CSCI-1680

Link Layer III

Nick DeMarinis

Based partly on lecture notes by Rodrigo Fonseca, David Mazières, Phil Levis, John Jannotti

Administrivia

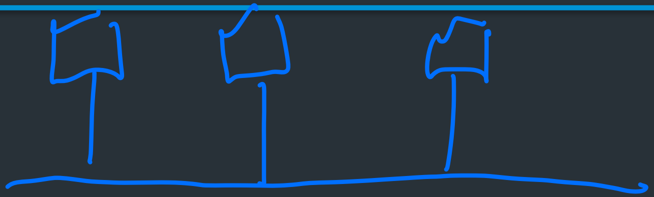
- Snowcast: Due tomorrow (Feb 16), 11:59pm
- HW1: Out today, due next Tuesday
- IP Project: Out Thursday (Intro in class)
- My office hours today
  - 2-3pm (Remote, join via Hours)
  - 3-5pm (Group, CIT506)

Today: Link Layer (cont.)

Various switching topics

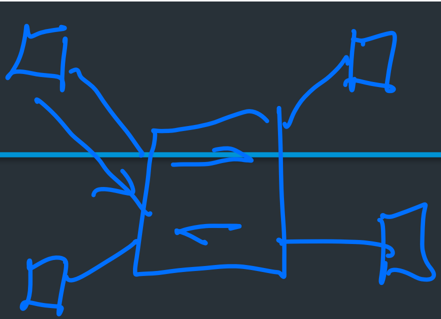
- VLANs
- Dealing with loops (Spanning Tree Protocol)
- Inside switches

Recap



- Media access control
- Ethernet
  - Carrier Sense Multiple Access / Collision Detection (CSMA/CD)
  - All hosts have a MAC address: (eg. 00:1c:43:00:3d:09)
  - Original Ethernet: same collision domain

Recap



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  - Now: switches separate collision domains per-link, but all hosts still in same broadcast domain
  - Broadcast frames more intelligently with MAC learning
- Some broadcast traffic is good!

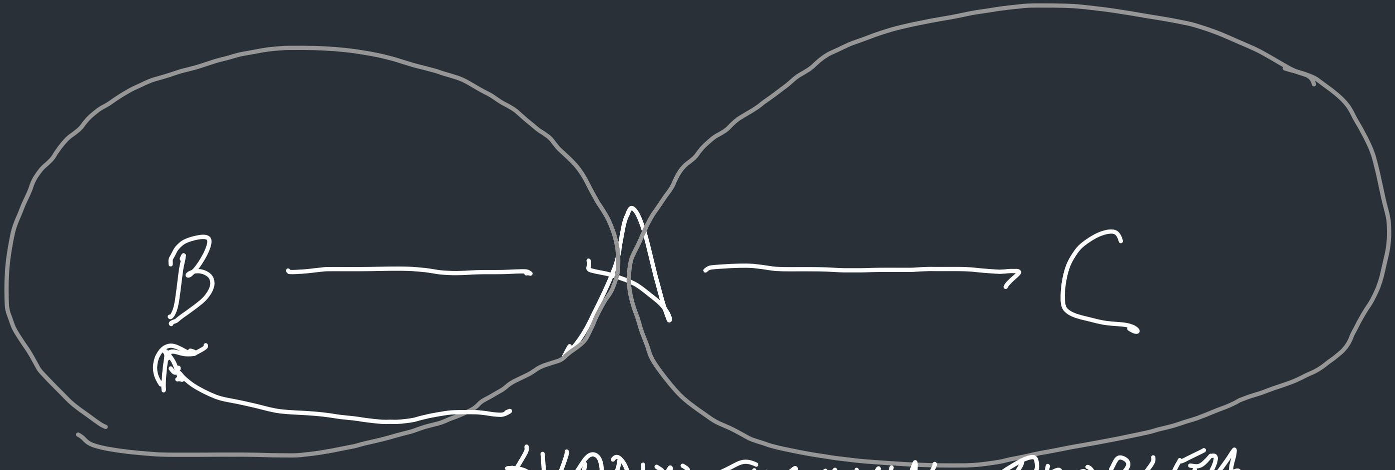
→ BROADCAST ADDRESS

What happens in wireless?

- Can we use CSMA/CD?

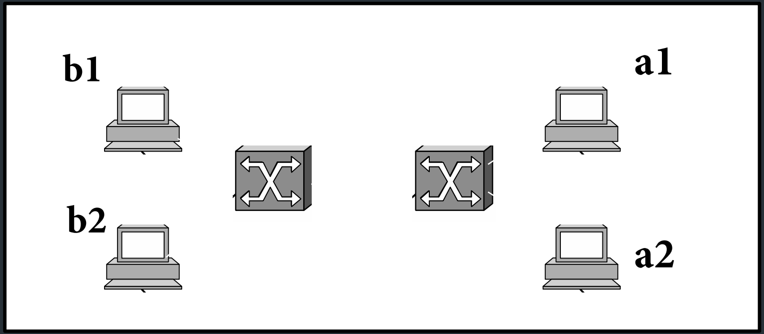
ETHERNET

COLLISION DETECTION



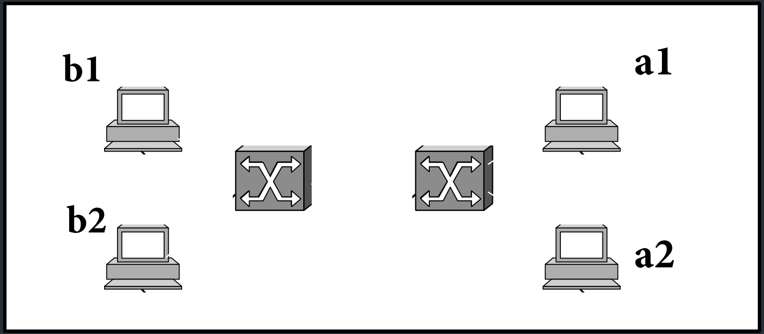
HIDDEN TERMINAL PROBLEM

VLANs



VLANs

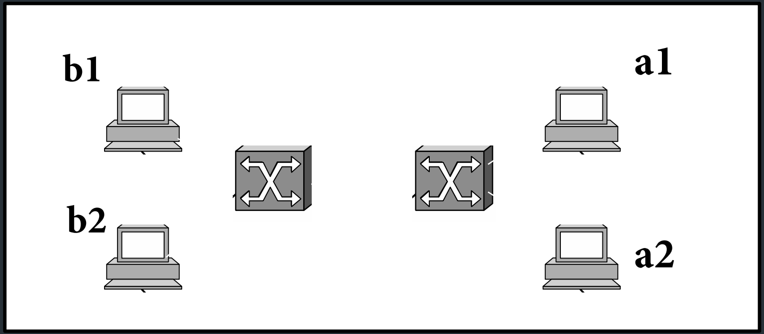
Consider: Company network, A and B departments



