Chapter 4 Network Layer: The Data Plane

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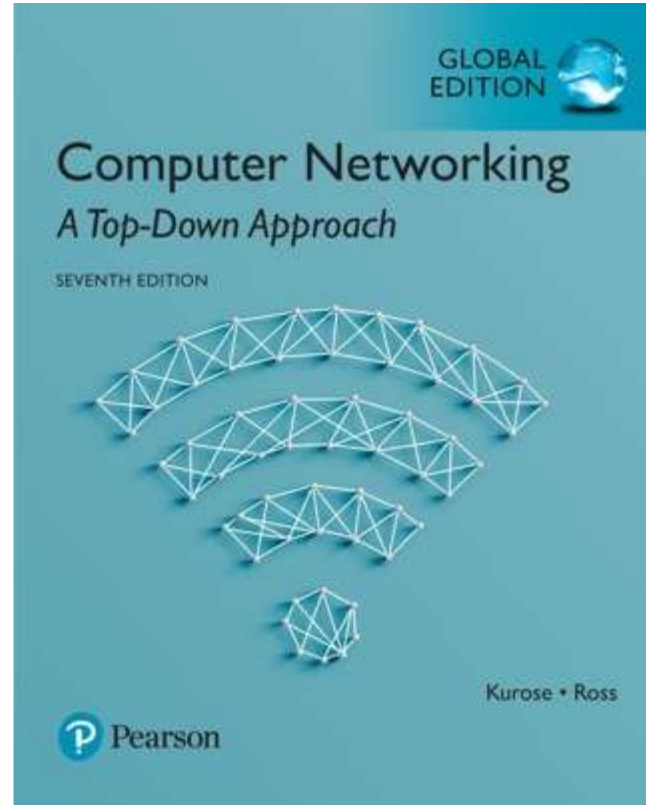


Computer Networking: A Top Down Approach

7th edition
Jim Kurose, Keith Ross
Pearson/Addison Wesley
April 2016

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

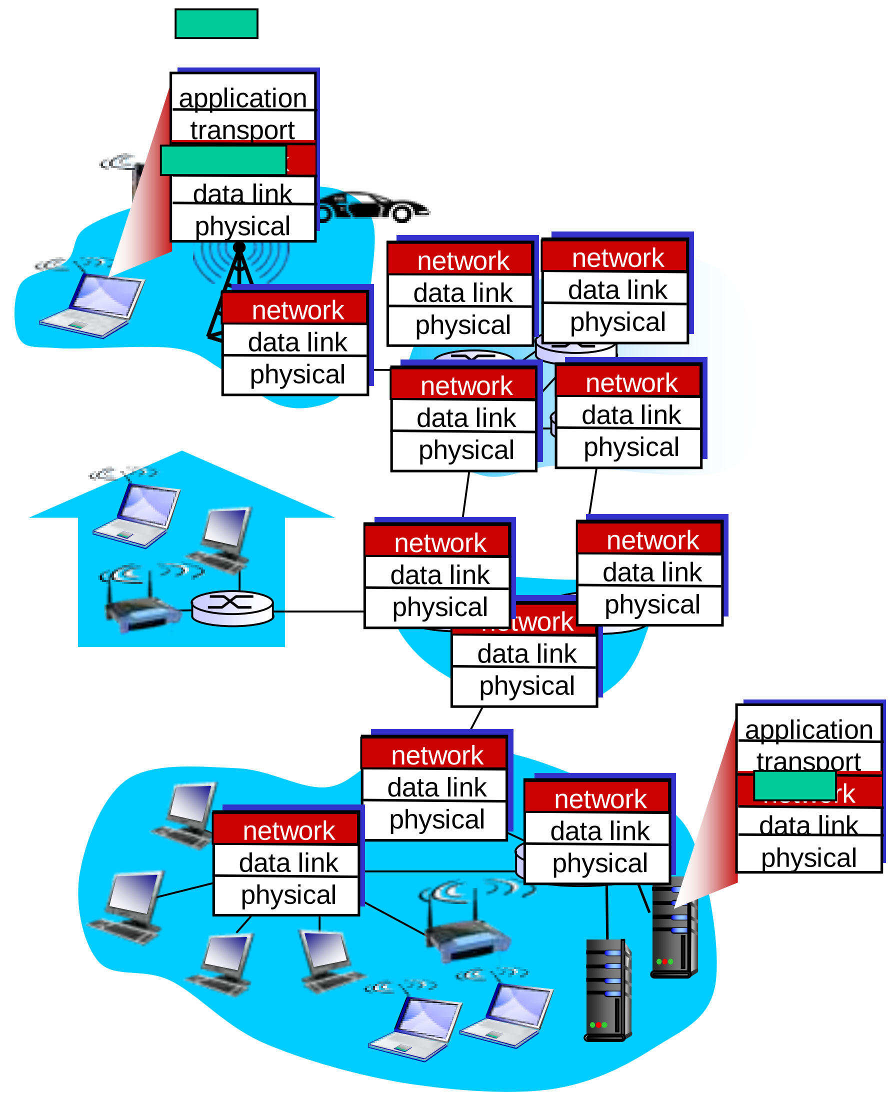
4.2 What's inside a router

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, router
- router examines header fields in all IP datagrams passing through it

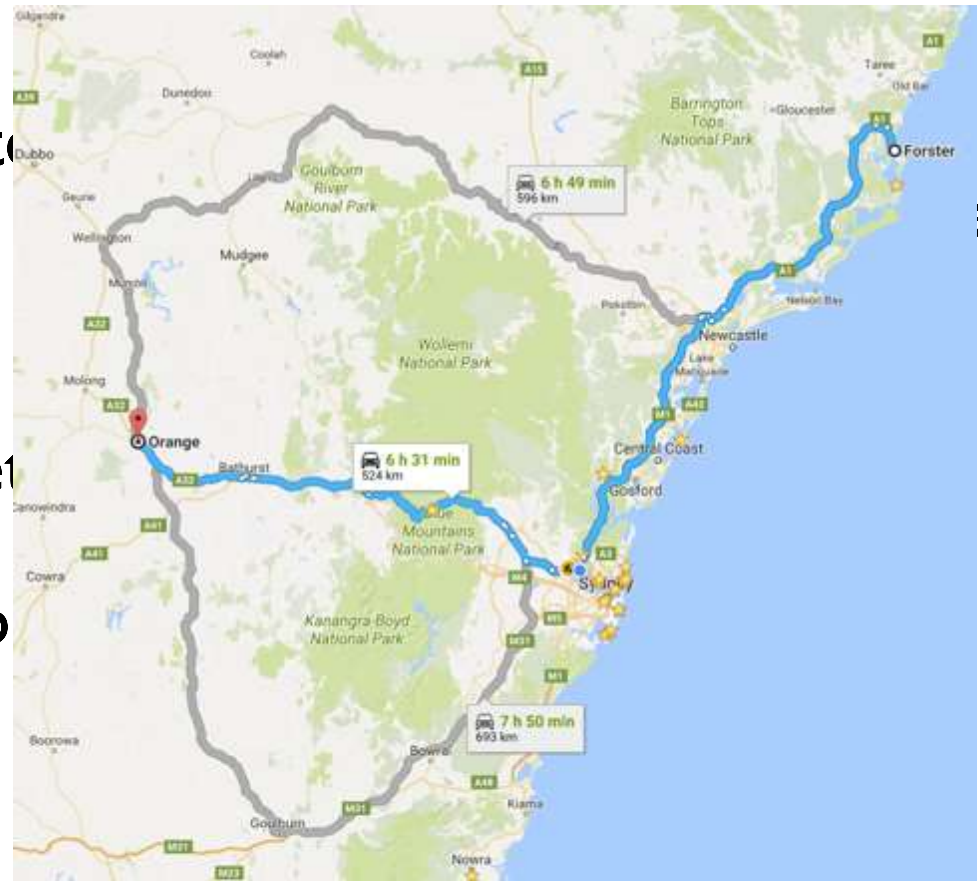


Two key network-layer functions

network-layer functions:

- *routing:* determine rout
taken by packets from e
source to destination
  - *routing algorithms*
- *forwarding:* move packet
from router' s input to
appropriate router outp

Trip: Foster → Orange



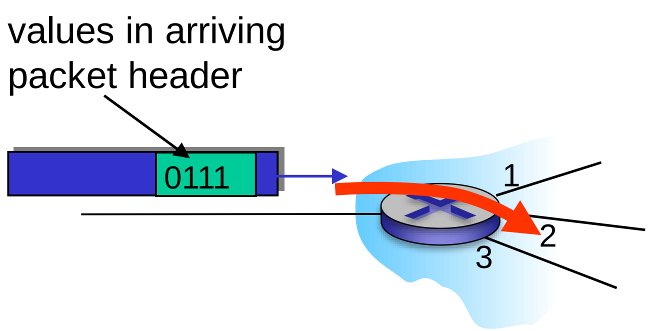
Network layer: data plane, control plane

