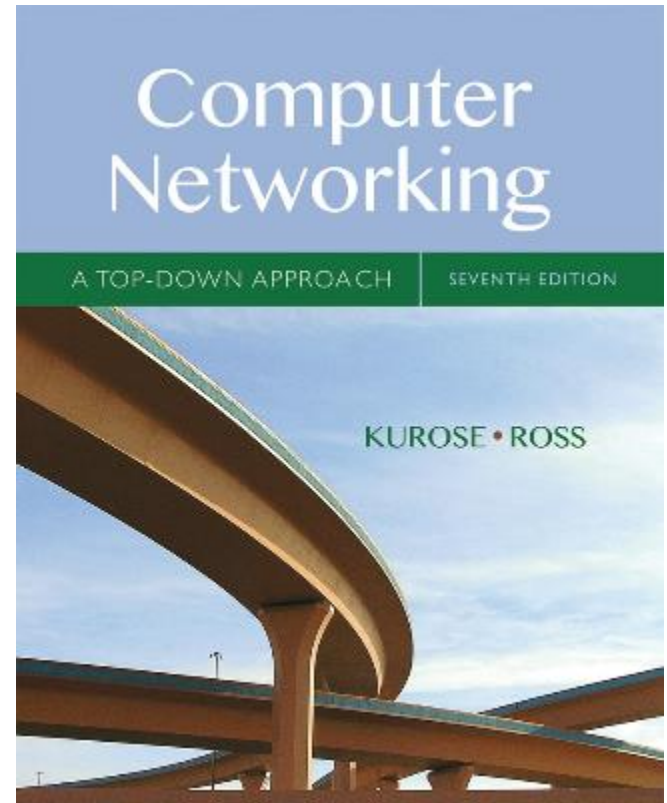
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Computer Networking: A Top Down Approach

7th edition

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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

Network-layer functions

Recall: two network-layer functions:

- *forwarding*: move packets from router's input to appropriate router output

data plane

- *routing*: determine route taken by packets from source to destination

control plane

Two approaches to structuring network control plane:

- per-router control (traditional)
- logically centralized control (software defined networking)

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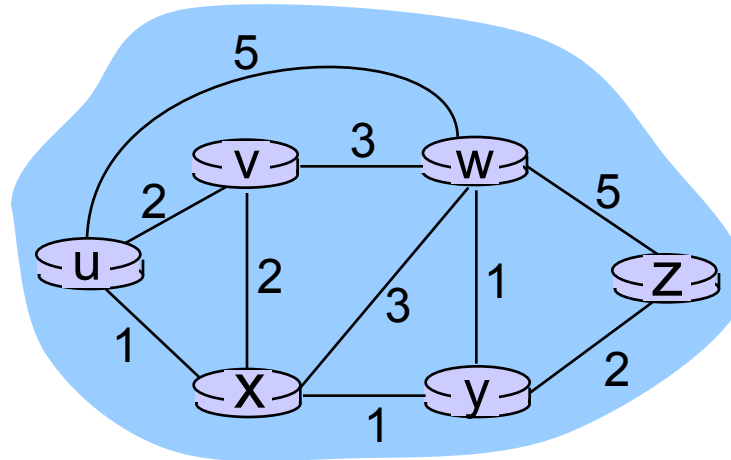
5.7 Network management and SNMP

Routing protocols

Routing protocol goal: determine “good” paths (equivalently, routes), from sending hosts to receiving host, through network of routers

- path: sequence of routers packets will traverse in going from given initial source host to given final destination host
- “good”: least “cost”, “fastest”, “least congested”
- routing: a “top-10” networking challenge!

