Problem: not all networks are directly connected

Limitations of directly connected networks:

- limit on the number of hosts supportable
- limit on the geographic span of the network

Packet Switching

Hongwei Zhang

http://www.cs.wayne.edu/~hzhang

Nature seems … to reach her ends by long circuitous routes.

--- Rudolph Lotze

Acknowledgement: this lecture is partially based on the slides of Dr. Larry Peterson

Outline

- Switching and Forwarding
- Bridges and Extended LANs
- Cell Switching

- Implementation
- Discussion

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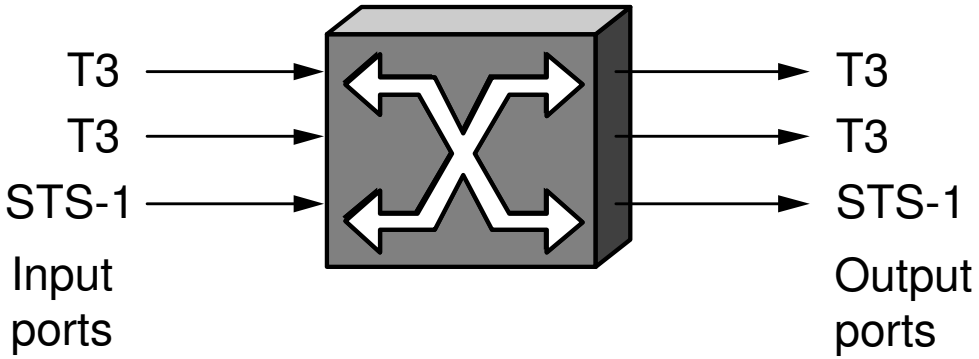
Scalable Networks using switches

- Switch
  - forwards packets from input port to output port
  - port selected based on address in packet header

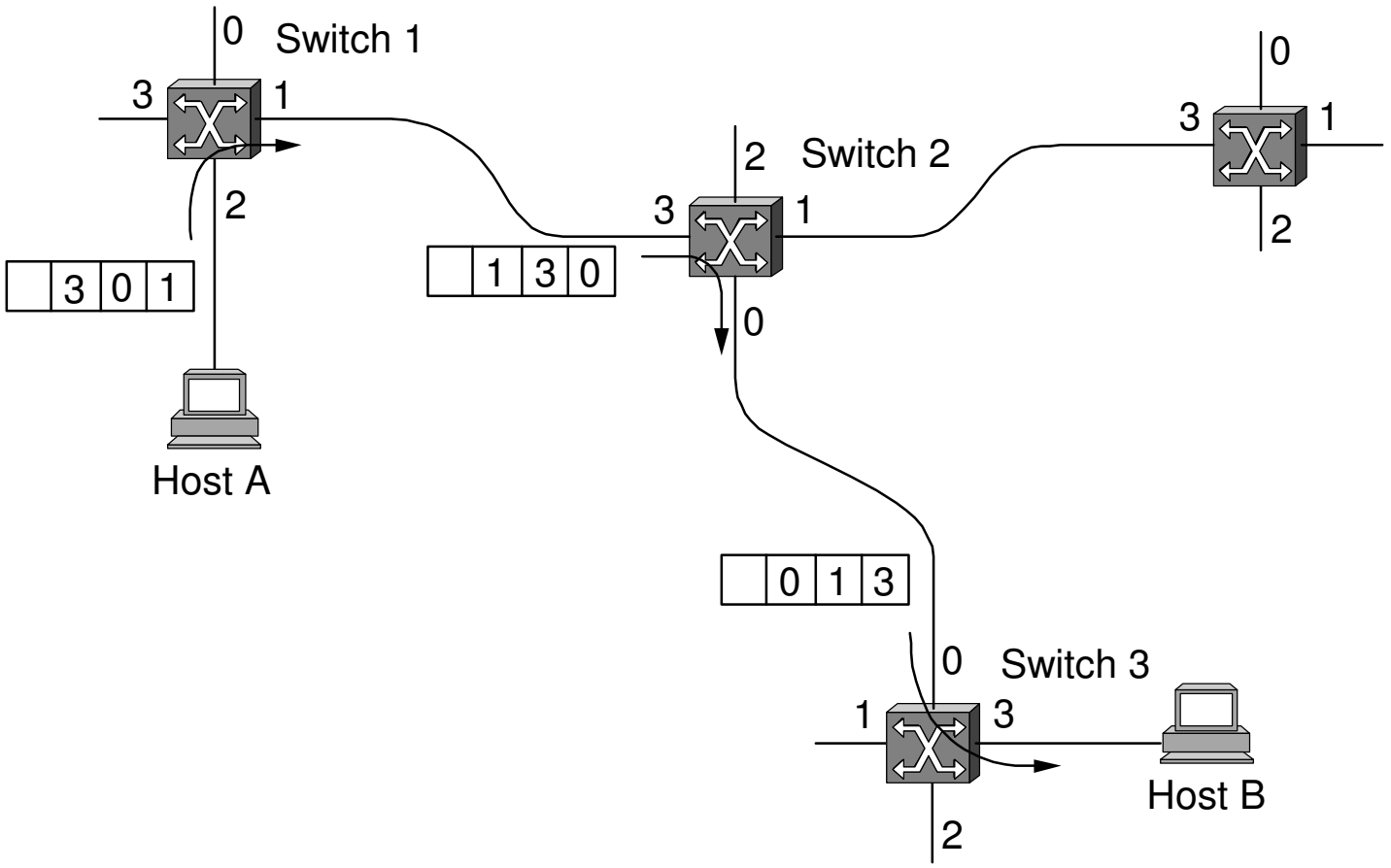


- Advantages
  - support large numbers of hosts (scalable bandwidth)
  - cover large geographic area (tolerate latency)

Problem statement

- Given a multi-hop network where nodes may not be directly connected, *how does a switch decide where (e.g., which output port) to forward each packet*?

