Chapter 5
Network Layer: Control Plane

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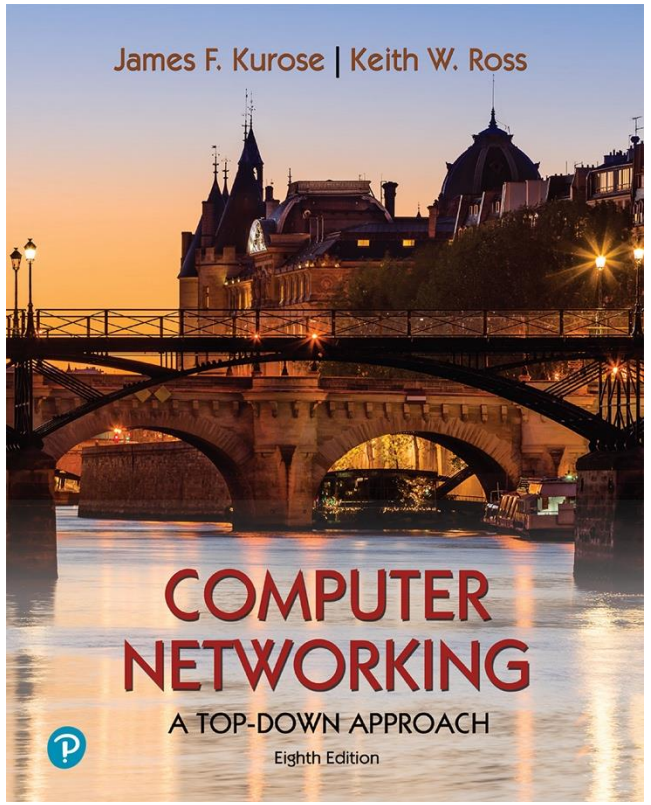


Computer Networking: A Top-Down Approach
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Adapted from the slides of the book's authors

Network layer: "control plane" roadmap

- introduction
- routing protocols
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol

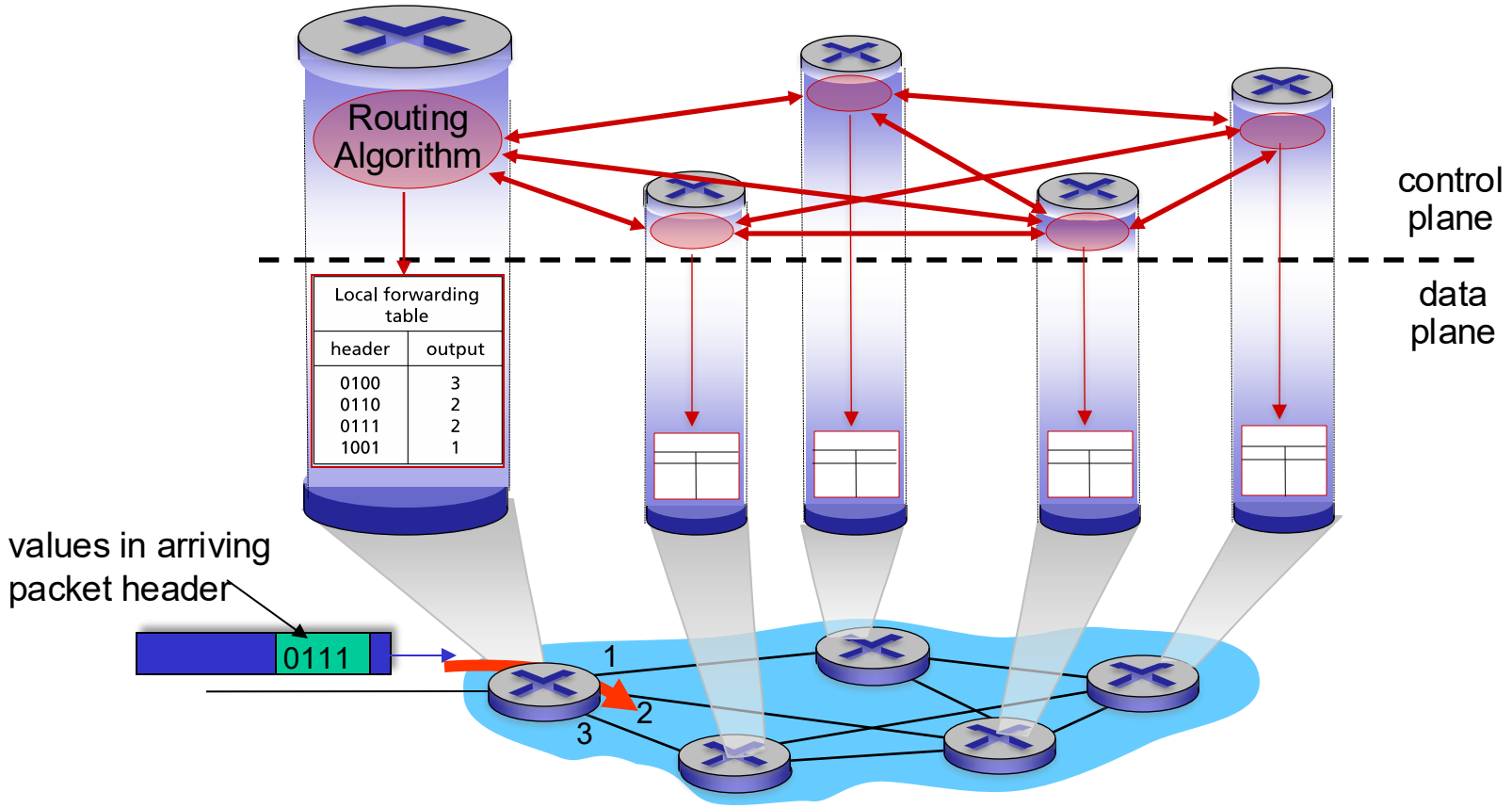
- Measurement

Software defined networking (SDN)

- Internet network layer: historically implemented via distributed, per-router control 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

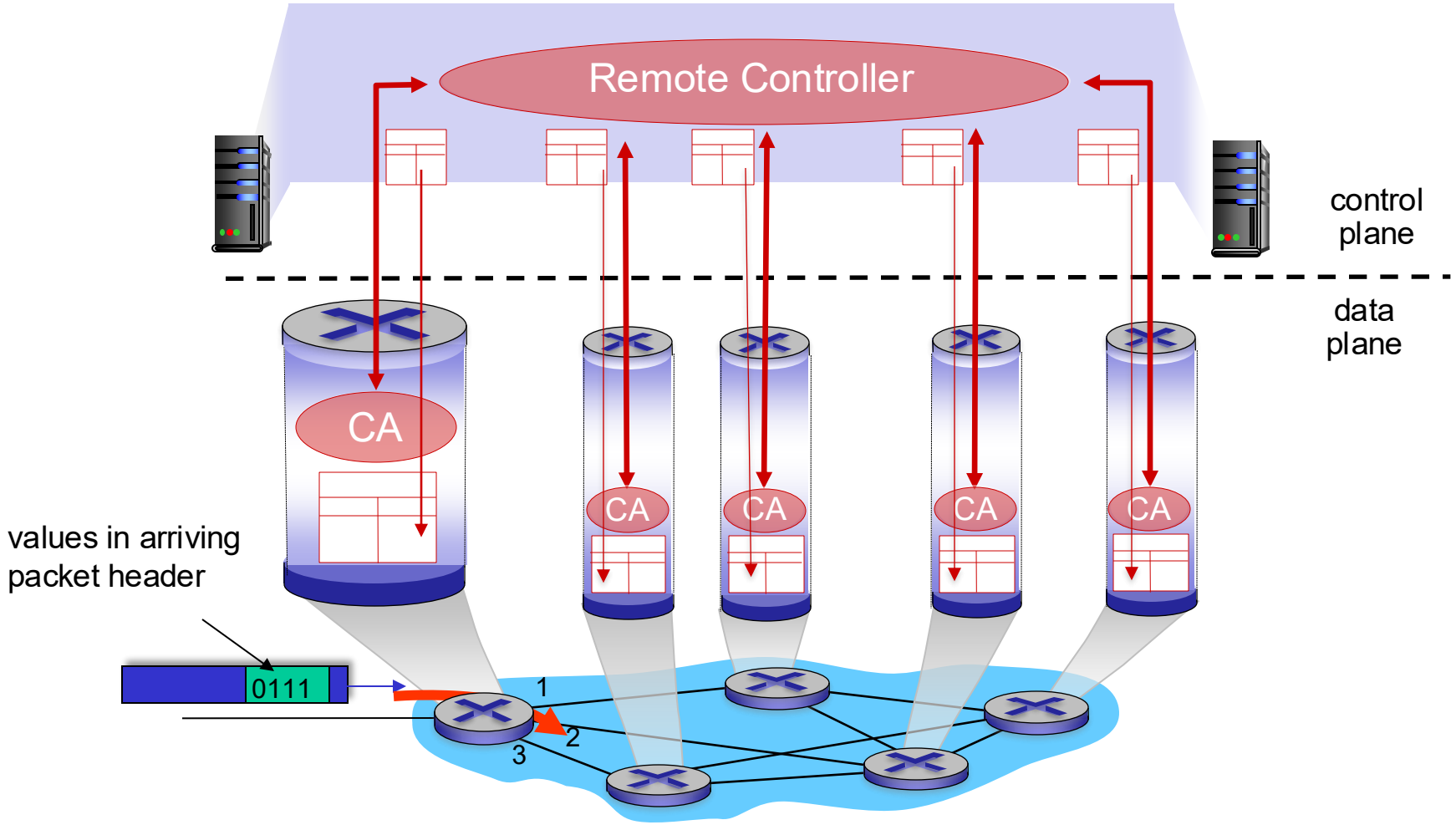
Per-router control plane

Individual routing algorithm components *in each and every router* interact in the control plane to computer forwarding tables



Software-Defined Networking (SDN) control plane

Remote controller computes, installs forwarding tables in routers

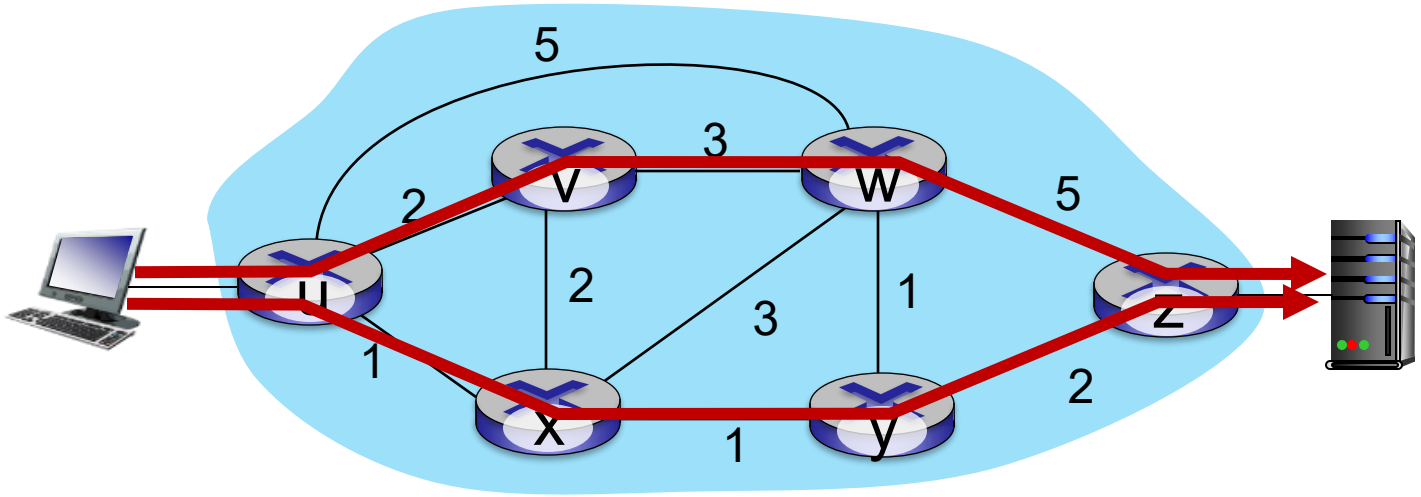


Software defined networking (SDN)

