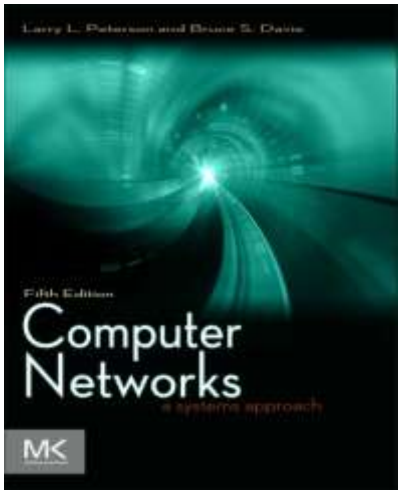


Chapter 3

Internetworking

Problems

- In Chapter 2 we saw how to connect one node to another, or to an existing network. How do we build networks of global scale?
- How do we interconnect different types of networks to build a large global network?

Chapter Outline

- Switching and Bridging
- Basic Internetworking (IP)
- Routing

Chapter Goal

- Understanding the functions of switches, bridges and routers
- Discussing Internet Protocol (IP) for interconnecting networks
- Understanding the concept of routing

Switching and Forwarding

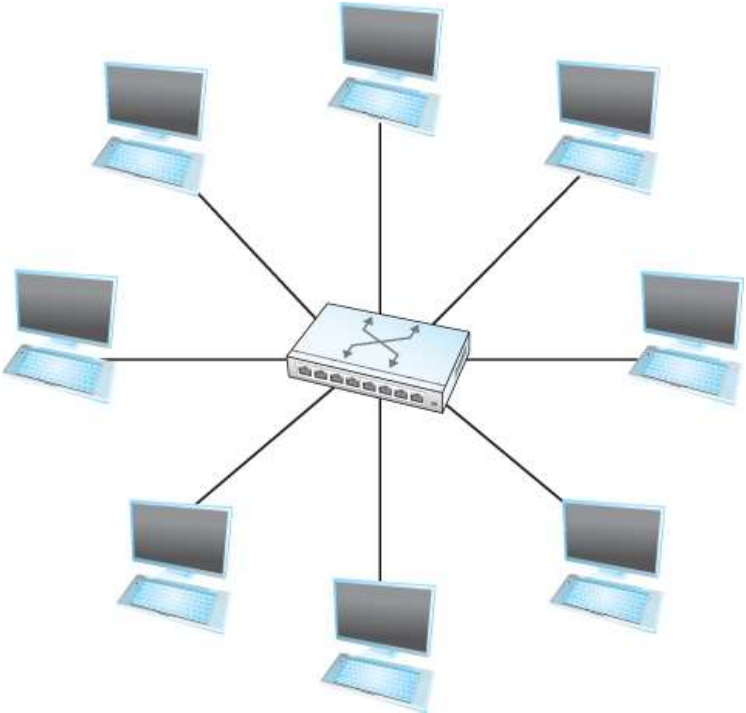
- Store-and-Forward Switches
- Bridges and Extended LANs
- Cell Switching
- Segmentation and Reassembly

Switching and Forwarding

- Switch
  - A mechanism that allows us to interconnect links to form a large network
  - A multi-input, multi-output device which transfers packets from an input to one or more outputs

Switching and Forwarding

Adds the star topology to the point-to-point link, bus (Ethernet), and ring (802.5 and FDDI) topologies



Switching and Forwarding

Properties of this star topology

- Even though a switch has a fixed number of inputs and outputs, which limits the number of hosts that can be connected to a single switch, large networks can be built by interconnecting a number of switches
- We can connect switches to each other and to hosts using point-to-point links, which typically means that we can build networks of large geographic scope
- Adding a new host to the network by connecting it to a switch does not necessarily mean that the hosts already connected will get worse performance from the network

Switching and Forwarding

The last claim cannot be made for the shared media network (discussed in Chapter 2)

- It is impossible for two hosts on the same Ethernet to transmit continuously at 10Mbps because they share the same transmission medium
- Every host on a switched network has its own link to the switch
  - So it may be entirely possible for many hosts to transmit at the full link speed (bandwidth) provided that the switch is designed with enough aggregate capacity

Switching and Forwarding

- A switch is connected to a set of links and for each of these links, runs the appropriate data link protocol to communicate with that node
- A switch's primary job is to receive incoming packets on one of its links and to transmit them on some other link
  - This function is referred as *switching and forwarding*
  - According to OSI architecture this is the main function of the network layer

Switching and Forwarding

- How does the switch decide which output port to place each packet on?
  - It looks at the header of the packet for an identifier that it uses to make the decision
  - Two common approaches
    - *Datagram or Connectionless approach*
    - *Virtual circuit or Connection-oriented approach*
  - A third approach *source routing* is less common

Switching and Forwarding

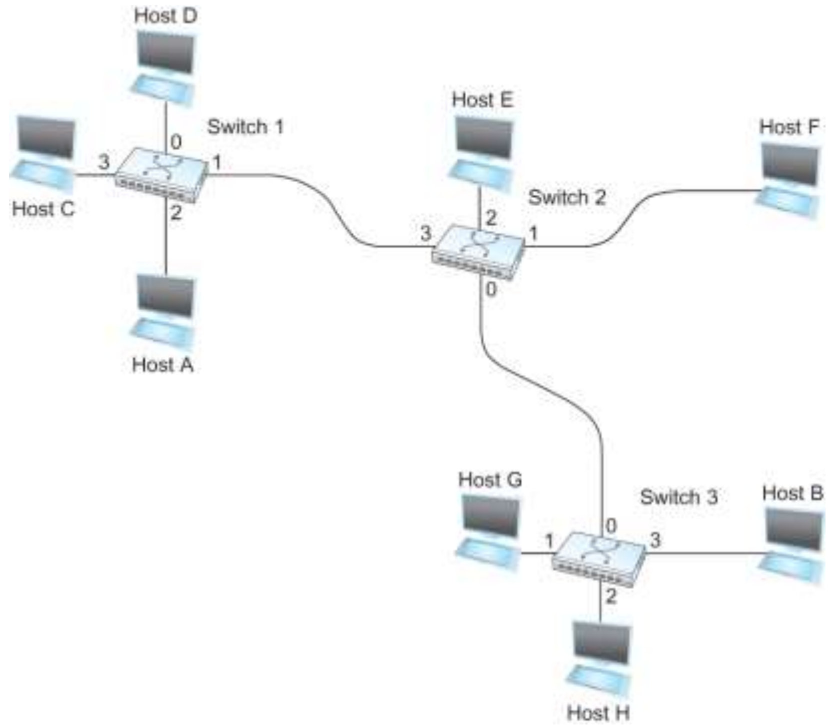
- Assumptions
  - Each host has a globally unique address
  - There is some way to identify the input and output ports of each switch
    - We can use numbers
    - We can use names

Switching and Forwarding

- Datagrams
  - Key Idea
    - Every packet contains enough information to enable any switch to decide how to get it to destination
      - Every packet contains the complete destination address

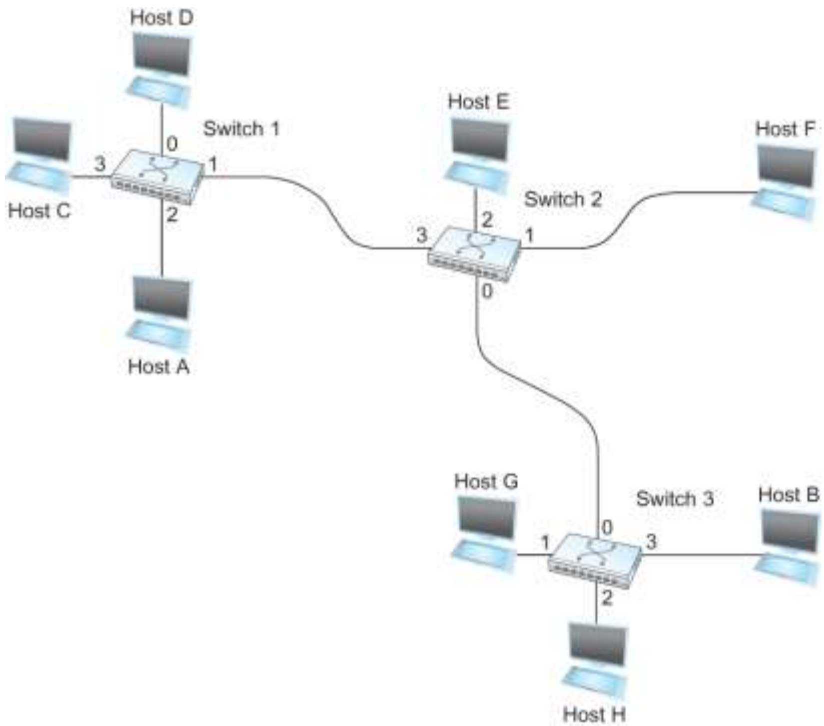
Switching and Forwarding

An example network



- To decide how to forward a packet, a switch consults a *forwarding table* (sometimes called a *routing table*)

Switching and Forwarding



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

Forwarding Table for Switch 2

Switching and Forwarding

Characteristics of Connectionless (Datagram) Network

- A host can send a packet anywhere at any time, since any packet that turns up at the switch can be immediately forwarded (assuming a correctly populated forwarding table)
- When a host sends a packet, it has no way of knowing if the network is capable of delivering it or if the destination host is even up and running
- Each packet is forwarded independently of previous packets that might have been sent to the same destination.
  - Thus two successive packets from host A to host B may follow completely different paths
- A switch or link failure might not have any serious effect on communication if it is possible to find an alternate route around the failure and update the forwarding table accordingly

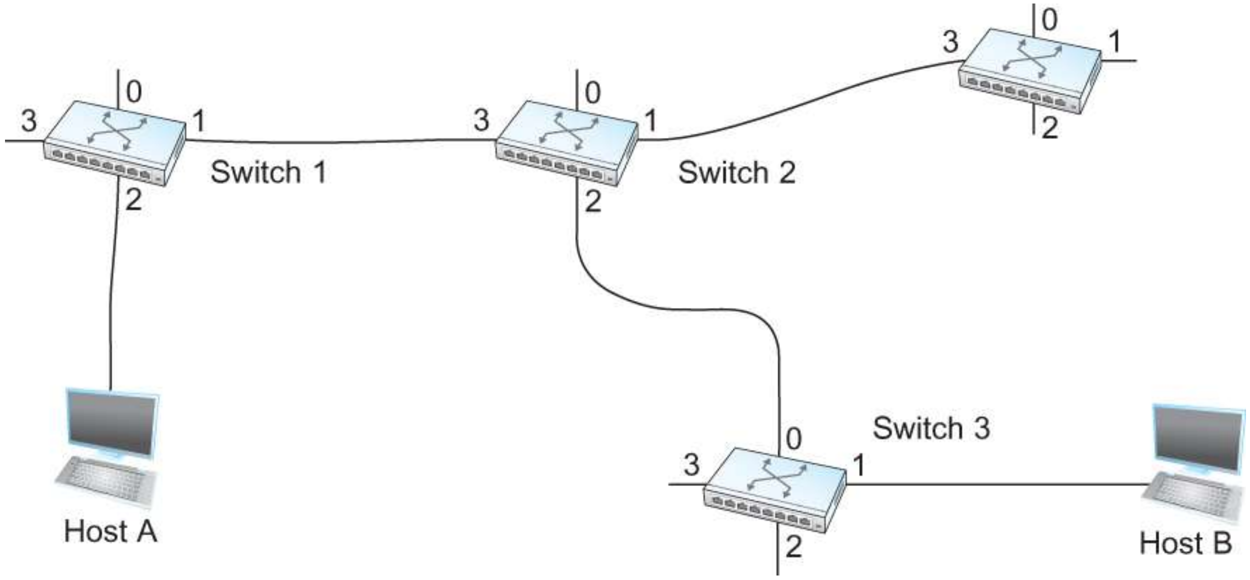
Switching and Forwarding

Virtual Circuit Switching

- Widely used technique for packet switching
- Uses the concept of *virtual circuit* (VC)
- Also called a connection-oriented model
- First set up a virtual connection from the source host to the destination host and then send the data

Switching and Forwarding

- Host A wants to send packets to host B



Switching and Forwarding

Two-stage process

- Connection setup
- Data Transfer

- Connection setup
  - Establish "connection state" in each of the switches between the source and destination hosts
  - The connection state for a single connection consists of an entry in the "VC table" in each switch through which the connection passes

Switching and Forwarding

One entry in the VC table on a single switch contains

- A virtual circuit identifier (VCI) that uniquely identifies the connection at this switch and that will be carried inside the header of the packets that belong to this connection
- An incoming interface on which packets for this VC arrive at the switch
- An outgoing interface in which packets for this VC leave the switch
- A potentially different VCI that will be used for outgoing packets

- The semantics for one such entry is
  - If a packet arrives on the designated incoming interface and that packet contains the designated VCI value in its header, then the packet should be sent out the specified outgoing interface with the specified outgoing VCI value first having been placed in its header

Switching and Forwarding

Note:

- The combination of the VCI of the packets as they are received at the switch and the interface on which they are received uniquely identifies the virtual connection
- There may be many virtual connections established in the switch at one time
- Incoming and outgoing VCI values are not generally the same
  - VCI is not a globally significant identifier for the connection; rather it has significance only on a given link
- Whenever a new connection is created, we need to assign a new VCI for that connection on each link that the connection will traverse
  - We also need to ensure that the chosen VCI on a given link is not currently in use on that link by some existing connection.

