Chapter 4 Network Layer: The Data Plane

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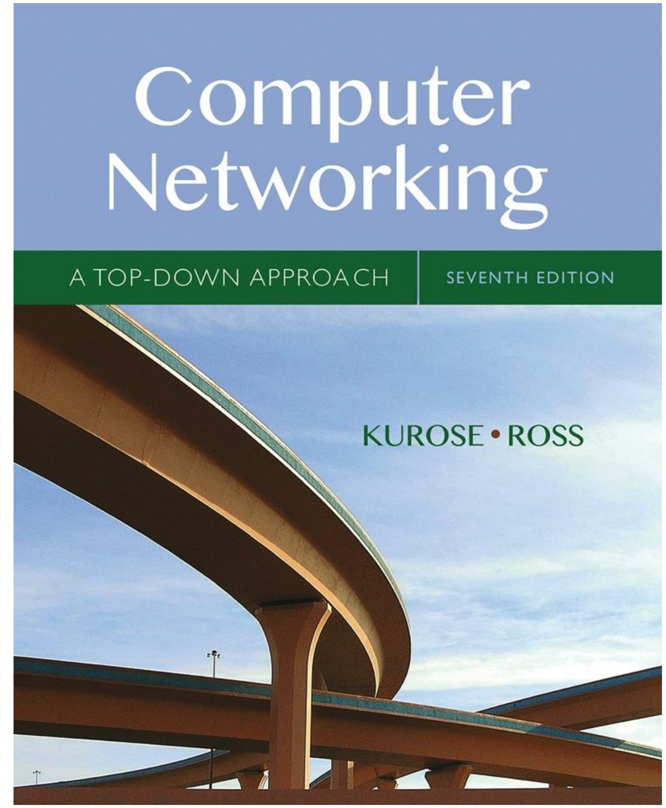


Computer Networking: A Top Down Approach

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

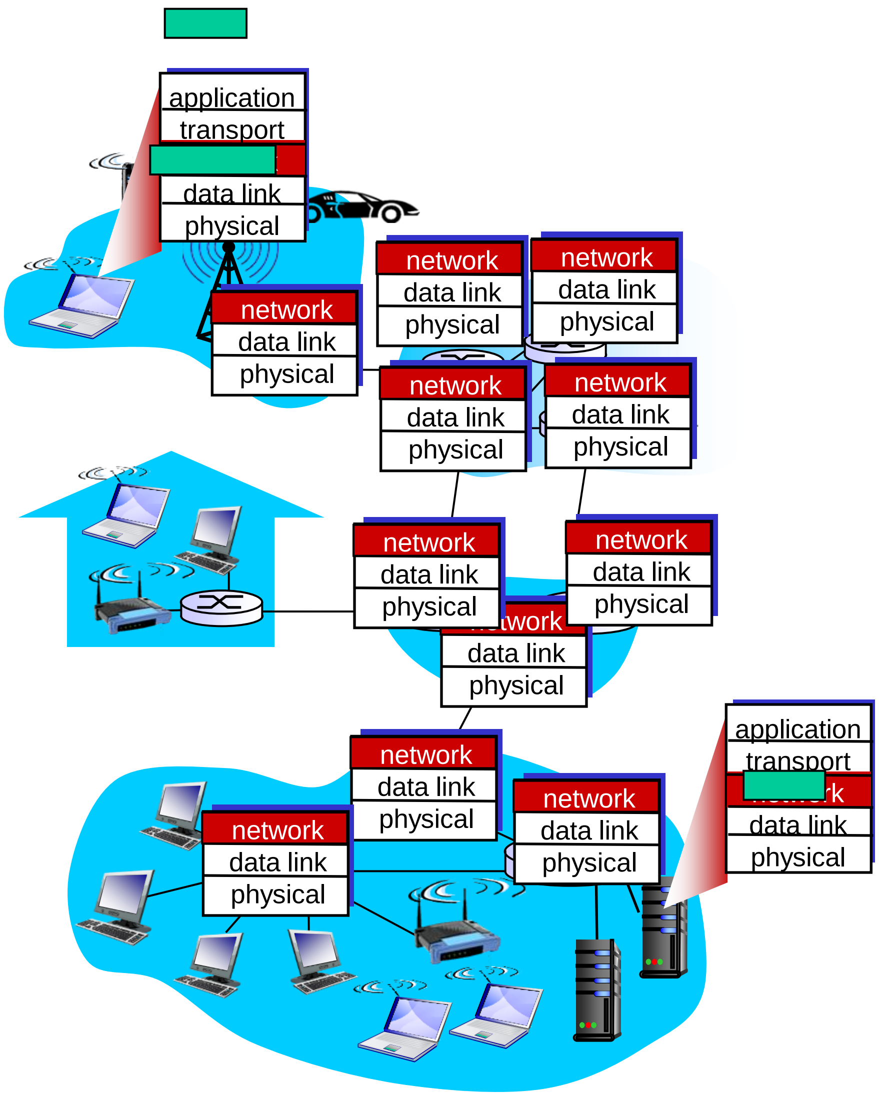
Chapter 4: network layer

chapter goals:

- understand principles behind network layer services, focusing on data plane:
  - network layer service models
  - forwarding versus routing
  - how a router works
  - generalized forwarding
- instantiation, implementation in the Internet

Network layer

- transports segments 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:

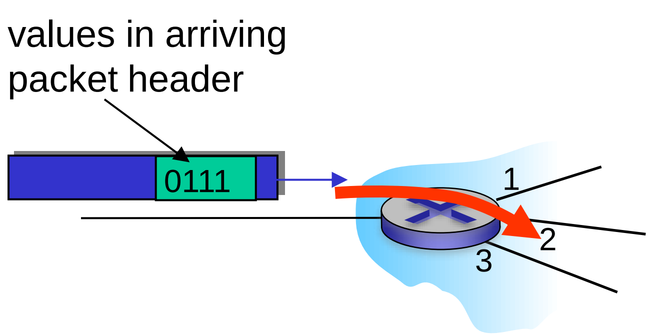
- *forwarding:* move packets from router's input to appropriate router output → Data Plane (chapter#4)

- *routing:* determine route taken by packets from source to destination →Control Plane (Chapter#5)
  - *routing algorithms*

Network layer: data plane, control plane

Data plane (chapter#4)

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

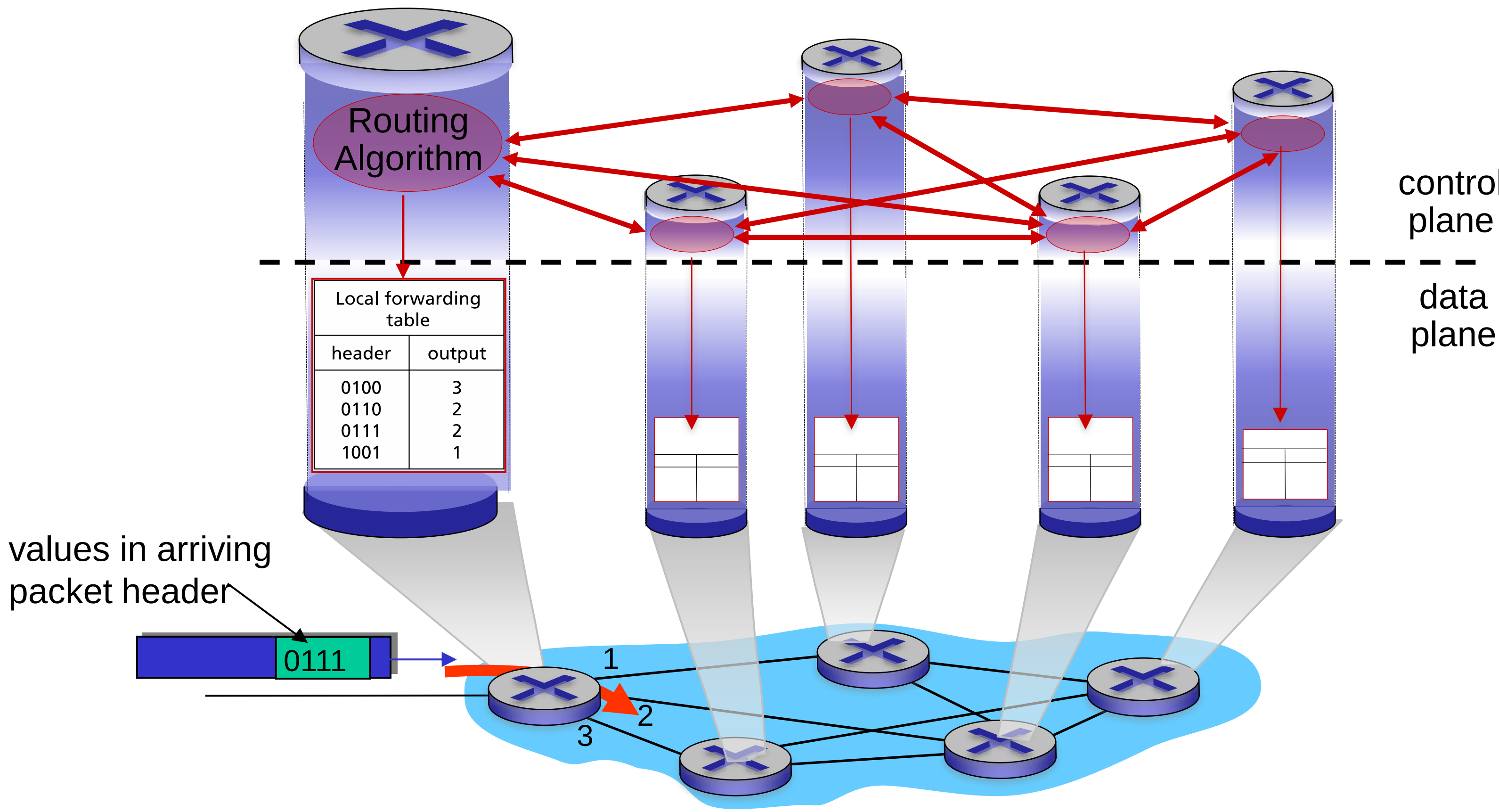


Control plane (chapter#5)

- 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

Per-router control plane

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



Network service model

Q: What possible services network layer could provide?

