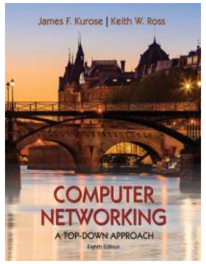
AinShams University
Faculty of Engineering

CSE 351: Computer networks
Section 7

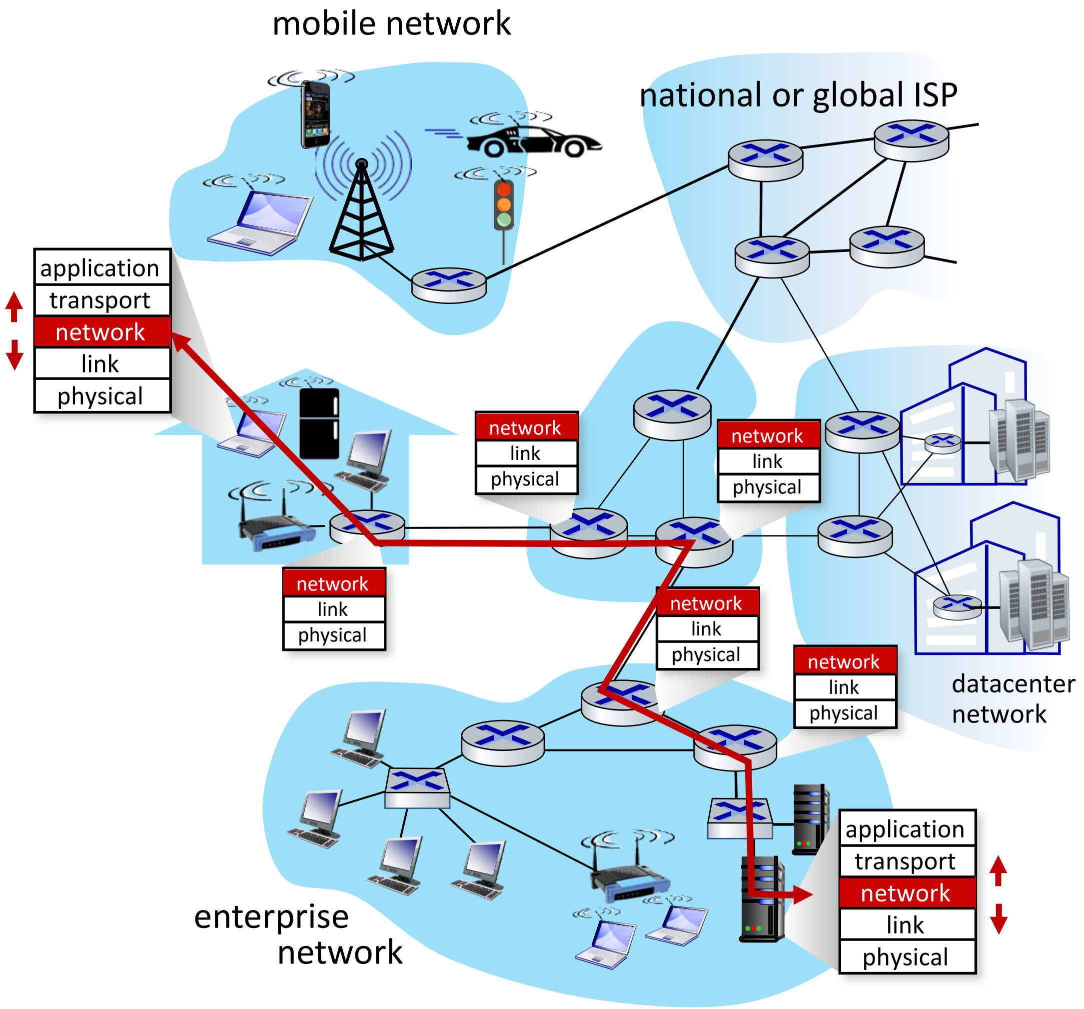
Eng. Noha Wahdan

Class textbook:
Computer Networking: A Top-Down Approach (8^{th} ed.)
J.F. Kurose, K.W. Ross
Pearson, 2020
http://gaia.cs.umass.edu/kurose_ross



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



Sheet 5 Q1

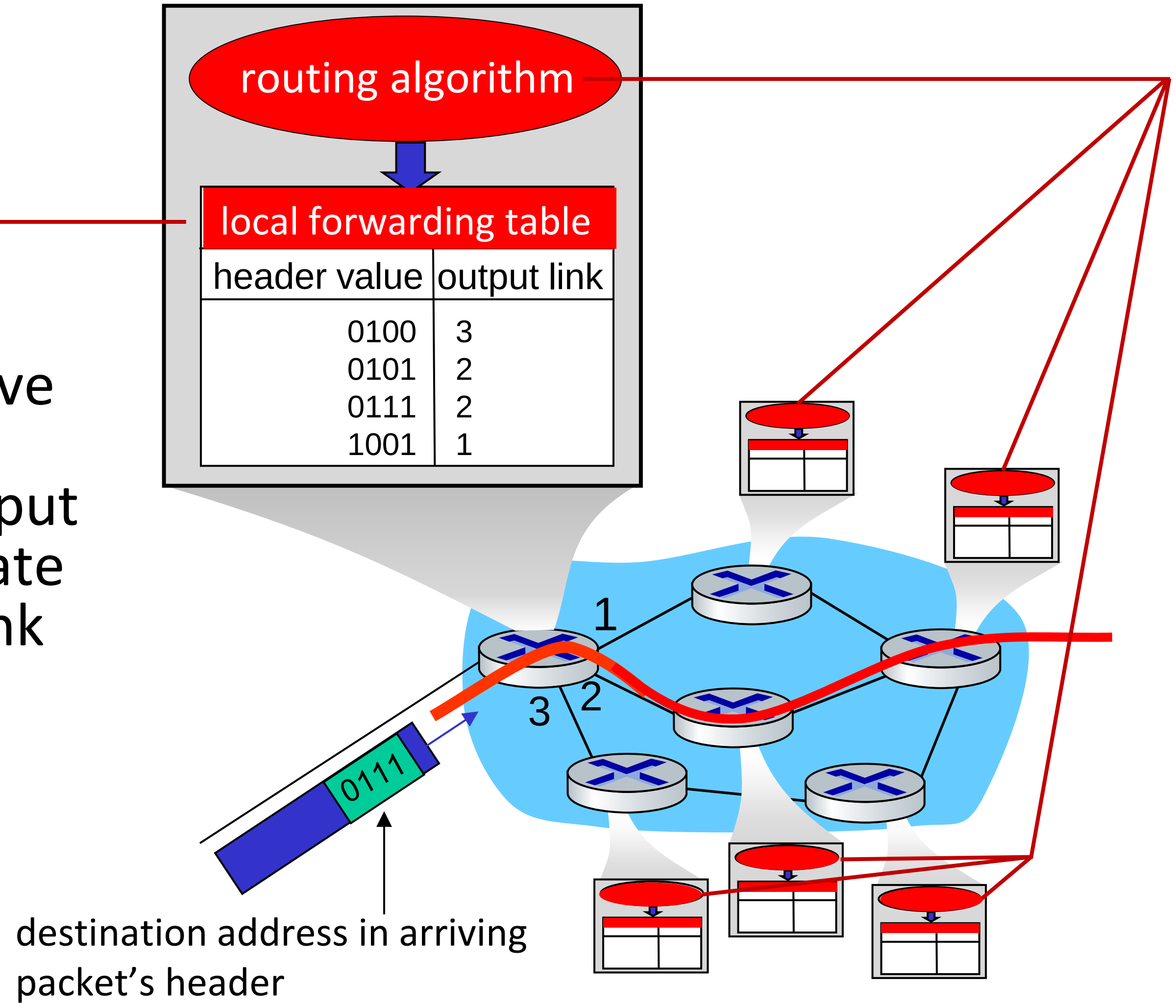
- Recall that the name of a transport-layer packet is segment and that the name of a link-layer packet is frame. What is the name of a network-layer packet?
- Recall that both routers and link-layer switches are called packet switches. What is the fundamental difference between a router and link-layer switch?

> - A network-layer packet is a datagram.
> - A router forwards a packet based on the packet's IP (layer 3) address.
> - A link-layer switch forwards a packet based on the packet's MAC (layer 2) address.

