Chapter 4
Network Layer: The Data Plane

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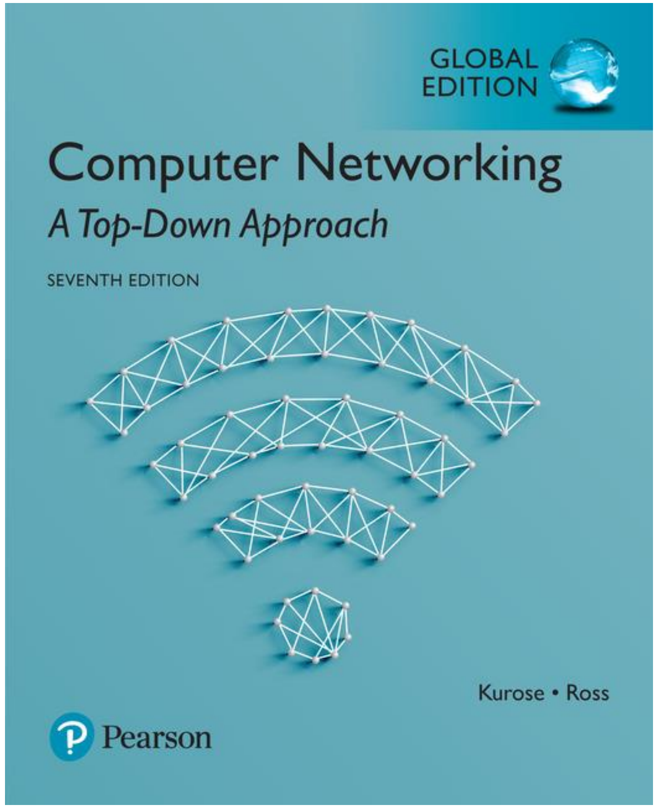


Computer Networking: A Top Down Approach

7th Edition, Global Edition
Jim Kurose, Keith Ross
Pearson
April 2016

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

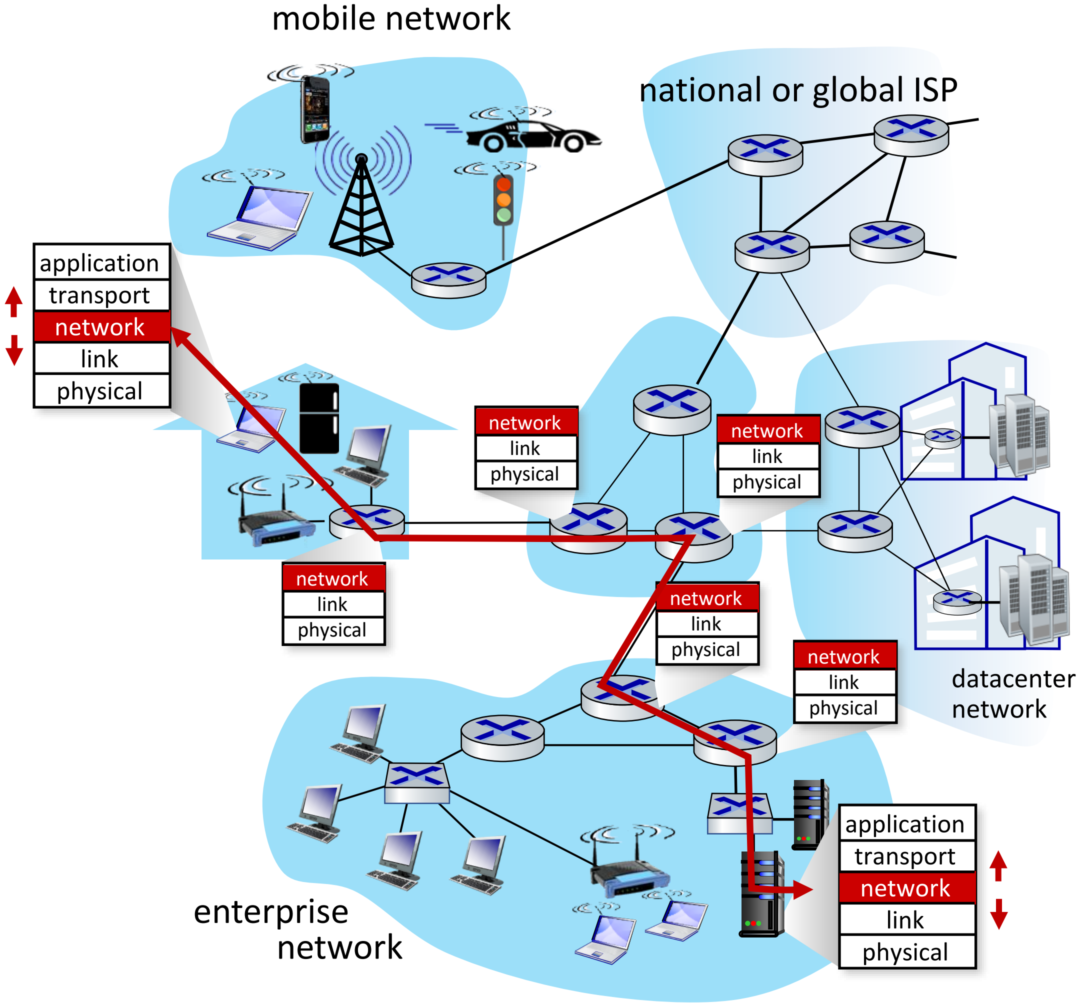
4.2 What's inside a router

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forward and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

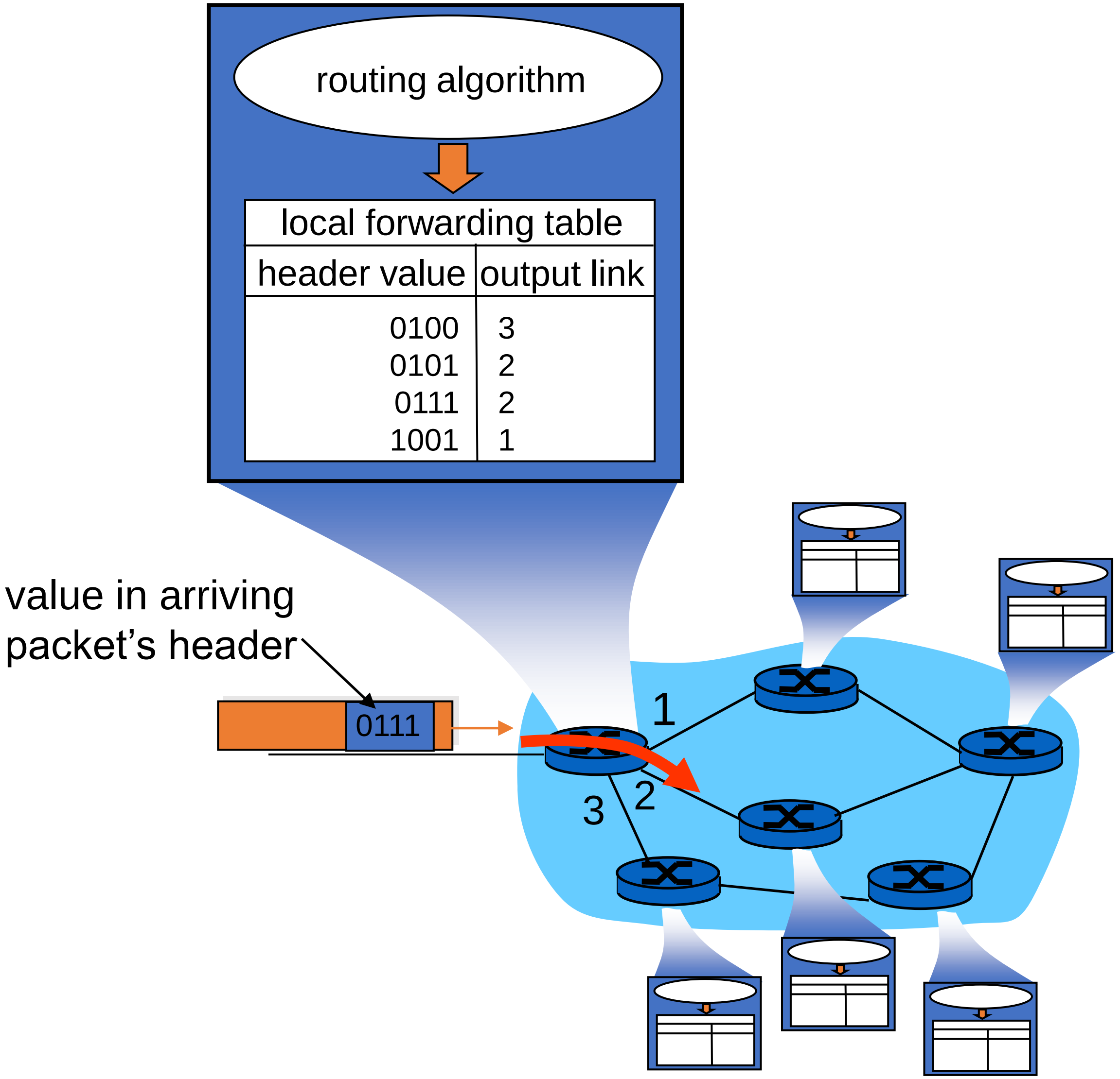
Network layer

- Transport segment from sending to receiving host
- On sending side, encapsulates segments into datagrams
- On receiving side, delivers segments to transport layer
- Network layer protocols in *every* host and router
- Router examines header fields in all IP datagrams passing through it



Two Key Network-Layer Functions

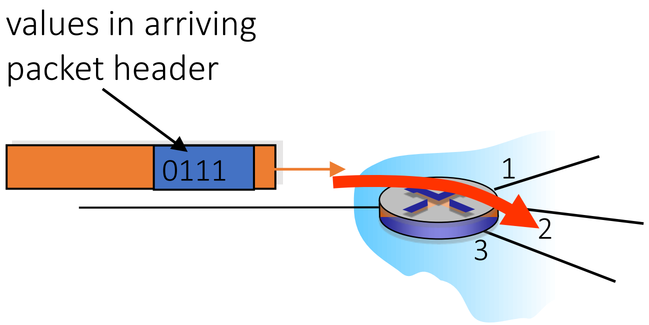
- Forwarding: move packets from router's input to appropriate router output
- Routing: determine the path taken by packets as they flow from a sender to a receiver
  - Routing algorithms – run at routers to determine "paths";
  - Routers have a forwarding table
    - Destination address-based in Datagram networks
    - Virtual circuit number-based in VC Networks



Network Layer: Data Plane & Control Plane

Data plane

- local, per-router function
- determines how datagram arriving at router input port is forwarded to router output port
- forwarding function

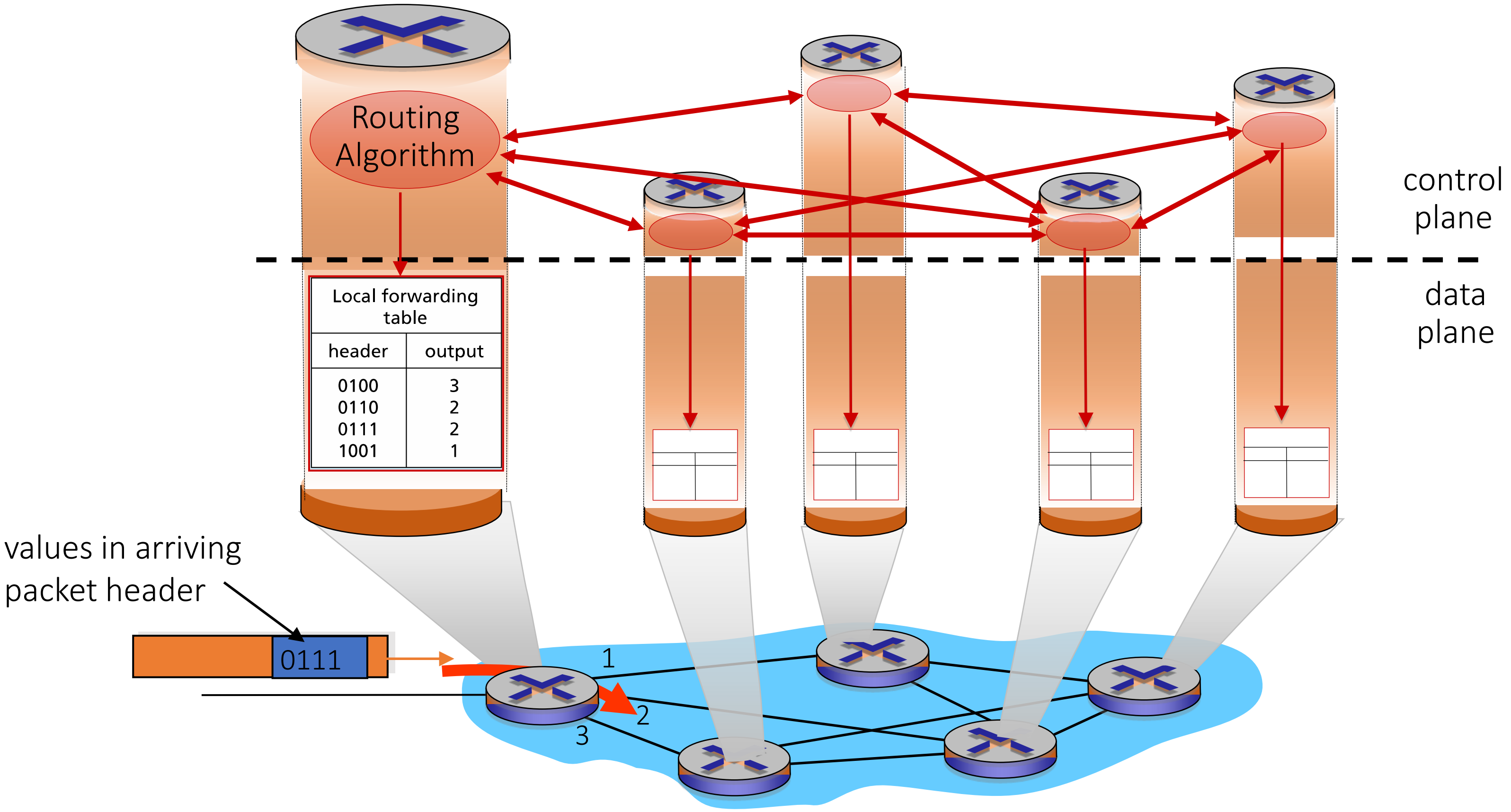


Control plane

- network-wide logic
- determines how datagram is routed among routers along end-to-end path from source host to destination host
- two control-plane approaches:
  - *(1) traditional routing algorithms:* implemented in routers
  - *(2) software-defined networking (SDN)*: implemented in (remote) servers

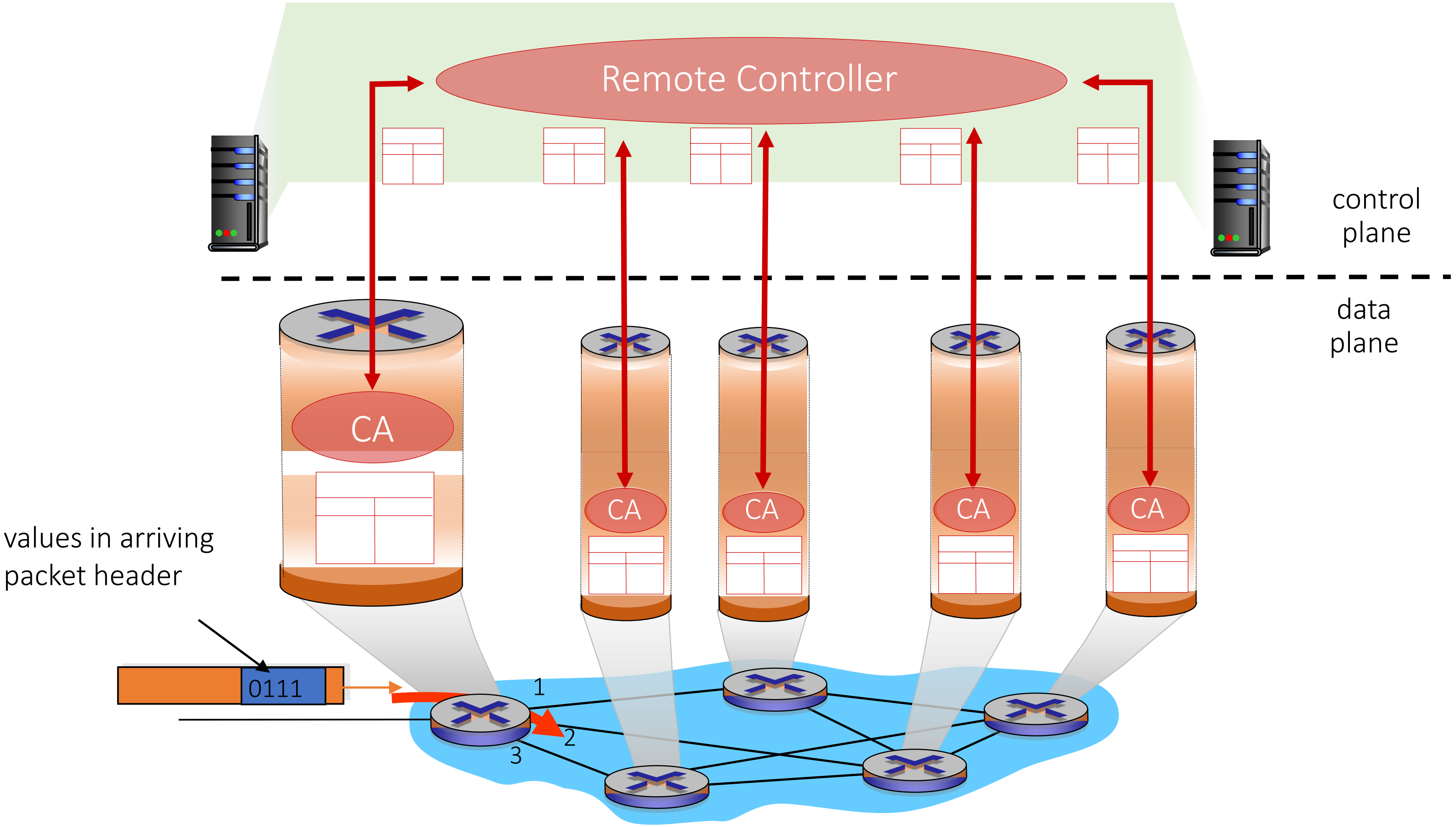
(1) Per-Router Control Plane

Individual routing algorithm components *in each and every router* interact with each other, in the control plane



(2) Software-Defined Networking (SDN) Control Plane

A distinct (typically remote) controller interacts with local control agents (CAs), computes, installs forwarding tables in routers.



Network Service Model

Q: What *service model* for "channel" transporting datagrams from sender to receiver?

example services for individual datagrams:

- guaranteed delivery
- guaranteed delivery with bounded delay e.g. less than 40 msec

example services for a flow of datagrams:

- in-order datagram delivery
- guaranteed minimum bandwidth to flow
- Security by encryption

The Internet's network layer (IP) provides a single service, known as **best-effort** service.

IP's best effort service model has arguably proven to be more than "good enough" to enable an amazing range of applications, including streaming video services such as Netflix and voice-and-video-over-IP, real-time conferencing applications such as Skype and Facetime.

