Computer Networks
@CS.NYTU

Lecture 4: Network Layer: Data Plane

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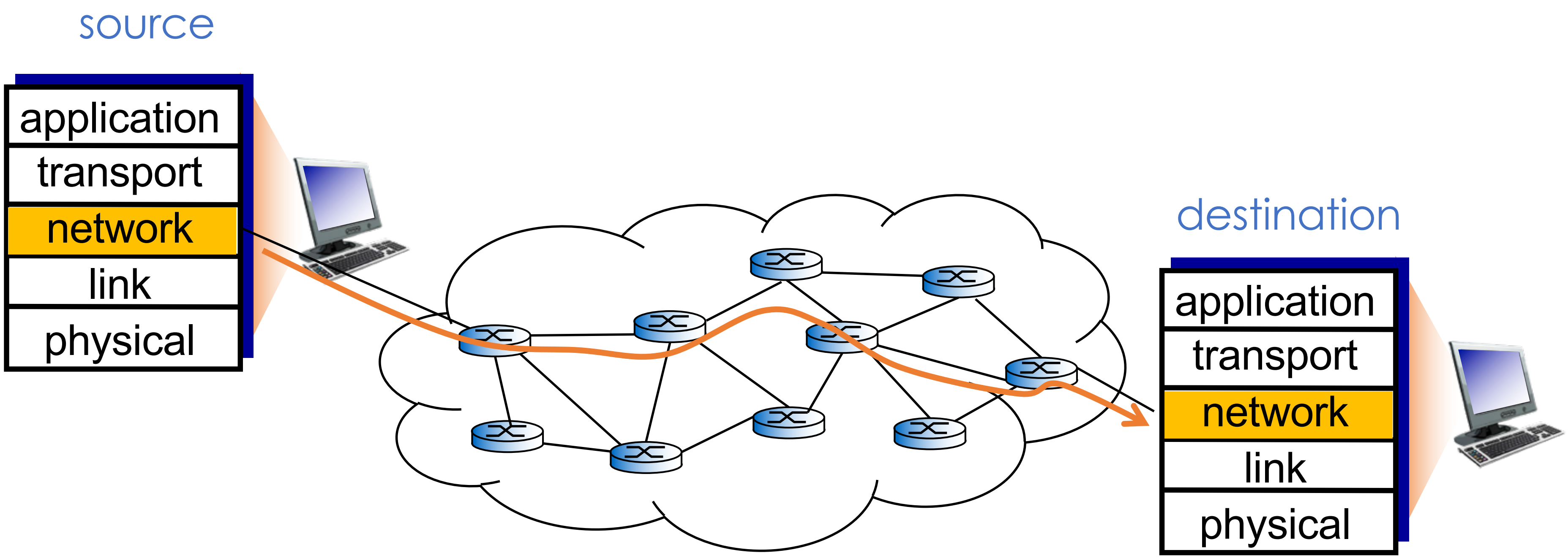
Slides modified from
"Computer Networking: A Top-Down Approach" 7th Edition

from end system to another end system: **routing!**



Outline

- **Overview of network layer**
- What's inside a router
- IP: Internet Protocol
  - Datagram format
  - IPv4 addressing
  - DHCP
  - Network address translation (NAT)
  - IPv6
- Software defined networking

Two Components

- **Data plane**
  - Per-router function: forwarding
  - For every packet, what should be the output link?
  - Local view

- **Control plane**
  - Network-wise logic: routing
    - traditional routing algorithms: implemented in routers
    - software-defined networking (SDN): implemented in remote servers (controllers)
  - What is the exact path from a source to a destination?
  - Global view

Forwarding vs. Routing

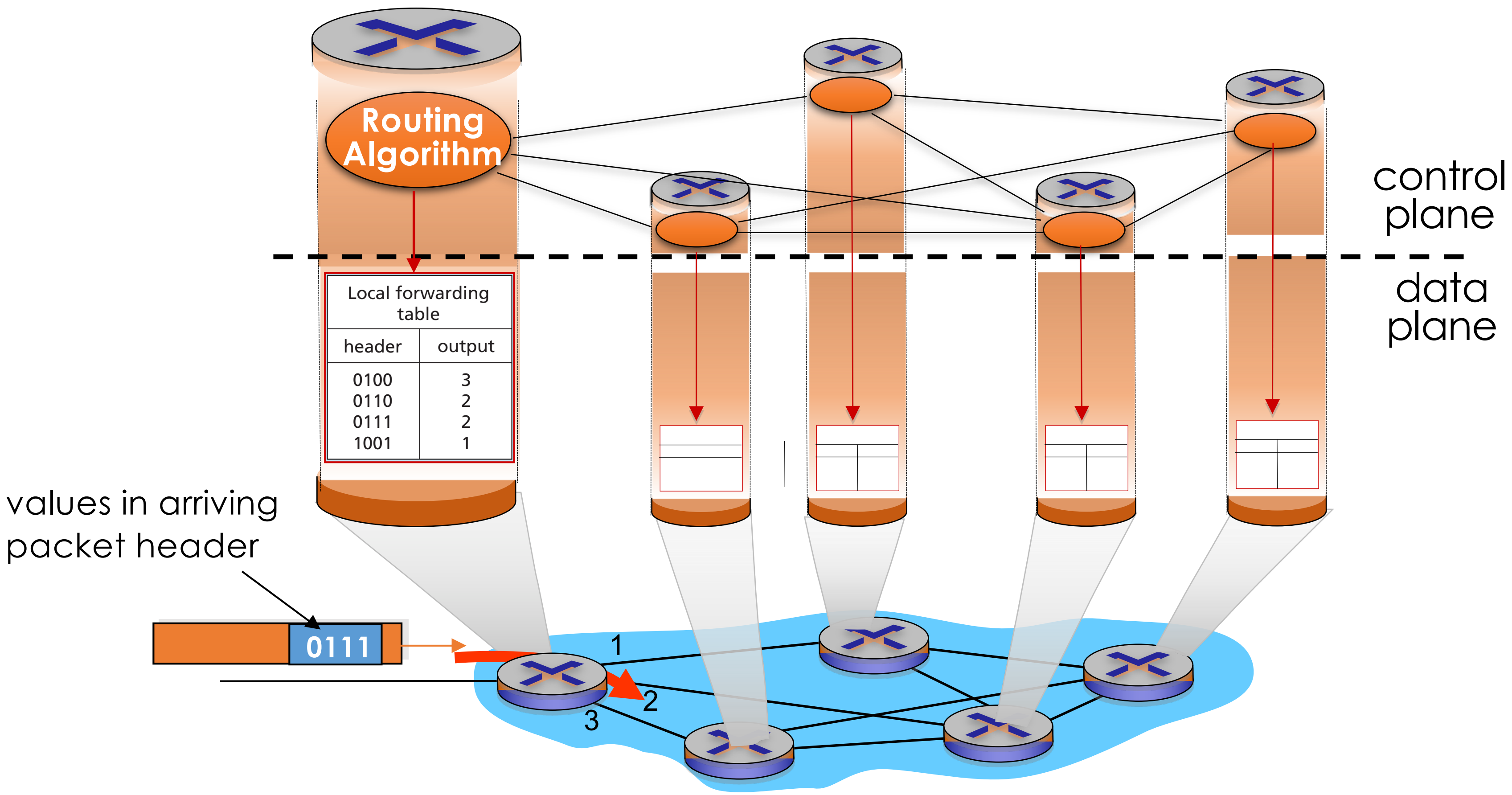
Turn right? Turn left?
(forwarding)

Types of Control Plane

- **Per-router control plane**
  - Controller within each router
- **Centralized control plane**
  - Remote server as a controller, controlling all the routers

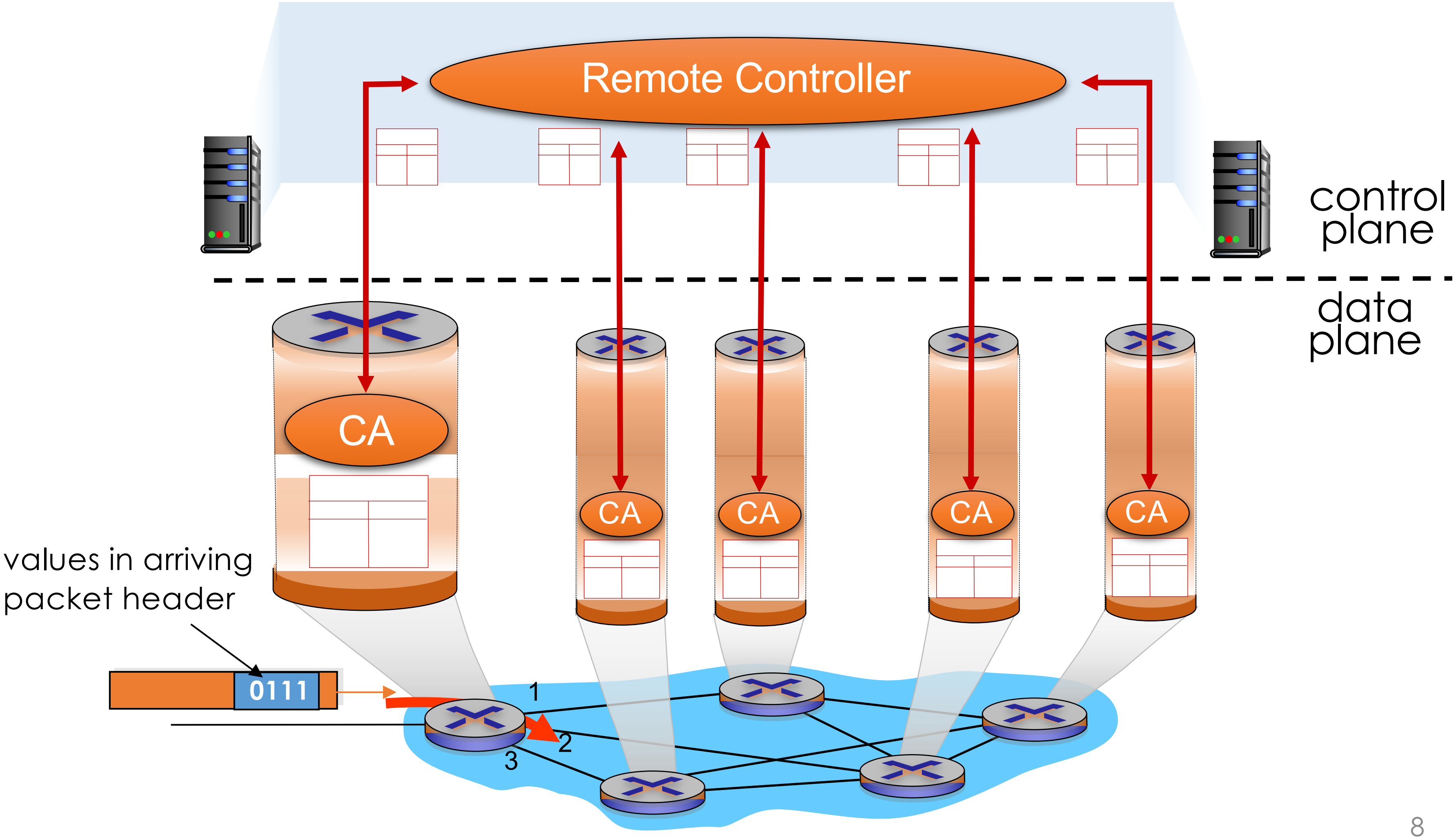
Per-Router Control Plane

- Individual forwarding components in every router interact in the control plane



Centralized Control Plane

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



Network Service Model

- What are the services required by end-to-end delivery
  - Guaranteed delivery?
  - Bounded delay?
  - In-order packet delivery?
  - Guaranteed minimal bandwidth?
  - Security?
- Types of network protocols
  - **Best-effort**
    - neither delay nor bandwidth is guaranteed
    - **IP (Internet protocol)**
  - **Guaranteed**
    - in-order, bounded delay, min-bandwidth
    - **ATM (Asynchronous Transfer Mode)**