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

However, Internet's network layer provides a single service, known as ***best-effort service***.

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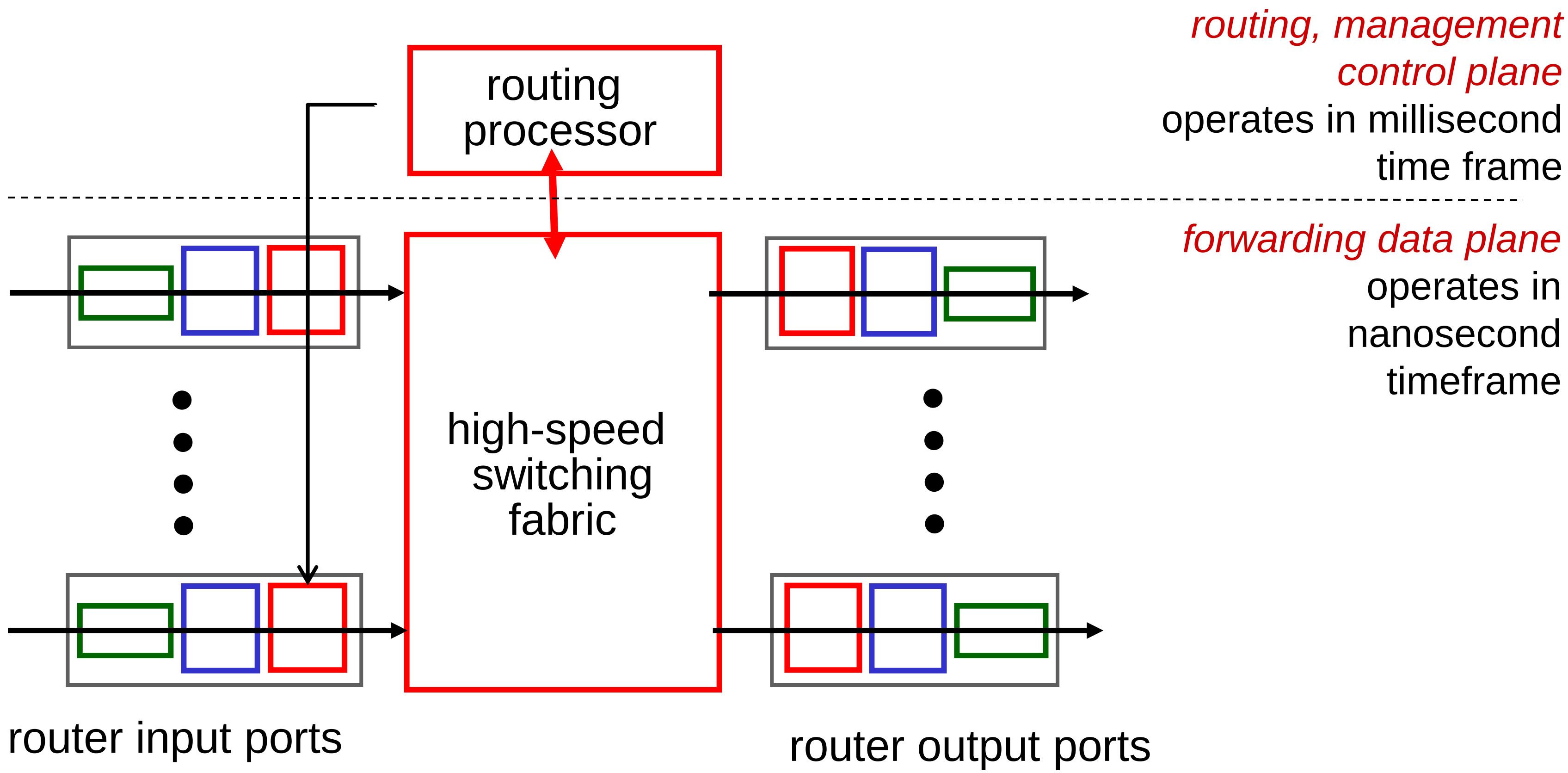
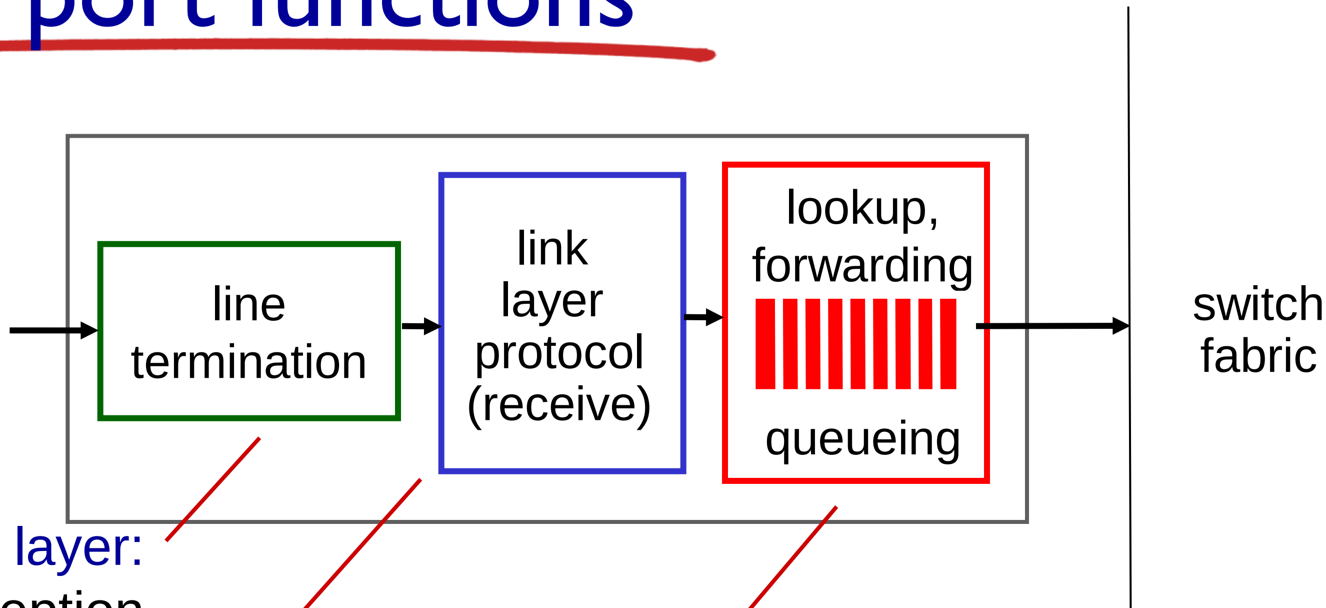
Router architecture overview

- high-level view of generic router architecture:



Input port functions



physical layer:
bit-level reception

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

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 into switch fabric

Destination-based forwarding

forwarding table

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111	0
11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111	1
11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111	2
otherwise	3

Longest prefix matching

longest prefix matching

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

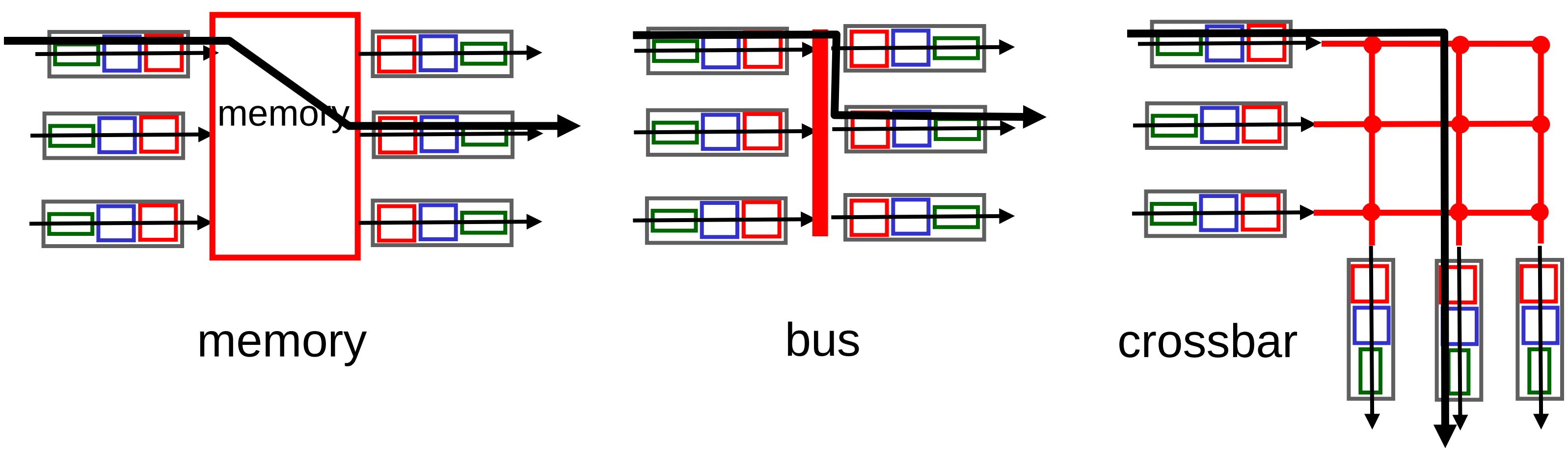
Longest prefix matching

- longest prefix matching: often performed using ternary content addressable memories (TCAMs)
  - Cisco Catalyst: holds up to ~1M routing table entries in TCAM

