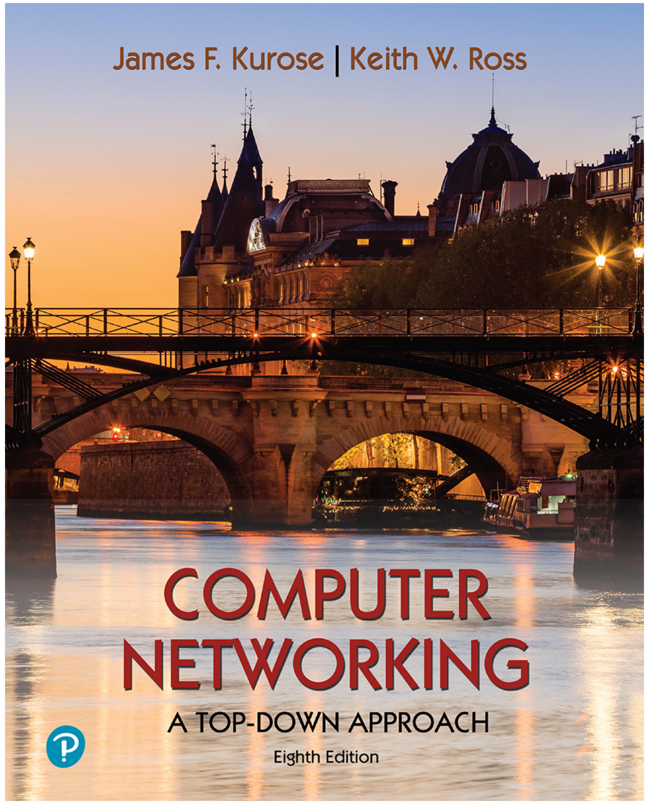
# Chapter 4
# Network Layer: Data Plane




*Computer Networking: A Top-Down Approach*
8th edition
Jim Kurose, Keith Ross
Pearson, 2020

Acknowledgement: Based on the textbook's website:
https://gaia.cs.umass.edu/kurose_ross/index.php

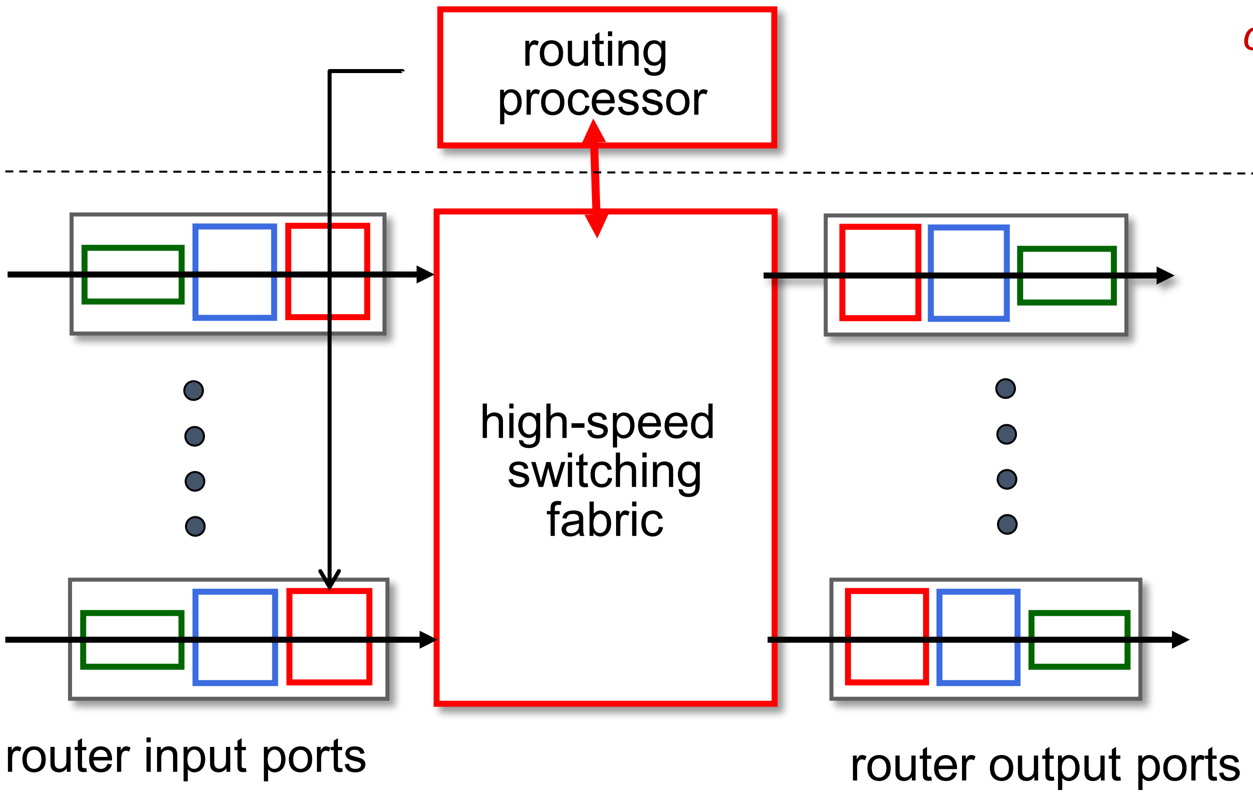
# Network layer: “data plane” roadmap

- 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

# Router architecture overview

high-level view of generic router architecture:

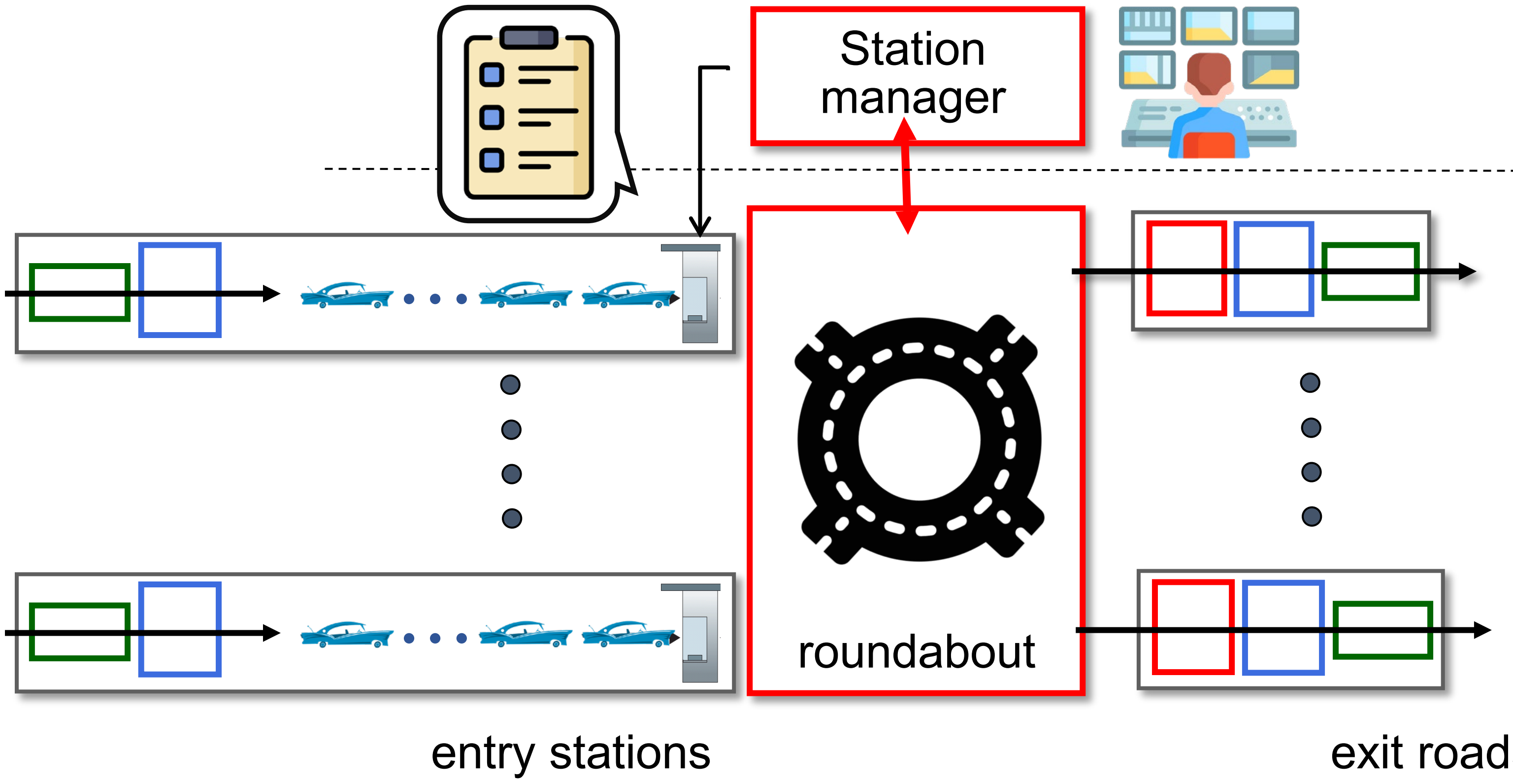



*routing, management control plane* (software) operates in millisecond time frame

*forwarding data plane* (hardware) operates in nanosecond timeframe

# Router architecture overview

analogy view of generic router architecture:




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

*forwarding data plane*
(hardware) operates
in nanosecond
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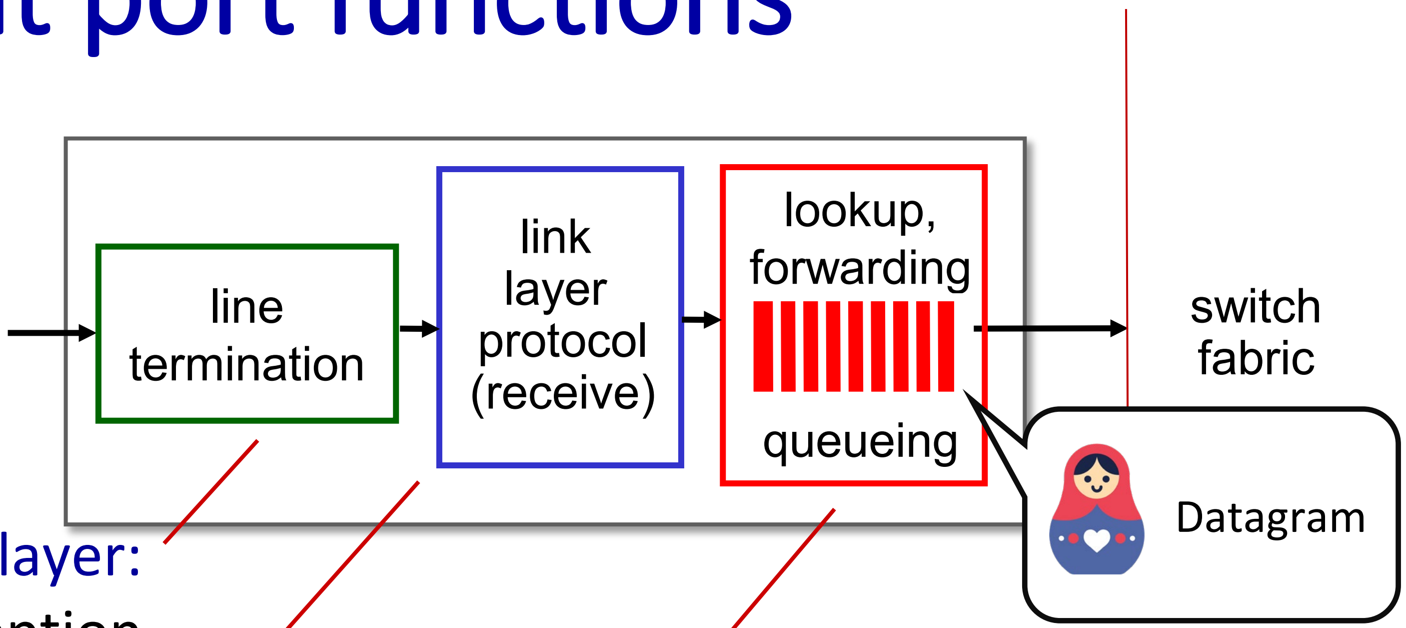
# Input port functions




