Problem: There is more than one network (heterogeneity & scale)

Internetworking:

- Internet Protocol (IP)
- Routing and scalability
- Group Communication

Internetworking

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Every seeming equality conceals a hierarchy.

--- Mason Cooley

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

Outline

- Best Effort Service Model
- Global Addressing Scheme
- Datagram forwarding

- Address translation (ARP)
- Host configuration (DHCP)
- Error reporting (ICMP)
- Virtual private networks and IP tunnels

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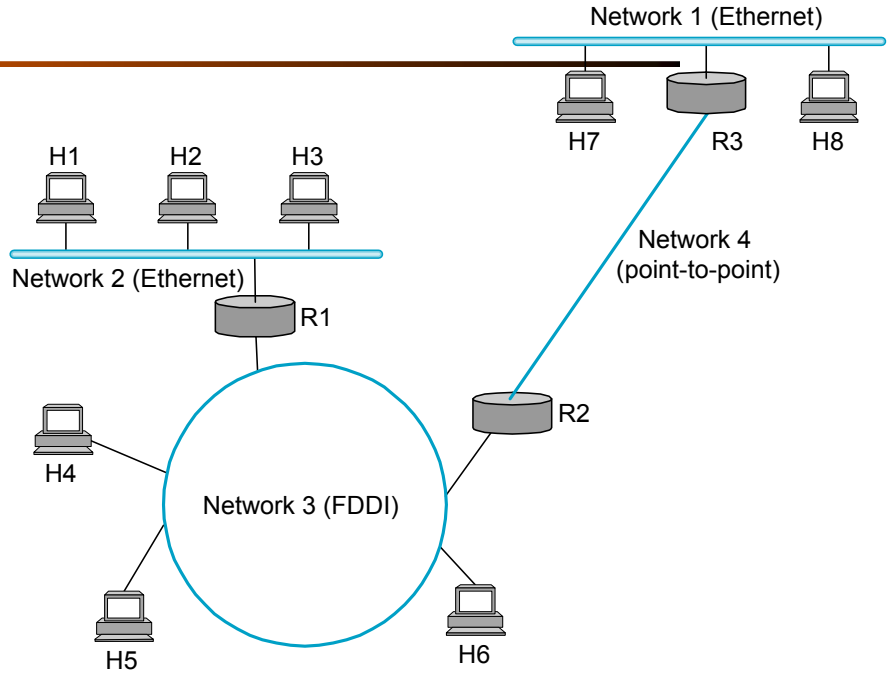
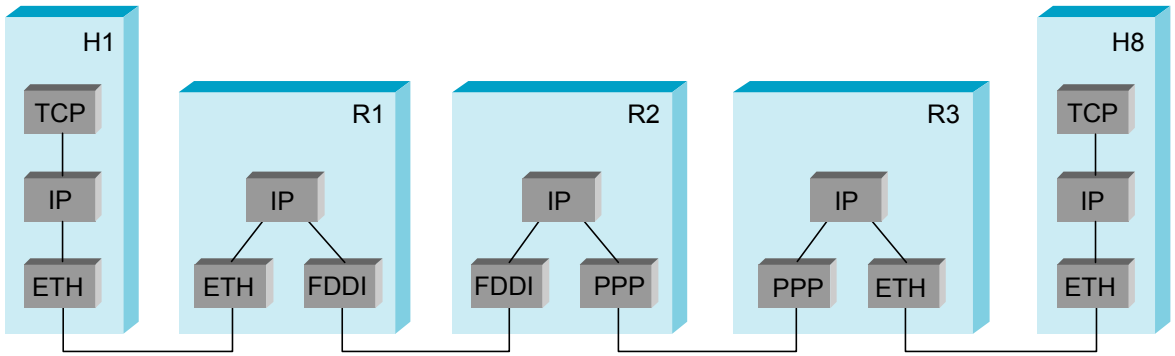
IP Internet