Network-layer service model

Network Architecture	Service Model	Quality of Service (QoS) Guarantees ?			
		Bandwidth	Loss	Order	Timing
Internet	best effort	none	no	no	no

Internet "best effort" service model

No guarantees on*:*

i. successful datagram delivery to destination
ii. timing or order of delivery
iii. bandwidth available to end-end flow

Network-layer service model

Network Architecture	Service Model	Quality of Service (QoS) Guarantees ? Bandwidth	Loss	Order	Timing
Internet	best effort	none	no	no	no
ATM	Constant Bit Rate	Constant rate	yes	yes	yes
ATM	Available Bit Rate	Guaranteed min	no	yes	no
Internet	Intserv Guaranteed (RFC 1633)	yes	yes	yes	yes
Internet	Diffserv (RFC 2475)	possible	possibly	possibly	no

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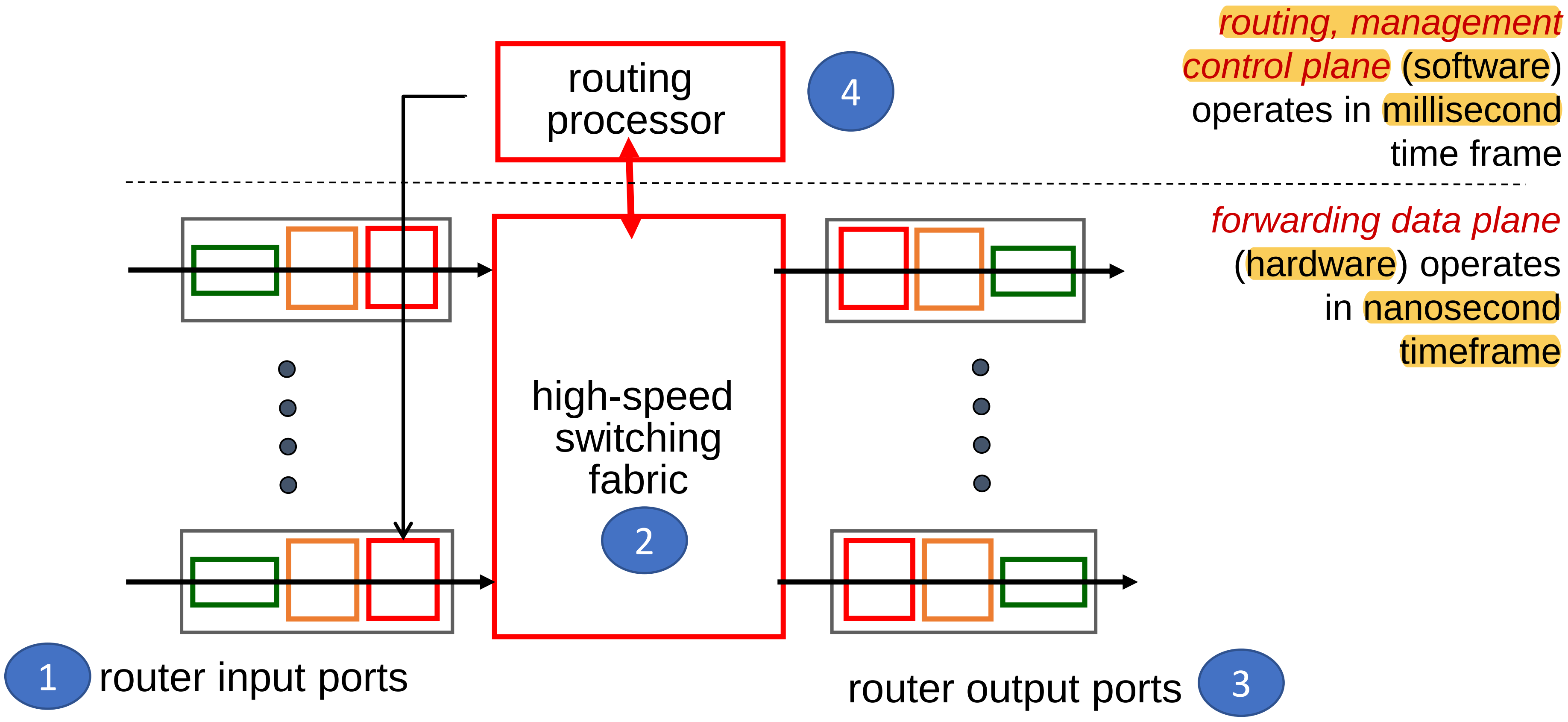
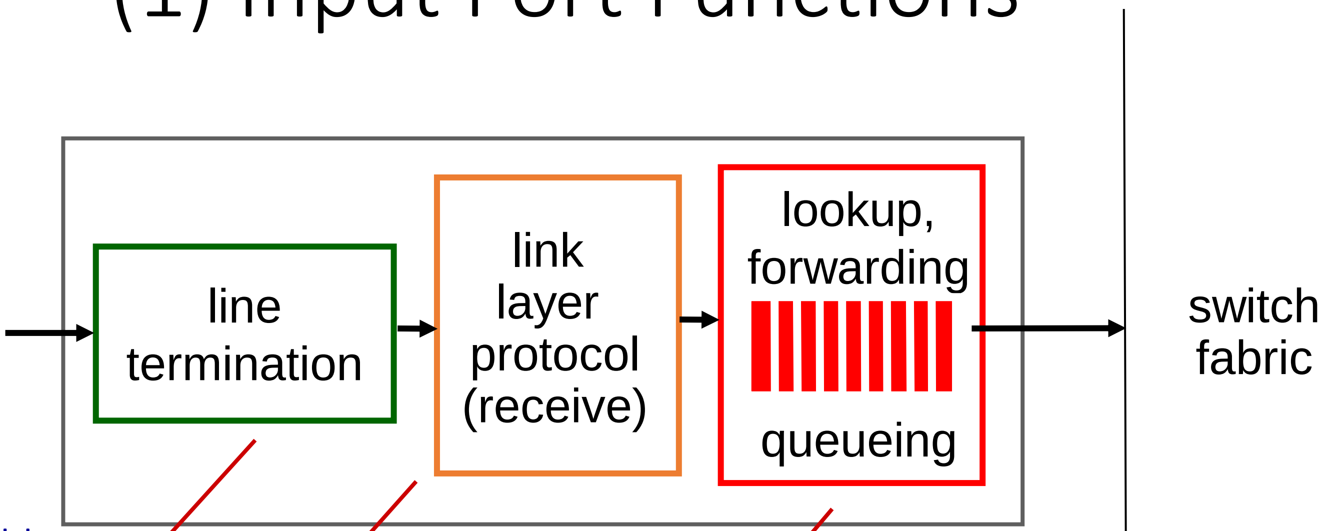
Router Architecture Overview

High-level view of generic router architecture (4 router components):



(1) Input Port Functions



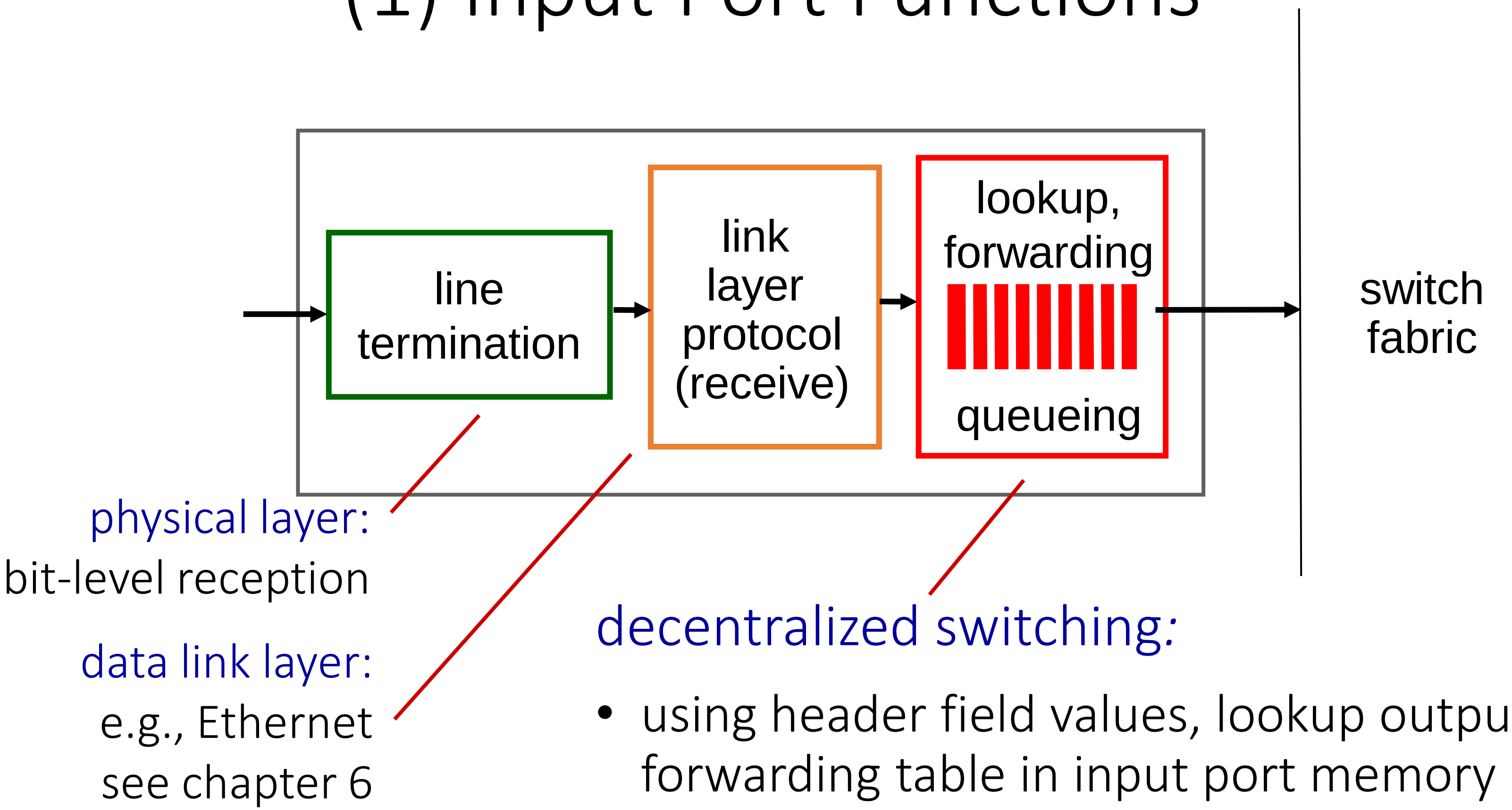
physical layer:
bit-level reception

data link layer:
e.g., Ethernet
see chapter 6

decentralized switching:

- using header field values, lookup output port using forwarding table in input port memory *("match plus action")*
- goal: complete input port processing at 'line speed'
- queuing: if datagrams arrive faster than forwarding rate on switch fabric

(1) Input Port Functions



decentralized switching:

- using header field values, lookup output port using forwarding table in input port memory *("match plus action")*
- *destination-based forwarding:* forward based only on destination IP address (traditional)
- *generalized forwarding:* forward based on any set of header field values

Destination-based forwarding

forwarding table

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through	0
11001000 00010111 00010000 00000100 through 11001000 00010111 00010000 00000111	3
11001000 00010111 00011000 11111111	
11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111	2
otherwise	3

Q: but what happens if ranges don't divide up so nicely?

Longest prefix matching

longest prefix match

when looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.

Destination Address Range	Link interface
11001000 00010111 00010*** ********	0
11001000 00010111 00011000 ********	1
11001000 00010111 00011*** ********	2
otherwise	3

examples:

11001000 00010111 00010110 10100001 which interface?

11001000 00010111 00011000 10101010 which interface?

Longest prefix matching

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when looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.

Destination Address Range	Link interface
11001000 00010111 00010*** ********	0
11001000 00010111 00011000 ********	1
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otherwise	3

match!

examples:

11001000 00010111 00010110 10100001 which interface?

11001000 00010111 00011000 10101010 which interface?

Longest prefix matching

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Destination Address Range				Link interface
11001000	00010111	00010***	********	0
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match!

examples:

11001000	00010111	00010110	10100001	which interface?
11001000	00010111	00011000	10101010	which interface?

Longest prefix matching

longest prefix match

when looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.

Destination Address Range				Link interface
11001000	00010111	00010***	********	0
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otherwise				3

match!

examples:

11001000	00010111	00010110	10100001	which interface?
11001000	00010111	00011000	10101010	which interface?

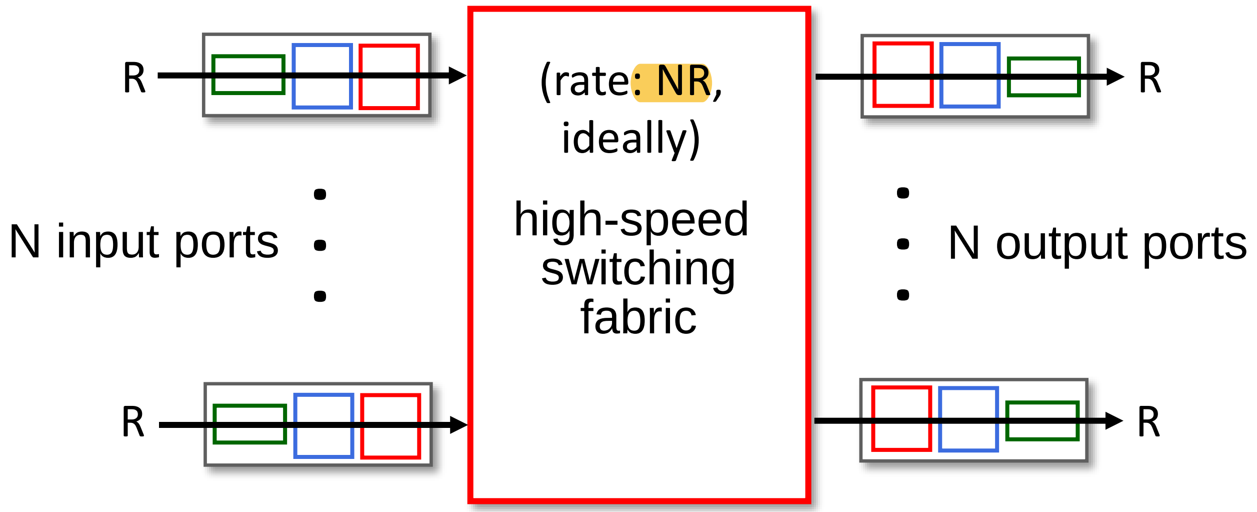
Longest Prefix Matching

- we'll see *why* longest prefix matching is used shortly, when we study addressing
- longest prefix matching: often performed using ternary content addressable memories (TCAMs)
  - *content addressable:* present address to TCAM: retrieve address in one clock cycle, regardless of table size
  - Cisco Catalyst: can support up to ~1M routing table entries in TCAM

(2) Switching Fabrics

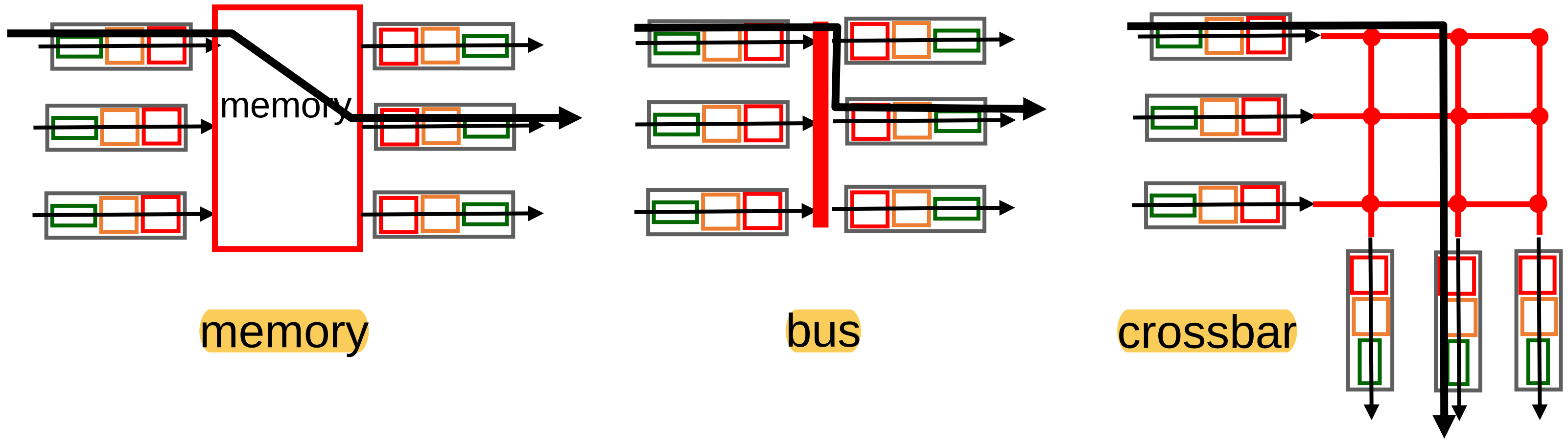
From buffer to buffer

- transfer packet from input buffer to appropriate output buffer
- switching rate: rate at which packets can be transfer from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable (rate: NR ideally)



(2) Switching Fabrics

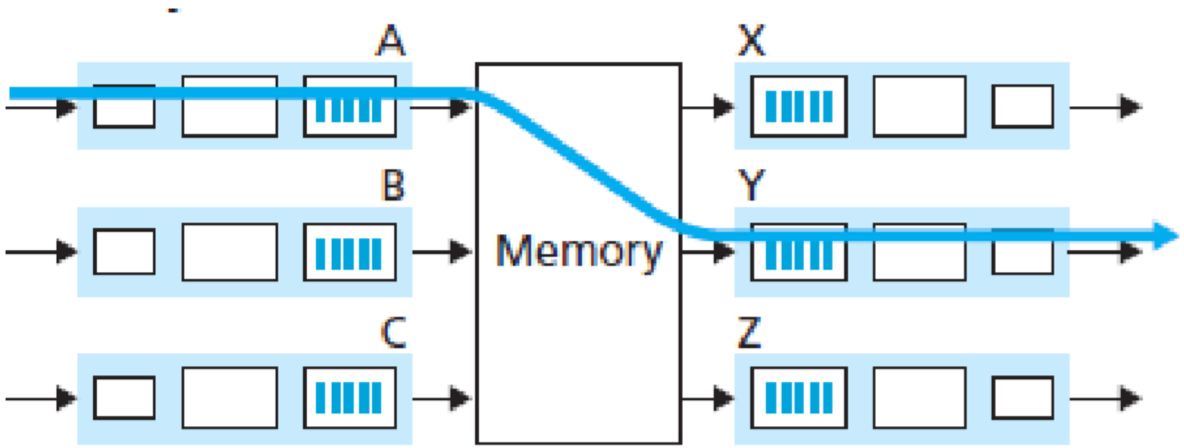
- transfer packet from input buffer to appropriate output buffer
- switching rate: rate at which packets can be transfer from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable (rate: NR ideally)
- three types of switching fabrics



