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Computer Networks

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Material with thanks to James F. Kurose, Mosharaf Chowdhury, and other colleagues.

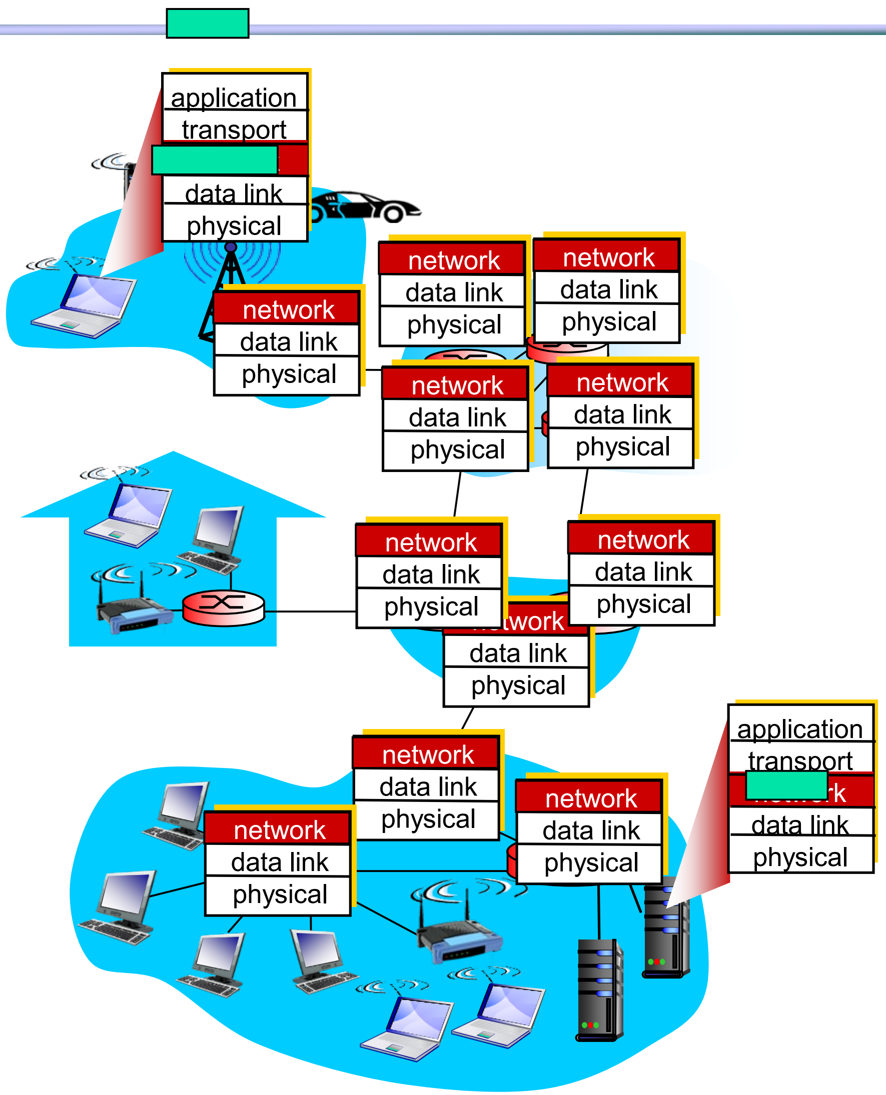
Chapter 3. Network Layer

- Network Layer Functions
- IP Routers
- Virtual Circuit and Datagram Networks

Network Layer Functions

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

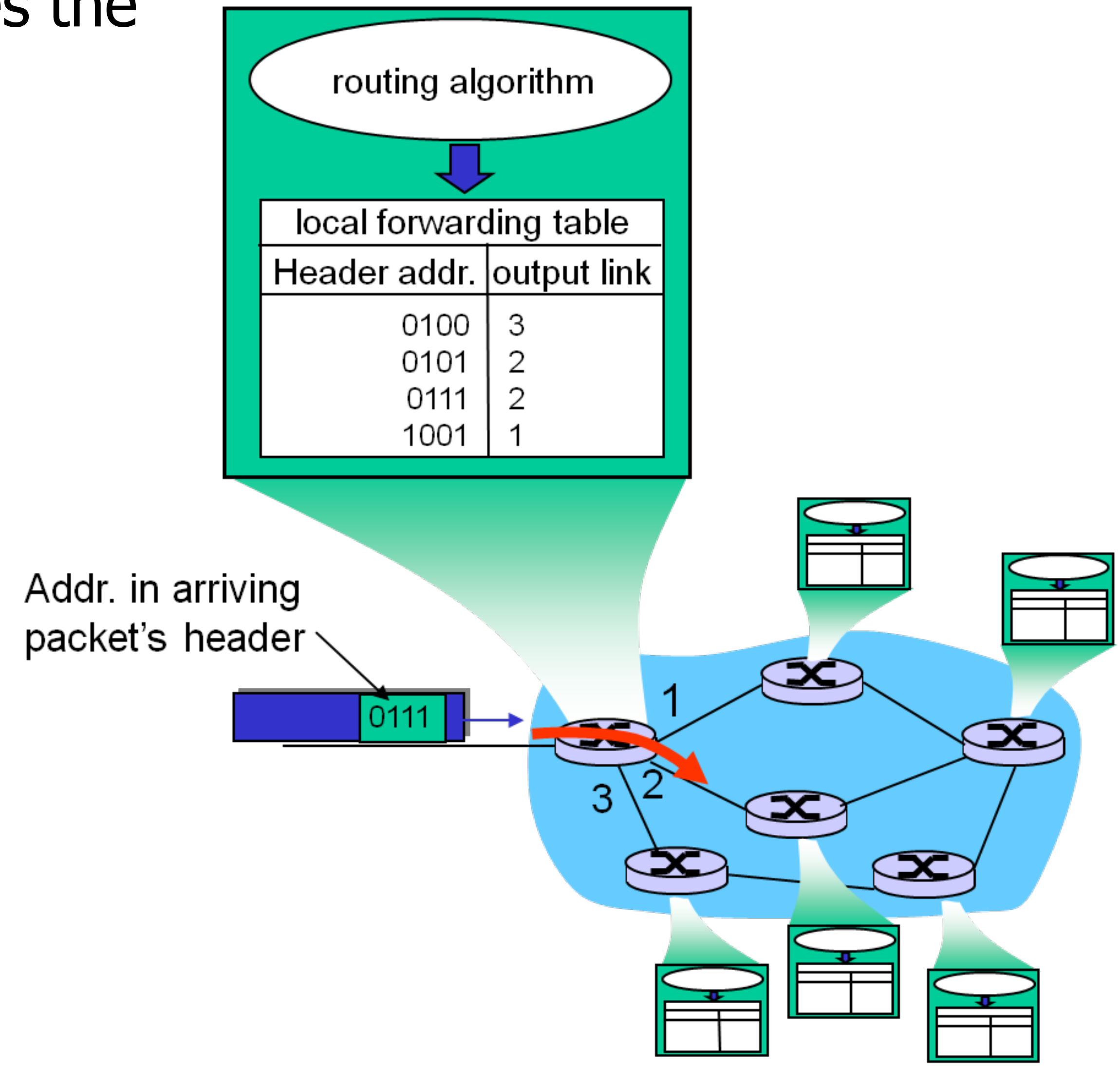
- OSI network-layer functions:
- Switching / Routing
  - Determine route taken by packets from source to destination (multiple nodes)
  - Shortest path from source to destination
  - Routing algorithms
- Forwarding
  - Move packets from input to designated output determined by switching (single node)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

