COMPUTER NETWORKS
CS 45201
CS 55201

CHAPTER 3
Switching and Forwarding

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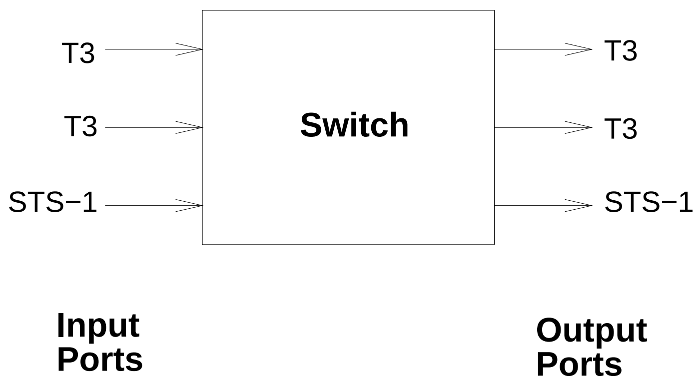
Contents

Switching and Forwarding

Scalable Networks

- *Switch:* Forwards packets from input port to output port; port selected based on destination address in packet header.



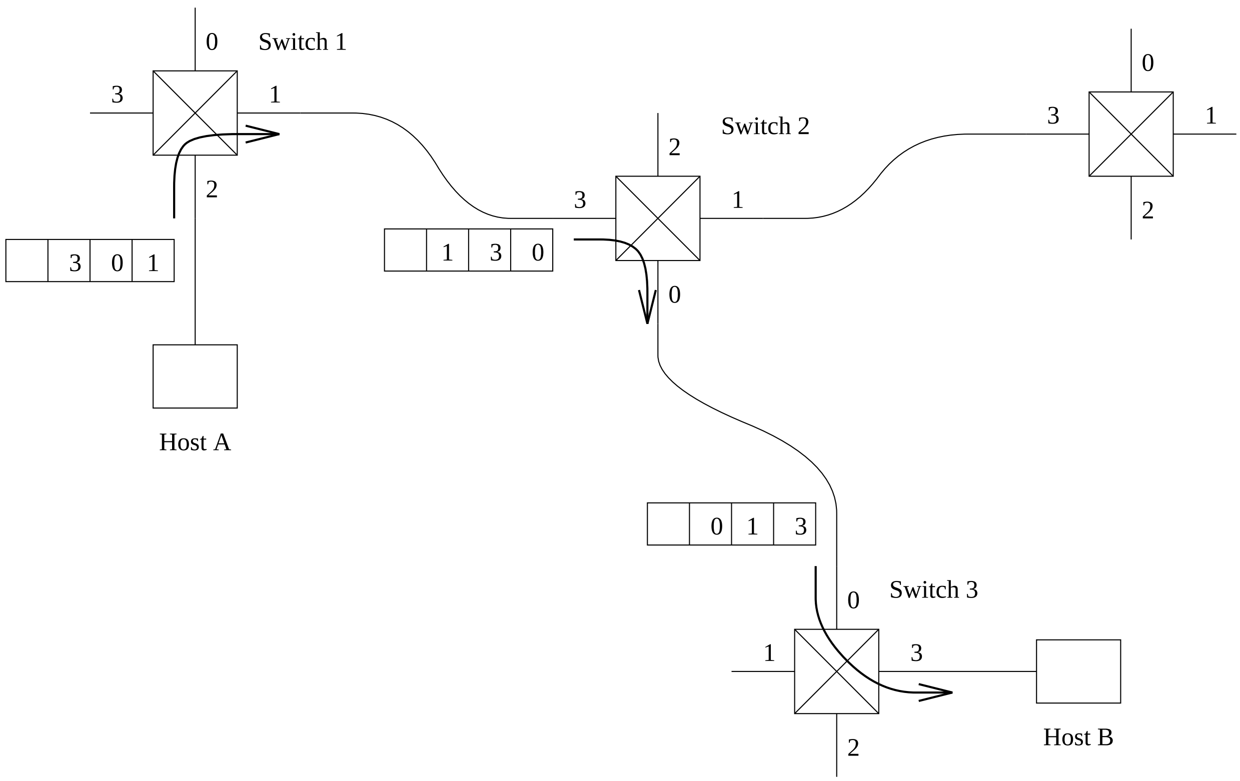
- Can build networks that cover large geographic area
- Can build networks that support large numbers of hosts
- Can add new hosts without affecting performance of existing hosts

Routing Techniques Elements

- Performance criterion
  - ⟹ Number of hops
  - ⟹ Distance
  - ⟹ Speed
  - ⟹ Delay
  - ⟹ Cost
- Decision time
  - ⟹ Packet Session
- Decision place
  - ⟹ Distributed
  - ⟹ Centralized
  - ⟹ Source
- Information sources
  - ⟹ None
  - ⟹ Local
  - ⟹ Adjacent nodes
  - ⟹ Nodes along route
  - ⟹ All nodes
- Routing strategy
  - ⟹ Fixed
  - ⟹ Adaptive
  - ⟹ Random
  - ⟹ Flooding
- Adaptive routing update time
  - ⟹ Continuous
  - ⟹ Periodic
  - ⟹ When topology changes
  - ⟹ Major load changes

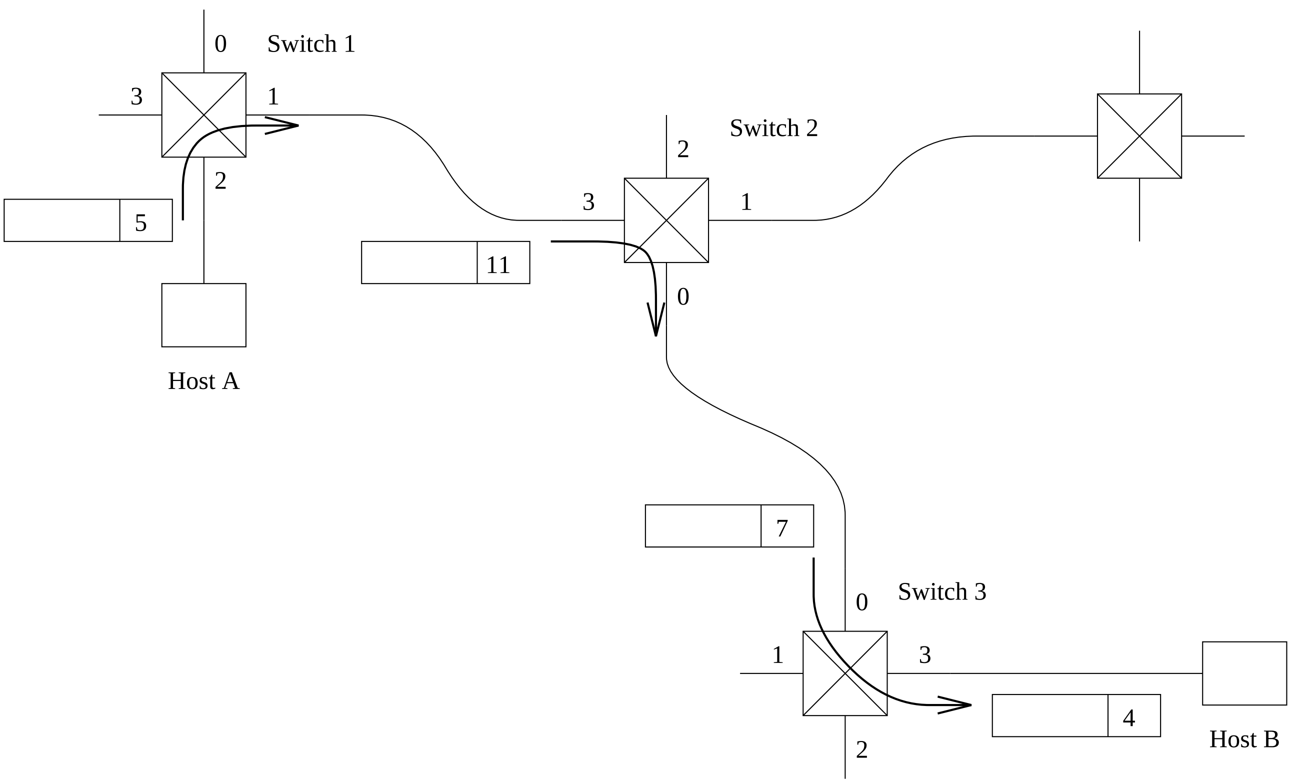
Source Routing

- Address contains a sequence of ports on path from source to destination.