Switching fabrics

- Switching fabric:
  - Connects input ports to its output ports
  - forwards packet from input buffer to appropriate output buffer
- switching rate, R_{switch} : rate at which packets can be transferred from inputs to outputs
  - often measured as multiple of input/output line rate denoted as R_{line}
  - N inputs: switching rate R_{switch} , N times line rate is desirable
- three types of switching fabrics

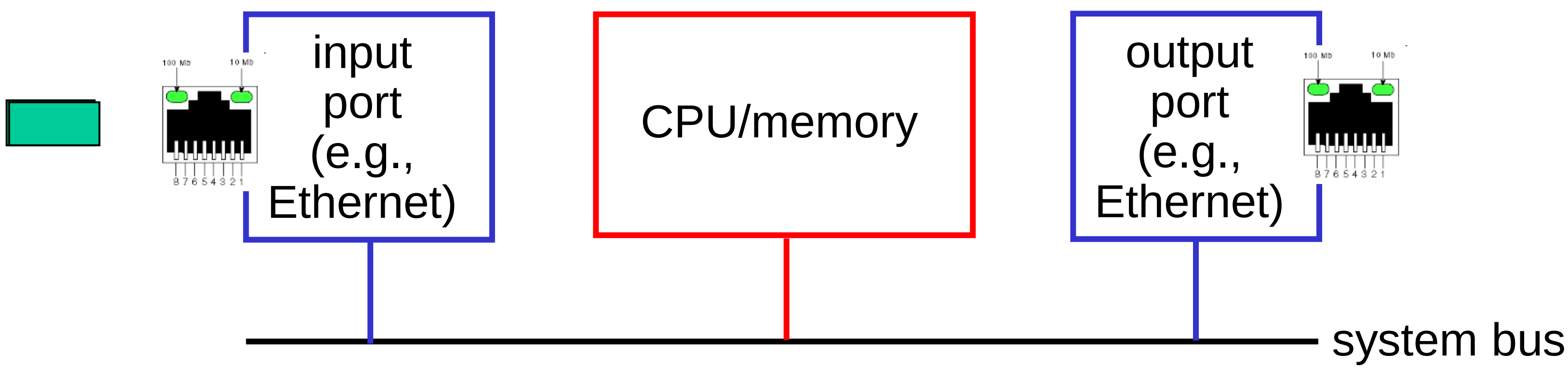
(1) Switching via memory (2) via Bus (3) via interconnection network



Switching via memory

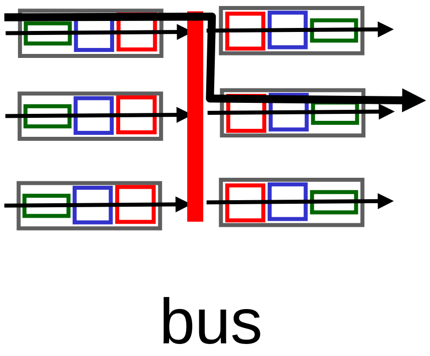
first generation routers:

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



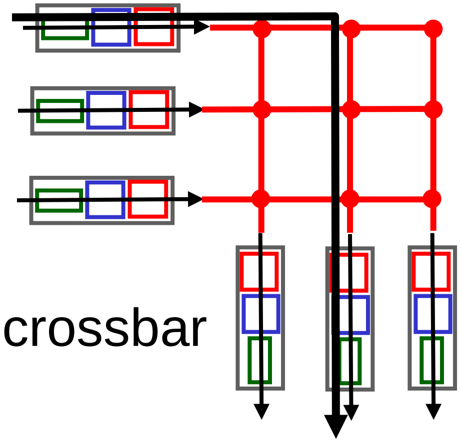
Switching via a bus

- Only one 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

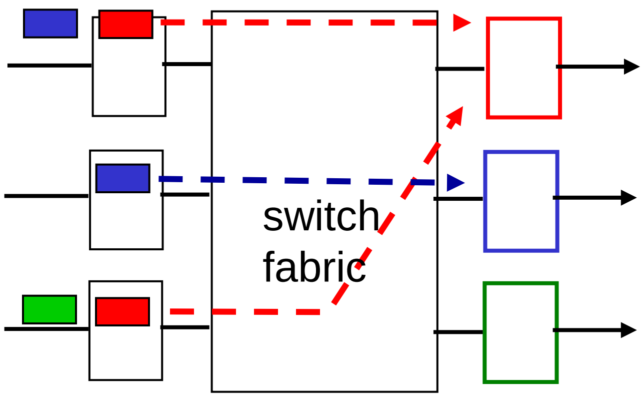
- overcome bus bandwidth limitations
- Allows datagrams to be transferred from multiple input ports to multiple output ports simultaneously
- Cisco 12000 series switches use a crossbar switching network



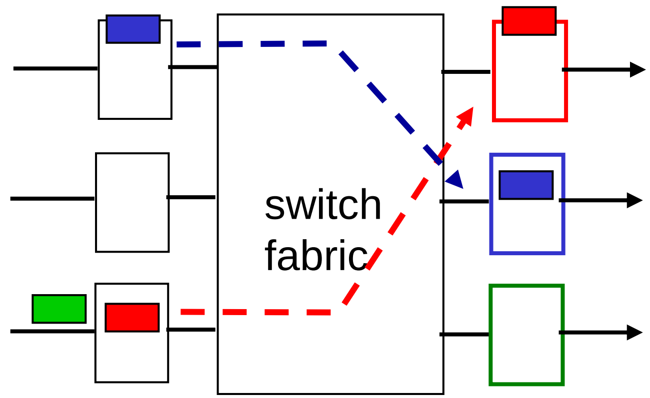
crossbar

Input port queuing

- fabric slower than input ports combined, $R_{switch} < N x R_{line}$
  - 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

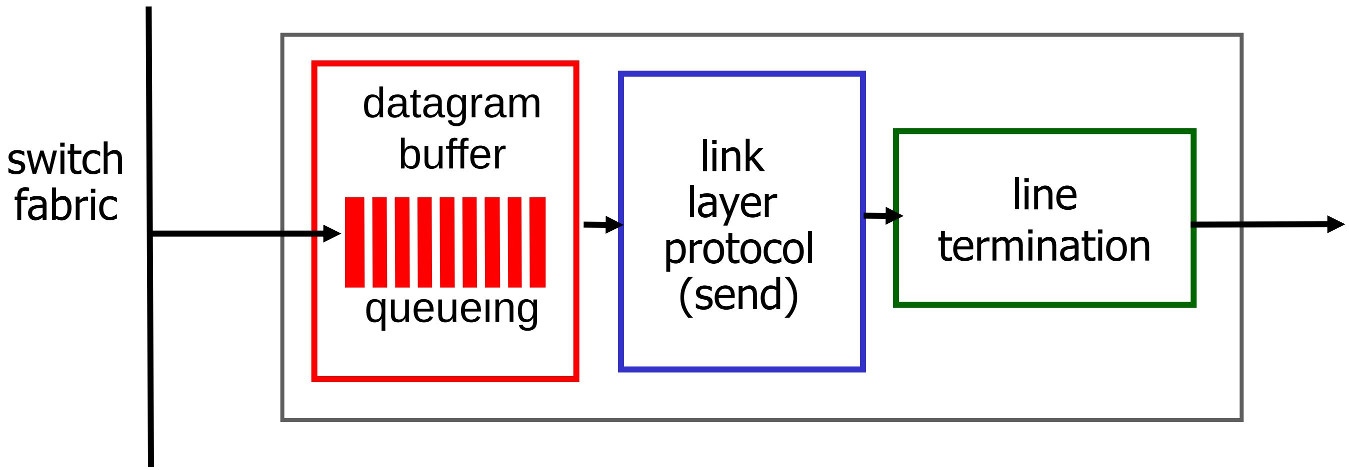


output port contention: only one red datagram can be transferred.
lower red packet is blocked



one packet time later: green packet experiences HOL blocking

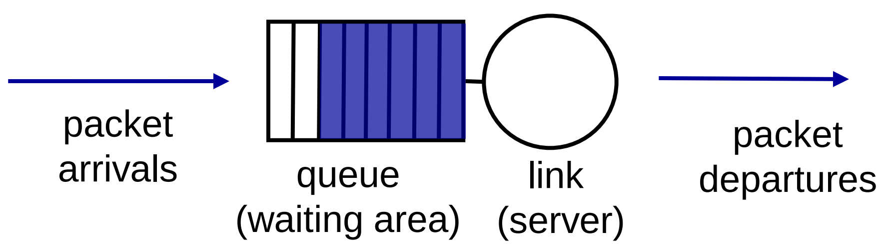
Output ports: Buffering and Queueing



- *buffering* required when datagrams arrive from fabric faster than the transmission rate
- *scheduling discipline* chooses among queued datagrams for transmission
- *queueing (delay) and loss due to output port buffer overflow!*