Control plane

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

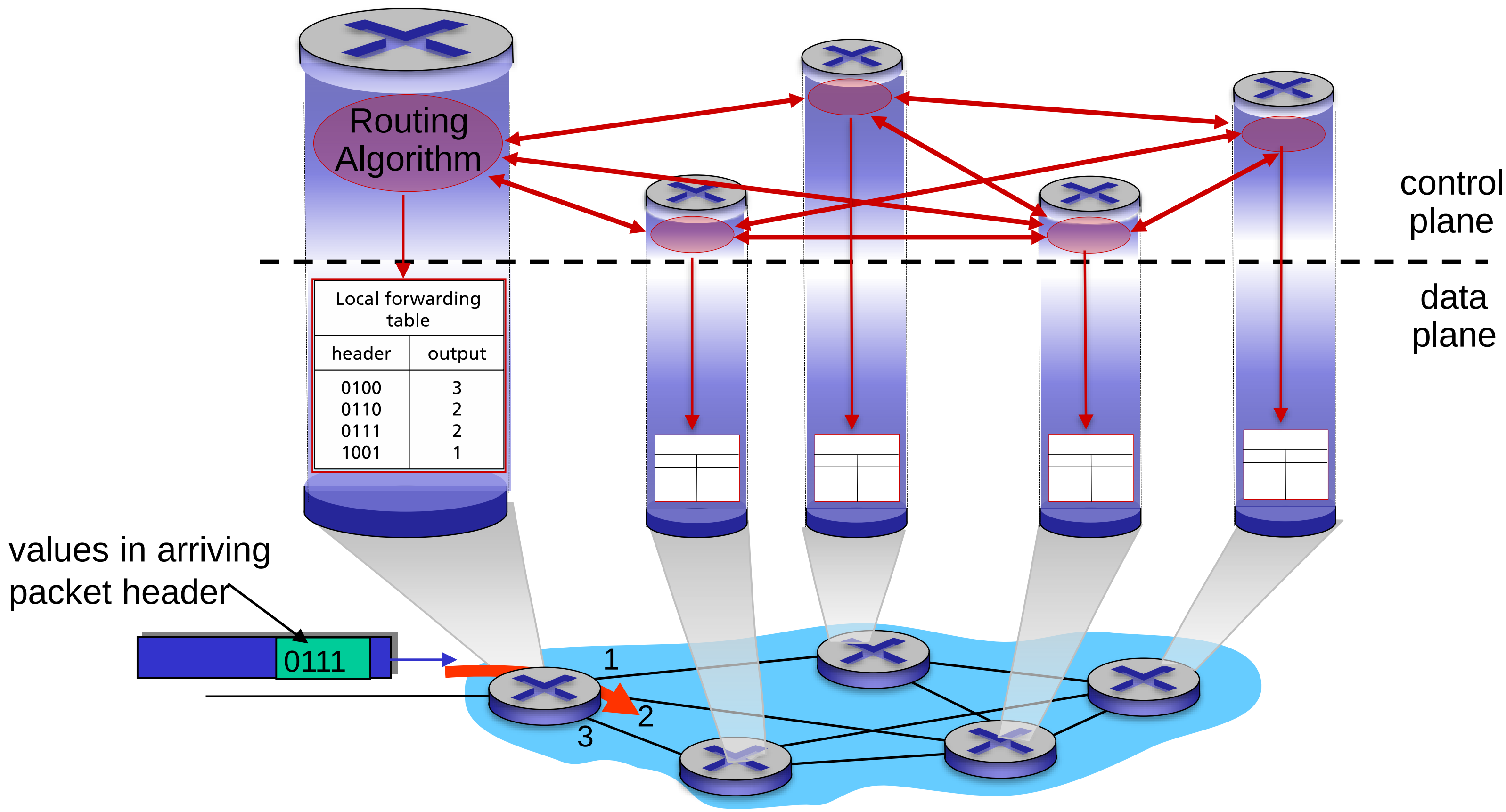
Data plane

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



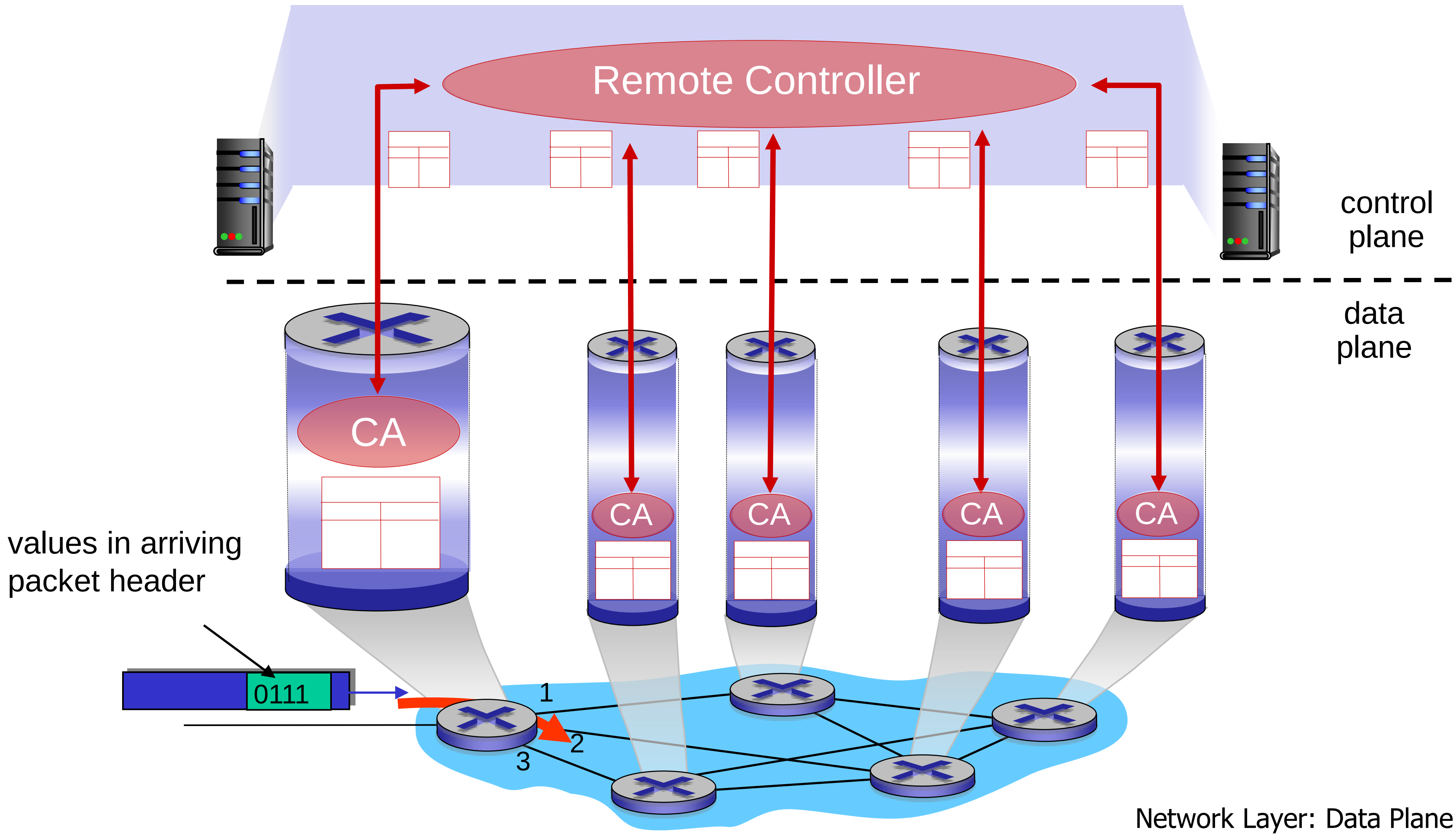
Per-router control plane

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



Logically centralized control plane

A distinct (typically remote) controller interacts with local control agents (CAs)



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 less than 40 msec delay

example services for a flow of datagrams:

- in-order datagram delivery
- guaranteed minimum bandwidth to flow
- restrictions on changes in inter-packet spacing

Network layer service models:

Network Architecture	Service Model	Guarantees ? Bandwidth	Loss	Order	Timing	Congestion feedback
Internet	best effort	none	no	no	no	no (inferred via loss)

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- match
- action
- OpenFlow examples of match-plus-action in action

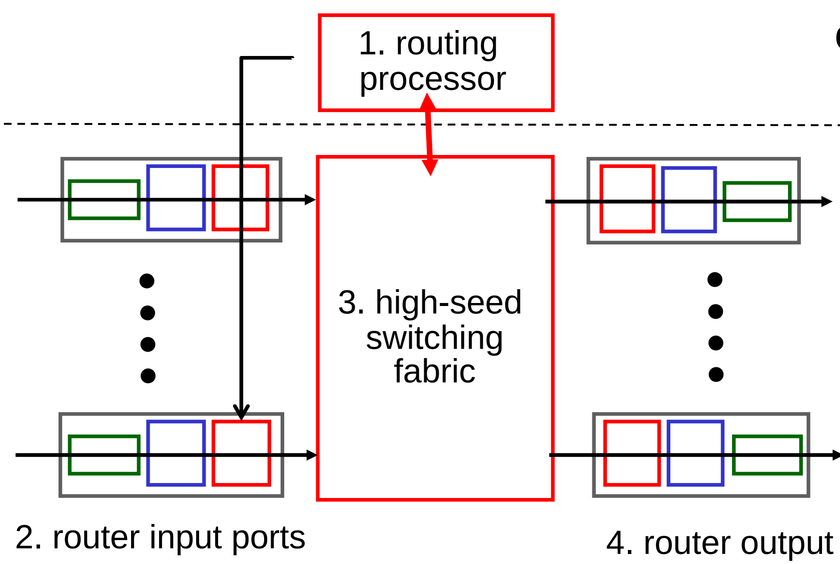
Router architecture overview

- high-level view of generic router architecture:
- Four parts:
  1. routing processor — Software
  2. Input ports
  3. Switching fabrics
  4. Output ports

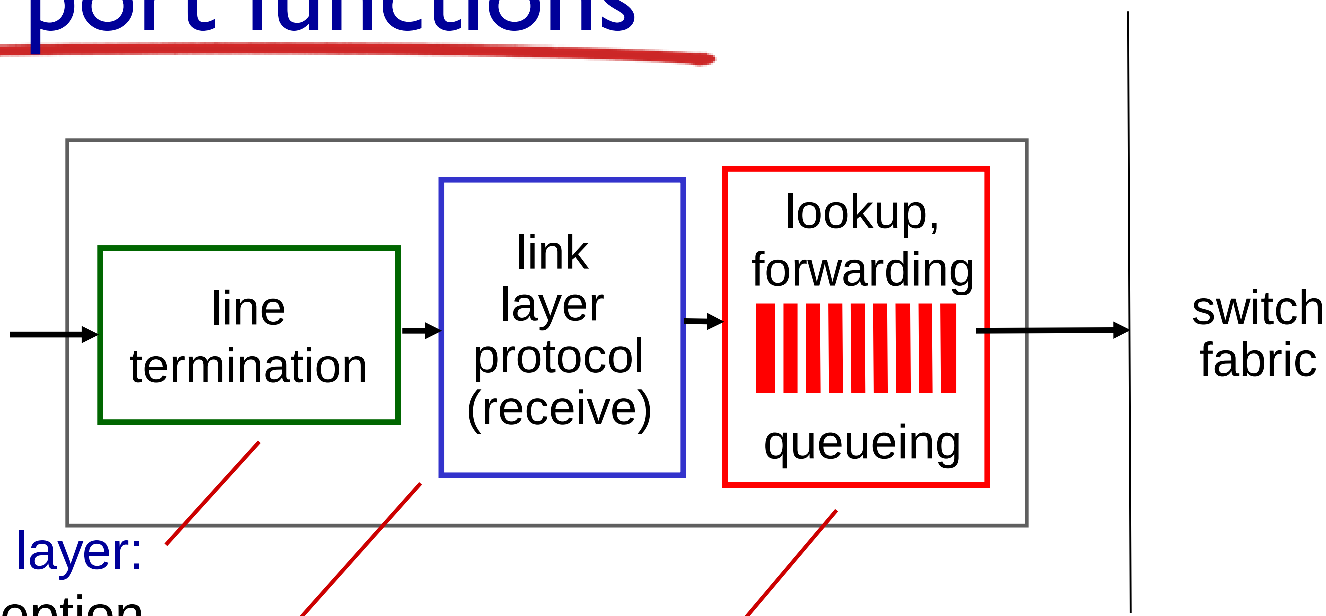
  (parts 2–4: Hardware)

routing, management control plane (<u>software</u>) operates in millisecond time frame

forwarding data plane (<u>hardware</u>) operates in nanosecond timeframe



Input port functions



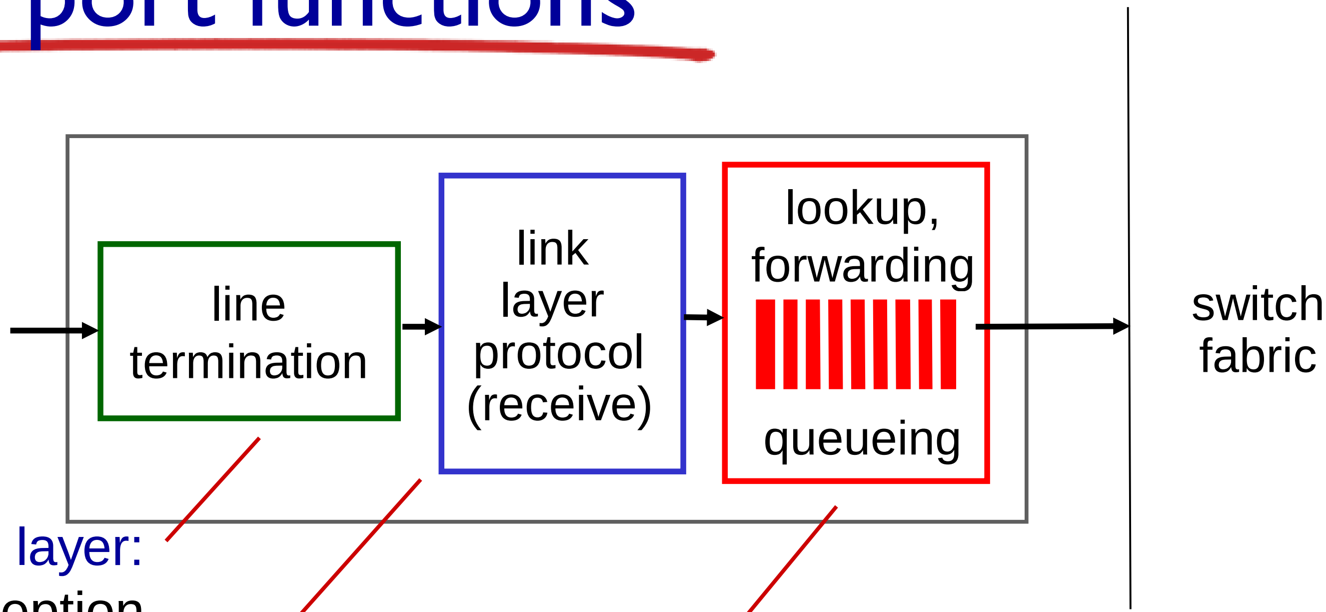
physical layer:
bit-level reception

data link layer:
e.g., Ethernet
see chapter 5

decentralized switching:

- using header field values, <u>lookup</u> 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 into switch fabric

Input port functions



physical layer:
bit-level reception

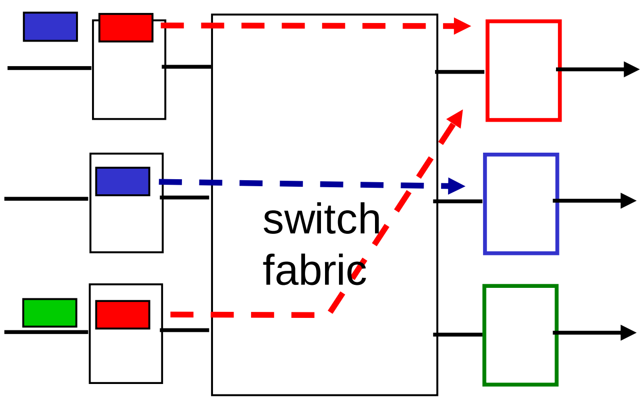
data link layer:
e.g., Ethernet
see chapter 5

decentralized switching:

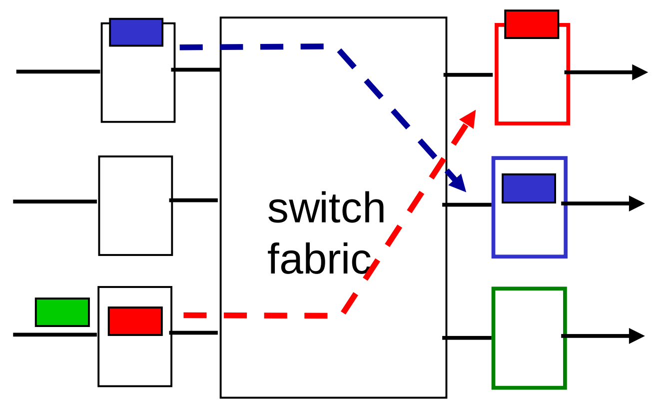
- using header field values, lookup output port using forwarding table in input port memory *("match plus action")*
- *destination-based forwarding:* forward based only on destination IP address (traditional)
- *generalized forwarding (e.g. SDN):* forward based on any set of header field values

Input port queuing

- fabric slower than input ports combined -> queueing may occur at input queues
  - *queueing 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



