

Chapter 5

Network Layer:

The Control Plane

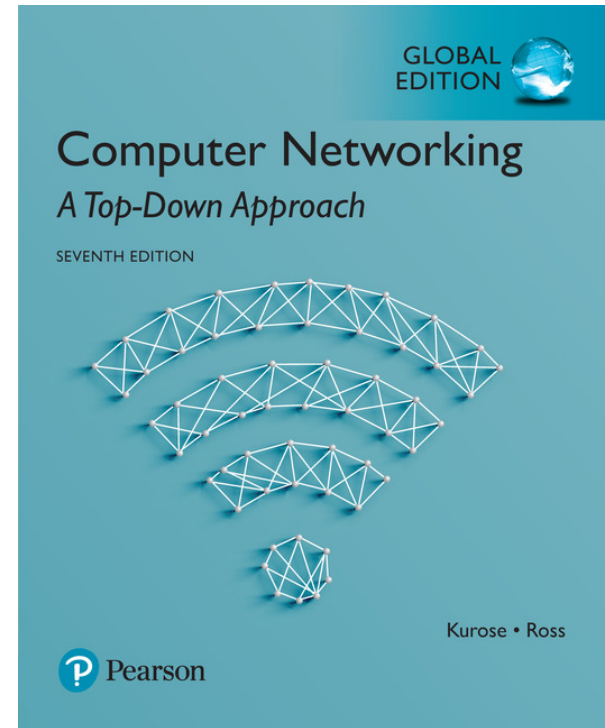
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Computer Networking: A Top Down Approach

7th Edition, Global Edition
Jim Kurose, Keith Ross
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Chapter 5: network layer control plane

chapter goals: understand principles behind network control plane

- ❖ traditional routing algorithms
- ❖ SDN controllers
- ❖ Internet Control Message Protocol
- ❖ network management

and their instantiation, implementation in the Internet:

- ❖ OSPF, BGP, OpenFlow, ODL and ONOS controllers, ICMP, SNMP

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

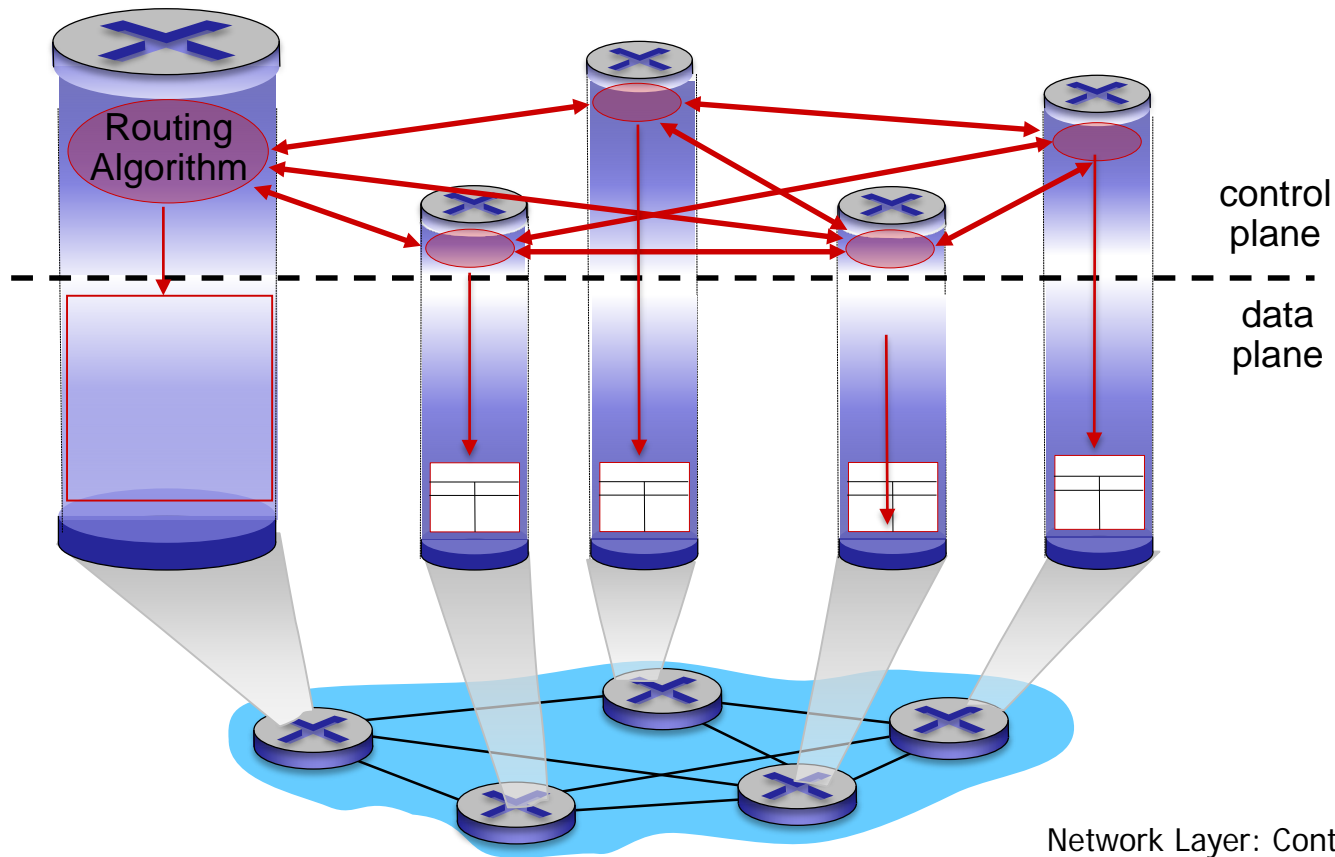
control plane

Two approaches to structuring network control plane:

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

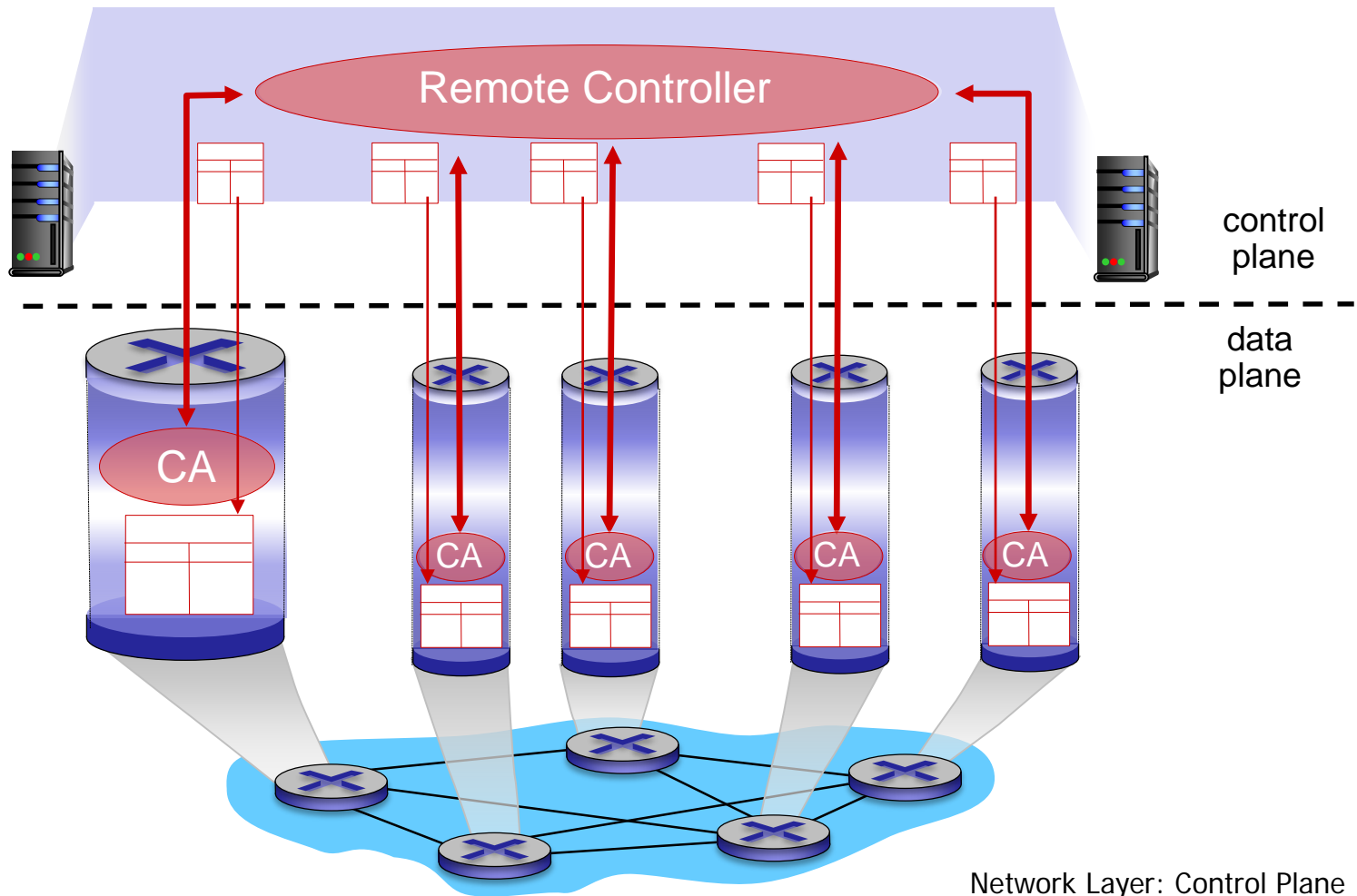
Per-router control plane

Individual routing algorithm components *in each and every router* interact with each other in control plane to compute forwarding tables



Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables



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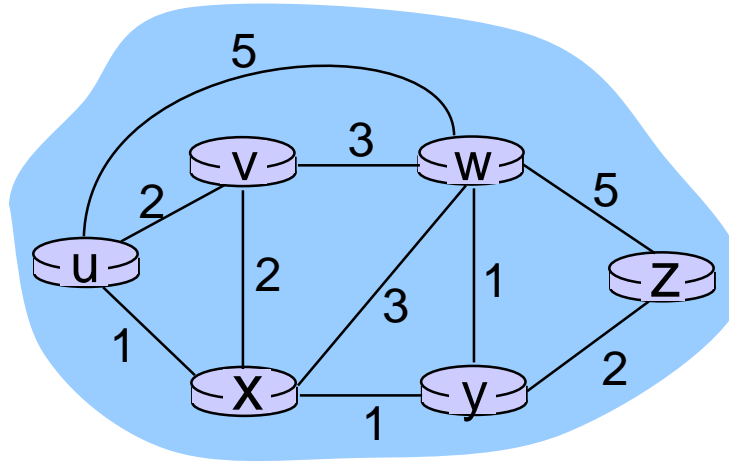
5.7 Network management and SNMP

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



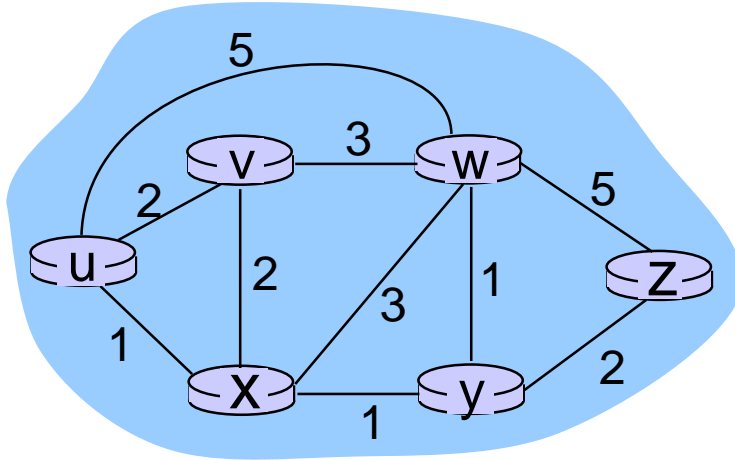
graph: $G = (N, E)$

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 $D(v) = c(u,v)$, $p(v) = u$