Switching and Forwarding

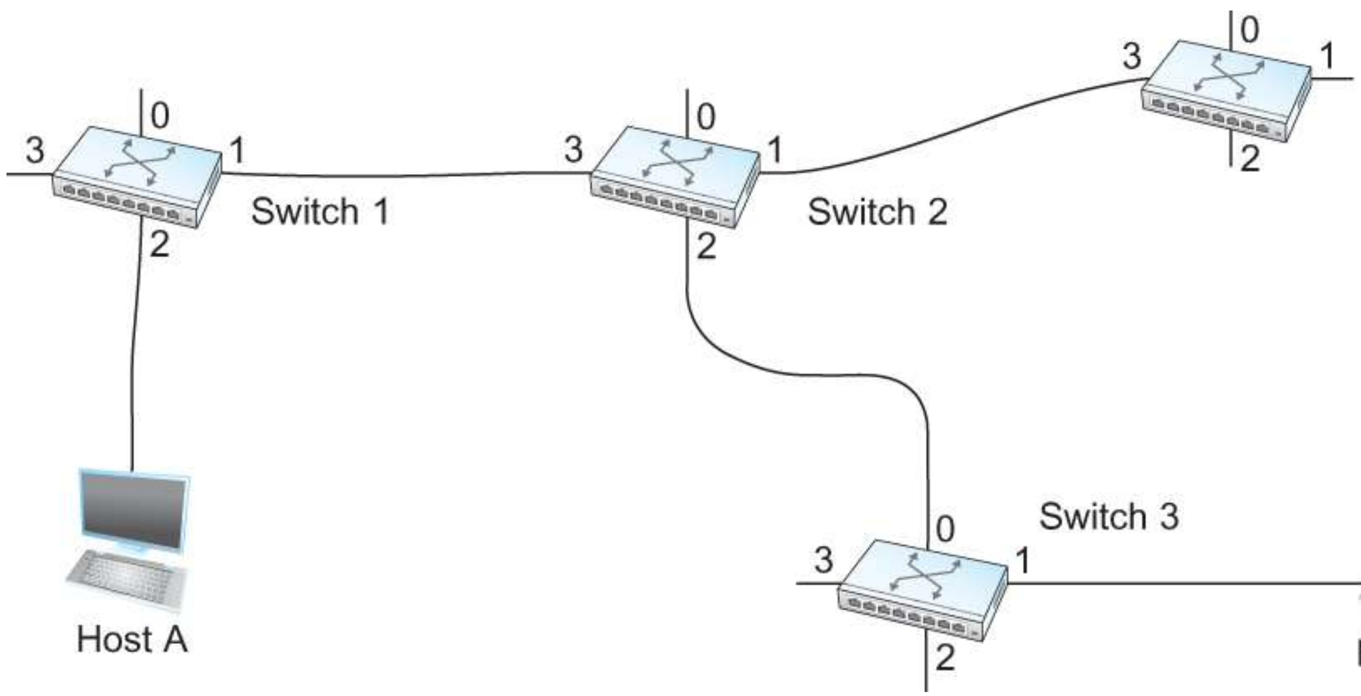
Two broad classes of approach to establishing connection state

- Network Administrator will configure the state
  - The virtual circuit is permanent (PVC)
  - The network administrator can delete this
  - Can be thought of as a long-lived or administratively configured VC
- A host can send messages into the network to cause the state to be established
  - This is referred as signalling and the resulting virtual circuit is said to be switched (SVC)
  - A host may set up and delete such a VC dynamically without the involvement of a network administrator

Switching and Forwarding

Let's assume that a network administrator wants to manually create a new virtual connection from host A to host B

- First the administrator identifies a path through the network from A to B



Switching and Forwarding

The administrator then picks a VCI value that is currently unused on each link for the connection

- For our example,
  - Suppose the VCI value 5 is chosen for the link from host A to switch 1
  - 11 is chosen for the link from switch 1 to switch 2
  - So the switch 1 will have an entry in the VC table

Incoming Interface	Incoming VC	Outgoing Interface	Outgoing VC
2	5	1	11

Switching and Forwarding

Similarly, suppose

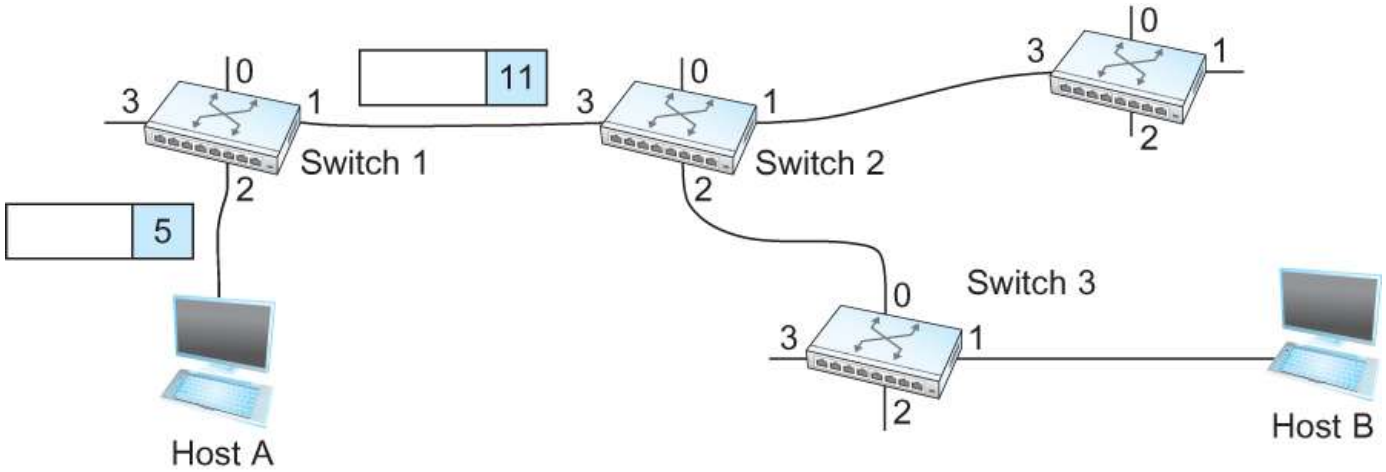
- VCI of 7 is chosen to identify this connection on the link from switch 2 to switch 3
- VCI of 4 is chosen for the link from switch 3 to host B
- Switches 2 and 3 are configured with the following VC table

Incoming Interface	Incoming VC	Outgoing Interface	Outgoing VC
3	11	2	7

Incoming Interface	Incoming VC	Outgoing Interface	Outgoing VC
0	7	1	4

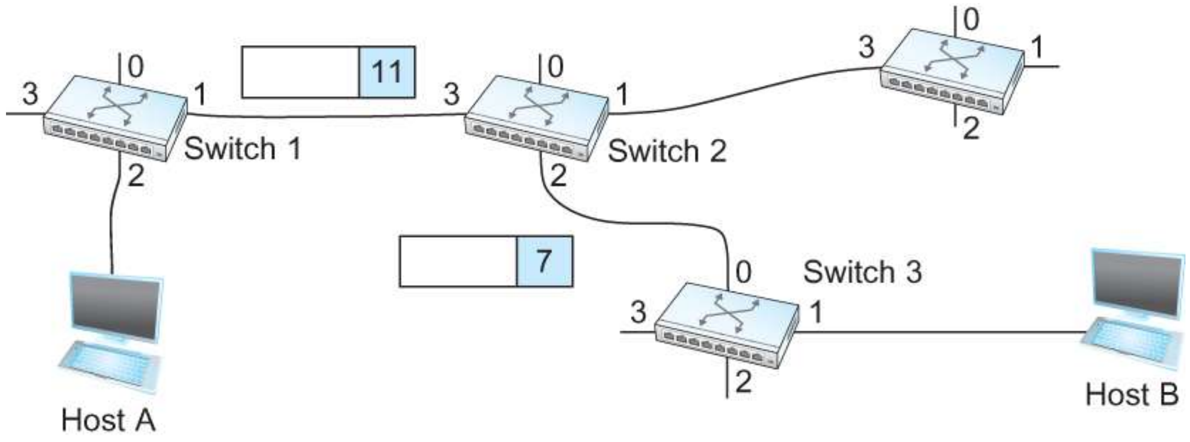
Switching and Forwarding

- For any packet that A wants to send to B, A puts the VCI value 5 in the header of the packet and sends it to switch 1
- Switch 1 receives any such packet on interface 2, and it uses the combination of the interface and the VCI in the packet header to find the appropriate VC table entry.
- The table entry on switch 1 tells the switch to forward the packet out of interface 1 and to put the VCI value 11 in the header



Switching and Forwarding

- Packet will arrive at switch 2 on interface 3 bearing VCI 11
- Switch 2 looks up interface 3 and VCI 11 in its VC table and sends the packet on to switch 3 after updating the VCI value appropriately
- This process continues until it arrives at host B with the VCI value of 4 in the packet
- To host B, this identifies the packet as having come from host A



Switching and Forwarding

- In real networks of reasonable size, the burden of configuring VC tables correctly in a large number of switches would quickly become excessive
  - Thus, some sort of signalling is almost always used, even when setting up “permanent” VCs
  - In case of PVCs, signalling is initiated by the network administrator
  - SVCs are usually set up using signalling by one of the hosts

Switching and Forwarding

- How does the signalling work
  - To start the signalling process, host A sends a setup message into the network (i.e. to switch 1)
    - The setup message contains (among other things) the complete destination address of B.
    - The setup message needs to get all the way to B to create the necessary connection state in every switch along the way
    - It is like sending a datagram to B where every switch knows which output to send the setup message so that it eventually reaches B
    - Assume that every switch knows the topology to figure out how to do that
  - When switch 1 receives the connection request, in addition to sending it on to switch 2, it creates a new entry in its VC table for this new connection
    - The entry is exactly the same shown in the previous table
    - Switch 1 picks the value 5 for this connection

Switching and Forwarding

- How does the signalling work (contd.)
  - When switch 2 receives the setup message, it performs the similar process and it picks the value 11 as the incoming VCI
  - Similarly switch 3 picks 7 as the value for its incoming VCI
    - Each switch can pick any number it likes, as long as that number is not currently in use for some other connection on that port of that switch
  - Finally the setup message arrives at host B.
  - Assuming that B is healthy and willing to accept a connection from host A, it allocates an incoming VCI value, in this case 4.
    - This VCI value can be used by B to identify all packets coming from A

Switching and Forwarding

- Now to complete the connection, everyone needs to be told what their downstream neighbor is using as the VCI for this connection
  - Host B sends an acknowledgement of the connection setup to switch 3 and includes in that message the VCI value that it chose (4)
  - Switch 3 completes the VC table entry for this connection and sends the acknowledgement on to switch 2 specifying the VCI of 7
  - Switch 2 completes the VC table entry for this connection and sends acknowledgement on to switch 1 specifying the VCI of 11
  - Finally switch 1 passes the acknowledgement on to host A telling it to use the VCI value of 5 for this connection

Switching and Forwarding

- When host A no longer wants to send data to host B, it tears down the connection by sending a teardown message to switch 1
- The switch 1 removes the relevant entry from its table and forwards the message on to the other switches in the path which similarly delete the appropriate table entries
- At this point, if host A were to send a packet with a VCI of 5 to switch 1, it would be dropped as if the connection had never existed

Switching and Forwarding

- Characteristics of VC
  - Since host A has to wait for the connection request to reach the far side of the network and return before it can send its first data packet, there is at least one RTT of delay before data is sent
  - While the connection request contains the full address for host B (which might be quite large, being a global identifier on the network), each data packet contains only a small identifier, which is only unique on one link.
    - Thus the per-packet overhead caused by the header is reduced relative to the datagram model
  - If a switch or a link in a connection fails, the connection is broken and a new one will need to be established.
    - Also the old one needs to be torn down to free up table storage space in the switches
  - The issue of how a switch decides which link to forward the connection request on has similarities with the function of a routing algorithm

Switching and Forwarding

- Good Properties of VC
  - By the time the host gets the go-ahead to send data, it knows quite a lot about the network-
    - For example, that there is really a route to the receiver and that the receiver is willing to receive data
  - It is also possible to allocate resources to the virtual circuit at the time it is established

Switching and Forwarding

- For example, an X.25 network – a packet-switched network that uses the connection-oriented model – employs the following three-part strategy
  - Buffers are allocated to each virtual circuit when the circuit is initialized
  - The sliding window protocol is run between each pair of nodes along the virtual circuit, and this protocol is augmented with the flow control to keep the sending node from overrunning the buffers allocated at the receiving node
  - The circuit is rejected by a given node if not enough buffers are available at that node when the connection request message is processed

Switching and Forwarding

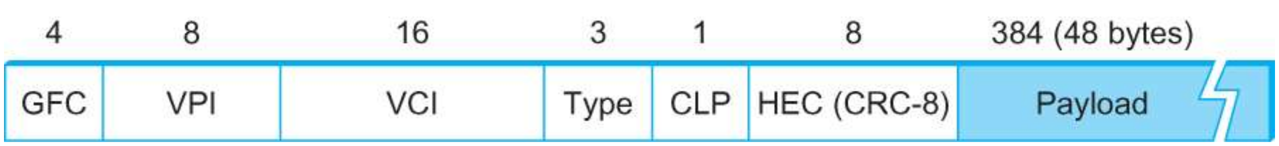
- Comparison with the Datagram Model
  - Datagram network has no connection establishment phase and each switch processes each packet independently
  - Each arriving packet competes with all other packets for buffer space
  - If there are no buffers, the incoming packet must be dropped
- In VC, we could imagine providing each circuit with a different quality of service (QoS)
  - The network gives the user some kind of performance related guarantee
    - Switches set aside the resources they need to meet this guarantee
      - For example, a percentage of each outgoing link's bandwidth
      - Delay tolerance on each switch
- Most popular examples of VC technologies are Frame Relay and ATM
  - One of the applications of Frame Relay is the construction of VPN