Switching via Memory

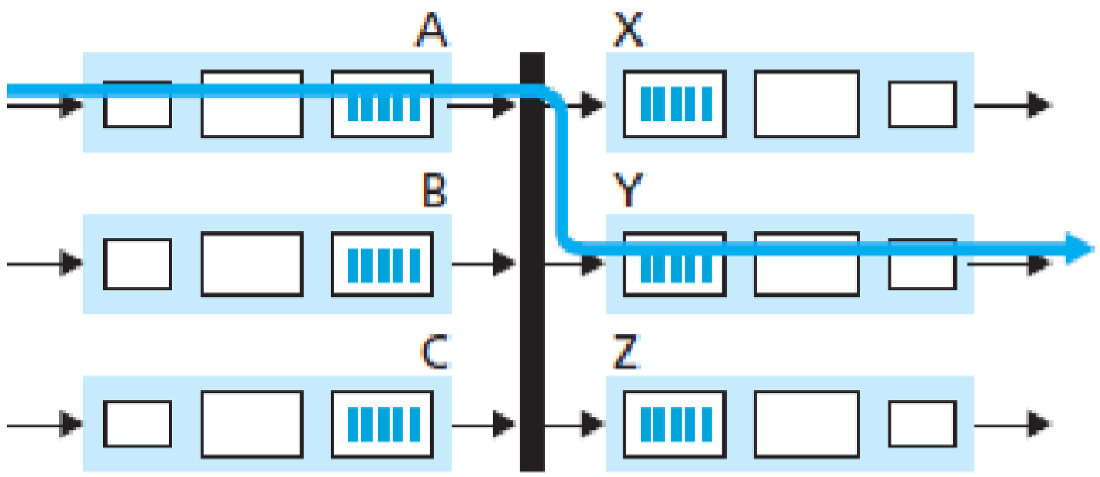
first generation routers:

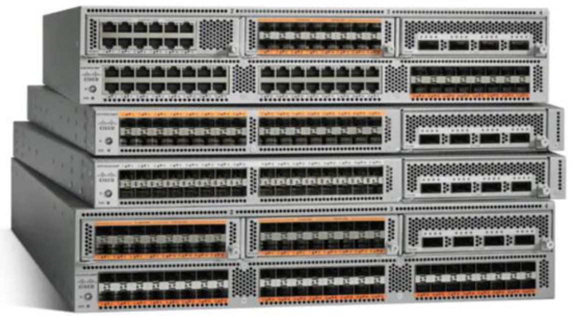
- traditional computers with switching under direct control of CPU
- packet copied to system's memory
- speed limited by memory bandwidth



Switching via a Bus

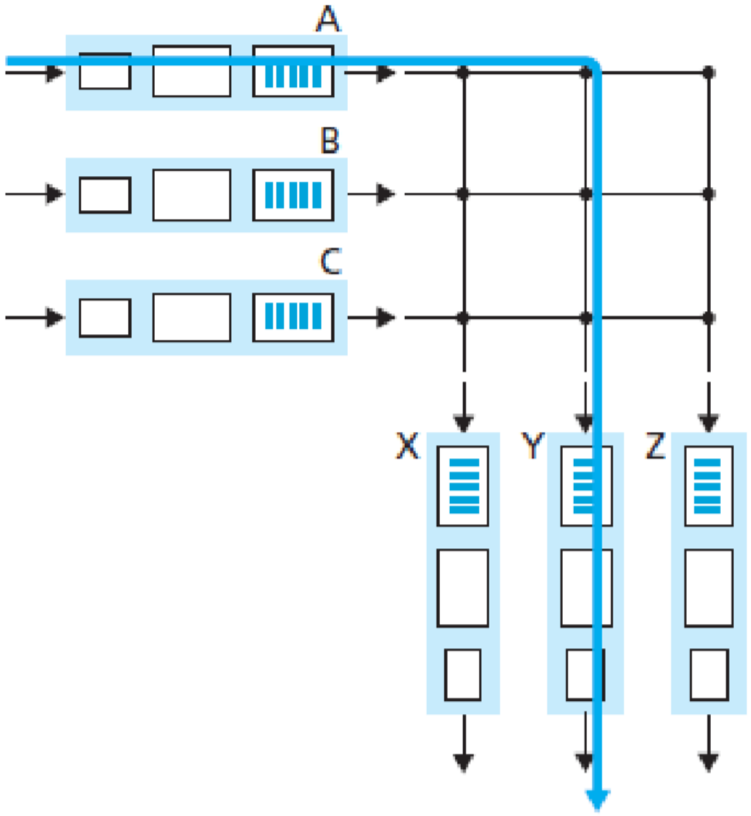
- datagram from input port memory to output port memory via a shared bus
- *bus contention:* switching speed limited by bus bandwidth
- 32 Gbps bus, Cisco 5600: sufficient speed for access and enterprise routers





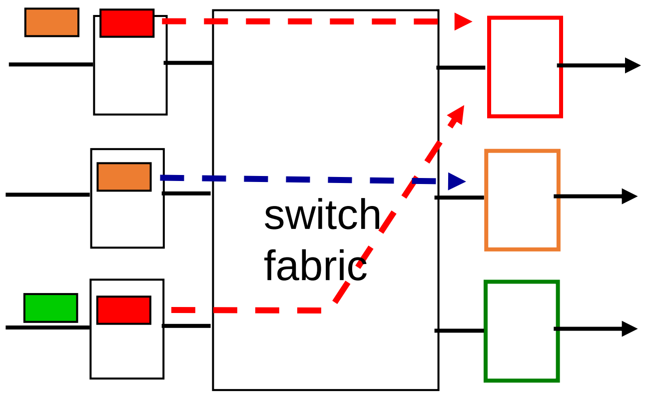
Switching via Interconnection Network

- overcome bus bandwidth limitations
- crossbar, other interconnection nets initially developed to connect processors in multiprocessor
- advanced design: (with multiple switching fabrics e.g. N fabrics) fragmenting datagram into fixed length cells, switch (spray) cells through the N fabrics, reassemble datagram at exit.
- Cisco 12000: switches 60 Gbps through the interconnection network

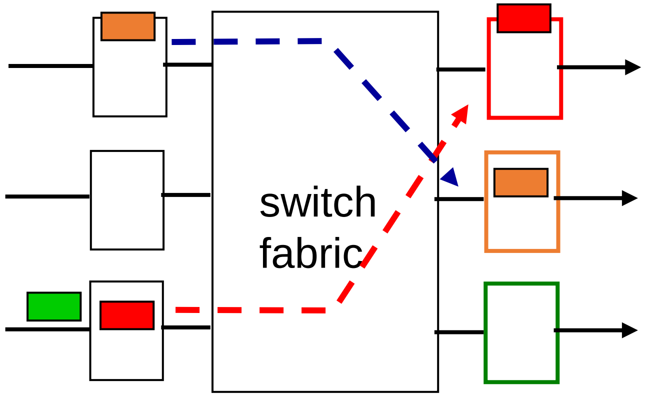


Input Port Queuing

- fabric slower than input ports combined -> queueing may occur at input queues
  - *queuing delay and loss due to input buffer overflow!*
- Head-of-the-Line (HOL) blocking: queued datagram at front of queue prevents others in queue from moving forward

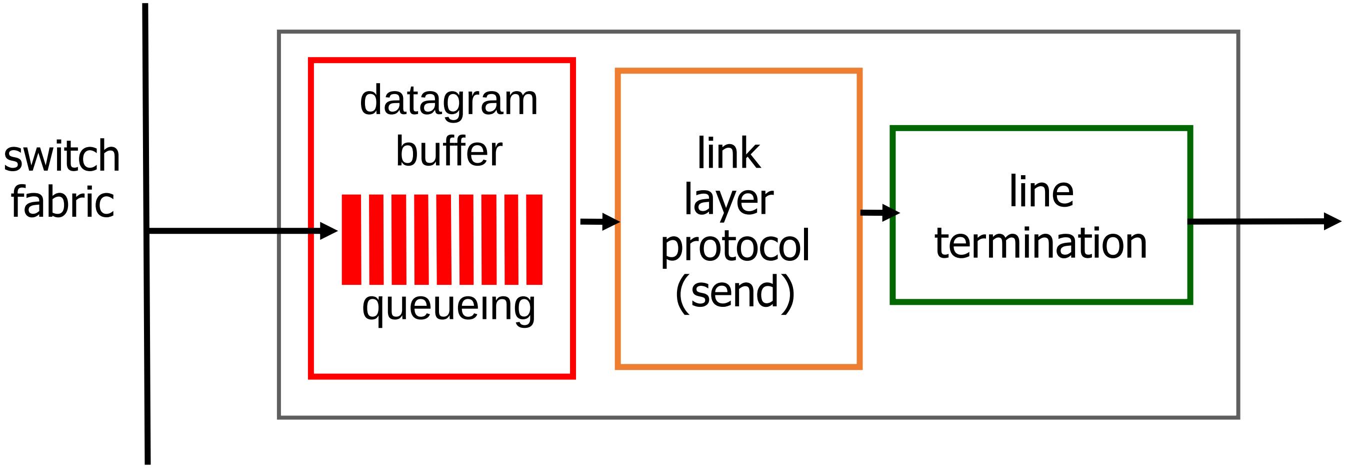


output port contention:
only one red datagram can be transferred.
lower red packet is blocked



one packet time later:
green packet experiences HOL blocking

(3) Output Ports

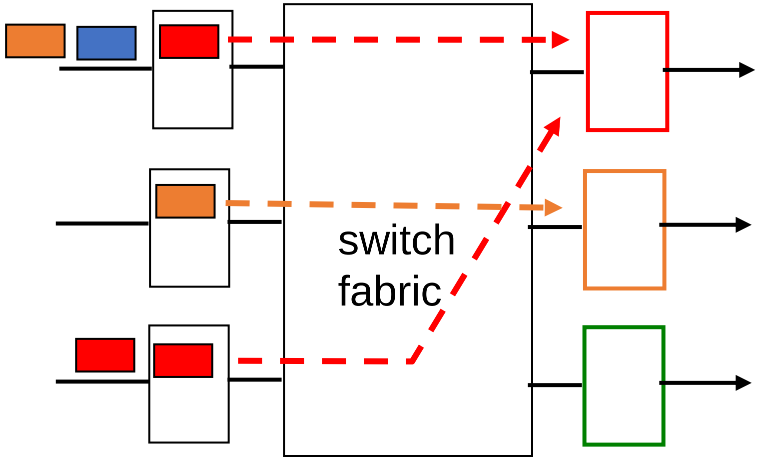


- *buffering* required when datagrams arrive from fabric faster than the transmission rate. Drop policy: which datagrams to drop if no free buffers?
- *scheduling discipline* chooses among queued datagrams for transmission

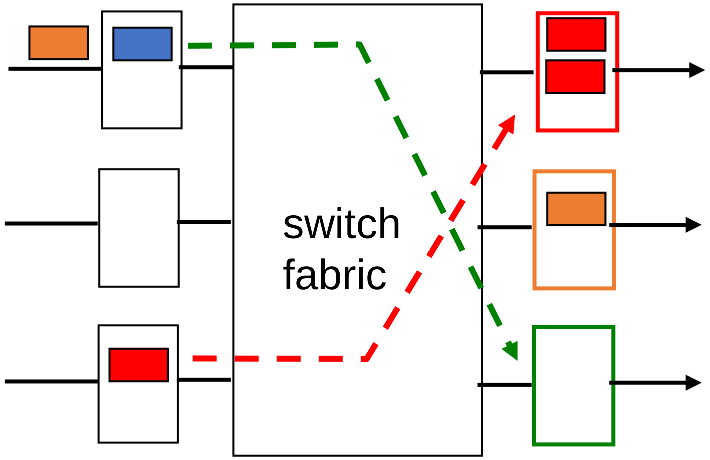
Datagram (packets) can be lost due to congestion, lack of buffers

Priority scheduling – who gets best performance

Output Port Queuing



at *t*, packets more
from input to output

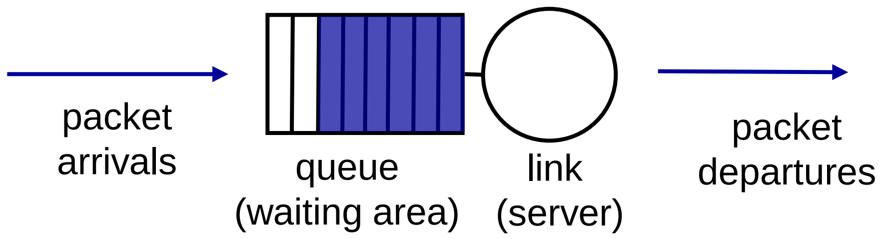


one packet time later

- buffering when arrival rate via switch exceeds output line speed
- *queueing (delay) and loss due to output port buffer overflow!*

Scheduling Mechanisms

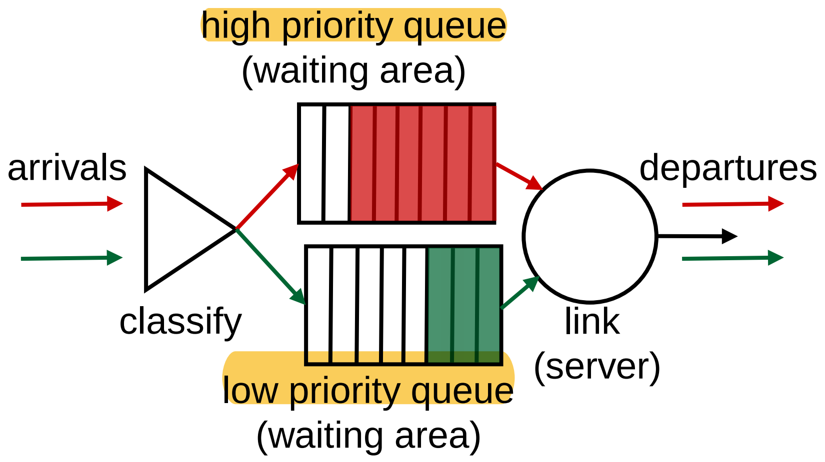
- *scheduling:* choose next packet to send on link
- *FIFO (first in first out) scheduling:* send in order of arrival to queue
    - real-world example?
    - *discard policy:* if packet arrives to full queue: who to discard?
        - *tail drop:* drop arriving packet
        - *priority:* drop/remove on priority basis
        - *random:* drop/remove randomly

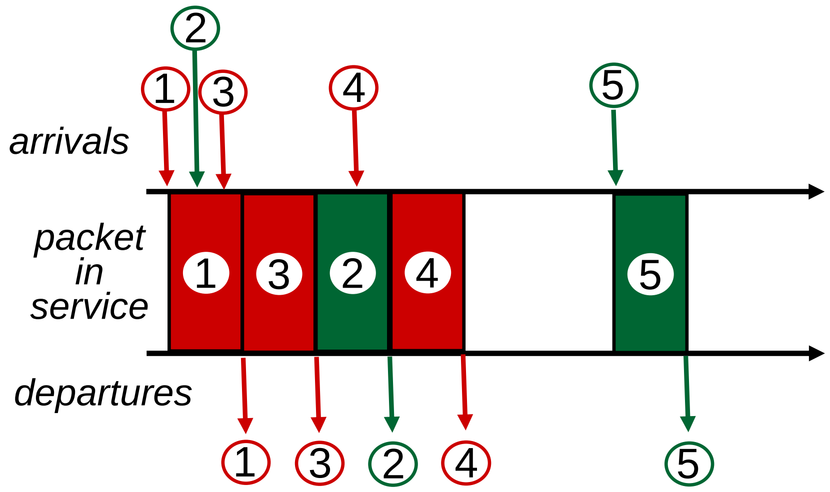


Scheduling Policies: Priority

priority scheduling: send highest priority queued packet

- multiple *classes*, with different priorities
  - class may depend on marking or other header info, e.g. IP source/dest, port numbers, etc.
  - real world example?

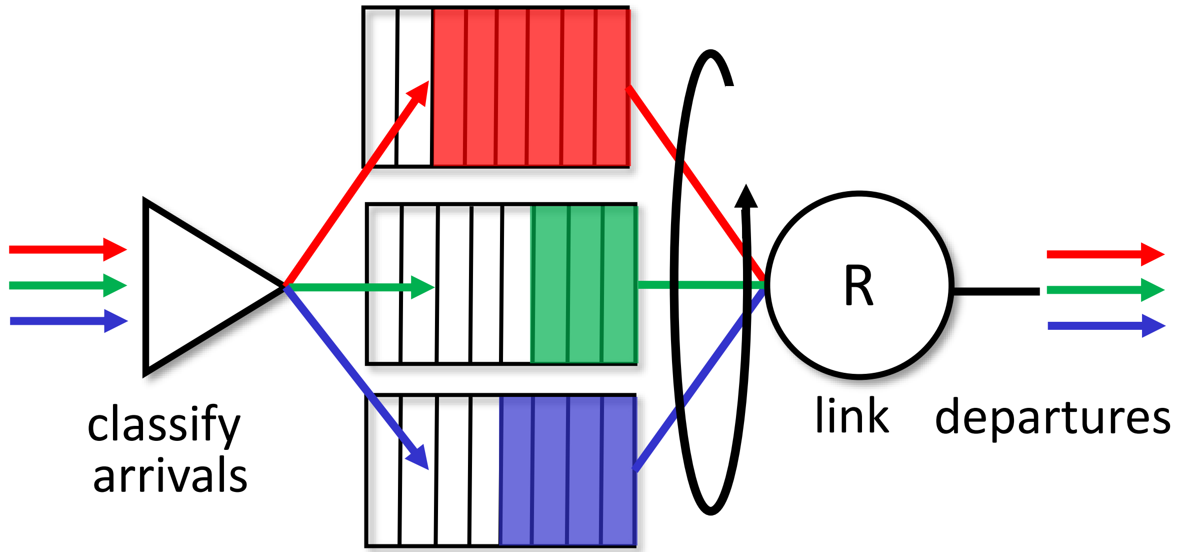


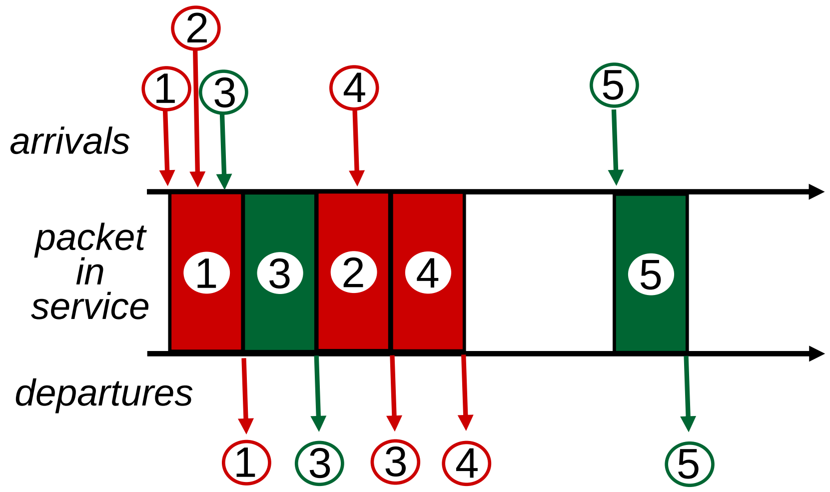


Scheduling Policies: still more

Round Robin (RR) scheduling:

- multiple classes
- cyclically scan class queues, sending one complete packet from each class (if available)
- real world example?

