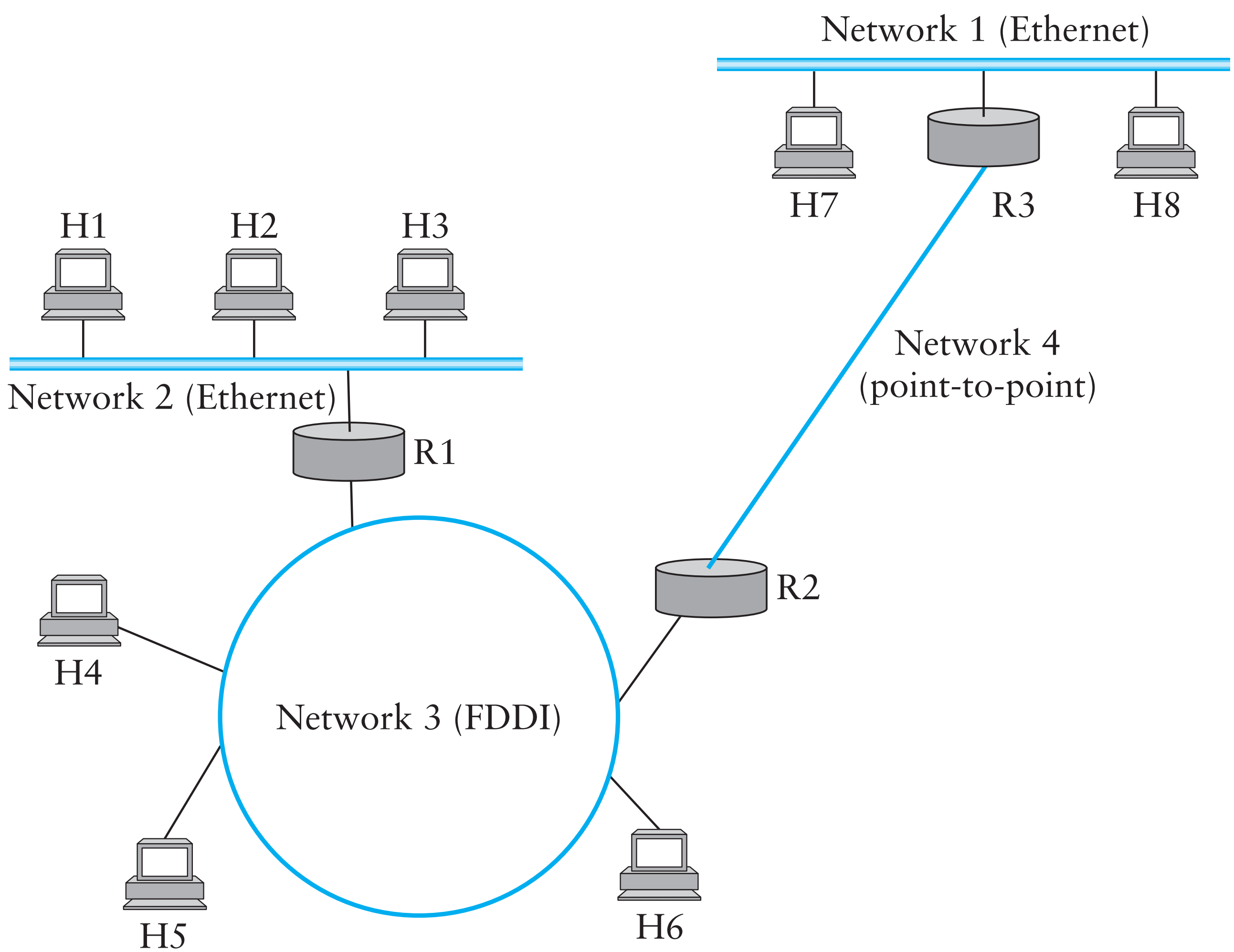
Overview

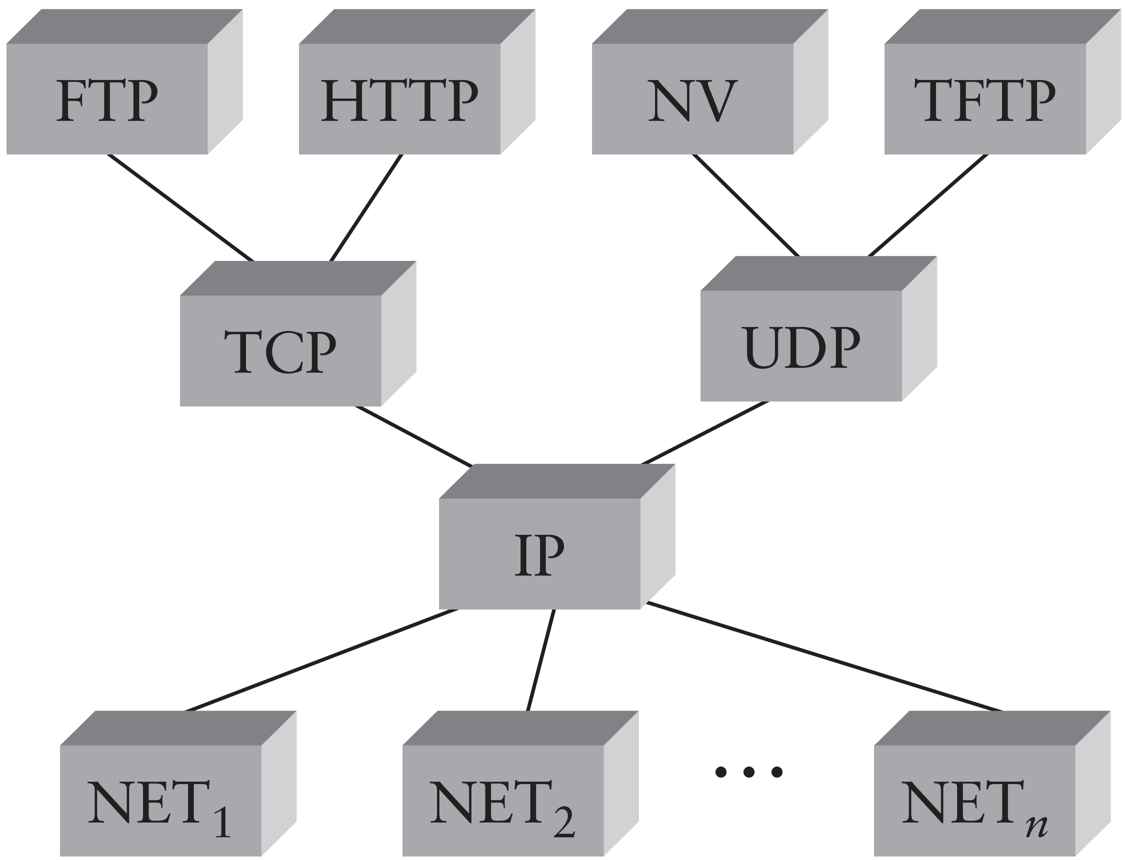
- **Internet Protocol**
  - What it provides and its header
  - Fragmentation and assembly
  - IP address assignment
- **Address mapping and allocation**
- **Forwarding: switching, circuits, and source routing**