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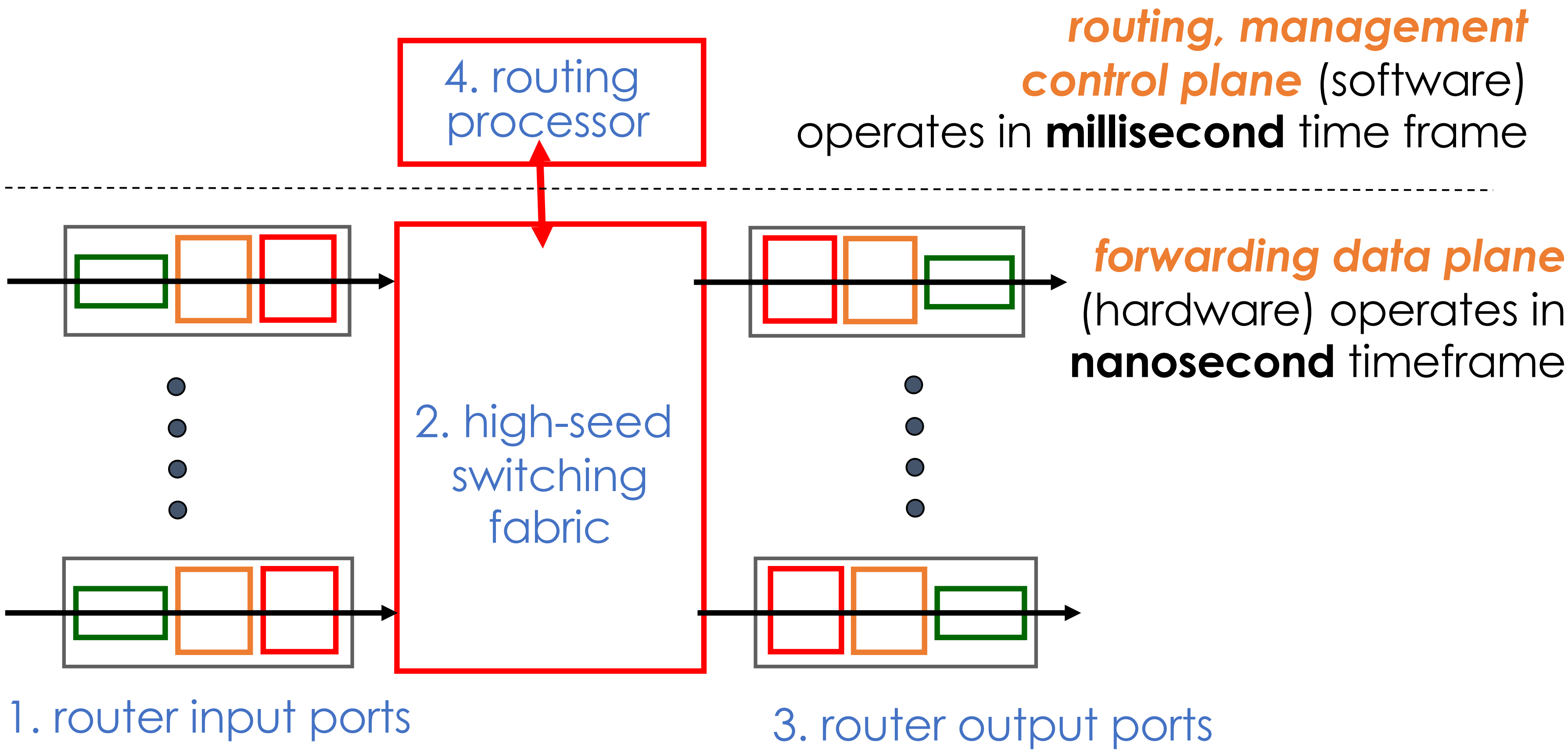
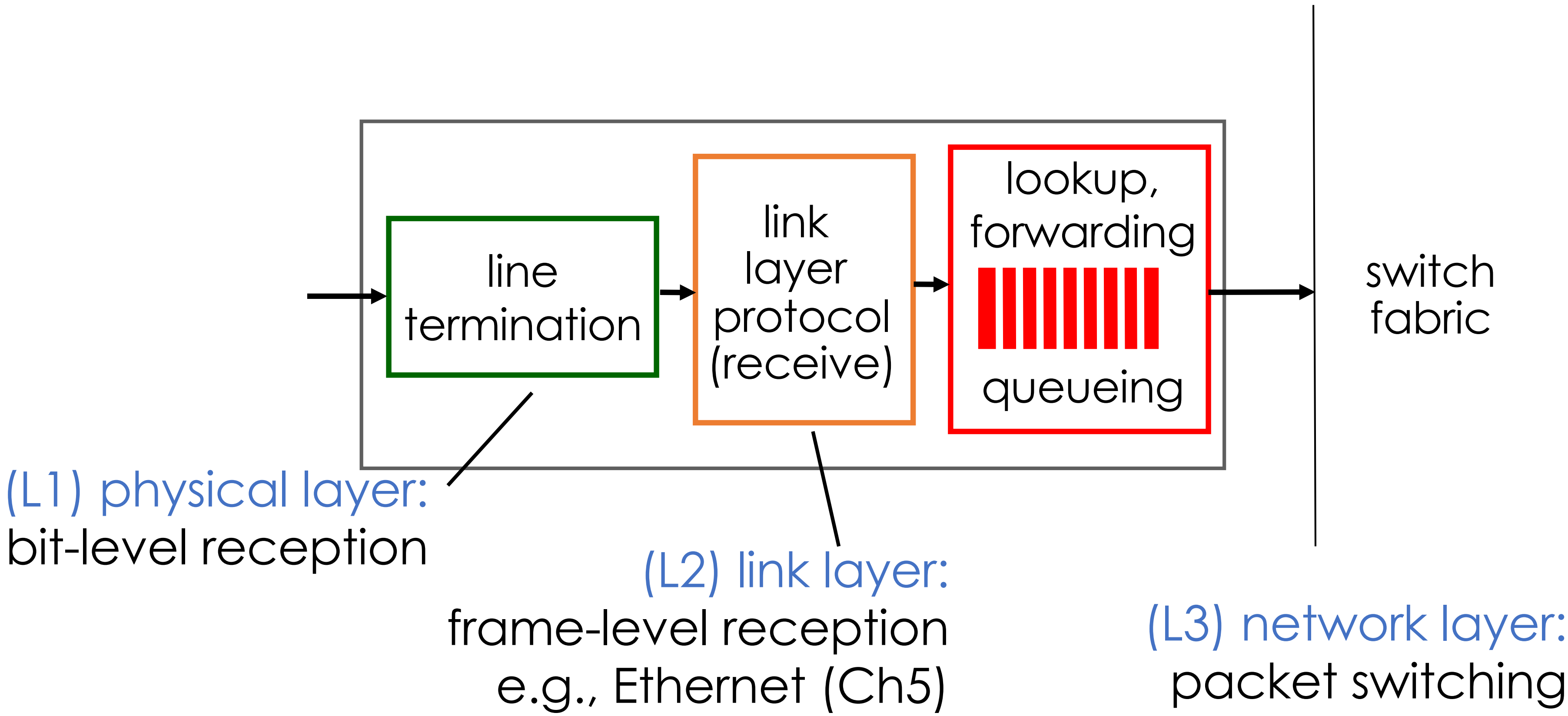
Generic Router Architecture

- 4 components



1. Input Ports



Input Ports: Decentralized Switching

- Using header field values, lookup output port using forwarding table in input port memory ("match plus action")
- Why challenging?
  - processing at "line speed"
  - queuing: if datagrams arrive faster than forwarding rate into switch fabric
- Perform lookup function
  - Forwarding table used to determine the output port of each arriving packet
  - Control packets forwarded to routing processor
  - Can be updated by routing processor or remote SDN controller

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

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

Q: what happens if multiple entries are matched?

Longest Prefix Matching

- When a destination address matches multiple entries, use the one with longest prefix matching
- Example
  - What is the output port of
    `11001000 00010111 00011000 10101010`
  - Port 1 or 2?

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

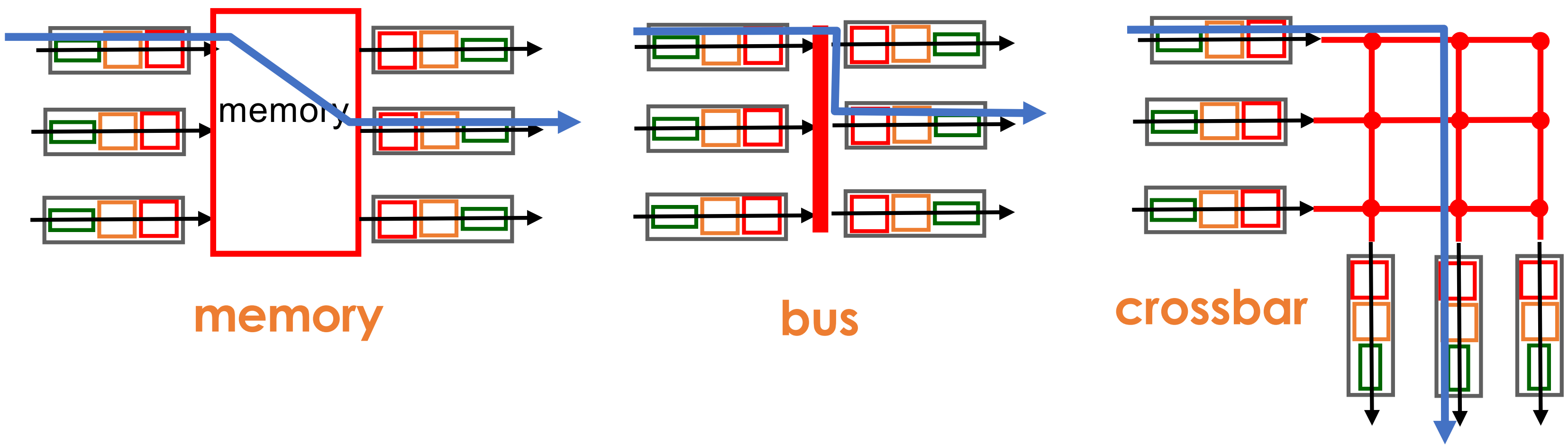
Longest Prefix Matching

- The entire table should be searched!
  - Time consuming
  - Packet arrival rate can be Gpbs