- Concatenation of Networks



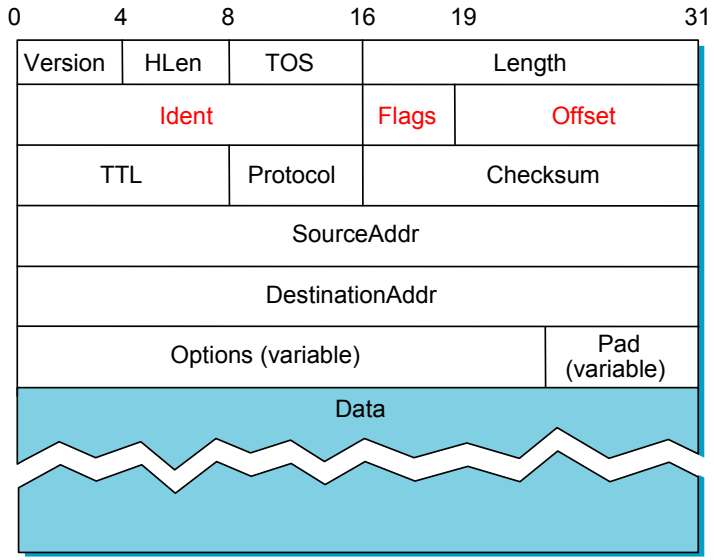
- Protocol Stack: H1 -> H8



Service Model

- Connectionless (datagram-based)
  - No need for connection setup and related control logic (e.g., assigning VC id and setting up forwarding table)
- Best-effort delivery (unreliable service)
  - packets can be lost
  - packets can be delivered out of order
  - duplicate copies of a packet can be delivered
  - packets can be delayed for a long time