Internet Protocol Goal

- **Glue lower-level networks together**



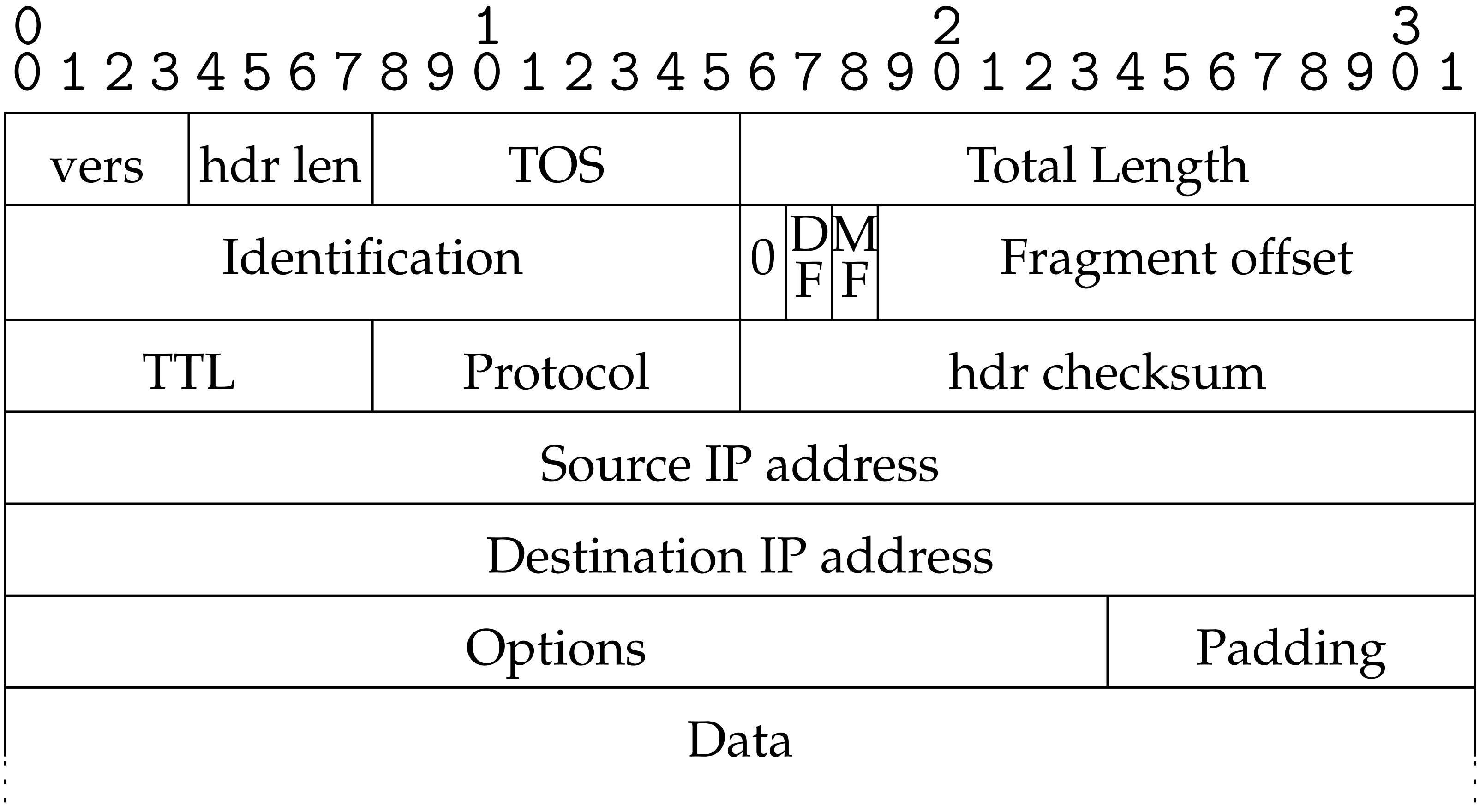
The Hourglass, Revisited



Internet Protocol

- **Connectionless (datagram-based)**
- **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

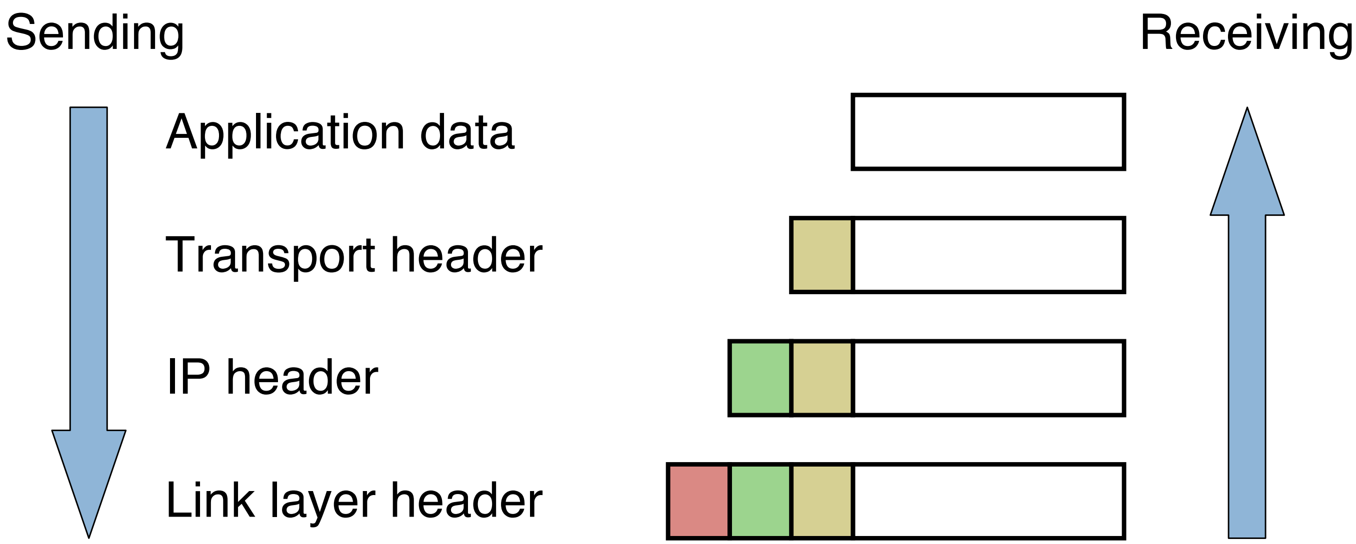
IPv4 packet format



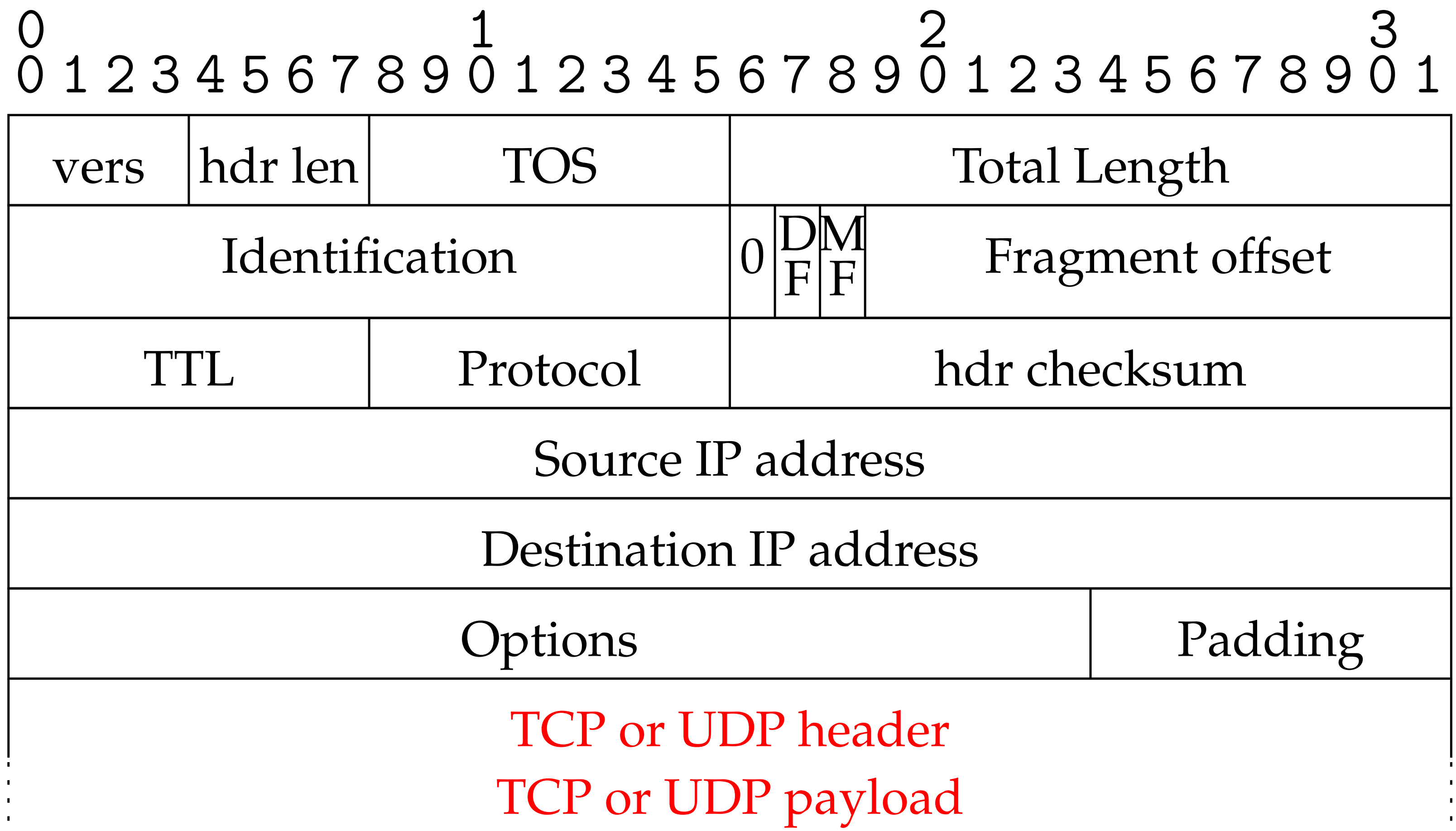
IP header details

- **Routing is based on destination address**
- **TTL (time to live) decremented at each hop (avoids loops)**
  - TTL mostly saves from routing loops
  - But other cool uses. . .
- **Fragmentation possible for large packets**
  - Fragmented in network if crosses link w. small frame size
  - MF bit means more fragments for this IP packet
  - DF bit says "don't fragment" (returns error to sender)
- **Following IP header is "payload" data**
  - Typically beginning with TCP or UDP header