- Lookup principles
  - Performed in hardware
  - Simple linear search
  - Short memory access time (e.g., done in **Ternary Content Addressable Memories, TCAM**)
    - Expensive and power consuming
    - Limited capacity: ~1M routing table entries

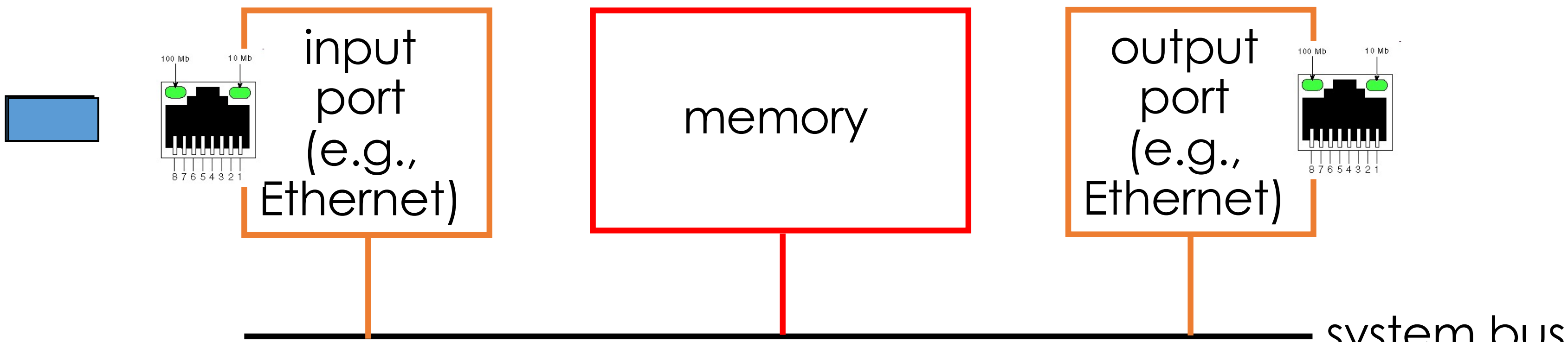
2. Switching Fabrics

- Where packets are actually switched!
  - Transfer a packet from an input port to an output port
- **Switching rate**:
  - Total number of packets transferred per second
  - Switching rate vs. line rate?
    - Some packets might be dropped if switching rate is not high enough to support the line rate
  - Three types:



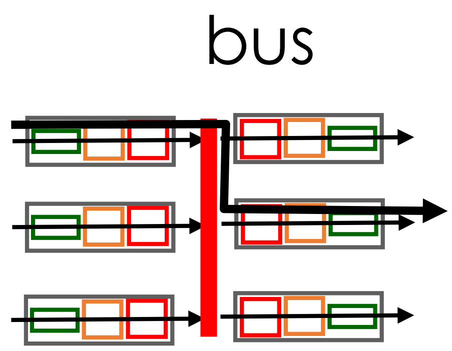
2.1 Switch via Memory

- Simplest, first generation
- Packets copied to processor memory
  - Processor looks up the table and determine the output port
- Memory bandwidth B
  - One memory read/write at a time
  - Forwarding throughput ≤ B/2



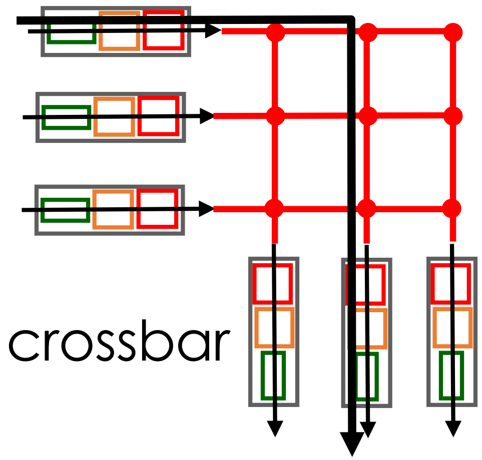
2.2 Switching via Bus

- Packets directly go through a shared bus
    - without intervention by the routing processor
- The input port tags a label to each packet, indicating the output port
    - All output ports receive the packet
    - The matching output port removes the label and forward
    - The others drop the packet
- **Bus contention:** switching speed limited by bus bandwidth
    - Cisco 6500: 32-GBps bus

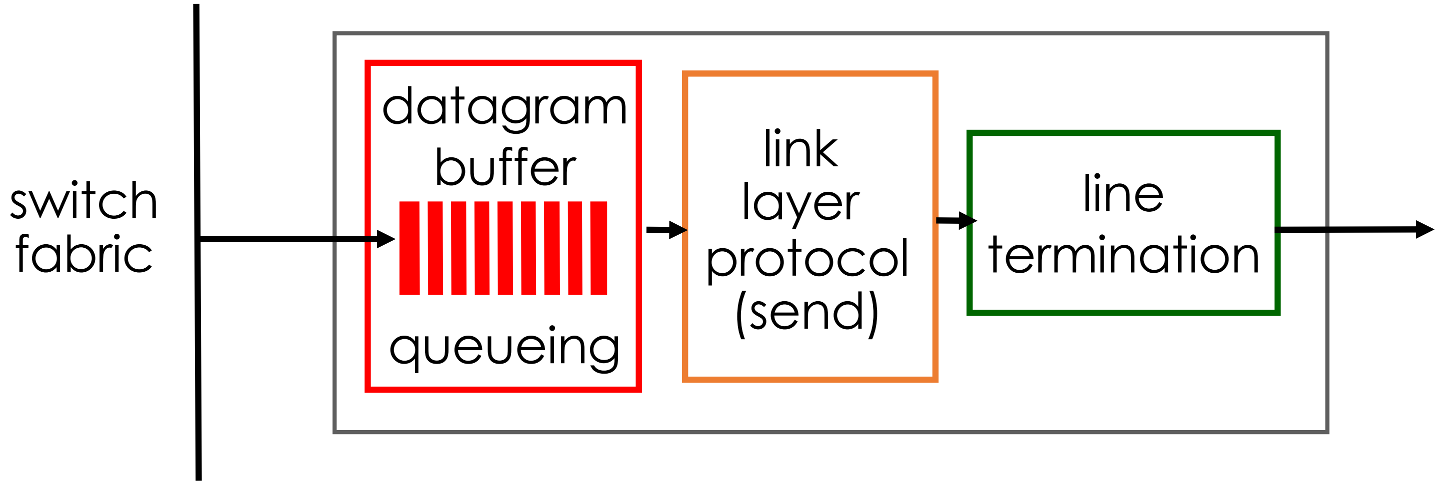


2.3 Switching via Crossbar

- Overcome the bus limitation
  - Cisco 12000: switches 60 Gbps through the interconnection network
- **2N** buses for N input/output ports
- **Non-blocking**
  - Can forward multiple packets in parallel
- Advanced version: **multi-staged switching fabric**
  1. Packets from different input ports can be sent to the same output port
  2. An input port breaks a packet to K chunks, forwarded by multiple switching fabrics



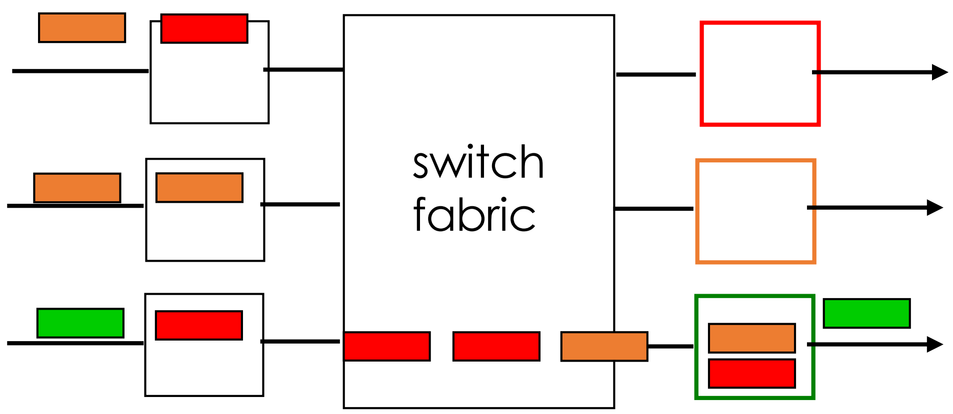
3. Output Port



- **Buffering** required when datagrams arrive from fabric faster than the transmission rate
  - Packet loss due to congestion (overflow)
- **Scheduling discipline** chooses among queued datagrams for transmission
  - Priority or not? (who goes first)

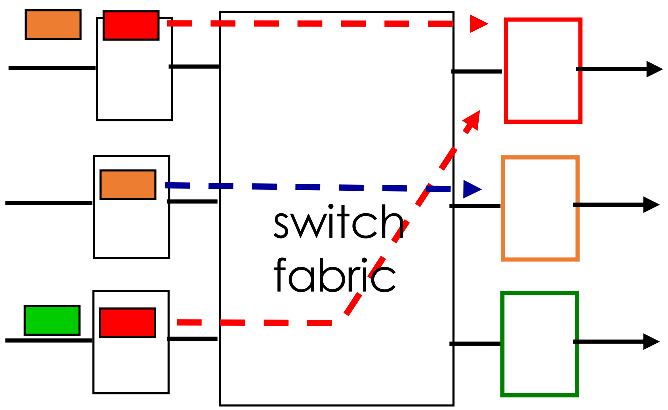
Packet Queueing

- **Input queueing**
  - Arrival rate > switch fabric speed
- **Output queueing**
  - Switch fabric speed > Forwarding rate
- Example:
  - $N * R_{line} = R_{switch}$
    all input ports send to the same output port

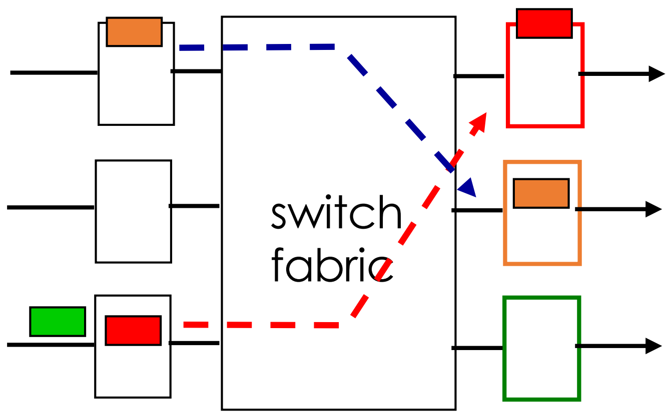


Input Port Queueing

- fabric slower than the aggregated input ports combined → buffer may overflow
- **Head-of-the-Line (HOL) blocking**:
  - queued datagram at front of queue prevents others in queue from moving forward