Scheduling mechanisms

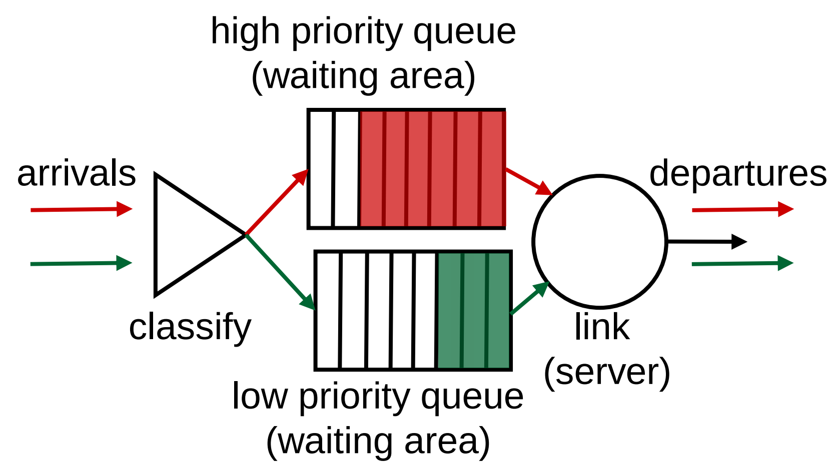
- *scheduling:* choose next packet to send on link
- *FIFO (first in first out) scheduling:* send in order of arrival to queue
  - real-world example?
  - *discard policy:* if packet arrives to full queue: who to discard?
    - *tail drop:* drop arriving packet
    - *priority:* drop/remove on priority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

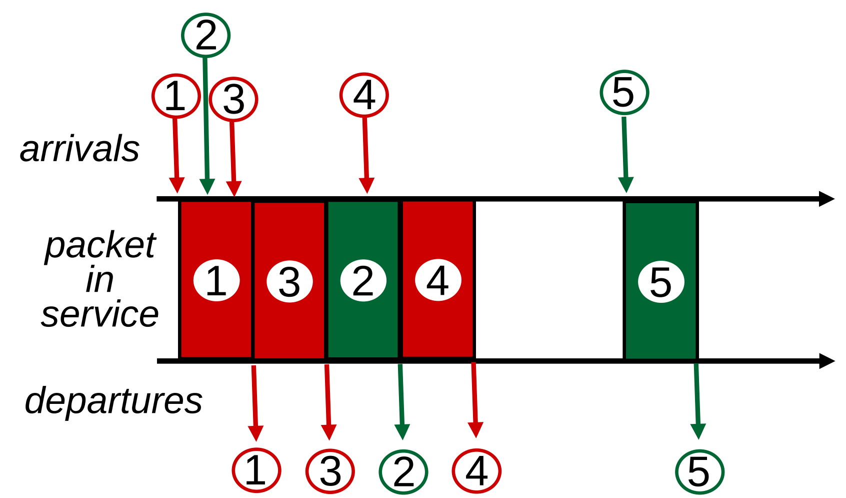


Scheduling policies: priority

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?

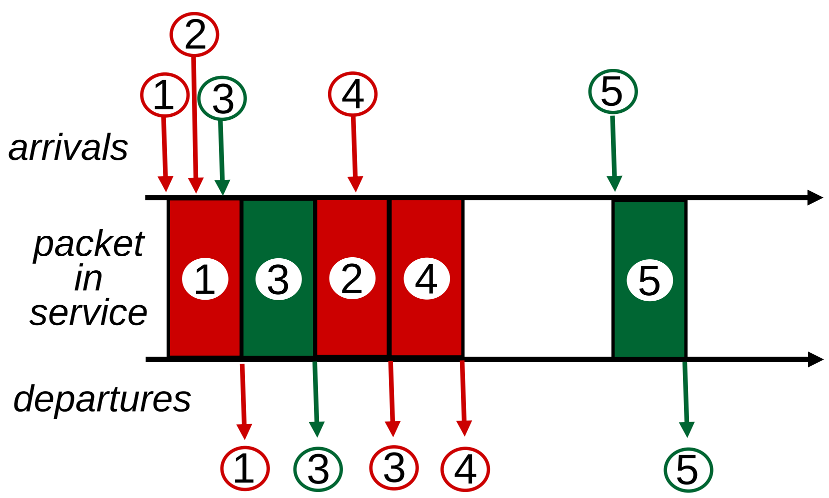




Scheduling policies: still more

Round Robin (RR) scheduling:

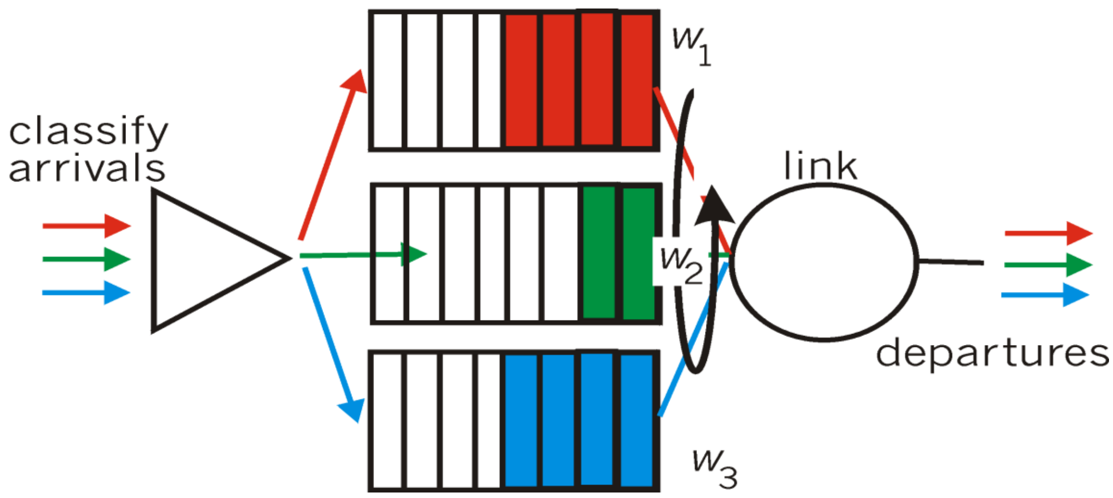
- multiple classes
- cyclically scan class queues, sending one complete packet from each class (if available)
- real world example?



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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- datagram format
- fragmentation
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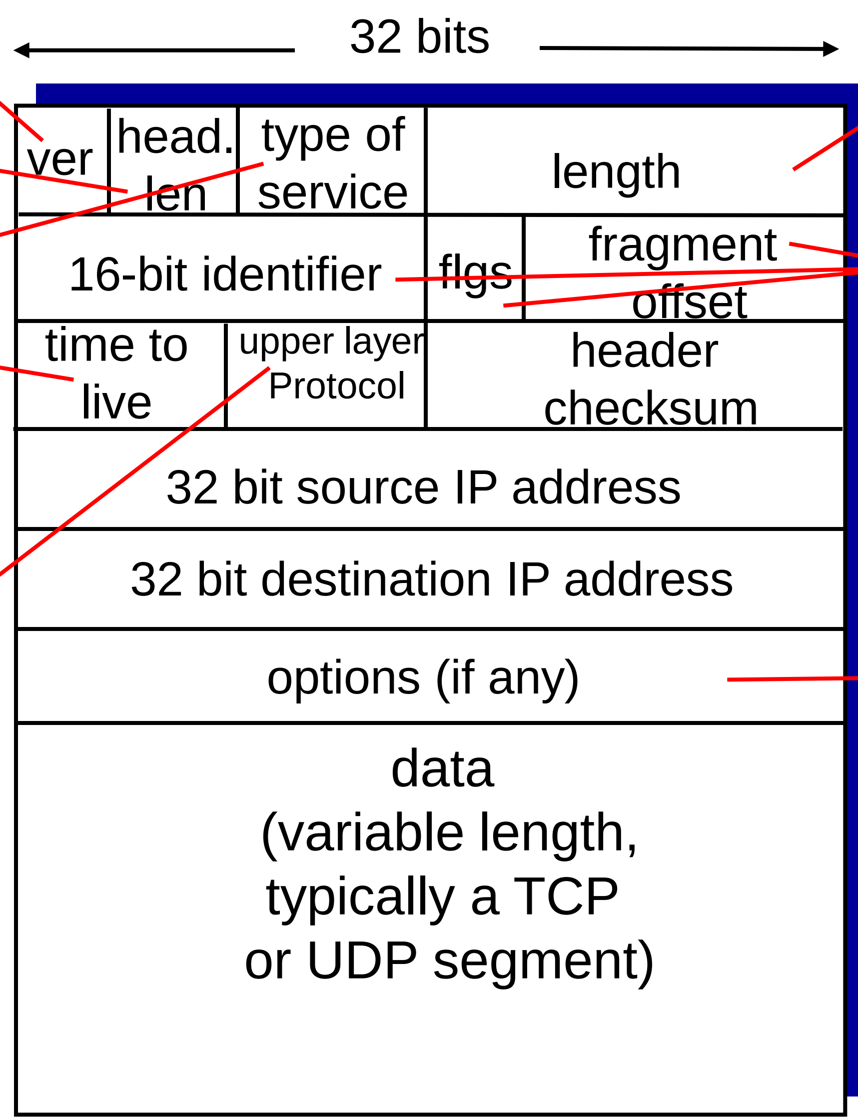
- network address translation

