

Network layer: [Slides lightly modified from Kurose & Ross]

Chapter: Network Layer: 4-1

- Network layer: overview

- data plane
- control plane

- What's inside a router

- input ports, switching, output ports
- buffer management, scheduling

- IP: the Internet Protocol

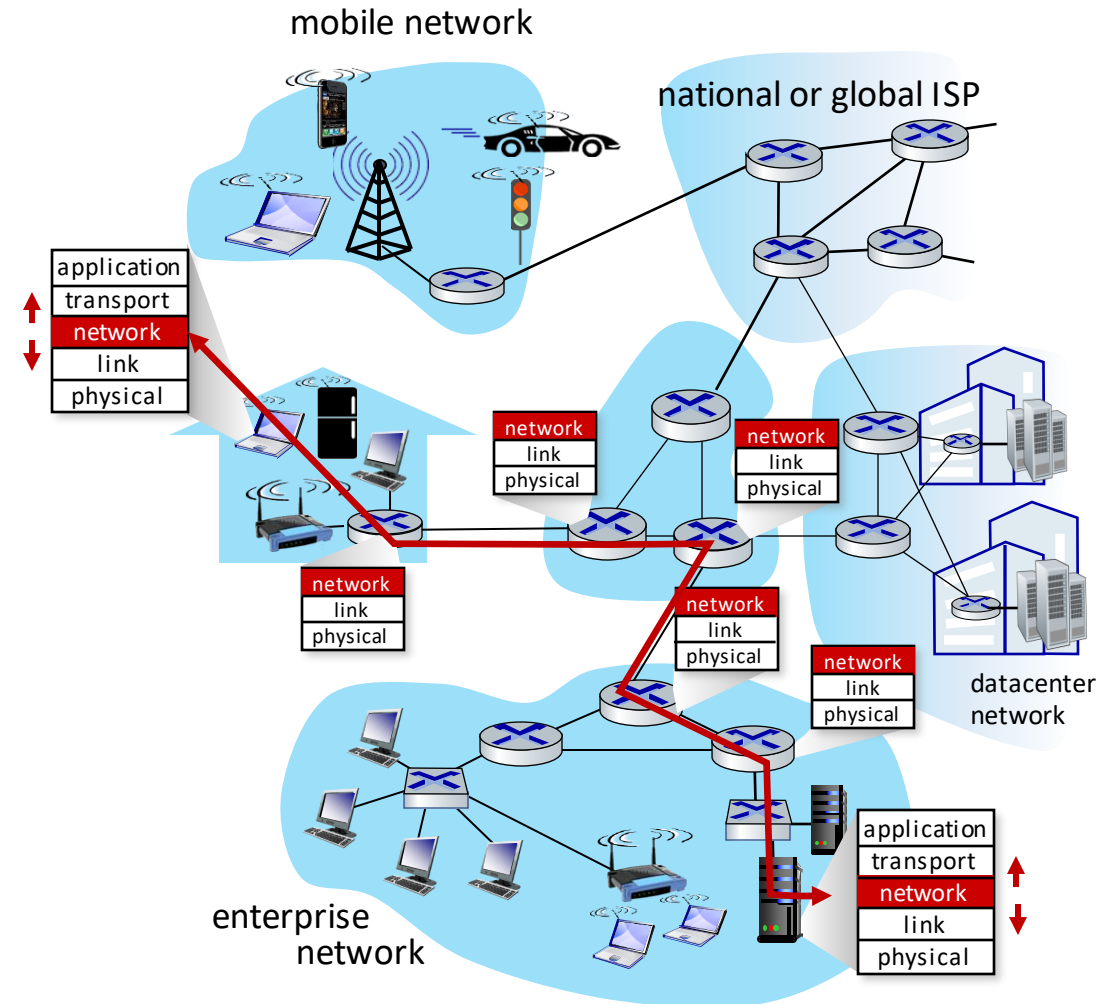
- datagram format
- addressing
- network address translation
- IPv6



- Generalized Forwarding, SDN
 - Match+action
 - OpenFlow: match+action in action
- Middleboxes

Network-layer services and protocols

- transport segment from sending to receiving host
 - **sender:** encapsulates segments into datagrams, passes to link layer
 - **receiver:** delivers segments to transport layer protocol
- network layer protocols in *every Internet device*: hosts, routers
- **routers:**
 - examines header fields in all IP datagrams passing through it
 - moves datagrams from input ports to output ports to transfer datagrams along end-end path



Two key network-layer functions

network-layer functions:

- *forwarding*: move packets from a router's input link to appropriate router output link
- *routing*: determine route taken by packets from source to destination
 - *routing algorithms*

analogy: taking a trip

- *forwarding*: process of getting through single interchange
- *routing*: process of planning trip from source to destination



forwarding



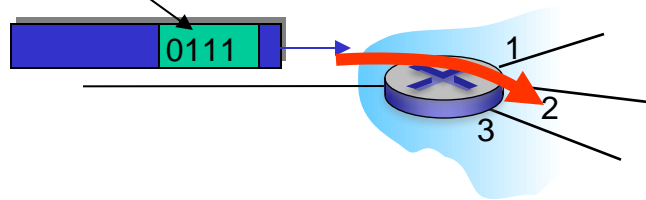
routing

Network layer: data plane, control plane

Data plane:

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

values in arriving
packet header

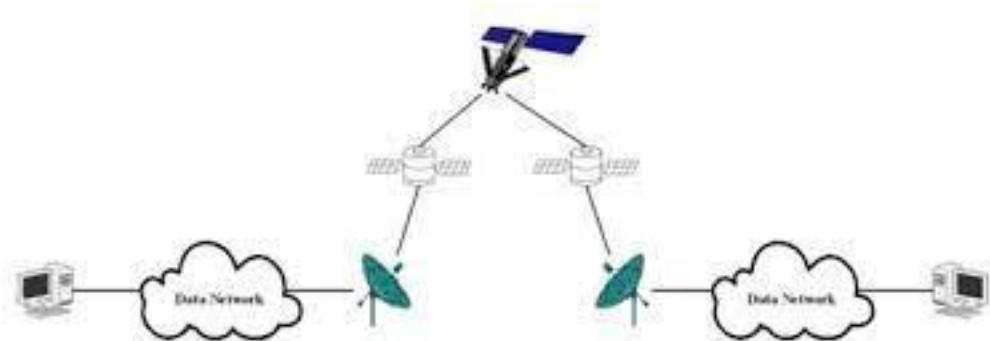
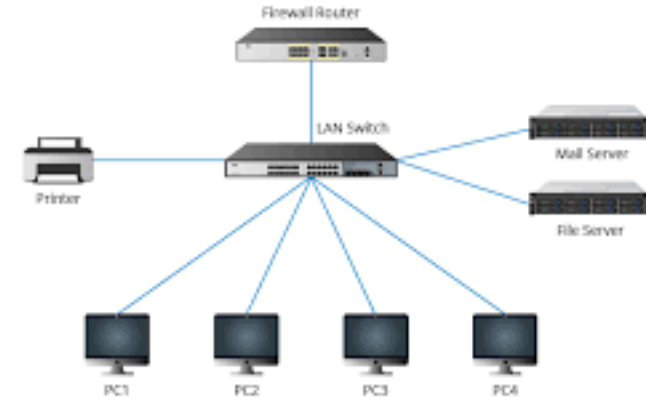


Control plane

- *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

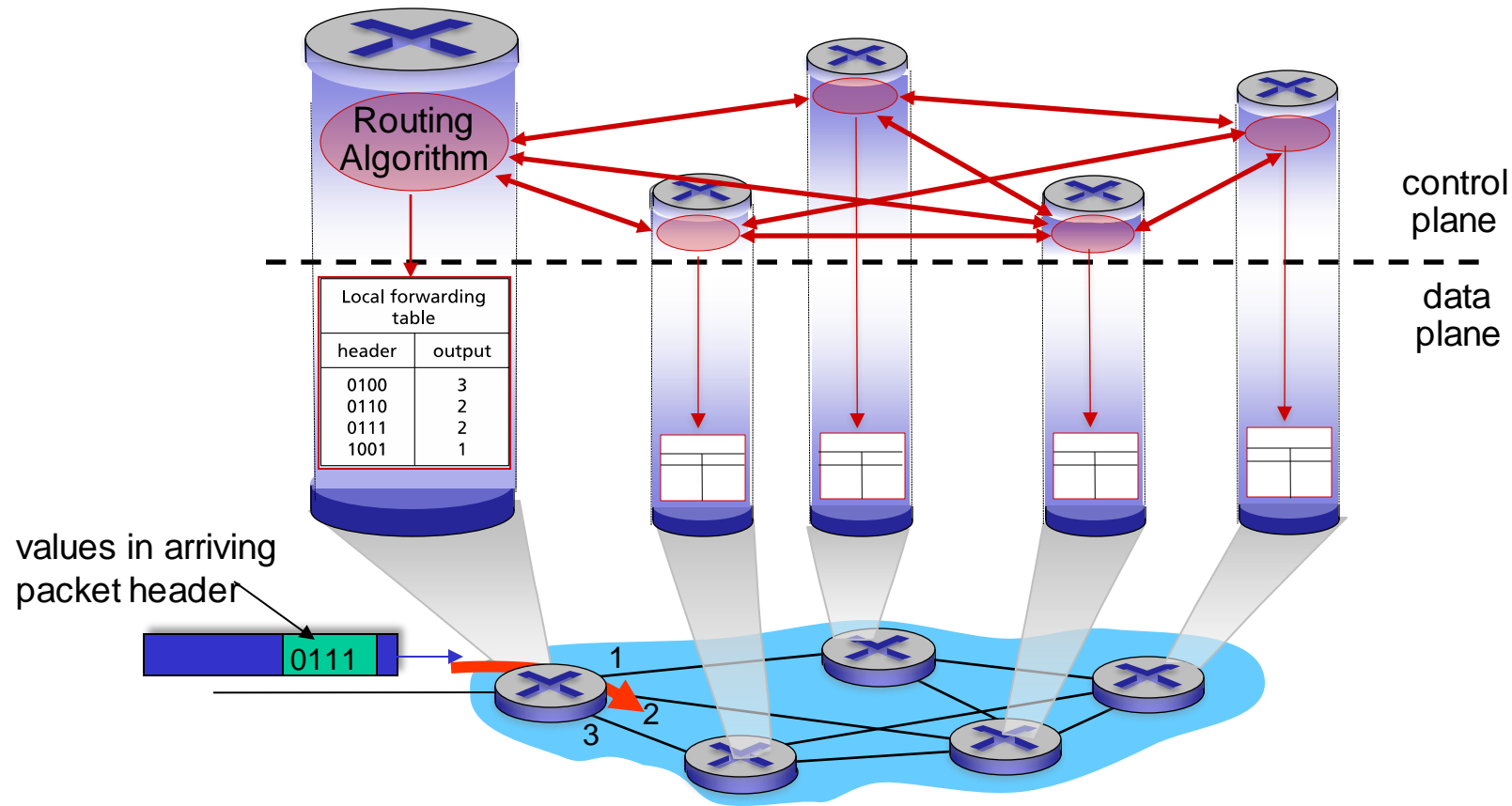
Access Networks

- If access network is “switched”
 - Just like any other packet-switched network
 - Layer 2 (switched on Mac addresses)
- If the access network is *shared* medium, then we need to figure out how to share the medium
 - Wireless (eg WiFi, Satellite)
 - Classical ethernet



