



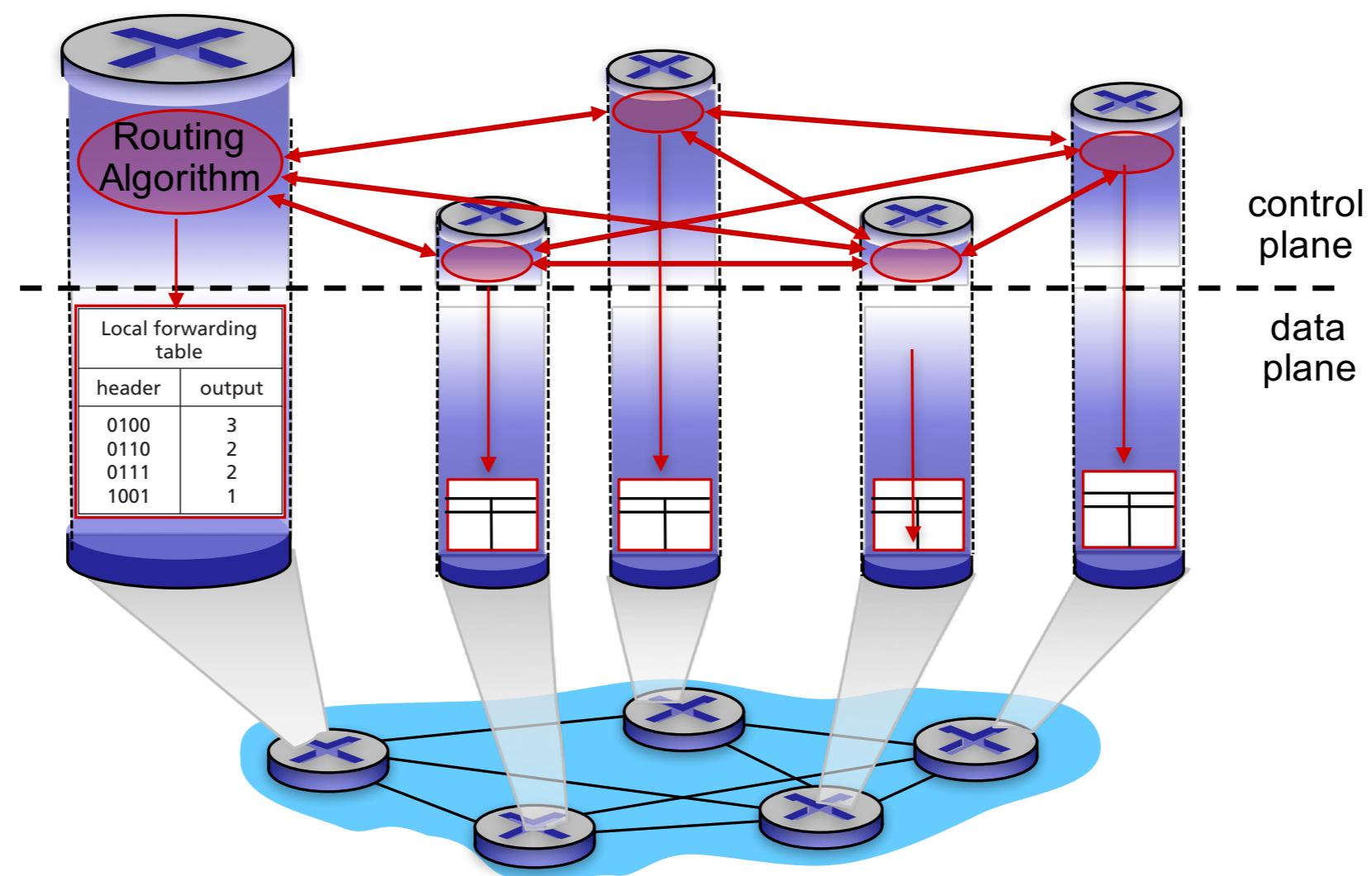
Computer Networking and Security

Instructor: Dr. Hao Wu

Week 3 – Routing

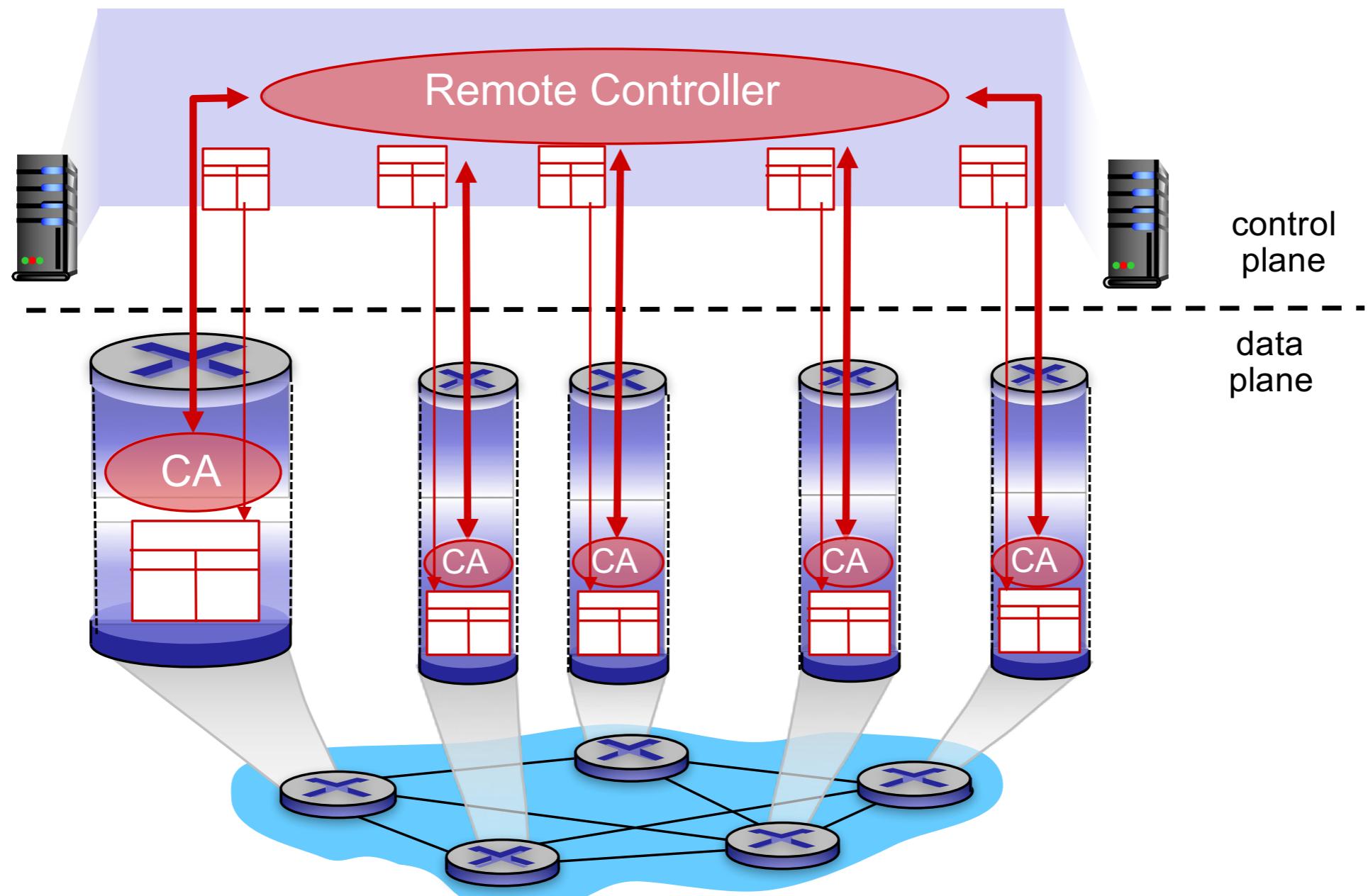
Pre-router control plane

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

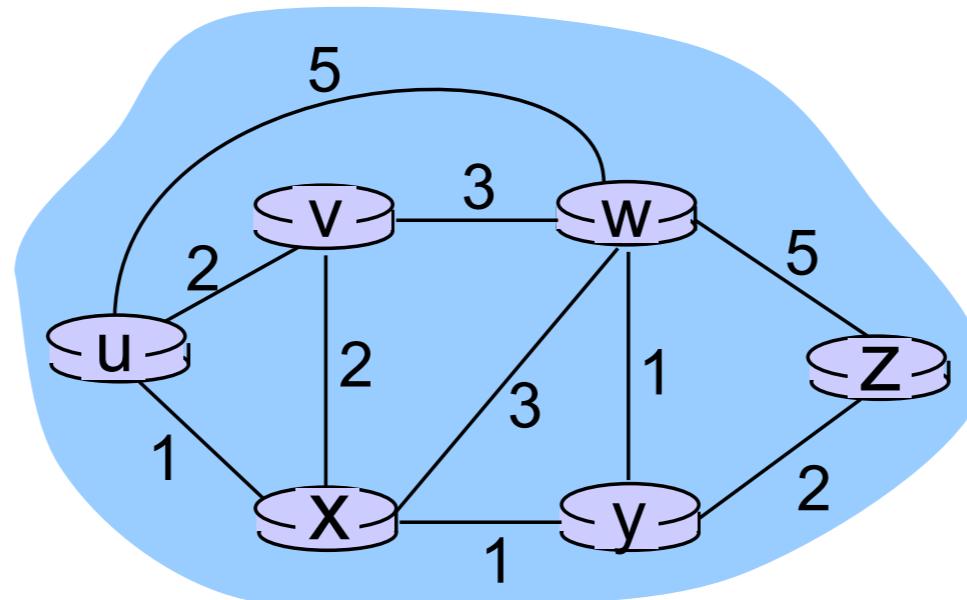


Routing protocols

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



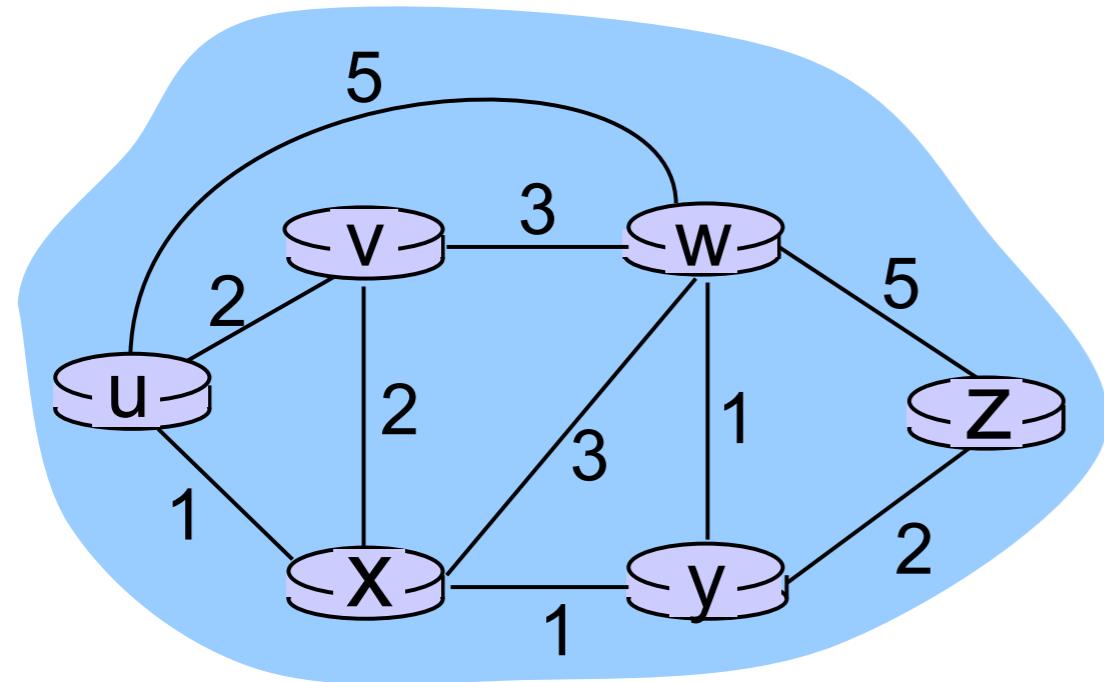
graph: $G = (N, E)$

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

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

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



$c(x, x')$ = 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

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

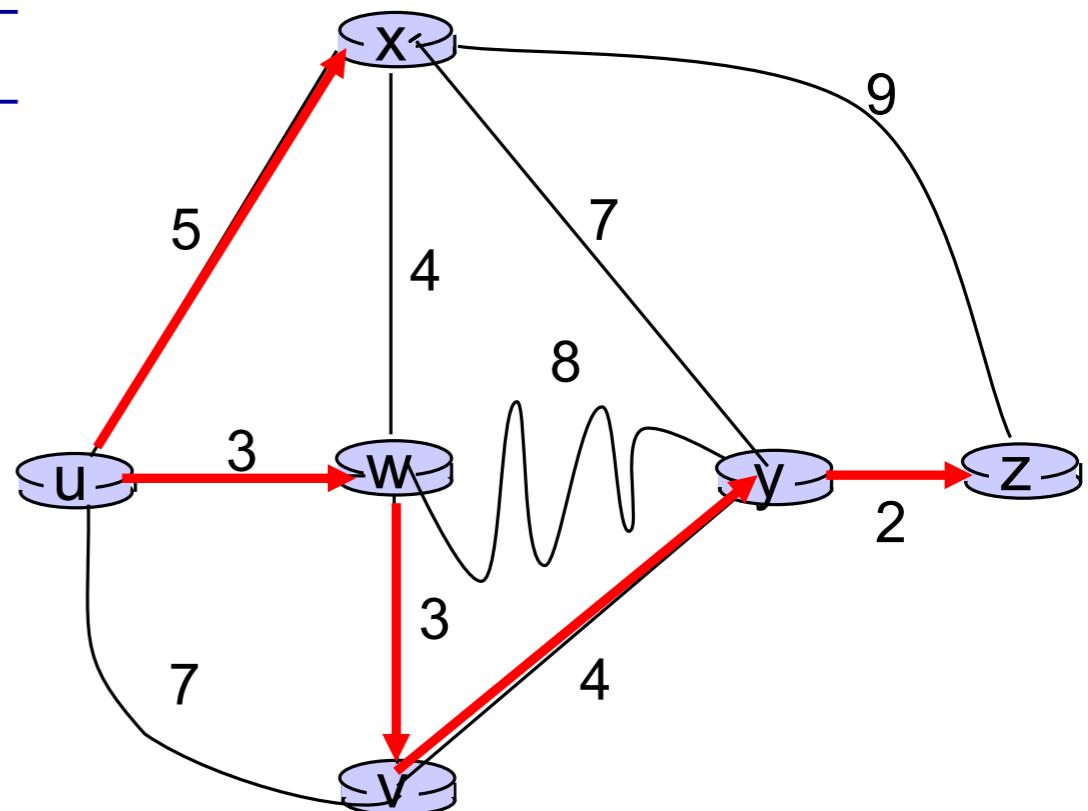
```
1 Initialization:
2   N' = {u}
3   for all nodes v
4     if v adjacent to u
5       then D(v) = c(u,v)
6     else D(v) = ∞
7
8 Loop
9   find w not in N' such that D(w) is a minimum
10  add w to N'
11  update D(v) for all v adjacent to w and not in N' :
12    D(v) = min( D(v), D(w) + c(w,v) )
13  /* 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)	D(w)	D(x)	D(y)	D(z)
		p(v)	p(w)	p(x)	p(y)	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)



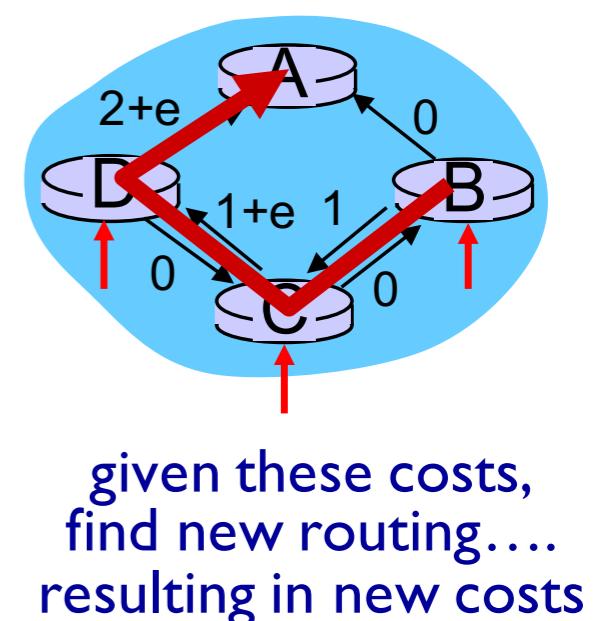
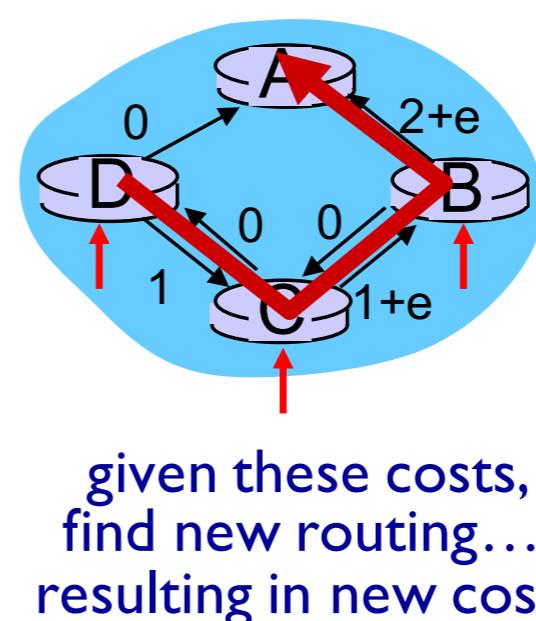
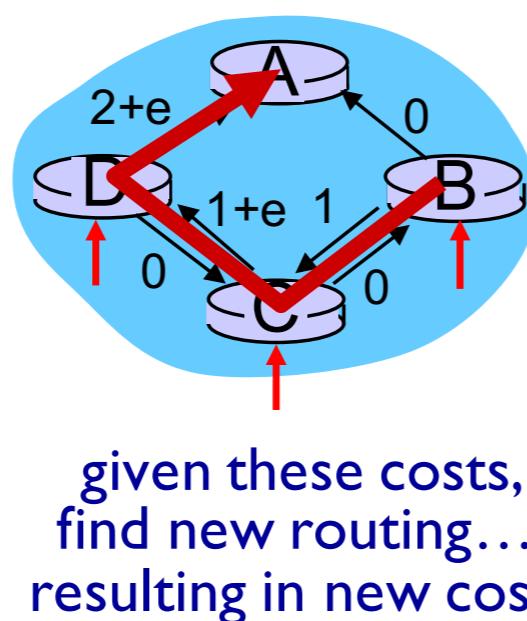
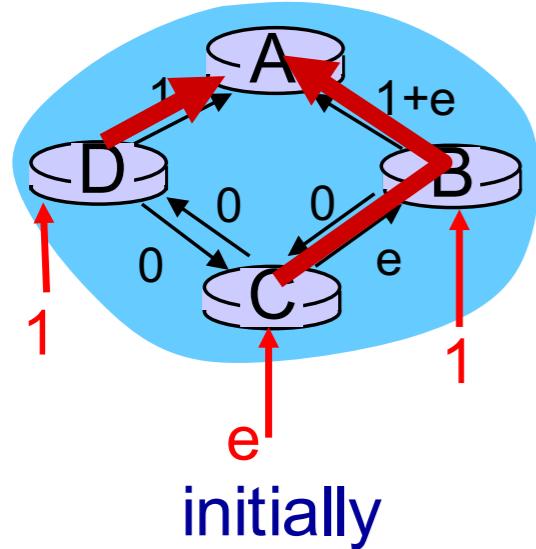
Dijkstra's algorithm, discussion

