Computer Networks and Distributed Systems

Computer Networks – Network Layer

Course 527 – Spring Term 2014-2015

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Contents

- Interconnecting networks (Layers 1 to 3)
  - Repeaters, bridges, routers

- Network Layer
  - **Routing**
    - Static, distance vector, link state
  - **Internet Protocol** (IP)
    - Datagrams (packets)
    - IP addressing
    - Fragmentation
    - Other protocols (ARP, ICMP)

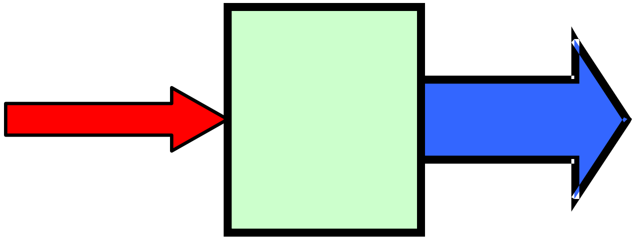
Inter-Networks

- Inter-networks formed from smaller networks
  - Extending physical limits of networks
  - Separating traffic (to spread load or administration)

- Different devices interconnect with different low-level protocols
  - Cooperation at higher layers to provide uniform service

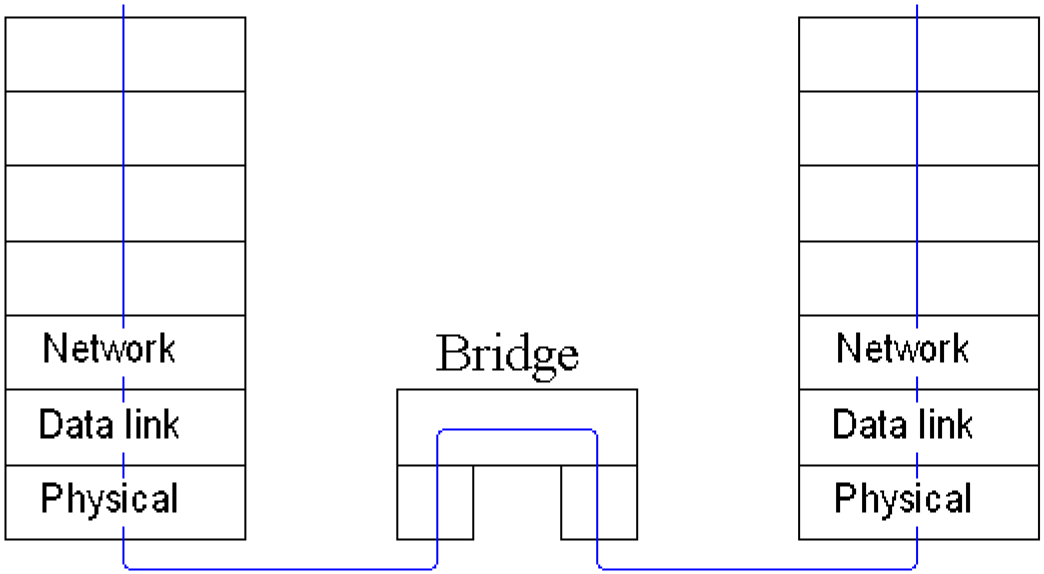
Repeater

- Amplifies electrical signal
  - Makes two wires appear as one
  - Improves signal propagation distance



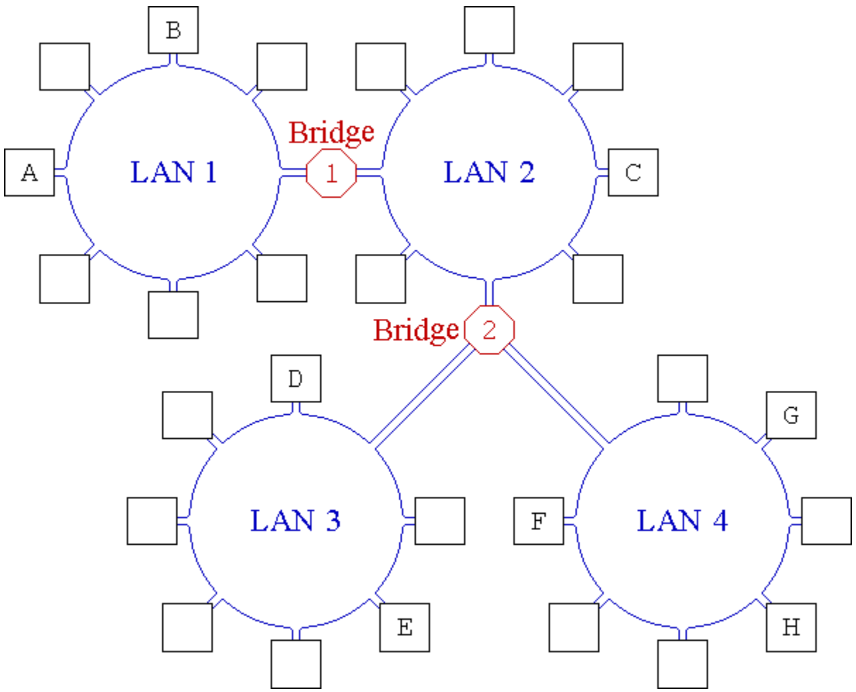
- Operates at physical layer
  - Transparent to higher layers
  - No checking/generating of checksums
  - CSMA/CD must cope with longer propagation delays
    - Ethernet (10Mb/s): up to 4 repeaters with 2.5km max length

Bridge/Switch



- Interconnecting LANs with traffic isolation
- Conditional forwarding → Only forward frames destined for other LAN
- Operates at data link layer
  - Reduces load on sub-network
  - Idea of store & forward results in higher delay
  - Network layers must be same (but not processed)
  - Physical layers may be different