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
  - foster innovation: let 1000 flowers bloom

Traffic engineering: difficult with traditional routing

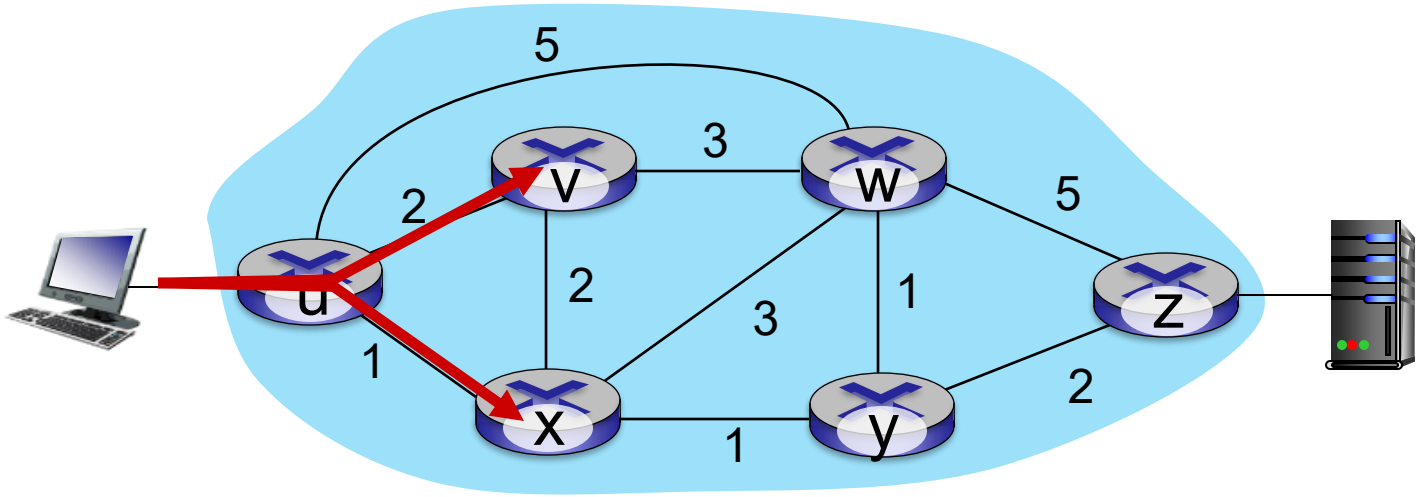


Q: what if network operator wants u-to-z traffic to flow along *uvwz*, rather than *uxyz*?

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

link weights are only control "knobs": not much control!

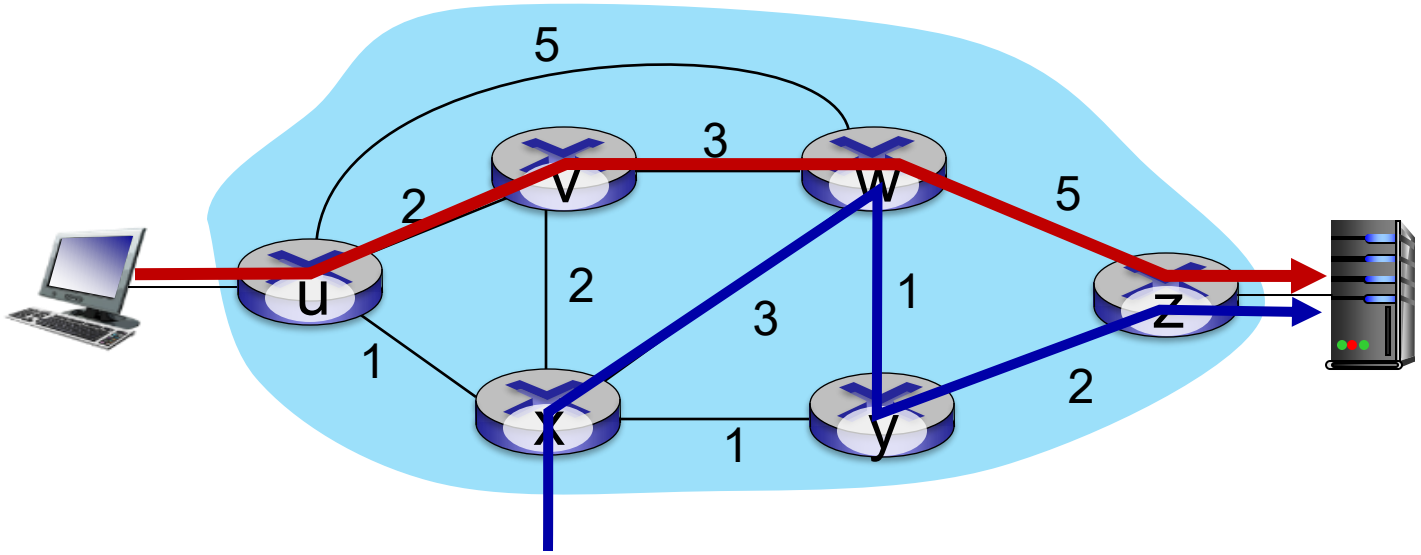
Traffic engineering: difficult with traditional routing



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 with traditional routing



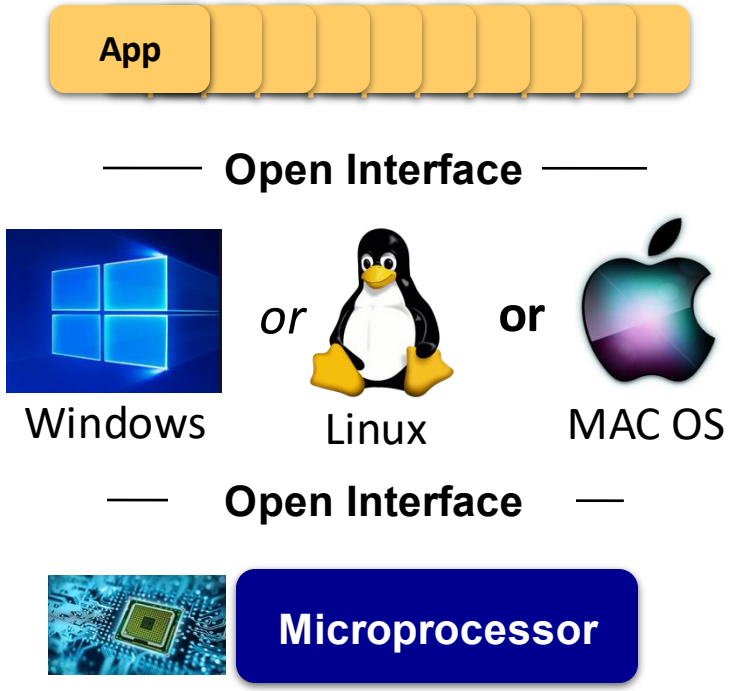
Q: what if w wants to route blue and red traffic differently from w to z?

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

We learned in Chapter 4 that generalized forwarding and SDN can be used to achieve *any* routing desired

SDN analogy: mainframe to PC revolution

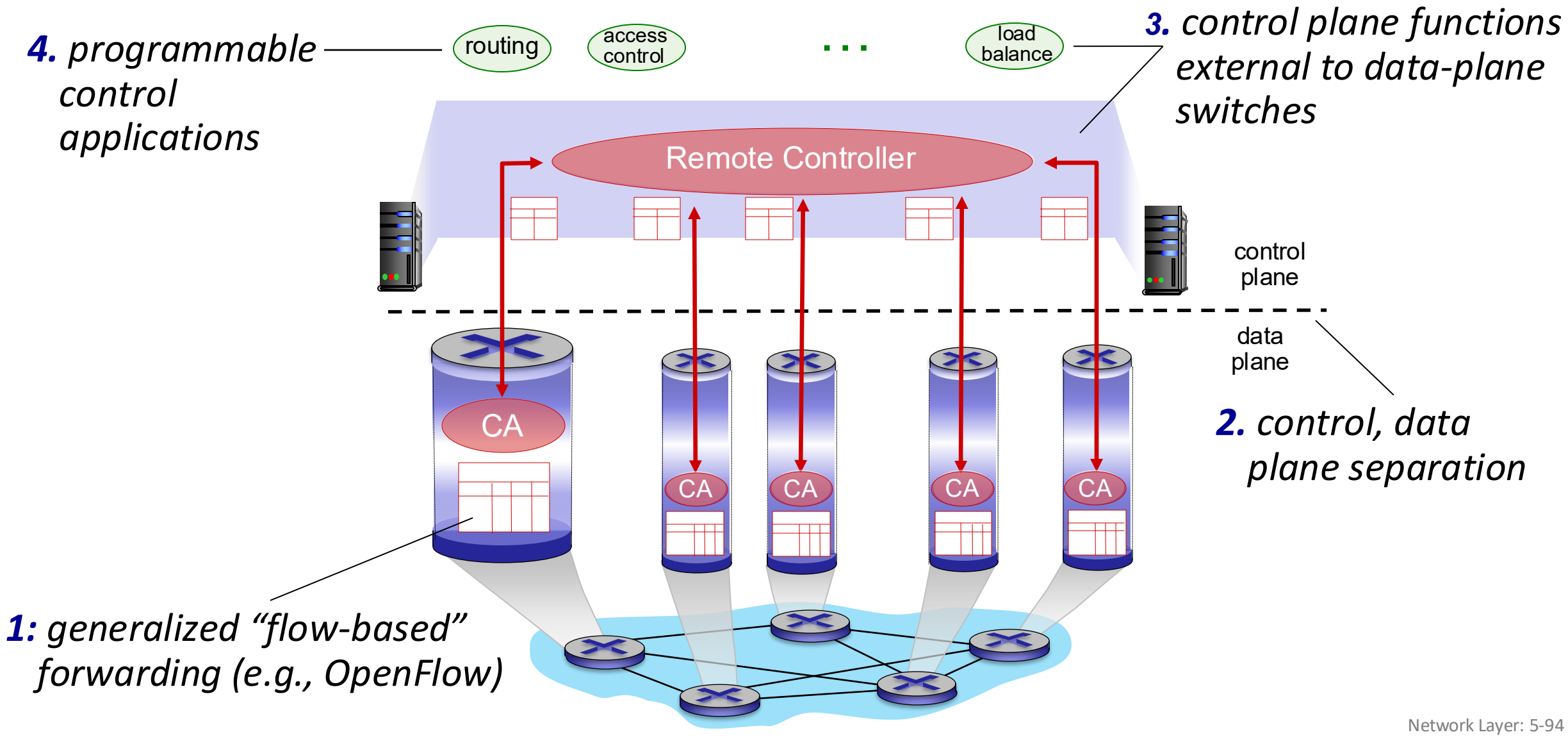
Vertically integrated
Closed, proprietary
Slow innovation
Small industry