Switching and Forwarding

- ATM (Asynchronous Transfer Mode)
  - Connection-oriented packet-switched network
  - Packets are called cells
    - 5 byte header + 48 byte payload
  - Fixed length packets are easier to switch in hardware
    - Simpler to design
    - Enables parallelism

Switching and Forwarding

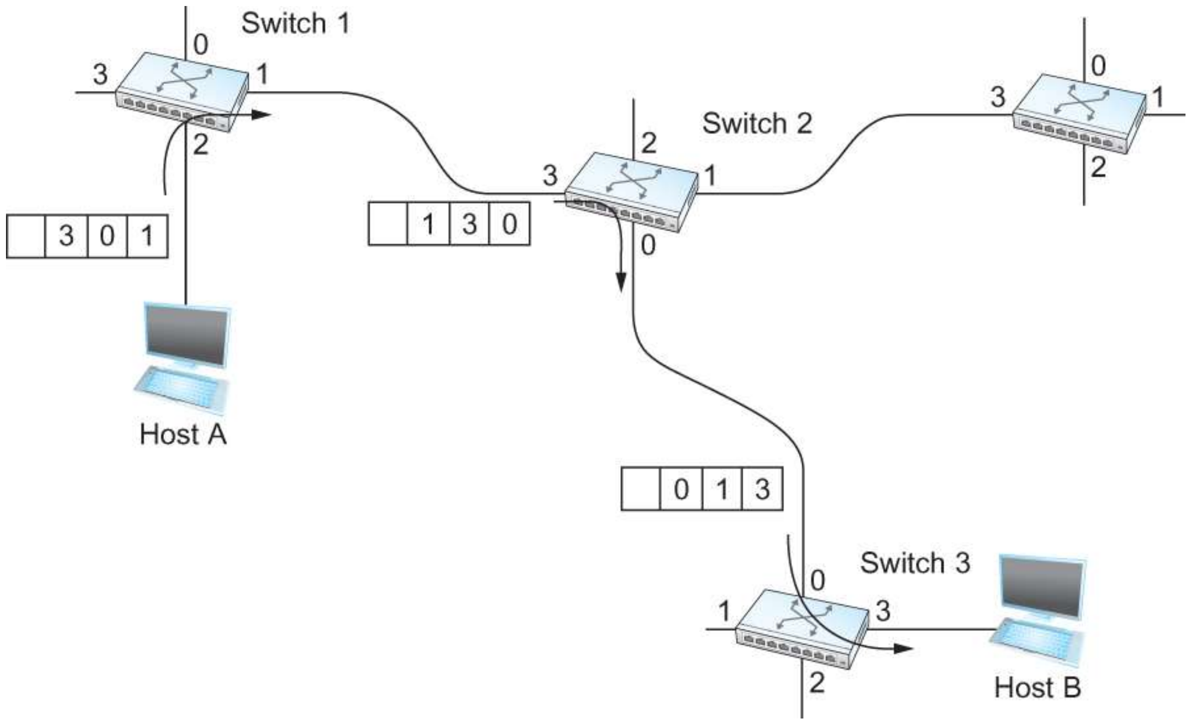
- ATM
  - User-Network Interface (UNI)
    - Host-to-switch format
    - GFC: Generic Flow Control
    - VCI: Virtual Circuit Identifier
    - Type: management, congestion control
    - CLP: Cell Loss Priority
    - HEC: Header Error Check (CRC-8)



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

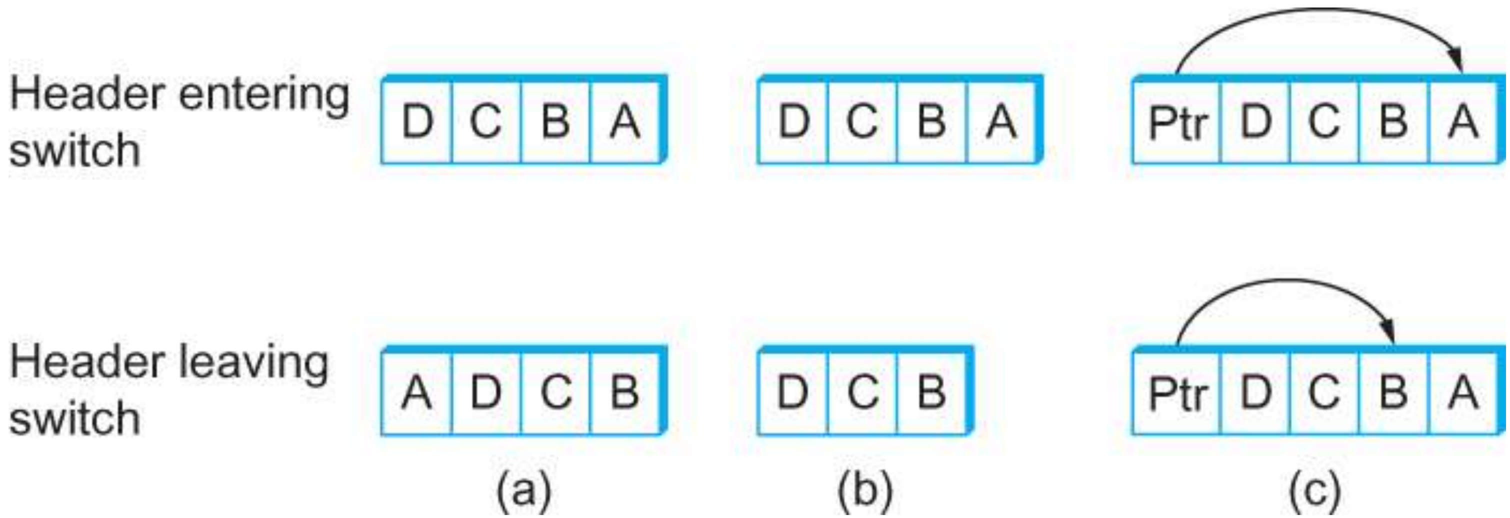
Switching and Forwarding

- Source Routing
  - All the information about network topology that is required to switch a packet across the network is provided by the source host



Switching and Forwarding

- Other approaches in Source Routing



Bridges and LAN Switches

- Bridges and LAN Switches
  - Class of switches that is used to forward packets between shared-media LANs such as Ethernets
    - Known as LAN switches
    - Referred to as Bridges
  - Suppose you have a pair of Ethernets that you want to interconnect
    - One approach is put a repeater in between them
      - It might exceed the physical limitation of the Ethernet
        - No more than four repeaters between any pair of hosts
        - No more than a total of 2500 m in length is allowed
    - An alternative would be to put a node between the two Ethernets and have the node forward frames from one Ethernet to the other
      - This node is called a **Bridge**
      - A collection of LANs connected by one or more bridges is usually said to form an **Extended LAN**

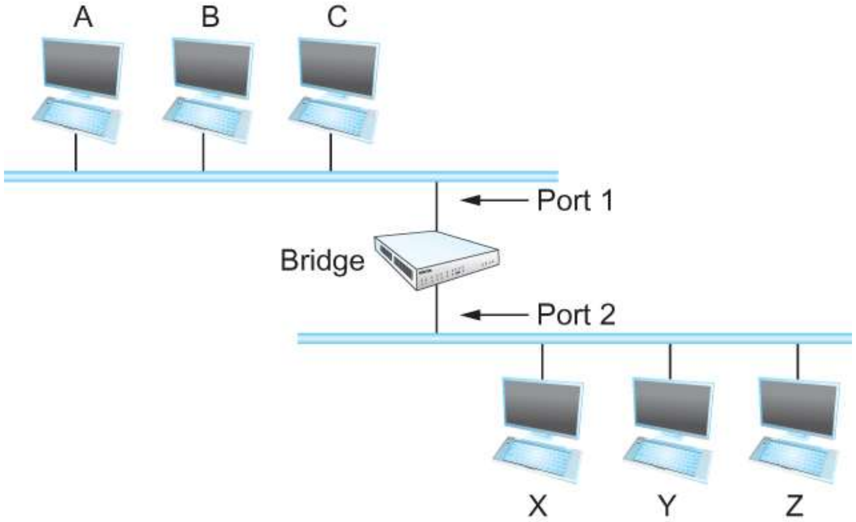
Bridges and LAN Switches

- Simplest Strategy for Bridges
  - Accept LAN frames on their inputs and forward them out to all other outputs
  - Used by early bridges

- Learning Bridges
  - Observe that there is no need to forward all the frames that a bridge receives

Bridges and LAN Switches

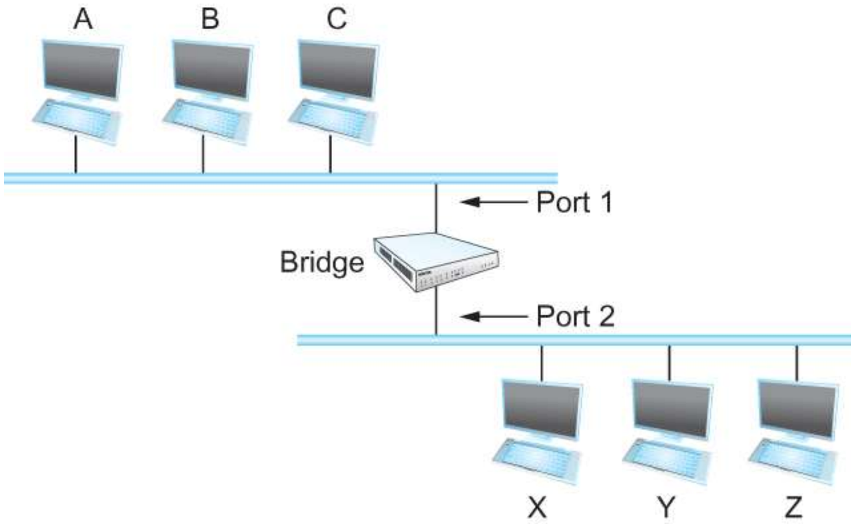
- Consider the following figure
  - When a frame from host A that is addressed to host B arrives on port 1, there is no need for the bridge to forward the frame out over port 2.



  - How does a bridge come to learn on which port the various hosts reside?

Bridges and LAN Switches

- Solution
  - Download a table into the bridge



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

  - Who does the download?
    - Human
      - Too much work for maintenance

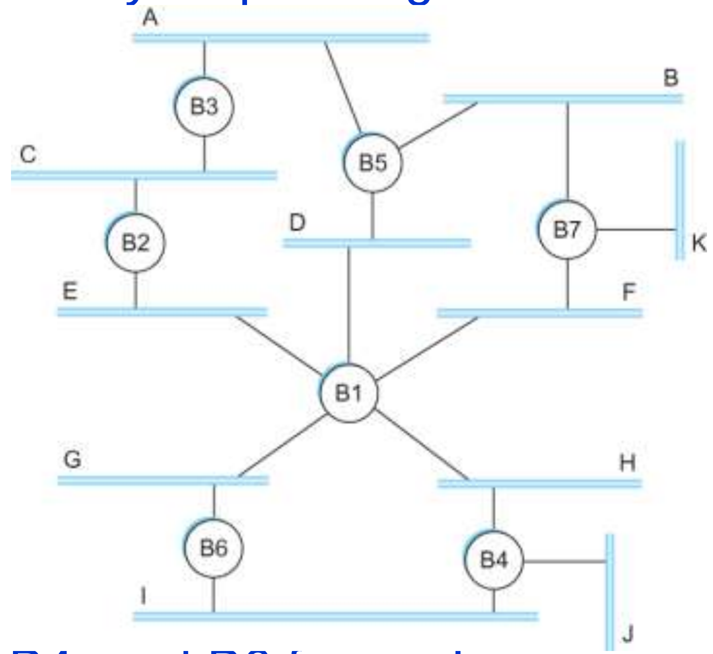
Bridges and LAN Switches

- Can the bridge learn this information by itself?
  - Yes

- How
  - Each bridge inspects the source address in all the frames it receives
  - Record the information at the bridge and build the table
  - When a bridge first boots, this table is empty
  - Entries are added over time
  - A timeout is associated with each entry
  - The bridge discards the entry after a specified period of time
    - To protect against the situation in which a host is moved from one network to another
- If the bridge receives a frame that is addressed to host not currently in the table
  - Forward the frame out on all other ports

Bridges and LAN Switches

- Strategy works fine if the extended LAN does not have a loop in it
- Why?
  - Frames potentially loop through the extended LAN forever



  - Bridges B1, B4, and B6 form a loop

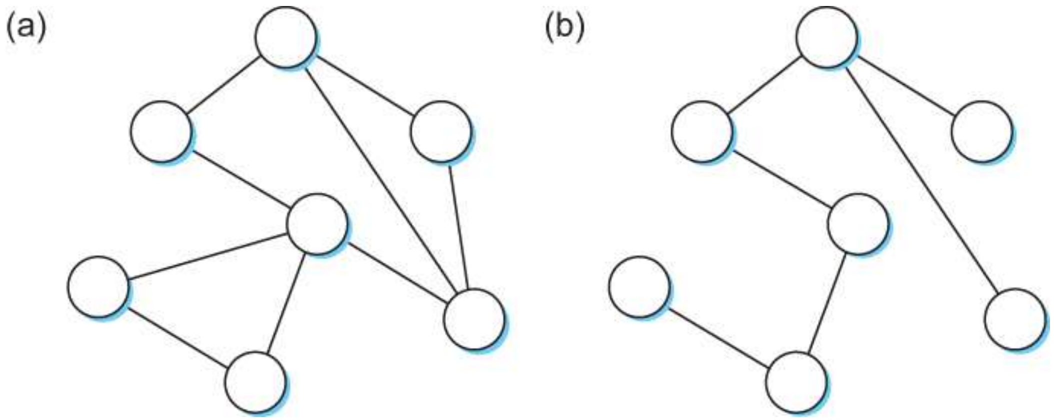
Bridges and LAN Switches

- How does an extended LAN come to have a loop in it?
  - Network is managed by more than one administrator
    - For example, it spans multiple departments in an organization
    - It is possible that no single person knows the entire configuration of the network
      - A bridge that closes a loop might be added without anyone knowing
  - Loops are built into the network to provide redundancy in case of failures
- Solution
  - Distributed Spanning Tree Algorithm

Spanning Tree Algorithm

- Think of the extended LAN as being represented by a graph that possibly has loops (cycles)

- A spanning tree is a sub-graph of this graph that covers all the vertices but contains no cycles
  - Spanning tree keeps all the vertices of the original graph but throws out some of the edges



Example of (a) a cyclic graph; (b) a corresponding spanning tree.

