

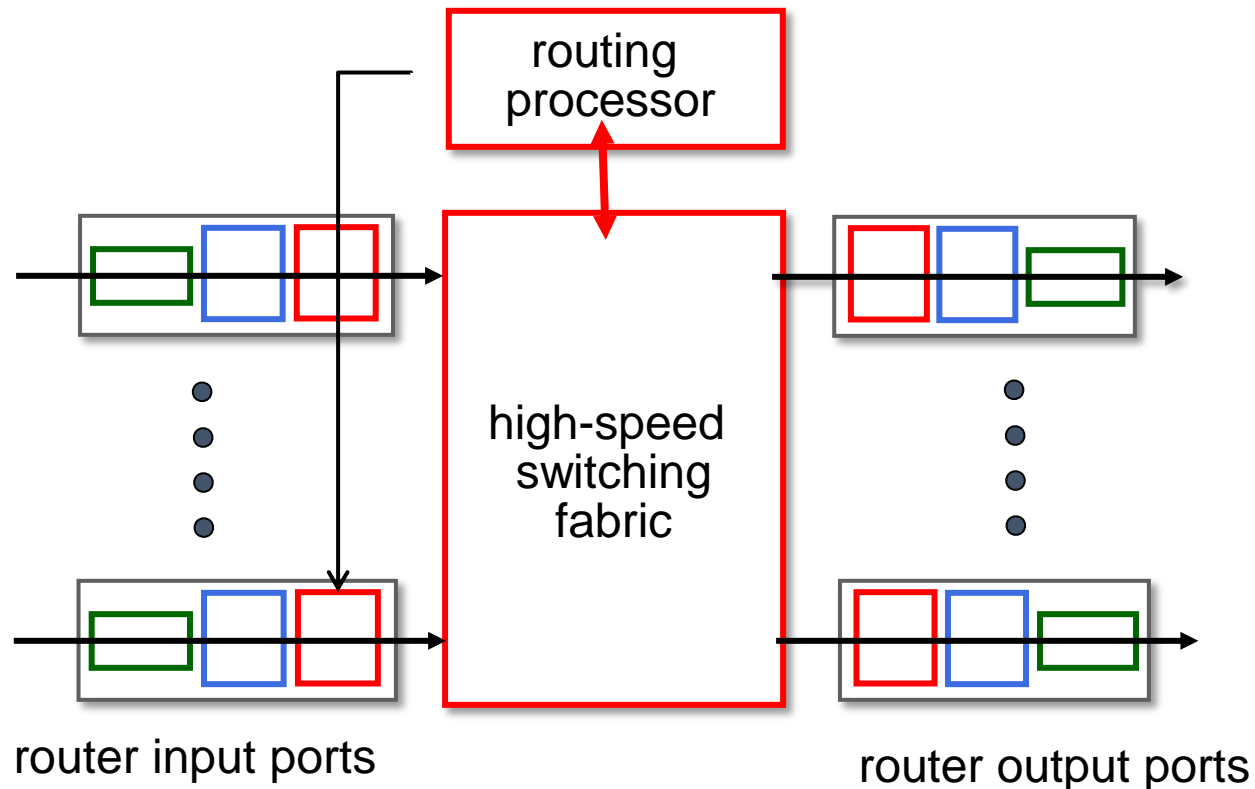
Network layer: “data plane” roadmap

- 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



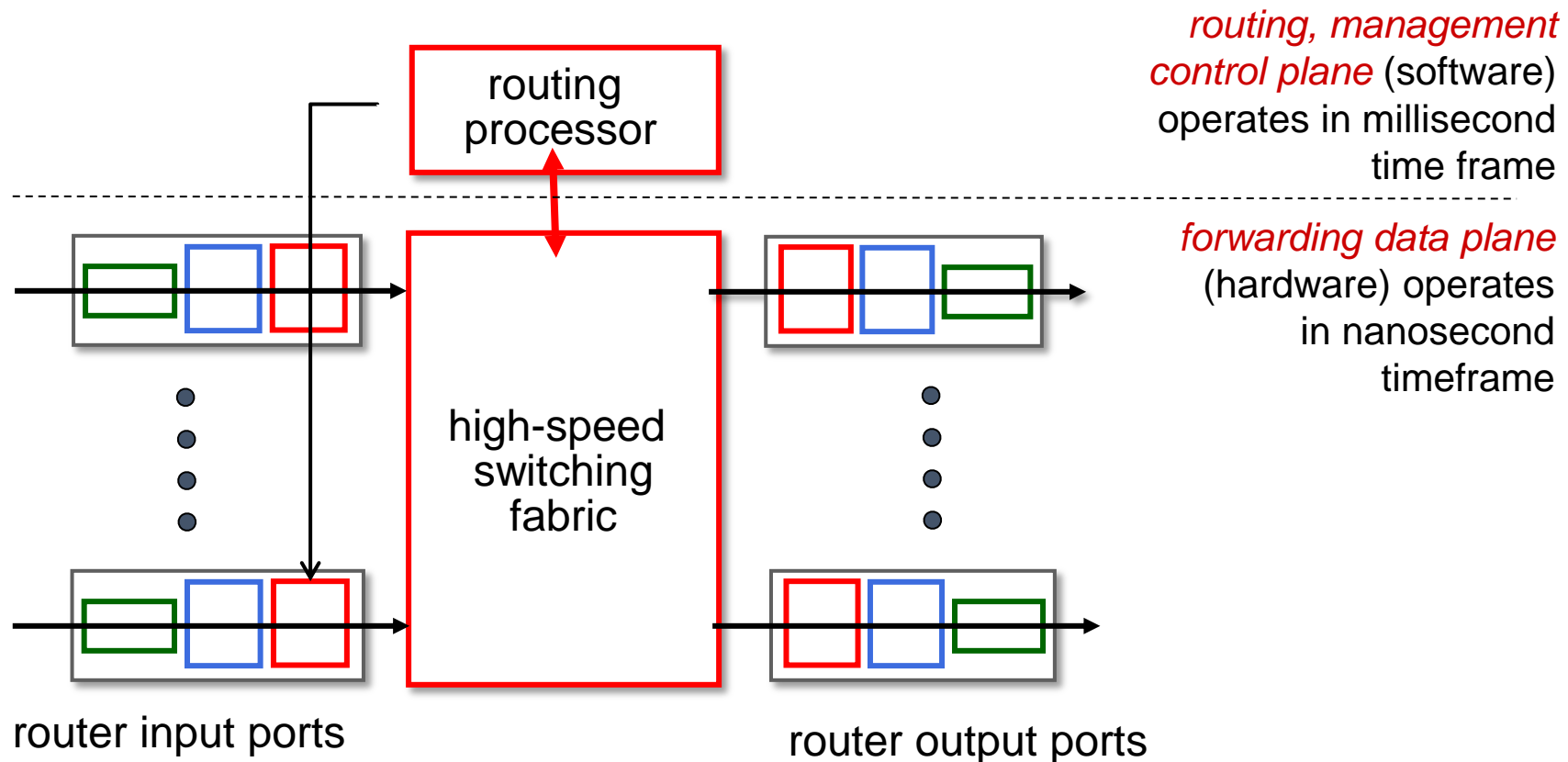
Router architecture overview

high-level view of generic router architecture:

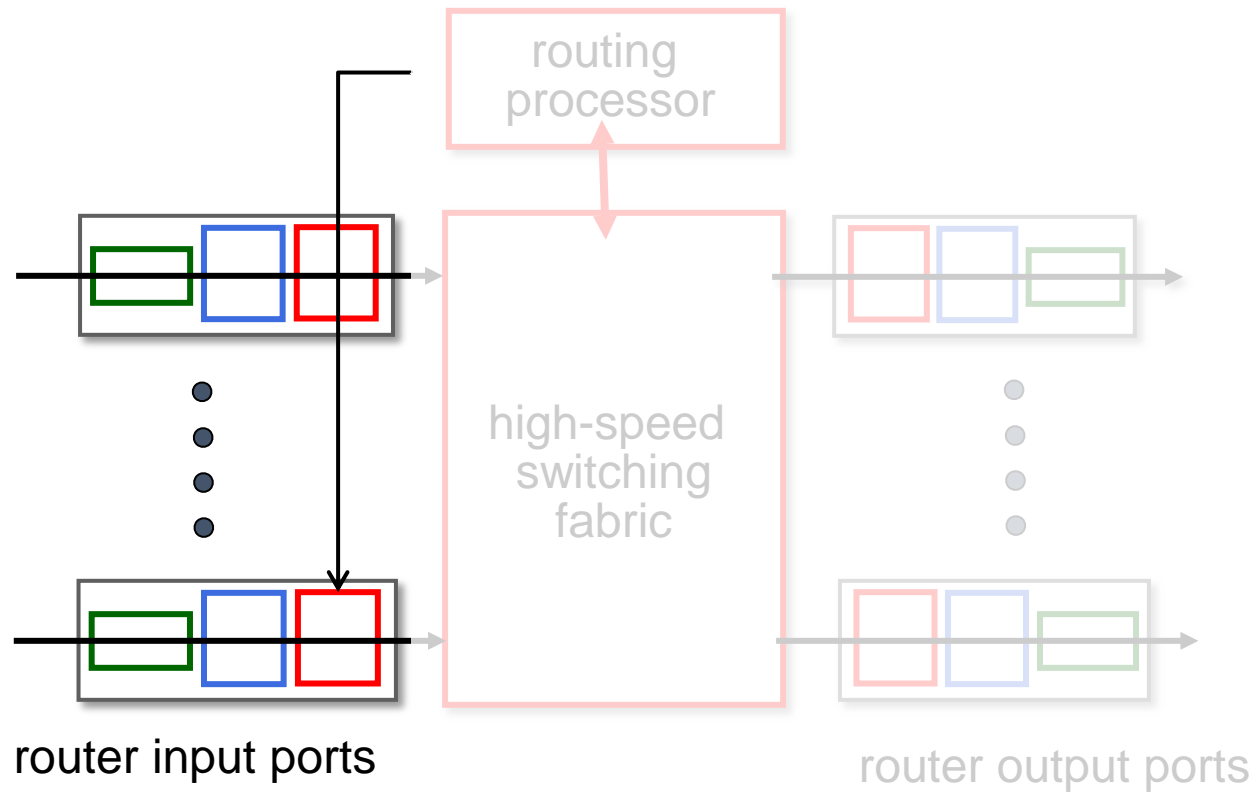


Router architecture overview

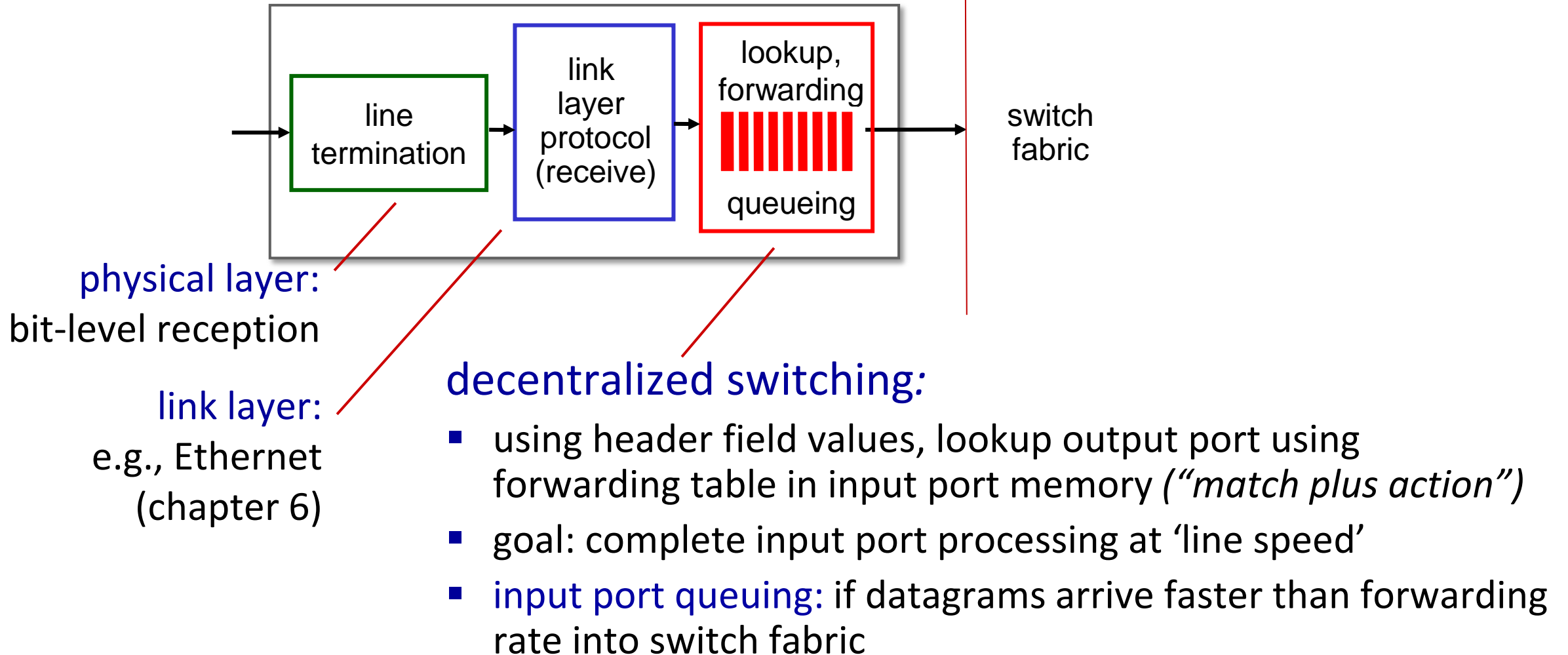
high-level view of generic router architecture:



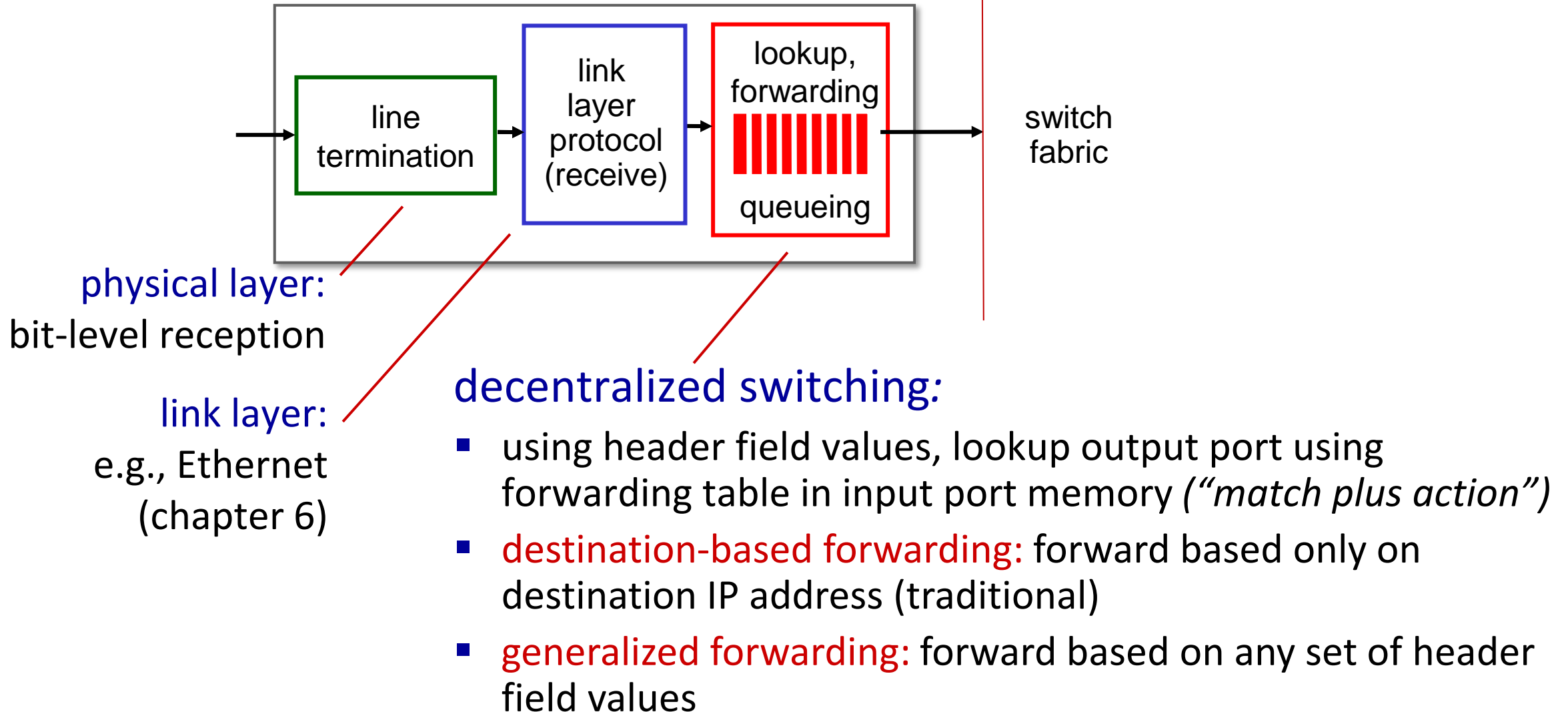
1) Input ports



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 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 |

Destination-based forwarding

forwarding table

| Destination Address Range | Link Interface |
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| 11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111 | 0 |
| 11001000 00010111 00010000 00000100 through 11001000 00010111 00010000 00000111 | 3 |
| 11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111 | 1 |
| 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

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 match! 1 00011*** ***** | 2 |
| otherwise | 3 |

examples:

11001000 00010111 00010110 10100001 which interface?
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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 | 00010111 | 00011*** | ***** | 2 |
| otherwise | | | | 3 |

match!

examples:

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

Longest prefix matching

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| 11001000 00010111 00010*** ***** | 0 |
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| 11001000 00010111 00011*** ***** | 2 |
| otherwise | 3 |

match!

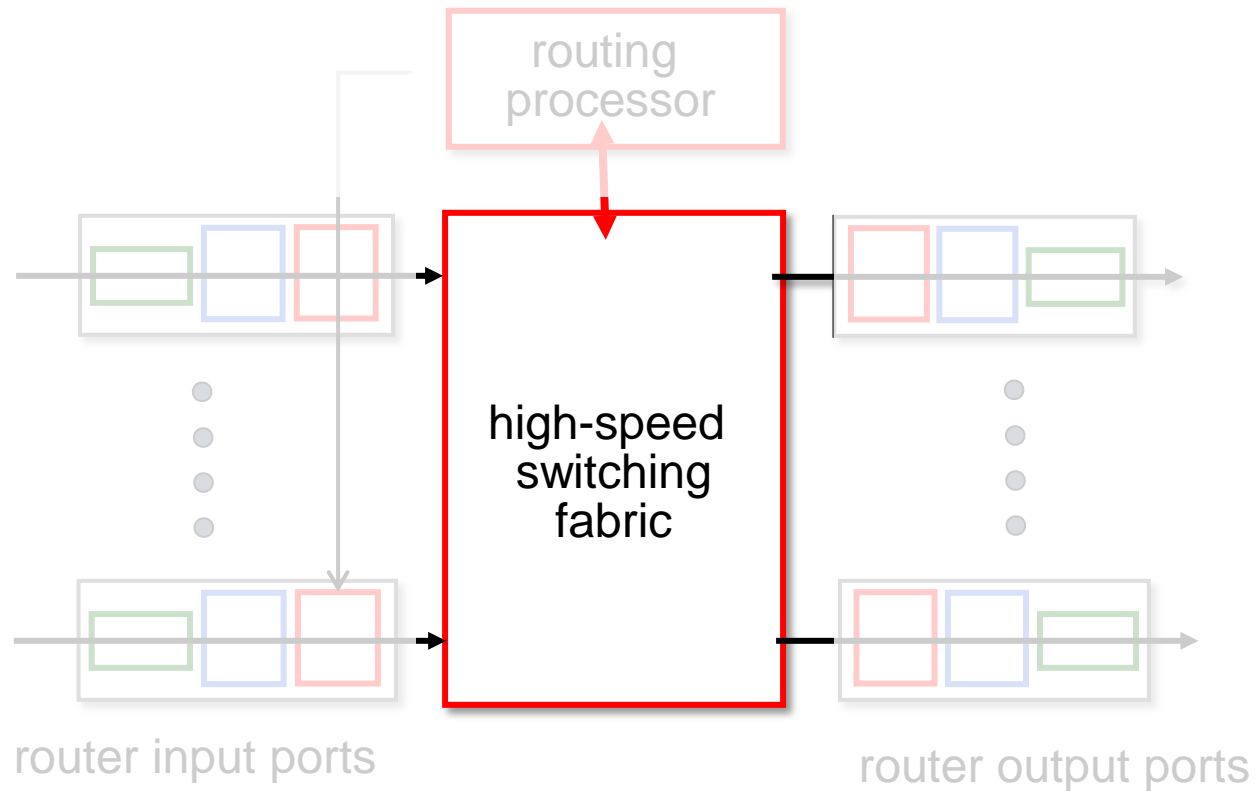
examples:

| | |
|-------------------------------------|------------------|
| 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