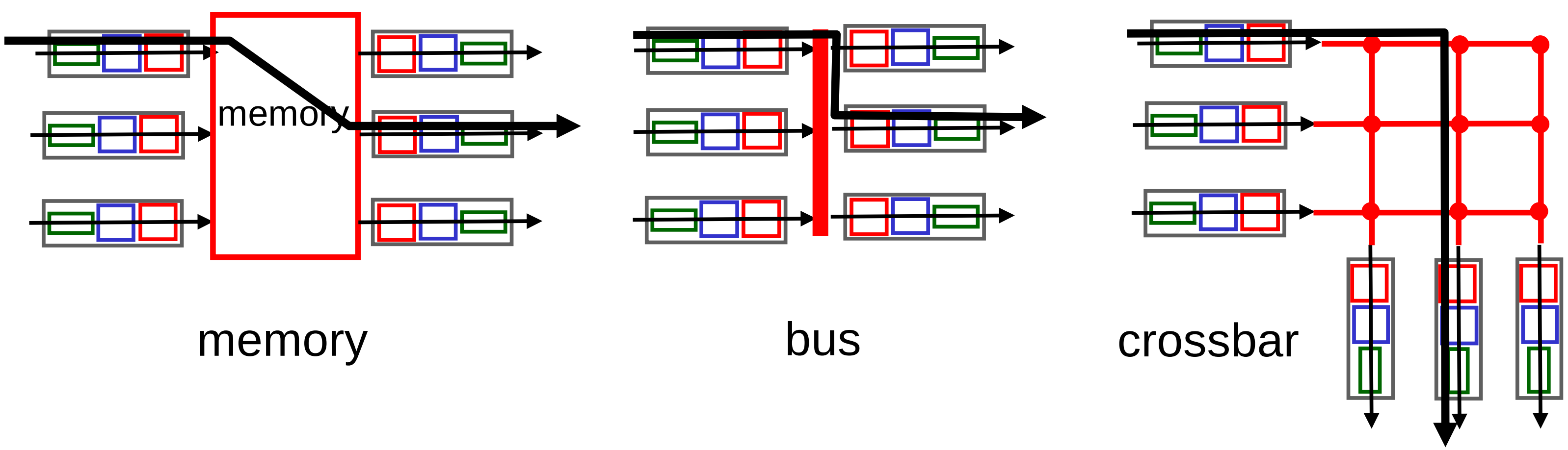
output port contention: only one red datagram can be transferred.
lower red packet is blocked



one packet time later: green packet experiences HOL blocking

Switching fabrics

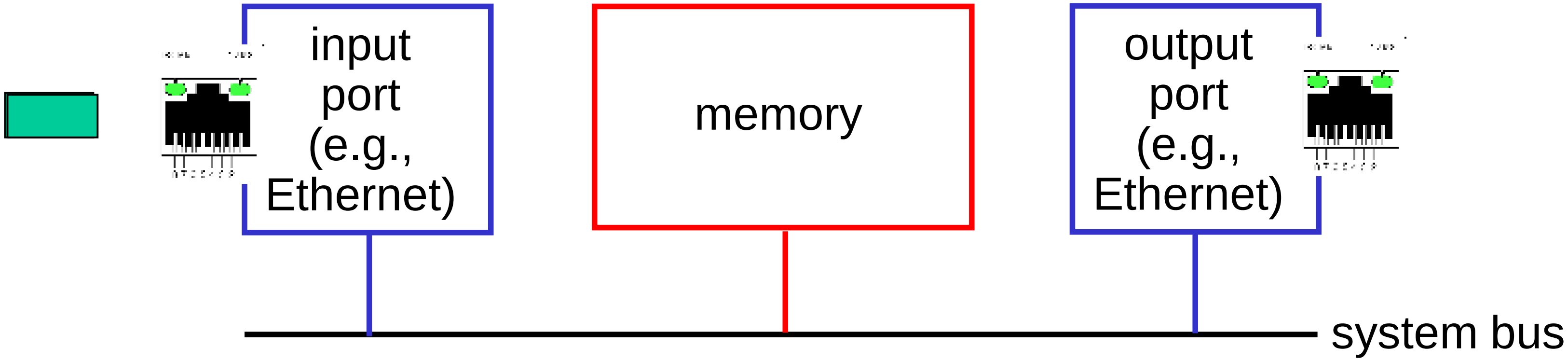
- transfer packet from input buffer to appropriate output buffer
- switching rate: rate at which packets can be transfer from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable
- three types of switching fabrics



Switching via memory

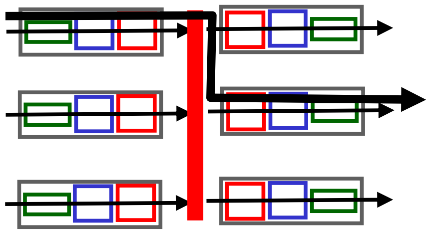
first generation routers:

- traditional computers with switching under direct control of CPU
- packet copied to system's memory
- speed limited by memory bandwidth (2 bus crossings per datagram)



Switching via a bus

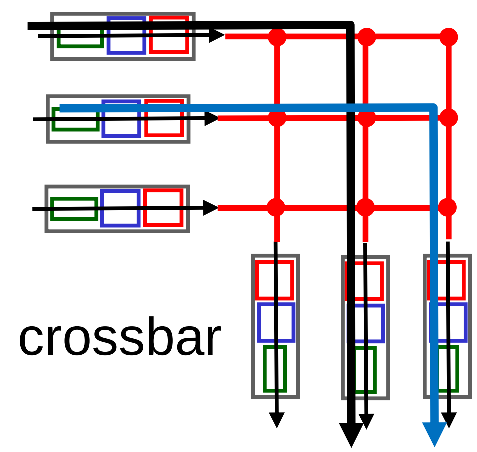
- datagram from input port memory to output port memory via a shared bus
- *bus contention:* switching speed limited by bus bandwidth
- 32 Gbps bus, Cisco 5600: sufficient speed for access and enterprise routers



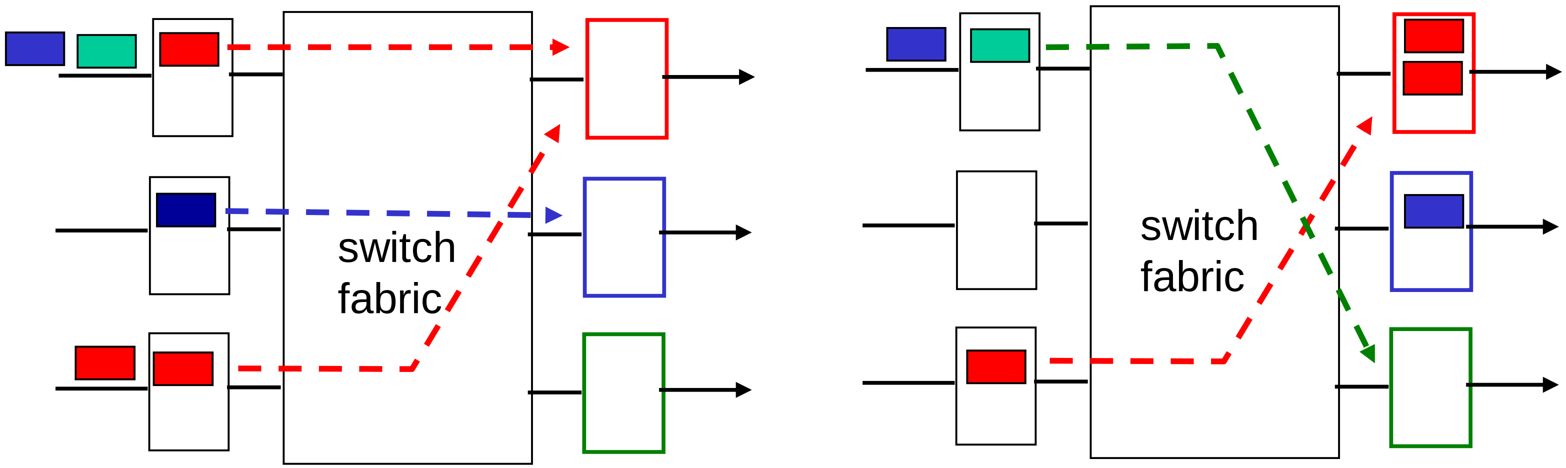
bus

Switching via interconnection network (crossbar)

- overcome bus bandwidth limitations
- banyan networks, crossbar, other interconnection nets initially developed to connect processors in multiprocessor
- advanced design: fragmenting datagram into fixed length cells, switch cells through the fabric.
- Cisco 12000: switches 60 Gbps through the interconnection network



Output port queueing

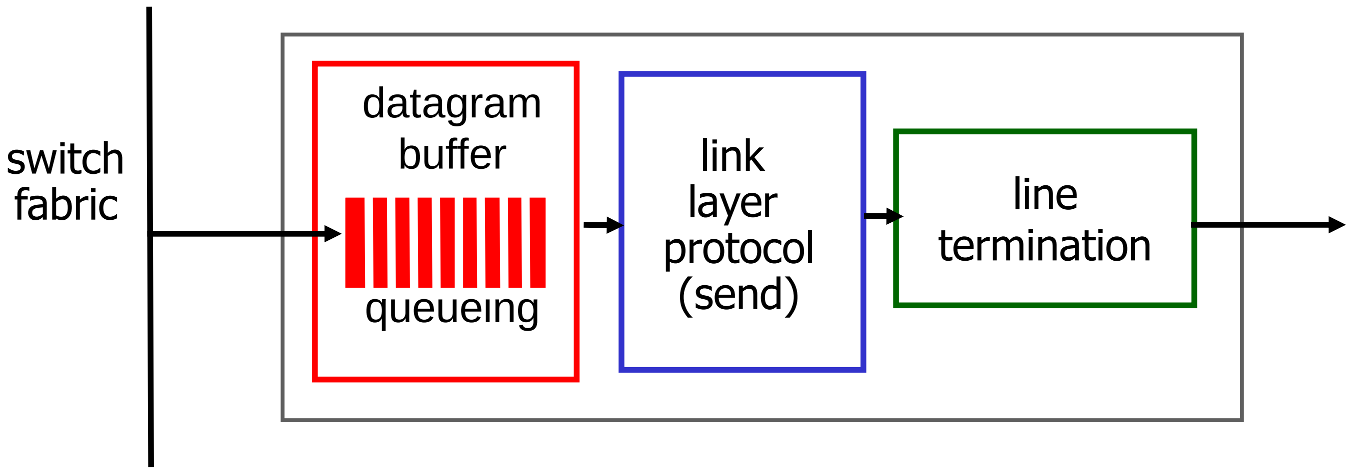


at *t,* packets more from input to output

one packet time later

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

Output ports



- *buffering* required from fabric faster rate
- *scheduling* datagrams

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

Priority scheduling – who gets best performance, network neutrality

How much buffering?

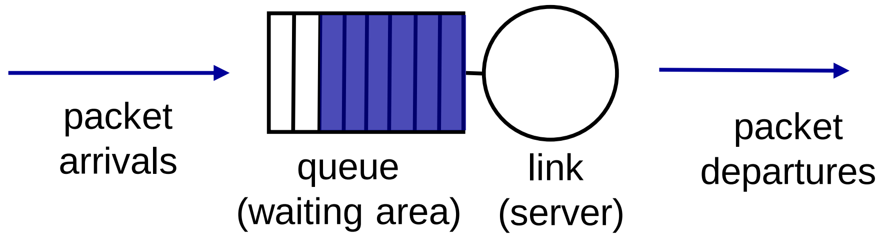
- RFC 3439 rule of thumb: average buffering equal to "typical" RTT (say 250 msec) times link capacity C
  - e.g., C = 10 Gpbs link: 2.5 Gbit buffer
- recent recommendation: with *N* flows, buffering equal to

$$\frac{RTT \cdot C}{\sqrt{N}}$$

Optional – not tested

Scheduling mechanisms

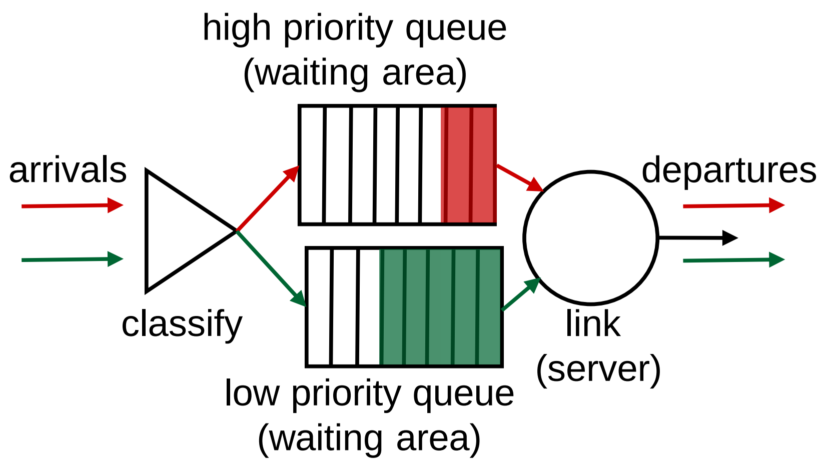
- *scheduling:* choose next packet to send on link
- *FIFO (first in first out) scheduling:* send in order of arrival to queue
  - real-world example?
  - *discard policy:* if packet arrives to full queue: who to discard?
    - *tail drop:* drop arriving packet
    - *priority:* drop/remove on priority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

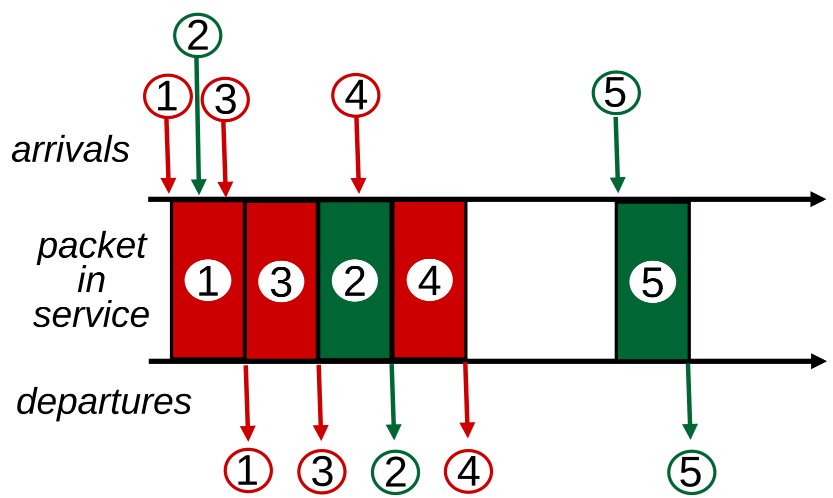


Scheduling policies: priority

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?



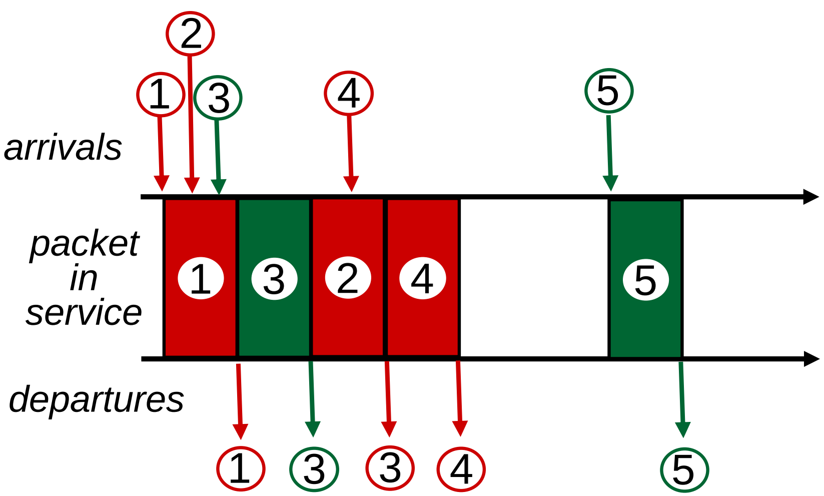


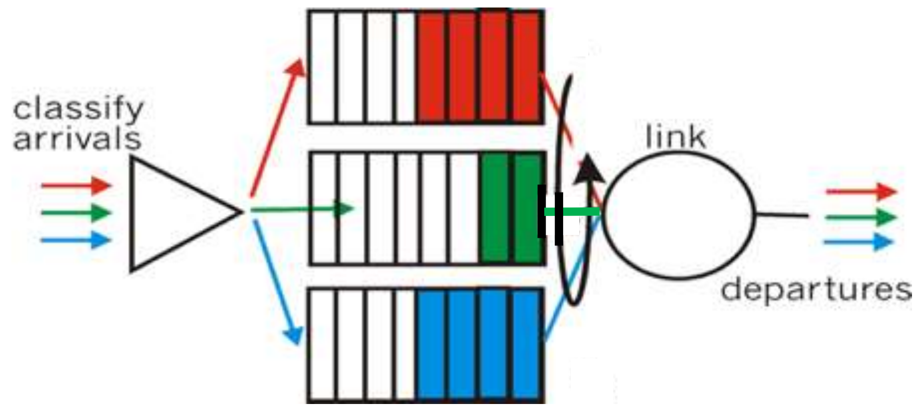
airline:
- first/business class
- economy class

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?