analogy: Trip Planning

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

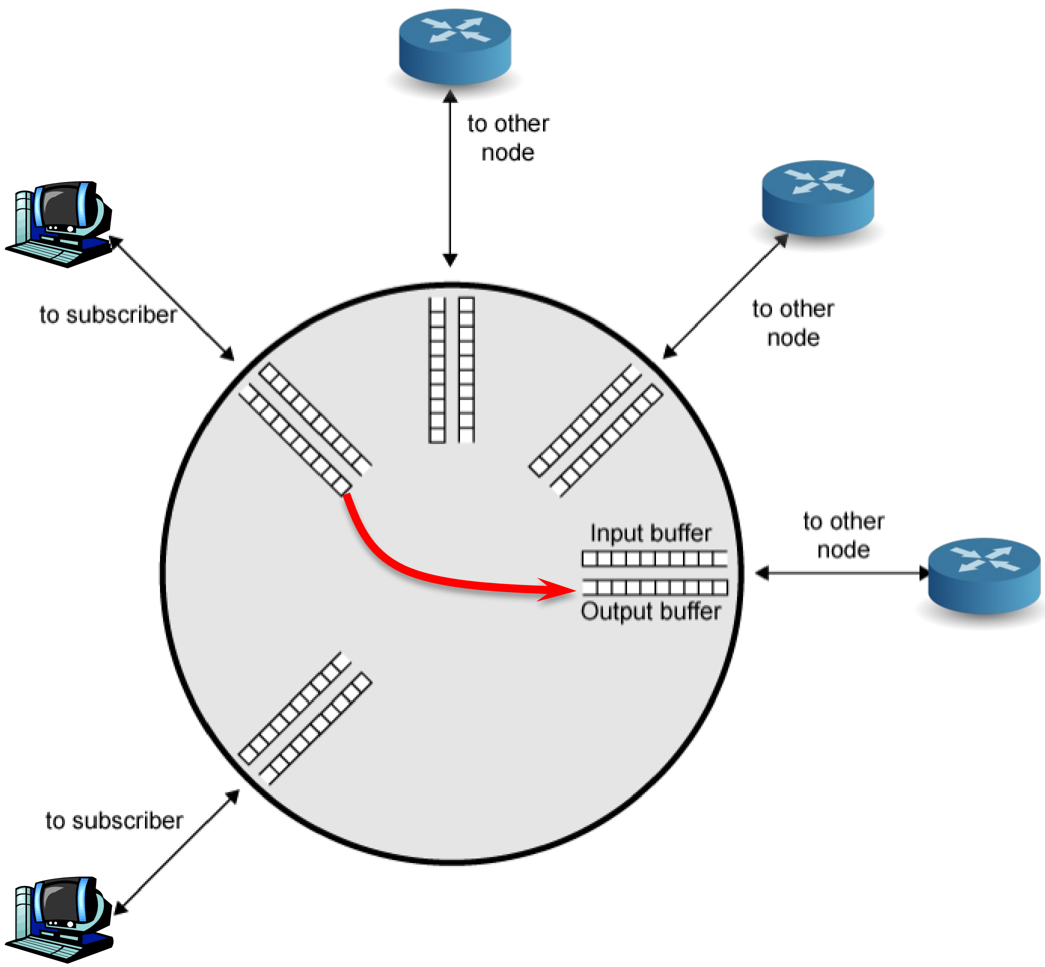
Switch Functions

- Routing determines the forwarding table



Forwarding Functions

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



Connection setup

- 3^{rd} important function in *some* network architectures:
  - ATM, frame relay, X.25
- Before datagrams flow, two end hosts *and* intervening routers establish virtual connection
  - Routers get involved
- Network vs transport layer connection service:
  - *network:* between two hosts (may also involve intervening routers in case of VCs)
  - *transport:* between two processes

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 ? Bandwidth	Loss	Order	Timing	Congestion feedback
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