Source Routing Bridge



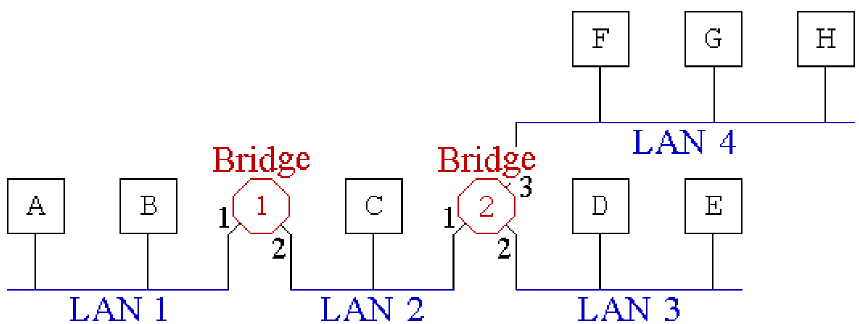
- Sender issues **discovery frame**
  - Copied down every link, recording path list
- Destination chooses route based on discovery frames
  - Or, sends discovery frames back to sender for decision
- Routing path carried in data frames
  - Connection-oriented

Source Routing Bridge

- Keeps bridges simple but end hosts complex
  - Hosts must discover routes and put routes in frames
- Route exploration can wipe out benefits
  - Bad for networks with high degree of connectivity
  - Must cache routes or be very inefficient
- Have to rerun discovery if bridge/route fails
- Token Ring networks use this

Transparent Bridge

- Transparent
  - Hosts and routers are oblivious to their presence in the network
- Records MAC addresses and links in table
  - If destination MAC on same link as source ➔ do not forward
  - If link for destination MAC known ➔ only forward on that link
  - Otherwise use flooding ➔ Send on all links except source link
- Used in Ethernet



Host	A	B	C	D	E	F	G	H												
Link	1	1	2	2	2	2	2	2												

Transparent Bridge

- Backwards learning
  - Listen to traffic on your links and build host/link tables
- Loops in topology
  - Make determining location of source impossible
  - Causes frames to proliferate
- Network layer protocol often handles loops
  - Packets may have limited lifetime
- Build spanning tree (loop-free subset)

Transparent Bridge

- Two types
  - Store-and-Forward
    - Store the entire frame and verify CRC before forwarding frame
  - Cut-Through
    - Forward frame after reading destination MAC and without performing a CRC check

Comparison: Types of Bridges

Transparent

- Connectionless
  - Low overhead to send one frame
  - Failures handled by bridge
- Transparent at hosts
  - Backwards learning to locate hosts
- Sub-optimal routing
- Complexity in bridge

Source Routing

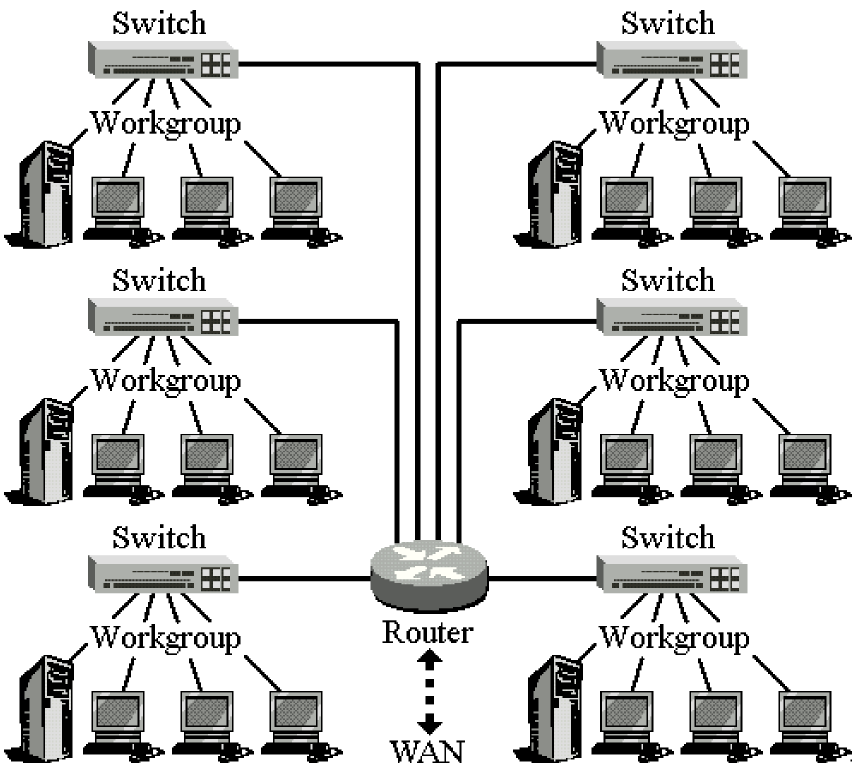
- Connection-oriented
  - Overhead of discovery on first frame
  - Failures handled by hosts
- Not transparent at hosts
  - Discovery frames locate host
- Optimal routing
- Complexity in hosts

Combination: Mixed Media Bridge

- Interconnect different networks
  - e.g. Ethernet and Token Ring
  - Can be source-routing/transparent on different sides
  - Holds routing tables which differentiate network type

