Packet Switching

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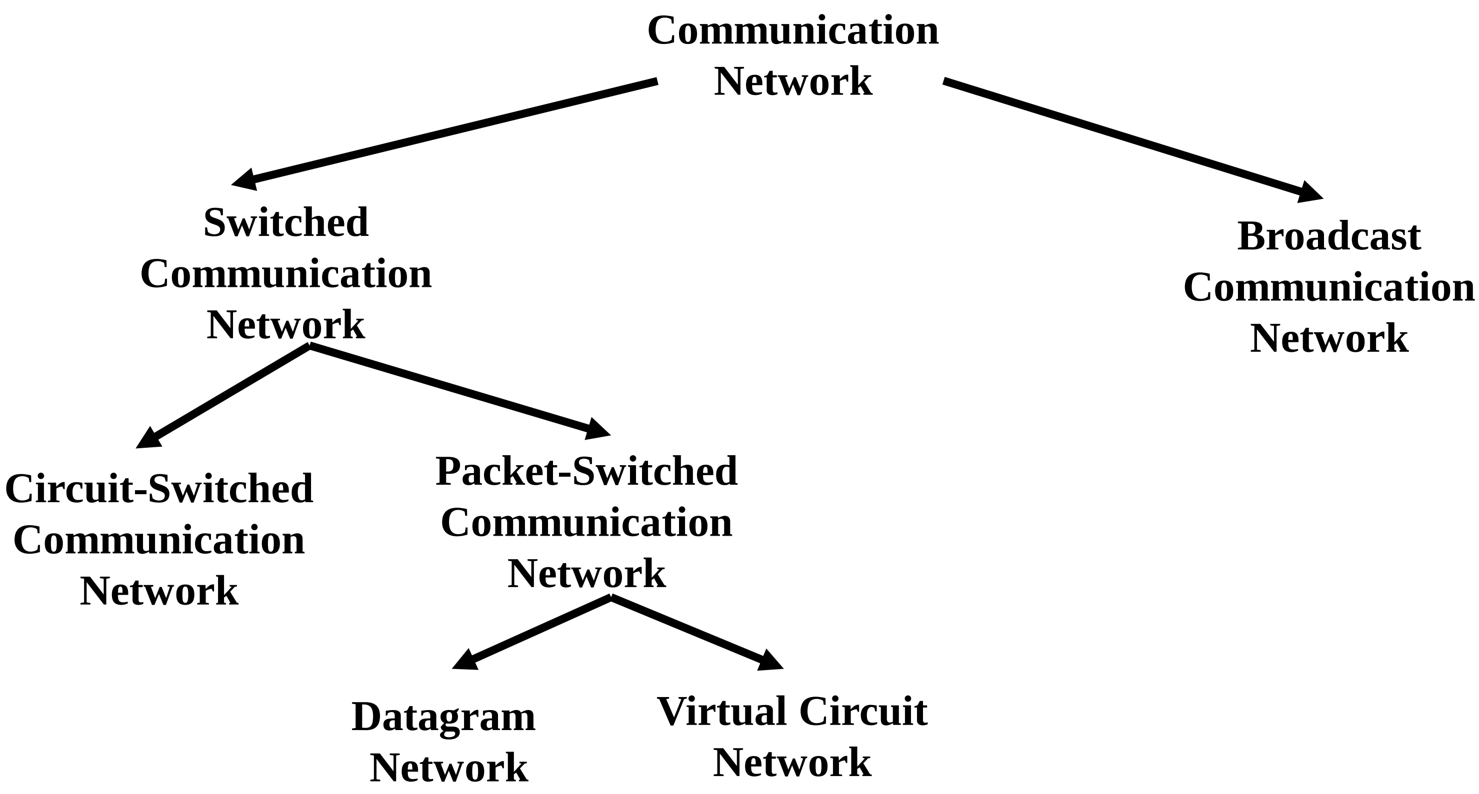
Outline

- Basics of switching
- Packet switching mechanisms
  - Datagram switching, virtual circuit switching
- Network performance
  - Throughput, delay, delay x bandwidth product, application needs

A Taxonomy of Communication Networks

- Based on the way in which nodes exchange information



Broadcast Networks

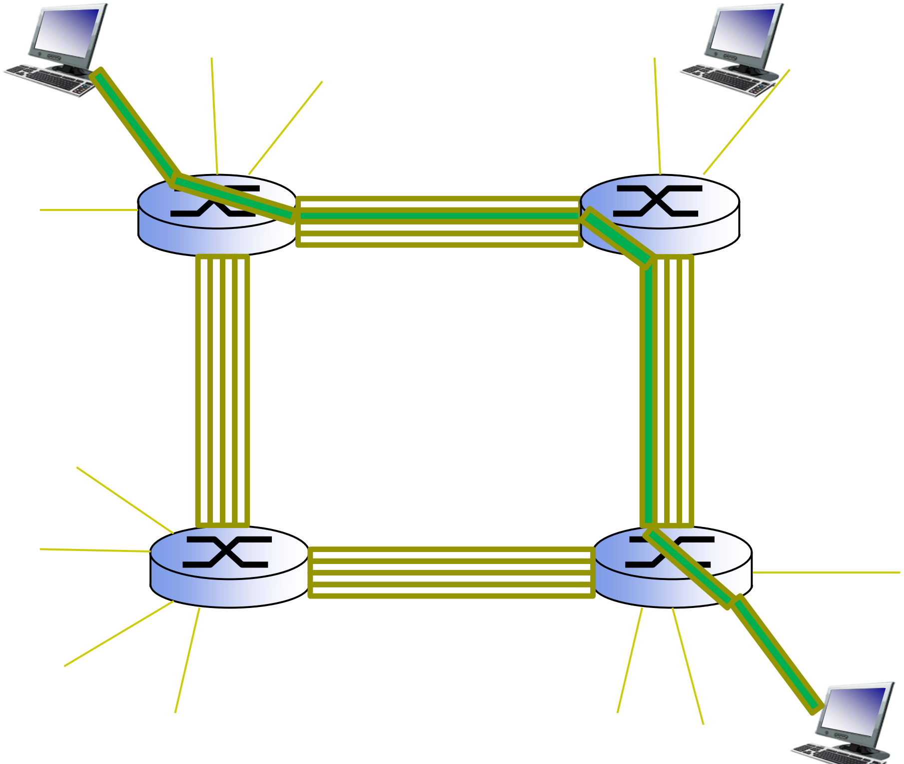
- Information sent by a node is broadcasted and hence received by every other node on the network
  - e.g., wireless LAN, shared Ethernet
- Inherent problem: how to coordinate the accesses of all nodes to the shared communications medium
  - Solution: Media Access Control (MAC) protocols
- Pros and cons
  - Low cost of deployment: few number of links and devices needed
  - Ease of usage and deployment (wireless only)
  - Limited capacity: total capacity determined by shared medium, and shared by all nodes
  - Limited coverage: caused by broadcasting
    - Local area networks (LANs), trunking communications networks

Switched Networks

- Information is transmitted to designated node(s), e.g., WANs (Telephony Network, Internet)
- Basic problem: how to forward information to intended node(s)
  - Basic idea: Design and deploy specialized nodes (e.g., routers, switches) for information delivery
- Pros and cons
  - High capacity: total capacity can be approximated with the sum of access link rates
  - Scalability: supports a large number of terminals
  - Large coverage: by adding new switches and links, able to spread around arbitrarily large geographic area
  - Cost-effectiveness: low cost per unit of capacity
  - Needs of infrastructure deployment: per-terminal links, switches

Circuit Switching

- Basics: network resources allocated to and reserved for "call" between source and destination
  - end-end resources (e.g., bandwidth) are divided into "pieces"
  - resource pieces allocated to calls
- How to divide link bandwidth into "pieces"
  - frequency division
  - time division