VLANs

Consider: Company network, A and B departments

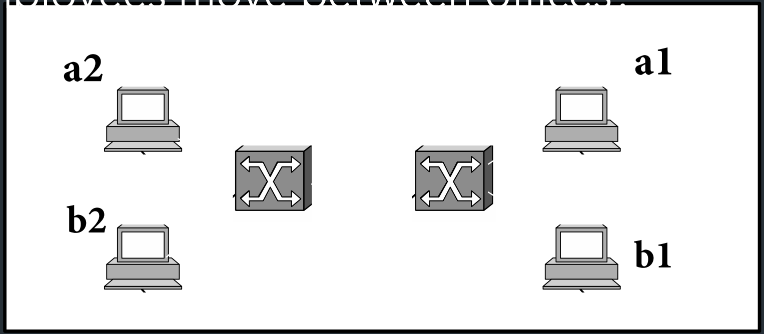
- Broadcast traffic does not scale
- May not want traffic between the two departments
- Topology has to mirror physical locations



VLANs

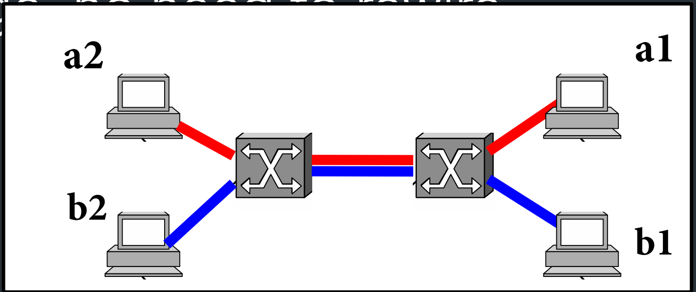
Consider: Company network, A and B departments

- Broadcast traffic does not scale
- May not want traffic between the two departments
- Topology has to mirror physical locations
- What if employees move between offices?



VLANs

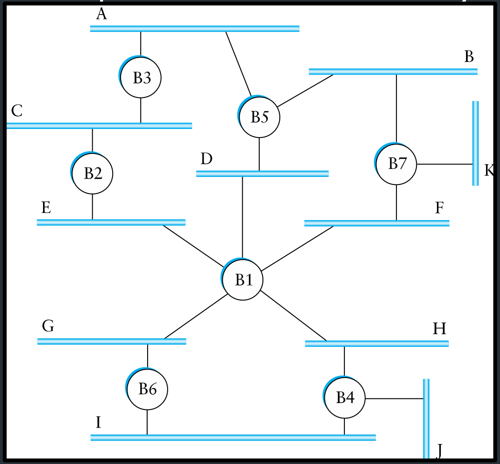
- Solution: Virtual LANs
  - Assign switch ports to a VLAN ID (color)
  - Isolate traffic: only same color
  - Trunk links may belong to multiple VLANs
  - Encapsulate packets: add 12-bit VLAN ID
- Easy to change, no need to rewire



Dealing with Loops

Problem: people may create loops in LAN!

- Accidentally, or to provide redundancy
- Don’t want to forward packets indefinitely

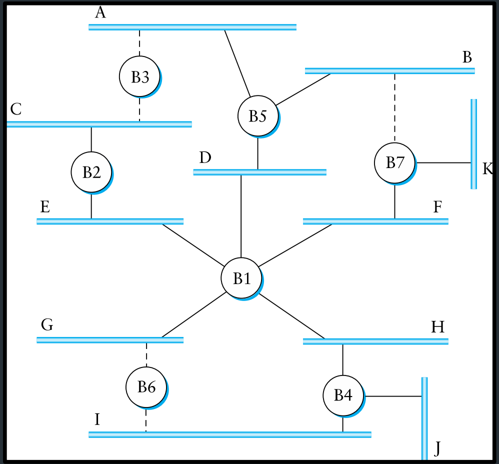


Enter Radia Perlman

"…we have designed an algorithm that allows the extended network to consist of an arbitrary topology. (…) The algorithm (…) computes a subset of the topology that connects all LANs yet is loop-free (a spanning tree)."

Perlman, Radia (1985). "An Algorithm for Distributed Computation of a Spanning Tree in an Extended LAN". *ACM SIGCOMM Computer Communication Review*. **15** (4): 44–53. doi:10.1145/318951.319004

Spanning Tree



- Need to disable ports, so that no loops in network
- Like creating a spanning tree in a graph
  - View switches and networks as nodes, ports as edges

Distributed Spanning Tree Algorithm

- Every bridge has a unique ID (Ethernet address)
- Goal:
  - Bridge with the smallest ID is the root
  - Each segment has one designated bridge, responsible for forwarding its packets towards the root
    - Bridge closest to root is designated bridge
    - If there is a tie, bridge with lowest ID wins

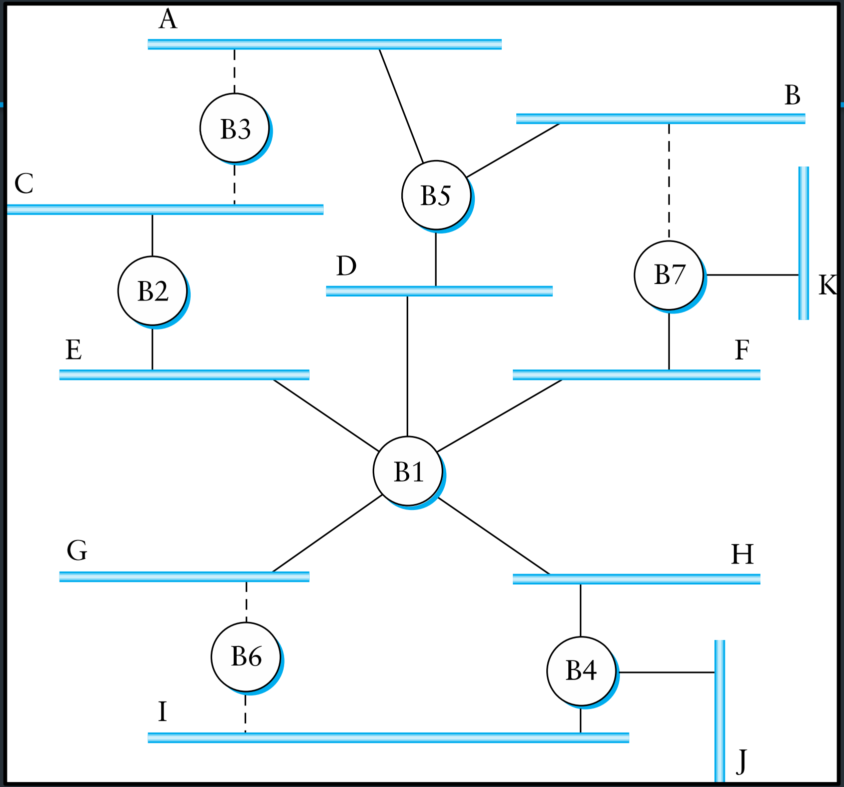
Spanning Tree Protocol

- Send message when you think you are the root
- Otherwise, forward messages from best known root
  - Add one to distance before forwarding
  - Don’t forward over discarding ports (see next slide)
- Switches pick best configuration from each port (lowest cost to root)
- In the end, only root is generating messages

Spanning Tree Protocol (cont.)