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 */

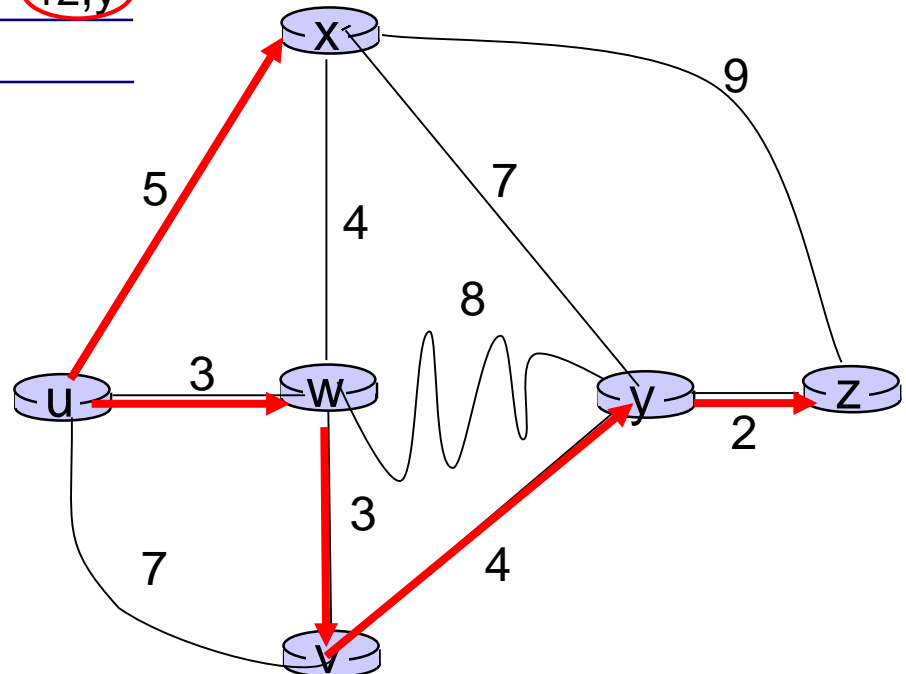
15 **until all nodes in N'**

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					

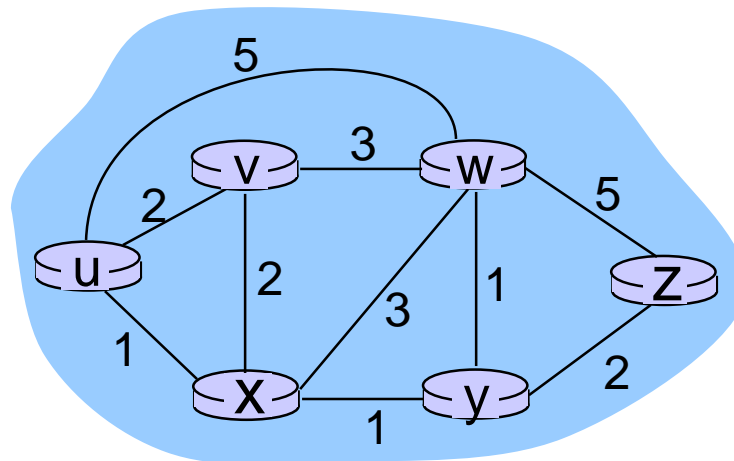
notes:

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



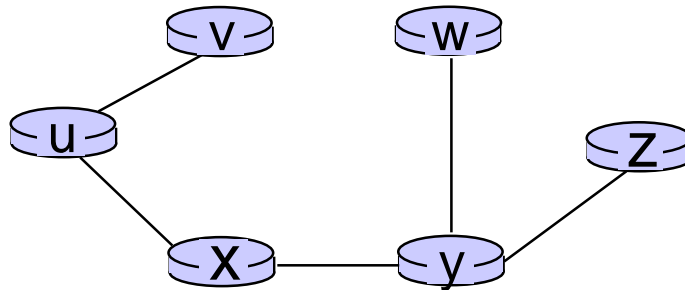
Dijkstra's algorithm: another example

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					



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)

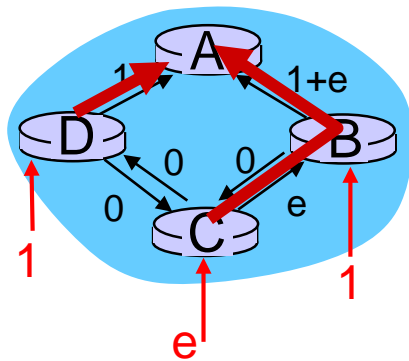
Dijkstra's algorithm, discussion

algorithm complexity: n nodes

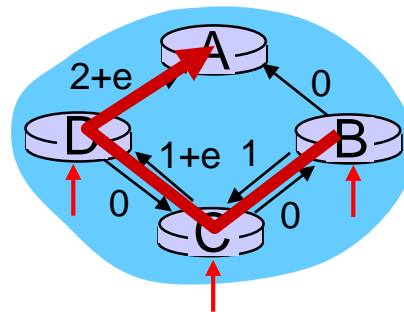
- ❖ each iteration: need to check all nodes, w, not in N
- ❖ $n(n+1)/2$ comparisons: $O(n^2)$
- ❖ more efficient implementations possible: $O(n \log n)$

oscillations possible:

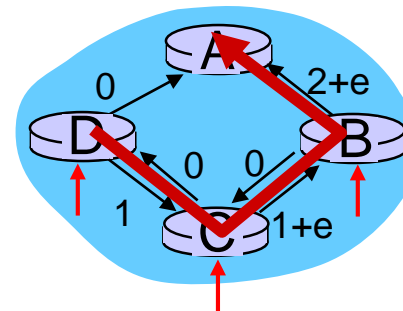
- ❖ e.g., support link cost equals amount of carried traffic:



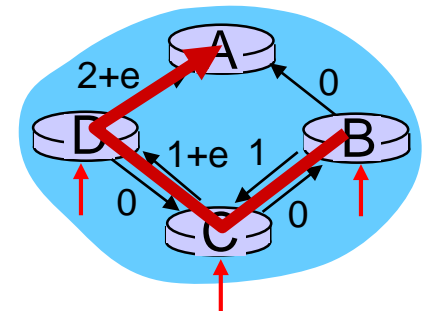
initially



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

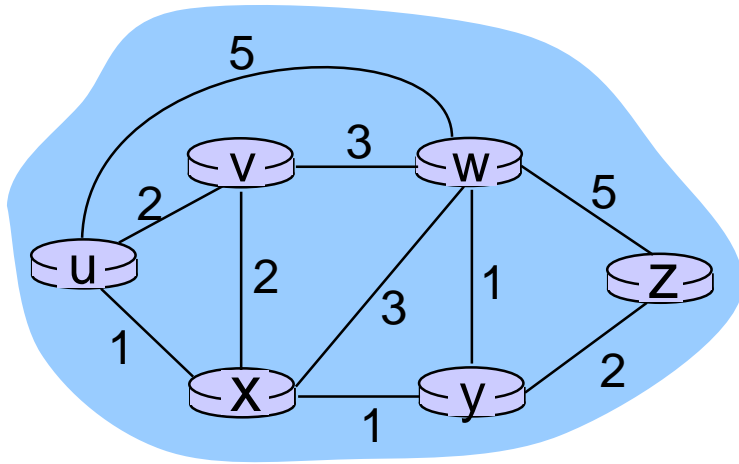
$$d_x(y) = \min_v \{ c(x,v) + d_v(y) \}$$

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:

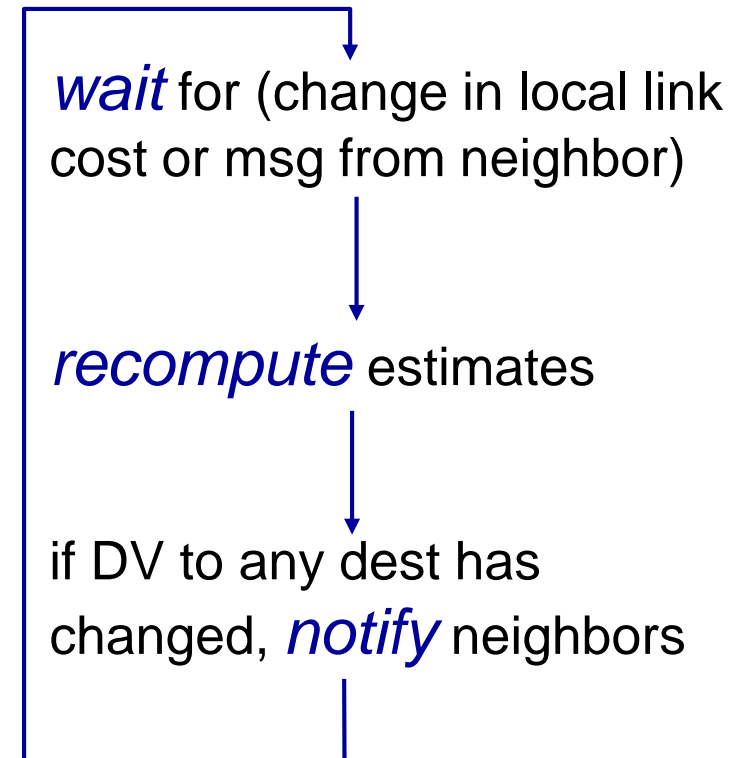
each local iteration
caused by:

- ❖ 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	∞	∞	∞

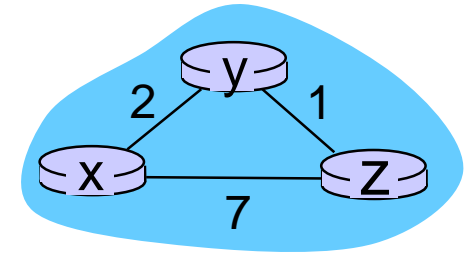
		cost to		
		x	y	z
from	x	0	2	3
	y	2	0	1
	z	7	1	0

**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
	y	∞	∞	∞
	z	∞	∞	∞

**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

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

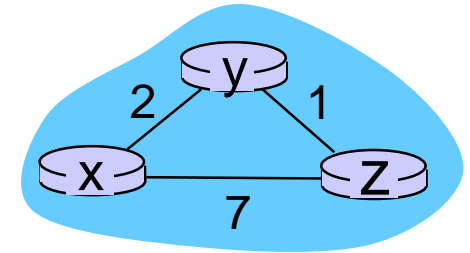
		cost to		
		x	y	z
from	x	0	2	7
	y	2	0	1
	z	7	1	0

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

		cost to		
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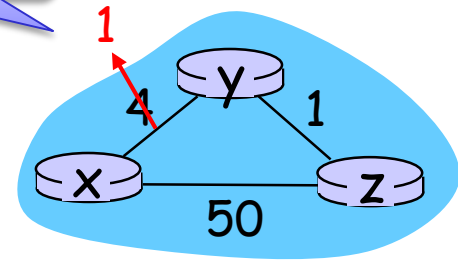
time

Distance vector: link cost changes

link cost changes:

- ❖ node detects local link cost change
- ❖ updates routing info, recalculates distance vector
- ❖ if DV changes, notify neighbors

Link cost from y to x changes from 4 to 1



“good
news
travels
fast”

t_0 : y detects link-cost change, updates its DV, informs its neighbors.

t_1 : z receives update from y, updates its table, computes new least cost to x, sends its neighbors its DV.

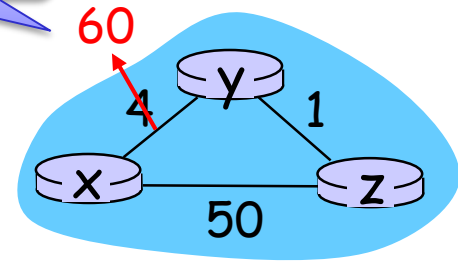
t_2 : y receives z's update, updates its distance table. y's least costs do *not* change, so y does *not* send a message to z.