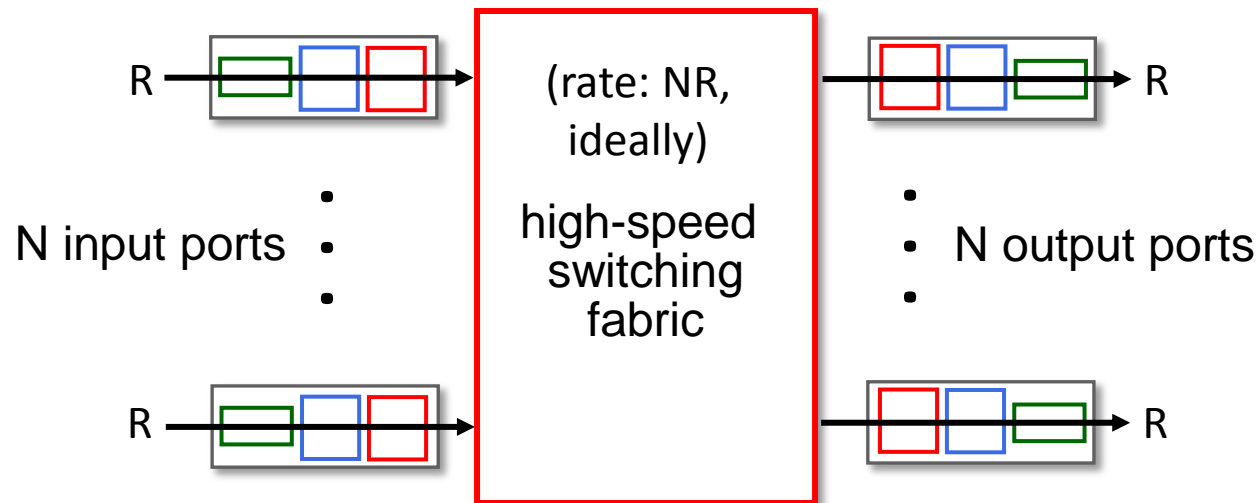
2)Switching Fabric



Connects input ports to the output ports (& the routing processor)

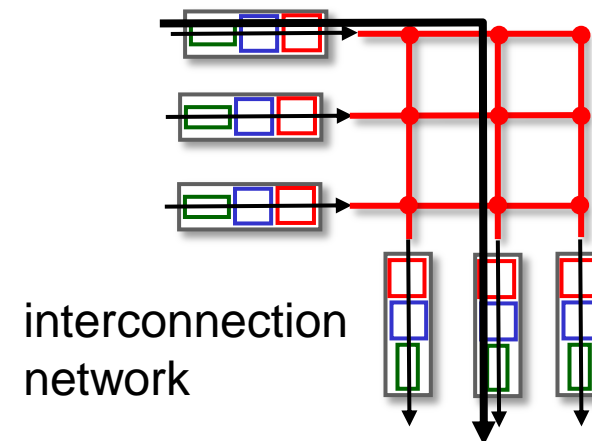
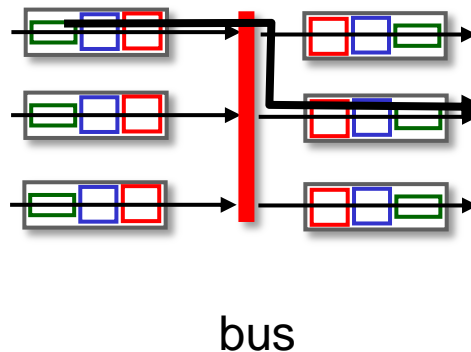
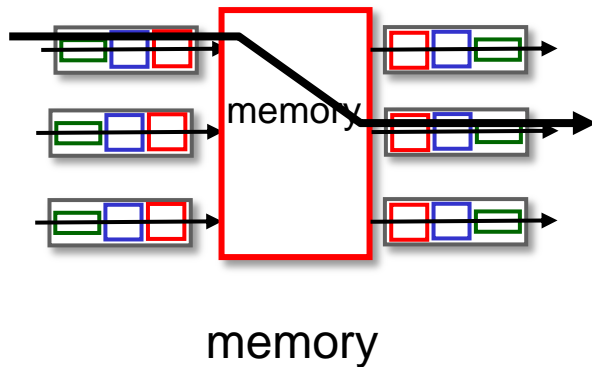
Switching fabrics

- 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

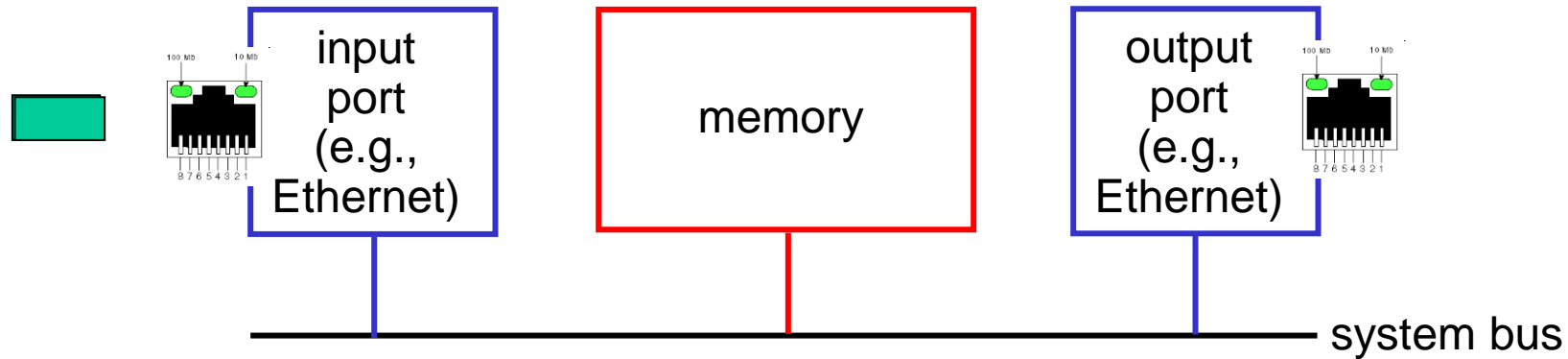
- transfer packet from input link to appropriate output link
- **switching rate**: rate at which packets can be transfer from inputs to outputs
 - often measured as multiple of input/output line rate
 - N inputs: switching rate N times line rate desirable
- three major types of switching fabrics:



Switching via memory

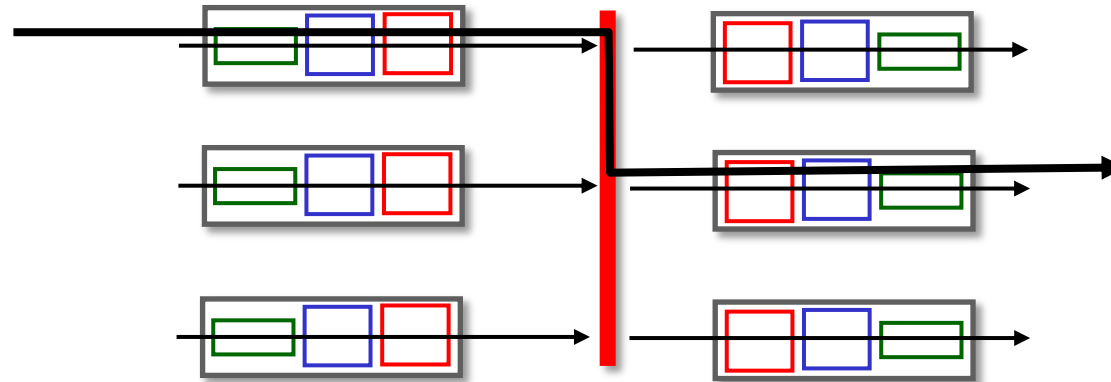
first generation routers:

- 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)



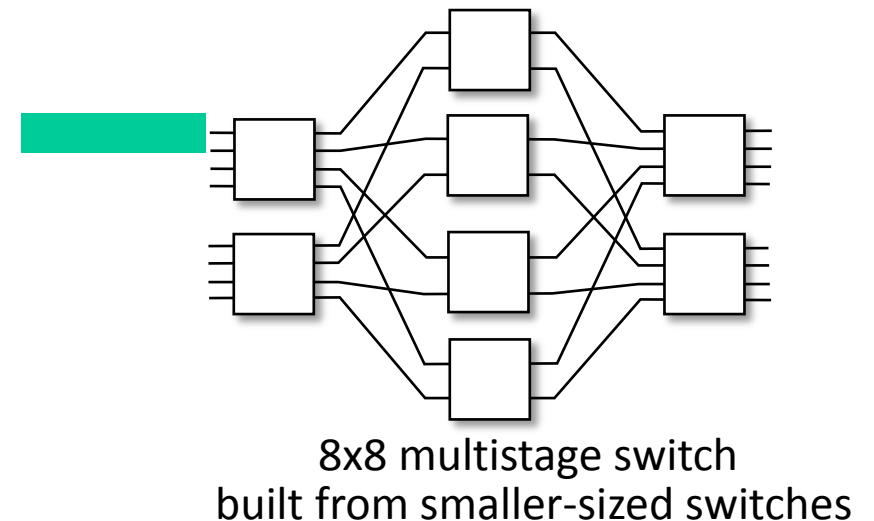
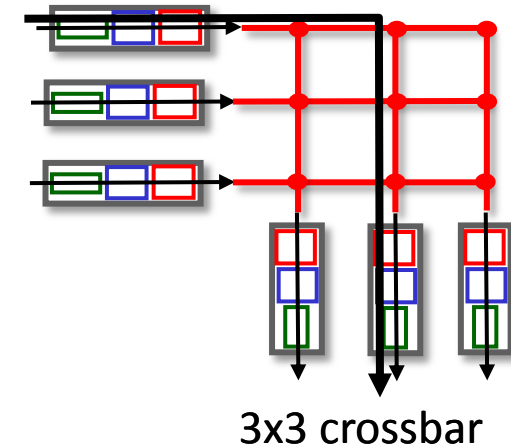
Switching via a bus