- Forwarding and Broadcasting
- Port states*:
  - **Root port**: a port the bridge uses to reach the root
  - **Designated port**: the lowest-cost port attached to a single segment
  - If a port is not a root port or a designated port, it is a **discarding port**.

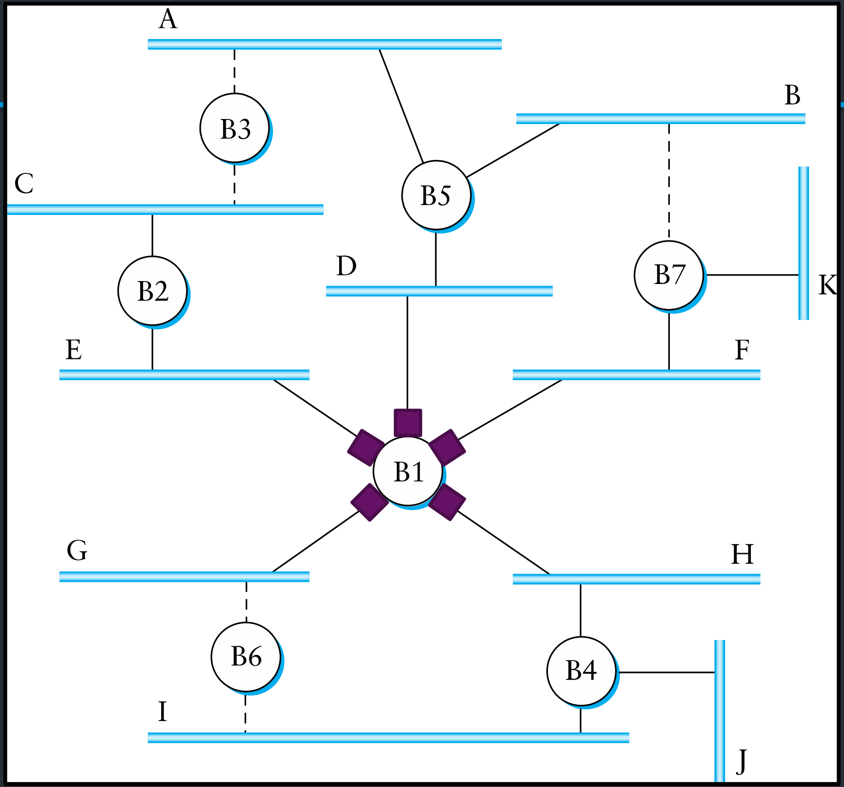
* In a later protocol RSTP, there can be ports configured as backups and alternates.



▲ Root Port

■ Designated Port

🚫 Discarding Port



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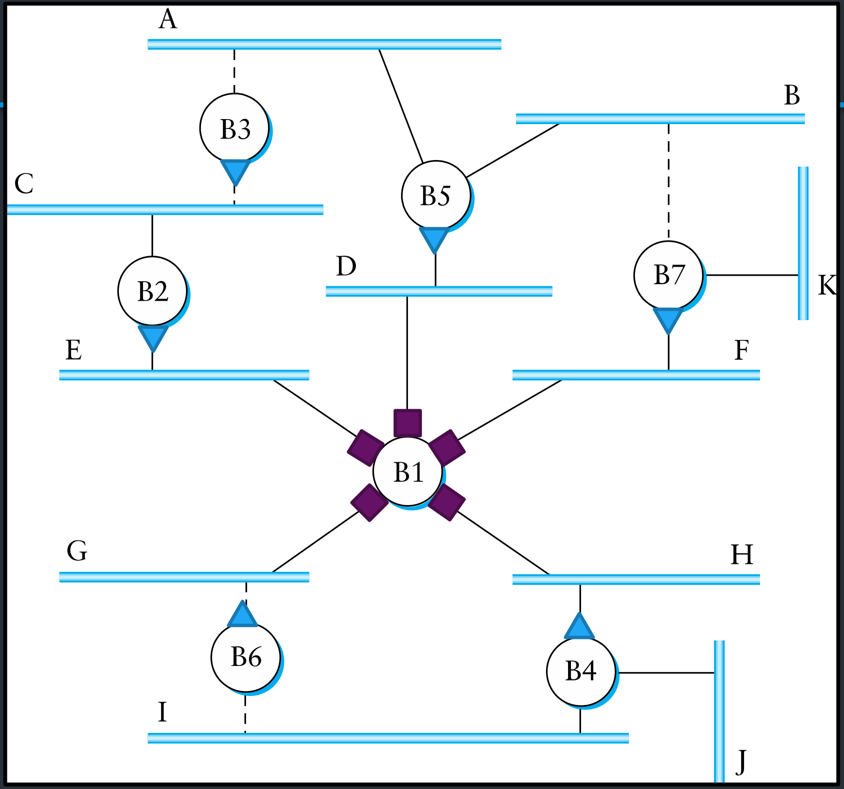

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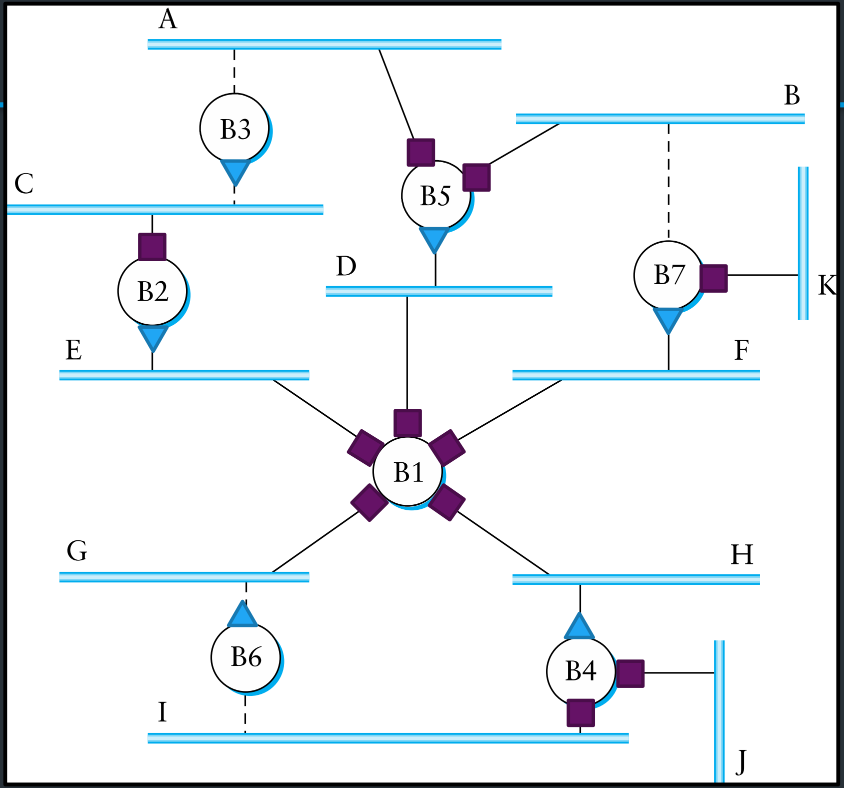