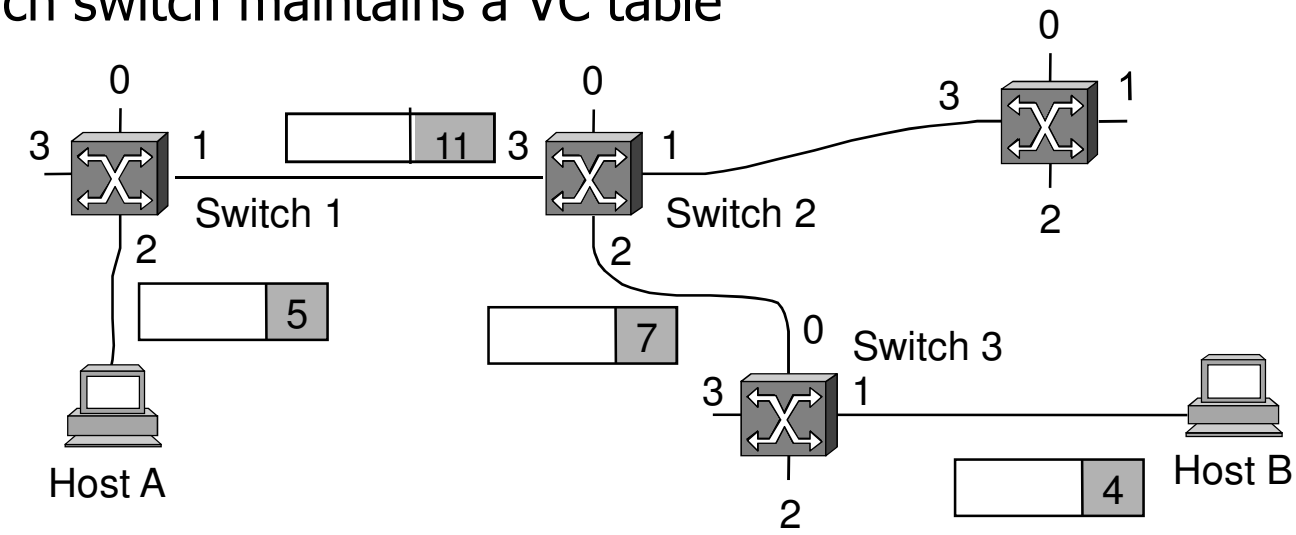
Source Routing



Host A -→ Host B

Virtual Circuit Switching

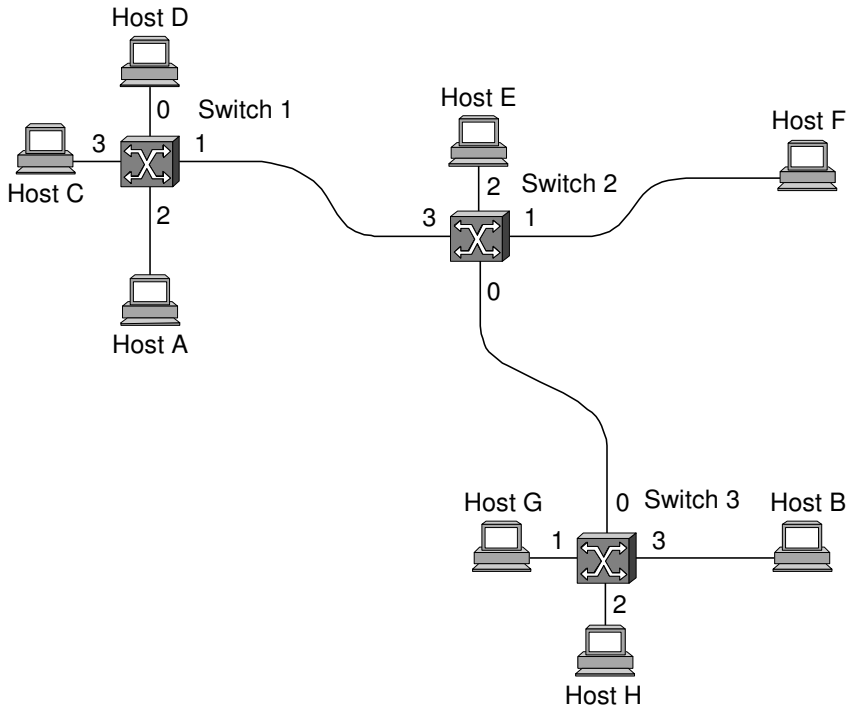
- Explicit connection setup (and tear-down) phase
- Subsequence packets follow same circuit
- Sometimes called *connection-oriented* model
- Analogy: phone call
- Each switch maintains a VC table



Q: how does VC Switching differ from Circuit Switching?

Datagram Switching

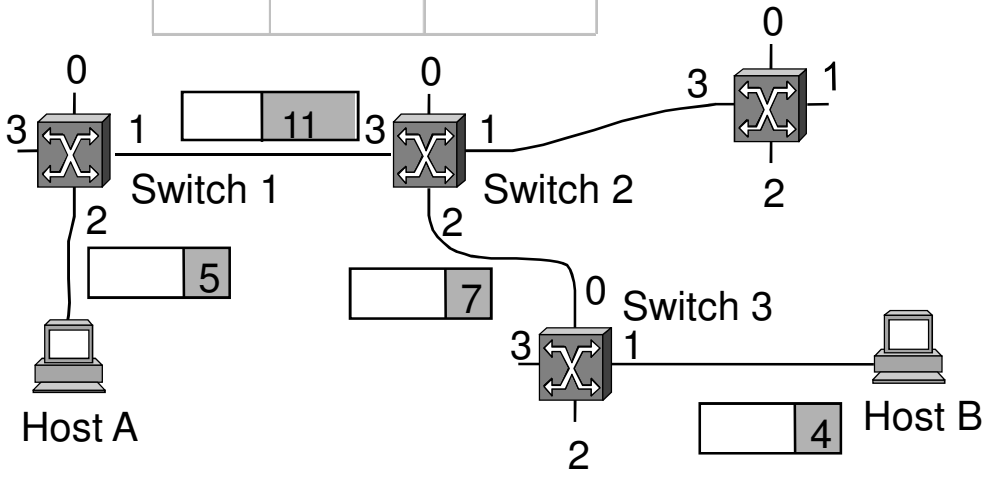
- No connection setup phase
- Each packet forwarded independently
- Sometimes called *connectionless* model
- Analogy: postal system
- Each switch maintains a forwarding (routing) table



Example Tables

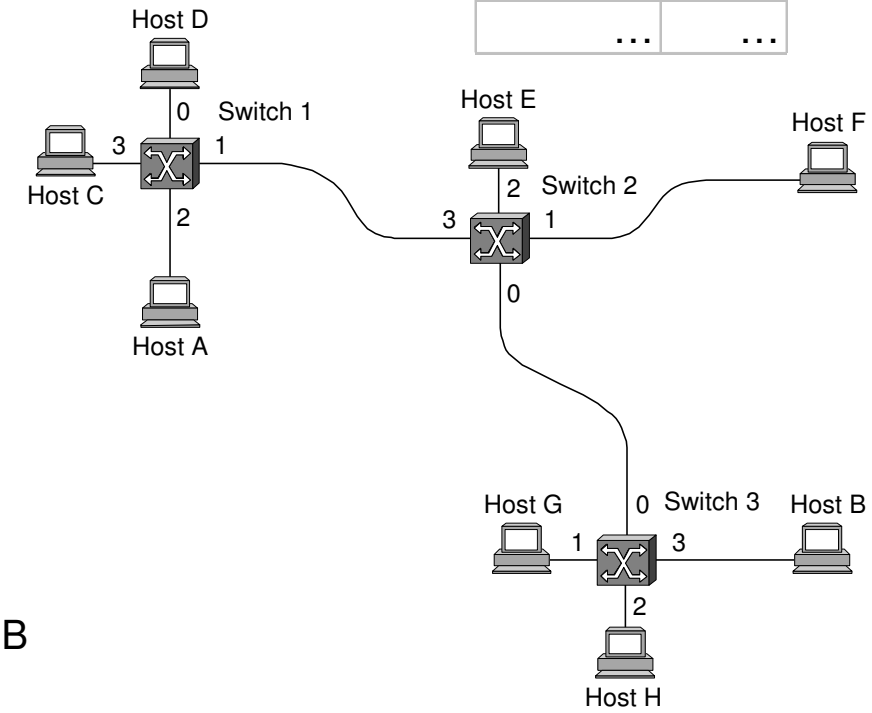
- Circuit Table (switch 1, port 2)

