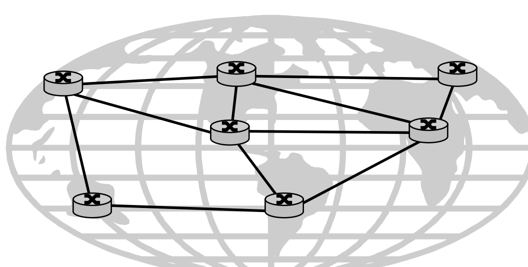
HELSINKI UNIVERSITY OF TECHNOLOGY
Networking Laboratory

Internetworking

Problem

- Aim: Build networks connecting millions of users around the globe
  - also spanning networks based on **any** technology



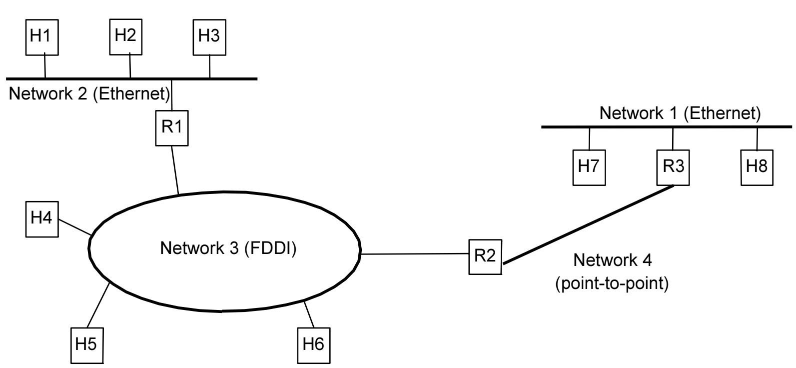
- Problems: heterogeneity and scalability
  - bridges can be used to connect different LANs (extended LANs)
  - heterogeneity: need to support different LANs, point-to-point technologies, switched networks, different addressing formats
  - scalability: addressing (management and configuration) and routing must be able to handle millions of hosts
  - in this lecture, we examine the (original) IP protocol, IP addressing, packet forwarding

Outline

- Internet architecture
- IP service model
- IP forwarding
- Address translation (ARP)
- Automatic host configuration (DHCP) and error reporting (ICMP)
- Virtual Private Networks (VPNs)

IP Internet

- Terminology
  - network = network based on LAN or extended LAN technology
  - internet = “network of networks”
  - Internet = internet using IP
  - routers = nodes connecting networks
  - IP = Internet Protocol, current version IPv4 (IP Version 4)

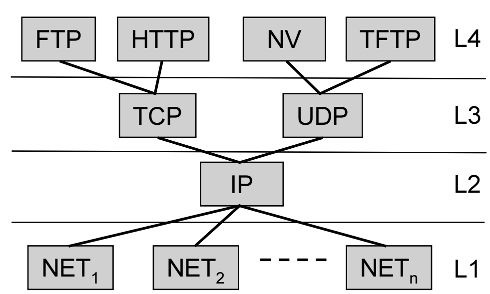


IP design principles

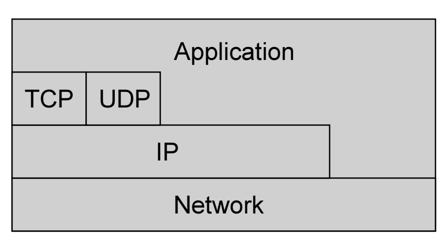
- Cerf and Kahn's internet design principles (1974)
  - minimalism, autonomy
    - no internal changes required to interconnect networks
    - network is self-configuring as much as possible
    - network can survive node and link failures
  - best effort service model
    - packets are not offered any guarantees
    - simplifies packet processing
  - stateless routers
    - network does not store information of any "connections" or user state
    - routers forward autonomous packets
  - decentralized control
    - enables high survivability (in presence of, e.g., link or node failures)

Internet architecture

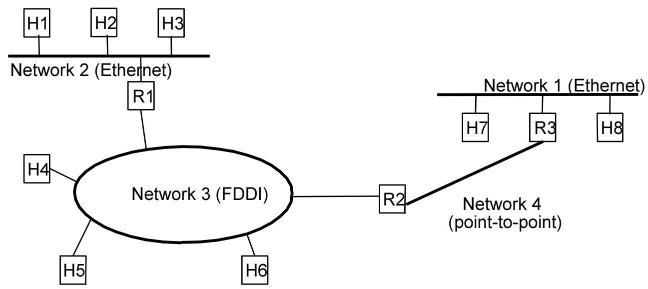
- Internet architecture has only 4 layers
  - L4 (Application layer): FTP, HTTP, …
  - L3 (Transport layer): TCP (reliable byte transfer) and UDP (unreliable datagram delivery) provide logical channels to applications
  - L2 (IP layer): IP protocol interconnects multiple networks into a single logical network
  - L1 ("Link" layer): wide variety of LAN and point-to-point protocols

