Outline

- TCP flow control
- TCP congestion control
- TCP congestion control wrap-up
- Router assisted congestion control

Recap: TCP problems

- Misled by non-congestion losses
- Fills up queues leading to high delays
- Short flows complete before discovering available capacity
- AIMD impractical for high speed links
- Saw tooth discovery too choppy for some apps
- Unfair under heterogeneous RTTs
- Tight coupling with reliability mechanisms
- End hosts can cheat

Routers tell endpoints if they're congested

Routers tell endpoints what rate to send at

Routers enforce fair sharing

Could fix many of these with some help from routers!

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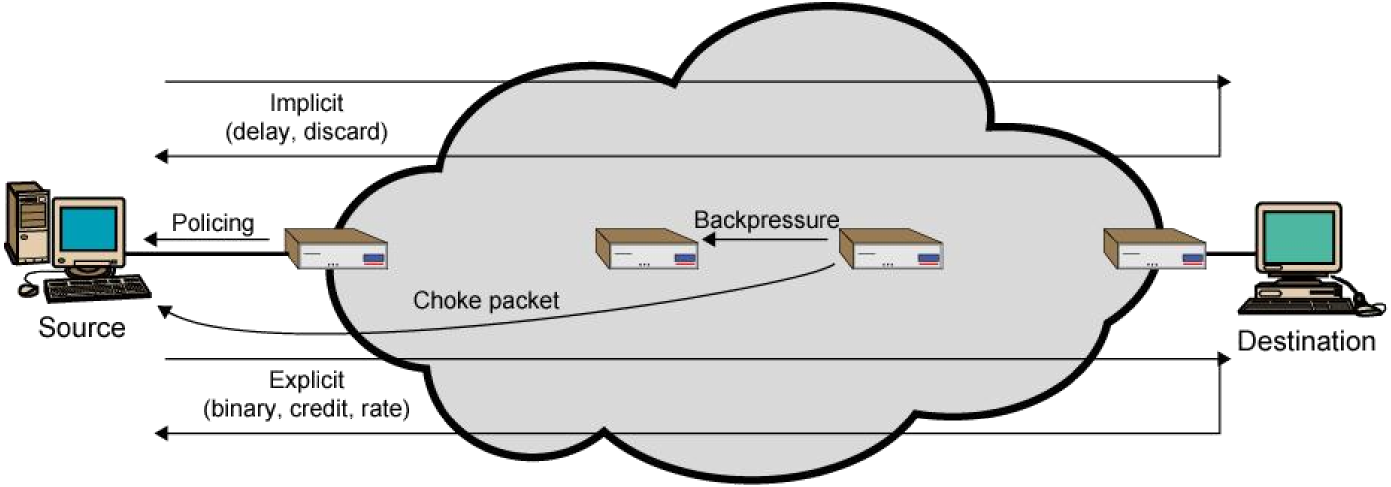
Mechanisms for Congestion Control



- Choke Packet
- Backpressure
- Warning bit
- Random early discard
- Fair Queuing (FQ)

- 抑制分组
- 反压
- 警告位
- 随机早期丢弃
- 公平队列

Warning Bit

Explicit Congestion Notification (ECN)

- Single bit in packet header; set by congested routers
  - If data packet has bit set, then ACK has ECN bit set
- Many options for when routers set the bit
  - Tradeoff between (link) utilization and (packet) delay
- Congestion semantics can be exactly like that of drop
  - i.e., end-host reacts as though it saw a drop

ECN

- Advantages:
  - Don't confuse corruption with congestion; recovery w/ rate adjustment
  - Can serve as an early indicator of congestion to avoid delays
  - Easy (easier) to incrementally deploy
    - ✓ Today: defined in RFC 3168 using ToS/DSCP bits in the IP header
    - ✓ Common in datacenters

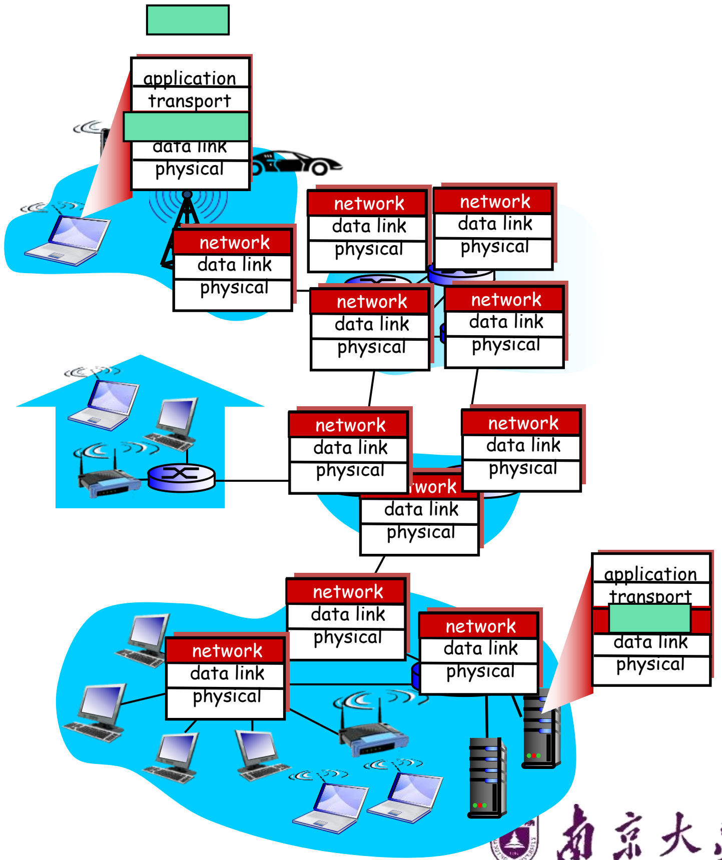
网络层: 数据平面

Outline

- Network Layer Functions
- Routers
- IP Packet Structure

Network Layer

- transport segment from sending to receiving host
- on sending side encapsulates segments into datagrams
- on receiving side, delivers segments to transport layer
- network layer protocols in every host, router
- router examines header fields in all IP datagrams passing through it



Two Key Network-layer Functions

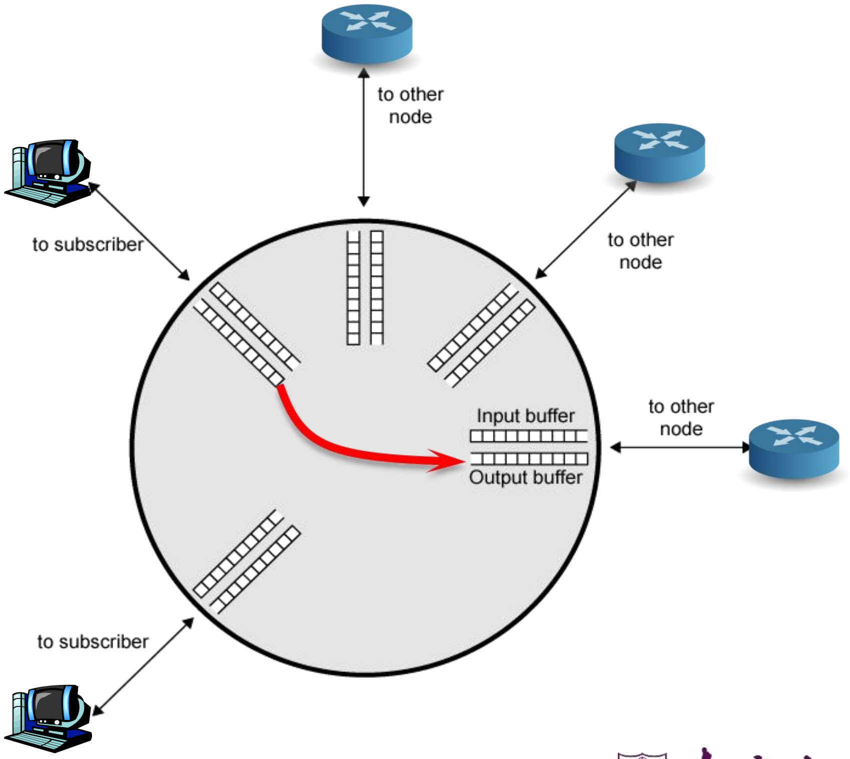
- OSI network-layer functions:
- Forwarding (Data plane)
  - Move packets from input to designated output determined by switching (single node)
  - Error handling, queuing and scheduling
- Switching / Routing (Control plane)
  - Determine route taken by packets from source to destination (multiple nodes)
  - Shortest path from source to destination
  - Routing algorithms

analogy: Trip Planning

- forwarding: getting through single city (e.g., entering and leaving Suzhou Station)
- routing: planning the route from Nanjing to Shanghai (e.g., Nanjing-Wuxi-Suzhou-Shanghai)