Horizontal
Open interfaces
Rapid innovation
Huge industry

* Slide courtesy: N. McKeown

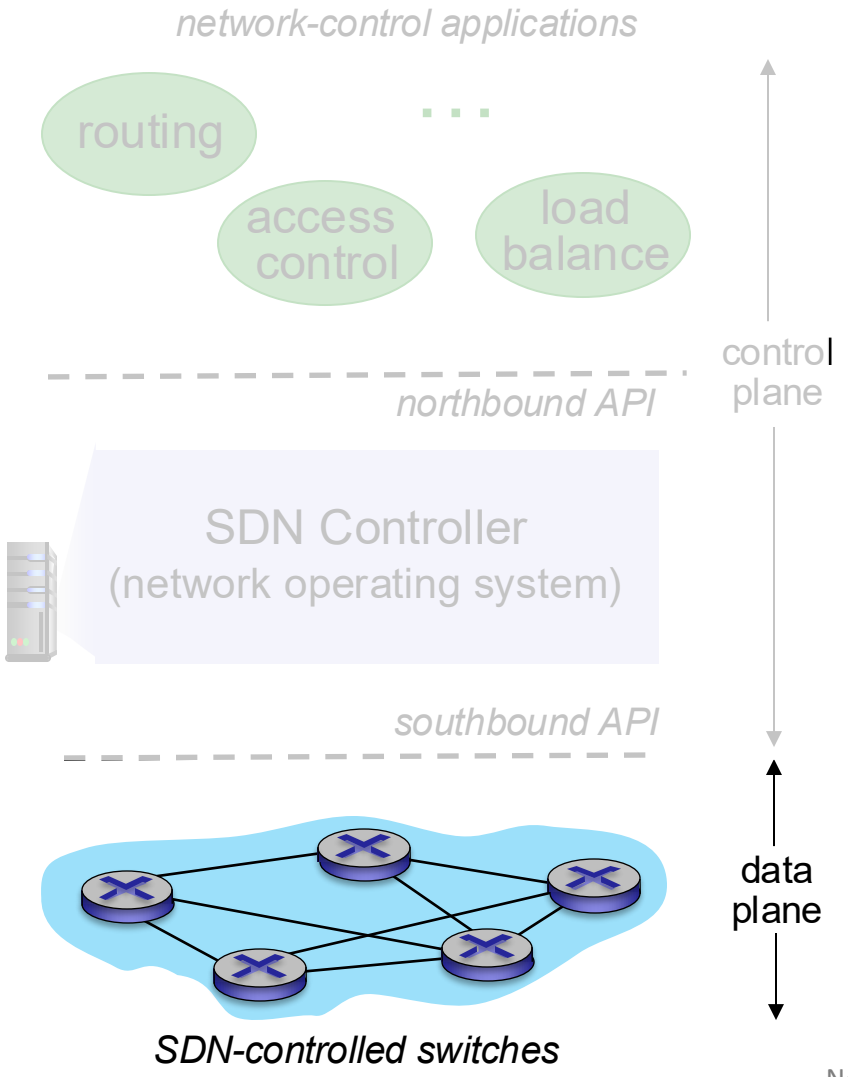
Software defined networking (SDN)



Software defined networking (SDN)

Data-plane switches:

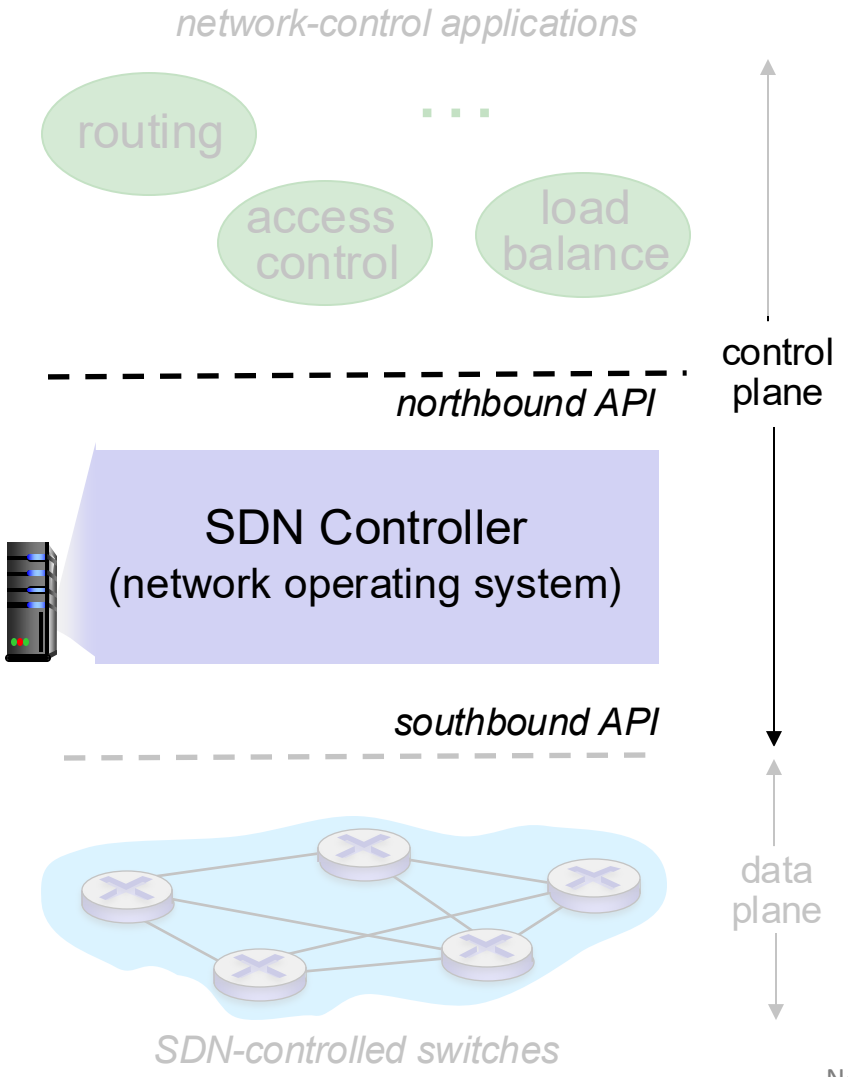
- fast, simple, commodity switches implementing generalized data-plane forwarding (Section 4.4) in hardware
- flow (forwarding) table computed, installed under controller supervision
- API for table-based switch control (e.g., OpenFlow)
  - defines what is controllable, what is not
- protocol for communicating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



Software defined networking (SDN)

SDN controller (network OS):

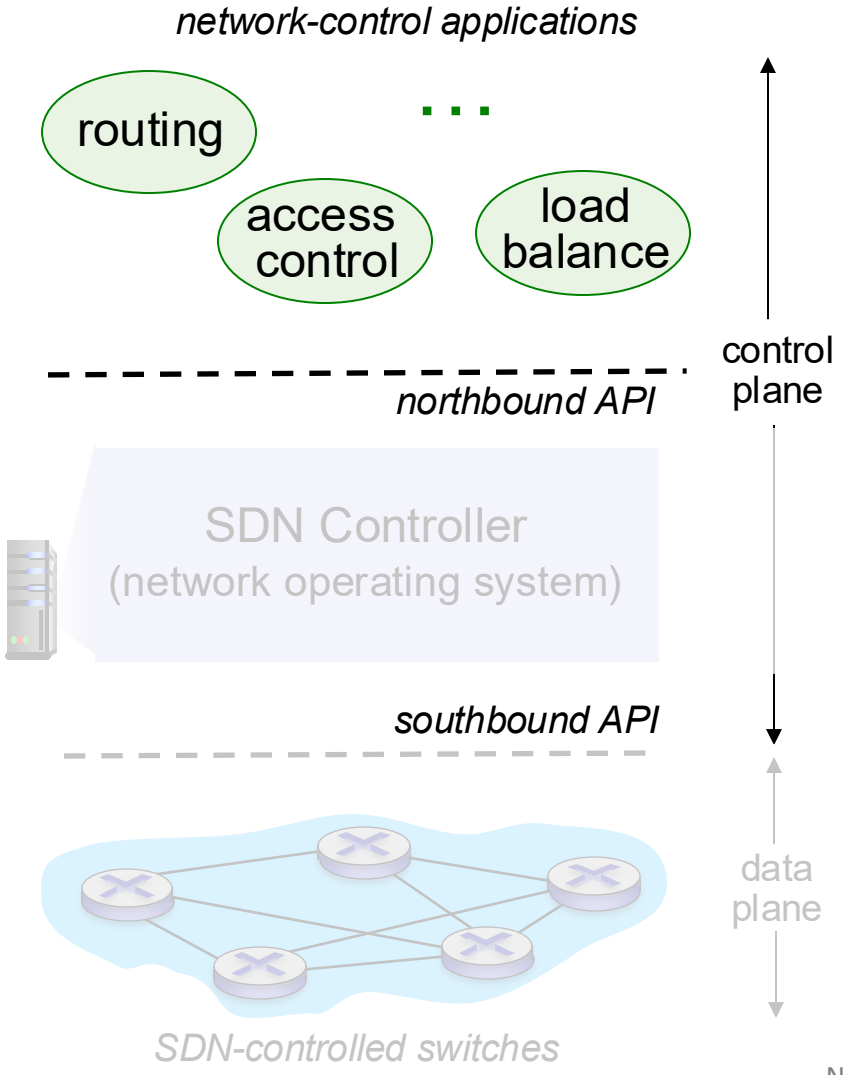
- maintain network state information
- interacts with network control applications “above” via northbound API
- interacts with network switches “below” via southbound API
- implemented as distributed system for performance, scalability, fault-tolerance, robustness



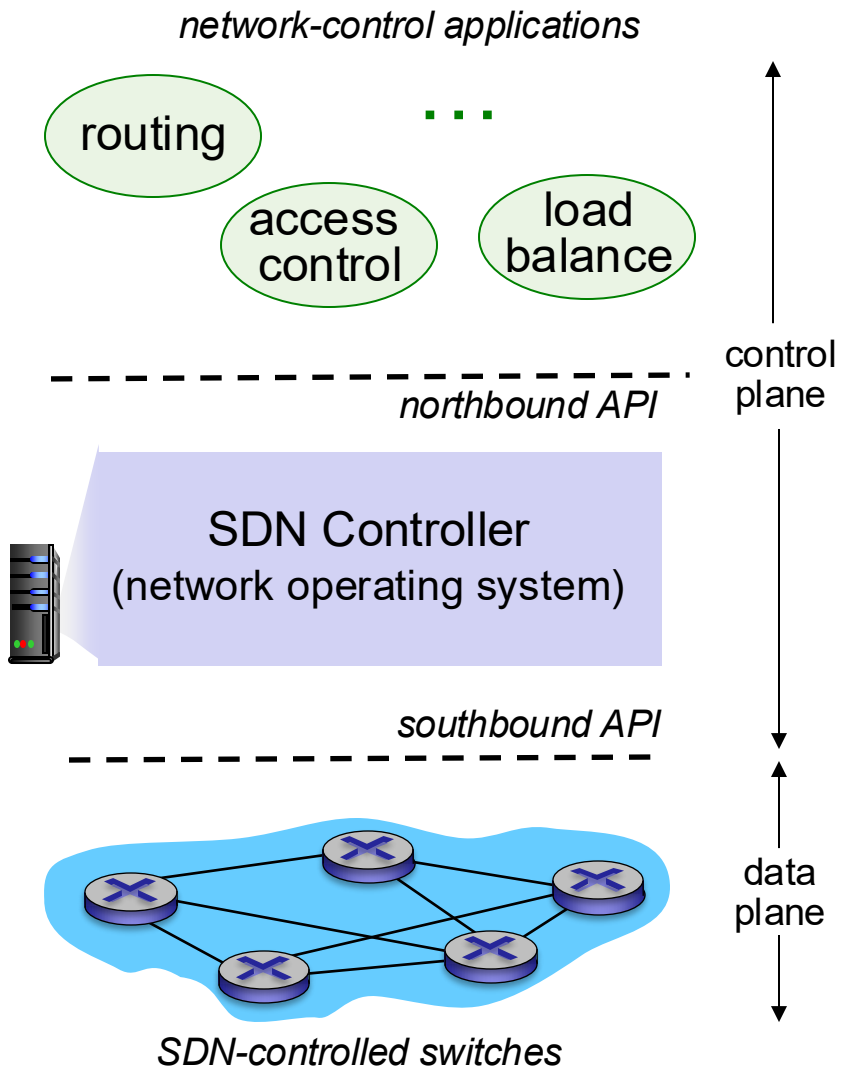
Software defined networking (SDN)