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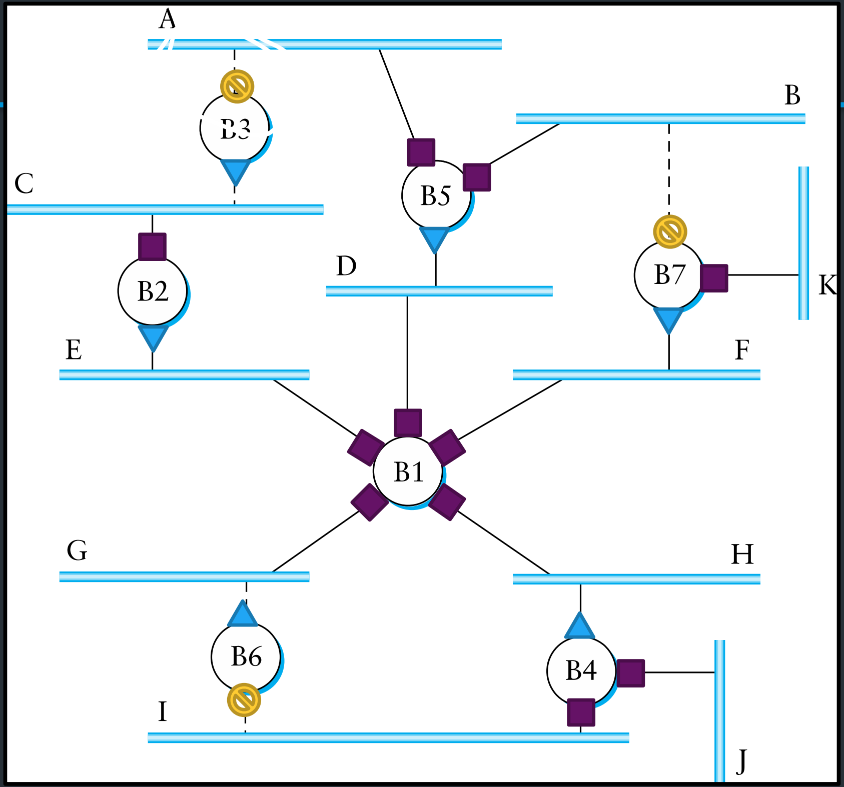

▲ Root Port

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🚫 Discarding Port

Algorhyme

I think that I shall never see
a graph more lovely that a tree.
A tree whose crucial property
is loop-free connectivity.
A tree that must be sure to span
so packet can reach every LAN.
First the root must be selected.
By ID, it is elected.
Least cost paths from root are traced.
In the tree, these paths are placed.
A mesh is made by folks like me,
then bridges find a spanning tree.

Radia Perlman

Modern Spanning Tree

Modern Spanning Tree

- Does this scale?

Modern Spanning Tree

- Does this scale?

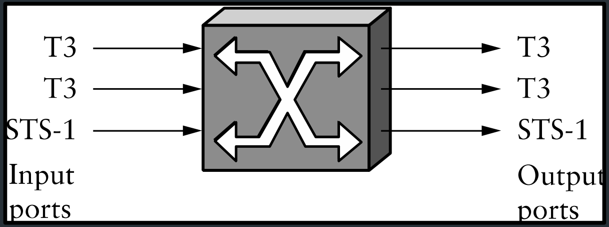
Modern STP variants

- Rapid Spanning Tree Protocol
- Multiple Spanning Tree Protocol
- Shortest Path Bridging

BACKUP LINKS

— SHARED / "BONDED" LINKS

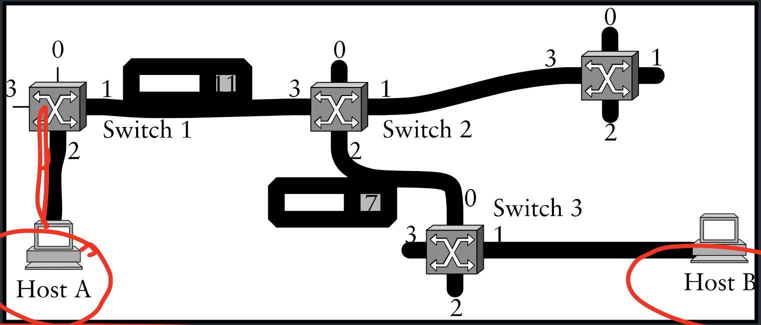
Switching



Switches must be able to, given a packet, determine the outgoing port

- 3 ways to do this:
  - Virtual Circuit Switching
  - Datagram Switching
  - Source Routing

Virtual Circuit Switching



- Explicit set-up and tear down phases
  - Establishes Virtual Circuit Identifier on each link
  - Each switch stores VC table
- Subsequent packets follow same path
  - Switches map [in-port, in-VCI] : [out-port, out-VCI]
- Also called connection-oriented model

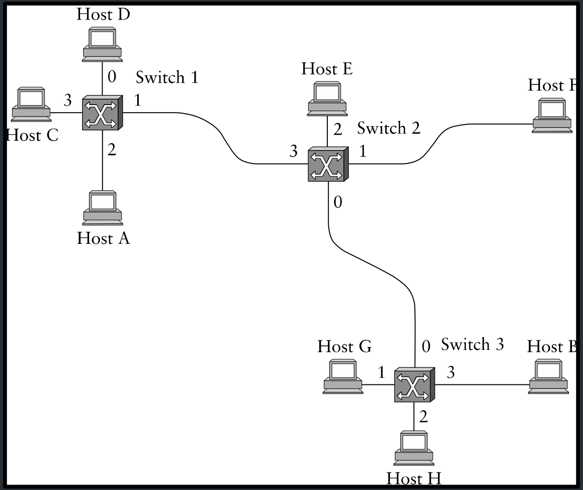
- SETUP COST TO ALLOCATE PATH

- "RESERVE CAPACITY"