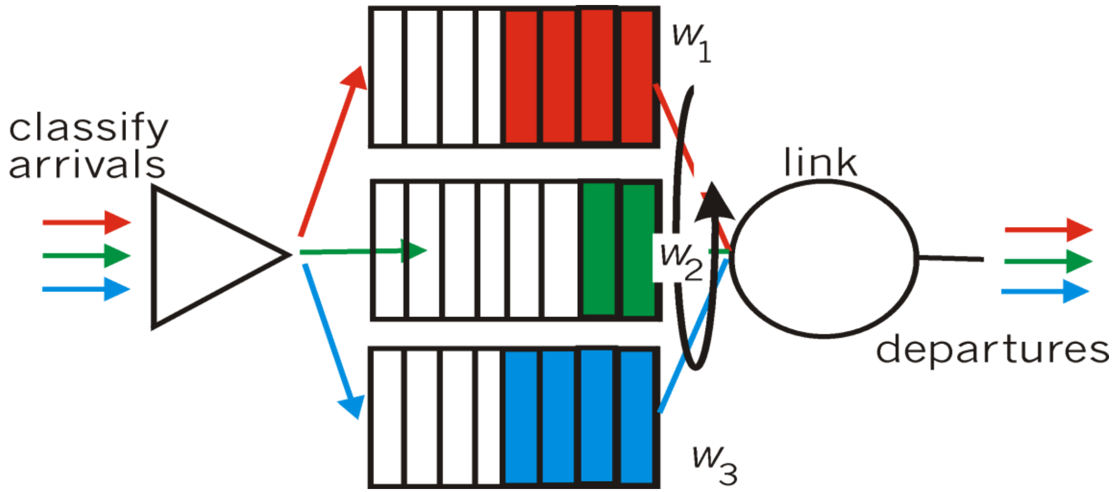




Scheduling Policies: still more

Weighted Fair Queuing (WFQ):

- generalized Round Robin
- each class gets weighted amount of service in each cycle
- real-world example?



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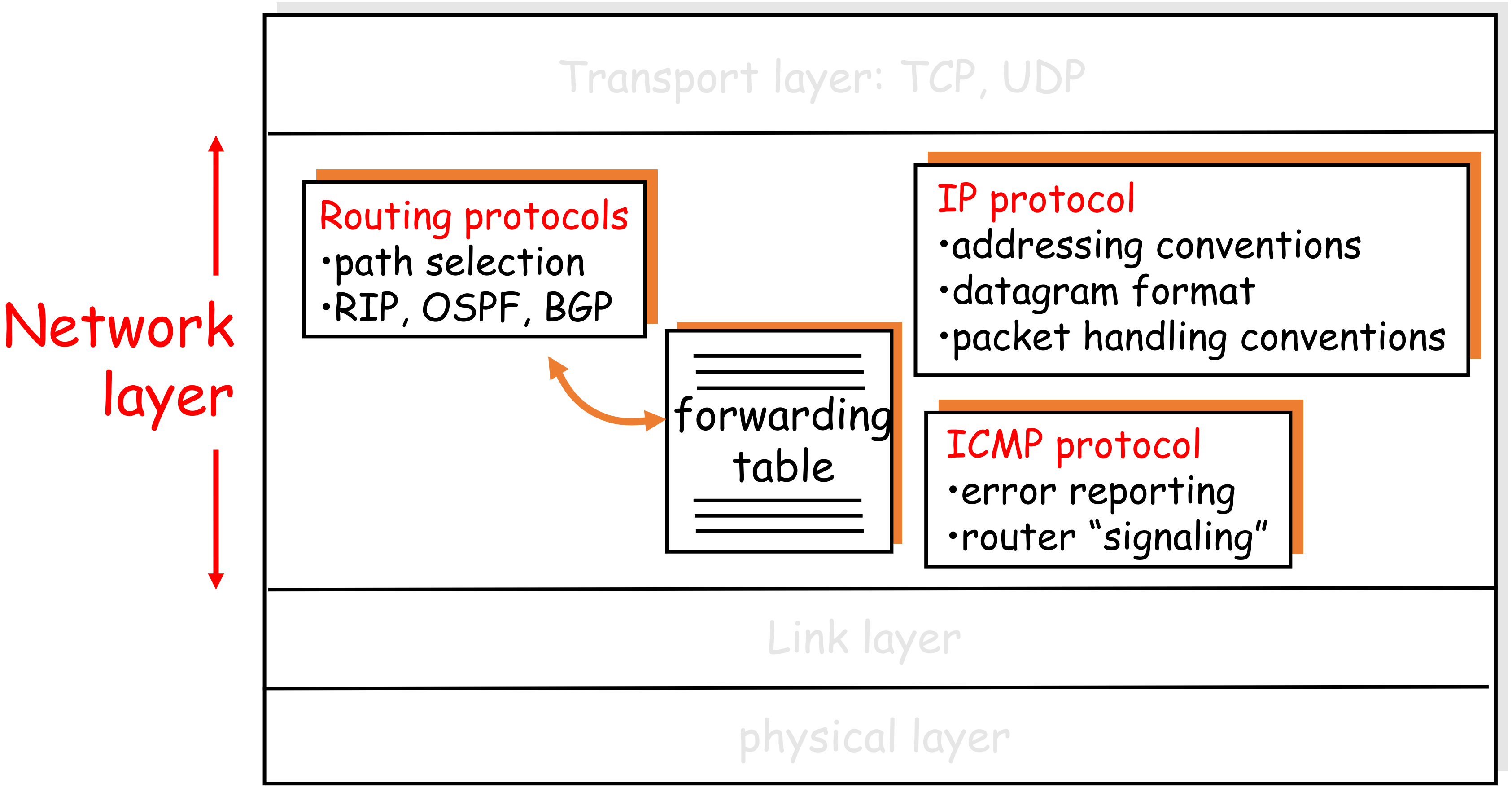
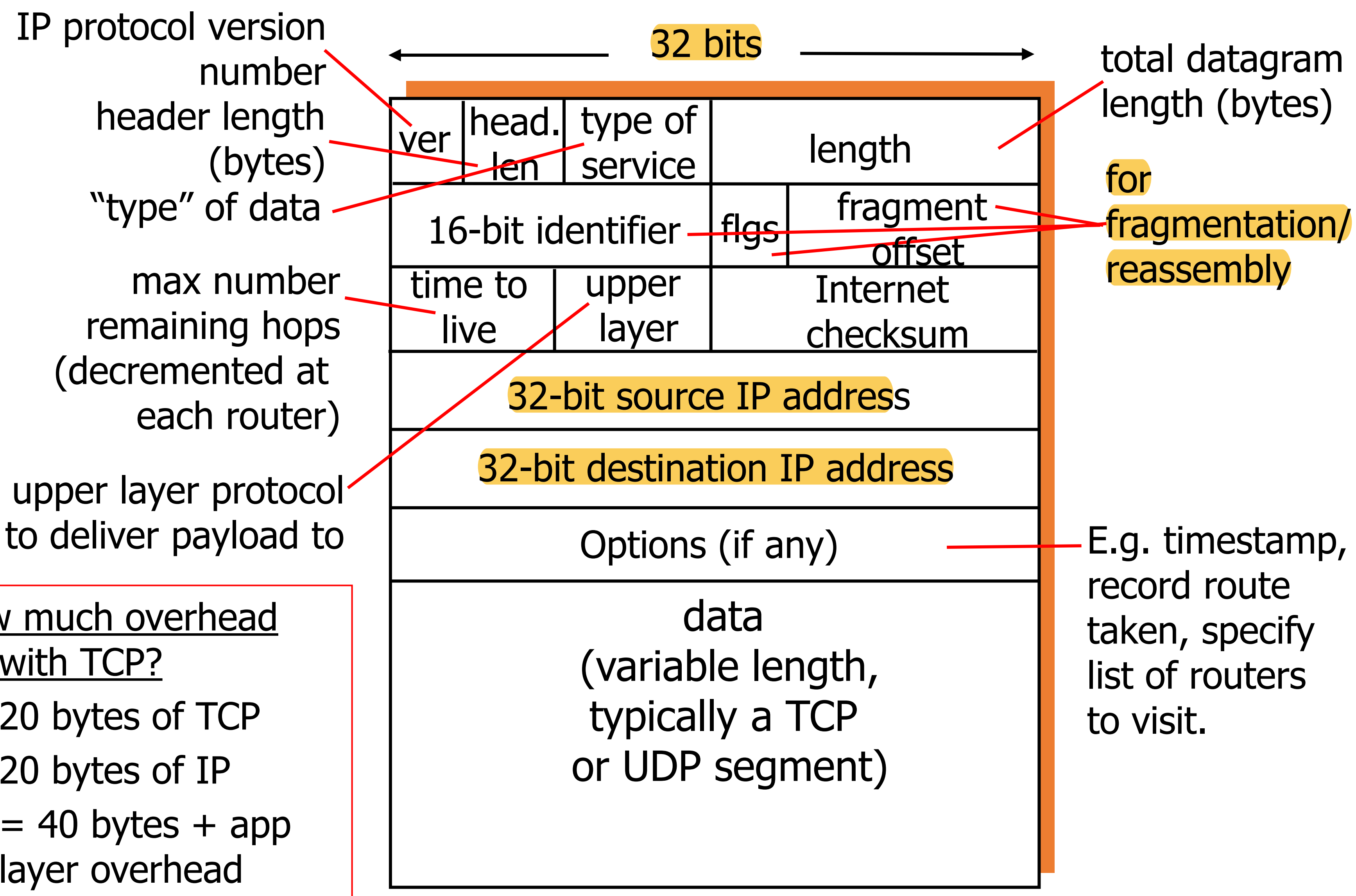
What does the Network layer consist of?

Host, router network layer functions:



IP Datagram Format



<u>how much overhead with TCP?</u>

- 20 bytes of TCP
- 20 bytes of IP
- = 40 bytes + app layer overhead

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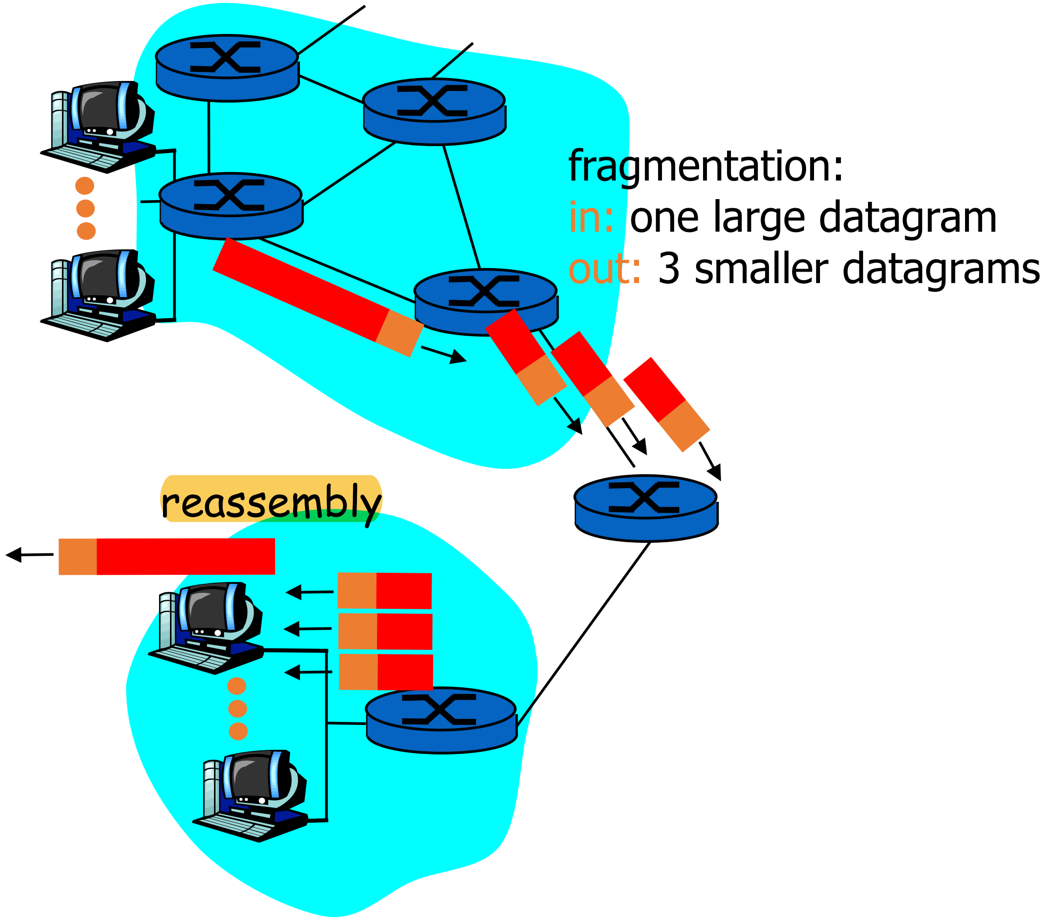
IP Fragmentation & Reassembly

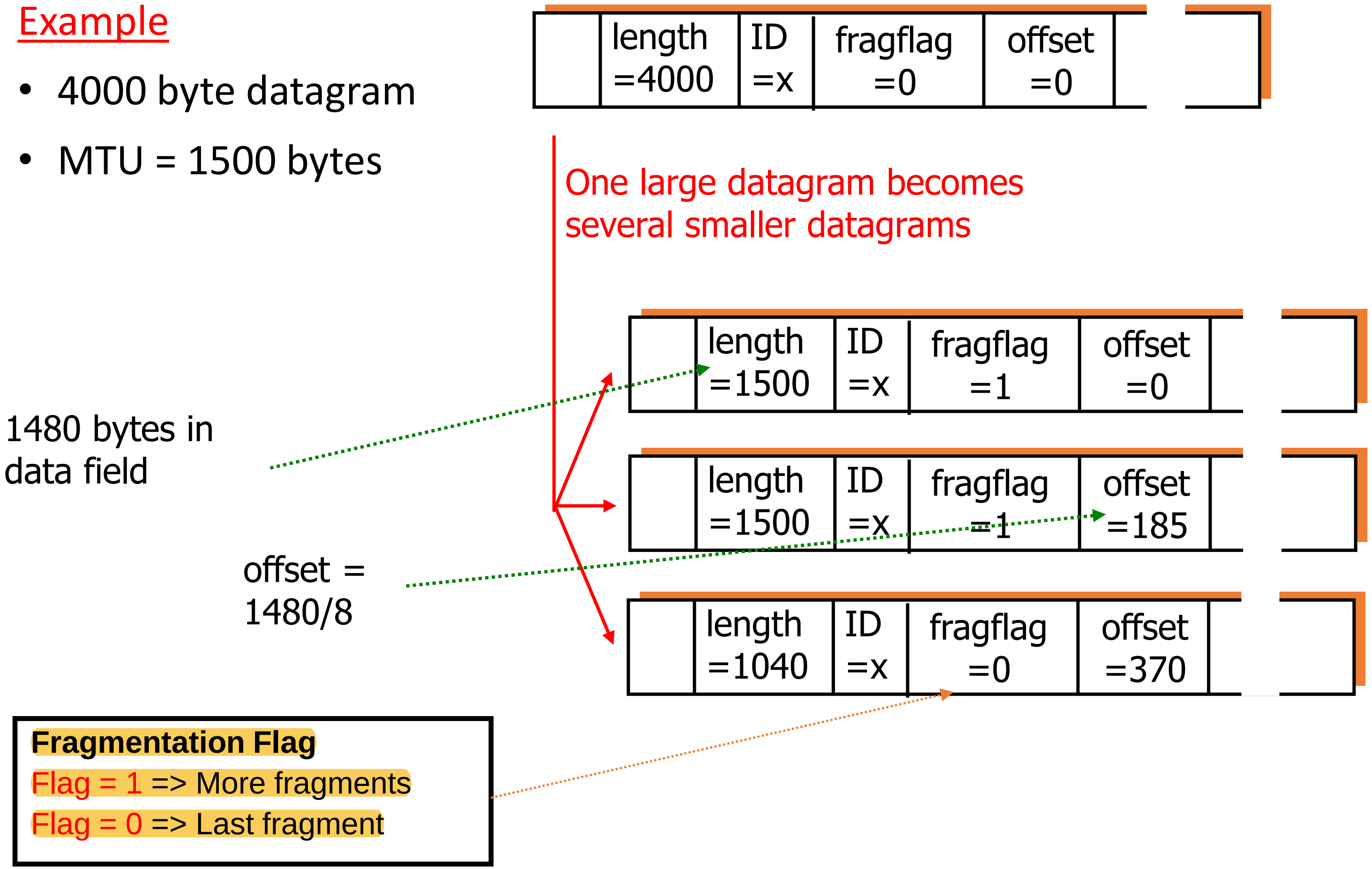
- network links have MTU (max. transmission unit) - largest possible link-level frame.
  - different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only at final destination
  - IP header bits used to identify, order related fragments