VC In	VC Out	Port Out
5	11	1
6	8	1
…	…	…



- Forwarding Table (switch 1)

Address	Port
A	2
C	3
F	1
G	1
…	…



Virtual Circuit Model

- (+) Connection setup provides an opportunity to reserve resources.
- (+) While the connection request contains the full address for destination, each data packet contains only a small identifier, making the per-packet header overhead small.
- (-) Typically wait full RTT for connection setup before sending first data packet.
- (-) If a switch or a link in a connection fails, the connection is broken and a new one needs to be established.

VC model: systems

- X.25
  - Buffer allocated during connection setup phase
    - Circuit is rejected if a node does not have enough buffers at the time of connection setup
  - *Hop-by-hop* flow control: "sliding window protocol + flow control" between each pair of nodes along a circuit
- Frame Relay:
  - Permanent Virtual Circuit (PVC) => virtual private networks (VPNs)
  - Basic QoS and congestion avoidance, but rather lightweight compared to X.25 and ATM
- Asynchronous Transfer Mode (ATM)
- GMPLS: Generalized Multi-Protocol Label Switching

Datagram Model

- (+) There is no round trip delay waiting for connection setup; a host can send data as soon as it is ready.
- (+) Since packets are treated independently, it is possible to route around link and node failures
- (-) Source host has no way of knowing if the network is capable of delivering a packet or if the destination host is even up.
- (-) Since every packet must carry the full address of the destination, the overhead per packet is higher than for the connection-oriented model.

Outline

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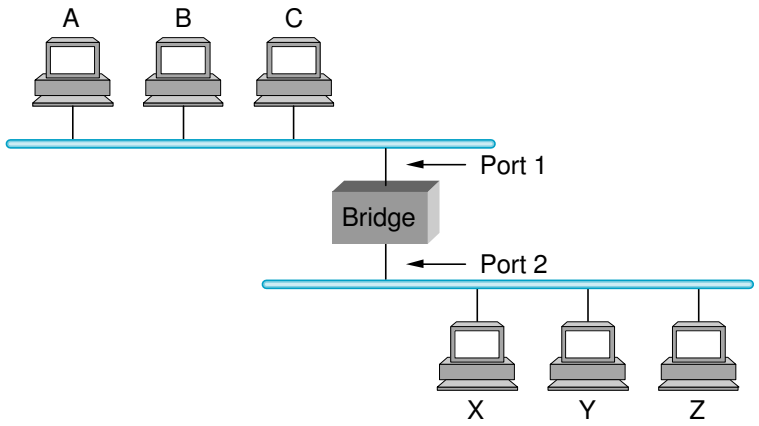
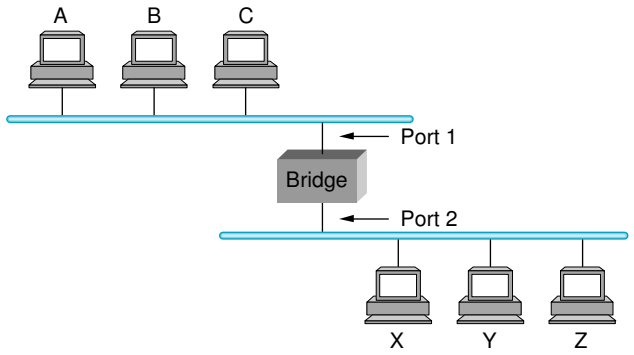
Bridges and Extended LANs

- LANs have physical limitations (e.g., 4 repeaters, 2500m)
- Connect two or more LANs with a *bridge*
  - accept and forward strategy
  - level 2 connection (does not add packet header)



Learning Bridges

- Do not forward when unnecessary
- Maintain forwarding table

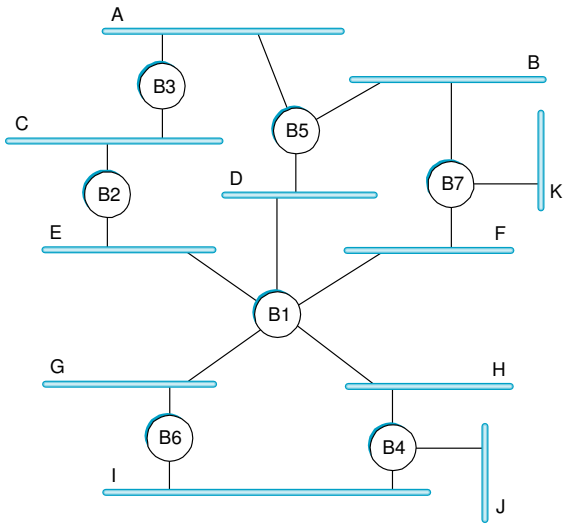


Host	Port
A	1
B	1
C	1
X	2
Y	2
Z	2

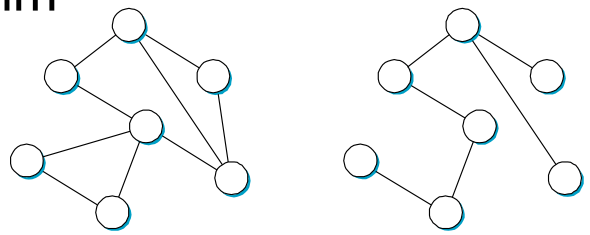
- Learn table entries based on *source address*
- Table is an optimization; need not be complete
  - Will learn a route to a node only *after* seeing a packet from the node
- Always forward broadcast frames

Spanning Tree Algorithm

- Problem: broadcast storm as a result of loops (because of the initial broadcast before learning the route to a node)
  - Q: how?