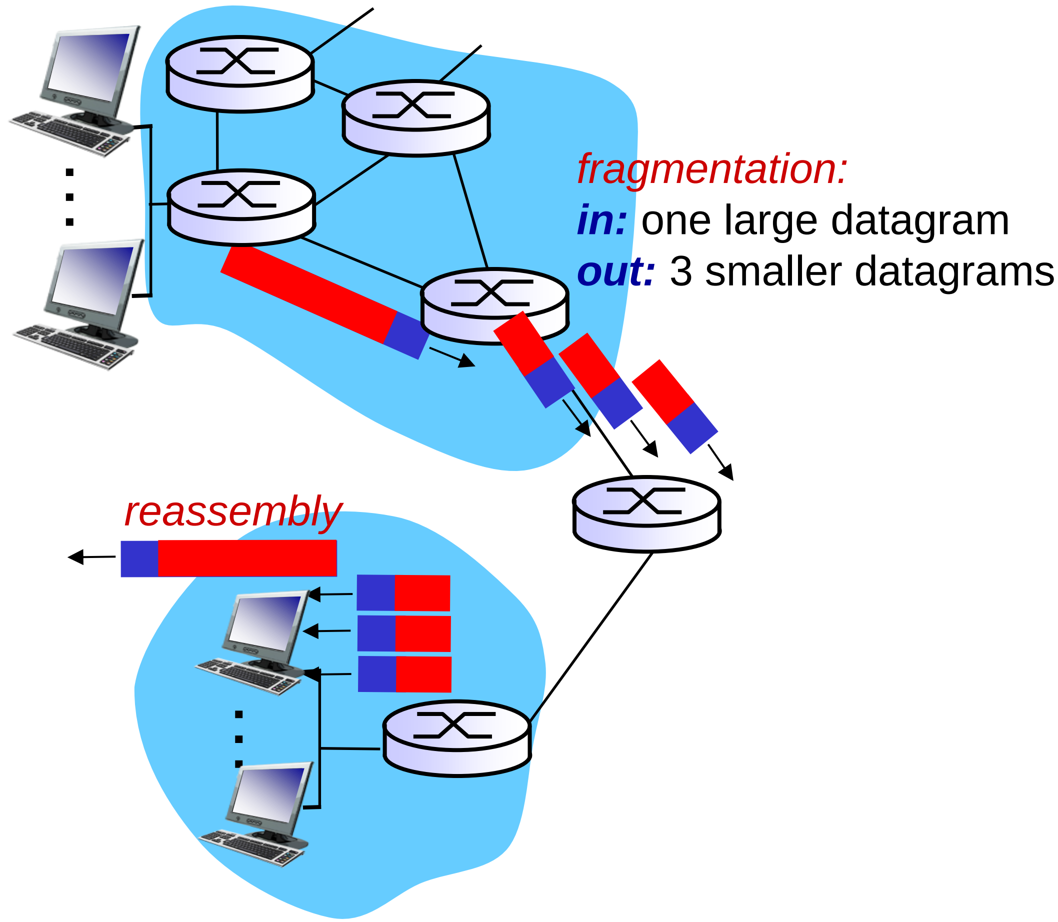
IP datagram format



how much overhead?
- 20 bytes of TCP
- 20 bytes of IP
- = 40 bytes

IP fragmentation, reassembly

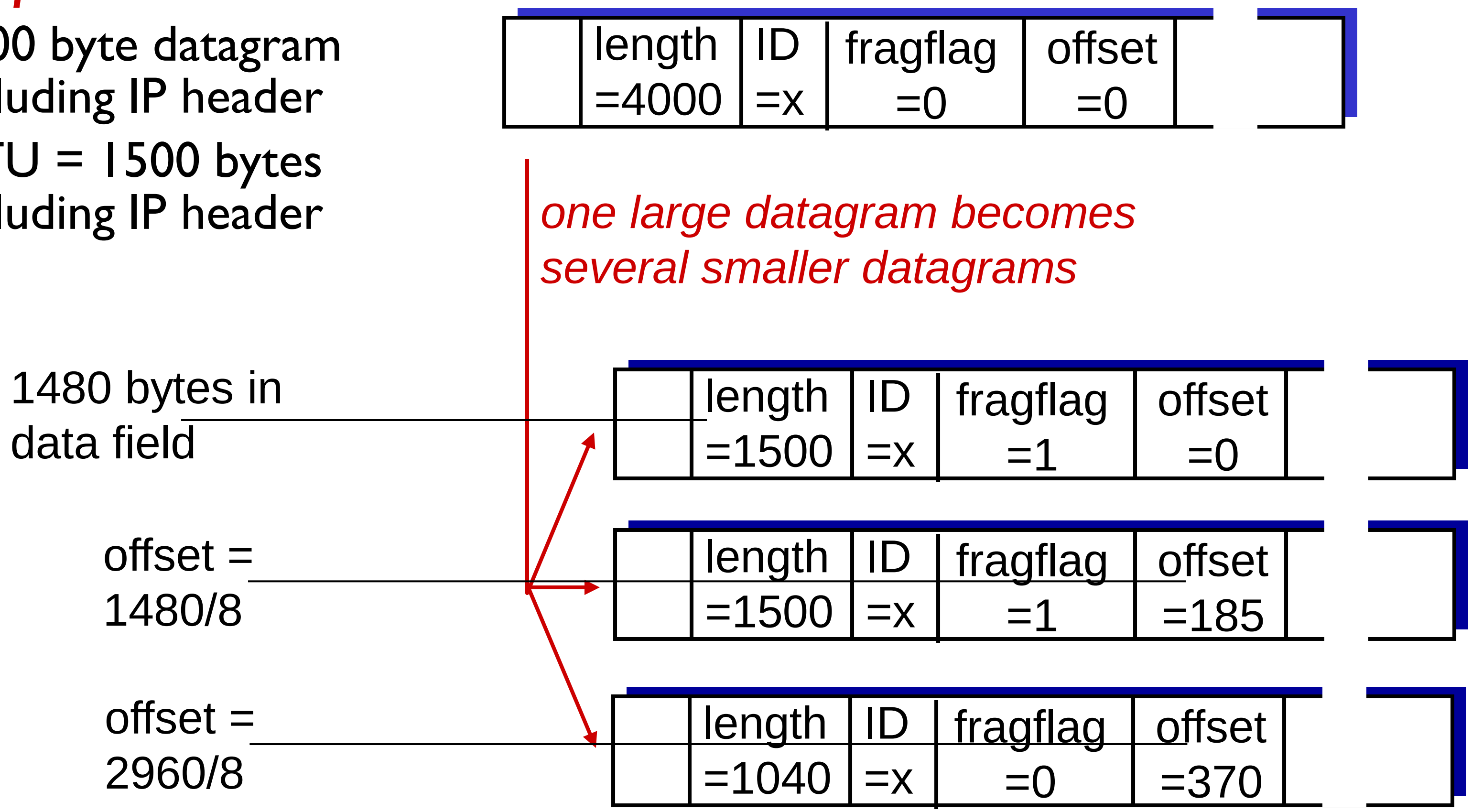
- network links have MTU (max. transfer unit) - largest possible link-level frame
  - different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only at final destination (receiver host)
  - IP header bits used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



IP fragmentation, reassembly

example:

- 4000 byte datagram including IP header
- MTU = 1500 bytes including IP header



IP fragmentation, reassembly

example:

- 8060 byte datagram including IP header
- MTU = 1500 bytes including IP header

	length =8060	ID =x	fragflag =0	offset =0	

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- IPv6

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 typically has one active interface
- *IP addresses associated with each interface*

Address Class	Bit Pattern of First Byte	First Byte Decimal Range	Host Assignment Range in Dotted Decimal
A	0xxxxxxx	1 to 127	1.0.0.1 to 126.255.255.254
B	10xxxxxx	128 to 191	128.0.0.1 to 191.255.255.255.254
C	110xxxxx	192 to 223	192.0.0.1 to 223.255.255.254
D	1110xxxx	224 to 239	224.0.0.1 to 239.255.255.254
E	11110xxx	240 to 255	240.0.0.1 to 255.255.255.255