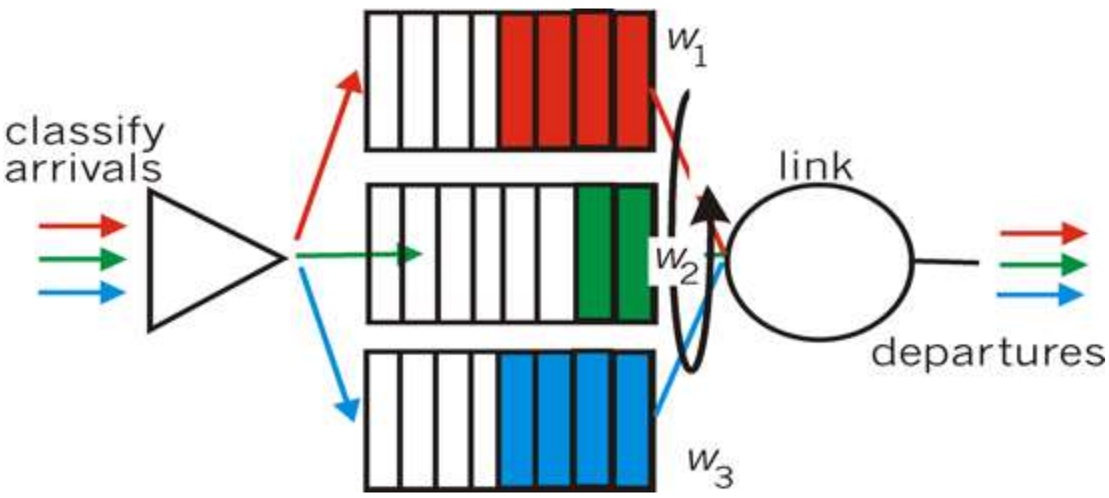
RTA, medicare: true round robin, or?

Scheduling policies: still more

Weighted Fair Queuing (WFQ):

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

RTA, medicare: true round robin, or WFQ?



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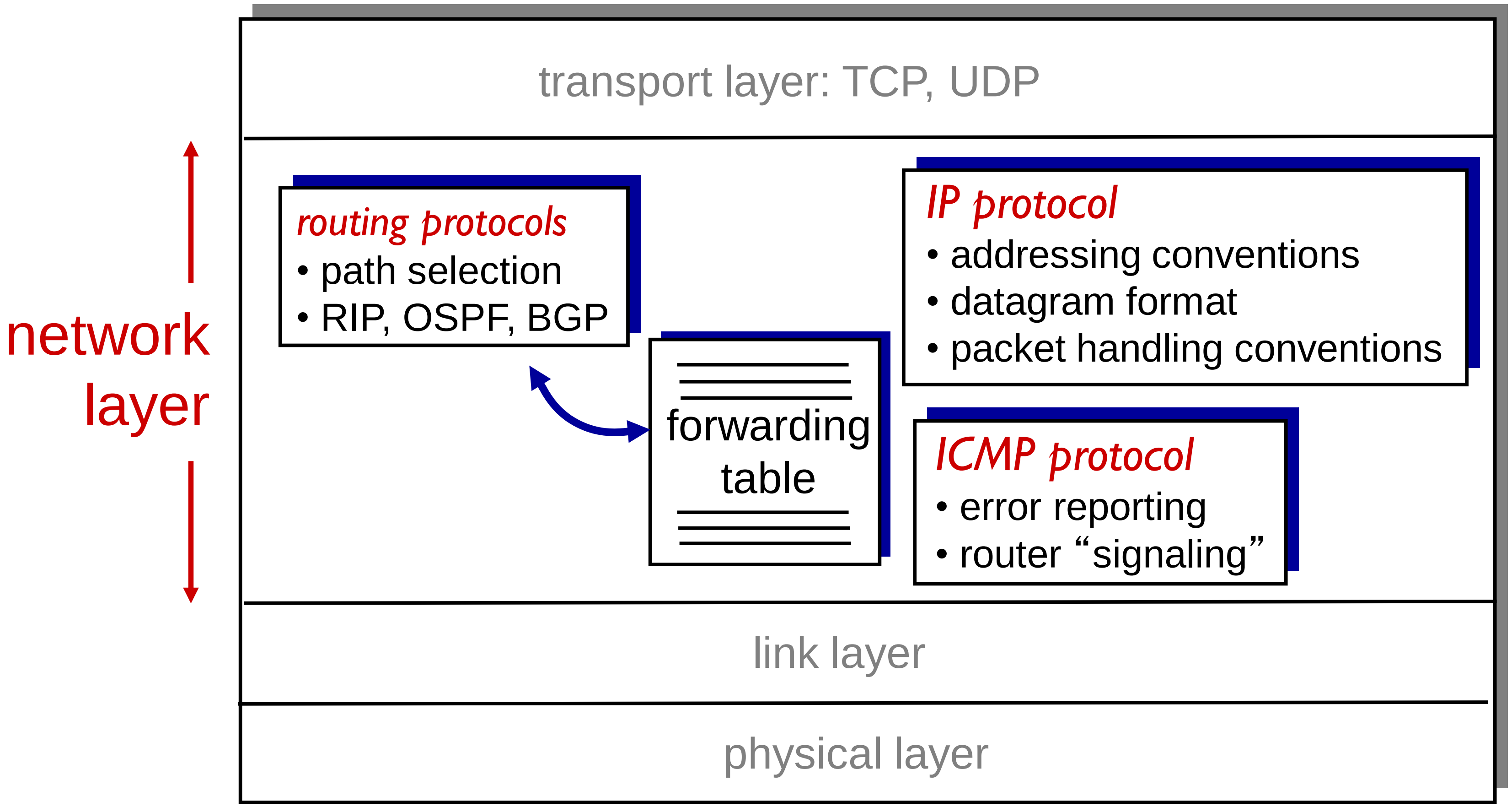
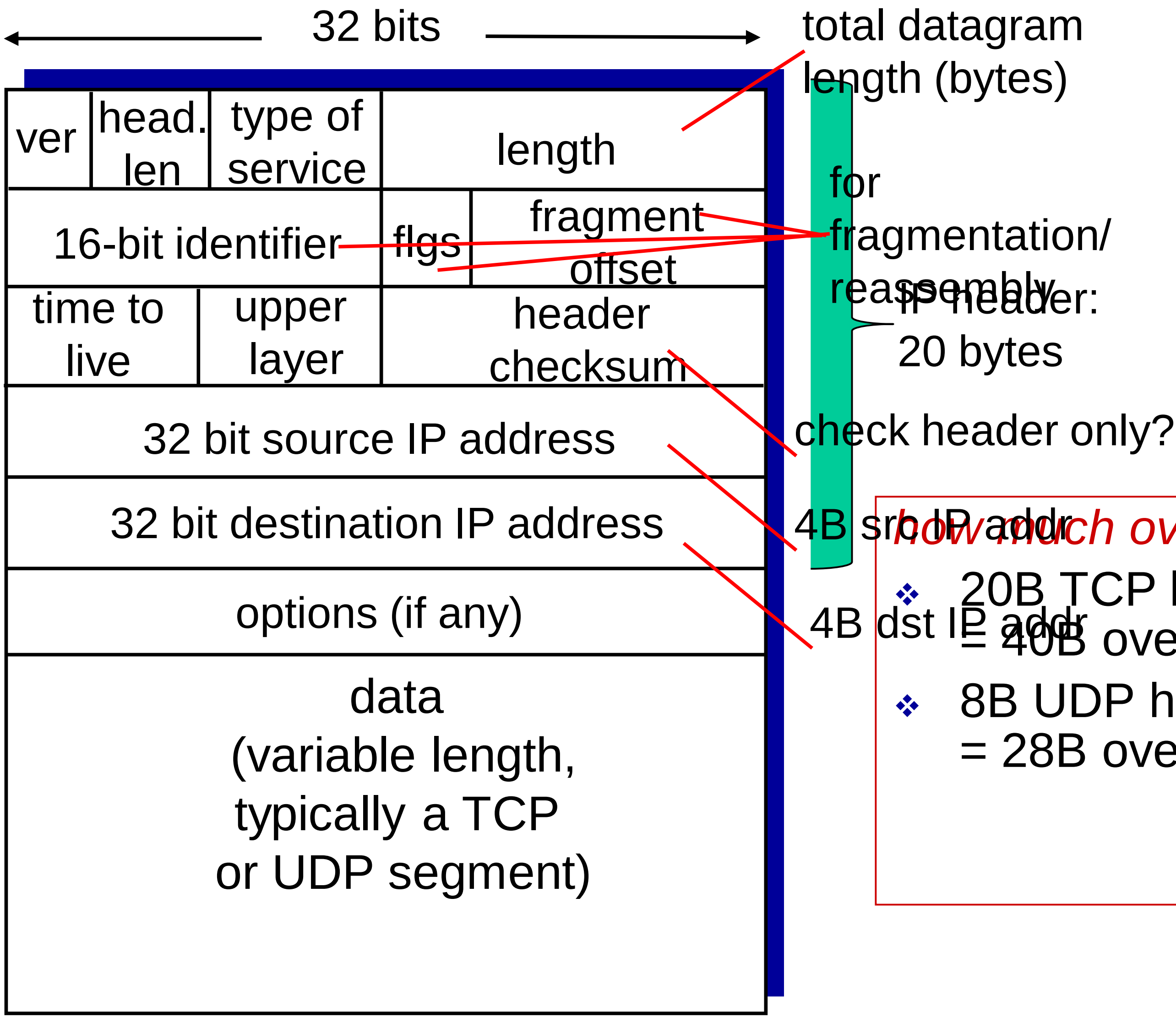
The Internet network layer

host, router network layer functions:



IP datagram format

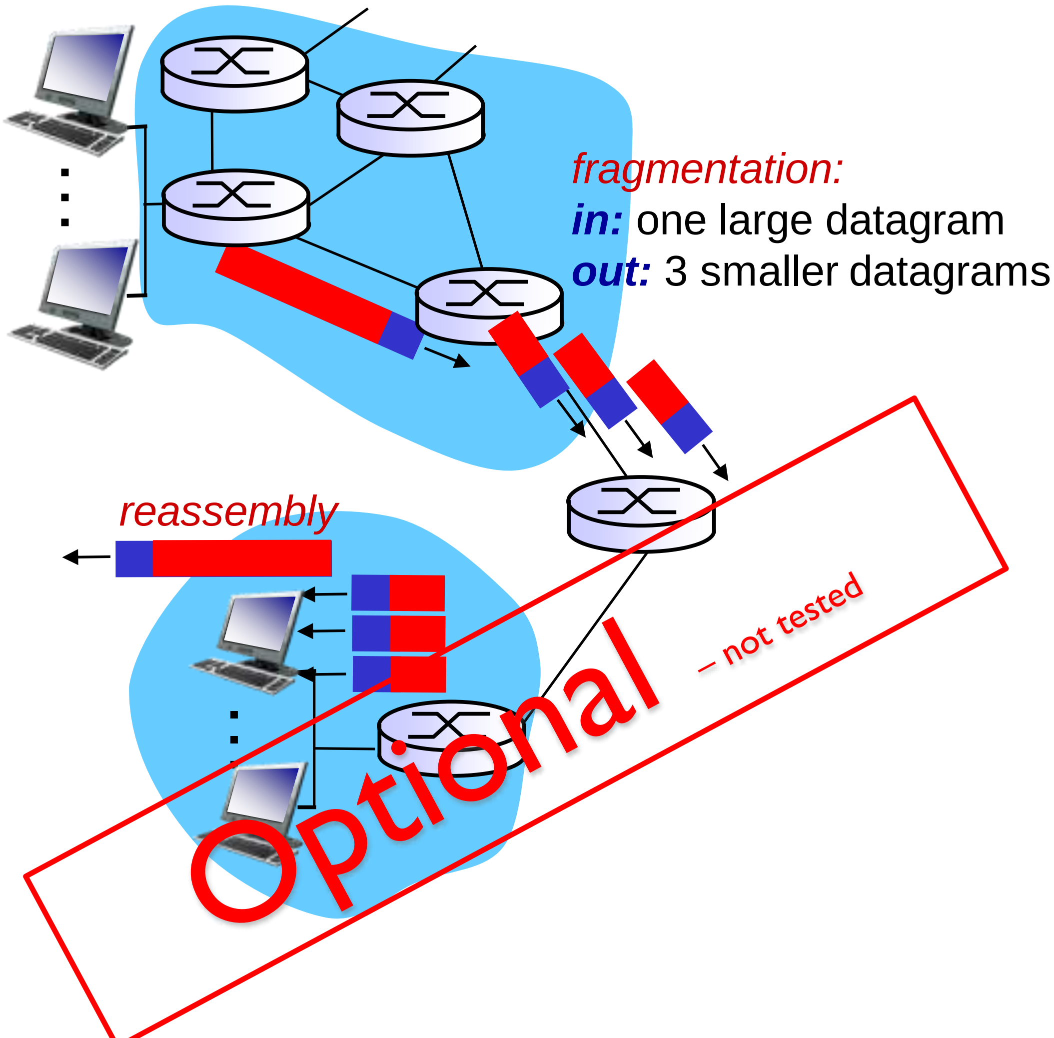


how much overhead?

