Network Layer: Control Plane

Goal: understand principles behind network control plane

- traditional (intra-domain) routing algorithms
- SDN controllers

and their instantiation, implementation in the Internet:

- OSPF, RIP, OpenFlow, ODL and ONOS controllers

The following will be discussed in separate lecture notes

- inter-domain routing & BGP
- Internet Control Message Protocol: ICMP
- network management and SNMP

Readings: Textbook: Chapter 5, Sections 5.1-5.3 & 5.5

Network Layer Functions

Recall: two network-layer functions:

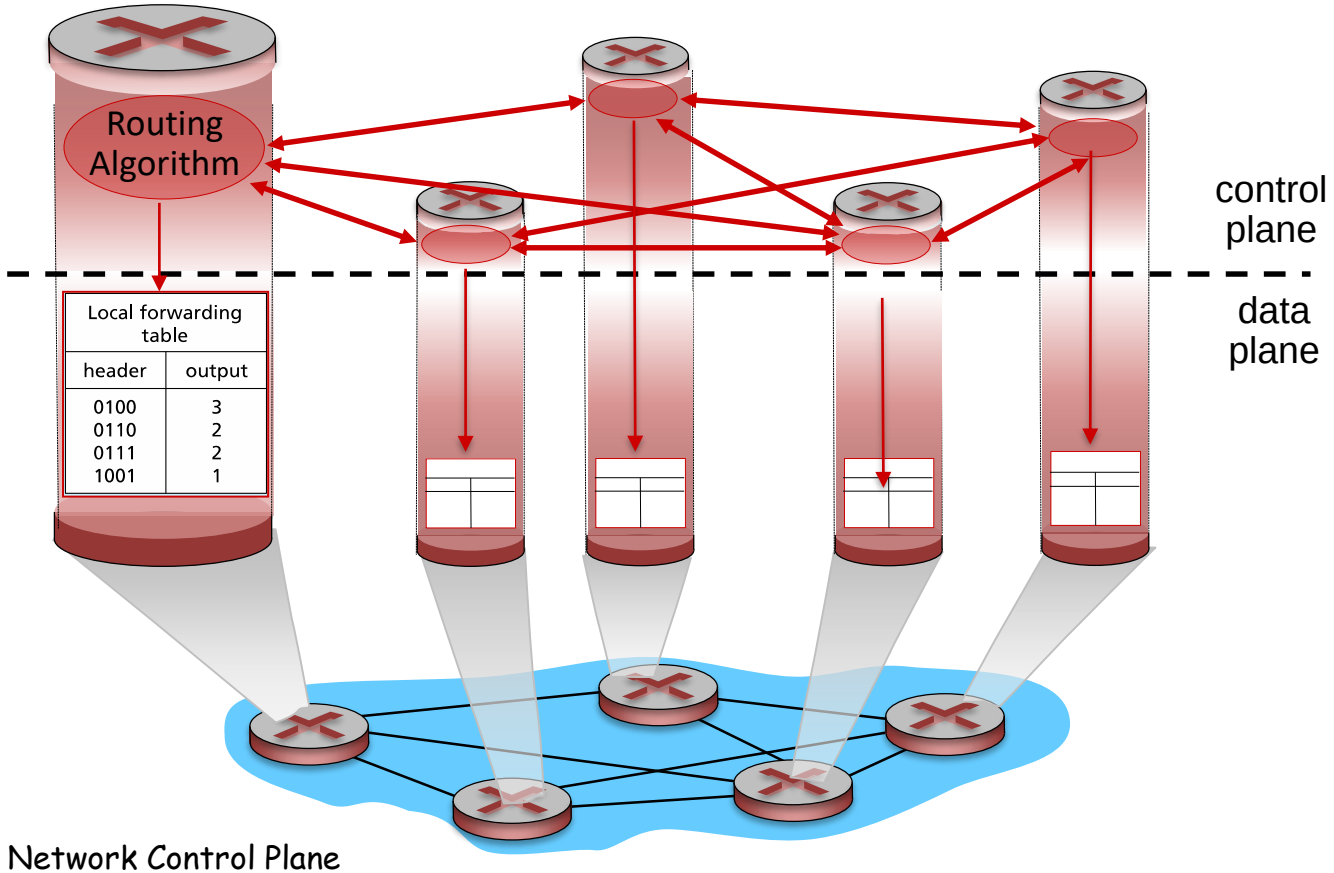
- *forwarding:* move packets from router's input to appropriate router output — *data plane*
- *routing:* determine route taken by packets from source to destination — *control plane*

Two approaches to structuring network control plane:

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

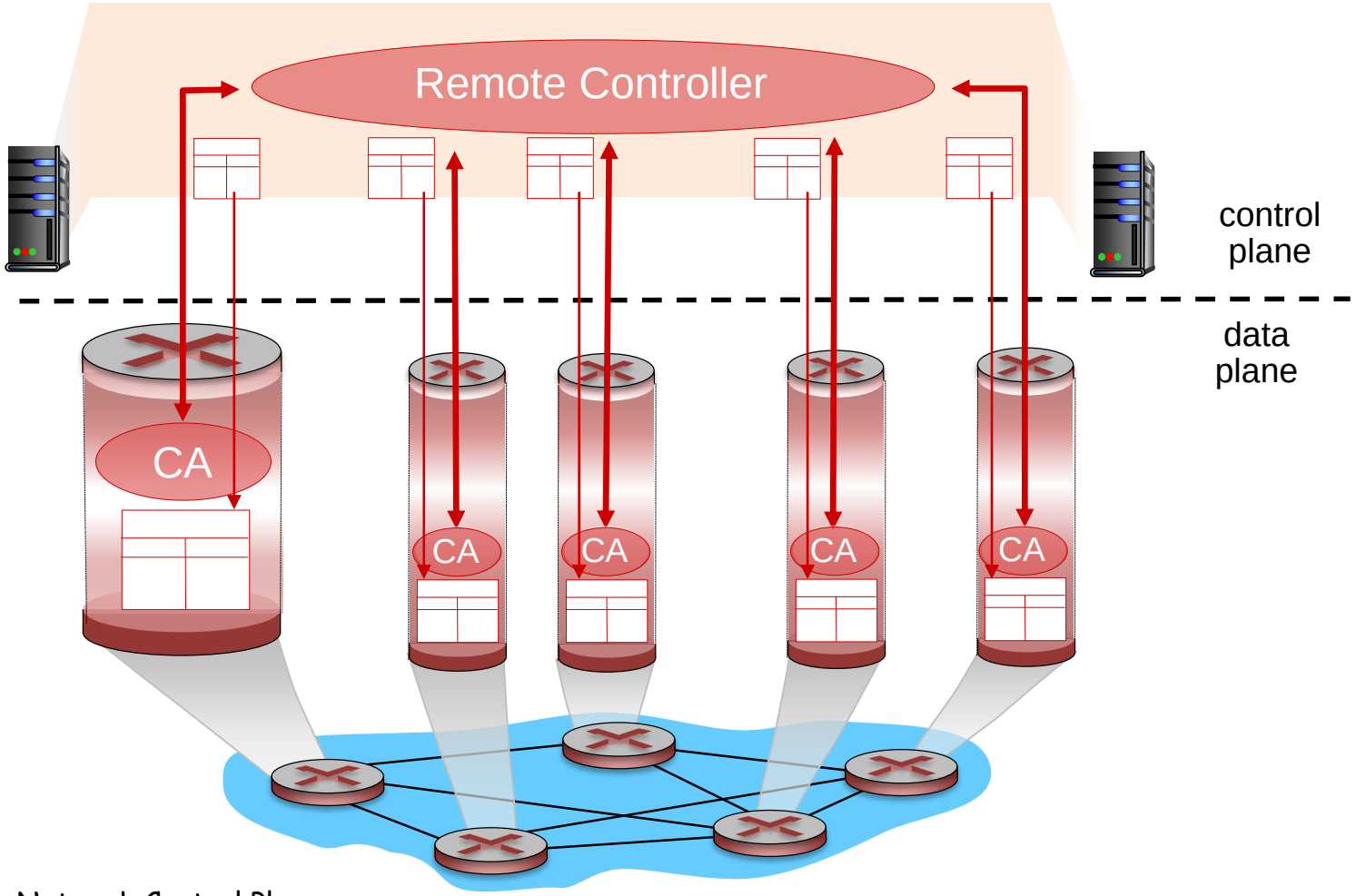
Per-router Distributed Control Plane

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

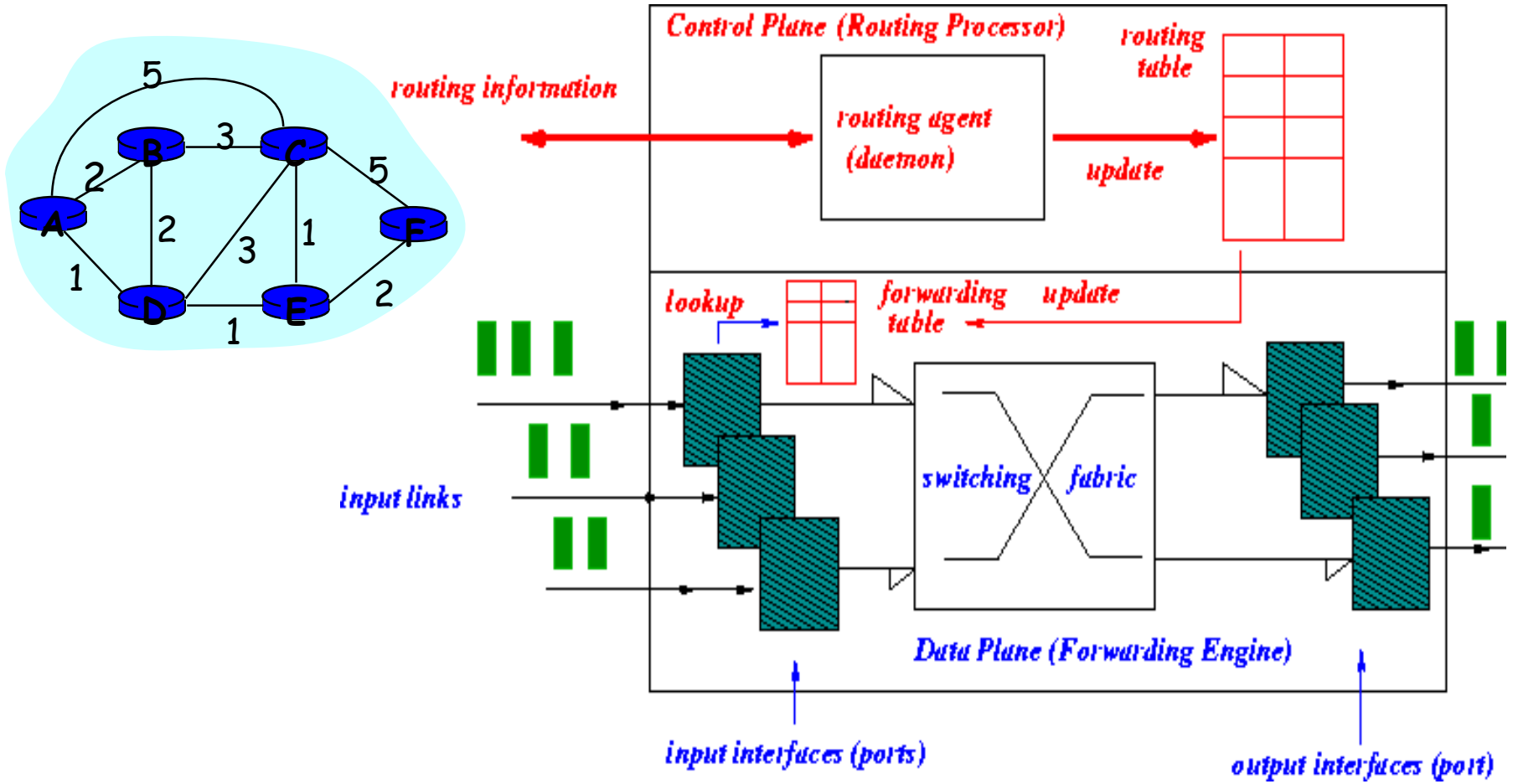


Logically Centralized Control Plane

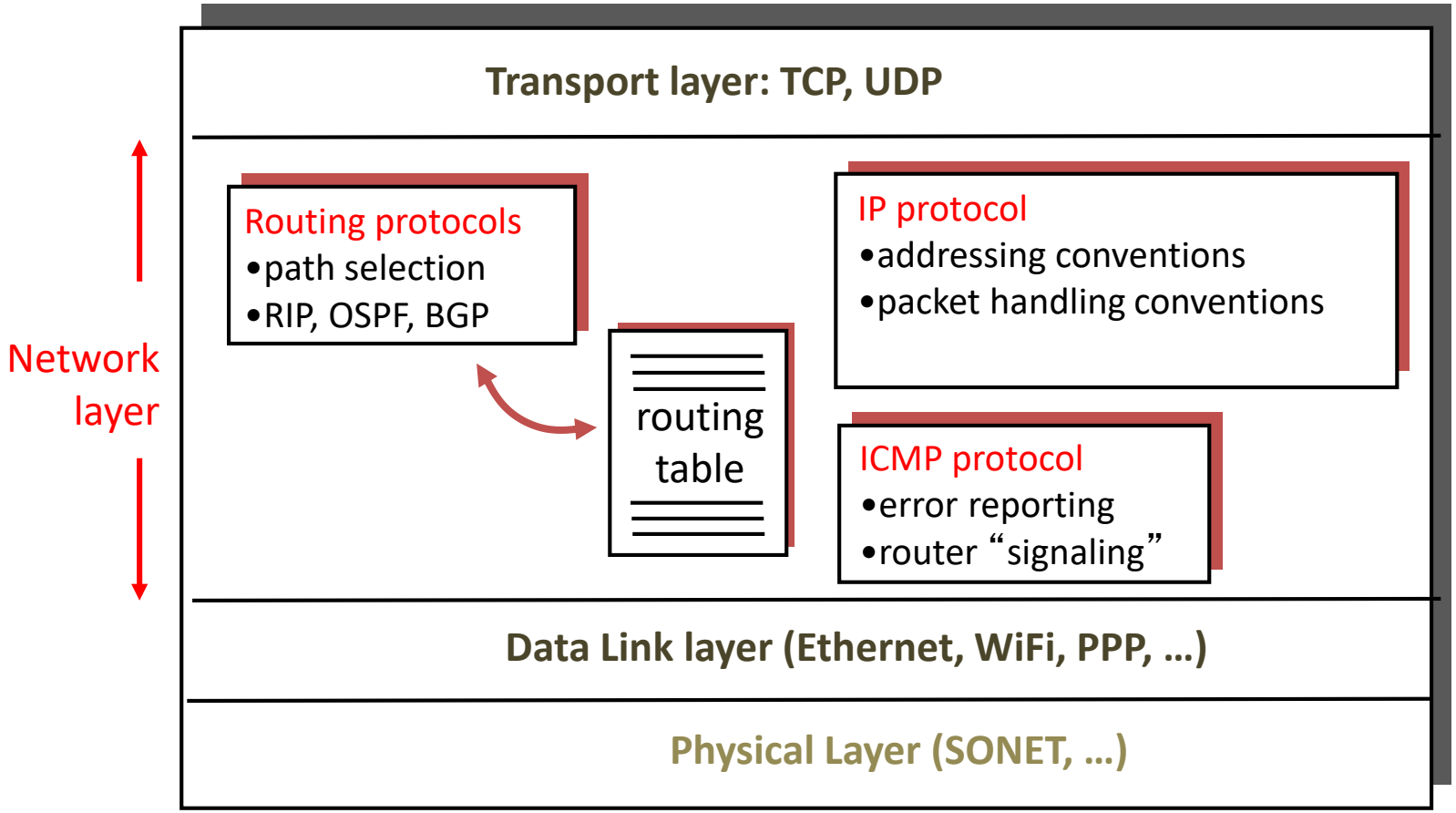
A distinct (typically remote) controller interacts with local control agents (CAs) in routers to compute forwarding tables



Routing & Forwarding:
Logical View of a (Classical) Router



IP Forwarding & IP/ICMP Protocol



Routing: Issues

- How are routing tables determined?
- Who determines table entries?
- What info used in determining table entries?
- When do routing table entries change?
- Where is routing info stored?
- How to control routing table size?

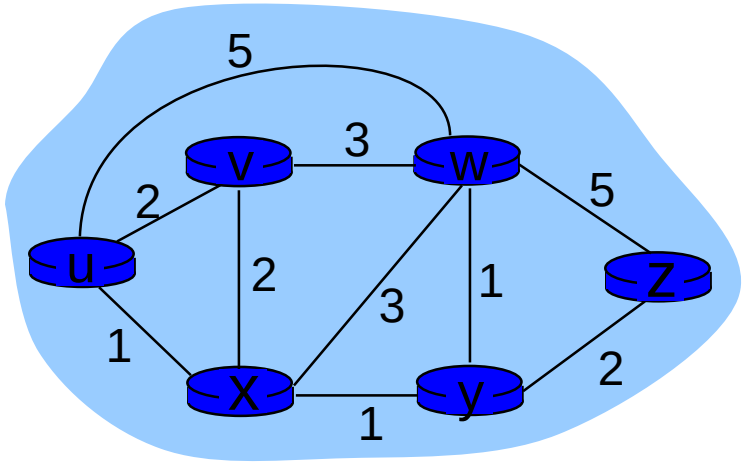
Answer these questions, we are done!

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



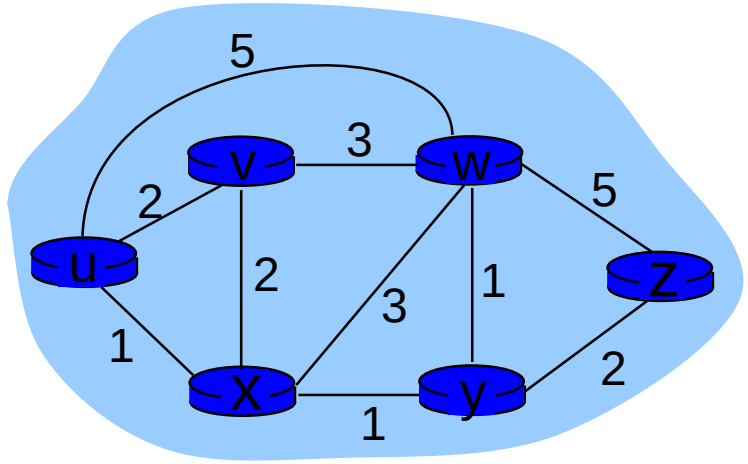
graph: G = (N,E)

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') = 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 $(x_1, x_2, x_3, \ldots, x_p) = c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$

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

Routing Algorithms/Protocols

Issues Need to Be Addressed:

- Route selection may depend on different criteria
  - Performance: choose route with smallest delay
  - Policy: choose a route that doesn't cross .gov network
- Adapt to changes in network topology or condition
  - Self-healing: little or no human intervention
- Scalability
  - Must be able to support large number of hosts, routers

Classical Distributed Routing Paradigms

- Hop-by-hop Routing
  - Each packet contains destination address
  - Each router chooses next-hop to destination
    - routing decision made at each (intermediate) hop!
    - packets to same destination may take different paths!
  - Example: IP's default datagram routing
- Source Routing
  - Sender selects the path to destination precisely
  - Routers forward packet to next-hop as specified
    - Problem: if specified path no longer valid due to link failure!
  - Example:
    - IP's loose/strict source route option (you'll see later)
    - virtual circuit setup phase (or MPLS)

Centralized vs. Distributed Routing Algorithms

Centralized:

- A centralized route server collects routing information and network topology, makes route selection decisions, then distributes them to routers

Distributed:

- Routers cooperate using a distributed protocol
  - to create mutually consistent routing tables
- Two standard distributed routing algorithms
  - Link State (LS) routing
  - Distance Vector (DV) routing

Link State *vs.* Distance Vector

- Both assume that
  - The address of each neighbor is known
  - The cost of reaching each neighbor is known
- Both find global information
  - By exchanging routing info among neighbors
- Differ in info exchanged and route computation
  - LS: tells every other node its distance to neighbors
  - DV: tells neighbors its distance to every other node