Example Encapsulation



IPv4 packet format



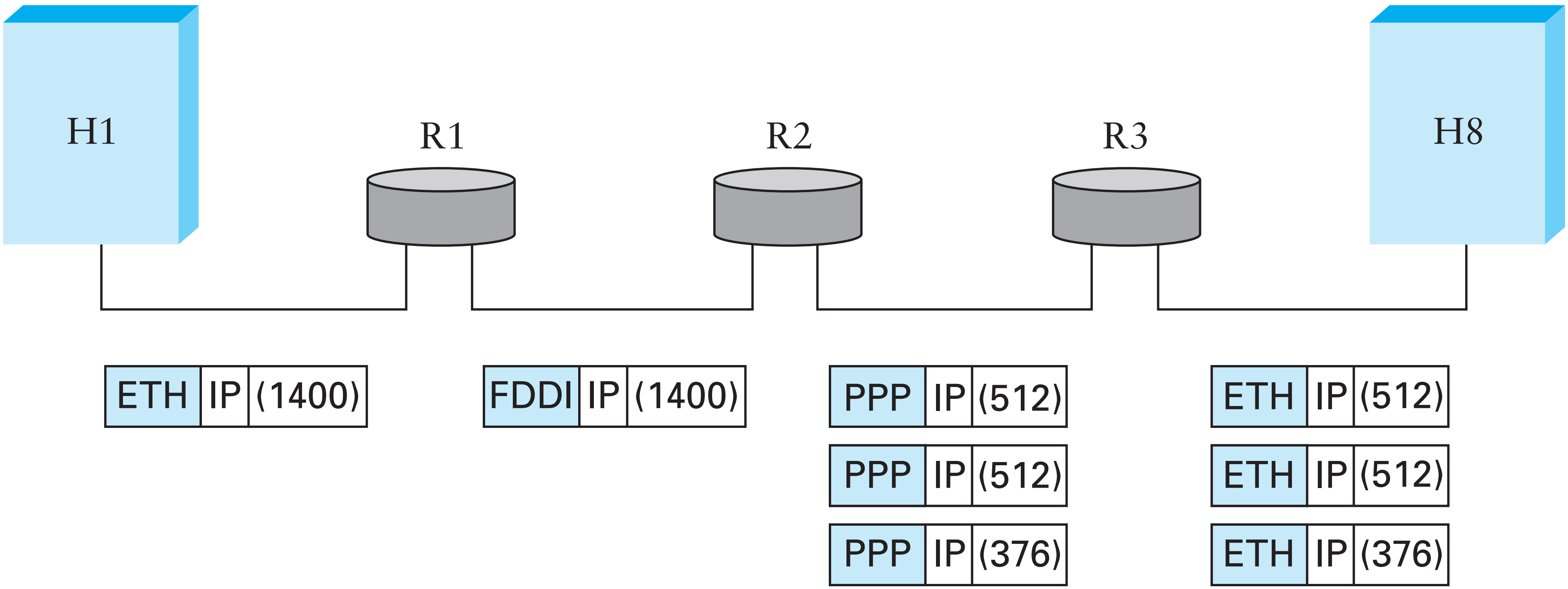
Other IP Fields

- Version: 4 (IPv4) for most packets, there's also IPv6 (lecture 9)
- Header length (in case of options)
- Type of Service (diffserv, we won't go into this)
- Protocol identifier (UDP: 17, TCP: 6, ICMP:1, why is TCP earlier?)
- Checksum over the header
- Let's look at a packet with wireshark

Fragmentation & Reassembly

- **Each network has some maximum transmission unit (MTU)**
- **Strategy**
  - Fragment when necessary (MTU < size of Datagram)
  - Source host tries to avoid fragmentation
    When fragment is lost, whole packet must be retransmitted!
  - Re-fragmentation is possible
  - Fragments are self-contained datagrams
  - Delay reassembly until destination host
  - Do not recover from lost fragments

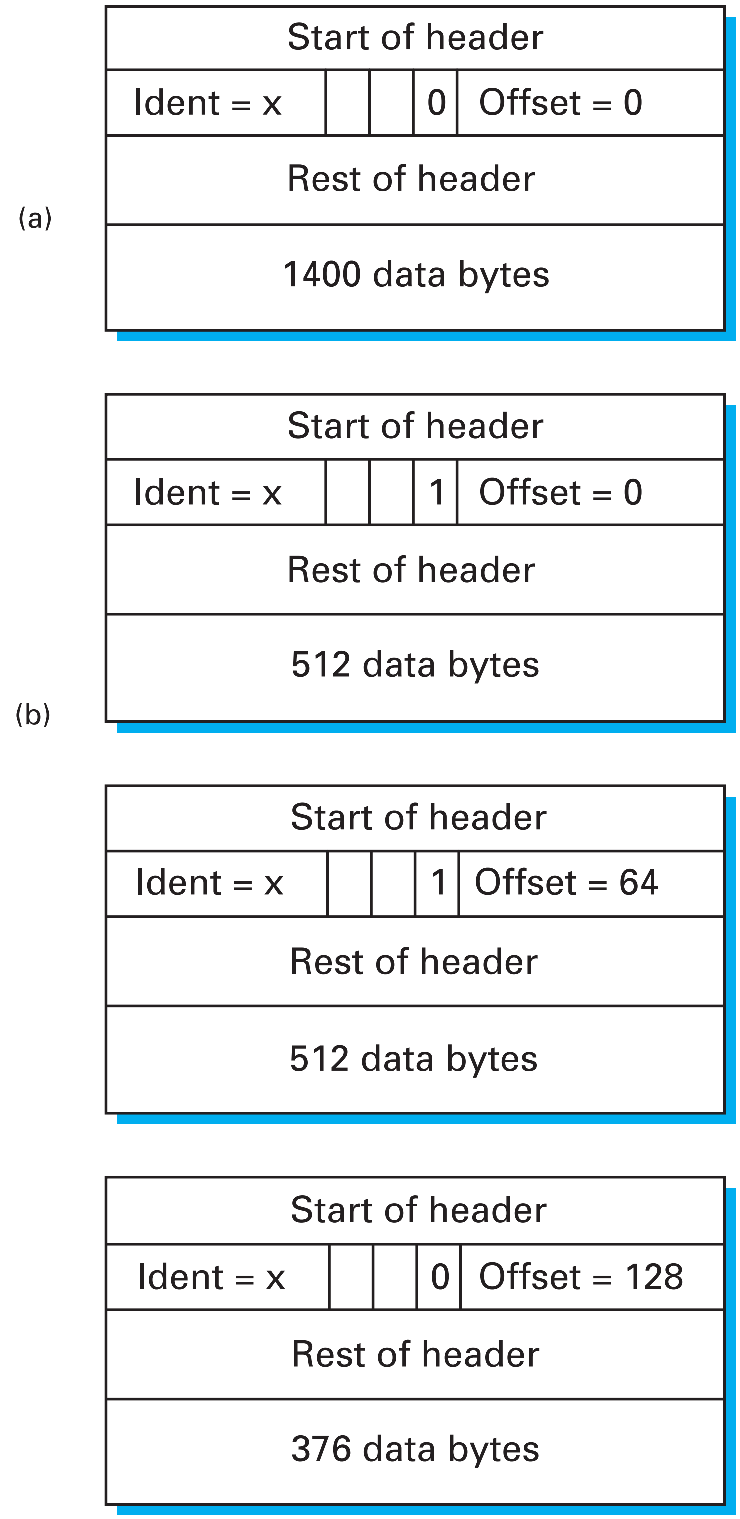
Fragmentation example



- **Ethernet MTU is 1,500 bytes**
- **PPP MTU is 576 bytes**
  - R2 Must fragment IP packets to forward them

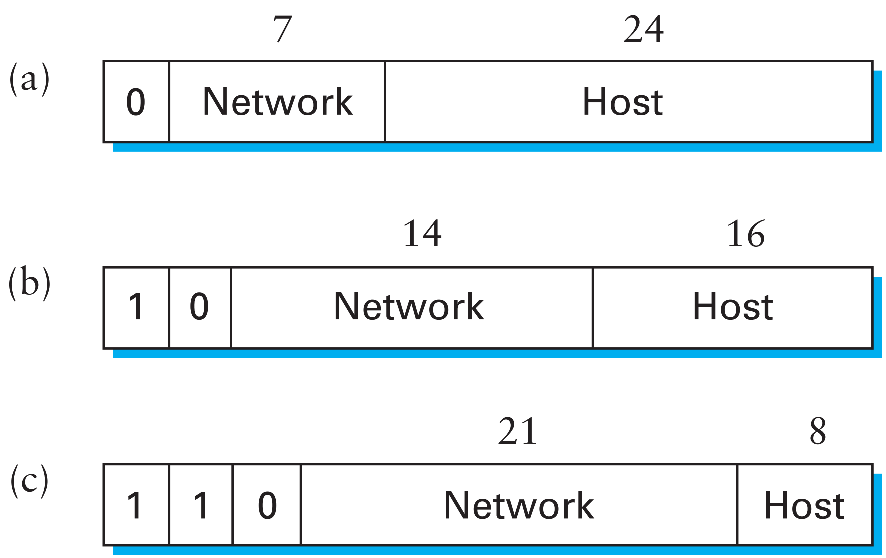
Fragmentation example (continued)

- **IP addresses plus ident field identify fragments belonging to same packet**
- **MF (more fragments) bit is 1 in all but last fragment**
- **Fragment size multiple of 8 bytes**
  - Multiply offset field by 8 to get fragment position within original packet



Format of IP addresses

- **Globally unique (or made to seem that way)**
- **Hierarchical: network + host**
  - Aggregating addresses saves memory in routers, simplifies routing (as we will see next lecture)
- **Originally, routing prefix embedded in address:**



(Still hear "class A," "class B," "class C")

- **Now, routing info on "CIDR" blocks, addr+prefix-len**
  - E.g., 171.67.0.0/16

Translating IP to lower-level addresses

- **Map IP addresses into physical addresses**
  - E.g., Ethernet address of destination host
  - Or Ethernet address of next hop router
- **Techniques**
  - Encode link layer address in host part of IP address (option is available, but only in IPv6)
  - Each network node maintains a lookup table (link→IP)
- **ARP – *address resolution protocol***
  - Table of IP to link layer address bindings
  - Broadcast request if IP address not in table
  - Everybody learns physical address of requesting node (broadcast)
  - Target machine responds with its link layer address
  - Table entries are discarded if not refreshed

Need for Address Translation

- **Layer 2 (link) address names a hardware interface**
  - E.g., my wireless ethernet 00:13:42:d2:93:11
    [digits changed to protect the weak MAC-layer filtering]
- **Layer 3 (network) address names a host**
  - E.g., www6.stanford.edu is 171.67.22.48
- **Details:**
  - A single host can have multiple hardware interfaces, so multiple link layer addresses for a single network address
  - A node is asked to forward a packet to another IP address: out which hardware interface does it send the packet?