Spanning Tree Algorithm

- Developed by Radia Perlman at Digital
  - A protocol used by a set of bridges to agree upon a spanning tree for a particular extended LAN
  - IEEE 802.1 specification for LAN bridges is based on this algorithm

  - Each bridge decides the ports over which it is and is not willing to forward frames
    - In a sense, it is by removing ports from the topology that the extended LAN is reduced to an acyclic tree
    - It is even possible that an entire bridge will not participate in forwarding frames

Spanning Tree Algorithm

- Algorithm is dynamic
  - The bridges are always prepared to reconfigure themselves into a new spanning tree if some bridges fail
- Main idea
  - Each bridge selects the ports over which they will forward the frames

Spanning Tree Algorithm

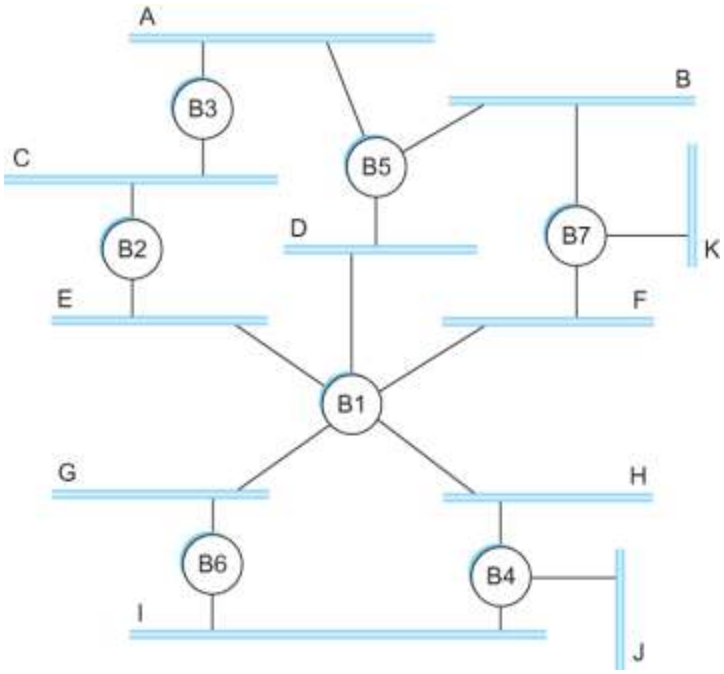
- Algorithm selects ports as follows:
  - Each bridge has a unique identifier
    - B1, B2, B3,…and so on.
  - Elect the bridge with the smallest id as the root of the spanning tree
  - The root bridge always forwards frames out over all of its ports
  - Each bridge computes the shortest path to the root and notes which of its ports is on this path
    - This port is selected as the bridge’s preferred path to the root
  - Finally, all the bridges connected to a given LAN elect a single *designated bridge* that will be responsible for forwarding frames toward the root bridge

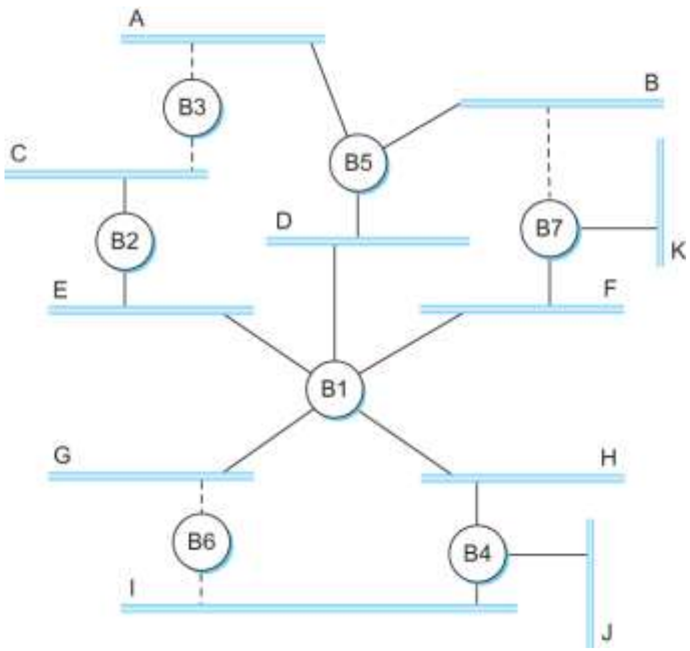
Spanning Tree Algorithm

- Each LAN's designated bridge is the one that is closest to the root
- If two or more bridges are equally close to the root,
  - Then select bridge with the smallest id
- Each bridge is connected to more than one LAN
  - So it participates in the election of a designated bridge for each LAN it is connected to.
  - Each bridge decides if it is the designated bridge relative to each of its ports
  - The bridge forwards frames over those ports for which it is the designated bridge

Spanning Tree Algorithm

- B1 is the root bridge
- B3 and B5 are connected to LAN A, but B5 is the designated bridge
- B5 and B7 are connected to LAN B, but B5 is the designated bridge





Spanning Tree Algorithm

- Initially each bridge thinks it is the root, so it sends a configuration message on each of its ports identifying itself as the root and giving a distance to the root of 0
- Upon receiving a configuration message over a particular port, the bridge checks to see if the new message is *better* than the current best configuration message recorded for that port
- The new configuration is better than the currently recorded information if
  - It identifies a root with a smaller id or
  - It identifies a root with an equal id but with a shorter distance or
  - The root id and distance are equal, but the sending bridge has a smaller id

Spanning Tree Algorithm

- If the new message is better than the currently recorded one,
  - The bridge discards the old information and saves the new information
  - It first adds 1 to the distance-to-root field

- When a bridge receives a configuration message indicating that it is not the root bridge (that is, a message from a bridge with smaller id)
  - The bridge stops generating configuration messages on its own
  - Only forwards configuration messages from other bridges after 1 adding to the distance field

Spanning Tree Algorithm

- When a bridge receives a configuration message that indicates it is not the designated bridge for that port

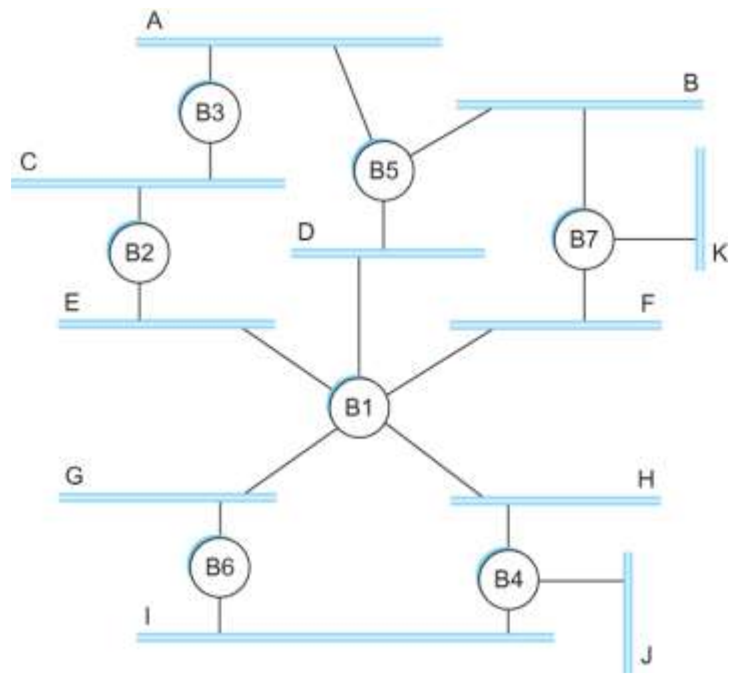
  => a message from a bridge that is closer to the root or equally far from the root but with a smaller id

    - The bridge stops sending configuration messages over that port

- When the system stabilizes,
  - Only the root bridge is still generating configuration messages.
  - Other bridges are forwarding these messages only over ports for which they are the designated bridge

Spanning Tree Algorithm

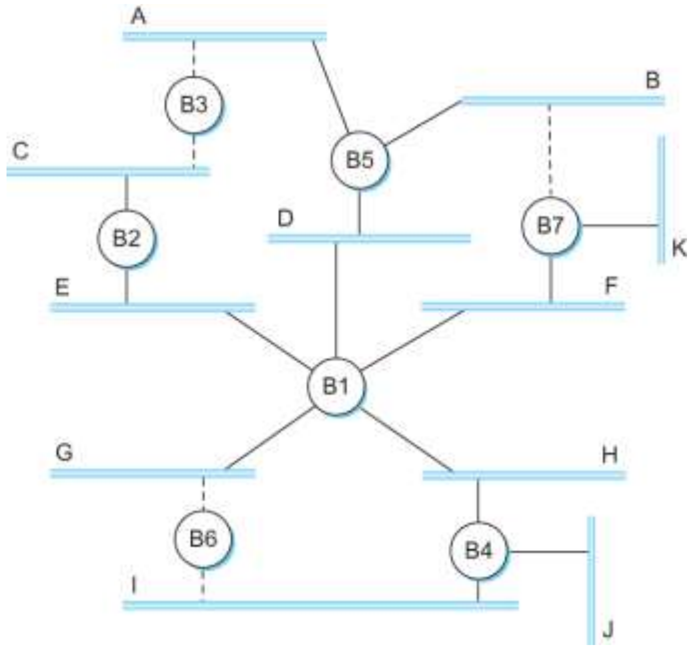
- Consider the situation when the power had just been restored to the building housing the following network



- All bridges would start off by claiming to be the root

Spanning Tree Algorithm

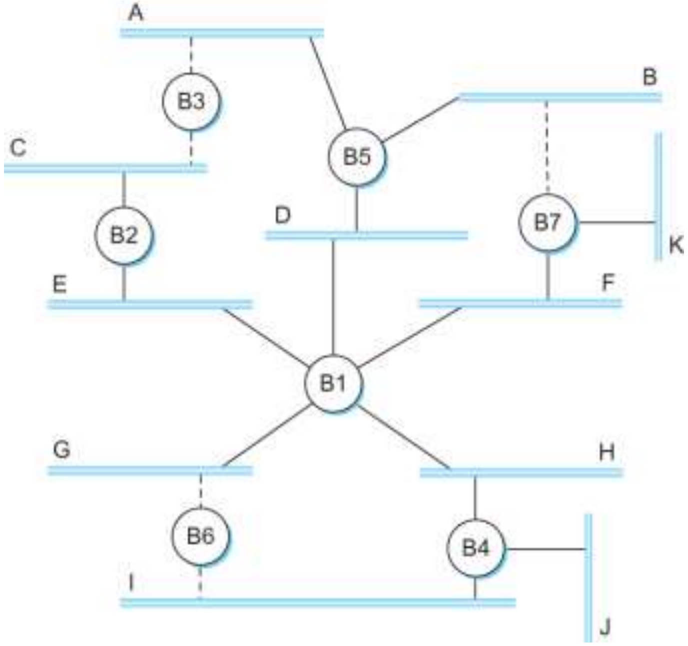
- Denote a configuration message from node X in which it claims to be distance d from the root node Y as (Y, d, X)



- Consider the activity at node B3

Spanning Tree Algorithm

- B3 receives (B2, 0, B2)
- Since 2 < 3, B3 accepts B2 as root
- B3 adds 1 to the distance advertised by B2 and sends (B2, 1, B3) to B5
- Meanwhile B2 accepts B1 as root because it has the lower id and it sends (B1, 1, B2) toward B3
- B5 accepts B1 as root and sends (B1, 1, B5) to B3
- B3 accepts B1 as root and it notes that both B2 and B5 are closer to the root than it is.
  - Thus B3 stops forwarding messages on both its interfaces
  - This leaves B3 with both ports not selected