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:



Distance vector algorithm

Bellman-Ford equation (dynamic programming)

let

$d_x(y) := \text{cost of least-cost path from } x \text{ to } y$

then

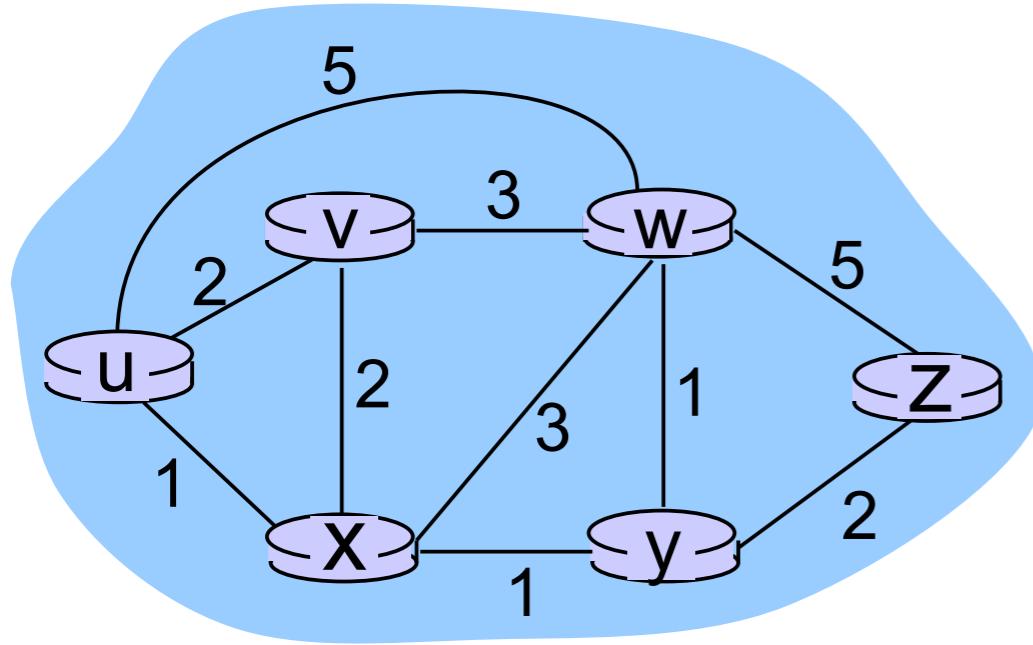
$$d_x(y) = \min_v \{ c(x,v) + d_v(y) \}$$

cost to neighbor v

cost from neighbor v to destination y

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 $D_x = [D_x(y): y \in N]$
- node x :
 - knows cost to each neighbor v : $c(x,v)$
 - maintains its neighbors' distance vectors. For each neighbor v , x maintains
 $D_v = [D_v(y): y \in N]$

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:
- ❖ 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:

wait for (change in local link cost or msg from neighbor)

recompute estimates

if DV to any dest has changed, *notify* neighbors

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

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

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

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

node x table

	x	y	z
x	0	2	7
y	∞	∞	∞
z	∞	∞	∞

node y table

	x	y	z
x	∞	∞	∞
y	2	0	1
z	∞	∞	∞

node z table

	x	y	z
x	∞	∞	∞
y	∞	∞	∞
z	7	1	0

	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

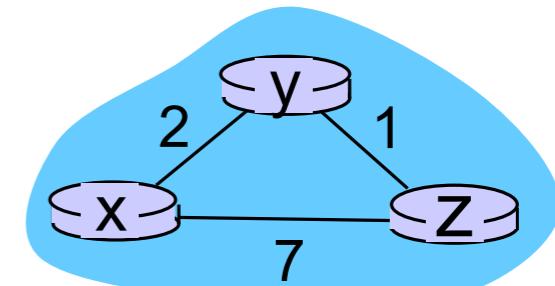
	x	y	z
x	0	2	7
y	2	0	1
z	7	1	0

	x	y	z
x	0	2	7
y	2	0	1
z	3	1	0

	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0