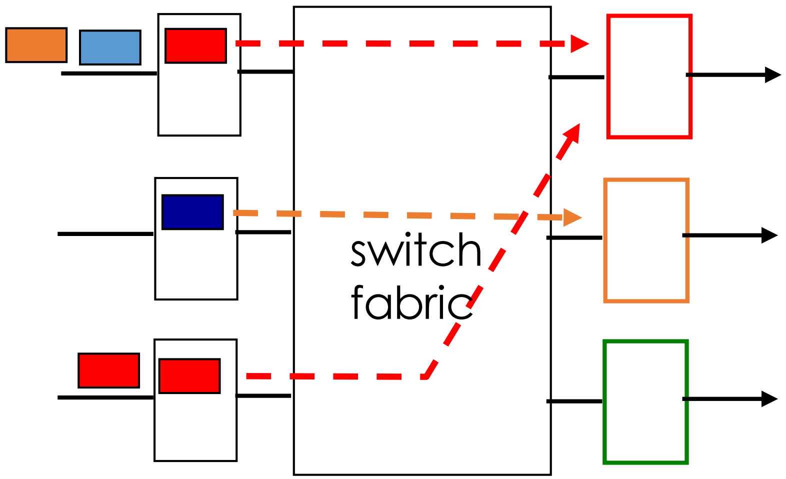
output port contention:
only one red datagram
can be transferred.
lower red packet is blocked



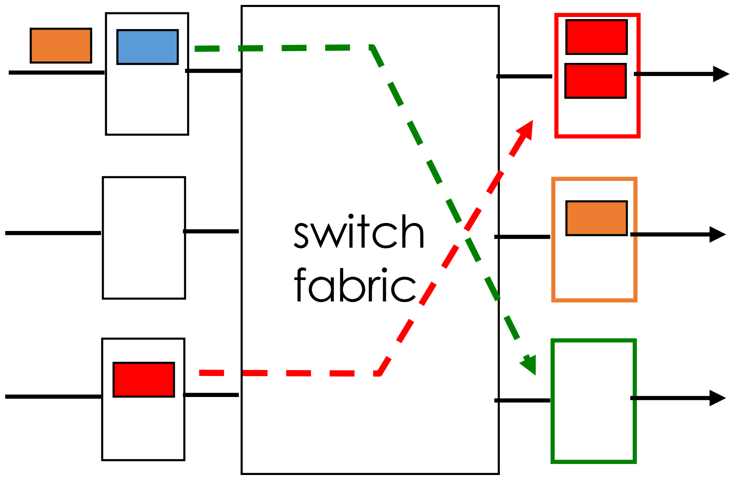
one packet time later:
green packet
experiences HOL blocking

Output Port Queueing

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



at *t*, packets more from input to output



one packet time later

How Much Buffering?

- RFC 3439 rule of thumb
  - average buffering = RTT x link capacity
  - e.g., RTT = 250ms, C = 10 Gbps

    → buffer = 10 * .25 = 2.5 Gb

- [Appenzeller 2004] When N TCP flows pass through a link (as N is large),

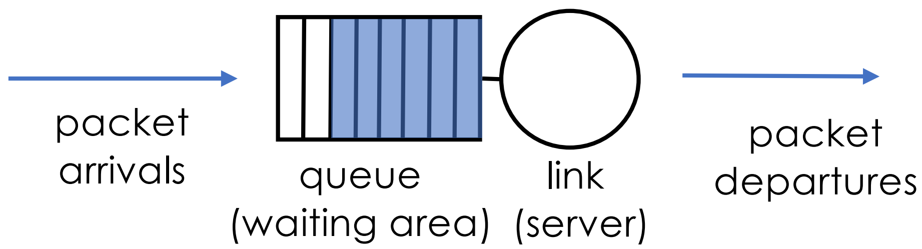
$$\text{buffering} = \frac{RTT \cdot C}{\sqrt{N}}$$

4. Packet Scheduling

- Determine the order of packet forwarding
- Four strategies
  - First-in-first-out (FIFO) or first-come-first-serve (FCFS)
  - Priority queue
  - Round robin
  - Weighted fair queueing (WFQ)

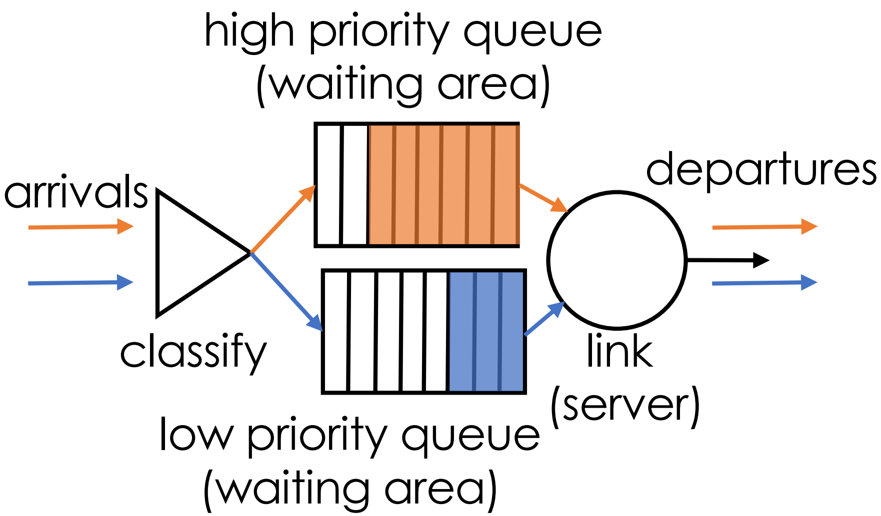
First In First Out

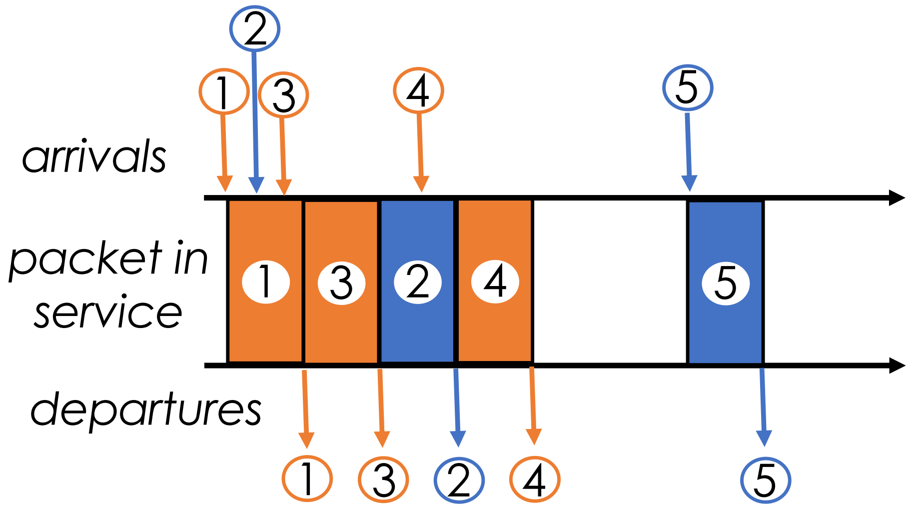
- Packets leave in the same order in which they arrived
- Packet discarding policy:
  - tail drop: drop arriving packet
  - priority: drop/remove on priority basis
  - random: drop/remove randomly



Priority Queueing

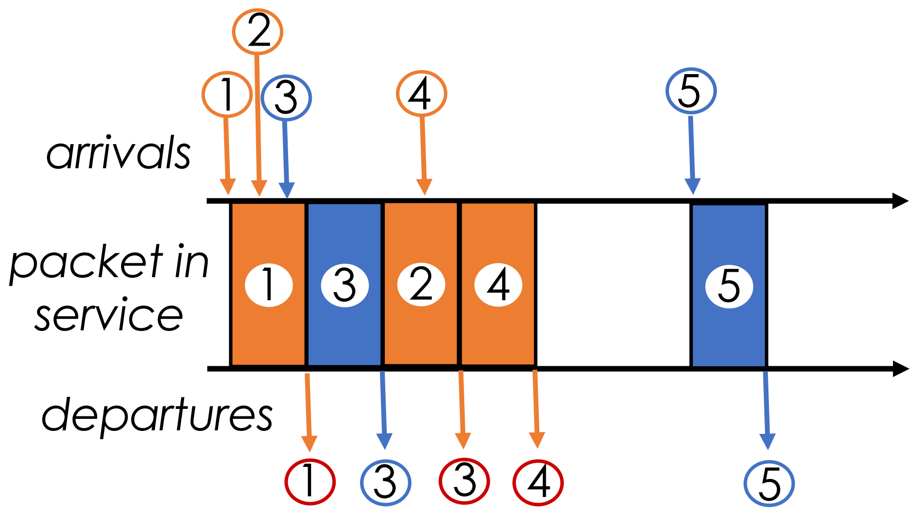
- Packets classified into multiple classes
  - Real-time: voice-over-IP
  - Best effort: SMTP, FTP
- Send highest priority queued packet
  - Intra-class: FIFO
- Non-preemptive: no interruption





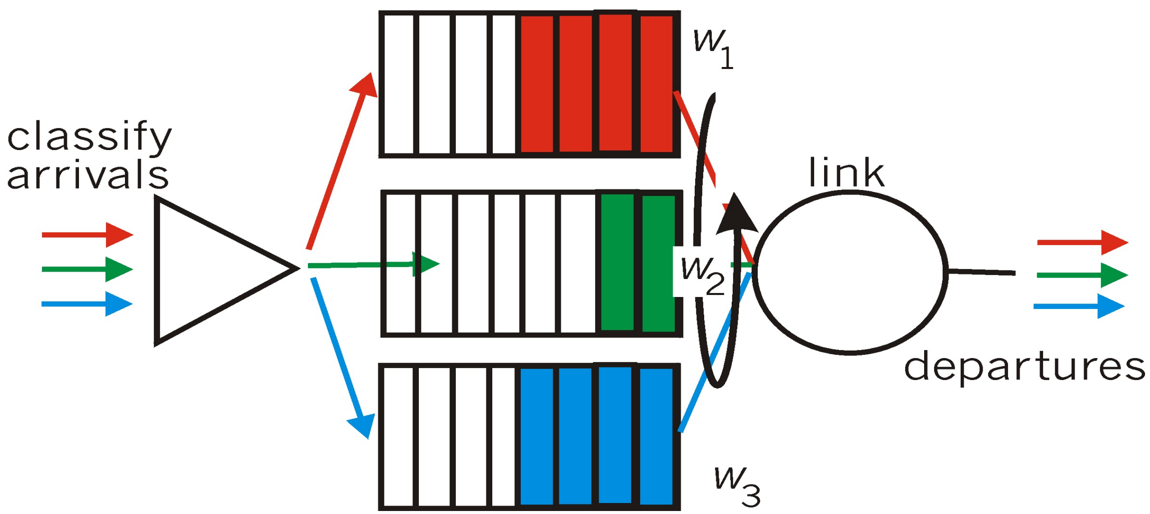
Round Robin

- Packets also classified into multiple classes
- Cyclically scan class queues
  - Send one packet for each class (*if possible*)
- Throughput of each class?
  - Determined by the arrival rate of each class