IP addressing: introduction

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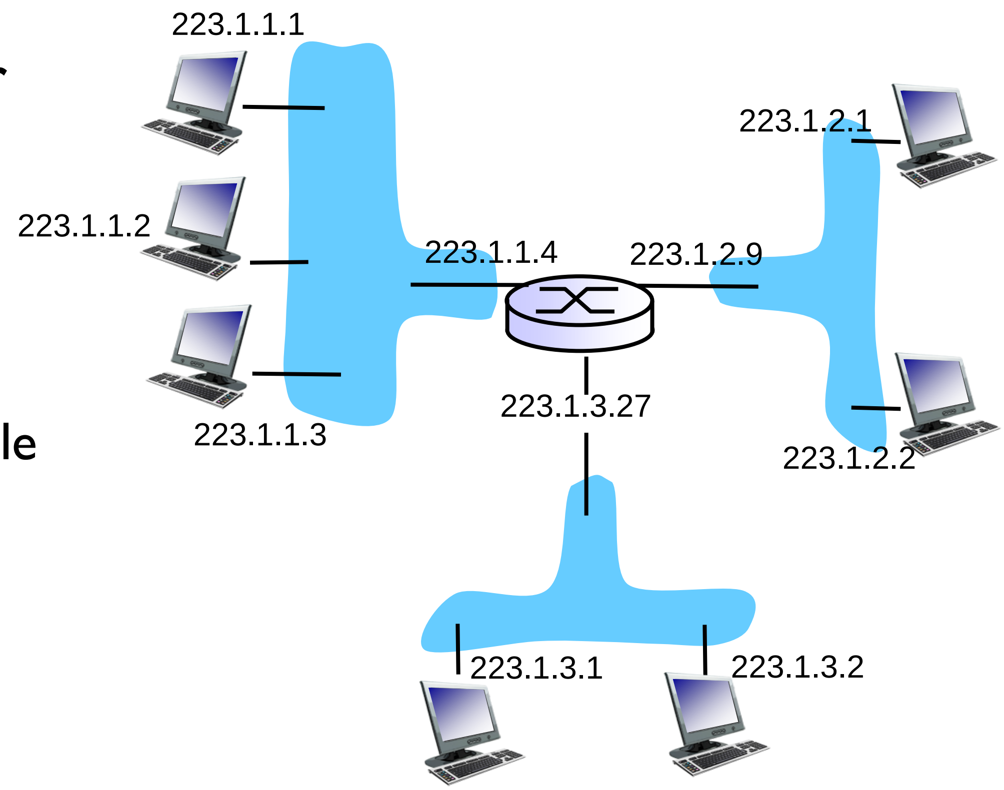
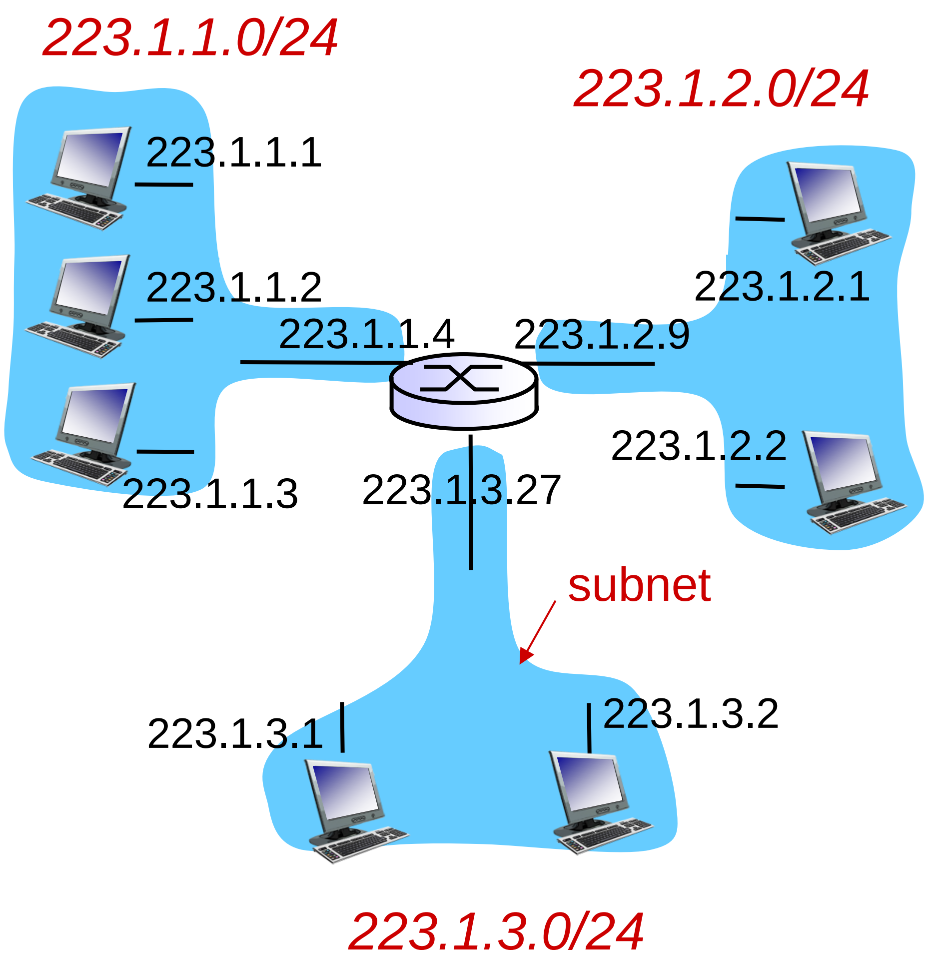


$$223.1.1.1 = \underbrace{11011111}_{223}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}$$

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*



- each isolated network is called a *subnet*

subnet mask: /24

IP addressing: CIDR

CIDR: Classless InterDomain Routing

- subnet portion of address of arbitrary length
- address format: a.b.c.d/x, where x is # of 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?

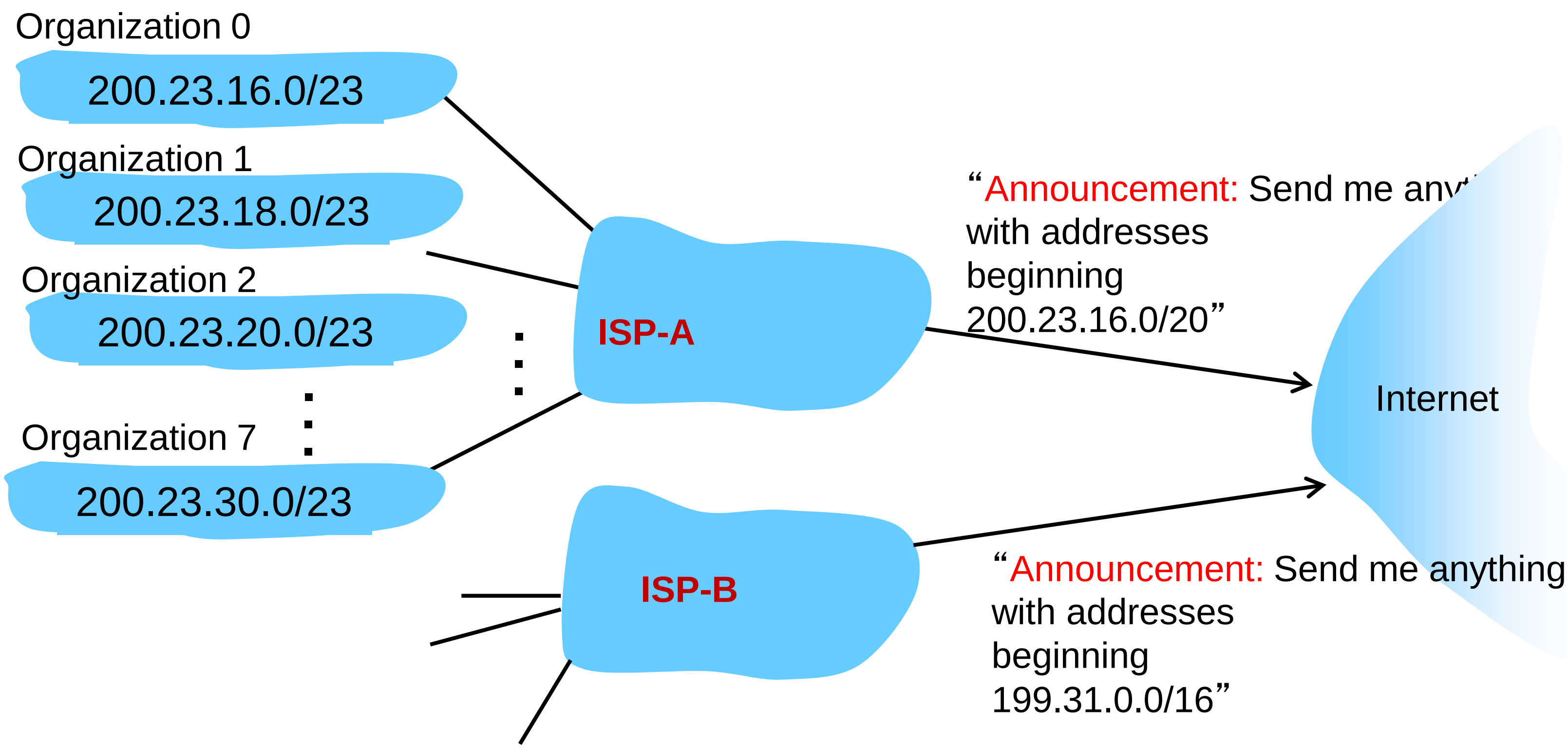
Q: how does *network* get subnet part of IP addr?