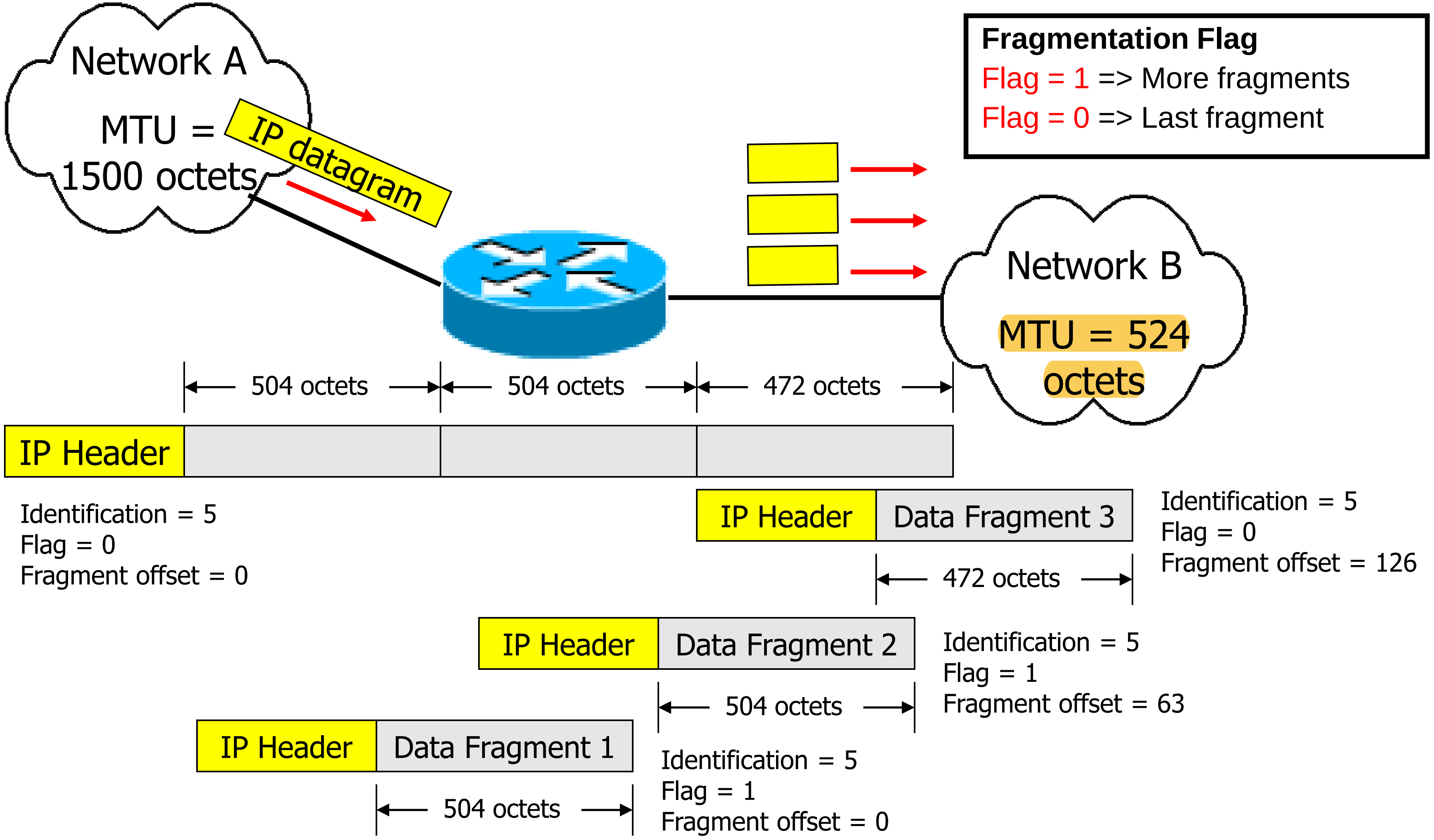
IP Fragmentation & Reassembly

Example

- 4000 byte datagram
- MTU = 1500 bytes



Fragmentation Flags & Fragment Offset



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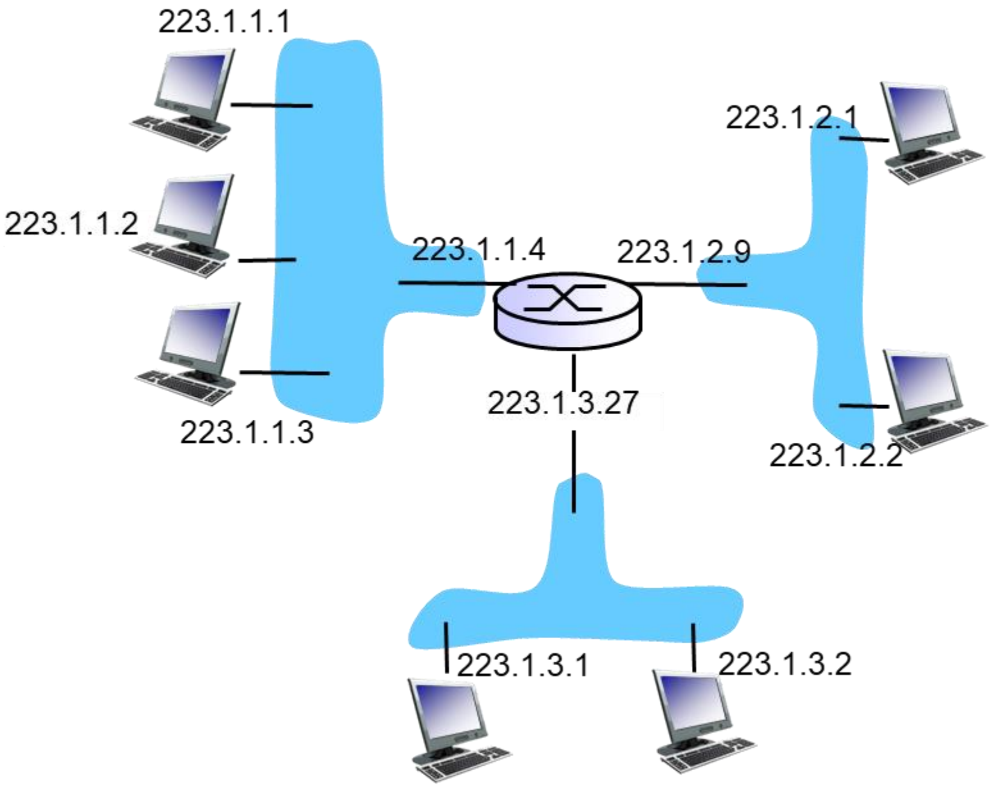
IP Addressing: Introduction

- IP address: 32-bit identifier for host, router interface
- Interface: connection between host/router and physical link
  - router's typically have multiple interfaces
  - host may have multiple interfaces
  - IP addresses associated with each interface

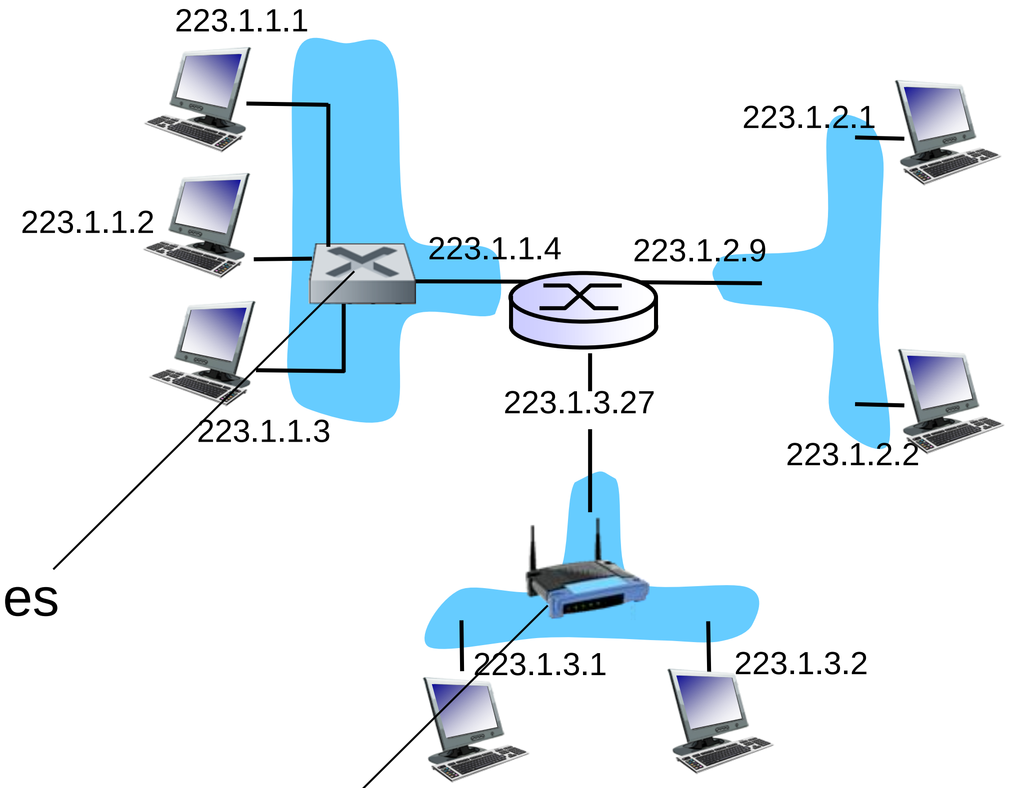


$$223.1.1.1 = \underbrace{11011111}_{223}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}$$

IP Addressing: Introduction

Q: how are interfaces actually connected?

A: we'll learn about that in chapters 6, 7.



A: wired Ethernet interfaces connected by Ethernet switches

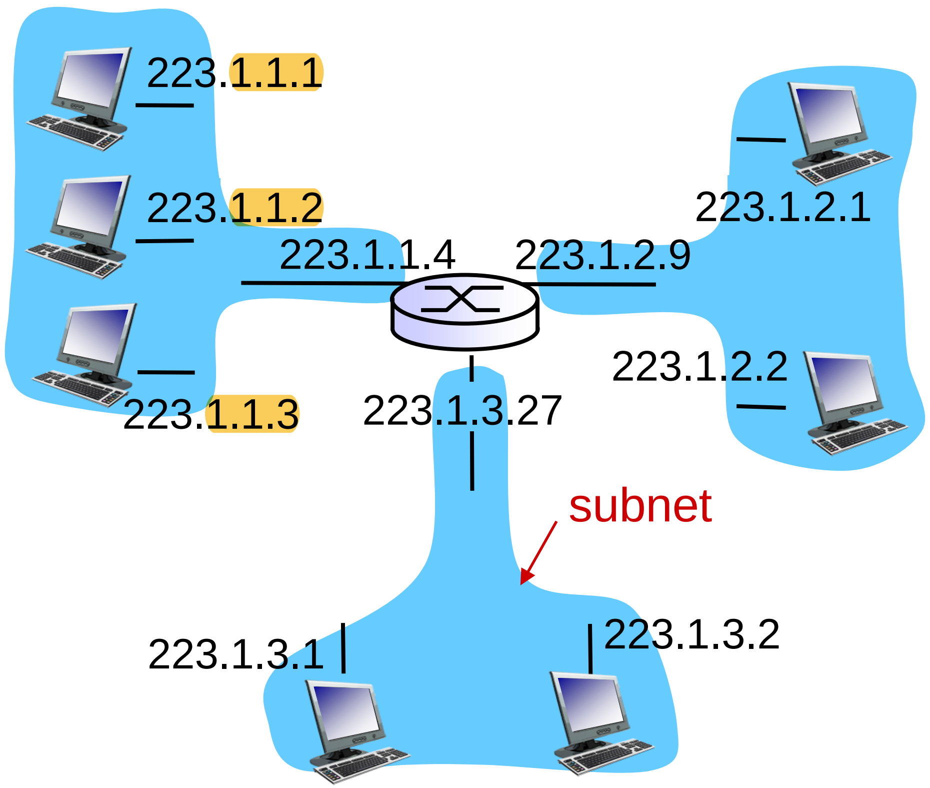
For now: don't need to worry about how one interface is connected to another (with no intervening router)

A: wireless WiFi interfaces connected by WiFi base station

Subnets

- IP address:
  - subnet part (high order bits)
  - host part (low order bits)

- What's a subnet ?
  - device interfaces with same subnet part of IP address can physically reach each other without intervening router

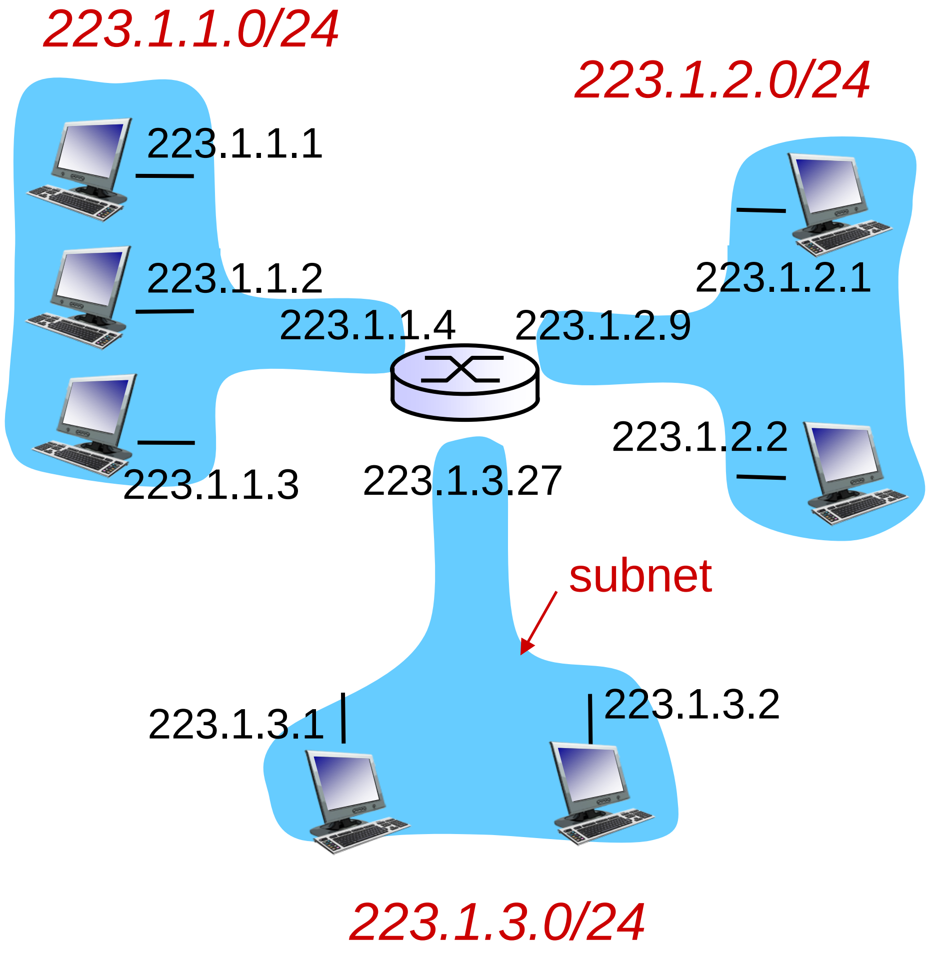


network consisting of 3 subnets

Subnets

<u>Recipe</u>

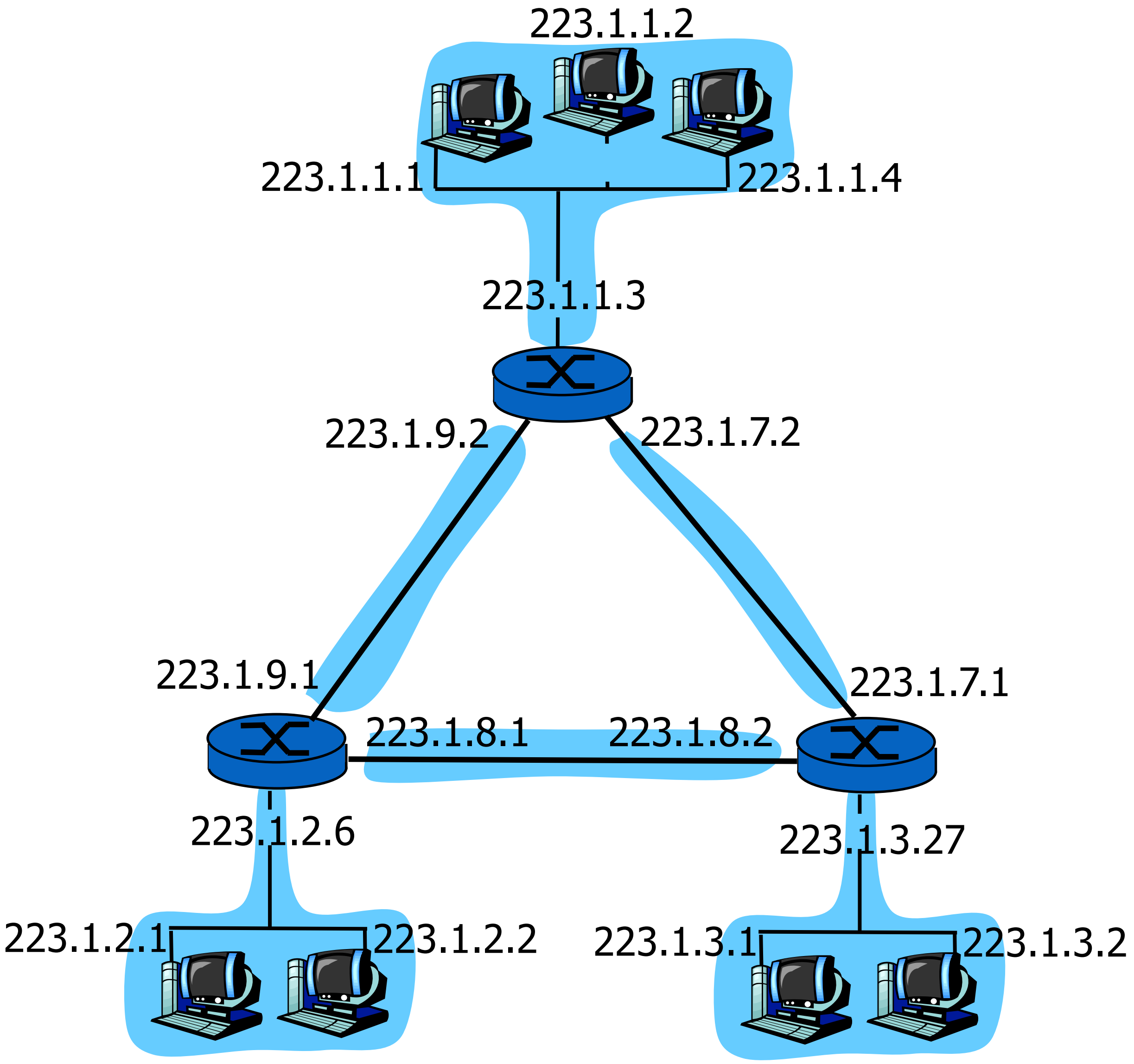
To determine the subnets, detach each interface from its host or router, creating islands of isolated networks. Each isolated network is called a subnet.



subnet mask: /24

Subnets

How many subnets?



Addressing in the Internet

CIDR: Classless InterDomain Routing

- subnet portion of address of arbitrary length
- address format: a.b.c.d/x, where x is # bits in subnet portion of address
- Before CIDR, Internet used a class-based addressing scheme where x could be 8, 16, or 24 bits. These correspond to classes A, B, and C respectively.

subnet part   host part

11001000 00010111 00010000 00000000

200.23.16.0/23

IP addresses: how to get one?

Q: How does *host* get IP address?