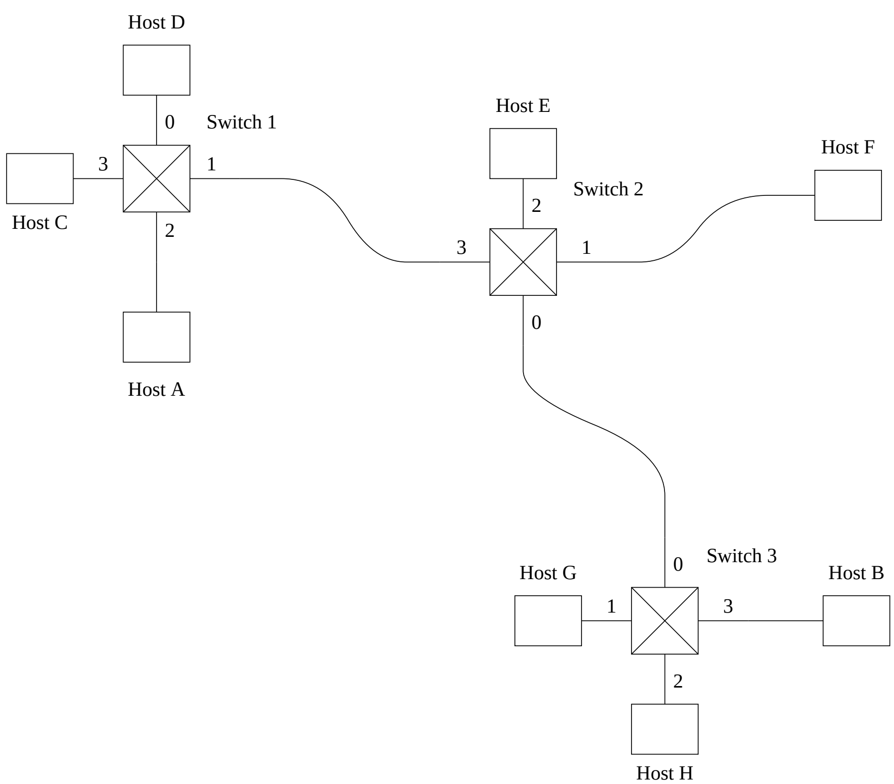
Virtual Circuit Switching

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



Datagrams

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

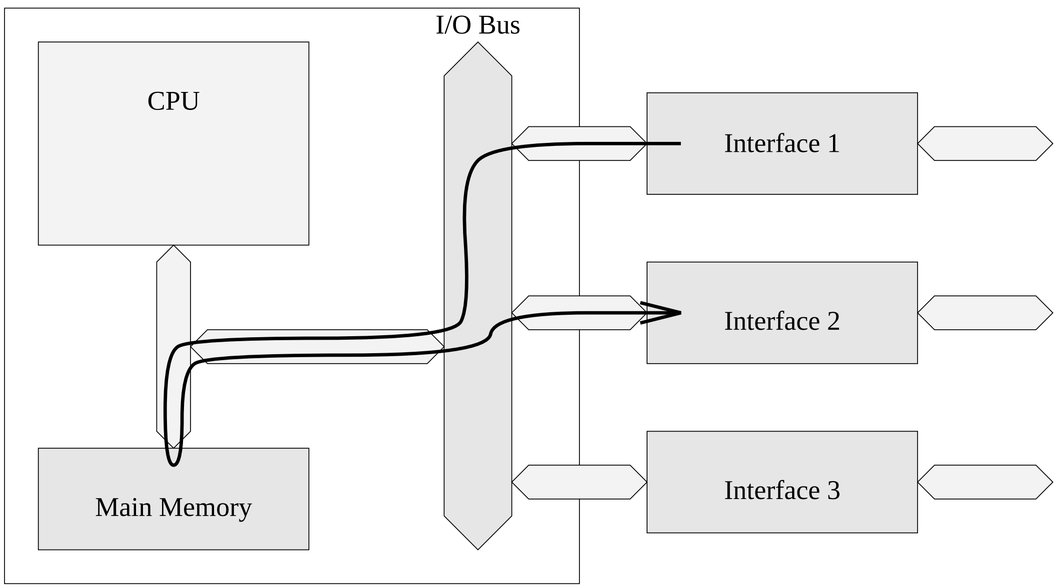


Virtual Circuit vs. Datagram

- *Virtual Circuit Model:*
  - Typically wait full RTT for connection setup before sending first data packet.
  - 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.
  - If a switch or a link in a connection fails, the connection is broken and a new one needs to be established.
  - Connection setup provides an opportunity to reserve resources.
- *Datagram Model:*
  - There is no round trip time delay waiting for connection setup; a host can send data as soon as it is ready.
  - 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 packets are treated independently, it is possible to route around link and node failures.
  - Since every packet must carry the full address of the destination, the overhead per packet is higher than for the connection-oriented model.

Performance

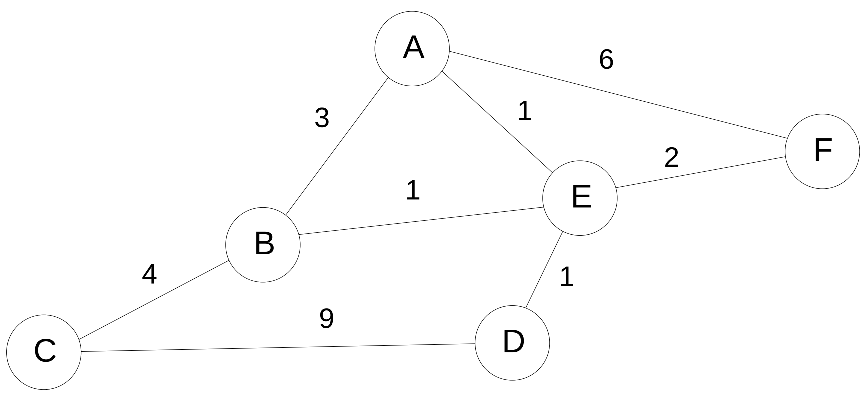
- Switches can be built from a general-purpose workstations; will consider special-purpose hardware later.