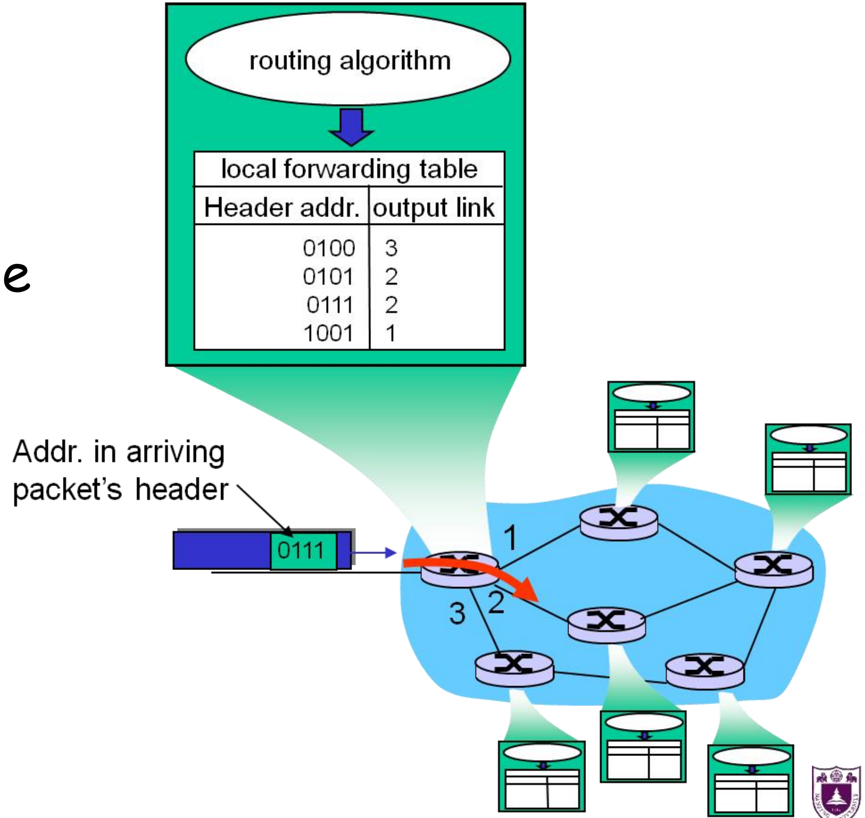
Forwarding Functions

- Queuing and scheduling
  - Host to Switch
  - Switch to Host
  - Switch to Switch



Switch Functions

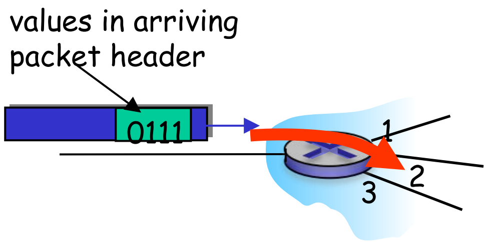
- Routing determines the forwarding table



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



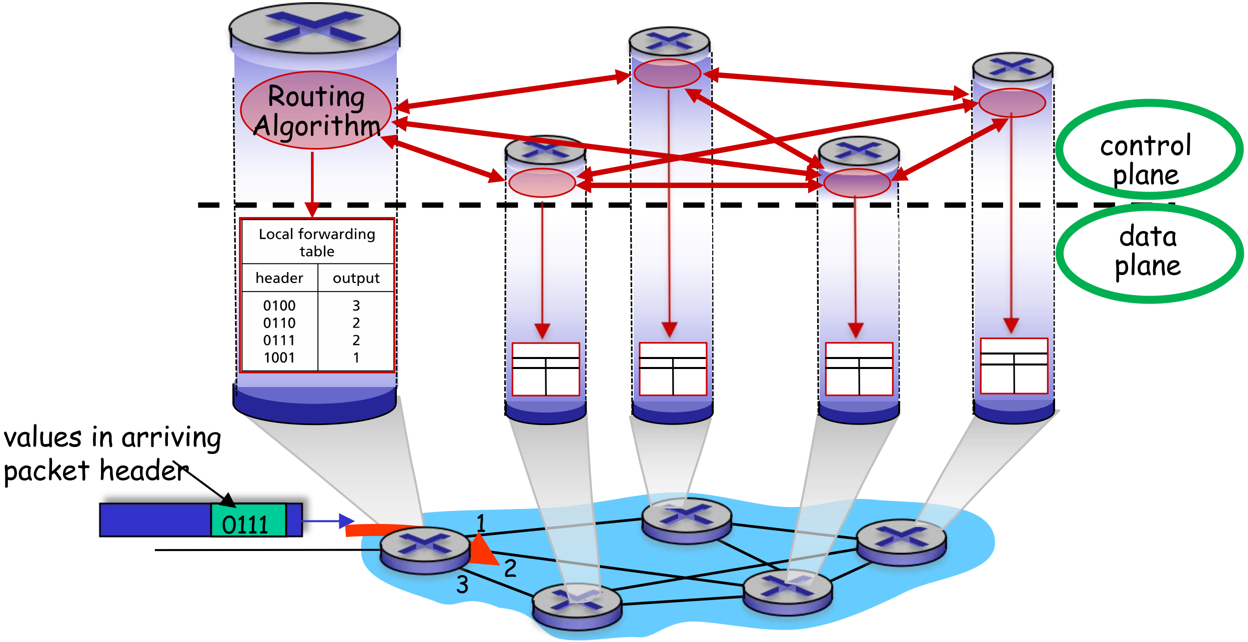
Control plane

- 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

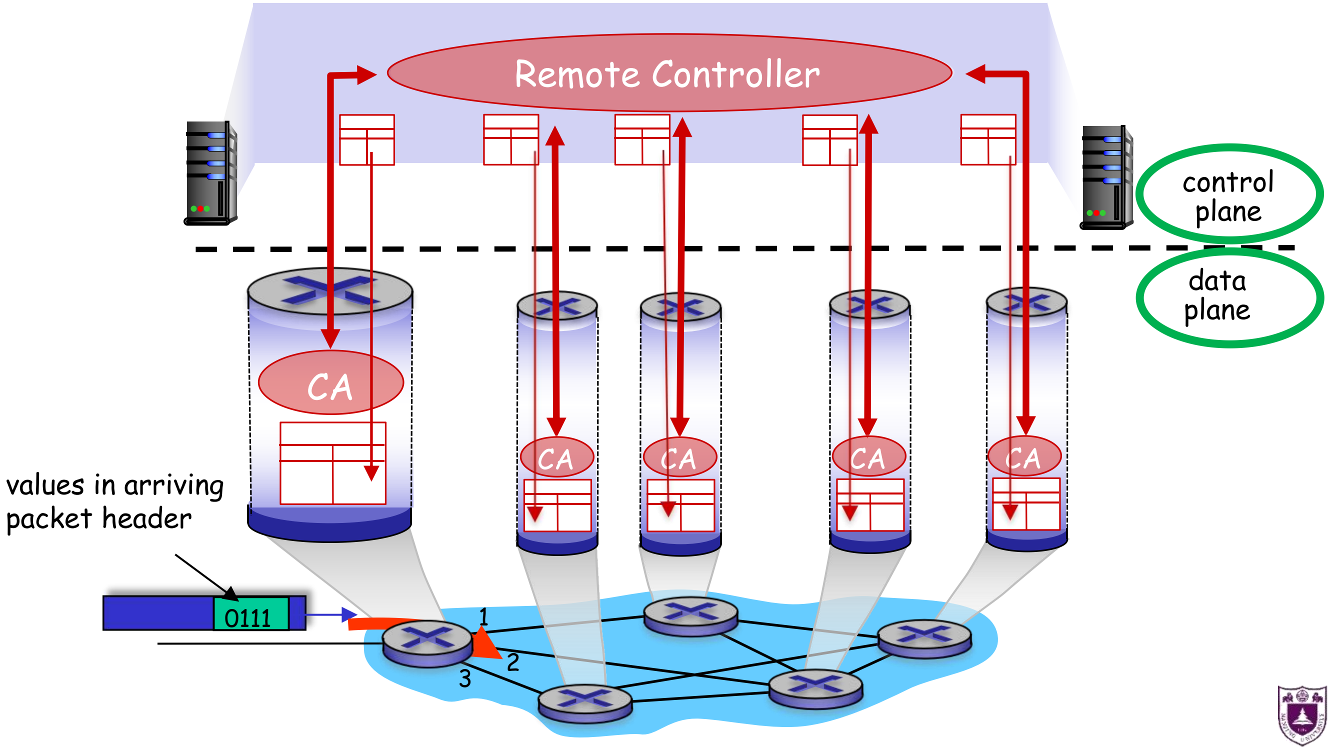
Per-router control plane

- 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?