Weighted Fair Queueing (WFQ)

- Achieved by leveraging round robin queueing
- Each class gets weighted amount of service in each cycle
- How?
  - Control the arrival rate of each class
  - Specifically, the interval of pushing a packet into a class queue is controlled



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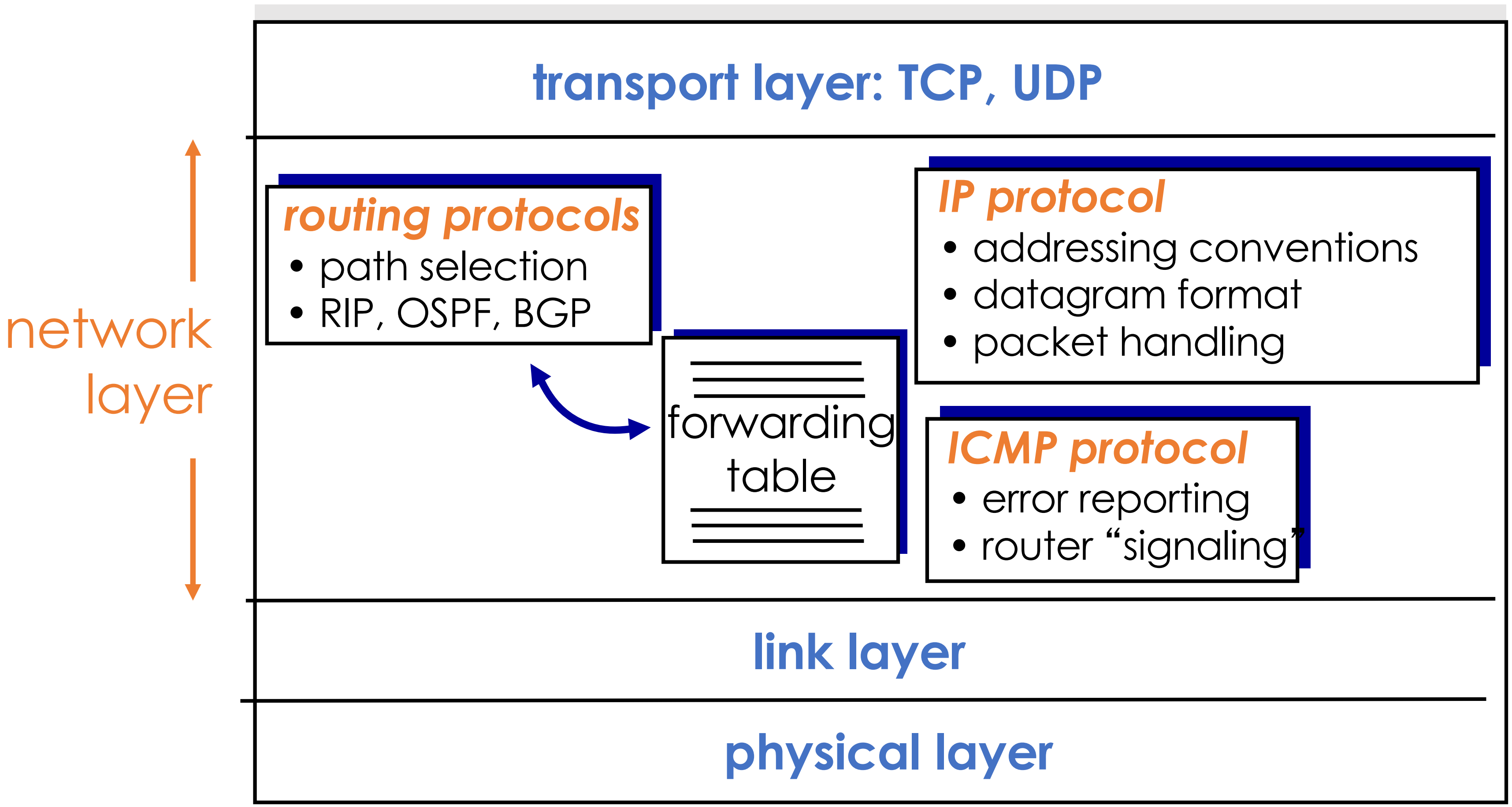
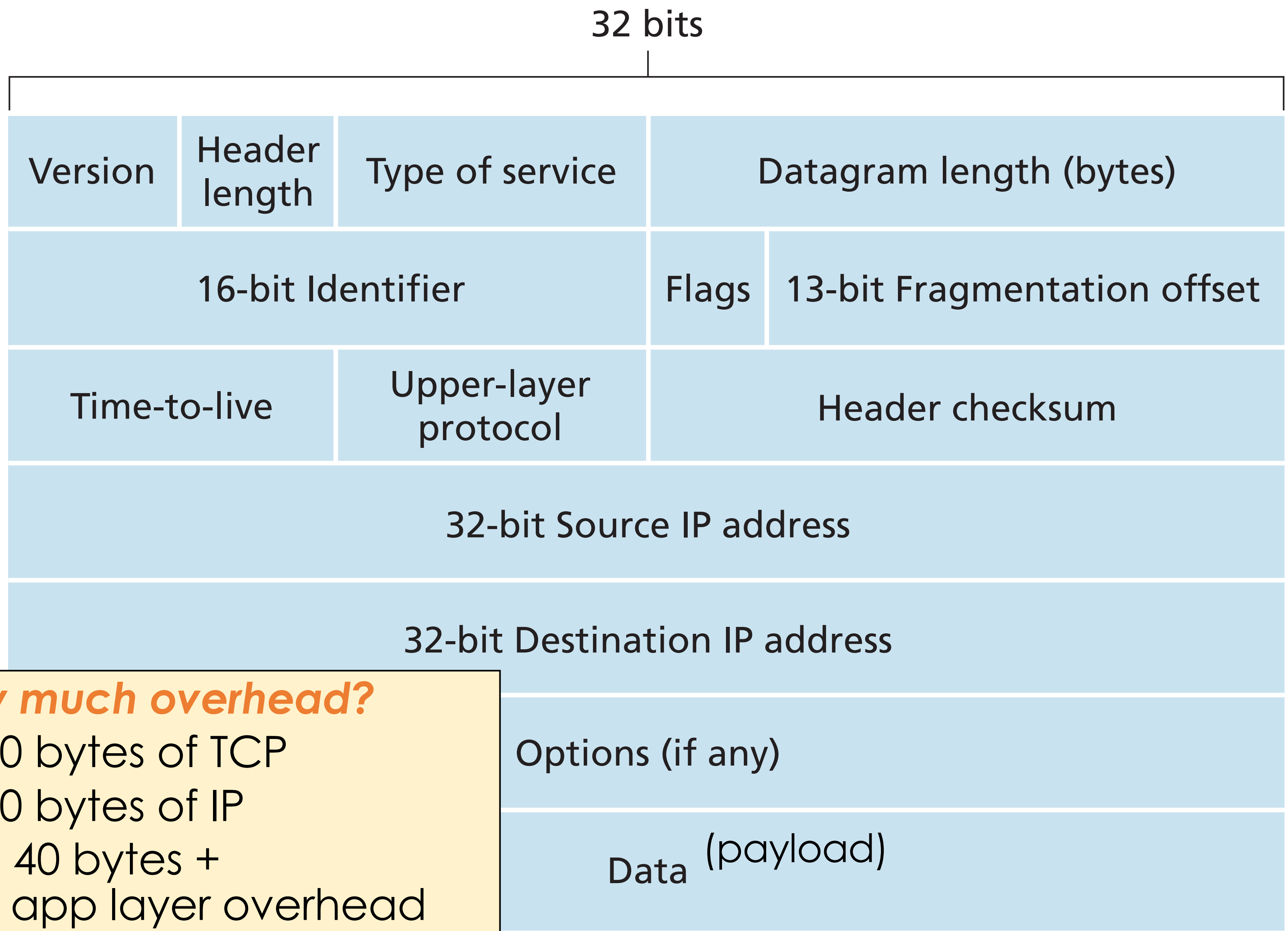
Internet Network Layer



IP Datagram Format



how much overhead?

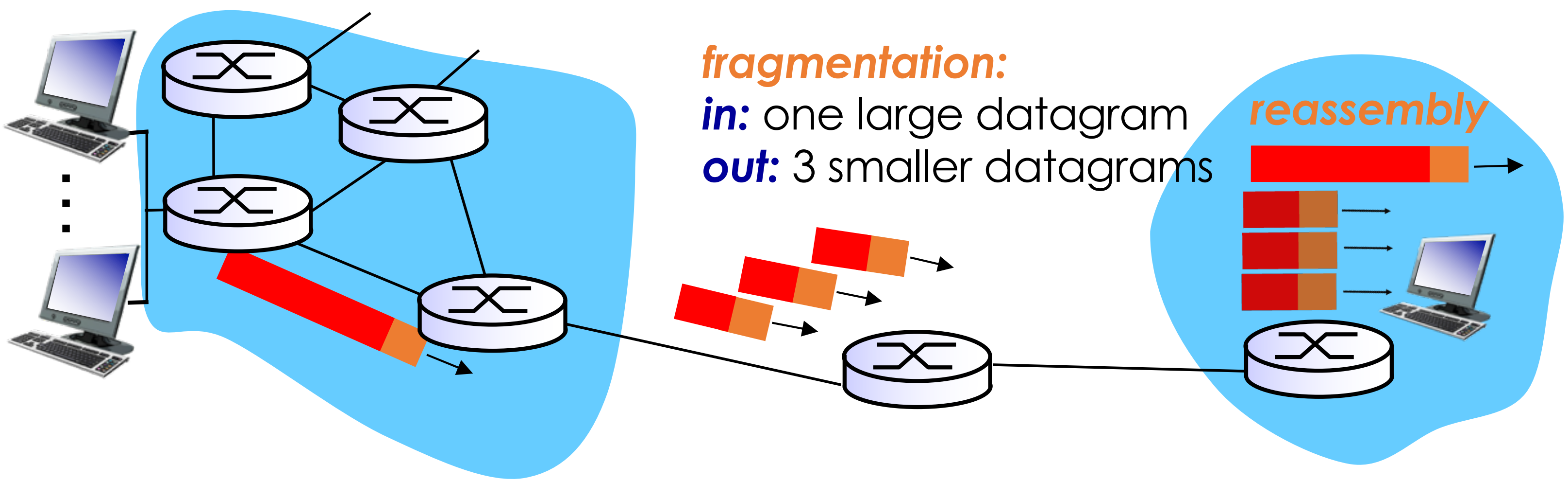
- 20 bytes of TCP
- 20 bytes of IP
- = 40 bytes + app layer overhead