physical layer:
bit-level reception

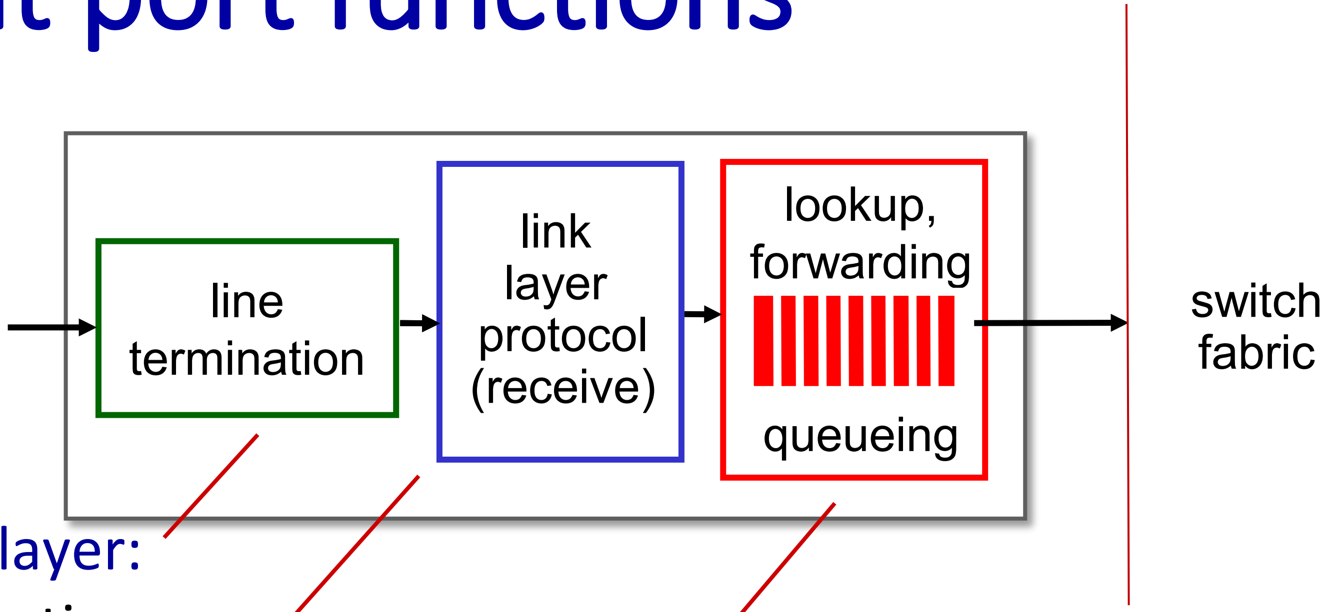
link layer:
e.g., Ethernet
(chapter 6)


Frame

## decentralized 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'
- input port queuing: if datagrams arrive faster than forwarding rate into switch fabric

# Input port functions




**physical layer:**
bit-level reception

**link layer:**
e.g., Ethernet
(chapter 6)

**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: forward based on any set of header field values

# Destination-based forwarding

*forwarding table*

| Destination Address Range | Link Interface |
|---|---|
| 11001000 00010111 00010000 00000000<br>through | 0 |
| 11001000 00010111 00010000 00000100<br>through<br>11001000 00010111 00010000 00000111 | 3 |
| 11001000 00010111 00011000 11111111 | |
| 11001000 00010111 00011001 00000000<br>through<br>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?

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match!

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examples:

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| otherwise | | | | 3 |

match!

examples:

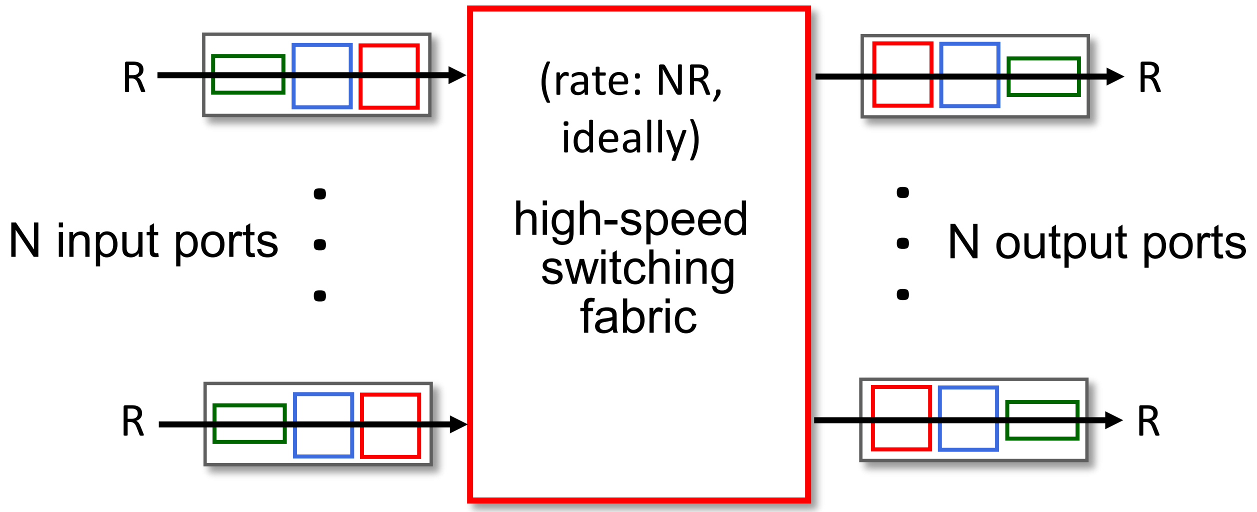
| | | | | |
|---|---|---|---|---|
| 11001000 | 00010111 | 00010110 | 10100001 | which interface? |
| 11001000 | 00010111 | 00011000 | 10101010 | which interface? |

# 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
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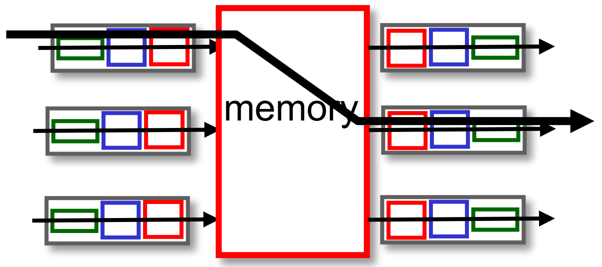
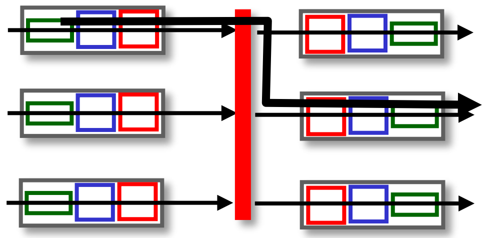
  - N inputs: switching rate N times line rate desirable
- three major types of switching fabrics:

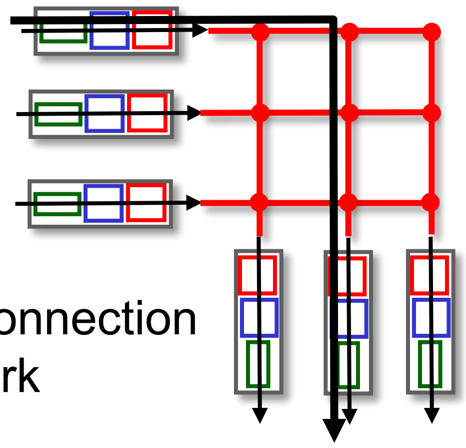



memory



bus

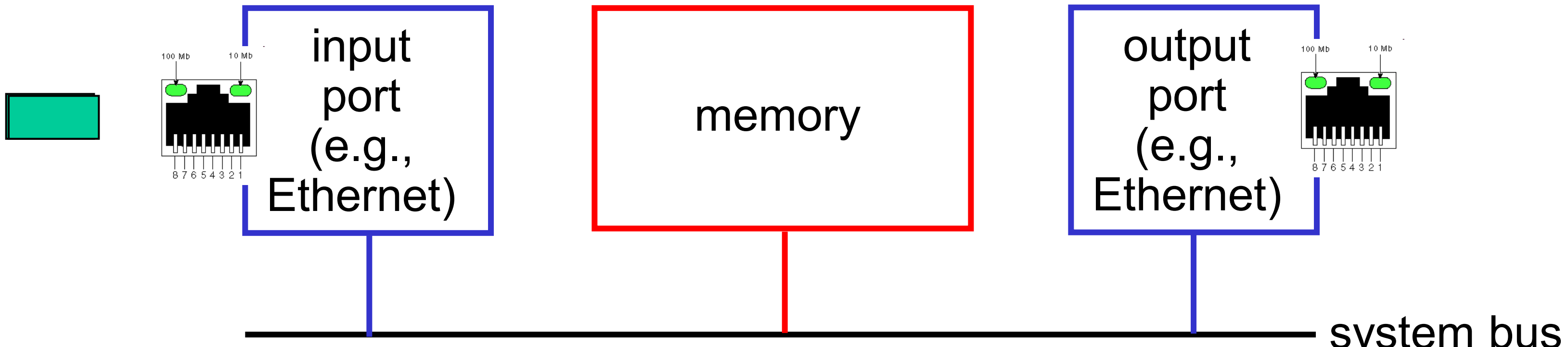
interconnection network



# Switching via memory

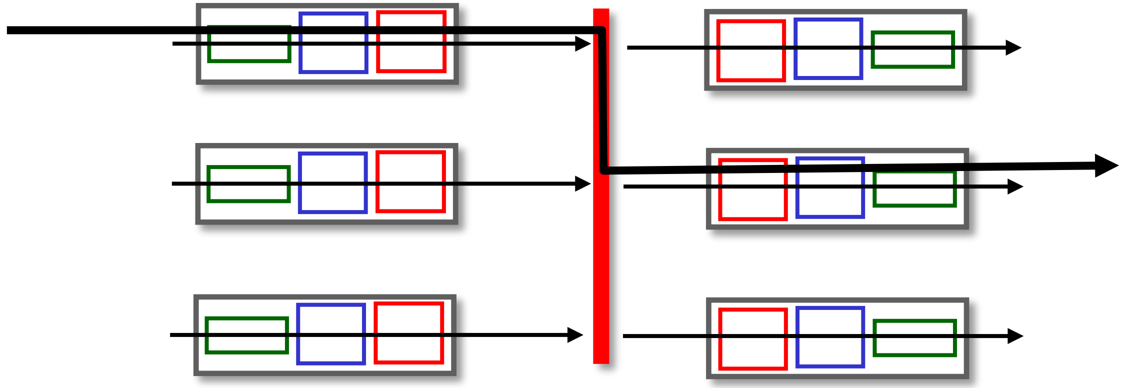
**first generation routers:**

- 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)



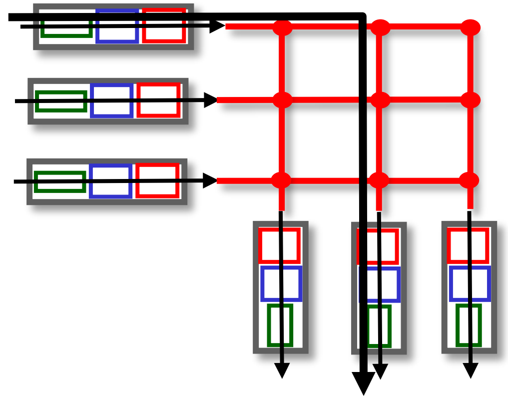
# Switching via a bus

- 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

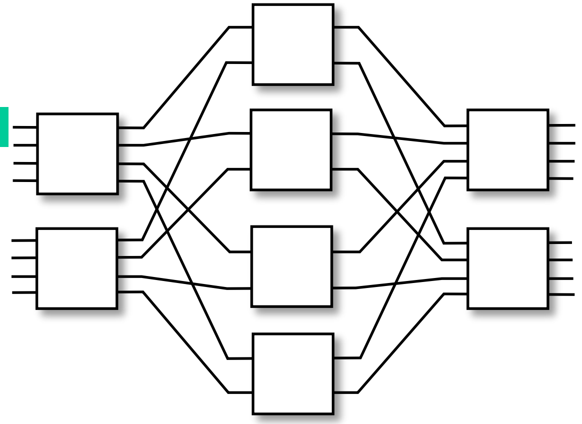


# Switching via interconnection network

- Crossbar, Clos networks, other interconnection nets initially developed to connect processors in multiprocessor
- multistage switch: *nxn* 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