- 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



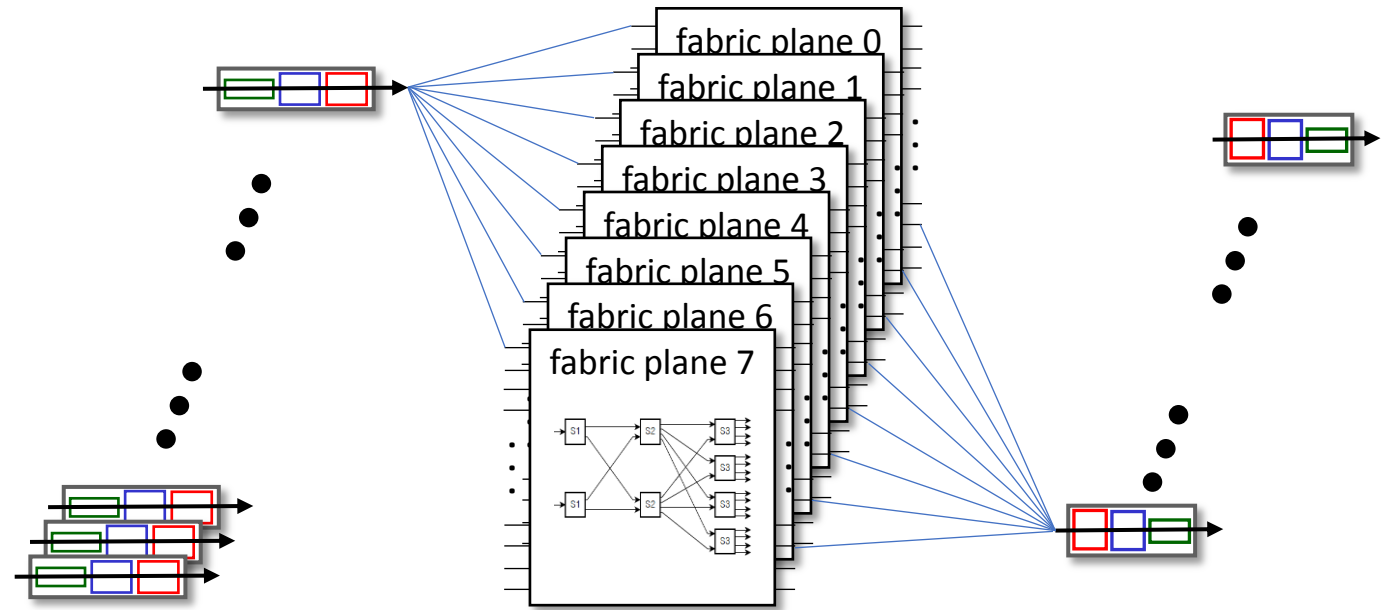
Switching via interconnection network

- 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



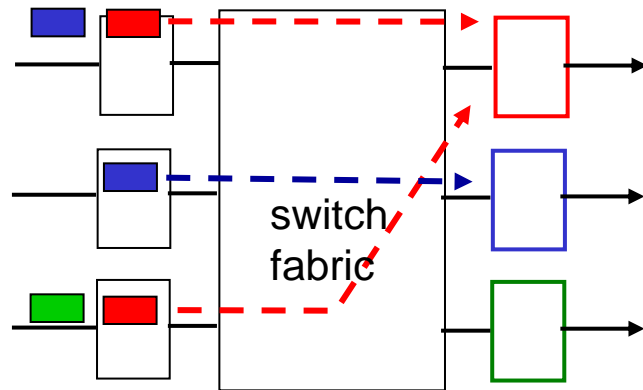
Switching via interconnection network

- 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

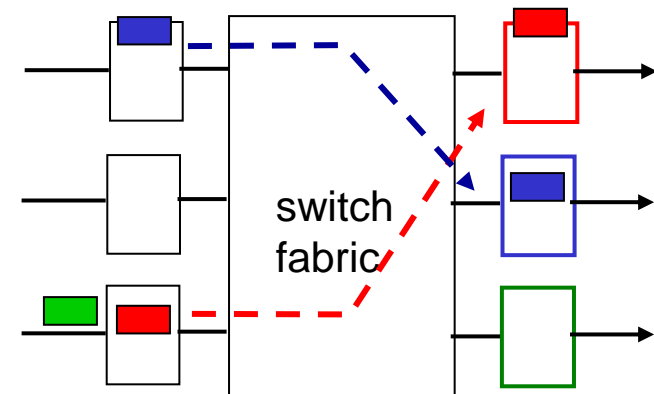


Input port queuing

- 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

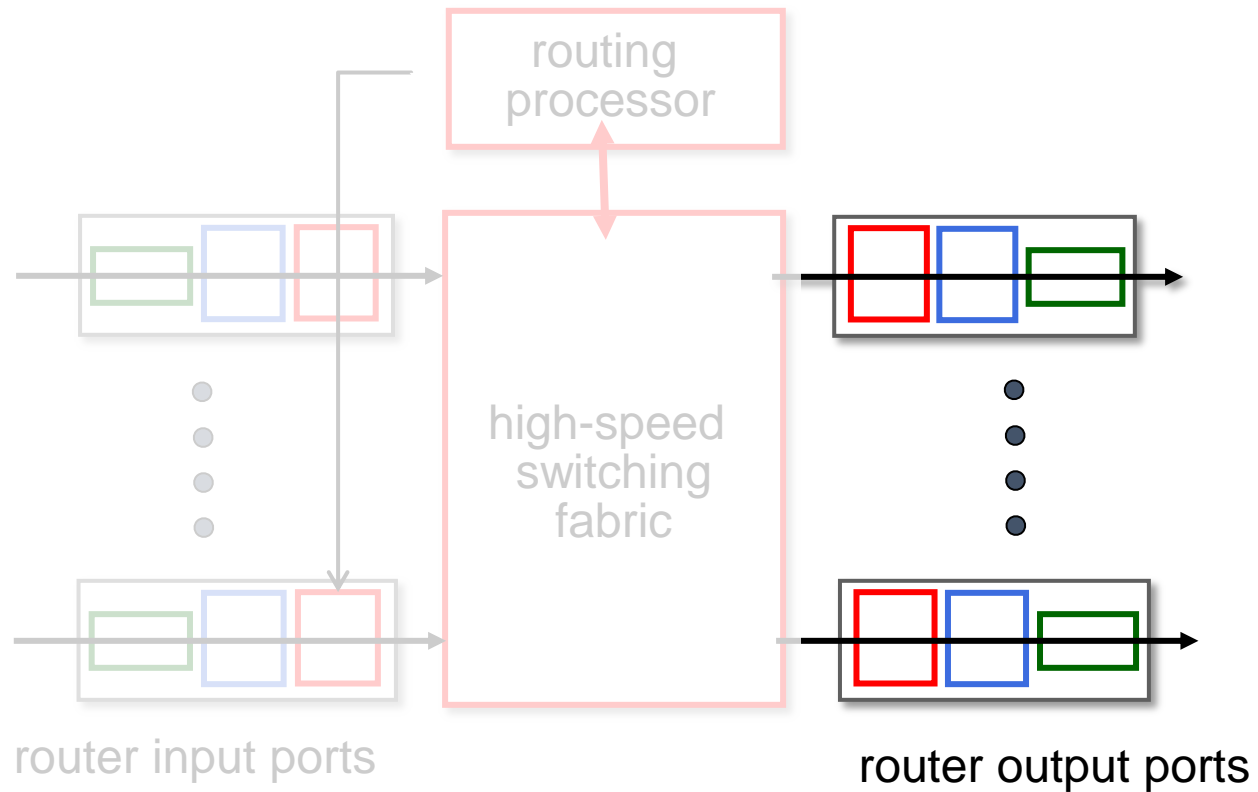


output port contention: only one red datagram can be transferred. lower red packet is *blocked*