Distance vector: link cost changes

link cost changes:

- ❖ node detects local link cost change
- ❖ *bad news travels slow* - “count to infinity” problem!
- ❖ 44 iterations before algorithm stabilizes: see text

Link cost from y to x changes from 4 to 60



poisoned reverse:

- ❖ If Z routes through Y to get to X :
 - Z tells Y its (Z' s) distance to X is infinite (so Y won't route to X via Z)
- ❖ will this completely solve count to infinity problem?

from	x	y	z	→	x	y	z	
	x	0	4		x	0	4	
	y	4	0		y	6	0	
	z	5	1		z	5	1	
	x	y	z	→	x	y	z	
	x	0	4		x	0	4	
	y	6	0		y	6	0	
	z	5	1		z	7	1	
	x	y	z	→	x	y	z	
	x	0	4		x	0	4	
	y	6	0		y	8	0	
	z	7	1		z	7	1	

Comparison of LS and DV algorithms

message complexity

- ❖ **LS:** with n nodes, E links, $O(nE)$ msgs sent
- ❖ **DV:** exchange between neighbors only
 - convergence time varies

speed of convergence

- ❖ **LS:** $O(n^2)$ algorithm requires $O(nE)$ msgs
 - may have oscillations
- ❖ **DV:** convergence time varies
 - may be routing loops
 - count-to-infinity problem

robustness: what happens if router malfunctions?

LS:

- node can advertise incorrect *link* cost
- each node computes only its own table

DV:

- DV node can advertise incorrect *path* cost
- each node's table used by others
 - error propagate thru network

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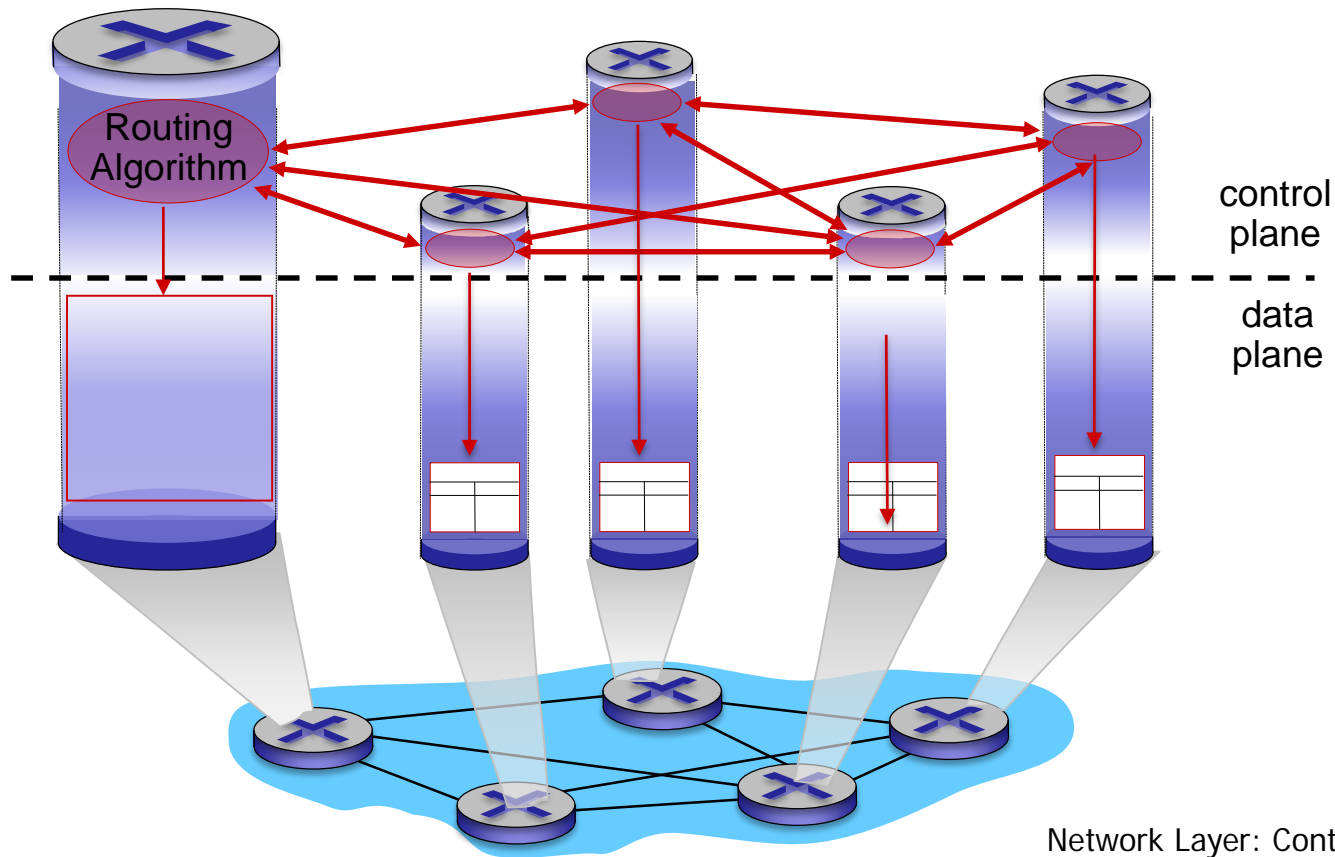
5.7 Network management and SNMP

Software defined networking (SDN)

- ❖ Internet network layer: historically has been implemented via distributed, per-router approach
 - *monolithic* router contains switching hardware, runs proprietary implementation of Internet standard protocols (IP, RIP, IS-IS, OSPF, BGP) in proprietary router OS (e.g., Cisco IOS)
 - different “middleboxes” for different network layer functions: firewalls, load balancers, NAT boxes, ..
- ❖ ~2005: renewed interest in rethinking network control plane

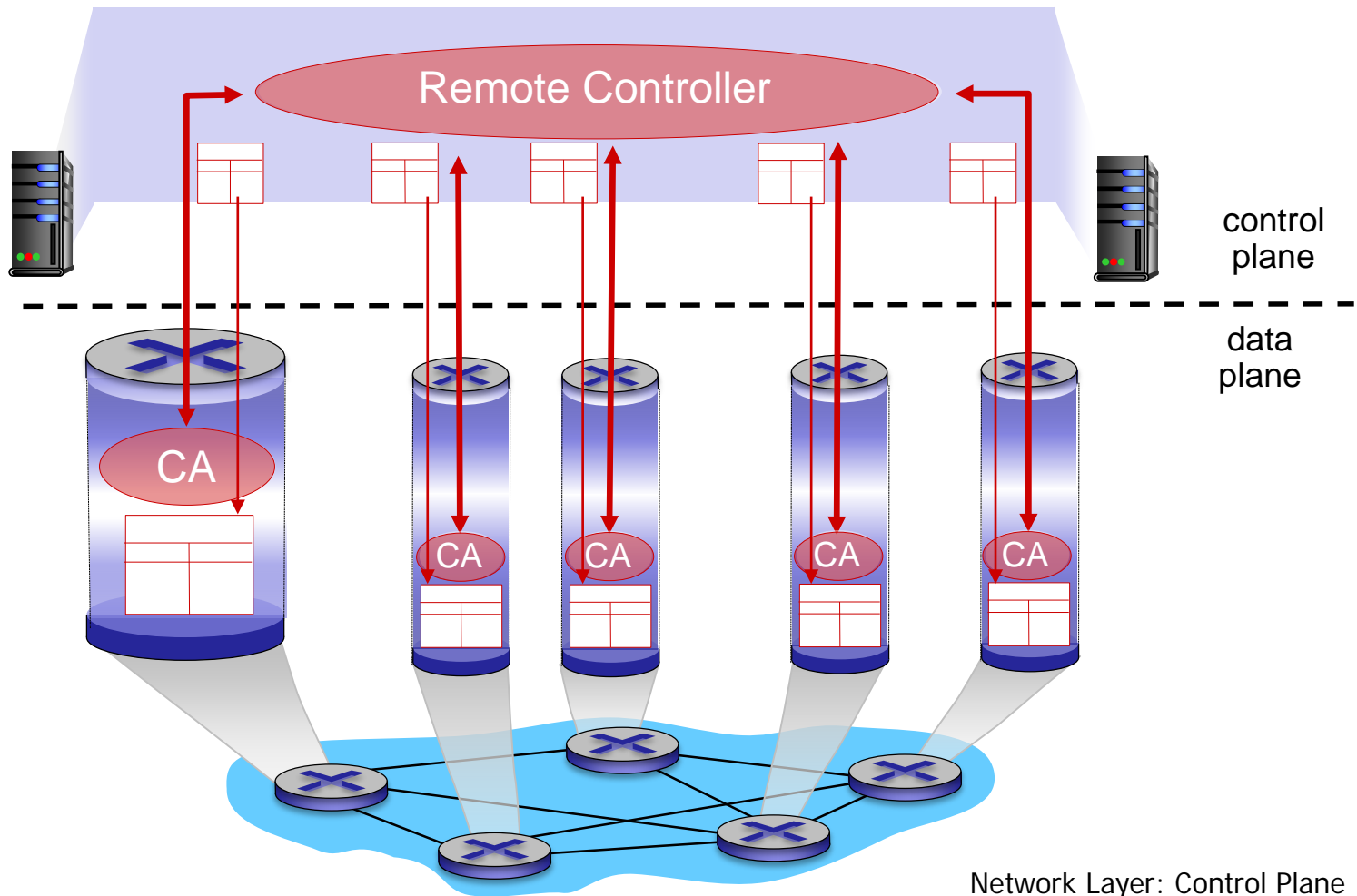
Recall: per-router control plane

Individual routing algorithm components *in each and every router* interact with each other in control plane to compute forwarding tables



Recall: logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables



Software defined networking (SDN)

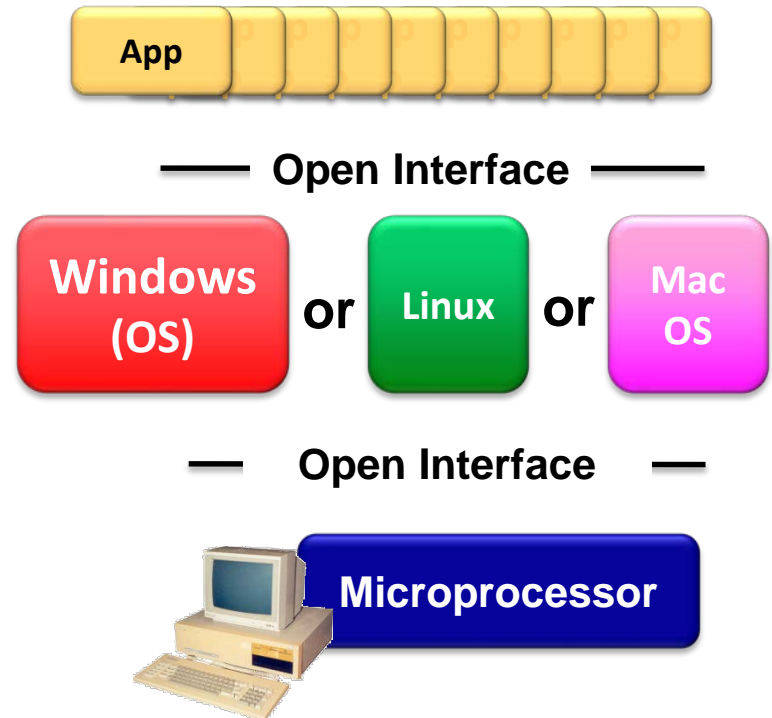
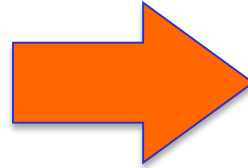
Why a *logically centralized* control plane?