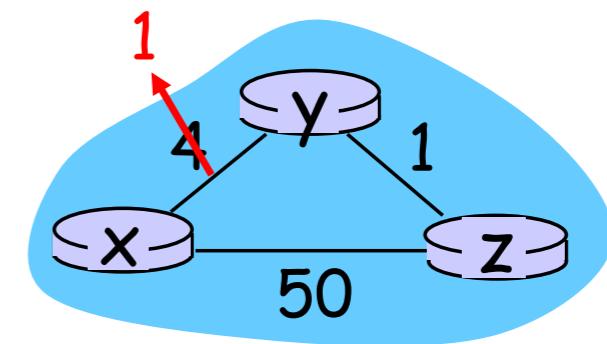
	x	y	z
x	0	2	3
y	2	0	1
z	3	1	0



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



“good
news
travels
fast”

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

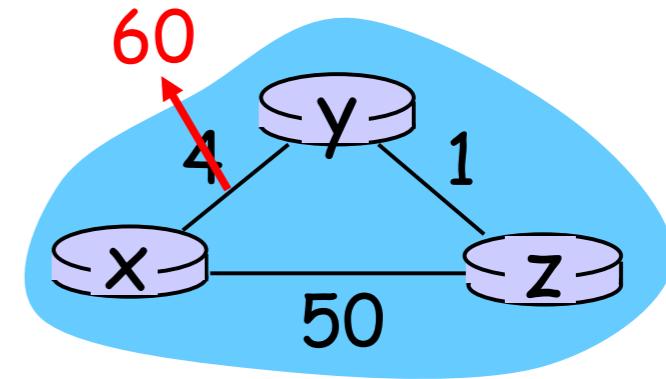
t_1 : z receives update from y , updates its table, computes new least cost to x , sends its neighbors its DV.

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



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?

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

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”)

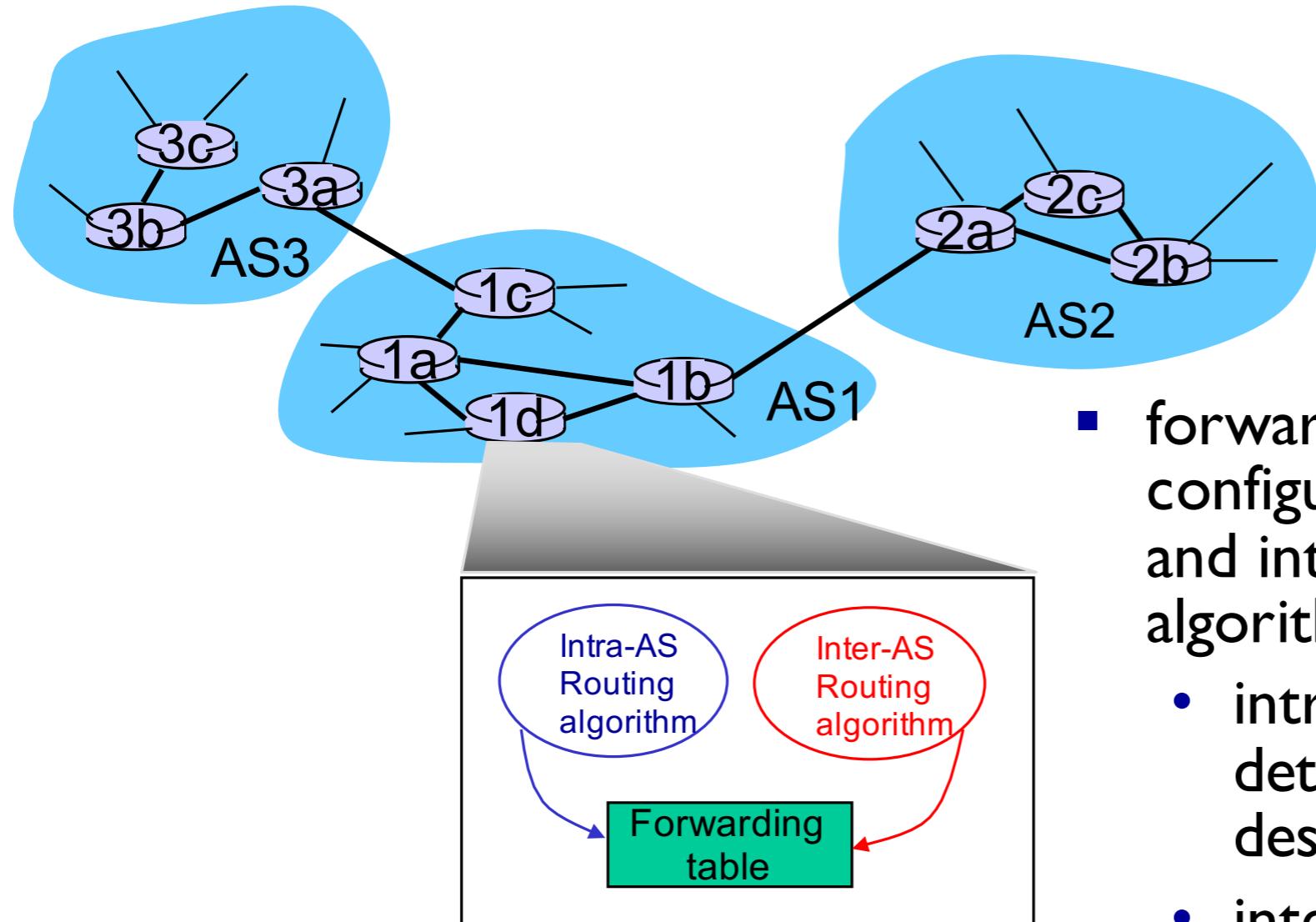
intra-AS routing

- 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

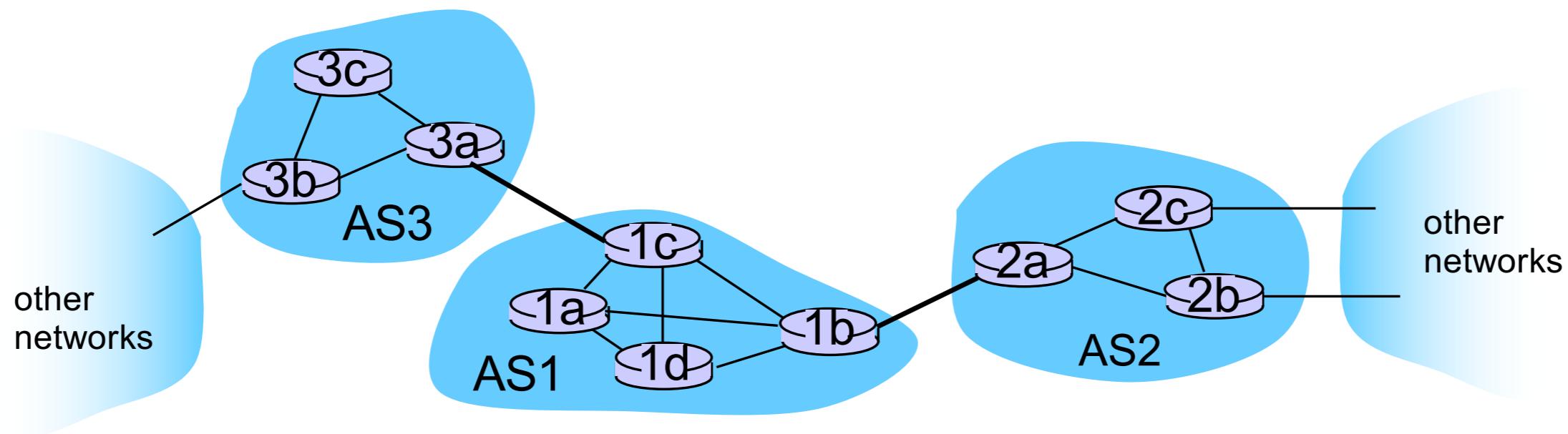
Inter-AS tasks

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

AS1 must:

- I. 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
 - OSPF: Open Shortest Path First (IS-IS protocol essentially same as OSPF)
 - IGRP: Interior Gateway Routing Protocol
(Cisco proprietary for decades, until 2016)

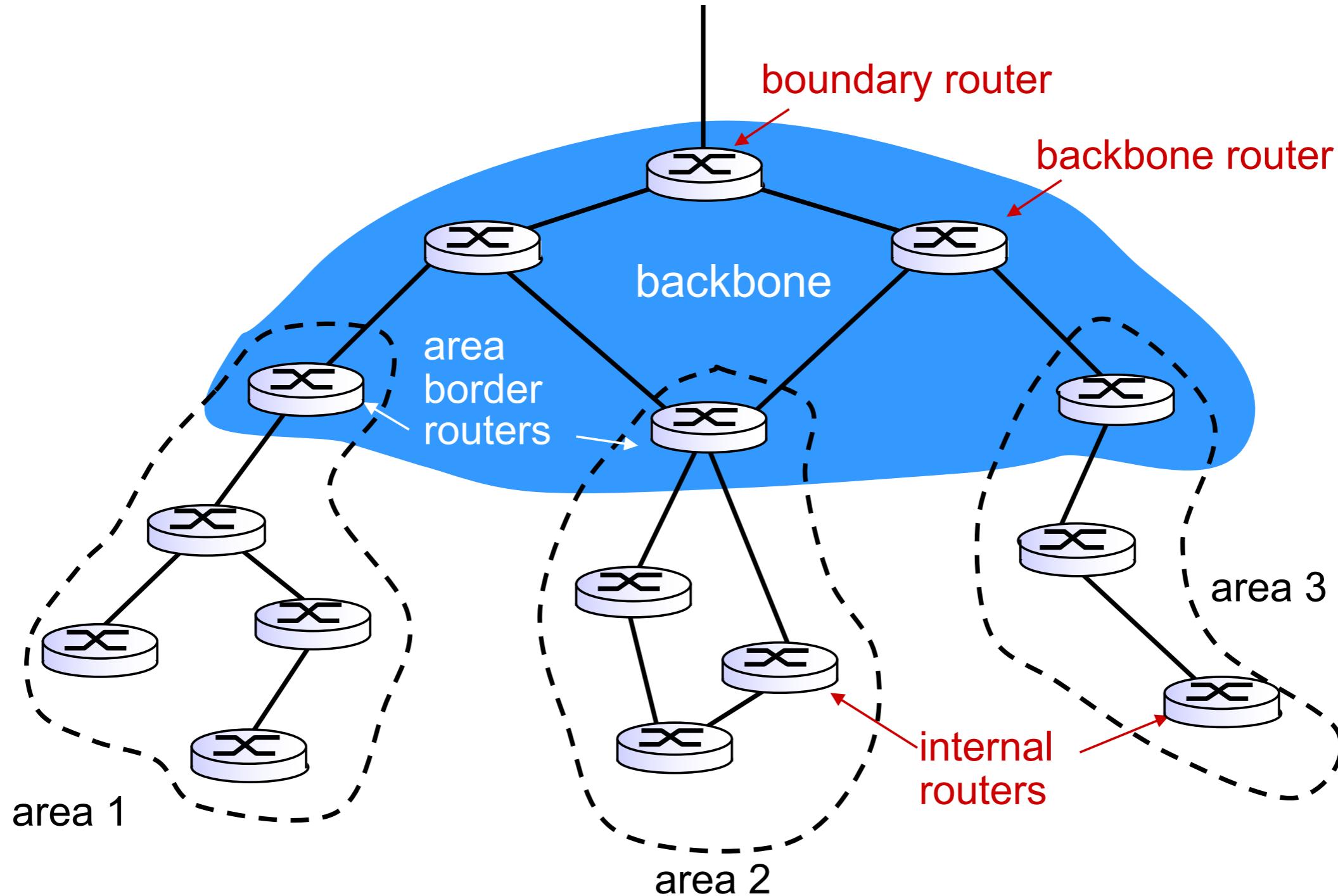
OSPF (Open Shortest Path First)

- “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.

Hierarchical OSPF



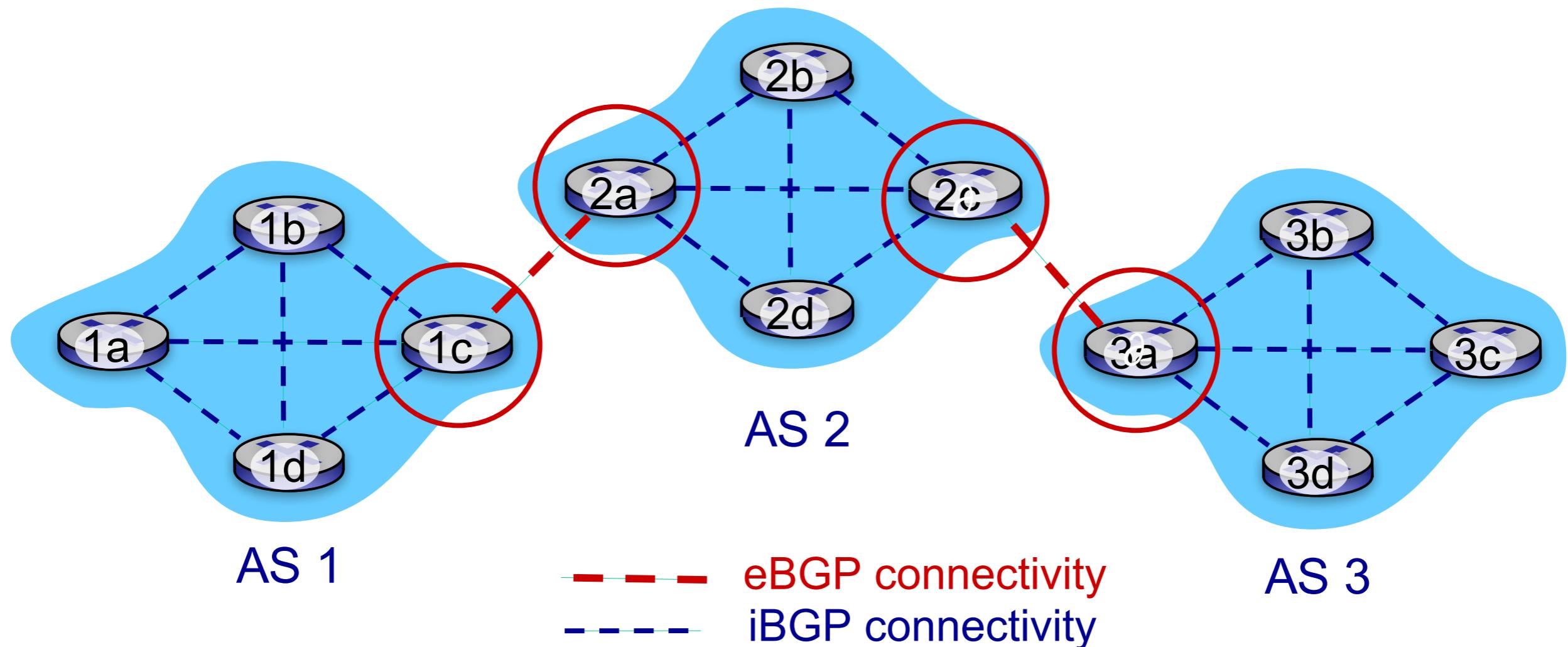
Hierarchical OSPF

- ***two-level hierarchy:*** local area, backbone.
 - link-state advertisements only in area
