Internetworking: addressing, forwarding, resolution, fragmentation

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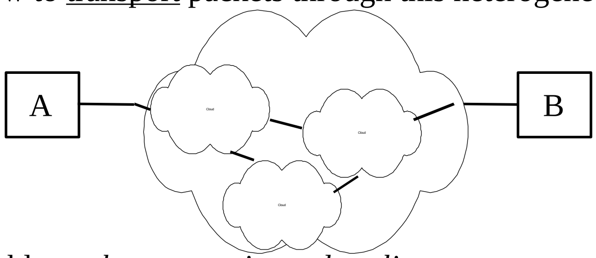
Based in part upon the slides of Prof. Raj Jain (OSU), S. Keshav (Cornell), L. Peterson (Arizona)

- Internetworking: heterogeneity & scale
- IP solution:
  - Provide new packet format and overlay it on subnets.
  - Implications: Hierarchical address, address resolution, fragmentation/re-assembly, packet format design, forwarding algorithm etc
  - Protocols: IP and ARP

The Internetworking Problem

- Two nodes communicating across a "***network of networks***"… How to transport packets through this heterogeneous mass ?



- Problems: *heterogeneity and scaling*
- *Heterogeneity*:
  - How to interconnect a large number of disparate *networks* ? (lower layers)
  - How to support a wide variety of *applications* ? (upper layers)

The Internetworking Problem

- *Scaling:*
  - How to support a large number of end-nodes and applications in this interconnected network ?
- *Possible solutions:*
  - *Translation* (eg: bridges): specify a separate mapping between every pair of protocols
    - (+) No software changes in networks required.
    - (-) Need to specify N mappings when a new lower layer protocol is added to the list
    - (-) When many networks, subset = 0
    - (-) Mapping may be asymmetric
  - *Overlay model:* Define a new protocol (IP) and map all networks to IP

The Internetworking Problem

- (+) Require only one mapping (IP -> new protocol) when a new protocol is added
- (+) Global address space can be created for universal addressibility/scaling
- (-) Requires some changes in lower networks (eg: protocol type field for IP)
- (-) IP has to be necessarily simple else mapping will be hard.
  - Even in its current form mapping IP to ATM has proven to be really hard.
  - Basis for "best-effort" forwarding
- (-) Mapping infrastructure needed: address hierarchy, address resolution, fragmentation

Internet's Architectural principles

- ***End-to-end principle:*** (Dave Clark, MIT)
  - Network provides minimum functionality (connectionless forwarding, routing)
  - Value-added functions at hosts (control functions): *opposite of telephony model (phone simple, network complex)*
  - Idea originated in security: trust the network or the end-systems (what's finally received) ?
  - Beat the X.25 approach: stateful, connection-oriented, hop-by-hop control.

Architectural principles (contd)

- ***IP over everything:*** (Vint Cerf, VP, MCI)
  - An internetworking protocol which works over all underlying sub-networks and provides a single, simple service model ("best-effort delivery") to the user.

Architectural Principles (Contd)

- ***Connectivity is its own reward:***
  - The more the users of the Internet, the more valuable it is (Metcalfe's law)
  - Pragmatic design:
    - Support all platforms, all kinds of users.
    - "Understand/receive as many formats as possible; send using a standard format"
    - Build *de facto* standards: requires rough consensus and running code**.** Anyone can participate in standardization.

History (1960s)

- **1961:** The first paper on packet switching by *Leonard Kleinrock*, UCLA.
- **1962:** ARPA computer program begins …
- **1965:** First actual network experiment, Lincoln Labs (now part of MIT) TX-2 tied to SDC's Q32 by *Larry Roberts*.
- **1966-67:** ARPAnet program begins
- **1968:** *Bob Karn's* team at BBN builds first Interface Message Processor (IMP) later known as a "router".

History (1970s)

- **1969:** First RFC written
- **1970:** ARPAnet spans US (total: ~10 nodes)
- **1972:** Email, ftp born (due to *Dave Crocker*)
- **1973:** *Bob Metcalfe* at Xerox designs Ethernet
- **1974:** *Vint Cerf & Kahn* build first version of TCP**,** ARPAnet routing is revised
- **1977-78:** TCP split into TCP and IP
- **1980-83:** ARPAnet splits into ARPAnet and MILNET, and offers software at low cost to universities. NSF invests in CSNET connecting computer science departments.