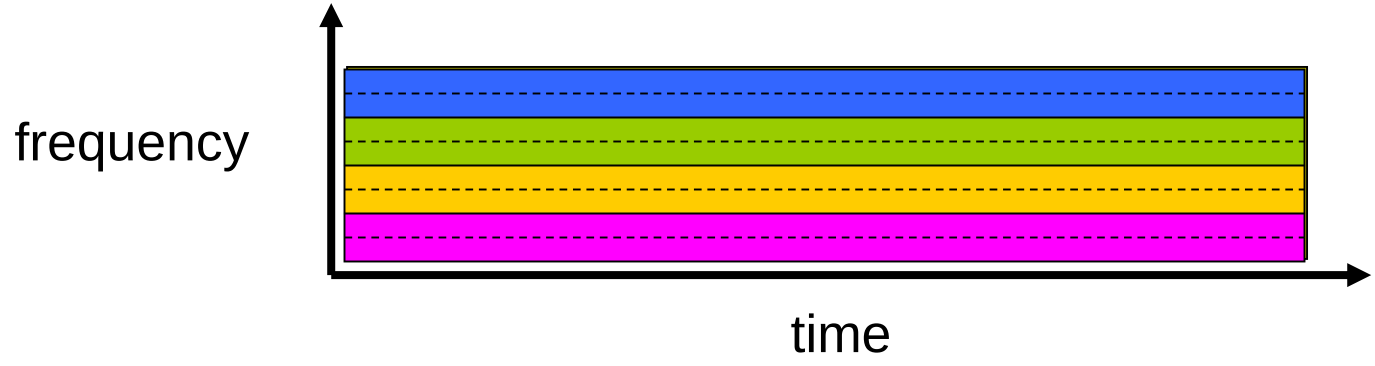


TDM, FDM

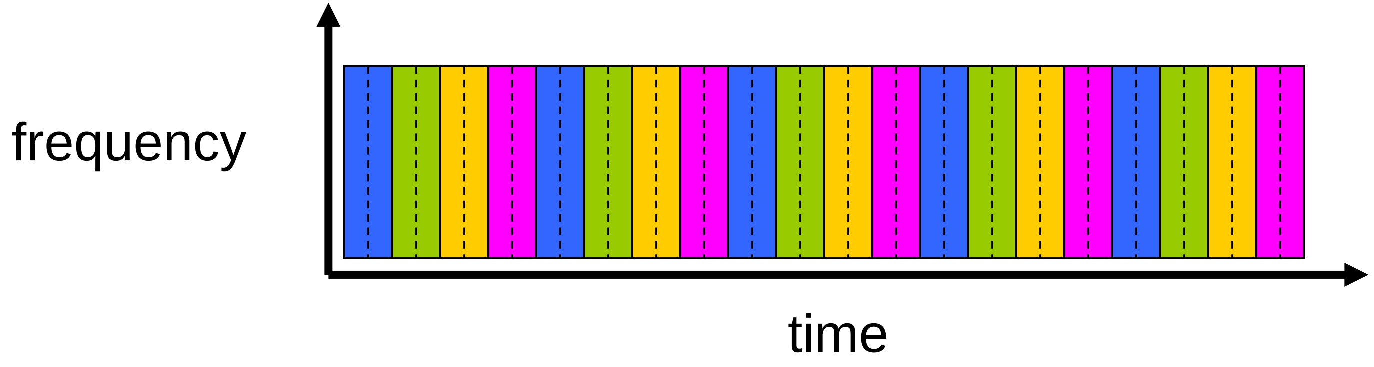
Example:

4 users

FDM: Frequency Division Multiplexing



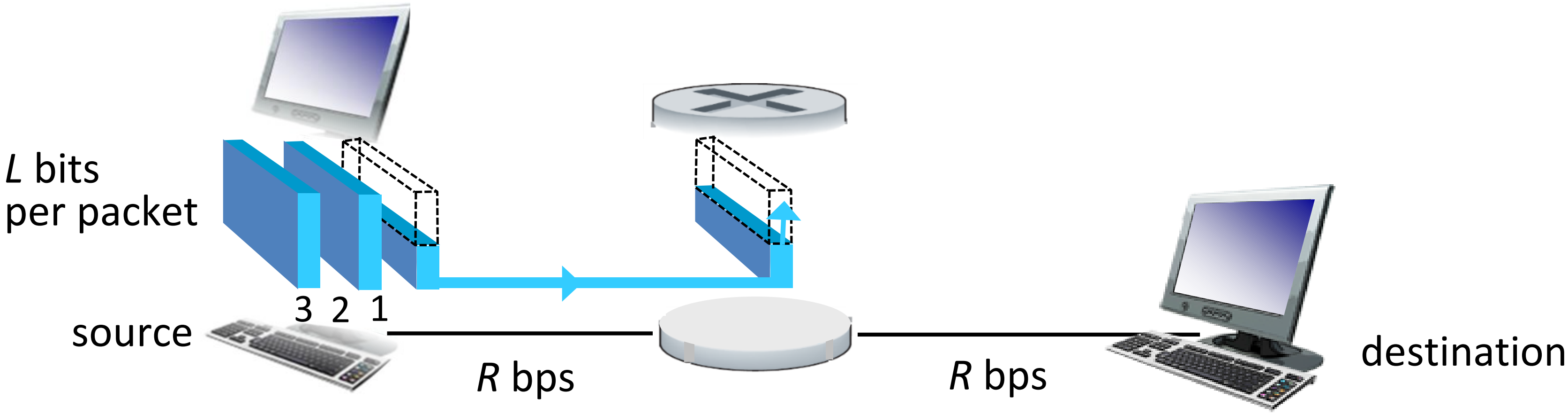
TDM: Time Division Mutlplexing



Circuit Switching: Resource Sharing

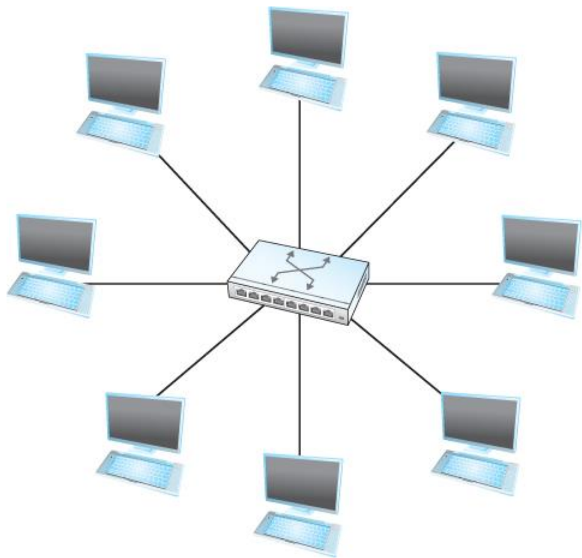
- TDM/FDM lead to deterministic resource occupations — deterministic multiplexing
  - while a sender has no data to send, its share of resource (time slot, or frequency band) remains idle, i.e., cannot be used by other senders
- The maximum number of resource pieces, e.g., time slots, is limited
  - only limited number of hosts can send data at a moment
- Remarks: not suitable for computer communications (usually quite burst!)

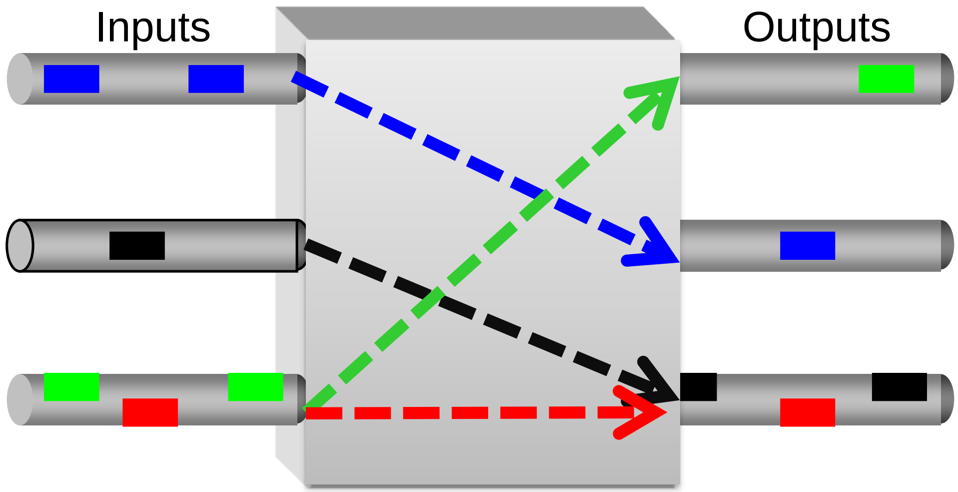
Packet Switching



- Basics
  - hosts break application messages into packets
  - packets are forwarded from one switch to the next, across links on path from source to destination
  - each packet is transmitted at full link capacity
- Store-and-forward
  - entire packet must arrive at a switch before it can be transmitted on next link