 - each node has detailed area topology; only know direction (shortest path) to nets in other areas.
- ***area border routers:*** “summarize” distances to nets in own area, advertise to other Area Border routers.
- ***backbone routers:*** run OSPF routing limited to backbone.
- ***boundary routers:*** connect to other AS' es.

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*”

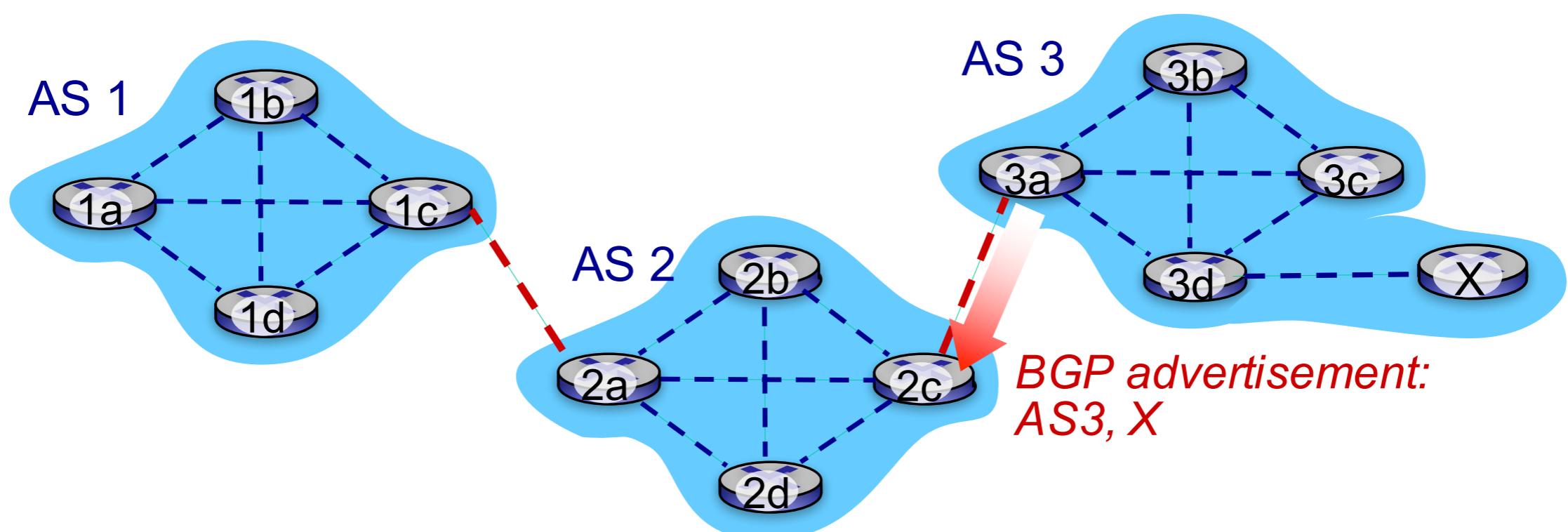
eBGP, iBGP connections



gateway routers run both eBGP and iBGP protocols

BGP basics

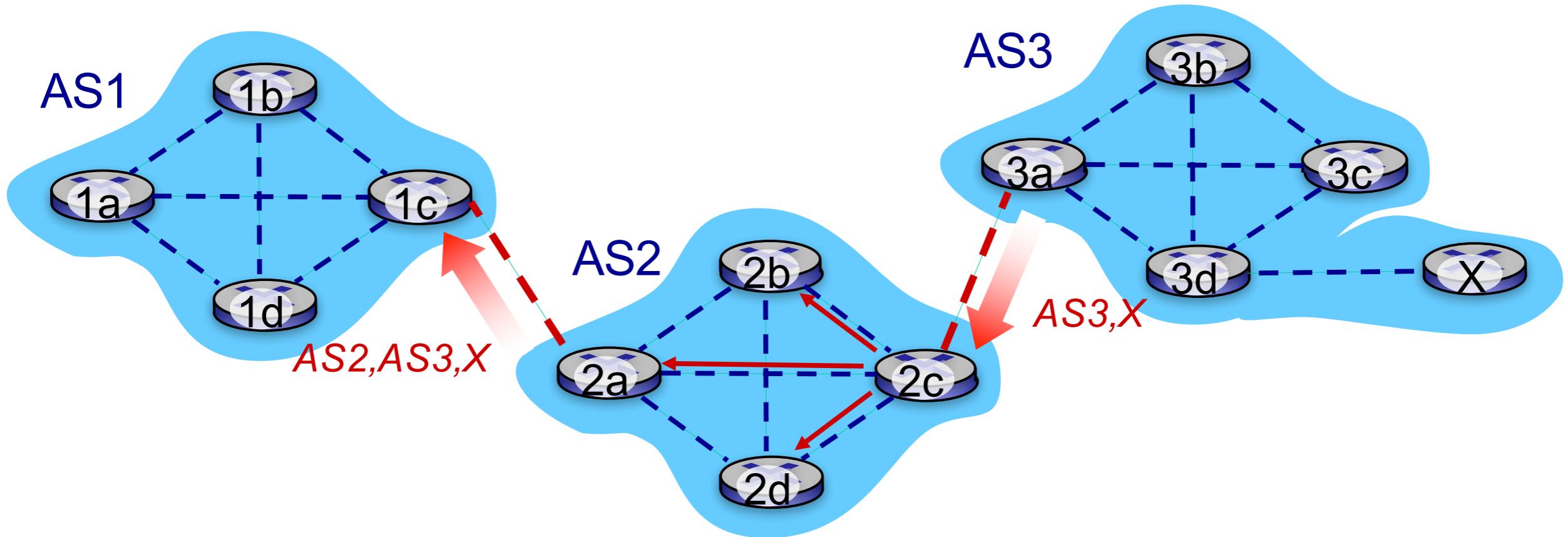
- **BGP session:** two BGP routers (“peers”) exchange BGP messages over semi-permanent TCP connection:
 - advertising *paths* to different destination network prefixes (BGP is a “path vector” protocol)
- when AS3 gateway router 3a advertises path **AS3,X** to AS2 gateway router 2c:
 - AS3 *promises*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



Path attributes and BGP routes

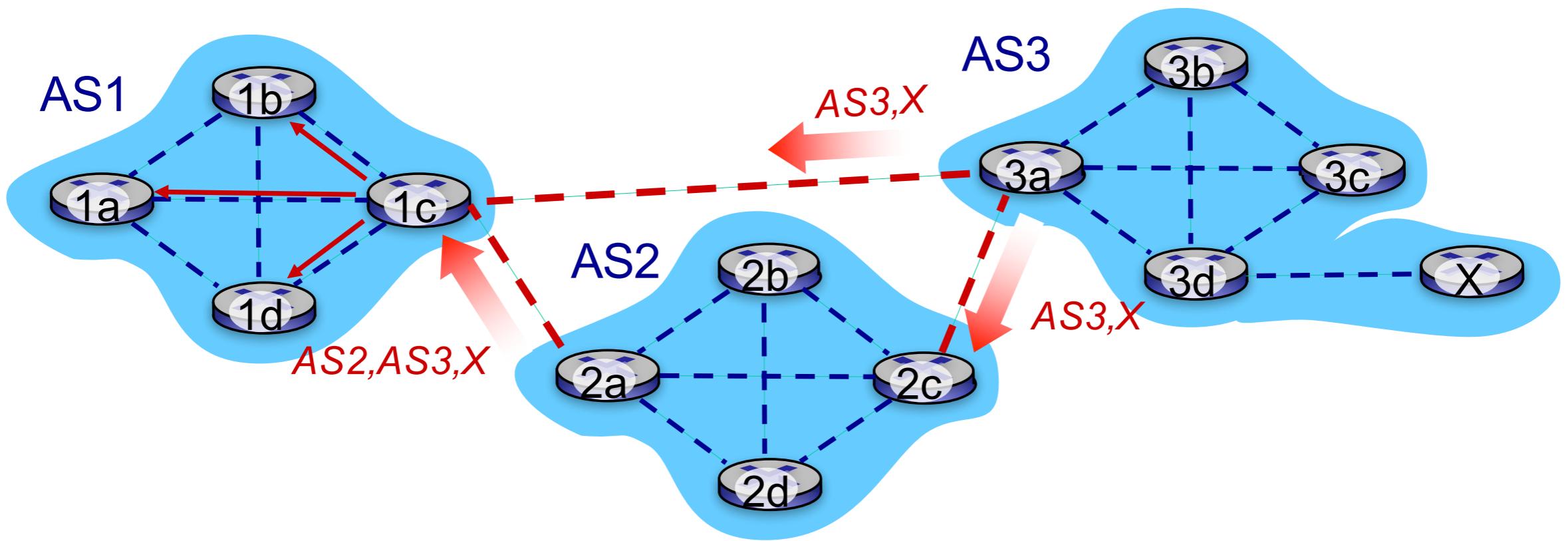
- advertised prefix includes BGP attributes
 - prefix + attributes = “route”
- two important attributes:
 - **AS-PATH**: list of ASes through which prefix advertisement has passed
 - **NEXT-HOP**: indicates specific internal-AS router to next-hop AS
- *Policy-based routing*:
 - gateway receiving route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

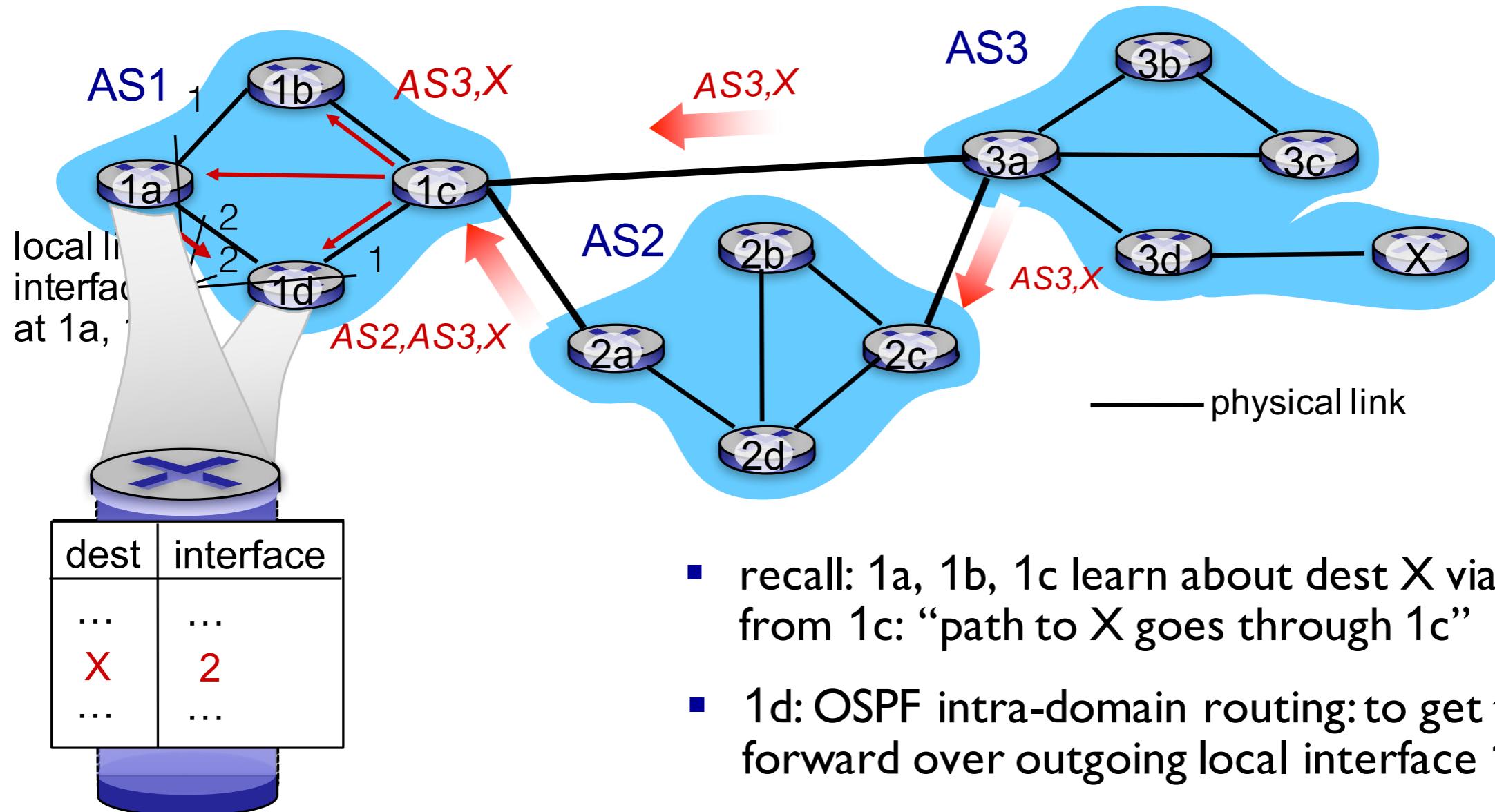
- AS1 gateway router 1c learns path **AS2,AS3,X** from 2a