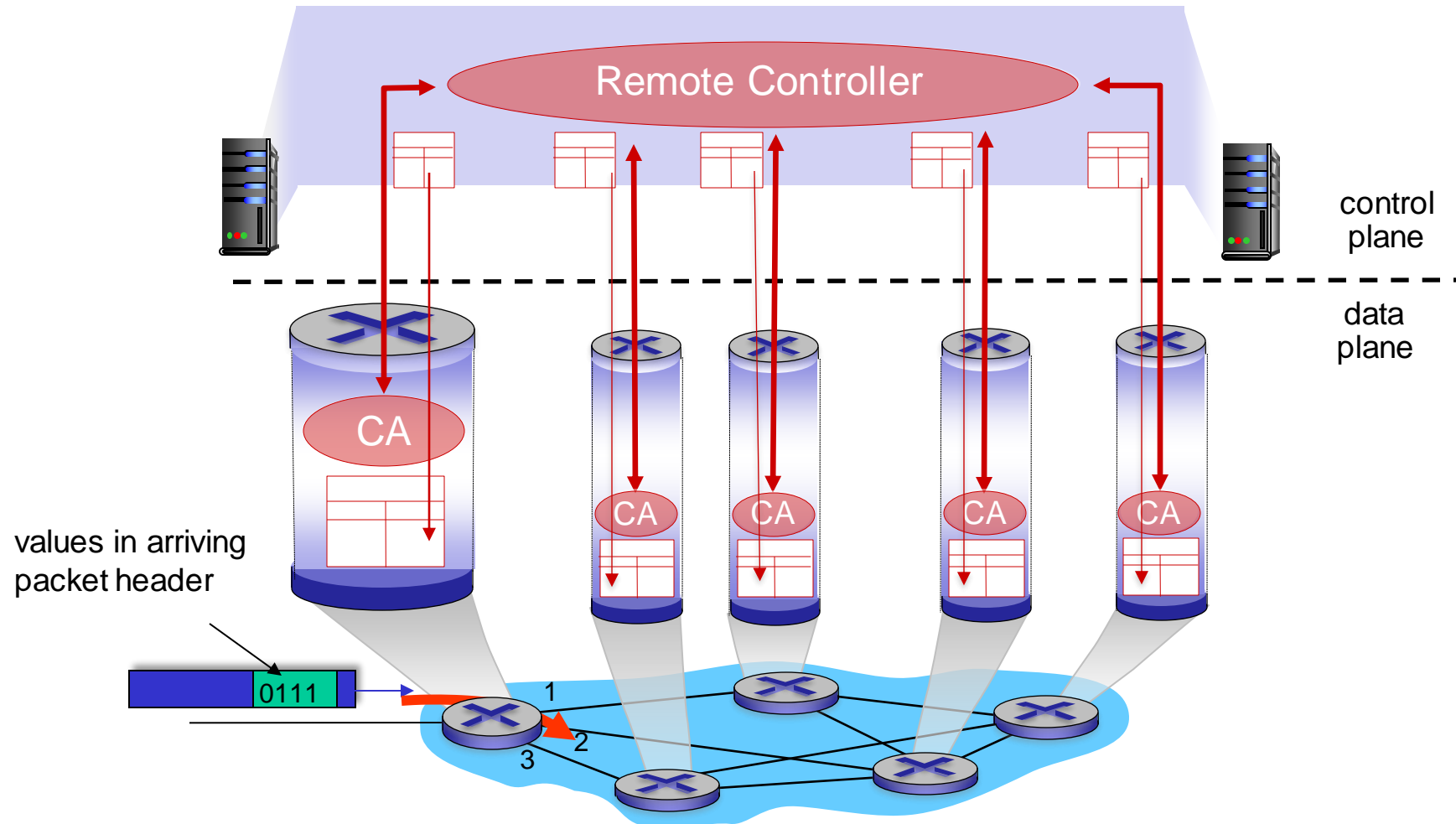
Per-router control plane

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



Software-Defined Networking (SDN) control plane

Remote controller 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 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 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

Reflections on best-effort service:

- **simplicity of mechanism** has allowed Internet to be widely deployed adopted
- sufficient **provisioning of bandwidth** allows performance of real-time applications (e.g., interactive voice, video) to be “good enough” for “most of the time”
- **replicated, application-layer distributed services** (datacenters, content distribution networks) connecting close to clients’ networks, allow services to be provided from multiple locations
- congestion control of “elastic” services helps

It's hard to argue with success of best-effort service model

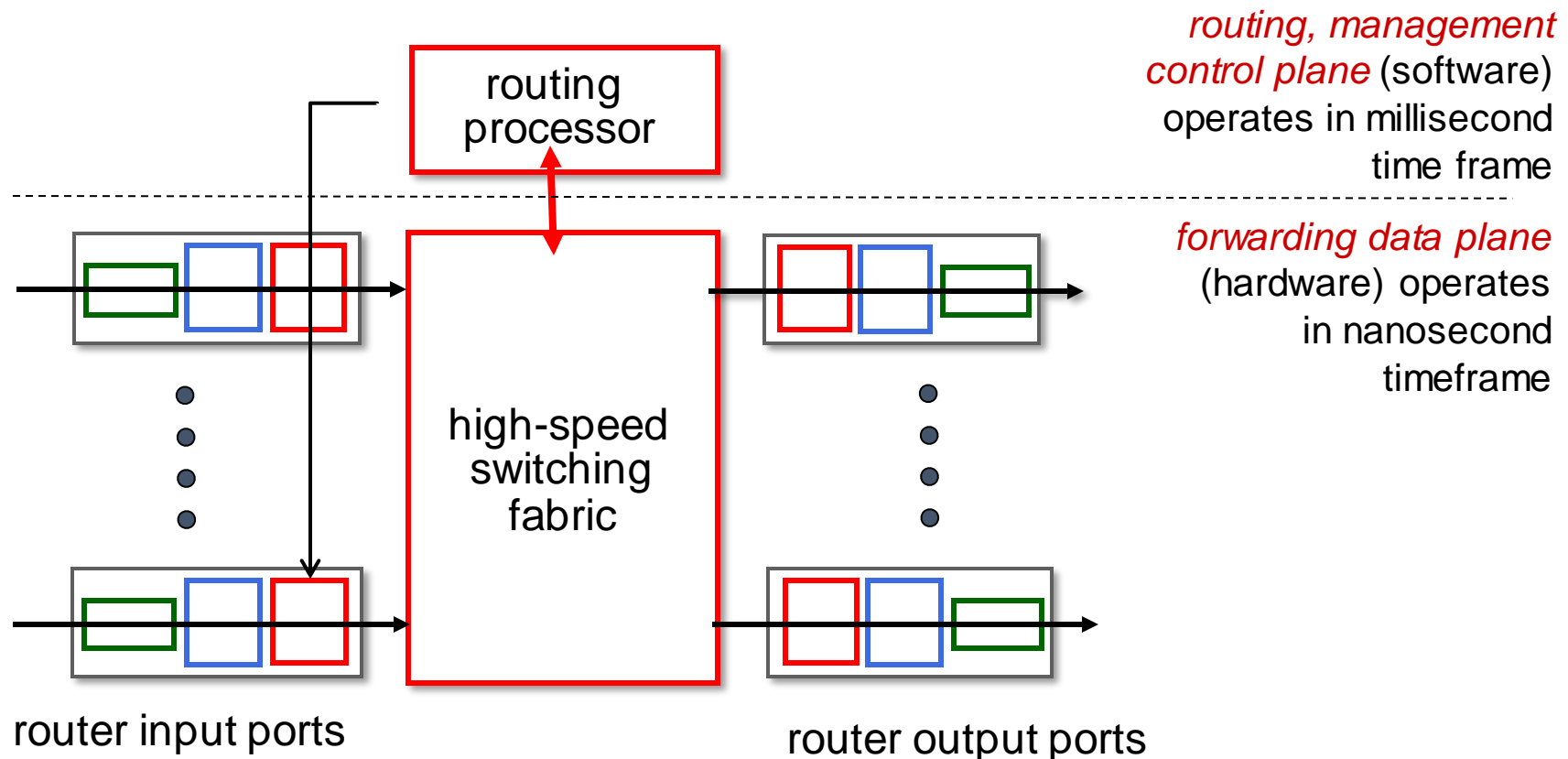
Network layer: “data plane” roadmap

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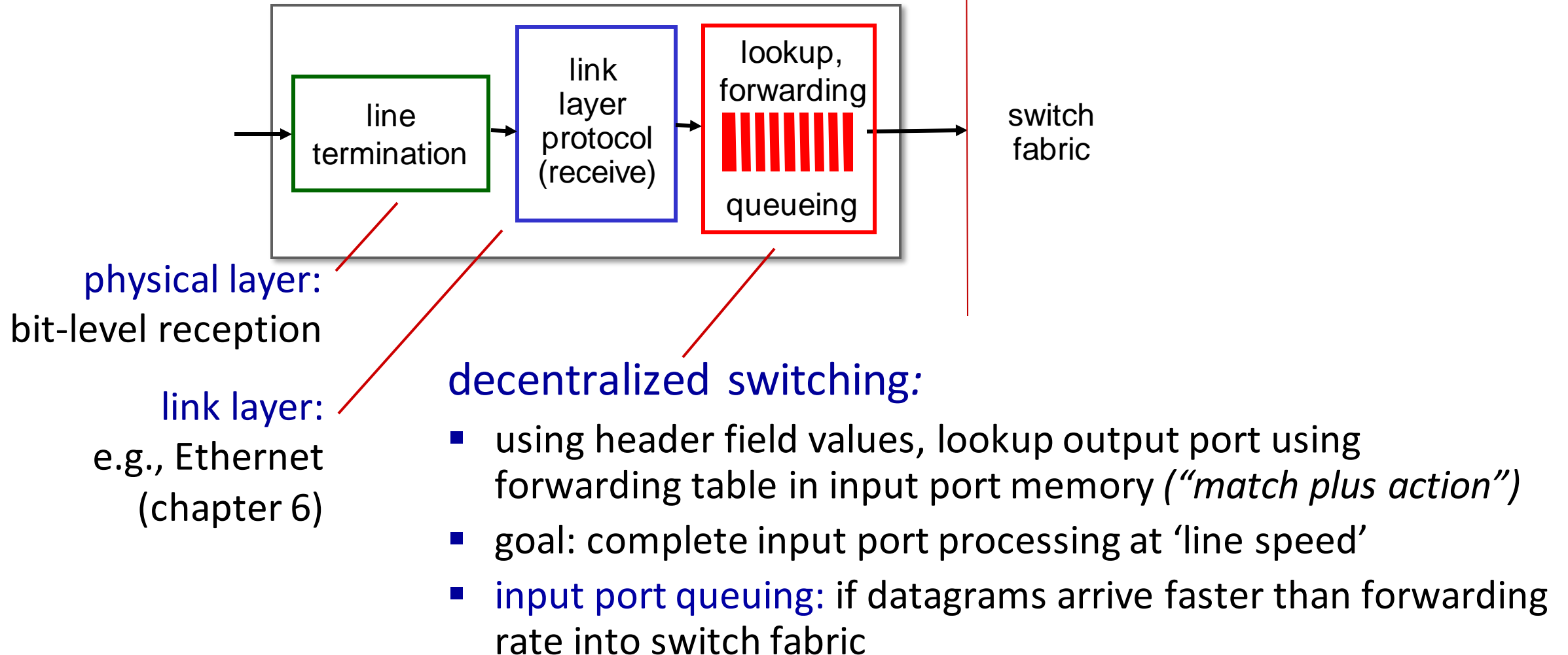