Two key network-core functions

Forwarding:

- aka "switching"
- *local* action: move arriving packets from router's input link to appropriate router output link



Routing:

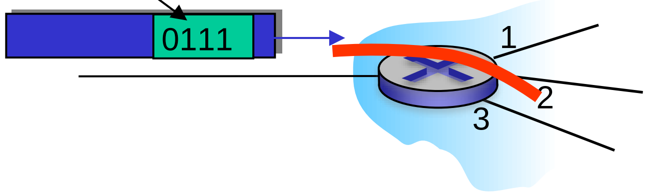
- *global* action: determine source-destination paths taken by packets
- routing algorithms

Network layer: data plane, control plane

Data plane:

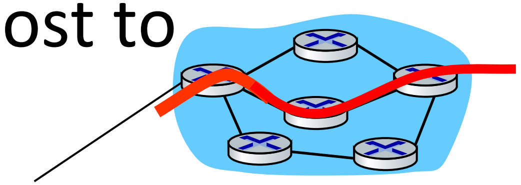
- *local*, per-router function
- determines how datagram arriving on router input port is *forwarded* to router output port

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



Sheet 5 Q2

What are the key differences between routing and forwarding?

forwarding	Routing
the router’s ***local* action** of transferring packets from its input interfaces to its output interfaces	the ***network-wide* process** that determines the end-to-end paths that packets take from sources to destinations.
takes place at very **short** timescales (typically a few nanoseconds),	takes place on much **longer** timescales (typically seconds),
typically implemented in **hardware**	often implemented in **software**

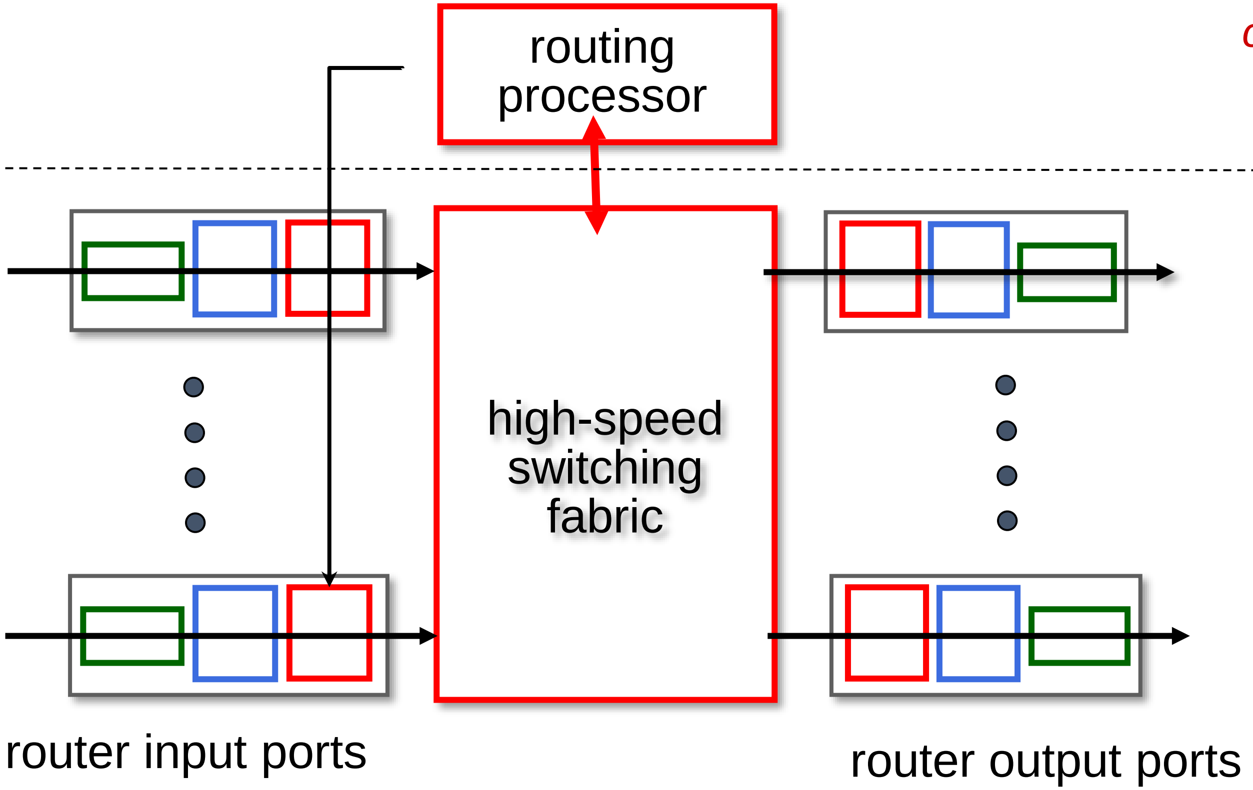
Sheet 5 Q3

What is the role of the forwarding table within a router?

The role of the forwarding table within a router is to hold entries to determine the outgoing link interface to which an arriving packet will be forwarded via switching fabric.

What's inside the Router

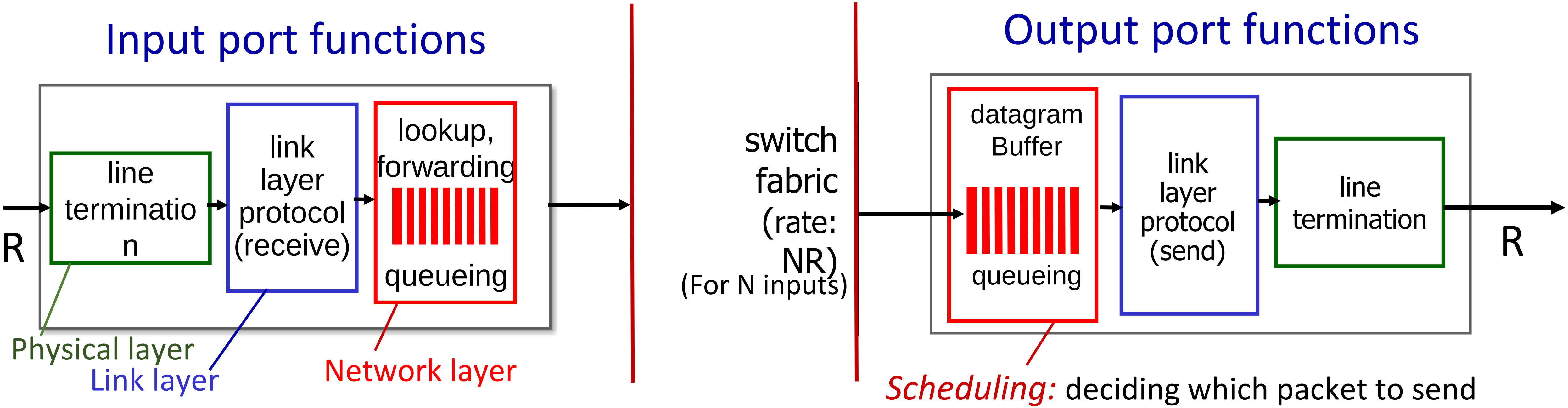
high-level view of generic router architecture:



routing, management control plane (software) operates in millisecond time frame

forwarding data plane (hardware) operates in nanosecond timeframe

Router architecture overview

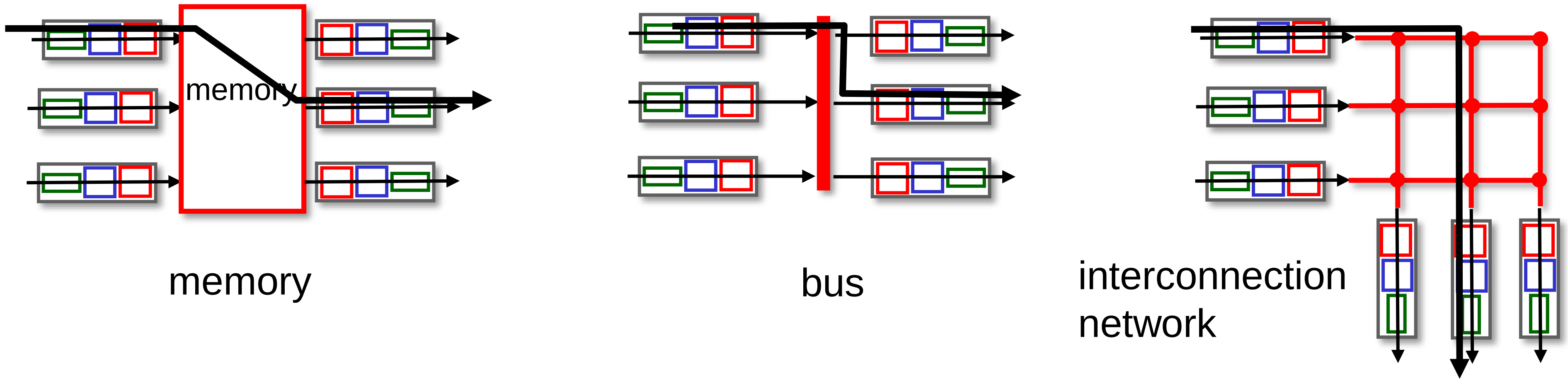


Scheduling: deciding which packet to send next on link

➡ lookup output port using headers & forwarding table *("match plus action")*

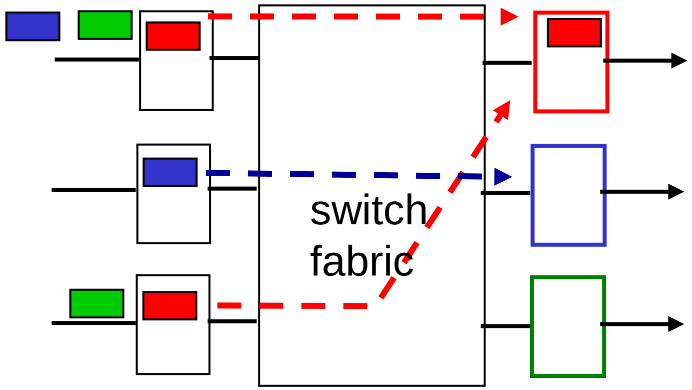
Switching fabrics

- 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:



Input / Output port queuing

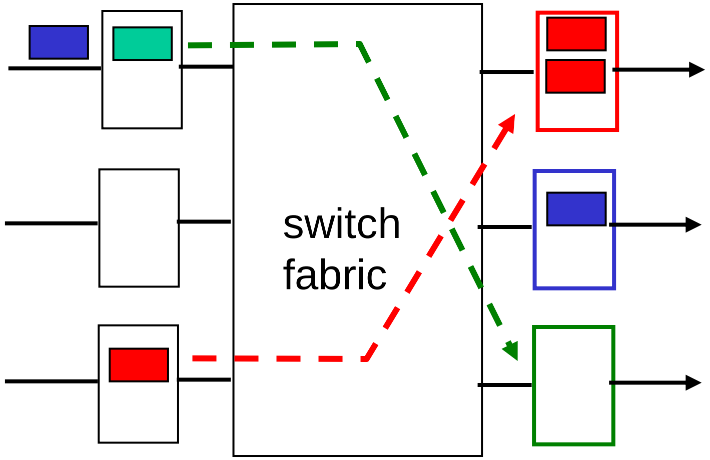
Input port queuing



When
- datagrams arrive faster than forwarding rate into switch fabric or switch fabric is slower than input ports

- Head-of-the-Line (HOL) blocking: queued datagram at front of queue prevents others in queue from moving forward

Output port queuing



When arrival rate from switch fabric exceeds output line speed

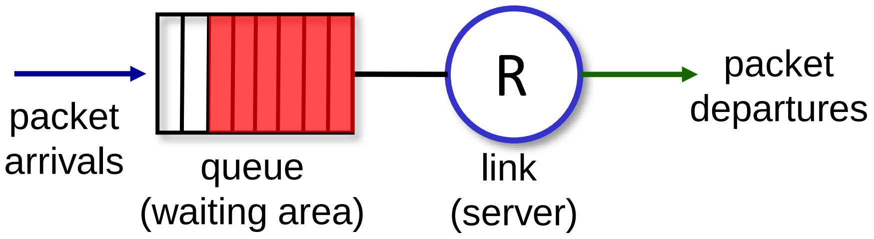
queuing (buffering) delay and loss may occur due to Input / Output port buffer overflow!

Output port: Buffer Management

packet scheduling: deciding which packet to send next on link

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

Abstraction: queue



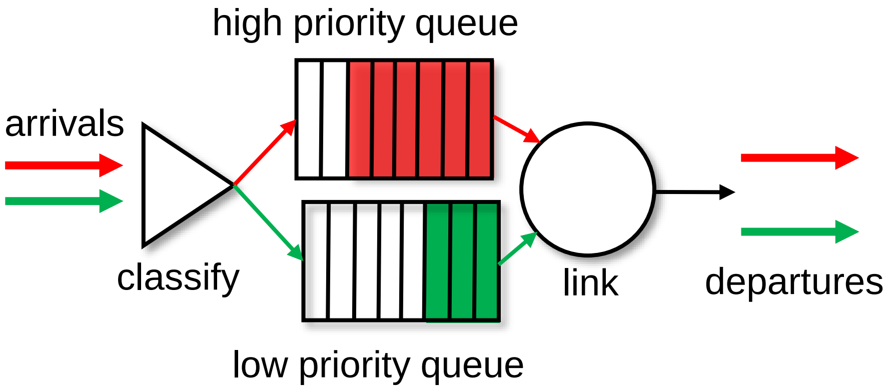
FCFS: packets transmitted in order of arrival to output port

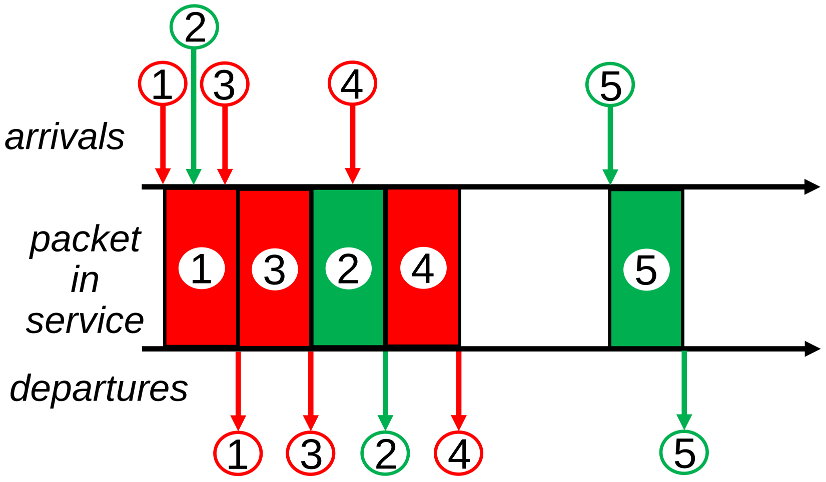
- also known as: First-in-first-out (FIFO)