- ❖ easier network management: avoid router misconfigurations, greater flexibility of traffic flows
- ❖ table-based forwarding (recall OpenFlow API) allows “programming” routers
 - centralized “programming” easier: compute tables centrally and distribute
 - distributed “programming” more difficult: compute tables as result of distributed algorithm (protocol) implemented in each and every router
- ❖ open (non-proprietary) implementation of control plane

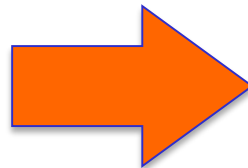
Analogy: mainframe to PC evolution*



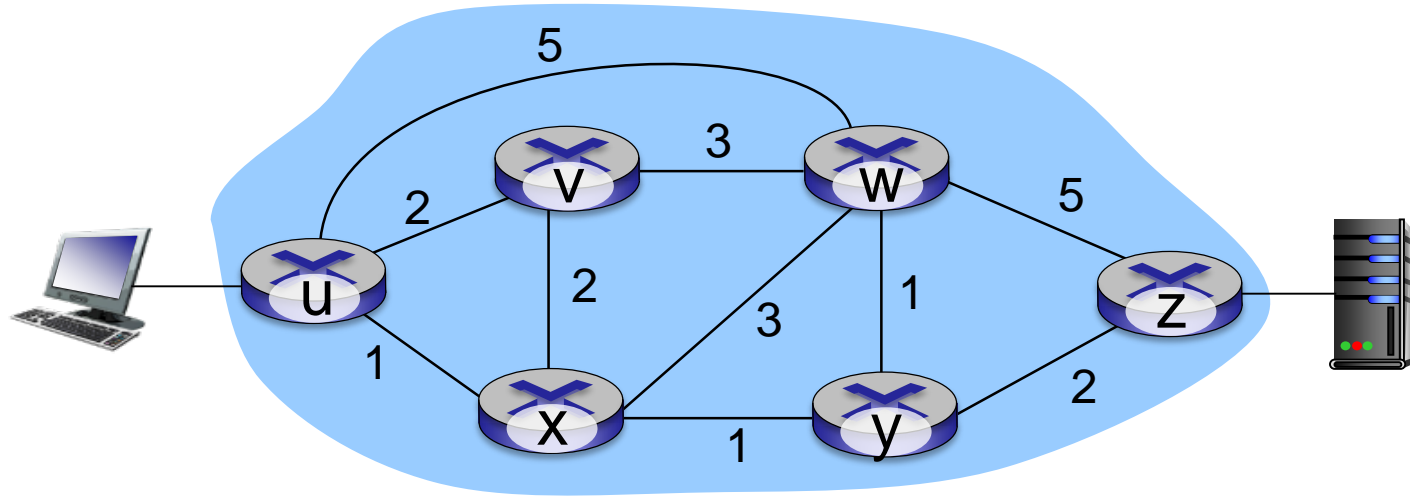
Vertically integrated
Closed, proprietary
Slow innovation
Small industry



Horizontal
Open interfaces
Rapid innovation
Huge industry



Traffic engineering: difficult traditional routing

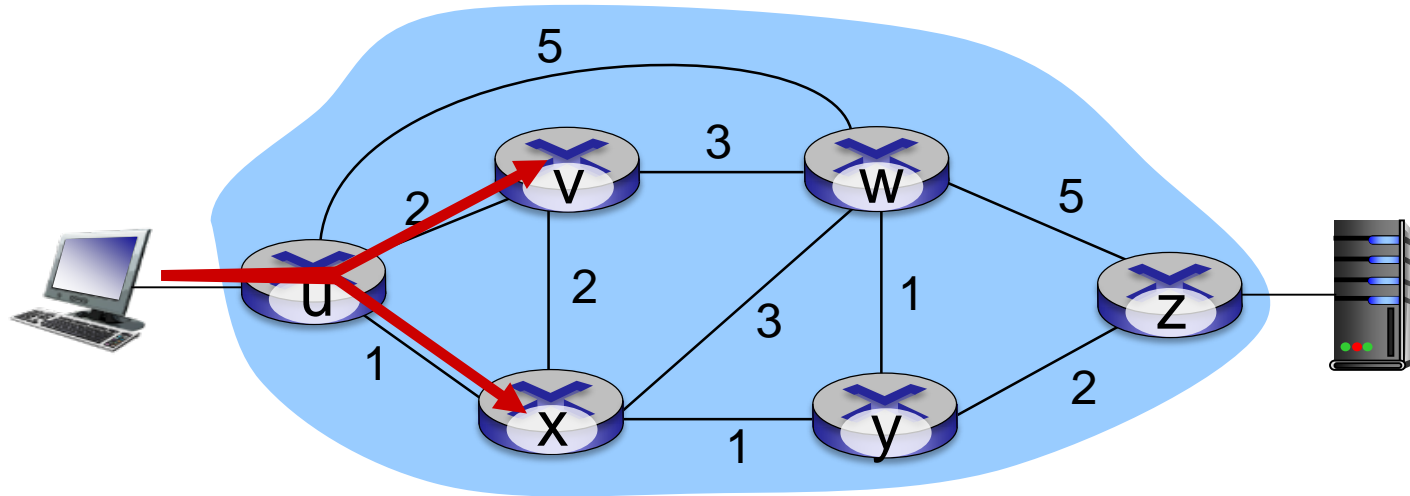


Q: what if network operator wants u-to-z traffic to flow along $uvwz$, x-to-z traffic to flow $xwyz$?

A: need to define link weights so traffic routing algorithm computes routes accordingly (or need a new routing algorithm)!

Link weights are only control “knobs”: wrong!

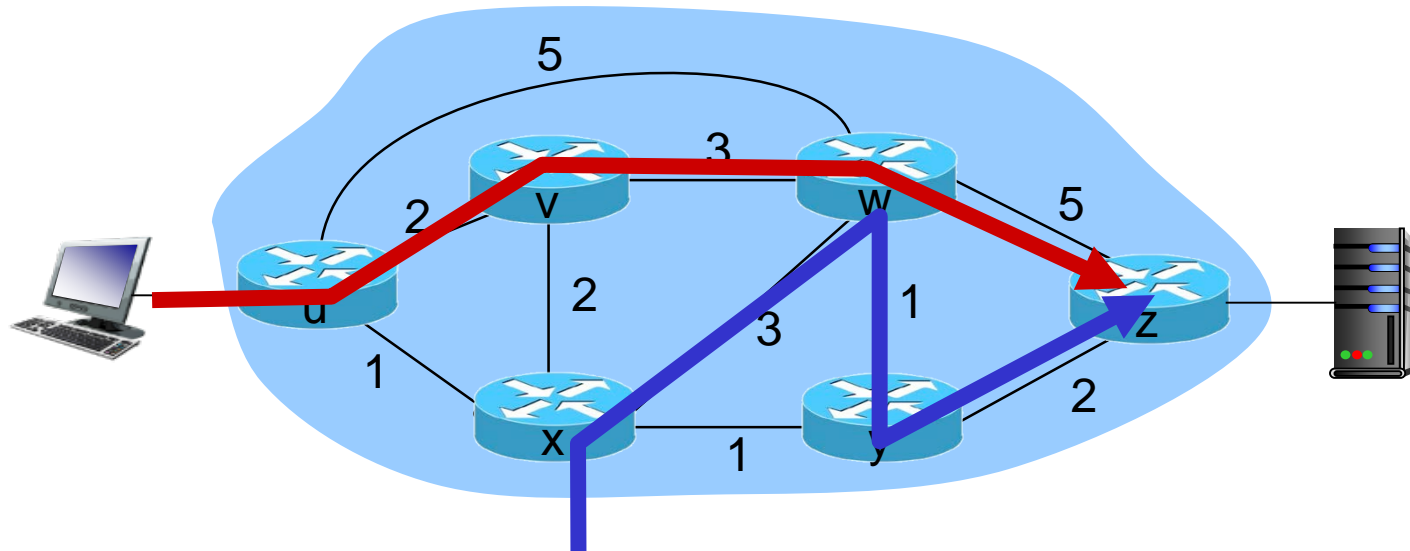
Traffic engineering: difficult



Q: what if network operator wants to split u-to-z traffic along uvwz *and* uxyz (load balancing)?

A: can't do it (or need a new routing algorithm)

Traffic engineering: difficult



Q: what if w wants to route blue and red traffic differently?

A: can't do it (with destination based forwarding, and LS, DV routing)

Software defined networking (SDN)

4. programmable control applications

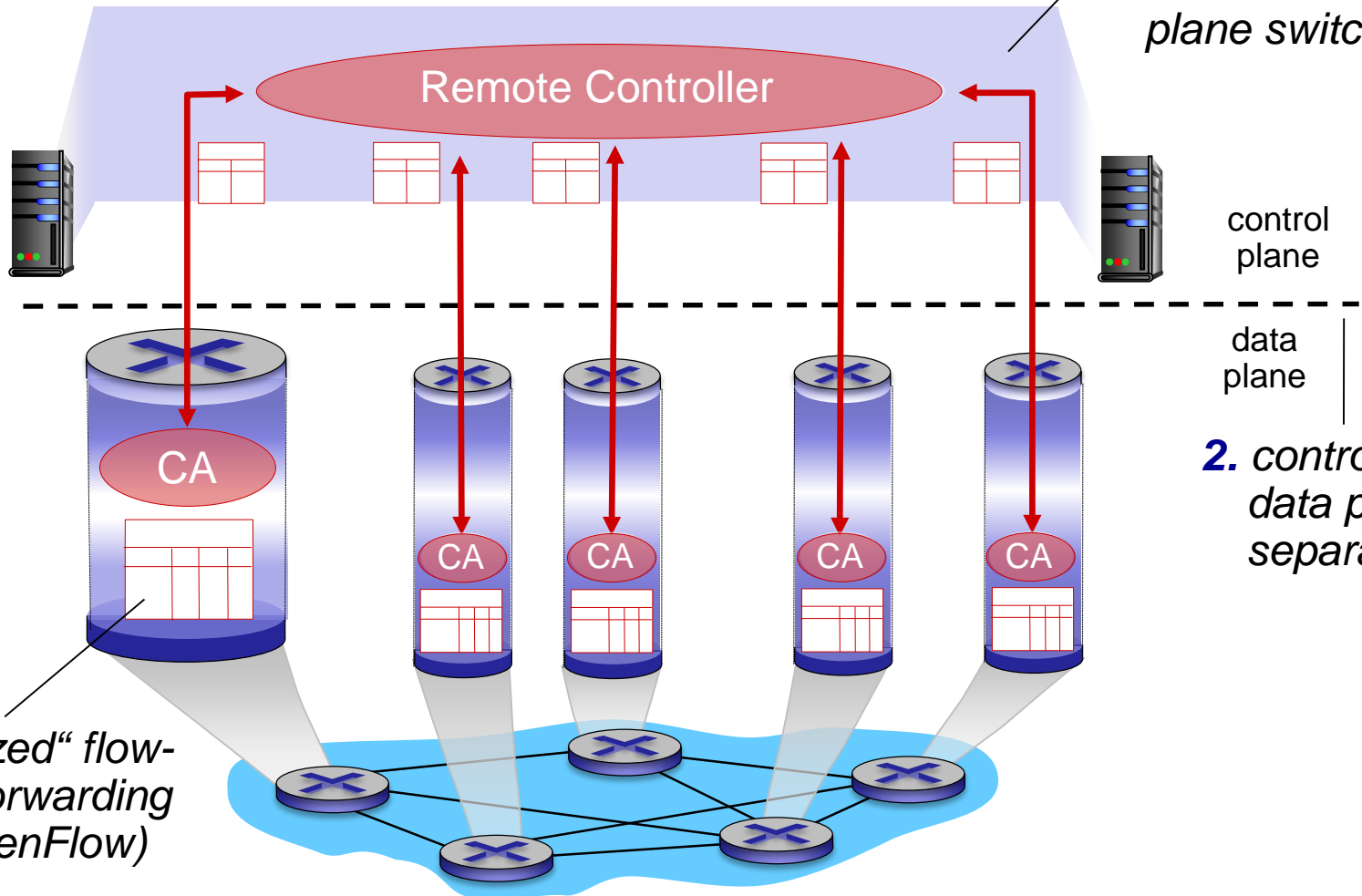
routing

access control

...