IP datagram format

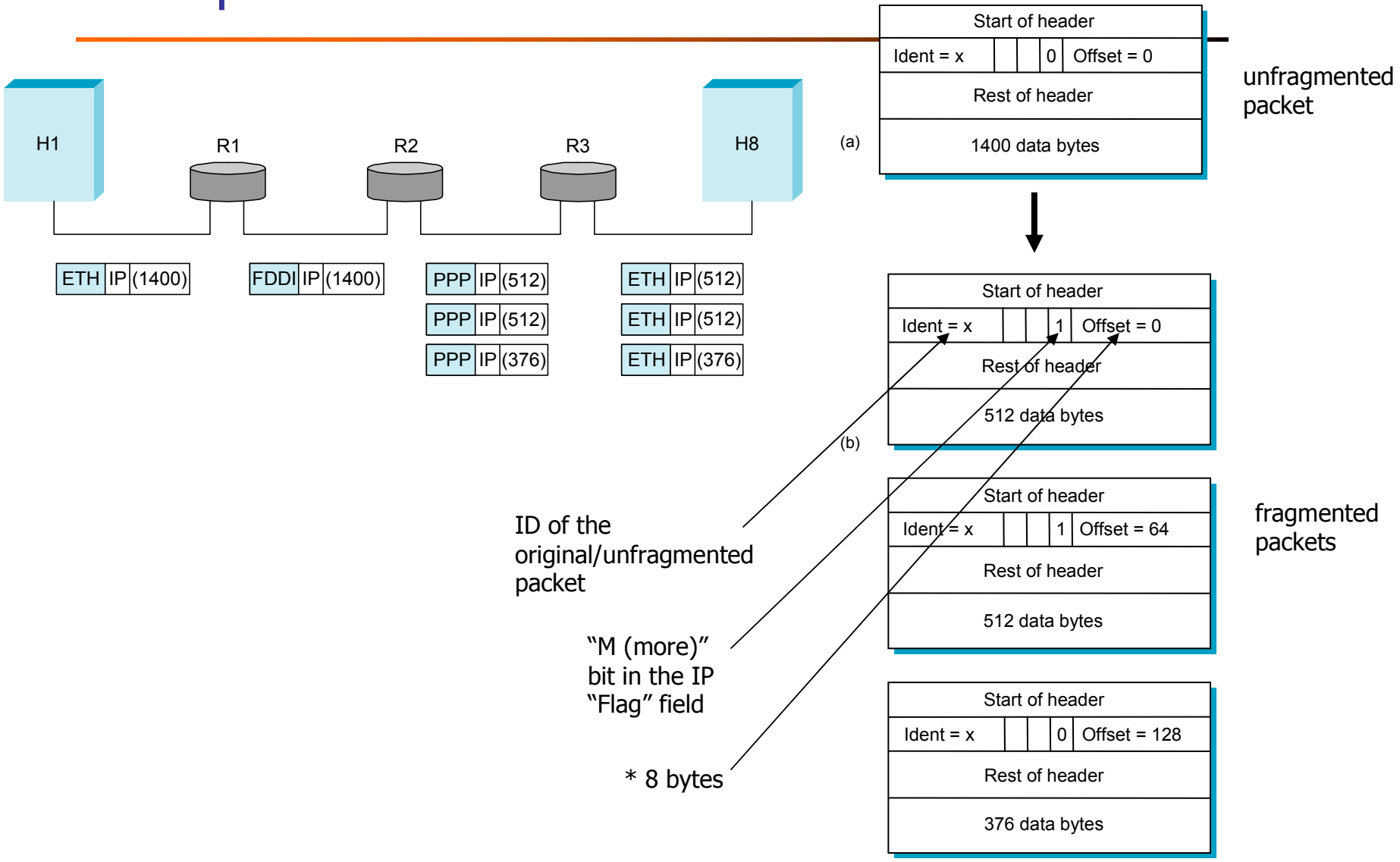


- HLen: header length in # of 32-bit words
- TOS: types of service to differentiate different application traffic
- Length: datagram length (including header) in # of bytes
- <Ident, Flags, Offset>: fragmentation & reassembly
- TTL: avoiding loops (# of hops)
- Protocol: demultiplexing key
- Checksum: calculated by regarding IP header as a sequence of 16-bit works

Fragmentation and Reassembly

- Each network has some maximum transmission unit (MTU)
- Design decisions
  - *fragment when necessary* (MTU < Datagram)
  - try to avoid fragmentation at source host
    - by choosing datagram size to be no more than MTU for the link associated with source
  - re-fragmentation is possible
    - when a downstream link has smaller MTU than an upstream link
  - fragments are self-contained datagrams
  - delay reassembly until destination host, for
    - simplicity: not knowing the right size to reassemble
    - efficiency: not knowing whether will be fragmented again
  - do not recover from lost fragments; i.e., a whole IP datagram is discarded if a single fragment gets lost
    - thus fragmentation is a good thing to avoid, for instance, by performing "path MTU discovery"

Example


H1
R1
R2
R3
H8
ETH IP (1400)
FDDI IP (1400)
PPP IP (512)
PPP IP (512)
PPP IP (376)
ETH IP (512)
ETH IP (512)
ETH IP (376)
(a)
Start of header
Ident = x
0
Offset = 0
Rest of header
1400 data bytes
unfragmented packet
(b)
Start of header
Ident = x
1
Offset = 0
Rest of header
512 data bytes
Start of header
Ident = x
1
Offset = 64
Rest of header
512 data bytes
Start of header
Ident = x
0
Offset = 128
Rest of header
376 data bytes
fragmented packets
ID of the original/unfragmented packet
"M (more)" bit in the IP "Flag" field
* 8 bytes

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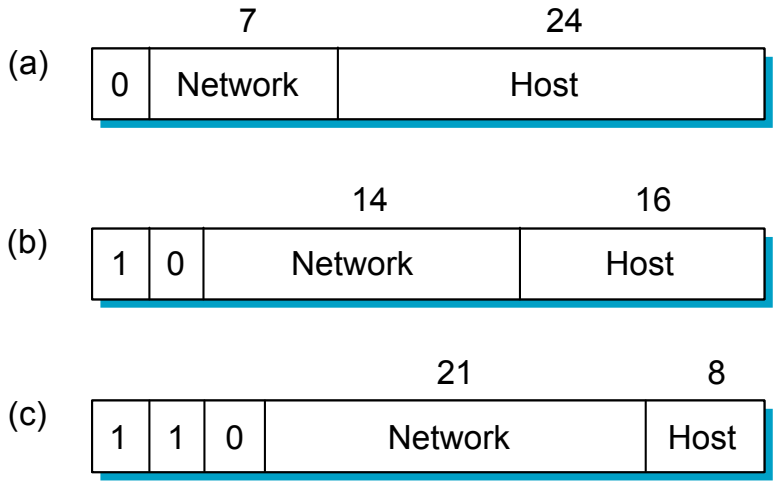
Global Addresses

- Properties
  - globally unique
  - global support by different technologies
  - hierarchical: network + host
- Classful addressing & Dot Notation
  - Class A: 10.3.2.4
  - Class B: 128.96.33.81
  - Class C: 192.12.69.77
- Classless addressing (to be discussed)