- Aggregate bandwidth
  - 1/2 of the I/O bus bandwidth
  - capacity is shared among all hosts connected to switch
  - Example: 800Mbps bus can support 8 T3 ports
- Packets-per-second
  - Must be able to switch small packets
  - 100,000 packets-per-second is an achievable number
  - Example: 64-byte packets implies 51.2Mbps

Routing

- Forwarding versus Routing
  - forwarding: selects an output port based on destination address and routing table
  - routing: process by which routing table is built
- Network as a Graph



- Problem: Find the lowest cost path between any two nodes
- Factors:
  - Static: topology
  - Dynamic: load

- Interior Gateway Protocols (IGP)
- used for Intra-domain routing e.g. between routers within Kent campus
- Two major approaches
  - *Diatance Vector:* Each router sends a vector of distances to its neighbors. The vector contains distances to all nodes in the network
  - Example: RIP (Routing Information Protocol)
  - *Link State:* Each router sends a vector of distances to all nodes. The vector contains only distances to neighbors $\Longrightarrow$ newer method used in Internet
  - Example: OSPF (Open Shortest Path First)
- We will discuss RIP and OSPF later in Chapter 4 together with inter-domain routing using BGP

Distance Vector

- Each node maintains a set of triples:

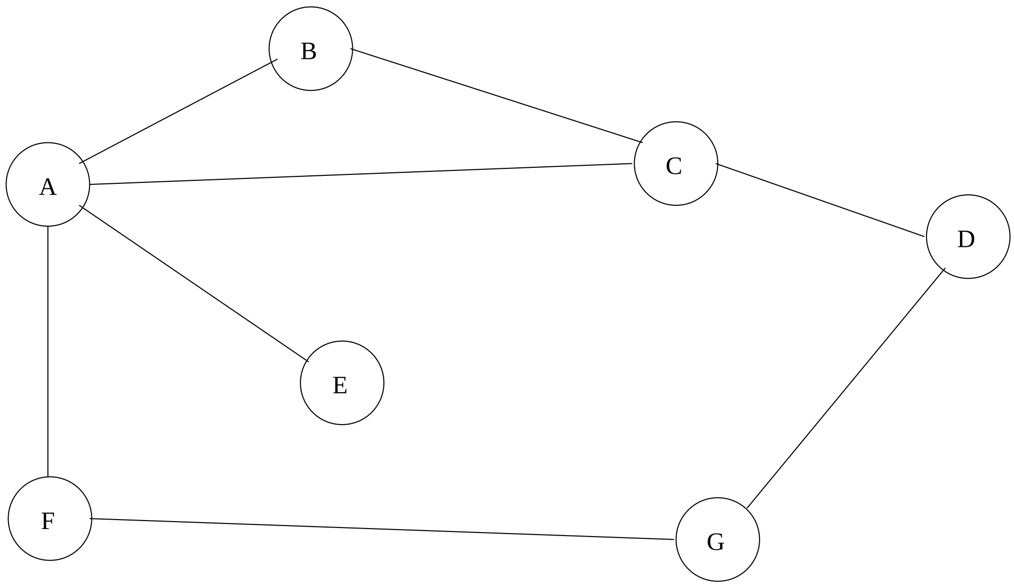
  `(Destination, Cost, NextHop)`

- Each node sends updates to (and receives updates from) its directly connected neighbors
  - periodically (on the order of several seconds)
  - whenever its table changes (called *triggered* update)
- Each update is a list of pairs:

  `(Destination, Cost)`

- Update local table if receive a "better" route
  - smaller cost
  - came from next-hop
- Refresh existing routes; delete if they time out
- How do you tell a node is down?
  - send test packet e.g. ping
  - don't see periodic update

Example



- Routing table at node B

Destination	Cost	NextHop
A	1	A
C	1	C
D	2	C
E	2	A
F	2	A
G	3	A

Routing Loops

- Example 1
  - F detects that link to G has failed
  - F sets distance to G to infinity and sends update to A
  - A sets distance to G to infinity since it uses F to reach G
  - A receives periodic update from C with 2-hop path to G
  - A sets distance to G to 3 and sends update to F
  - F decides it can reach G in 4 hops via A
- Example 2
  - Link from A to E fails
  - A advertises distance of infinity to E
  - B and C advertise a distance of 2 to E
  - B decides it can reach E in 3 hops; advertises this to A
  - A decides it can reach E in 4 hops; advertises this to C
  - C decides that it can reach E in 5 hops......
- Heuristics to break routing loops
  - set infinity to 16
  - split horizon - don't send back to origin i.e. don't send (E,2)
  - split horizon with poison reverse - send (E,∞)
  - only works for 2 node loops

Link State

- Strategy: Send to all nodes (not just neighbors) information about directly connected links (not entire routing table).
- Link State Packet (LSP)
  - id of the node that created the LSP
  - cost of link to each directly connected neighbor
  - sequence number (SEQNO)
  - time-to-live (TTL) for this packet
- Reliable Flooding
  - store most recent LSP from each node
  - forward LSP to all nodes but one that sent it
  - generate new LSP periodically (hours) or on topology change; increment SEQNO
  - start SEQNO at 0 when reboot
  - decrement TTL of each stored LSP before flooding and also by “ageing”; reflood and discard when TTL=0

Route Calculation (in theory)

- Dijkstra's shortest path algorithm
- N denotes set of nodes in the graph
- $l(i, j)$ denotes non-negative cost (weight) for edge (i, j)
- $s \in N$ denotes this node
- M denotes the set of nodes incorporated so far
- $C(n)$ denotes cost of the path from s to node n

$M = \{s\}$
`for each` n `in` $N - \{s\}$
    $C(n) = l(s, n)$
`while` $(N \neq M)$
    $M = M$ `union` $\{w\}$ `such that` $C(w)$
    `is the minimum for all` w `in` $(N - M)$
    `for each` n `in` $(N - M)$
        $C(n) = \texttt{MIN}(C(n), C(w) + l(w, n))$

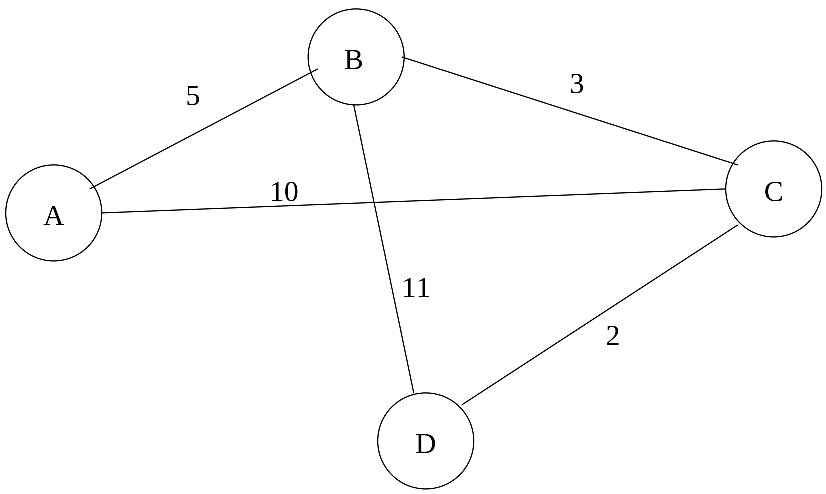
Route Calculation (in practice)

- Forward search algorithm
- Each switch maintains two lists:

  `Tentative` and `Confirmed`

- Each list contains a set of triples:

  `(Destination, Cost, NextHop)`



1. Initialized `Confirmed` with entry for me; cost $= 0$.
2. For the node just added to `Confirmed` (call it `Next`) select its LSP.
3. For each `Neighbor` of `Next`, calculate the `Cost` to reach this `Neighbor` as the sum of the cost from me to `Next` and from `Next` to `Neighbor`.

3.1. If `Neighbor` is currently in neither `Confirmed` or `Tentative`, add `(Neighbor, Cost, NextHop)` to `Tentative`, where `NextHop` is the direction to reach `Next`.

3.2. If `Neighbor` is currently in `Tentative` and `Cost` is less that current cost for `Neighbor`, then replace current entry with `(Neighbor, Cost, NextHop)`, where `NextHop` is the direction to reach `Next`.

4. If `Tentative` is empty, stop. Otherwise, pick entry from `Tentative` with the lowest cost, move it to `Confirmed`, and return to step 2.