Output port: Buffer Management

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

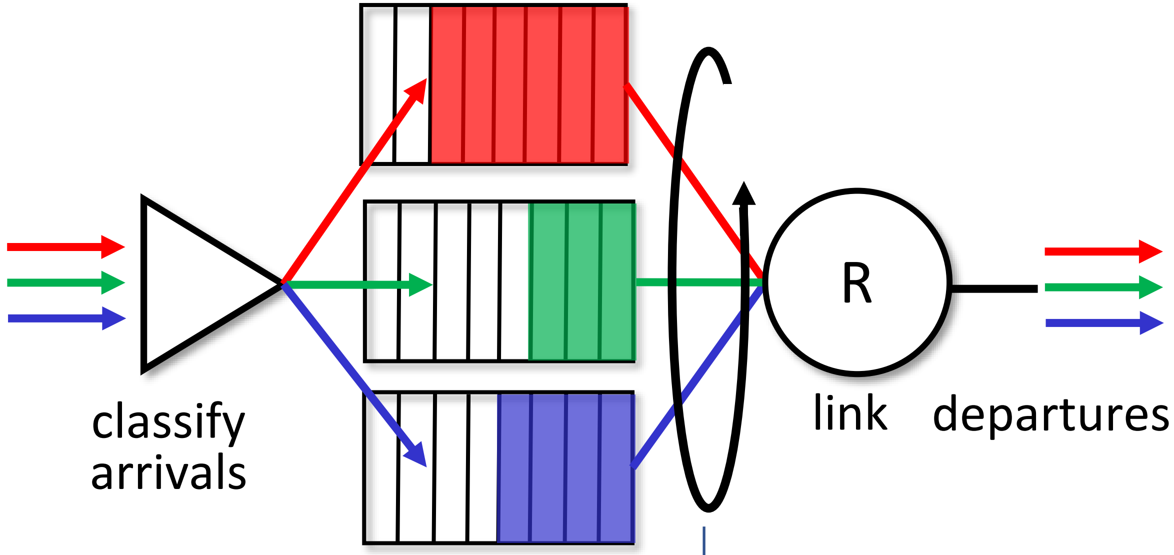




Output port: Buffer Management

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



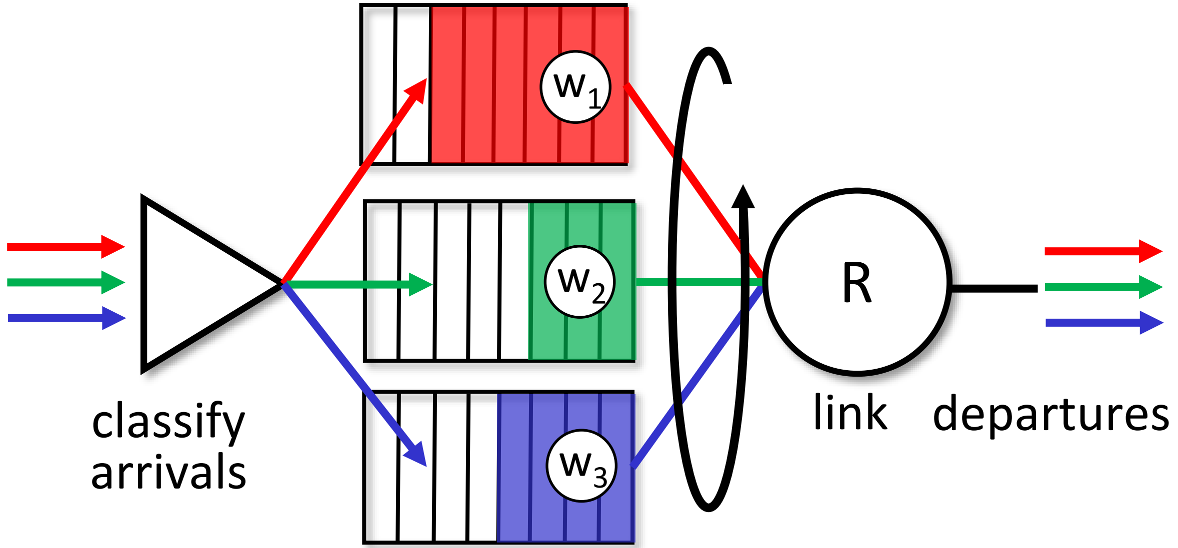
Output port: Buffer Management

Weighted Fair Queuing (WFQ):

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

$$\frac{w_i}{\Sigma_j w_j}$$

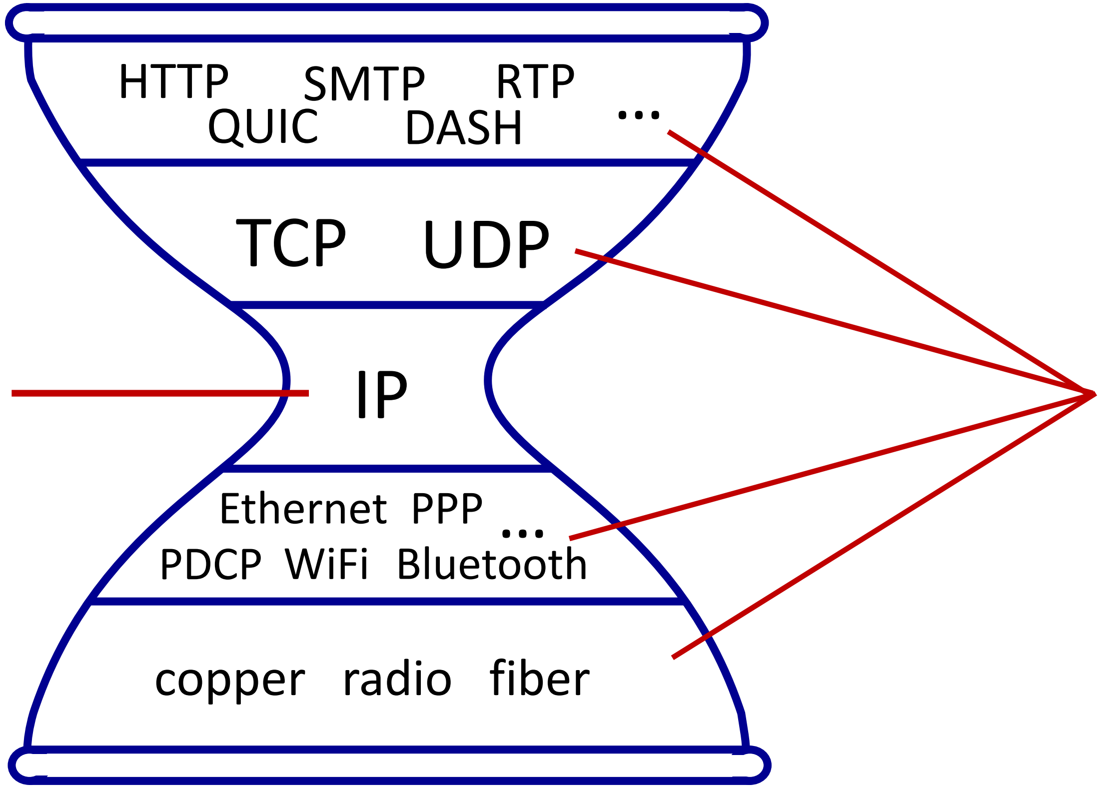
- minimum bandwidth guarantee (per-traffic-class)



The IP hourglass

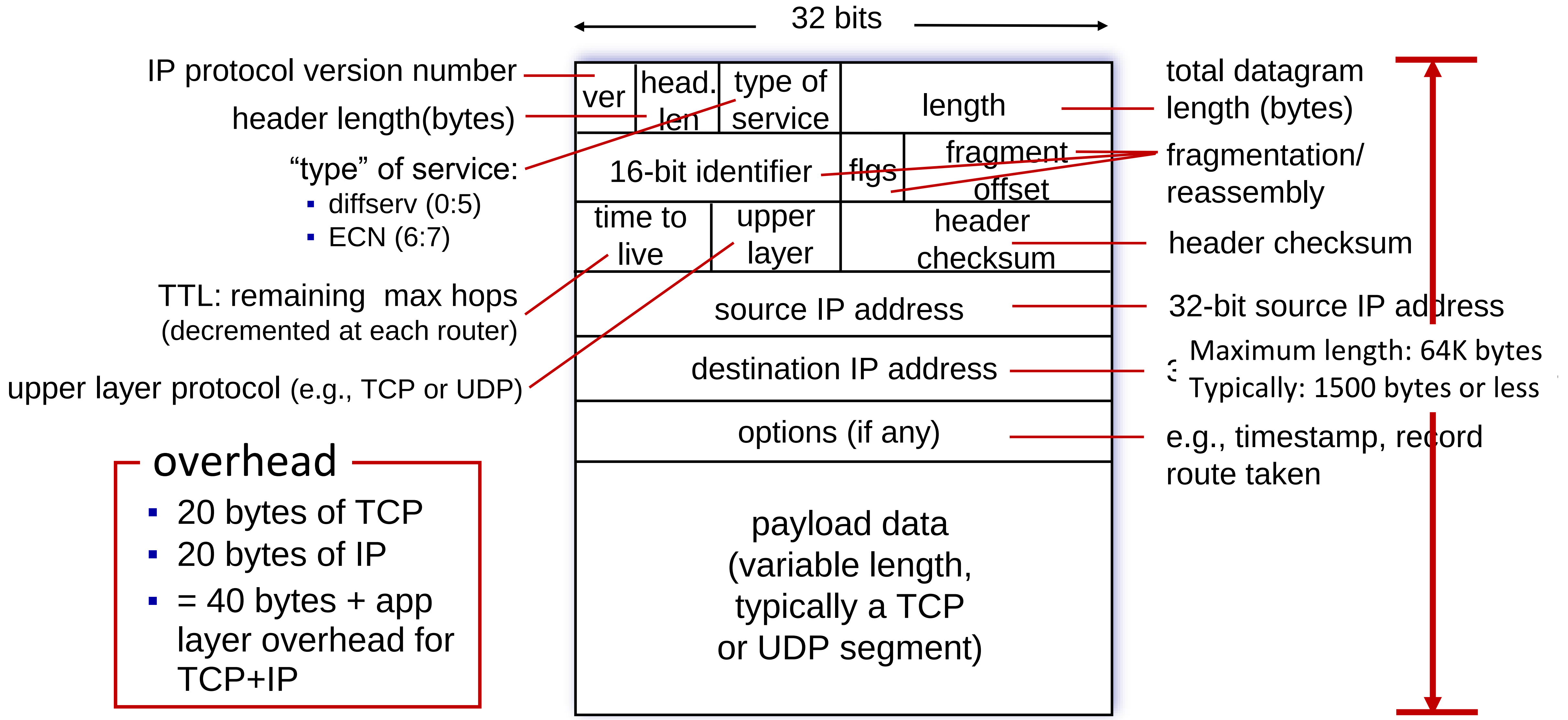
Internet's "thin waist":