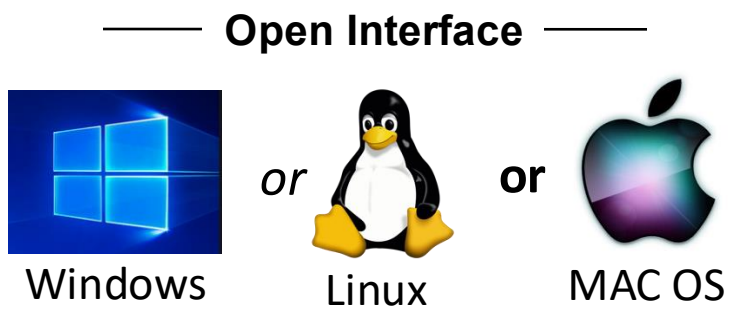
network-control apps:

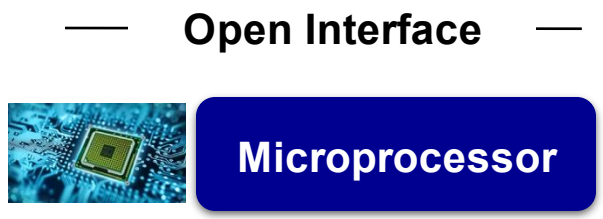
- "brains" of control: implement control functions using lower-level services, API provided by SDN controller
- *unbundled:* can be provided by 3rd party: distinct from routing vendor, or SDN controller



Software defined networking (SDN)





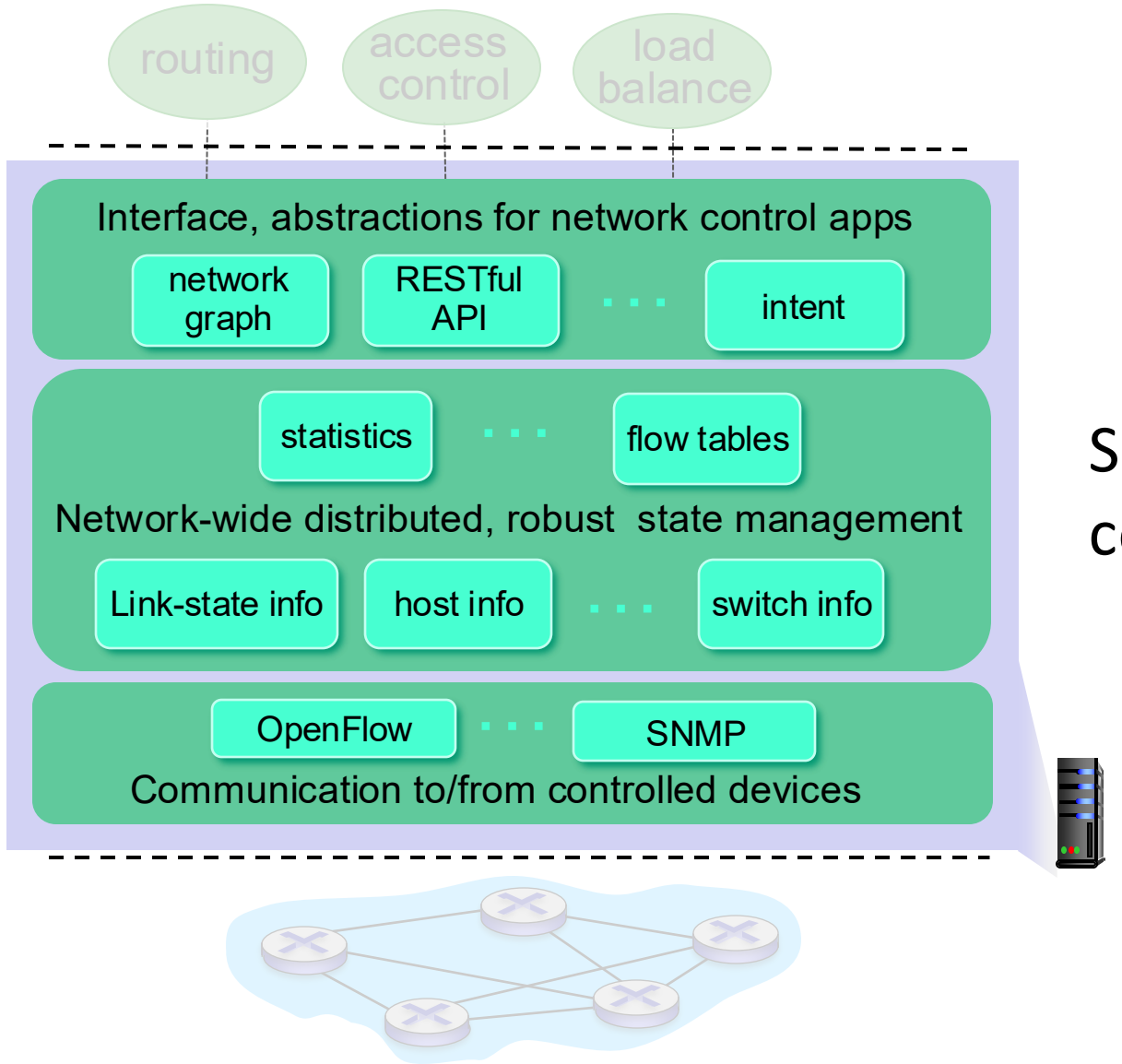


Components of SDN controller

interface layer to network control apps: abstractions API

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

communication: communicate between SDN controller and controlled switches

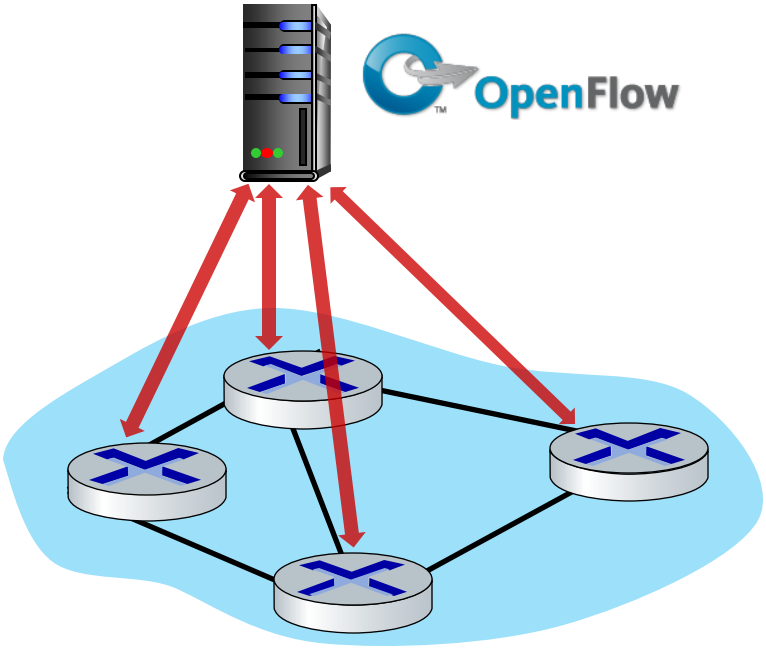


SDN controller

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.)
- distinct from OpenFlow API
  - API used to specify generalized forwarding actions