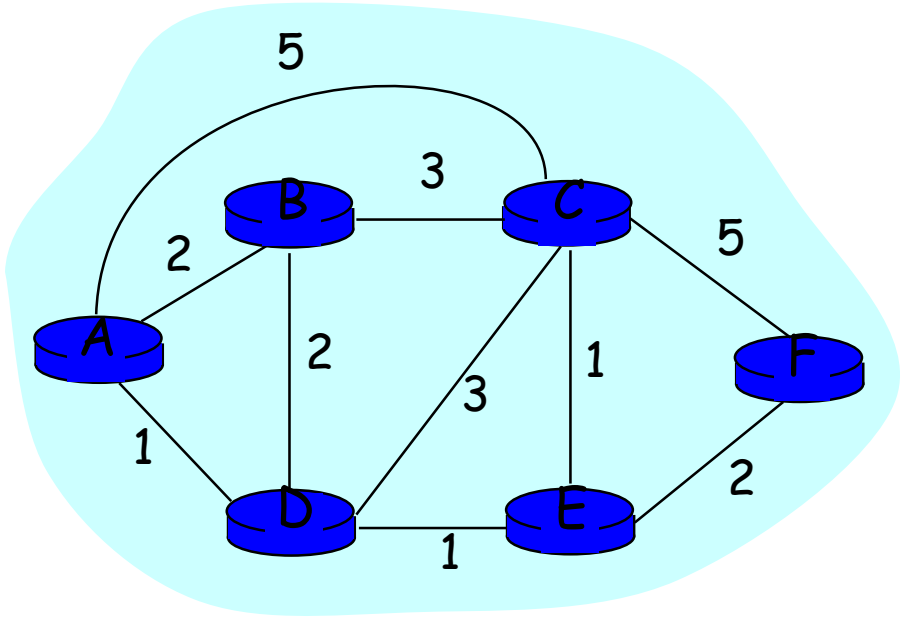
Link State Algorithm

- Basic idea: Distribute to all routers
  - Topology of the network
    - Cost of each link in the network
- Each router independently computes optimal paths
  - From itself to every destination
  - Routes are guaranteed to be loop free if
    - Each router sees the same cost for each link
    - Uses the same algorithm to compute the best path

Topology Dissemination

- Each router creates a set of link state packets (LSPs)
  - Describing its links to neighbors
  - LSP contains
    - Router id, neighbor's id, and cost to its neighbor
- Copies of LSPs are distributed to all routers
  - Using controlled flooding
- Each router maintains a topology database
  - Database containing all LSPs

Topology Database: Example



c(x,y)	A	B	C	D	E	F
A	0	2	5	1	∞	∞
B	2	0	3	2	∞	∞
C	5	3	0	3	1	5
D	1	2	3	0	1	∞
E	∞	∞	1	1	0	2
F	∞	∞	5	∞	2	0

link state database

Constructing Routing Table: Dijkstra's Algorithm

- Given the network topology
  - How to compute shortest path to each destination?
- Some notation
  - X: source node
  - N: set of nodes to which shortest paths are known so far
    - N is initially empty
  - D(V): cost of known shortest path from source X
  - C(U,V): cost of link U to V
    - C(U,V) = ∞ if not neighbors

Dijsktra's Algorithm (at Node X)

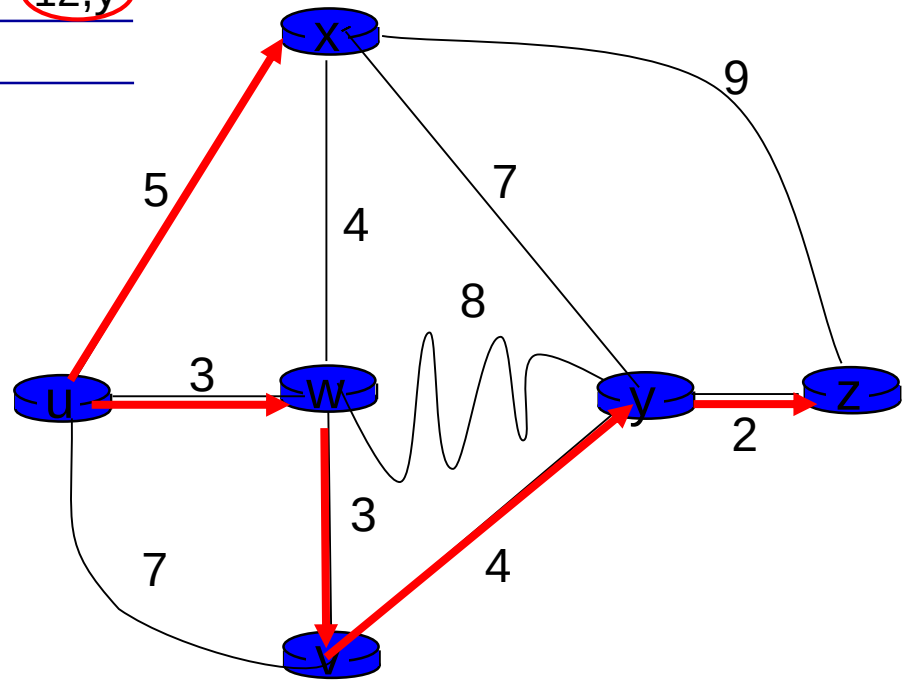
- Initialization
  - N = {X}
  - For all nodes V
    - If V adjacent to X, D(V) = C(X,V)
    - else D(V) = ¥
- Loop
  - Find U not in N such that D(U) is smallest
  - Add U into set N
  - Update D(V) for all V not in N
    - D(V) = min{D(V), D(U) + C(U,V)}
  - Until all nodes in N

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					

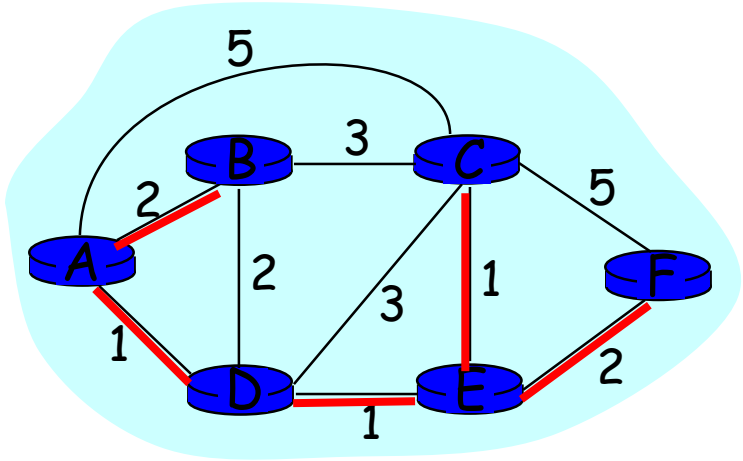
notes:

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



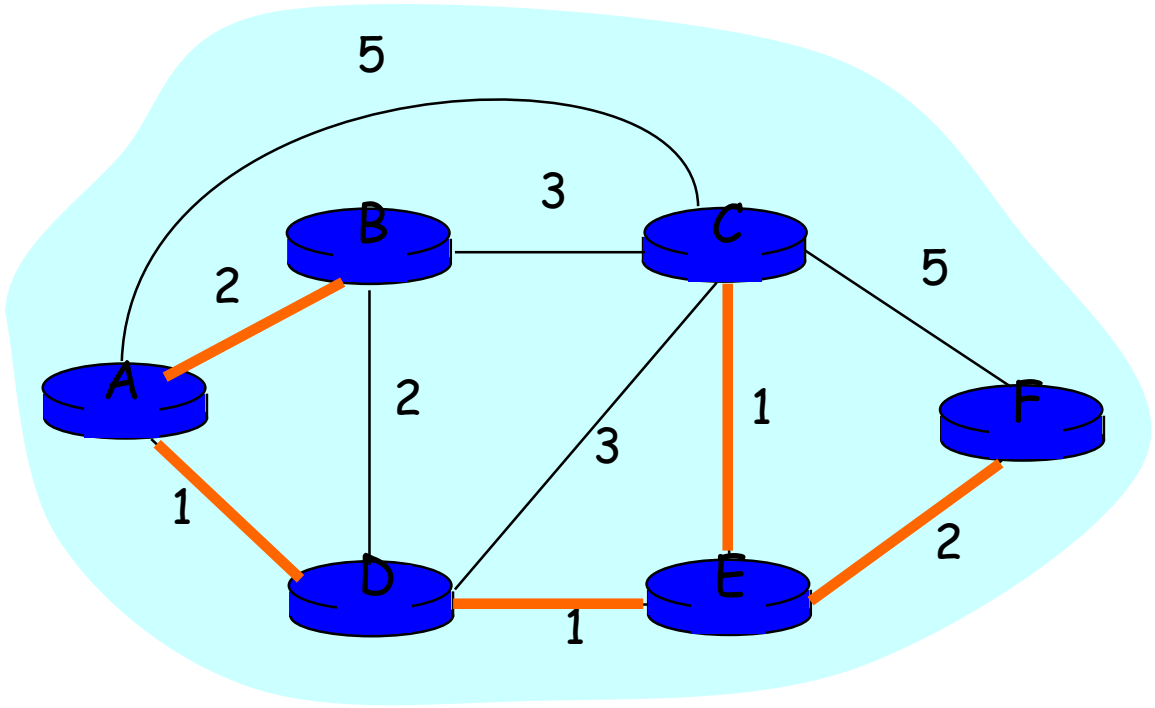
Dijkstra's Algorithm: Another Example

Step	start N	D(B),p(B)	D(C),p(C)	D(D),p(D)	D(E),p(E)	D(F),p(F)
→ 0	A	2,A	5,A	1,A	infinity	infinity
→ 1	AD	2,A	4,D		2,D	infinity
→ 2	ADE	2,A	3,E			4,E
→ 3	ADEB		3,E			4,E
→ 4	ADEBC					4,E
5	ADEBCF					



Routing Table Computation

dest	next
B	B
C	D
D	D
E	D
F	D



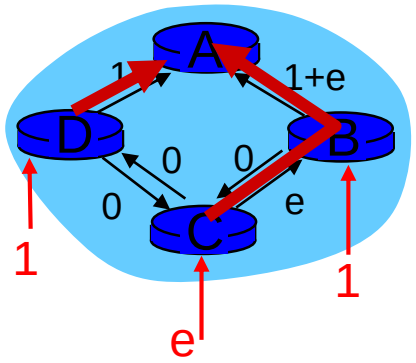
Dijkstra's Algorithm: Discussion

algorithm complexity: n nodes

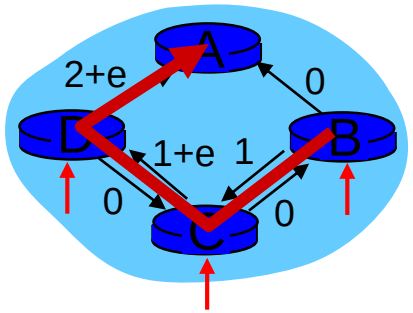
- each iteration: need to check all nodes, w, not in N
- n(n+1)/2 comparisons: $O(n^2)$
- more efficient implementations possible: O(nlogn)

oscillations possible:

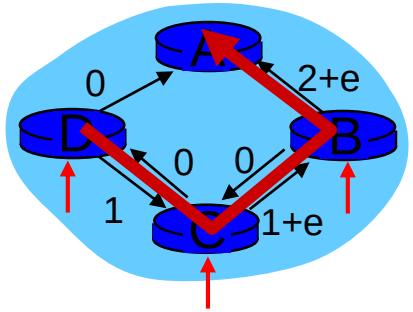
- e.g., support link cost equals amount of carried traffic:



initially



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



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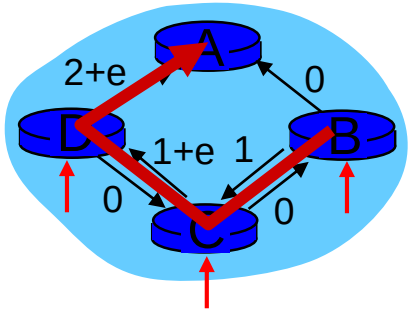
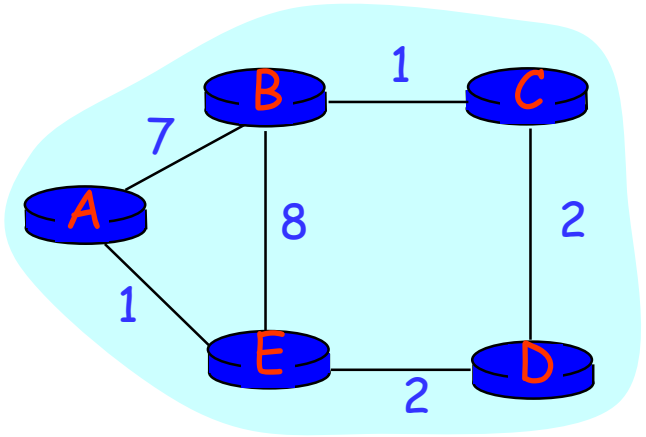


given these costs, find new routing…. resulting in new costs

Distance Vector Routing

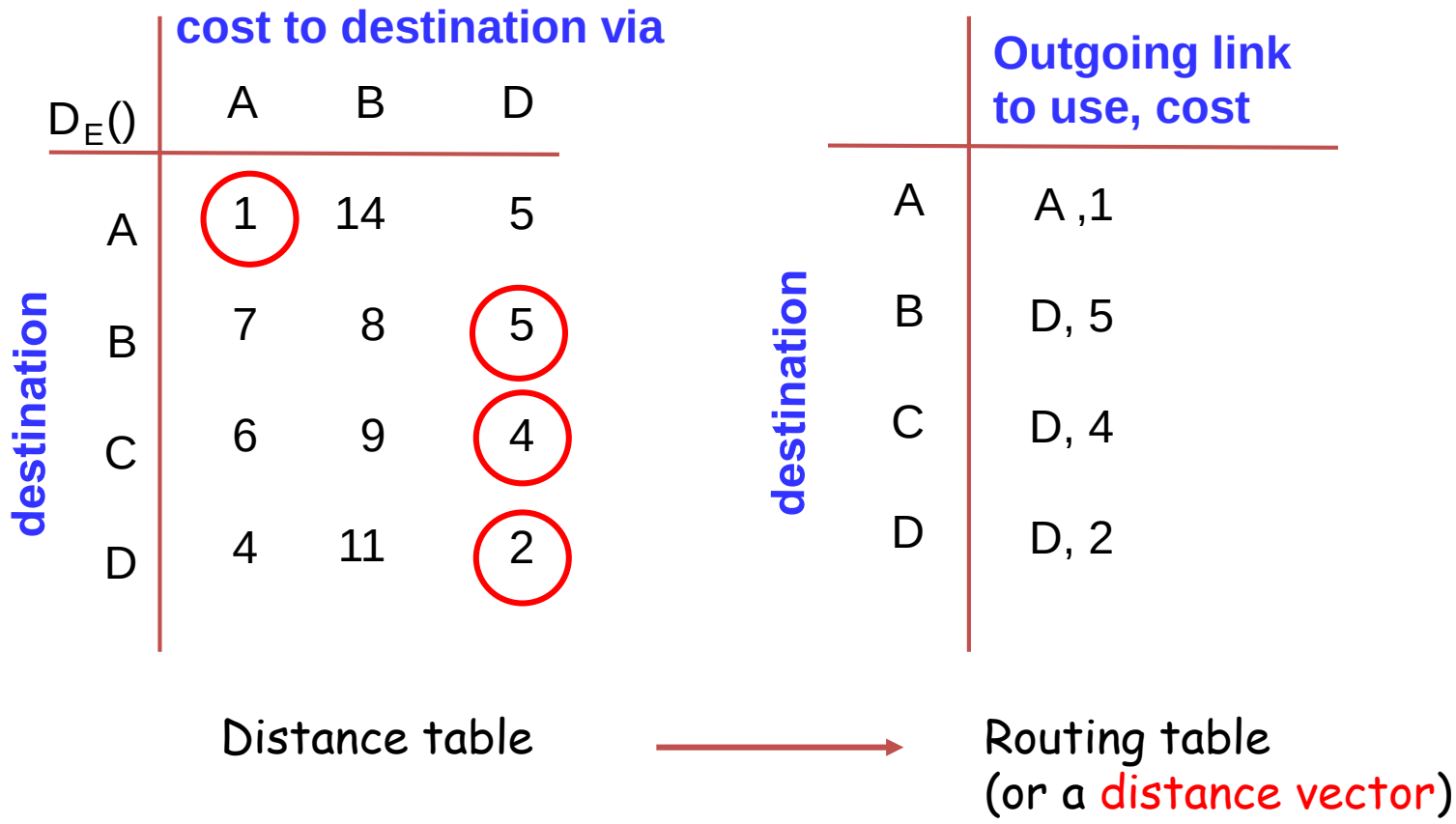
- A router tells neighbors its distance to every router
  - Communication between neighbors only
- Based on Bellman-Ford algorithm
  - Computes "shortest paths"
- Each router maintains a distance table
  - A row for each possible destination
  - A column for each neighbor
    - $D_X(Y,Z)$: distance from X to Y via Z
    - $D_X(Y)$: = $\min_Z\{D_x(Y,Z)\}$: shortest path from X to Y
- Exchanges distance vector with neighbors
  - Distance vector: current least cost from X to each destination

Distance Table: Example



$D_E()$	cost to destination via A	B	D
destination A	1	14	5
B	7	8	5
C	6	9	4
D	4	11	2

From Distance Table to Routing Table



Distance Vector Algorithm

Bellman-Ford equation (dynamic programming)

let

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

then

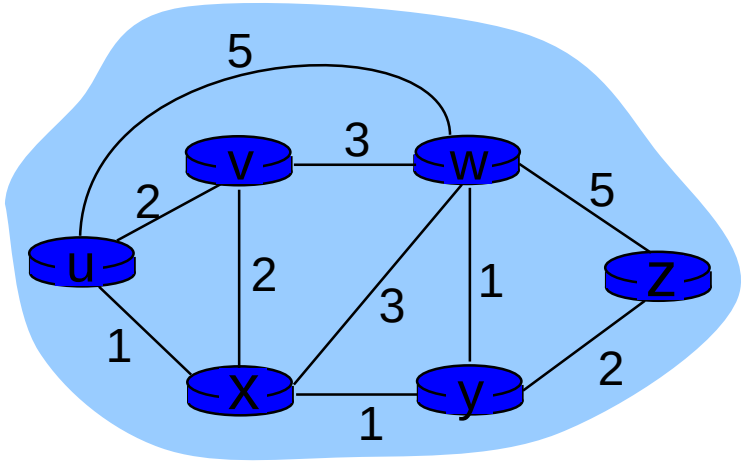
$$d^x(y) = \min_v \{c(x,v) + d^v(y)\}$$

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:

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

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

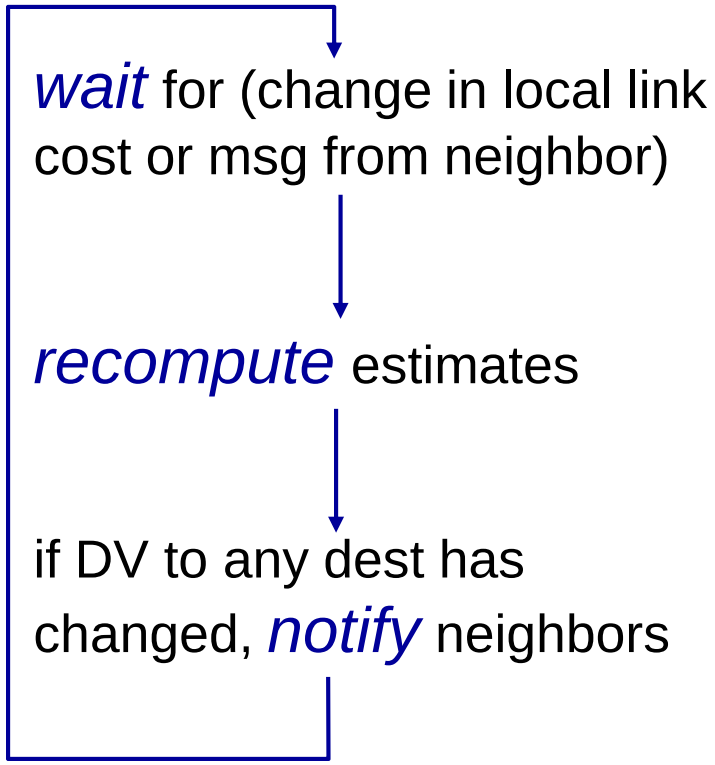
iterative, asynchronous:
each local iteration caused by:

- 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

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

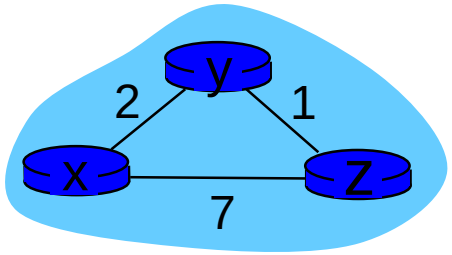
from \ cost to	x	y	z
x	0	2	3
y	2	0	1
z	7	1	0

node y table

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

node z table

from \ cost to	x	y	z
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

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

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

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

node y table

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

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

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

node z table

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

from \ cost to	x	y	z
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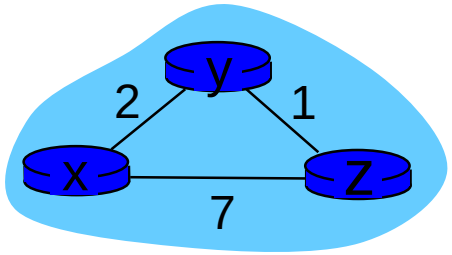
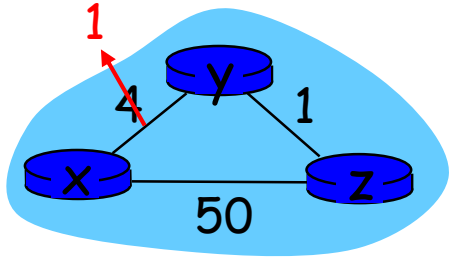


time

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



"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.