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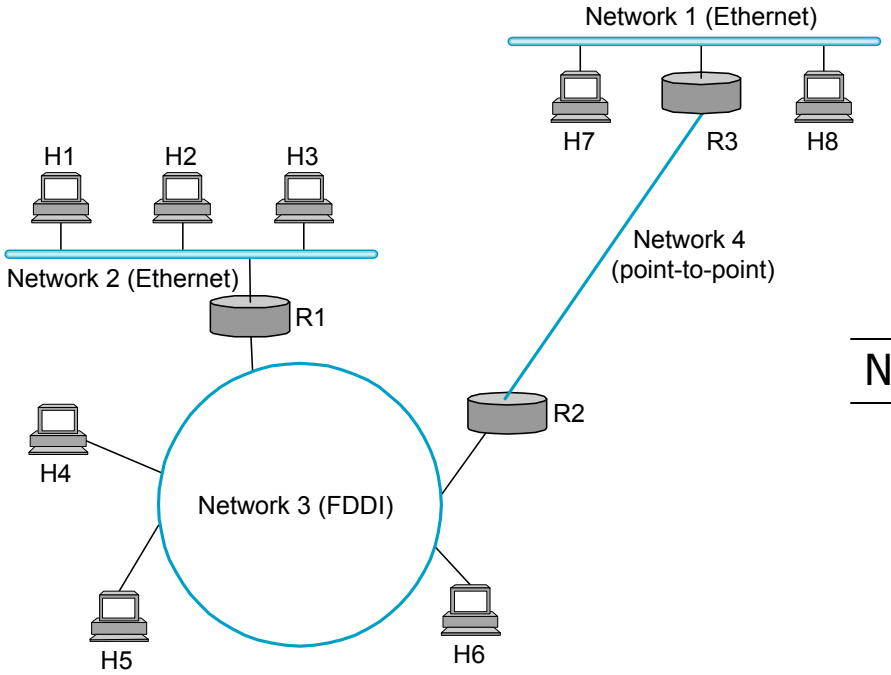
Datagram Forwarding

- Strategy
  - every datagram contains destination's address
  - if directly connected to destination network (via a local physical network), then forward to host
  - if not directly connected, 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 forwarding table: R2



Network Number	Next Hop
1	R3
2	R1
3	interface 1
4	interface 0

Hierarchical addressing improves scalability: routers maintain table for "networks" rather than "hosts"

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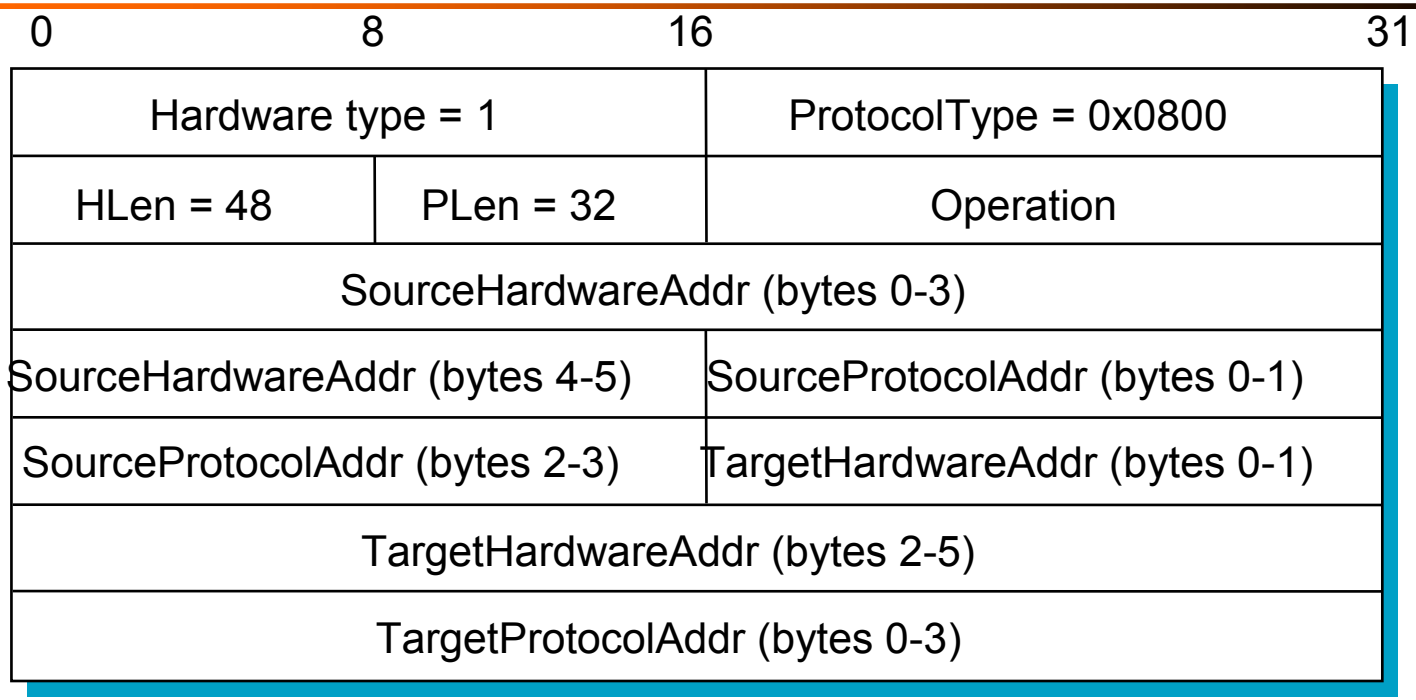
Address Translation