Graph abstraction of the network



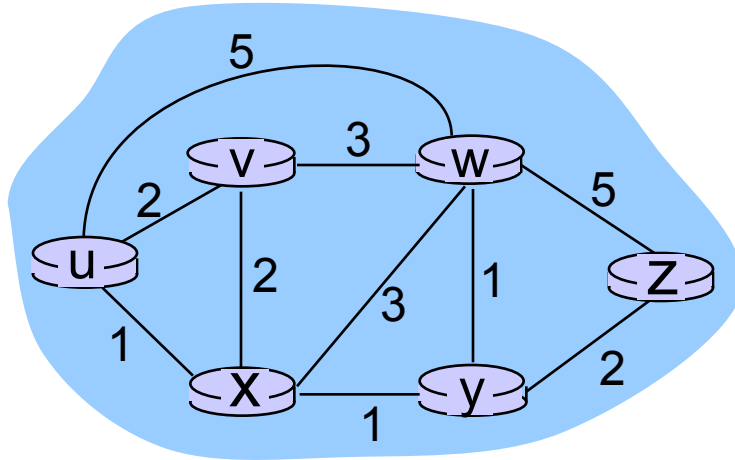
graph: $G = (N, E)$

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

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

aside: graph abstraction is useful in other network contexts, e.g., P2P, where N is set of peers and E is set of TCP connections

Graph abstraction: costs



$c(x, x') = \text{cost of link } (x, x')$
e.g., $c(w, z) = 5$

cost could always be 1, or
inversely related to bandwidth,
or inversely related to
congestion

cost of path $(x_1, x_2, x_3, \dots, x_p) = c(x_1, x_2) + c(x_2, x_3) + \dots + c(x_{p-1}, x_p)$

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

Routing algorithm classification

Q: global or decentralized information?

global:

- all routers have complete topology, link cost info
- “link state” algorithms

decentralized:

- router knows physically-connected neighbors, link costs to neighbors
- iterative process of computation, exchange of info with neighbors
- “distance vector” algorithms

Q: static or dynamic?

static:

- routes change slowly over time

dynamic:

- routes change more quickly
 - periodic update
 - in response to link cost changes

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A link-state routing algorithm

Dijkstra's algorithm

- net 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 dest.'s

notation:

- $c(x,y)$: link cost from node x to y; $= \infty$ if not direct neighbors
- $D(v)$: current value of cost of path from source to dest. v
- $p(v)$: predecessor node along path from source to v
- N' : set of nodes whose least cost path definitively known

Dijkstra's algorithm

1 **Initialization:**

2 $N' = \{u\}$

3 for all nodes v

4 if v adjacent to u

5 then $D(v) = c(u,v)$

6 else $D(v) = \infty$

7

8 **Loop**

9 find w not in N' such that $D(w)$ is a minimum

10 add w to N'

11 update $D(v)$ for all v adjacent to w and not in N' :

12 **$D(v) = \min(D(v), D(w) + c(w,v))$**

13 /* new cost to v is either old cost to v or known

14 shortest path cost to w plus cost from w to v */

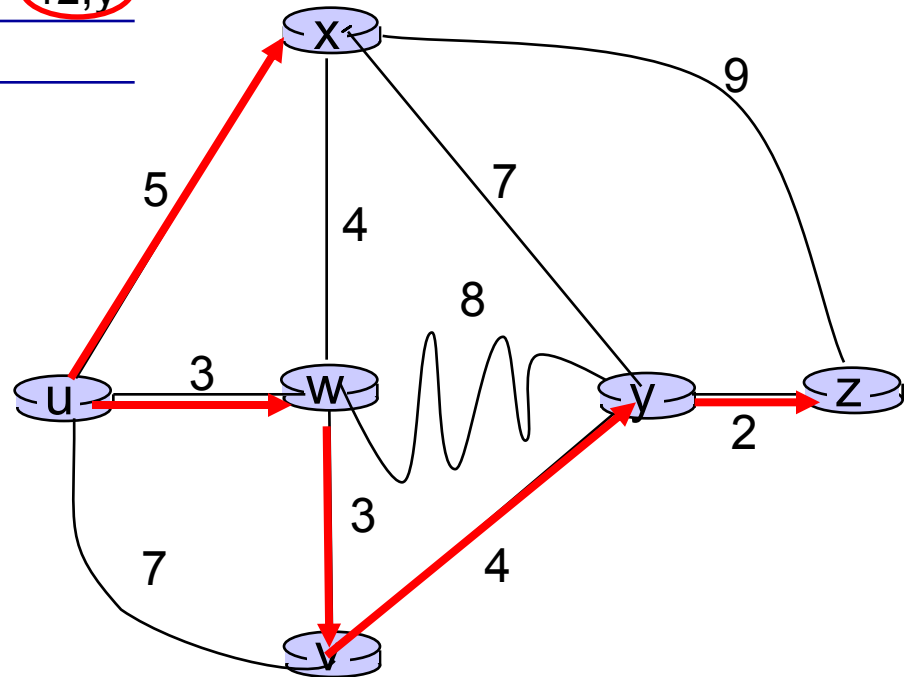
15 **until all nodes in N'**

Dijkstra's algorithm: example

Step	N'	D(v) p(v)	D(w) p(w)	D(x) p(x)	D(y) p(y)	D(z) p(z)
0	u	7,u	3,u	5,u	∞	∞
1	uw	6,w		5,u	11,w	∞
2	uwx	6,w			11,w	14,x
3	uwxv				10,v	14,x
4	uwxvy					12,y
5	uwxvyz					