OpenFlow Controller

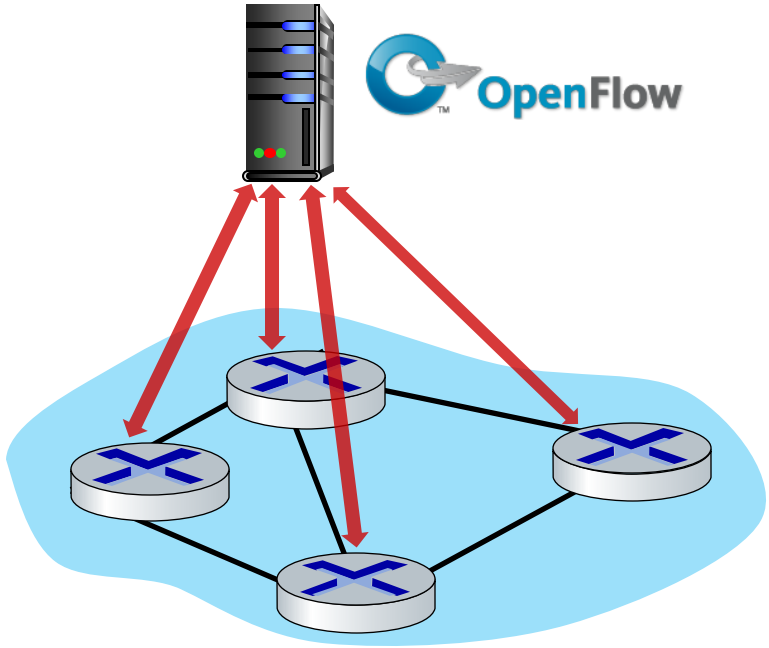


OpenFlow: controller-to-switch messages

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 Controller

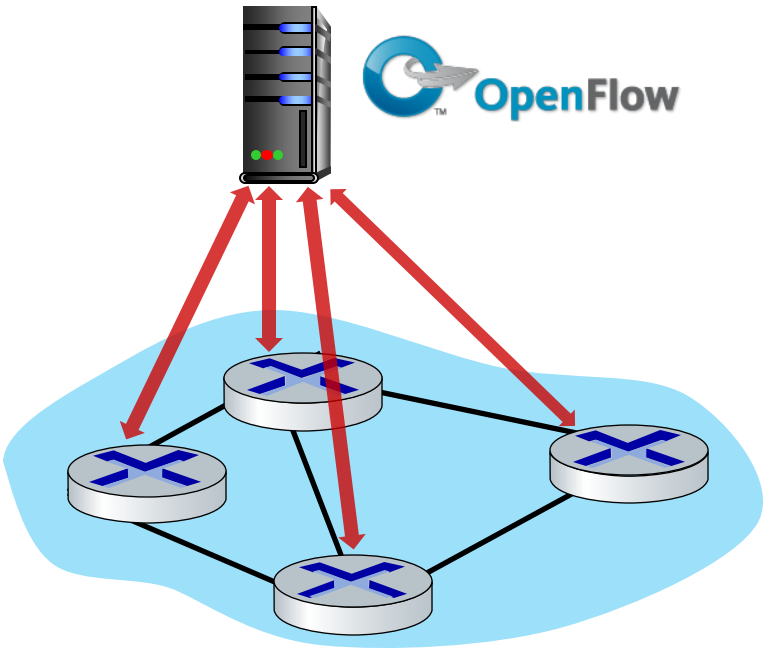


OpenFlow: switch-to-controller messages

Key switch-to-controller messages

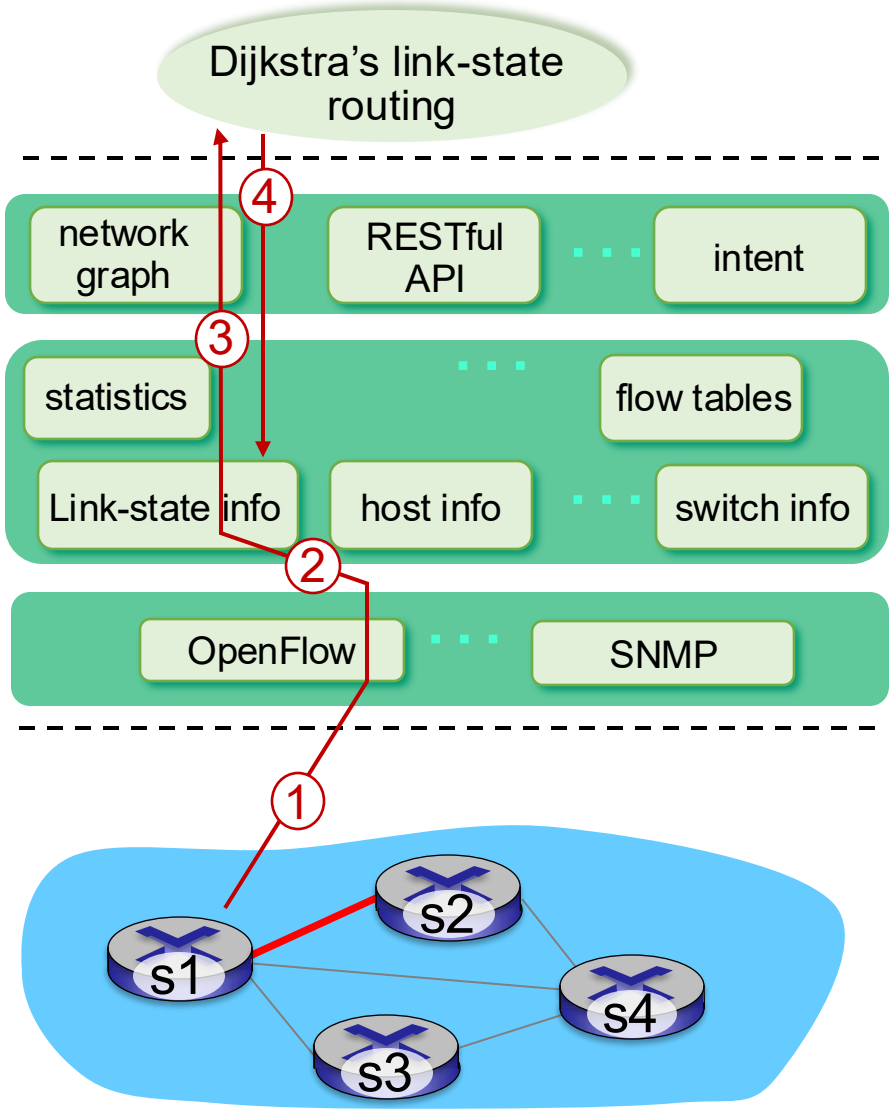
- *packet-in:* transfer packet (and its control) to controller. See packet-out message from controller
- *flow-removed:* flow table entry deleted at switch
- *port status:* inform controller of a change on a port.

OpenFlow Controller



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



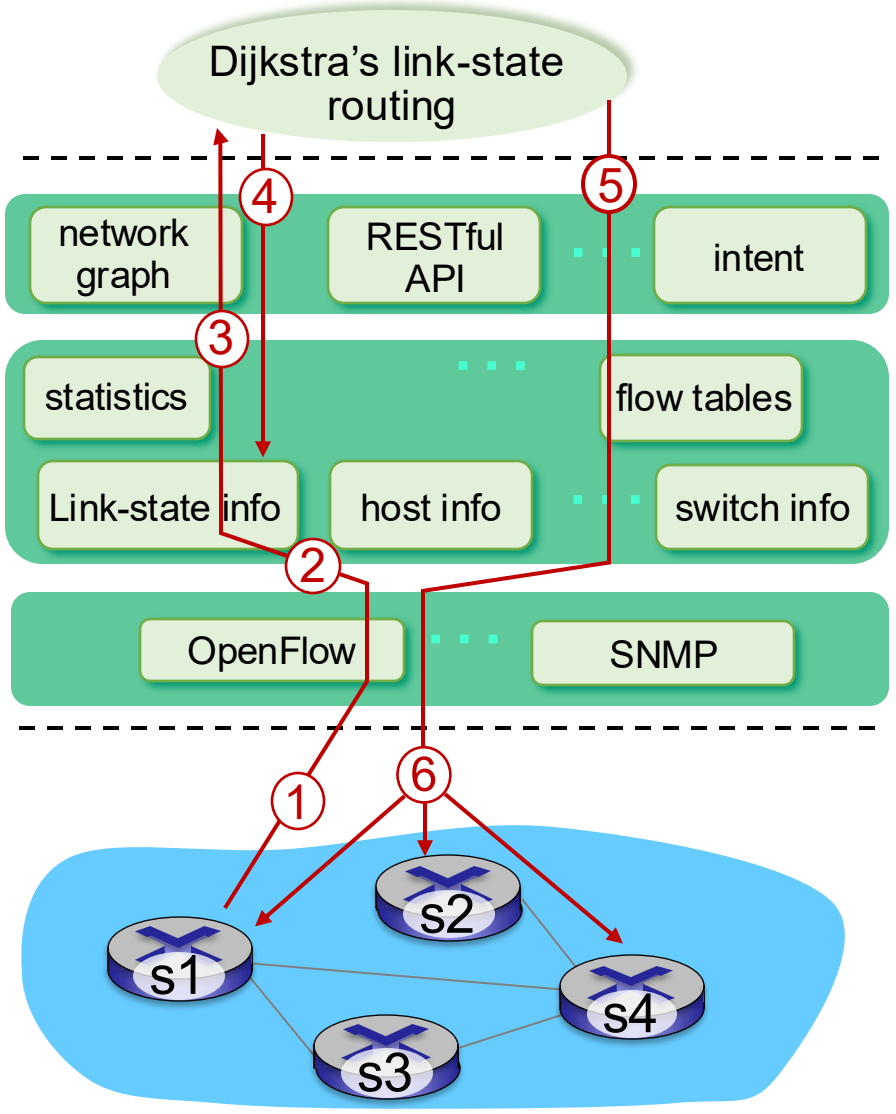
① S1, experiencing link failure uses OpenFlow port status message to notify controller

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

SDN: selected challenges

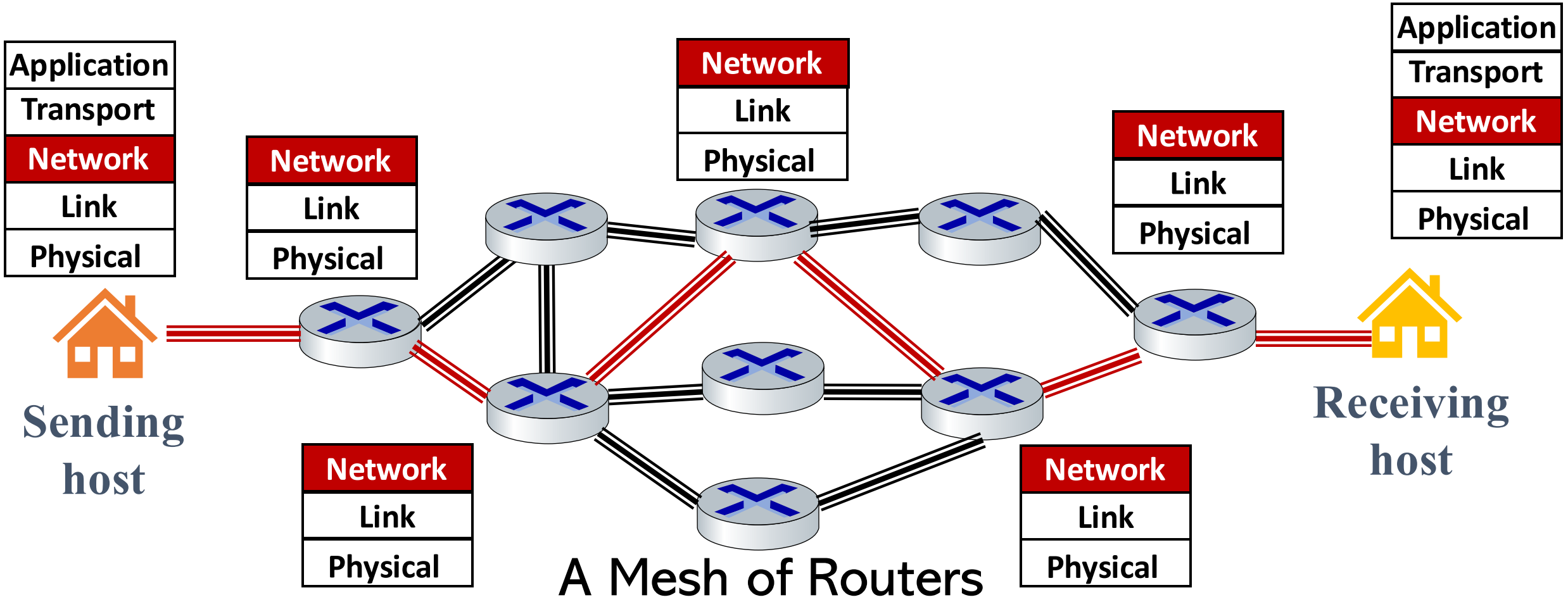
- hardening the control plane: dependable, reliable, performance-scalable, secure distributed system
  - robustness to failures: leverage strong theory of reliable distributed system for control plane
  - dependability, security: “baked in” from day one?
- networks, protocols meeting mission-specific requirements
  - e.g., real-time, ultra-reliable, ultra-secure
- Internet-scaling: beyond a single AS
- SDN critical in 5G cellular networks

Network layer: "control plane" roadmap

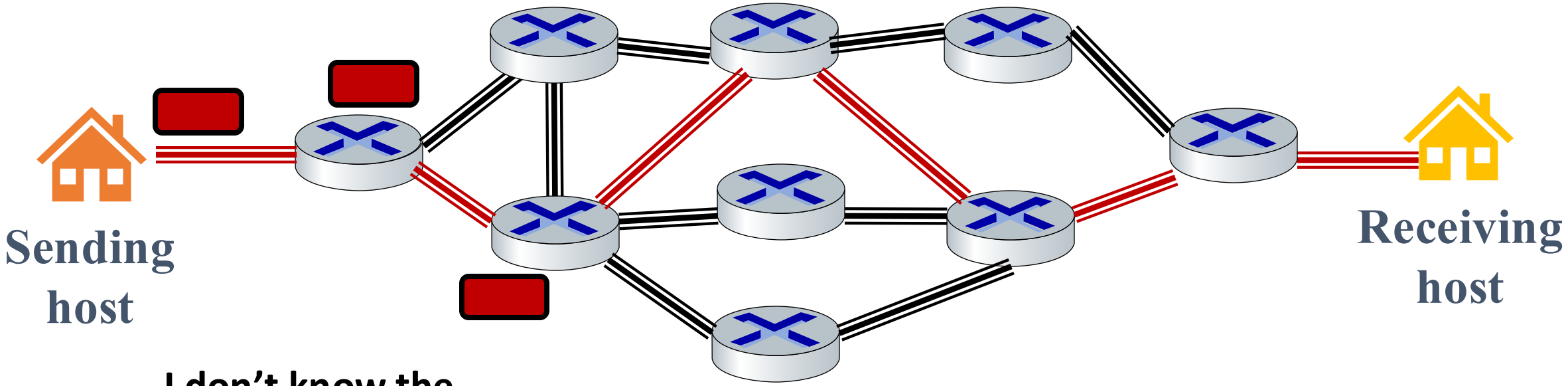
- introduction
- routing protocols
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol

- Measurement

End-to-end VS edge to router



End-to-end VS edge to router

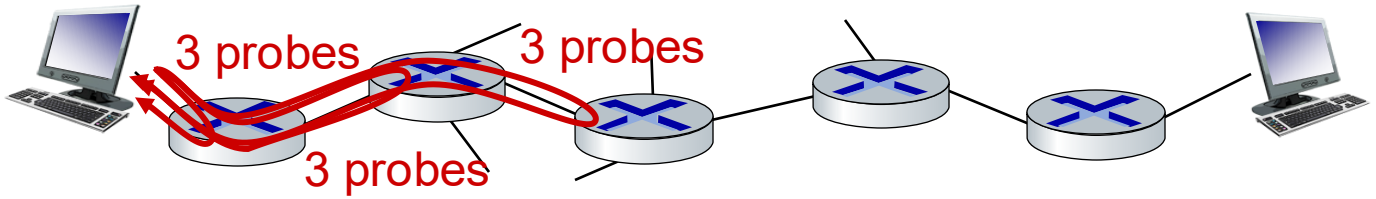


ICMP: internet control message protocol

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

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

Traceroute and ICMP



- source sends sets of UDP segments to destination
  - 1st set has TTL =1, 2nd set has TTL=2, etc.
- datagram in *n*th set arrives to nth router:
  - router discards datagram and sends source ICMP message (type 11, code 0)
  - ICMP message possibly includes name of router & IP address
- when ICMP message arrives at source: record RTTs

stopping criteria:

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

Network layer: "control plane" roadmap

- introduction
- routing protocols
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol

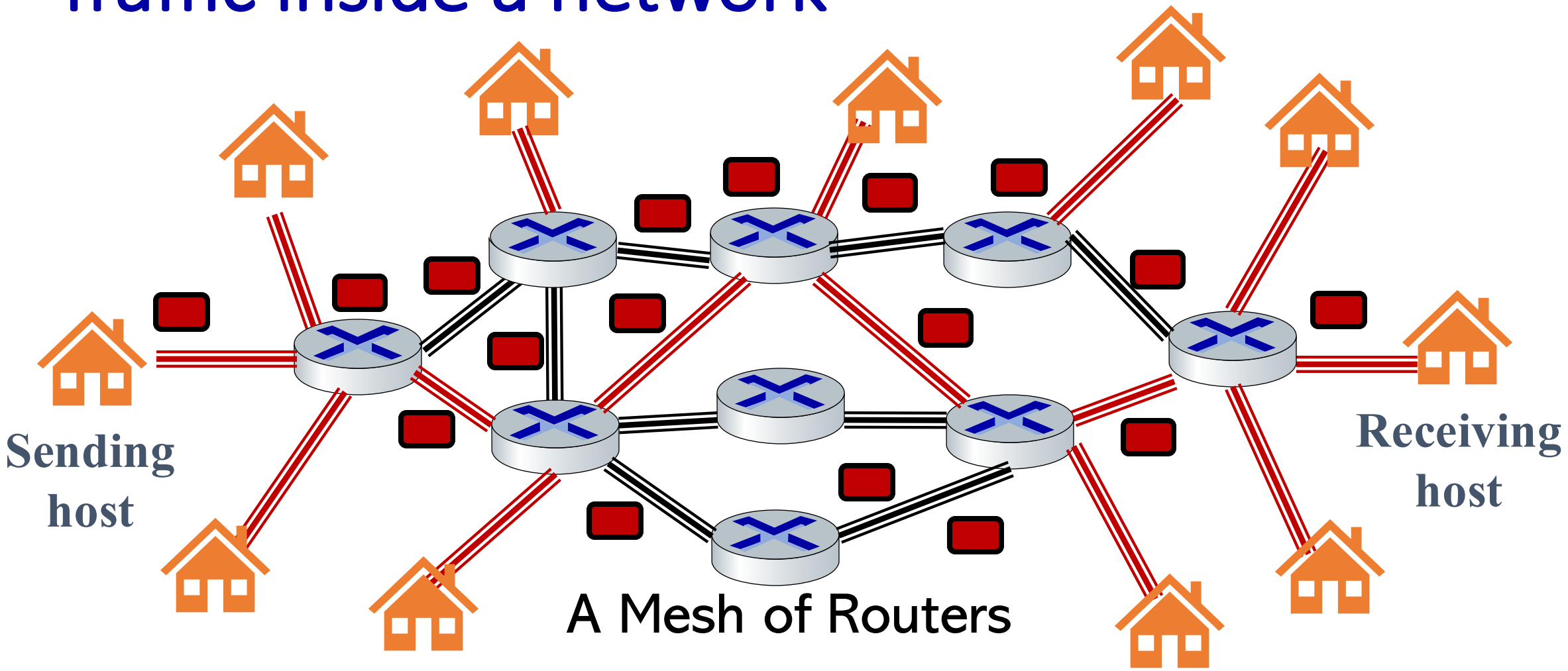
- Measurement

Why Measure the Network?

- Scientific discovery
  - Characterizing traffic, topology, performance –
  - Understanding protocol performance and dynamics

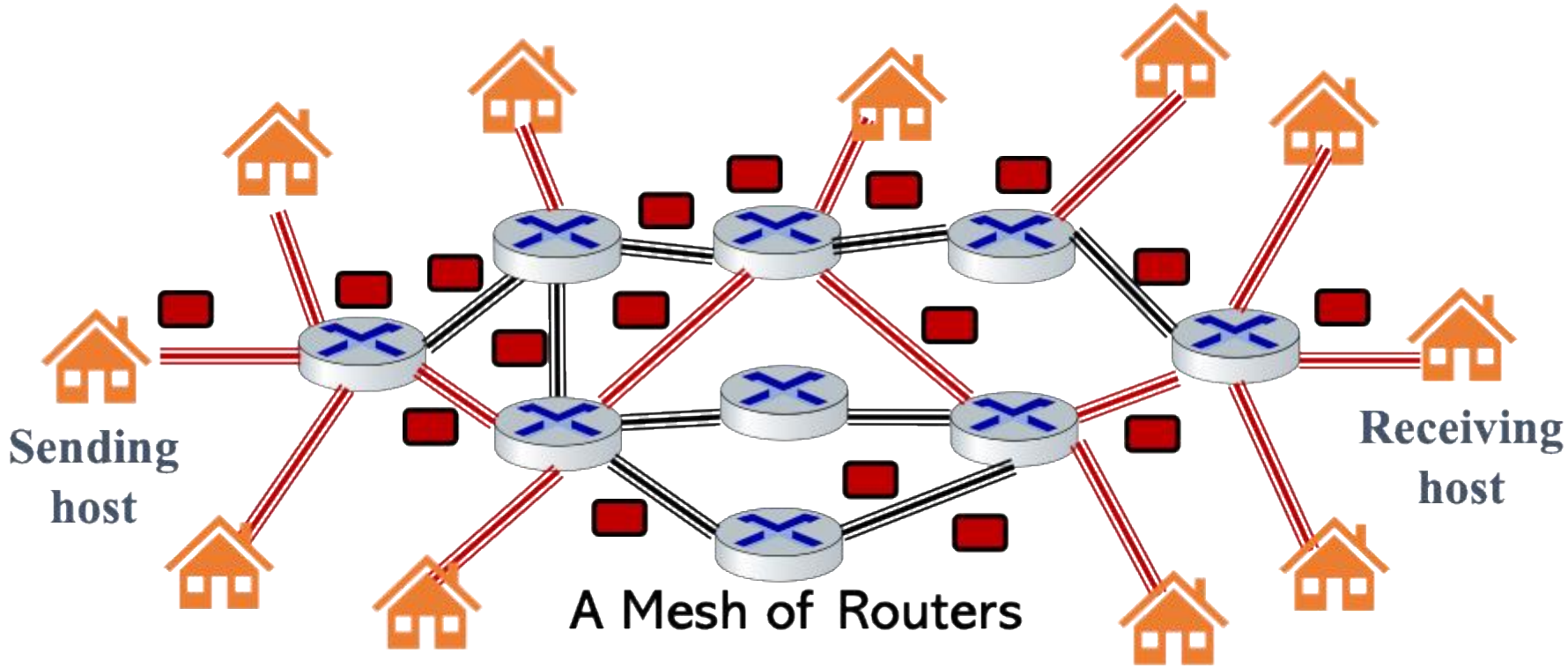
- Network operation
  - Billing customers
  - Detecting, diagnosing, and fixing problem
  - Planning outlay of new equipment

Traffic inside a network



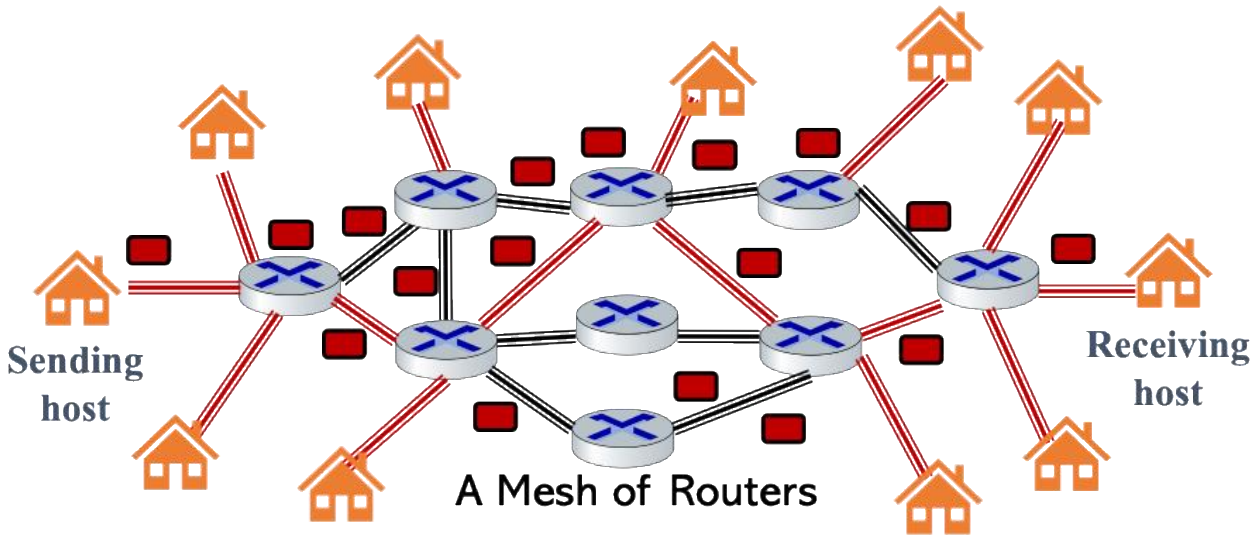
Active VS Passive Measurement

- Active Measurement
  - Injecting test traffic
  - Ping Traceroute
- Passive Measurement
  - Observes existing traffic
  - Wireshark, NetFlow



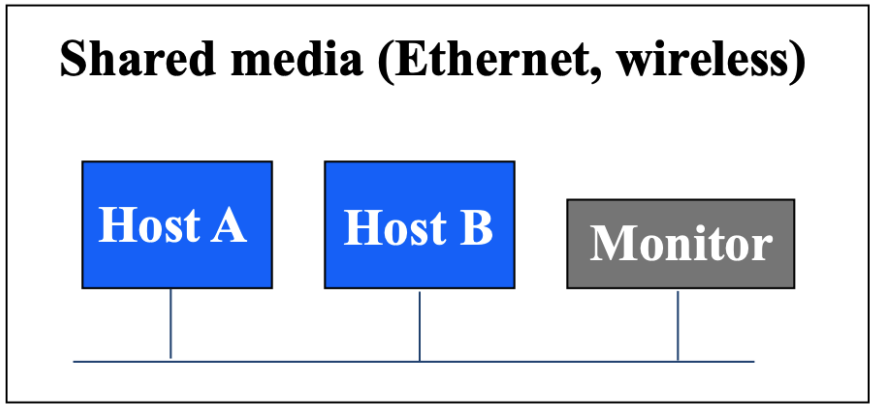
Packet level measurement

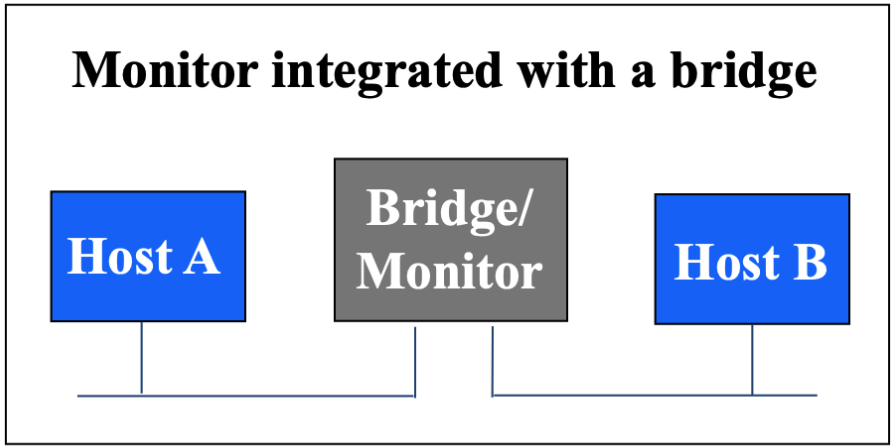
- Definition
  - Passively collecting IP packets on one or more links
  - Recording IP, TCP/UDP, or application layer traces