Step	Confirmed	Tentative
1.	(D,0,-)	
2.	(D,0,-)	(B,11,B) (C,2,C)
3.	(D,0,-) (C,2,C)	(B,11,B)
4.	(D,0,-) (C,2,C)	(B,5,C) (A,12,C)
5.	(D,0,-) (C,2,C) (B,5,C)	(A,12,C)
6.	(D,0,-) (C,2,C) (B,5,C)	(A,10,C)
7.	(D,0,-) (C,2,C) (B,5,C) (A,10,C)	

Metrics

- Original ARPANET metric
  - measured number of packets enqueued on each link
  - took neither latency or bandwidth into consideration
- New ARPANET metric
  - stamp each incoming packet with its arrival time (`AT`)
  - record departure time (`DT`)
  - when link-level ACK arrives, compute

    `Delay = (DT - AT) + Transmit + Latency`
  - if timeout, reset `DT` to departure time for retransmission
  - link cost = average delay over some time period
- Problems with “New” metric
  - under low load, static factors dominated cost; worked OK
  - under high load, congested links had very hight costs; packets oscillated between congested and idle links
  - range of costs too large; prefered path of 126 lightly loaded 56Kbps links to a 1-hop 9.6Kbps path
- Revised ARPANET metric
  - replaced delay measurement with link utilization
  - average to surpress sudden changes
    - compressed dynamic range (see Fig 4.21)

- highly loaded link never has a cost more than 3 times its idle cost
- most expensive link only 7 times the cost of the least expensive
- high-speed satellite link more attractive than low-speed terrestrial link
- cost is a function of link utilization only at moderate to high loads.
- changes not instantaneous - only notify changes when exceed threshold

Bridges and LAN switches

Bridges

- *Simple Bridge*: a node which accepts frames from an Ethernet (port) and forwards them on all other Ethernet (ports)
- Improvement would be to forward frames only to port with the destination host
- How does bridge get this information?
  - Human download
  - *Learning Bridge*: Bridge inspects *source* address in all frames - knows which port host is on
  - Create table - timeout entries in case host moved

Spanning Tree Algorithm

- Problem: If use multiple learning bridges can get loops
- How get loop? Human error or for redundancy
- Solution: *Distributed Spanning Tree Algorithm*
- Can represent extended LAN as Graph.
- Spanning Tree is subgraph that covers all the vertices but with no cycles
- Theory:
  - pick bridge with lowest id as root - it forwards all frames
  - Each bridge computes shortest path to root - and uses port involved to forward towards root
  - Each LAN picks bridge closest to root

Practical Algorithm

- Exchange configuration messages containing
  - the id for the sending bridge
  - the id of what it believes is the root
  - distance in hops to root
- Bridge records the current best message on each port, adding one to distance to root
- Best if
  - root id is smaller or
  - root id equal but distance shorter or
  - both equal but sending bridge has lower id
- Bridge forwards rather than generates messages when realizes not root
- Bridge stops forwarding messages on port when it's not designated bridge for LAN
- Can extend spanning tree to prune multicasts - not widely done.

Limitations of Bridges

- Spanning Tree scales linearly
- Can only connect networks with same frame headers
- Congestion and dropped frames possible at bridges
- Latency and variability may increase
- Want to reduce broadcast traffic
  - VLAN - virtual LAN: partition exetended LAN into multiple VLAN
  - Broadcast packets are only sent on ports that are in same VLAN
  - Adds VLAN header after Ethernet header to do this

Asynchronous Transfer Mode (ATM)

Overview

- Connection-oriented packet-switched network
- Used in both WAN and LAN settings
- Signalling (connection setup) Protocol: Q.2931
- Specified by ATM Forum
- Packets are called *cells*: 5-byte header + 48-byte payload
- Commonly transmitted over SONET (but not necessarily)

Cells

- Variable versus Fixed-Length
  - no optimal fixed-length
    - if small: high header-to-data overhead
    - if large: low utilization for small messages
  - fixed-length are easier to switch in hardware
    - simpler
    - enables parallelism

- Small size improves queue behavior
  - finer-grained pre-emption point for scheduling link
    - maximum packet = 4KB
    - link speed = 100Mbps
    - transmission time = $4096 \times 8/100 = 327.68\mu$s
    - high priority packet may sit in the queue 327.68μs
    - in contrast, $53 \times 8/100 = 4.24\mu$s for ATM
  - near cut-through behavior
    - two 4KB packets arrive at same time
    - link idle for 327.68μs while both arrive
    - at end of 327.68μs, still have 8KB to transmit
    - in contrast, can transmit first cell after 4.24μs
    - at end of 327.68μs, just over 4KB left in queue
- Carrying Voice in Cells
  - 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 cancellors
- Settled on compromise of 48 bytes: (32+64)/2

Cell Format

- User-Network Interface (UNI)

4	8	16	3	1	8	384 (48 bytes)
GFC	VPI	VCI	Type	CLP	HEC(CRC-8)	Payload

  - host-to-switch format
  - GFC: Generic Flow Control (still being defined)
  - VCI: Virtual Circuit Identifier
  - VPI: Virtual Path 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

ATM Adaptation Layer (AAL)

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

AAL 3/4

- Convergence Sublayer Protocol Data Unit (CS-PDU)

8	8	16	<64kbytes	8	0-24	8	16
CPI	Btag	BASize	User Data	Pad	0	Etag	Len

  - CPI: common part indicator (version field)
  - Btag/Etag: beginning and ending tag
  - BAsize: hint on amount of buffer space to allocate
  - Length: size of whole PDU

- Cell Format

40	2	4	10	352 (44 bytes)	6	10
ATM header	Type	SEQ	MID	Payload	Length	CRC-10

  - Type
    - BOM: beginning of message
    - COM: continuation of message
    - EOM: end of message
  - SEQ: sequence number
  - MID: message id
  - Length: number of bytes of PDU in this cell

AAL5

- CS-PDU Format

<64kB	0-47 bytes	16	16	32
Data	Pad	Reserved	Len	CRC-32

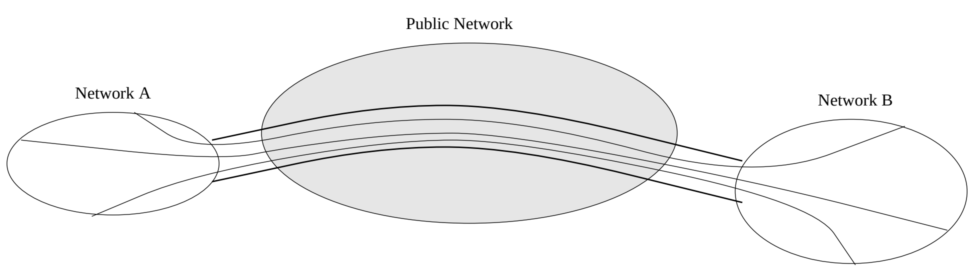
  - pad so trailer always falls at end of ATM cell
  - Length: size of PDU (data only)
  - CRC-32 (detects missing or misordered cells)

- Cell Format
  - end-of-PDU bit in Type field of ATM header

VPI/VCI

- Host: treat as 24-bit circuit identifier
  - if cheap: one-per application; use for demultiplexing
  - if expensive: multiplex several applications onto one VCI