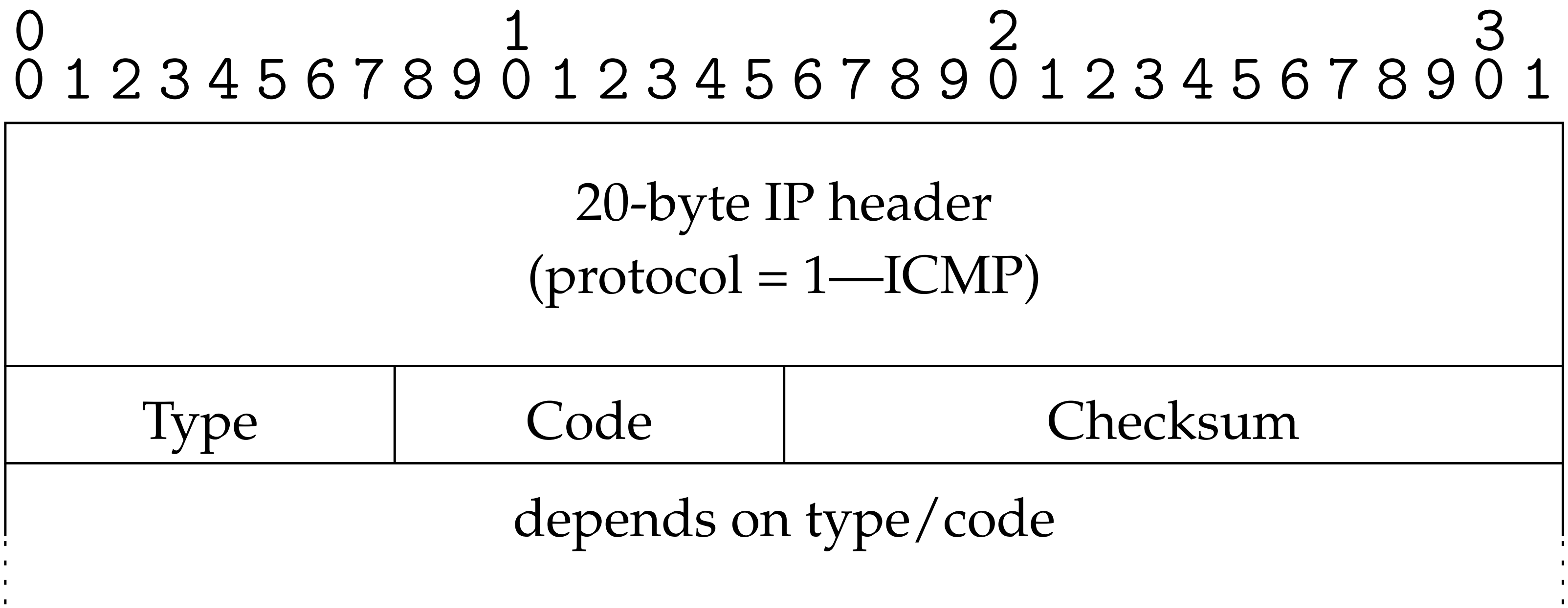
Arp Ethernet packet format

<table>
<tr><td>0</td><td>8</td><td>16</td><td>31</td></tr>
<tr><td colspan="2">Hardware type = 1</td><td colspan="2">ProtocolType = 0x0800</td></tr>
<tr><td>HLen = 48</td><td>PLen = 32</td><td colspan="2">Operation</td></tr>
<tr><td colspan="4">SourceHardwareAddr (bytes 0–3)</td></tr>
<tr><td colspan="2">SourceHardwareAddr (bytes 4–5)</td><td colspan="2">SourceProtocolAddr (bytes 0–1)</td></tr>
<tr><td colspan="2">SourceProtocolAddr (bytes 2–3)</td><td colspan="2">TargetHardwareAddr (bytes 0–1)</td></tr>
<tr><td colspan="4">TargetHardwareAddr (bytes 2–5)</td></tr>
<tr><td colspan="4">TargetProtocolAddr (bytes 0–3)</td></tr>
</table>

Internet Control Message Protocol (ICMP)

- **Echo (ping)**
- **Redirect (from router to source host)**
- **Destination unreachable (protocol, port, or host)**
- **TTL exceeded (so datagrams don't cycle forever)**
- **Checksum failed**
- **Reassembly failed**
- **Cannot fragment**
- **Many ICMP messages include part of packet that triggered them**
  - Example: Traceroute

ICMP message format



- **Types include:**
  - echo, echo reply, destination unreachable, time exceeded, ...
  - See http://www.iana.org/assignments/icmp-parameters

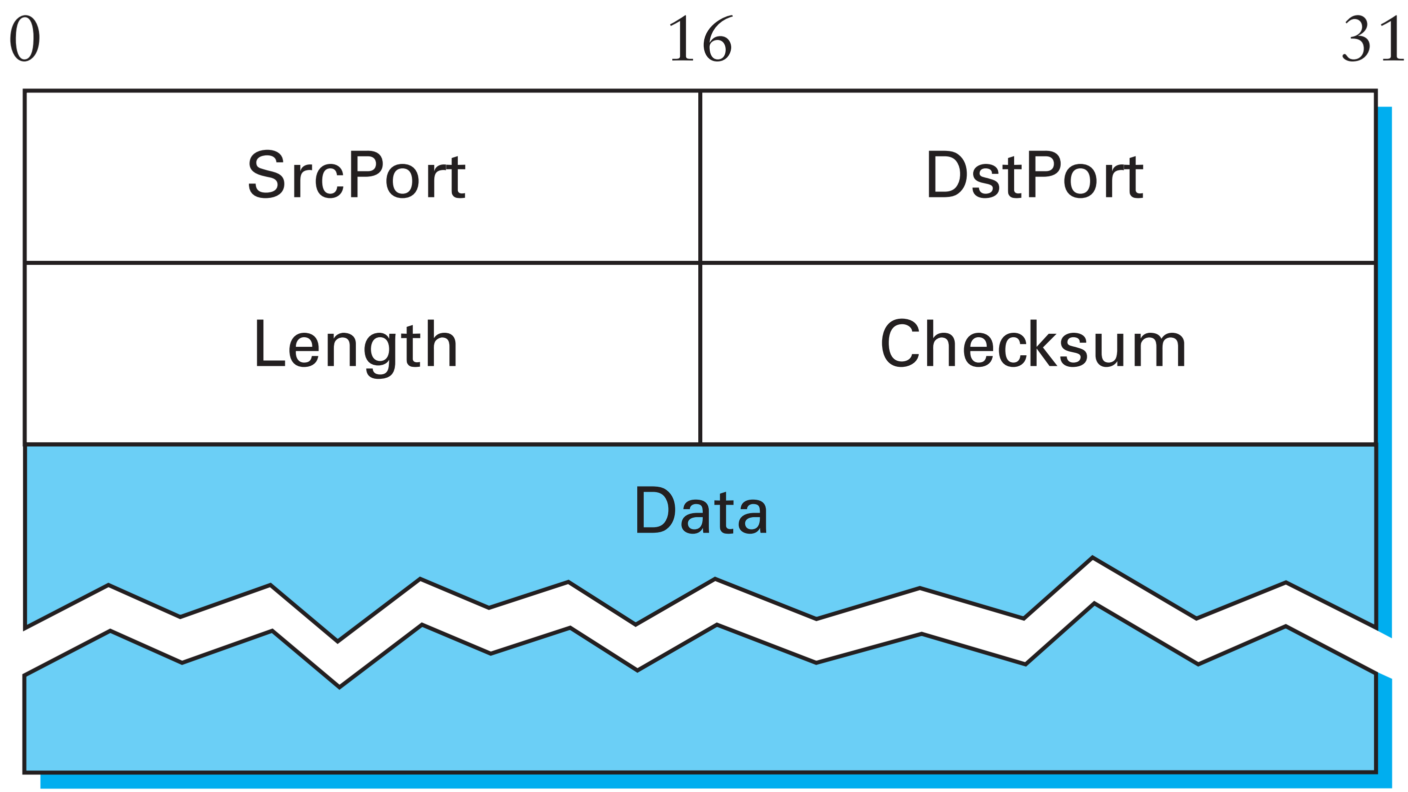
Example: Time exceeded

```
0                   1                   2                   3
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
```

20-byte IP header (protocol = 1—ICMP)		
Type = 11	Code	Checksum
unused		
IP header + first 8 payload bytes of packet that caused ICMP to be generated		

- **Code usually 0 (TTL exceeded in transit)**
- **Discussion: How does traceroute work?**

Recall: UDP packet format



- **First 8 bytes of UDP packet is UDP header**
  - Which is conveniently included in ICMP packets