IP Datagram Format

- L3 packet is referred to as a **datagram**
- **Version num**: IPv4 or IPv6
- **Header length**: where the payload begins (typically 20byte)
- **Type of service**: real-time or non-real-time
- **Datagram length**: total length of IP (header + data)
- **Identifier, flag, fragmentation offset**: index for fragments (IPv6 does not support fragmentation)
- **Time-to-live**: TTL, maximum number of hop counts
- **Protocol** : transport-layer protocol, e.g., TCP,UDP
- **Header checksum**: for error detection
  - Recalculated by each router since TTL is updated
  - Why checksum again? TCP/UDP and IP may not used at the same time

IP Fragmentation, Reassembly

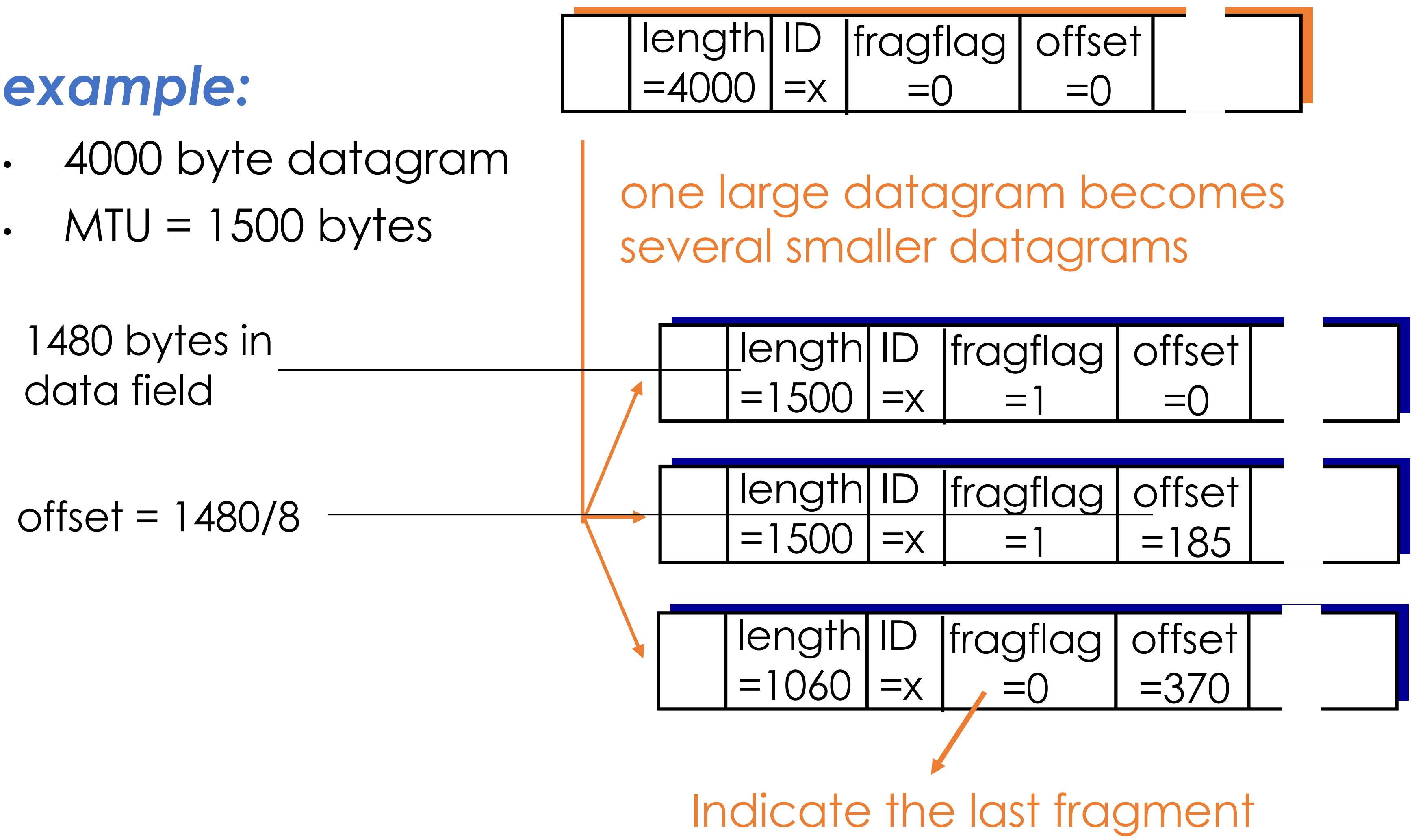
- Each link has (link-layer) **MTU** (maximum transmission unit)
- Large IP datagram divided ("fragmented")
  - one datagram becomes several datagrams
  - "reassembled" only at final destination
  - IP header bits used to identify, order related fragments



IP Fragmentation, Reassembly

example:

- 4000 byte datagram
- MTU = 1500 bytes



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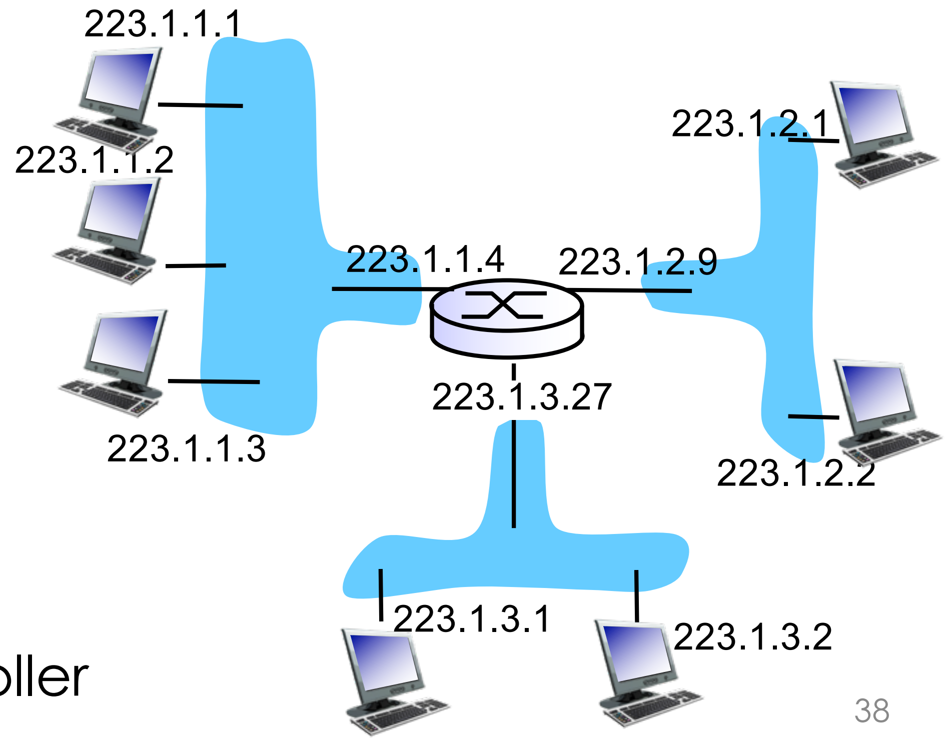
IPv4 Addressing

- **32-bit identifier**
  - Dotted-decimal notation: 140.113.94.87
  - Binary: 10001100 01110001 01011110 01010111
- Each **“interface”** needs an IP
  - Interface: connection between a host and a link
  - Try `ifconfig` (Ethernet, WLAN)
  - A router typically has multiple interfaces (IPs)

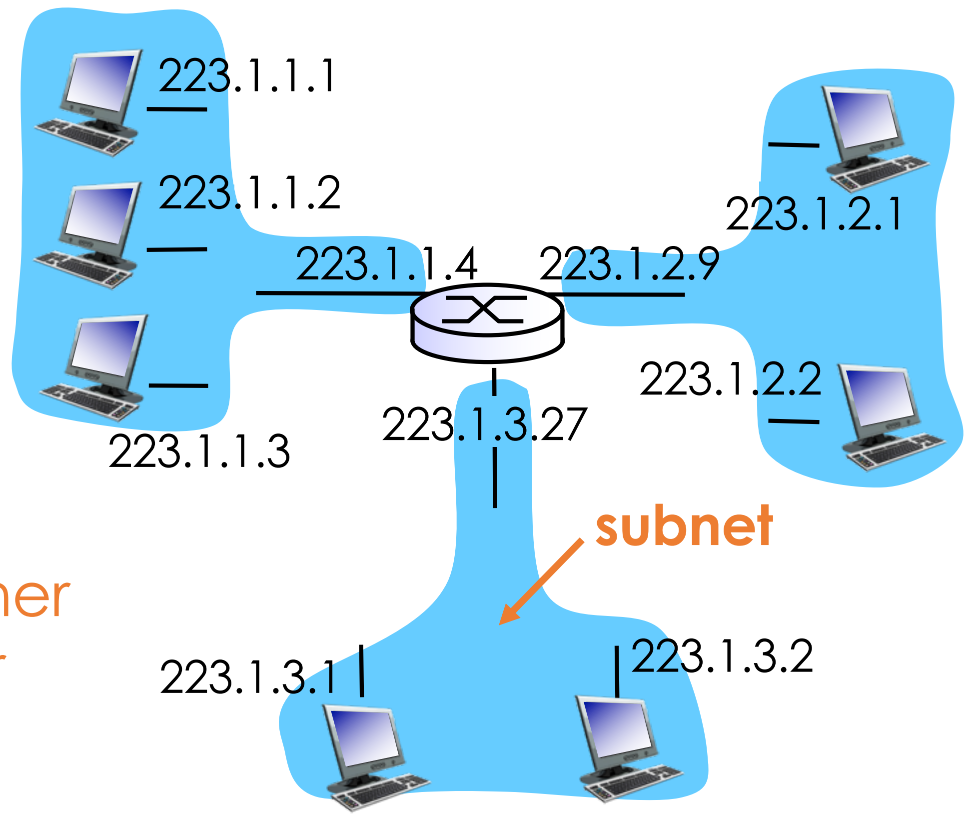
NIC: network interface controller



Subnet

- IP address:
  - Subnet part: prefix
  - Host part: low order bits
- What is a subnet?
  - Interfaces with the same subnet part of IP address
  - Physically reach each other without intervening router
- **Subnet mask**
  - Bitmask used to get the subnet part
  - For 223.1.1.0/24: /24 (255.255.255.0) is the subnet mask