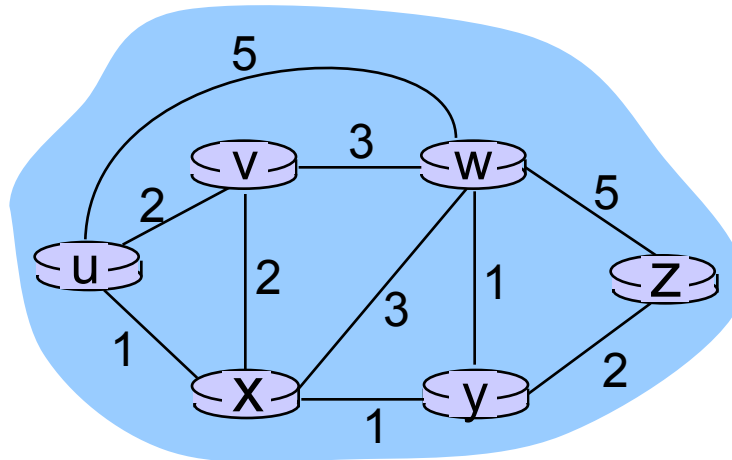
notes:

- ❖ construct shortest path tree by tracing predecessor nodes
- ❖ ties can exist (can be broken arbitrarily)



Dijkstra's algorithm: another example

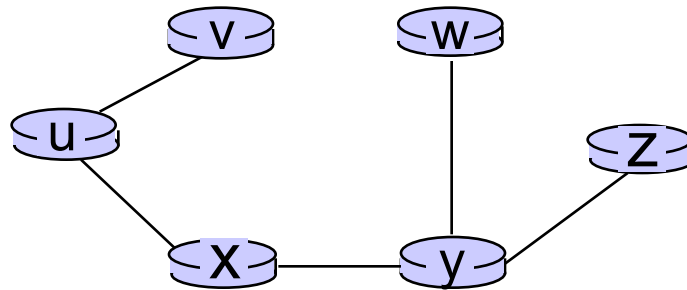
Step	N'	D(v),p(v)	D(w),p(w)	D(x),p(x)	D(y),p(y)	D(z),p(z)
0	u	2,u	5,u	1,u	∞	∞
1	ux	2,u	4,x		2,x	∞
2	uxy	2,u	3,y			4,y
3	uxyv		3,y			4,y
4	uxyvw					4,y
5	uxyvwz					



* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

Dijkstra's algorithm: example (2)

resulting shortest-path tree from u:



resulting forwarding table in u:

destination	link
v	(u,v)
x	(u,x)
y	(u,x)
w	(u,x)
z	(u,x)

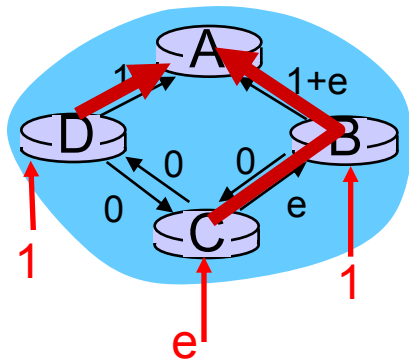
Dijkstra's algorithm, discussion

algorithm complexity: n nodes

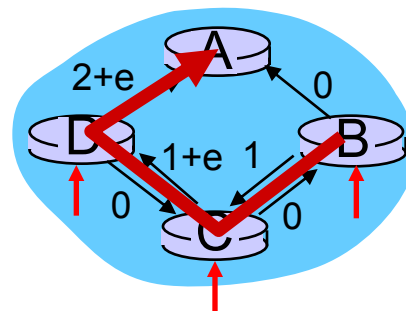
- each iteration: need to check all nodes, w, not in N
- $n(n+1)/2$ comparisons: $O(n^2)$
- more efficient implementations possible: $O(n \log n)$

oscillations possible:

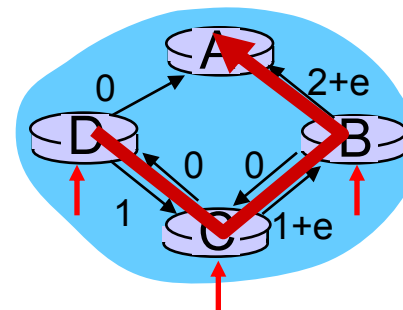
- e.g., support link cost equals amount of carried traffic:



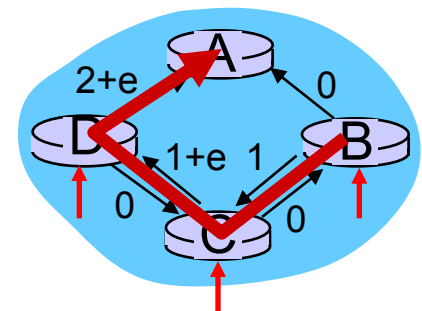
initially



given these costs,
find new routing....
resulting in new costs



given these costs,
find new routing....
resulting in new costs



given these costs,
find new routing....
resulting in new costs

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Distance vector algorithm

Bellman-Ford equation (dynamic programming)

let

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

then

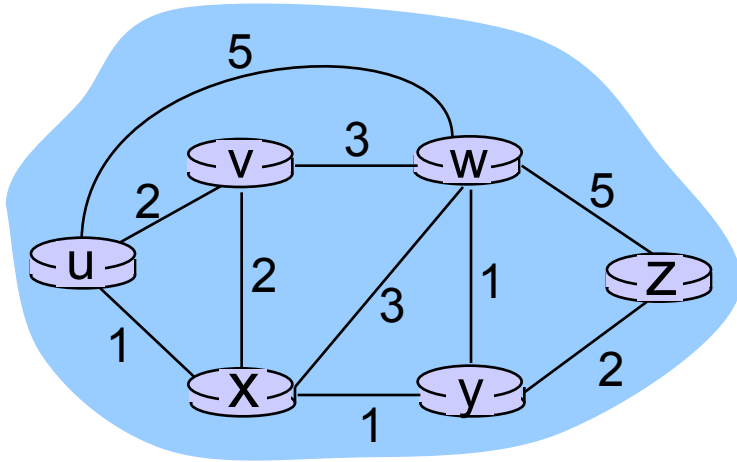
$$d_x(y) = \min_v \{ c(x,v) + d_v(y) \}$$

cost from neighbor v to destination y

cost to neighbor v

\min taken over all neighbors v of x

Bellman-Ford example



clearly, $d_v(z) = 5$, $d_x(z) = 3$, $d_w(z) = 3$

B-F equation says:

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

node achieving minimum is next
hop in shortest path, used in forwarding table

Distance vector algorithm

- $D_x(y)$ = estimate of least cost from x to y
 - x maintains distance vector $\mathbf{D}_x = [D_x(y): y \in N]$
- node x :
 - knows cost to each neighbor v : $c(x,v)$
 - maintains its neighbors' distance vectors. For each neighbor v , x maintains $\mathbf{D}_v = [D_v(y): y \in N]$

Distance vector 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 $d_x(y)$

Distance vector algorithm

iterative, asynchronous:

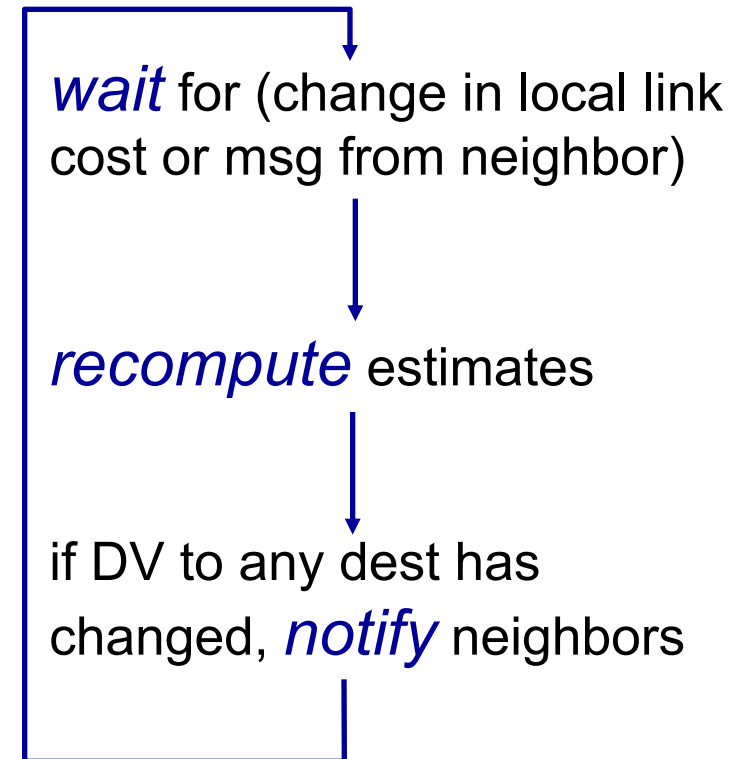
each local iteration
caused by:

- local link cost change
- DV update message from neighbor

distributed:

- each node notifies neighbors *only* when its DV changes
 - neighbors then notify their neighbors if necessary

each node:



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

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

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

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

**node x
table**

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

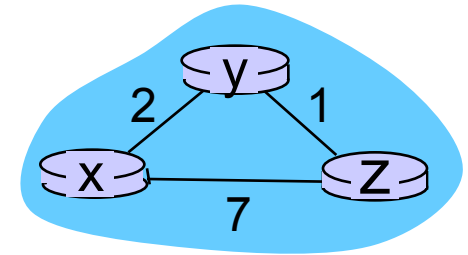
		cost to		
		x	y	z
from	x	0	2	3
	y	2	0	1
	z	7	1	0

**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



time

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

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

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

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

**node x
table**

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

**node y
table**

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

**node z
table**

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

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

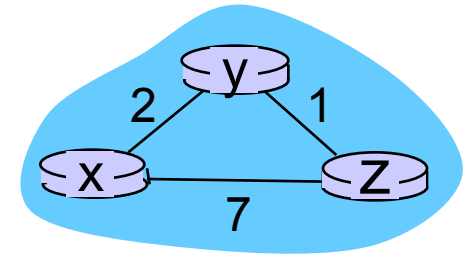
	cost to		
	x	y	z
from x	0	2	7
from y	2	0	1
from z	7	1	0

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

	cost to		
	x	y	z
from x	0	2	3
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time →

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Making routing scalable

our routing study thus far - idealized

- 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”)