Spanning Tree Algorithm

- Even after the system has stabilized, the root bridge continues to send configuration messages periodically
  - Other bridges continue to forward these messages
- When a bridge fails, the downstream bridges will not receive the configuration messages
- After waiting a specified period of time, they will once again claim to be the root and the algorithm starts again
- Note
  - Although the algorithm is able to reconfigure the spanning tree whenever a bridge fails, it is not able to forward frames over alternative paths for the sake of routing around a congested bridge

Spanning Tree Algorithm

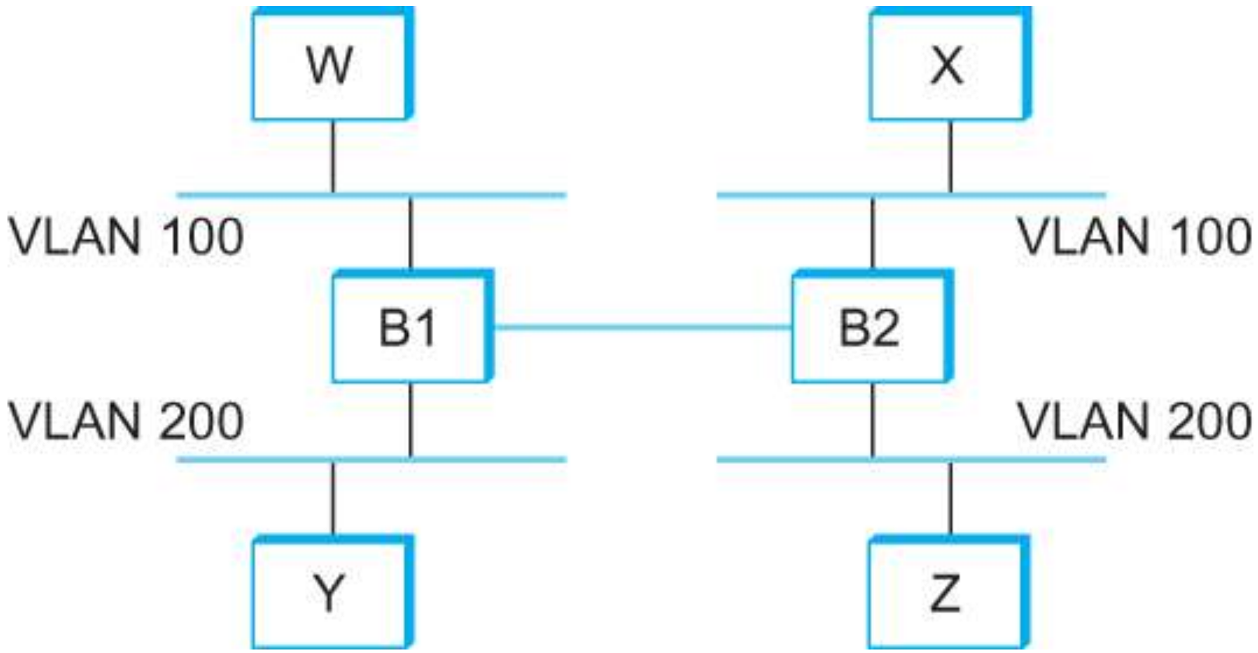
- Broadcast and Multicast
  - Forward all broadcast/multicast frames
    - Current practice
  - Learn when no group members downstream
  - Accomplished by having each member of group G send a frame to bridge multicast address with G in source field

Spanning Tree Algorithm

- Limitation of Bridges
  - Do not scale
    - Spanning tree algorithm does not scale
    - Broadcast does not scale
  - Do not accommodate heterogeneity

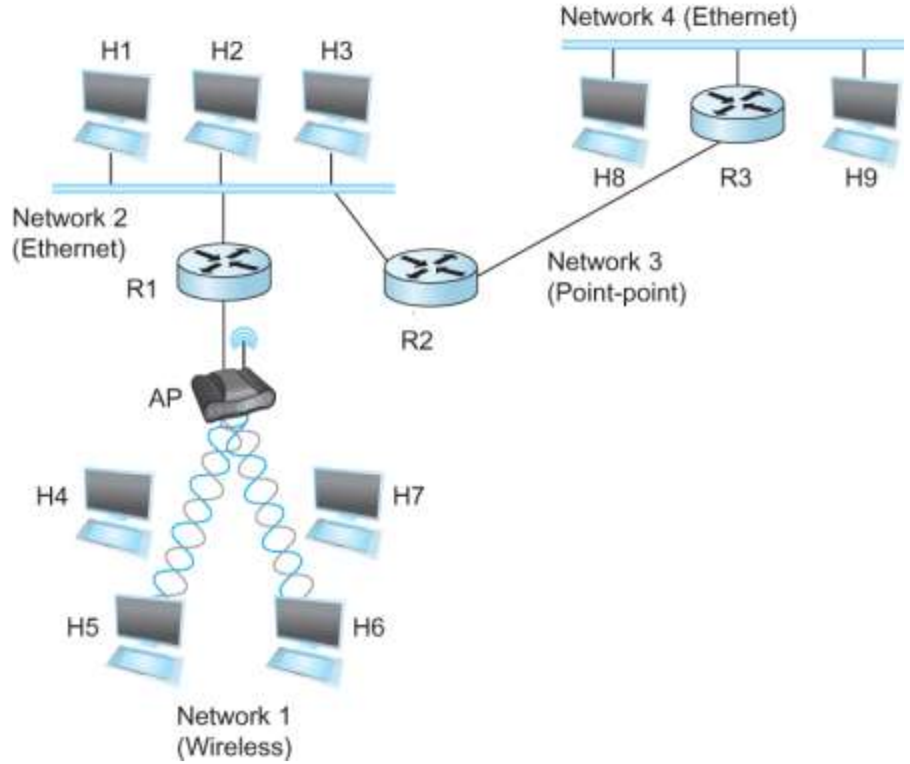
Spanning Tree Algorithm

- Virtual LAN



Internetworking

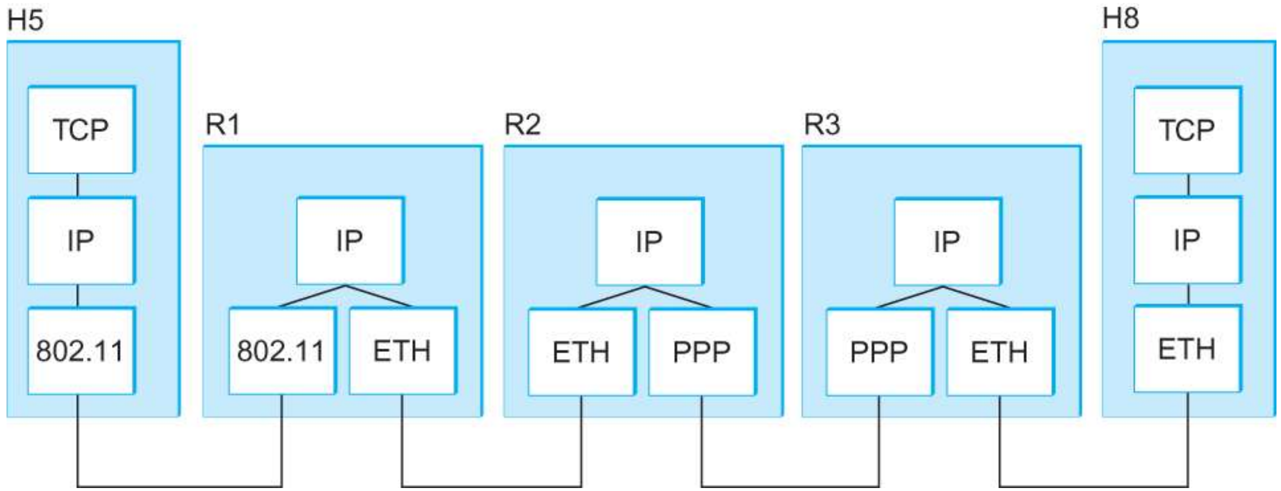
- What is internetwork
  - An arbitrary collection of networks interconnected to provide some sort of host-host to packet delivery service



A simple internetwork where H represents hosts and R represents routers

Internetworking

- What is IP
  - IP stands for Internet Protocol
  - Key tool used today to build scalable, heterogeneous internetworks
  - It runs on all the nodes in a collection of networks and defines the infrastructure that allows these nodes and networks to function as a single logical internetwork



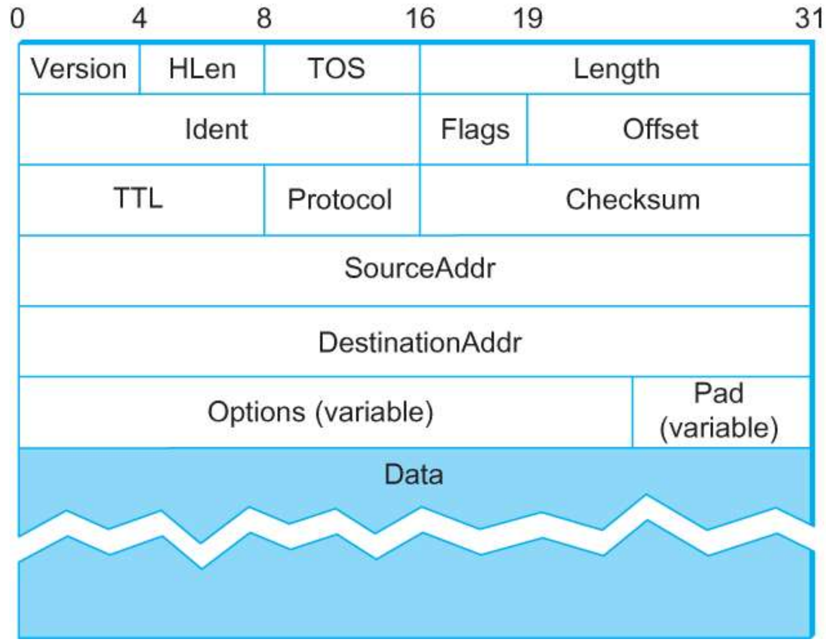
A simple internetwork showing the protocol layers

IP Service Model

- Packet Delivery Model
  - Connectionless model for data delivery
  - Best-effort delivery (unreliable service)
    - packets are lost
    - packets are delivered out of order
    - duplicate copies of a packet are delivered
    - packets can be delayed for a long time
- Global Addressing Scheme
  - Provides a way to identify all hosts in the network

Packet Format

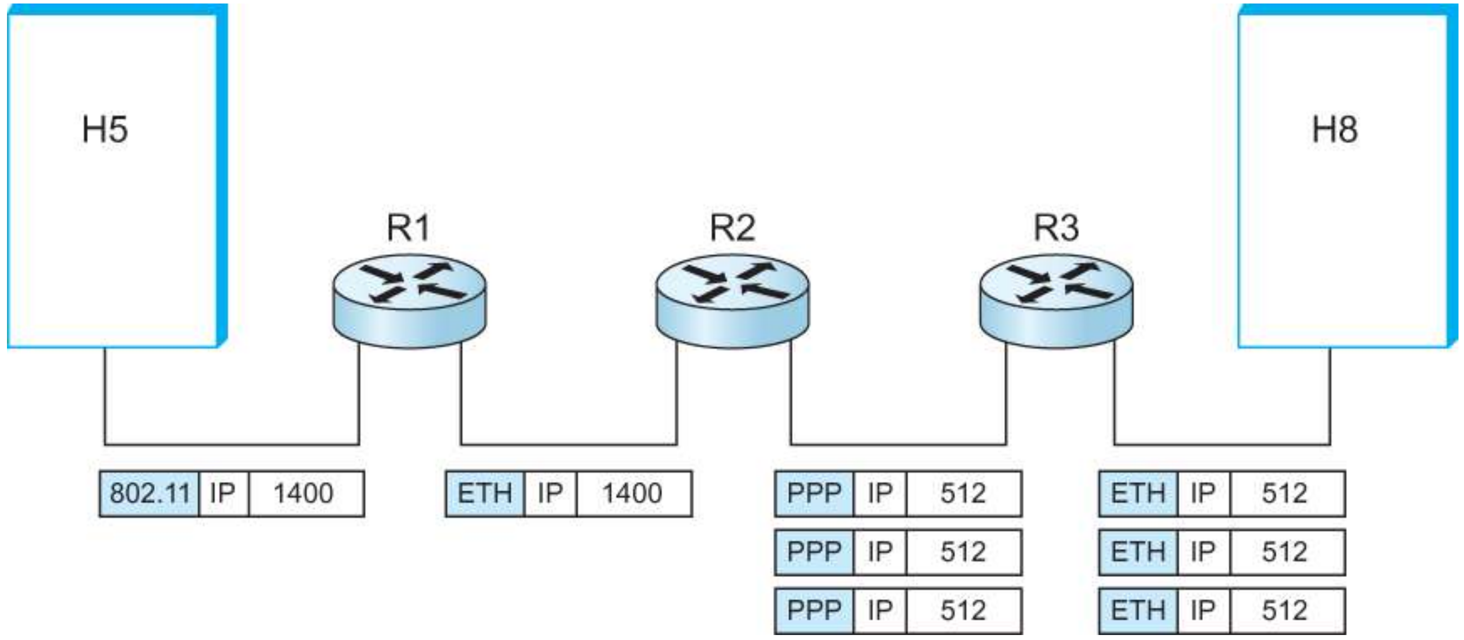
- Version (4): currently 4
- Hlen (4): number of 32-bit words in header
- TOS (8): type of service (not widely used)
- Length (16): number of bytes in this datagram
- Ident (16): used by fragmentation
- Flags/Offset (16): used by fragmentation
- TTL (8): number of hops this datagram has traveled
- Protocol (8): demux key (TCP=6, UDP=17)
- Checksum (16): of the header only
- DestAddr & SrcAddr (32)