History (1980-90s)

- **1983:** UC Berkeley and BBN integrate TCP/IP into UNIX 4.2 BSD. Berkeley develops network utilities and sockets API.
- **1985-87:** Decentralization of naming & addressing. NSF lets regional networks to connect to ARPAnet via a backbone, NSFnet.
- **1987-90:** Companies join Internet. EBONE (Europe) connected to NSFnet. TCP improved to handle congestion by *Van Jacobson.*
- **1990-93:** *Steve Deering* pioneers multicast and IPv6 work in IETF. *Marc Andresson* writes the first Mosaic browser.

The 1990s

- **1993-present:** Internet still grows exponentially. NSFnet is privatized. ATM networks promise new future for backbones. Internet access through telephones, cable, television, and electric companies. ISPs, E-commerce, security, real-time services are the talk of the town. Cisco stock grows 100-fold.

Internet = Virtual Network

- Any computer can talk to any other computer

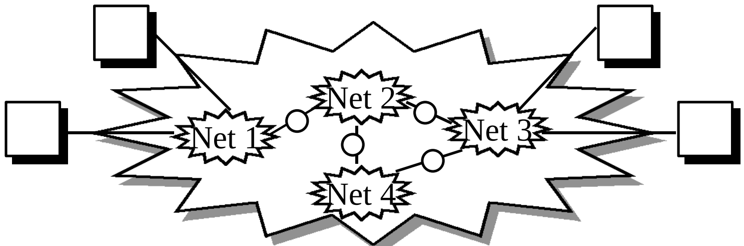


Fig 13.3

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How does IP forwarding work ?

- A) *Source & Destination in same network (fig 3.3 in text)*
  - Recognize that destination IP address is on same network. [1]
  - Find the destination LAN address. [2]
  - Send IP packet encapsulated in LAN frame directly to the destination LAN address.
    - Encapsulation => source/destination IP addresses don't change

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IP forwarding (contd)

- B) *Source & Destination in different networks (fig 3.4 in text)*
  - Recognize that destination IP address is not on same network. [1]
  - Look up destination IP address in a (routing) table to find a match, called the next hop router IP address.
  - Send packet encapsulated in a LAN frame to the LAN address corresponding to the IP address of the next-hop router. [2]

Addressing & Resolution

- *[1] How to find if destination is in the same network ?*
  - IP address = network ID + host ID. *Source and destination network IDs match => same network*
  - Splitting address into multiple parts is called hierarchical addressing
- *[2]: How to find the LAN address corresponding to an IP address ?*
  - Address Resolution Problem.
  - Solution: ARP, RARP (next chapter)

Route Table Lookup

- Intermediate routers lookup the destination network-ID
  - Deliver datagrams to next-hop and finally to destination network, not to host directly
  - Hierarchical forwarding: routing tables scale.

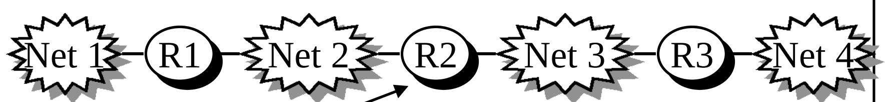
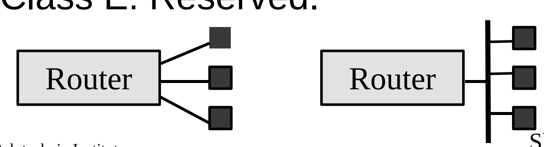


Table at R2:

Destination	Next Hop
Net 1	Forward to R1
Net 2	Deliver Direct
Net 3	Deliver Direct
Net 4	Forward to R3

IP Address Formats

- **Class A:** 0 | Network | Host — 1, 7, 24 bits
- Class B: 10 | Network | Host — 2, 14, 16 bits
- Class C: 110 | Network | Host — 3, 21, 8 bits
- Class D: 1110 | Multicast Group addresses — 4, 28 bits
- Class E: Reserved.