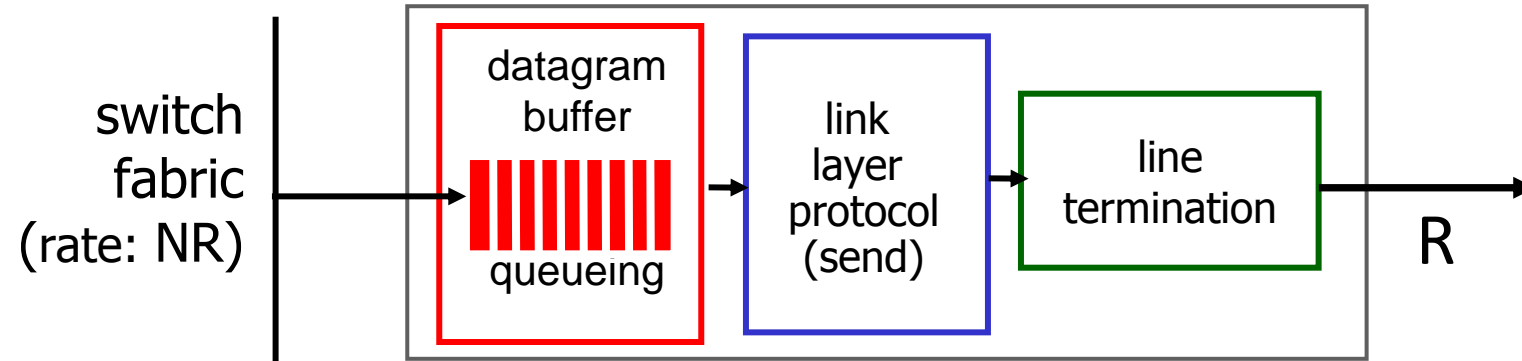


one packet time later: green packet experiences HOL blocking

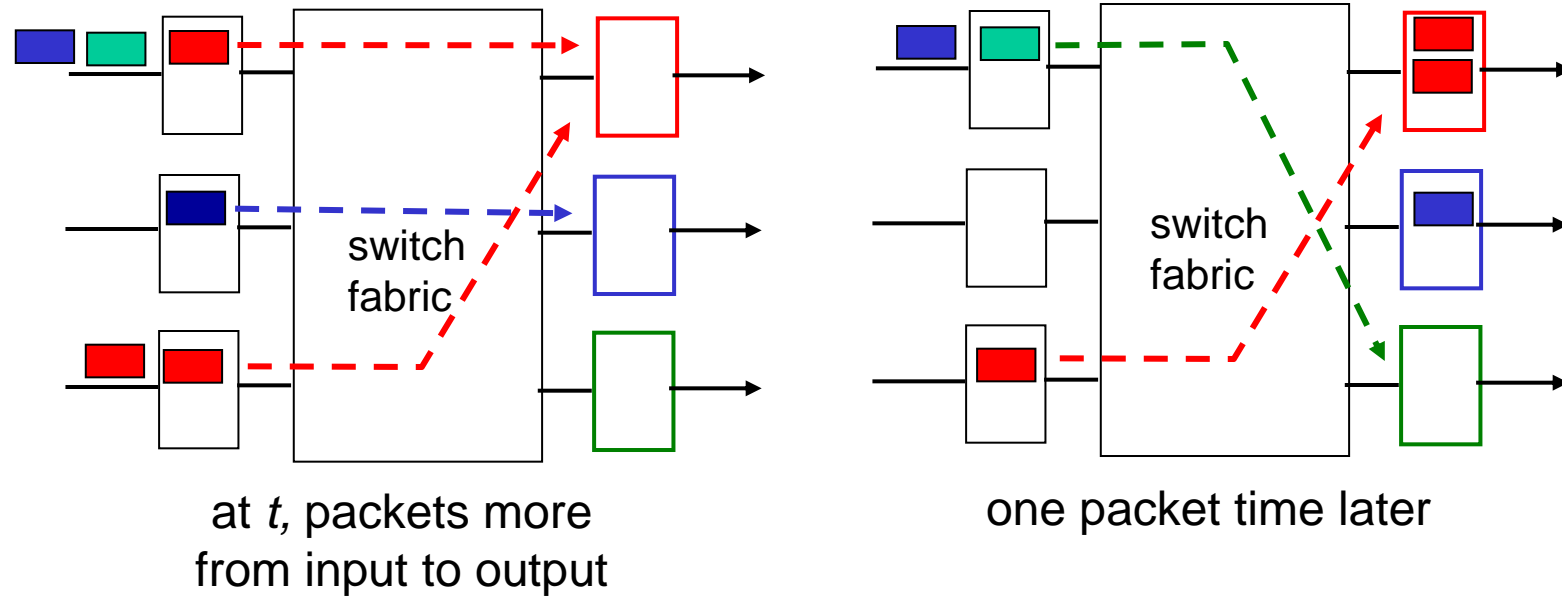
3) Output ports



Output port

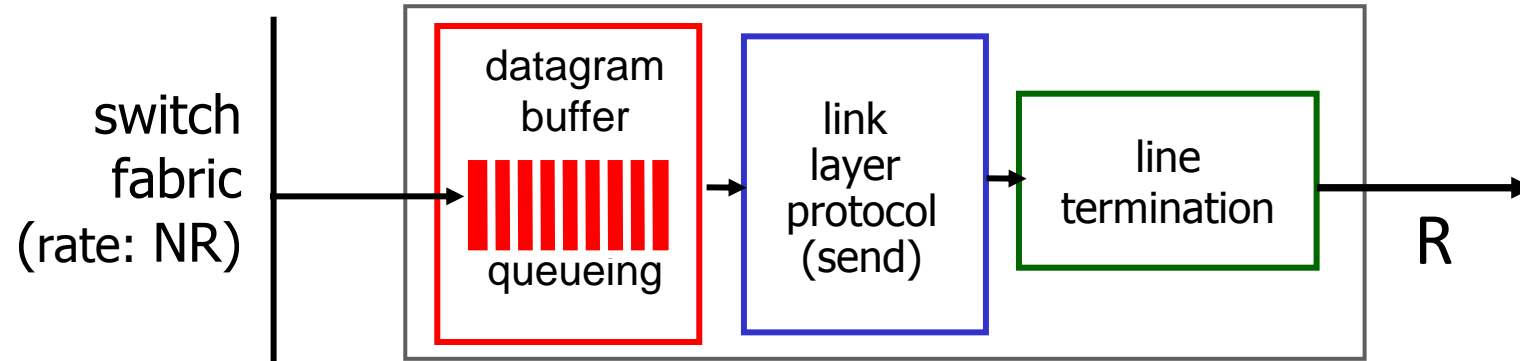


Output port queuing



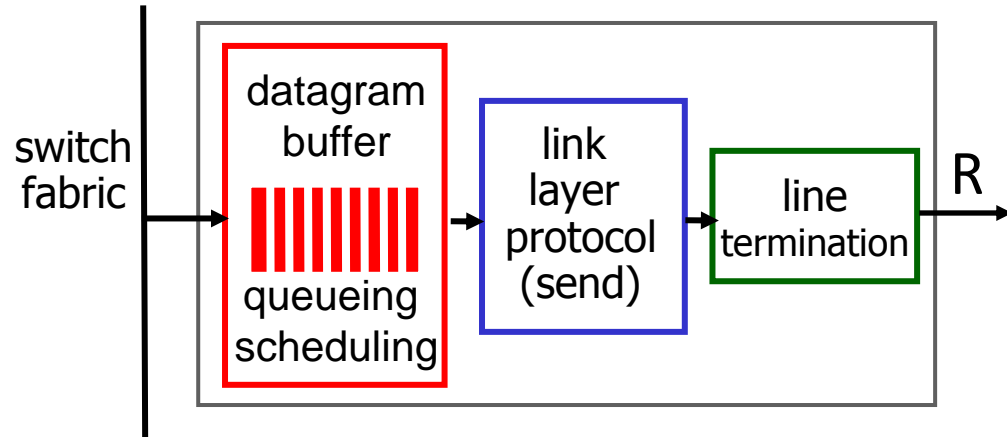
- buffering when arrival rate via switch exceeds output line speed
- *queueing (delay) and loss due to output port buffer overflow!*

Buffer Management

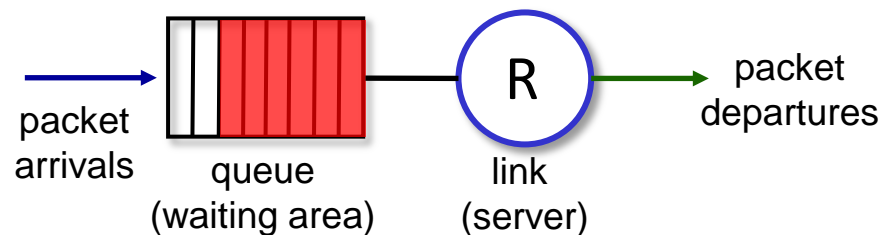


- *Drop policy*: which datagrams to drop if no free buffers?
- *Scheduling discipline* which datagram to choose among queued datagrams for transmission?