- Based on policy, AS1 gateway router 1c chooses path **AS3,X, and advertises path within AS1 via iBGP**

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?

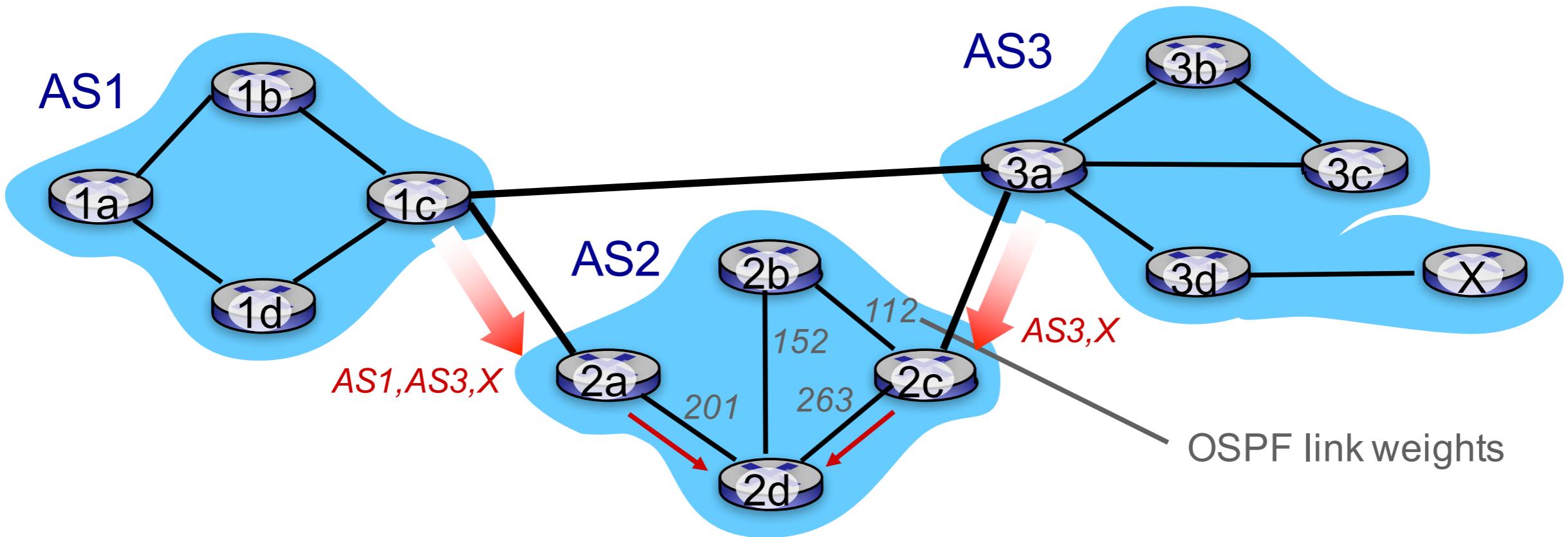


- recall: 1a, 1b, 1c learn about dest X via iBGP from 1c: “path to X goes through 1c”
- 1d: OSPF intra-domain routing: to get to 1c, forward over outgoing local interface 1
- 1a: OSPF intra-domain routing: to get to 1c, forward over outgoing local interface 2

BGP route selection

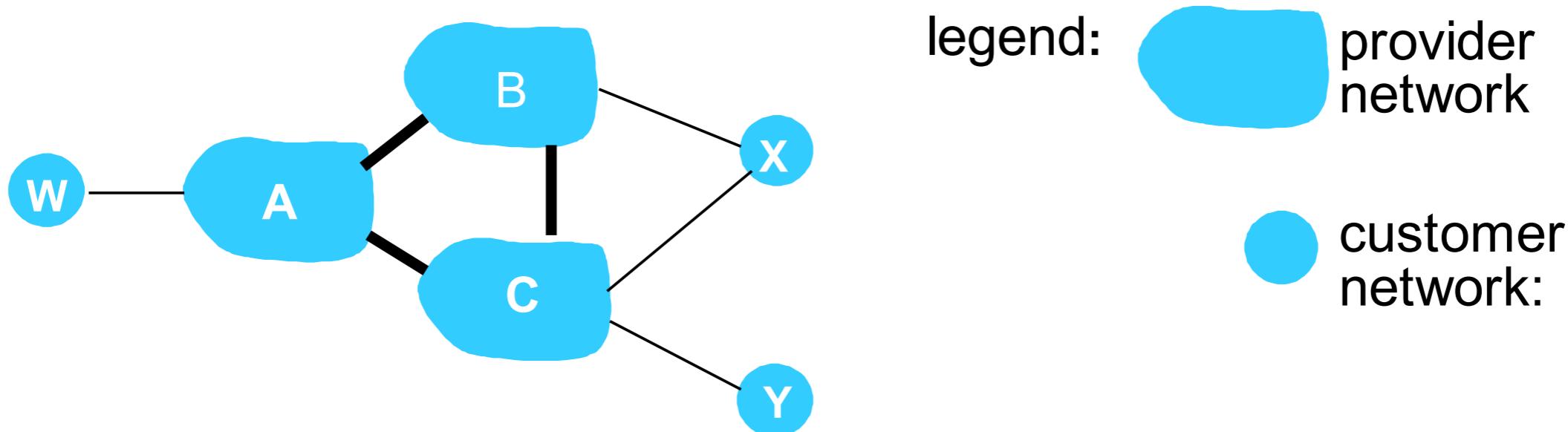
- router may learn about more than one route to destination AS, selects route based on:
 1. local preference value attribute: policy decision
 2. shortest AS-PATH
 3. closest NEXT-HOP router: hot potato routing
 4. additional criteria

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!

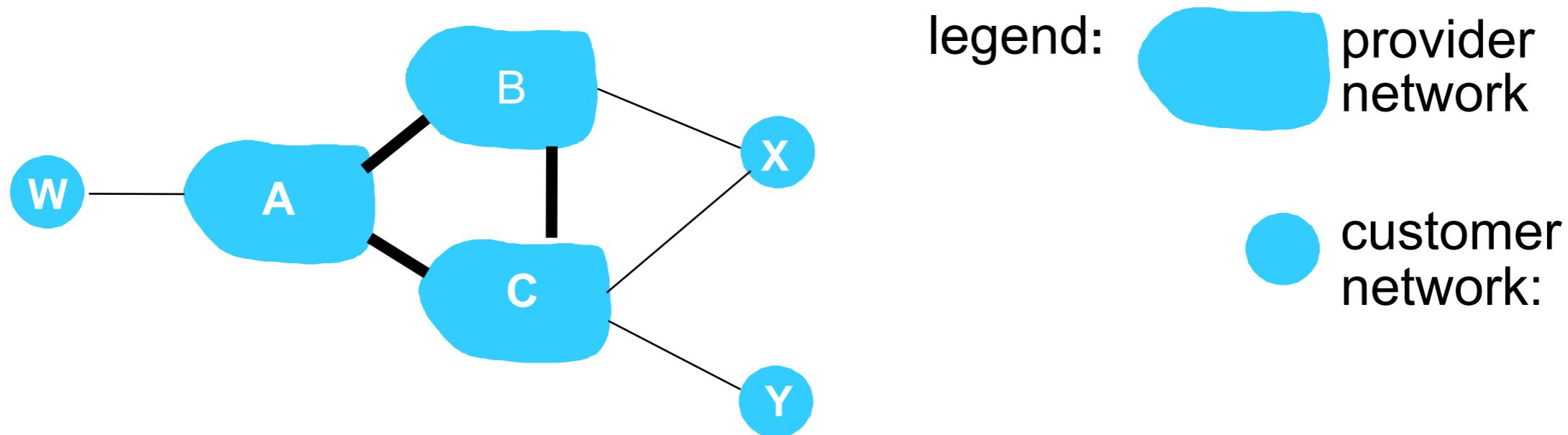
BGP: achieving policy via advertisements



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 *chooses not to advertise* BAw to C:
 - B gets no “revenue” for routing CBAw, since none of C, A, w are 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)

- 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

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:

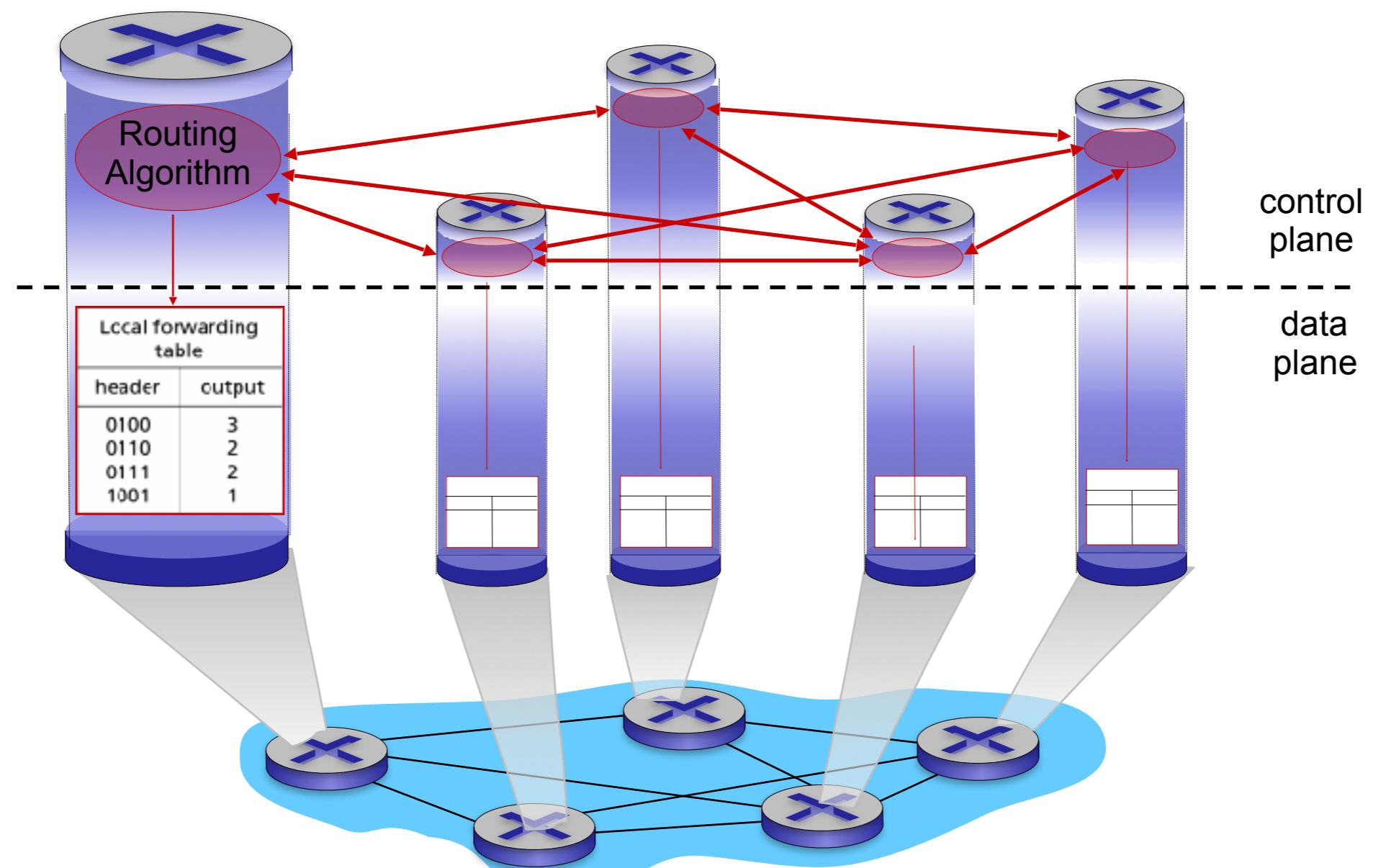
- intra-AS: can focus on performance
- inter-AS: policy may dominate over performance

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