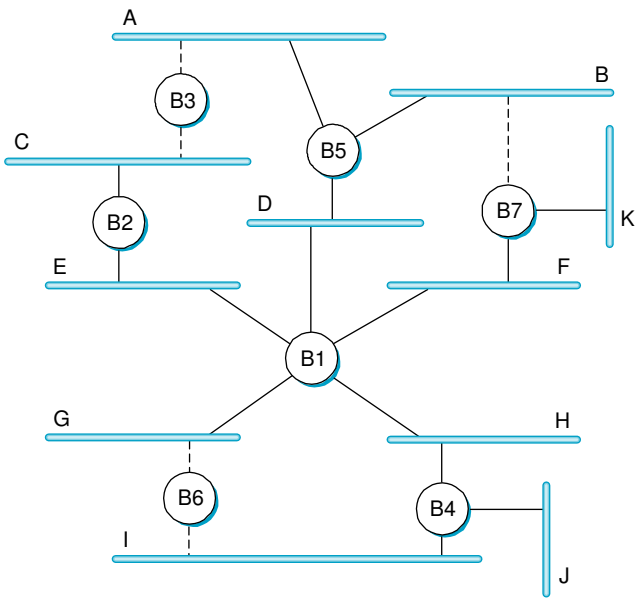


- Bridges run a distributed spanning tree algorithm
  - select which bridges actively forward
  - developed by Radia Perlman (DEC)
  - now IEEE 802.1 specification



Algorithm Overview

- Each bridge has unique id (e.g., B1, B2, B3)
- Basic approaches:
  - Bridge with the smallest id becomes the root
  - Each bridge computes the shortest path to the root
    - break ties randomly (e.g., to enable freedom of load-balancing algorithms)
  - On each LAN, the bridge closest to root becomes the designated bridge
    - use id to break ties (Q: why not randomly?)
- Each bridge forwards frames over each LAN for which it is the designated bridge



Q: distributed algorithm?

Algorithm Details

- Bridges exchange configuration messages
  - id for what the sending bridge believes to be root bridge
  - distance (hops) from sending bridge to root bridge
  - id for bridge sending the message
- Initially, each bridge believes it is the root
- Each bridge records current best configuration message for each port
  - Best: smallest *<root id, hop length, own node id>*

Algorithm Detail (contd.)

- When learn not root, stop generating config messages
  - in steady state, only root generates configuration messages
- When learn not designated bridge for a port/LAN, stop forwarding config. messages over that port/LAN
  - in steady state, only designated bridges forward config messages
- Root continues to periodically send config messages
- If any bridge does not receive config message after a period of time, it starts generating config messages claiming to be the root

Bridge i

variables root.i, dist.i, P.i;
connected_bridges.m : each port m;
designated.m : each port m;

Actions:

Initialization (Boot up) → root.i, dist.i := i, 0;
P.i := i;

[]

RCV $\langle K, d.kj, j \rangle$ via port m → if $K <$ root.i → root.i := K;
dist.i := $d.kj + 1$;
P.i := j;

[]

K = root.i $\wedge$ $d.kj <$ dist.$i - 1$ →
dist.i := $d.kj + 1$;
P.i := j;

fi

update connected_bridges.m & designated.m.

if designated.j == TRUE, $\forall j \neq m$ →
broadcast $\langle$root.i, dist.i, $i\rangle$ via port j

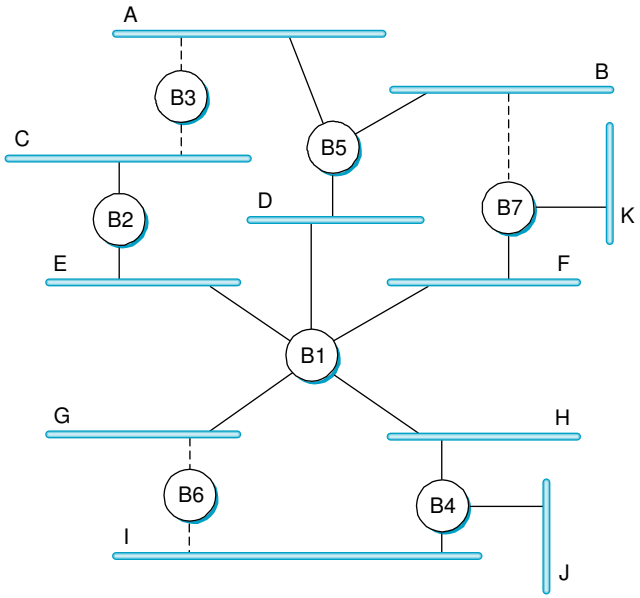
fi

[]

if root.i == i → broadcast $\langle$root.i, dist.i, $i\rangle$ to all ports

Example

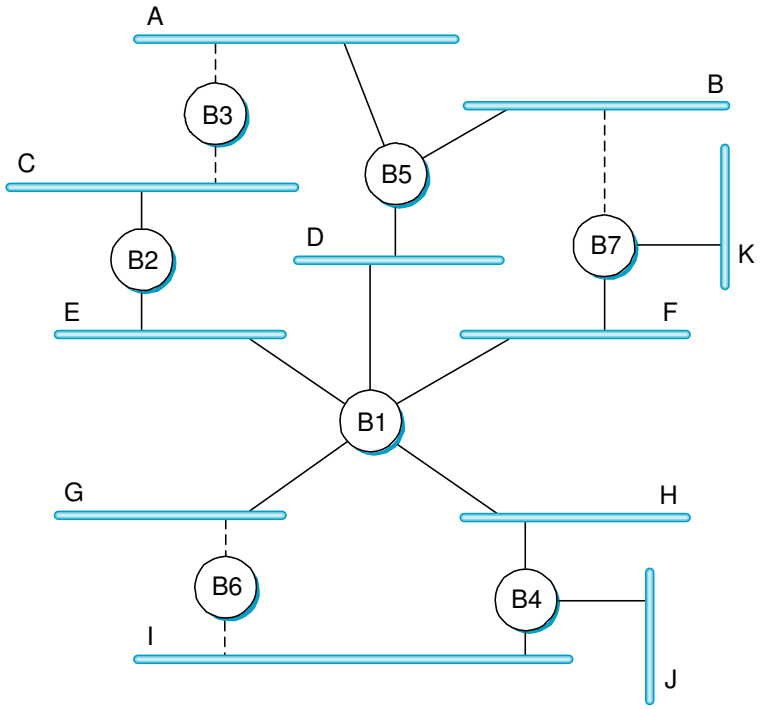
- For simplicity, assume synchrony across nodes (which is usually not the case in practice)
- Focus on how B3 behaves



- Step 0: B1, B2, B5, B3 sets themselves as roots
- Step 1: B2 and B5 set B1 as roots; B3 sets B2 as root
- Step 2: B3 sets B1 as its root, and stops forwarding messages on both interfaces since B3 is not the designated bridge on LANs A and C