IP Fragmentation and Reassembly

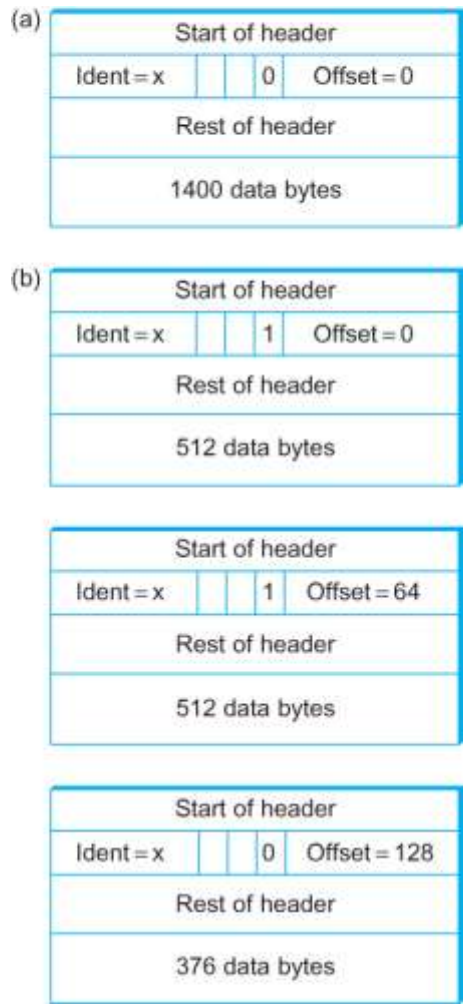
- Each network has some MTU (Maximum Transmission Unit)
  - Ethernet (1500 bytes), FDDI (4500 bytes)
- Strategy
  - Fragmentation occurs in a router when it receives a datagram that it wants to forward over a network which has (MTU < datagram)
  - Reassembly is done at the receiving host
  - All the fragments carry the same identifier in the *Ident* field
  - Fragments are self-contained datagrams
  - IP does not recover from missing fragments

IP Fragmentation and Reassembly



IP datagrams traversing the sequence of physical networks

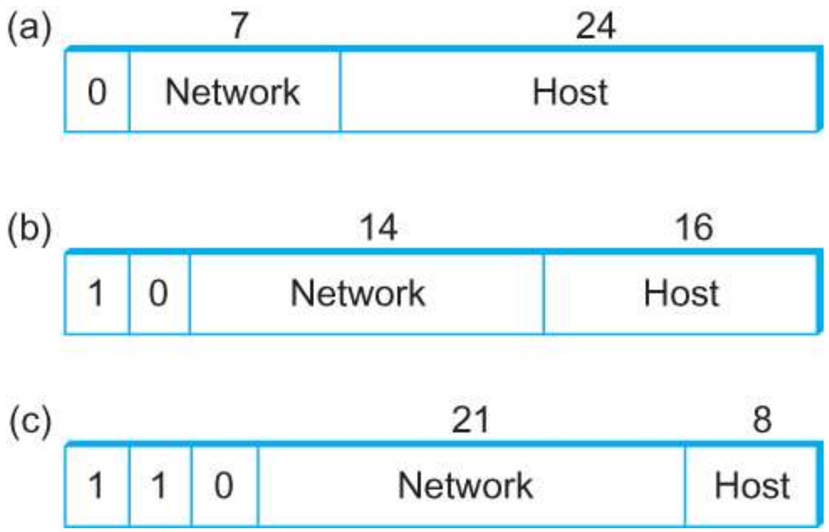
IP Fragmentation and Reassembly



Header fields used in IP fragmentation. (a) Unfragmented packet; (b) fragmented packets.

Global Addresses

- Properties
  - globally unique
  - hierarchical: network + host
  - 4 Billion IP address, half are A type, ¼ is B type, and 1/8 is C type
- Format



- Dot notation
  - 10.3.2.4
  - 128.96.33.81
  - 192.12.69.77

IP Datagram Forwarding

- Strategy
  - every datagram contains destination's address
  - if directly connected to destination network, then forward to host
  - if not directly connected to destination network, then forward to some router
  - forwarding table maps network number into next hop
  - each host has a default router
  - each router maintains a forwarding table
- Example (router R2)

NetworkNum	NextHop
1	R1
2	Interface 1
3	Interface 0
4	R3

IP Datagram Forwarding

- Algorithm

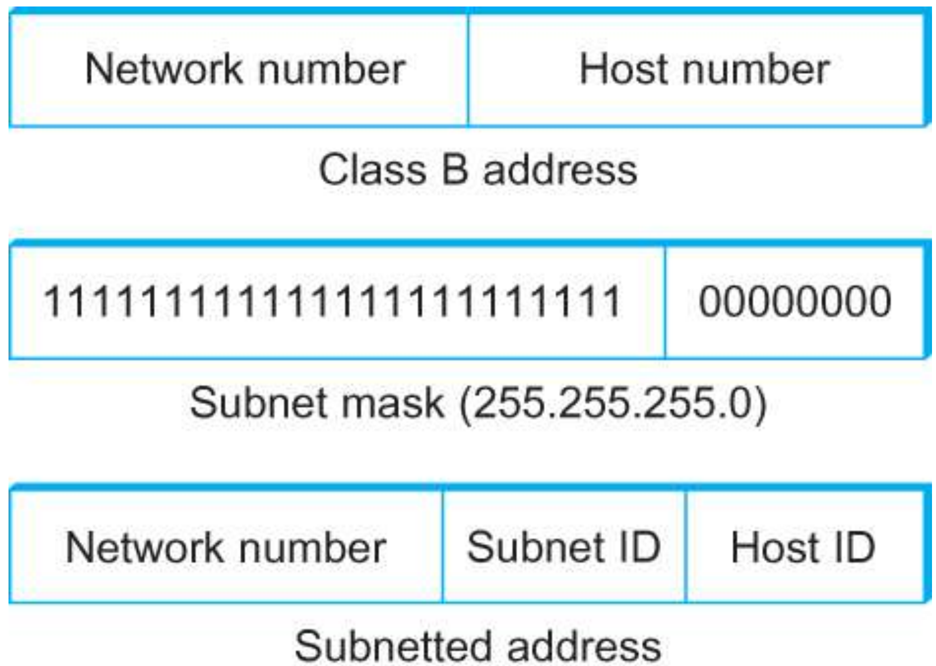
```
if (NetworkNum of destination = NetworkNum of one of my
   interfaces) then
   deliver packet to destination over that interface
else
   if (NetworkNum of destination is in my forwarding table)
   then
         deliver packet to NextHop router
   else
         deliver packet to default router
```

For a host with only one interface and only a default router in its forwarding table, this simplifies to

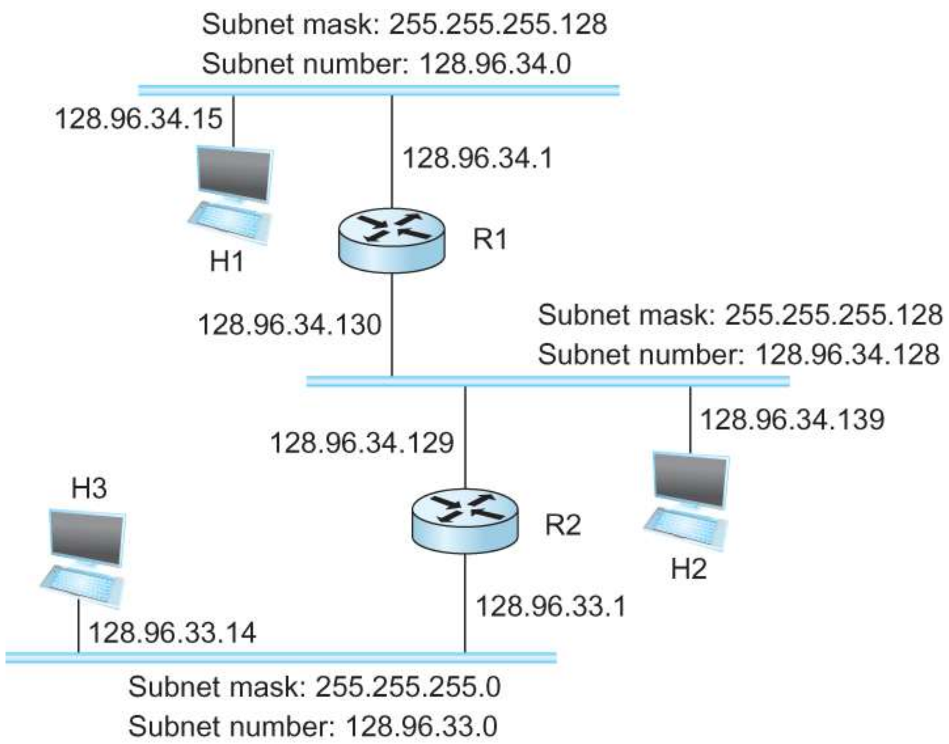
```
if (NetworkNum of destination = my NetworkNum) then
   deliver packet to destination directly
else
   deliver packet to default router
```

Subnetting

- Add another level to address/routing hierarchy: *subnet*
- *Subnet masks* define variable partition of host part of class A and B addresses
- Subnets visible only within site



Subnetting



- Forwarding Table at Router R1

SubnetNumber	SubnetMask	NextHop
128.96.34.0	255.255.255.128	Interface 0
128.96.34.128	255.255.255.128	Interface 1
128.96.33.0	255.255.255.0	R2

Subnetting

Forwarding Algorithm

```
D = destination IP address
for each entry < SubnetNum, SubnetMask, NextHop>
   D1 = SubnetMask & D
   if D1 = SubnetNum
      if NextHop is an interface
         deliver datagram directly to destination
      else
         deliver datagram to NextHop (a router)
```

Subnetting

Notes

- Would use a default router if nothing matches
- Not necessary for all ones in subnet mask to be contiguous
- Can put multiple subnets on one physical network
- Subnets not visible from the rest of the Internet

Classless Addressing

- Classless Inter-Domain Routing
  - A technique that addresses two scaling concerns in the Internet
    - The growth of backbone routing table as more and more network numbers need to be stored in them
    - Potential exhaustion of the 32-bit address space
  - Address assignment efficiency
    - Arises because of the IP address structure with class A, B, and C addresses
    - Forces us to hand out network address space in fixed-size chunks of three very different sizes
      - A network with two hosts needs a class C address
        - Address assignment efficiency = 2/255 = 0.78
      - A network with 256 hosts needs a class B address
        - Address assignment efficiency = 256/65535 = 0.39

Classless Addressing

- Exhaustion of IP address space centers on exhaustion of the class B network numbers
- Solution
  - Say “NO” to any Autonomous System (AS) that requests a class B address unless they can show a need for something close to 64K addresses
  - Instead give them an appropriate number of class C addresses
  - For any AS with at least 256 hosts, we can guarantee an address space utilization of at least 50%
- What is the problem with this solution?

Classless Addressing

- Problem with this solution
  - Excessive storage requirement at the routers.
- If a single AS has, say 16 class C network numbers assigned to it,
  - Every Internet backbone router needs 16 entries in its routing tables for that AS
  - This is true, even if the path to every one of these networks is the same
- If we had assigned a class B address to the AS
  - The same routing information can be stored in one entry
  - Efficiency = 16 × 255 / 65, 536 = 6.2%

Classless Addressing

- CIDR tries to balance the desire to minimize the number of routes that a router needs to know against the need to hand out addresses efficiently.