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

IP Routers

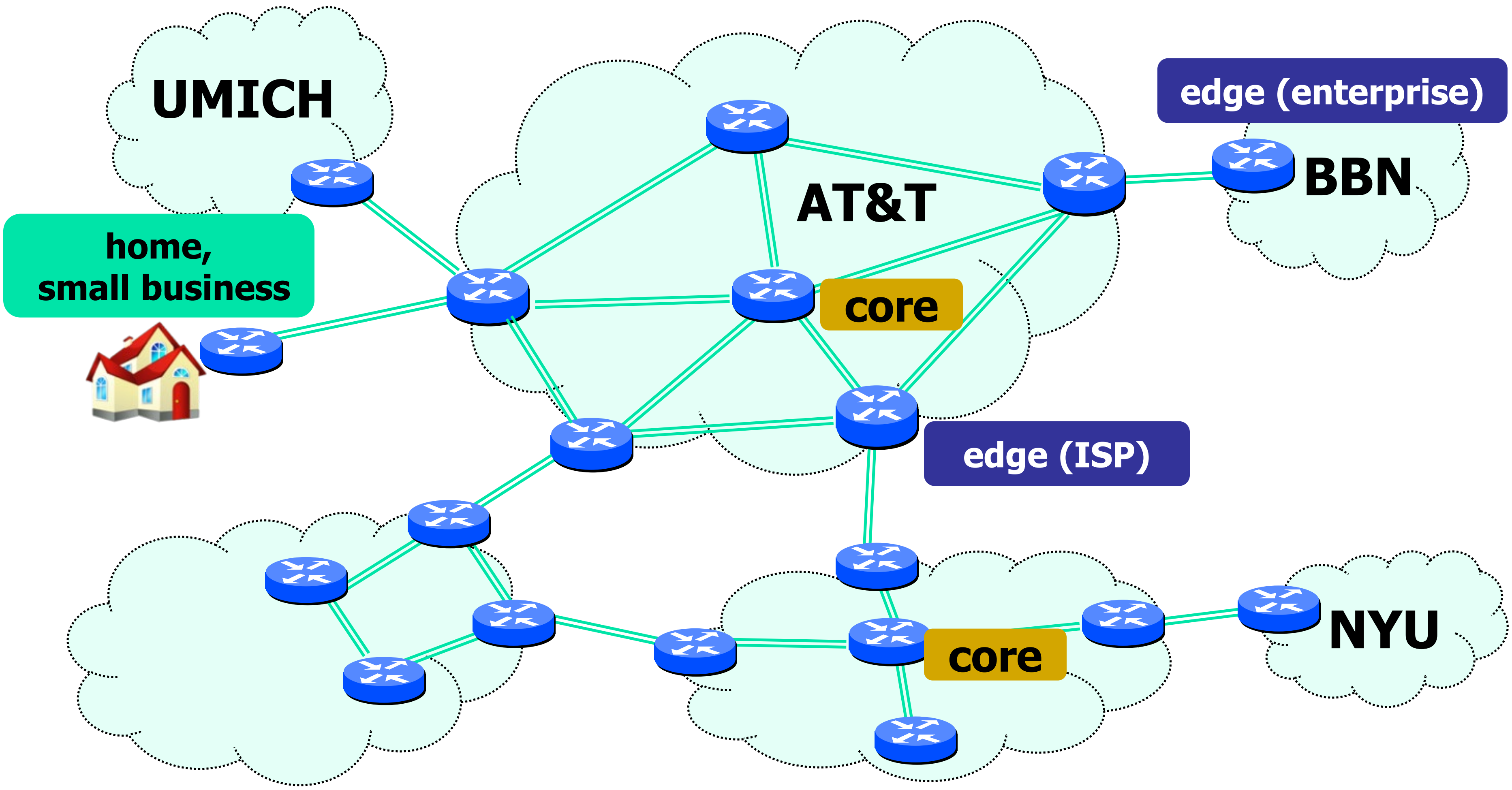
IP routers

- 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



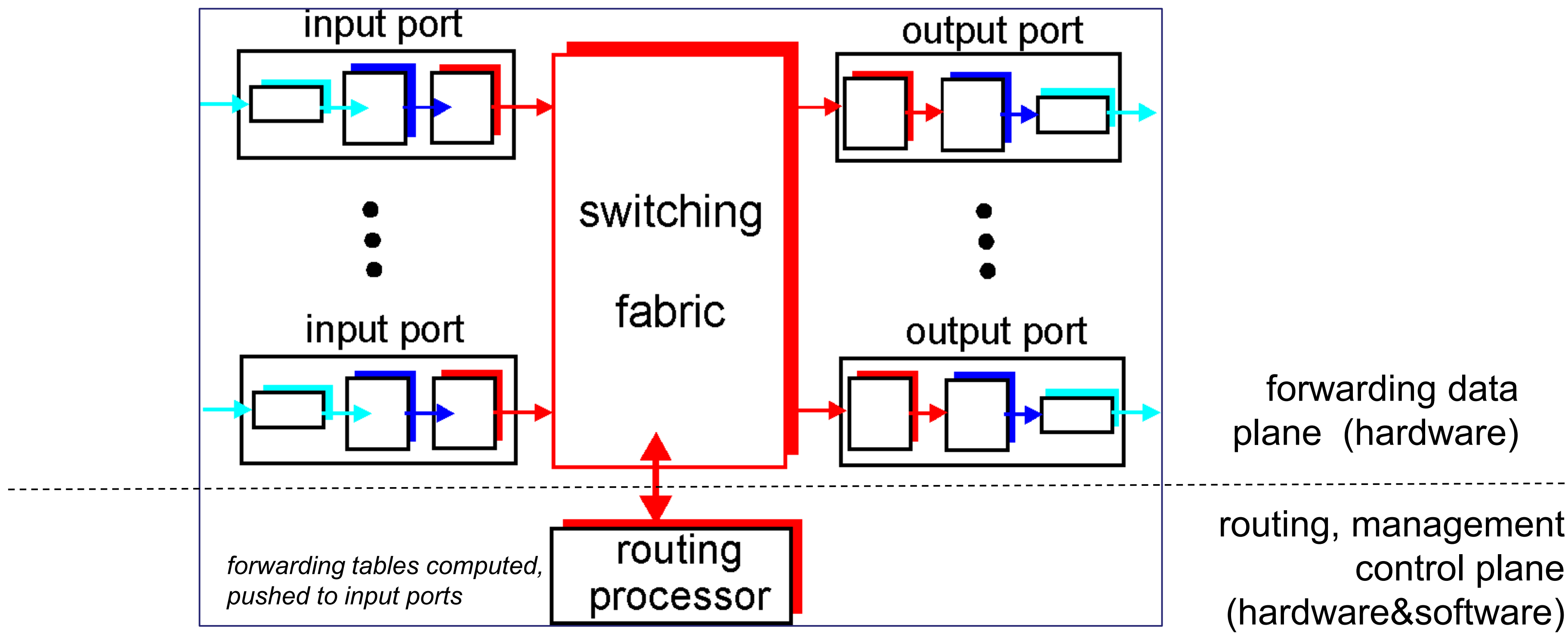
Many types of routers

- 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

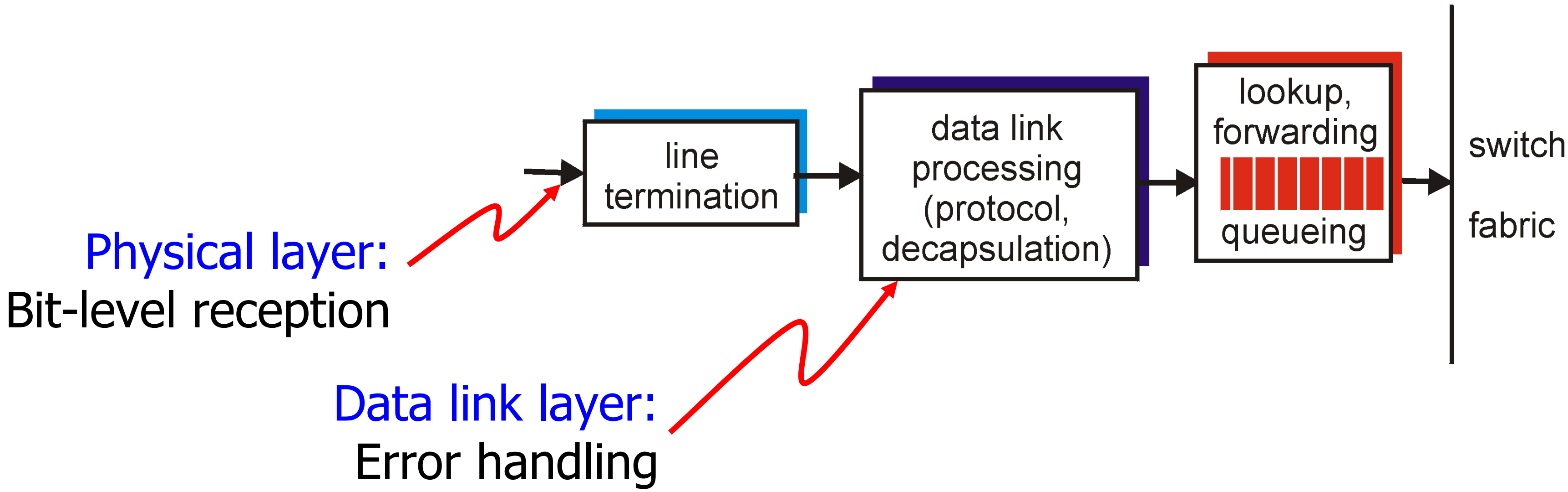
Inside a Router: Architecture Overview

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
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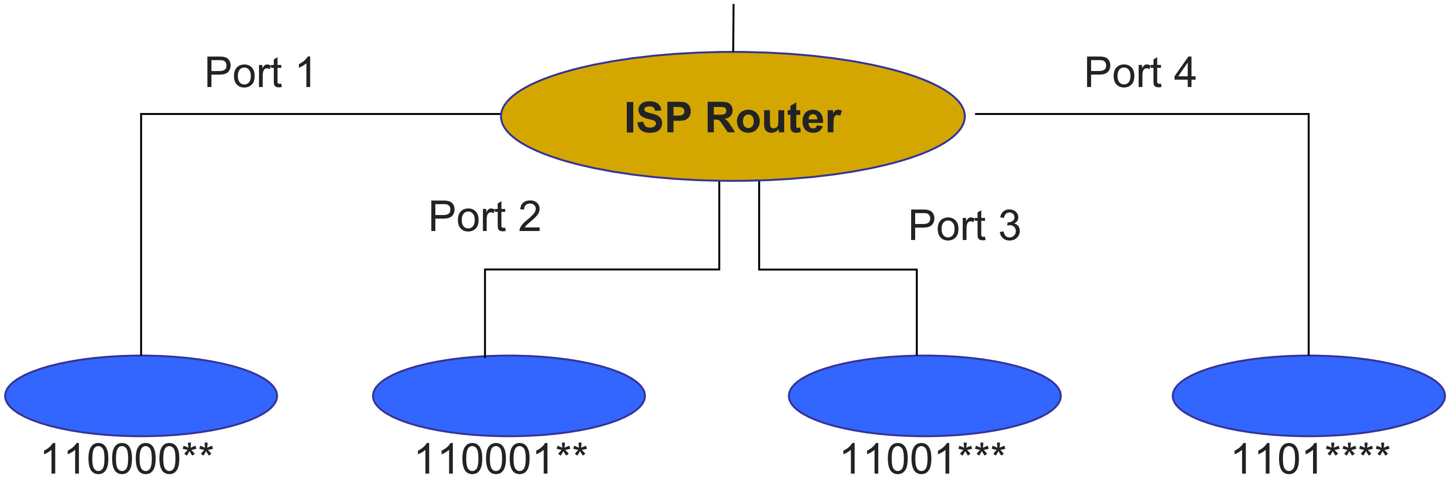
  - 11 01 00 00 to 11 01 11 11: Port 4