Router architecture overview

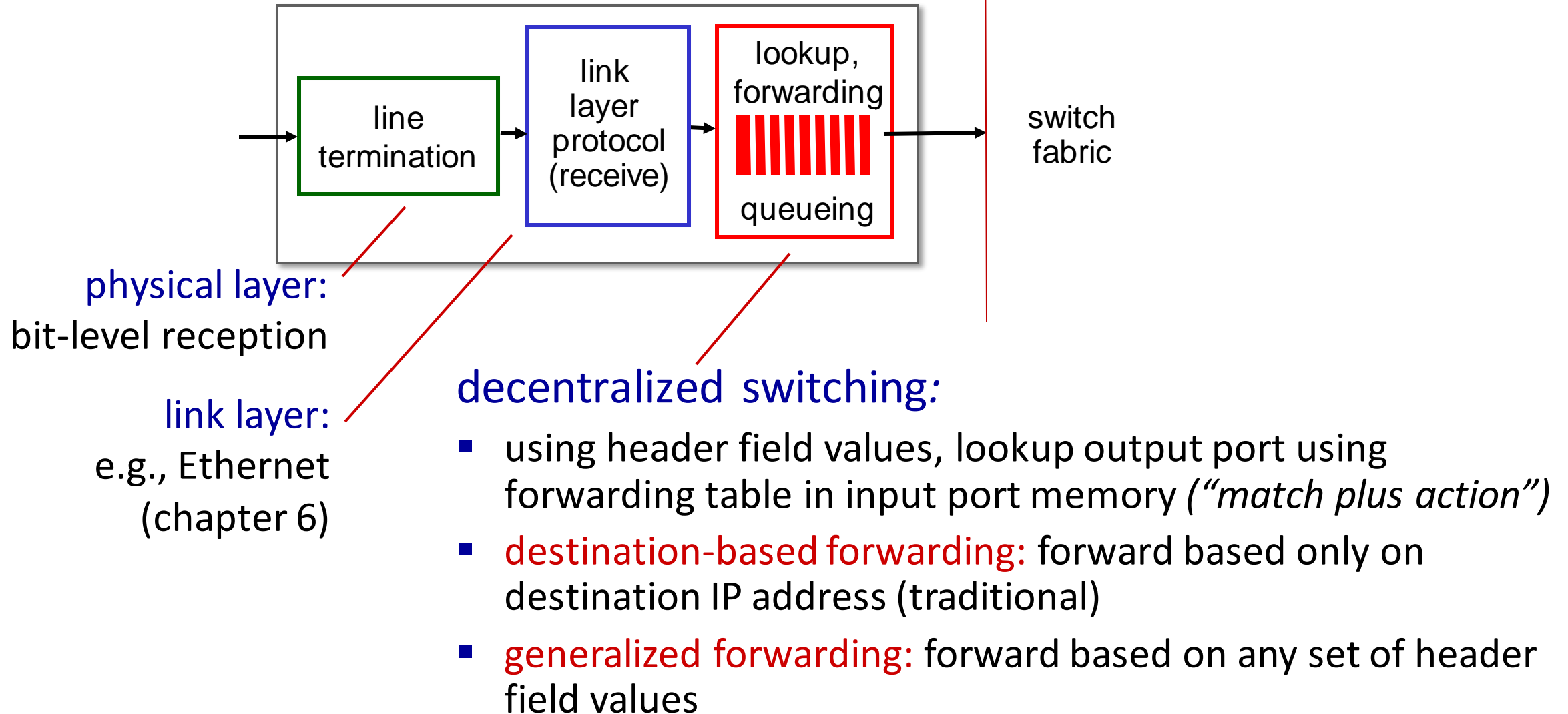
high-level view of generic router architecture:



Input port functions



Input port functions



Destination-based forwarding

<i>forwarding table</i>	
Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010000 00000100	n 3
11001000 00010111 00010000 00000111	
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
11001000 match! 1 00011*** *****	2
otherwise	3

examples:

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

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match!

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match!

examples:

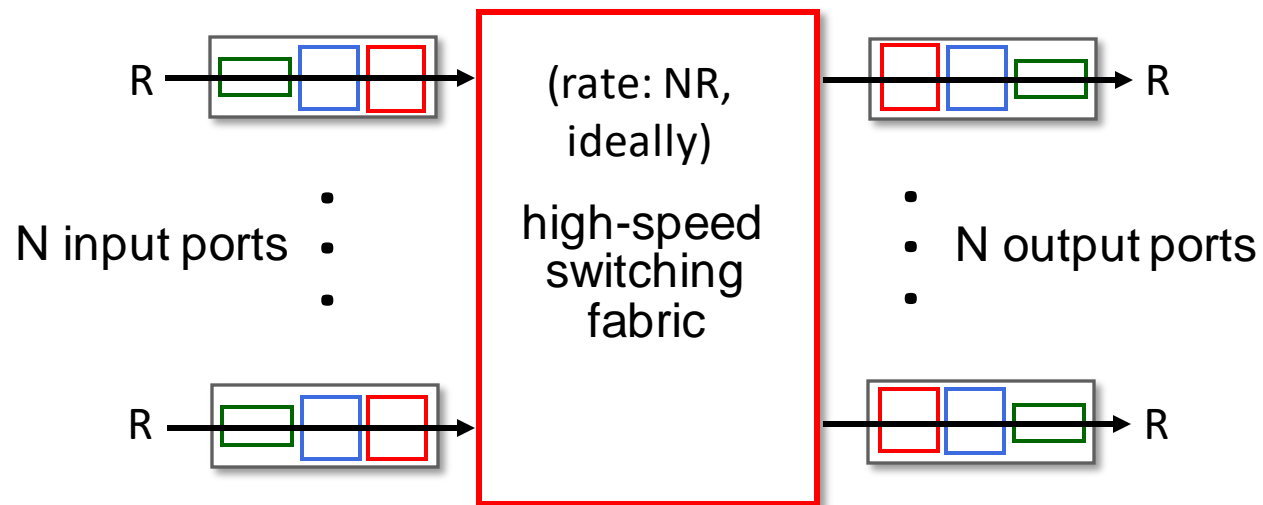
11001000 00010111 00010110 10100001	which interface?
11001000 00010111 00011000 10101010	which interface?

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: ~1M routing table entries in TCAM

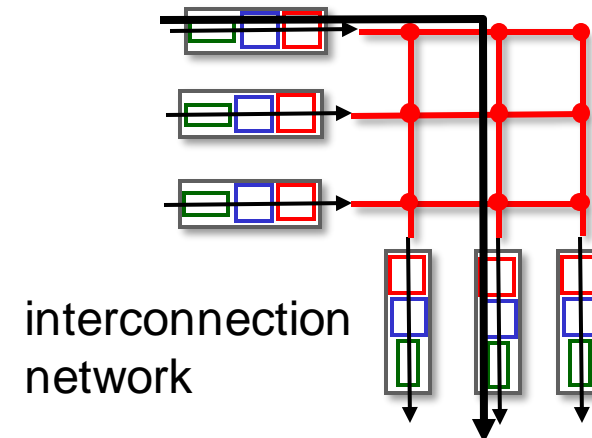
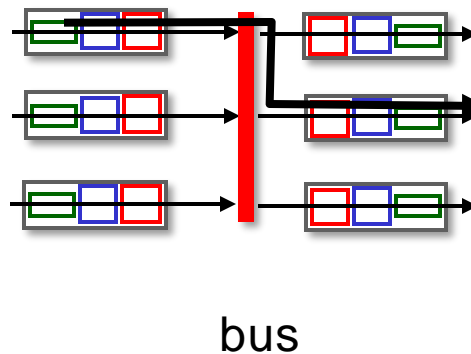
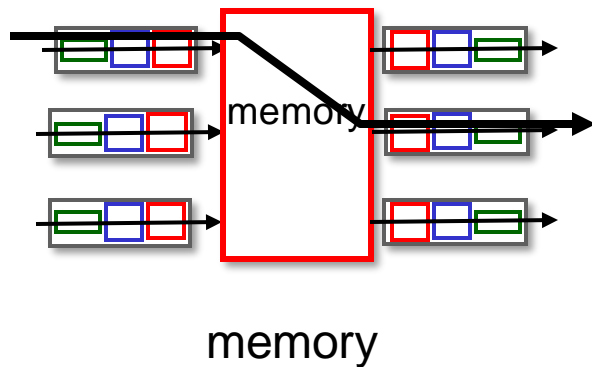
Switching fabrics

- transfer packet from input link to appropriate output link
- **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



Switching fabrics

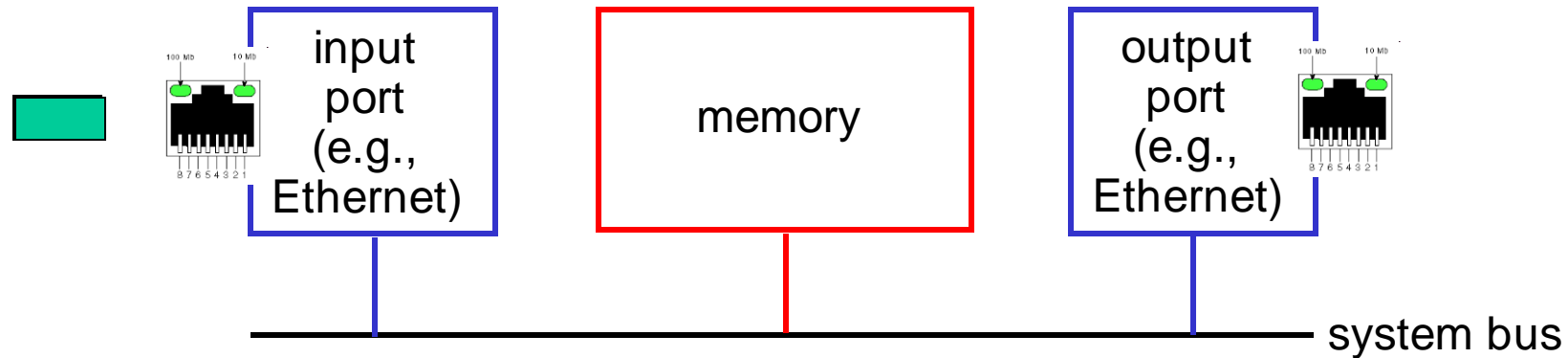
- transfer packet from input link to appropriate output link
- **switching rate**: rate at which packets can be transfer from inputs to outputs
 - often measured as multiple of input/output line rate
 - N inputs: switching rate N times line rate desirable
- three major types of switching fabrics:



Switching via memory

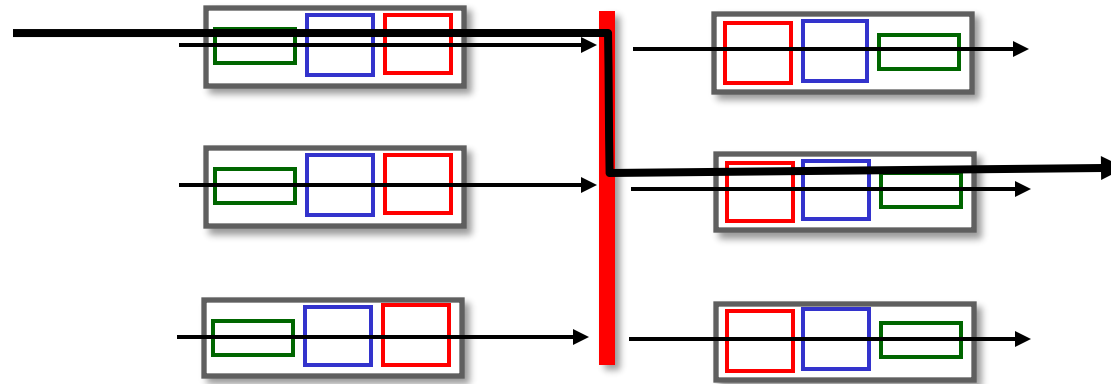
first generation routers:

- 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)



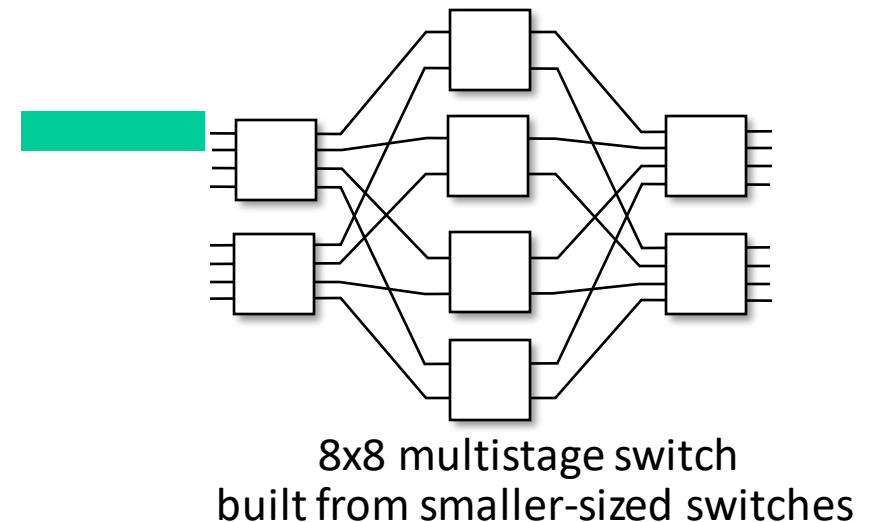
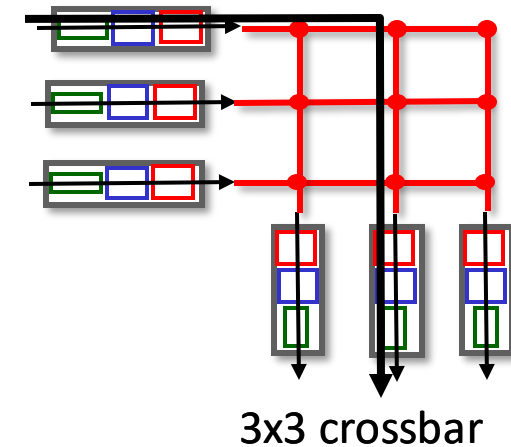
Switching via a bus

- 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 routers



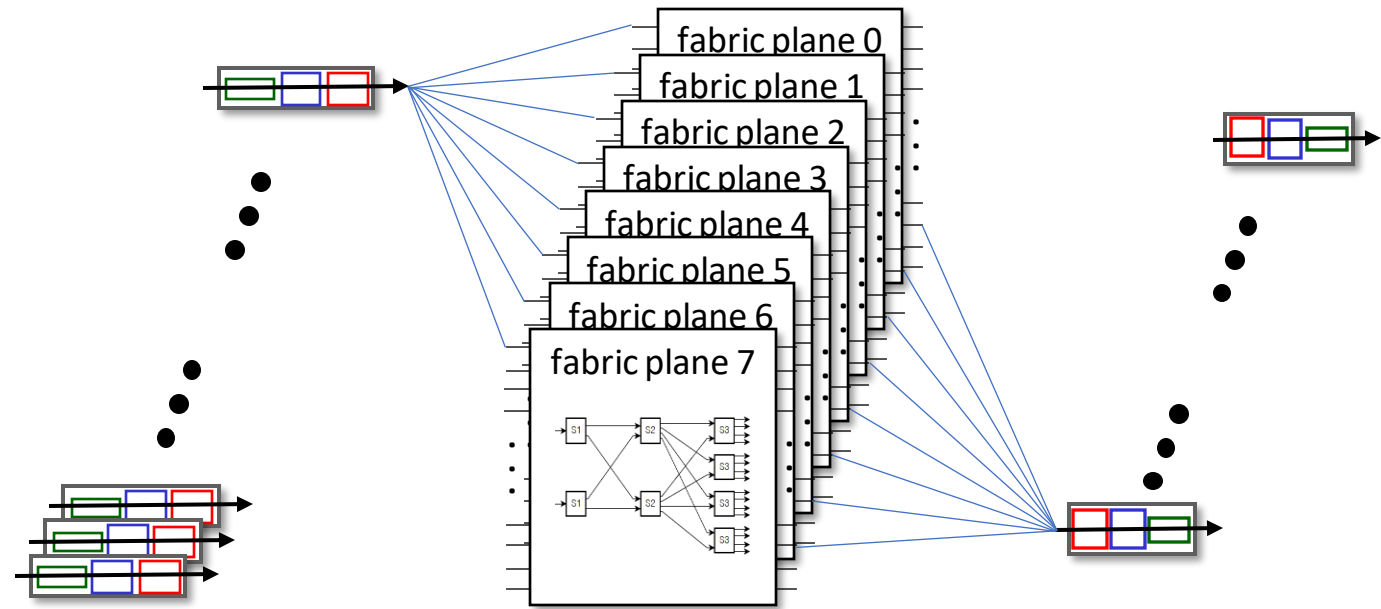
Switching via interconnection network

- Crossbar, Clos networks, other interconnection nets initially developed to connect processors in multiprocessor
- **multistage switch**: $n \times n$ switch from multiple stages of smaller switches
- **exploiting parallelism**:
 - fragment datagram into fixed length cells on entry
 - switch cells through the fabric, reassemble datagram at exit



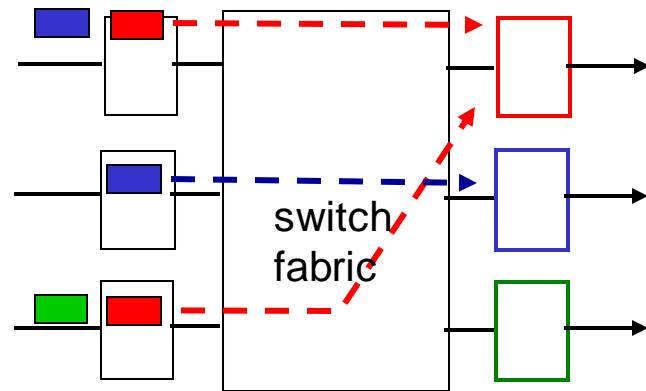
Switching via interconnection network

- scaling, using multiple switching “planes” in parallel:
 - speedup, scaleup via parallelism
- Cisco CRS router:
 - basic unit: 8 switching planes
 - each plane: 3-stage interconnection network
 - up to 100's Tbps switching capacity

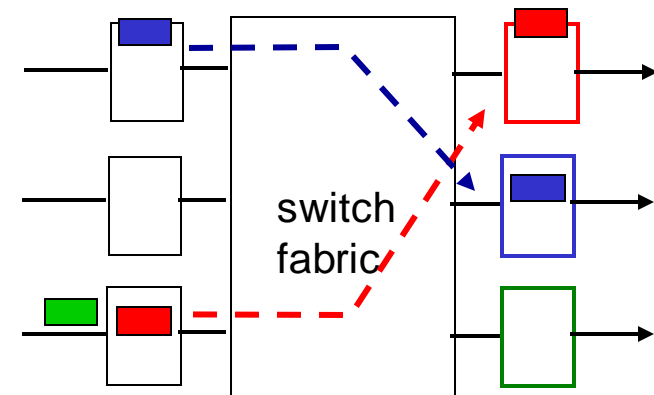


Input port queuing

- If switch 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

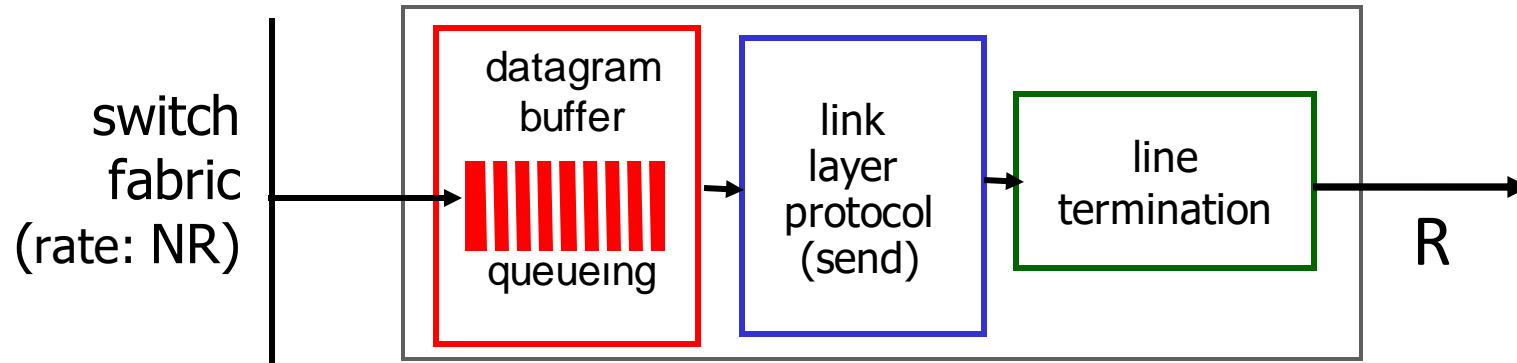


output port contention: only one red datagram can be transferred. lower red packet is *blocked*