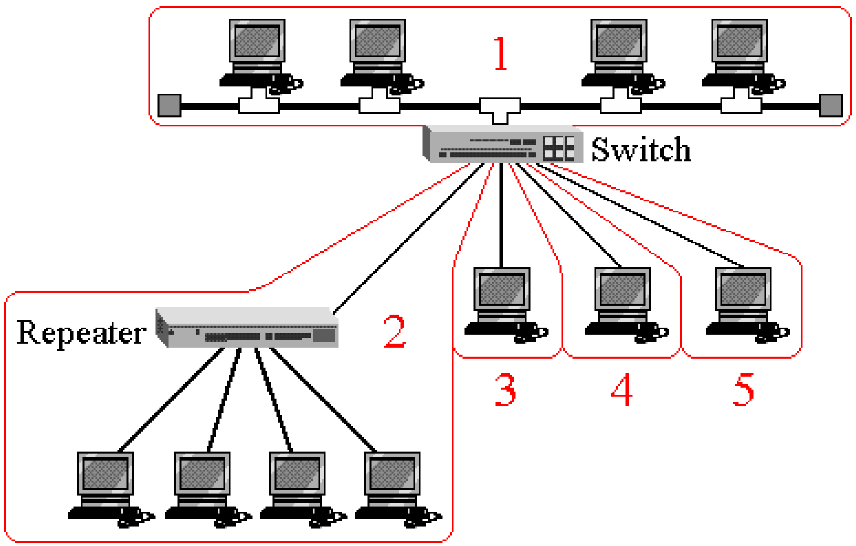
- Handles different **maximum frame lengths** (segmentation/fragmentation)
  - 1518 Bytes on Ethernet
  - 4KB on 4Mb/s token ring
  - 17.6KB on 16Mb/s token ring

Segmentation with Switches



- Switches can segment traditional networks
- **Collapsed backbone**
  - Backbone in switch rather than shared wire

Separating Collision Domains

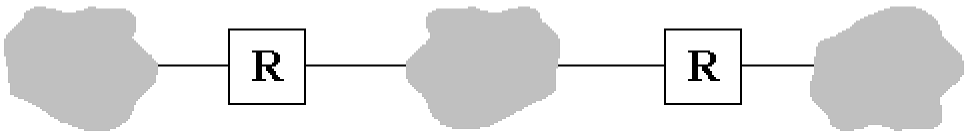


- Shared medium requires CSMA/CD to arbitrate
  - Contention can be problem on busy network
  - Hosts in separate collision domains not competing for media
- Switches form ends of collision domains

Hub, Switches vs. Routers

- Network Switch
  - Lives at Datalink layer
    - Knows about MAC addresses and frames
  - Interconnects network segments
- Hub
  - Lives at Datalink layer
    - Knows about MAC addresses and frames
  - Passively interconnects ports
    - Acts as single network segment
- Router
  - Lives at Network Layer
    - Knows about IP addresses and IP packets
  - Interconnects separate networks
  - Carries out more intelligent routing decisions

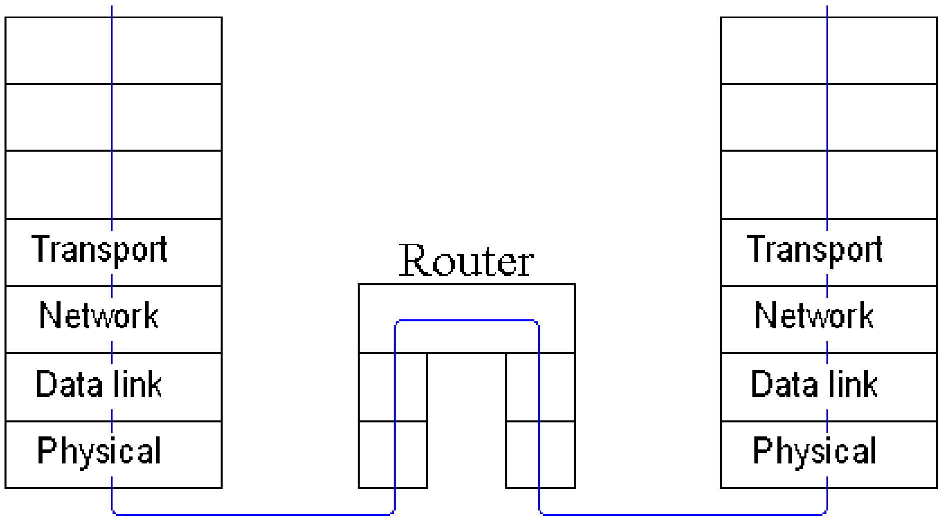
Routing



- Problem: No single network can serve all users
  - Network too long, too much traffic, too complex for lower layers, can't maintain complete network plan
  - Think Internet scale!

- Solution
  - LANs (subnets) interconnected using routers
  - Routing refers to selecting path from source to destination across multiple subnets
  - Network layer must cope with differing underlying LANs

Router/Gateway



- Determines next hop for packet, depending on destination address
- Lookup in routing table
- Operates at network layer
  - Router forwards packets based on destination networks, unlike bridges, which use hosts
- Verifies/modifies packets
  - Updates fields affected by routing
  - Checks/recalculates checksum

Router/Gateway

- Typically used for connecting sites
  - Overcome physical and administrative boundaries
  - Greater management and traffic isolation

- Not transparent to end nodes
  - Frames addressed to router’s data link address
  - Host needs to know whether/which router to send to

Routing: Objectives

- Correctness: Find a route (if it exists)
- Efficiency: Routes should provide good performance
  - Should use minimal resources
- Robustness: Return route even when links/nodes fail
- Fairness: Hosts should have equal access to network
  - Respect priority markings for Quality of Service (QoS)
- Adaptability: Routes should reflect network conditions
  - But no overreacting to problems
- Simplicity: Cheap, predictable and verifiable

Routing: Metrics

- Efficiency → find routes with good properties in terms of
  - Available bandwidth
  - Delay
    - Link latencies
    - Hop count
  - Price
  - Priority for traffic types

Routing: Properties

- No centralised control
  - No knowledge of topology or underlying protocols

- Interconnection on global (Internet) scale
  - May use intermediate networks to get to destination
  - Hide underlying interconnection of networks from users
  - Networks may be not completely inter-connected