- *one* network layer protocol: IP
- *must* be implemented by every (billions) of Internet-connected devices



many protocols in physical, link, transport, and application layers

IP Datagram format



overhead

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

Sheet 5 Q6

Suppose Host A sends Host B a TCP segment encapsulated in an IP datagram. When Host B receives the datagram, how does the network layer in Host B know it should pass the segment (that is, the payload of the datagram) to TCP rather than to UDP or to some other upper-layer protocol?

The 8-bit protocol field in the IP datagram contains information about which transport layer protocol the destination host should pass the segment to.

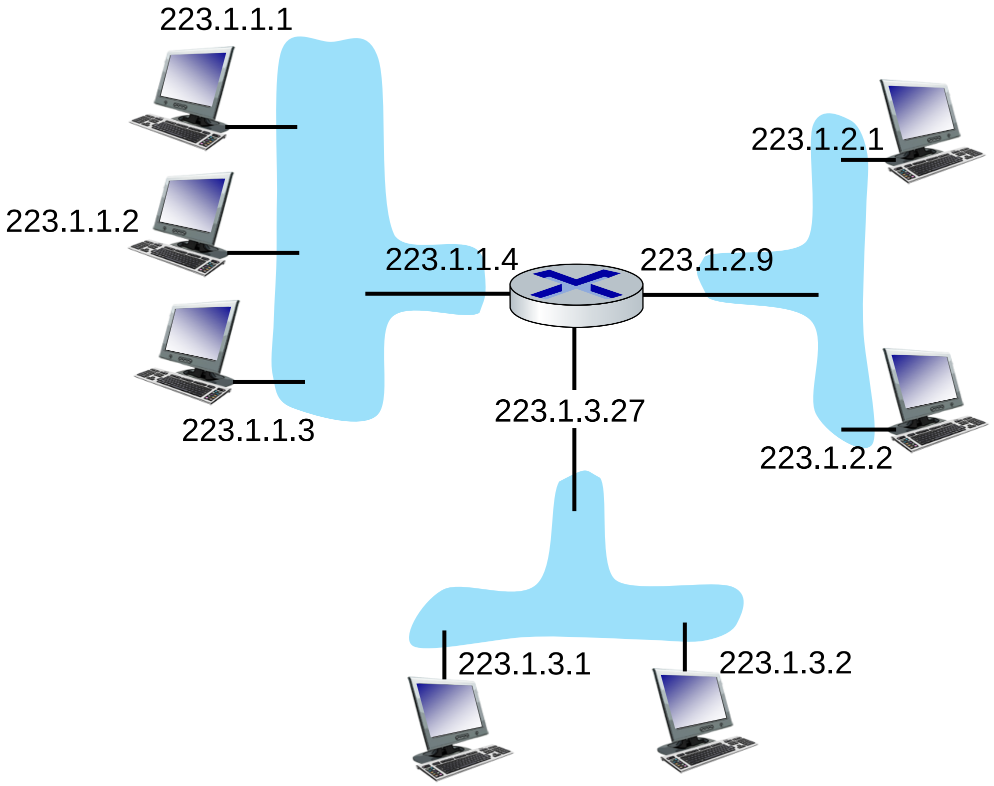
Sheet 5 Q15

Suppose datagrams are limited to 1,500 bytes (including header) between source Host A and destination Host B. Assuming a 20-byte IP header, how many datagrams would be required to send an MP3 consisting of 5 million bytes? Explain how you computed your answer.

MP3 file size = 5 million bytes. Assume the data is carried in TCP segments, with each TCP segment also having 20 bytes of header. Then each datagram can carry 1500-40=1460 bytes of the MP3 file.
Number of datagrams required = $(5\times10^6)/1460=3425$ datagrams.

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:

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

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

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

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
11001000 00010111 00011000 ********	1
11001000 00010111 00011*** ********	2
otherwise	3

match!

examples:

11001000 00010111 00010110 10100001 which interface?

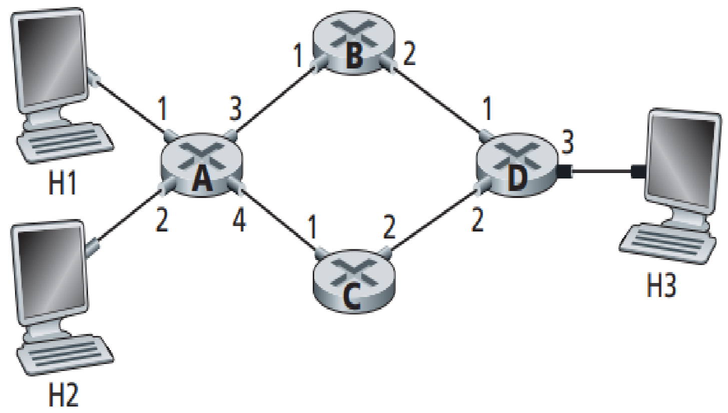
11001000 00010111 00011000 10101010 which interface?

Sheet 5 Q5

- Consider the network below.
- Show the forwarding table in router A, such that all traffic destined to host H3 is forwarded through interface 3.
- Can you write down a forwarding table in router A, such that all traffic from H1 destined to host H3 is forwarded through interface 3, while all traffic from H2 destined to host H3 is forwarded through interface 4?
  - Data destined to host H3 is forwarded through interface 3

Destination Address	Link Interface
H3	3

  - No, because forwarding rule is only based on destination address



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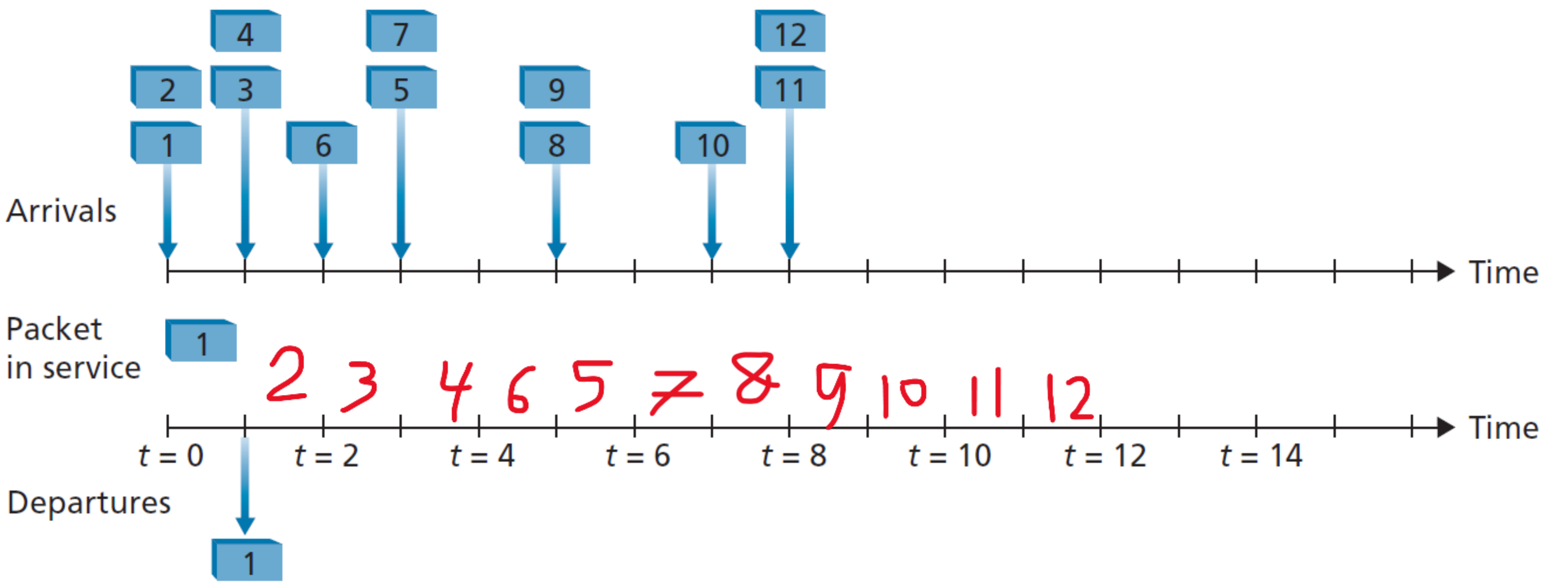
Sheet (5): Network Layer