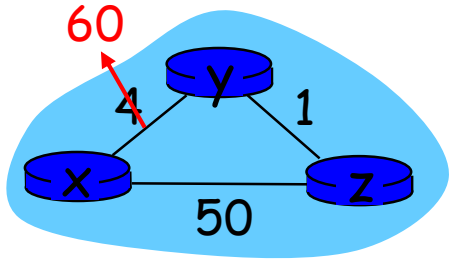
t_2 : *y* receives *z*'s update, updates its distance table. *y*'s least costs do *not* change, so *y* does *not* send a message to *z*.

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

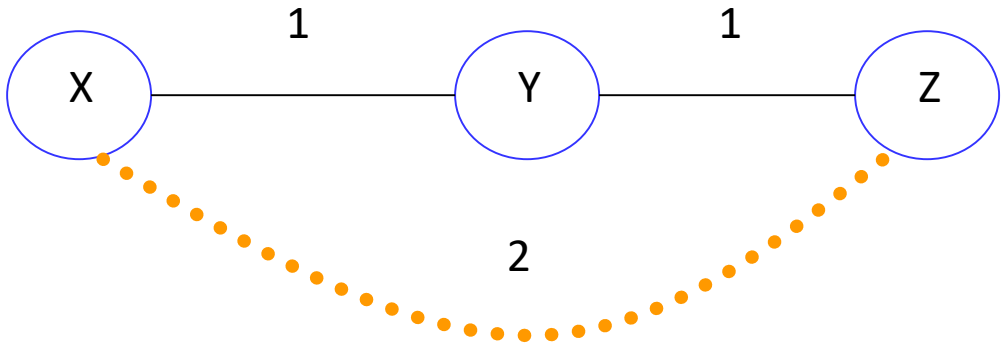
Distance Vector: Link Cost Changes

link cost changes:

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



"Count-to-Infinity" Problem: A Simple Example



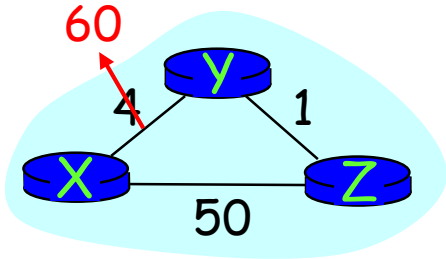
"Fixes" to Count-to-Infinity Problem

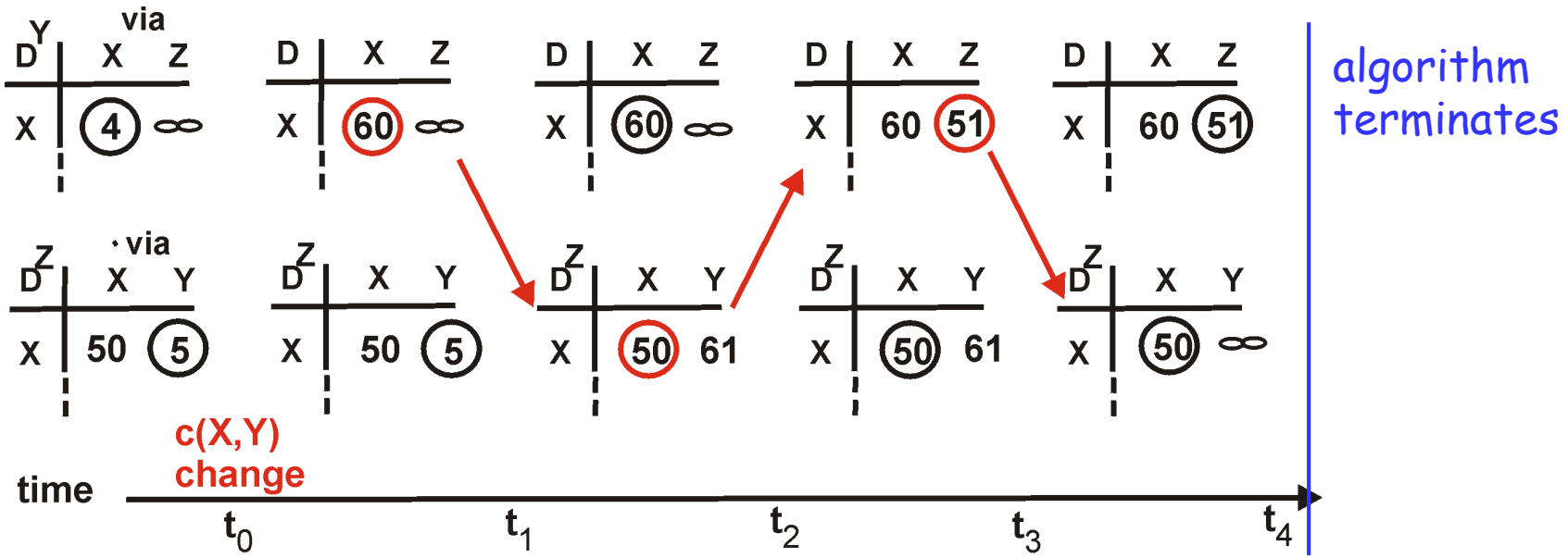
- Split horizon
  - A router never advertises the cost of a destination to a neighbor
    - If this neighbor is the next hop to that destination
- Split horizon with poisonous reverse
  - If X routes traffic to Z via Y, then
    - X tells Y that its distance to Z is infinity
      - Instead of not telling anything at all
  - Accelerates convergence

Split Horizon with 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)





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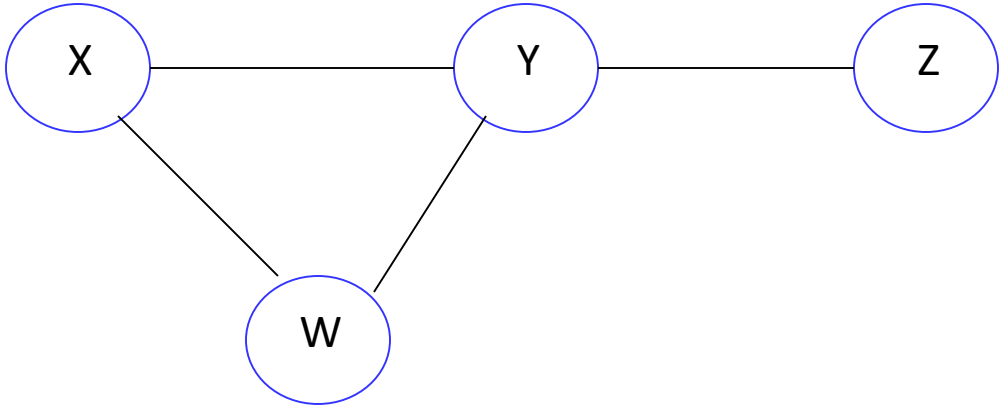
    - X tells Y that its distance to Z is infinity
      - Instead of not telling anything at all
  - Accelerates convergence
- Will this completely solve count to infinity problem?

Count-to-Infinity Problem Revisited



Link State *vs* Distance Vector

- Tells everyone about neighbors
- Controlled flooding to exchange link state
- Dijkstra's algorithm
- Each router computes its own table
- May have oscillations
- Open Shortest Path First (OSPF)

- Tells neighbors about everyone
- Exchanges distance vectors with neighbors
- Bellman-Ford algorithm
- Each router's table is used by others
- May have routing loops
- Routing Information Protocol (RIP)

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

Routing in the Real World

Our routing study thus far - idealization

- all routers identical
- network "flat"

How to do routing in the Internet

- scalability and policy issues

scale: with 200 million destinations:

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

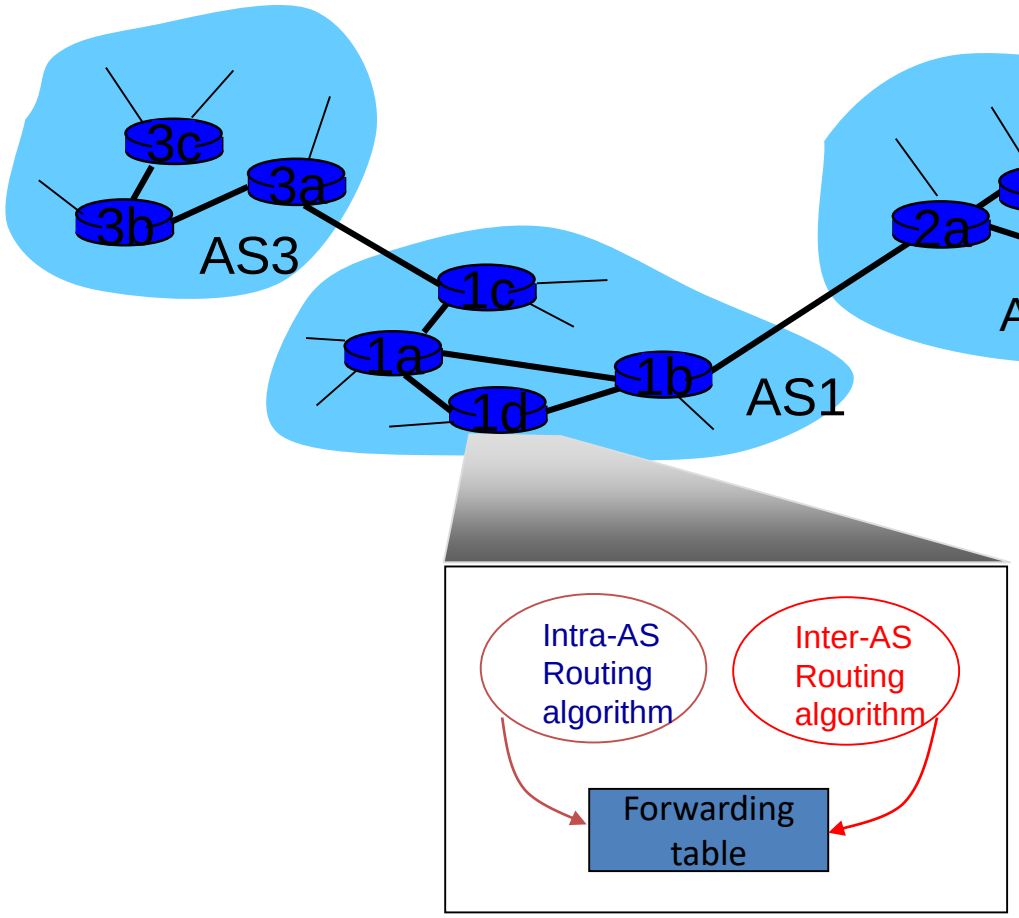
administrative autonomy

- internet = network of networks
- each network admin may want to control routing in its own network

Routing in the Internet

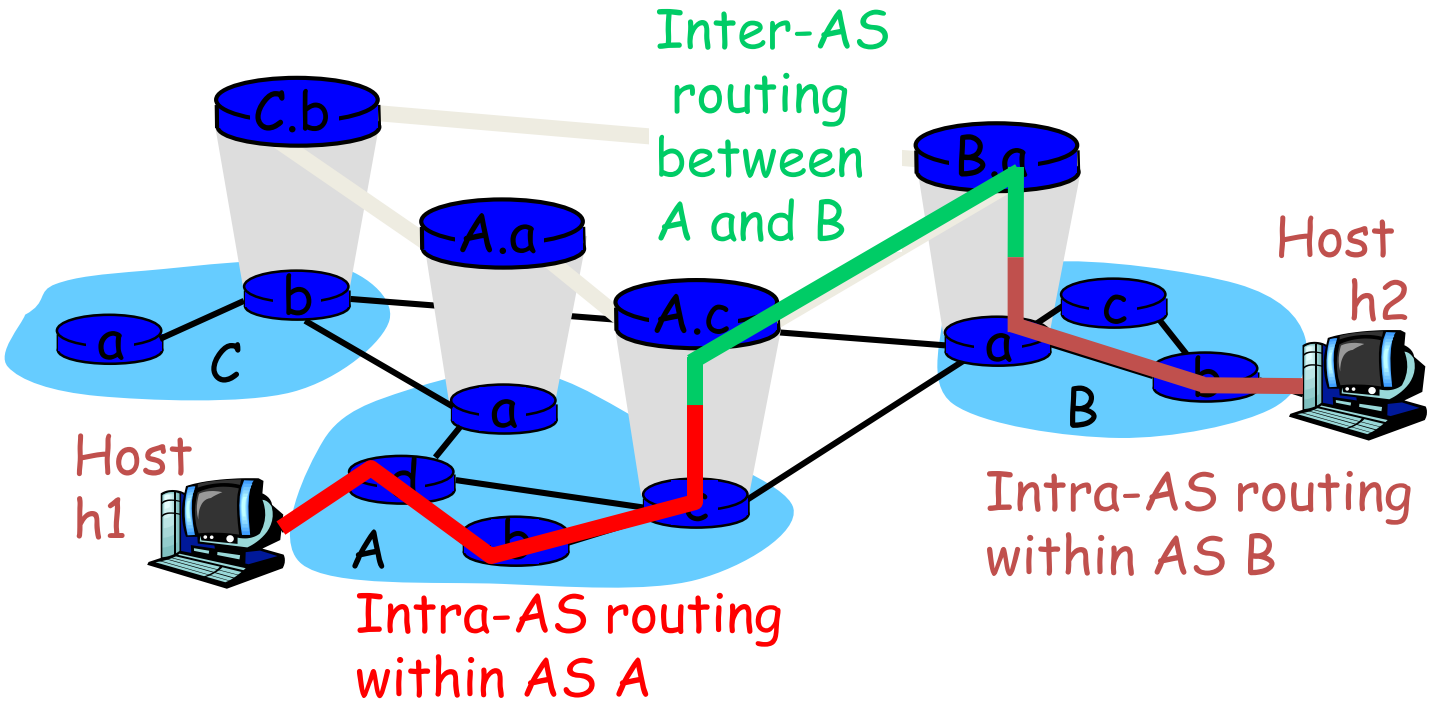
- The Global Internet consists of Autonomous Systems (AS) interconnected with each other:
  - Stub AS: small corporation: one connection to other AS's
  - Multihomed AS: large corporation (no transit): multiple connections to other AS's
  - Transit AS: provider, hooking many AS's together
- Two-level routing:
  - Intra-AS: administrator responsible for choice of routing algorithm within network
  - Inter-AS: unique standard for inter-AS routing: BGP

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 vs. Inter-AS Routing



Why Different Intra- and 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, update traffic

Performance:

- Intra-AS: can focus on performance
- Inter-AS: policy may dominate over performance

Will Talk about Inter-AS routing (& BGP) later!

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: Intermediate System to Intermediate System (OSI Standard)
  - EIGRP: Extended Interior Gateway Routing Protocol (Cisco proprietary)

RIP (Routing Information Protocol)

- Distance vector algorithm
- Included in BSD-UNIX Distribution in 1982
- Distance metric: # of hops (max = 15 hops)
  - *Can you guess why?*

- Distance vectors: exchanged among neighbors every 30 sec via Response Message (also called **advertisement**)
- Each advertisement: list of up to 25 destination nets within AS

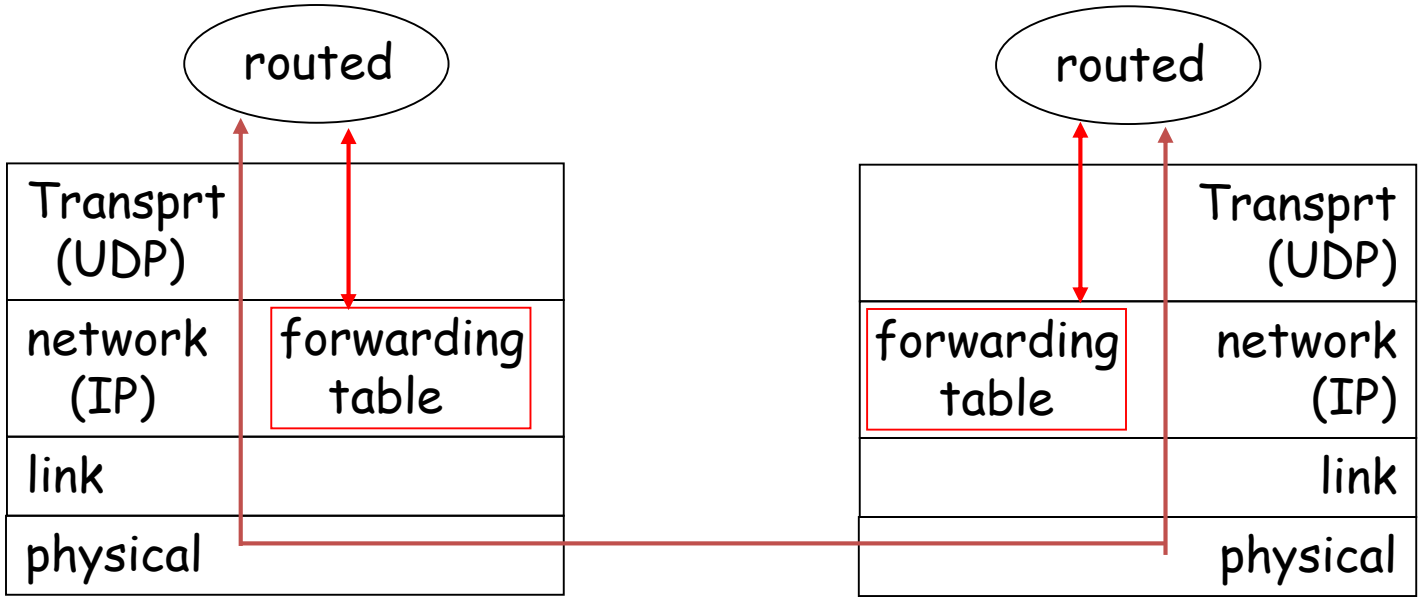
RIP: Link Failure and Recovery

If no advertisement heard after 180 sec --> neighbor/link declared dead

- routes via neighbor invalidated
- new advertisements sent to neighbors
- neighbors in turn send out new advertisements (if tables changed)
- link failure info quickly propagates to entire net
- poison reverse used to prevent ping-pong loops (infinite distance = 16 hops)

RIP Table Processing

- RIP routing tables managed by **application-level** process called route-d (daemon)
- advertisements sent in UDP packets, periodically repeated



OSPF (Open Shortest Path First)