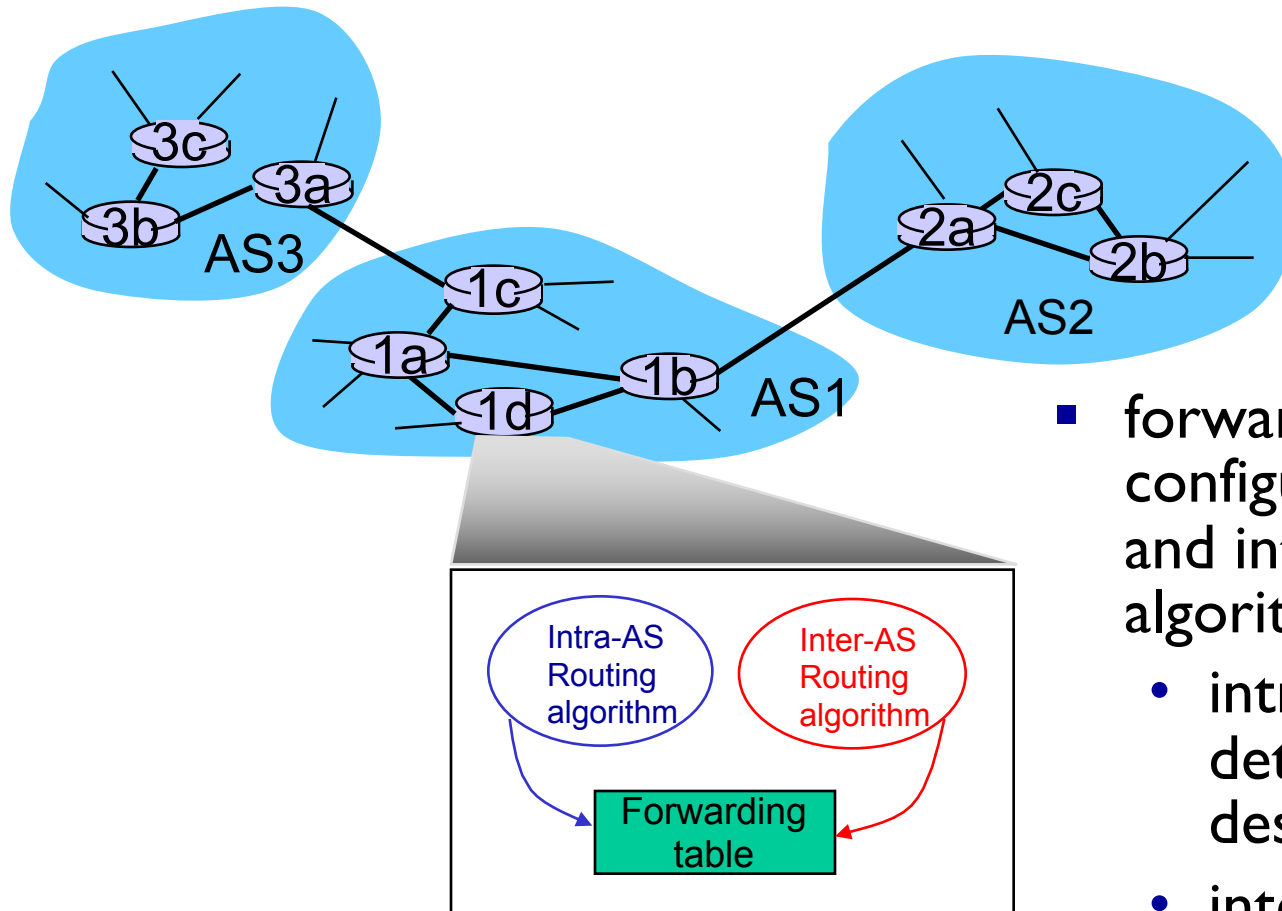
intra-AS routing

- 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

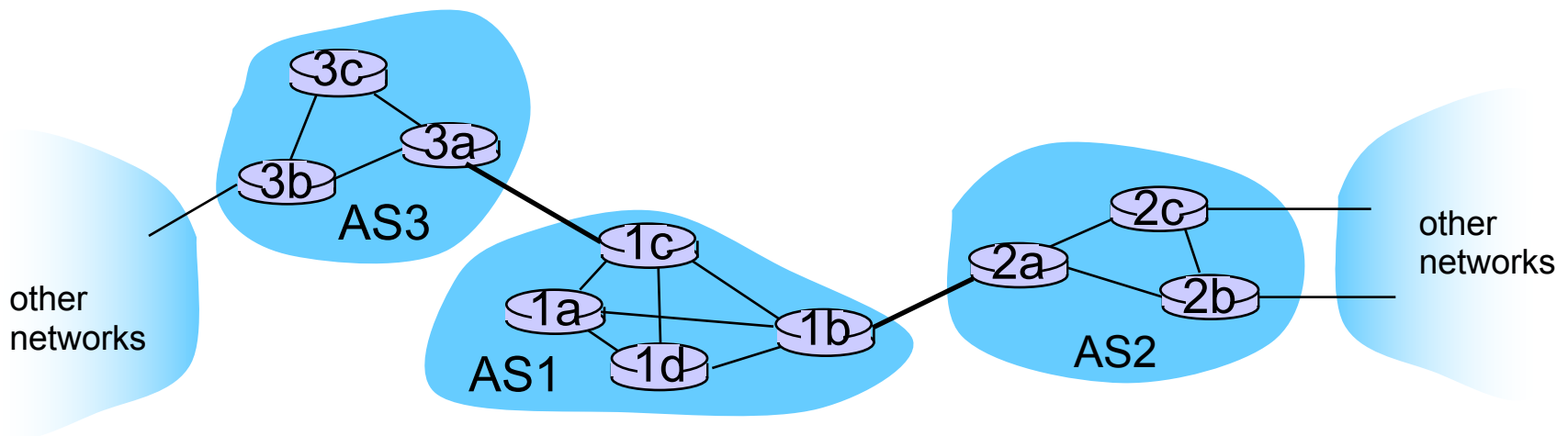
Inter-AS tasks

- 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!