Determining Output Ports





- When forwarding packets, switch should determine appropriate output port(s) toward destination(s)
- Classification based on means of determining output ports
  - using switching table: datagram switching, virtual circuit switching
  - indicated by source: source routing

Packet Switching: Resource Sharing

- Network resource is shared on-demand by flows of packets — statistical multiplexing
  - a flow of packets has no fixed pattern
- Efficient network resource utilization
- Appropriate to burst computer communications
- Therefore, modern Advanced Computer Networking use packet switching

- Also causes two common problems
  - Network congestion: network links may get congested due to large number of packets injected shortly
  - Challenges of resource allocation to guarantee quality of service, required by some network applications, e.g., multimedia streaming

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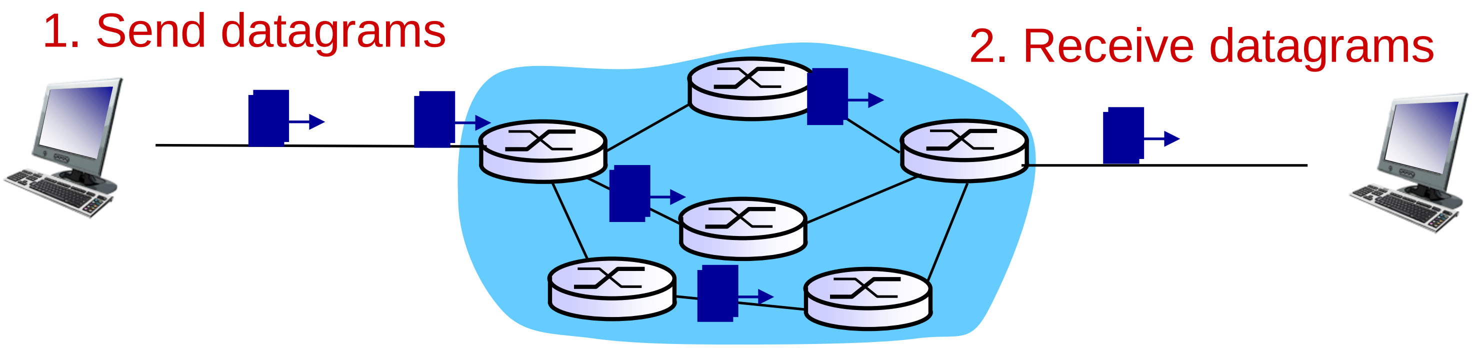
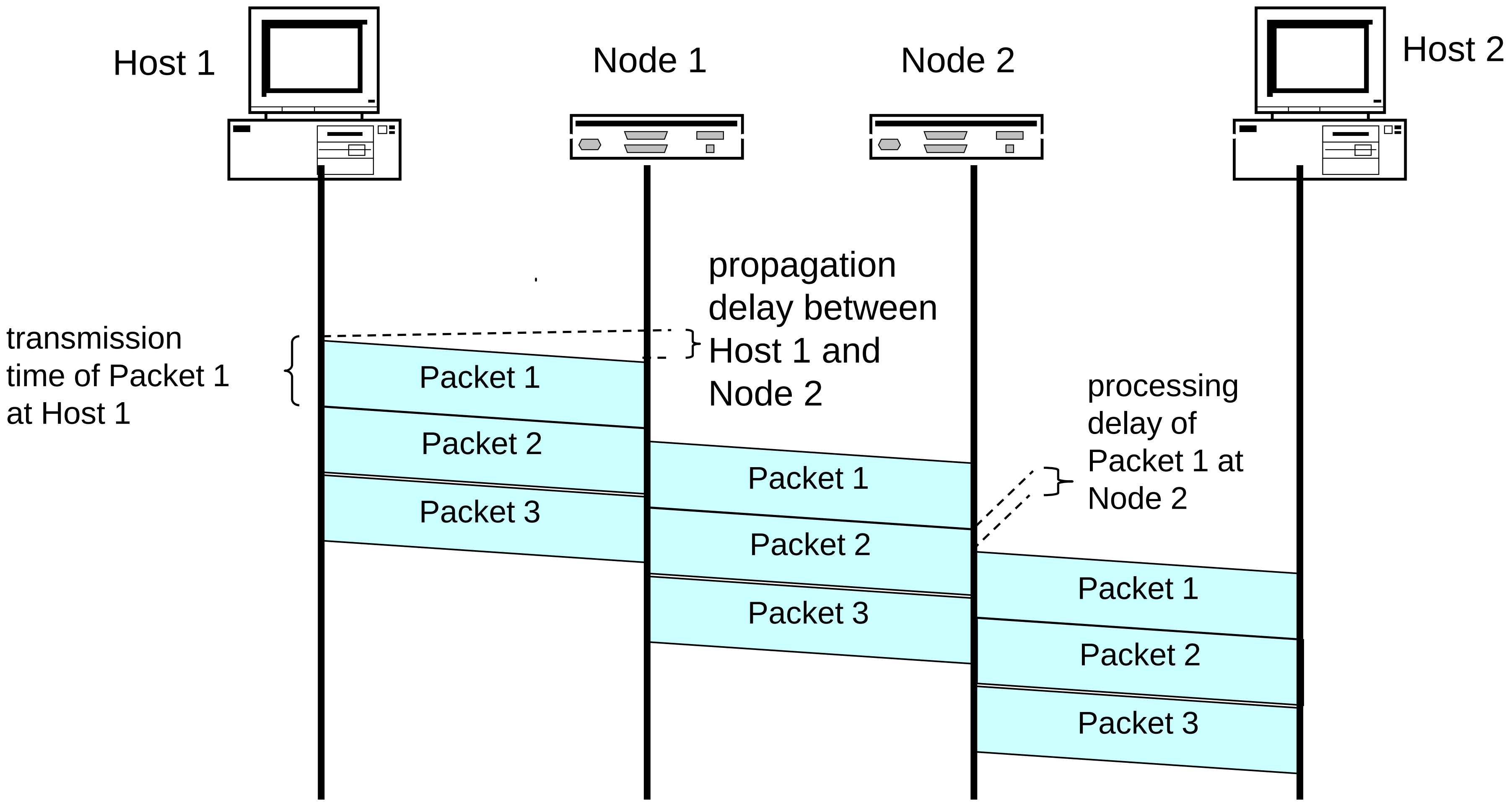
Datagram Switching