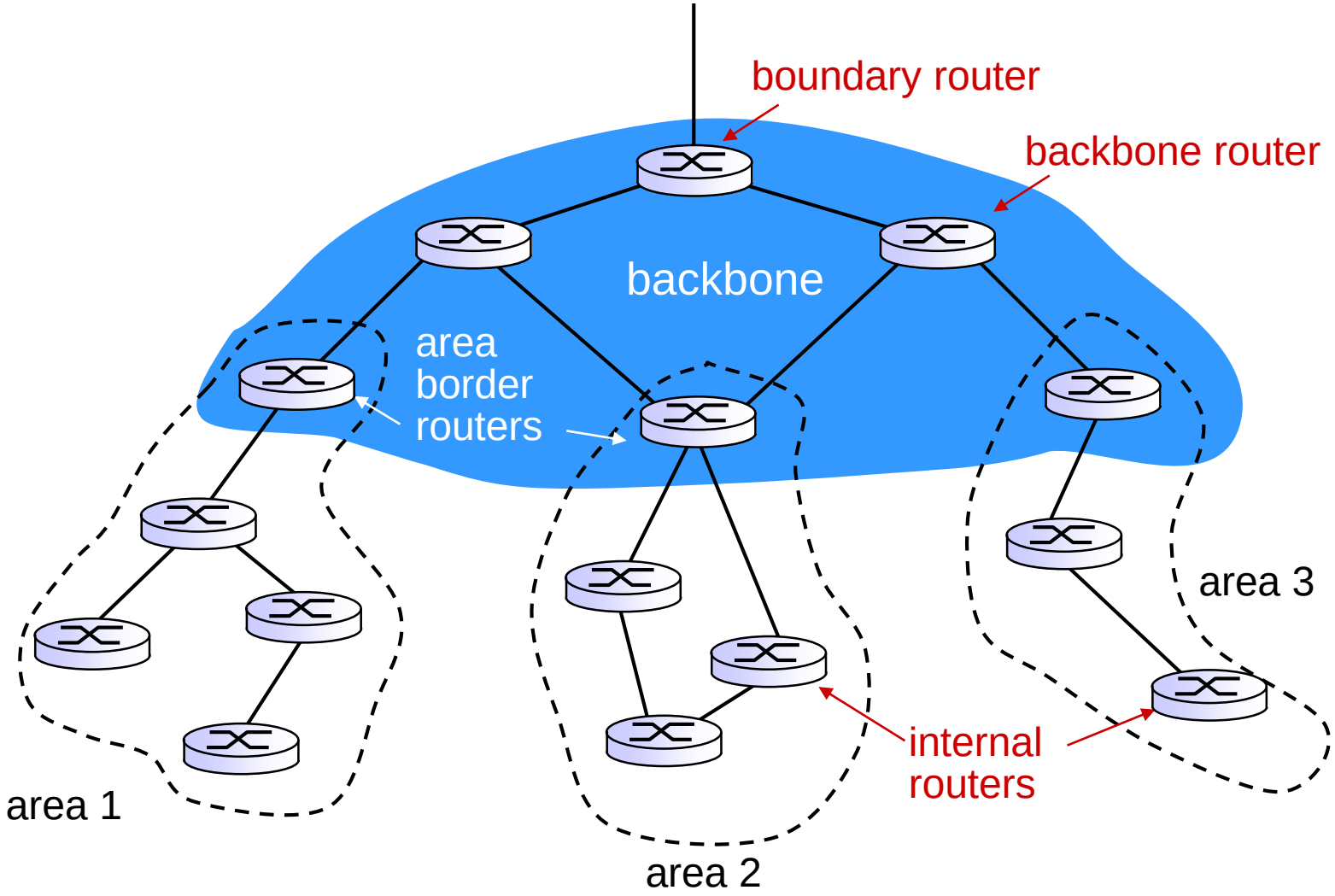
- "open": publicly available
- uses link-state algorithm
  - link state packet dissemination
  - topology map at each node
  - route computation using Dijkstra's algorithm
- router floods OSPF link-state advertisements to all other routers in *entire* AS
  - carried in OSPF messages directly over IP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

OSPF "Advanced" Features (not in RIP)

- 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 ("Type-of-Services")
  - e.g., satellite link cost set "low" for best effort; high for real time)

- Hierarchical OSPF in large domains.

Hierarchical OSPF



Hierarchical OSPF

- Two-level hierarchy: local area, backbone.
  - Link-state advertisements only in area
  - each nodes 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 ASes.

Software Defined Networking (SDN)

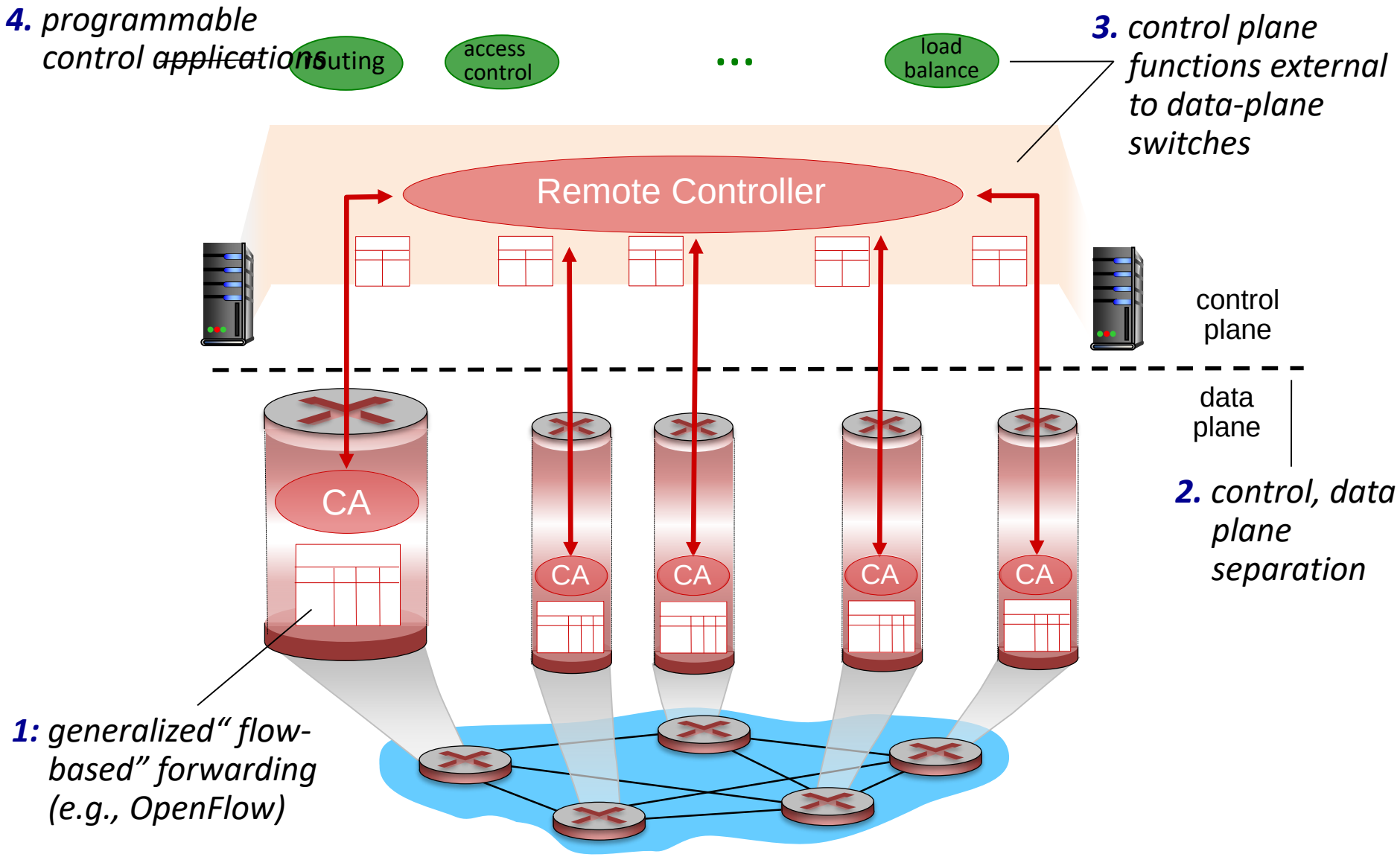
- Internet network layer: historically has been implemented via distributed, per-router approach
  - *monolithic* router contains switching hardware, runs proprietary implementation of Internet standard protocols (IP, RIP, IS-IS, OSPF, BGP) in proprietary router OS (e.g., Cisco IOS)
  - different "middleboxes"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

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

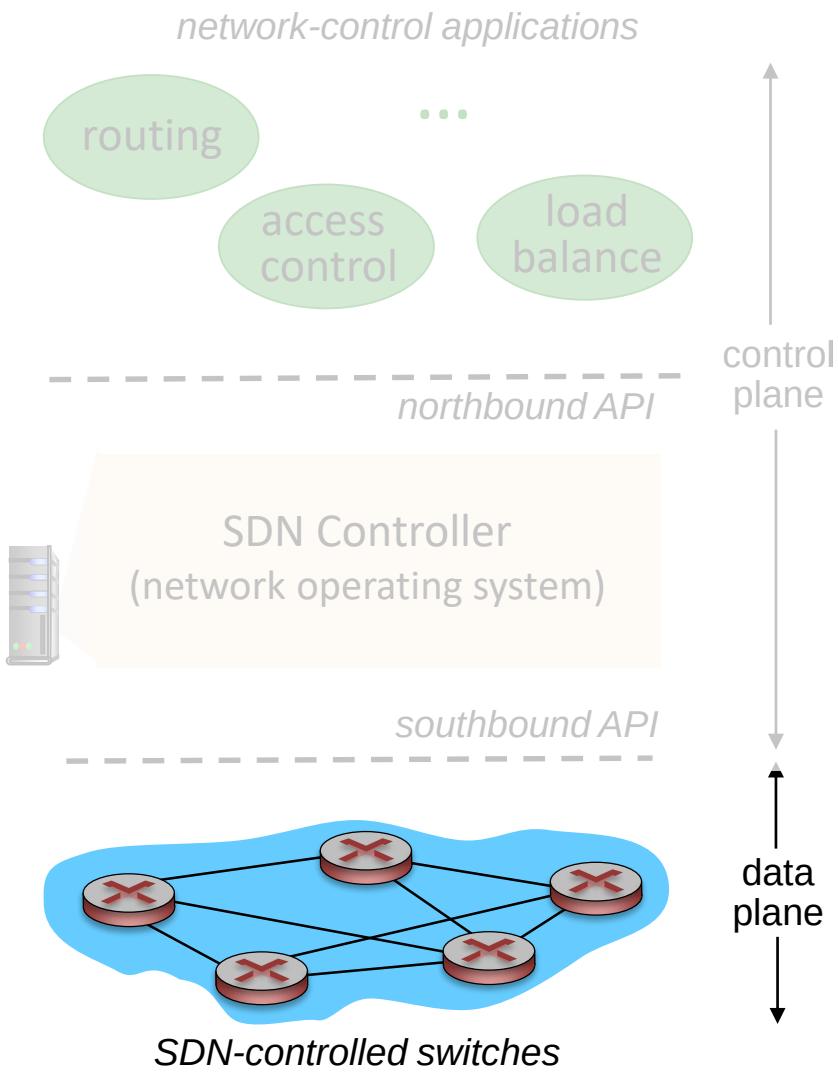
Software Defined Networking (SDN)