- Map IP addresses into physical/link-layer addresses
  - destination host
  - next hop router
- Techniques
  - encode physical address in *host* part of IP address
    - (-) constrains the length of physical address
  - table-based look up
- Address resolution protocol (ARP)
  - 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 (e.g., within 10 minutes)

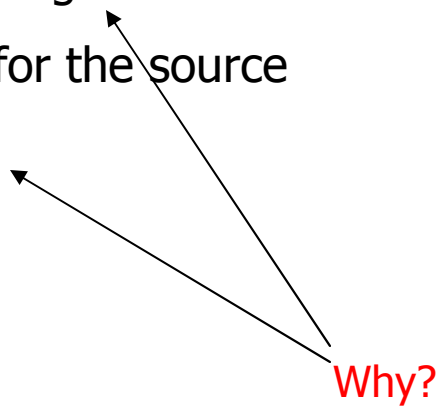
ARP Packet Format



- 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

ARP Details

- ARP Request carries information about IP & physical addresses of the source
- A node receiving the ARP request
  - updates table with source when it is the target
  - refreshes table if it already has an entry for the source
  - otherwise, does not refresh/update table



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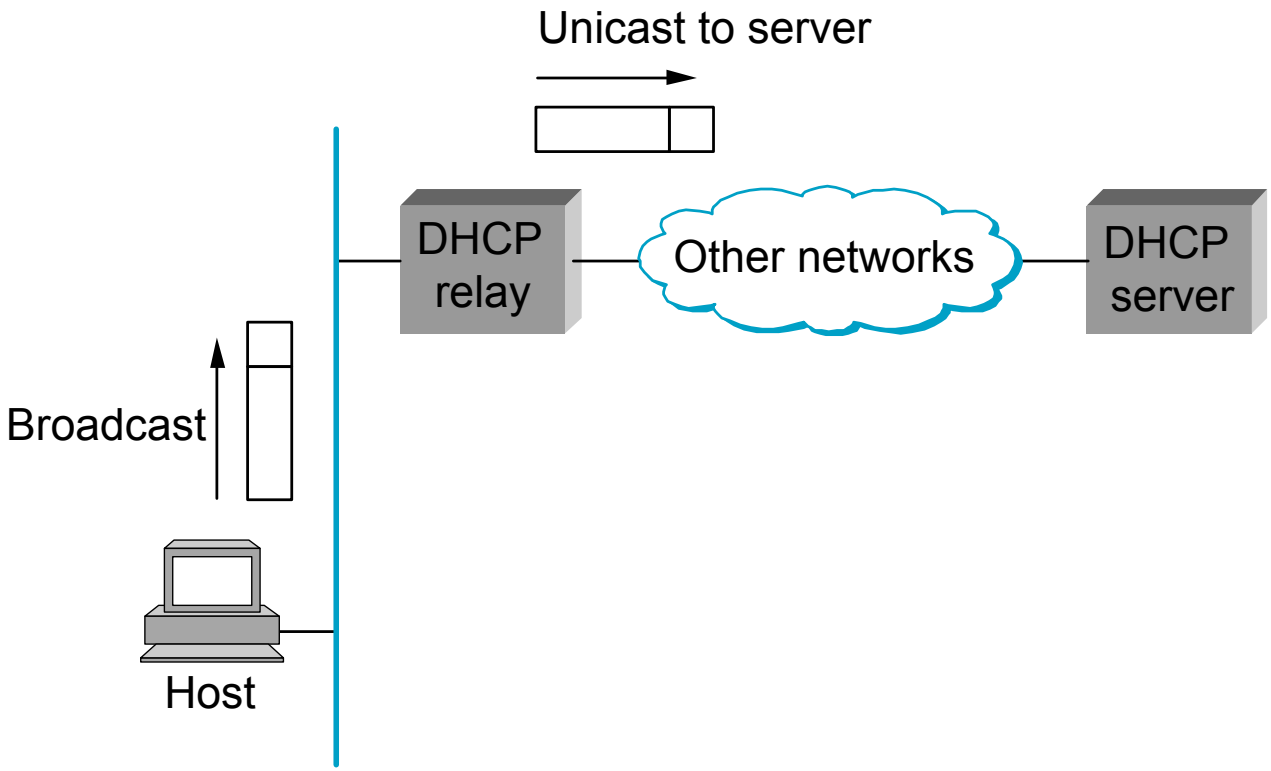
Dynamic host configuration protocol (DHCP)