- hard-coded by system admin in a file
  - Win: control-panel->network->configuration->tcp/ip->properties
  - UNIX: /etc/rc.config

- DHCP: Dynamic Host Configuration Protocol: dynamically get address from a server
  - this is becoming very popular

DHCP: Dynamic Host Configuration Protocol

goal: allow host to *dynamically* obtain its IP address from network server when it joins network

- can renew its lease on address in use
- allows reuse of addresses (only hold address while connected/"on")
- support for mobile users who want to join network (more shortly)

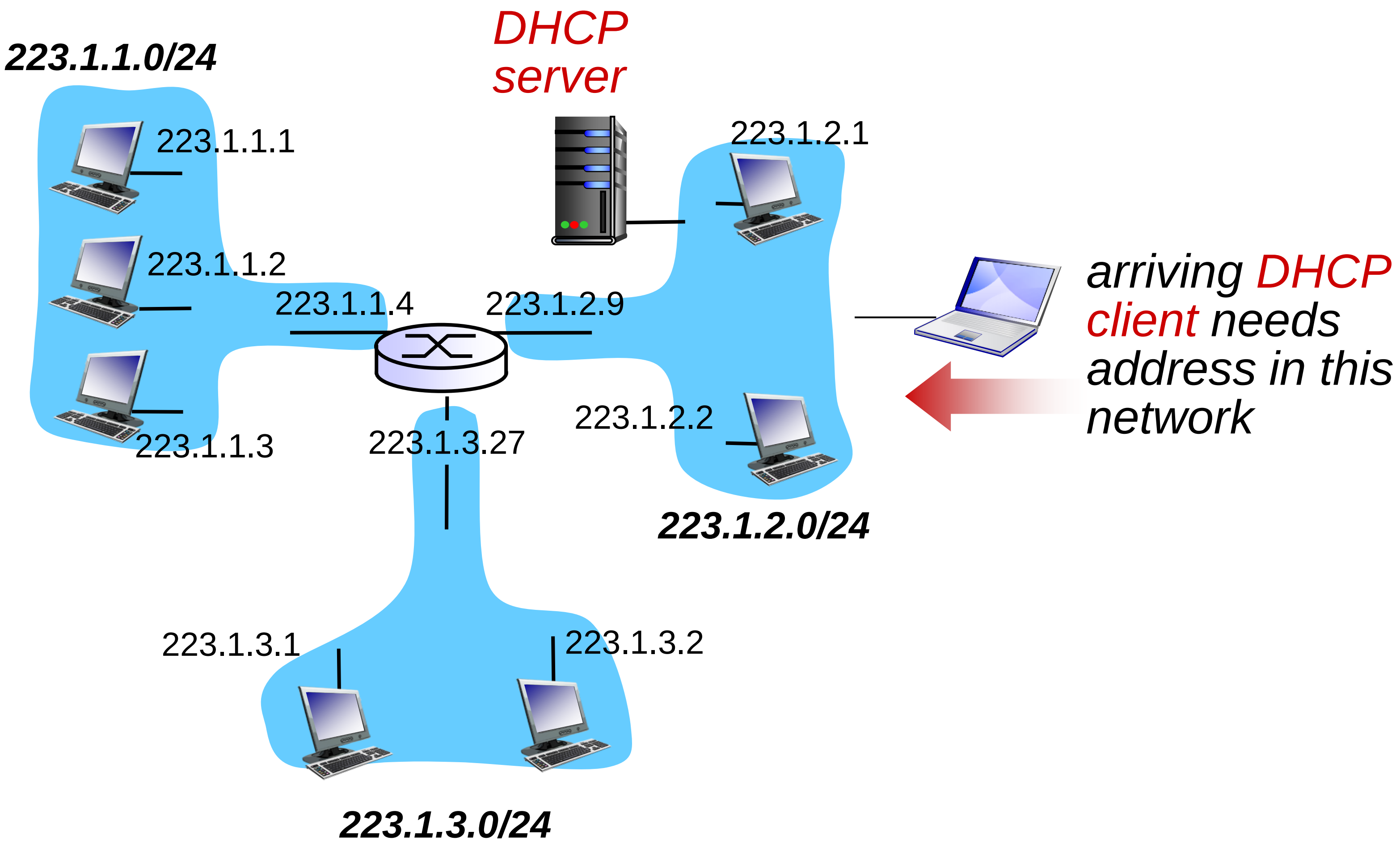
DHCP overview:

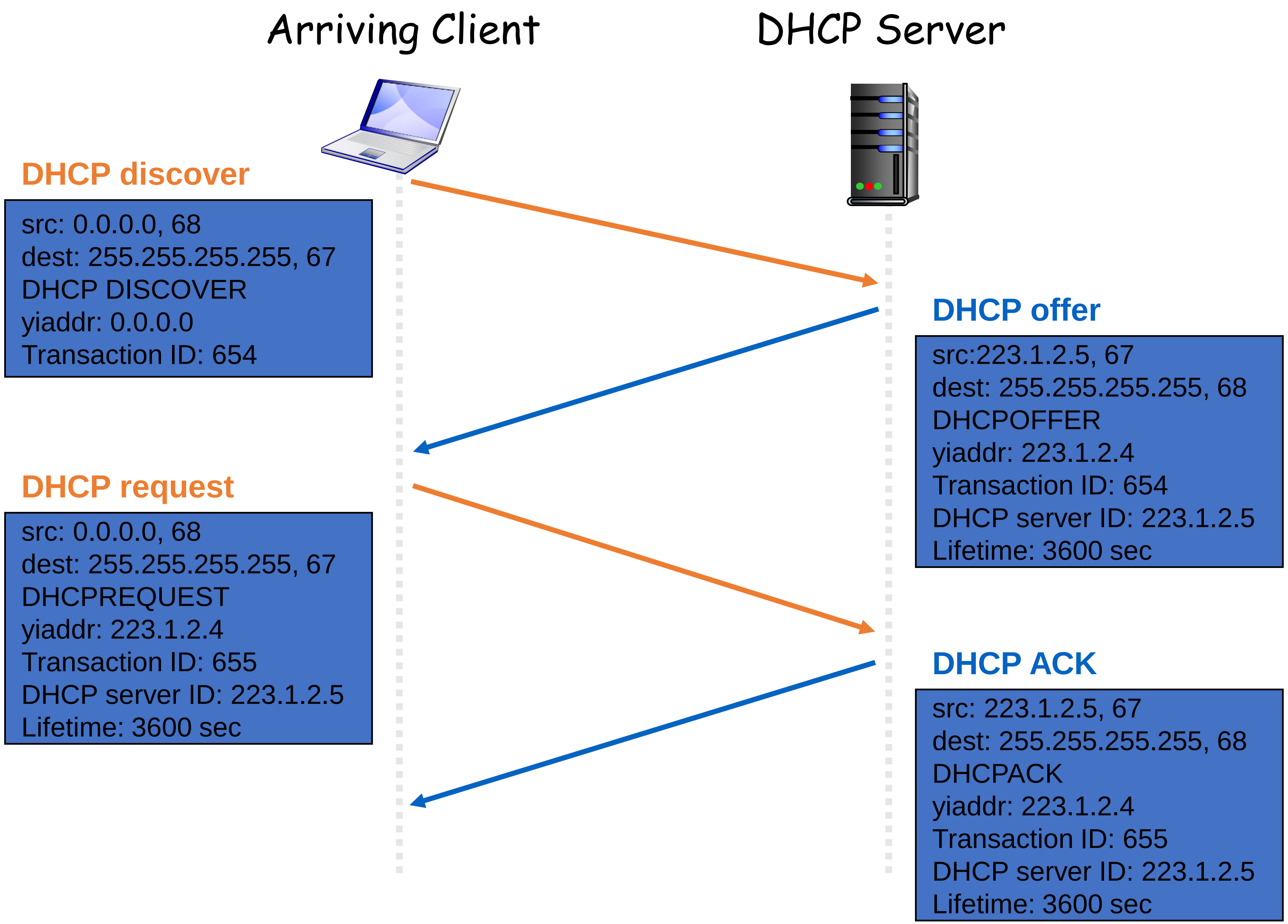
- host broadcasts "DHCP discover" msg [optional]
- DHCP server responds with "DHCP offer" msg [optional]
- host requests IP address: "DHCP request" msg
- DHCP server sends address: "DHCP ack" msg

DHCP: Dynamic Host Configuration Protocol

- Used to assign IP address to hosts dynamically.
- Client-server protocol.
- Clients : obtain network configuration information e.g. IP address, subnet mask, default gateway, DNS
- Server : allocates configuration information
  - If no server is present on the network, a DHCP relay agent (in a router that knows the address of DHCP server for that network) is need.

DHCP Client-Server Scenario




Arriving Client
DHCP Server
DHCP discover
src: 0.0.0.0, 68
dest: 255.255.255.255, 67
DHCP DISCOVER
yiaddr: 0.0.0.0
Transaction ID: 654
DHCP offer
src:223.1.2.5, 67
dest: 255.255.255.255, 68
DHCPOFFER
yiaddr: 223.1.2.4
Transaction ID: 654
DHCP server ID: 223.1.2.5
Lifetime: 3600 sec
DHCP request
src: 0.0.0.0, 68
dest: 255.255.255.255, 67
DHCPREQUEST
yiaddr: 223.1.2.4
Transaction ID: 655
DHCP server ID: 223.1.2.5
Lifetime: 3600 sec
DHCP ACK
src: 223.1.2.5, 67
dest: 255.255.255.255, 68
DHCPACK
yiaddr: 223.1.2.4
Transaction ID: 655
DHCP server ID: 223.1.2.5
Lifetime: 3600 sec

DHCP: more than IP addresses

DHCP can return more than just allocated IP address on subnet:

- address of first-hop router (default router/gateway) for client
- name and IP address of DNS sever
- network mask (indicating network versus host portion of address)

IP addresses: how to get one?

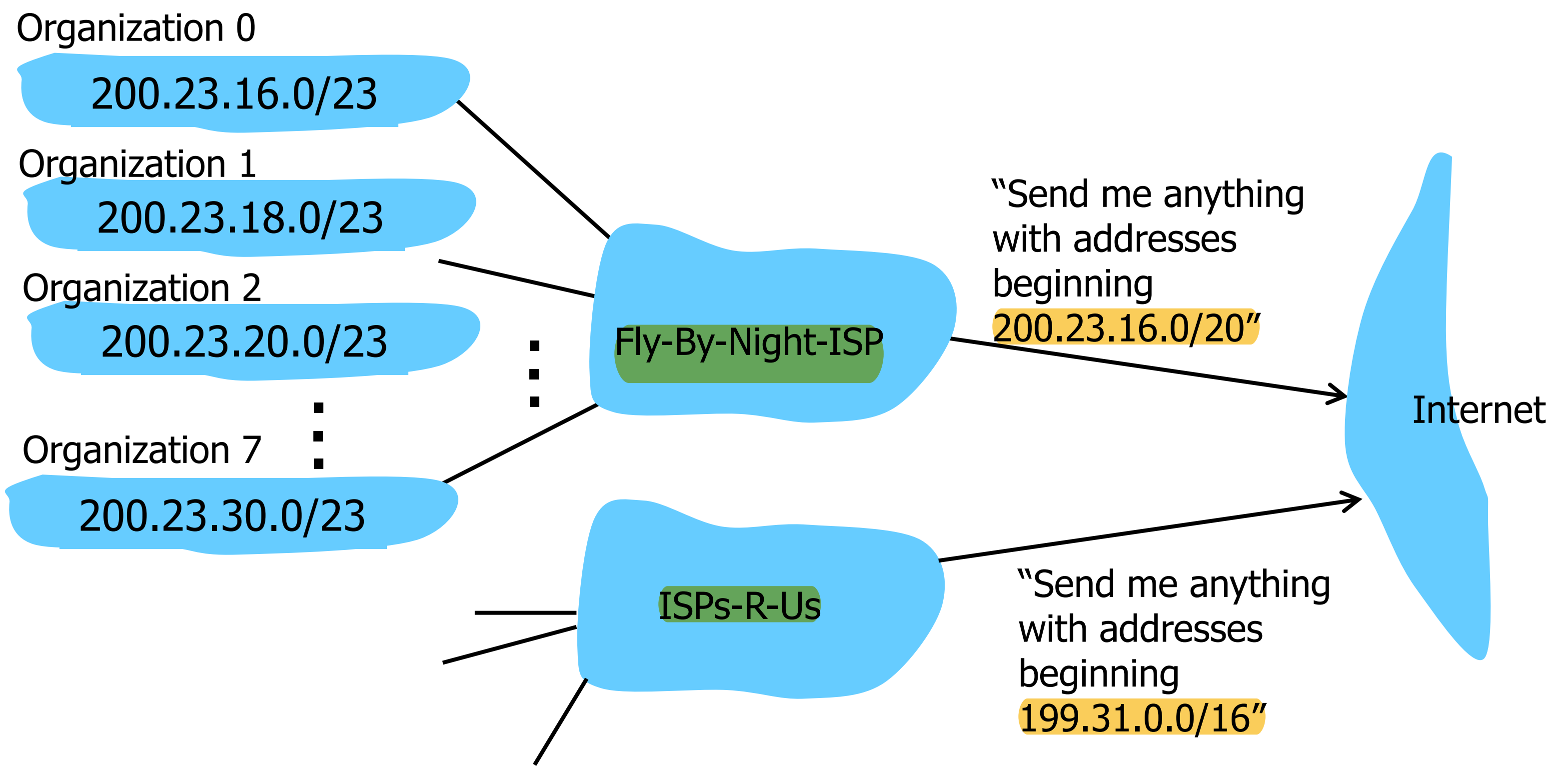
<u>Q:</u> How does *network* get subnet part of IP address?

<u>A:</u> Gets allocated portion of its provider ISP's address space

ISP's block	<u>11001000 00010111 0001</u>0000	00000000	200.23.16.0/20
Organization 0	<u>11001000 00010111 0001000</u>0	00000000	200.23.16.0/23
Organization 1	<u>11001000 00010111 0001001</u>0	00000000	200.23.18.0/23
Organization 2	<u>11001000 00010111 0001010</u>0	00000000	200.23.20.0/23
...	…..	….	….
Organization 7	<u>11001000 00010111 0001111</u>0	00000000	200.23.30.0/23

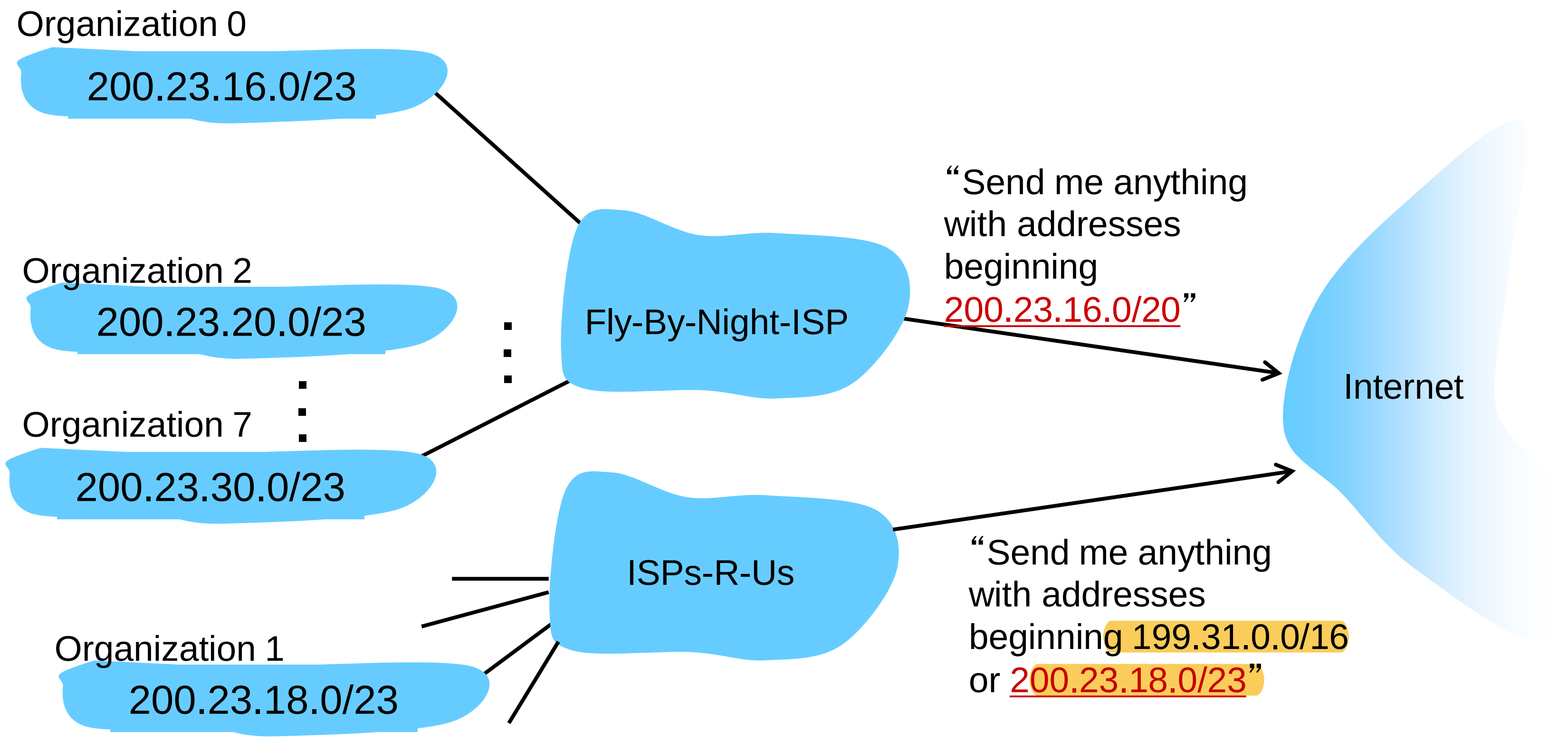
Hierarchical addressing: Route Aggregation

- ISP has an address block; it can further divide this block into sub-blocks and assign them to subscriber organizations.
- Hierarchical addressing allows efficient advertisement of routing information:



Hierarchical Addressing: more specific routes

ISPs-R-Us has a more specific route to Organization 1



Forwarding: Longest prefix matching

Prefix Match	Link Interface
11001000 00010111 00010	0
11001000 00010111 00011000	1
11001000 00010111 00011	2
otherwise	3

Examples

DA: 11001000 00010111 00010110 10100001 **Which interface?**

DA: 11001000 00010111 00011000 10101010 **Which interface?**

IP addressing: the last word...

Q: How does an ISP get block of addresses?