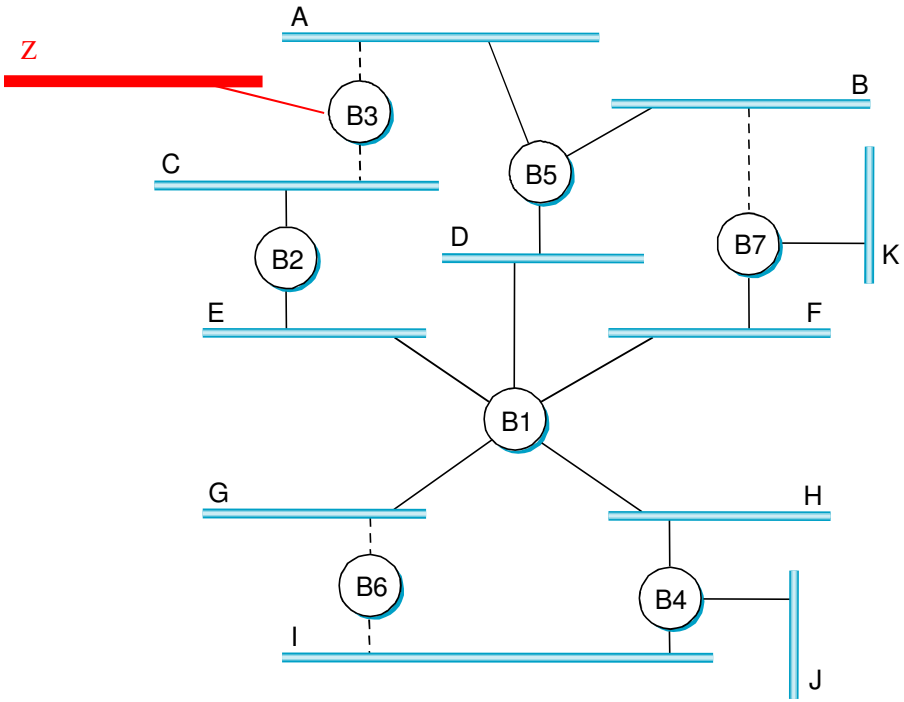
Example (contd.)

- Q: What if B2 fail-stops?



Example (contd.)

- Q: What if B3 has another LAN attached? Unique spanning tree?



Broadcast and Multicast

- Broadcast: simply forwarded to all the output ports specified in the spanning tree
- Multicast: same as broadcast; destination hosts decide whether to accept the received frames
  - current practice
- Can we do better for multicast?
  - Learn when no group members downstream
  - Accomplished by having each member of group G send a frame to bridge multicast address with G in source field
  - Proposed, but not yet implemented as of today

Limitations of Bridges

- Do not scale
  - spanning tree algorithm does not scale: single level rather than hierarchical
  - broadcast does not scale
- Do not accommodate heterogeneity
  - Bridges use "address" field from frame headers, thus they only support networks with the same format for addresses
    - E.g., Ethernet and ATM cannot directly communicate via basic bridges

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Cell Switching (ATM)

- 1980s and early 1990s; embraced by telephone industry
- Used in both WAN and LAN settings
- Specified by ATM forum

- Connection-oriented (virtual circuit switching), packet-switched network
  - Signaling (connection setup) Protocol: Q.2931

- Packets are called *cells*: 5-byte header + 48-byte payload
- Commonly transmitted over SONET
  - other physical layers possible

Variable vs. Fixed-Length Packets

- No Optimal Length => variable-length packet
  - if small: high header-to-data overhead
  - if large: low utilization for small messages
- Fixed-Length Easier to Switch in Hardware
  - Simpler to implement
  - Enables parallelism (since length is known and fixed)

Big vs. Small Packets

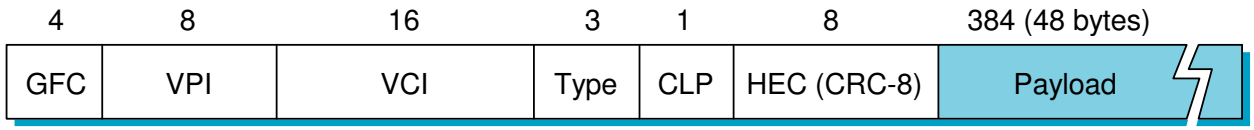
- Small Improves Queue behavior
  - finer-grained preemption point for scheduling link
    - maximum packet = 4KB
    - link speed = 100Mbps
    - transmission time = 4096 x 8/100 = 327.68us
    - high priority packet may sit in the queue 327.68us
    - in contrast, 53 x 8/100 = 4.24us for ATM
  - near cut-through behavior
    - two 4KB packets arrive at same time
    - link idle for 327.68us while both arrive
      - Because the switch must wait to receive the whole first packet before starting transmitting it
    - at end of 327.68us, still have 8KB to transmit
    - in contrast, can transmit first cell after 4.24us
    - at end of 327.68us, just over 4KB left in queue

Big vs. Small (contd.)

- Small Reduces Latency (for voice)
  - voice digitally encoded at 64KBps (8-bit samples at 8KHz)
  - need full cell's worth of samples before sending cell
  - example: 1000-byte cells implies 125ms per cell (too long)
  - smaller latency implies no need for echo cancellers (since a very small latency feels like "0 latency")
- ATM Compromise: 48 bytes
  - US: would like it to be 64 bytes (has echo canceller, thus can afford large packets to reduce header-to-payload ratio
  - Europe: advocates 32 bytes (no echo canceller, thus need small packet)
  - Compromise: 48 = (32+64)/2

Cell Format

- User-Network Interface (UNI): host-to-switch format

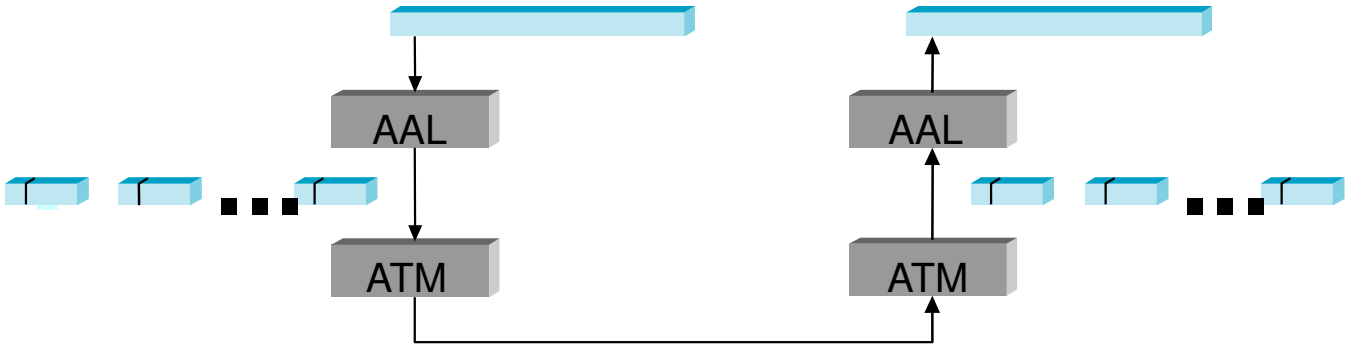


  - GFC: Generic Flow Control
  - *VPI: Virtual Path Identifier*
  - *VCI: Virtual Circuit Identifier*
  - *Type*: management, congestion control, AAL5 (later)
  - CLP: Cell Loss Priority
  - HEC: Header Error Check (CRC-8)

- Network-Network Interface (NNI): switch-to-switch format
  - GFC becomes part of VPI field

Segmentation and Reassembly

- Accomplished by ATM Adaptation Layer (AAL)