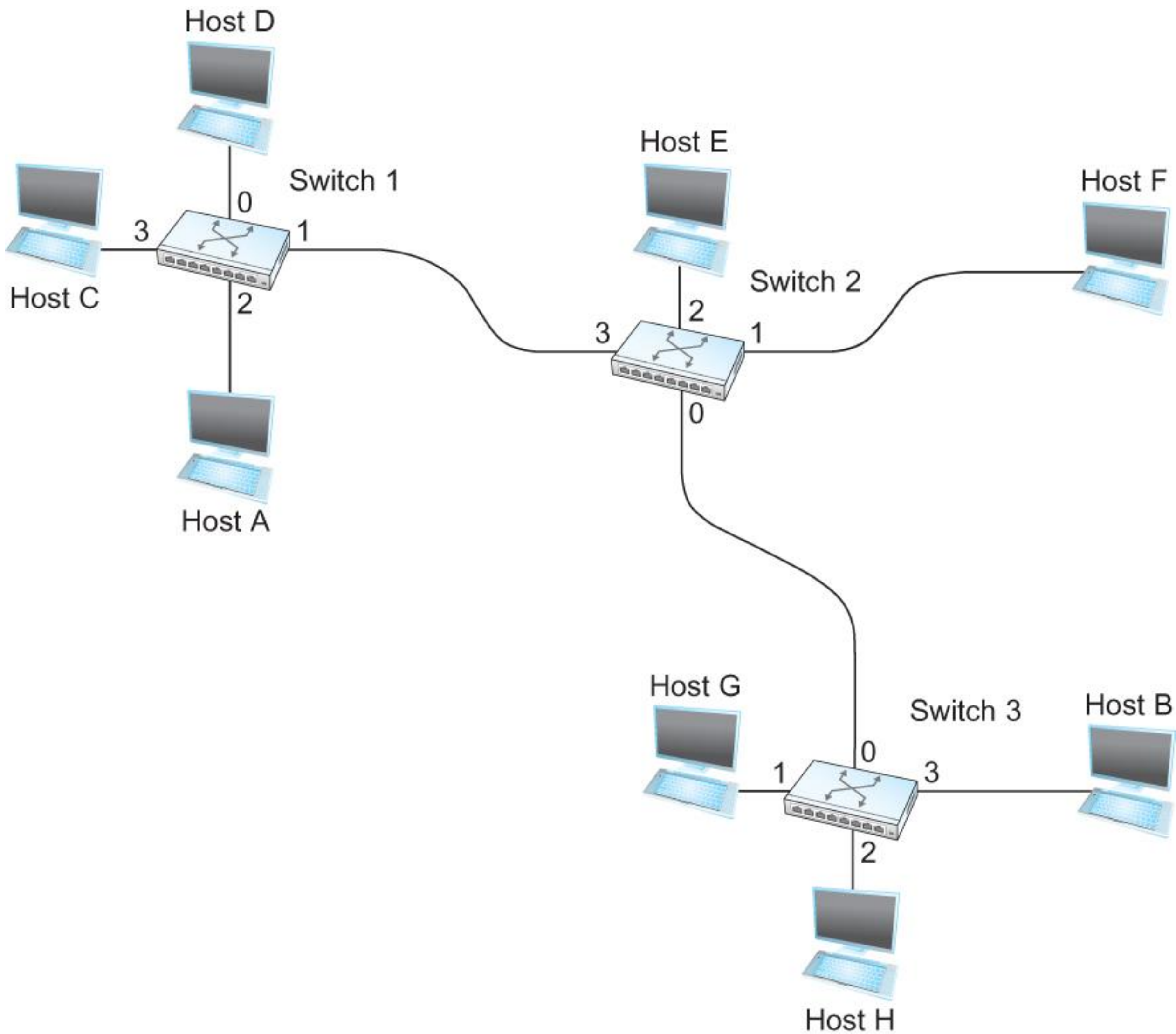


- A host can send packets anywhere at any time
  - Each packet (also referred to as datagram) contains complete destination address
- Upon receiving a packet, a switch
  - looks at the packet's destination address,
  - consults its switching table to determine output port,
  - and stores-and-forwards this packet
- Examples: switched Ethernet, IP networks

Datagram Switching: Timing



Datagram Switching Table: Example



Destination	Port
A	3
B	0
C	3
D	3
E	2
F	1
G	0
H	0

Switching table in switch 2

Datagram Forwarding Path

- All datagrams, even from the same source and to the same destination, are independently forwarded by the switches based on their switching tables

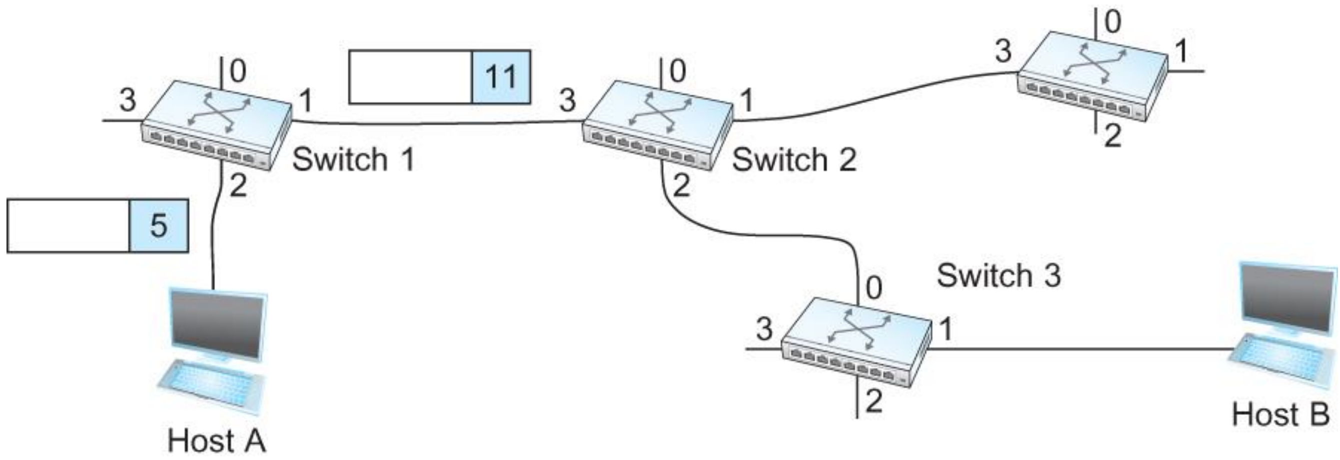
- Datagram forwarding paths are actually specified by corresponding entries in switches' switching tables

- Datagram switches run specific algorithms/protocols to build up their switching tables
  - Algorithms/protocols: how to figure out switching tables
  - Concerns: topology, …?

Features of Datagram Switching

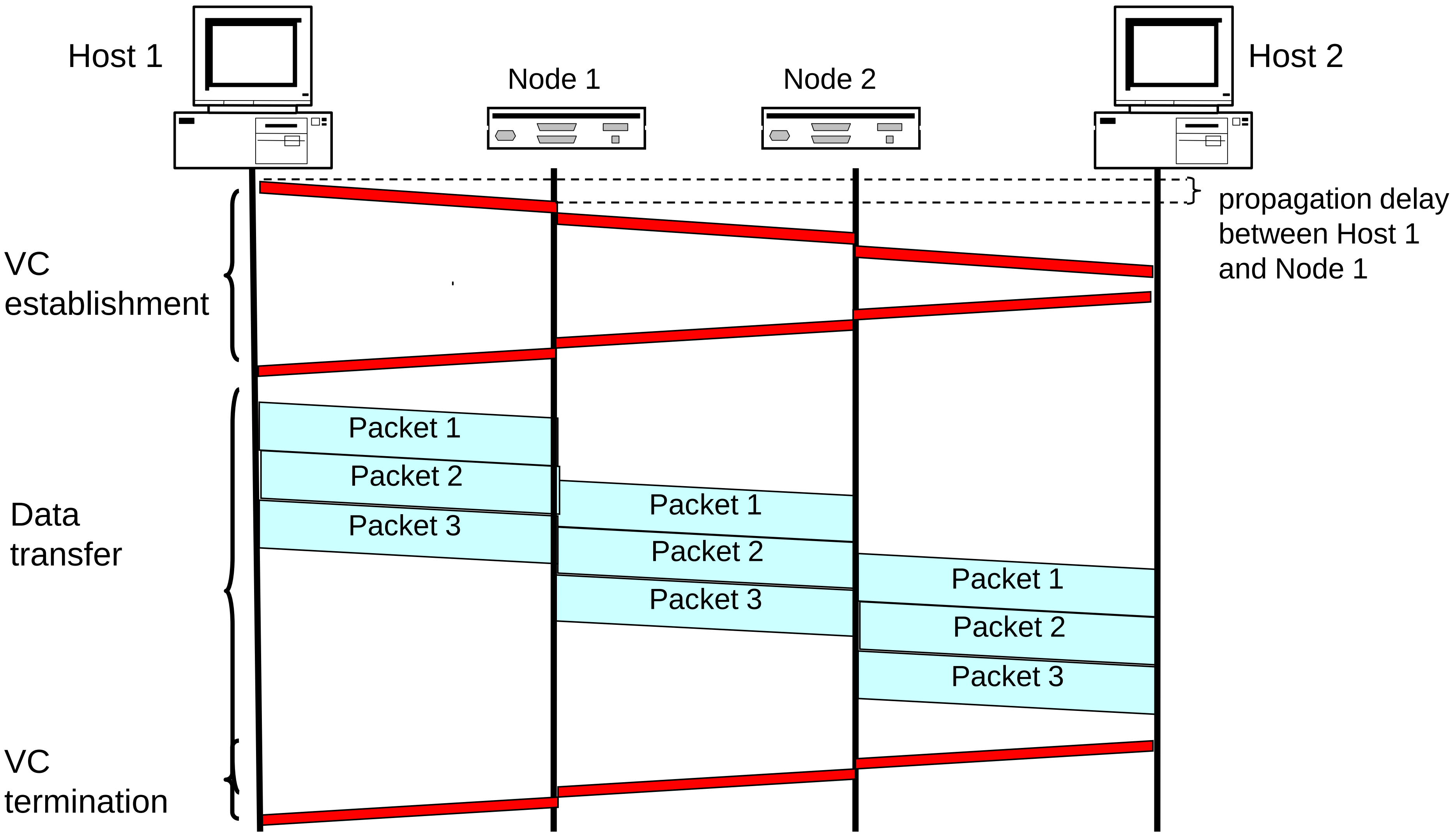
- Connectionless
  - No state information (associated with connections) maintained at a host/switch
- Per-packet processing (i.e., stateless)
  - All packets, even from the same source and to the same destination, are independently forwarded along their paths
- Effect of network failure
  - Failure of a switch or a link might not have any serious impacts on communications
- Hard to guarantee delivery service