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

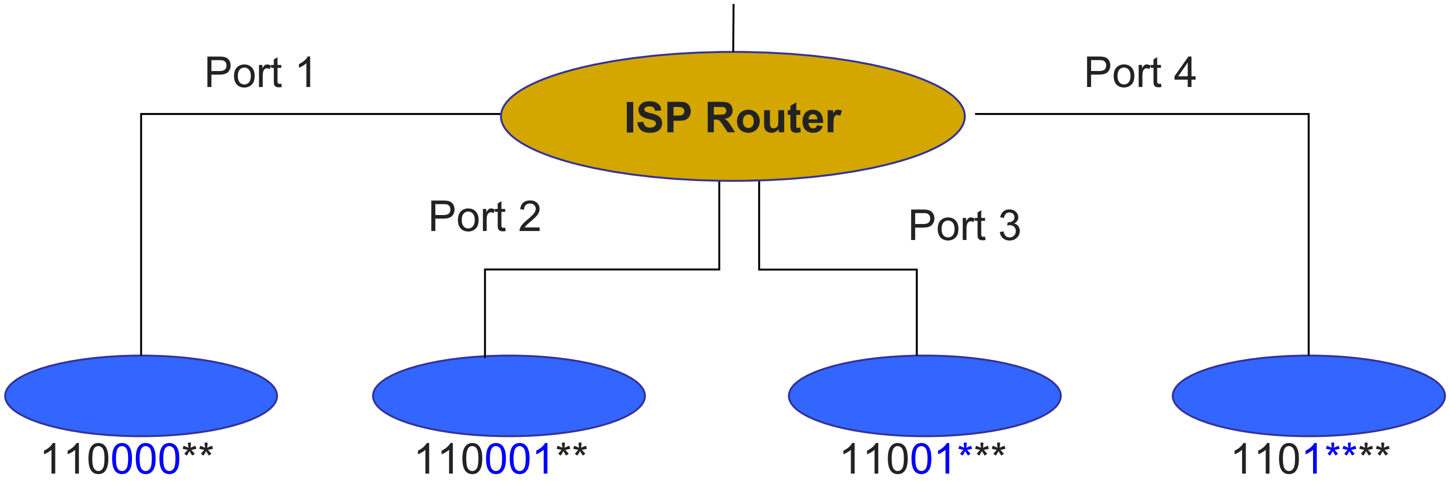
Longest prefix matching



Finding match efficiently

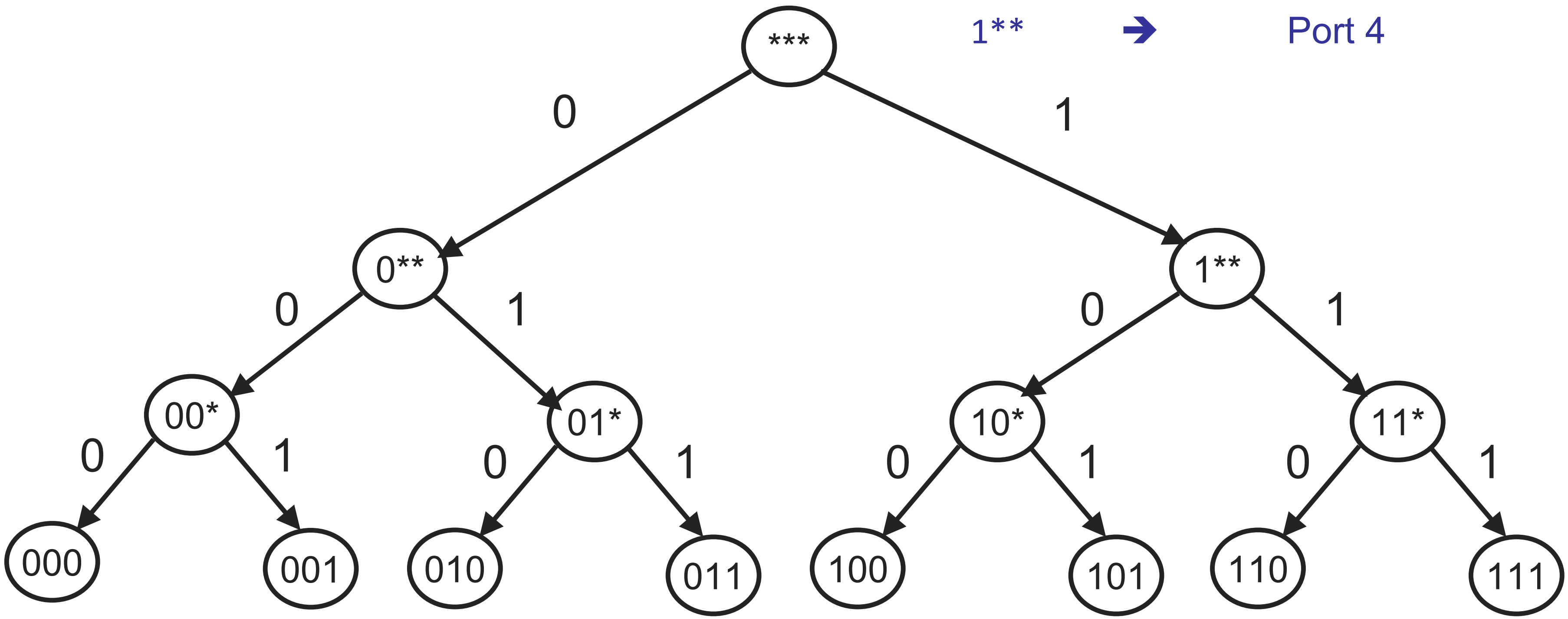
- Testing each entry to find a match scales poorly
  - On average: O(number of entries)
- Leverage tree structure of binary strings
  - Set up tree-like data structure