Routing Strategies

- Static (non-adaptive) routing
  - Compute routes once and load into router
  - Worked for early ARPANET
- Dynamic (adaptive) routing
  - Change routes to reflect changes in topology/load (as seen through congestion)
  - Usually used in packet-switched networks
  - Distance Vector Routing and Link State Routing

Non-Adaptive Routing

- Routing using fixed directory
  - Full address maps of how to route to host
  - Default link for unknown hosts
- All packets for host pair always take same route
- Often used with list of known hosts/links
  - May be set up by pathfinder algorithm (similar to source-routing bridge)
- Static routing tables for workstations use this
  - Most traffic sent to default gateway/router

Adaptive Routing: Flooding + Random

- Flooding
  - Send packet to all neighbours except source
    - Unless packet seen before (remove loops)
  - Shortest path and fast discovery
  - Good for pathfinders and essential/low latency data
  - But inefficient and leads to high load on network

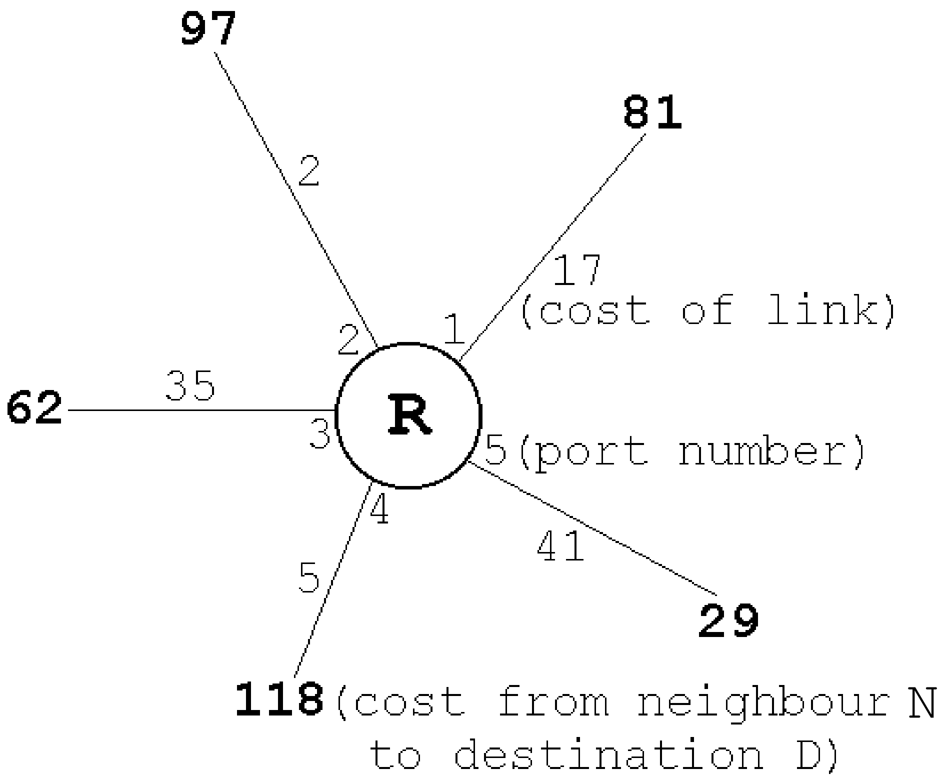
- Random
  - Forward packet to random link
  - Highly robust but slow convergence and inefficient

Adaptive Routing: Distance Vector

- Used in ARPANET and Internet until 1979
  - By Bellman-Ford (1957), Ford-Fulkerson (1962)
  - Implemented as Routing Information Protocol (RIP)

- Router maintains table (vector) of distances
  - Usually delay/queue length to each neighbour
  - Periodically exchanges this information with neighbours
  - Re-computes distance and updates its tables

Example: Distance Vector Routing



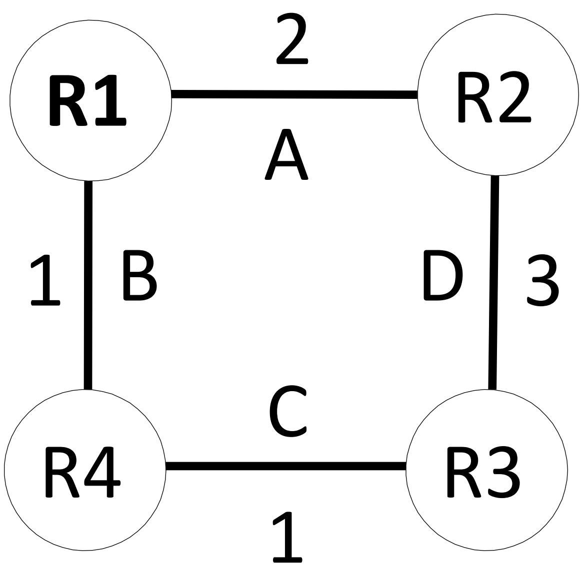
cost (R → D) =
cost (R → N) + cost (N → D)

Port 1 → 17 + 81 = 98
Port 2 → 2 + 97 = 99
Port 3 → 35 + 62 = 97
Port 4 → 5 + 118 = 123
Port 5 → 41 + 29 = 70

Best choice here is port 5, with distance vector of 70

Example: Distance Vector Routing

Step 3



To

	R1	R2	R3	R4
Vector R2	2	0		4
Vector R4	1	4		0
Routing Table R1	0	2	∞	1
	-	A	-	B

Distance Vector Problems

- Poor efficiency
  - Slow to converge after changes
  - Distance vectors increase linearly with network size
    - May not fit inside packet
- Route finding suboptimal
  - Only considers delay not bandwidth of links
  - Prone to oscillations in cost
    - Routing tables do not include paths