Virtual Circuit Switching



- A connection, referred to as virtual circuit (VC), should be established between source and destination before data transfer
- Packets are forwarded along their VCs respectively
  - Each packet includes its virtual circuit identifier (VCI), other than complete destination address
  - Upon receiving a packet, a switch consults its VC table the packet's VCI, to determine output port, and stores-and-forwards this packet
- Examples: MPLS, ATM, Frame Relay, X.25

Virtual Circuit Switching: Timing



Virtual Circuit Table

- Each entry includes four fields
  - incoming interface
  - incoming virtual circuit identifier (VCI)
  - outgoing interface
  - outgoing VCI
- VCI has local significance only on a given link, not globally significant for the VC
- Pair <incoming interface, incoming VCI> uniquely identifies a specific VC through a switch

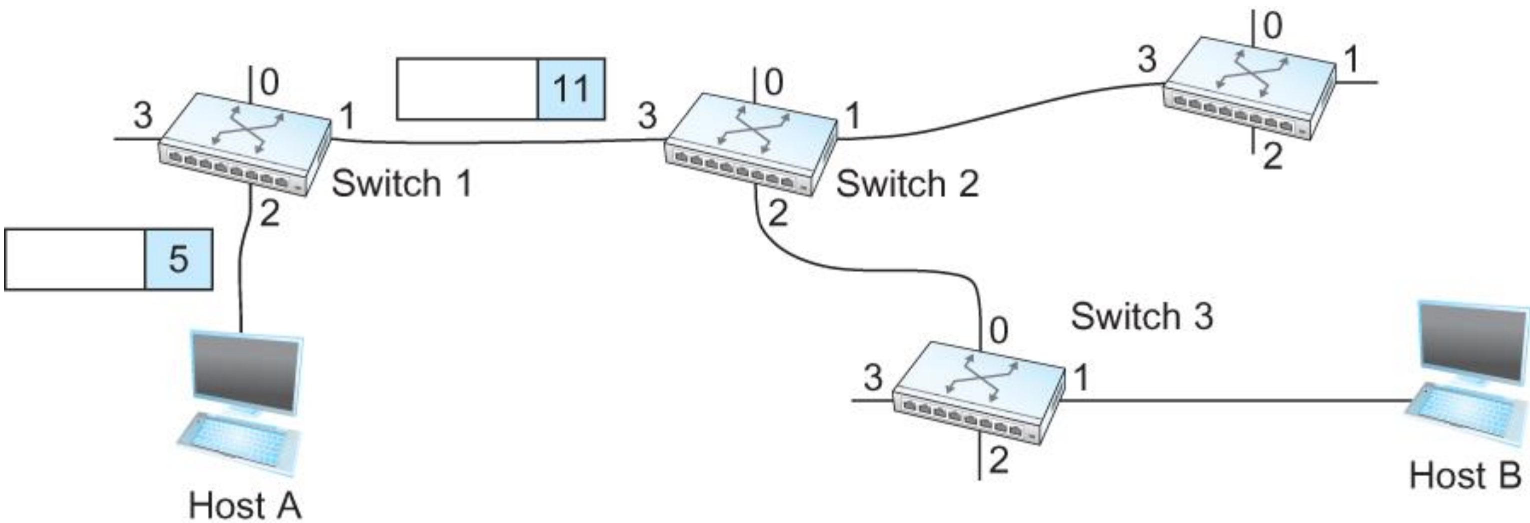
Virtual Circuit Table: Example

VC table in switch 1

IfIn	VCIIn	IfOut	VCIOut
2	5	1	11
…	…	…	…

VC table in switch 2

IfIn	VCIIn	IfOut	VCIOut
3	11	2	7
…	…	…	…



IfIn	VCIIn	IfOut	VCIOut
0	7	1	4
…	…	…	…

VC table in switch 3

Virtual Circuits

- Two types
  - permanent virtual circuits (PVC)
  - switched virtual circuits (SVC)

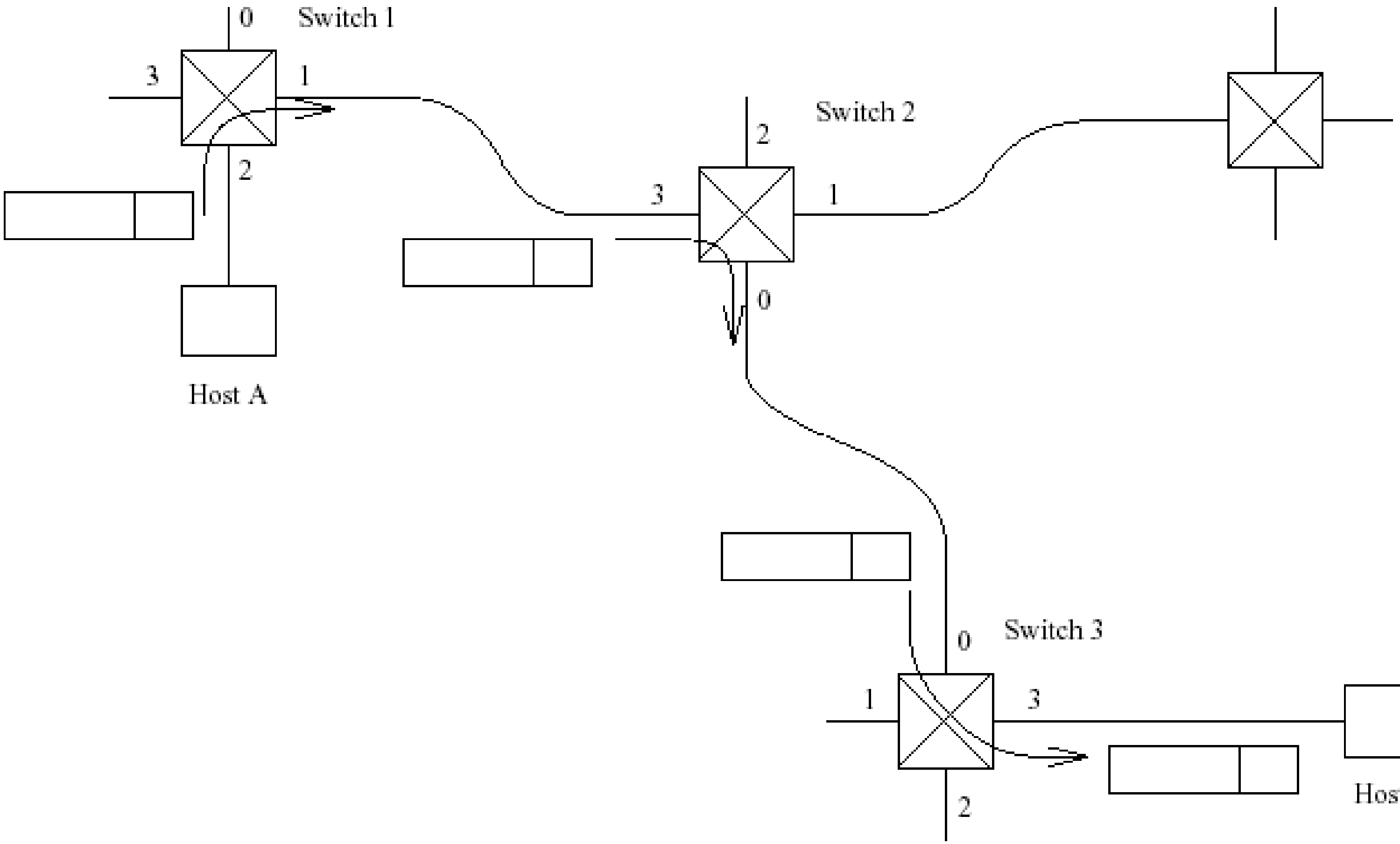
- PVC
  - manually set up by network administrator, or signaling started by network administrator
  - long-lived

- SVC
  - dynamically set up by signaling started by a host
  - short-lived

SVC Setup Process

- Source host
  - sends a setup message, which includes complete address of destination
- Intermediate switches
  - note port number over which the setup message arrives
  - choose an unused VCI number
  - determine the output port number
  - create an entry in the VC table
  - forward the setup message to downstream switch
- Destination host
  - chooses an available VCI value
  - sends acknowledgement message along the reverse path
- Intermediate switches
  - complete the VC table entry