SDN Perspective: Data Plane Switches

Data plane switches

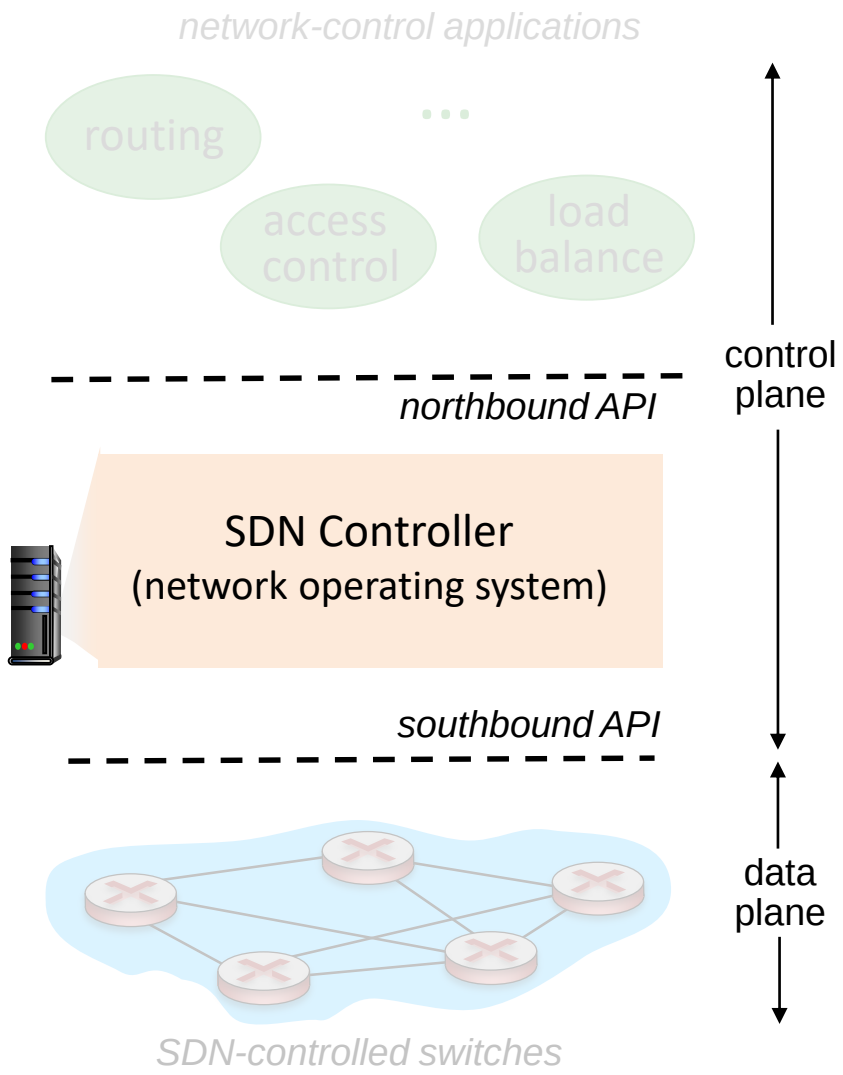
- fast, simple, commodity switches implementing generalized data-plane forwarding (Section 4.4) in hardware
- switch flow table computed, installed by controller
- API for table-based switch control (e.g., OpenFlow)
  - defines what is controllable and what is not
- protocol for communicating with controller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



SDN perspective: SDN Controller

SDN controller (network OS):

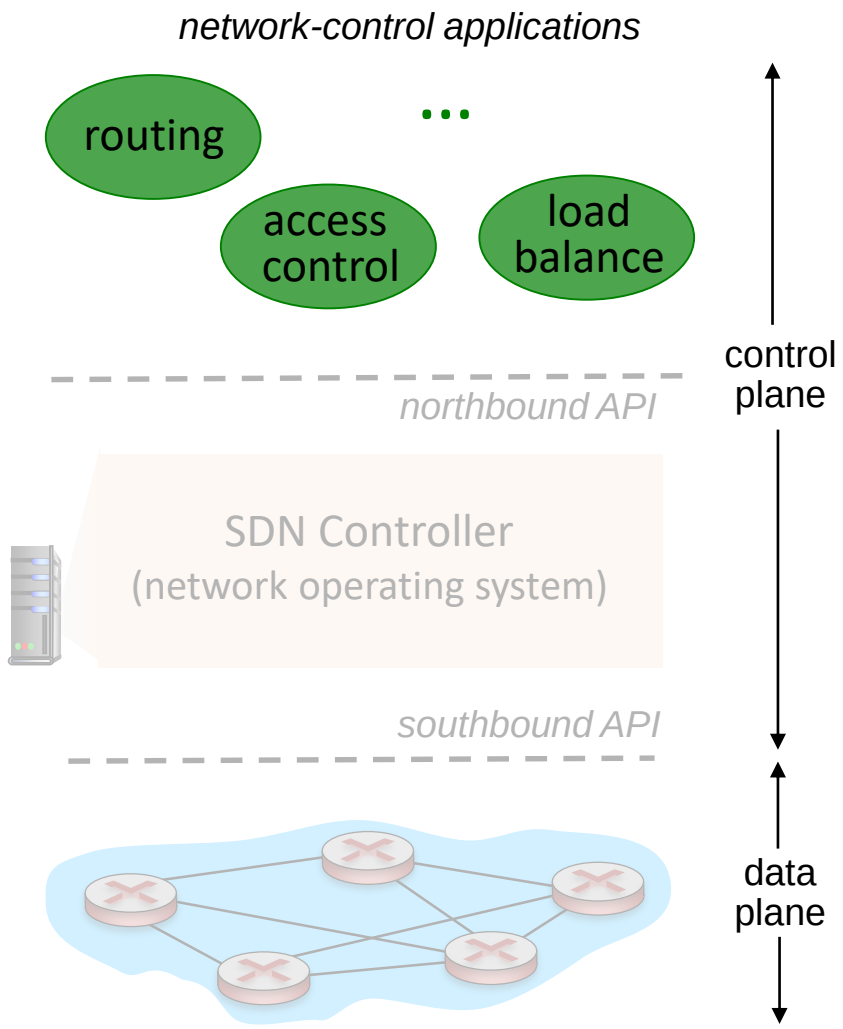
- maintain network state information
- interacts with network control applications "above" via northbound API
- interacts with network switches "below" via southbound API
- implemented as distributed system for performance, scalability, fault-tolerance, robustness



SDN Perspective: Control Applications

network-control apps:

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

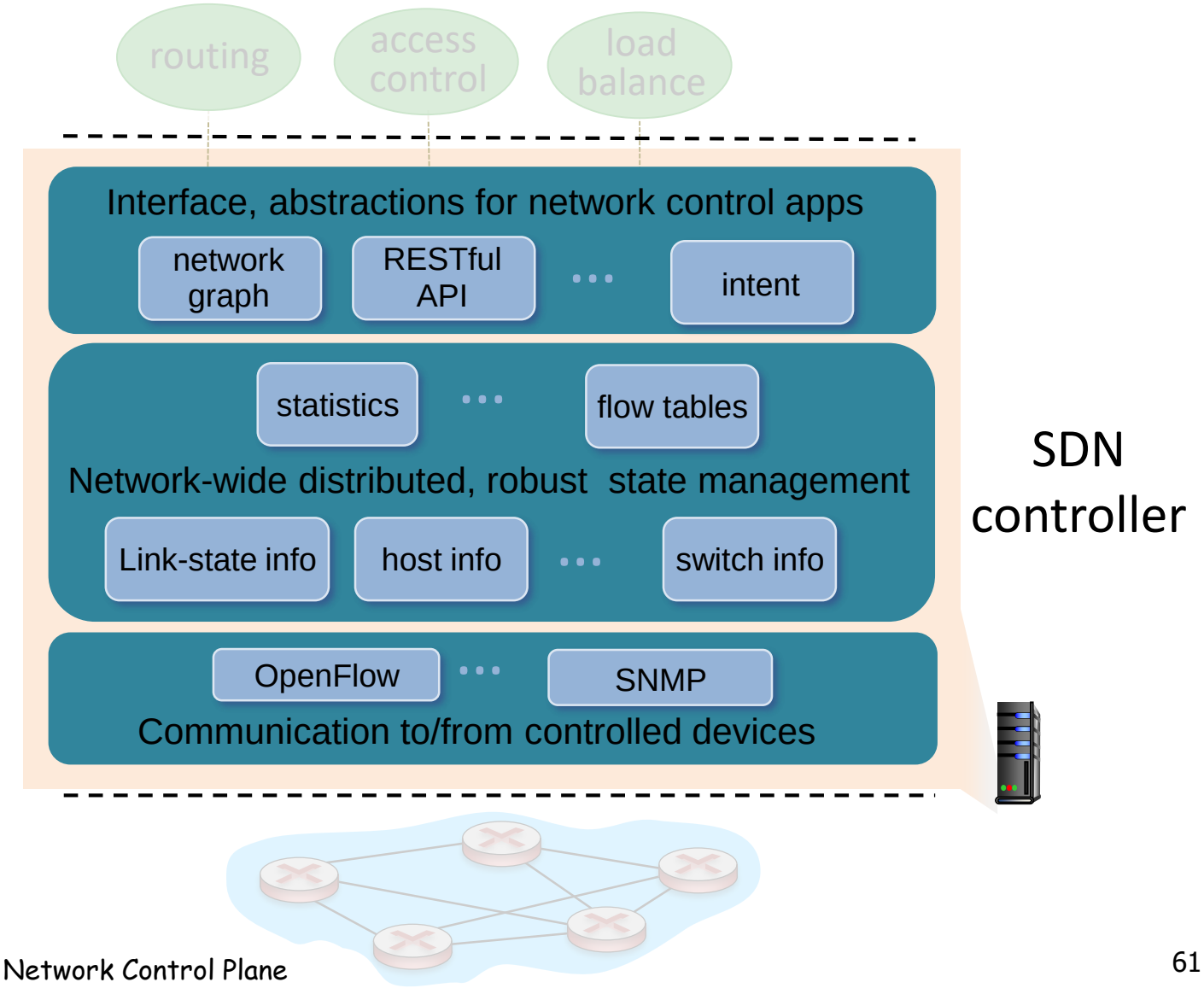


Components of SDN Controller

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



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