load balance

3. control plane functions external to data-plane switches



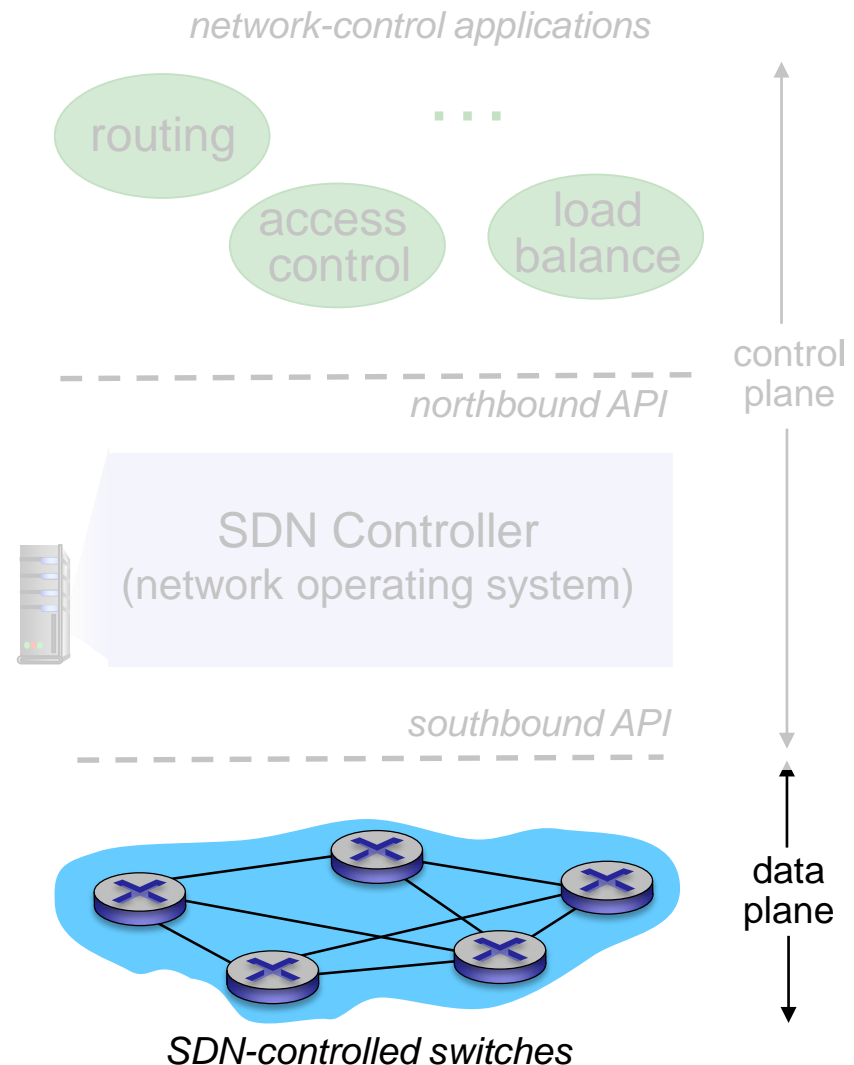
1. generalized "flow-based" forwarding (e.g., OpenFlow)

2. control, data plane separation

SDN perspective: data plane switches

Data plane switches

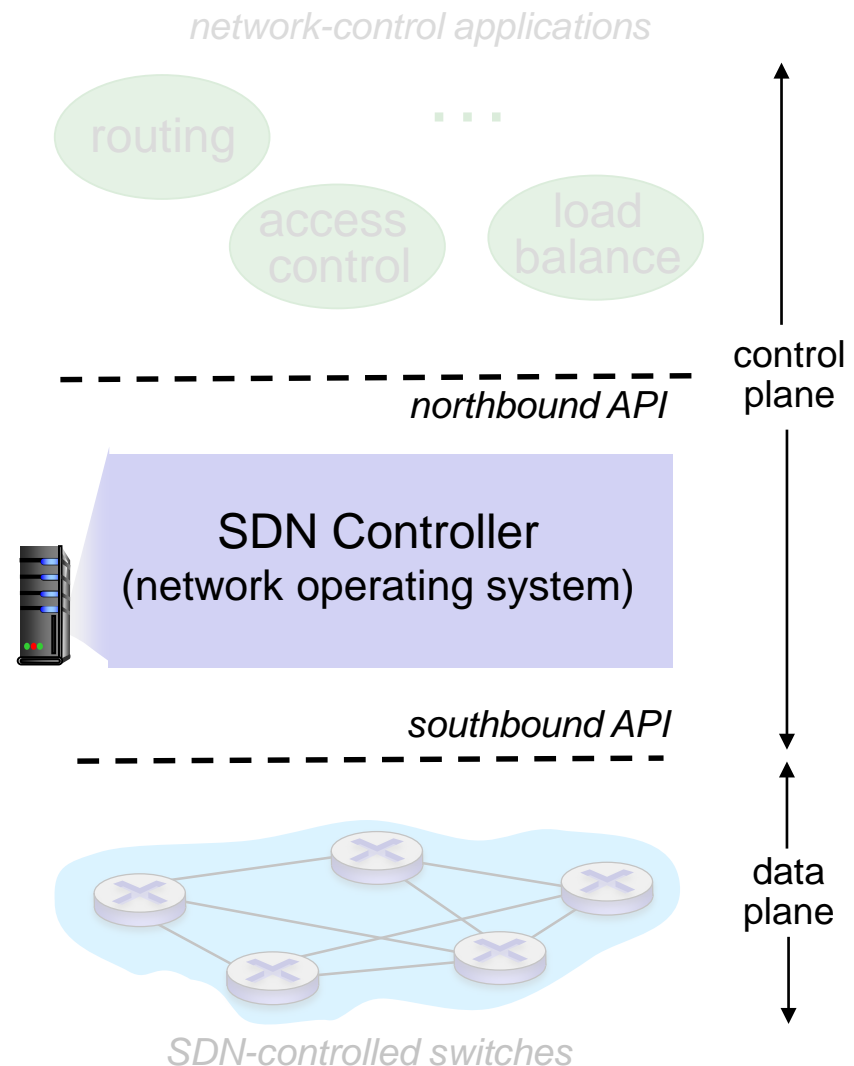
- ❖ fast, simple, commodity switches implementing generalized data-plane forwarding (Section 4.4) in hardware
- ❖ switch flow table computed, installed by controller
- ❖ API for table-based switch control (e.g., OpenFlow)
 - defines what is controllable and what is not
- ❖ protocol for communicating with controller (e.g., OpenFlow)



SDN perspective: SDN controller

SDN controller (network OS):

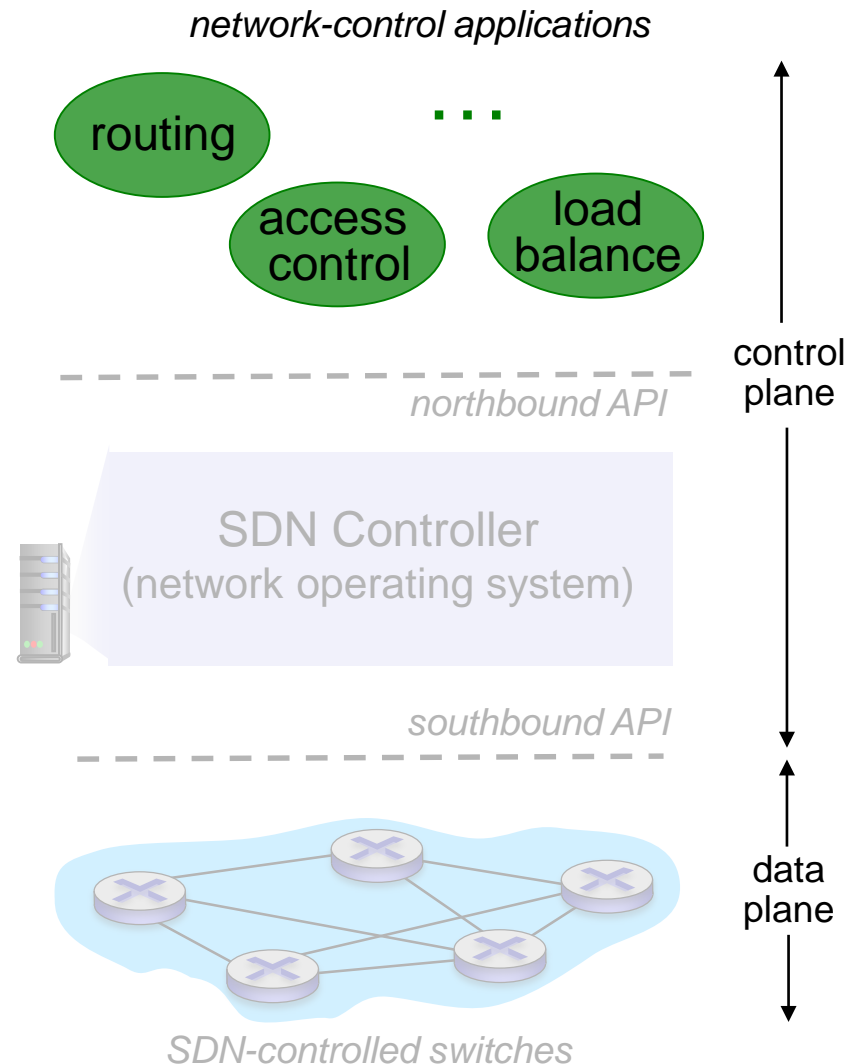
- maintain network state information
- interacts with network control applications “above” via northbound API
- interacts with network switches “below” via southbound API
- implemented as distributed system for performance, scalability, fault-tolerance, robustness



SDN perspective: control applications

network-control apps:

- “brains” of control: implement control functions using lower-level services, API provided by SDN controller
- *unbundled*: can be provided by 3rd party: distinct from routing vendor, or SDN controller