Virtual Circuit Model

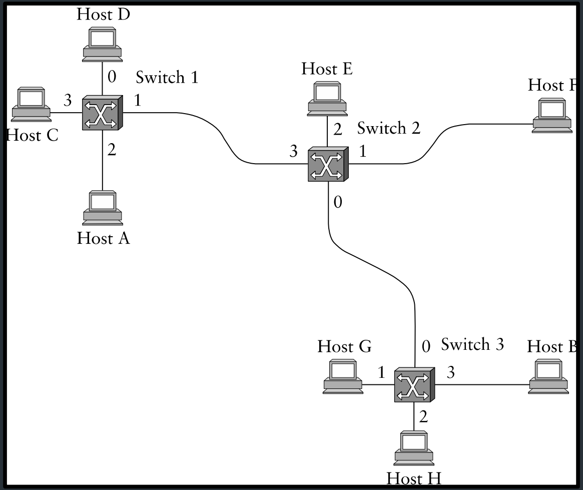
- Requires one RTT before sending first packet
- Connection request contain full destination address, subsequent packets only small VCI
- Setup phase allows reservation of resources, such as bandwidth or buffer-space
  - Any problems here?
- If a link or switch fails, must re-establish whole circuit
- Example: ATM, MPLS

Datagram Switching



Datagram Switching

- Each packet carries destination address



Datagram Switching

- Each packet carries destination address
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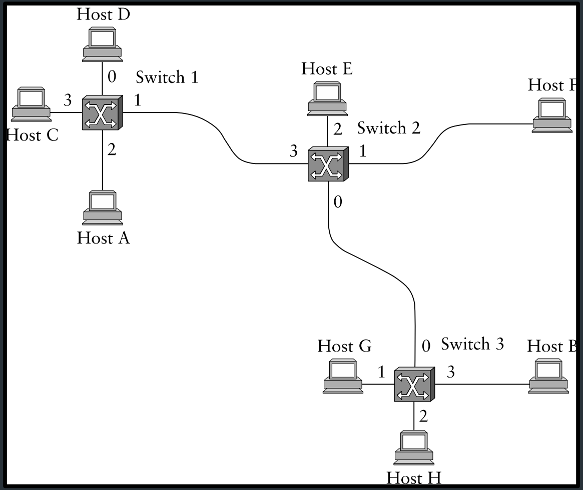
  - Maps [destination address]:[out-port]



Datagram Switching

BUILD w/ MAC LEARNING

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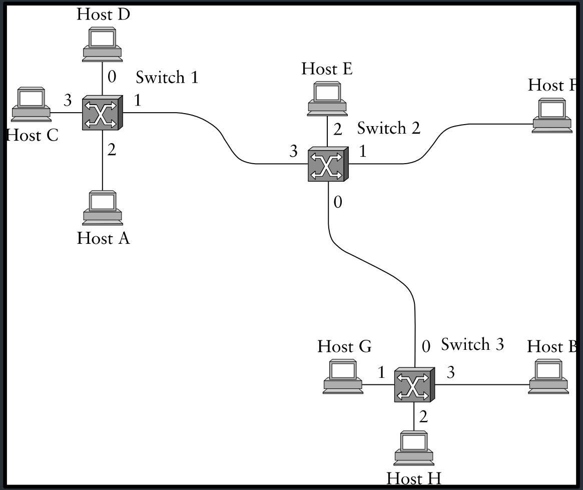

Switch 2

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

Datagram Switching

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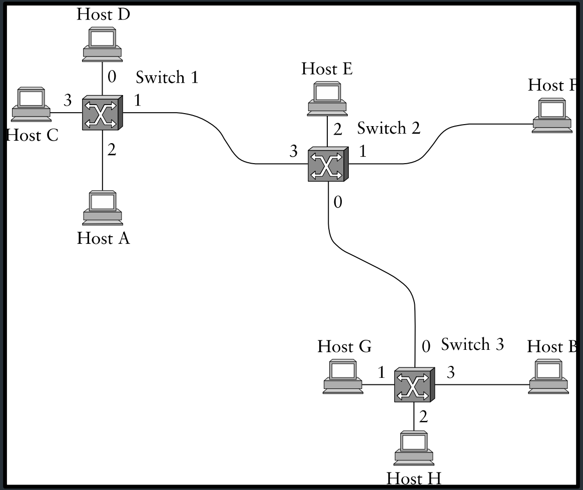
    - Maps [destination address]:[out-port]
- Also called connectionless model



Switch 2

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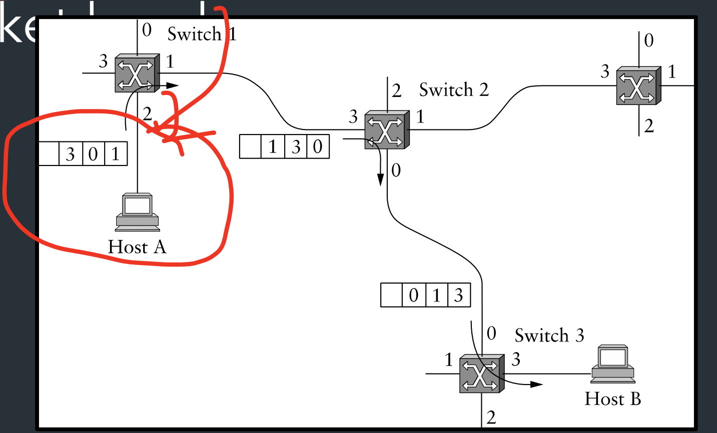
Datagram Switching

- No delay for connection setup
- Source can’t know if network can deliver a packet
- Possible to route around failures
- Higher overhead per-packet
- Potentially larger tables at switches

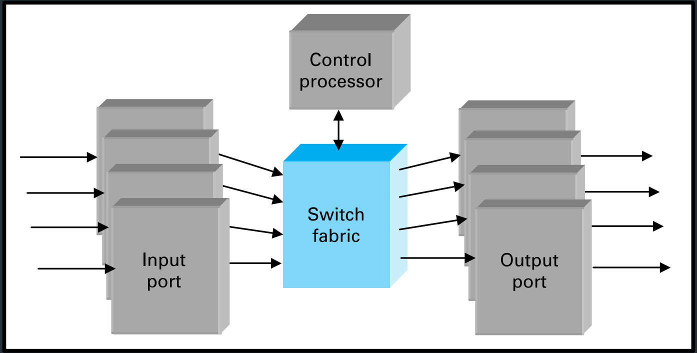
Source Routing

- Packets carry entire route: ports
- Switches need no tables!
  - But end hosts must obtain the path information
- Variable packe