Longest prefix matching



Tree structure

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



Tree structure

000	→	Port 1
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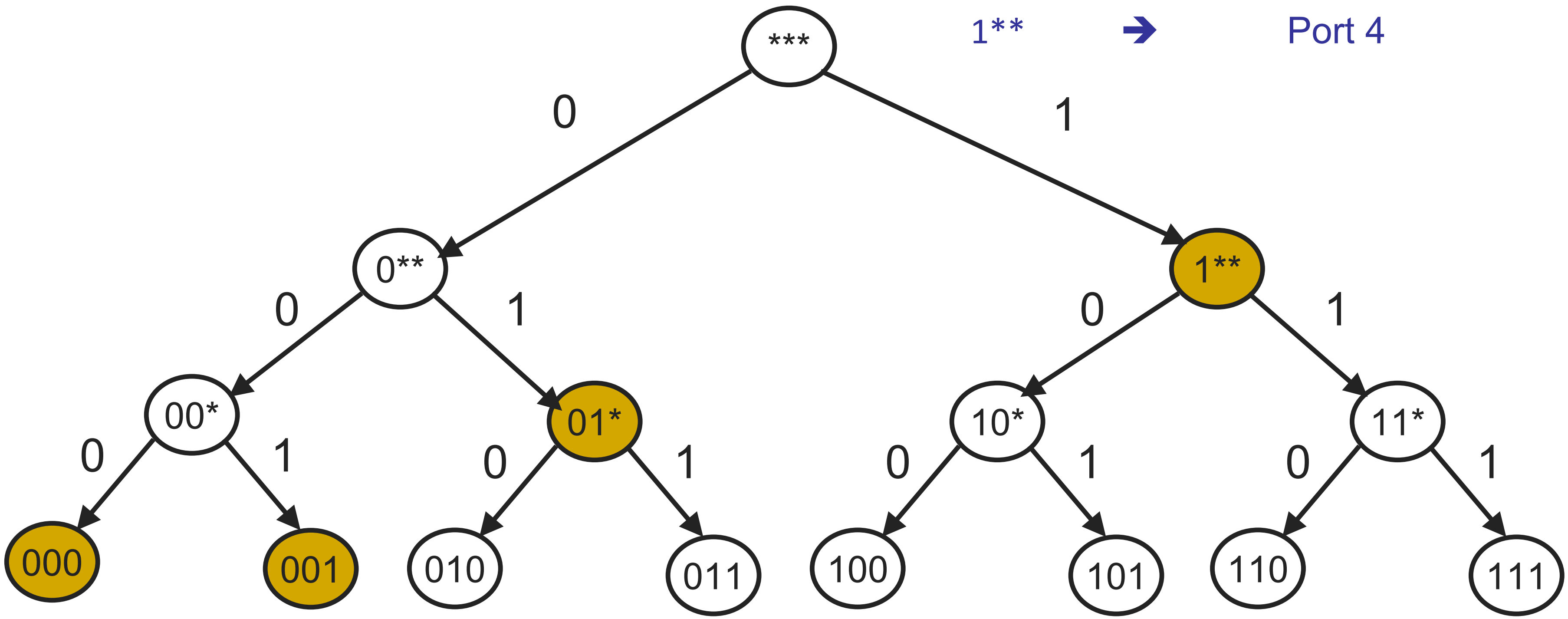
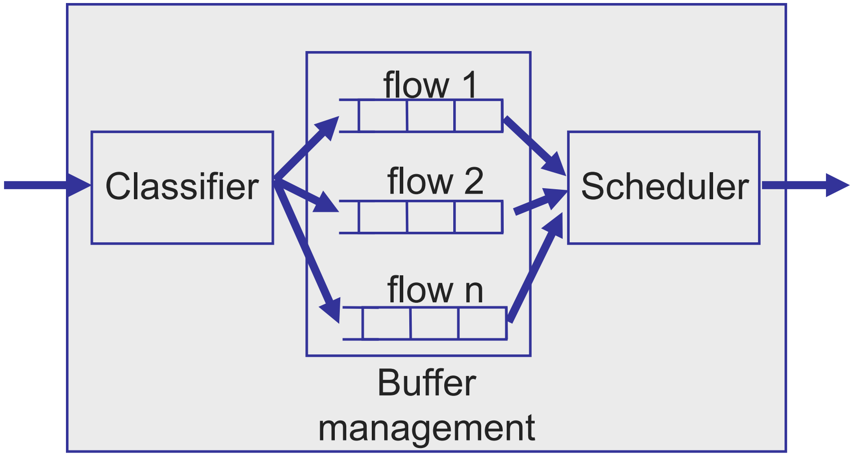


Record port associated with latest match, and only override when it matches another prefix during walk down tree

Input Port

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

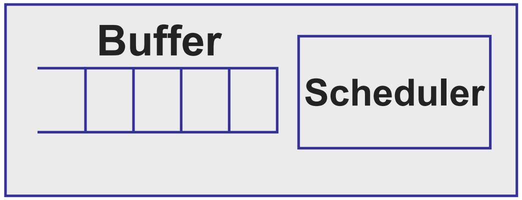
Output Port Functions



- 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

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



Packet classification

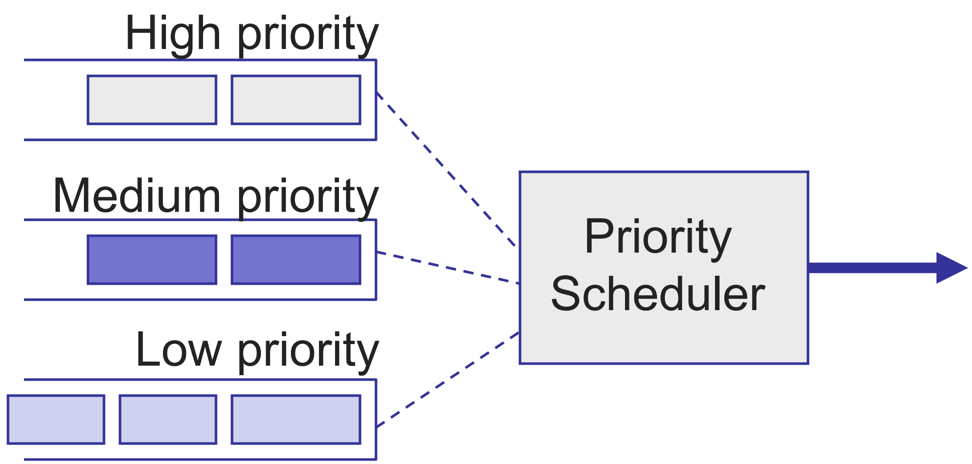
- Classify an IP packet based on a number of fields in the packet header, e.g.,
  - Source/destination IP address (32 bits)
  - Source/destination TCP port number (16 bits)
  - Type of service (TOS) byte (8 bits)
  - Type of protocol (8 bits)
- In general fields are specified by range
  - Classification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

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.)

Priority scheduler

- Priority scheduler: packets in the highest priority queue are always served before the packets in lower priority queues



Round-robin scheduler

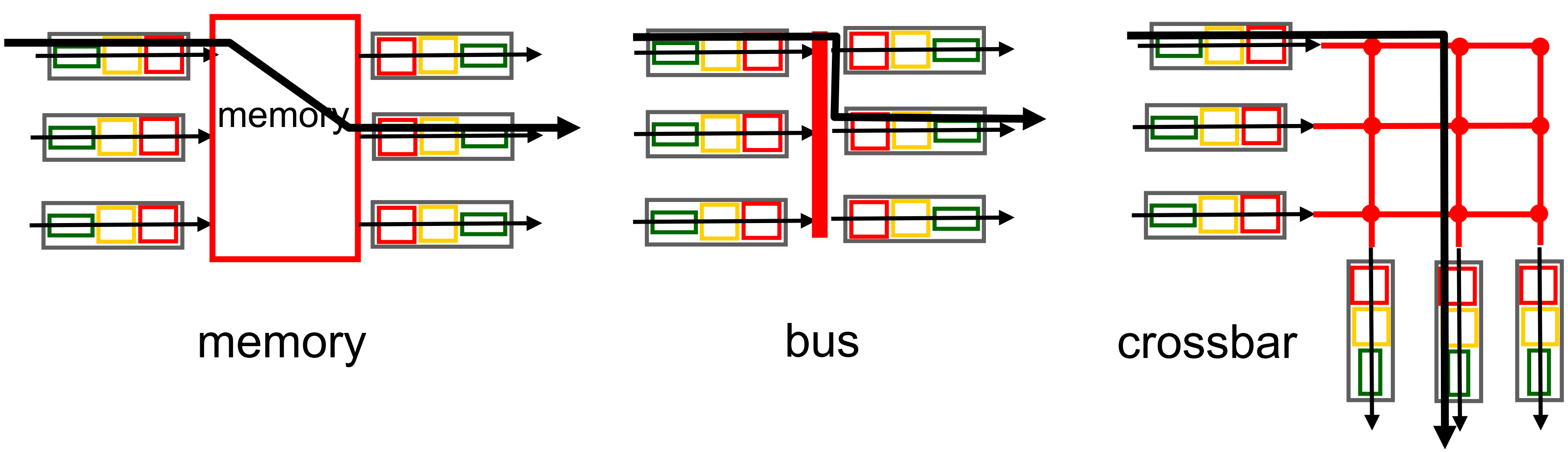
- Round robin: packets are served from each queue in turn
- Fair queuing (FQ): round-robin for packets of different size
- Weighted fair queueing (WFQ): serve proportional to weight
  - FQ gives equal weight to each flow