3x3 crossbar

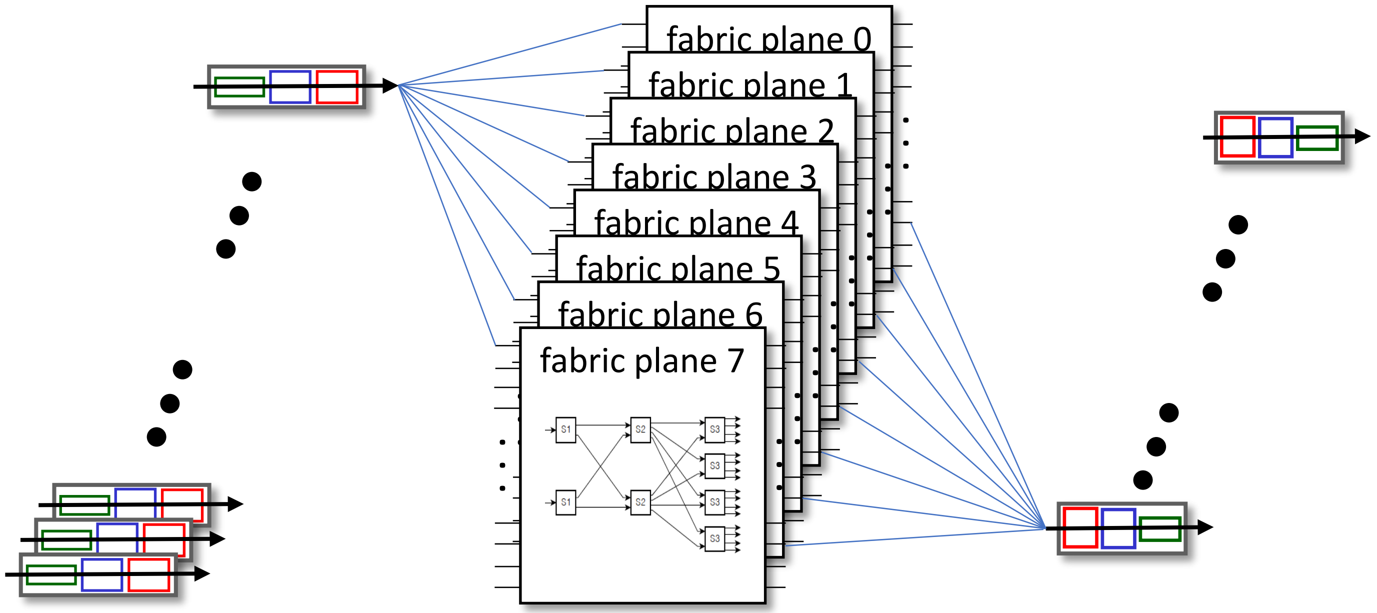


8x8 multistage switch
built from smaller-sized switches

# Switching via interconnection network

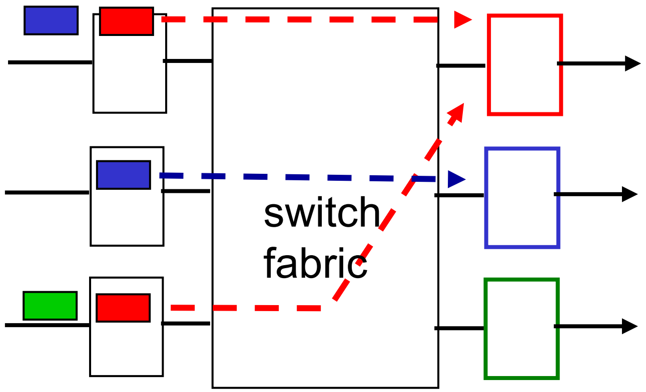
- scaling, using multiple switching “planes” in parallel:
  - speedup, scaleup via parallelism

- Cisco CRS router:
  - basic unit: 8 switching planes
  - each plane: 3-stage interconnection network
  - up to 100’s Tbps switching capacity

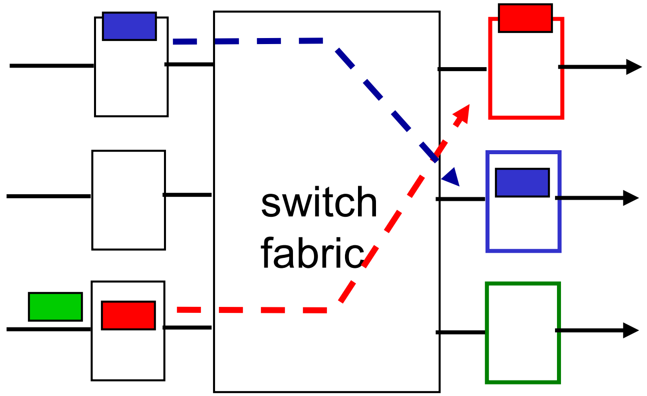


# Input port queuing

- 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

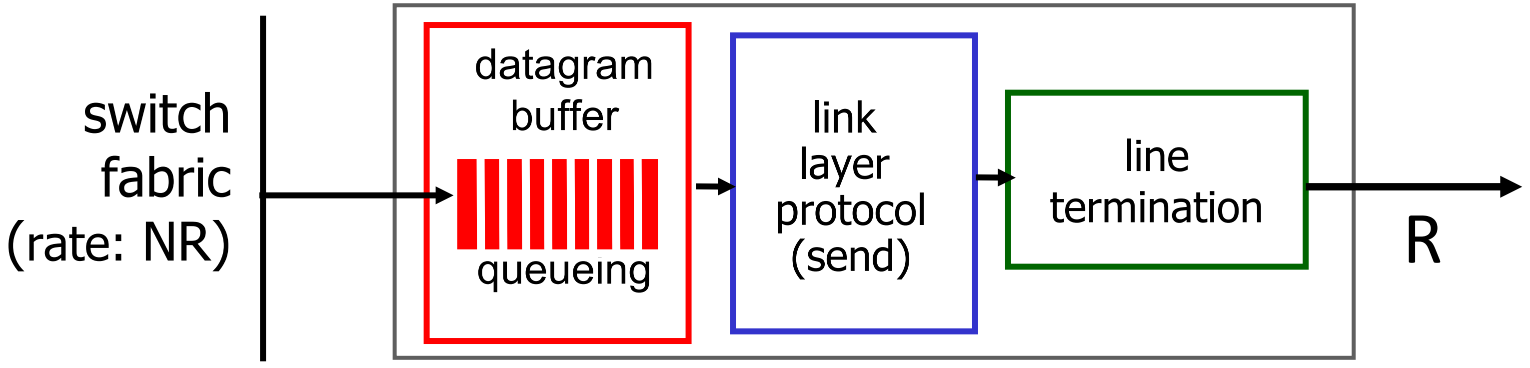



output port contention: only one red datagram can be transferred. lower red packet is *blocked*