- Network: aggregate multiple circuits into one path

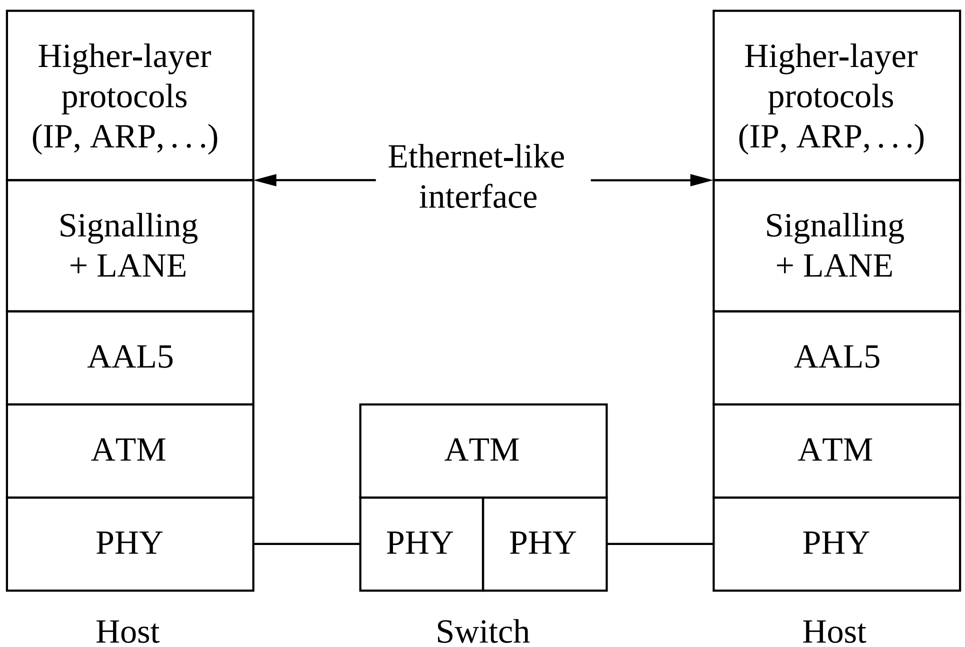


ATM in the LAN

- Originally WAN technology
- Adopted for LANs because
  - it was switched (as opposed to Ethernet which was shared),
  - fast (155Mbps and above),
  - lack of distance limitation
- Problem with implementing broadcast if don't know all node addresses and setup VCs to them
- Solution:
  - Redesign protocols e.g. ATMARP
  - LAN emulation (LANE) - effectively shared media emulation

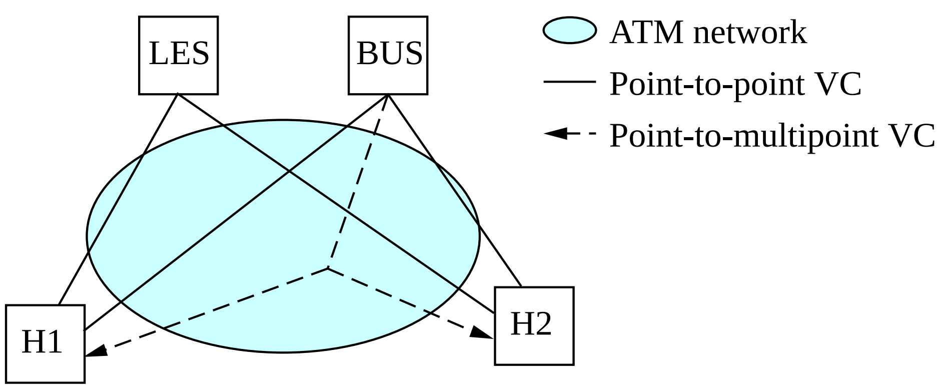
LAN emulation

- Addresses: ATM address (used to establish VC), LANE MAC address, VCI
- LANE uses various servers and LAN emulation clients (LECs) – hosts, routers, etc to make LANE layer appear like standard MAC layers to higher layers



LANE uses:

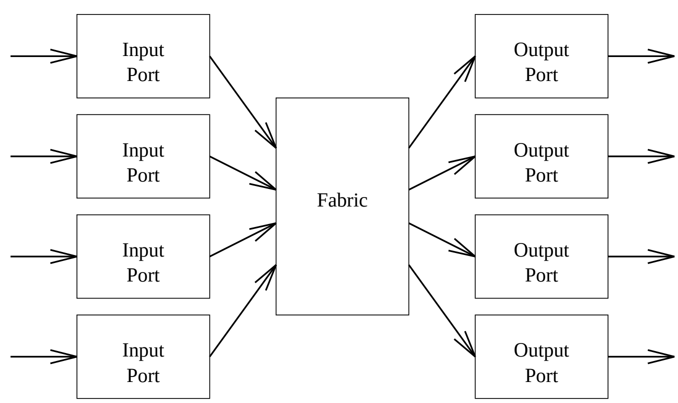
- LANE configuration server (LECS): collects ATM addresses of clients, supplies MAC parameters (LES, type, MTU etc)
- LANE server (LES): clients register ATM/MAC addresses, gets addr of BUS
- broadcast and unknown server (BUS) : maintains point-to-multipoint VC to all registered clients, delivers multicast packets and first unicast between clients, supplies ATM addr corresponding to MAC addr



Switching Hardware

Overview

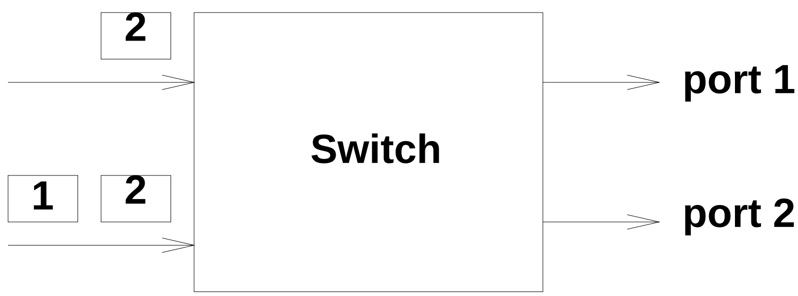
- Terminology: $n \times m$ switch has n inputs and m outputs
- Design Goals
  - throughput (depends on traffic model)
  - scalability (a function of n)
- Ports and Fabrics



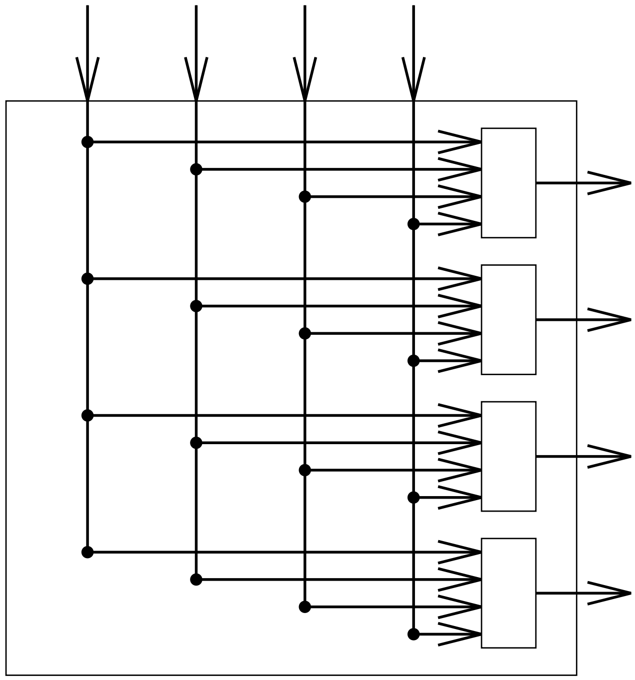
  - ports
    - circuit management (e.g., map VCIs, route datagrams)
    - buffering (input and/or output)
  - fabric
    - as simple as possible
    - sometimes do buffering (internal)

Buffering

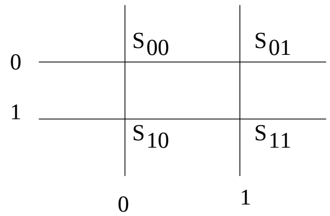
- Wherever contention is possible
  - input port (contend for fabric)
  - internal (contend for output port)
  - output port (contend for link)
- Head-of-Line Blocking
  - input buffering



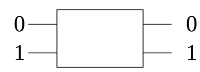
Crossbar Switches



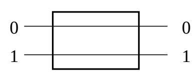
- Crossbar switches are nonblocking and simple but with N^2 complexity.
- They have been used in small networks or as building blocks.
- Although it is nonblocking, in packet mode it becomes a blocking network.
- A queueing function is added to the crossbar to overcome this problem in three ways.
  - Input queueing
  - Output queueing
  - Crosspoint queueing