Connecting inputs to outputs: Switching fabric

- Mini-network
- Three primary ways to switch
  - Switching via shared memory
  - Switching via a bus
  - Switching via an inter-connection network
    - For example, cross-bar

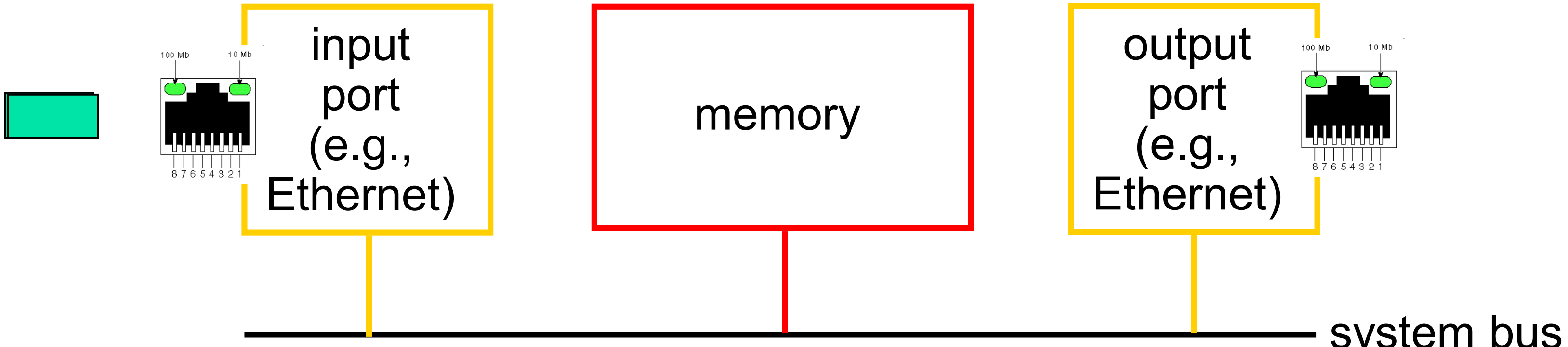
Three Types of Switching Fabrics

- Connecting inputs to outputs: Switching fabric
  交换结构
- Transfer packet from input buffer to appropriate output buffer
- 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 types of switching fabrics



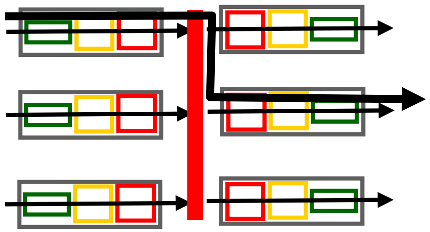
Switching via Memory

- 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)



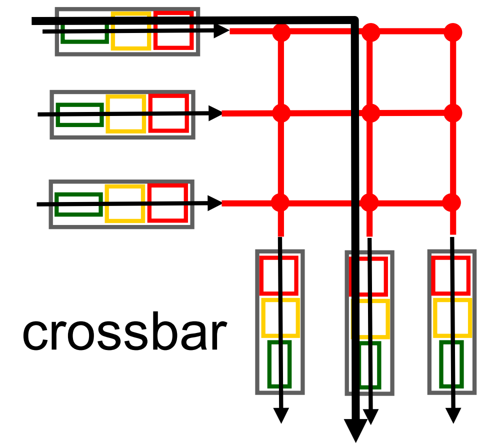
Switching via a Bus

- 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



Virtual Circuit and Datagram Networks

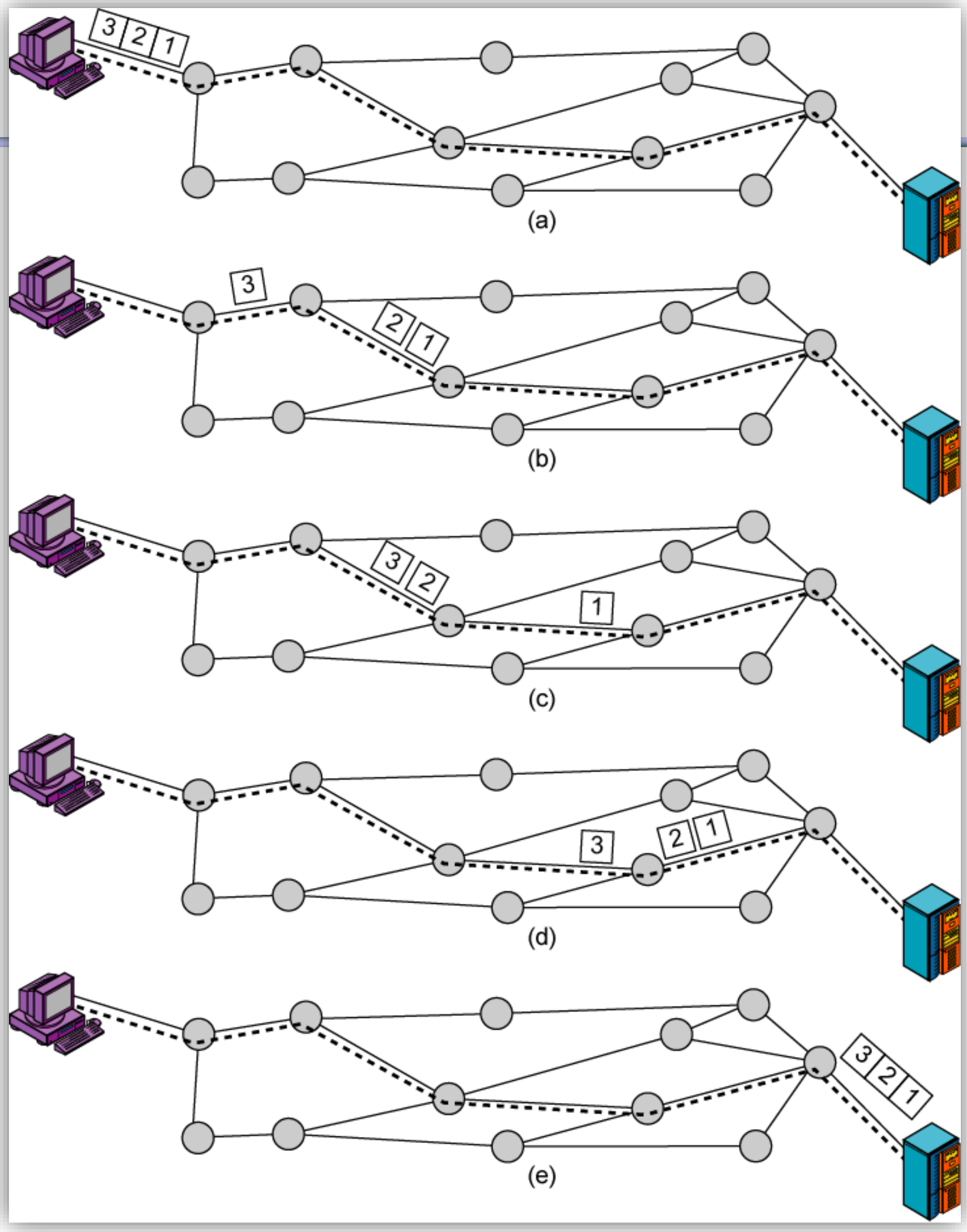
Recap: Circuit Switching & Packet Switching