one packet time later: green packet experiences HOL blocking

# Output port queuing




This is a really important slide

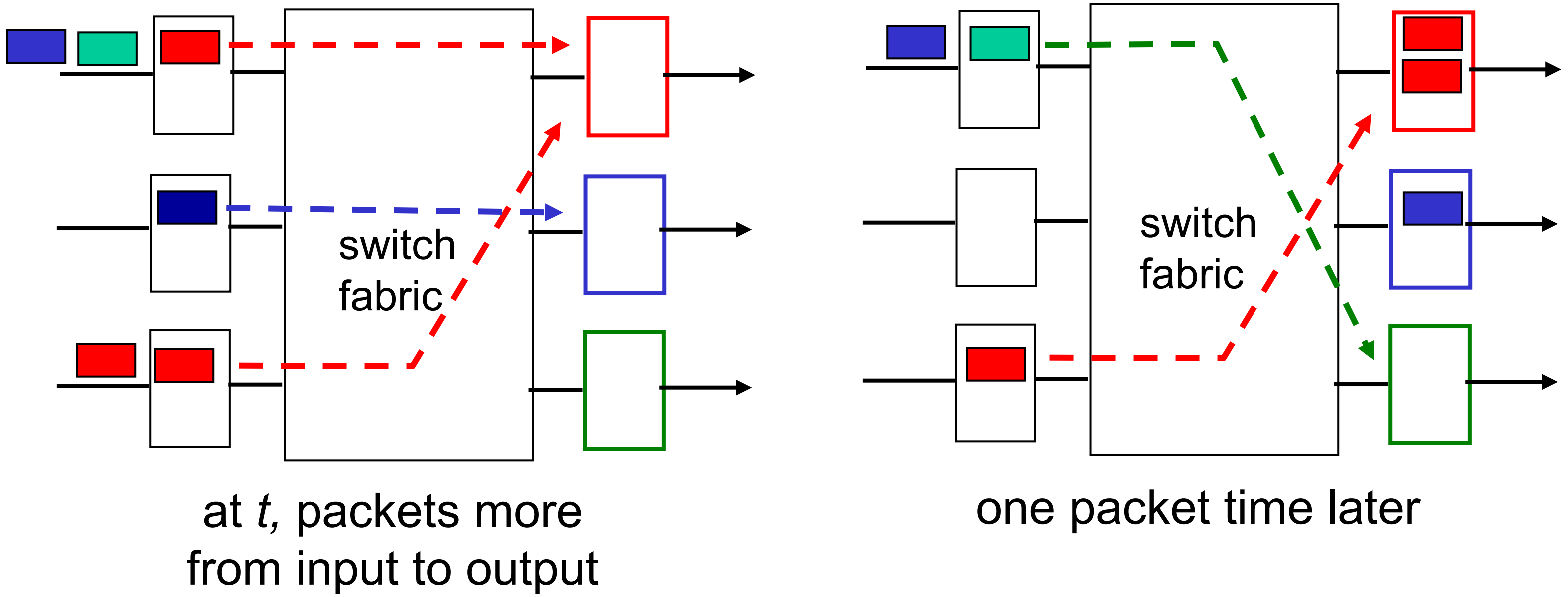
- *Buffering* required when datagrams arrive from fabric faster than link transmission rate. *Drop policy:* which datagrams to drop if no free buffers?

Datagrams can be lost due to congestion, lack of buffers

- *Scheduling discipline* chooses among queued datagrams for transmission

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!*

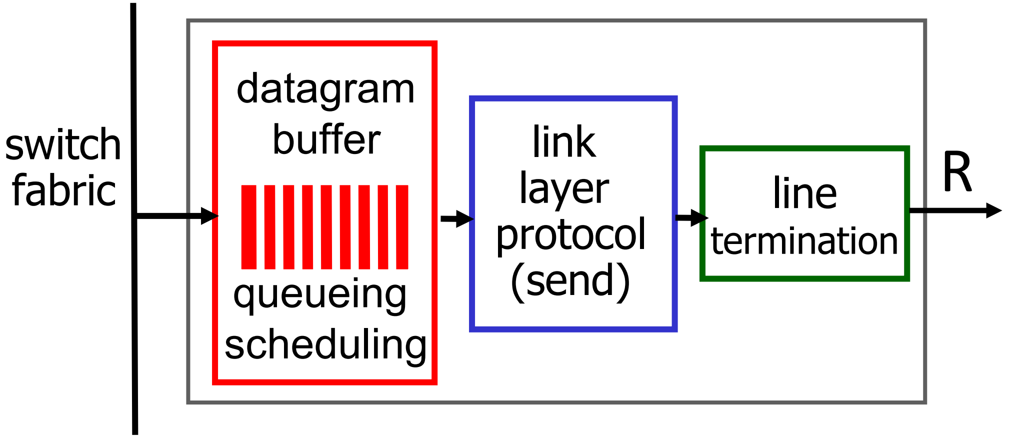
# How much buffering?

- 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

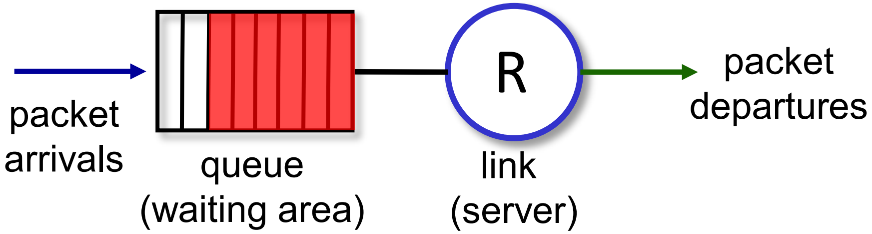
$$\frac{RTT \cdot C}{\sqrt{N}}$$

- but *too* much buffering can increase delays (particularly in home routers)
  - long RTTs: poor performance for real-time 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:

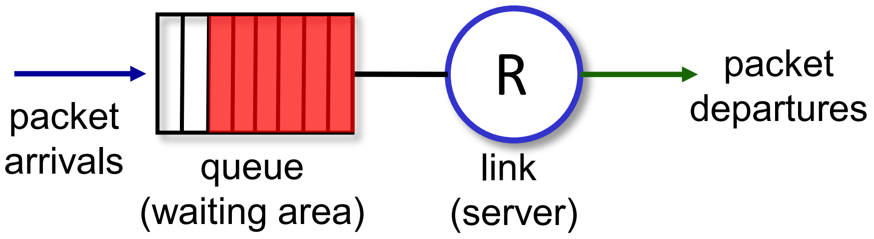
- drop: which packet to add, drop when buffers are full
  - tail drop: drop arriving packet
  - priority: drop/remove on priority basis
- marking: which packets to mark to signal congestion (ECN, RED)