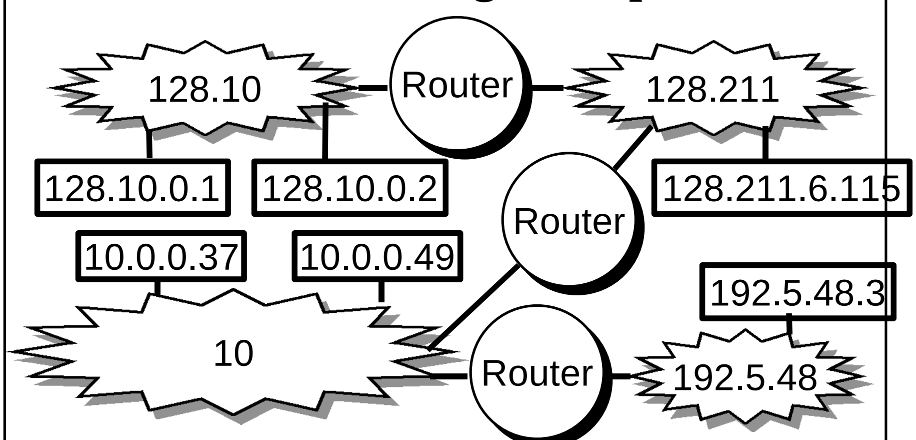


Dotted Decimal Notation

- Binary: 11000000 00000101 00110000 00000011
  Hex Colon: C0:05:30:03
  Dotted Decimal: 192.5.48.3

Class	Range
A	0 through 127
B	128 through 191
C	192 through 223
D	224 through 239
E	240 through 255

An Addressing Example



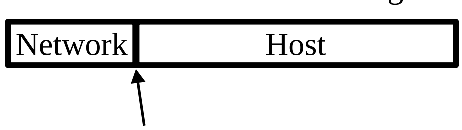
- All hosts on a network have the same network prefix (I.e. network ID)

Some special IP addresses

- All-0s ⇒ This computer
- All-1s ⇒ All hosts on this net (*limited broadcast*: *don't forward out of this net)*
- All-0 *host suffix* ⇒ Network Address (*'0'* means *'this'*)
- All-1 *host suffix* ⇒ All hosts on the destination net (directed broadcast).
- 127.*.*.* ⇒ Loopback through IP layer
- Further classification in fig 3.9 of text

Subnet Addressing

- Classful addressing inefficient: Everyone wants class B addresses
- Can we split class A, B addresses spaces and accommodate more networks ?
  - Need another level of hierarchy. Defined by "***subnet mask***", which is general specifies the sets of bits belonging to the network address and host address respectively
  - External routers send to "network" specified by the "network ID" and have smaller routing tables

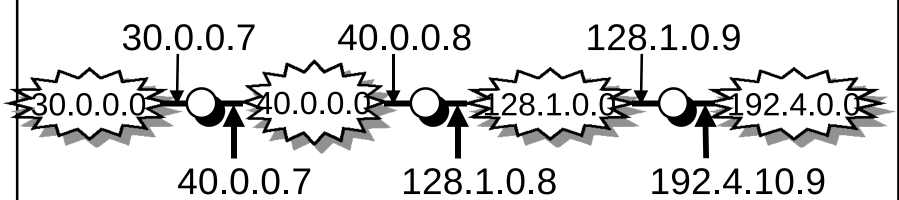


Boundary is flexible, and defined by subnet mask

Subnet Addressing (Contd)

- Internal routers & hosts use subnet mask to identify "subnet ID" and route packets between "subnets" within the "network".
- Eg: Mask: 255.255.255.0 => subnet ID = 8 bits with upto 62 hosts/subnet
- Route table lookup:
  - IF ((Mask[i] & Destination Addr) = =
    Destination[i])
    Forward to NextHop[i]
- Subnet mask can end on any bit.
- Mask must have contiguous 1s followed by contiguous zeros. Routers do not support other types of masks.