- Circuit Switching
  - End-to-end resources reserved for "call"
    - Link bandwidth, switch capacity
  - Dedicated resources: no sharing
  - Guaranteed performance
  - Call setup/teardown required
- Packet Switching
  - Each end-to-end data stream divided into packets
  - Application A, B packets share network resources
  - Store and forward: packets move one hop at a time, stored (queued) at switches
  - Resource contention: aggregate (burst-up) resource demand can exceed amount available
  - Congestion: packets queue and wait for link use

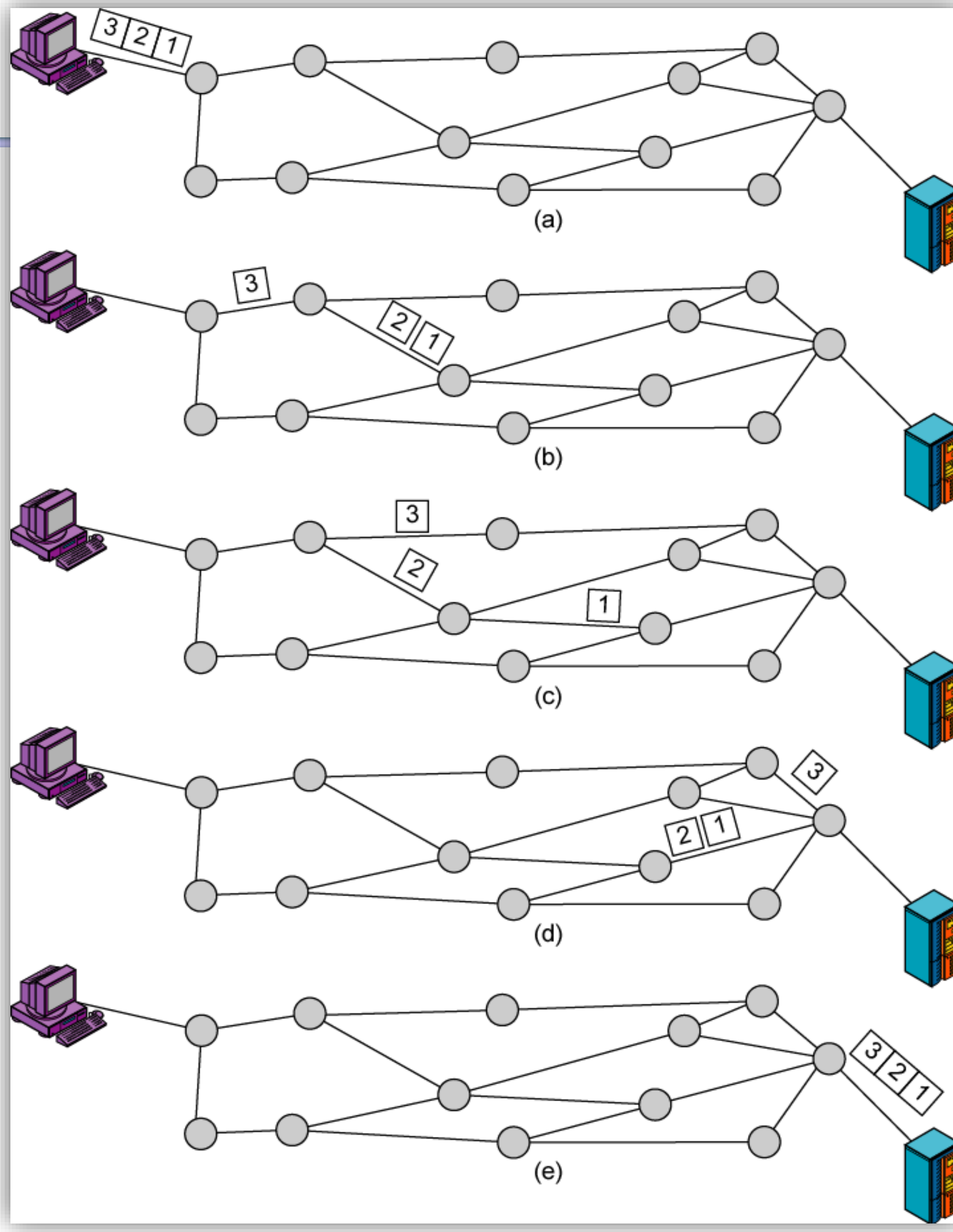
Virtual Circuit and Datagram Networks

- Two types of Package Switch Networks
  - Virtual circuit networks
    - Network service provided on flow of packets
    - VC network provides network-layer connection oriented service
    - E.g., ATM, X.25, Frame Relay
  - Datagram networks
    - Network service provided on singular packet
    - Datagram network provides network-layer connectionless service
    - E.g., IP network

Routing in Virtual Circuit



Routing in Datagram Nets



Virtual Circuit Networks

- Connection setup, teardown for each flow of packets
- Each packet carries VC identifier (not destination host address)

- Every switch on source-destination path maintains "state" for each passing connection
- Link, switch resources (bandwidth, buffers) may be allocated to VC
  - Dedicated resources = predictable quality of service

Connection Setup

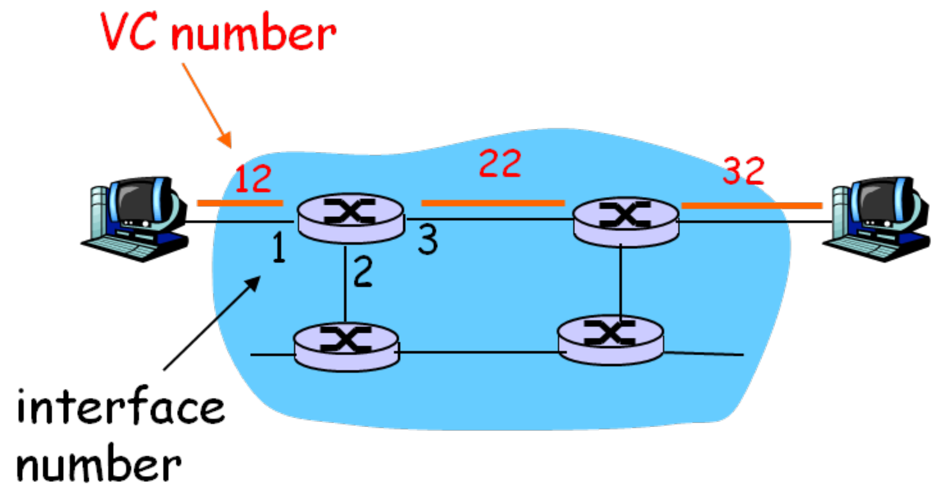
- Essential function for virtual circuit networks
  - E.g. ATM, frame relay, X.25
- Two end hosts and intervening switches pre-establish a path for virtual connection
- Routing is used for finding a suitable (shortest) path

VC Implementation

- A VC consists of
  - Path from source to destination
  - VC numbers, maybe one number for each link along the path
  - Entries in forwarding tables in switches along the path