Adaptive Routing: Link State

- Each router maintains (partial) map of network
  - Consists of more than just neighbours
  - May include bandwidth and other metrics

- Properties
  - Faster convergence and more reliable
  - Less bandwidth intensive than DVR
  - But more complex and memory/CPU intensive

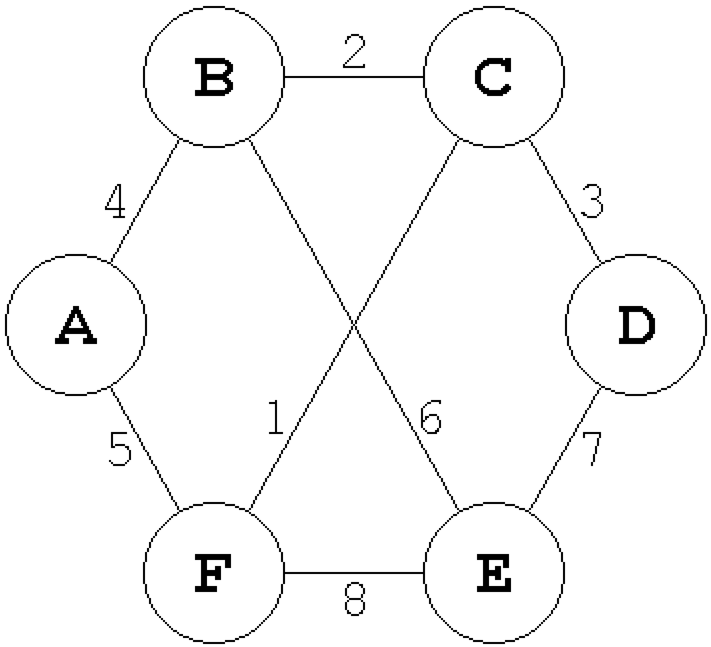
Adaptive Routing: Link State

- Each router does the following

  1. Discover identities of all neighbours
  2. Measure delay (or cost) to neighbours (ECHO packet)
  3. Construct and send Link State packet to all routers
  4. Compute shortest path to every other router
     - Use Dijkstra's algorithm

- When link state changes
  - Notification packet flooded throughout network
  - All routers re-compute routes

Link State Packets



A	
Seq No	
TTL	
B	4
F	5

B	
Seq No	
TTL	
A	4
C	2
E	6

C	
Seq No	
TTL	
B	2
D	3
F	1

D	
Seq No	
TTL	
C	3
E	7

E	
Seq No	
TTL	
B	6
D	7
F	8

F	
Seq No	
TTL	
A	5
C	1
E	8

- ID of source, sequence number (to handle order & loss)
- Time-to-live (decremented each second until discarded)
- List of neighbours with costs

Link State Distribution

- Based on flooding algorithm
  - Don’t send on incoming link
- Sequence number to ensure only newer state packets forwarded
  - Drop old & duplicate packets
  - Some delay in forwarding to wait for newer packets
- Different routers have different views of topology
  - Inconsistencies, loops, unreachable nodes

Hierarchical Routing

- Complete Internet map in every router infeasible
- Instead exploit hierarchy and use regions
  - Router knows local topology in detail
  - Router knows route to other regions
    - But not their internal arrangements

- Regions may map to
  - Geographical area (e.g. London academic network routes between universities)
  - Organisation’s network (e.g. Imperial has routers in core network, routing between departments and to external links)

Internet Routing

- Autonomous systems (AS) are regions on the Internet
- Within ASs: Open Shortest Path First (OSPF)
  - Variant of Link State Routing
  - Supports load balancing over multiple lines
  - Routing includes type of service (but not used)
- Between ASs: Border Gateway Protocol (BGP)
  - Variant of Distance Vector Protocol
  - Records exact path used
  - Supports custom routing policies

Internet Protocol (IP)

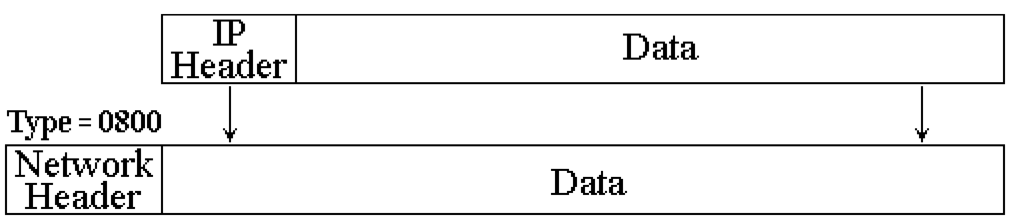
- Basic protocol for the Internet
  - Defined in RFC 791 (updated in 1349, 2474, 6864)
- Datagram oriented
  - Treats packets independently
  - Packets contain complete addressing information
  - Unreliable delivery (no notification)
  - Variable sized data payload
  - No checksum on data payload, just on header