Route Table Lookup: Example



Destination	Mask	Next Hop
30.0.0.0	255.0.0.0	40.0.0.7
40.0.0.0	255.0.0.0	Deliver direct
128.1.0.0	255.255.0.0	Deliver direct
192.4.10.0	255.255.255.0	128.1.0.9

Variable Length Subnet Mask (VLSM)

- ***Basic subneting:*** refers to a fixed mask in addition to natural mask (i.e. class A, B etc).
  - I.e. only a single mask (eg:: 255.255.255.0) can be used for all networks covered by the natural mask.
- ***VLSM:*** Multiple different masks possible in a single class address space.
  - Eg: 255.255.255.0 and 255.255.254.0 could be used to subnet a single class B address space.
  - Allows more efficient use of address space.

Summary

- Addressing:
  - Unique IP address per interface
  - Classful (A,B,C) => address allocation not efficient
  - Hierarchical => smaller routing tables
  - Provision for broadcast, multicast, loopback addresses
  - Subnet masks allow “subnets” within a “network” => improved address allocation efficiency
- Forwarding:
  - Simple *“next-hop”* forwarding.
  - Last hop forwards directly to destination
  - *Best-effort delivery :* No error reporting. Delay, out-of-order, corruption, and loss possible => problem of higher layers!
  - Forwarding vs routing: tables setup by separate algorithm (s)

IP Features

- Connectionless service
- Addressing
- Data forwarding
- Fragmentation and reassembly
- Supports variable size datagrams
- Best-effort delivery: Delay, out-of-order, corruption, and loss possible. Higher layers should handle these.
- Provides only "Send" and "Delivery" services
  Error and control messages generated by
  Internet Control Message Protocol (ICMP)

What IP does NOT provide

- End-to-end data reliability & flow control (done by TCP or application layer protocols)
- Sequencing of packets (like TCP)
- Error detection in payload (TCP, UDP or other transport layers)
- Error reporting (ICMP)
- Setting up route tables (RIP, OSPF, BGP etc)
- Connection setup (it is connectionless)
- Address/Name resolution (ARP, RARP, DNS)
- Configuration (BOOTP, DHCP)
- Multicast (IGMP, MBONE)

IP Datagram Format

0	4	8	16		32
Vers	H Len	TOS	Total Length		
Identification			Flags	Fragment Offset	
Time to live		Protocol	Header Checksum		
Source IP Address					
Destination IP Address					
IP Options (if any)					Padding
Data					

IP Datagram Format

- First Word purpose: info, variable size header & packet.
  - Version (4 bits)
  - Internet header length (4 bits): *units of 32-bit words.* Min header is 5 words or 20 bytes.
  - Type of service (TOS: 8 bits): Reliability, precedence, delay, and throughput. Not widely supported
  - Total length (16 bits): header + data. *Units of bytes.* Total must be less than 64 kB.

IP Header (Cont)

- 2nd Word Purpose: fragmentation
  - Identifier (16 bits): Helps uniquely identify the datagram between any source, destination address
  - Flags (3 bits): More Flag (MF):more fragments
    Don’t Fragment (DF)
    Reserved
  - Fragment offset (13 bits): *In units of 8 bytes*

IP Header (Cont)

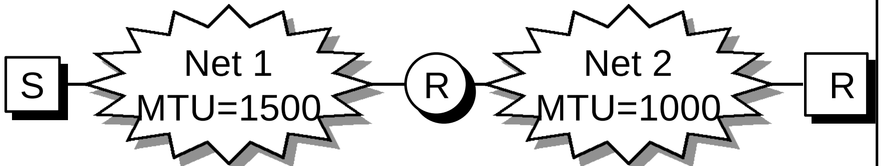
- Third word purpose: demuxing, error/looping control, timeout.
  - Time to live (8 bits): Specified in router hops
  - Protocol (8 bits): Next level protocol to receive the data: for de-multiplexing.
  - Header checksum (16 bits): 1’s complement sum of all 16-bit words in the header.
    - Change header => modify checksum using 1’s complement arithmetic.
- Source Address (32 bits): Original source. Does not change along the path.