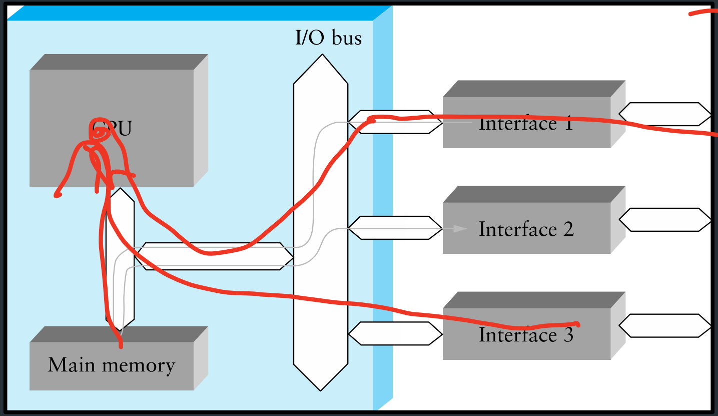
Generic Switch Architecture

- Goal: deliver packets from input to output ports
- Three potential performance concerns:
  - Throughput in bytes/second
  - Throughput in packets/second
  - Latency



Shared Memory Switch

- 1st Generation – like a regular PC



- TRANSIT CPU, MAIN MEMORY

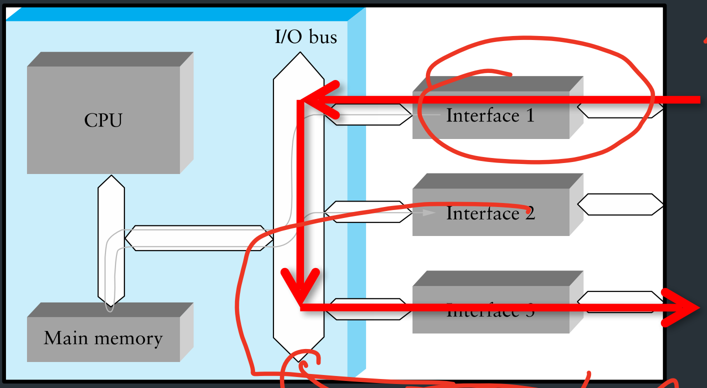
- LOW THROUGHPUT

< 1 GBPS

Shared Bus Switch

- 2^{st} Generation
  - NIC has own processor, cache of forwarding table
  - Shared bus, doesn't have to go to main memory

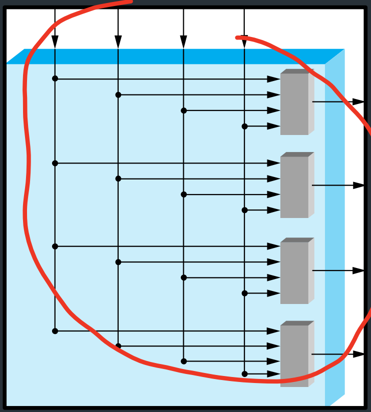
DMA (DIRECT MEM ACCESS)



I/O BUS IS LIMITING FACTOR

Point to Point Switch

- 3rd Generation: overcomes single-bus bottleneck
- Example: Cross-bar switch
  - Any input-output permutation
  - Multiple inputs to same output requires trickery
  - Cisco 12000 series: 60Gbps



EXPENSIVE TO "WIRE"

Cut through vs. Store and Forward

Cut through vs. Store and Forward

- Two approaches to forwarding a packet ✓
  - Receive a full packet, then send to output port
  - Start retransmitting as soon as you know output port, before full packet

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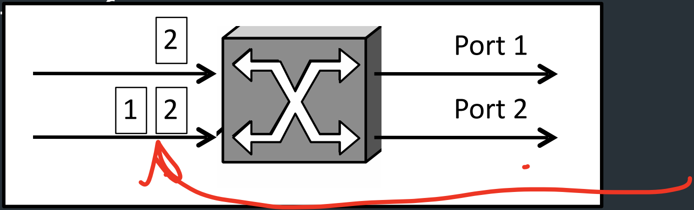
  - Receive a full packet, then send to output port
  - Start retransmitting as soon as you know output port, before full packet
- Cut-through routing can greatly decrease latency
- Disadvantage
  - Can waste transmission (classic optimistic approach)
    - CRC may be bad
    - If Ethernet collision, may have to send runt packet on output link

Buffering

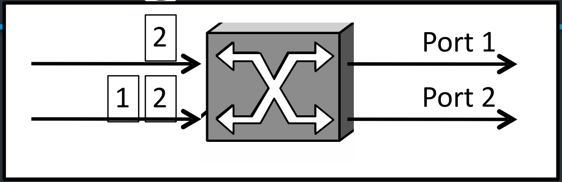
- Buffering of packets can happen at input ports, fabric, and/or output ports
- Consider FIFO + input port buffering
  - Only one packet per output port at any time
  - If multiple packets arrive for port 2, they may block packets to other ports tha



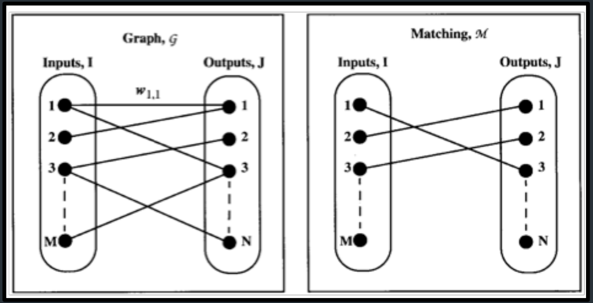
HEAD OF LINE BLOCKING

* For independent, uniform traffic, with same-size frames

Head-of-Line Blocking



- Solution: Virtual Output Queueing
  - Each input port has n FIFO queues, one for each output
  - Switch using matching in a bipartite graph
  - Shown to achieve 100% throughput*

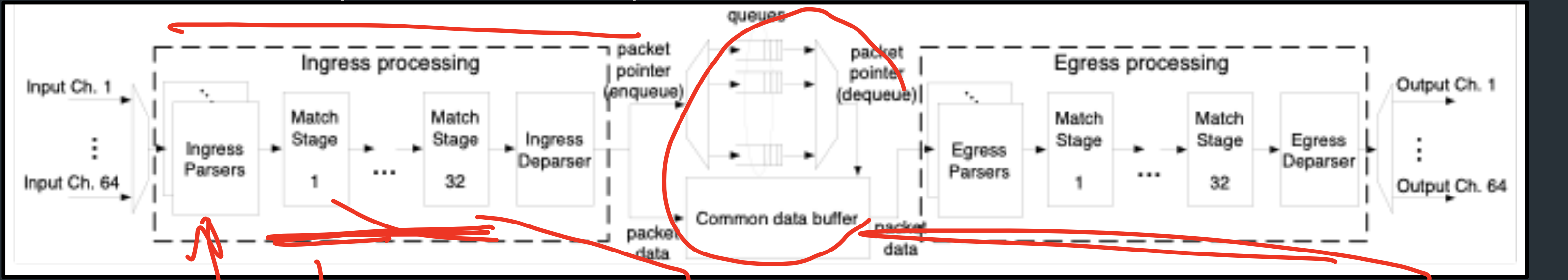


*MCKEOWN *et al.*: ACHIEVING 100% THROUGHPUT IN AN INPUT-QUEUED SWITCH, 1999

Current Developments

MATCH-ACTION PARADIGM.