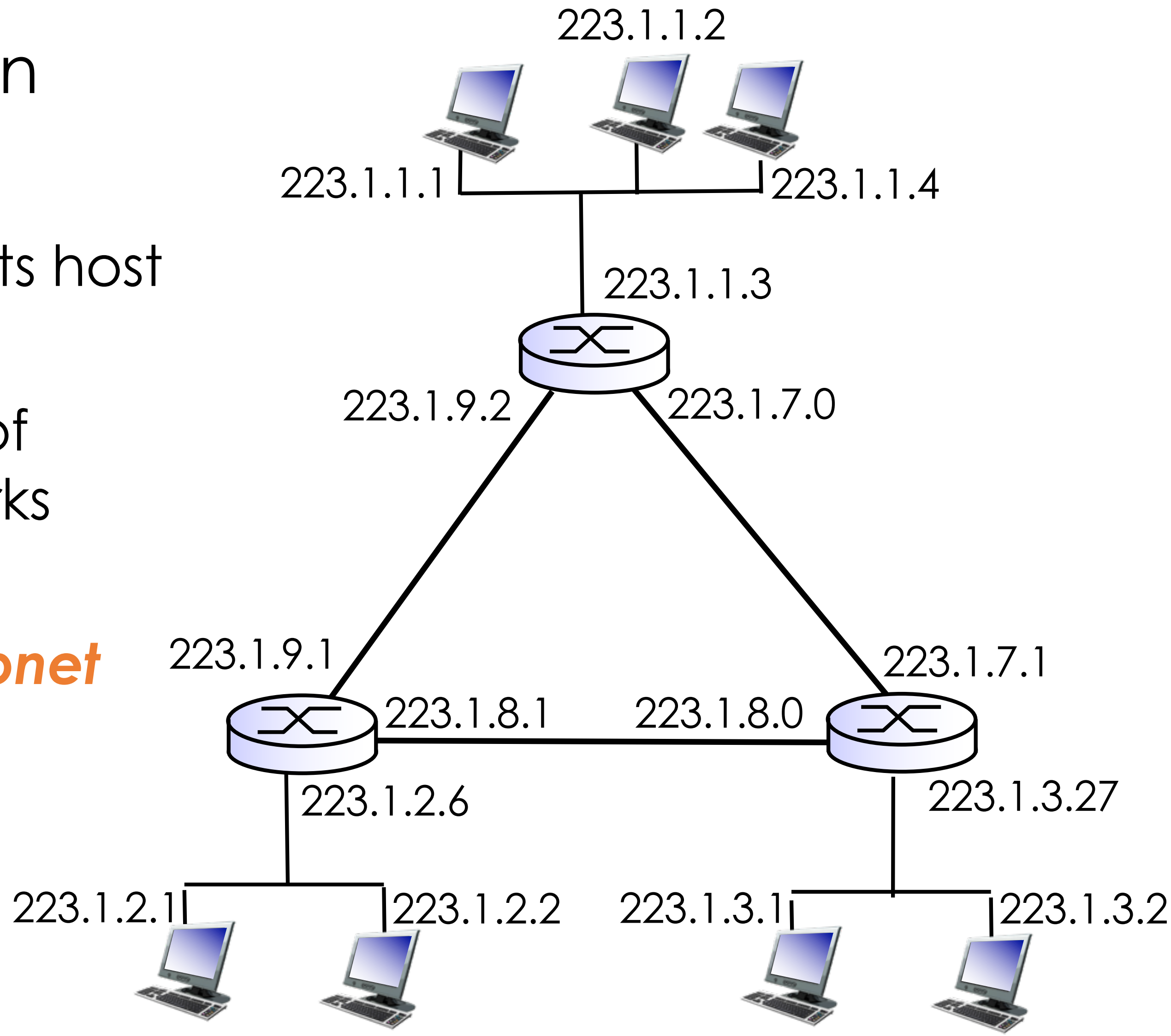
network consisting of 3 subnets



Subnet

- Formal definition

1. detach each interface from its host or router
2. create islands of isolated networks
3. each isolated network is a ***subnet***



CIDR

- **Classful addressing:** 8-, 16, 24-bit subnet
  - 24bit subnet: each only includes 2^8-2 hosts
  - 16bit subnet: each includes 65,534 hosts
- **C**lassless **I**nter-**D**omain **R**outing
  - Introduced by IETF in 1993
  - Goal: slow the growth of routing tables on routers
- **Variable-length subnet masking**!
  - Subnet part can be of arbitrary length
  - a.b.c.d/**x**, where **x** is # bits in subnet portion of address