one packet time later: green packet experiences HOL blocking

Output port queuing



This is a really important slide

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

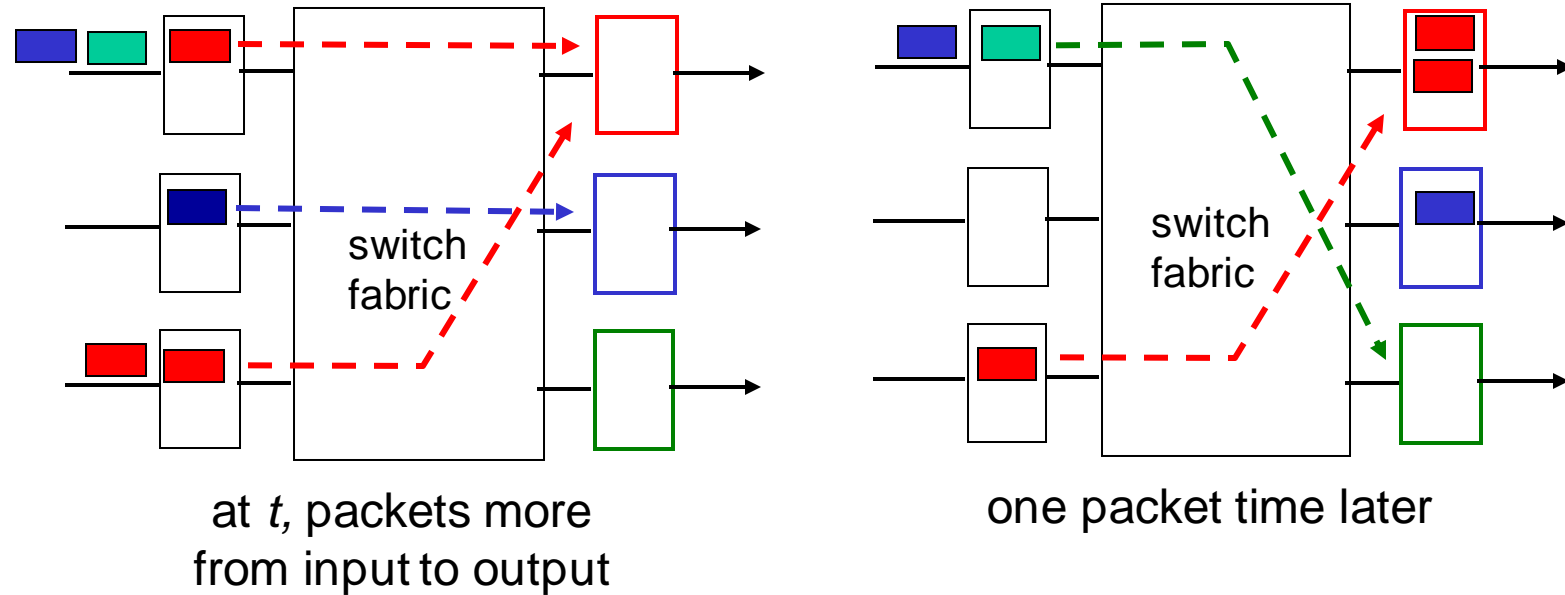


Datagrams can be lost due to congestion, lack of buffers



Priority scheduling – who gets best performance, network neutrality

Output port queuing



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

How much buffering?

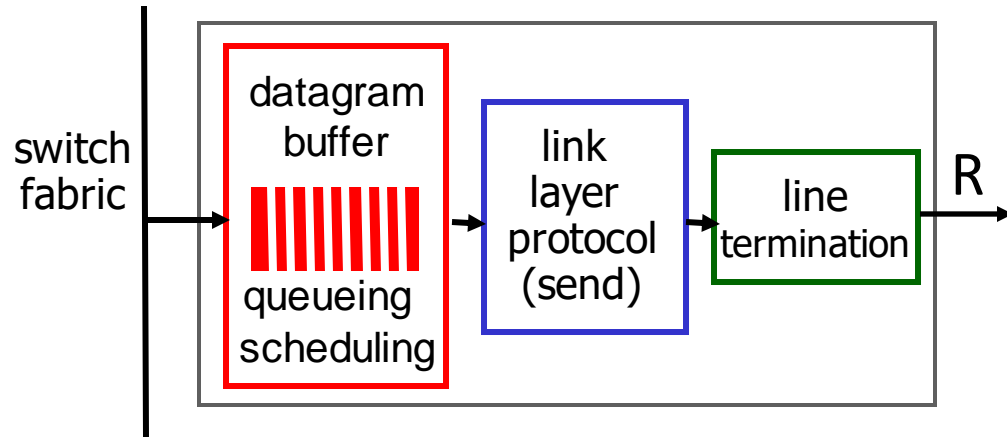
- RFC 3439 rule of thumb: average buffering equal to “typical” RTT (say 250 msec) times link capacity C
 - e.g., $C = 10$ Gbps link: 2.5 Gbit buffer

- more recent recommendation: with N flows, buffering equal to

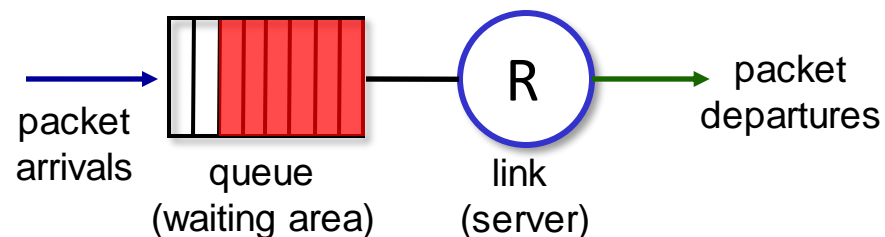
$$\frac{RTT \cdot C}{\sqrt{N}}$$

- but *too* much buffering can increase delays (particularly in home routers)
 - long RTTs: poor performance for realtime apps, sluggish TCP response
 - recall delay-based congestion control: “keep bottleneck link just full enough (busy) but no fuller”

Buffer Management



Abstraction: queue



buffer management:

- **drop**: which packet to add, drop when buffers are full
 - **tail drop**: drop arriving packet
 - **priority**: drop/remove on priority basis
- **marking**: which packets to mark to signal congestion (ECN, RED)

Packet Scheduling: FCFS

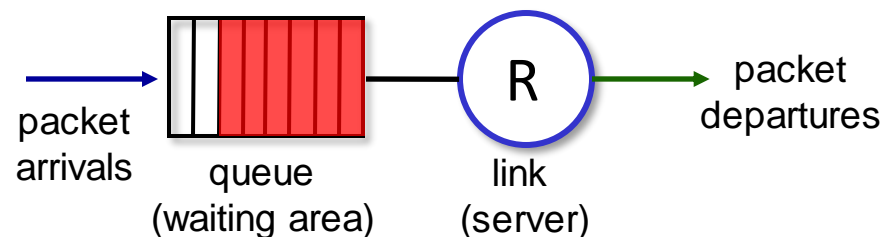
packet scheduling: deciding which packet to send next on link

- first come, first served
- priority
- round robin
- weighted fair queueing

FCFS: packets transmitted in order of arrival to output port

- also known as: First-in-first-out (FIFO)
- real world examples?

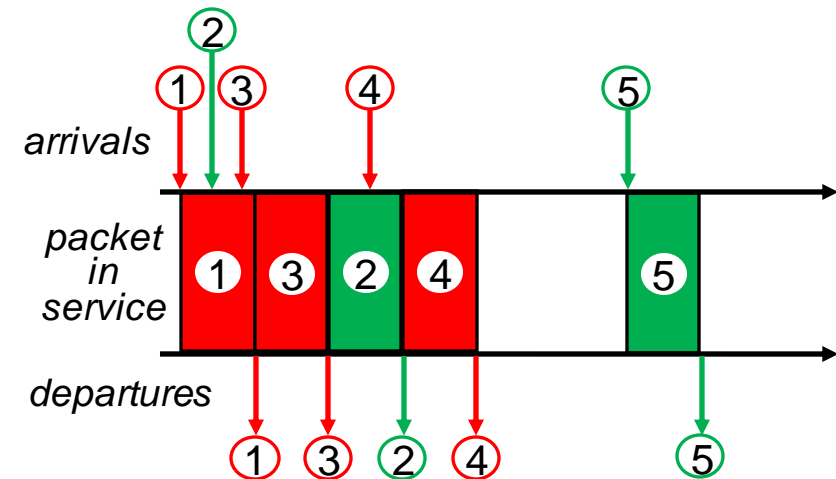
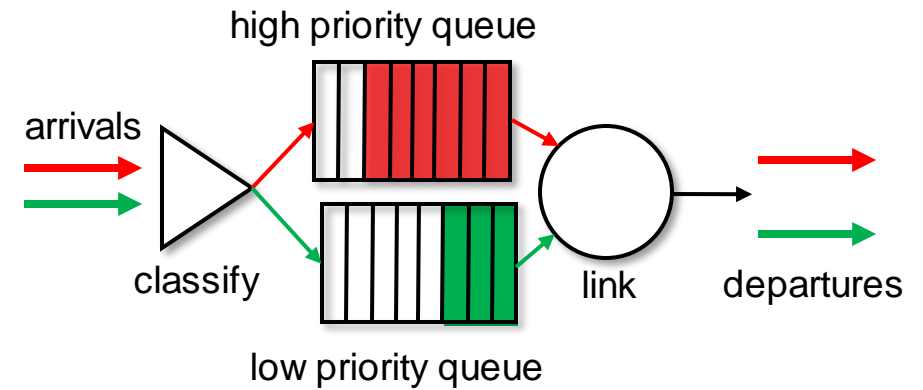
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Scheduling policies: priority

Priority scheduling:

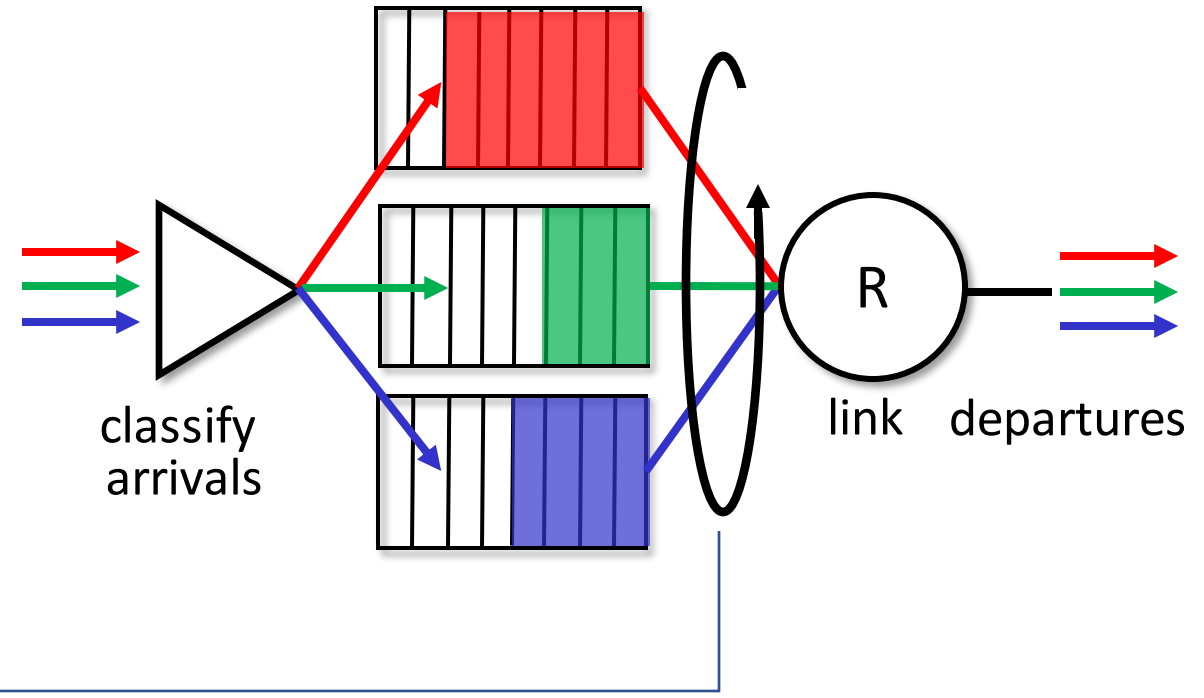
- arriving traffic classified, queued by class
 - any header fields can be used for classification
- send packet from highest priority queue that has buffered packets
 - FCFS within priority class