Header Format (contd)

- Destination Address (32 bits): Final destination. Does not change along the path.
- Options (variable length): Security, source route, record route, stream id (used for voice) for reserved resources, timestamp recording
- Padding (variable length):
  Makes header length a multiple of 4
- Payload Data (variable length): Data + header ≤ 65,535 bytes

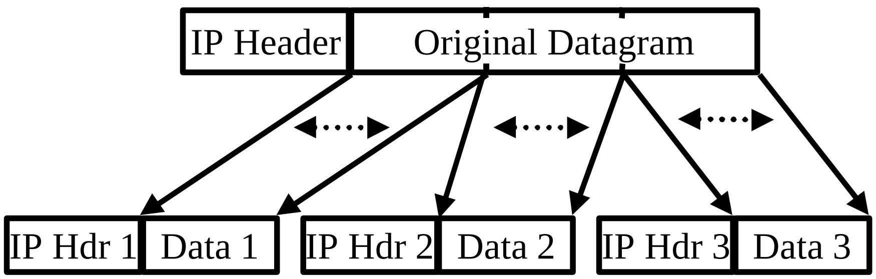
Maximum Transmission Unit

- Each subnet has a maximum frame size
  Ethernet: 1518 bytes
  FDDI: 4500 bytes
  Token Ring: 2 to 4 kB
- Transmission Unit = IP datagram (data + header)
- Each subnet has a maximum IP datagram length (header + payload) = MTU

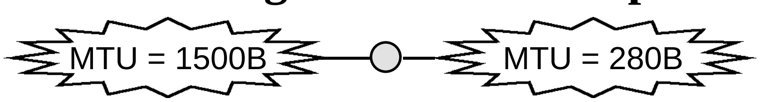


Fragmentation

- Datagrams larger than MTU are fragmented
- Original header is copied to each fragment and then modified (fragment flag, fragment offset, length,...)
- Some option fields are copied (see RFC 791)



Fragmentation Example



IHL = 5, ID = 111, More = 0
Offset = 0W, Len = 472B

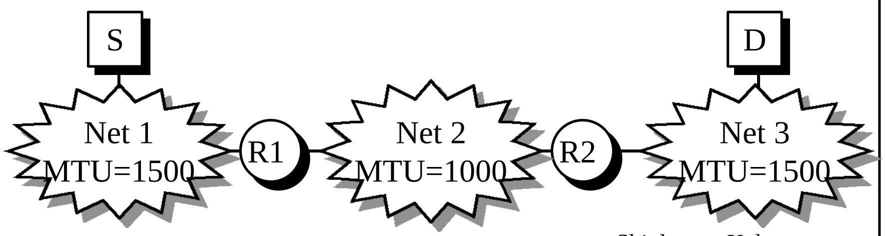
IHL=5, ID = 111, More = 1
Offset = 0W, Len = 276B

IHL=5, ID = 111, More = 0
Offset = 32W, Len = 216B

- Payload size 452 bytes needs to be transmitted across a Ethernet (MTU=1500B) and a SLIP line (MTU=280B)
- Length = 472B, Header = 20B => Payload = 452B
- Fragments need to be multiple of 8-bytes.
  - Nearest multiple to 260 (280 -20B) is 256B
  - First fragment length = 256B + 20B = 276B.
  - Second fragment length = (452B- 256B) + 20B = 216B

Reassembly

- ❑ Reassembly only at the final destination
- ❑ Partial datagrams are discarded after a timeout
- ❑ Fragments can be further fragmented along the path. Subfragments have a format similar to fragments.
- ❑ Minimum MTU along a path ⇒ Path MTU



Further notes on Fragmentation

- ❑ Performance: single fragment lost => entire packet useless. Waste of resources all along the way. Ref: Kent & Mogul, 1987
- ❑ Don't Fragment (DF) bit set => datagram discarded if need to fragment. ICMP message generated: may specify MTU (default = 0)
- ❑ Used to determine Path MTU (in TCP & UDP)
- ❑ The transport and application layer headers do not appear in all fragments. Problem if you need to peep into those headers.

Discussion on IP Header Design

- If fragmentation is going to be avoided all the time, why not have the 4-bytes of fragmentation info as an IP option ?
- Is 32-bit addresses going to be enough ?
- Why mess with variable length headers ? Can the variability in header length be controlled to allow better encoding ?
- Are the IP options really that useful ? Why variable length option headers ?
- Many of these issues addressed in IPv6.