- Network service model
  - Service model for "channel" transporting packets from sender to receiver
  - Called Quality of Service from host perspective

Example services for individual packets

- Guaranteed delivery
- Guaranteed delivery with less than 40 msec delay

Example services for a flow of packets

- In-order packet delivery
- Guaranteed minimum bandwidth to flow
- Restrictions on changes in inter-packet spacing

Example: Network Service Model of ATM

In decreasing priority

- Constant Bit Rate (CBR) and Variable Bit Rate (VBR)
- Available Bit Rate (ABR) and Unspecified Bit Rate (UBR)

Network Architecture	Service Model	Guarantees ?				Congestion feedback
		Bandwidth	Loss	Order	Timing	
Internet	best effort	none	no	no	no	no (inferred via loss)
ATM	CBR	constant rate	yes	yes	yes	no congestion
ATM	VBR	guaranteed rate	yes	yes	yes	no congestion
ATM	ABR	guaranteed minimum	no	yes	no	yes
ATM	UBR	none	no	yes	no	no

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Example: Network Service Model of IP

- Best effort

Network Architecture	Service Model	Bandwidth Guarantee	No-Loss Guarantee	Ordering	Timing	Congestion Indication
Internet	Best Effort	None	None	Any order possible	Not maintained	None
ATM	CBR	Guaranteed constant rate	Yes	In order	Maintained	Congestion will not occur
ATM	ABR	Guaranteed minimum	None	In order	Not maintained	Congestion indication provided

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.

Outline

- Network Layer Functions
- Routers
- IP Packet Structure

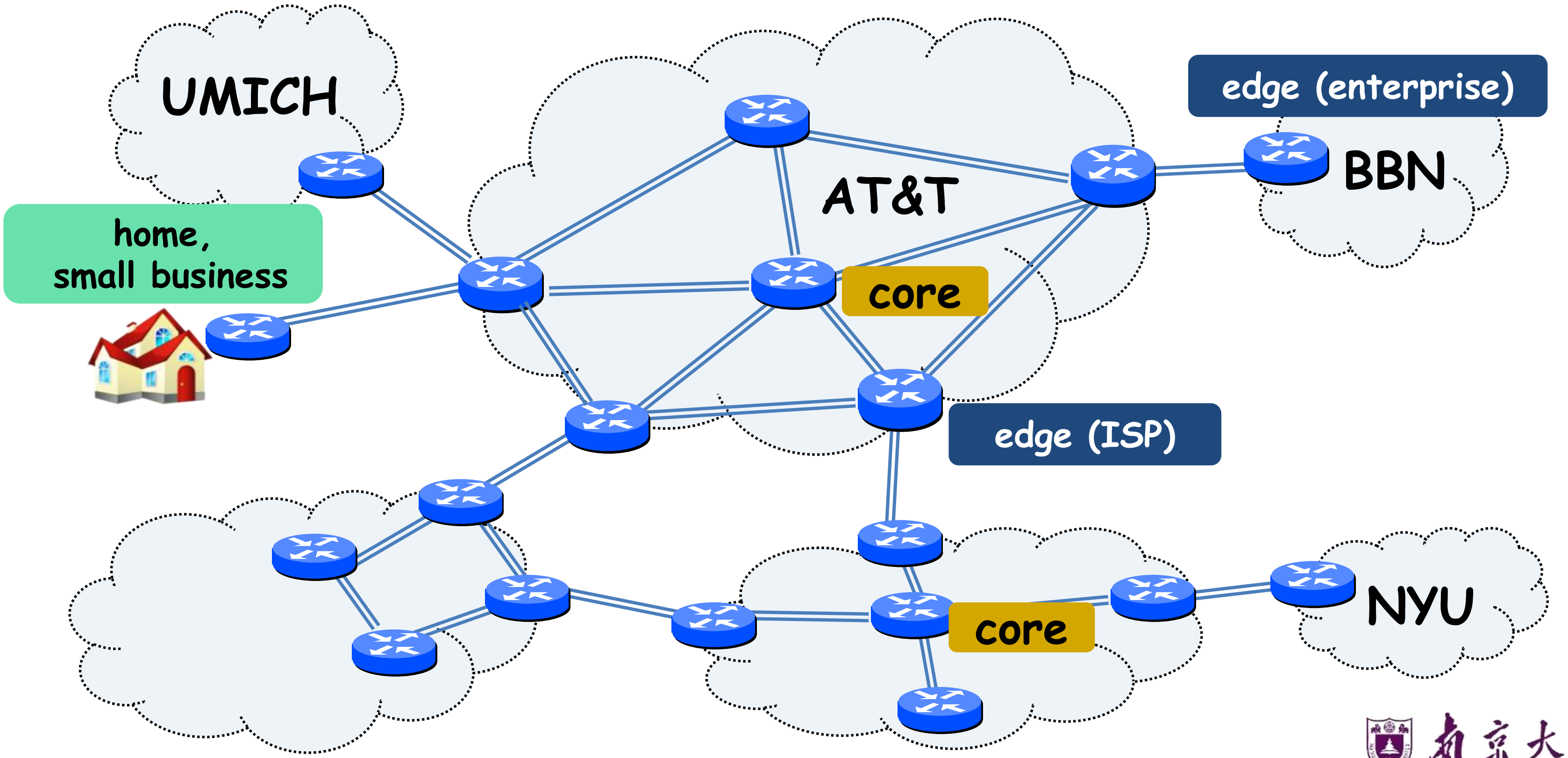
Routers

- Core building block of the Internet infrastructure
- $120B+ industry
- Vendors: Cisco, Huawei, Juniper, Alcatel-Lucent (account for >90%)

Router definitions

- Router capacity = N x R
- N = Number of external router “ports”
- R = Speed (“line rate”) of a port