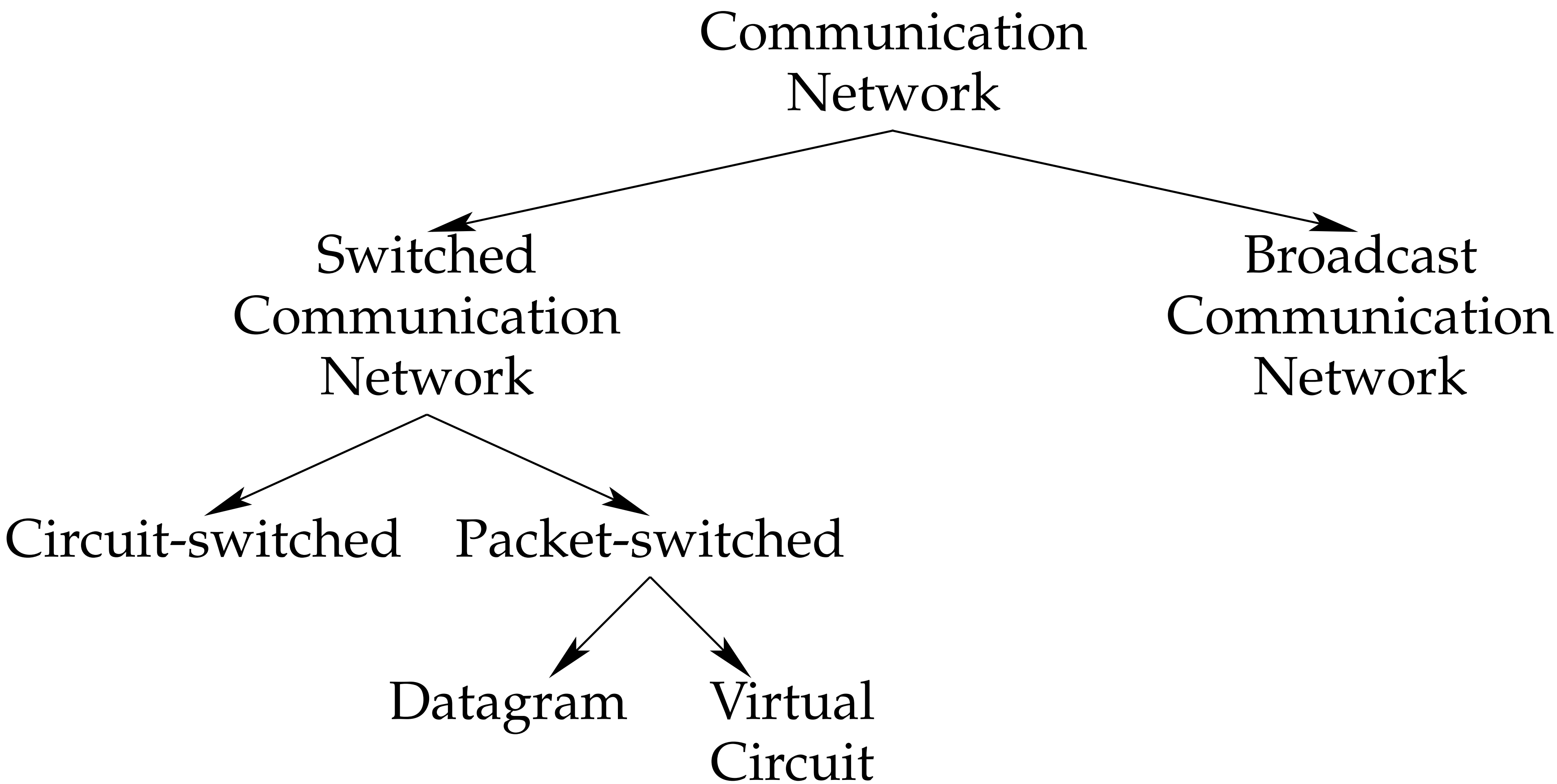
DHCP

- **Hosts need IP addrs for their network interfaces**
- **Sometimes assign manually (but this is a pain)**
- **Or use Dynamic Host Configuration Protocol**
  - Client broadcasts *DHCP discover* message
  - One or more DHCP servers send back *DHCP offer*
    - Sent to offered IP address (client hasn't accepted yet)
    - But sent to client's Ethernet address (not broadcast)
  - Client picks one offer, broadcasts *DHCP request*
  - Server replies with *DHCP ack*
- **Discussion: why also a gateway and netmask?**

IP forwarding

- **IP routers have multiple input/output ports**
- **Note distinction between *forwarding* and *routing***
  - Forwarding is passing packets from input to output port
  - Routing is figuring out the rules for mapping packets to output ports (topic of next two lectures)
- **IP forwarding maps packet to output port based on destination address**
  - Operates at network layer, not link layer
  - May forward between different kinds of networks (E.g., Ethernet on one side, cable TV wire on the other)
  - Does certain required processing on network-layer header (TTL, etc.)

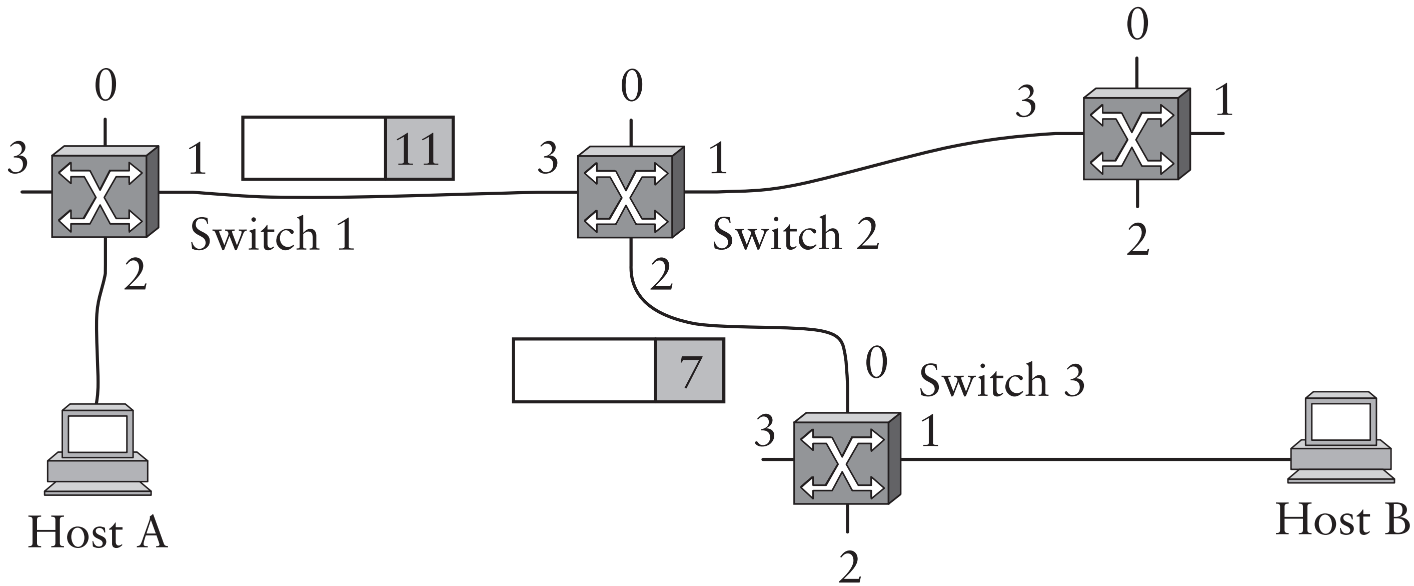
Big Picture


Communication Network
Switched Communication Network
Broadcast Communication Network
Circuit-switched
Packet-switched
Datagram
Virtual Circuit