1. Consider the figure below. Answer the following questions:

   a. Assuming FIFO service, indicate the time at which packets 2 through 12 each leave the queue. For each packet, what is the delay between its arrival and the beginning of the slot in which it is transmitted? What is the average of this delay over all 12 packets?



Packet Index	Leave queue time	Delay (Departure time – Arrival time)	Average delay
1	1	1	35/12 = 2.93 seconds
2	2	2	
3	3	2	
4	4	3	
5	6	3	
6	5	3	
7	7	4	
8	8	3	
9	9	4	
10	10	3	
11	11	3	
12	12	4	

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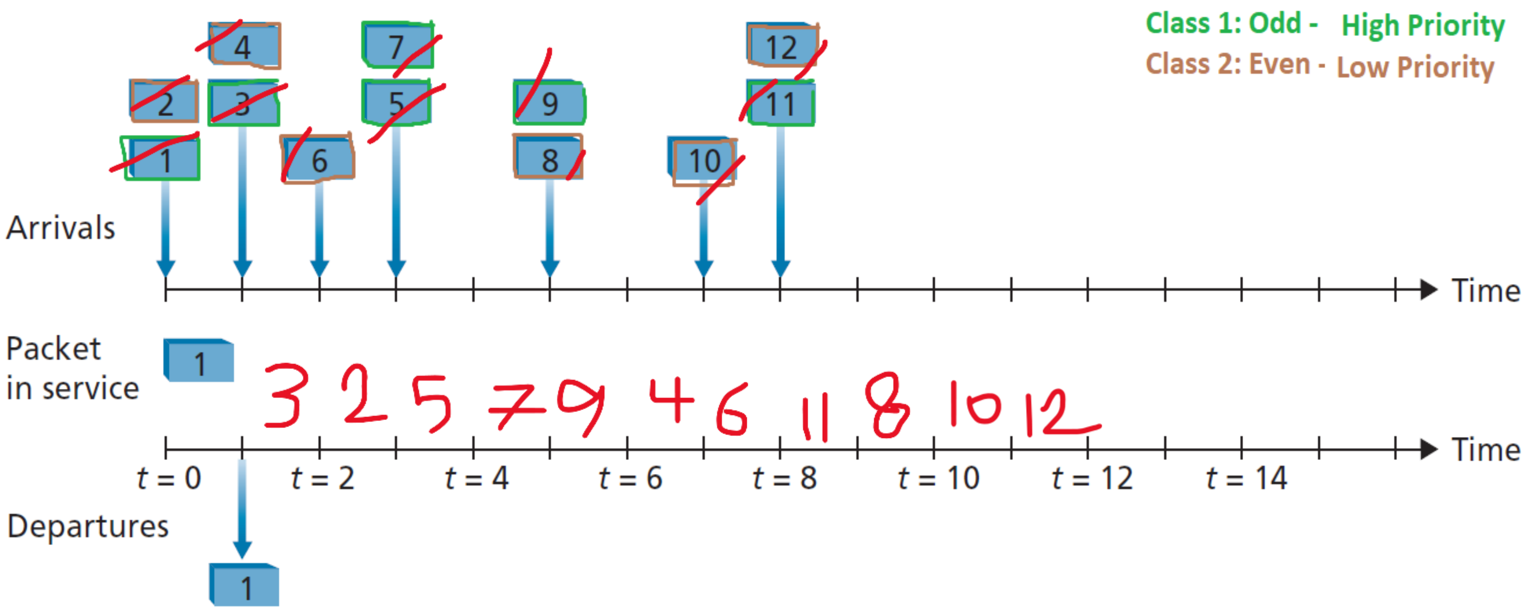
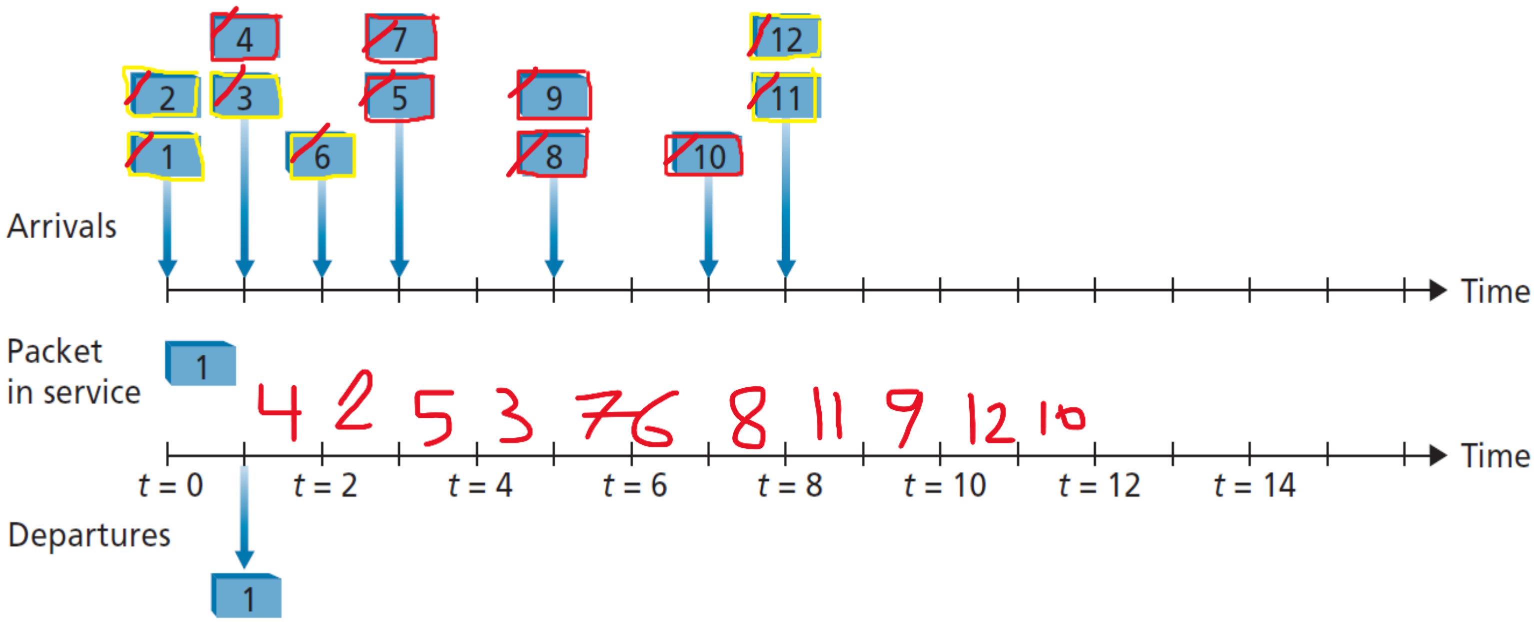
b. Now assume a priority service and assume that odd-numbered packets are high priority, and even-numbered packets are low priority. Indicate the time at which packets 2 through 12 each leave the queue. For each packet, what is the delay between its arrival and the beginning of the slot in which it is transmitted? What is the average of this delay over all 12 packets?