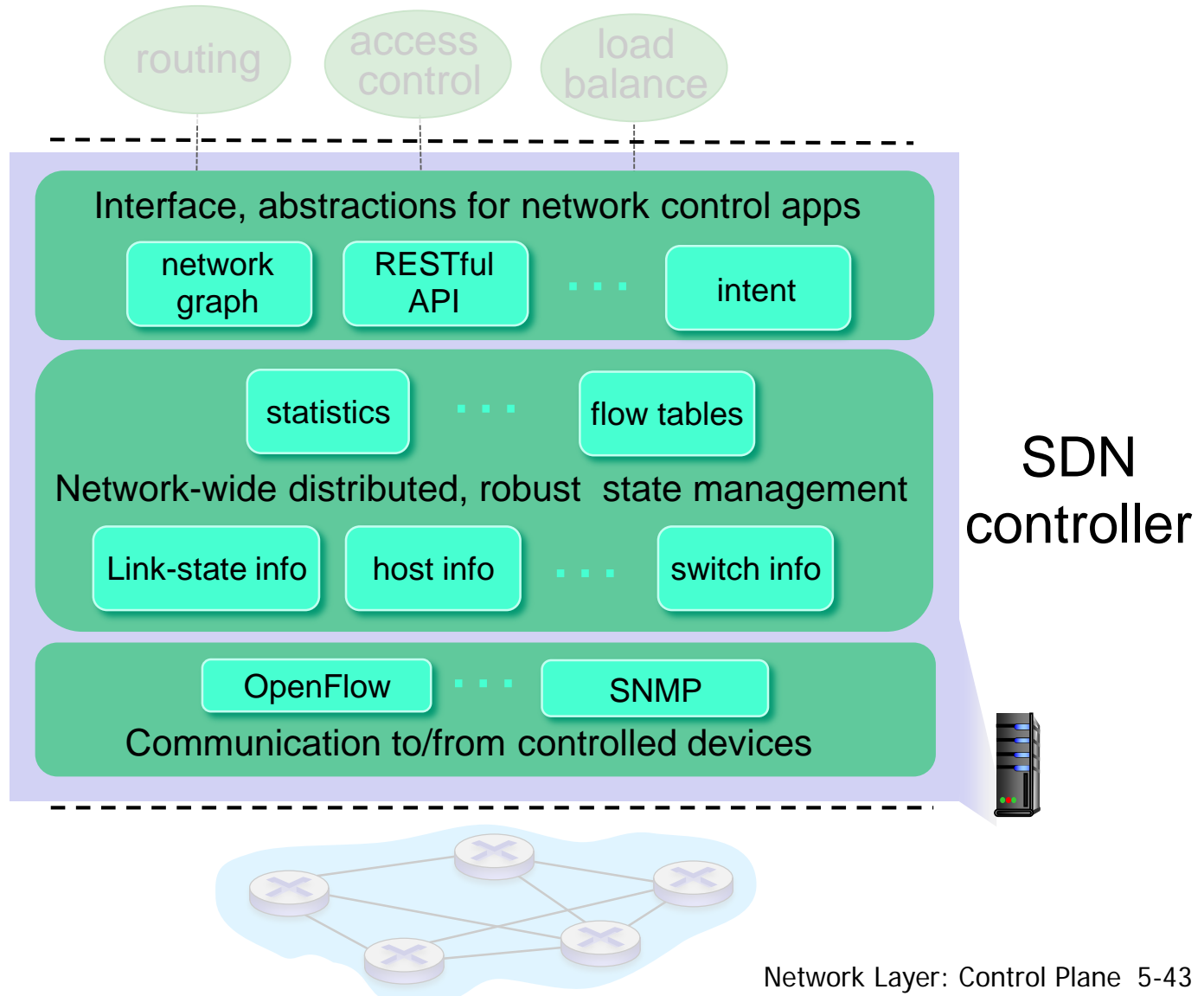


Components of SDN controller

Interface layer to network control apps: abstractions API

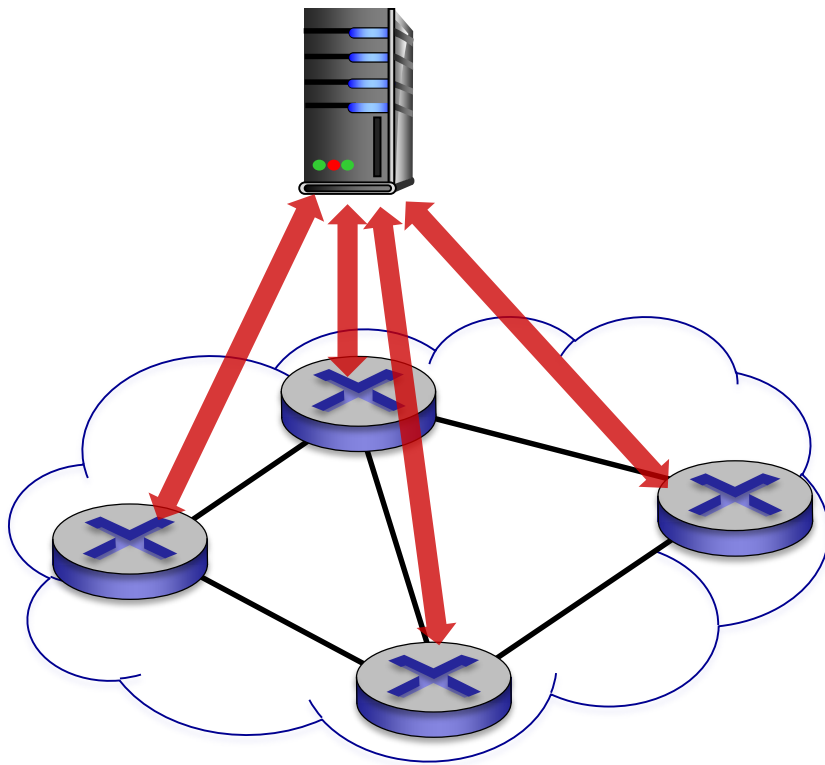
Network-wide state management layer: state of networks links, switches, services: a *distributed database*

communication layer: communicate between SDN controller and controlled switches



OpenFlow protocol

OpenFlow Controller

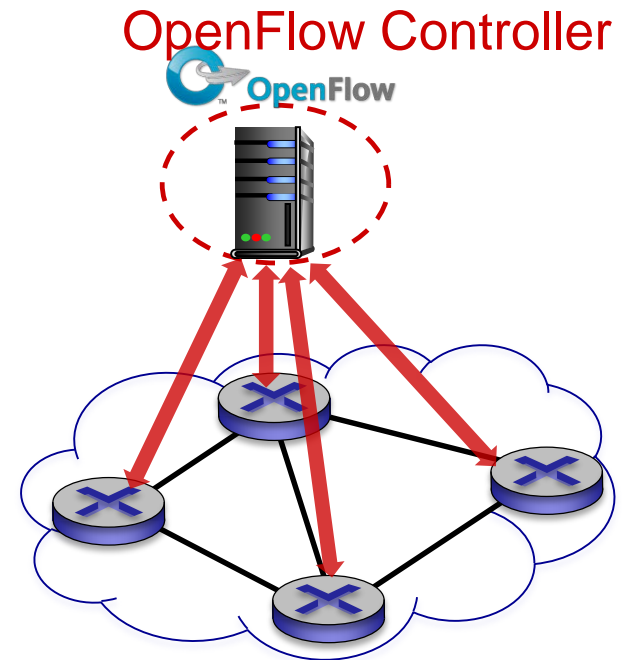


- ❖ operates between controller, switch
- ❖ TCP used to exchange messages
 - optional encryption
- ❖ three classes of OpenFlow messages:
 - controller-to-switch
 - asynchronous (switch to controller)
 - symmetric (misc)

OpenFlow: controller-to-switch messages

Key controller-to-switch messages

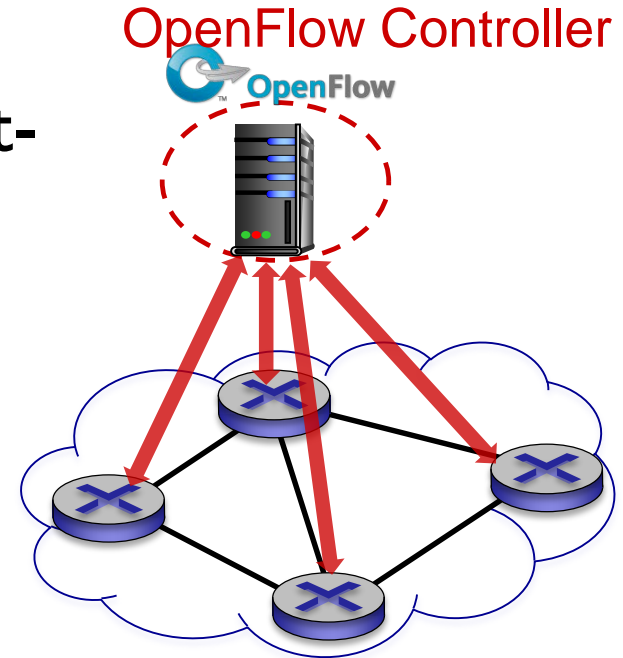
- ❖ *features*: controller queries switch features, switch replies
- ❖ *configure*: controller queries/sets switch configuration parameters
- ❖ *modify-state*: add, delete, modify flow entries in the OpenFlow tables
- ❖ *packet-out*: controller can send this packet out of specific switch port



OpenFlow: switch-to-controller messages

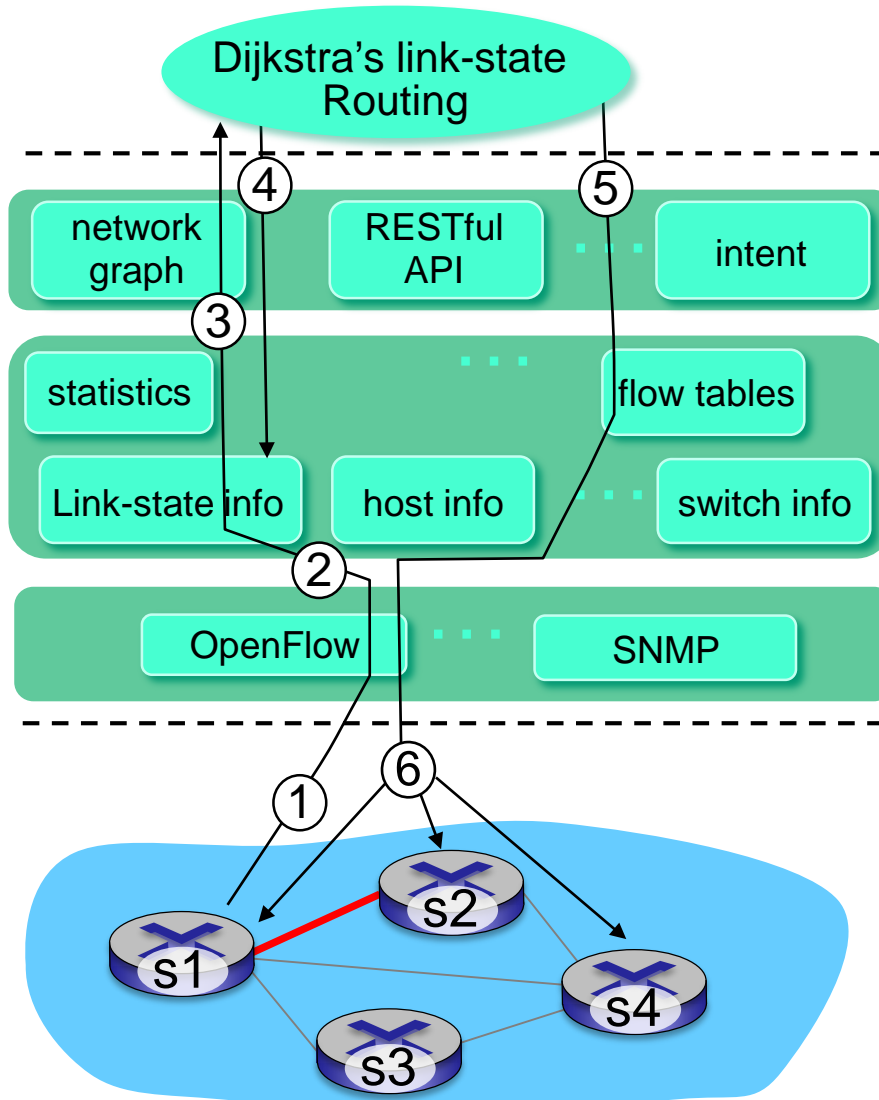
Key switch-to-controller messages

- ❖ **packet-in**: transfer packet (and its control) to controller. See packet-out message from controller
- ❖ **flow-removed**: flow table entry deleted at switch
- ❖ **port status**: inform controller of a change on a port.