- Switches are becoming programmable
  - Custom protocols, encapsulation, metering, monitoring



MAC ADDR VLAN TAG

- Current speeds reach 12.8Tbps (32x400Gbps or 256x50Gbps) on a single programmable switching chip

We did not cover these…

Medium Access Control

- Control access to shared physical medium
  - E.g., who can talk when?
  - If everyone talks at once, no one hears anything]

- Two conflicting goals
  - Maximize utilization when one node sending
  - Approach 1/N allocation when N nodes sending

Different Approaches

- Partitioned Access
  - Time Division Multiple Access (TDMA)
  - Frequency Division Multiple Access (FDMA)
  - Code Division Multiple Access (CDMA)

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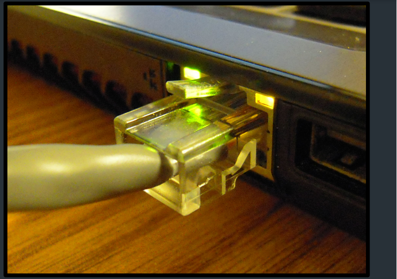
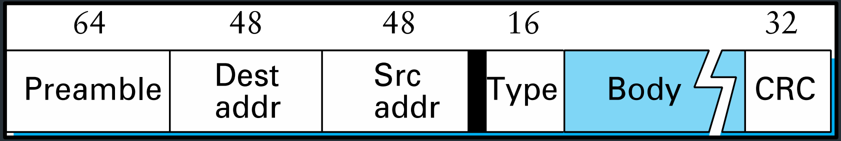
- Partitioned Access
  - Time Division Multiple Access (TDMA)
  - Frequency Division Multiple Access (FDMA)
  - Code Division Multiple Access (CDMA)
- Random Access
  - ALOHA/ Slotted ALOHA
  - Carrier Sense Multiple Access / Collision Detection (CSMA/CD)
  - Carrier Sense Multiple Access / Collision Avoidance (CSMA/CA)
  - RTS/CTS (Request to Send/Clear to Send)
  - Token-based

Ethernet (IEEE 802.3)

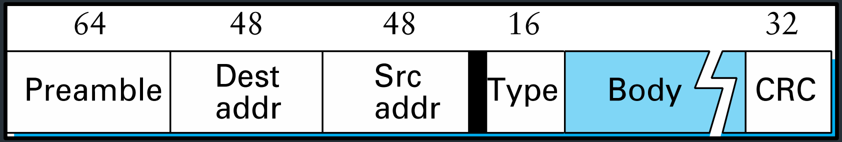


- Dominant wired LAN technology
- Original version (1983): 10Mbps
- Now: 1Gbps (1000BASE-T), 10Gbps, …
- CSMA/CD: Carrier Sense / Multiple Access / Collision Detection
- L1: Manchester encoding



64	48	48	16		32
Preamble	Dest addr	Src addr	Type	Body	CRC

Ethernet Addressing



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Globally unique, 48-bit unicast address per adapter

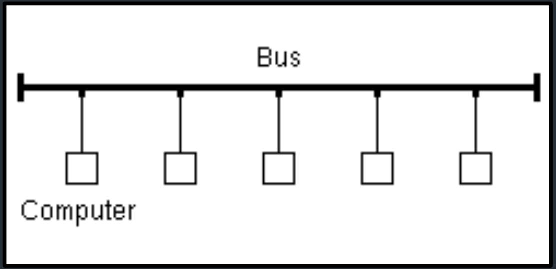
- Example: 00:1c:43:00:3d:09 (Samsung adapter)
- First 24 bits: Registered to manufacturers
- http://standards.ieee.org/develop/regauth/oui/oui.txt

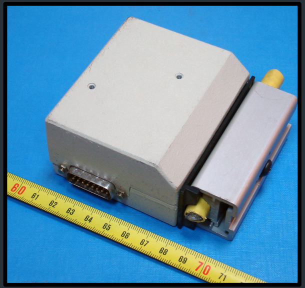
Other protocols have adopted this address format
(eg. Wifi, Bluetooth, …)

- Nowadays, we call them "mac addresses" or "hardware addresses"

Ethernet's evolution

Originally, a shared medium with all hosts





- Basic idea: all hosts can see all frames, read a frame if it matches your hardware address
- Implications?

Ethernet MAC: CSMA/CD

- Problem: shared medium, all hosts in the same “collision domain”

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- Problem: shared medium, all hosts in the same “collision domain”
- Transmit algorithm
  - If line is idle, transmit immediately
  - Upper bound message size of 1500 bytes
  - If line is busy: wait until idle and transmit immediately

Ethernet MAC: CSMA/CD

- Problem: shared medium, all hosts in the same “collision domain”
- Transmit algorithm
  - If line is idle, transmit immediately
  - Upper bound message size of 1500 bytes
  - If line is busy: wait until idle and transmit immediately
- Generally possible to detect collisions

When to transmit again?

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- Delay and try again: exponential backoff

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- nth time: k × 51.2μs, for k = $U\{0..(2^{\min(n,10)}-1)\}$
  - 1st time: 0 or 51.2μs
  - 2nd time: 0, 51.2, 102.4, or 153.6μs

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- Exponential backoff is a useful, general technique

Capture Effect

- Exponential backoff leads to self-adaptive use of channel
- A and B are trying to transmit, and collide
- Both will back off either 0 or 51.2μs
- Say A wins.

Capture Effect

- Exponential backoff leads to self-adaptive use of channel
- A and B are trying to transmit, and collide
- Both will back off either 0 or 51.2µs
- Say A wins.
- Next time, collide again.
  - A will wait between 0 or 1 slots
  - B will wait between 0, 1, 2, or 3 slots
- …

Ethernet Recap

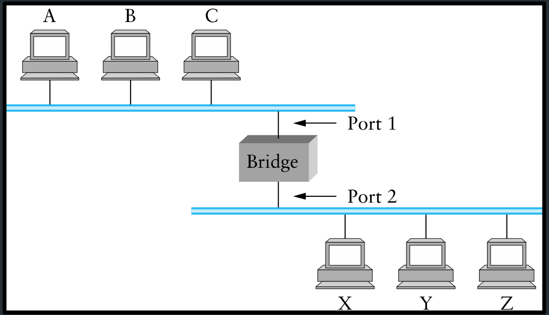
- Service provided: send frames among stations with specific addresses
- Addresses are just names, no topology information
  - Special broadcast and multicast addresses
- All nodes in the same “broadcast domain”
  - Is this what we want?