IP Services

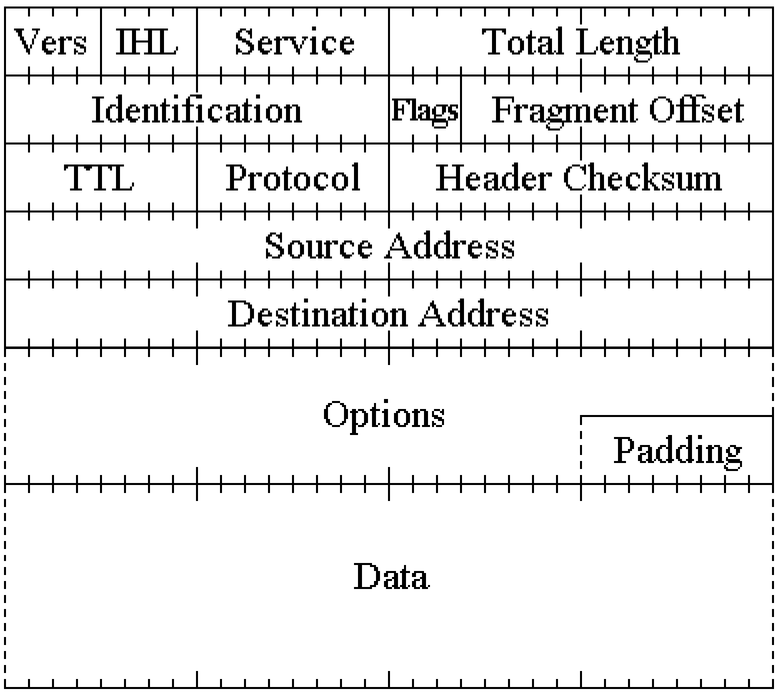
- Addressing
- Packet timeouts
  - Avoid congestion and routing problems
- Fragmentation
  - May split packets if underlying network requires it
- Type of Service through priorities
  - Requires routers on path to read and treat differently
- Other options
  - Source routing requirements, route recording, security labels

IP Datagrams

- IP datagrams are “virtual” or “universal” packets
  - IP dest addr is always final destination address
  - Physical dest addr in frame is changed at each hop
- Along the path each router
  - Removes packet from LAN frame
  - Determines next router/local link
  - Re-encapsulates in appropriate LAN frame for next hop



IP Datagram Format



- Version: IP version (usually 4)
- Internet Header Length
  - In 4 byte multiples (5 <= IHL <= 15)
  - Options increase this
  - Gives data offset
- Type of Service
  - Trade-off between delay, reliability and throughput
- Total Length
  - Max 64KB with IPv4

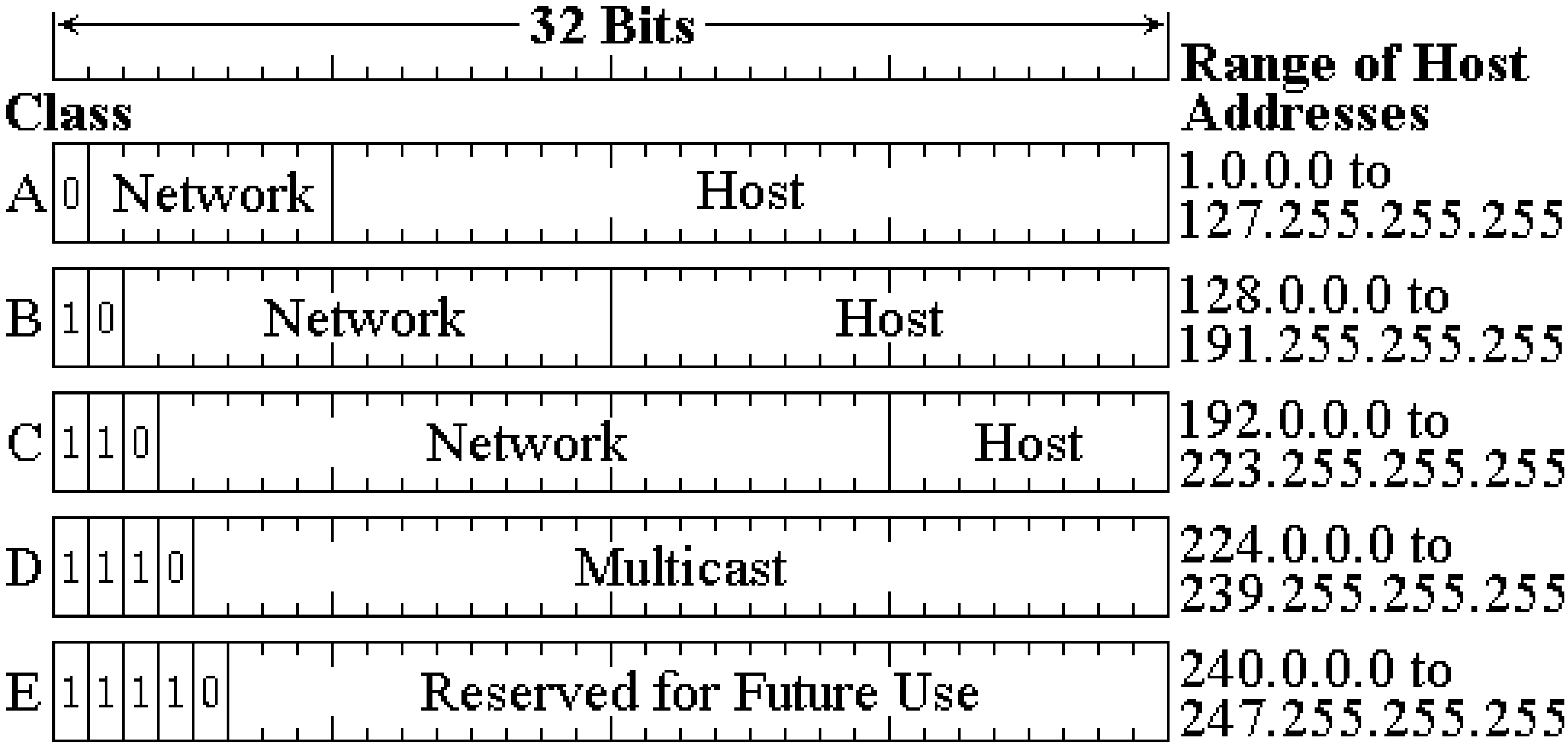
IP Datagram Format

- Time to Live (TTL)
  - Handles routing loops
  - Decremented each routing hop
  - Datagram dropped when = 0
- Protocol
  - 0 = reserved, 1 = ICMP, 6 = TCP, 17 = UDP
  - Similar to Ethernet protocol type field
- Header checksum
  - 1s complement sum of header (not data)
  - Sum of header and checksum should = 0
- Source and destination addresses
- Options
  - Security, loose/strict source routing, record route, stream ID, timestamp, …
  - Padded to multiples of 32 bits