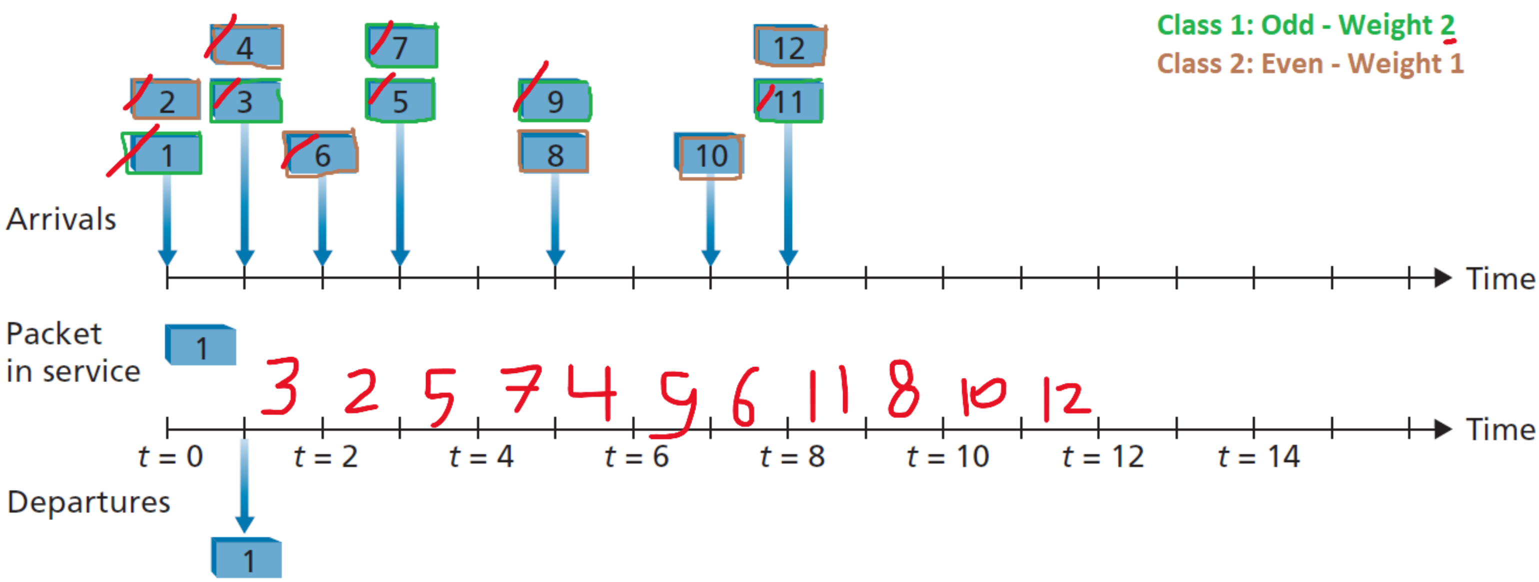
Packet Index	Leave queue time	Delay (Departure time – Arrival time)	Average delay
1	1	1	35/12 = 2.93 seconds
2	3	3	
3	2	1	
4	7	6	
5	4	1	
6	8	6	
7	5	2	
8	10	6	
9	6	1	
10	11	4	
11	9	1	
12	12	4	

c. Now assume round robin service. Assume that packets 1, 2, 3, 6, 11, and 12 are from class 1, and packets 4, 5, 7, 8, 9, and 10 are from class 2. Indicate the time at which packets 2 through 12 each leave the queue. For each packet, what is the delay between its arrival and its departure? What is the average delay over all 12 packets?



Packet Index	Leave queue time	Delay (Departure time – Arrival time)	Average delay
1	1	1	35/12 = 2.93 seconds
2	3	3	
3	5	4	
4	2	1	
5	4	1	
6	7	5	
7	6	3	
8	8	3	
9	10	5	
10	12	5	
11	9	1	
12	11	3	

d. Now assume weighted fair queueing (WFQ) service. Assume that odd-numbered packets are from class 1, and even-numbered packets are from class 2. Class 1 has a WFQ weight of 2, while class 2 has a WFQ weight of 1. Note that it may not be possible to achieve an idealized WFQ schedule as described in the text, so indicate why you have chosen the particular packet to go into service at each time slot. For each packet what is the delay between its arrival and its departure? What is the average delay over all 12 packets?



Packet Index	Leave queue time	Delay (Departure time – Arrival time)	Average delay
1	1	1	35/12 = 2.93 seconds
2	3	3	
3	2	1	
4	6	5	
5	4	1	
6	8	6	
7	5	2	
8	10	5	
9	7	2	
10	11	4	
11	9	1	
12	12	4	

e. What do you notice about the average delay in all four cases (FIFO, RR, priority, and WFQ)?

All average delays remain the same.

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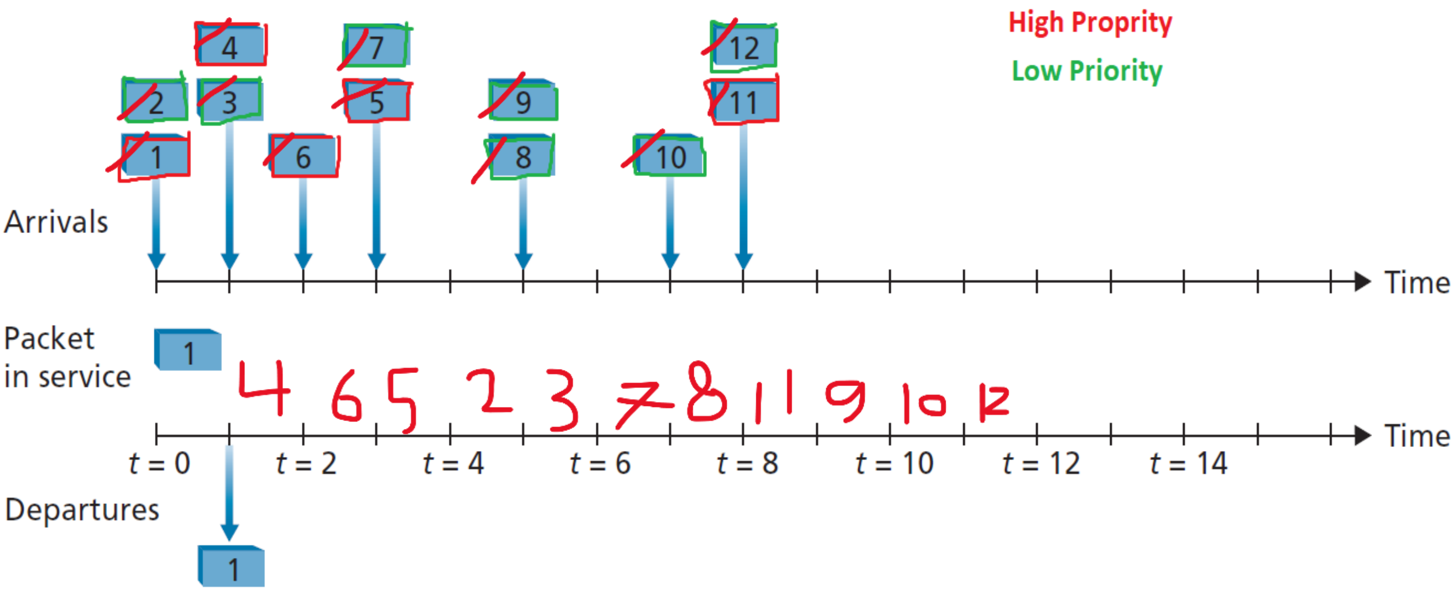
Sheet (5): Network Layer

2. Consider again the figure from previous problem,
   a. Assume a priority service, with packets 1, 4, 5, 6, and 11 being high-priority packets. The remaining packets are low priority. Indicate the slots in which packets 2 through 12 each leave the queue.