- Automatically configure information such as IP address, gateway/default router, DNS, etc.
  - Reduces the overhead and probability of errors in manual configuration
  - Uses available IP addresses efficiently: not all nodes are up all the time
  - Also support *fixed binding* of IP and MAC-address through manual configuration at DHCP server side
- System setup: clients $\leftrightarrow$ DHCP server

DHCP: with relay agent

- Not want to maintain a DHCP server for every network



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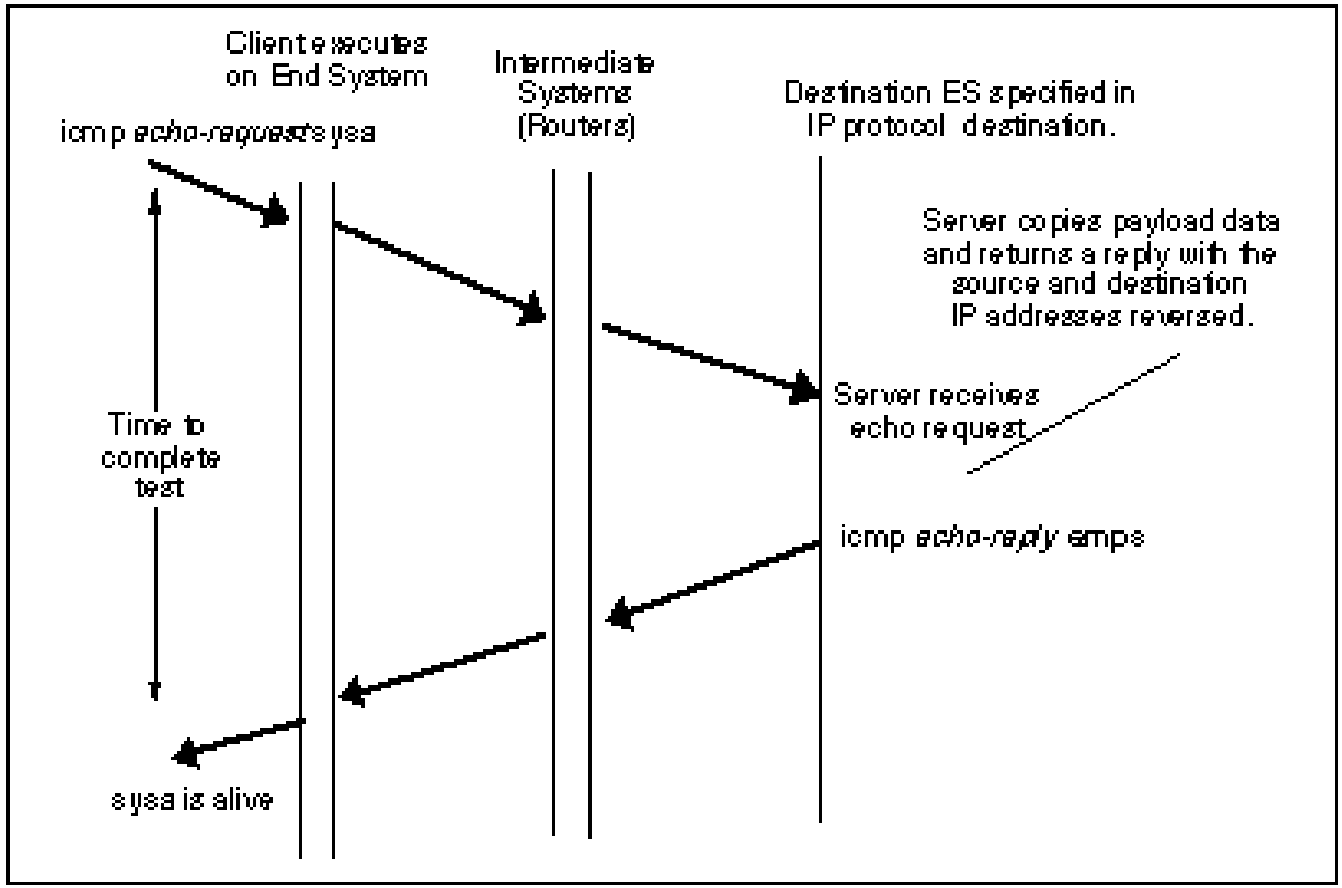
Internet Control Message Protocol (ICMP)