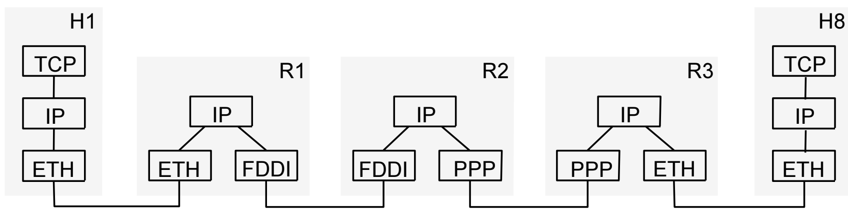


- Internet architecture features
  - Does not imply strict layering
  - IP defines a common way for exchanging packets among widely differing networks
  - "Hour glass"-shape
- Aim: heterogeneity and scalability



IP protocol stack





IETF (Internet Engineering Task Force)

- Majority of Internet development (standardization) done by IETF
  - offers a mutual forum for the development of the Internet to vendors, users, researchers, service providers and network managers
  - develops architectures and protocols for solving technical issues
  - gives recommendations on the use of protocols
  - performs dissemination of the recommendations of IRTF (Internet Research Task Force) which is responsible for long term development of Internet
  - IETF requires always working implementations before any protocol specification is accepted as a standard (“we believe in running code”)
- Working methods
  - has meetings 3 times a year
  - work conducted within study groups (> 100 study groups)
    - joining a group done via e-mail to the mailing list
  - study groups belong to 8 different fields
- work reported in Internet drafts and RFCs (Request for Comments)
    - Internet drafts have no official status, serve as basis for RFCs
    - not all RFCs are standards (Informational, Best Current Practice, …)
    - http://www.ietf.org

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Service model

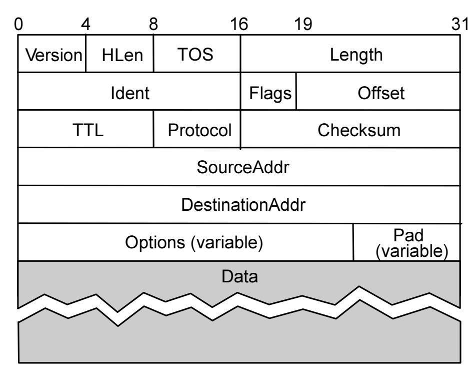
- Idea in the Internet service model:
  - Make it undemanding enough that IP can be run over anything
  - One of the major reasons for the success of IP technology
- Service model consists of 2 parts:
  - Model for data delivery
  - Addressing scheme

Data delivery model

- Data delivery in Internet
  - IP network connectionless (datagram-based)
  - IP network offers 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
    - ⇒ “intelligence” implemented at the end hosts
  - datagram format (next slide)

IP datagram format details

- Format aligned at 32 bit words
  - simplifies packet processing in sw
- Fields
  - Version: currently version 4 (6 is coming)
  - HLen: header length, 32 bit words (min 5)
  - TOS: type of service, used to give priorities to packets (QoS lecture)
  - Length: datagram+header length, in bytes
  - 2nd word for fragmentation/reassembly
  - TTL: time to live, nof times packet allowed to be forwarded (nof hops), default 64, detects packets caught in routing loop
  - Protocol: identifies upper layer protocols, TCP (6), UDP (17)
  - Checksum: erroneous packets discarded
  - Addresses: global Internet addresses
  - Options: rarely used