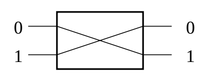
A 2 x 2 cros-bar



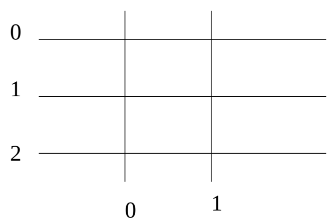
A representation for a 2 x 2 cross-bar



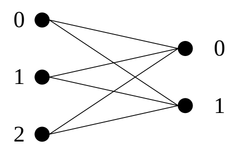
On-state
0



Off-state
1



An example of 3 x 2 cross-bar



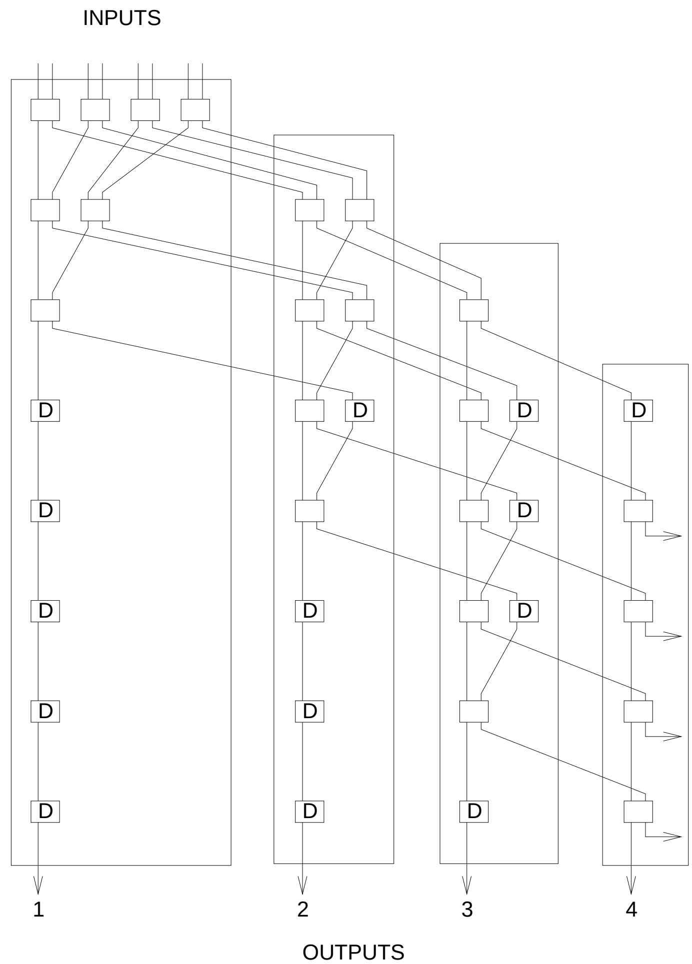
A graph representation of a 3 x 2 cross-bar

- A central controller sets up the cross-points and schedules the packet delivery. It is simple, but the central controller is the bottleneck.
- It is very expensive for large switch.
- Output queueing provides ideal performance.

Knockout Switch

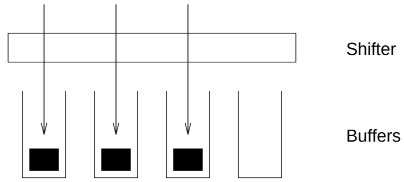
- It is designed for packet switching with fixed length (Knockout I) or variable length (Knockout II) packets.
- It uses one broadcast input bus for each input port to all output ports.
- Each output port has a bus interface that prevents contention on the bus and allows simultaneous packets to the same output port.
- Packet filters detect the address of each packet and implement the self routing function.
- When two packets arrive to a 2×2 switch, one is selected randomly.

- Example of Crossbar

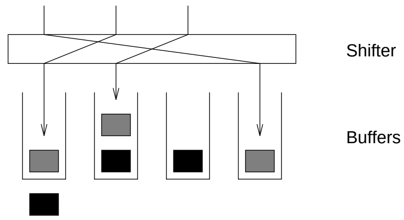


- Boxes with D introduce 1 bit delay to keep the competition synchronous.
- Concentrator: select L of N packets
- Complexity: N^2

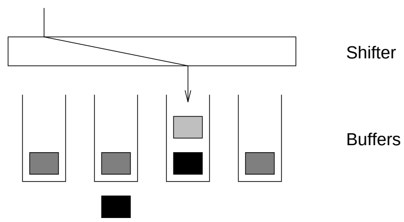
- Output Buffer
- The concentrator selects L packets and store them into a shared buffer based on their time of arrival.
- Selecting L packets out of N contenders is analogous to a knockout tournament.
- For an $N \times L$ knockout concentrator, there are L rounds of competitions.