Networks and routers



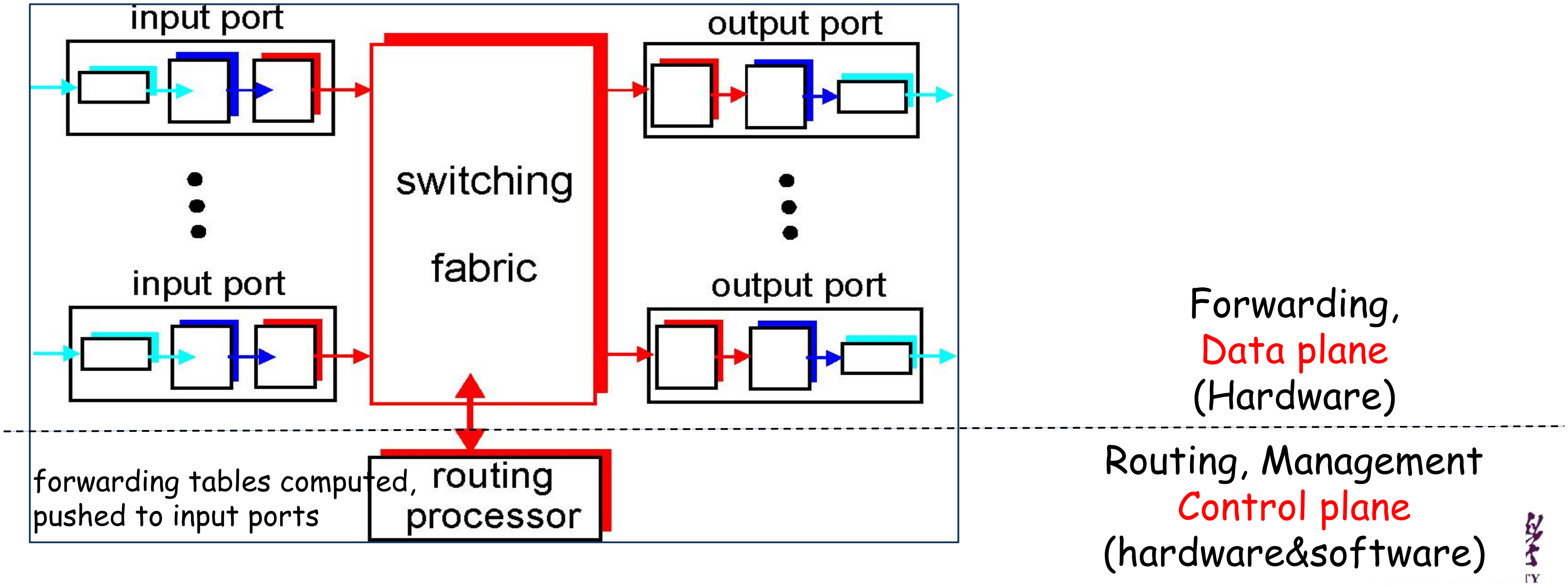
Many types of routers

- Core
  - R = 10/40/100/200/400 Gbps
  - NR = O(100) Tbps (Aggregated)
- Edge
  - R = 1/10/40/100 Gbps
  - NR = O(100) Gbps
- Small business
  - R = 1 Gbps
  - NR < 10 Gbps

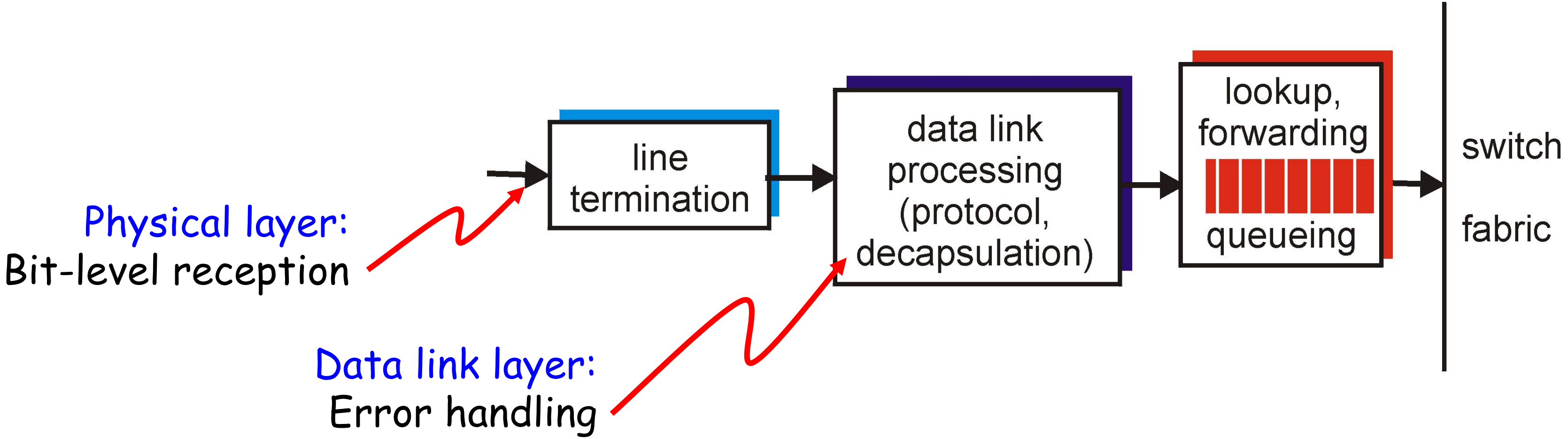
Inside a Router: Architecture Overview

Two key switch functions:

- Run routing algorithms/protocol
- Forwarding packets from incoming to outgoing link



Input Port Functions



Tasks

- Receive incoming packets (physical layer stuff)
- Update the IP header
  - TTL, Checksum, Options and Fragment (maybe)
- Lookup the output port for the destination IP address
- Queuing: if packets arrive faster than forwarding rate into switch fabric

Input Port

- Challenge: speed!
  - 100B packets @ 40Gbps → new packet every 20 nano secs!
  - Typically implemented with specialized ASICs (network processors)

Looking up the output port

- One entry for each address → 4 billion entries!
- For scalability, addresses are aggregated

Example

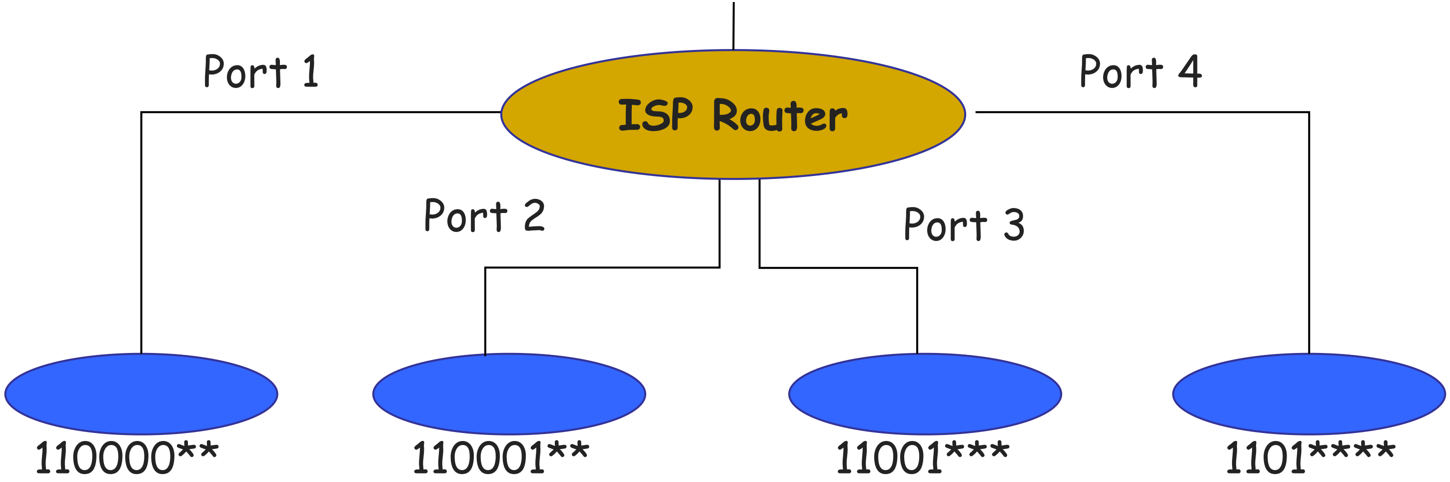
- Router with 4 ports
- Destination address range mapping
  - 11 00 00 00 to 11 00 00 11: Port 1
  - 11 00 01 00 to 11 00 01 11: Port 2
  - 11 00 10 00 to 11 00 11 11: Port 3
  - 11 01 00 00 to 11 01 11 11: Port 4

Example

- Router with 4 ports
- Destination address range mapping
  - 11 00 00 00 to 11 00 00 11: Port 1
  - 11 00 01 00 to 11 00 01 11: Port 2
  - 11 00 10 00 to 11 00 11 11: Port 3
  - 11 01 00 00 to 11 01 11 11: Port 4

Longest prefix matching rule: when looking for forwarding table entry for given destination address, use longest address prefix that matches destination address.