A: ICANN: Internet Corporation for Assigned Names and Numbers

- allocates addresses
- manages DNS
- assigns domain names, resolves disputes

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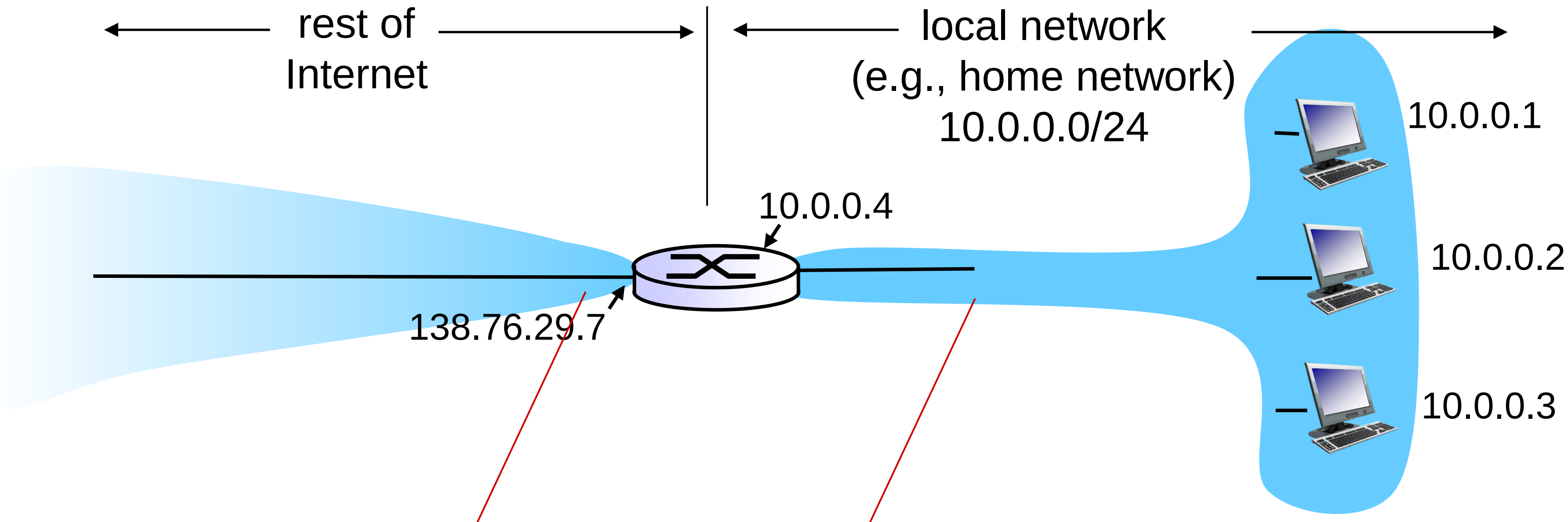
NAT: network address translation



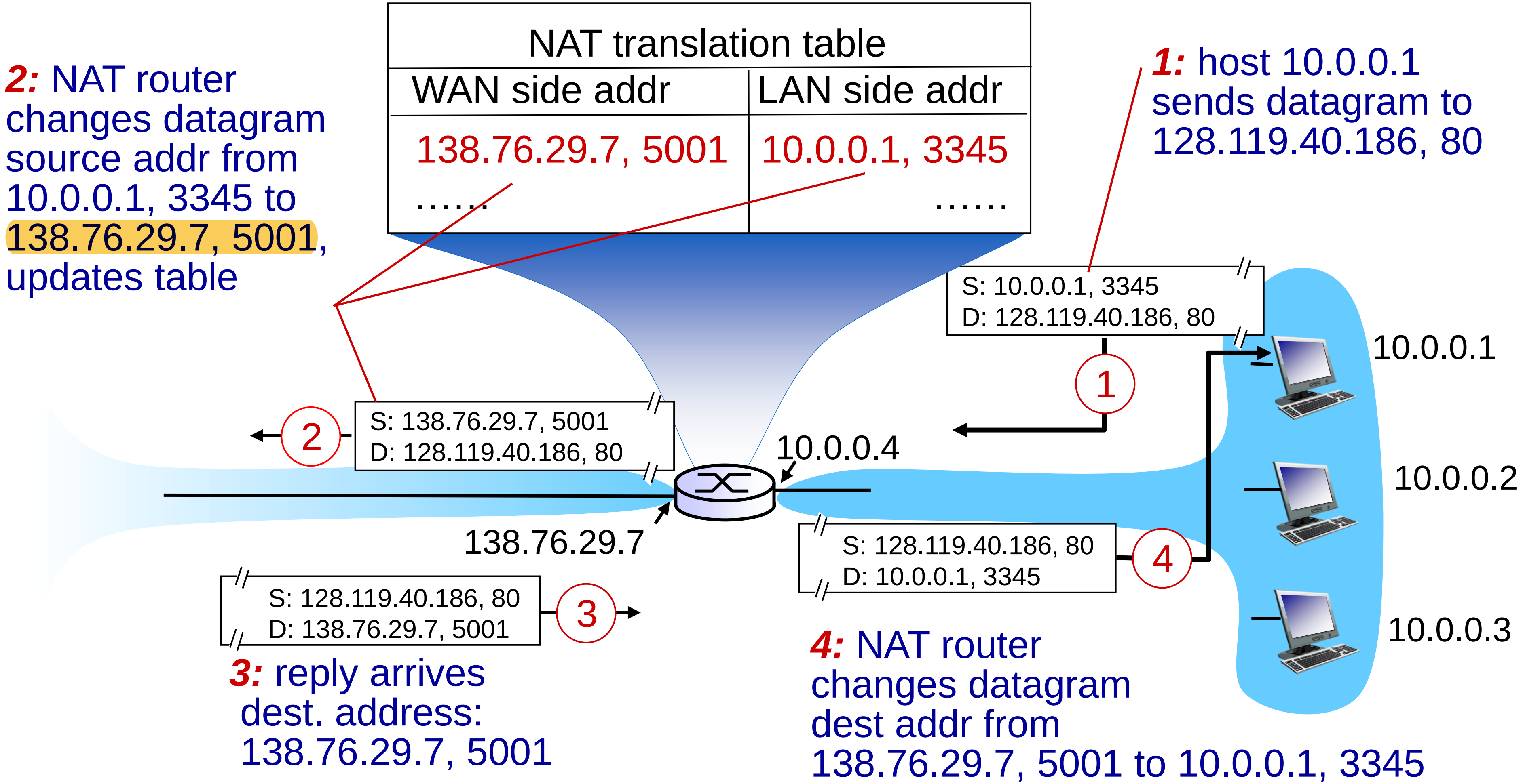
all datagrams *leaving* local network have *same* single source NAT IP address: 138.76.29.7,different source port numbers

datagrams with source or destination in this network have 10.0.0.0/24 address for source, destination (as usual)

NAT: Network Address Translation

- Motivation: local network uses just one IP address as far as outside word is concerned:
  - no need to be allocated range of addresses from ISP: just one IP address is used for all devices
  - can change addresses of devices in local network without notifying outside world
  - can change ISP without changing addresses of devices in local network
  - devices inside local net not explicitly addressable and invisible by outside world (a security plus)

NAT: network address translation



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

NAT: Network Address Translation

- 16-bit port-number field:
  - 60,000 simultaneous connections with a single WAN-side address!
- NAT is controversial:
  - routers should only process up to layer 3
  - address shortage should be solved by IPv6
  - violates end-to-end argument
    - NAT possibility must be taken into account by app designers, e.g., P2P applications
  - NAT traversal: what if client wants to connect to server behind NAT?

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IPv6: motivation

- *initial motivation:* 32-bit address space soon to be completely allocated. (actually, all already allocated)
- additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS

IPv6 datagram format:

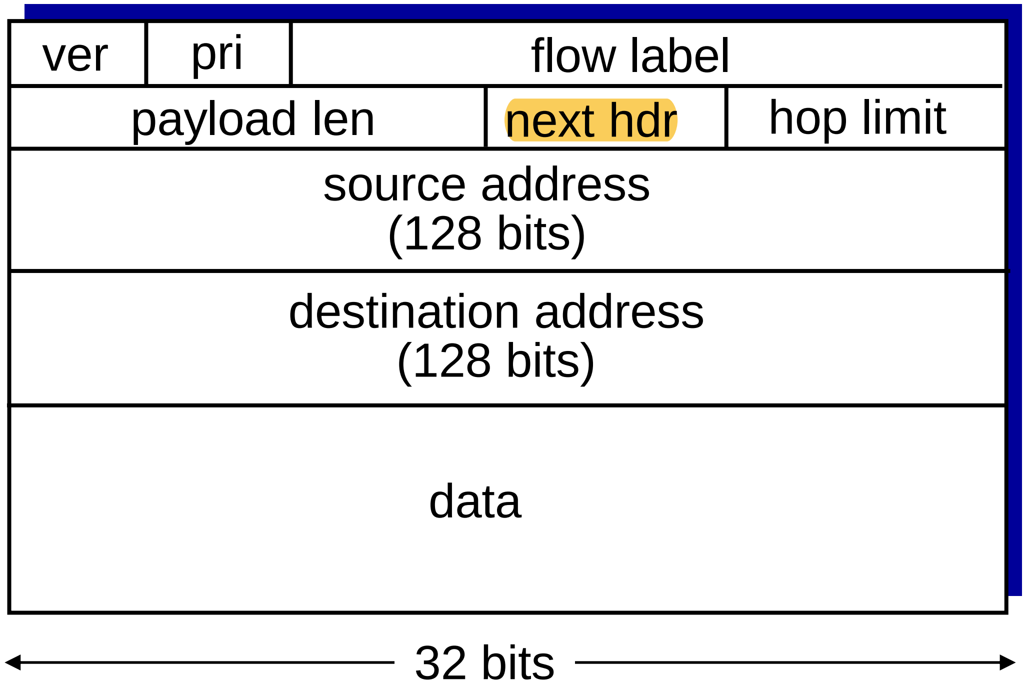
- fixed-length 40 byte header
- no fragmentation allowed

IPv6 datagram format

priority: identify priority among datagrams in flow

flow Label: identify datagrams in same "flow."
(concept of"flow" not well defined).

next header: identify upper layer protocol for data



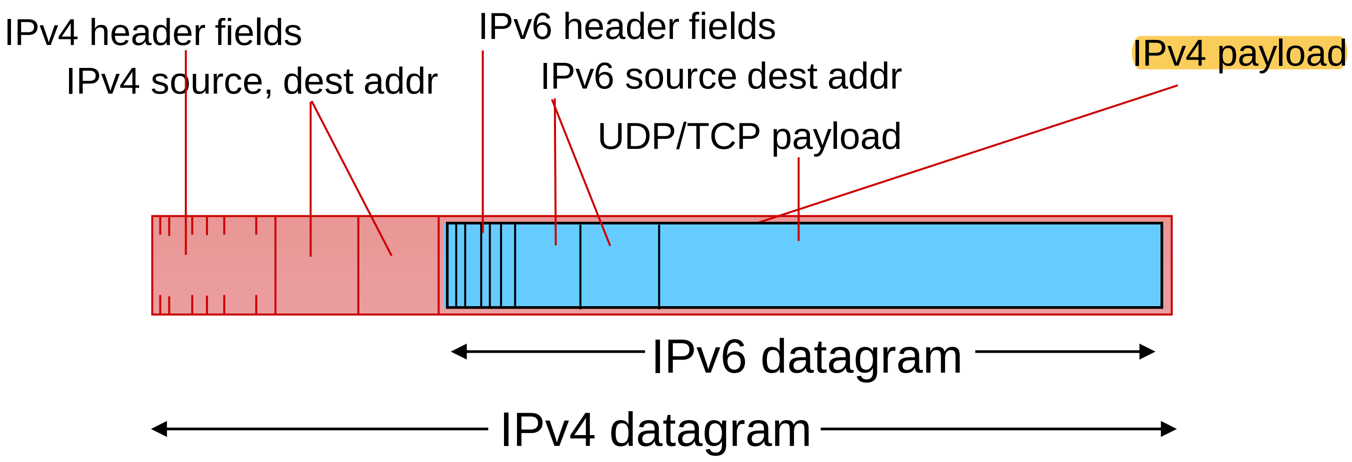
Other changes from IPv4

- *checksum*: removed entirely to reduce processing time at each hop
- *options:* allowed, but outside of header, indicated by "Next Header" field
- *ICMPv6:* new version of ICMP
  - additional message types, e.g. "Packet Too Big"
  - multicast group management functions

IPV6 VS IPV4
32 bits vs 128 bits
- no check sum

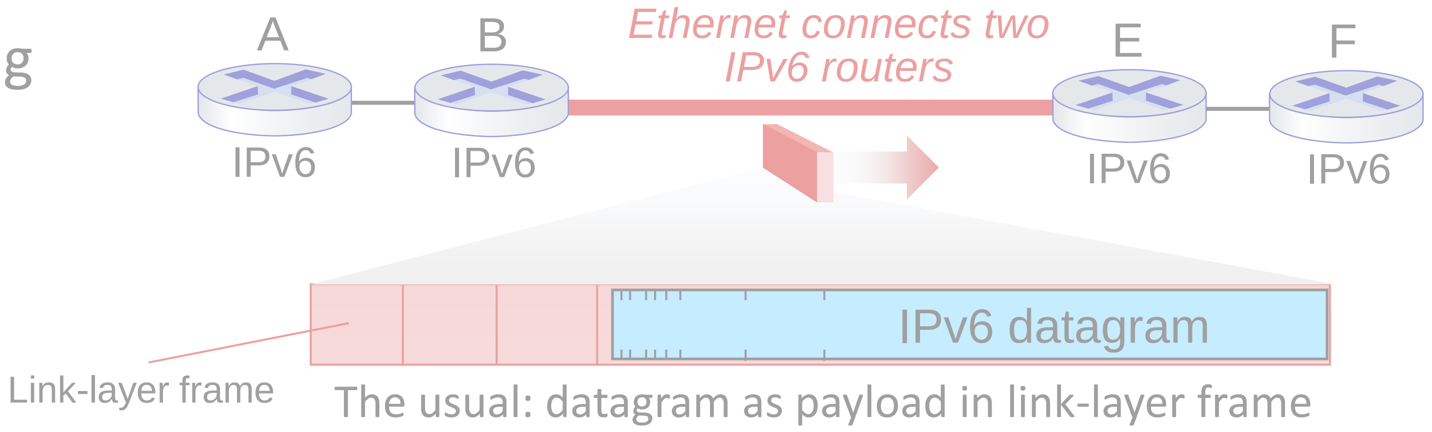
Transition from IPv4 to IPv6

- not all routers can be upgraded simultaneously
  - no "flag days"
  - how will network operate with mixed IPv4 and IPv6 routers?
- *tunneling:* IPv6 datagram carried as *payload* in IPv4 datagram among IPv4 routers

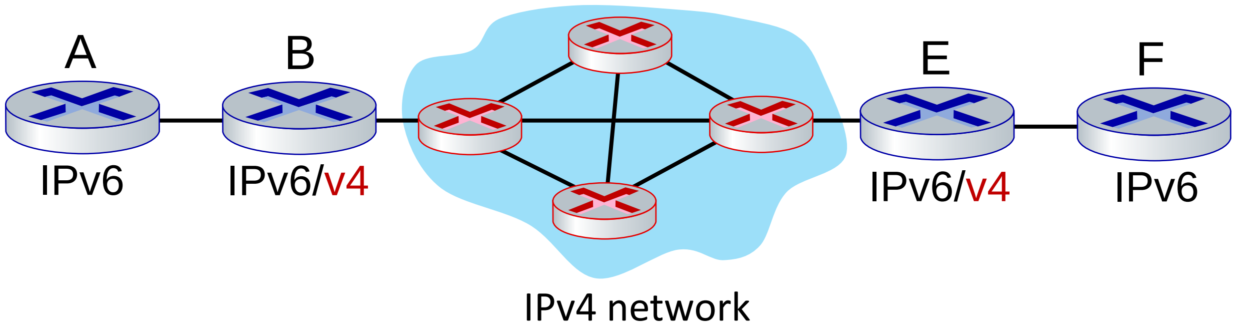


Tunneling and encapsulation

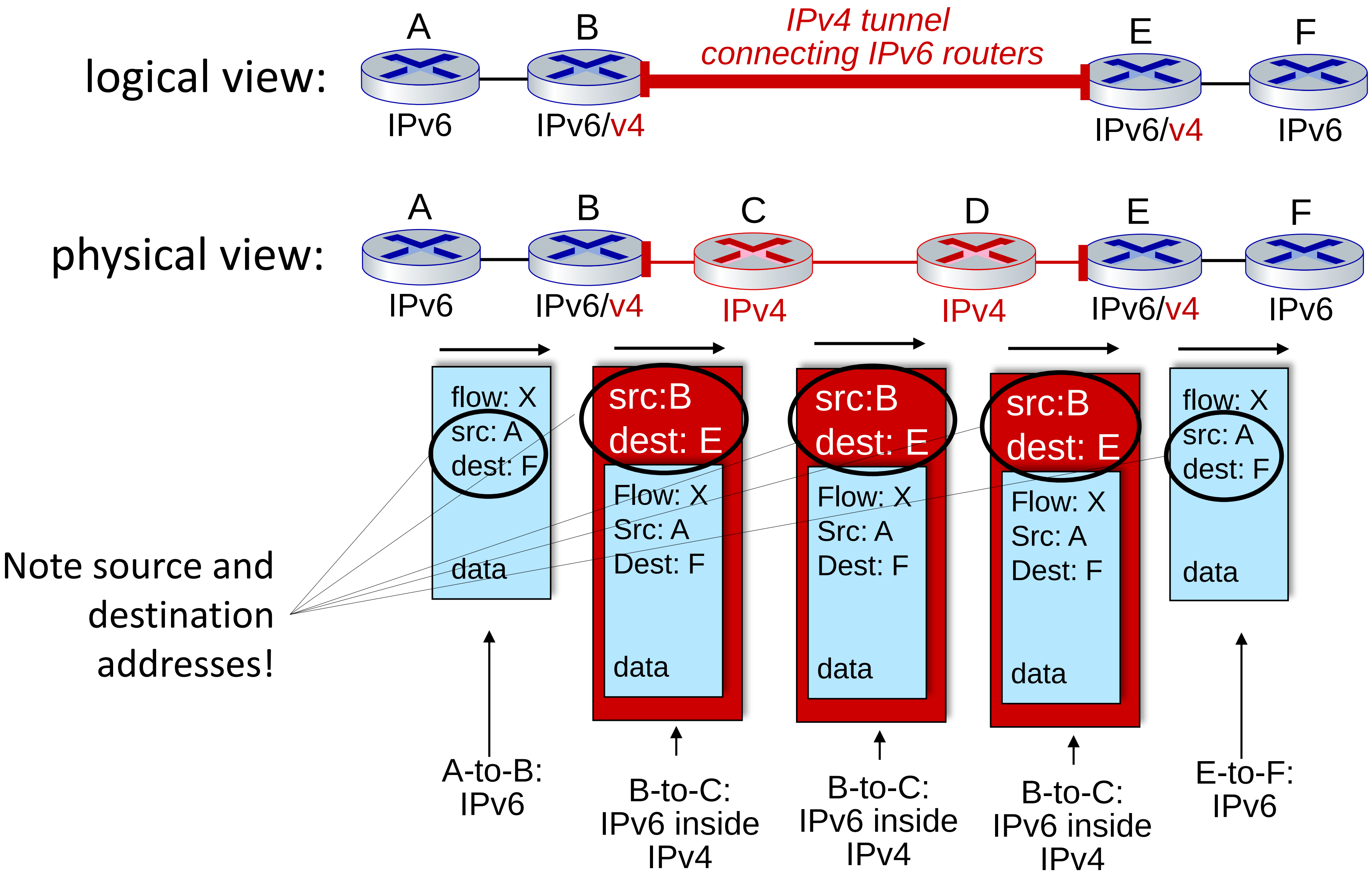
Ethernet connecting two IPv6 routers:



IPv4 network connecting two IPv6 routers



Tunneling



logical view:
A
B
IPv4 tunnel
connecting IPv6 routers
E
F
IPv6
IPv6/v4
IPv6/v4
IPv6
physical view:
A
B
C
D
E
F
IPv6
IPv6/v4
IPv4
IPv4
IPv6/v4
IPv6
flow: X
src: A
dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
flow: X
src: A
dest: F
data
Note source and destination addresses!
A-to-B: IPv6
B-to-C: IPv6 inside IPv4
B-to-C: IPv6 inside IPv4
B-to-C: IPv6 inside IPv4
E-to-F: IPv6

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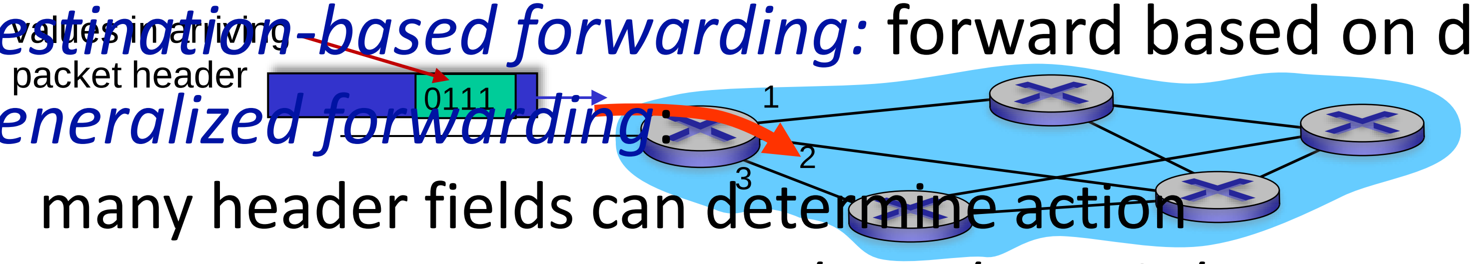
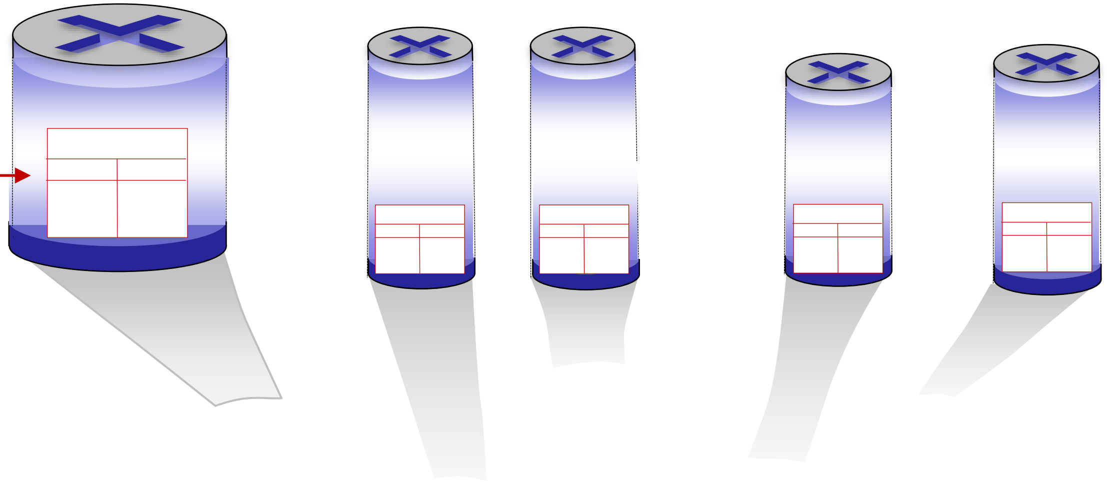
Generalized forwarding: match plus action