- 20B TCP hdr + 20B IP hdr = 40B overhead
- 8B UDP hdr + 20B IP hdr = 28B overhead

IP fragmentation, reassembly

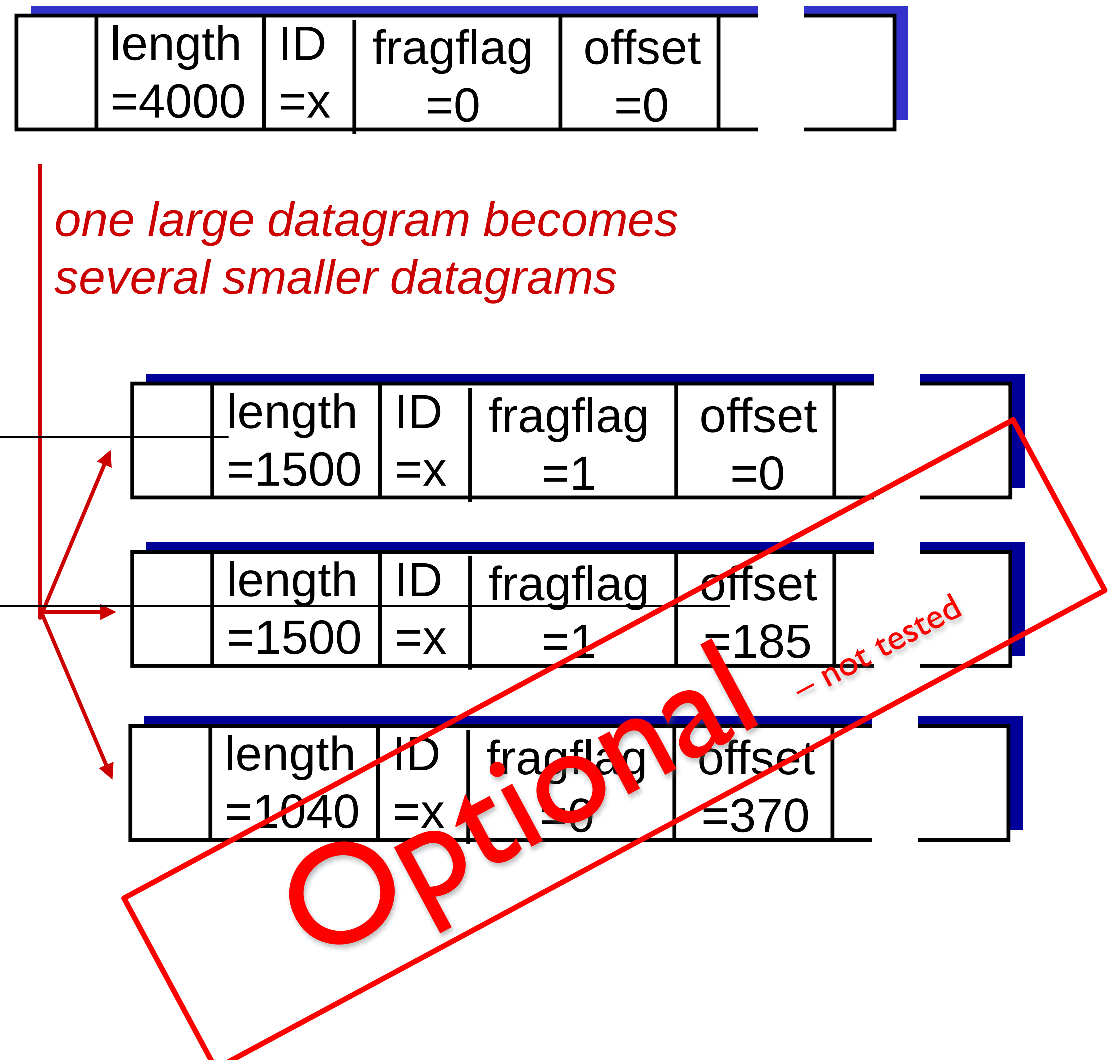
- network links have MTU (max.transfer size) - largest possible link-level frame
  - different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only at final destination
  - IP header bits used to identify, order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



IP fragmentation, reassembly

example:

- 4000 byte datagram
- MTU = 1500 bytes



1480 bytes in data field

offset = 1480/8

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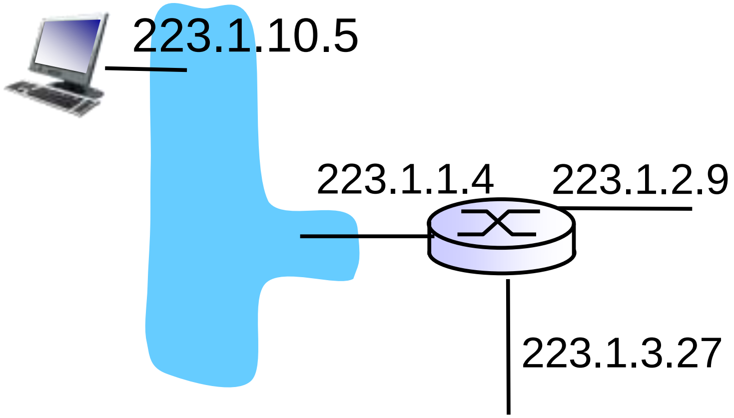
host IP address

- *IP address:* 32-bit, 4-byte identifier for host, router *interface*
- *interface:* connection between host/router and physical link
  - host typically has one or two interfaces (e.g., wired Ethernet, wireless 802.11)
  - router's typically have multiple interfaces
- *One IP address for each interface*

$223.1.10.5 = \underbrace{11011111}_{223}\ \underbrace{00000001}_{1}\ \underbrace{00001010}_{10}\ \underbrace{00000101}_{5}$



IP address: decimal ⇔ binary

223.1.10.5 = 11011111 00000001 00001010 00000101

11011111	00000001	00001010	00000101
223	1	10	5

1. Write down binary table:

7	6	5	4	3	2	1	0		i
128	64	32	16	8	4	2	1		2^i

2. convert 10 to binary: 10-8=2;   2-2=0. (deduct numbers: high to low)

3.

0	0	0	0	1	0	1	0

2. converting 100 to binary: deduct numbers: high to low

100 - 64 = 36; 36 - 32 = 4; 4 - 4 = 0

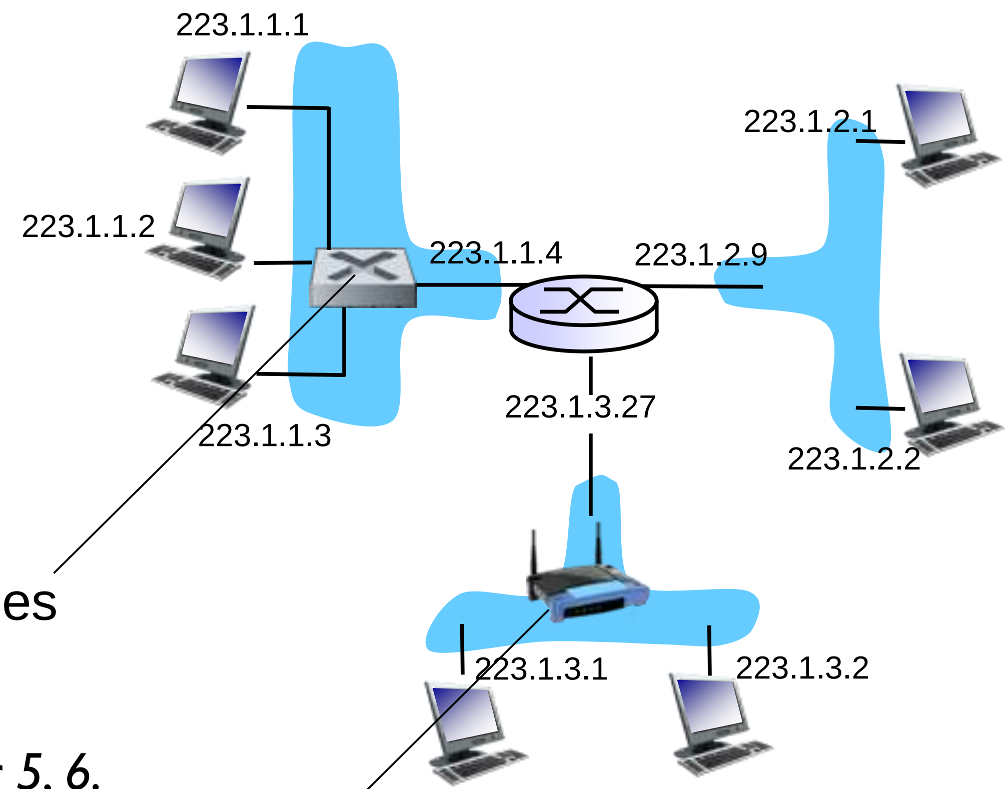
3.

0	1	1	0	0	1	0	0

Try 223?

Subnets

Q: how are interfaces actually connected?



A: wired Ethernet interfaces connected by Ethernet switches

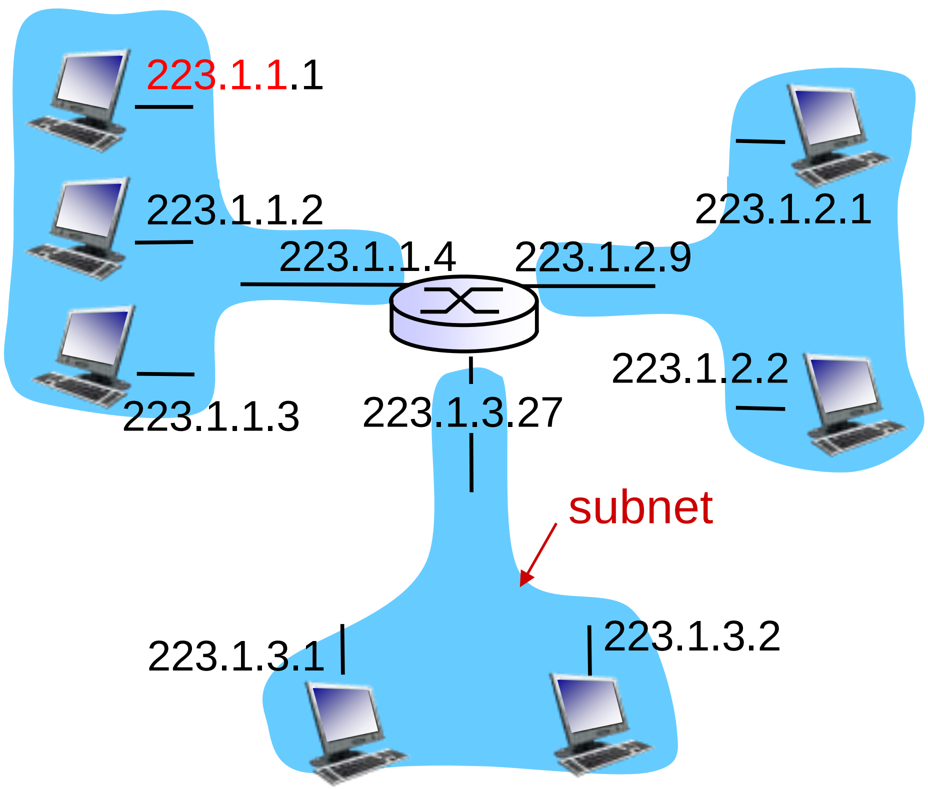
A: we'll learn about that in chapter 5, 6.

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 in networks

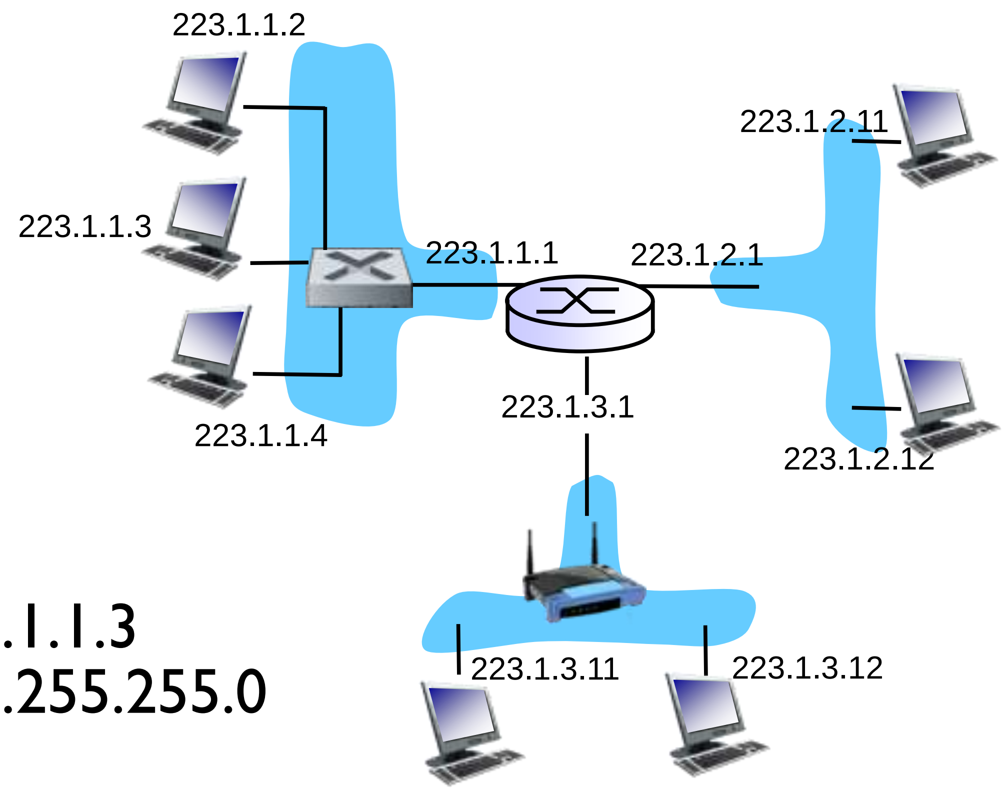
- IP address:
  - subnet part - high order bits
  - host part - low order bits
- *what 's a subnet ?*
  - device interfaces with same subnet part of IP address
  - can physically reach each other *without intervening router*