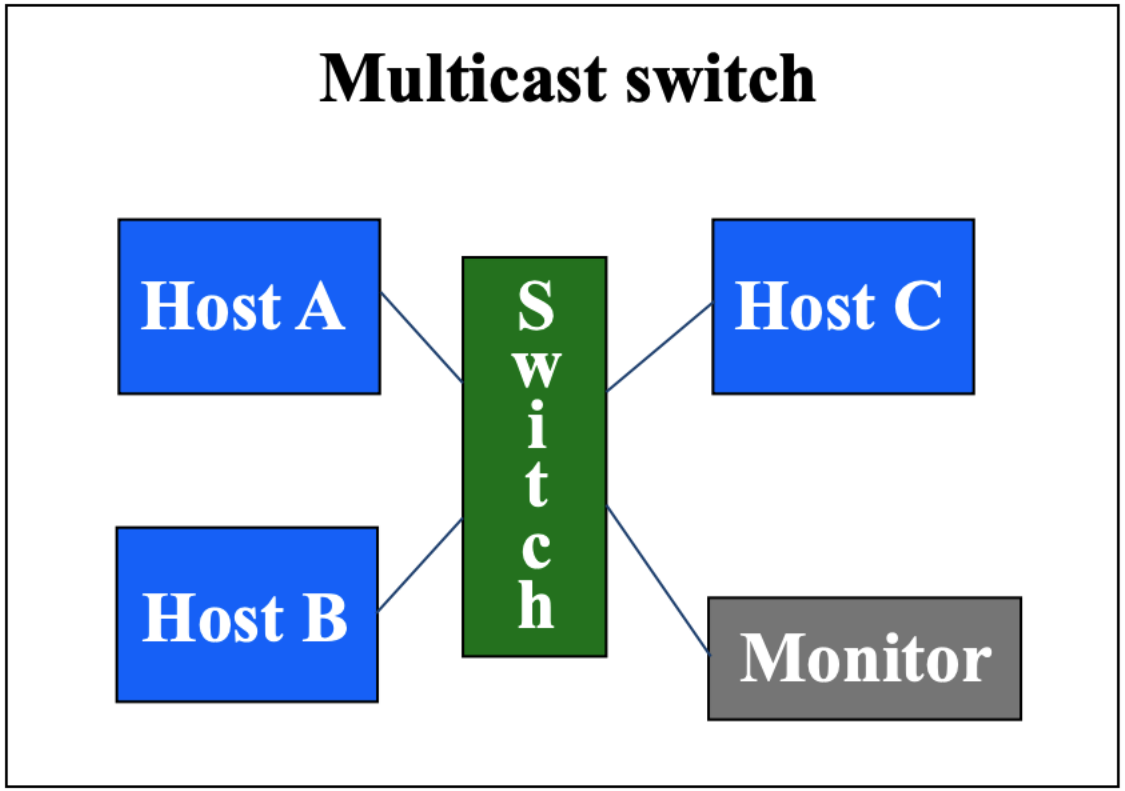


- Scope
  - Fine-grain information about user behavior
  - Passively monitoring the network infrastructure
  - Characterizing traffic and diagnosing problems

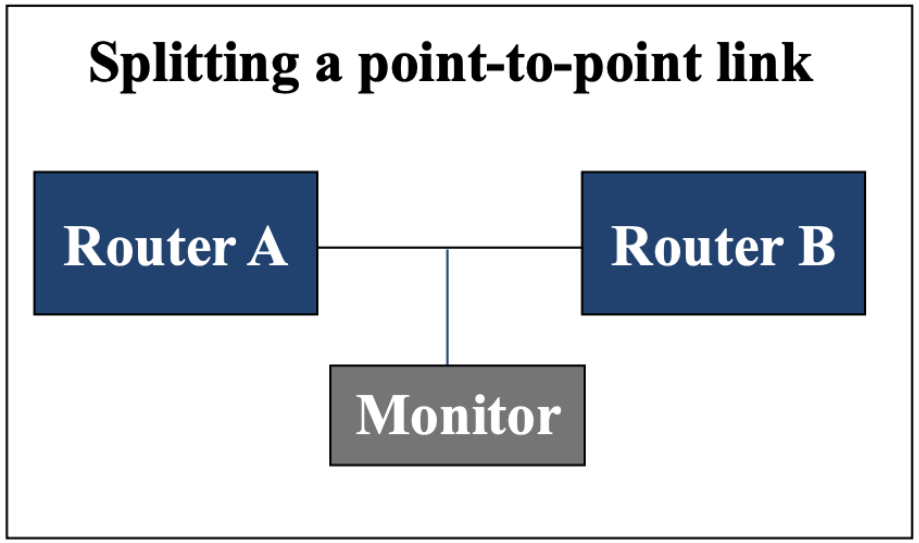
Packet level measurement: where? LAN

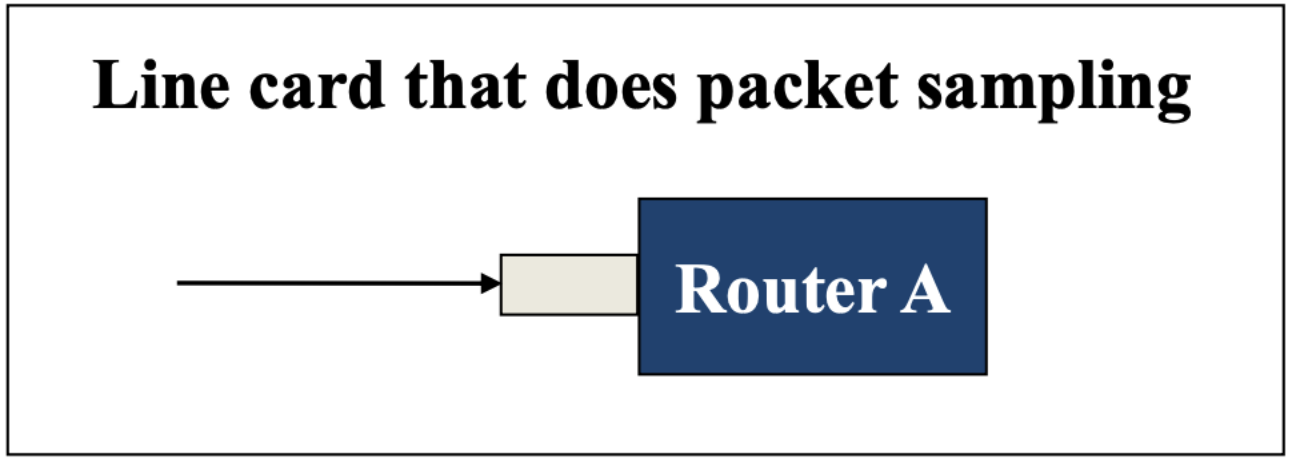




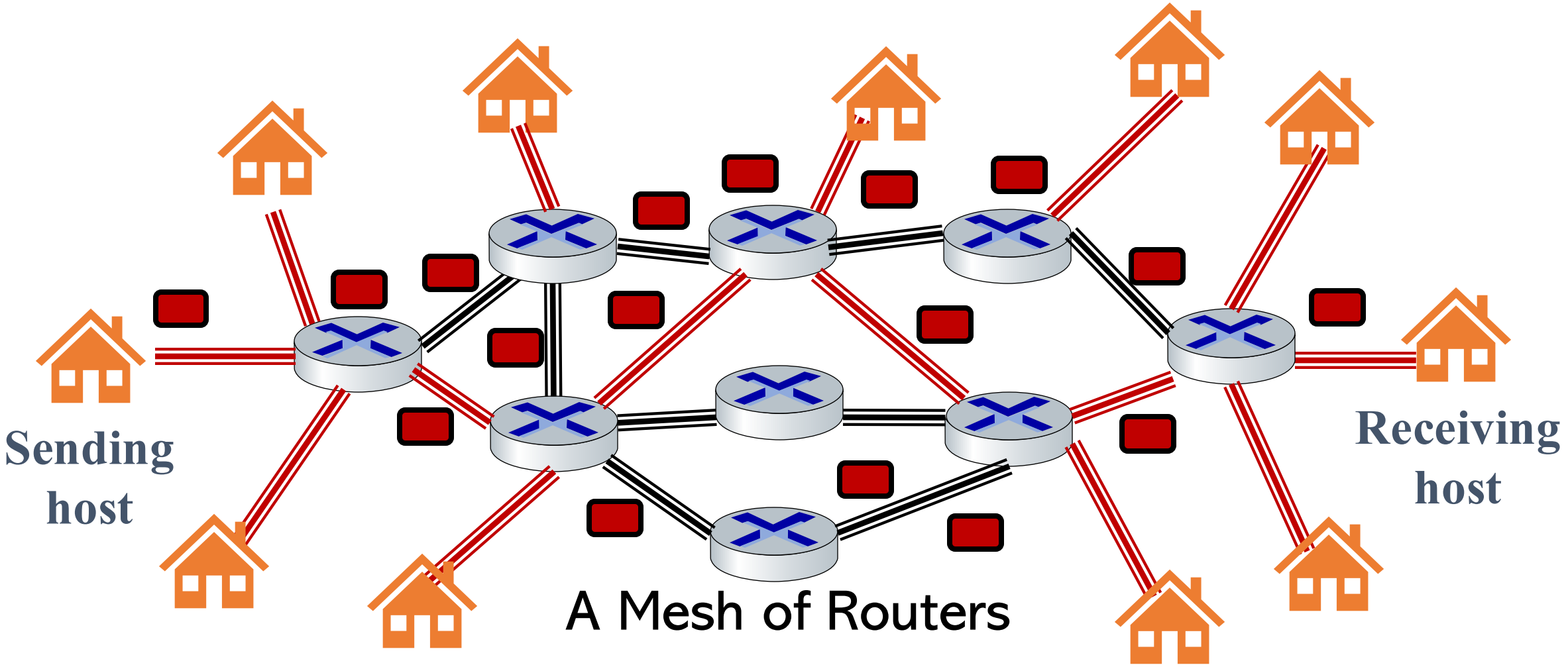


Packet level measurement: where? WAN





Billions of packets exchanged per second



Selecting the traffic

- Collect the headers
  - IP headers (20 bytes)
  - IP+UDP headers (28 bytes)
  - IP+TCP header (40 bytes)
  - Application-layer message (the entire packet)

Analysis of IP Header Traces

- Source and destination address
  - Identify popular web servers or heavy customers
- Distribution of packet delay through the routers
  - Identify typical delays and anomalies
- Throughput between pairs of src/dest address
  - Detection and diagnosis of performance problems

Analysis of TCP Header Traces

- Source and destination port
  - Popular applications
- Sequence/ACK numbers and packet timestamps
  - Out-of-order/lost packets, throughput and delay
- Number of packets/bytes per connection
  - Web transfer size, frequency of bulk transfers