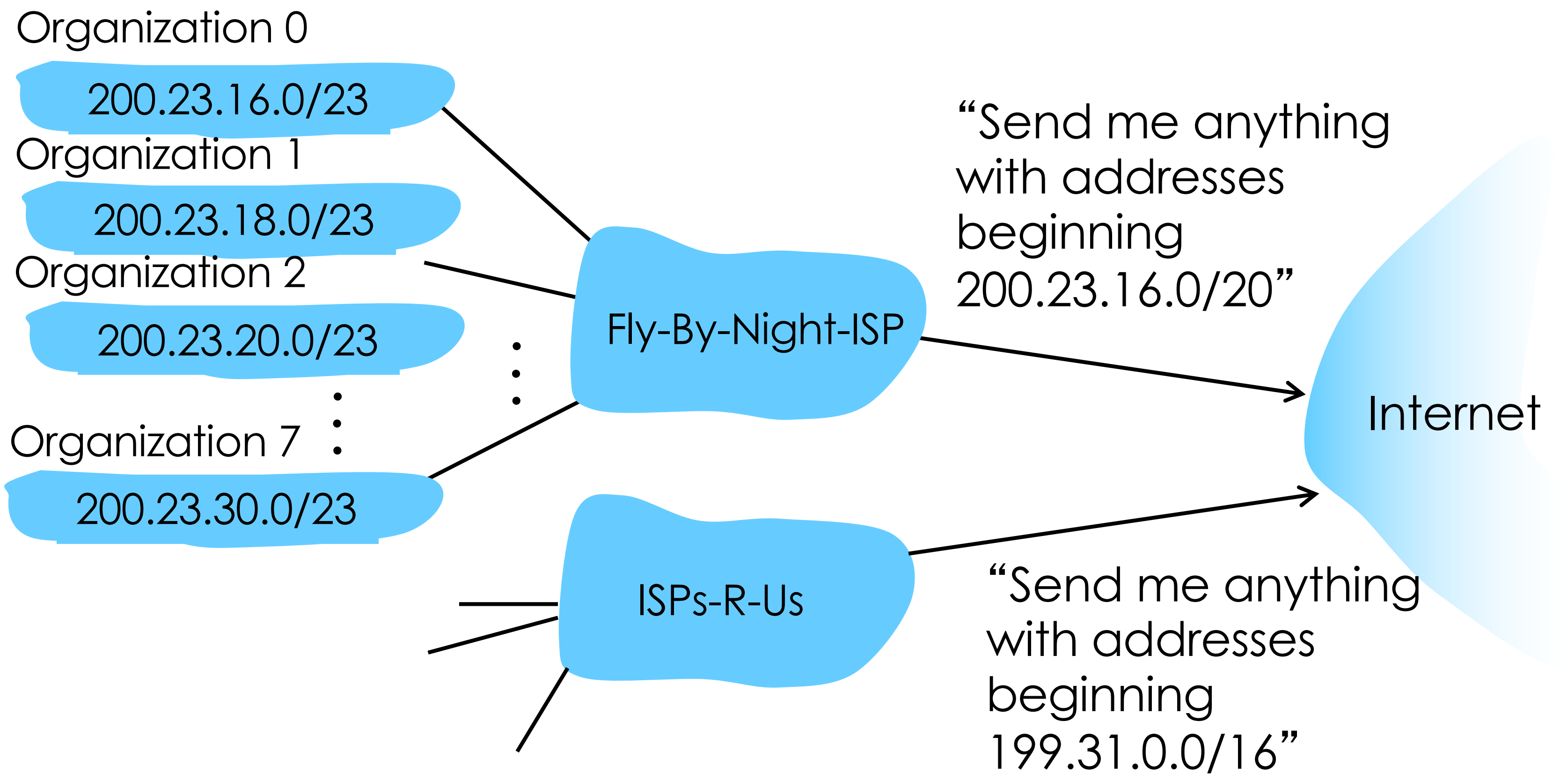
subnet part ⟵⟶ host part

11001000 00010111 00010000 00000000

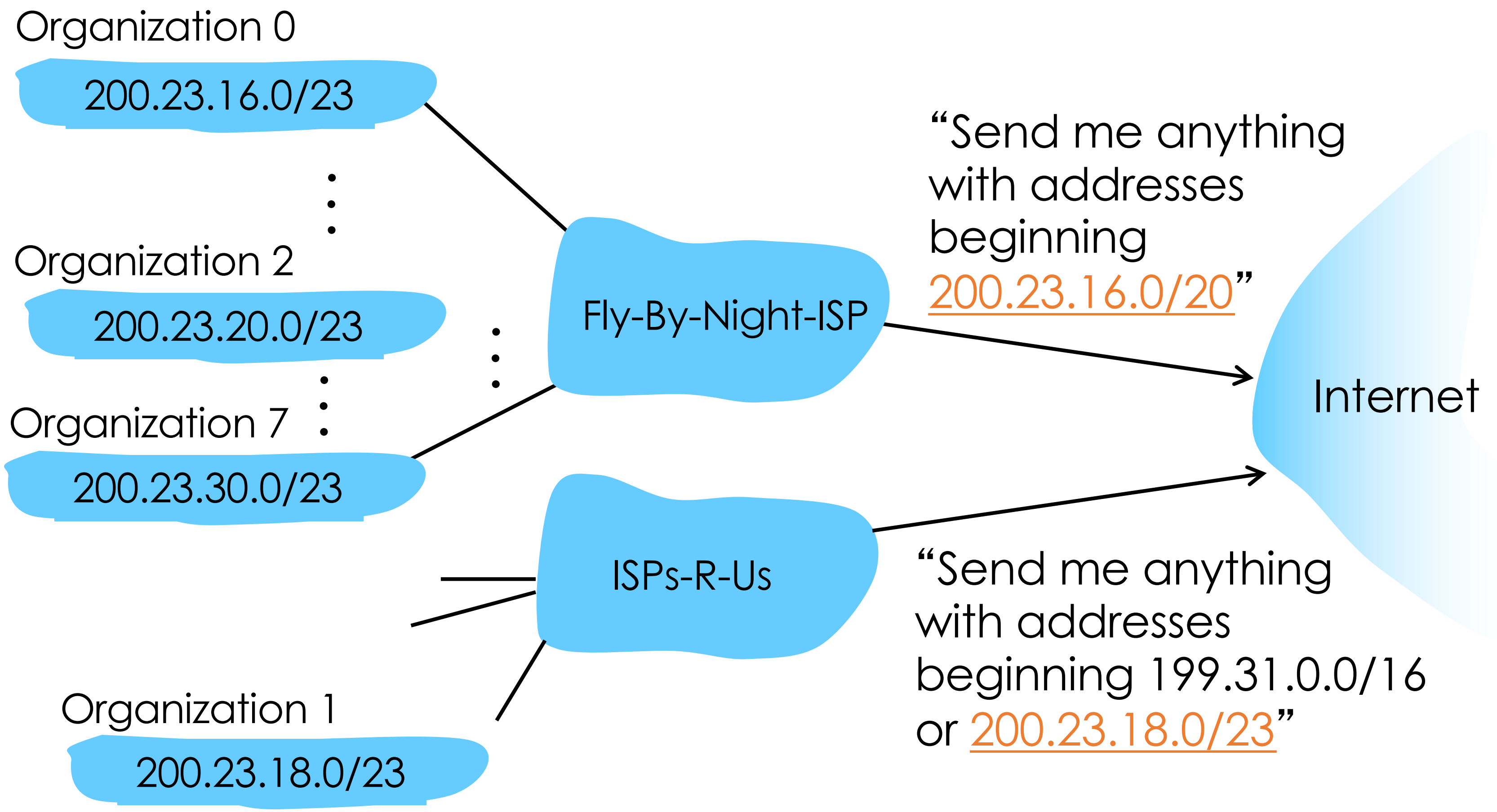
200.23.16.0/23

Hierarchical Addressing

- ISP assigns a block of IP addresses to a subnet



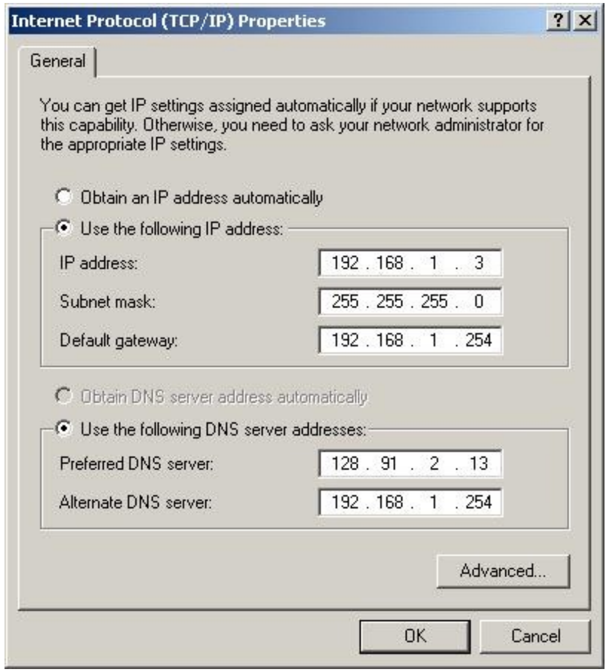
Specific Routes



IP Assignment

- How does a host get a unique IP address?
- **Static IP**
  - Manually configured
  - For Linux: `ifconfig eth0 140.113.94.87`
- **Dynamic IP**
  - DHCP: **D**ynamic **H**ost **C**onfiguration **P**rotocol
  - Temporary IP address
  - Plug-and-play
- Also need to configure
  - Subnet mask
  - Default gateway (router)
  - DNS servers

windows



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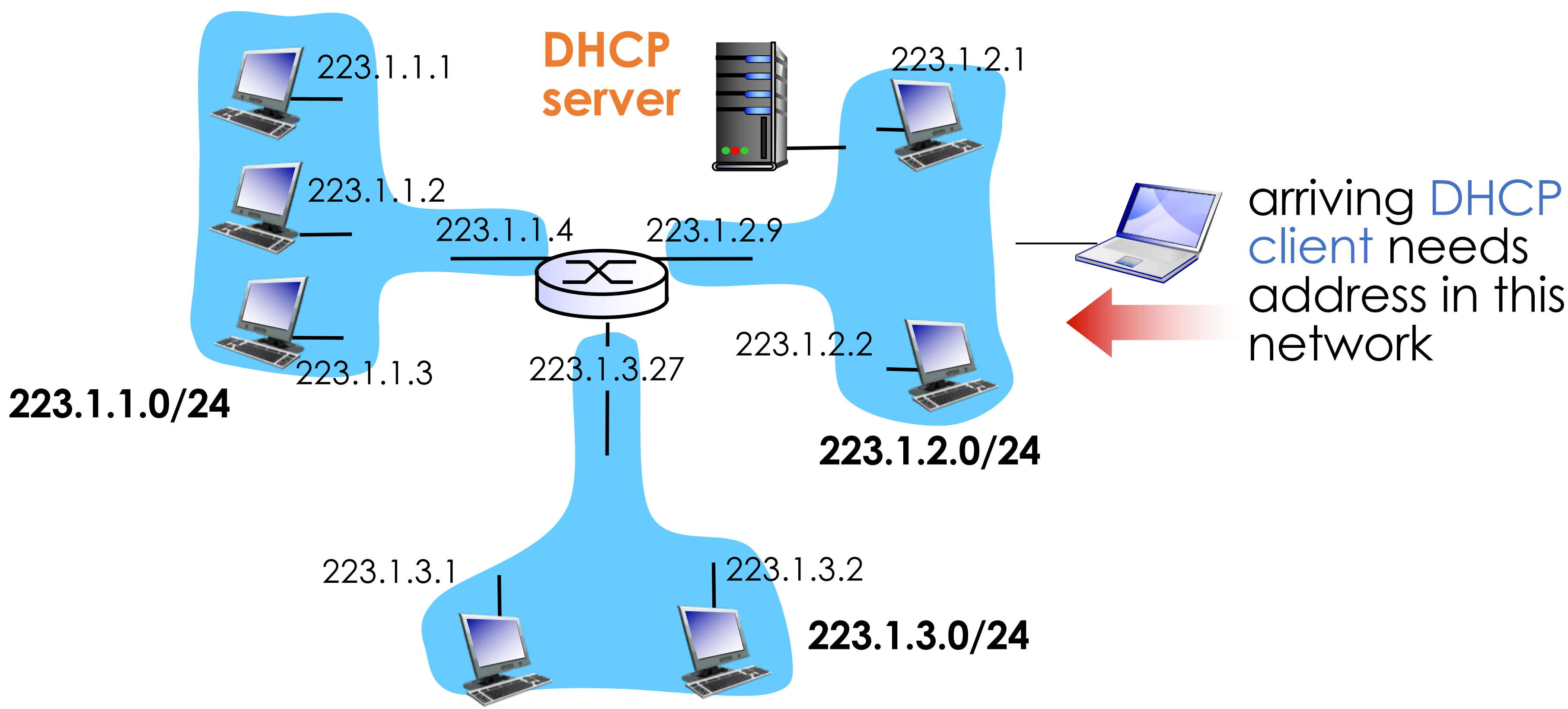
DHCP

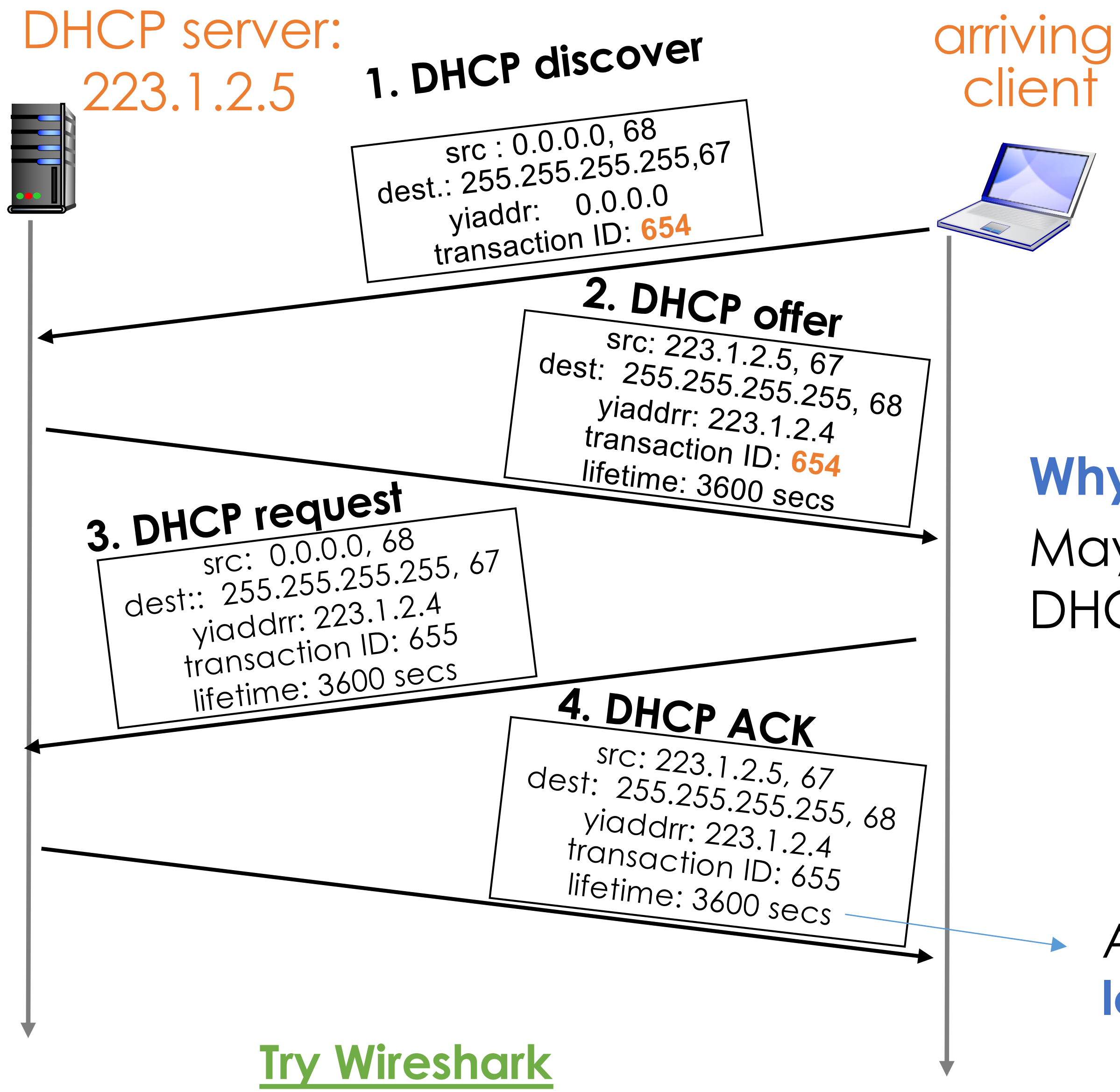
- Allow a host to *dynamically* and *automatically* get an IP address
  - Can renew its lease on address in use
  - Allow reuse of addresses (only hold address while connected/“on”)
  - Support for mobile users who want to join network → mobile IP (see Ch. 6)

- Client-server architecture
  - Server is found using **link-layer broadcasting**
  - Use UDP, port 67

DHCP Framework



DHCP Flow



Why steps 1- 2?

May have multiple DHCP servers in a subnet

Also known as **lease time**

Try Wireshark

Who Assign IP Addresses?

- ICANN: Internet Corporation for Assigned Names and Numbers http://www.icann.org/
  - Non-profit organization
  - Allocate addresses
  - Manage DNS
  - Assign domain names, resolves disputes

Quiz

- What is the subnet mask of 140.113.20.0/18
- Which subnet is larger?
  - 140.113.20.0/20
  - 140.113.20.0/23

Quiz

- Explain what doea *Longest Prefix Matching* mean
- What is the strength and shortage of TCAM?