Physical Circuit Diversion: Old PSTN

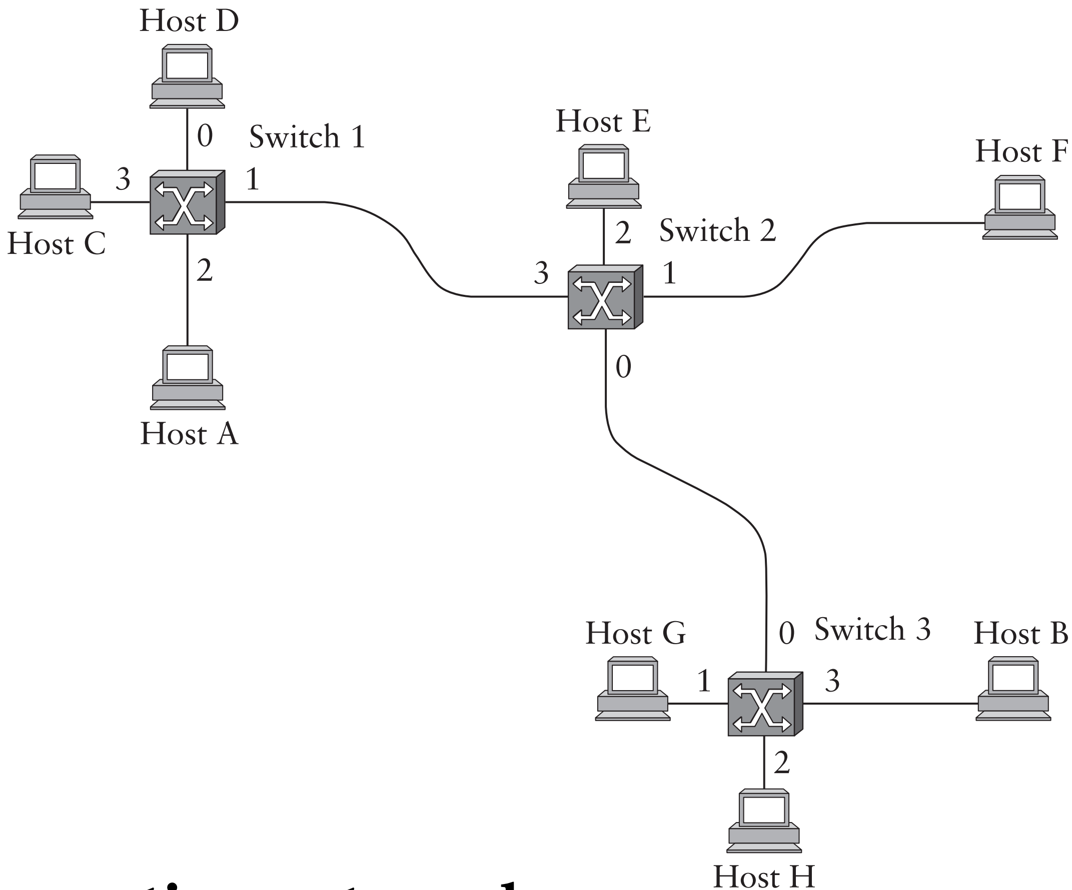
- A telephone number is a program
- Number sets up a physical wire connection to another phone
- Old phones used to click...

Virtual Circuit Switching



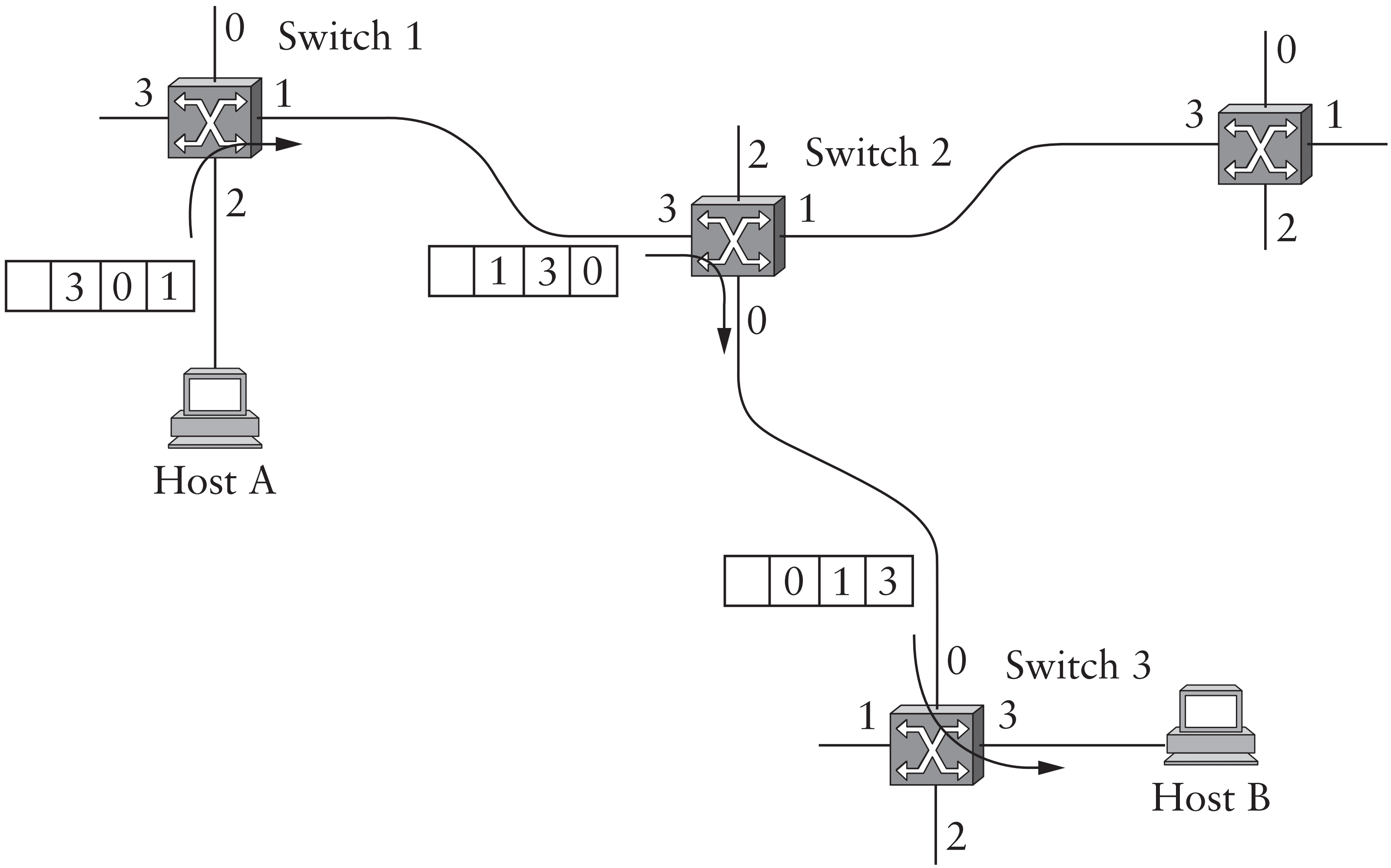
- **Explicit connection setup (and tear-down) phase**
  - Establishes virtual-circuit ID (VCI) on each link
- **Each switch maintains VC table**
  - Switch maps $\langle$in-link, in-VCI$\rangle \rightarrow \langle$out-link, out-VCI$\rangle$
  - Subsequent packets follow established circuit
- **Sometimes called *connection-oriented model***

Datagram switching



- **No connection setup phase**
  - Switches have routing table based on node addresses
- **Each packet forwarded independently**
- **Sometimes called *connectionless model***

Source routing



- **Simple way to do datagram switching (punt forwarding decisions to the sender)**

Virtual Circuit Model

– **Typically wait full RTT for connection setup before sending first data packet**

+ **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**

+ **Packets to the same destination can use different circuits**

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

+ It is possible to route around failures

– Overhead per packet is higher than for the connection-oriented model

– All packets to the same destination must use the same path

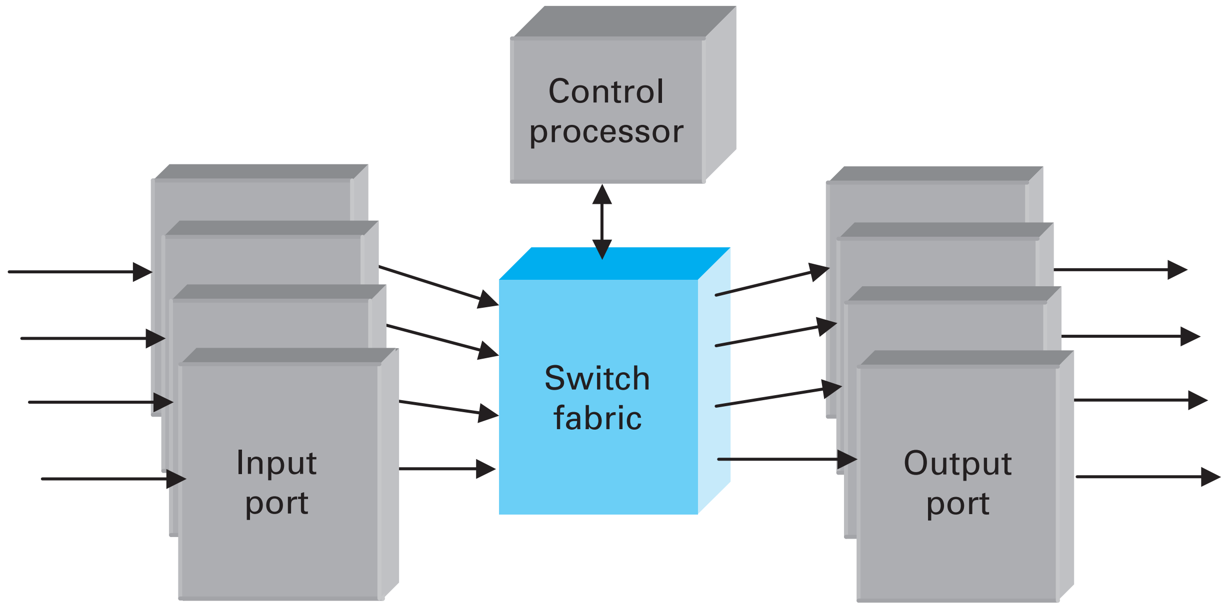
Cut through vs. store and forward

- **Two approaches to forwarding a packet**
  - Receive a full packet, then send it on output port
  - Start retransmitting as soon as you know output port, before you have even received the full packet (*cut-through*)
- **Cut-through routing can greatly decrease latency**
- **Disadvantage: Can't always send useful packet**
  - If packet corrupted, won't check CRC till after you started transmitting
  - Or if Ethernet collision, may have to send runt packet on output link, wasting bandwidth