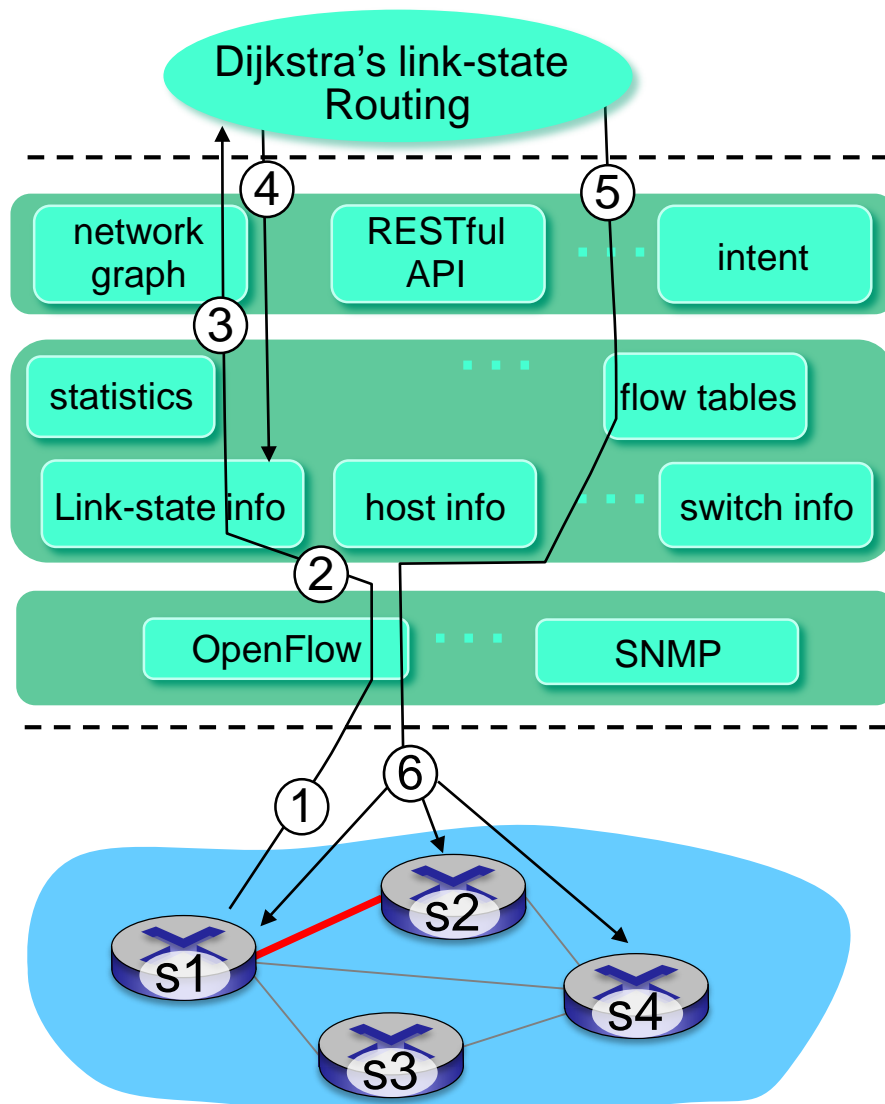
Fortunately, network operators don't "program" switches by creating/sending OpenFlow messages directly. Instead use higher-level abstraction at controller

SDN: control/data plane interaction example



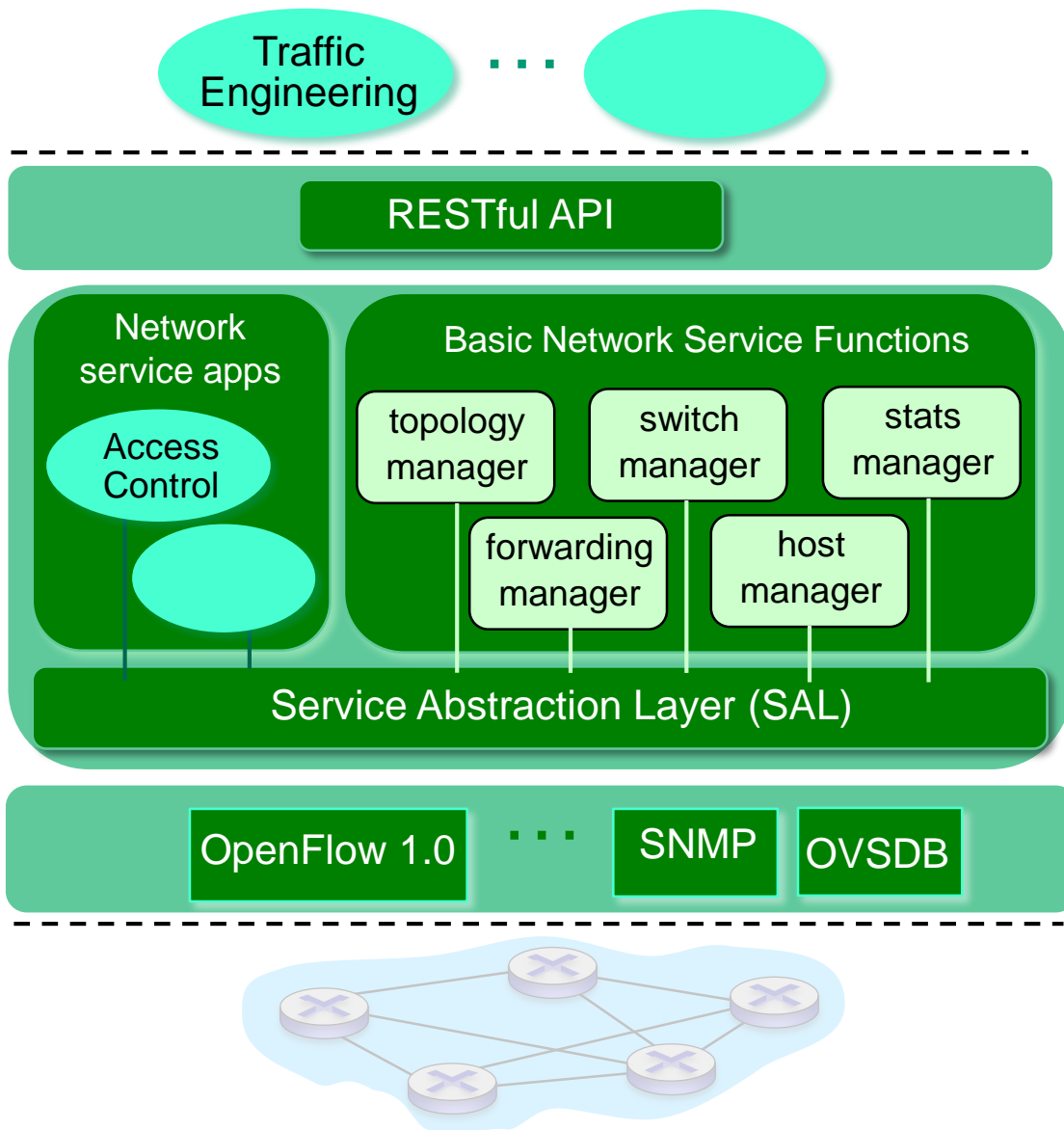
- ① s1, experiencing link failure using OpenFlow port status message to notify controller
- ② SDN controller receives OpenFlow message, updates link status info
- ③ Dijkstra's routing algorithm application has previously registered to be called when ever link status changes. It is called.
- ④ Dijkstra's routing algorithm access network graph info, link state info in controller, computes new routes

SDN: control/data plane interaction example



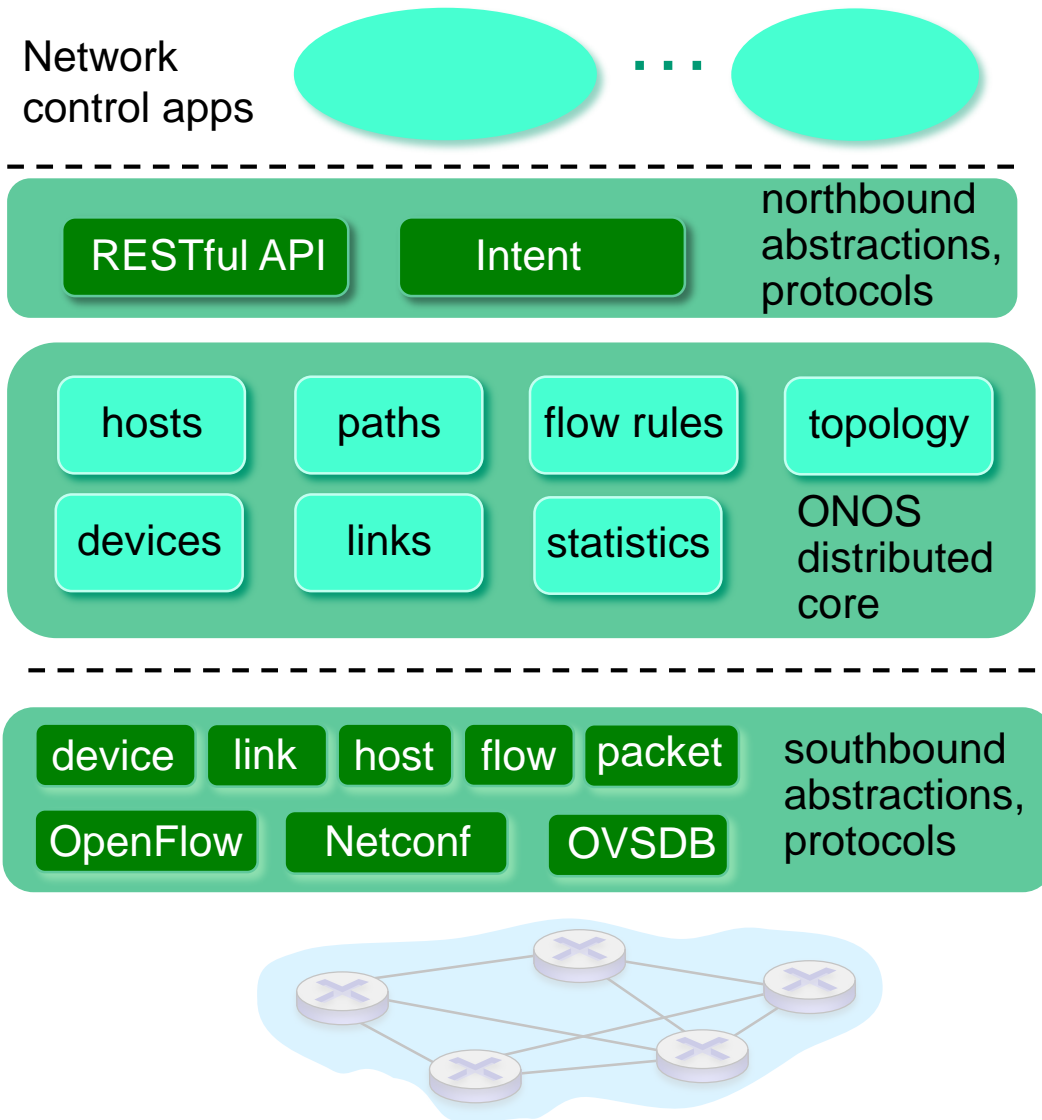
- ⑤ link state routing app interacts with flow-table-computation component in SDN controller, which computes new flow tables needed
- ⑥ Controller uses OpenFlow to install new tables in switches that need updating

OpenDaylight (ODL) controller



- ODL Lithium controller
- network apps may be contained within, or be external to SDN controller
- Service Abstraction Layer: interconnects internal, external applications and services

ONOS controller



- control apps separate from controller
- intent framework: high-level specification of service: what rather than how
- considerable emphasis on distributed core: service reliability, replication performance scaling

SDN: selected challenges

- ❖ hardening the control plane: dependable, reliable, performance-scalable, secure distributed system
 - robustness to failures: leverage strong theory of reliable distributed system for control plane
 - dependability, security: “baked in” from day one?
- ❖ networks, protocols meeting mission-specific requirements
 - e.g., real-time, ultra-reliable, ultra-secure
- ❖ Internet-scaling

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

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

<u>Type</u>	<u>Code</u>	<u>description</u>
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

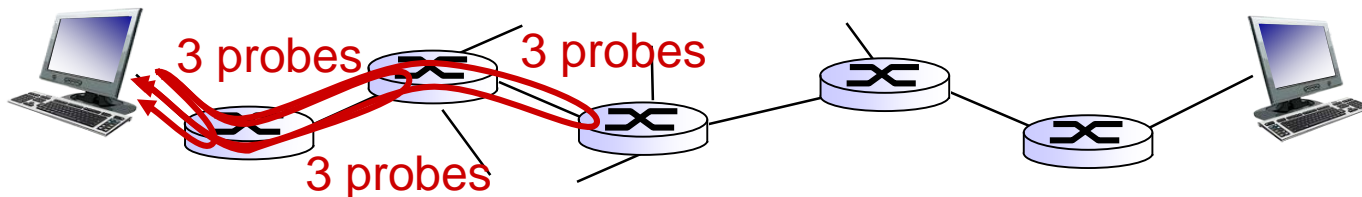
Traceroute and ICMP

- ❖ 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 n th router:
 - router discards datagram and sends source ICMP message (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



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

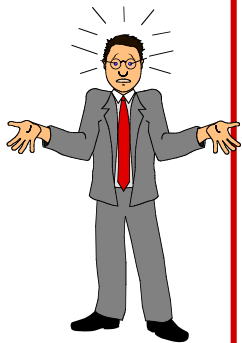
5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

What is network management?