Scheduling policies: round robin

Round Robin (RR) scheduling:

- arriving traffic classified, queued by class
 - any header fields can be used for classification
- server cyclically, repeatedly scans class queues, sending one complete packet from each class (if available) in turn



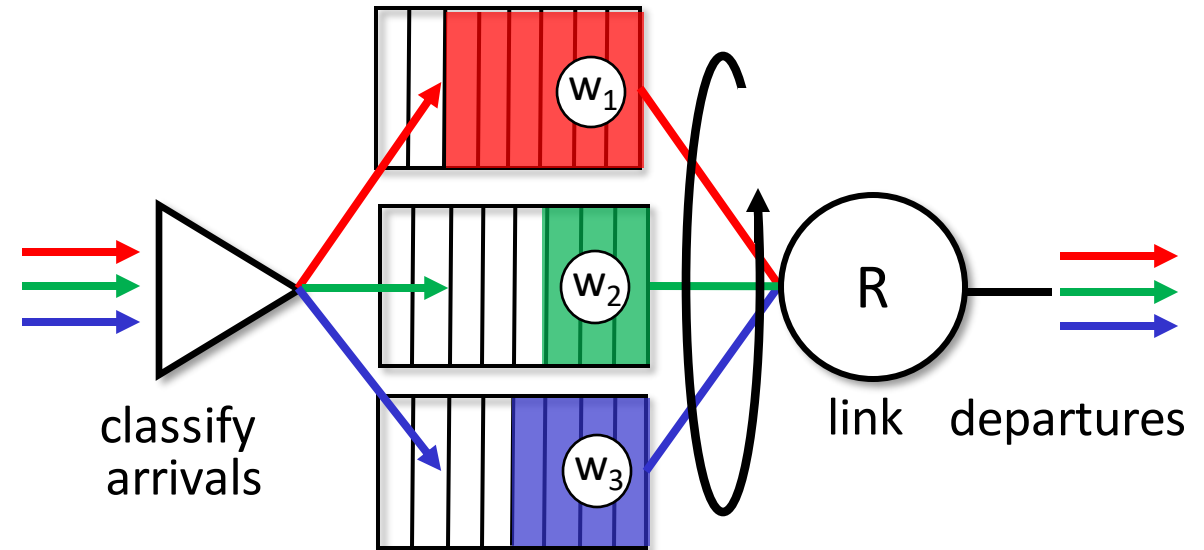
Scheduling policies: weighted fair queueing

Weighted Fair Queueing (WFQ):

- generalized Round Robin
- each class, i , has weight, w_i , and gets weighted amount of service in each cycle:

$$\frac{w_i}{\sum_j w_j}$$

- minimum bandwidth guarantee (per-traffic-class)



Sidebar: Network Neutrality

What is network neutrality?

- *technical*: how an ISP should share/allocation its resources
 - packet scheduling, buffer management are the *mechanisms*
- *social, economic* principles
 - protecting free speech
 - encouraging innovation, competition
- enforced *legal* rules and policies

Different countries have different “takes” on network neutrality

Sidebar: Network Neutrality

2015 US FCC *Order on Protecting and Promoting an Open Internet*: three “clear, bright line” rules:

- **no blocking** ... “shall not block lawful content, applications, services, or non-harmful devices, subject to reasonable network management.”
- **no throttling** ... “shall not impair or degrade lawful Internet traffic on the basis of Internet content, application, or service, or use of a non-harmful device, subject to reasonable network management.”
- **no paid prioritization.** ... “shall not engage in paid prioritization”

ISP: telecommunications or information service?

Is an ISP a “telecommunications service” or an “information service” provider?

- the answer *really* matters from a regulatory standpoint!

US Telecommunication Act of 1934 and 1996:

- *Title II*: imposes “common carrier duties” on *telecommunications services*: reasonable rates, non-discrimination and *requires regulation*
- *Title I*: applies to *information services*:
 - no common carrier duties (*not regulated*)
 - but grants FCC authority “... as may be necessary in the execution of its functions”⁴

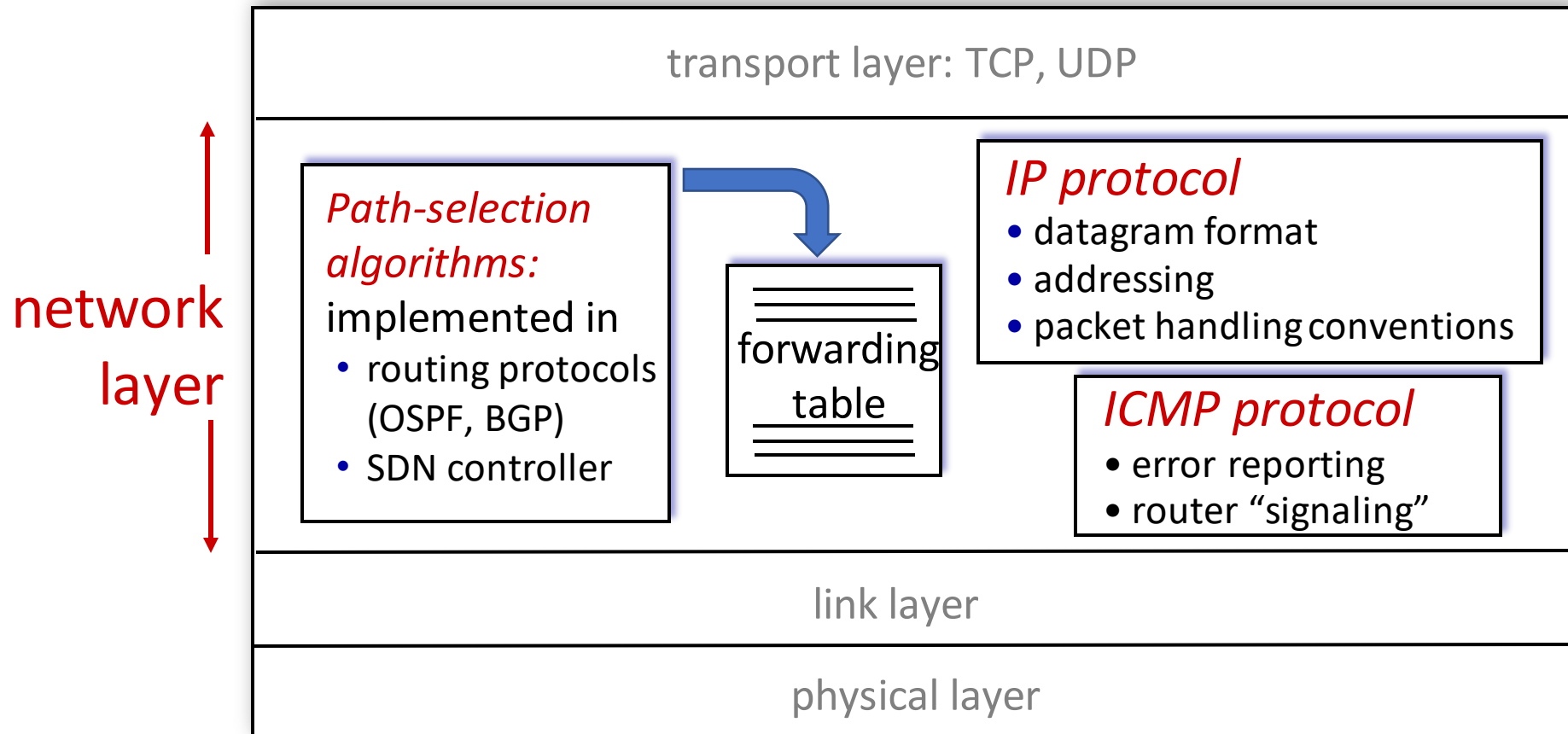
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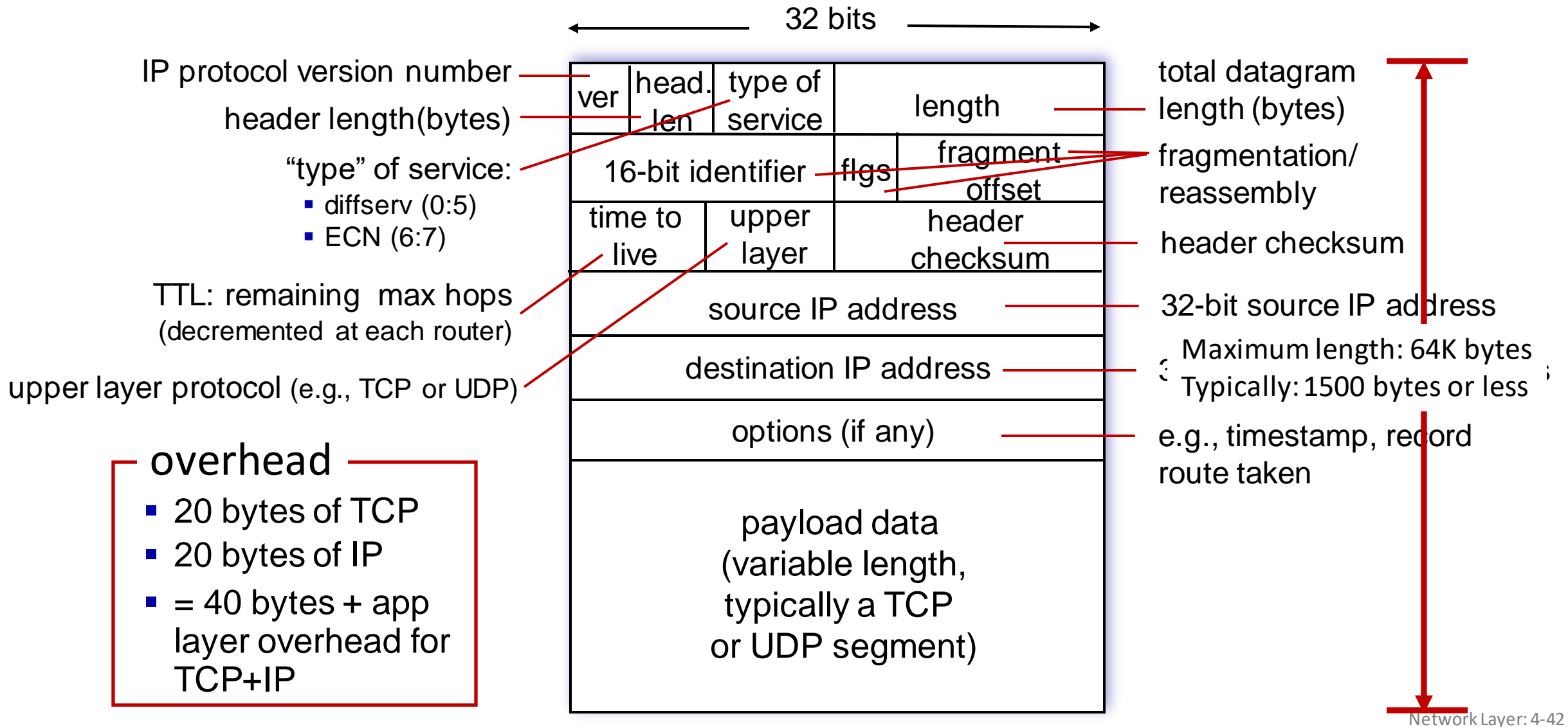