- Note:
  - Packet belonging to VC carries VC number (rather than addresses)
  - VC number can be changed on each link, forwarding table lists the new VC number

A Forwarding Table for VC



Forwarding table in
northwest switch

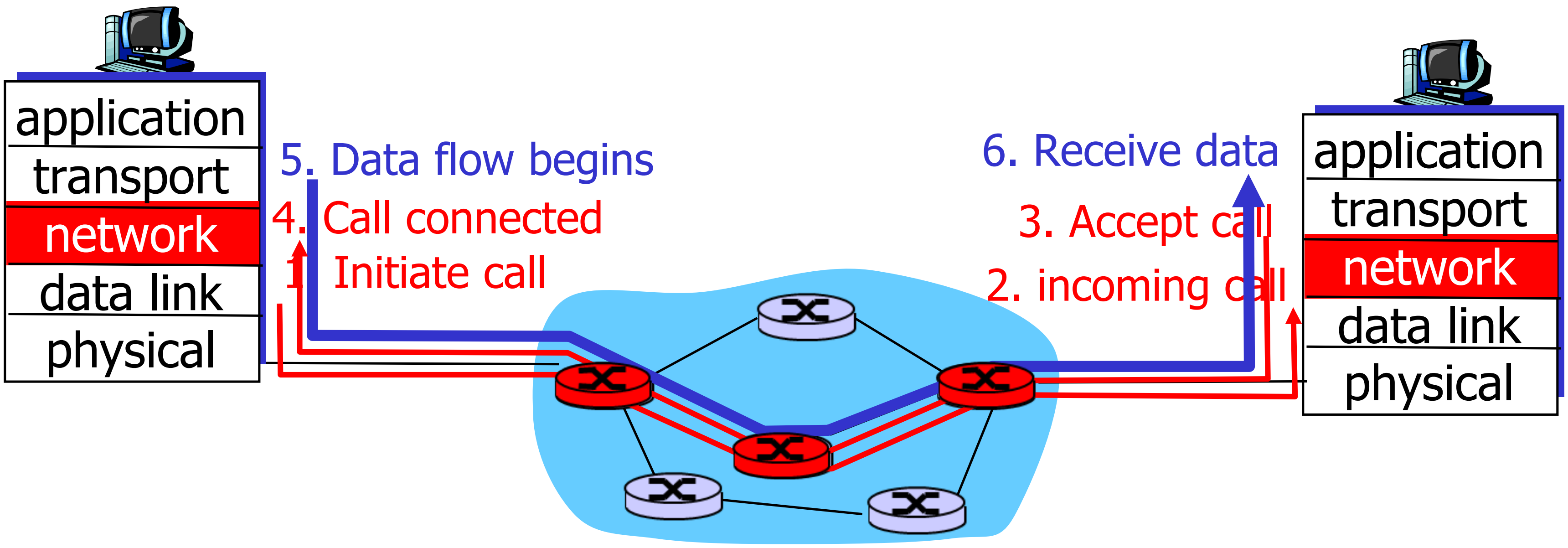
Incoming interface	Incoming VC #	Outgoing interface	Outgoing VC #
1	12	3	22
2	63	1	18
3	7	2	17
1	97	3	87
…	…	…	…

Table entries constitutes state information of a VC

Virtual Circuits: Signaling Protocols

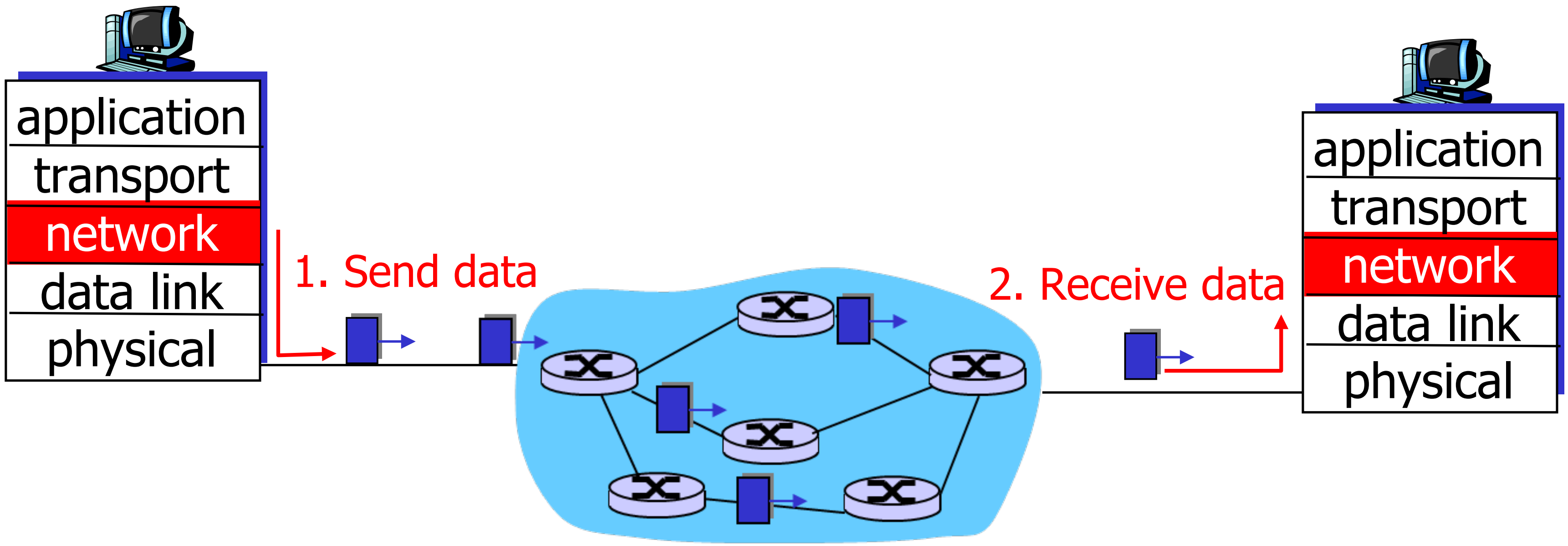
- Used to setup, maintain and teardown VC
- Used in ATM, frame-relay, X.25
- Not used in today's Internet

信令协议



Datagram Networks

- No call setup at network layer
- No network-level concept of "connection"
- Switches: no state about end-to-end connections
- Packets forwarded using destination host address
- Packets between same source-dest pair may take different paths



A Forwarding Table for Datagram Networks

- Also called routing table
- May reach 4 billion entries

- The destination address prefix may define a switch address or a subnet address

Dest Address Prefix	Address Mask	Link Interface
11001000 00010111 00010	11111111 11111111 11111000 00000000	0
11001000 00010111 00011000	11111111 11111111 11111111 00000000	1
11001000 00010111 000110	11111111 11111111 11111100 00000000	2
default	*	3

Datagram vs. Virtual Circuit

Datagram (Internet)

- Data exchange among computers
  - "Elastic" service, no strict timing
- "Smart" end systems (computers)
  - Can adapt, perform control, error recovery
  - Simple inside network, complexity at "edge"
- Many link types
  - Different characteristics
  - Uniform service difficult

Virtual Circuit (ATM)

- Evolved from telephony
- Human conversation:
  - Strict timing, reliability requirements
  - Need guaranteed service
- "Dumb" end systems
  - Telephones
  - Complexity inside network (switches)
- Link type standardized

Summary

- 网络层基本功能
  - 交换/路由，转发，建立连接
- 路由器的构成
- 两种分组交换网络
  - 虚电路网络
  - 数据报网络
    - IP网络

Homework

- 第四章：R1, R2, P1, P2