network consisting of 3 subnets

Subnets

- subnet . host#
  223.1.1.3
- street . house#
  Smith St . 3

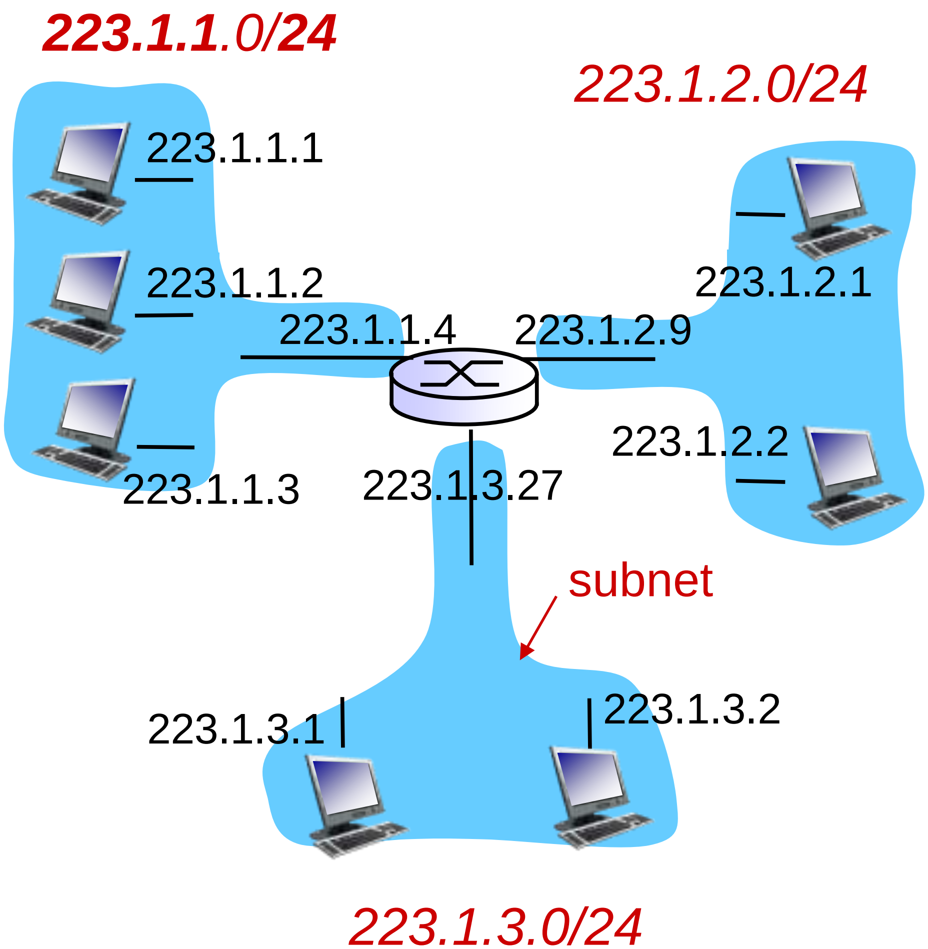


- Write IP address
  - IP address: 223.1.1.3
    subnet mask: 255.255.255.0
  - shorthand: 223.1.1.3/24

Subnets

recipe

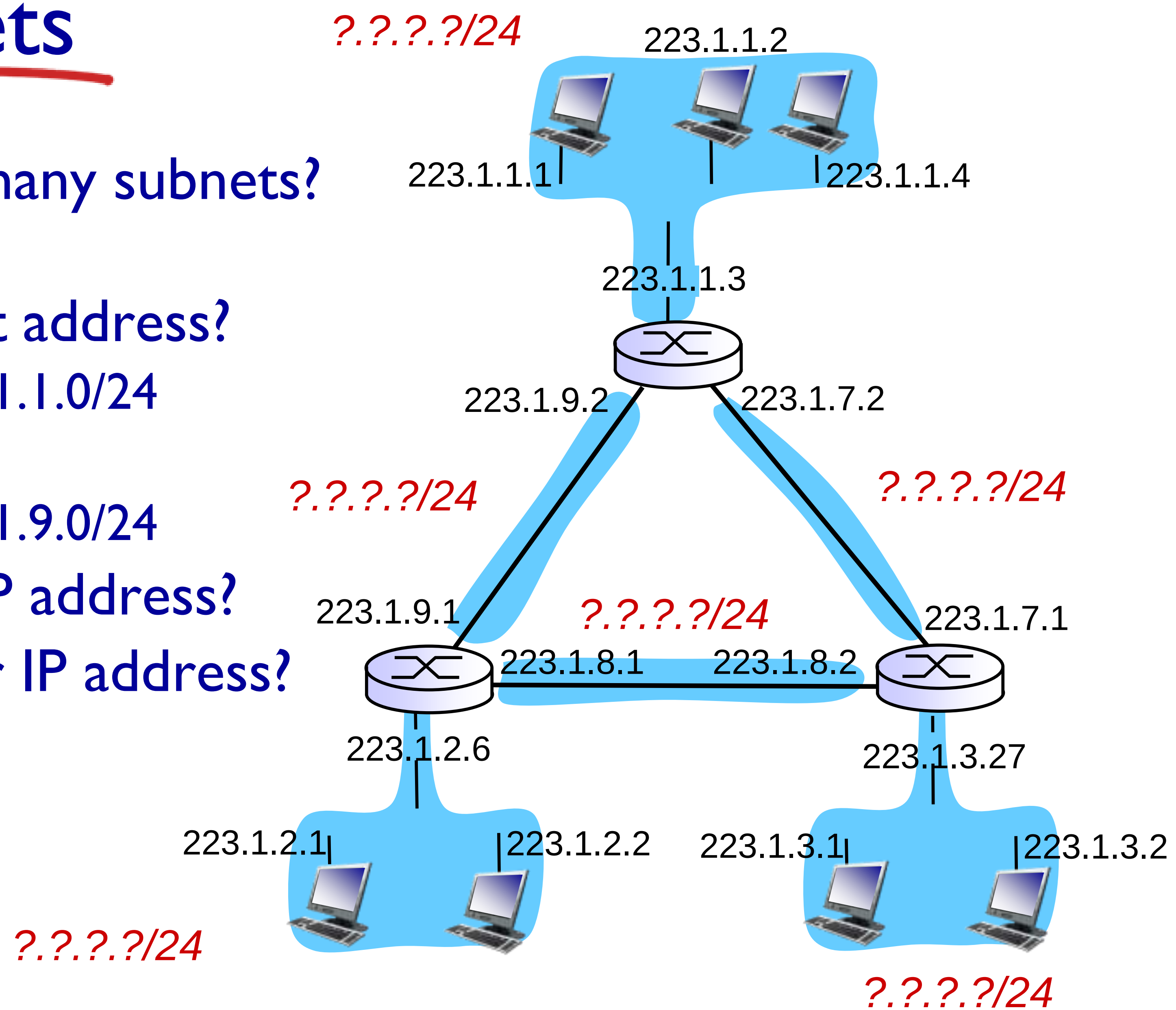
- to determine the subnets, detach each interface from its host or router, creating islands of isolated networks
- each isolated network is called a *subnet*
  - *223.1.1.0/24*
- Subnet mask:
  - /24 or 255.255.255.0



subnet mask: /24

Subnets

- how many subnets?
  - 6
- subnet address?
  - 223.1.1.0/24
  - …
  - 223.1.9.0/24
- host IP address?
- router IP address?



IP addressing: CIDR

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

subnet part | host part

11001000 00010111 00010000 00000000

200.23.16.0/23

IP addresses: how to get one?

Q: how does *network* get subnet part of IP addr?

A: gets allocated portion of its provider ISP's address space

Q: how does an ISP get block of addresses?

A: ICANN: Internet Corporation for Assigned Names and Numbers http://www.icann.org/

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

IP addresses: how to get one?

Q: How does a *host* get IP address?

- hard-coded by system admin in a file
  - Windows: control-panel->network->configuration->tcp/ip->properties
  - UNIX: /etc/rc.config
- DHCP: Dynamic Host Configuration Protocol: dynamically get address from as server
  - "plug-and-play"

DHCP: Dynamic Host Configuration Protocol

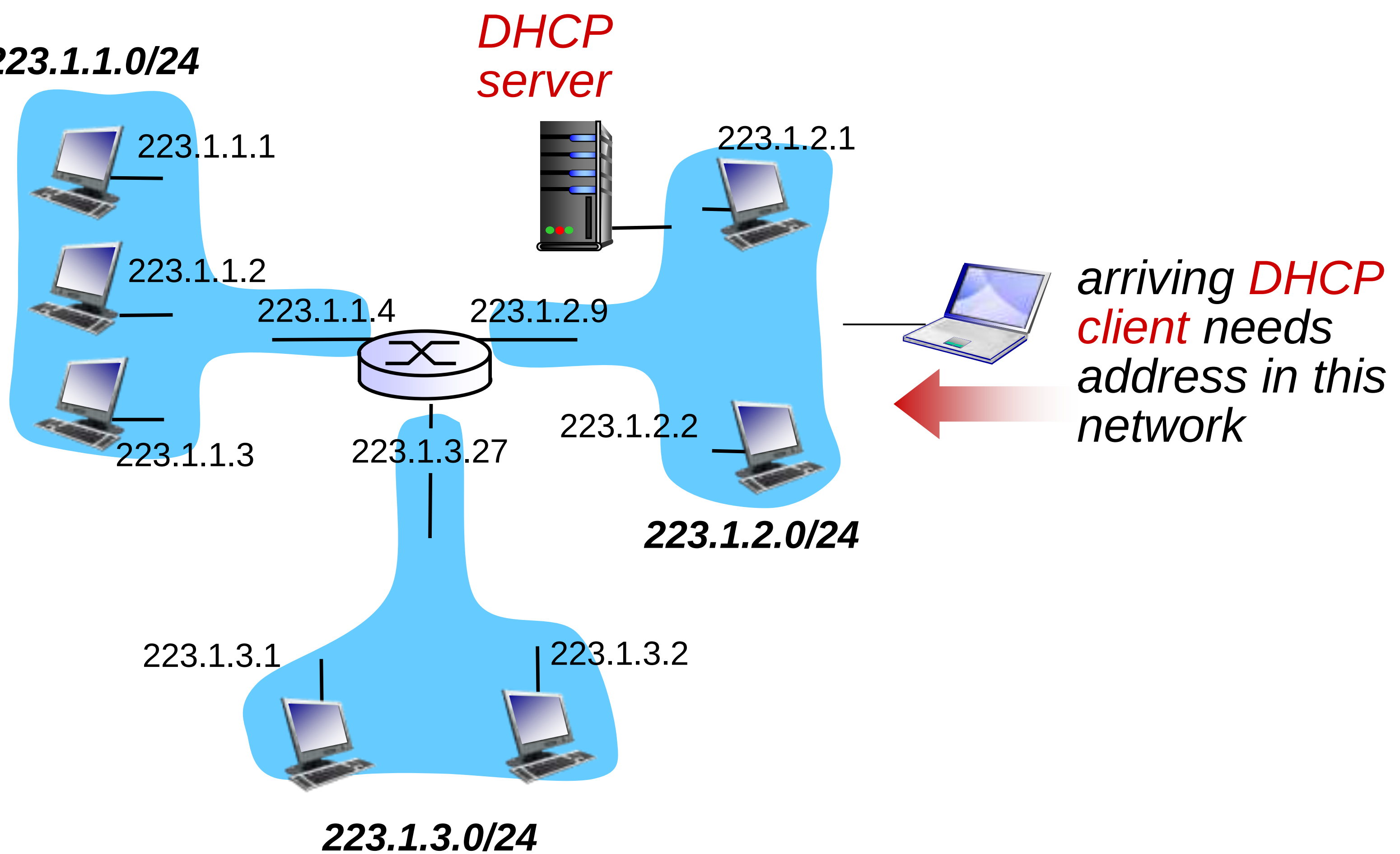
goal: allow host to *dynamically* obtain its IP address from network server when it joins network

- 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)

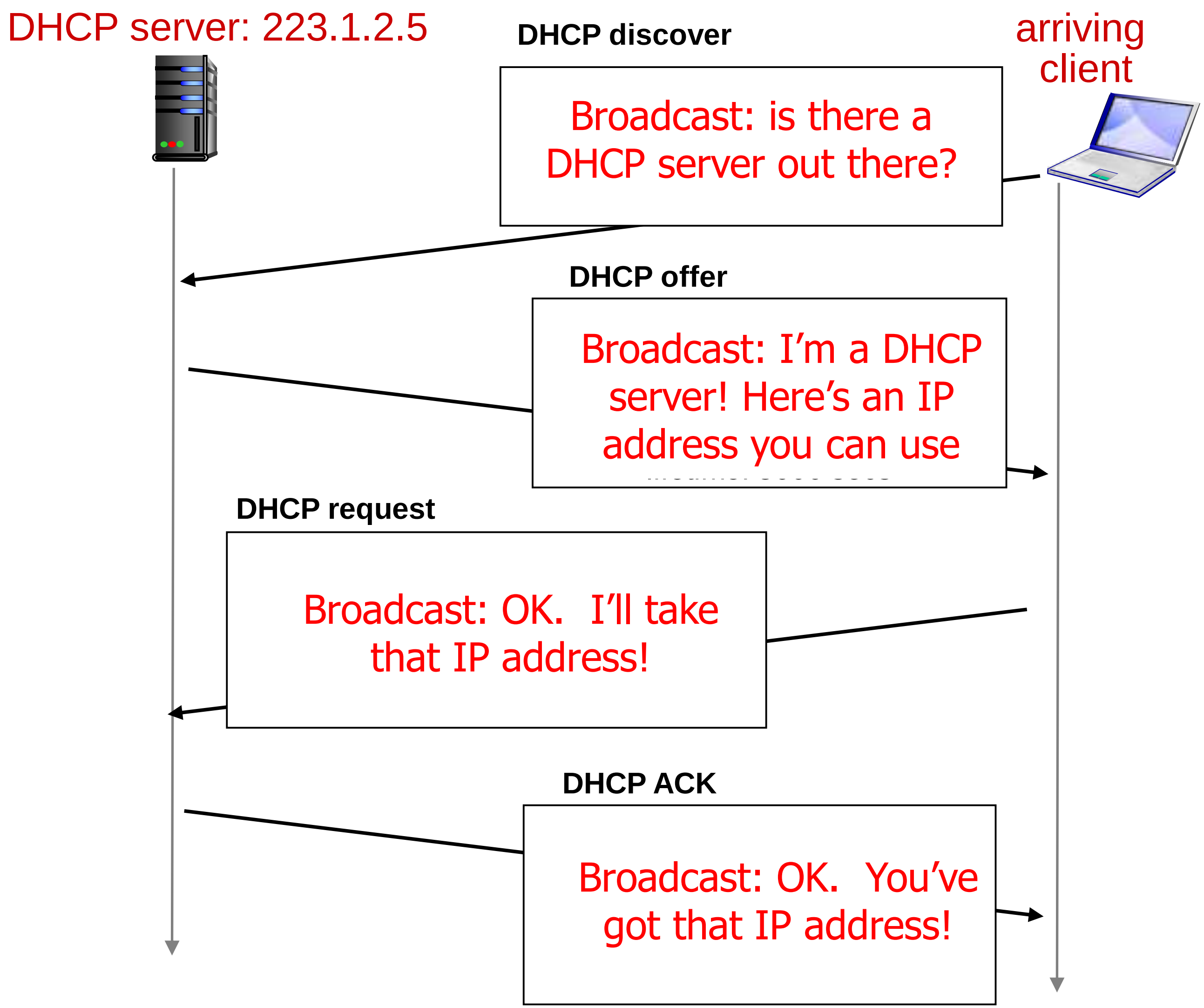
DHCP overview:

- 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 client-server scenario



DHCP client-server scenario

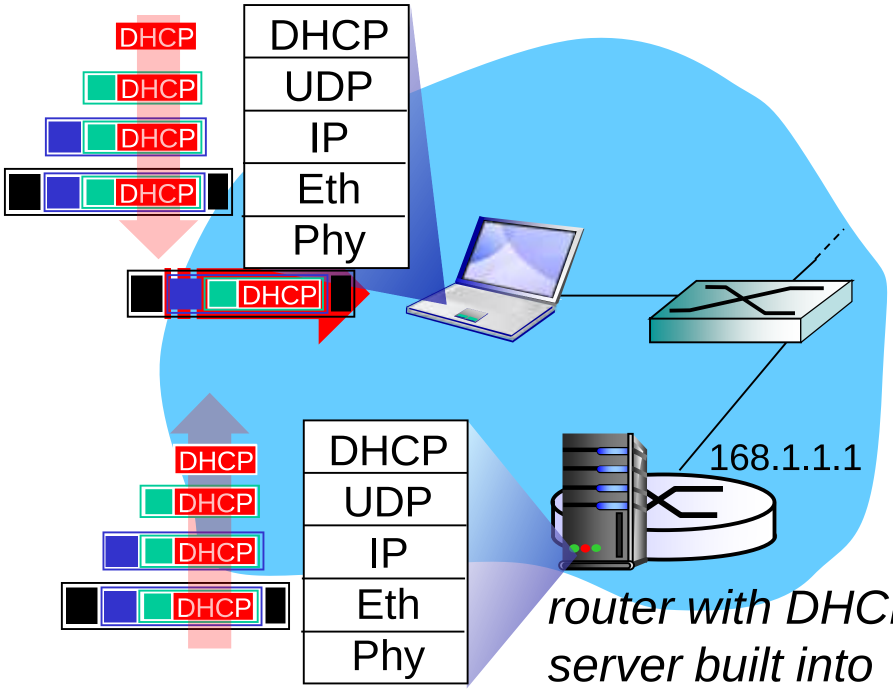


DHCP: more than IP addresses

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

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

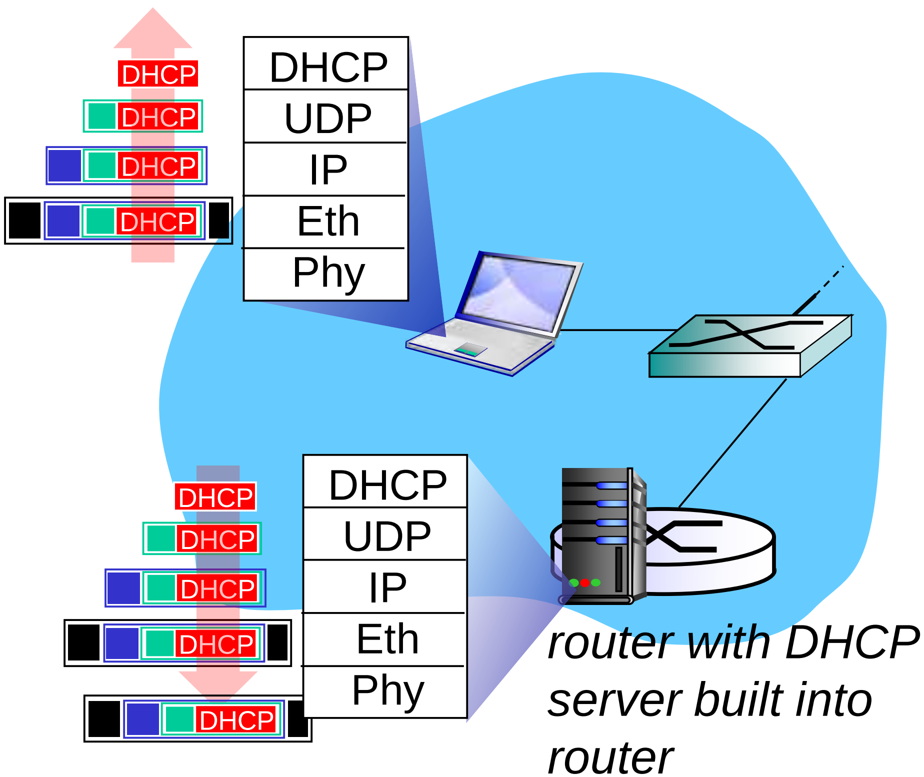
DHCP: example



router with DHCP server built into router

- connecting laptop needs its IP address, addr of first-hop router, addr of DNS server: use DHCP
- DHCP request encapsulated in UDP, encapsulated in IP, encapsulated in 802.1 Ethernet
- Ethernet frame broadcast (dest: FFFFFFFFFFFF) on LAN, received at router running DHCP server
- Ethernet demuxed to IP demuxed, UDP demuxed to DHCP

DHCP: example



- DCP server formulates DHCP ACK containing client's IP address, IP address of first-hop router for client, name & IP address of DNS server
- encapsulation of DHCP server, frame forwarded to client, demuxing up to DHCP at client
- client now knows its IP address, name and IP address of DSN server, IP address of its first-hop router

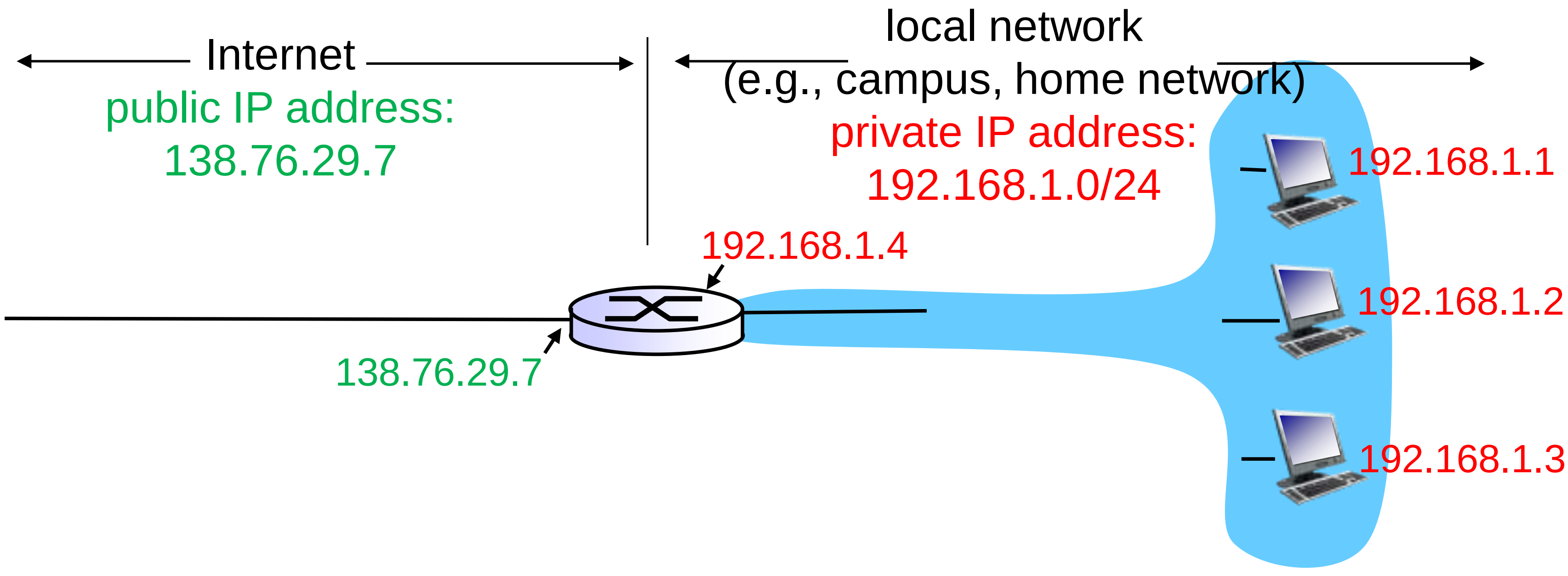
NAT: network address translation

motivation: Run out of public IP addresses! local network uses just one IP address as far as outside world is concerned:

- Use one public IP address to the outside
  - assigned by ISP
- Use private IP addresses internally
  - 10.0.0.0/8
  - 172.16-31.0.0/16
  - 192.168.0-255.0/24

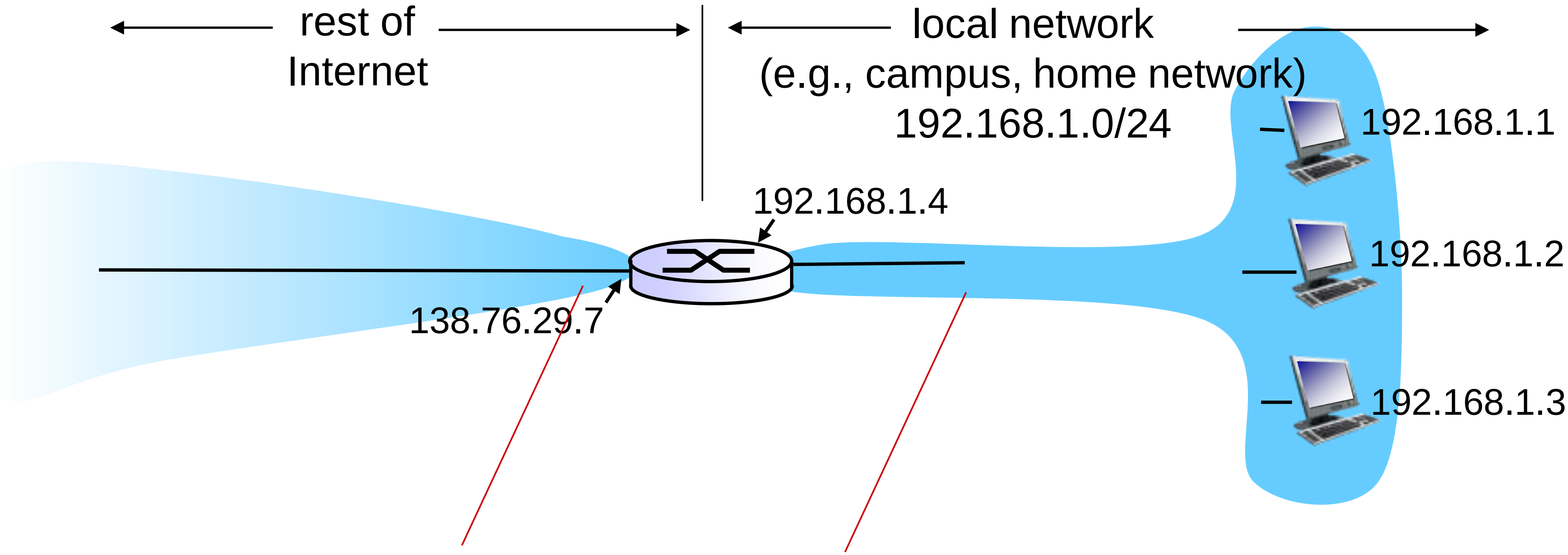
Class	Private IP address range	Subnet mask
A	10.0.0.0 - 10.255.255.255	255.0.0.0
B	172.16.0.0 - 172.16.31.255	255.255.0.0
C	192.168.0.0-192.168.255.255	255.255.255.0

Private IP Address



- Private IP address is free!
- Cannot go to public Internet

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 192.168.1.0/24 address for source, destination (as usual)

NAT: network address translation

implementation: NAT router must:

- *outgoing datagrams: replace* (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #)

  . . . remote clients/servers will respond using (NAT IP address, new port #) as destination addr

- *remember (in NAT translation table)* every (source IP address, port #) to (NAT IP address, new port #) translation pair

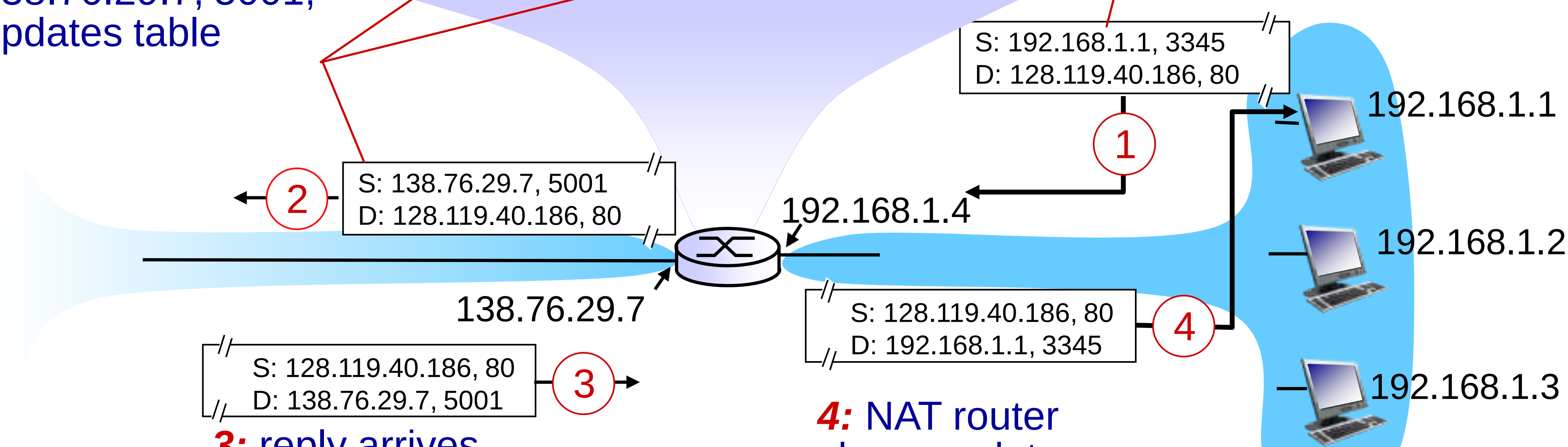
- *incoming datagrams: replace* (NAT IP address, new port #) in dest fields of every incoming datagram with corresponding (source IP address, port #) stored in NAT table

NAT: network address translation

NAT translation table	
WAN side addr	LAN side addr
138.76.29.7, 5001	192.168.1.1, 3345
……	……

1: host 192.168.1.1 sends datagram to 128.119.40.186, 80

2: NAT router changes datagram source addr from 192.168.1.1, 3345 to 138.76.29.7, 5001, updates table



3: reply arrives dest. address: 138.76.29.7, 5001

4: NAT router changes datagram dest addr from 138.76.29.7, 5001 to 192.168.1.1, 3345

* 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 LAN-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?