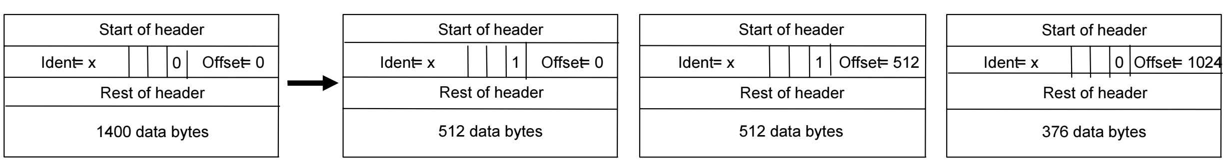


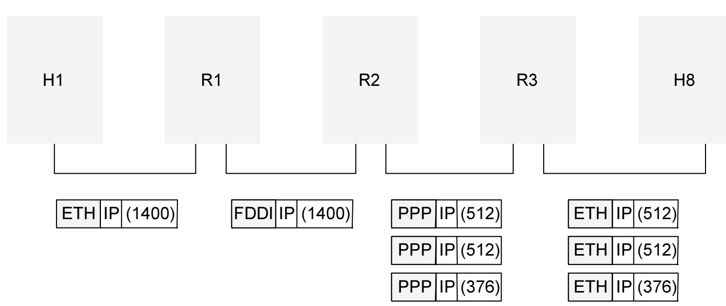
Fragmentation and reassembly

- Each network has an MTU (Maximum Transfer Unit)
  - Ethernet 1500 bytes, FDDI 4500 bytes, PPP 512 bytes
- Strategy
  - fragment when necessary (MTU < datagram length)
  - try to avoid fragmentation at source host
    - host sets datagram size equal to MTU of home network
    - for ATM MTU based on CS-PDU size (not cell size)
  - fragments are self-contained datagrams
    - each fragment contains a common identifier in Ident field
    - Flags (M-bit) and Offset used to guide fragmentation process
      - Offset measured in 8B units
    - fragmented packet can be again re-fragmented
  - reassembly performed only at destination host
  - reassembly does not try to recover from lost fragments

Fragmentation/reassembly example

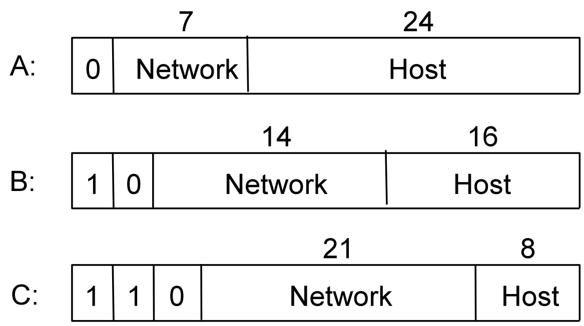
- Original message 1400B + 20B header





IP addressing

- Properties
  - globally unique, 32 bits
  - hierarchical: network + host
  - address identifies interface
    - end host has 1 interface
    - router has many interfaces
  - IP address ≠ domain name
- Original classful addressing
  - class A, B and C networks
  - defines different sized networks
  - idea: small nof WANs, modest nof campus networks, large nof LANs
- Dot Notation
  - 32 bit addresses represented as group of 8 bit integers
  - e.g., 10.3.2.4, 128.96.33.81



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IP forwarding (1)

- Some terminology:
  - **forwarding**:
    - process of taking a packet from input interface, and …
    - based on the contents of the **forwarding table**, determining the correct output interface for the packet
  - **routing**:
    - process of constructing forwarding tables that enable efficient routing of traffic in the network (lecture 5)

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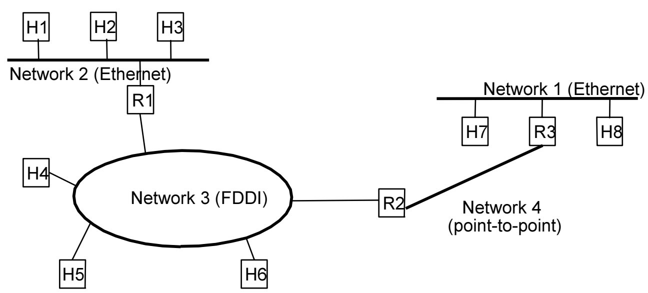
IP forwarding (2)

- Preliminaries
  - Every datagram contains destination's address
  - Every node has a forwarding table
    - normal hosts with one interface have only **default router** configured
    - routers maintain forwarding tables with multiple entries (contructed via routing process)
    - forwarding table maps network number into next hop router number or local interface number
- Strategy
  - Any node receiving a packet (router/host) checks destination **network address** of datagram and ...
    - if directly connected to destination network, then forward to host
      - need to map IP address to physical LAN address ⇒ ARP
    - if not directly connected to destination network, then forward to next hop router

IP forwarding example

- H1 → H3 : forwarding on the same network
- H1 → H8 : via R1 and R2



Forwarding table of H1

NetworkNum	NextHop
1	Default (R1)
2	Interface 0
3	Default (R1)
4	Default (R1)