IP Addressing

- Ethernet addresses are 48 bits and written as hex pairs
- IP addresses are 32 bits and written as dotted decimal
  - E.g. 146.169.7.41
  - No direct mapping of IP addrs to Ethernet addrs
- IP addr identifies network and host on that network
  - Not machine but connection to network
  - Device on n networks has n IP addrs – one for each
- Address space administered by ICANN (Internet Corporation for Assigned Names and Numbers)
  - Assigned addresses don't have to be connected

IP Address Classes



Special IP Addresses

32 bit

all 0s		This Host
all 0s	host	Host on this network
all 1s		Limited broadcast
network	all 1s	Directed broadcast
127	anything (often 1)	Loopback
network	all 0s	Network id

- Addrs with all bits 0 or 1 are not assigned to hosts
  - Useful at start-up if host/network not known
- Broadcast is never valid source address
- Loopback is for local inter-process communication (IPC)
  - Should never exist on the network wire

Private Internet Address Ranges

- Address ranges for internal use

  10.0.0.0 – 10.255.255.255 (10/8 bit prefix)

  172.16.0.0 – 172.31.255.255 (172.16/12 bit prefix)

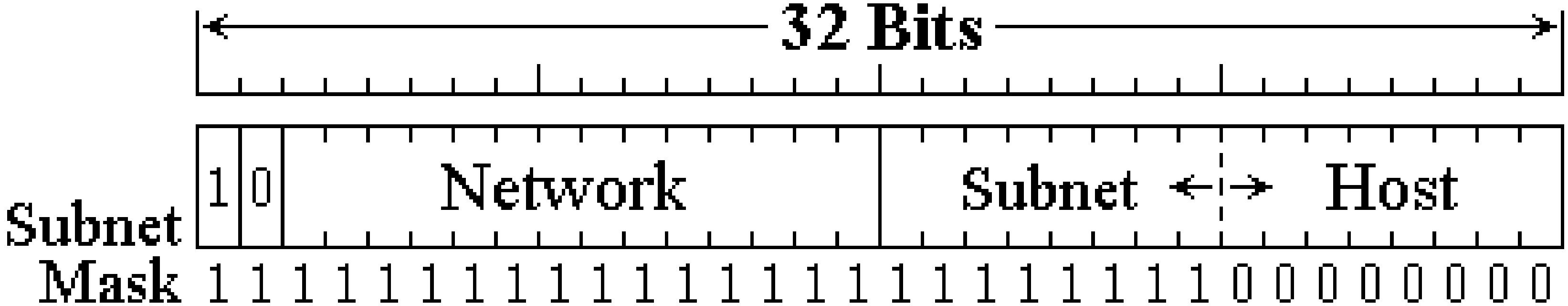
  192.168.0.0 – 192.168.255.255 (192.168/16 bit prefix)

- Addresses never routed on public Internet
  - Not all devices need to be globally visible
  - Used for testing and NAT (see later slides)

Subnets

- As organisations grow, need finer control over network sizes
  - Single class A/B/C network not good enough
- Subnet is sub-network within assigned IP network
  - To global Internet there is no distinction
  - Internally subnet addrs may be used for routing, admin
- Trade division into subnets for number of hosts in subnet
  - Subnets can be any size within host field

Subnets



- Use high-order bits from host field to create subnets within network class:

  subnet mask & address = network portion

- Number of hosts and subnets

  2^{subnet_bits} = number of subnets per network

  - Although usage of all 0s and 1s is not RFC-compliant

  $2^{(32 - network\_bits - subnet\_bits)} - 2$ = num of hosts per subnet

  - All 0s and all 1s are not valid addresses

Subnet Example

- In DoC, we have a class B network
  - 8 bits for subnets and 8 bits for hosts
  - Subnet mask 255.255.255.0 with class B net → 256 subnets, each with 254 hosts

- Example
  - 146.169.7.41 is global IP address of host 41 (maidenhair) on subnet 7 (DSE group) on IP network 146.169.0.0
  - Full DNS name: maidenhair.doc.ic.ac.uk
  - Broadcast to subnet on 146.169.7.255
  - 7-net subnet mask of 255.255.255.0, DoC network mask of 255.255.0.0

Mapping IP Addresses to Devices

- Need to translate between addresses
  - Data link layer → frames between devices use data link addrs, e.g. Ethernet MAC addrs
  - Network layer → hosts send packets using IP addrs

- Static mapping
  - May be sufficient for small isolated network
  - But Ethernet addr space is larger than IP addr space
- But IP addresses are virtual
  - No relation to hardware, maintained in software
- IP supports interconnections of different networks
  - Not all devices have Ethernet addresses

Dynamic Address Resolution

- Need to bind protocol address dynamically
  - Only possible for two devices on same network

- Table lookup
  - IP addr/data link addr in sequential/hash table
- Closed-form computation
  - Make physical addr simple function of IP addr
- Message exchange
  - Dedicated protocol for dynamic lookup, e.g. ARP
  - Usual method on TCP/IP networks with static addresses, e.g. Ethernet

Address Resolution Protocol (ARP)

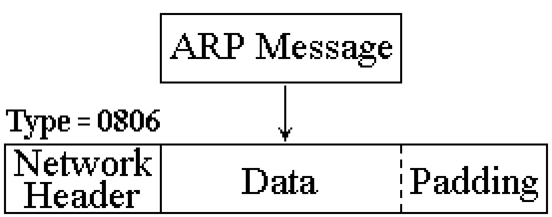
- Hosts maintain caches of IP/data link address mappings for LAN