Optical switches

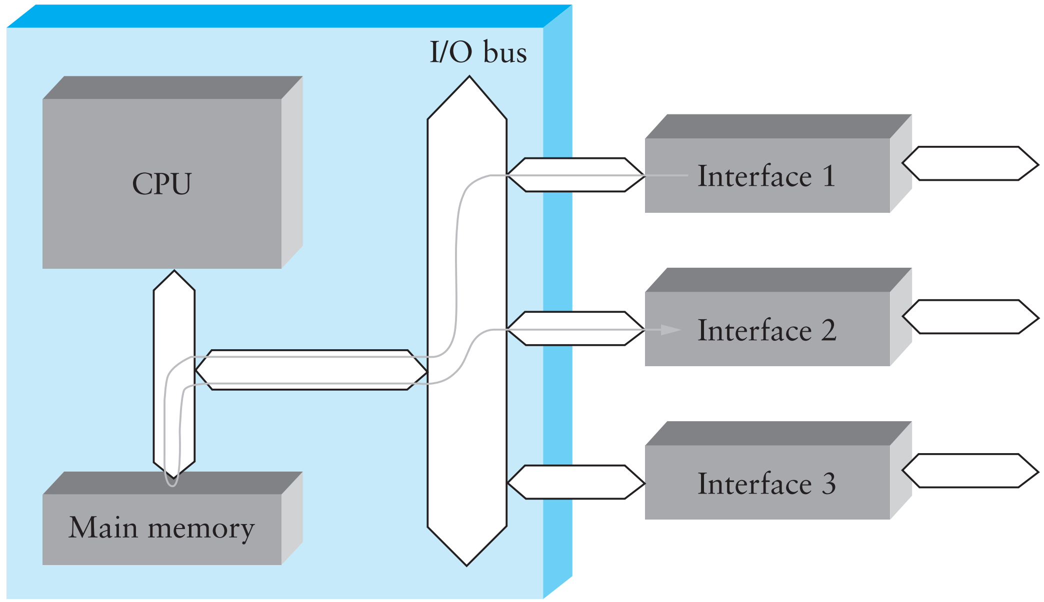
- **Already analog optical repeaters deployed**
  - Will amplify any signal
  - Can change your low-level transmission protocol w/o replacing repeaters
- **Could possibly do the same thing for switching**
  - Microscopic mirrors can redirect light to different ports
  - (The ultimate cut-through routing)
- **Technology exists, but not widely deployed**
  - Optical switch will not see packet headers
  - Instructions on where to send packet need to be out-of-band

Generic hardware switching architecture



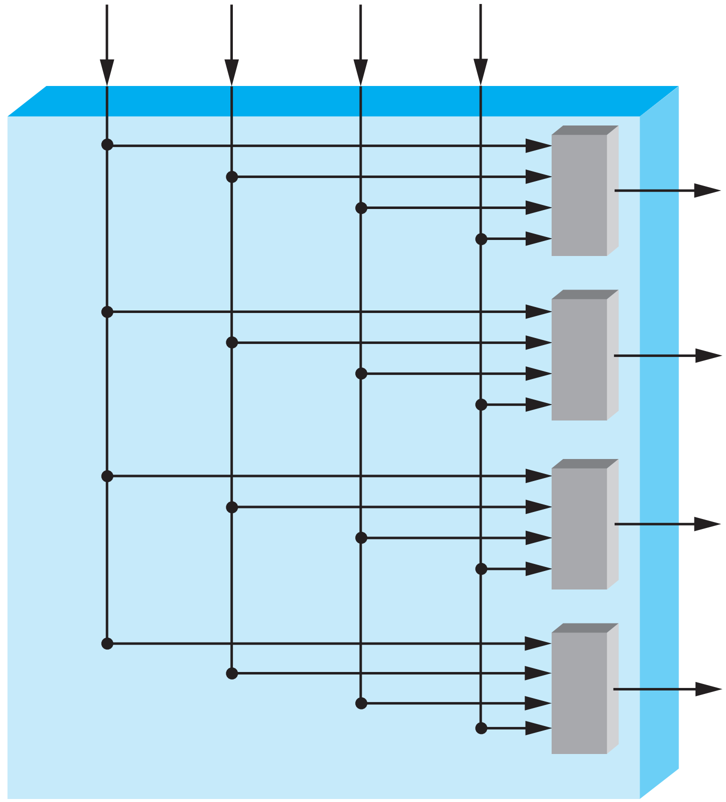
- **Goal: deliver packets from input to output ports**
- **Three potential performance concerns:**
  - Throughput in terms of bytes/time
  - Throughput in terms of packets/time
  - Latency

Shared bus switch



- **Shared bus – like your PC**
  - NIC DMAs packet to memory over I/O bus
  - CPU examines pkt header, sends to dest NIC over bus
  - I/O bus is serious bottleneck
  - For small packets, CPU may be limited, too
- **Shared memory – similar, has memory bottleneck**

Crossbar switch

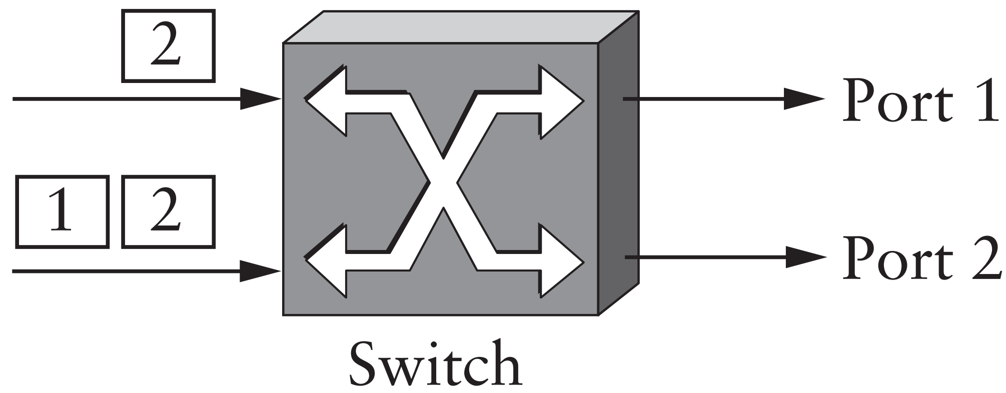


- **One [vertical] bus per input interface**
- **One [horizontal] bus per output interface**
- **Can connect any input to any output**
  - Trivially allows any input→output permutation
  - More than one input to same output requires trickery

Where to buffer?

- **At some point more than one input port will have packets for the same output port**
- **Where do you buffer the packet?**
  - Input port
  - Output port

Self-routing switches

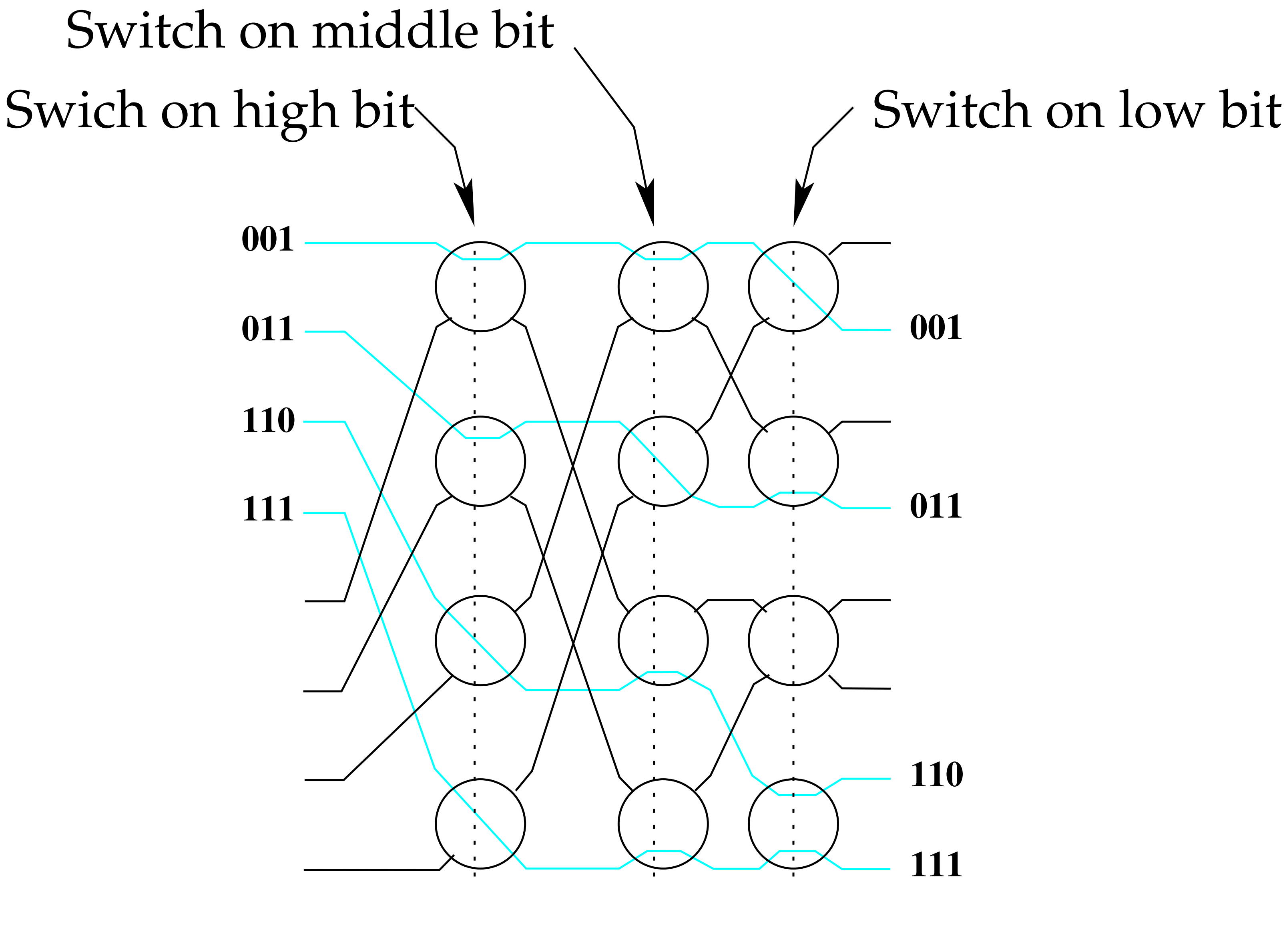


- **Idea: Build up switch out of 2×2 elements**
- **Each packet contains a "self-routing header"**
  - For each switch along the way, specifies the output
- **Must somehow compute a path when introducing packet**
  - Is there more than one path to chose from?
  - Will path collide with another packet?
- **Easy to implement stages once path computed**