Review: each router contains a forwarding table (aka: flow table)

- "match plus action" abstraction: match bits in arriving packet, take action
  - *destination-based forwarding:* forward based on dest. IP address
  - *generalized forwarding:*
    - many header fields can determine action
    - many action possible: drop/copy/modify/log packet

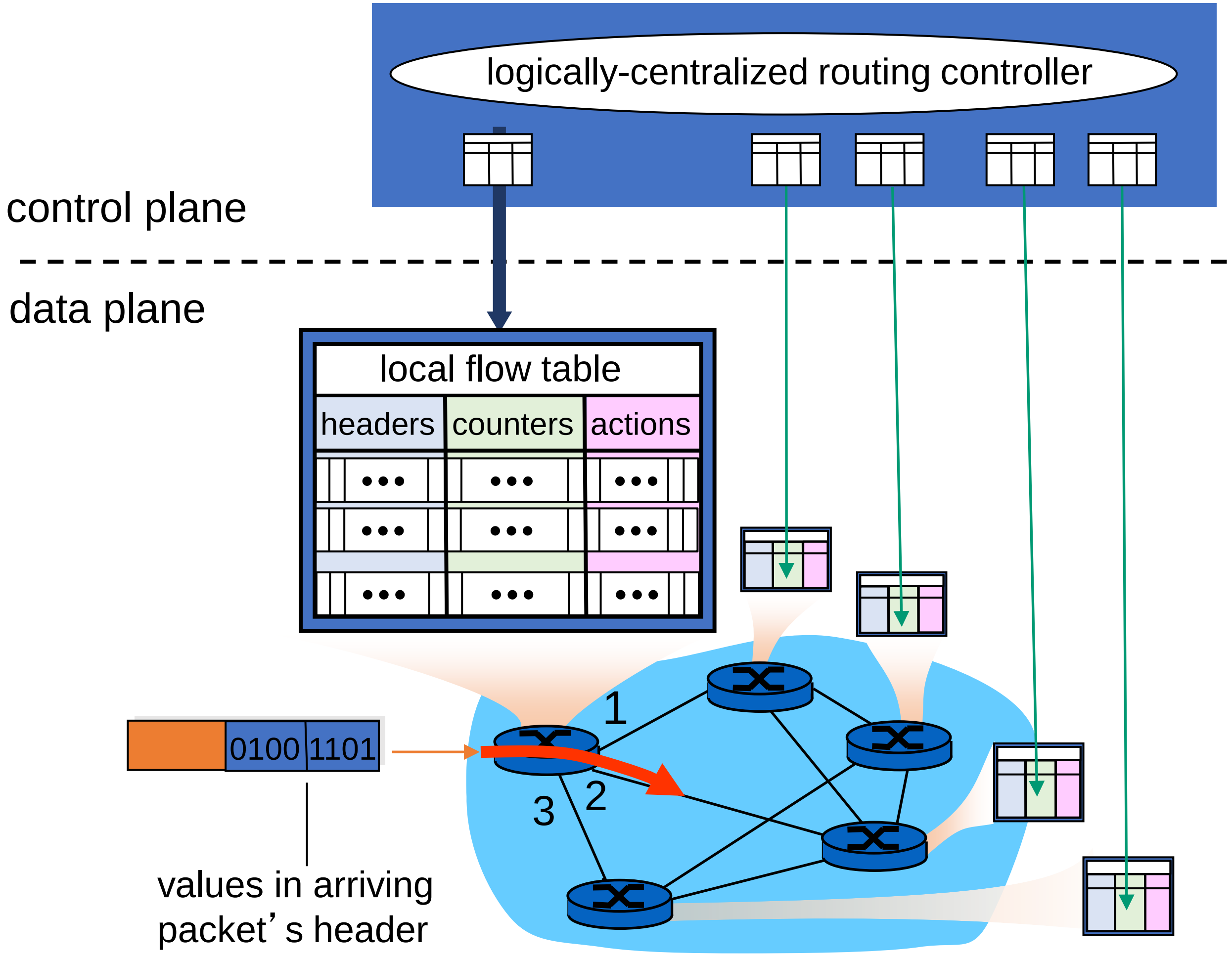


forwarding table
(aka: flow table)



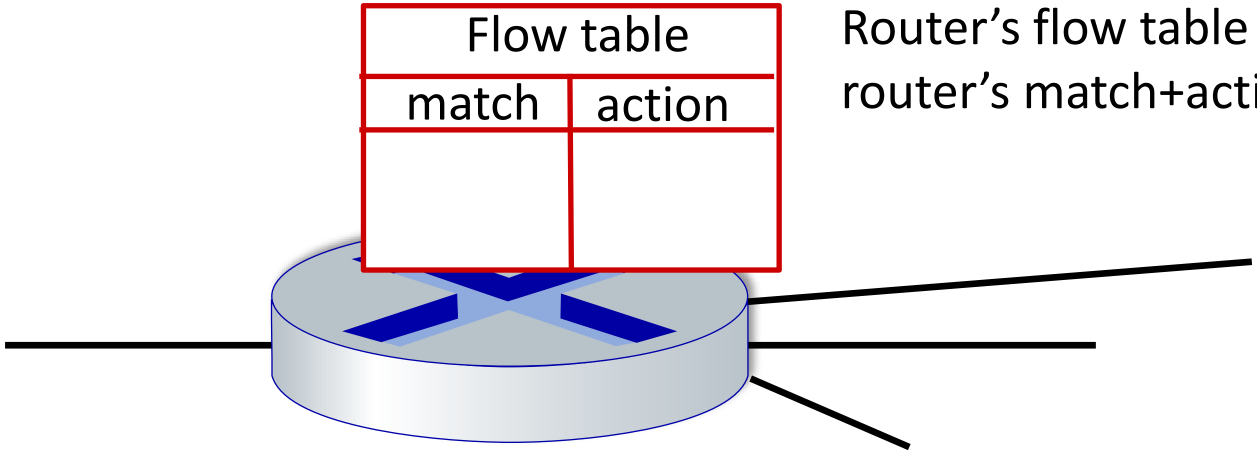
Generalized Forwarding and SDN

Each router contains a *flow table* that is computed and distributed by a *logically centralized* routing controller



OpenFlow data plane abstraction

- *flow*: defined by header fields
- generalized forwarding: simple packet-handling rules
  - *Pattern:* match values in packet header fields
  - *Actions: for matched packet:* drop, forward modify matched packet or send matched packet to controller
  - *Counters:* #bytes and #packets, and time since the table entry was last updated.



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

OpenFlow data plane abstraction

- *flow*: defined by header fields
- generalized forwarding: simple packet-handling rules
  - *Pattern:* match values in packet header fields
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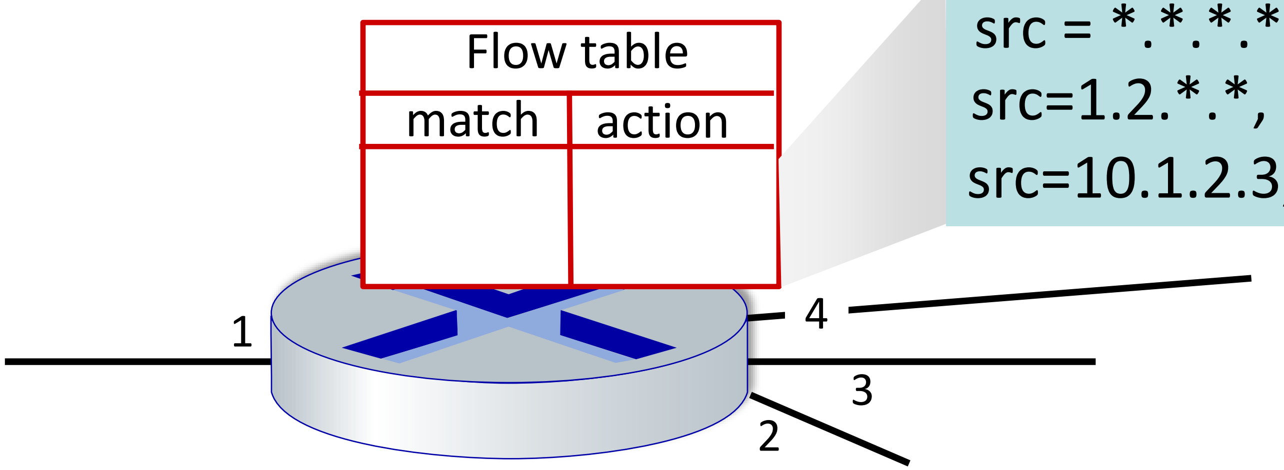
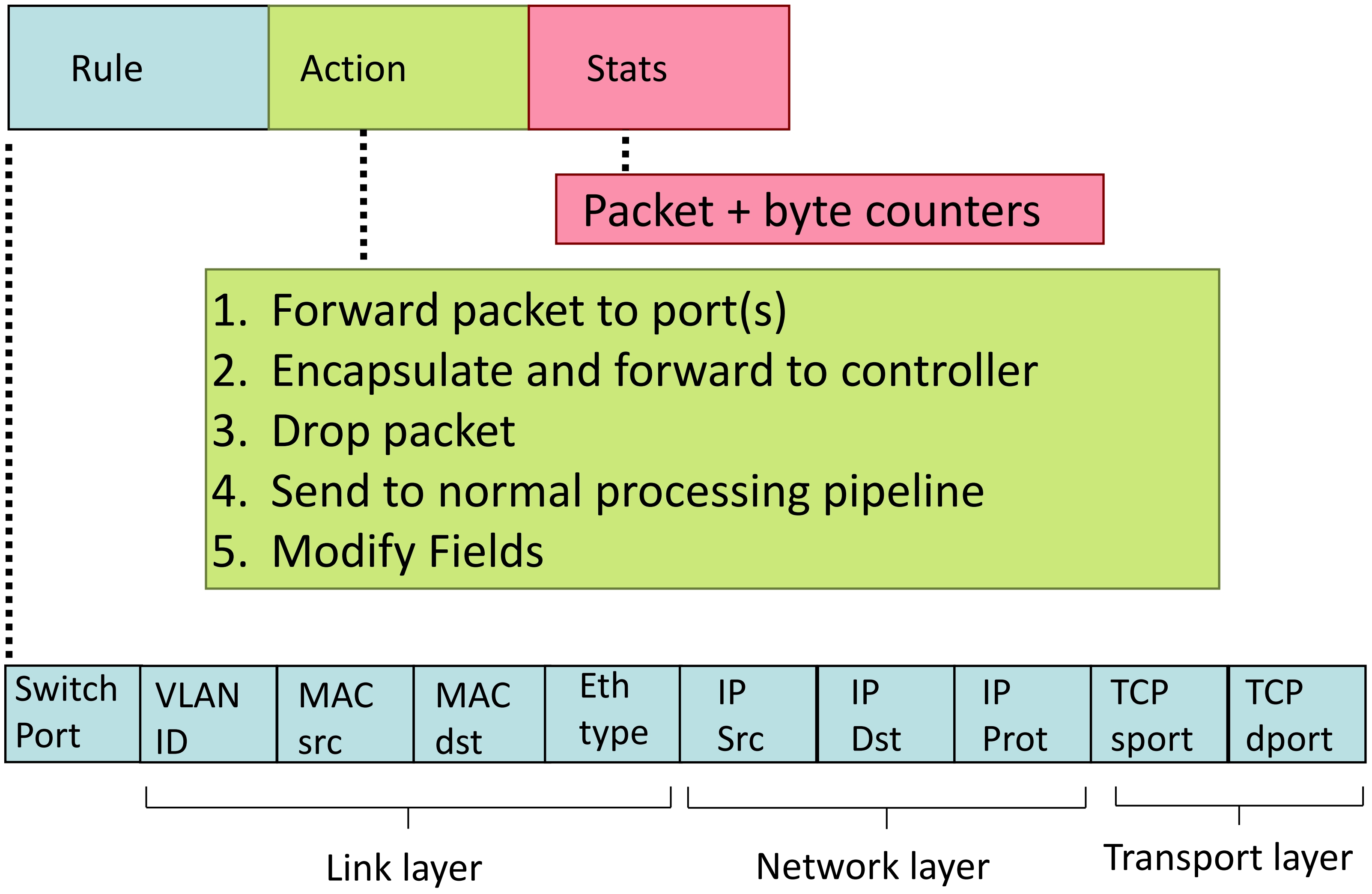


src = *.*.*.*, dest=3.4.*.*	forward(2)
src=1.2.*.*, dest=*.*.*.*	drop
src=10.1.2.3, dest=*.*.*.*	send to controller

* : wildcard

OpenFlow: Flow Table Entries



Examples

Destination-based forwarding:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	*	*	*	*	*	51.6.0.8	*	*	*	port6

IP datagrams destined to IP address 51.6.0.8 should be forwarded to router output port 6

Firewall:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Forward
*	*	*	*	*	*	*	*	*	22	drop

do not forward (block) all datagrams destined to TCP port 22

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Forward
*	*	*	*	*	128.119.1.1	*	*	*	*	drop

do not forward (block) all datagrams sent by host 128.119.1.1

Examples

Destination-based layer 2 (switch) forwarding:

Switch Port	MAC src	MAC dst	Eth type	VLAN ID	IP Src	IP Dst	IP Prot	TCP sport	TCP dport	Action
*	22:A7:23: 11:E1:02	*	*	*	*	*	*	*	*	port3

layer 2 frames from MAC address 22:A7:23:11:E1:02 should be forwarded to output port 3

OpenFlow abstraction

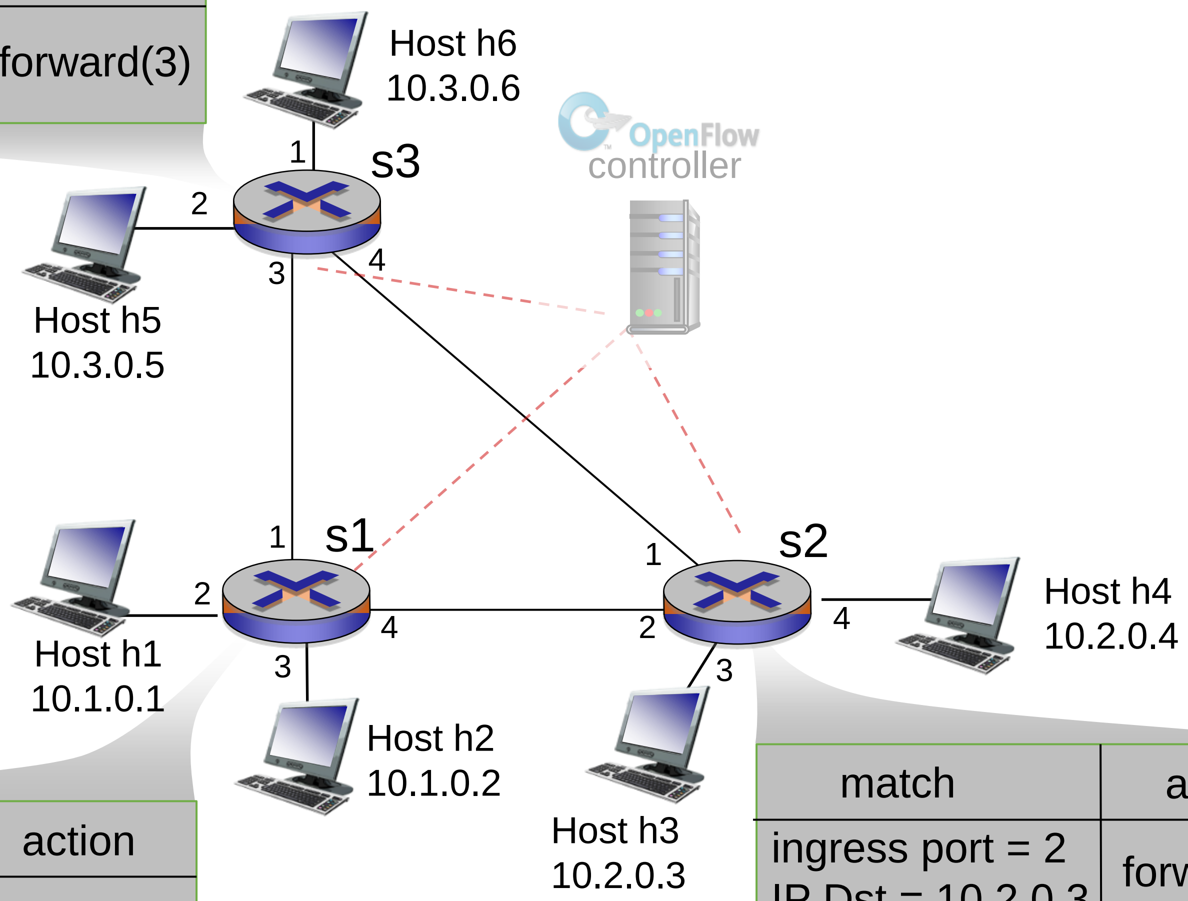
- *match+action:* unifies different kinds of devices

- Router
  - *match:* longest destination IP prefix
  - *action:* forward out a link
- Switch
  - *match:* destination MAC address
  - *action:* forward or flood
- Firewall
  - *match*: IP addresses and TCP/UDP port numbers
  - *action:* permit or deny
- NAT
  - *match:* IP address and port
  - *action:* rewrite address and port

OpenFlow example

Example: datagrams from hosts h5 and h6 should be sent to h3 or h4, via s1 and from there to s2

match	action
IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(3)



match	action
ingress port = 1 IP Src = 10.3.*.* IP Dst = 10.2.*.*	forward(4)

match	action
ingress port = 2 IP Dst = 10.2.0.3	forward(3)
ingress port = 2 IP Dst = 10.2.0.4	forward(4)

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Question: how do forwarding tables (destination-based forwarding) or flow tables (generalized forwarding) computed?

Answer: by the control plane (next chapter)