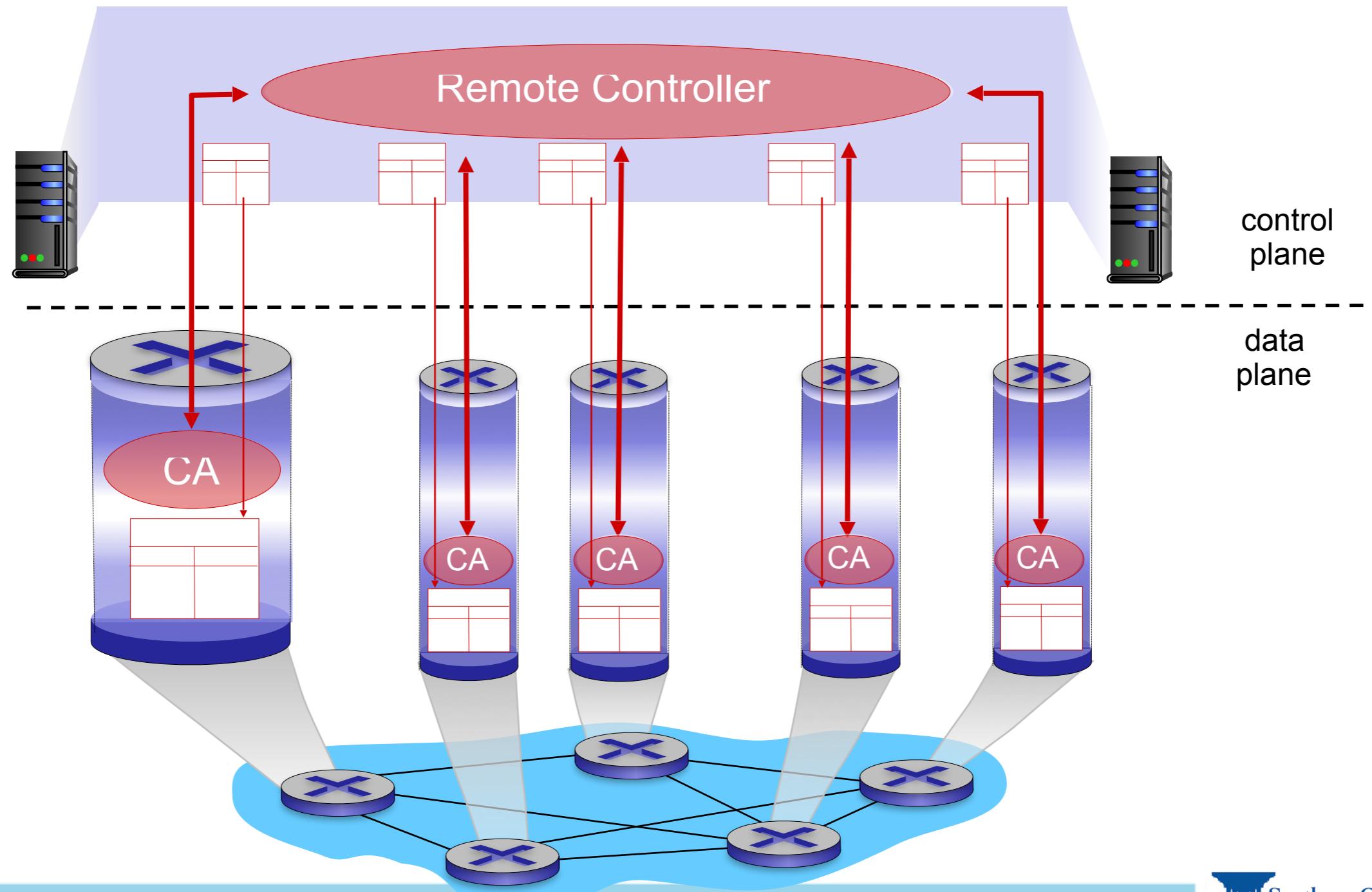
Recall: per-router control plane

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

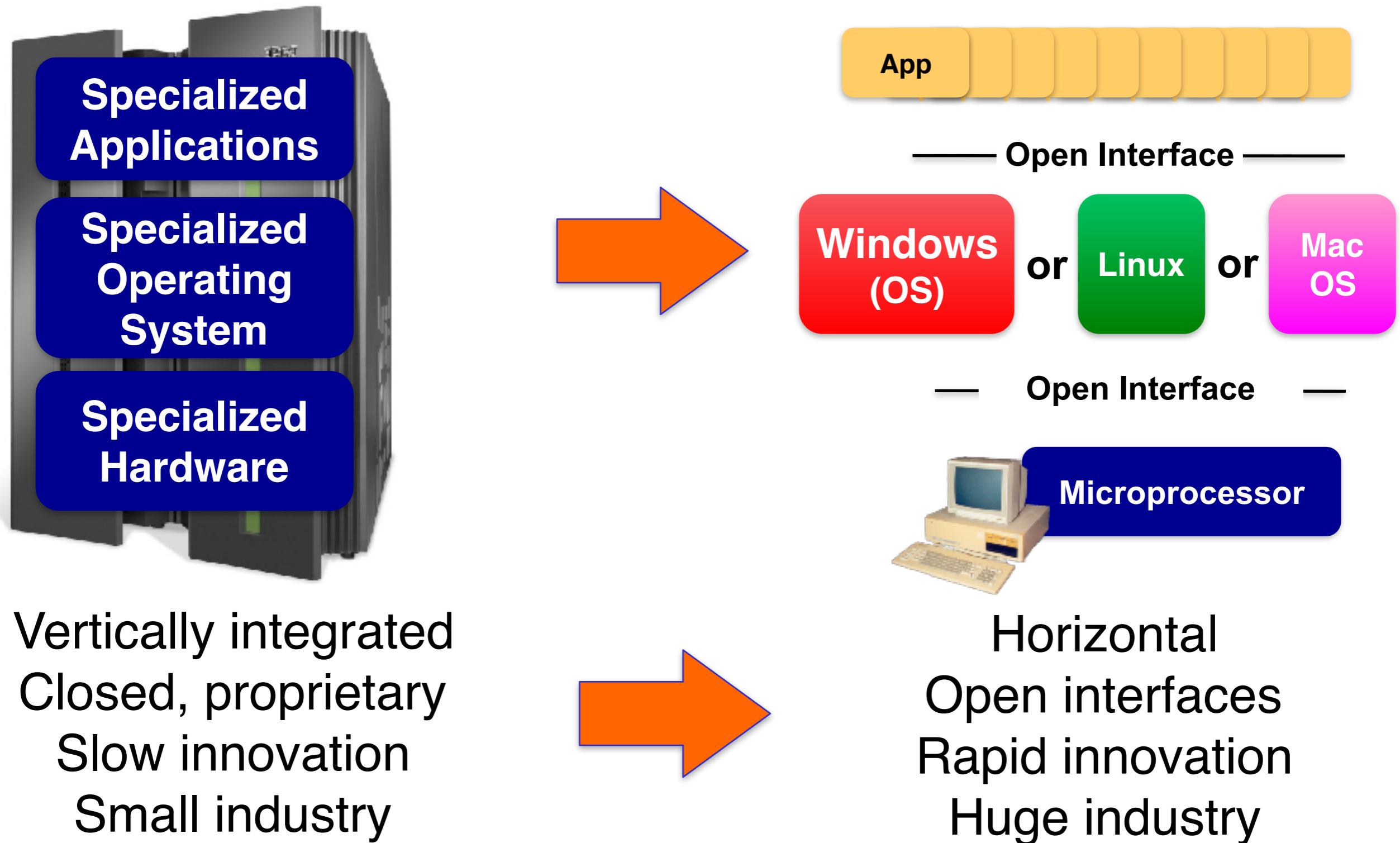


Software defined networking (SDN)

Why a *logically centralized* control plane?

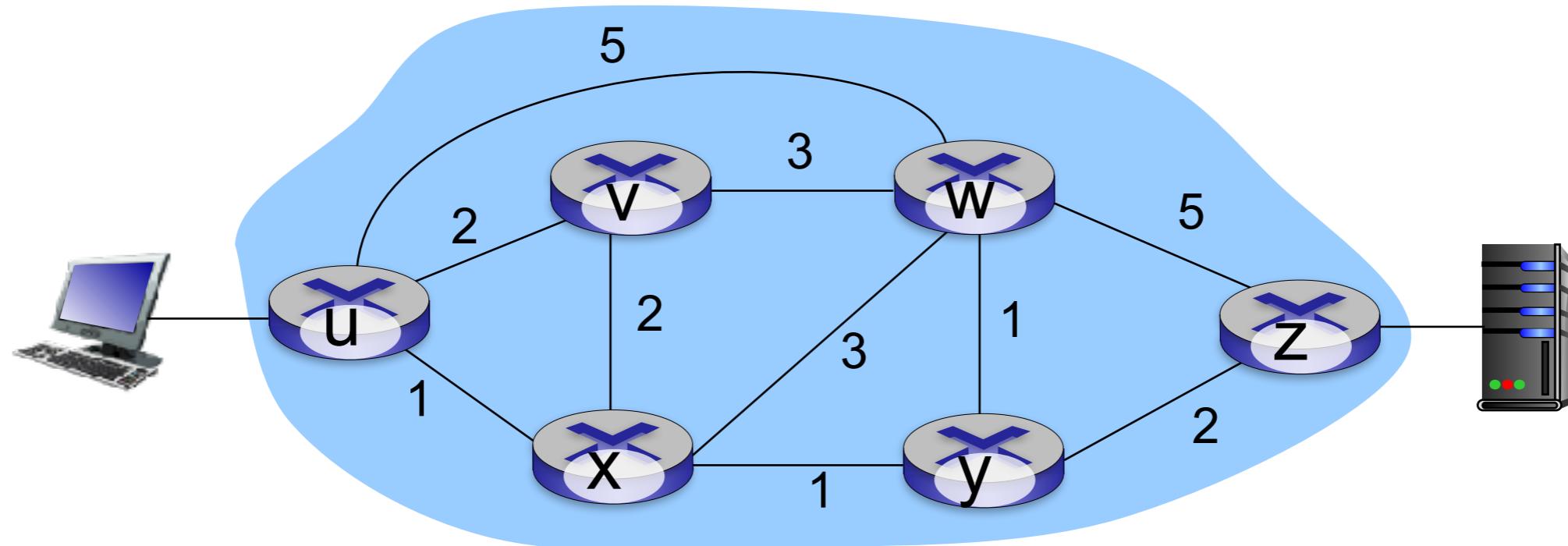
- easier network management: avoid router misconfigurations, greater flexibility of traffic flows
- table-based forwarding (recall OpenFlow API) allows “programming” routers
 - centralized “programming” easier: compute tables centrally and distribute
 - distributed “programming”: more difficult: compute 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*



* Slide courtesy: N. McKeown

Traffic engineering: difficult traditional routing

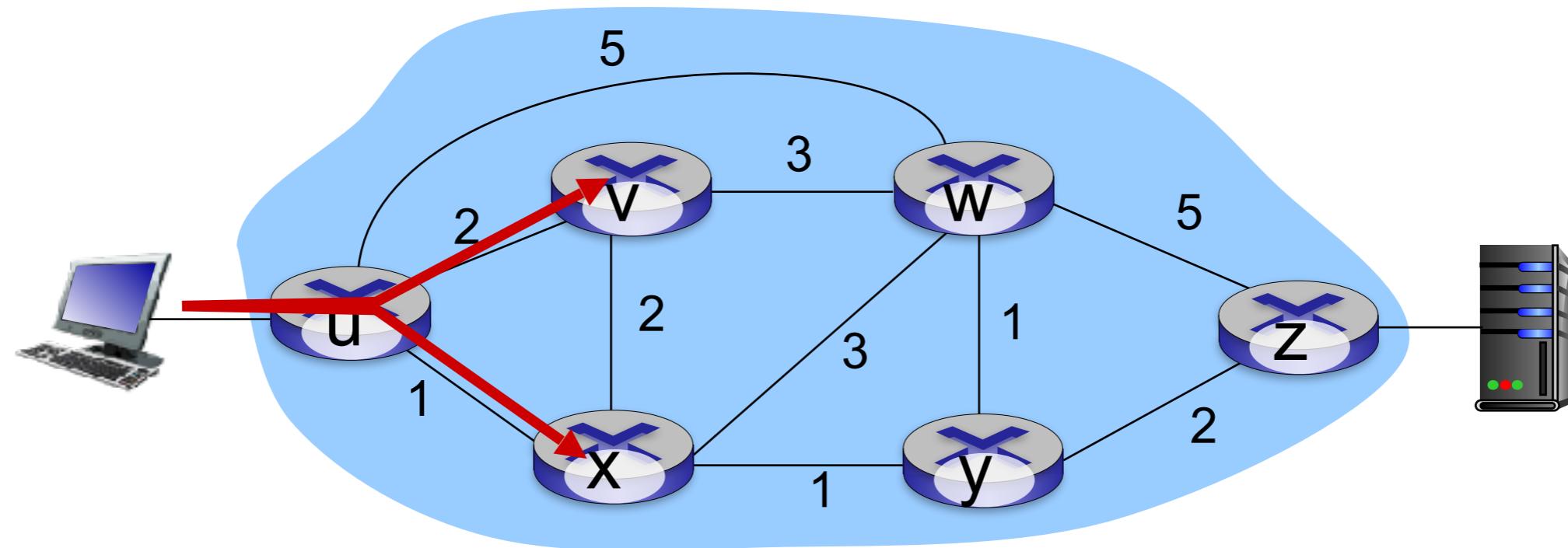


Q: what if network operator wants u-to-z traffic to flow along $uvwz$, x-to-z traffic to flow $xwyz$?

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

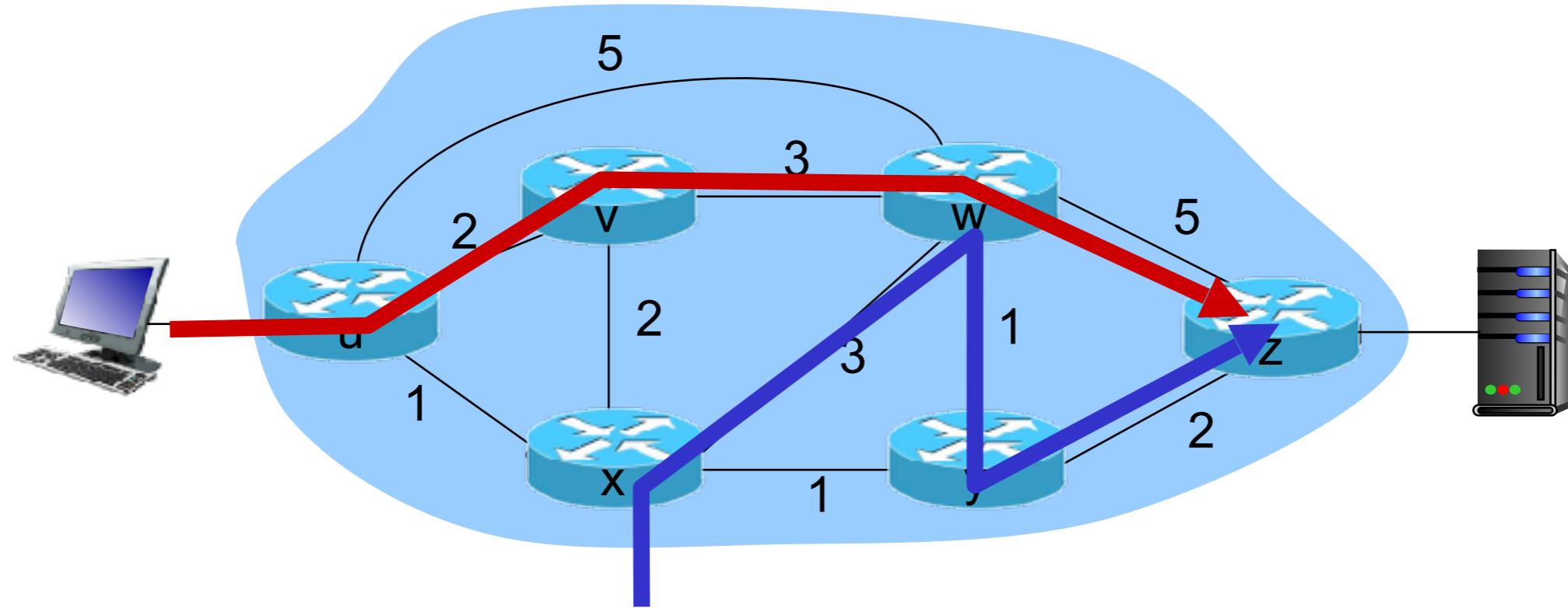
Link weights are only control “knobs”: wrong!

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

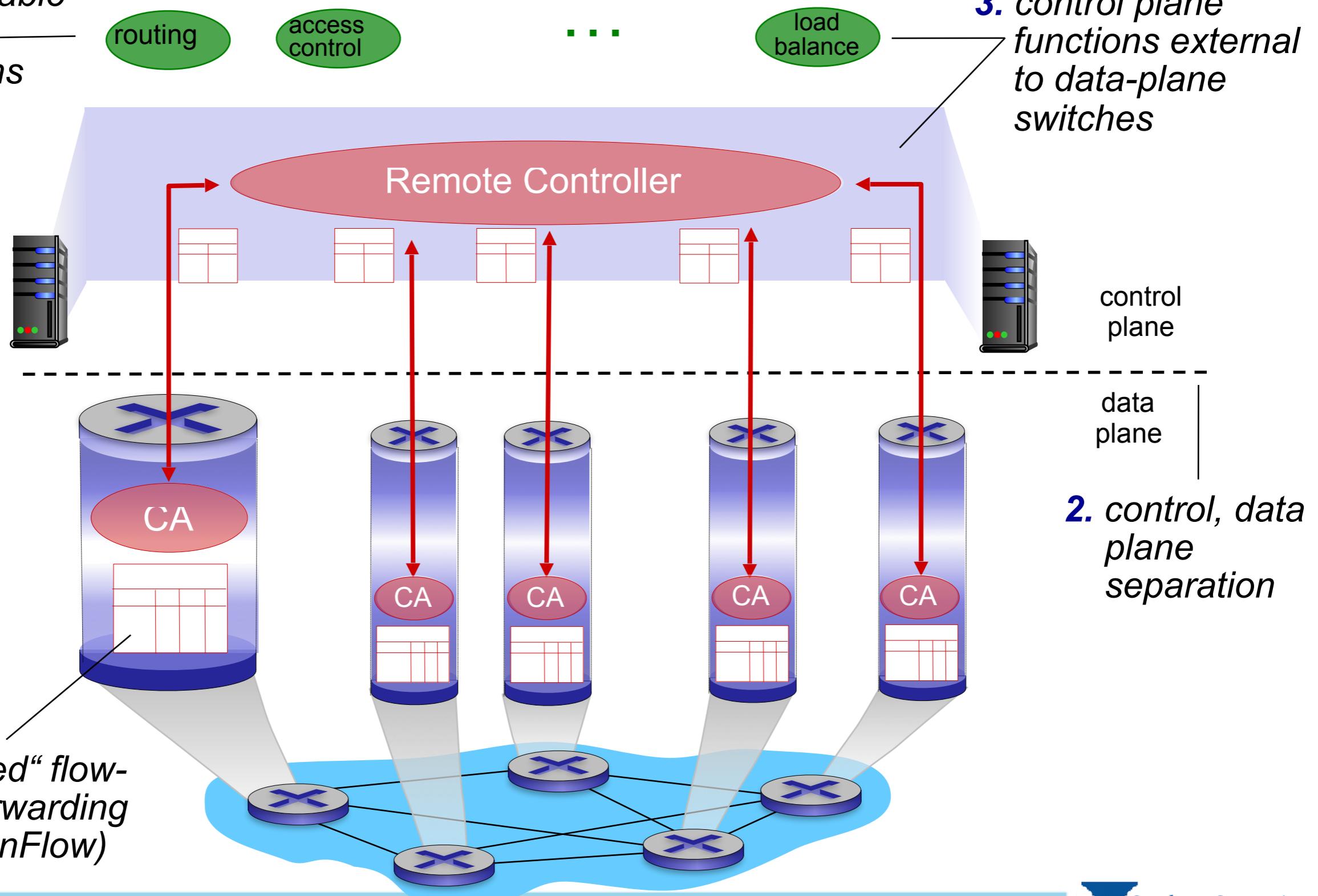
routing

access control

...

load balance

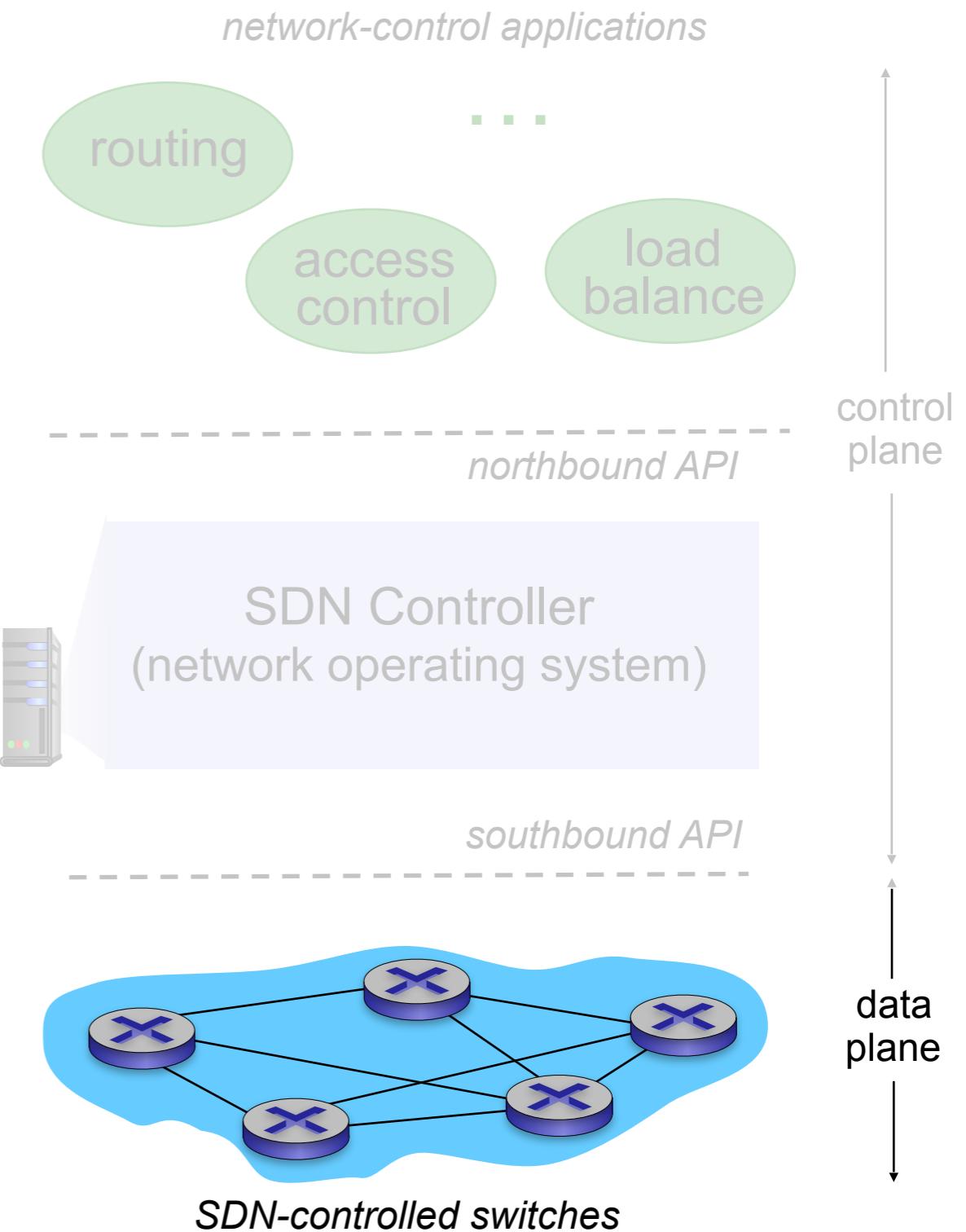
3. control plane functions external to data-plane switches



SDN perspective: data plane switches

Data plane switches

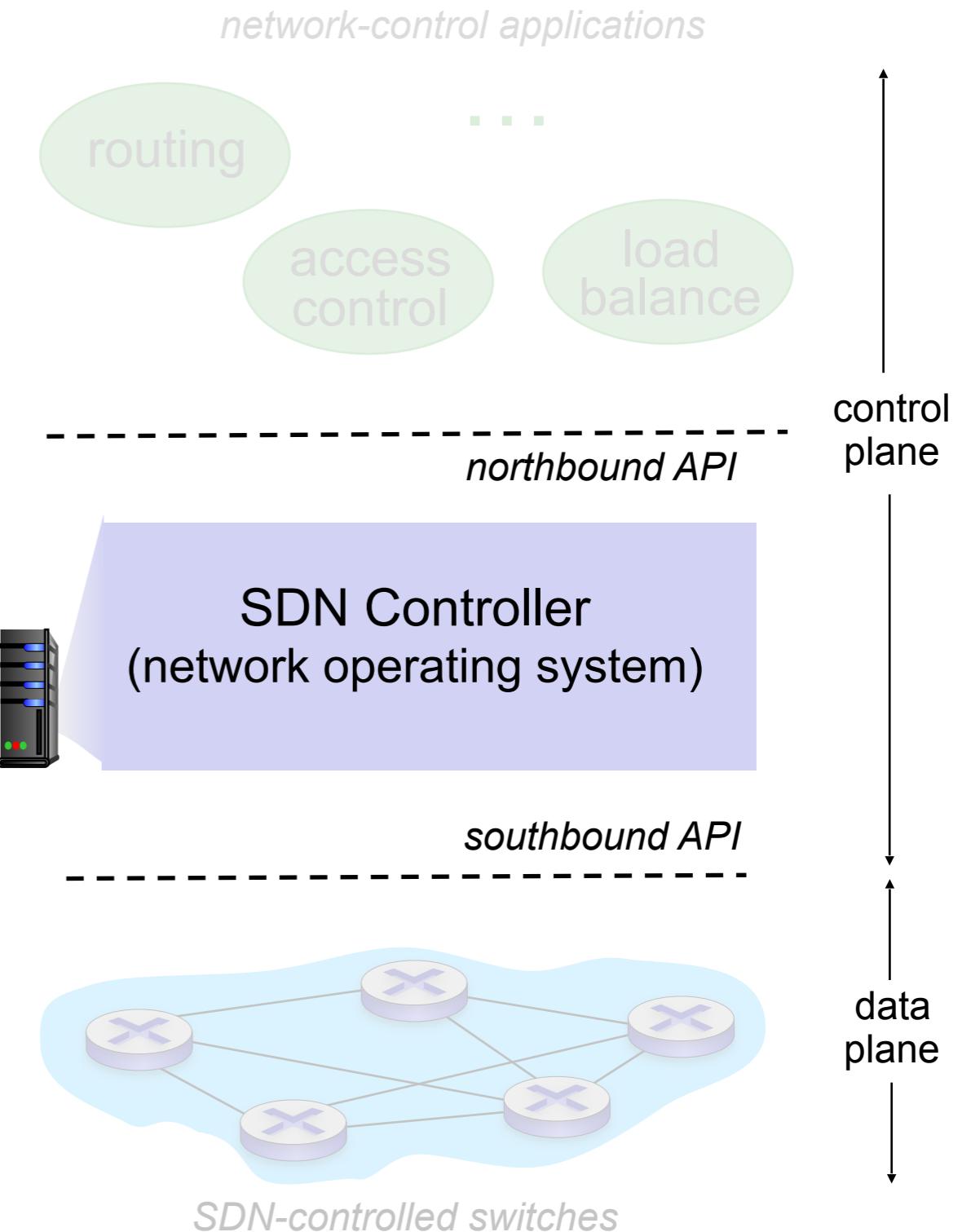
- fast, simple, commodity switches implementing generalized data-plane forwarding (Section 4.4) in hardware