(a) Three packets arrive



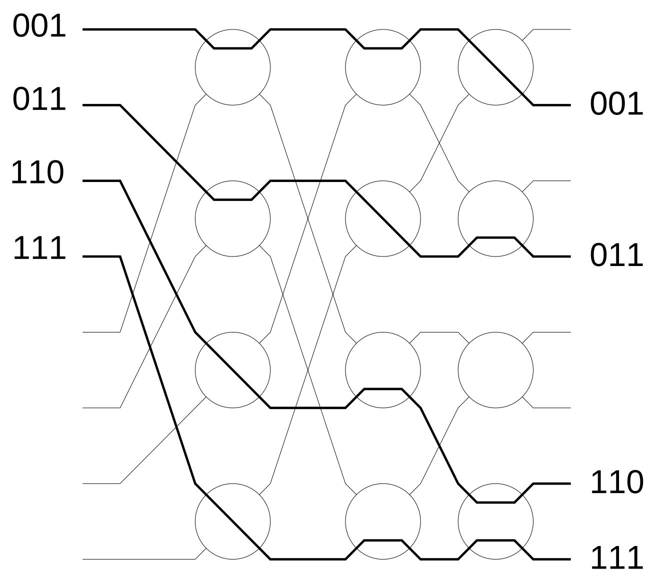
(b) Three packets arrive, one leaves



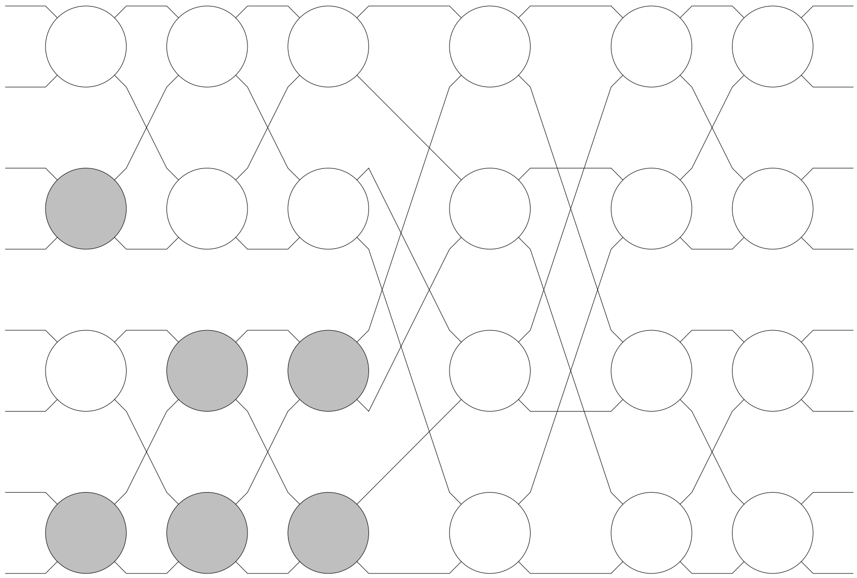
(c) One packets arrives, one leaves

Self-Routing Fabrics

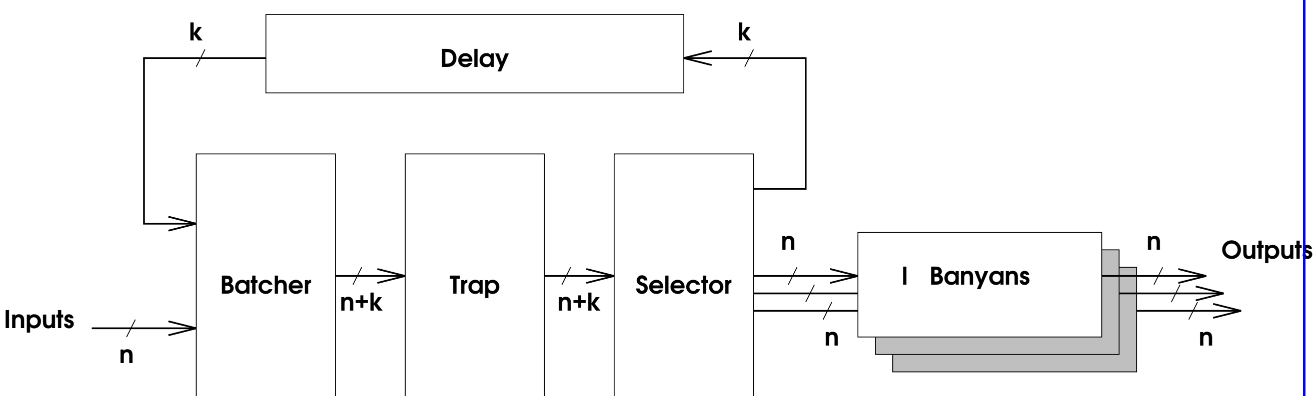
- Banyan Network
  - constructed from simple 2×2 switching elements
  - self-routing header attached to each packet
  - elements arranged to route based on this header
  - no collisions if input packets sorted into ascending order
  - complexity: $n \log_2 n$



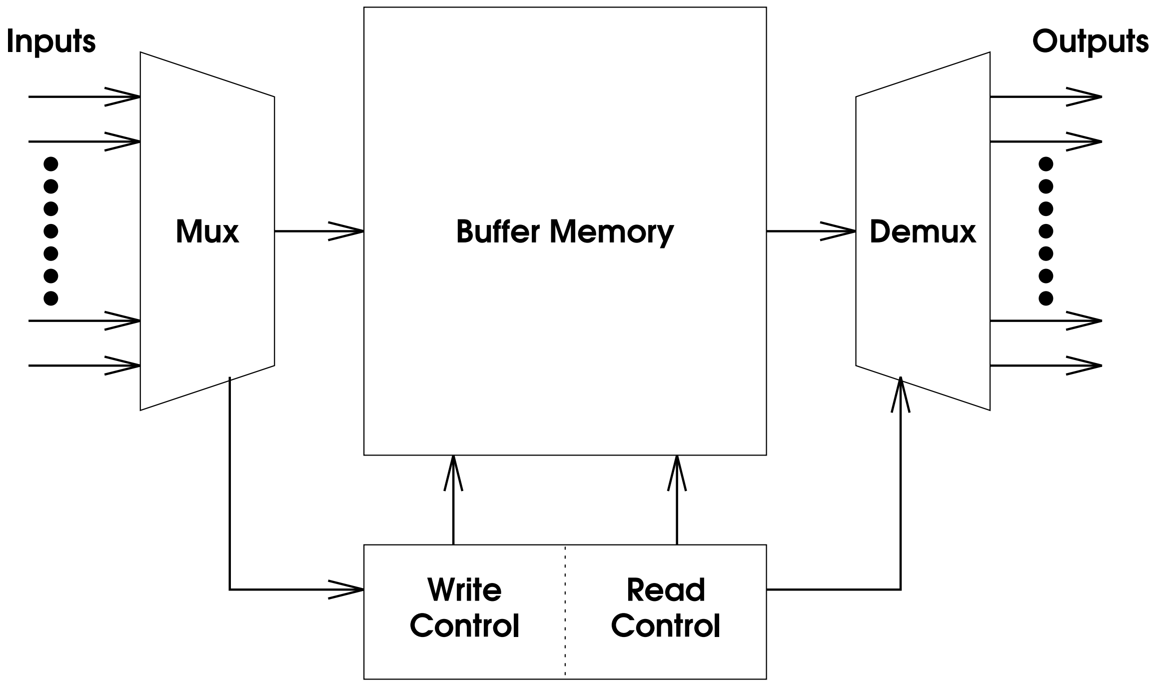
- Batcher Network
  - switching elements sort two numbers
    - some elements sort into ascending (clear)
    - some elements sort into descending (shaded)
  - elements arranged to implement merge sort
  - complexity: $n \log_2^2 n$



- Common Design: Batcher-Banyan Switching Fabric
- Sunshine Switch



Shared Media Switches



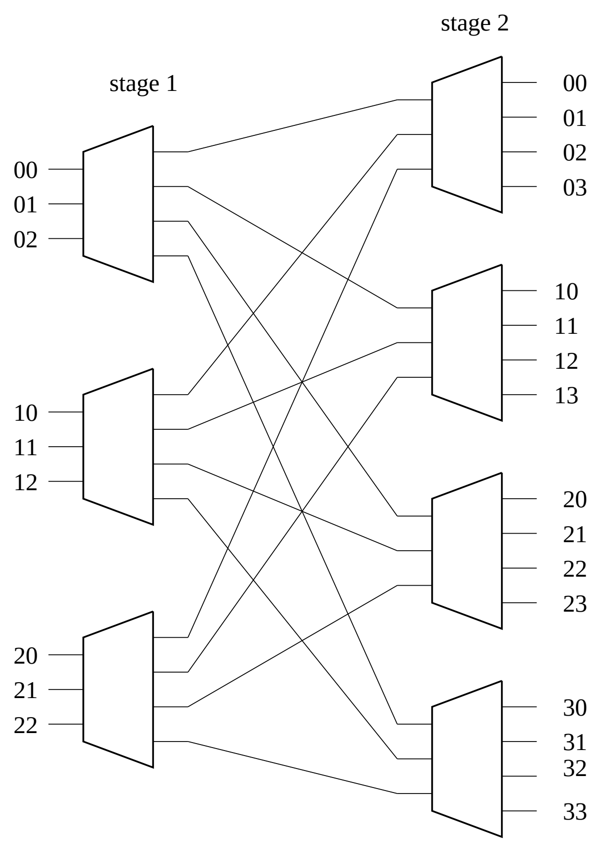
A Brief Summary of INs

- Most INs have been designed for a particular applications, such as voice data, signaling, etc.
- Different applications need different bandwidth requirements.
- Circuit switching concept has evolved to handle stream-type traffic (voice, video), with fixed throughput and constant delay.
- Packet switching has evolved as an efficient way to transport communication traffic with the following property.
  - Buffering
  - Statistical multiplexing
  - Variable throughput
  - Variable delay
  - It supports both virtual circuit and datagram techniques.
  - Very attractive for applications with low throughput and low delay, (inquiry/response), and hight throughput and high delay (file transfer).
  - It is not suitable for real-time type traffic such as voice, video, and computer-to-computer data transfer.

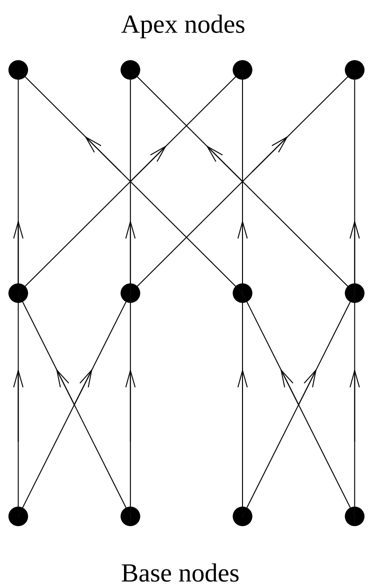
- Many switching fabrics have been designed to satisfy high-performance requirements that include
  - High degree of parallelism
  - Distributed control
  - Routing function on hardware
- Fast packet switching can be classified based on their internal fabric structures that include
  - Buffered-based banyan fabrics
  - Sort-banyan-based fabrics
  - Fabrics with disjoint-path topology and output queueing
  - Crossbar-based fabrics
  - Time division fabrics with common packet memory
  - Fabrics with shared medium.