Network Layer: Internet

host, router network layer functions:

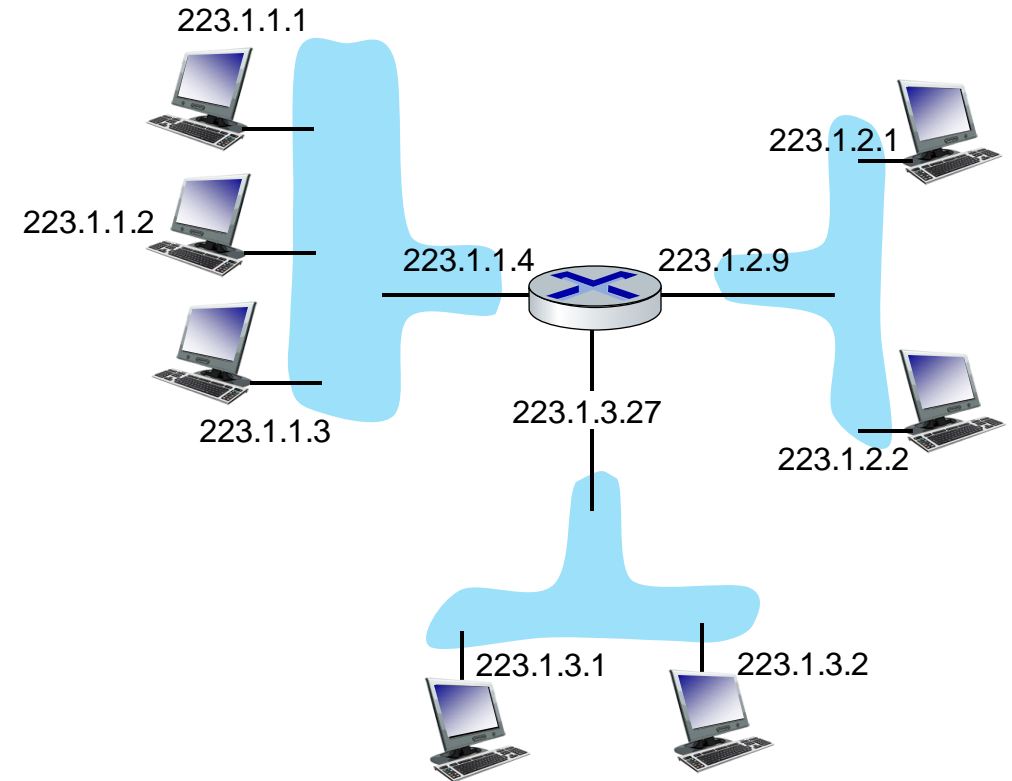


IP Datagram format



IP addressing: introduction

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

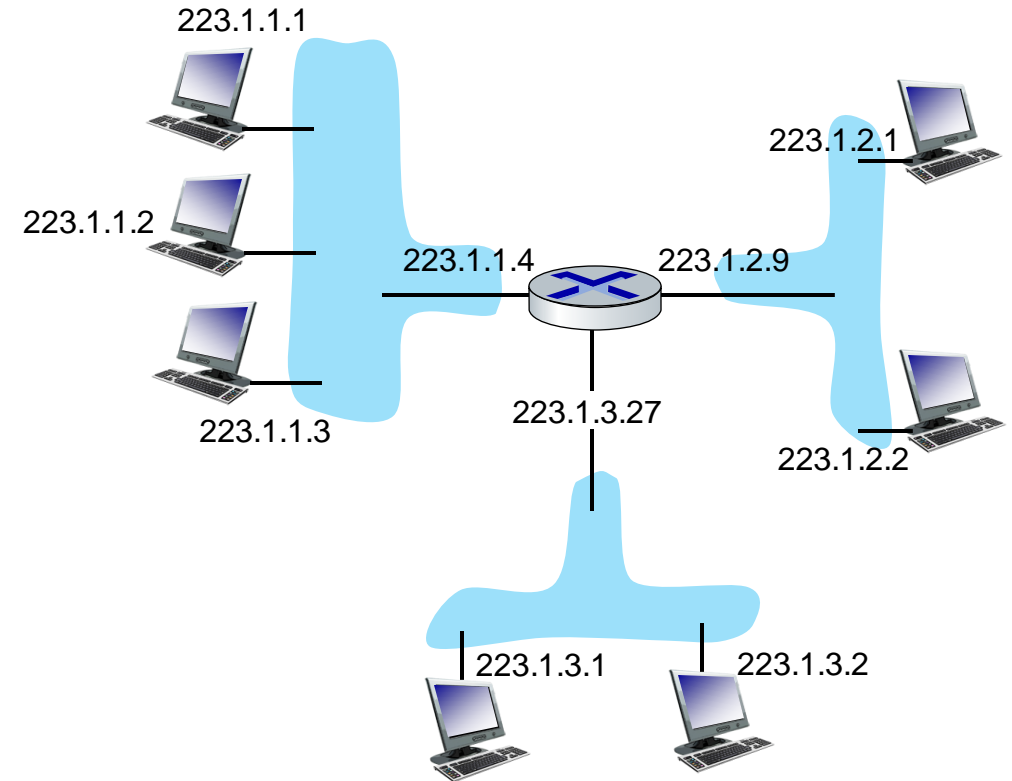


dotted-decimal IP address notation:

223.1.1.1 = $\underbrace{11011111}_{223} \underbrace{00000001}_1 \underbrace{00000001}_1 \underbrace{00000001}_1$

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dotted-decimal IP address notation:

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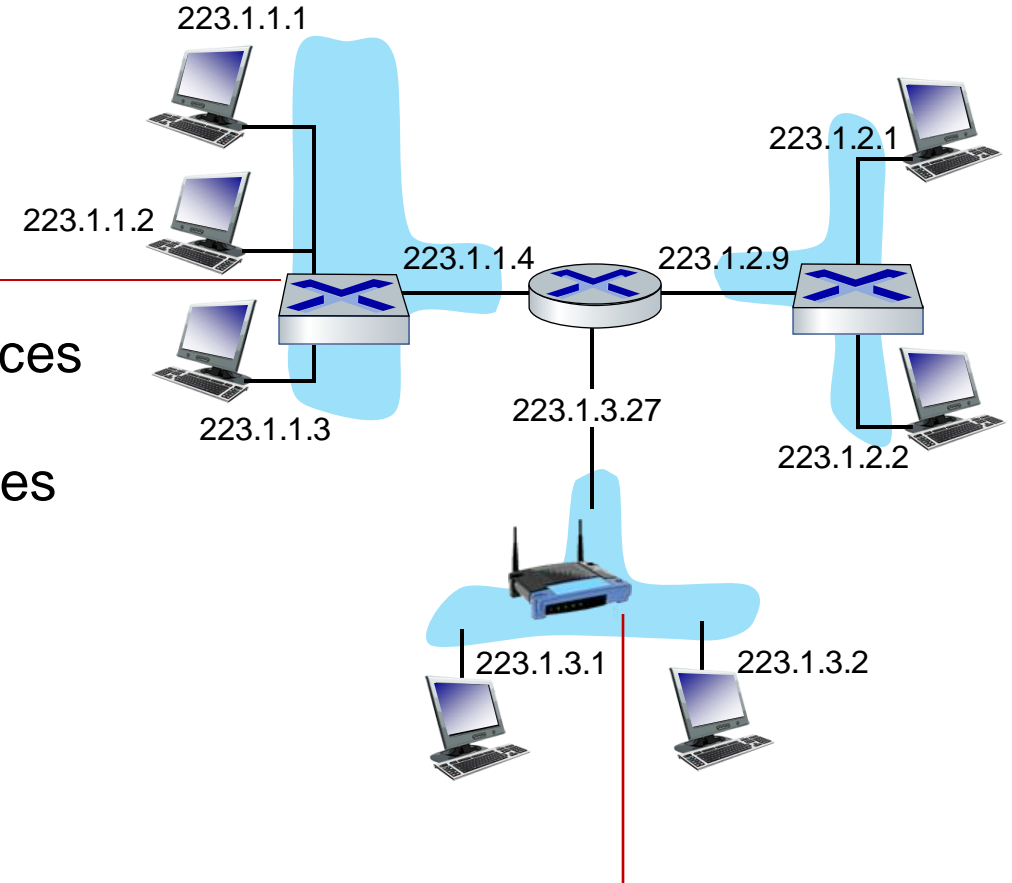
IP addressing: introduction

Q: how are interfaces actually connected?