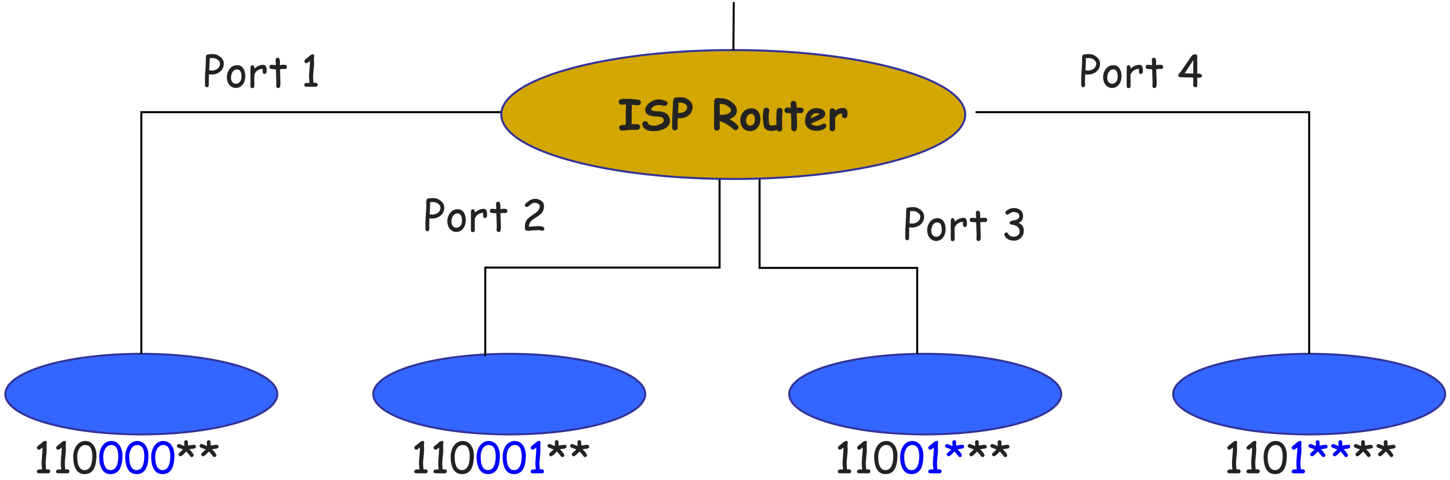
Longest prefix matching



Finding match efficiently

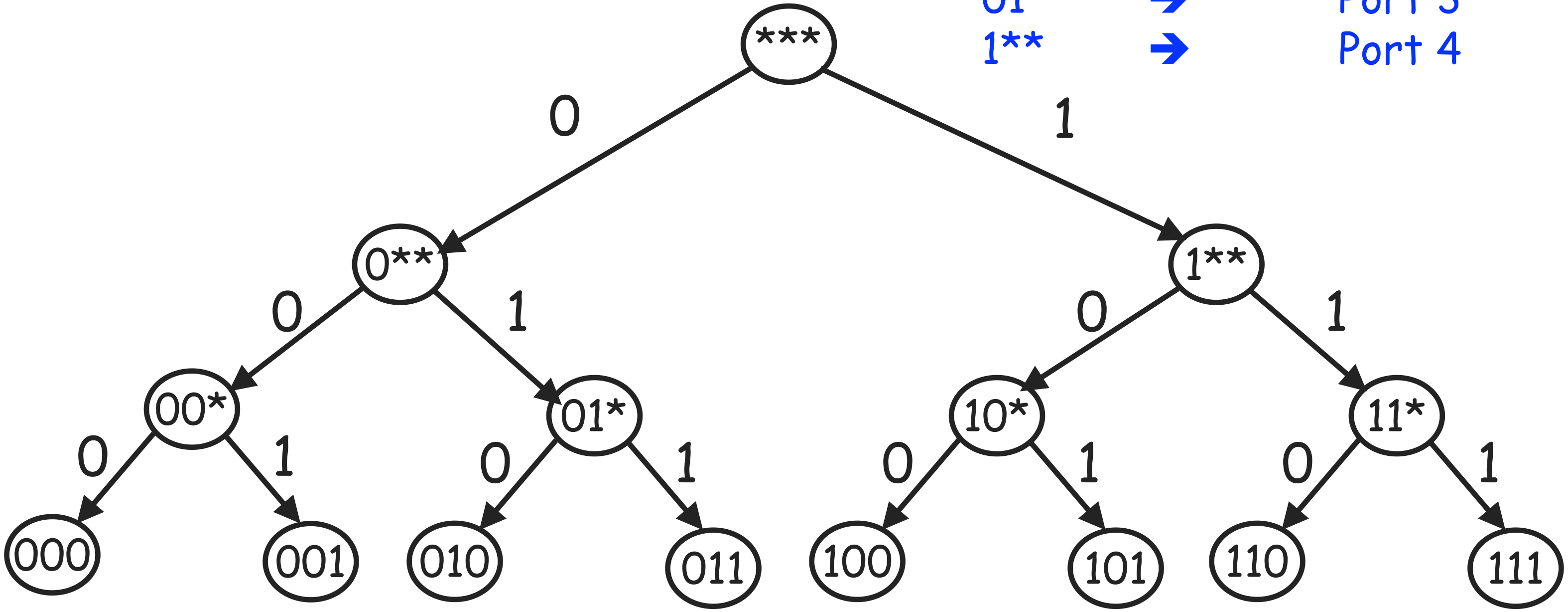
- Testing each entry to find a match scales poorly
  - On average: O(number of entries)
- Leverage tree structure of binary strings
  - Set up tree-like data structure

Longest prefix matching



Tree structure

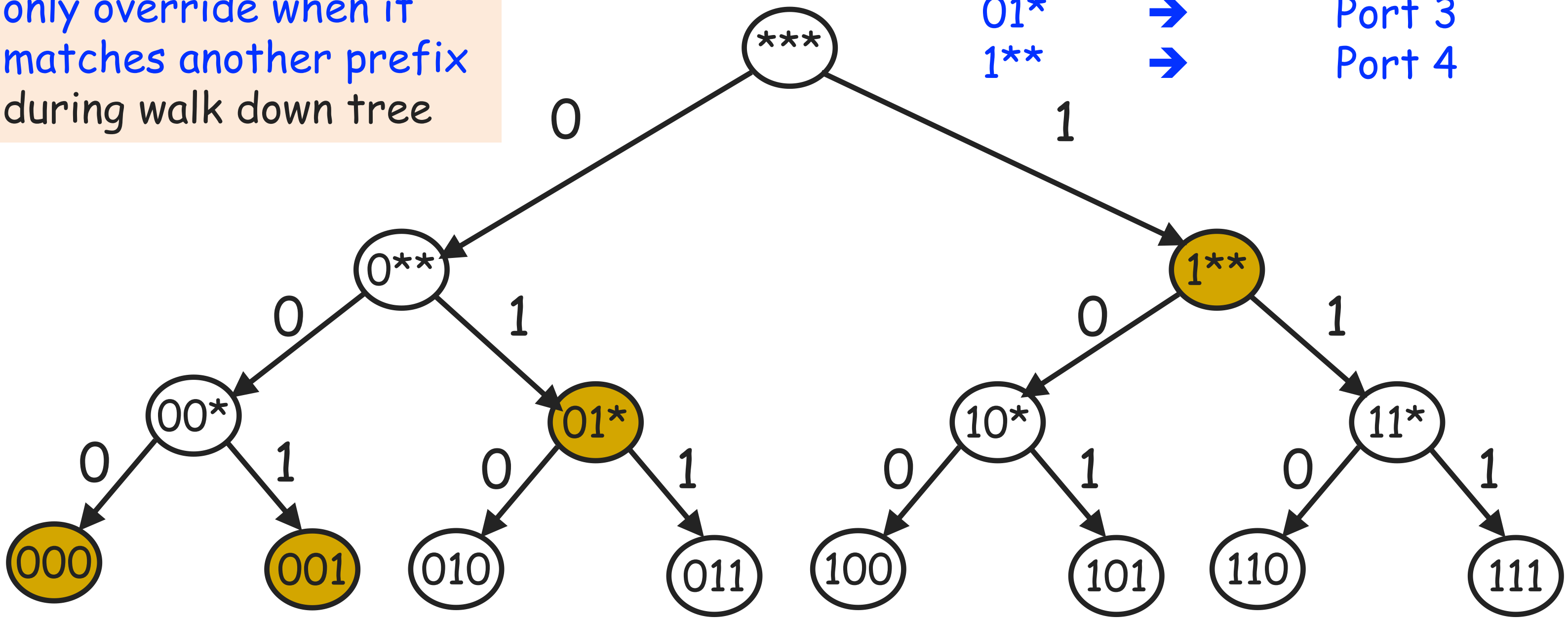
000	→	Port 1
001	→	Port 2
01*	→	Port 3
1**	→	Port 4



Tree structure

Record port associated with latest match, and only override when it matches another prefix during walk down tree