- CIDR uses aggregate routes
  - Uses a single entry in the forwarding table to tell the router how to reach a lot of different networks
  - Breaks the rigid boundaries between address classes

Classless Addressing

- Consider an AS with 16 class C network numbers.
- Instead of handing out 16 addresses at random, hand out a block of contiguous class C addresses
- Suppose we assign the class C network numbers from 192.4.16 through 192.4.31
- Observe that top 20 bits of all the addresses in this range are the same (11000000 00000100 0001)
  - We have created a 20-bit network number (which is in between class B network number and class C number)
- Requires to hand out blocks of class C addresses that share a common prefix

Classless Addressing

- Requires to hand out blocks of class C addresses that share a common prefix
- The convention is to place a /X after the prefix where X is the prefix length in bits
- For example, the 20-bit prefix for all the networks 192.4.16 through 192.4.31 is represented as 192.4.16/20
- By contrast, if we wanted to represent a single class C network number, which is 24 bits long, we would write it 192.4.16/24

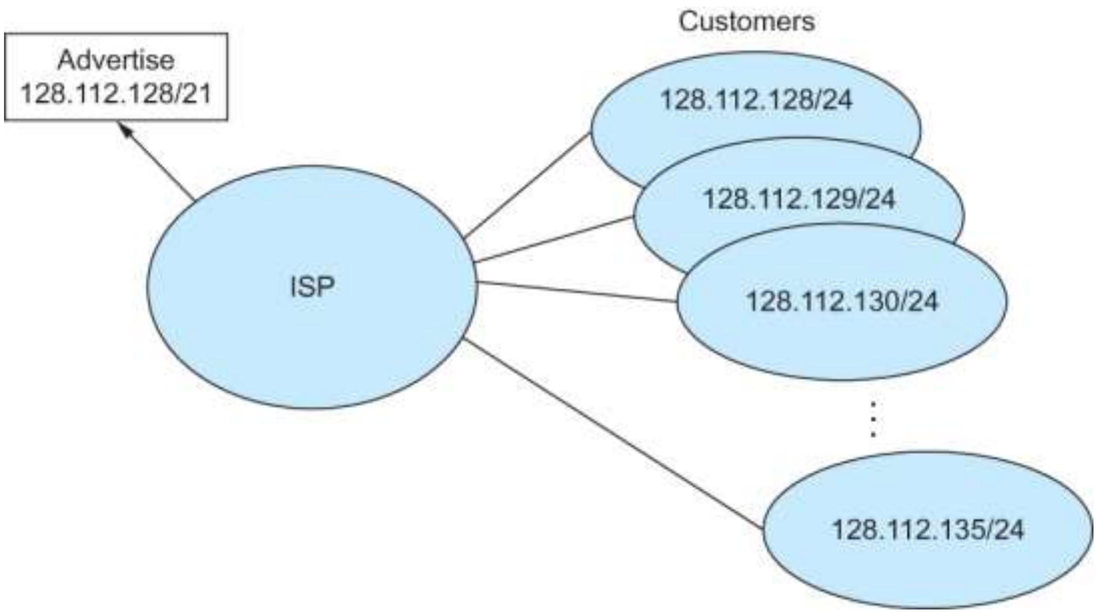
Classless Addressing

- How do the routing protocols handle this classless addresses
  - It must understand that the network number may be of any length
- Represent network number with a single pair

  `<length, value>`

- All routers must understand CIDR addressing

Classless Addressing



Route aggregation with CIDR

IP Forwarding Revisited

- IP forwarding mechanism assumes that it can find the network number in a packet and then look up that number in the forwarding table
- We need to change this assumption in case of CIDR
- CIDR means that prefixes may be of any length, from 2 to 32 bits

IP Forwarding Revisited

- It is also possible to have prefixes in the forwarding tables that overlap
  - Some addresses may match more than one prefix
- For example, we might find both 171.69 (a 16 bit prefix) and 171.69.10 (a 24 bit prefix) in the forwarding table of a single router
- A packet destined to 171.69.10.5 clearly matches both prefixes.
  - The rule is based on the principle of “longest match”
    - 171.69.10 in this case
- A packet destined to 171.69.20.5 would match 171.69 and not 171.69.10

Address Translation Protocol (ARP)

- Map IP addresses into physical addresses
  - destination host
  - next hop router
- Techniques
  - encode physical address in host part of IP address
  - table-based
- ARP (Address Resolution Protocol)
  - table of IP to physical address bindings
  - broadcast request if IP address not in table
  - target machine responds with its physical address
  - table entries are discarded if not refreshed

ARP Packet Format

0	8	16	31
Hardware type = 1		ProtocolType = 0x0800	
HLen = 48	PLen = 32	Operation	
SourceHardwareAddr (bytes 0–3)			
SourceHardwareAddr (bytes 4–5)		SourceProtocolAddr (bytes 0–1)	
SourceProtocolAddr (bytes 2–3)		TargetHardwareAddr (bytes 0–1)	
TargetHardwareAddr (bytes 2–5)			
TargetProtocolAddr (bytes 0–3)			

- HardwareType: type of physical network (e.g., Ethernet)
- ProtocolType: type of higher layer protocol (e.g., IP)
- HLEN & PLEN: length of physical and protocol addresses
- Operation: request or response
- Source/Target Physical/Protocol addresses

Host Configurations

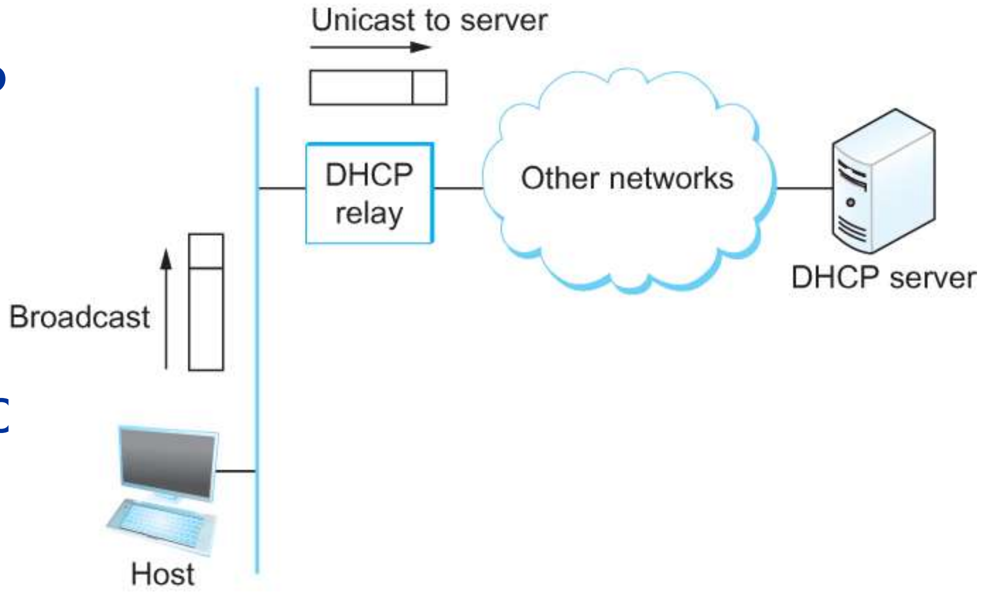
- Notes
  - Ethernet addresses are configured into network by manufacturer and they are unique
  - IP addresses must be unique on a given internetwork but also must reflect the structure of the internetwork
  - Most host Operating Systems provide a way to manually configure the IP information for the host
  - Drawbacks of manual configuration
    - A lot of work to configure all the hosts in a large network
    - Configuration process is error-prune
  - Automated Configuration Process is required

Dynamic Host Configuration Protocol (DHCP)

- DHCP server is responsible for providing configuration information to hosts
- There is at least one DHCP server for an administrative domain
- DHCP server maintains a pool of available addresses

DHCP

- Newly booted or attached host sends DHCPDISCOVER message to a special IP address (255.255.255.255)
- DHCP relay agent unicasts the message tc DHCP server and waits for the response



Internet Control Message Protocol (ICMP)

- Defines a collection of error messages that are sent back to the source host whenever a router or host is unable to process an IP datagram successfully
  - Destination host unreachable due to link /node failure
  - Reassembly process failed
  - TTL had reached 0 (so datagrams don't cycle forever)
  - IP header checksum failed
- ICMP-Redirect
  - From router to a source host
  - With a better route information

Internet Control Message Protocol (ICMP)

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- ICMP-Redirect
  - From router to a source host
  - With a better route information

Routing

Forwarding versus Routing

- Forwarding:
  - to select an output port based on destination address and routing table
- Routing:
  - process by which routing table is built

Routing

- Forwarding table VS Routing table
  - Forwarding table
    - Used when a packet is being forwarded and so must contain enough information to accomplish the forwarding function
    - A row in the forwarding table contains the mapping from a network number to an outgoing interface and some MAC information, such as Ethernet Address of the next hop
  - Routing table
    - Built by the routing algorithm as a precursor to build the forwarding table
    - Generally contains mapping from network numbers to next hops

Routing

(a)

Prefix/Length	Next Hop
18/8	171.69.245.10

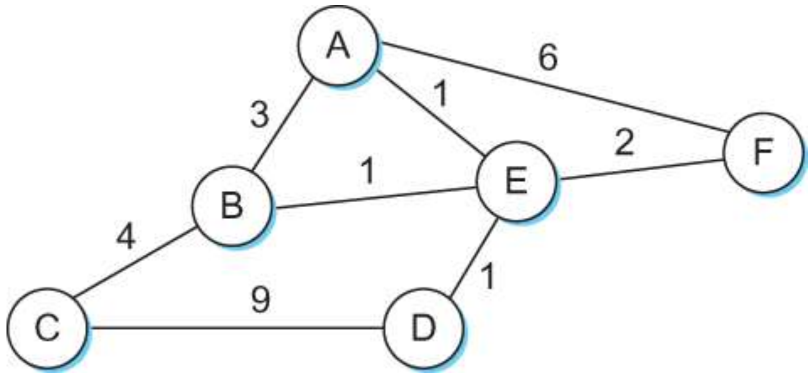
(b)

Prefix/Length	Interface	MAC Address
18/8	if0	8:0:2b:e4:b:1:2

Example rows from (a) routing and (b) forwarding tables

Routing

- Network as a Graph



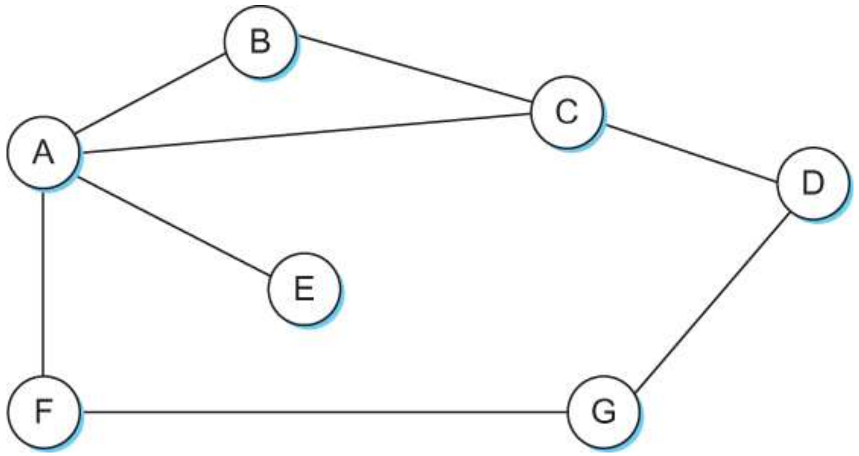
- The basic problem of routing is to find the lowest-cost path between any two nodes
  - Where the cost of a path equals the sum of the costs of all the edges that make up the path

Routing

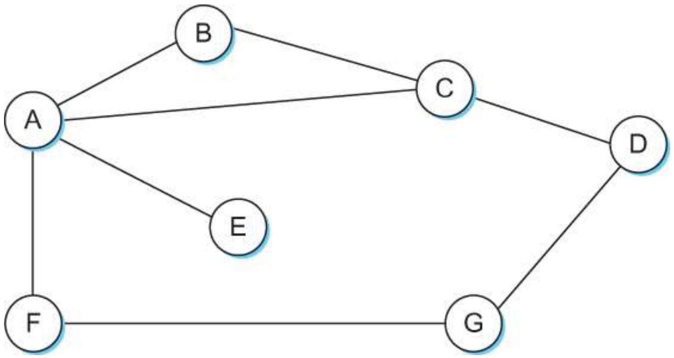
- For a simple network, we can calculate all shortest paths and load them into some nonvolatile storage on each node.
- Such a static approach has several shortcomings
    - It does not deal with node or link failures
    - It does not consider the addition of new nodes or links
    - It implies that edge costs cannot change
- What is the solution?
    - Need a distributed and dynamic protocol
    - Two main classes of protocols
        - Distance Vector
        - Link State

Distance Vector

- Each node constructs a one dimensional array (a vector) containing the "distances" (costs) to all other nodes and distributes that vector to its immediate neighbors
- Starting assumption is that each node knows the cost of the link to each of its directly connected neighbors



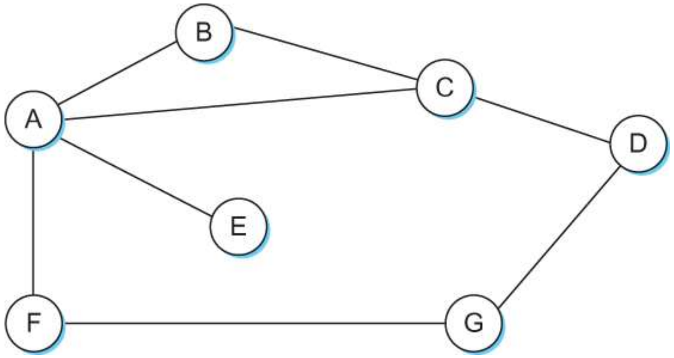
Distance Vector



Information Stored at Node	Distance to Reach Node						
	A	B	C	D	E	F	G
A	0	1	1	∞	1	1	∞
B	1	0	1	∞	∞	∞	∞
C	1	1	0	1	∞	∞	∞
D	∞	∞	1	0	∞	∞	1
E	1	∞	∞	∞	0	∞	∞
F	1	∞	∞	∞	∞	0	1
G	∞	∞	∞	1	∞	1	0

Initial distances stored at each node (global view)