Intra-AS Routing

- also known as *interior gateway protocols (IGP)*
- most common intra-AS routing protocols:
 - RIP: Routing Information Protocol (DV)
 - OSPF: Open Shortest Path First (LS)

OSPF (Open Shortest Path First)

- “open”: publicly available
- uses link-state algorithm
 - 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.

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Internet inter-AS routing: BGP

- **BGP (Border Gateway Protocol):** *the de facto inter-domain routing protocol*
 - “glue that holds the Internet together”
- 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”*

Why different Intra-, Inter-AS routing ?

policy:

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

scale:

- hierarchical routing saves table size, reduced update traffic

performance:

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

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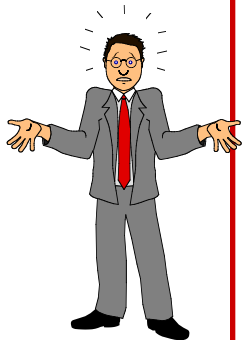
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What is network management?

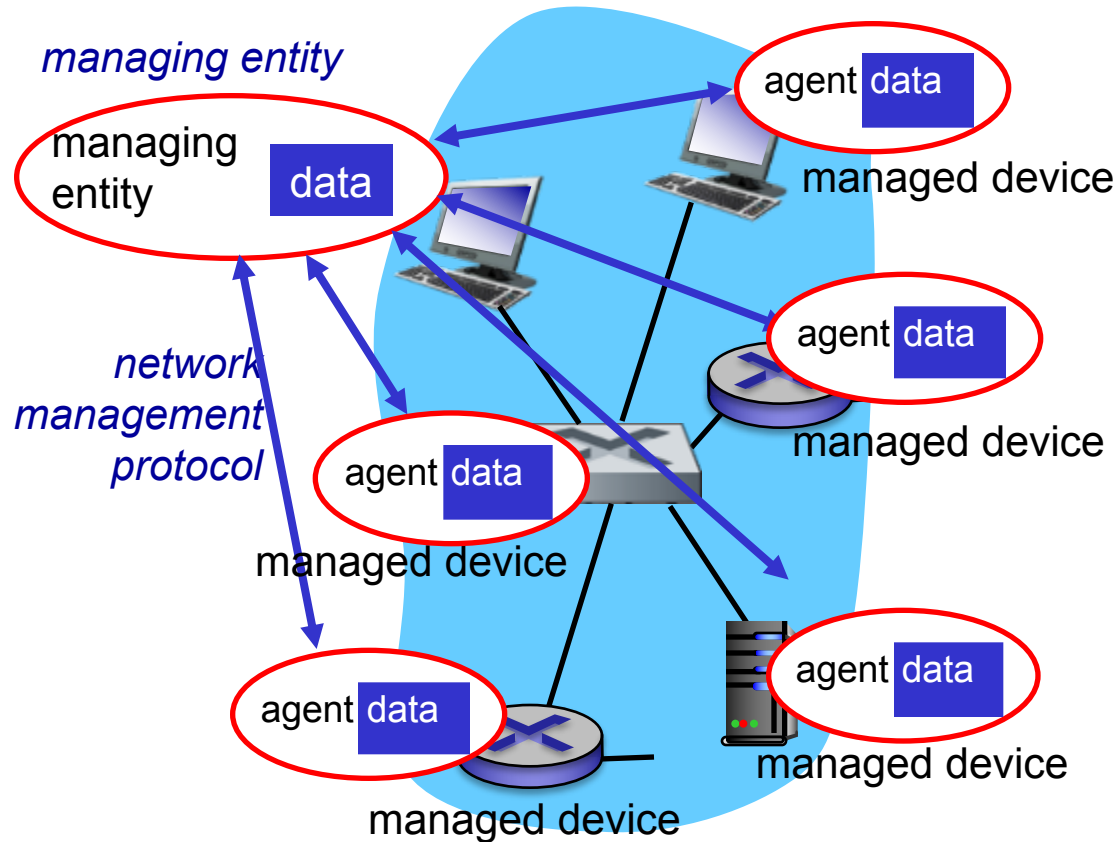
- **autonomous systems** (aka “network”): 1000s of interacting hardware/software components
- other complex systems requiring monitoring, control:
 - jet airplane
 - nuclear power plant
 - others?