SVC Setup: Example



Packet Forwarding Path and VC

- Packets are forwarded by the switches based on their VC tables
  - each packet is associated with a specific VC, indicated by the VCI in packet header
- VC is a logical connection
  - expressed by a concatenation of pairs <incoming interface., incoming VCI> stored in VC tables at the switches VC traverses
  - indicating the forwarding path of associated packets within a network
- When establishing a VC, switches should determine where to place it, i.e., what next switch to take
  - The problem here is similar to the one with datagram switching network in building up its switching table

Features of Virtual Circuit Switching

- Connection-oriented
  - state information (VCs) maintained at a node
  - a host waits at least one RTT for connection setup before sending first data packet

- Each packet is related with a VC, and forwarded along the path specified by this VC

- Effect of network failure
  - switch/link failure results in all VCs over it broken

- Feasible to reserve network resource for delivering the packets of a connection (VC), and consequently to guarantee some level of service

Outline

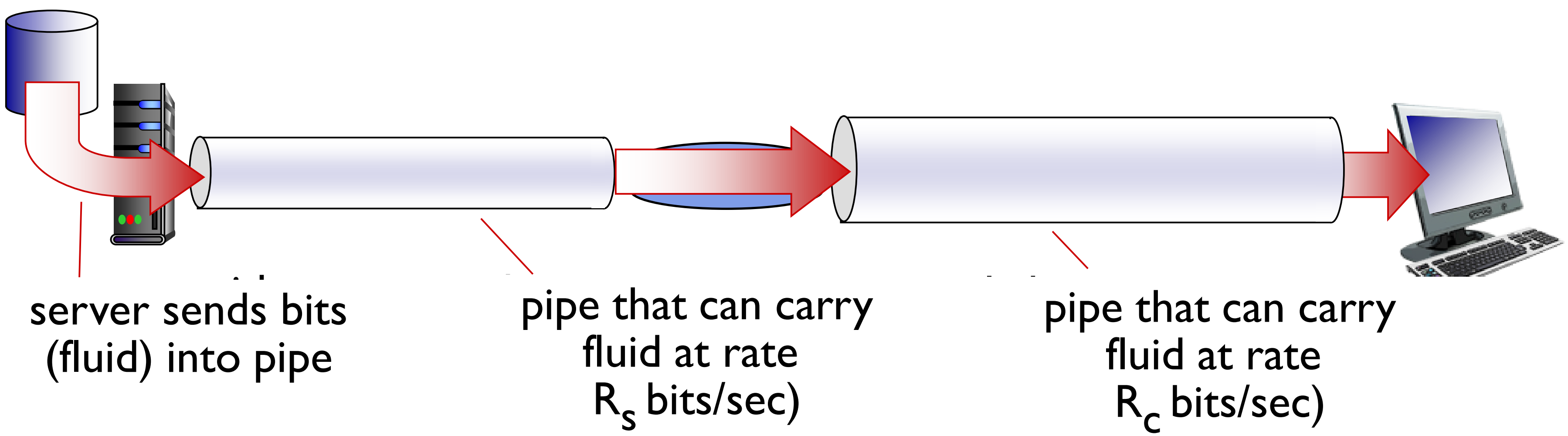
- Basics of switching

- Packet switching mechanisms
  - Datagram switching, virtual circuit switching

- Network performance
  - Throughput, delay, delay x bandwidth product, application needs

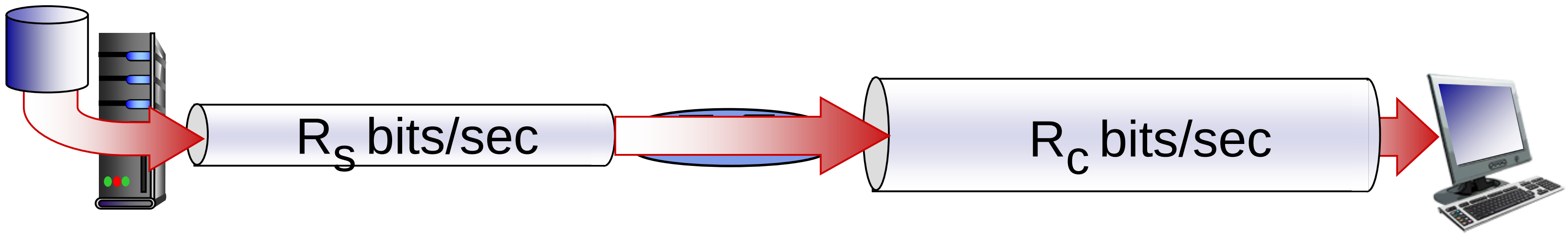
Flow Throughput

- Flow throughput: rate (bits/time unit) at which bits transferred between sender and receiver
  - instantaneous: rate at given point in time
  - average: rate over long(er) period of time



Flow Throughput (cont.)

- $R_s < R_c$ What is average end-to-end throughput?



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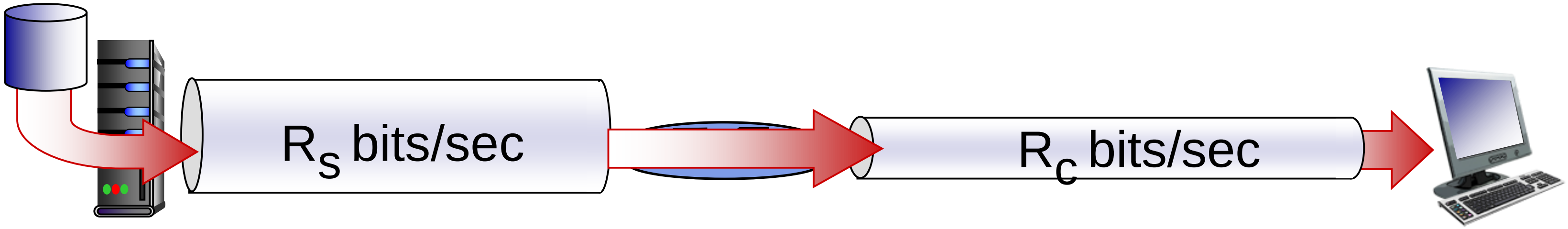
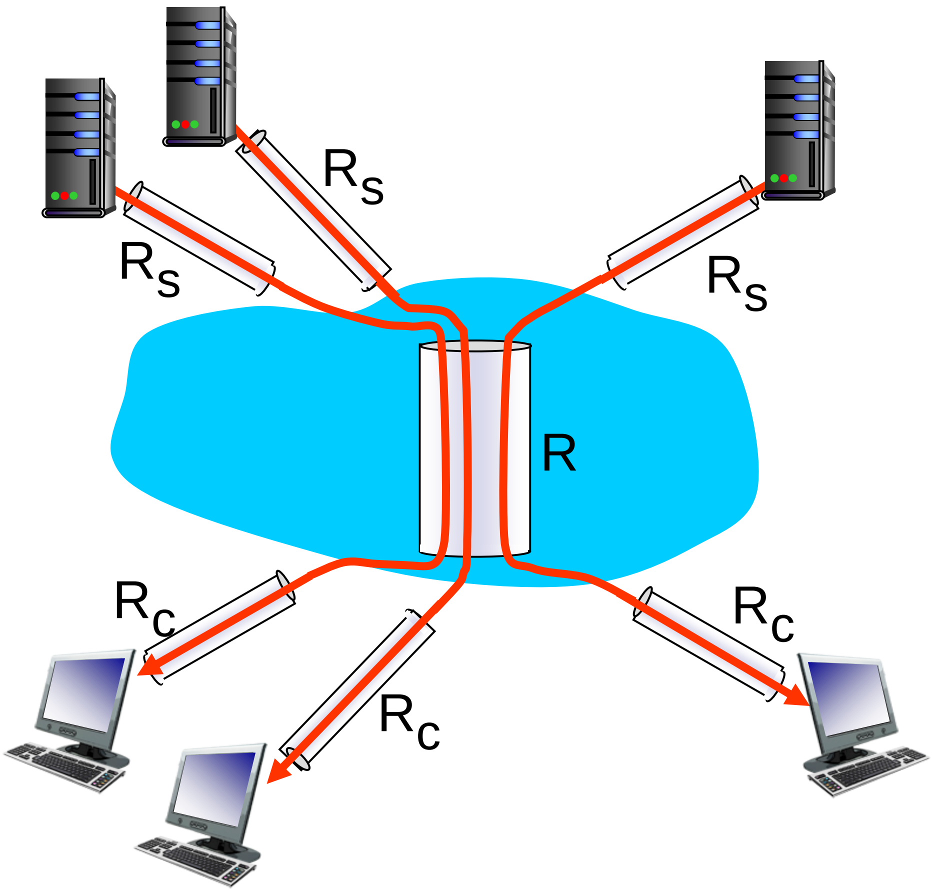


bottleneck link

link on end-end path that constrains end-end throughput

Flow Throughput: Network Scenario

- Per-flow throughput: $\min(R_c, R_s, R/10)$
- In practice
  - Backbone links' rates are very high, and access links' rates are low, i.e., R_c or R_s is often bottleneck