Forwarding table of R2

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

Routers vs. bridges

- Bridge (+/-)
  - \+ bridge operation simple, requires less processing
  - \+ transparent (no configuration needed when new nodes added to LAN)
  - – restricted topology (forwarding determined by a spanning tree)
  - – LANs use a flat addressing space (no hierarchical network structure)
- Router (+/-)
  - \+ arbitrary topologies, enables use of efficient routing algorithms for distributing traffic (helps traffic management)
  - \+ hierarchical addressing enables scalability:
    - scalability requires minimization of address info stored in routers
    - routing based on network numbers ⇒ forwarding tables contain info on all networks, **not** all nodes
  - – requires IP address configuration
  - – packet processing more demanding
- Summary: bridges do well in small (~ 100 hosts) networks while routers are used in large networks (1000s of hosts)

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Address translation

- Earlier, we skipped the part what to do when router/host notes that it is connected directly to the network where an arriving packet is destined.
- Need to map IP addresses into physical LAN addresses
  - destination host
  - next hop router
- Techniques
  - encode physical LAN address in host part of IP address
    - not scalable
  - table-based (maintain IP address, PHY address pairs)
    - $\Rightarrow$ ARP

ARP details

- ARP (Address Resolution Protocol)
  - utilizes LAN's broadcast capabilities
  - each node maintains table of IP to physical LAN address bindings
  - broadcast request if IP address not in table
  - target machine responds with its physical LAN address
- ARP request contains also source addresses (physical and IP)
  - all "interested" parties can learn the source address
- Node (host/router) actions:
  - table entries timeout in about 10 minutes
  - if node already has an entry for source, refresh timer
  - if node is the target, reply and update table with source info
  - if node not target and does not have entry for the source, ignore source info
- ARP info can be incorporated in the contents of forwarding table

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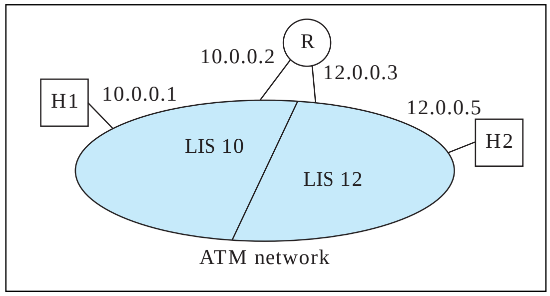
ARP Packet Format

- Request Format
  - HardwareType: type of physical network (e.g., Ethernet)
  - ProtocolType: type of higher layer protocol (e.g., IP)
  - HLen & PLen: length of physical and upper layer addresses
  - Operation: request or response
  - Physical/IP addresses of Source and Target

<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">ProtocolT ype = 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>

Classical IP over ATM

- Problem: ARP uses broadcast, but
  - ATM is connection oriented (no broadcasting)
- Solution:
  - LANE not useful if nodes spread over large area
  - Classical IP over ATM and ATMARP server



- Classical IP over ATM
  - group nodes of ATM network into several LIS (Logical IP Subnet)
  - nodes in same LIS have same IP network number
  - nodes in same LIS communicate with each other directly using ATM (AAL5)
  - nodes in different LIS communicate via IP router
  - can connect large nof hosts and routers to a big ATM network without assigning addresses from same IP network
  - scalability: ATMARP handles smaller nof hosts

ATMARP

- ATMARP server
  - resolves ATM addresses to IP addresses (like ARP translates ETH to IP)
  - does not rely on broadcast

- Functionality
  - each node in a LIS sets up VC to ATMARP and registers (sends own ⟨ATM, IP⟩ address pair)
  - ARP server builds table of ⟨ATM, IP⟩ address pairs for all registered nodes
  - nodes make queries to ARP server
  - nodes can keep cache of ⟨ATM, IP⟩ address mappings
    - like in traditional ARP
  - VC to a destination can be kept alive as long as needed

- Note! In Classical IP over ATM two nodes in same ATM network cannot communicate directly if they are in different subnets.