000	➔	Port 1
001	➔	Port 2
01*	➔	Port 3
1**	➔	Port 4

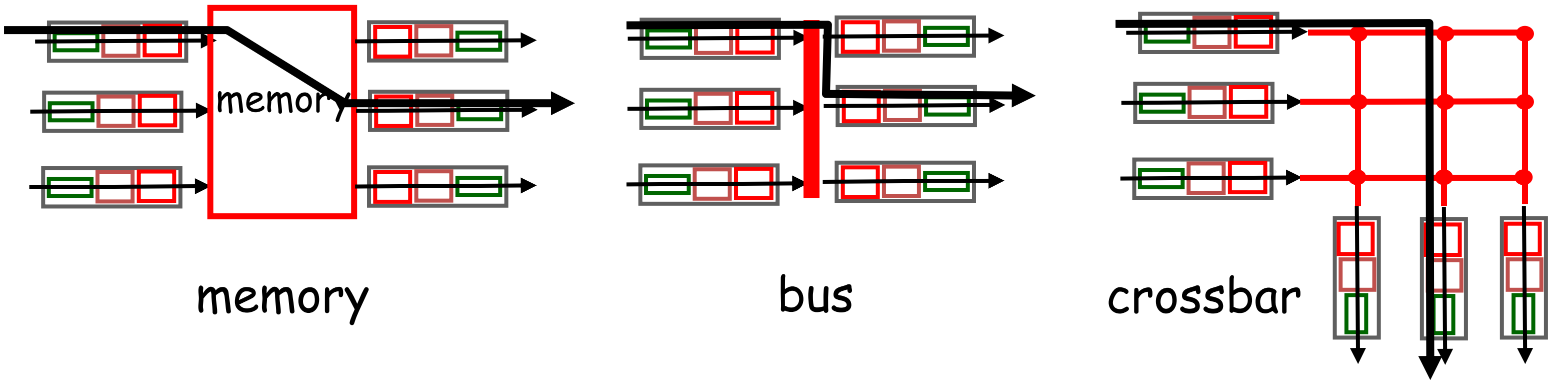


Input Port

- Main challenge is processing speeds
- Tasks involved:
  - Update packet header (easy)
  - LPM lookup on destination address (harder)
- Mostly implemented with specialized hardware

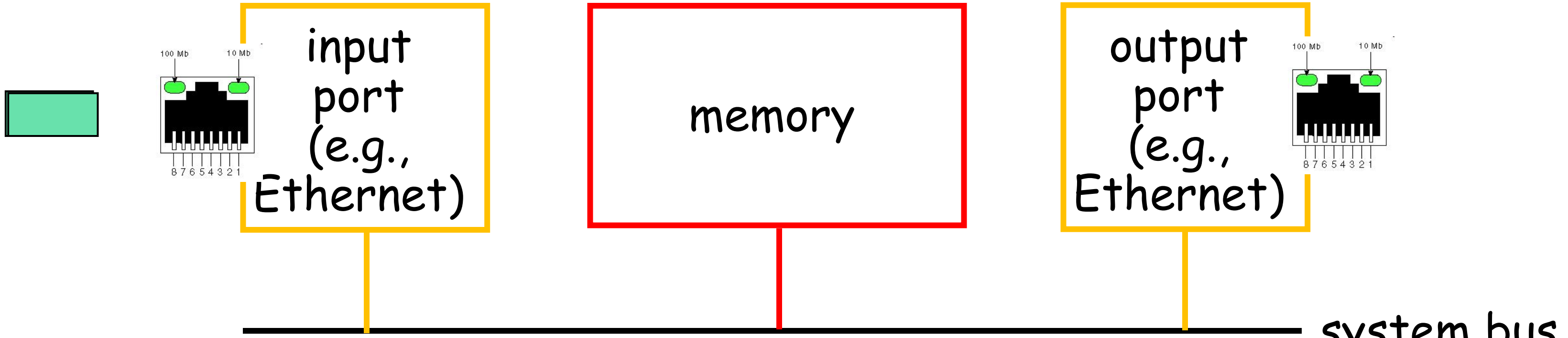
Connecting inputs to outputs: Switching fabric

- Connecting inputs to outputs: Switching fabric
- Transfer packet from input buffer to appropriate output buffer
- Switching rate: rate at which packets can be transfered from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable
- Three types of switching fabrics



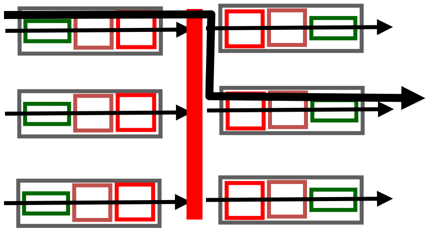
Switching via Memory

- 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)



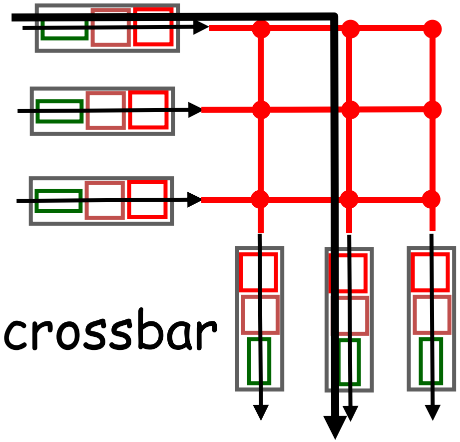
Switching via a Bus

- 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 and enterprise routers

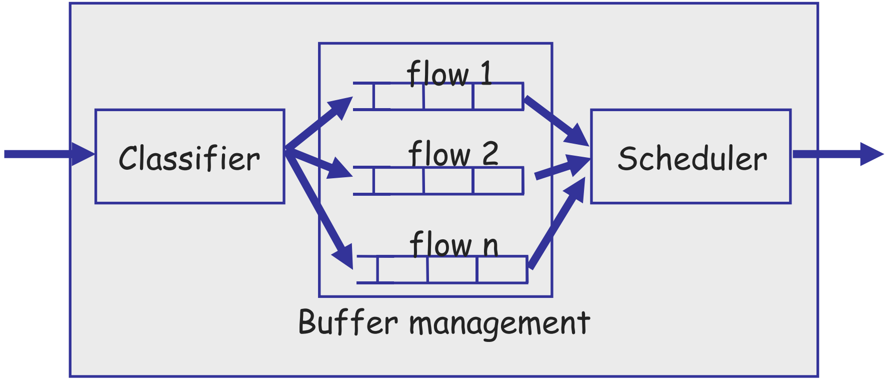


Switching via a Mesh

- Overcome bus bandwidth limitations
- Banyan networks, crossbar, other interconnection nets initially developed to connect processors in multiprocessor
- Advanced design: fragmenting datagram into fixed length cells, switch cells through the fabric.
- Cisco 12000: switches 60 Gbps through the interconnection network



Output Port Functions



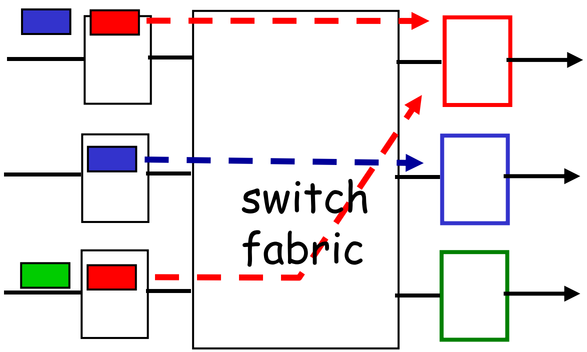
- Packet classification: map packets to flows
- Buffer management: decide when and which packet to drop
- Scheduler: decide when and which packet to transmit
  - Chooses among queued packets for transmission
  - Select packets to drop when buffer saturates

Packet classification

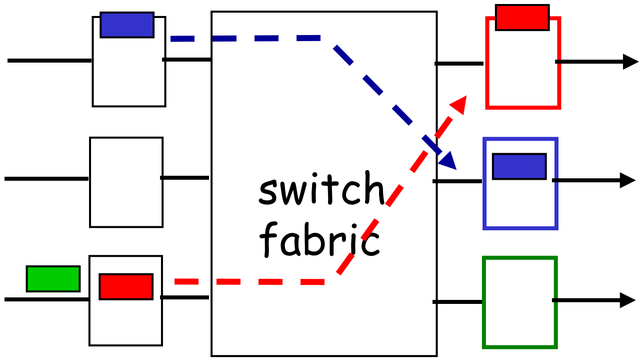
- Classify an IP packet based on a number of fields in the packet header, e.g.,
  - Source/destination IP address (32 bits)
  - Source/destination TCP port number (16 bits)
  - Type of service (TOS) byte (8 bits)
  - Type of protocol (8 bits)
- In general fields are specified by range
  - Classification requires a multi-dimensional range search!