Packet Index	Leave queue time
1	1
2	5
3	6
4	2
5	4
6	3
7	7
8	8
9	10
10	11
11	9
12	12

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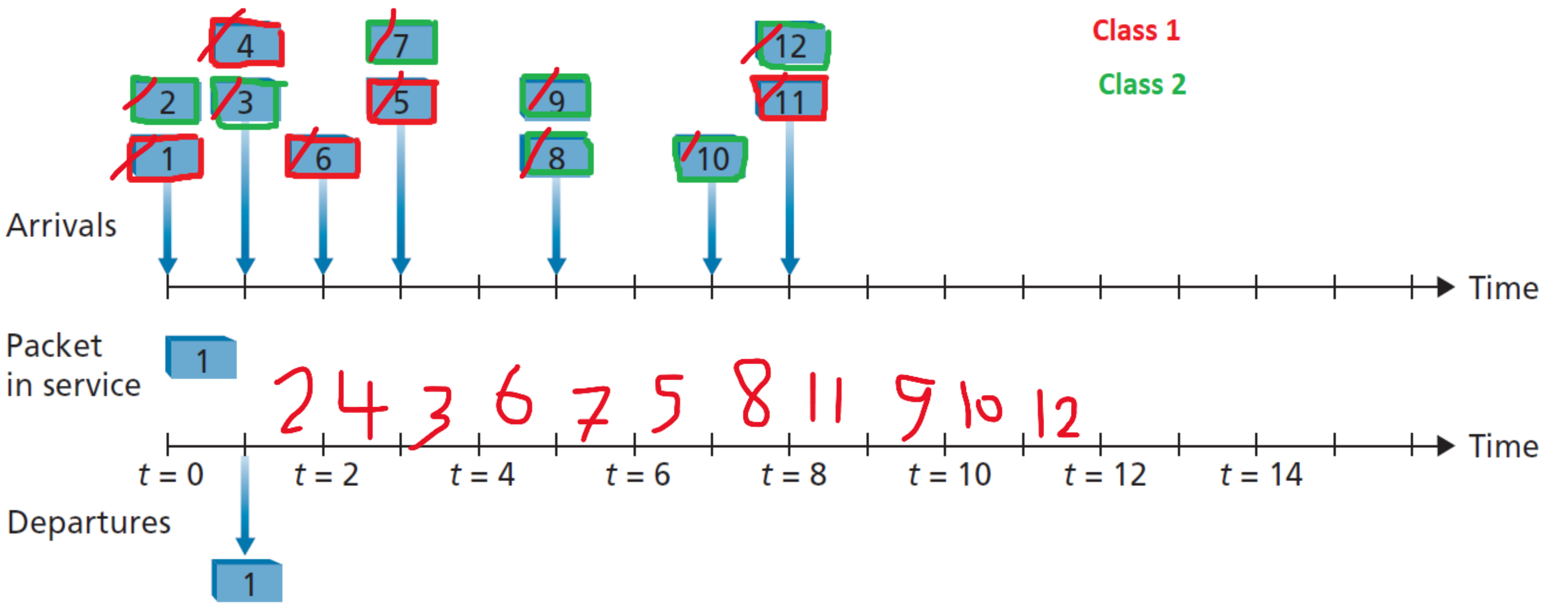
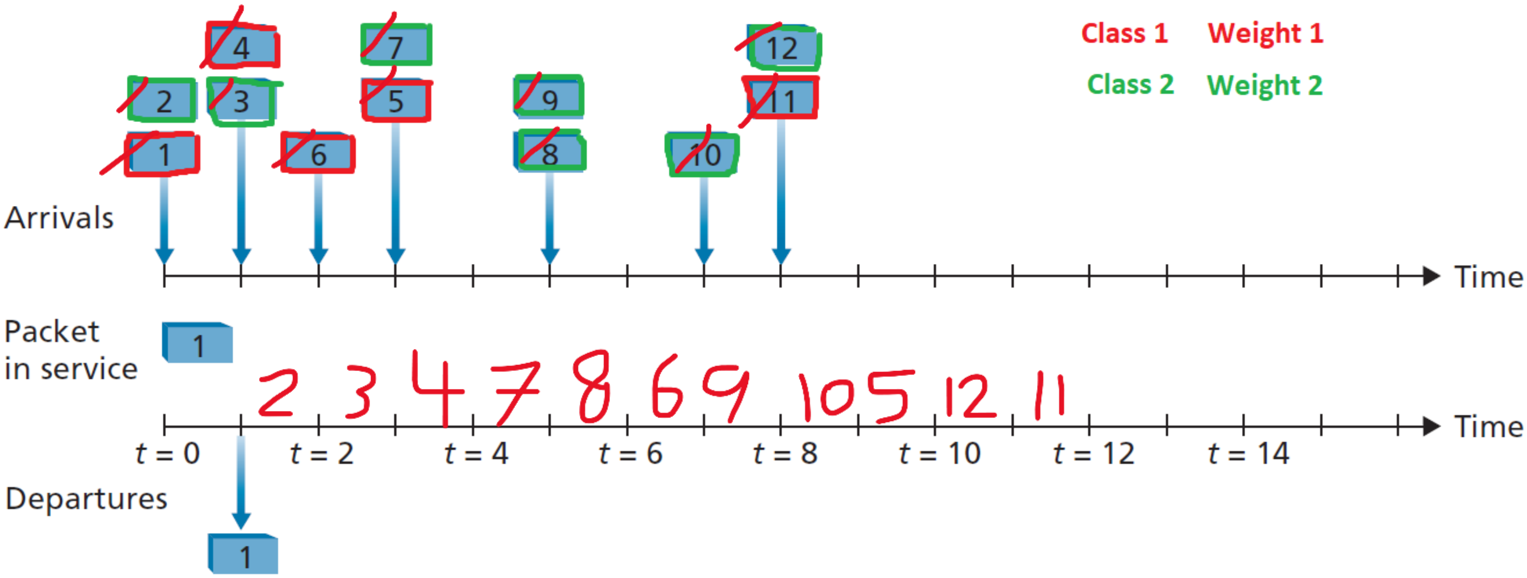
b. Now suppose that round robin service is used, with packets 1, 4, 5, 6, and 11 belonging to one class of traffic, and the remaining packets belonging to the second class of traffic. Indicate the slots in which packets 2 through 12 each leave the queue.



Packet Index	Leave queue time
1	1
2	2
3	4
4	3
5	7
6	5
7	6
8	8
9	10
10	11
11	9
12	12

c. Now suppose that WFQ service is used, with packets 1, 4, 5, 6, and 11 belonging to one class of traffic, and the remaining packets belonging to the second class of traffic. Class 1 has a WFQ weight of 1, while class 2 has a WFQ weight of 2 (note that these weights are different than in the previous question). Indicate the slots in which packets 2 through 12 each leave the queue. See also the caveat in the question above regarding WFQ service.



Packet Index	Leave queue time
1	1
2	2
3	3
4	4
5	10
6	7
7	5
8	6
9	8
10	9
11	12
12	11

3. Consider a datagram network using 32-bit host addresses. Suppose a router has four links, numbered 0 through 3, and packets are to be forwarded to the link interfaces as follows:

Destination Address Range	**Link Interface**
11100000 00000000 00000000 00000000 through **11100000 00**111111 11111111 11111111	0
11100000 01000000 00000000 00000000 through **11100000 01000000** 11111111 11111111	1
11100000 01000001 00000000 00000000 through **1110000**1 01111111 11111111 11111111	2
otherwise	3

   a. Provide a forwarding table that has five entries, uses longest prefix matching, and forwards packets to the correct link interfaces.

Prefix Match	Link Interface
11100000 00****** ******** ********	0
11100000 01000000 ******** ********	1
1110000* ******** ******** ********	2
11100001 1******* ******** ********	3
otherwise	3

b. Describe how your forwarding table determines the appropriate link interface for datagrams with destination addresses:

11001000 10010001 01010001 01010101
link interface: 3 (5th entry).

11100001 01000000 11000011 00111100
link interface: 2 (3rd entry).

11100001 10000000 00010001 01110111
link interface: 3 (4th entry).

4. Consider a datagram network using 8-bit host addresses. Suppose a router uses longest prefix matching and has the following forwarding table:

Prefix Match	Interface
1	0
10	1
111	2
Otherwise	3

For each of the four interfaces, give the associated range of destination host addresses and the number of addresses in the range.

Destination Address Range	Link Interface	No. of Addresses
11000000 through 11011111	0	32 addresses
10000000 through 10111111	1	64 addresses
11100000 through 11111111	2	32 addresses
00000000 through 01111111	3	128 addresses