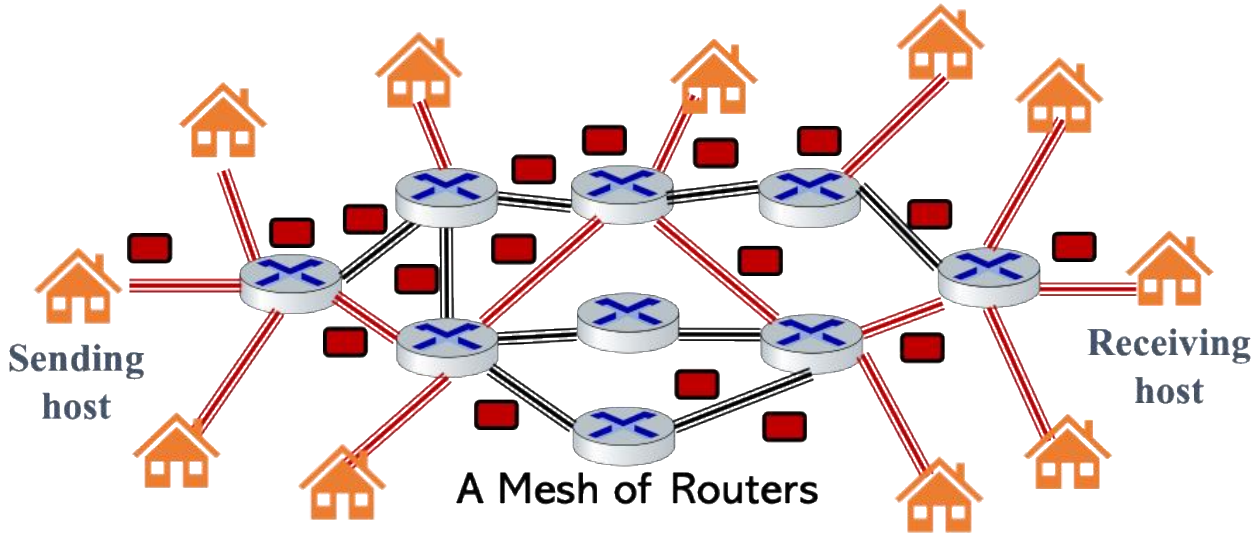
Application Layer Analysis

- URLs from HTTP request messages
  - Popular resources/sites; benefits of caching
- Meta-data in HTTP request/response messages
  - Content type, cacheability, change frequency, etc
- Contents of DNS messages
  - Common queries, error frequency, query latency

Selecting the traffic

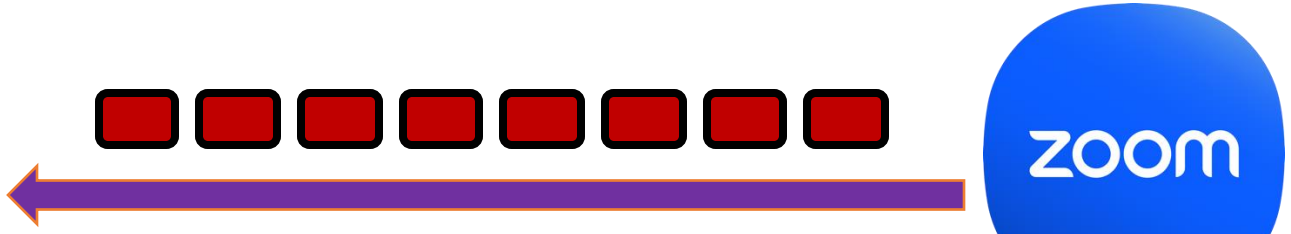
- Collect the headers
  - IP headers (20 bytes)
  - IP+UDP headers (28 bytes)
  - IP+TCP header (40 bytes)
  - Application-layer message (the entire packet)

- Filter to focus
  - IP address (source and dest)
  - Protocol (TCP, UDP or ICMP)
  - Port number (HTTP, DNS, BGP)



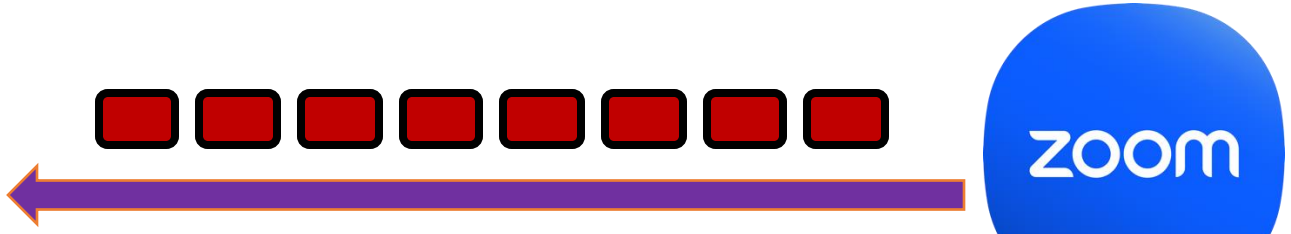
Monitoring Flow

- Set of packets that “belong together”
  - Source/destination IP addresses and port numbers
  - The same protocol
  - Same input/output interfaces at a router (if know)
- Packets that are “close” together in time
  - Maximum spacing between packets (e.g. 30 sec)



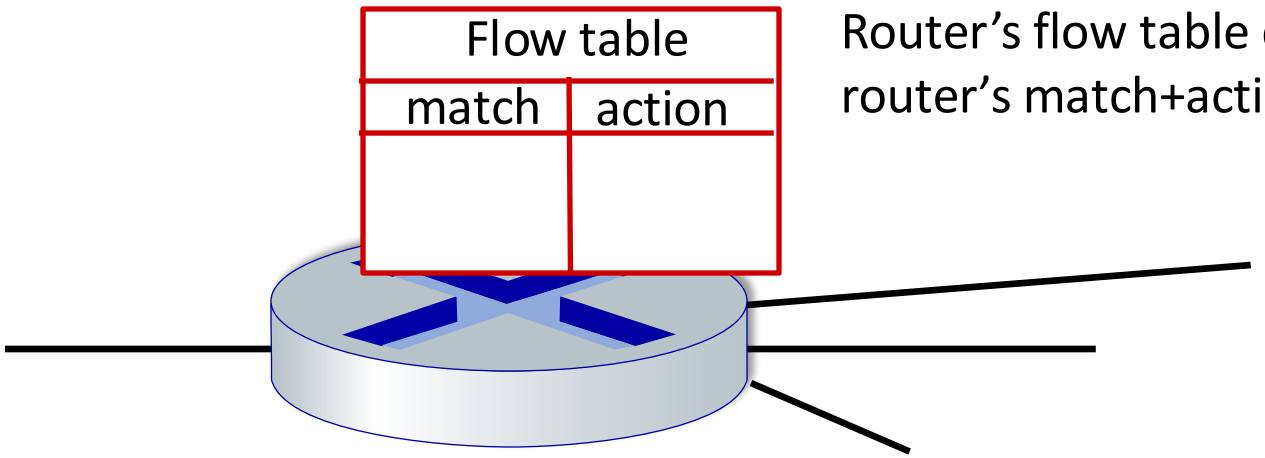
Monitoring Flow

- Packet header info
  - Source/destination IP addresses and port numbers
  - Other IP TCP UDP header fields
- Aggregate traffic information
  - Start and finish time (time of first & last packet)
  - Total # of bytes and number of packets in the flow



Flow table abstraction

- flow: defined by header field values (in link-, network-, transport-layer fields)
- generalized forwarding: simple packet-handling rules
  - match: pattern values in packet header fields
  - actions: for matched packet: drop, forward, modify, matched packet or send matched packet to controller
  - priority: disambiguate overlapping patterns
  - counters: #bytes and #packets



Router's flow table define router's match+action rules

Network measurement is important

- Measurement is crucial to network operations
  - Measure, model, control
  - Detect, diagnose, fix
- Network measurement is challenging
  - Large volume of measurement data
  - Multi-dimensional data
- Great way to understand the Internet
  - Popular application, traffic characteristics
  - Internet topology, routing dynamics

Network layer: 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 measurement

next stop: link layer!

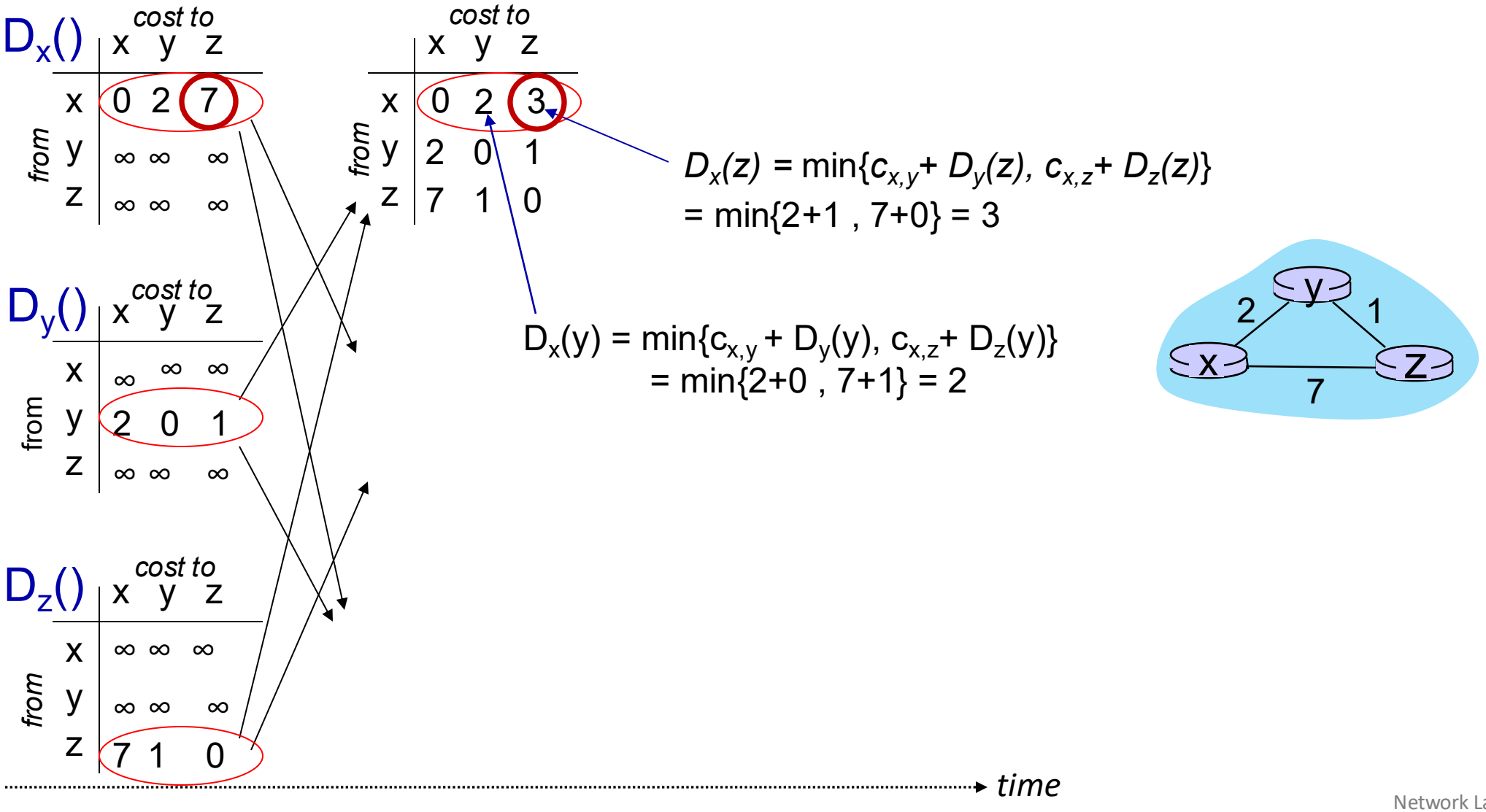
Network layer, control plane: Done!

- introduction
- routing protocols
  - link state
  - distance vector
- intra-ISP routing: OSPF
- routing among ISPs: BGP
- SDN control plane
- Internet Control Message Protocol

- network measurement

Additional Chapter 5 slides

Distance vector: another example



Distance vector: another example