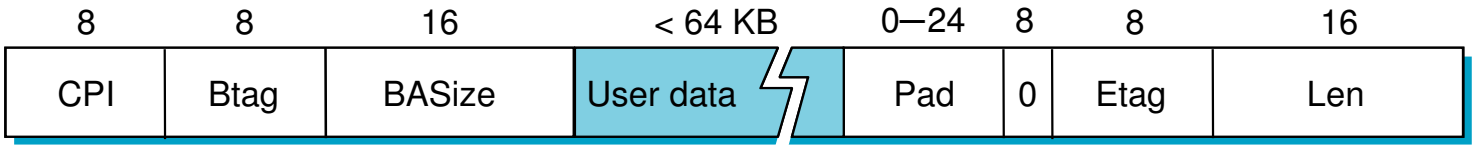
- Two sublayers:
  - Higher layer: Convergence Sublayer (CS)
    - responsible for packaging the higher layer PDU with *additional information required for the adaptation necessary* for specific service types (e.g., bit rate, connection-oriented or connectionless)
  - Lower layer: Segmentation and Reassembly (SAR)

Different types of AALs

- AAL 1 and 2 designed for applications that need guaranteed rate (e.g., voice, video)
- AAL 3/4 designed for data packet
- AAL 5 is an alternative standard for data packet

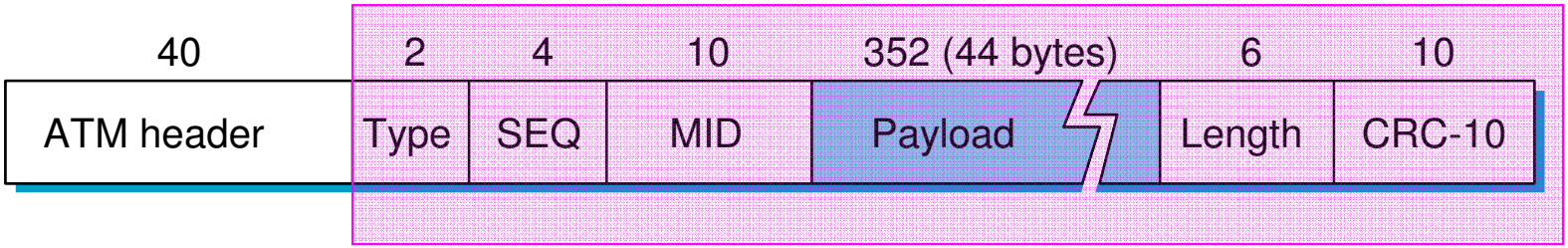
AAL 3/4

- Convergence Sublayer Protocol Data Unit (CS-PDU)



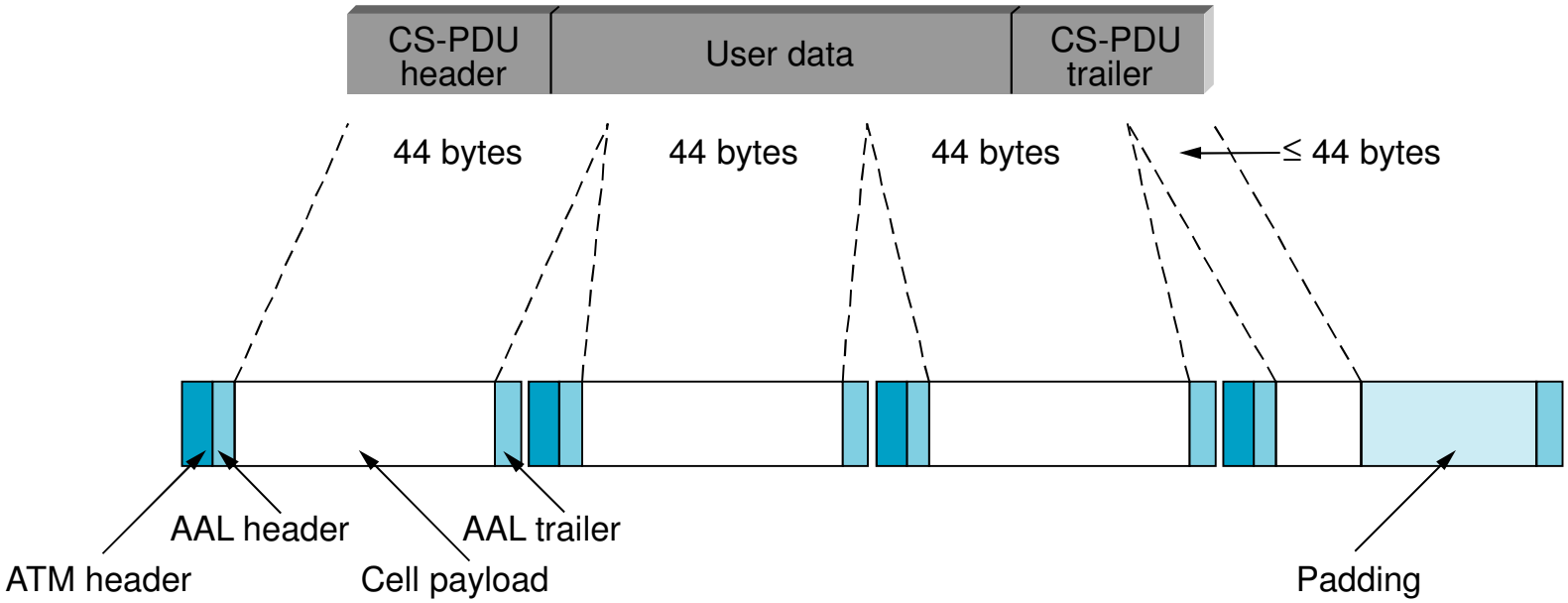
  - CPI: common part indicator (version field); not used yet
  - Btag/Etag: beginning and ending tag (deal with cell corruption)
  - *BAsize: hint on amount of buffer space to allocate*
  - Length: size of whole PDU

SAR: Cell Format --- payload



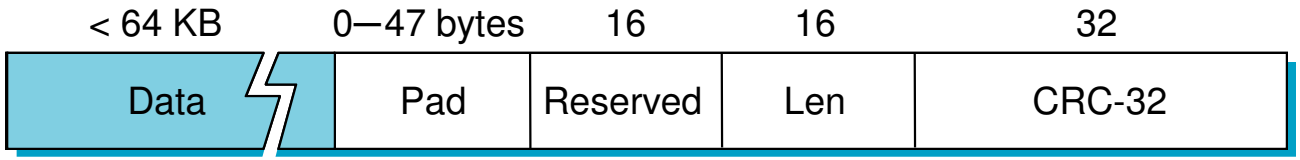
- **Type**
  - BOM: beginning of message
  - COM: continuation of message
  - EOM end of message
- SEQ: sequence number
- MID: multiplexing identifier
- Length: number of bytes of payload (from CS-PDU) in this cell; in bytes