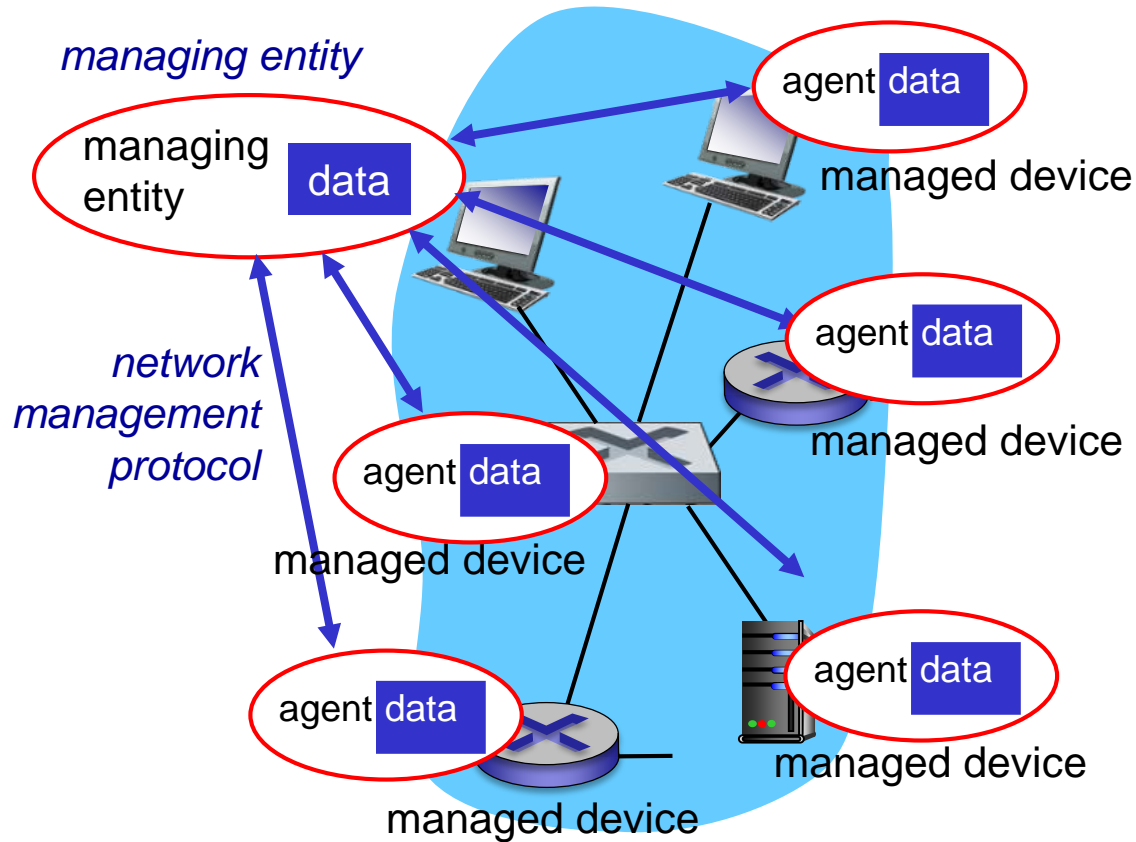
- ❖ **autonomous systems (aka “network”)**: 1000s of interacting hardware/software components
- ❖ other complex systems requiring monitoring, control:
 - jet airplane
 - nuclear power plant
 - others?



"**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

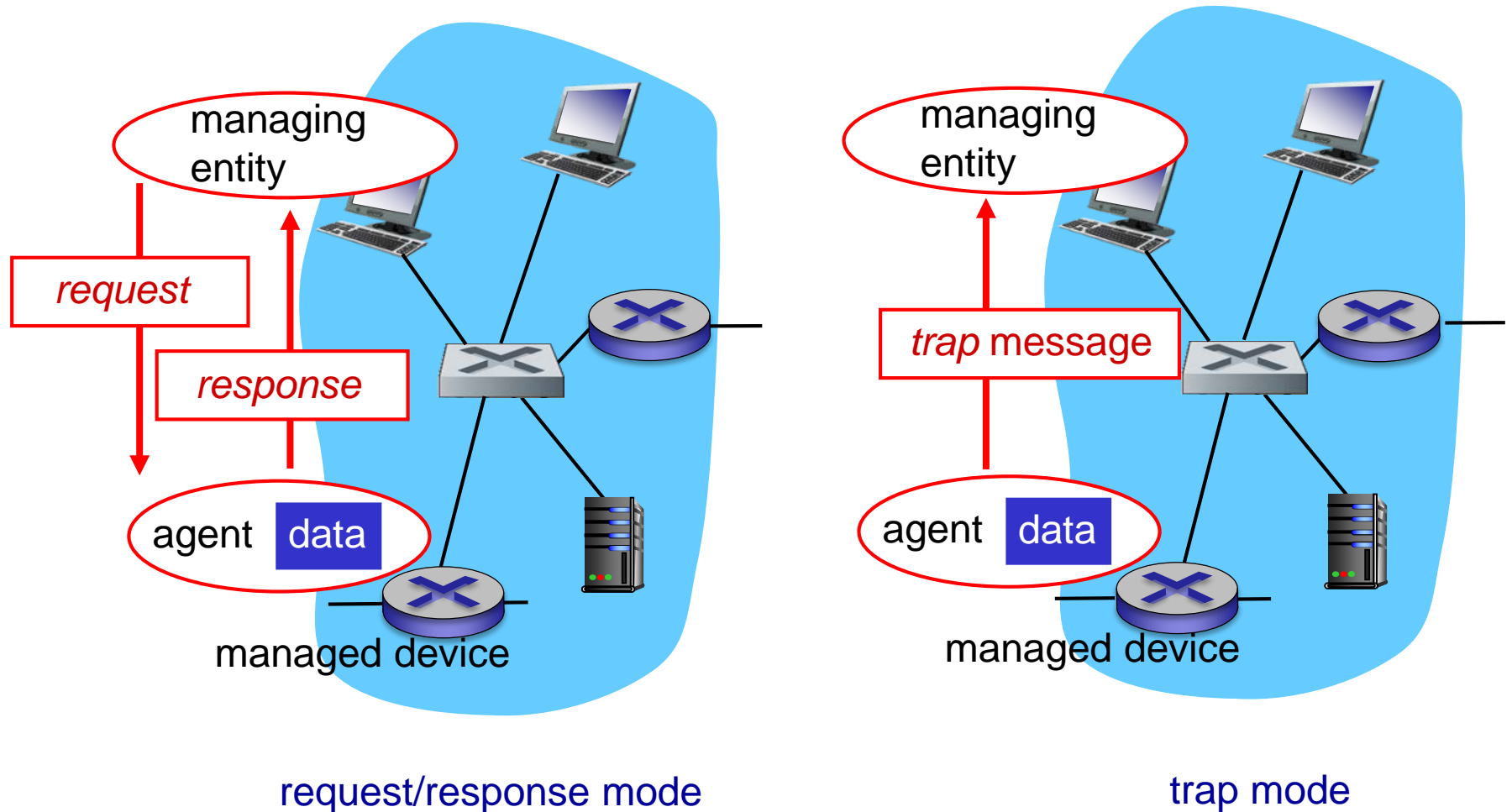
definitions:



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

SNMP protocol

Two ways to convey MIB info, commands:



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

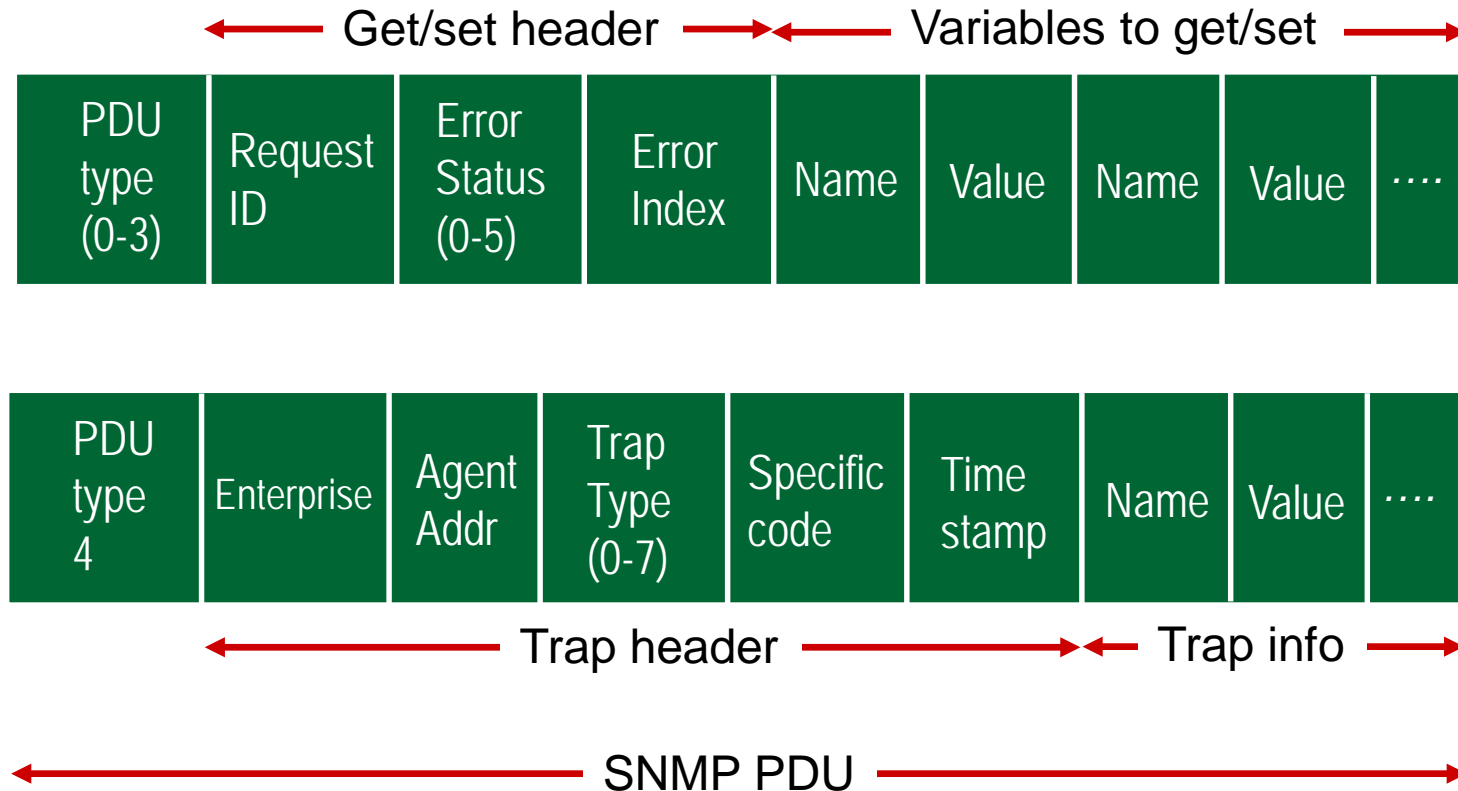
Response

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!