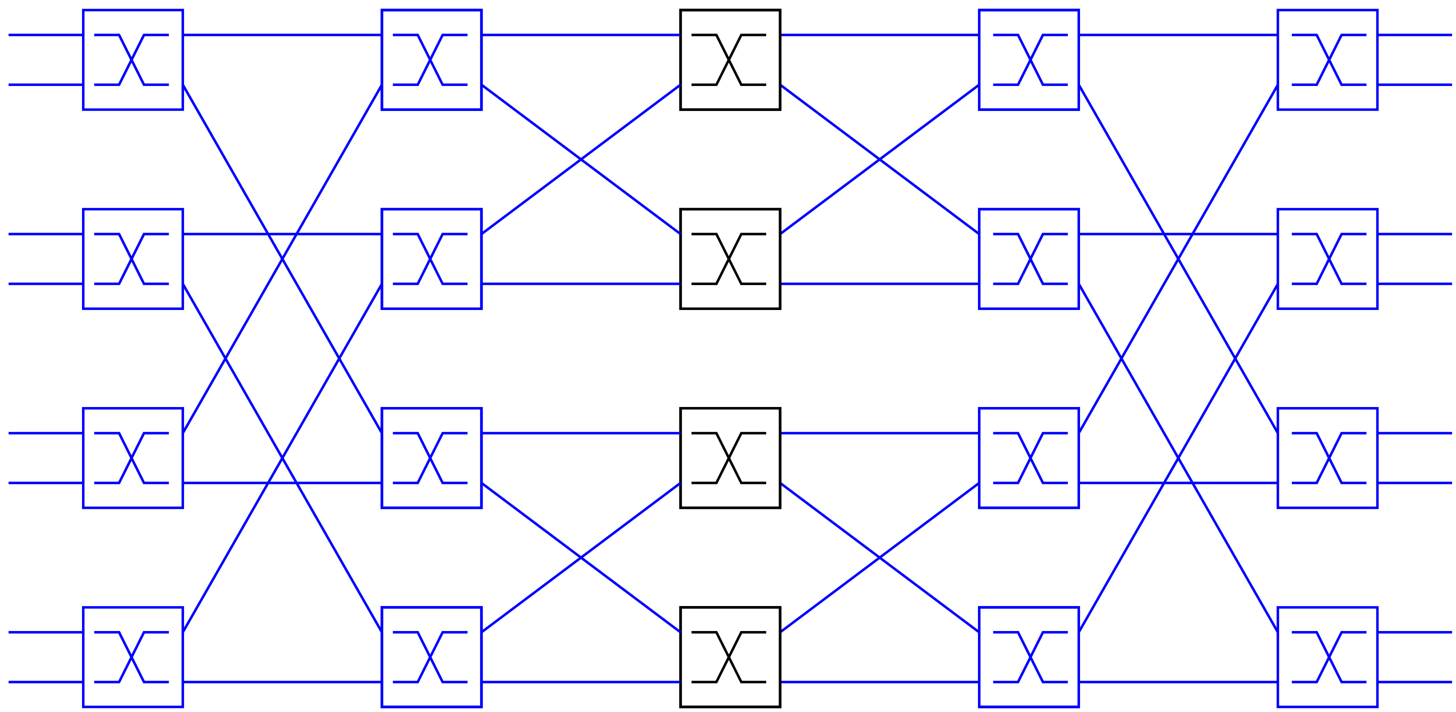
Banyan networks

- **A Banyan network has exactly one path from any input port to a given ouput port**
  - Example: Each stage can flip one bit of the port number
- **Easy to compute paths**
- **Problem: Not all permutations can be routed**
  - Might want $1 \rightarrow 0$ and $7 \rightarrow 1$, but both paths use same link
- **But: Can always route packets if sorted**
  - Leads to *batcher banyan* networks
  - Batcher phase sorts packets before banyan

Example: Banyan network



Beneš

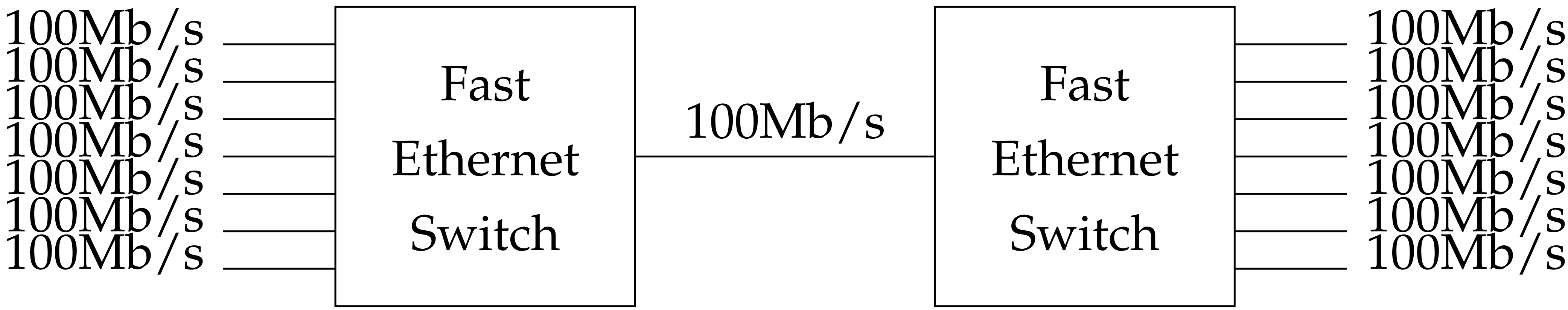


- **Two back-to-back Banyan networks**
  - Can route any permutation of inputs→outputs
  - (Can be proven by induction on size of network)
- **Unfortunately, figuring out schedule is global problem**

Bisection bandwidth

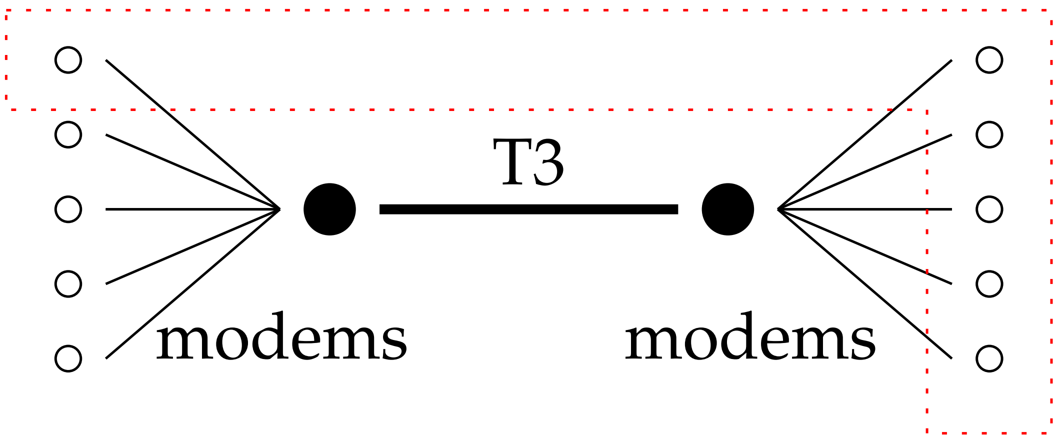
- **Can speak of the bandwidth between sets of ports**
  - Bandwidth is maximum achievable aggregate bandwidth between the two sets
- **Bisection bandwidth is important property of network**
  - Lowest possible bandwidth between equal-sized sets of ports
  - Or almost equal-sized if odd number of ports
- **A network with bad bisection bandwidth may offer poor behavior**
  - Even if no conflict between input and output link utilization, may have internal bottlenecks reducing throughput

Example: Poor bisection bandwidth



- **Connect two Ethernet switches with Ethernet**
  - Suppose all clients on left, and all servers on right. . .
  - Aggregate bandwidth between all clients and servers only 100Mbit/s

Example: Poor bisection bandwidth 2



- **Remember it's *worst case* cut**
  - Even with one fat link, don't have to slice down middle
  - Put fat link in one partition, and bisection b/w very small

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- **Forwarding: switching, circuits, and source routing**
- **Next lecture: routing – how forwarding tables are built**