Bridges and Extended LANs

- Single Ethernet collision domain has limitations
    - Limits performance, distance, …

Bridges and Extended LANs

- Single Ethernet collision domain has limitations
  - Limits performance, distance, …
- Next step: separate collision domains with bridges
  - Operates on Ethernet addresses
  - Forwards packets from one collision domain to others



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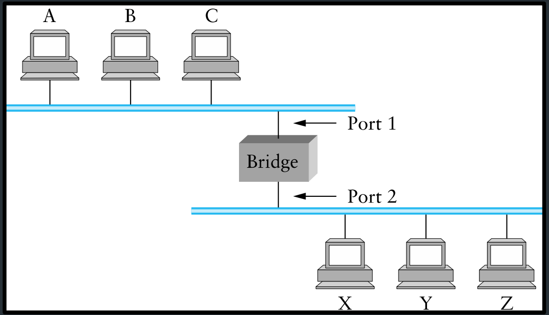
- Single Ethernet collision domain has limitations
  - Limits performance, distance, …
- Next step: separate collision domains with bridges
  - Operates on Ethernet addresses
  - Forwards packets from one collision domain to others
- Modern ethernet uses switches: all hosts directly connected to a bridge



Destinations for packets

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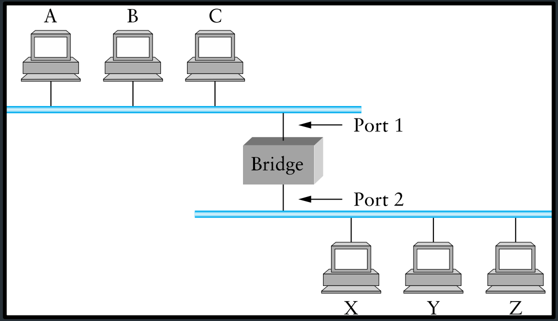
- Unicast: forward with filtering
- Broadcast: always forward
- Multicast: always forward or learn groups

- Can try to limit how we direct packets to a destination

Learning Bridges/Switches



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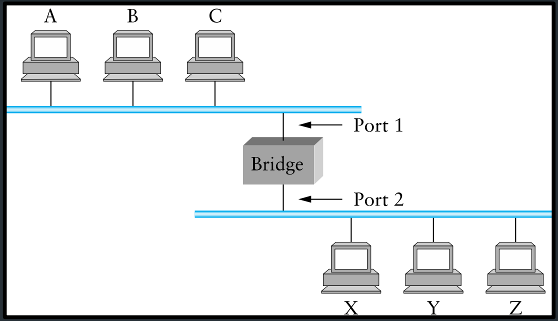

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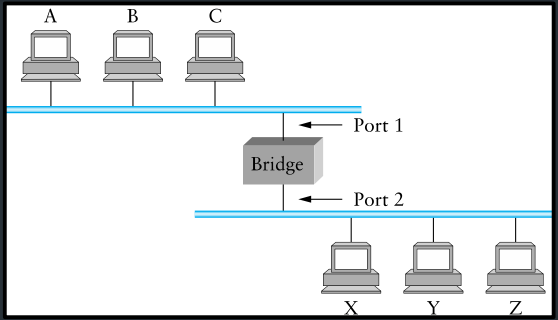

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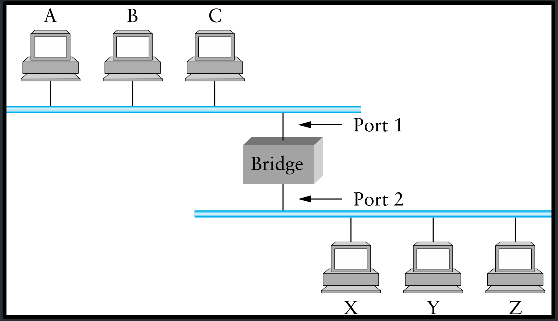

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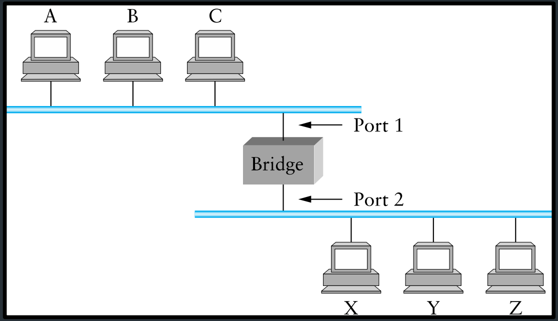

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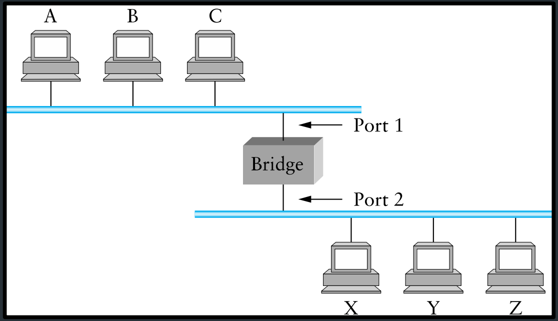

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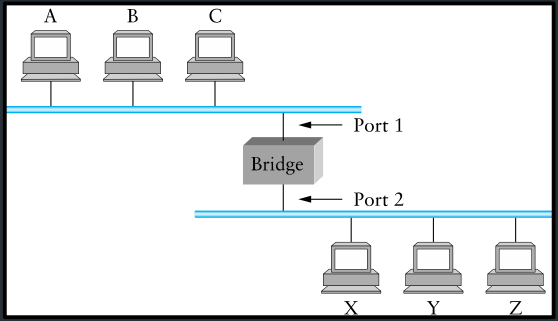

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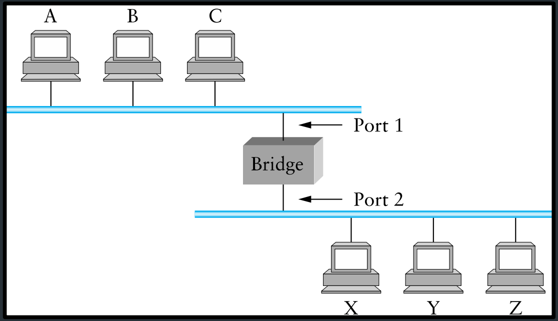

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- Table says when not to forward a packet
  - Doesn’t need to be complete for correctness

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- Different segment on a learning bridge: hard
  - Once bridge learns Bob's port, stop broadcasting
- How can Eve force the bridge to keep broadcasting?
  - Flood the network with frames with spoofed src addr!

Coming Up

- Connecting multiple networks: IP and the Network Layer