Queuing: 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

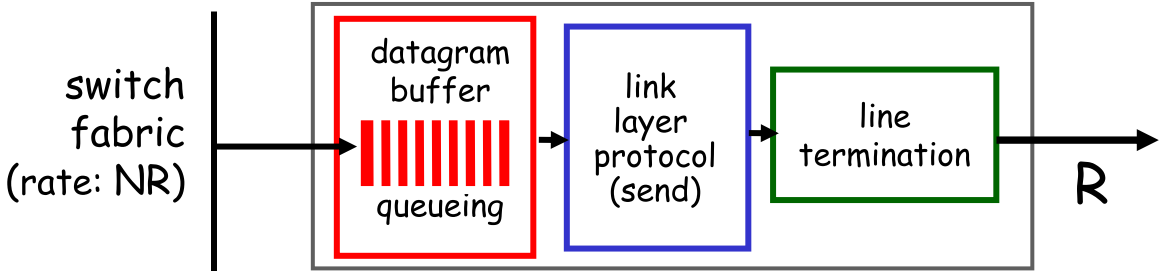


output port contention: only one red datagram can be transferred. lower red packet is blocked



one packet time later: green packet experiences HOL blocking

Queuing: Output port queuing



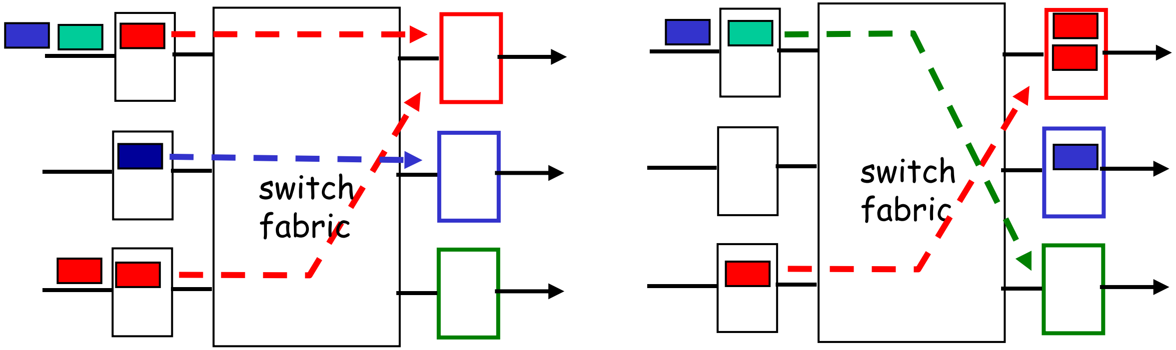
- Buffering required when datagrams arrive from fabric faster than link transmission rate. Drop policy: which datagrams to drop if no free buffers?

  → 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

Queuing: Output port queuing



at *t*, packets more from input to output

one packet time later

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

How much buffering?

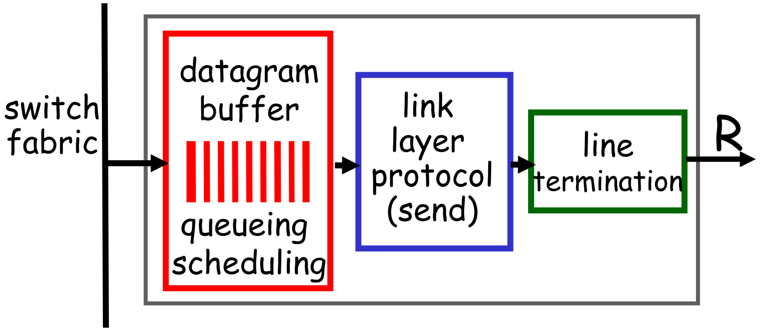
- RFC 3439 rule of thumb: average buffering equal to "typical" RTT (say 250 msec) times link capacity *C*
  - e.g., *C* = 10 Gbps link: 2.5 Gbit buffer

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

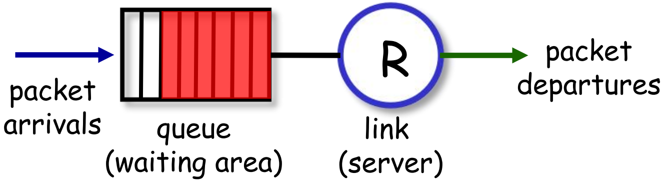
$$\frac{RTT \cdot C}{\sqrt{N}}$$

- 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:

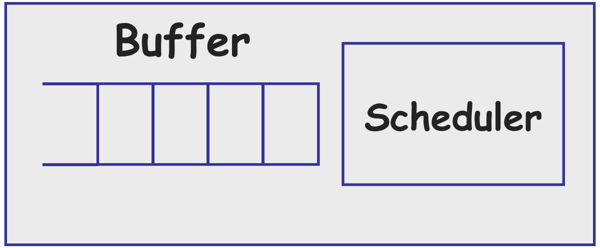
- drop: which packet to add, drop when buffers are full
  - tail drop: drop arriving packet
  - priority: drop/remove on priority basis
- marking: which packets to mark to signal congestion (ECN, RED)

Scheduler

- One queue per “flow”
- Scheduler decides when and from which queue to send a packet
- Goals of a scheduling algorithm
  - Fast!
  - Depends on the policy being implemented (fairness, priority, etc.)

Simplest: FIFO router

- No classification
- Drop-tail buffer management: when buffer is full drop the incoming packet
- First-In-First-Out (FIFO) Scheduling: schedule packets in the same order they arrive