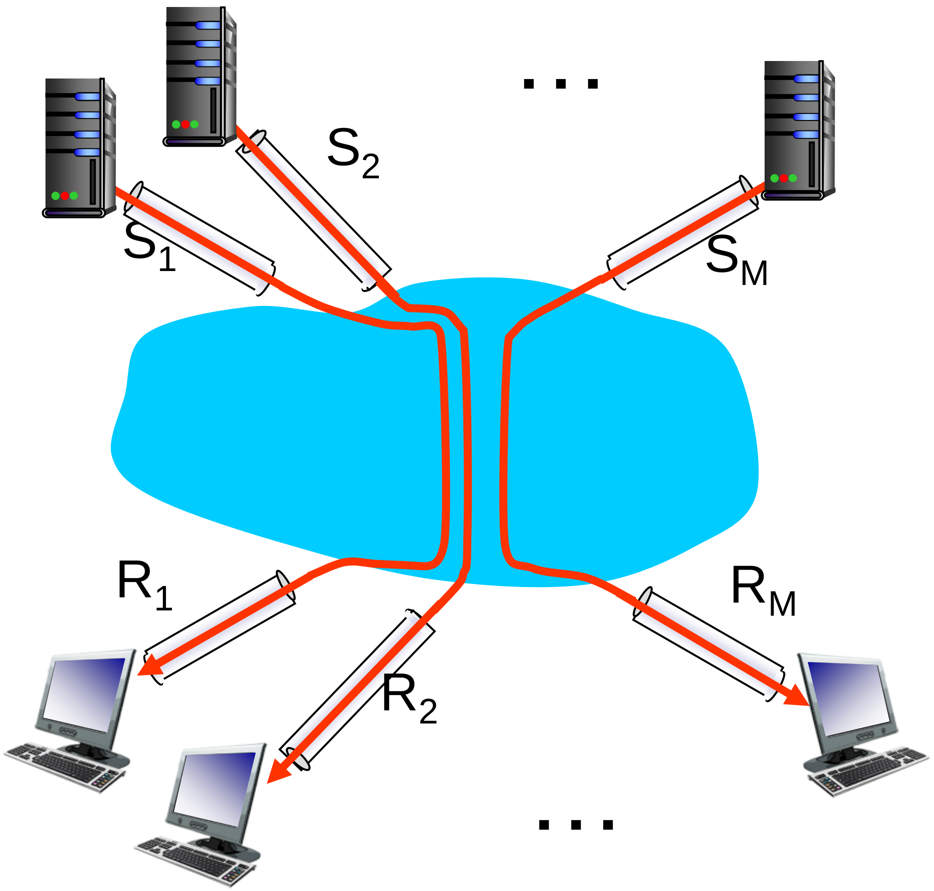
10 flows (fairly) share backbone bottleneck link R bits/sec

Network Throughput

- Network throughput: sum of output rates of all end-to-end flows in a network

  $\Sigma_i R_i$

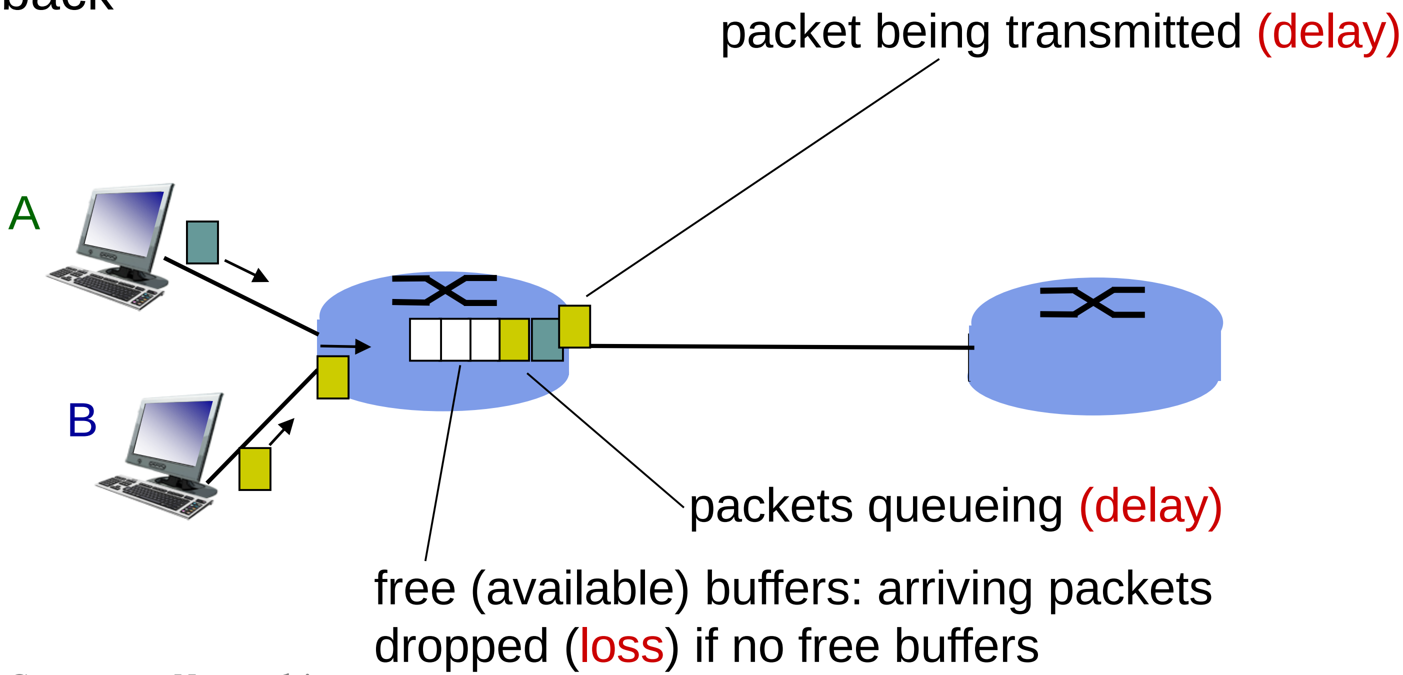
- Factors that influence network throughput?



M end-to-end packet flows

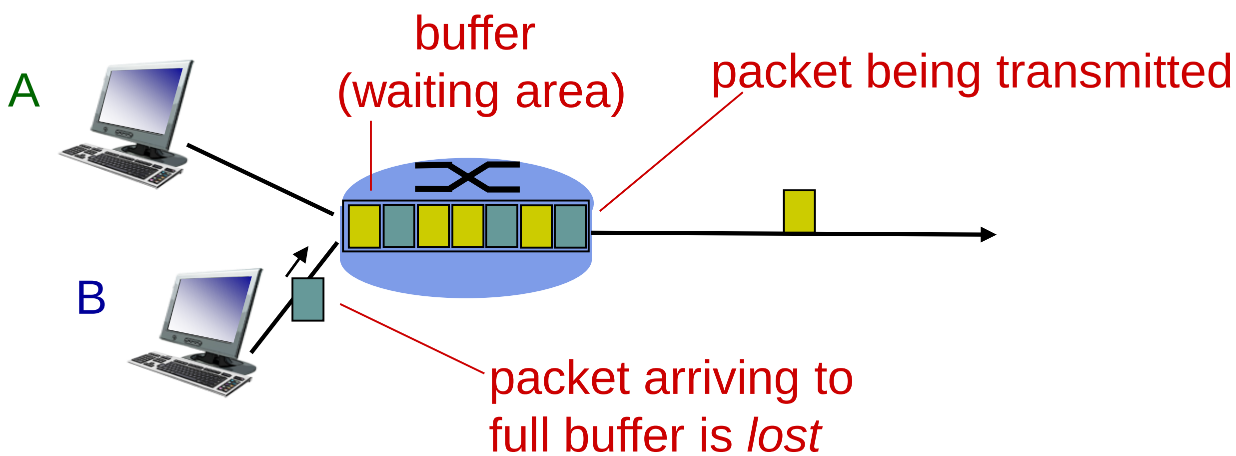
Delay

- Packets queue in switch buffers, i.e., store-and-forward
  - packet arrival rate exceeds output link capacity
  - packets queue, wait for turn
- Packet delay: how long it takes a packet to travel from one end of network to the other
- Round-Trip Time (RTT): two-way delay from sender to receiver and back