Encapsulation & segmentation for AAL3/4



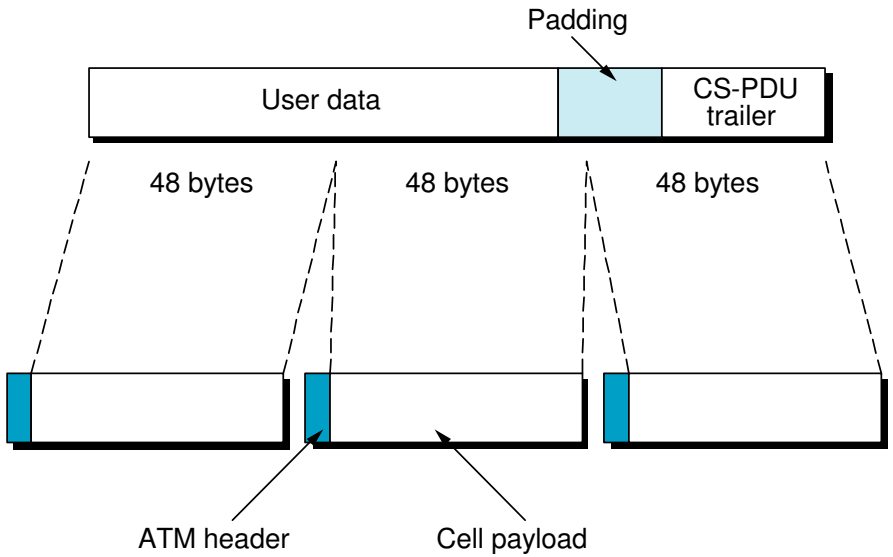
AAL5

- Simplifies the format of AAL ¾
- CS-PDU Format

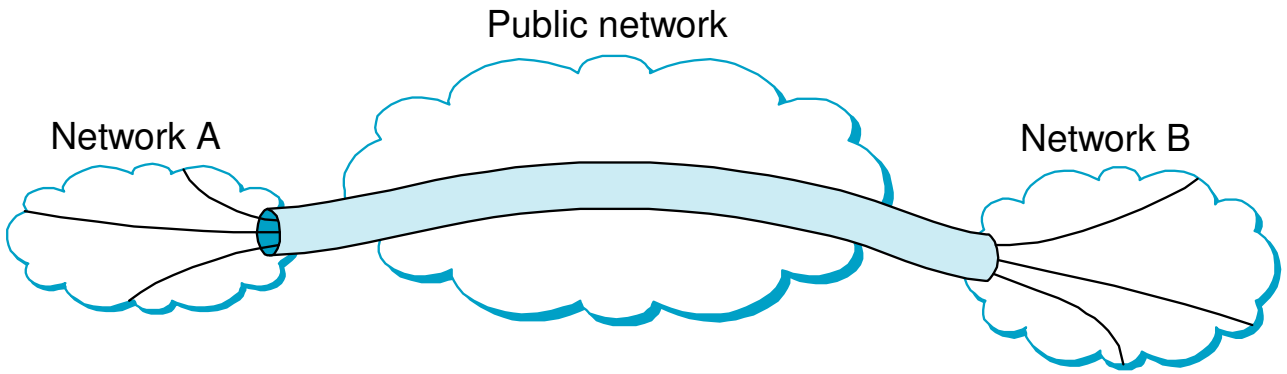


  - Pad, so trailer always falls at end of ATM cell
  - Len: size of PDU (data only); in bytes
  - CRC-32 (detects missing or misordered cells)
- SAR: Cell Format --- payload
  - **end-of-PDU** bit in Type field of ATM header
  - Compared with AAL 3/4 , AAL 5 does not provide an additional level of multiplexing onto one virtual circuit (which was achieved via MID in AAL¾)

Encapsulation & segmentation for AAL 5



Virtual path



- Two-level hierarchy of virtual connections
  - Virtual path (VP)
  - Virtual circuit (VC)
- Switches in public network only maintains state about VPs, which is much fewer than the number of VCs
  - Thus, improves systems scalability

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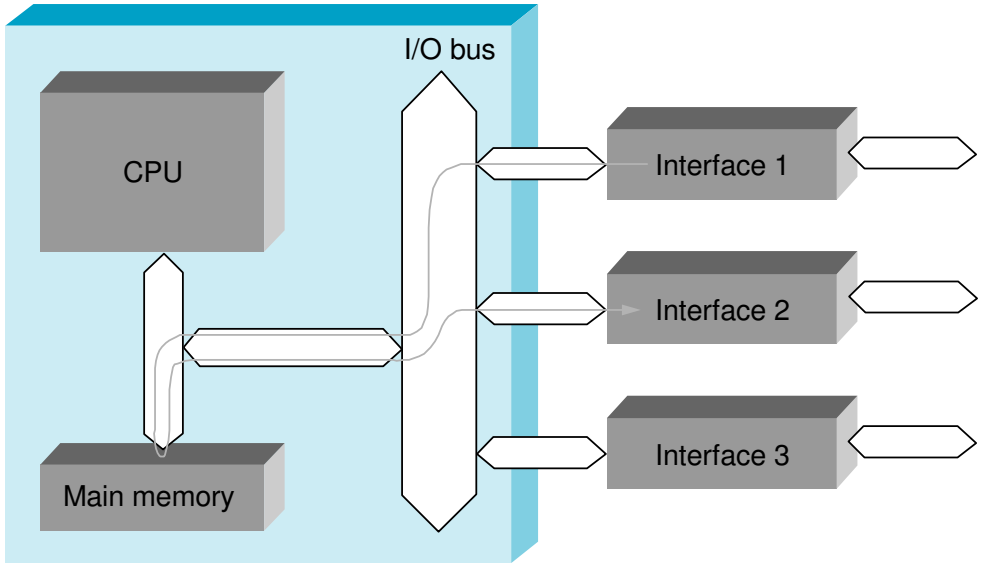
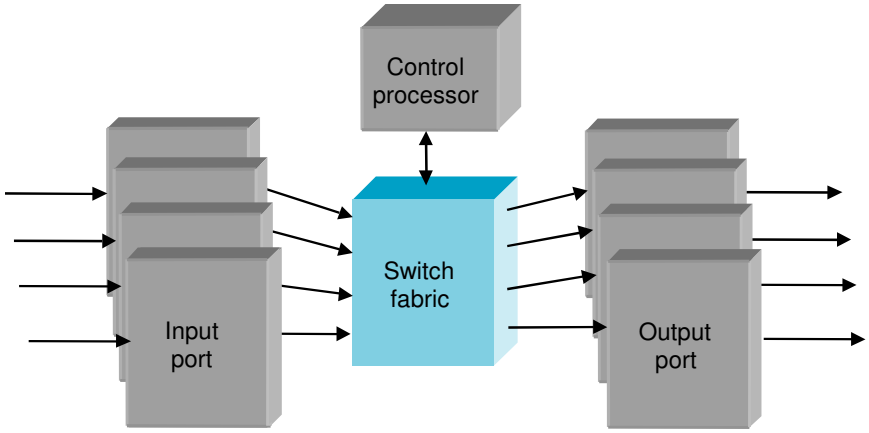
A workstation used as a packet switch