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Network management and scalability

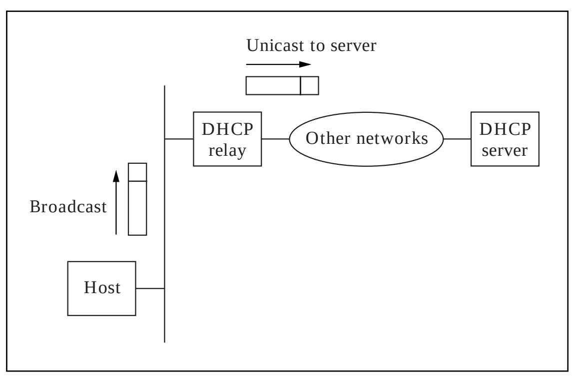
- Mechanisms in IP that enable heterogeneity and scalability
  - heterogeneity:
    - best effort service model that makes minimal assumptions on underlying network capabilities
    - common packet format, fragmentation used for networks with different MTUs
    - global address space (ARP maps physical addresses to IP)
  - scaling:
    - hierarchical aggregation of routing information (network/host number)
  - above focuses on minimizing network state info in devices

- Important also to consider management complexity as network grows
  - example: configuration of IP addresses via DHCP

Need for automatic configuration

- IP addresses need to be reconfigurable
  - Ethernet addresses hardwired onto the network adapter
  - IP address consists of network and host part
  - hosts can move between networks ⇒ host gets new address in each network
- Need for automated host configuration
  - hosts need other configuration info, e.g., the default router
  - configuration manually impossible (too much work and errors)
  - ⇒ Dynamic Host Configuration Protocol (DHCP)
- DHCP server
  - at least one DHCP server for each administrative domain
  - centralized repository for configuration info
  - two operation modes:
    - administrator chooses host addresses and configures them to DHCP
    - DHCP manages the addresses by allocating addresses dynamically from a pool of available addresses (more sophisticated)

DHCP operation



- Server discovery: host sends DHCPDISCOVER msg to IP broadcast address (255.255.255.255)
- Msg broadcasted only on same network
- If server on same network, host receives its IP address
- If not, msg picked up by DHCP relay agent
- Relay agent knows address of DHCP server, forwards the msg to DHCP server and host receives its IP address
- Use of DHCP relay agent makes it possible to have fewer DHCP servers (relay agent configuration simpler than DHCP server configuration)

DHCP packet format, etc.

- Packet format
  - carried on top of UDP
  - based on older protocol BOOTP (unused fields)
  - client puts its hardware address in chaddr
  - DHCP server puts client's IP address in yiaddr
  - other info placed in options (default router, subnet mask, DNS server)

Operation	HType	HLen	Hops
Xid			
Secs		Flags	
ciaddr			
yiaddr			
siaddr			
giaddr			
chaddr (16 bytes)			
sname (64 bytes)			
file (128 bytes)			
options			

- Handling dynamic addresses
  - problem: hosts may not return addresses (host crashes, is turned off, ...)
  - $\Rightarrow$ DHCP addresses only "leased" for a period of time
  - if lease is not refreshed, address placed back in pool

- DHCP improves manageability of network

Internet Control Message Protocol (ICMP)

- ICMP used for reporting errors in Internet

- Messages
  - Echo (ping)
  - Redirect (from router to source host if router knows of a better route to packet's destination)
  - Destination unreachable (protocol, port, or host)
  - TTL exceeded (so datagrams don't cycle forever)
  - Checksum failed
  - Reassembly failed
  - Cannot fragment

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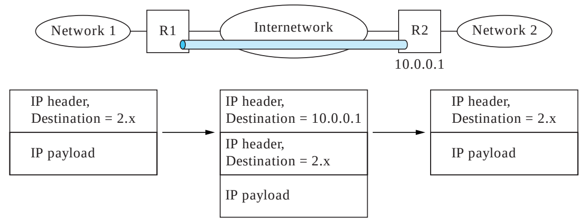
Virtual private networks (VPN)

- Problem:
  - group of isolated networks
  - geographically distant from each other
  - need to connect different networks together into a “private” network
  - e.g., company with many branch offices
- Solution:
  - VPN
  - connect individual networks together through a public network
- Technologies
  - leased virtual circuits from an ATM network operator or Frame Relay operator
  - possible with IP, but requires IP tunneling

VPN and IP tunneling



- Problem with IP
  - not possible to connect to Internet via router without the whole Internet also knowing about your network
- Tunneling
  - virtual point-to-point link btw. two nodes separated by arbitrary nof networks
  - created in R1 by providing it with address of R2
  - R1 encapsulates original packet in a new packet addressed to R2
  - packet forwarded normally inside IP network
  - R2 receives packet and strips off packet header and notices payload contains an encapsulated packet addressed to some host inside network 2
- IP tunneling used in
  - VPNs, Mobile IP
  - building logical networks of multicast or QoS enabled routers