Drop Policies



Abstraction: queue



- **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)

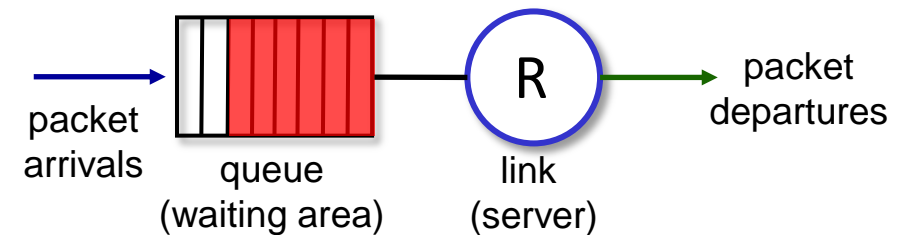
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Packet Scheduling

packet scheduling: deciding which packet to send next on link

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

Abstraction: queue



Packet Scheduling: FCFS

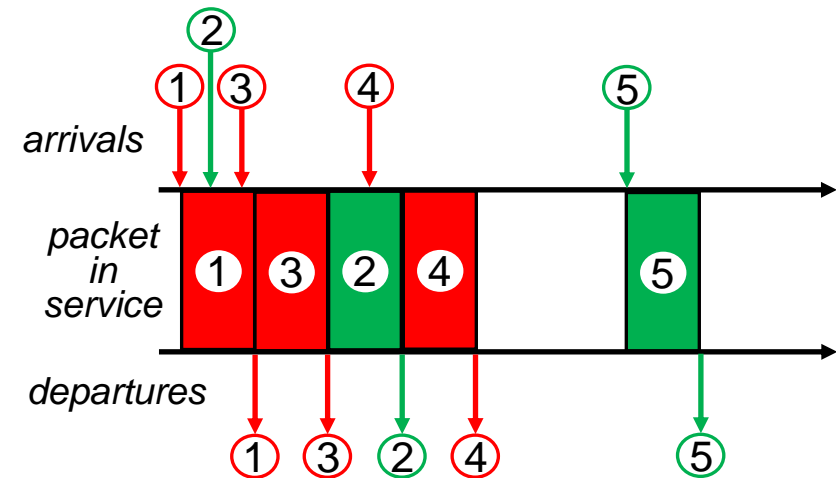
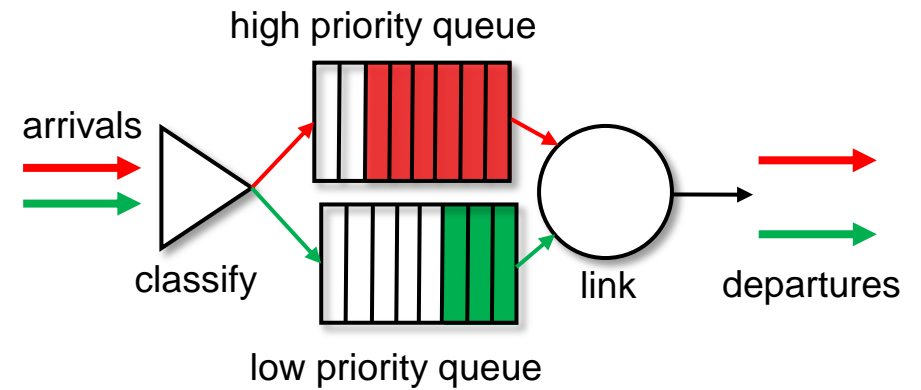
FCFS: packets transmitted in order of arrival to output port

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

Scheduling policies: priority

Priority scheduling:

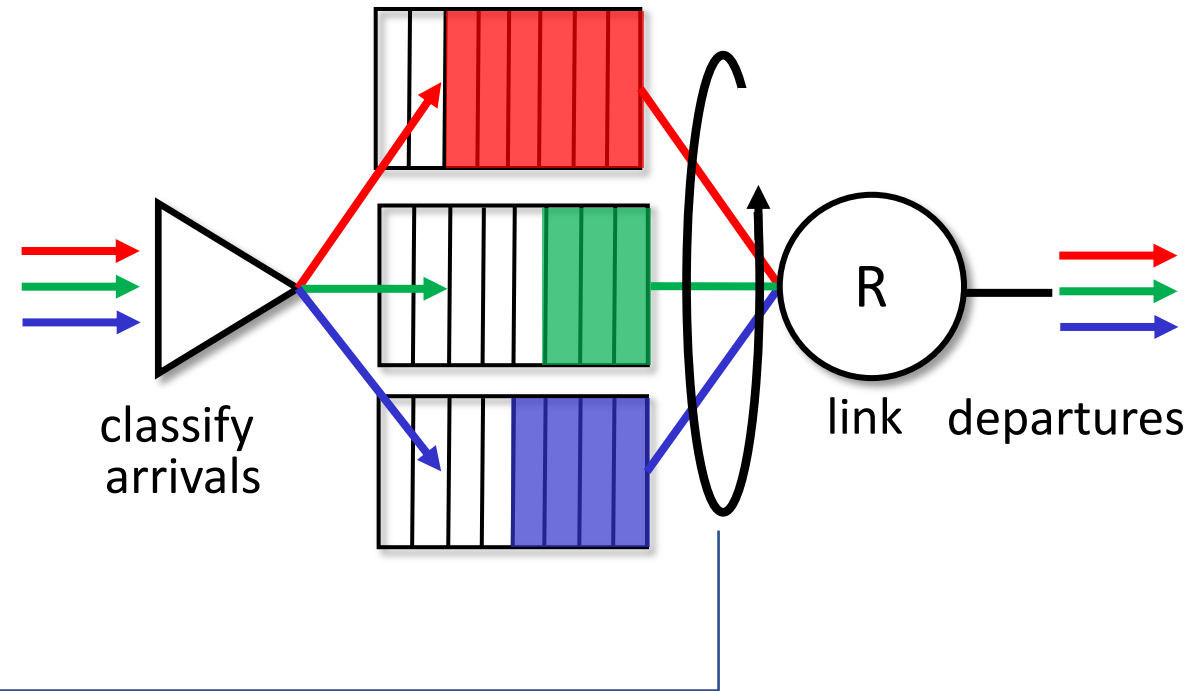
- arriving traffic classified, queued by class
 - any header fields can be used for classification
- send packet from highest priority queue that has buffered packets
 - FCFS within priority class



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:

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

- minimum bandwidth guarantee (per-traffic-class)