# Packet Scheduling: FCFS

packet scheduling: deciding which packet to send next on link

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

Abstraction: queue



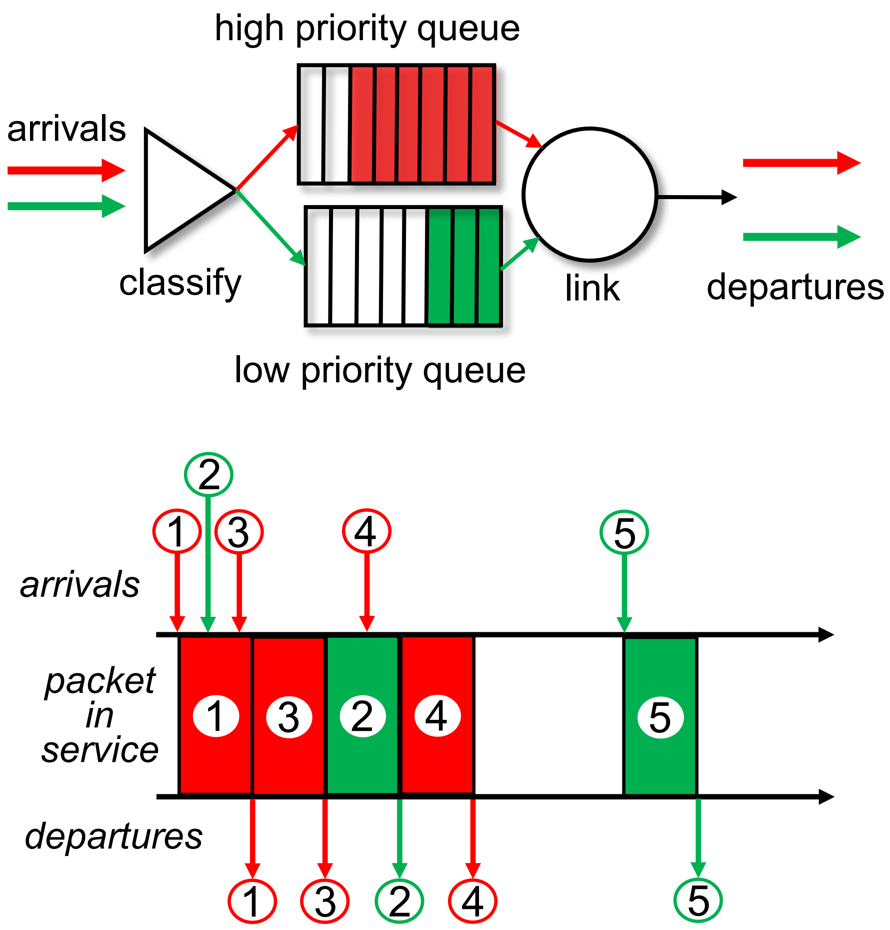

FCFS: packets transmitted in order of arrival to output port

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

# Scheduling policies: priority

*Priority scheduling:*

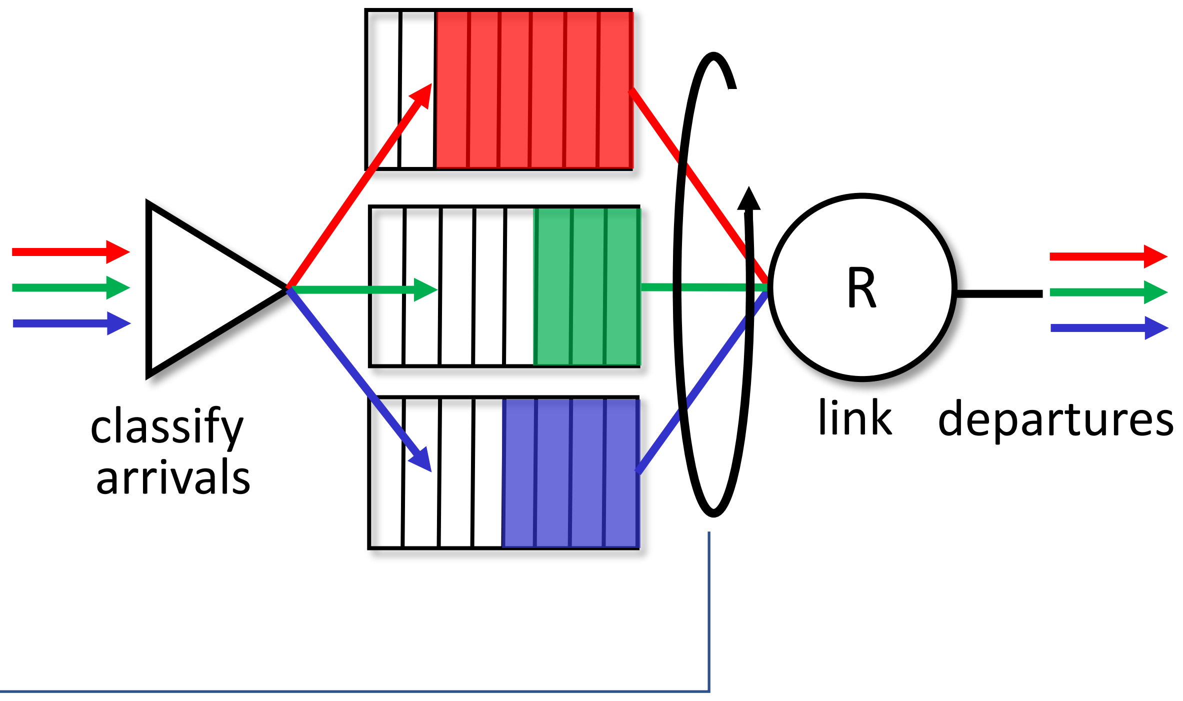
- arriving traffic classified, queued by class
  - any header fields can be used for classification
- send packet from highest priority queue that has buffered packets
  - FCFS within priority class



# 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 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)