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

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

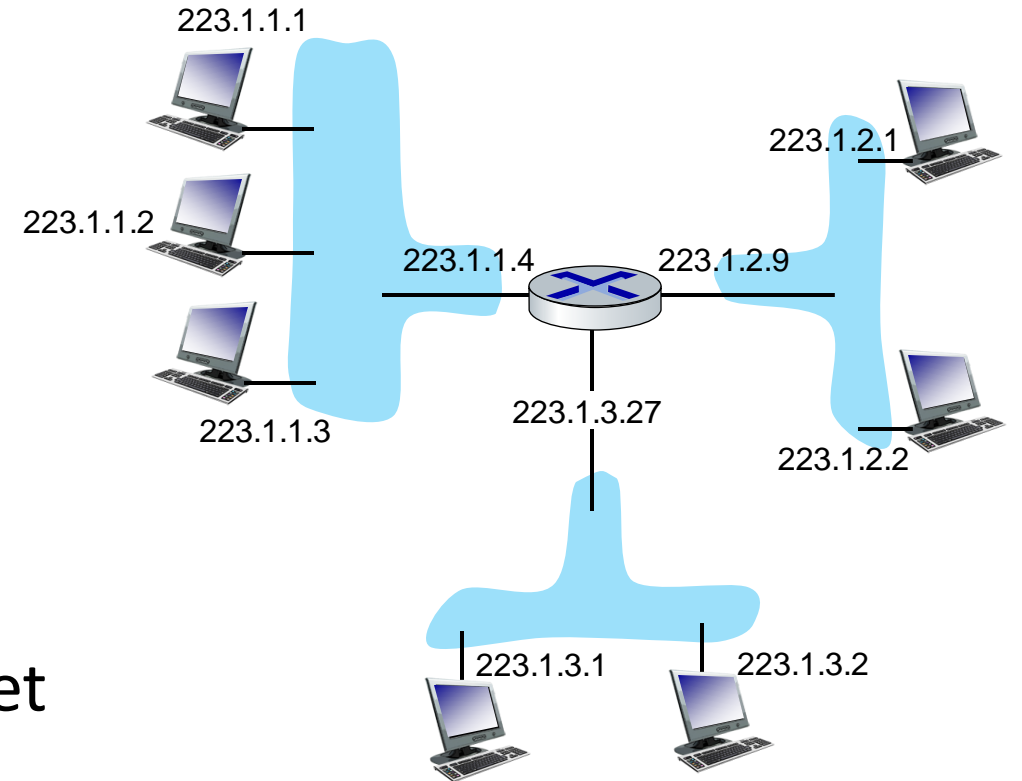
A: wired Ethernet interfaces connected by Ethernet switches



A: wireless WiFi interfaces connected by WiFi base station

Subnets

- *What's a subnet ?*
 - device interfaces that can physically reach each other **without passing through an intervening router**
- IP addresses have structure:
 - **subnet part**: devices in same subnet have common high order bits
 - **host part**: **remaining** low order bits

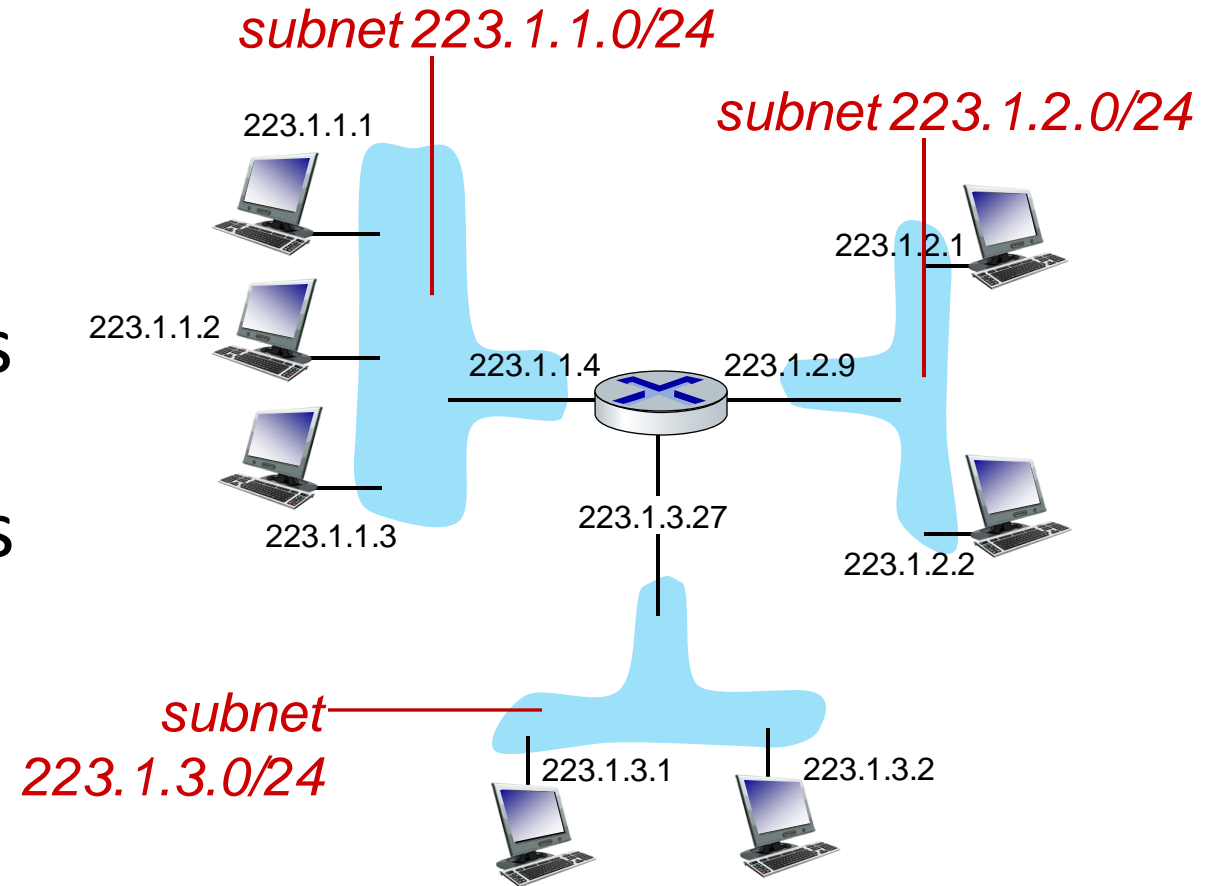


network consisting of 3 subnets

Subnets

Recipe for defining subnets:

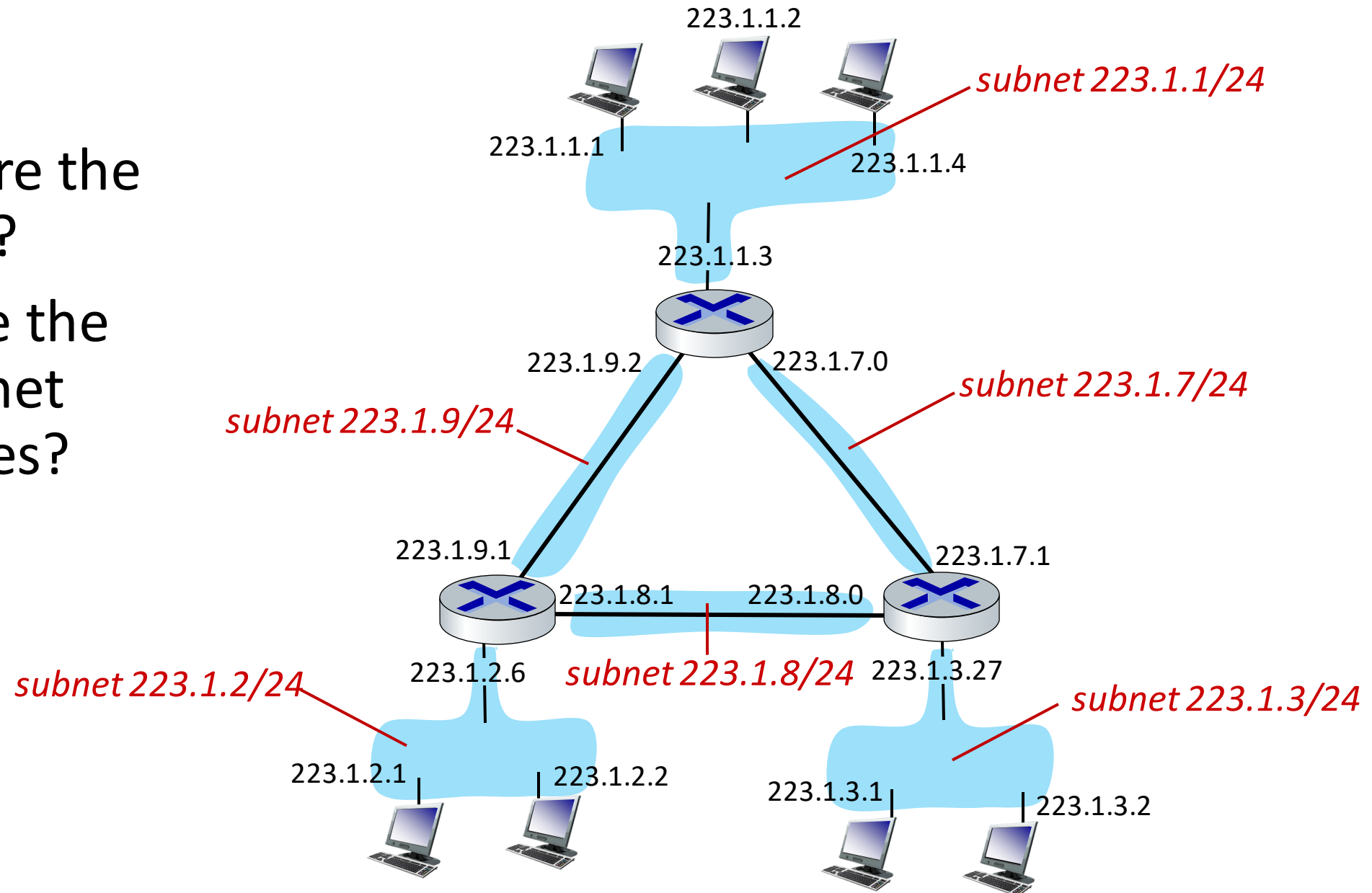
- detach each interface from its host or router, creating “islands” of isolated networks
- each isolated network is called a *subnet*



subnet mask: /24
(high-order 24 bits: subnet part of IP address)

Subnets

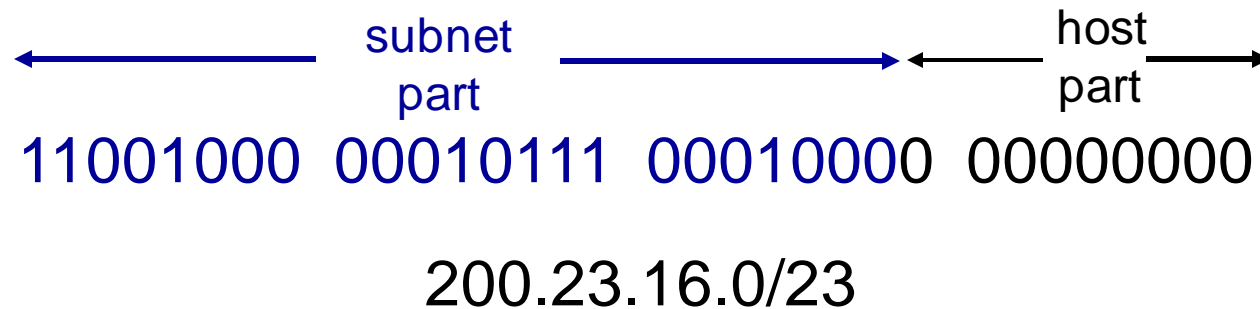
- where are the subnets?
- what are the /24 subnet addresses?



IP addressing: CIDR

CIDR: Classless InterDomain Routing (pronounced “cider”)

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



IP addresses: how to get one?

That's actually **two** questions:

1. Q: How does a *host* get IP address within its network (host part of address)?
2. Q: How does a *network* get IP address for itself (network part of address)

How does *host* get IP address?

- hard-coded by sysadmin in config file (e.g., /etc/rc.config in UNIX)
- **DHCP**: **D**ynamic **H**ost **C**onfiguration **P**rotocol: dynamically get address from as server
 - “plug-and-play”