- ICMP sits over IP
- *Error reporting*: from routers to source hosts
  - Destination unreachable (e.g., due to link failure)
  - TTL exceeded (so datagrams don't cycle forever)
  - Checksum failed
  - Reassembly failed
- *Utilities*
  - Redirect (from router to source host): a router informs a host of better route (e.g., in helping a host setting the best "default router")
  - "Echo (ping)" is implemented using ICMP packets

ping


Client executes on End System
Intermediate Systems (Routers)
Destination ES specified in IP protocol destination.
icmp *echo-request* sysa
Server copies payload data and returns a reply with the source and destination IP addresses reversed.
Server receives echo request
Time to complete test
icmp *echo-reply* smps
sysa is alive

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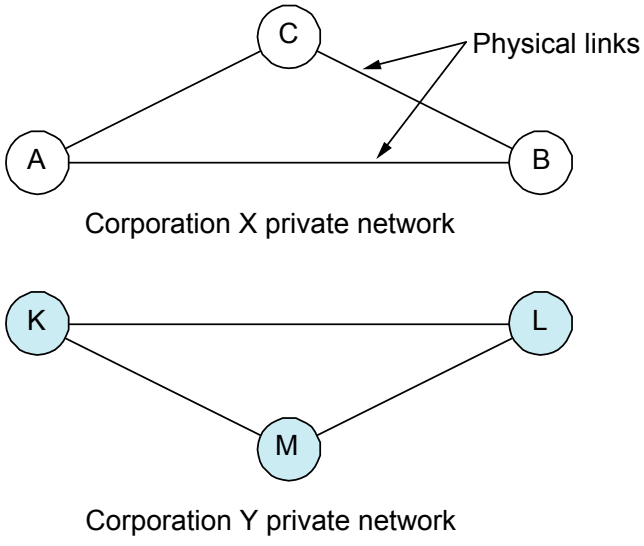
Virtual private networks (VPN)

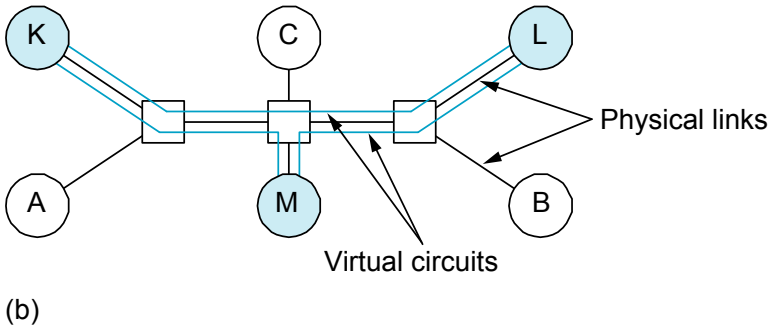
- To provide *controlled connectivity* among hosts for reasons such as security

- VPN via
  - Virtual circuits, LAN switching, etc (over a single network)
  - IP tunneling (over network of networks)

VPN via virtual circuits (frame relay, ATM, etc.)