"**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

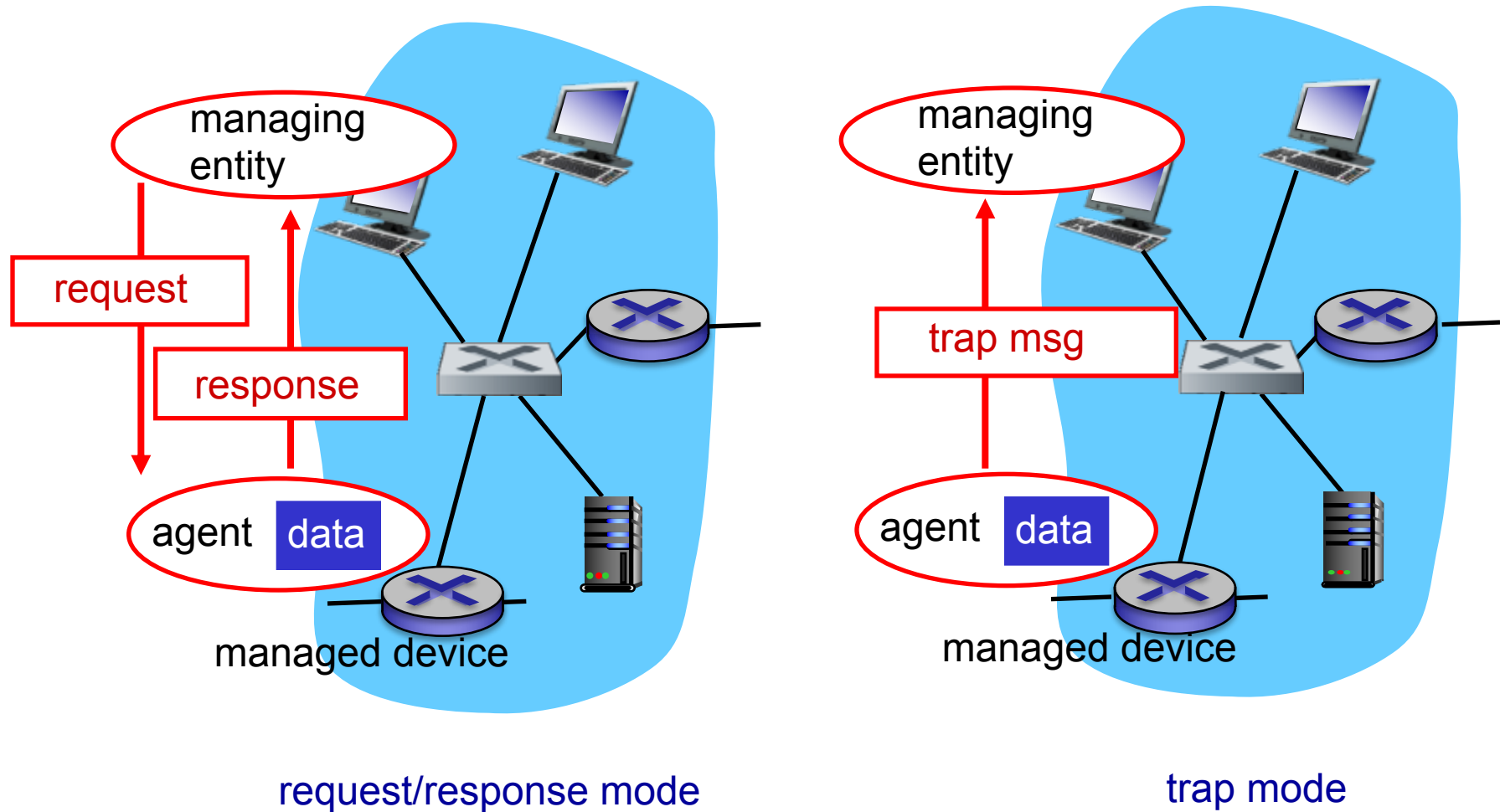
definitions:



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

SNMP protocol

Two ways to convey MIB info, commands:



request/response mode

trap mode