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

ISP's block	11001000 00010111 00010000 00000000	200.23.16.0/20
Organization 0	11001000 00010111 0001**000**0 00000000	200.23.16.0/23
Organization 1	11001000 00010111 0001**001**0 00000000	200.23.18.0/23
Organization 2	11001000 00010111 0001**010**0 00000000	200.23.20.0/23
...	....	....
Organization 7	11001000 00010111 0001**111**0 00000000	200.23.30.0/23

Hierarchical addressing: route aggregation

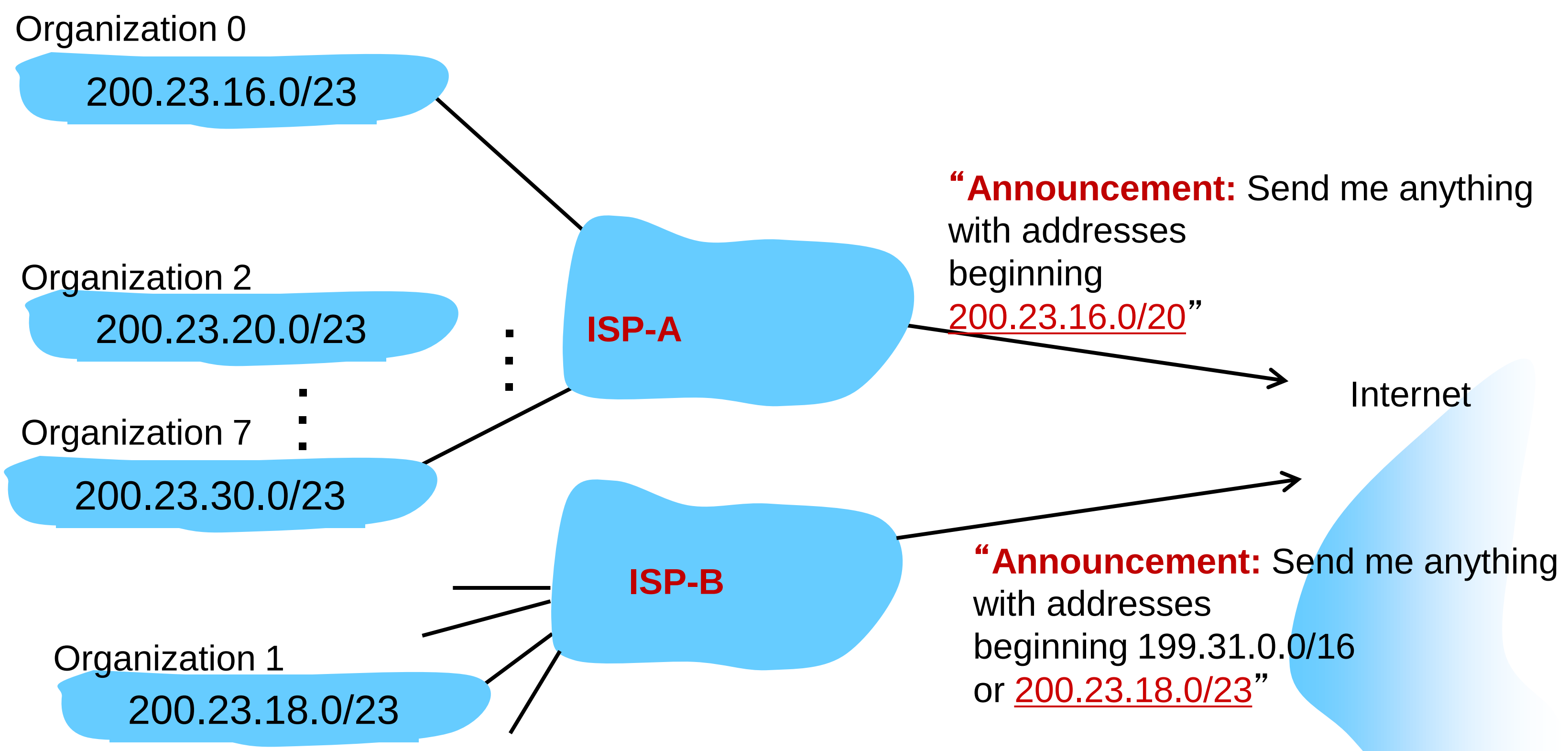
hierarchical addressing allows efficient advertisement of routing information:



Hierarchical addressing: more specific routes

Organization now moved under ISP-B

ISP-B has a more ***specific*** route to Organization 1



ISP-A	11001000 00010111 00010000 00000000	200.23.16.0/20
Organization 1	11001000 00010111 00010010 00000000	200.23.18.0/23

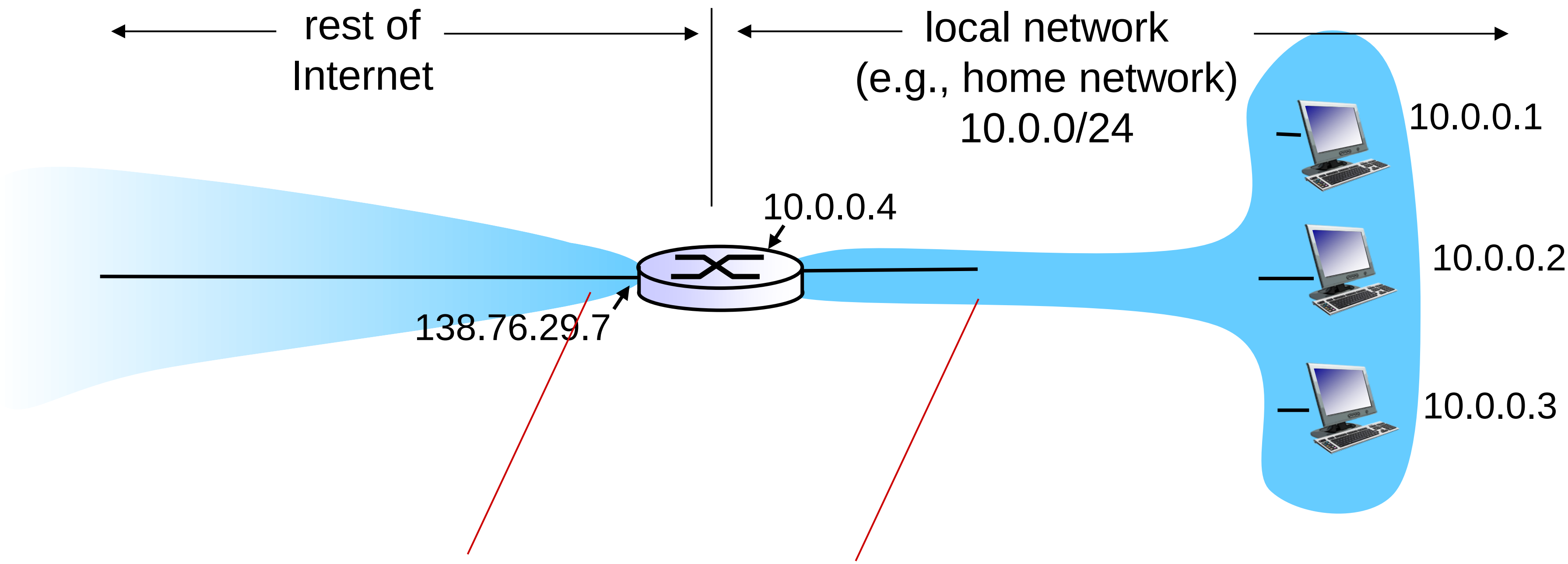
IP addressing: the last word...

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

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 10.0.0/24 address for source, destination (as usual)

NAT: network address translation

motivation: local network uses just one IP address as far as outside world is concerned:

- range of addresses not needed from ISP: just one IP address 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, visible by outside world (a security plus)

NAT: network address translation

implementation: NAT router must:

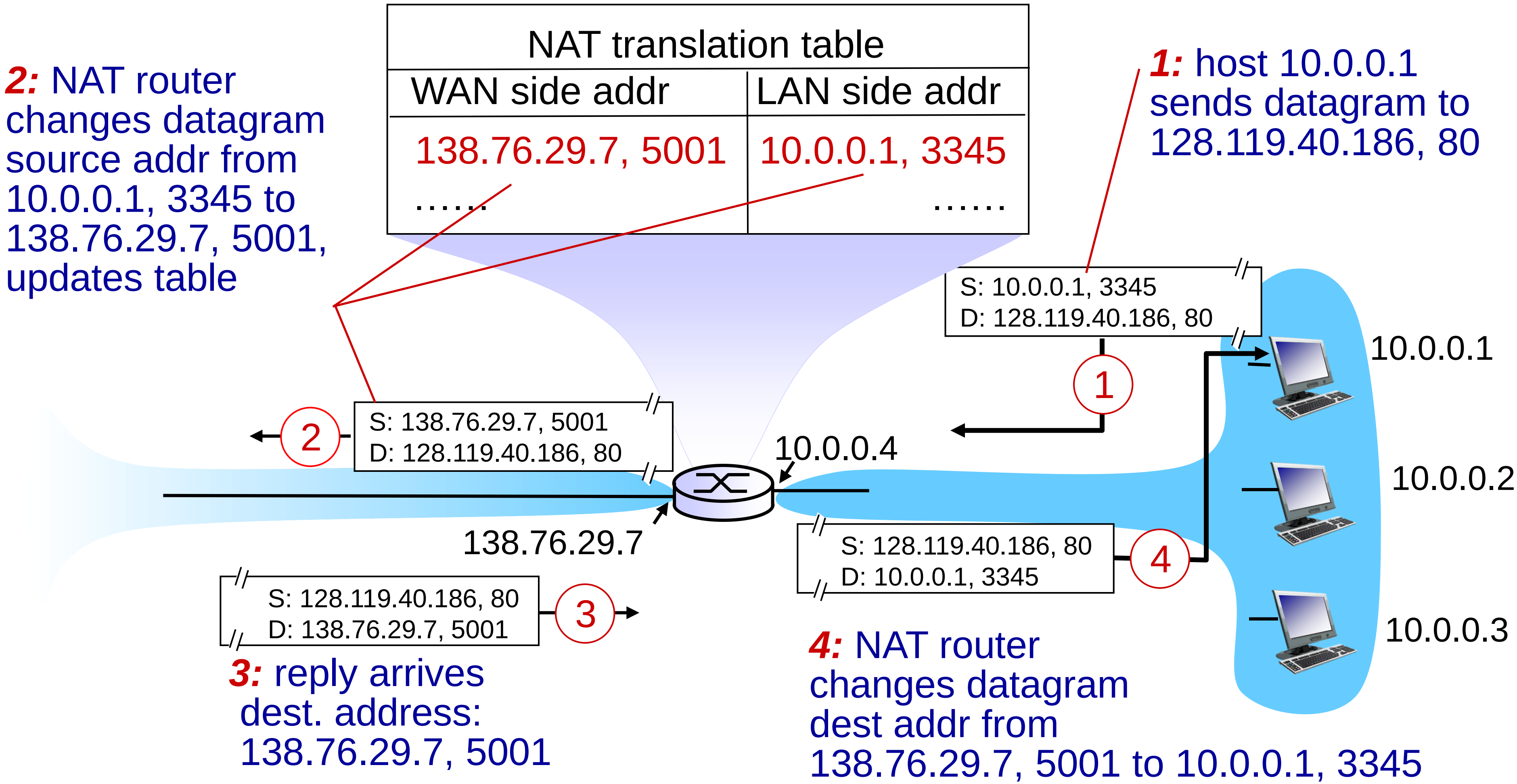
- *outgoing datagrams: replace* (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #)

  . . . 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

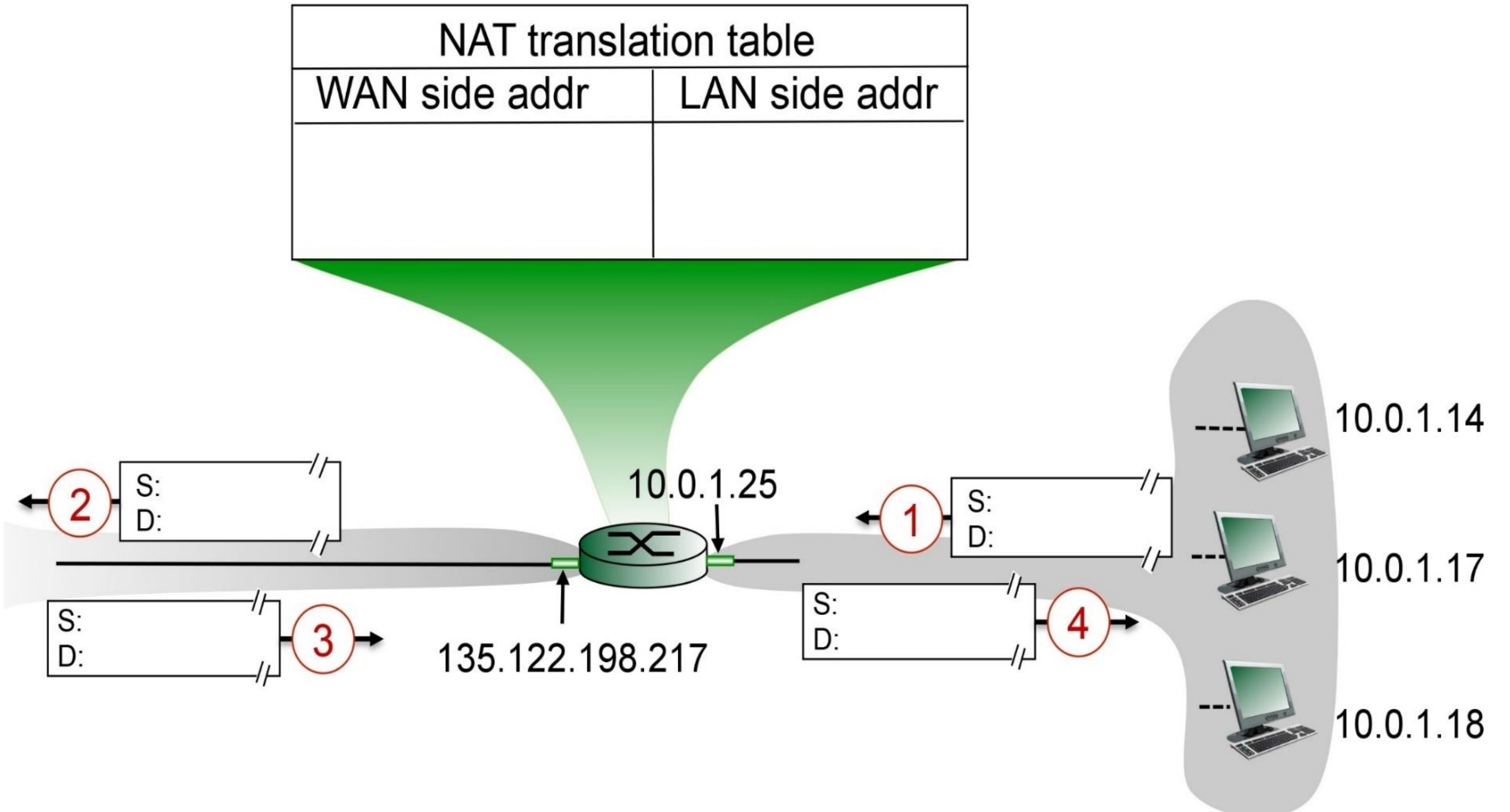


NAT: network address translation

- 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

NAT: network address translation

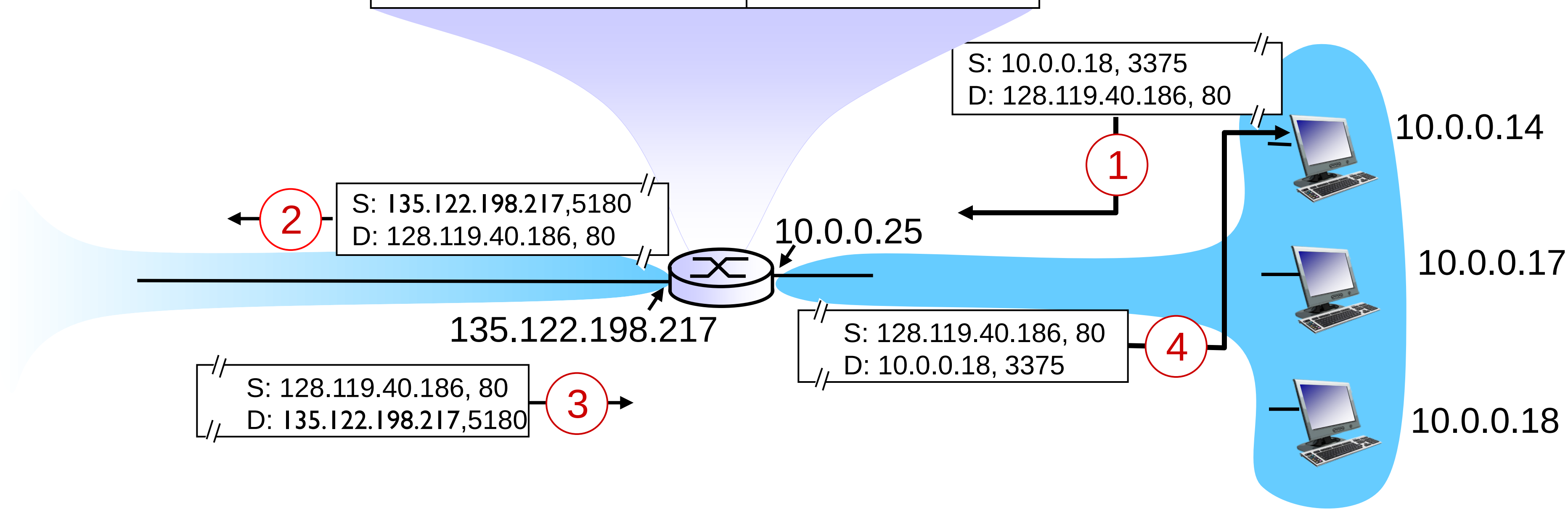
- Assume that the computer with IP address 10.0.1.18, port#3375 wants to communicate with a web server, 128.119.40.186, 80.



NAT: network address translation

NAT translation table

WAN side addr	LAN side addr
135.122.198.217, 3214	10.0.1.18, 3375
......	......



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Chapter 4: *done!*

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4.2 What's inside a router

4.3 IP: Internet Protocol

- datagram format
- fragmentation
- IPv4 addressing
- NAT

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

Answer: by the control plane (next chapter)