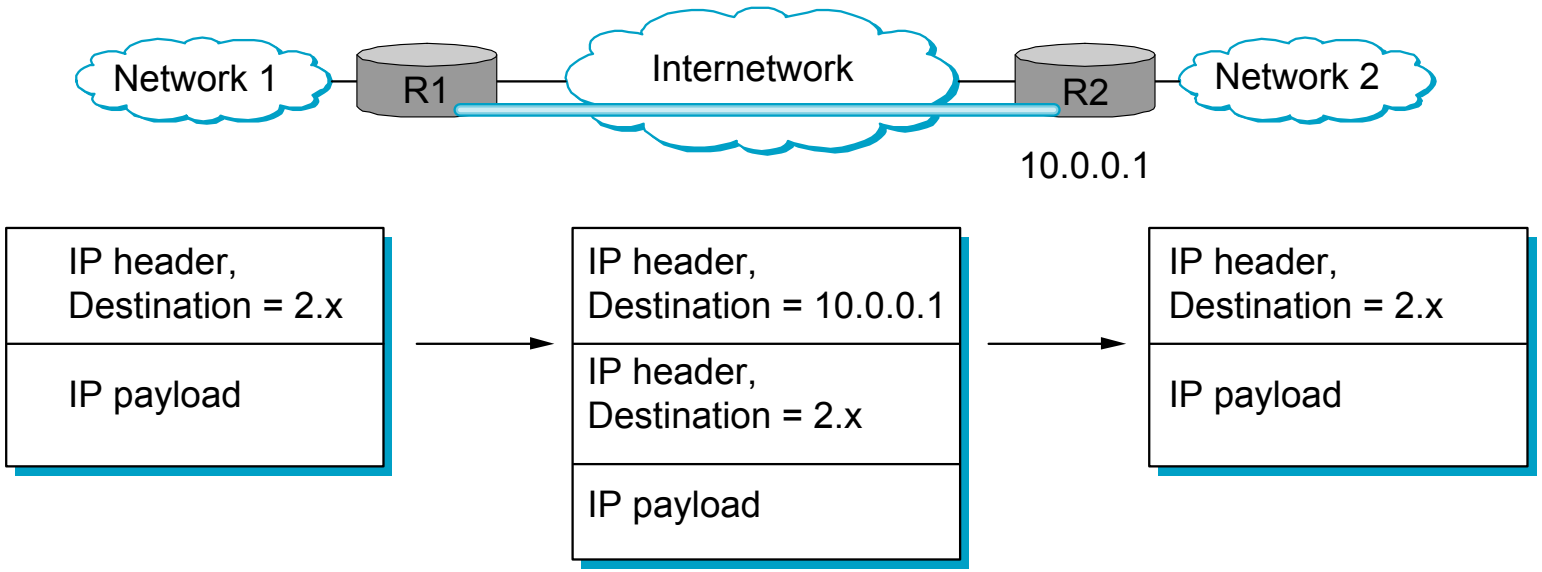


Two separate private networks



Two VPNs sharing common switches

VPN via IP tunneling



Benefits of IP tunneling

- Supplemented with encryption, a tunnel becomes a "private" link
- Incremental deployment of new network services (i.e., nodes in between two devices may not support the service)
  - E.g., MBone for network-layer multicast
  - Q: how are peer-to-peer networks different from "VPNs via IP tunneling"?
- Force a packet to be delivered to a particular place even if its original header might suggest otherwise
  - E.g., Mobile IP: packet redirection at the home host

Overhead of IP tunneling

- Increased header overhead, especially for short packets
- Management cost: configuring tunnels, etc

Summary of IP

- Deal with "heterogeneity"
  - Best-effort service: minimum assumption about underlying networks
  - A global address space
  - A common IP packet format
- Deal with "scale"
  - Hierarchical (network + host) address: reduces information maintained at routers (*scale in control state*)
  - Automatic configuration: DHCP, etc. (*scale in management*)
- IP tunneling for VPN