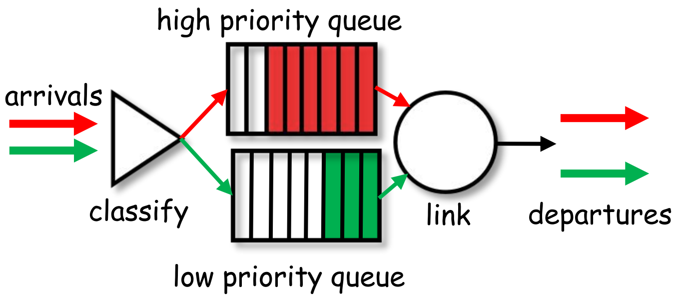


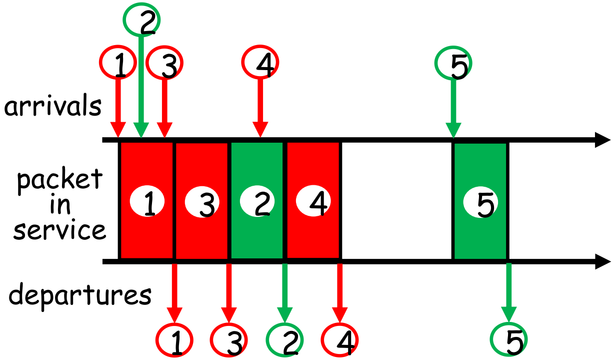
Scheduling policies: priority

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

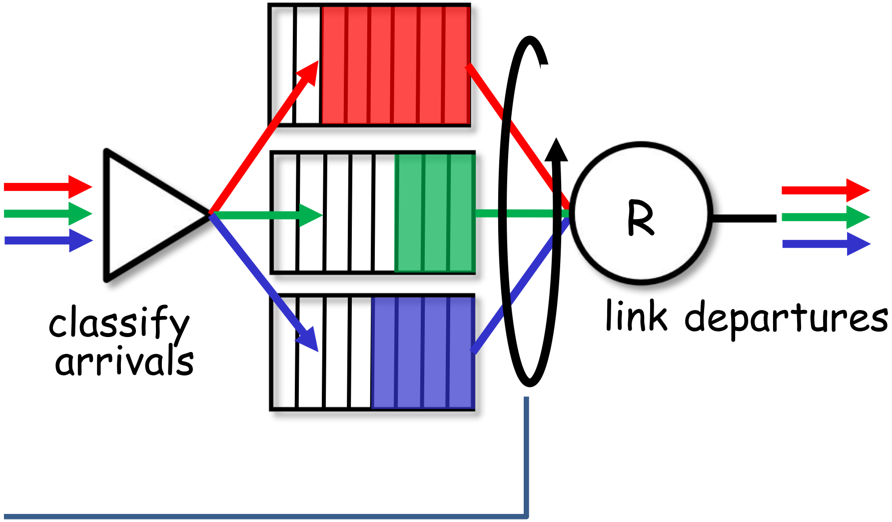




Scheduling policies: round robin

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



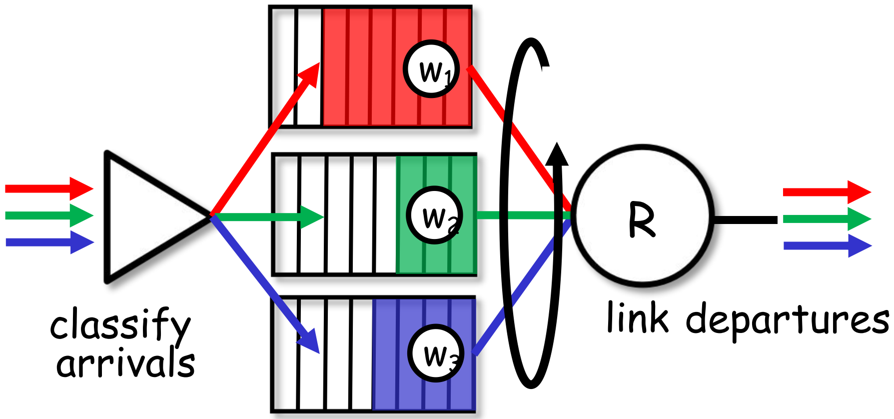
Scheduling policies: weighted fair queueing

Weighted Fair Queuing (WFQ):

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

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

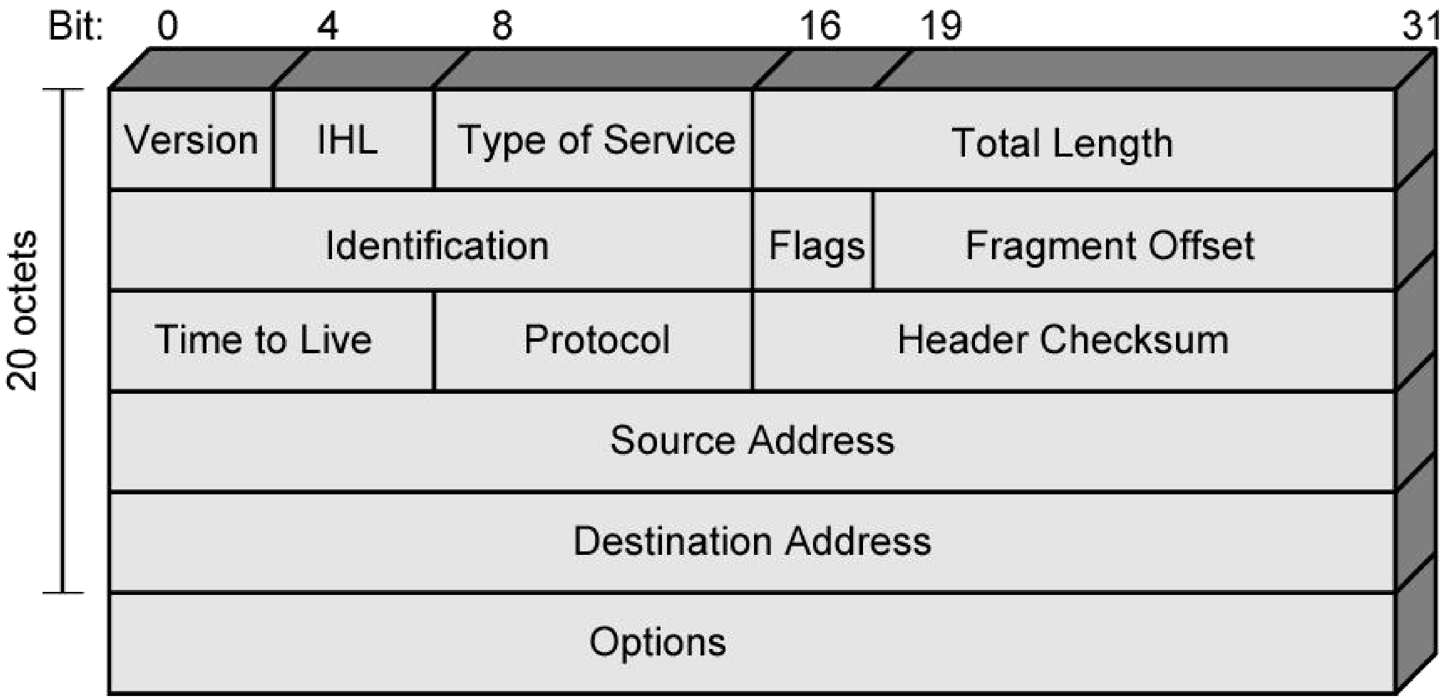
- minimum bandwidth guarantee (per-traffic-class)



Outline

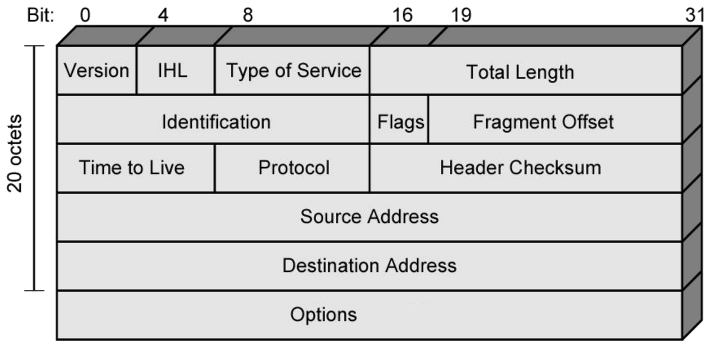
- Network Layer Functions
- Routers
- IP Packet Structure

IPv4 Header

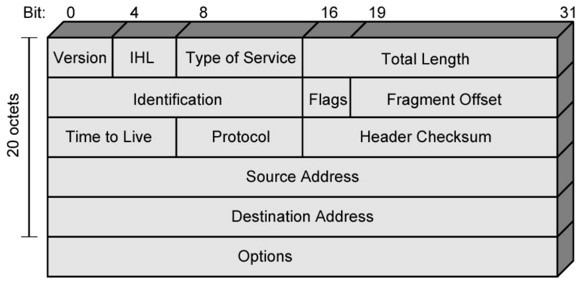

Bit:
0
4
8
16
19
31
20 octets
Version
IHL
Type of Service
Total Length
Identification
Flags
Fragment Offset
Time to Live
Protocol
Header Checksum
Source Address
Destination Address
Options

Header Fields (1)

- Version (4 bits)
  - Currently 4
  - IPv6 - see later
- Internet header length (IHL) (4 bits)
  - In 32 bit words (4 octets)
  - Minimum fixed header (20 octets) + options
- Type of service (8 bits)
  - Precedence: 3 bits, 8 levels defined
  - Reliability: 1 bit, Normal or high
  - Delay: 1 bit, Normal or low
  - Throughput: 1 bit, Normal or high

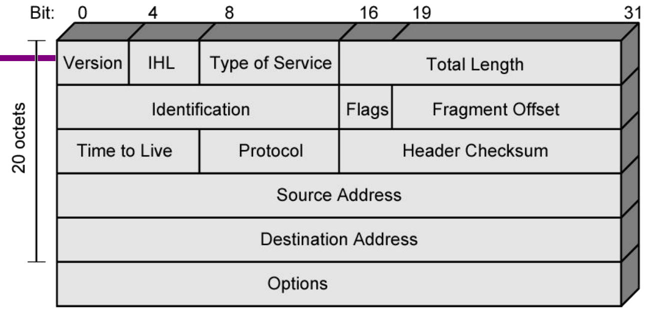


Header Fields (2)



- Total length (16 bits)
  - Of datagram, in octets
- Identification (16 bits)
  - Sequence number
  - Used with addresses and user protocol to identify datagram uniquely
- Flags (3 bits)
  - More flag, Don't fragment
- Fragmentation offset (13 bits)
- Time to live (8 bits)
- Protocol (8 bits)
  - Next higher layer to receive data field at destination

Header Fields (3)



- Header checksum (16 bits)
  - Complement sum of all 16 bit words in header
  - If not correct, router discards packets
  - Reverified and recomputed at each router, set to 0 during calculation. (Why?)
- Source address (32 bits)
- Destination address (32 bits)
- Options (variable ≤ 40 octets)

Data Field

- Carries user data from next layer up
- Multiple of 8 bits long (i.e. octet)
- Max length of datagram (header + data) 65,535 octets

Q & A