- switch flow table computed, installed by controller
- API for table-based switch control (e.g., OpenFlow)
 - defines what is controllable and what is not
- protocol for communicating with controller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



SDN perspective: SDN controller

SDN controller (network OS):

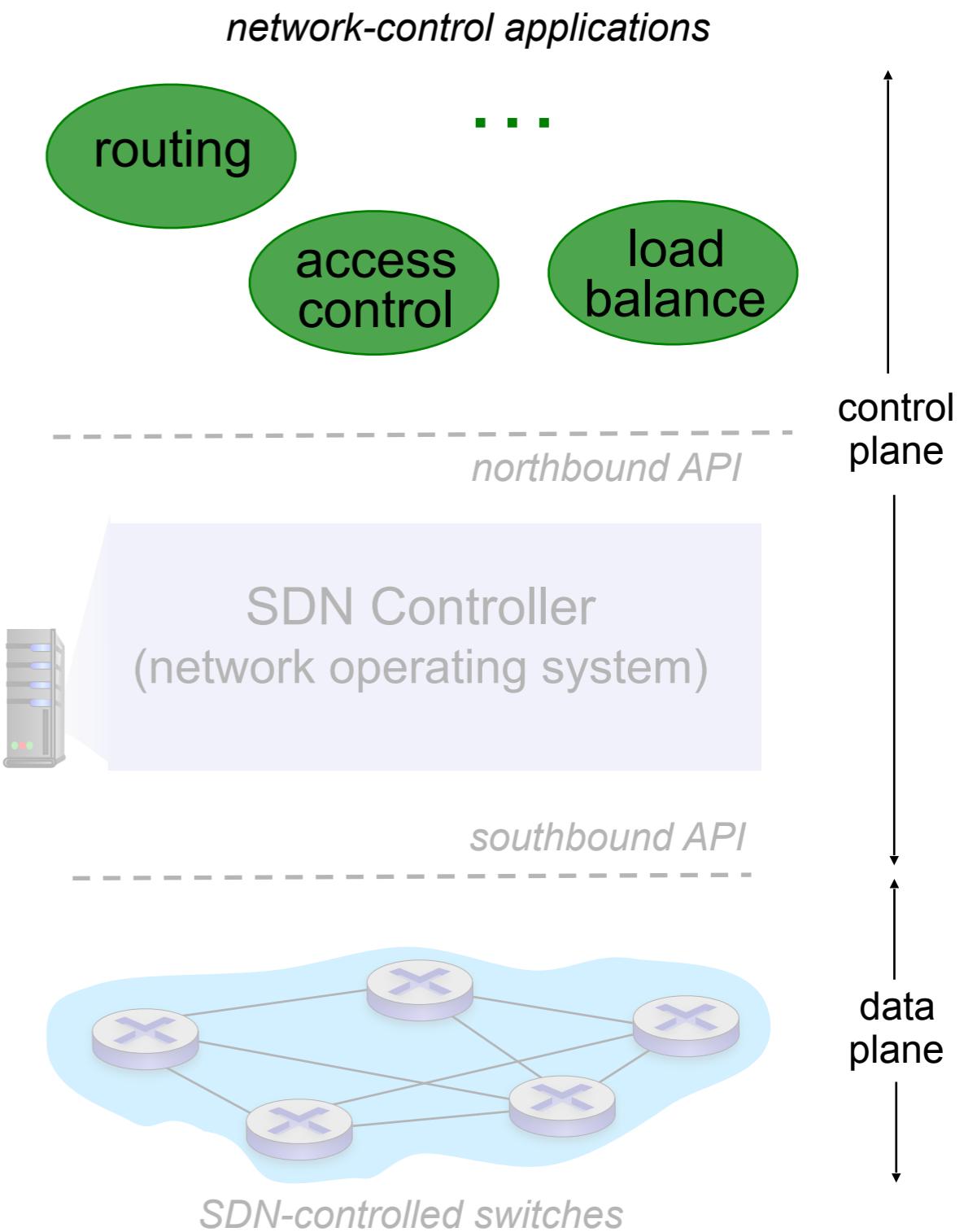
- maintain network state information
- interacts with network control applications “above” via northbound API
- interacts with network switches “below” via southbound API
- implemented as distributed system for performance, scalability, fault-tolerance, robustness



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

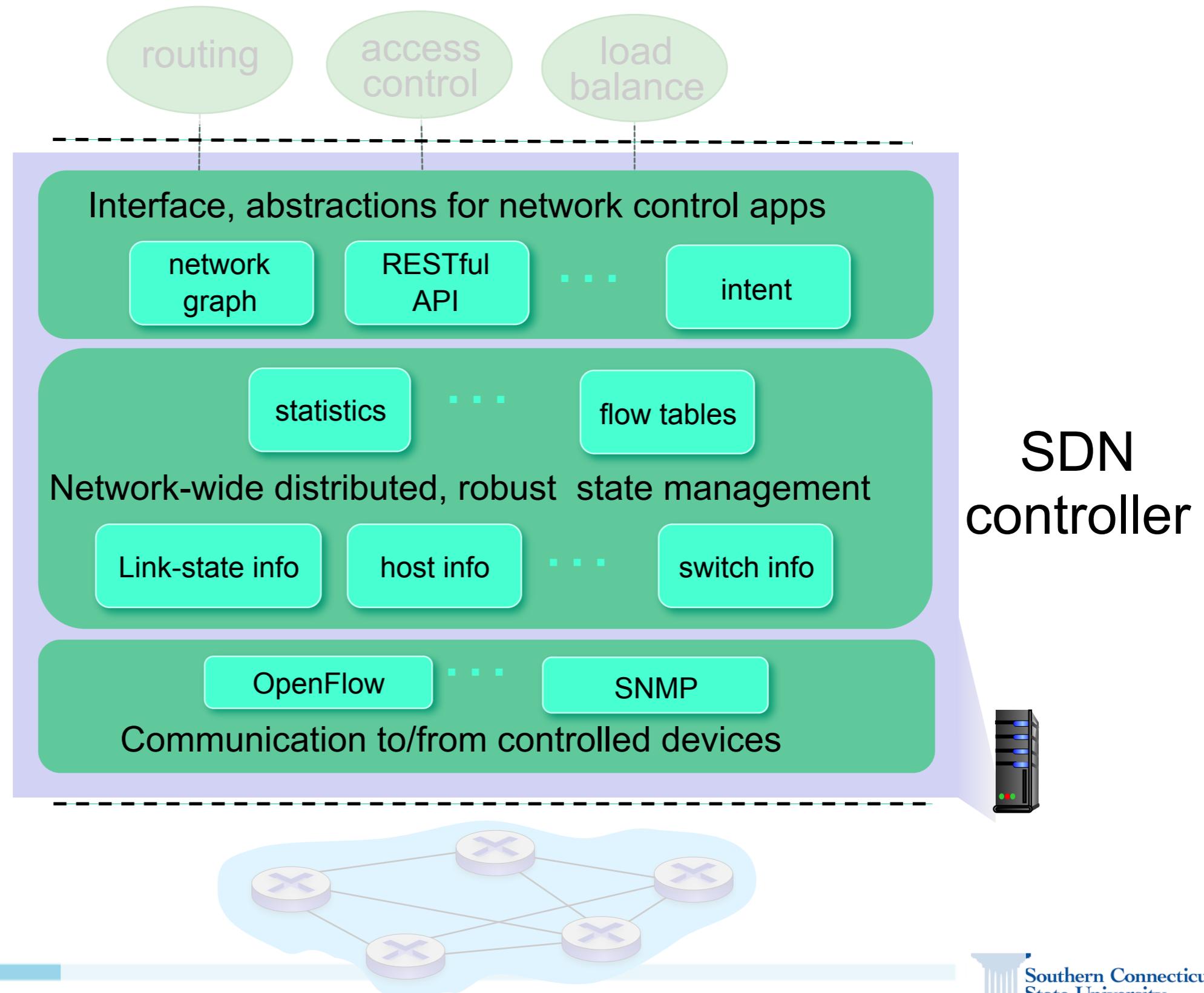


Components of SDN controller

Interface layer to network control apps: abstractions API

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

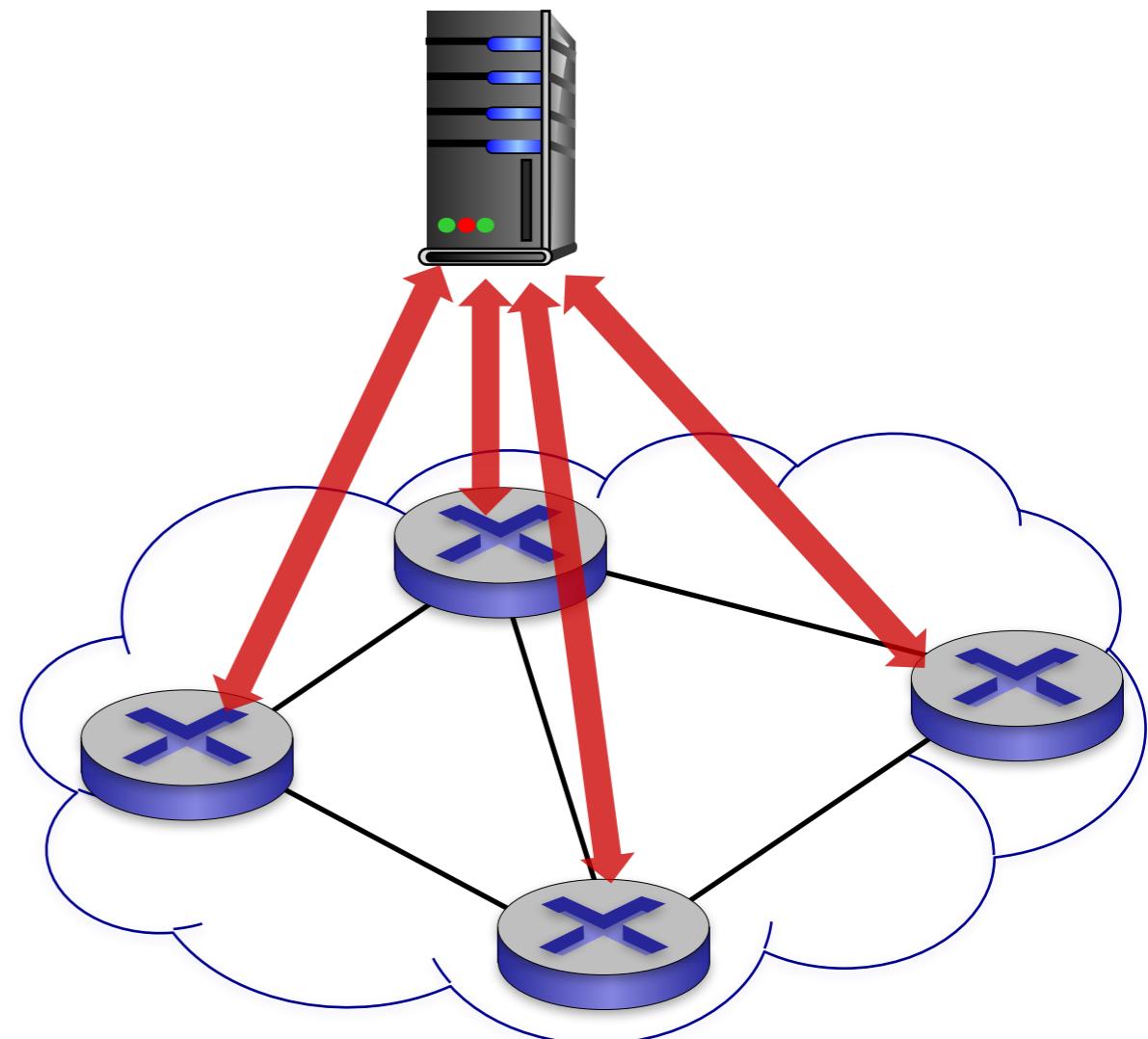
communication layer: communicate between SDN controller and controlled switches



OpenFlow protocol

- 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)

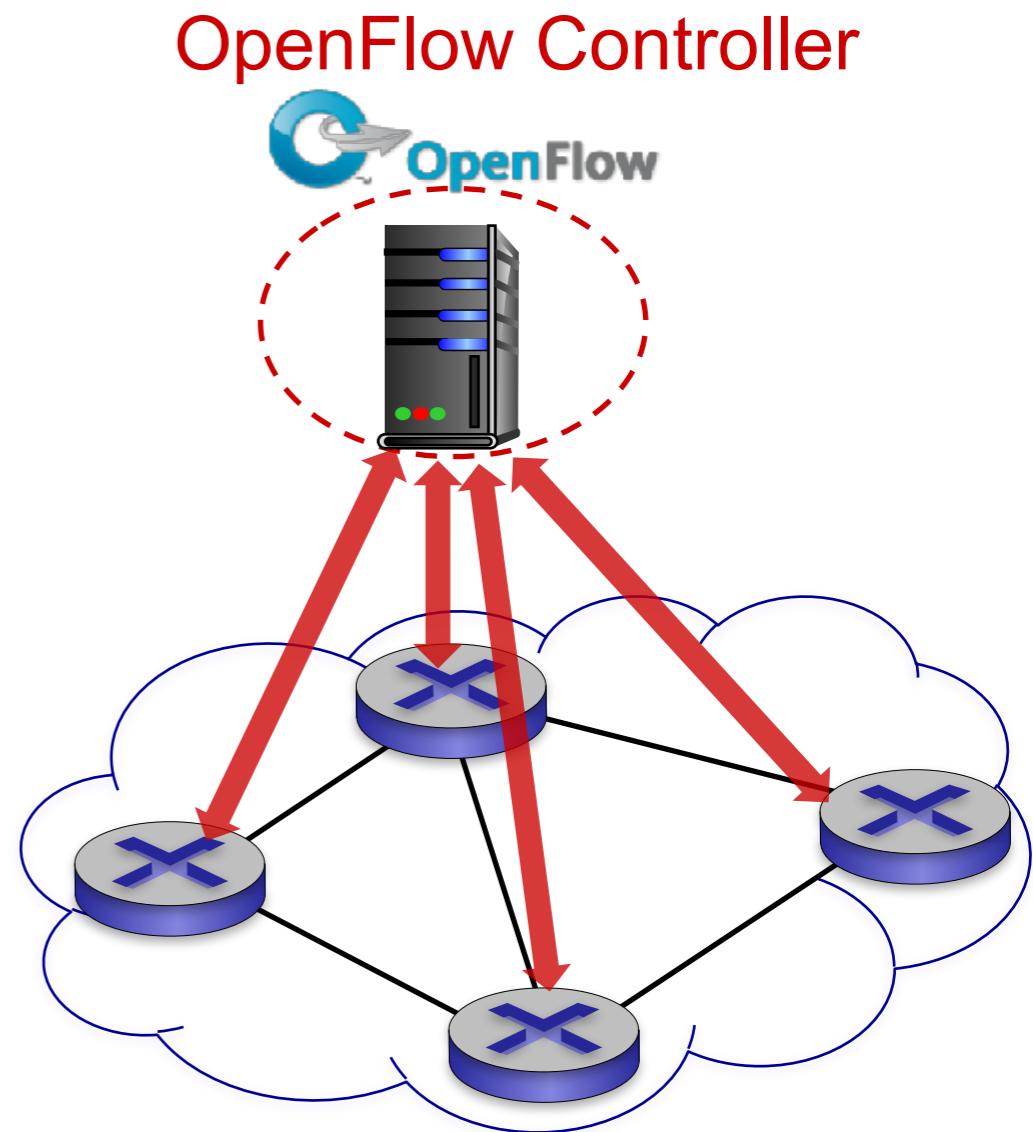
OpenFlow Controller



OpenFlow: controller-to-switch messages

Key controller-to-switch messages

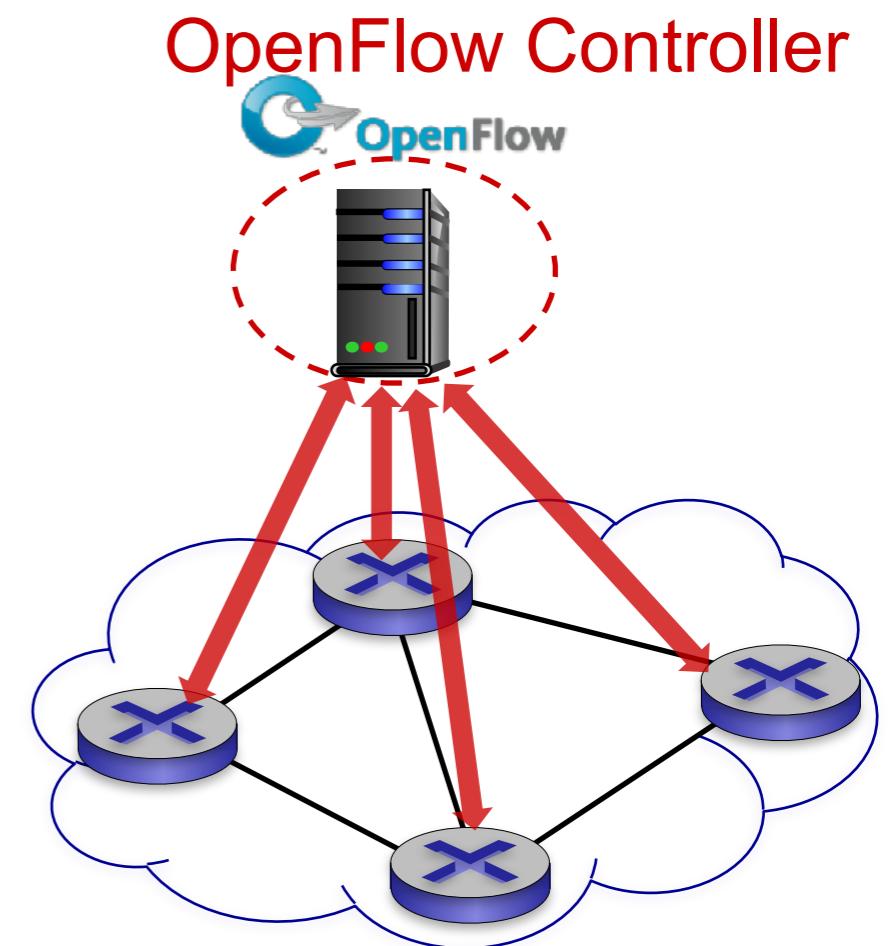
- **features**: controller queries switch features, switch replies
- **configure**: controller queries/sets switch configuration parameters