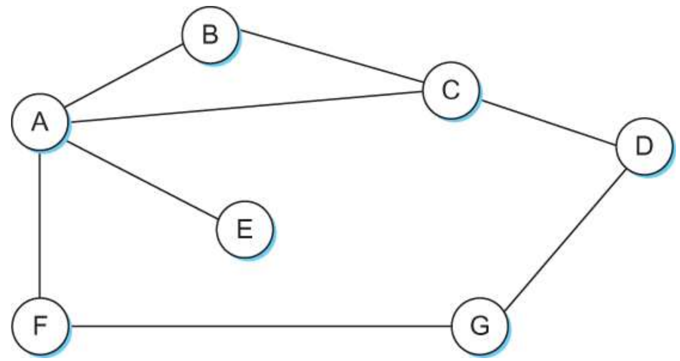
Distance Vector



Destination	Cost	NextHop
B	1	B
C	1	C
D	∞	—
E	1	E
F	1	F
G	∞	—

Initial routing table at node A

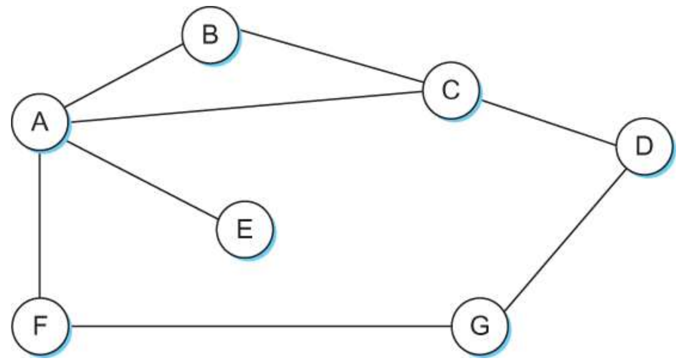
Distance Vector



Destination	Cost	NextHop
B	1	B
C	1	C
D	2	C
E	1	E
F	1	F
G	2	F

Final routing table at node A

Distance Vector



Information Stored at Node	Distance to Reach Node						
	A	B	C	D	E	F	G
A	0	1	1	2	1	1	2
B	1	0	1	2	2	2	3
C	1	1	0	1	2	2	2
D	2	2	1	0	3	2	1
E	1	2	2	3	0	2	3
F	1	2	2	2	2	0	1
G	2	3	2	1	3	1	0

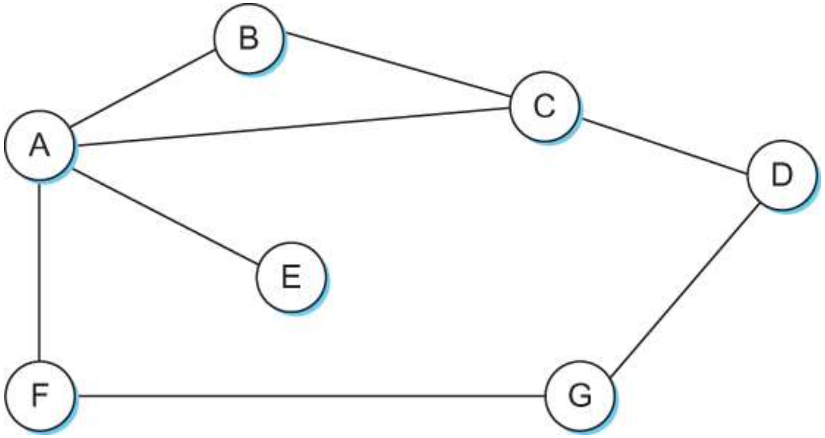
Final distances stored at each node (global view)

Distance Vector

- The distance vector routing algorithm is sometimes called as Bellman-Ford algorithm
- Every T seconds each router sends its table to its neighbor each each router then updates its table based on the new information
- Problems include fast response to good new and slow response to bad news. Also too many messages to update

Distance Vector

- When a node detects a link failure
  - 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



Distance Vector

- Slightly different circumstances can prevent the network from stabilizing
  - Suppose the link from A to E goes down
  - In the next round of updates, A advertises a distance of infinity to E, but B and C advertise a distance of 2 to E
  - Depending on the exact timing of events, the following might happen
    - Node B, upon hearing that E can be reached in 2 hops from C, concludes that it can reach E in 3 hops and advertises this to A
    - Node A concludes that it can reach E in 4 hops and advertises this to C
    - Node C concludes that it can reach E in 5 hops; and so on.
    - This cycle stops only when the distances reach some number that is large enough to be considered infinite
      - **Count-to-infinity problem**

Count-to-infinity Problem

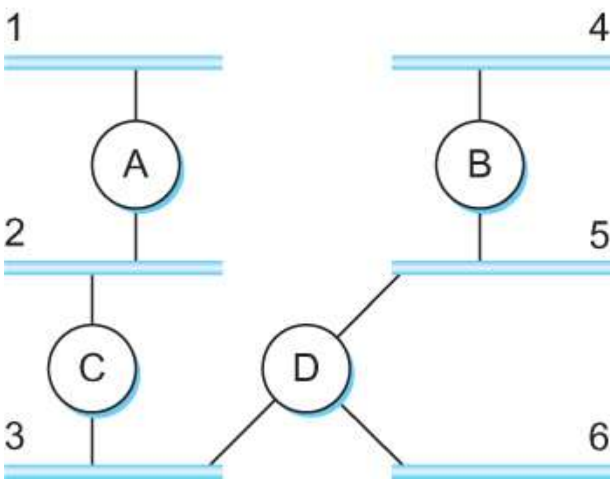
- Use some relatively small number as an approximation of infinity
- For example, the maximum number of hops to get across a certain network is never going to be more than 16

- One technique to improve the time to stabilize routing is called *split horizon*
  - When a node sends a routing update to its neighbors, it does not send those routes it learned from each neighbor back to that neighbor
  - For example, if B has the route (E, 2, A) in its table, then it knows it must have learned this route from A, and so whenever B sends a routing update to A, it does not include the route (E, 2) in that update

Count-to-infinity Problem

- In a stronger version of split horizon, called *split horizon with poison reverse*
  - B actually sends that back route to A, but it puts negative information in the route to ensure that A will not eventually use B to get to E
  - For example, B sends the route (E, ∞) to A

Routing Information Protocol (RIP)



Example Network running RIP

0	8	16 – 31
Command	Version	Must be zero
Family of net 1		Route Tags
Address prefix of net 1		
Mask of net 1		
Distance to net 1		
Family of net 2		Route Tags
Address prefix of net 2		
Mask of net 2		
Distance to net 2		

RIPv2 Packet Format

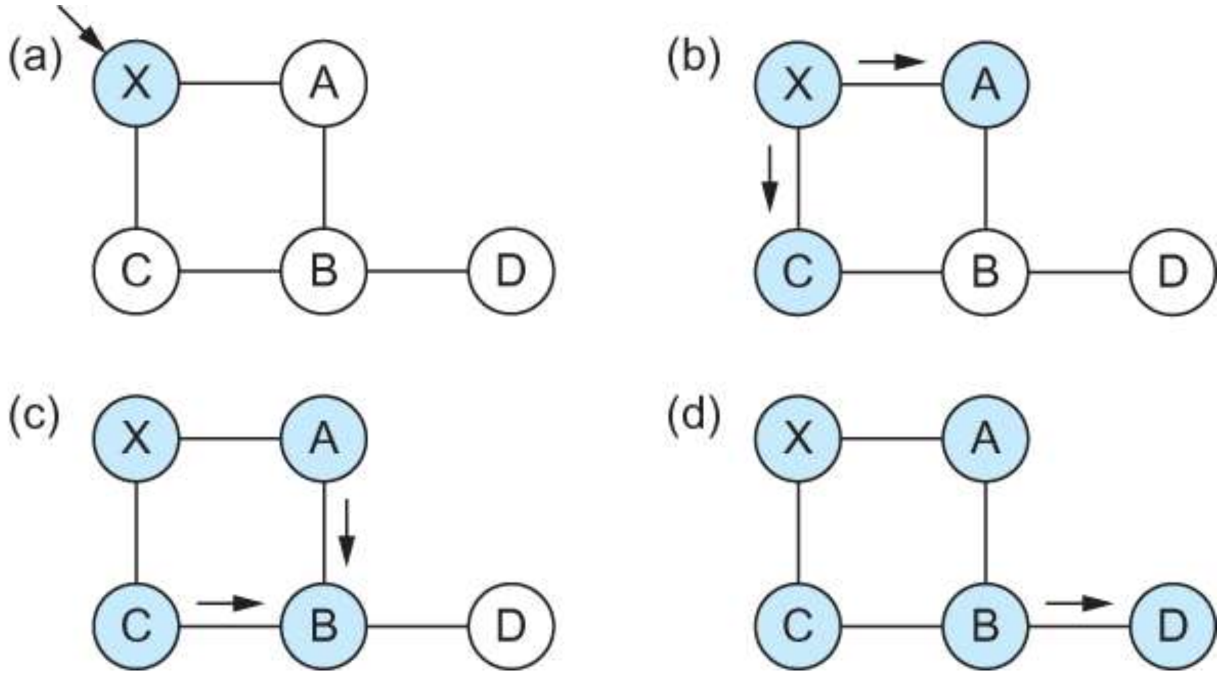
Link State Routing

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; increment SEQNO
  - start SEQNO at 0 when reboot
  - decrement TTL of each stored LSP; discard when TTL=0

Link State

Reliable Flooding



Flooding of link-state packets. (a) LSP arrives at node X; (b) X floods LSP to A and C; (c) A and C flood LSP to B (but not X); (d) flooding is complete

Shortest Path Routing

- Dijkstra's Algorithm - Assume non-negative link weights
  - N: set of nodes in the graph
  - l((i, j): the non-negative cost associated with the edge between nodes i, j $\in$N and l(i, j) = $\propto$ if no edge connects i and j
  - Let s $\in$N be the starting node which executes the algorithm to find shortest paths to all other nodes in N
  - Two variables used by the algorithm
    - M: set of nodes incorporated so far by the algorithm
    - C(n) : the cost of the path from s to each node n
    - The algorithm

```
M = {s}
For each n in N - {s}
    C(n) = l(s, n)
while ( N ≠ M)
  M = M ∪ {w} such that C(w) is the minimum
                            for all w in (N-M)
  For each n in (N-M)
          C(n) = MIN (C(n), C(w) + l(w, n))
```

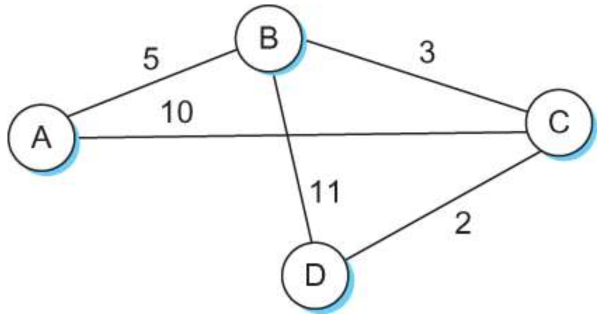
Shortest Path Routing

- In practice, each switch computes its routing table directly from the LSP's it has collected using a realization of Dijkstra's algorithm called the *forward search algorithm*
- Specifically each switch maintains two lists, known as **Tentative** and **Confirmed**
- Each of these lists contains a set of entries of the form (Destination, Cost, NextHop)

Shortest Path Routing

- The algorithm
  - Initialize the **Confirmed** list with an entry for myself; this entry has a cost of 0
  - For the node just added to the **Confirmed** list in the previous step, call it node **Next**, select its LSP
  - For each neighbor (Neighbor) of **Next**, calculate the cost (Cost) to reach this Neighbor as the sum of the cost from myself to Next and from Next to Neighbor
    - If Neighbor is currently on neither the **Confirmed** nor the **Tentative** list, then add (Neighbor, Cost, Nexthop) to the **Tentative** list, where Nexthop is the direction I go to reach Next
    - If Neighbor is currently on the **Tentative** list, and the Cost is less than the currently listed cost for the Neighbor, then replace the current entry with (Neighbor, Cost, Nexthop) where Nexthop is the direction I go to reach Next
  - If the **Tentative** list is empty, stop. Otherwise, pick the entry from the **Tentative** list with the lowest cost, move it to the **Confirmed** list, and return to Step 2.

Shortest Path Routing



Step	Confirmed	Tentative	Comments
1	(D,0,–)		Since D is the only new member of the confirmed list, look at its LSP.
2	(D,0,–)	(B,11,B) (C,2,C)	D's LSP says we can reach B through B at cost 11, which is better than anything else on either list, so put it on Tentative list; same for C.
3	(D,0,–) (C,2,C)	(B,11,B)	Put lowest-cost member of Tentative (C) onto Confirmed list. Next, examine LSP of newly confirmed member (C).
4	(D,0,–) (C,2,C)	(B,5,C) (A,12,C)	Cost to reach B through C is 5, so replace (B,11,B). C's LSP tells us that we can reach A at cost 12.
5	(D,0,–) (C,2,C) (B,5,C)	(A,12,C)	Move lowest-cost member of Tentative (B) to Confirmed, then look at its LSP.
6	(D,0,–) (C,2,C) (B,5,C)	(A,10,C)	Since we can reach A at cost 5 through B, replace the Tentative entry.
7	(D,0,–) (C,2,C) (B,5,C) (A,10,C)		Move lowest-cost member of Tentative (A) to Confirmed, and we are all done.

Open Shortest Path First (OSPF)

0	8	16	31
Version	Type	Message length	
SourceAddr			
AreaId			
Checksum		Authentication type	
Authentication			

OSPF Header Format

LS Age			Options	Type = 1
Link-state ID				
Advertising router				
LS sequence number				
LS checksum			Length	
0	Flags	0	Number of links	
Link ID				
Link data				
Link type		Num_TOS	Metric	
Optional TOS information				
More links				

OSPF Link State Advertisement

Summary

- We have looked at some of the issues involved in building scalable and heterogeneous networks by using switches and routers to interconnect links and networks.
- To deal with heterogeneous networks, we have discussed in details the service model of Internetworking Protocol (IP) which forms the basis of today's routers.
- We have discussed in details two major classes of routing algorithms
  - Distance Vector
  - Link State