- Flexible in trying out different routing/switching strategies
  - Experimental systems
- (-) high switching overhead, and thus potentially low throughput

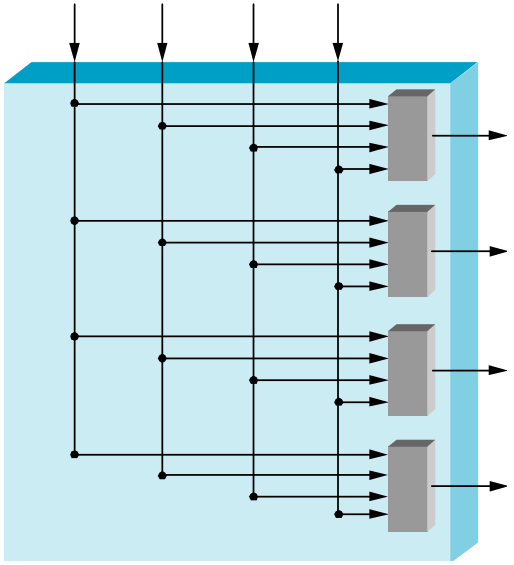
A 4×4 switch



- Input ports: switching logic control (e.g., which output ports to forward packets); usually do not buffer packets
- Switch fabric: forward packets from input ports to output ports; may have internal buffer space
- Output ports: buffering

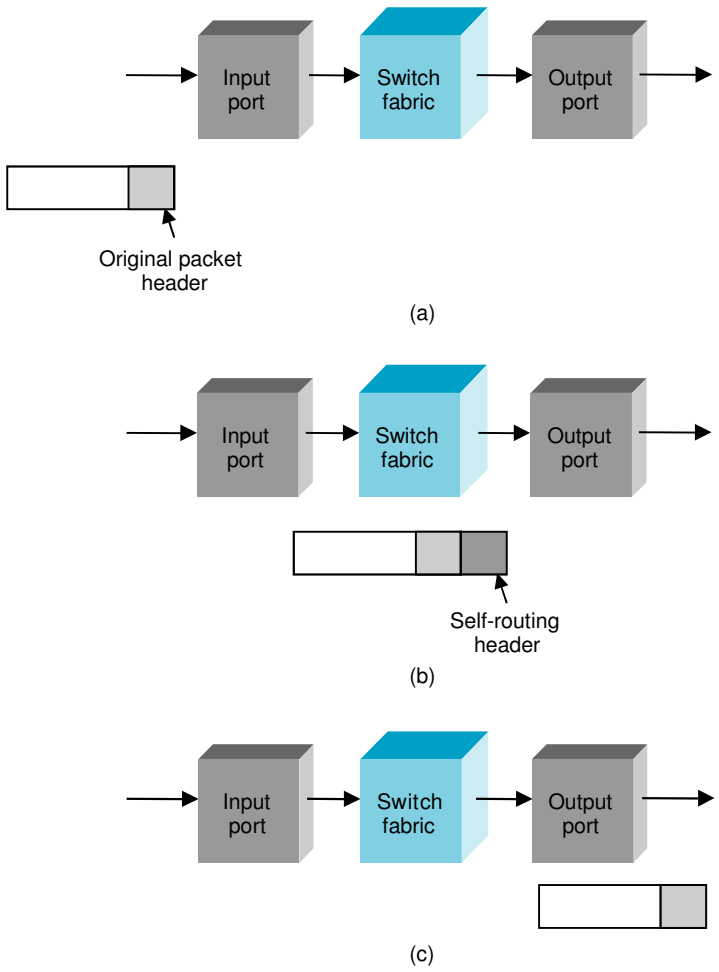
Switch fabrics

- Shared bus
- Shared memory
- Crossbar

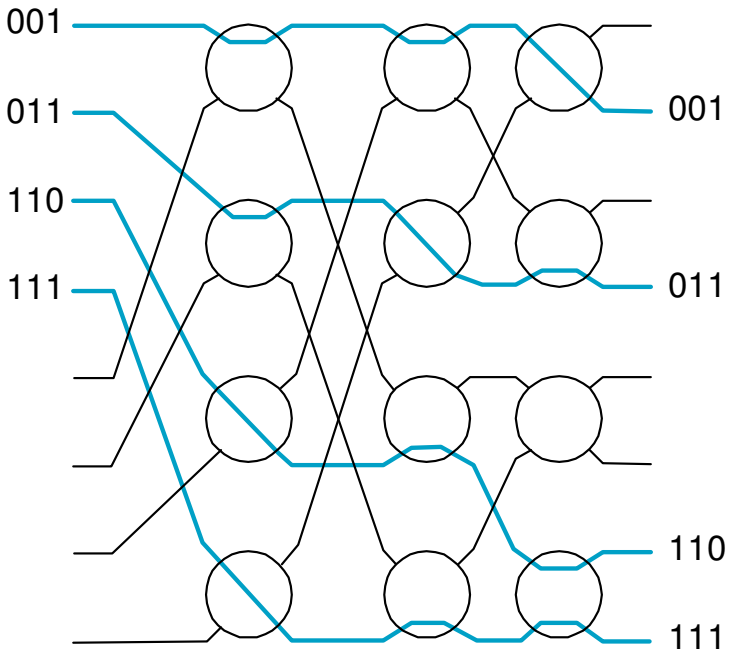


Switch fabrics (contd.)

- Self-routing fabric



• Banyan Network: switch elements in 1st column looks at the most significant bit of output port number: 0 -> route packet to the top; 1 -> route to bottom …



• Batcher-Banyan Switch design: Batcher network first sorts packets (for parallel tx.), then the packets are sent to Banyan network

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Further reading

- Spanning tree algorithm
  - R. Perlman, "An algorithm for distributed computation of spanning trees in an extended LAN", 9th Data Communication Symposium, 1985
- Cell switching
  - J. S. Turner, "Design of an integrated services packet network", 9th Data Communication Symposium, 1985
- Switch design (e.g., impact of correlated traffic)
  - J. N. Giacopelli et al., "Sunshine: A high-performance self-routing broadband packet-switched architecture", IEEE Journal of Selected Areas in Communications (JSAC) 9(8):1289-1298, Oct. 1991

Further reading (contd.)

- Traffic modeling
  - W. Leland, M. Taqqu, W. Lillinger, and D. Wilson, "On the self-similar nature of Ethernet traffic", IEEE/ACM Transactions on Networking, 2:1-15, Feb. 1994
  - V. Paxson, S. Floyd, "Wide-area traffic: The failure of Poisson modeling", ACM SIGCOMM'94

Summary

- Switching and Forwarding
- Bridges and Extended LANs
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- Implementation

Assignment - Chapter 3

- Exercise#2
  - Exercise 1
    - Hint: VCI should be unique for each (bidirectional) link
  - Exercises 15 and 17
  - Exercise 21
    - Hint: for 21 (a), you can regard B1 as a simple repeater that would rebroadcast whatever messages it receive but does not generate any new message.

- TinyExam#2