Resolution Problems and Solutions

- Indirection through addressing/naming => requires resolution
- Problem usually is to map destination layer N address to its layer N-1 address to allow packet transmission in layer N-1.
- **1. Direct mapping:** Make the physical addresses equal to the host ID part.
  - Mapping is easy.
  - Only possible if admin has power to choose both IP and physical address.
  - Ethernet addresses come preassigned (so do part of IP addresses!).
  - Ethernet addresses are 48 bits vs IP addresses which are 32-bits.

ARP techniques (contd)

- **2: Table Lookup:**
  Searching or indexing to get MAC addresses
  - Similar to lookup in /etc/hosts for names
  - Problem: change Ethernet card => change table

IP Address	MAC Address
197.15.3.1	0A:4B:00:00:07:08
197.15.3.2	0B:4B:00:00:07:00
197.15.3.3	0A:5B:00:01:01:03

ARP techniques (Cont)

- **3. Dynamic Binding: ARP**
  - The host *broadcasts* a request:
    "What is the MAC address of 127.123.115.08?"
  - The host whose IP address is 127.123.115.08 replies back: "The MAC address for 127.123.115.08 is 8A-5F-3C-23-45-56_{16}"
- All three methods are allowed in TCP/IP networks.

ARP Message Format

<table>
<tr><td>0</td><td>8</td><td>16</td><td>24   32</td></tr>
<tr><td colspan="2">H/W Address Type</td><td colspan="2">Protocol Address Type</td></tr>
<tr><td>H/W Adr Len</td><td>Prot Adr Len</td><td colspan="2">Operation</td></tr>
<tr><td colspan="4">Sender’s h/w address (6 bytes)</td></tr>
<tr><td colspan="2"></td><td colspan="2">Sender’s Prot Address (4 bytes)</td></tr>
<tr><td colspan="2"></td><td colspan="2">Target h/w address (6 bytes)</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td colspan="4">Target Protocol Address (4 bytes)</td></tr>
</table>

- Type: ARP handles many layer 3 and layer 2s
- Protocol Address type: 0x0800 = IP
- Operation: 1= Request, 2=Response
- ARP messages are sent directly to MAC layer

ARP Processing

- See ARP dynamics in figs 4.2, 4.4, 4.5
- ARP responses are cached. Replacement:
  - Cache table fills up => LRU policy used
  - Timeout: e.g., 20 minutes
  - Others may snoop on ARP, IP packets for address bindings
- Note:
  - A point-to-point link like SLIP does not require ARP.
  - Telephony does not require ARP.

Reverse ARP (RARP)

- H/w (MAC) address -> IP address
- Used by diskless systems
  - RARP server responds.
  - Once IP address is obtained, use "tftp" to get a boot image. Extra transaction!
- RARP design complex:
  - RARP request broadcast, not unicast!
  - RARP server is a user process and maintains table for multiple hosts (/etc/ethers). Contrast: no ARP server

RARP (contd)

- RARP cannot use IP
  - Needs to set unique Ethernet frame type (0x8035)
  - Works through a filter like BPF or nit_if/nit_pf streams modules (fig: A.1, A.2)
- Multiple RARP servers needed for reliability
  - RARP servers cannot be consolidated since RARP requests are broadcasts => router cannot forward
- BOOTP, DHCP replaces RARP

Discussion & Informal Exercises

- ARP, RARP, BOOTP, DHCP solve parts of the autoconfiguration (plug-and-play) problem.
- We will re-examine autoconfiguration later …
- Exercises:
  - Read the man page for the "arp" command
  - Approximate the tcpdump experiments given in the text using your rcs and networks lab accounts.
  - ARP requires a broadcast enabled LAN. What would happen on a non-broadcast medium access (NBMA) LAN ? Guess first and then see RFC 1735.

Summary

- Internet architectural principles
- IP header: supports connectionless delivery, variable length pkts/headers/options, fragmentation/reassembly,
- Fragmentation/Reassembly, Path MTU discovery.
- ARP, RARP: address mapping
- Additional reading: Addressing101 (on course web page)