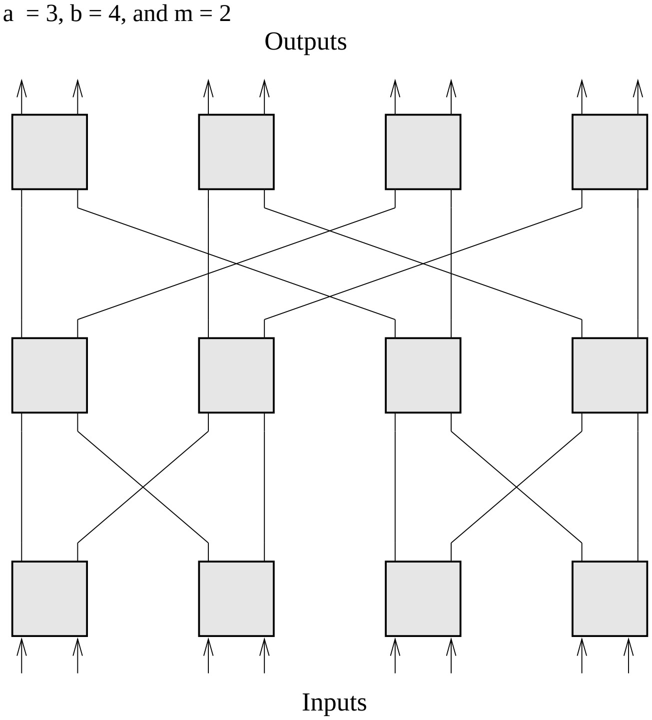
Banyan and Buffered Banyan Fabrics

- Banyan is a rich class that include regular and rectangular banyan networks, and delta networks.
- A $N = b^k$ delta network with self-routing property (*delta-b*) is constructed with k stages of of identical $b \times b$ switching elements.
- Many of the well-known INs such as omega, flip, cube, shuffle-exchange, and baseline belong to the class of delta networks.
- These networks are attractive for packet switching since several packets can be switched simultaneously and in parallel.
- Although these networks have different interconnection patterns, they have the same performance for packet switching.
- They all have the following properties
  - All consists of $\log_b N$ stages of $N/b \quad b \times b$ switches.
  - Self-routing (digit-controlled) in which a unique k digit base b destination address is used.
  - They can be constructed in a modular fashion from smaller networks (block structured).
  - They can operate in synchronous or asynchronous mode.
  - Their regularity makes the attractive for VLSI implementation.
- These networks become inherently blocking regardless of being blocking, nonblocking, and rearrangeable in circuit-switched implementations because packets could collide with each other.



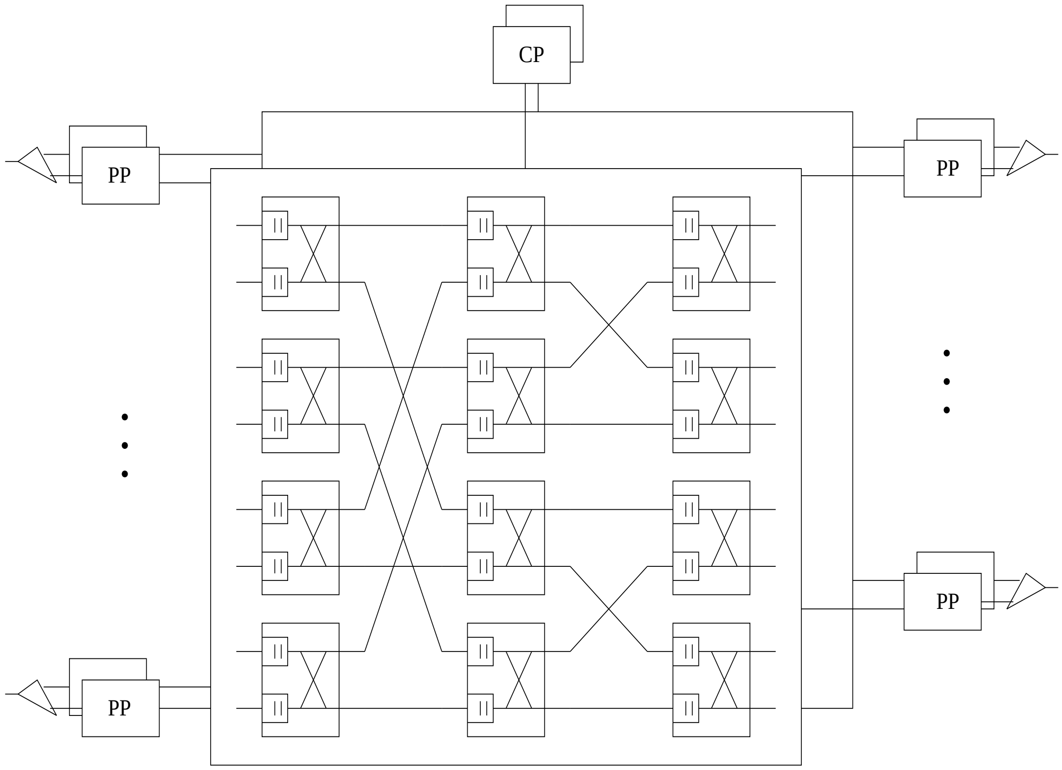
A delta network with a = 3, b = 4, and m = 2





Banyan graph and the corresponding banyan network

- There are two types of blocking
  - Internal link blocking: contention for a particular link inside the network.
  - Output port blocking: two or more packets are contending for the same output port.
- There are several ways to reduce the blocking (increase the through put) of banyan switches.
  - Increasing internal link speed.
  - Placing buffers in every switching node.
  - Using a handshaking or backpresure mechanism to delay the transfer of blocked packets.
  - Using multiple network to provide multiple paths or using multiple links for each switch.
  - Using a distribution network at the front of banyan for load balancing.
- The Integrated Services Packet Network(ISPN) is based on large high performance packet switch structure.
- The switch interfaces up to 1000 high-speed digital transmission facilities via packet processors(PP).
- A PP provides input buffering, adds the routing header, and performs the link level protocol functions.
- A control processor (CP) performs all connections control functions.
- The switch fabric consists of a 10-stage self-routing buffered banyan with 1024 ports of 5120 buffered 2×2 switching elements.



Turner's ISPN Packet Switch Structure

- The switch fabric uses backpresure flow control mechanisms between stages which prevent buffer overflow or packet loss.
- It uses the *virtual cut-through* buffering technique.
- When a packet arrives at a switching element and the output port is free, it bypasses the buffer and directly sends it to the output port.
- AT&T introduced a *wideband packet technology* network based on a 16×16 buffered banyan with 8 Mbits/s.
- Buffered banyan networks have been studied analytically and by simulations models based on different buffer-size, the position of buffers, traffic distributions, and switching size.

Sort-Banyan-Based Fabrics

- Banyan network is internally blocking; two packets destined for two different destinations may collide in one of the stages.
- If packets are first sorted based on their destination address, and then routed through the network, then the internal blocking can be avoided.
- Batcher-banyan is an example of sort-banyan network.
- Blocking still can happen if two or more packets have the same destination address.

Disjoint-Path and Output Queuing

- The switch fabrics is based on nonblocking fully interconnected topology.
- To resolve the output contention, output queueing is used.
- In general, a higher throughput can be achieved when output buffering is used since there is no HOL blocking.
- Infinite output buffering capability gives the best delay/throughput performance.

Fabric with Shared Medium

- A bus or ring network is used as switching medium.
- They provide flexibility in terms of access protocols and distribution of traffic.
- Their bandwidth and throughput are limited compared to multipath switch networks.
- Multiple rings or multiple buses can be used to increase the capacity.
- The frame duration of 125μs maintains complete time transparency for circuit-switched channel.