Packet Loss

- Queue preceding link in buffer has finite capacity
- Packet arriving to full queue dropped
- Lost packet may be retransmitted by previous node, by source end system, or not at all



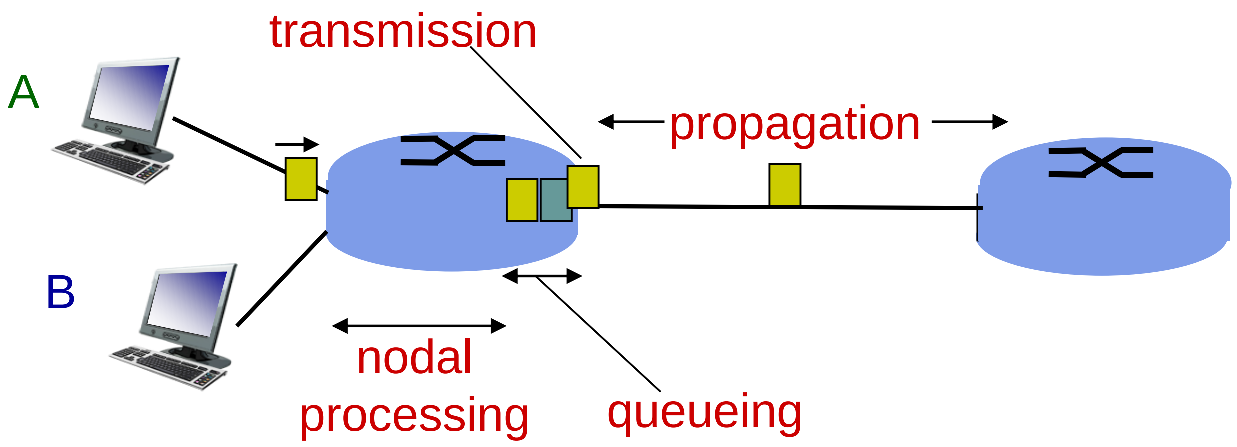
Sources of Delay

1. Nodal processing

- check bit errors
- determine output link

2. Queueing

- time waiting at output link for transmission
- depends on congestion level of router



Sources of Delay (cont.)

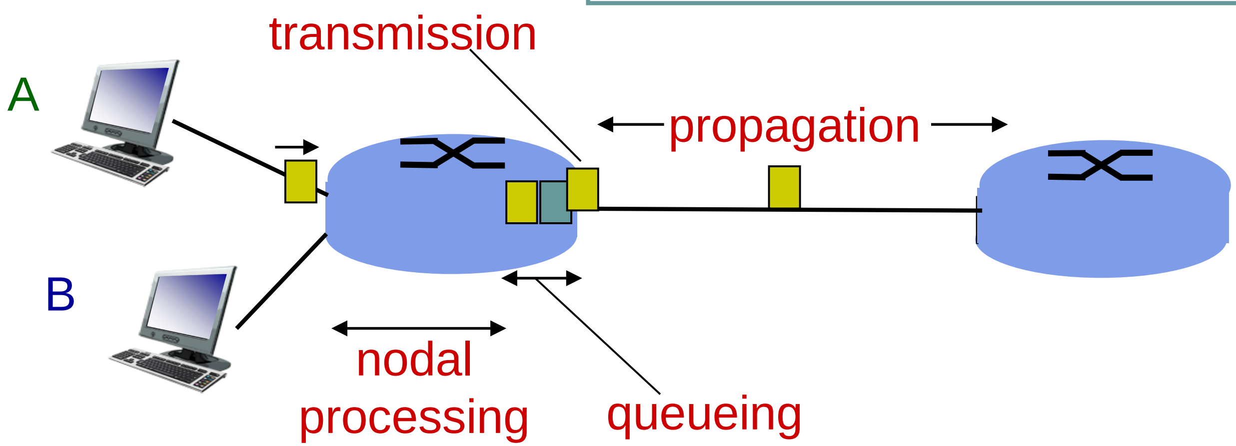
3. Transmission delay

- R = link bandwidth (bps)
- L = packet length (bits)
- time to send bits into link = L/R

4. Propagation delay

- d = length of physical link
- s = propagation speed in medium (~2×10^8 m/sec)
- propagation delay = d/s

Note: s and R are very different quantities!



Nodal Delay

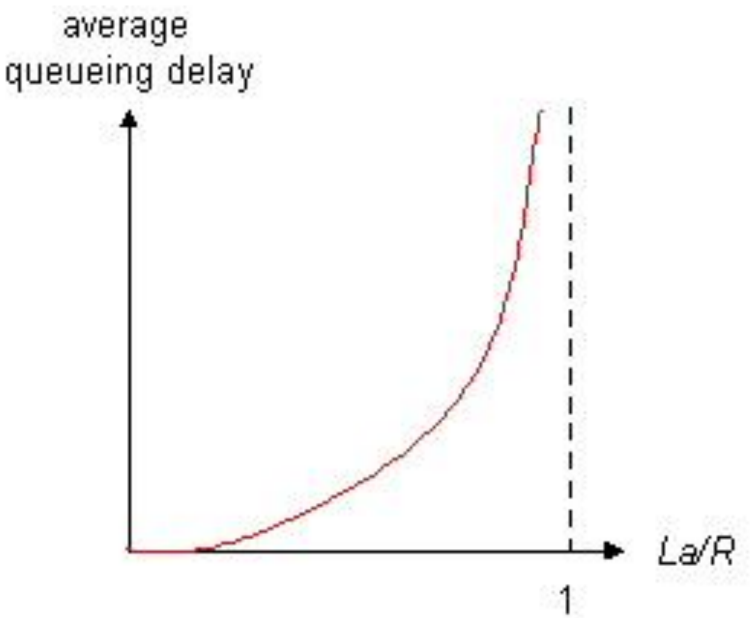
$$\boxed{d_{\text{nodal}} = d_{\text{proc}} + d_{\text{queue}} + d_{\text{trans}} + d_{\text{prop}}}$$

- d_{proc} = processing delay (usually omitted!)
  - typically a few microsecs or less
- d_{queue} = queuing delay
  - depends on congestion
- d_{trans} = transmission delay
  - = L/R, significant for low-speed links
- d_{prop} = propagation delay
  - a few microsecs to hundreds of msecs

Queueing Delay

- R = link bandwidth (bps)
- L = packet length (bits)
- a = average packet arrival rate

traffic intensity = La/R



- La/R ~ 0: average queueing delay small
- La/R -> 1: delays become large
- La/R > 1: more "work" arriving than can be serviced, average delay infinite!

Influence of Bandwidth and Delay

- Effective flow throughput from application's point of view
  - Transfer time = transfer size / bandwidth + RTT
  - Throughput = transfer size / transfer time
  - Example: 1MB file transferred across 1Gbps link with 100ms RTT, throughput?

- Network throughput
  - larger amount of data (from various end-to-end sessions) multiplexed, more efficient utilization of network resource

- High-speed network
  - higher speed, faster transmission of large amount of data
  - however, propagation delay is limited by physical law

Needs of Applications

- Variance of bandwidth requirement
  - average rate and burst
  - example: streaming compressed video
- Problems caused by rate variance
  - congestion, packet loss due to buffer overflow
  - solution: optimized design/allocation of buffer capacity/space
- Delay jitter
  - variation of delay, caused by the variance of queuing delay
- Problem caused by jitter
  - not smooth (especially for multimedia applications)
  - solution for playback application: delaying and buffering at destination host
    - but not complete for interactive multimedia and live streaming

Summary

- Basics of packet switching
  - Fundamentals of datagram switching, virtual circuit switching
- Performance of packet-switched network
  - Throughput, latency, loss, application needs

- References

  - Sec. 1.2, 1.5, textbook

  - Sec. 1.4, [KR12]