- **modify-state**: add, delete, modify flow entries in the OpenFlow tables
- **packet-out**: controller can send this packet out of specific switch port



OpenFlow: switch-to-controller messages

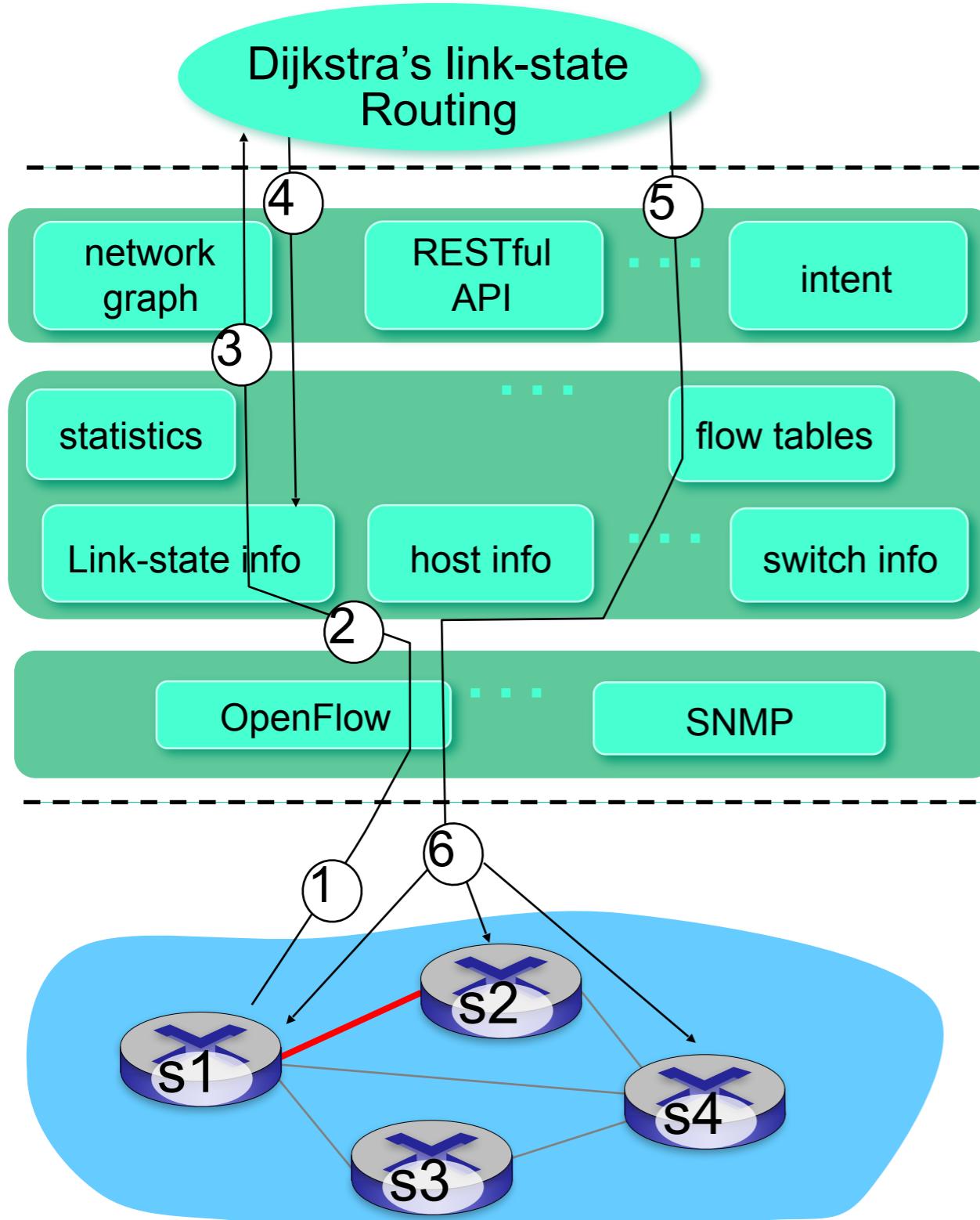
Key switch-to-controller messages

- ***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.



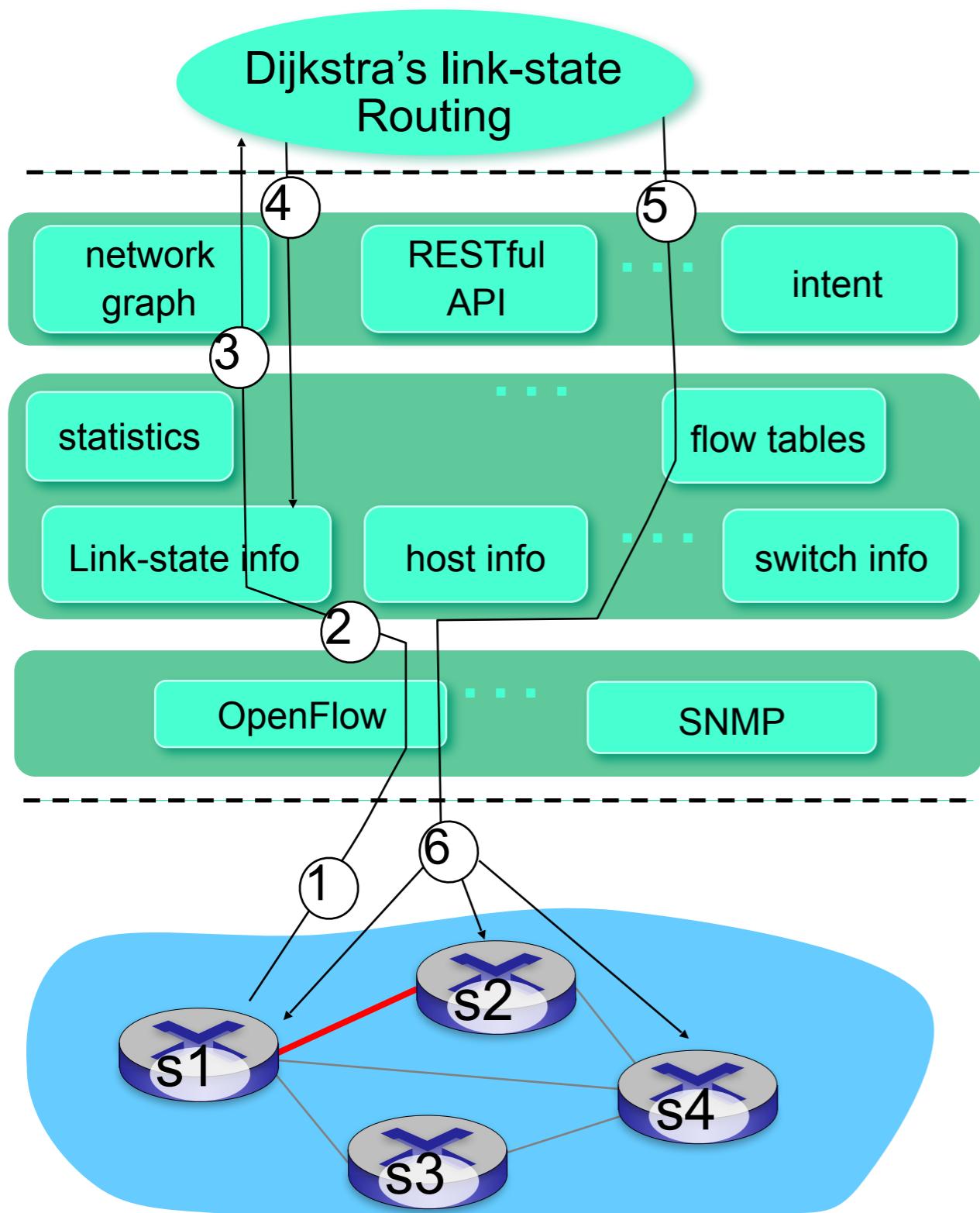
Fortunately, network operators don't "program" switches by creating/sending OpenFlow messages directly. Instead use higher-level abstraction at controller

SDN: control/data plane interaction example



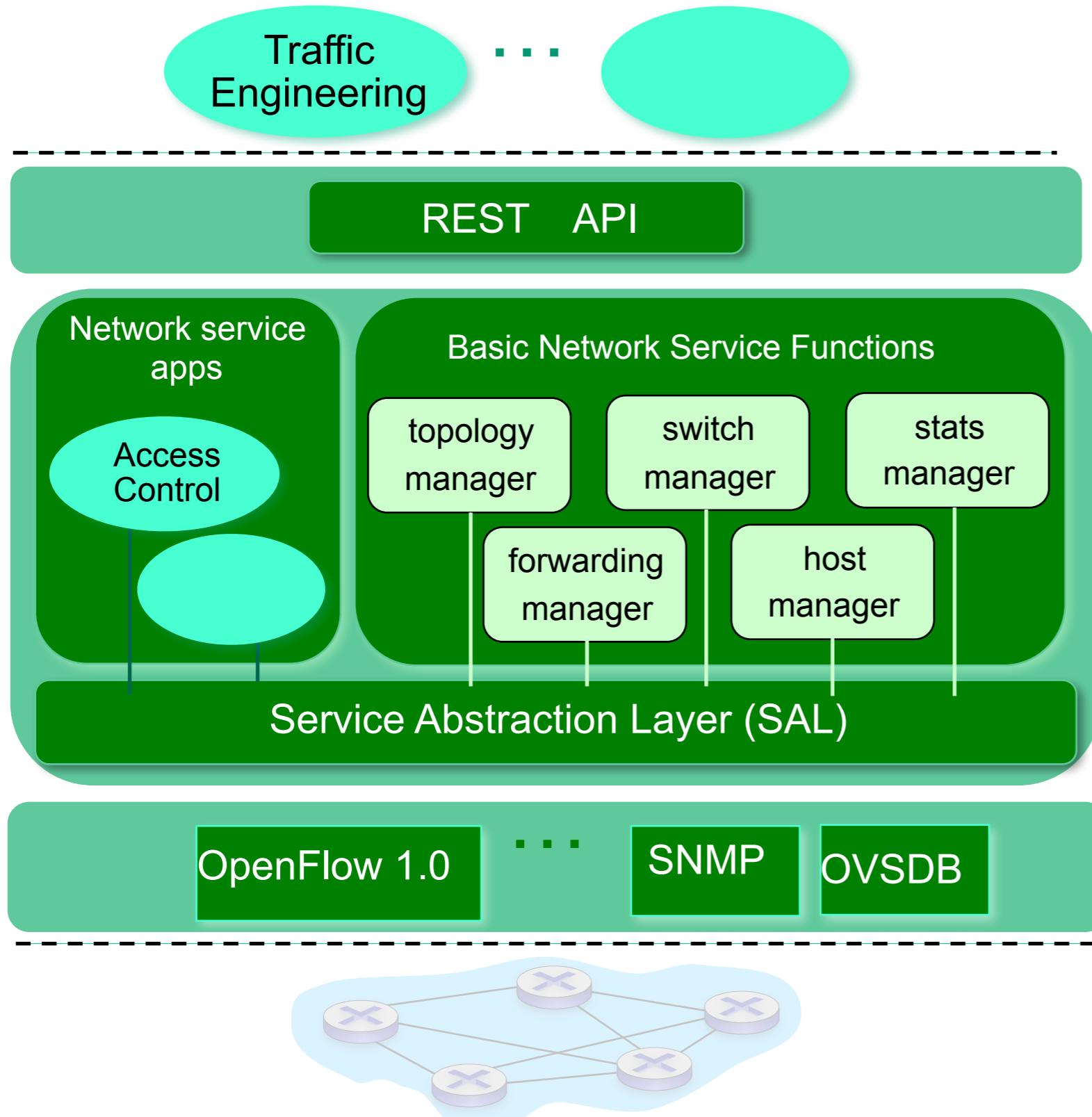
- ① S1, experiencing link failure using OpenFlow port status message to notify controller
- ② SDN controller receives OpenFlow message, updates link status info
- ③ Dijkstra's routing algorithm application has previously registered to be called whenever link status changes. It is called.
- ④ Dijkstra's routing algorithm access network graph info, link state info in controller, computes new routes

SDN: control/data plane interaction example



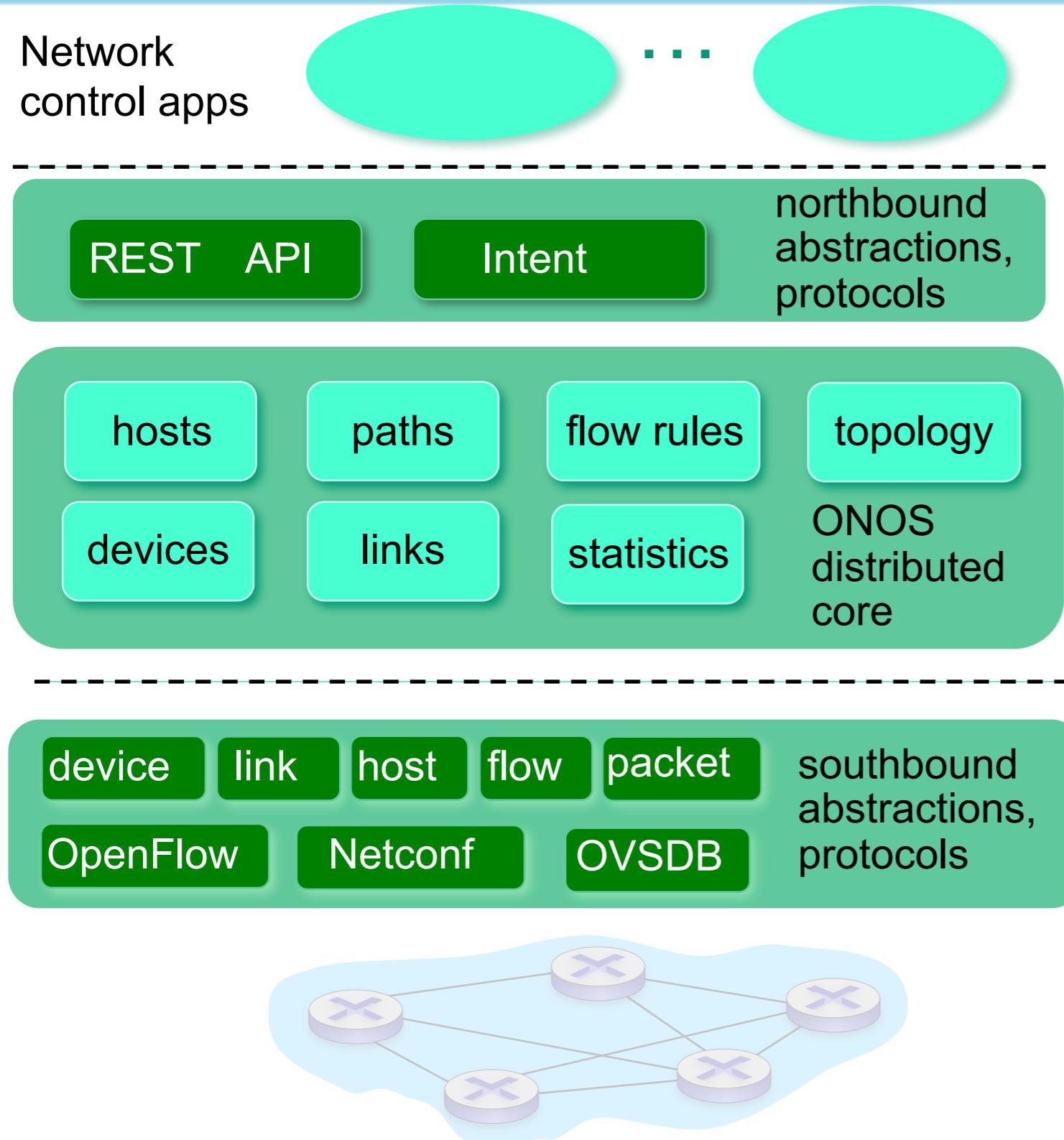
- ⑤ link state routing app interacts with flow-table-computation component in SDN controller, which computes new flow tables needed
- ⑥ Controller uses OpenFlow to install new tables in switches that need updating

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