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

IPv6: motivation

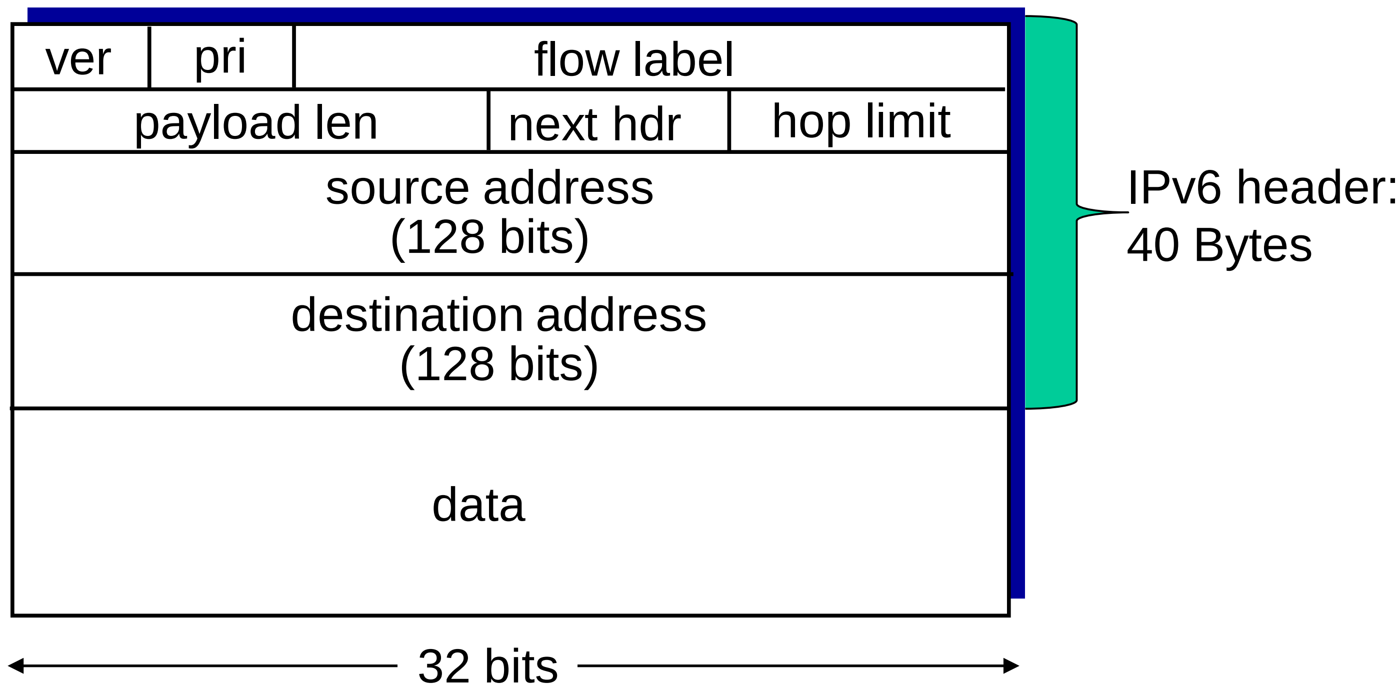
- *initial motivation:* 32-bit address space soon to be completely allocated.
- additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS

IPv6 datagram format:

- fixed-length 40 byte header
- IPv6 address: 128 bits, 16 bytes
- no fragmentation allowed

IPv6 datagram format

IPv6 Address: 16 bytes 128 bits
priority: identify priority among datagrams in flow
flow Label: identify datagrams in same "flow."
next header: identify upper layer protocol for data



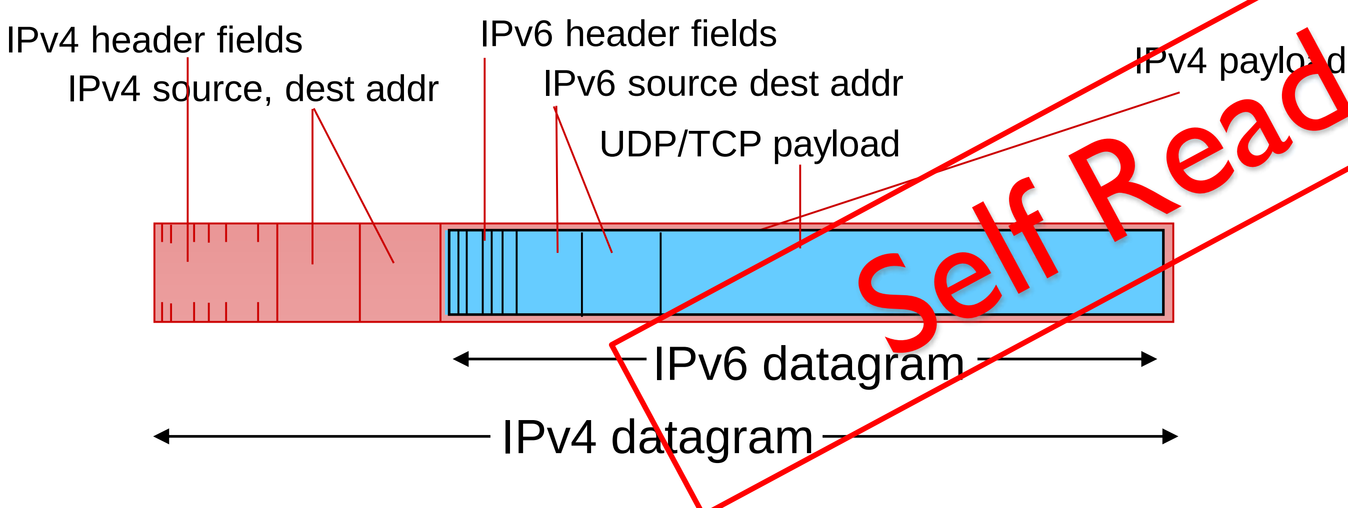
Other changes from IPv4

- *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

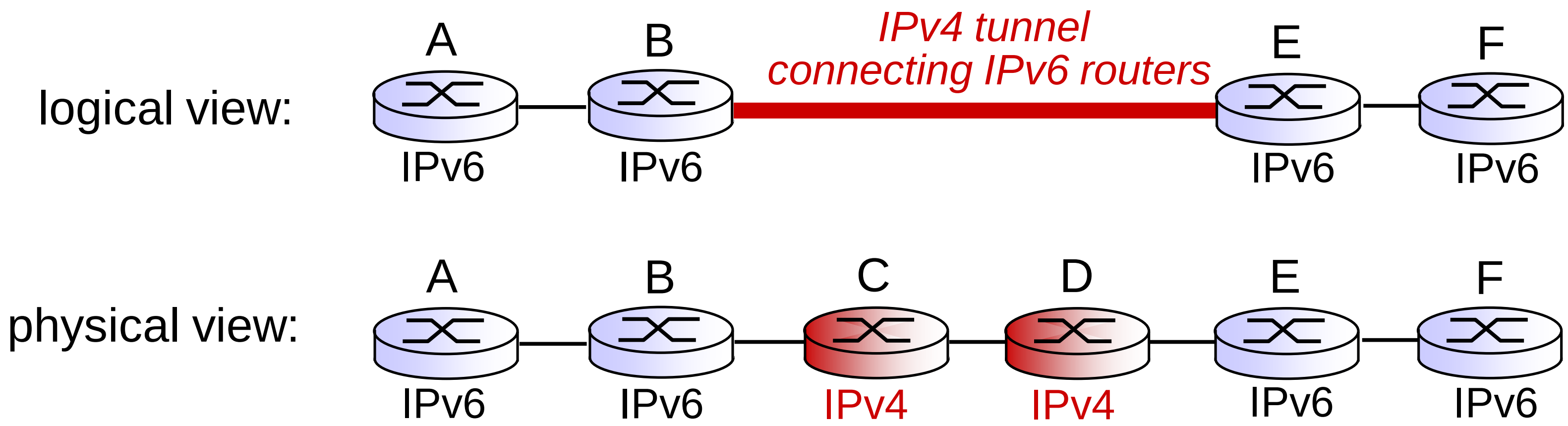
Self Read

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

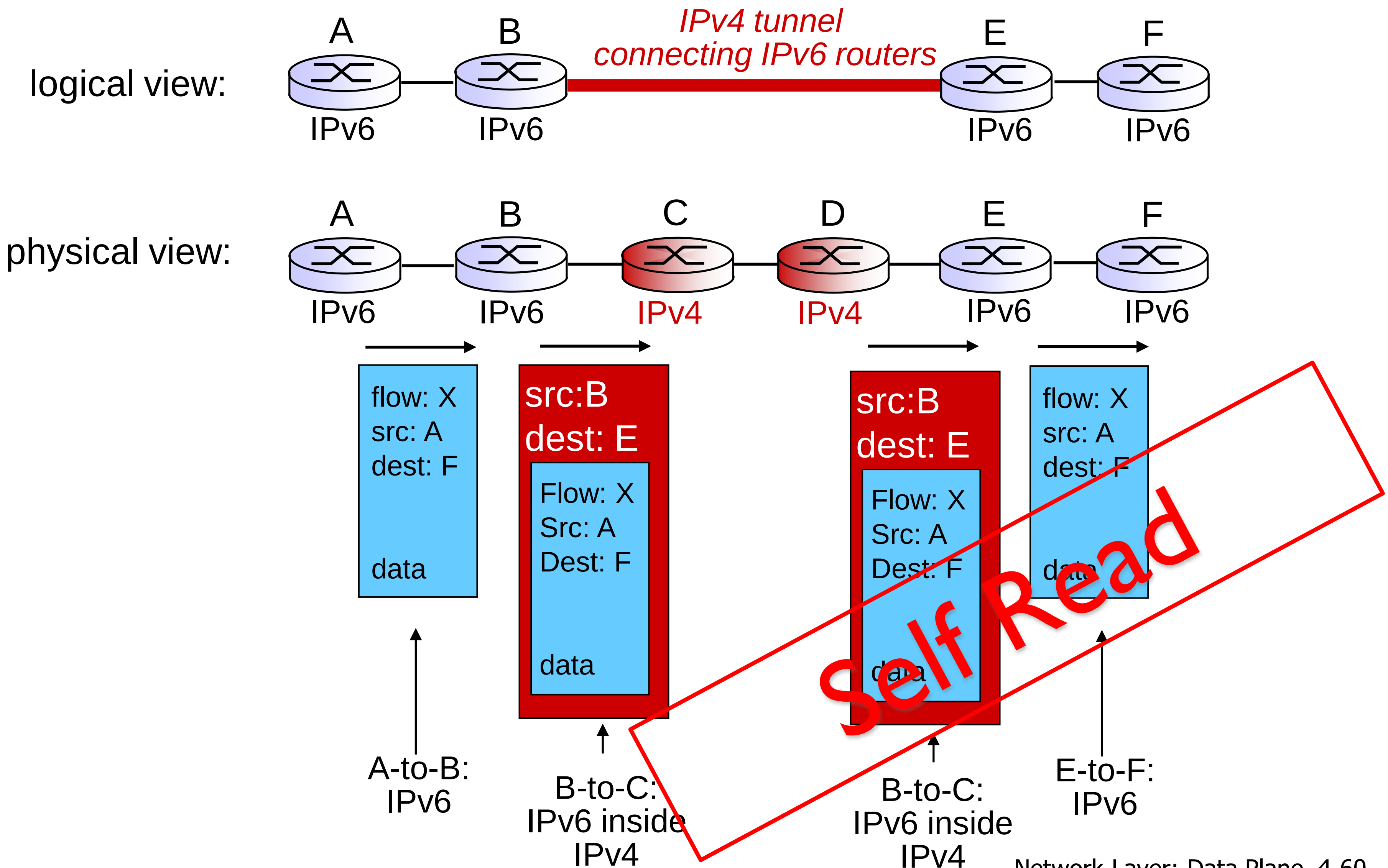


Tunneling



Self Read

Tunneling


logical view:
A
B
IPv4 tunnel
connecting IPv6 routers
E
F
IPv6
IPv6
IPv6
IPv6
physical view:
A
B
C
D
E
F
IPv6
IPv6
IPv4
IPv4
IPv6
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
flow: X
src: A
dest: F
data
A-to-B:
IPv6
B-to-C:
IPv6 inside
IPv4
B-to-C:
IPv6 inside
IPv4
E-to-F:
IPv6
Self Read

Chapter 4: *done!*

4.1 Overview of Network layer: data plane and control plane

4.2 What's inside a router

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- NAT
- IPv6

~~4.4 Generalized Forward and SDN~~
- ~~match plus action~~
- ~~OpenFlow example~~

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

Answer: by the control plane (next chapter)