- If host A has no entry for host B
  - A broadcasts ARP request
    - Requesting data link addr for B's IP address
  - B recognises its IP address
    - Returns ARP response with its data link address
  - B also caches A's data link/IP address mapping
    - Likely to need it in future exchanges

- ARP is network layer protocol, not visible to the user

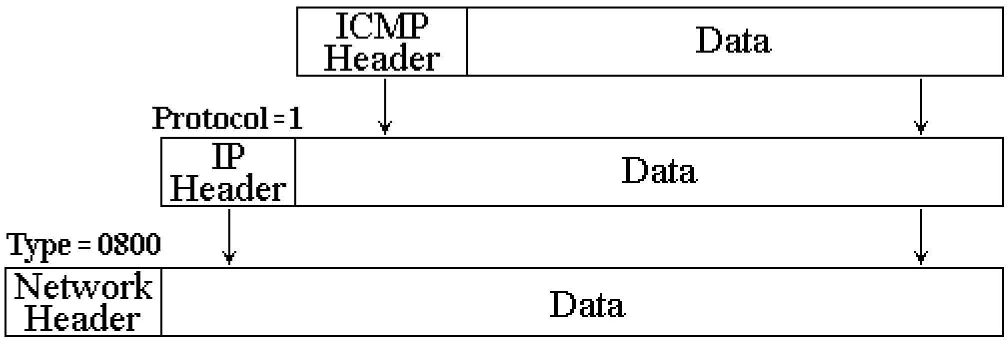
ARP Message Format

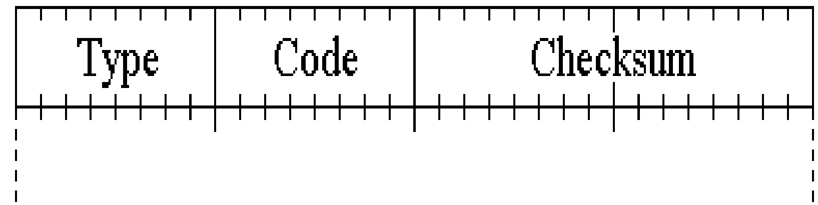
Hardware Address Type		Protocol Address Type	
HA Length	PA Length	Operation	
Sender HA (first 4 bytes)			
Sender HA (last 2 bytes)		Sender PA (first 2 bytes)	
Sender PA (last 2 bytes)		Target HA (first 2 bytes)	
Target HA (last 4 bytes)			
Target PA (all 4 bytes)			



- HW Addr Type: 1 = Ethernet
- Proto Addr Type: 0800h = IP
- HW Addr Length: 6 bytes
- Proto Addr Length: 4 bytes
- Operation: 1 = request, 2 = response
- Target HW Addr: undefined on request
- Target machine swaps target and sender in response

Internet Control Message Protocol (ICMP)





- Allows routers to send control/error msgs to other routers/hosts
  - Behaves as if higher level protocol, but integral to IP
- ICMP provides for feedback about comms problems
  - IP unreliable ➔ no guarantees of delivery, loss notification, control msg return

ICMP Message Format

- Type (8bit) + code (8bit) gives kind of message
- Type 3 codes

  0 = Net unreachable
  1 = Host unreachable
  2 = Protocol unreachable
  3 = Port unreachable
  4 = Fragmentation needed and DF set
  5 = Source route failed

- 1s compliment checksum of type & code

- Other types include

  0 = Echo reply
  5 = Redirect
  8 = Echo request (ping)
  11 = Time exceeded
  12 = Parameter problem
  13 = Timestamp
  14 = Timestamp reply
  15 = Information request
  16 = Information reply
  17 = Address mask request
  18 = Address mask reply

Issues with IP Addressing

- Support for mobility (laptops, phone, …)
  - Connect to different points in different networks
  - Routing depends on address used
- Expansion of networks
  - Renumbering/adding new number ranges hard
  - Hosts with multiple IP addresses
- Total size of address space limited

Address Space Problem

- Shortage of unallocated addresses
  - Practical address space in IPv4 is 100 million hosts
  - IP is more popular than its designers expected
- Some addr classes are unnecessarily large
  - Some organisations have more than they need
  - Class B is bigger than most people use
    - 64516 host addrs with 254 subnets of 254 hosts
    - Never mind class A!

Address Space Solutions

- Stricter access to allocation
  - Class A “virtually impossible” to obtain now
  - Blocks of class C now allocated in preference to class B
- Make address allocation more flexible
  - Classless Inter-Domain Routing (CIDR)
- Reuse addresses in different parts of network
  - Network Address Translation (NAT)
- Add more address bits
  - IPv6

Classless Inter-Domain Routing (CIDR)

- Partition world into four zones
- Allocate networks with subnet masks
  - Size according to need, not just fixed classes A/B/C
  - "Subnetting for global Internet"

- Advantages
  - More efficient allocation
  - Works alongside previous allocations

- Disadvantages
  - Makes routing harder
  - Not fundamentally larger address space

- Europe
  - 194.0.0.0 - 195.255.255.255
- North America
  - 198.0.0.0 – 199.255.255.255
- Central/South America
  - 200.0.0.0 – 201.255.255.255
- Asia & Pacific
  - 202.0.0.0 – 203.255.255.255
- Future use
  - 204.0.0.0 – 223.255.255.255

Network Address Translation (NAT)

- Often only fraction of hosts require external access
- Hide large network in small Internet address range
  - External addr → real, allocated IP address
  - Internal addrs → from private addresses range
  - Gateway box translates internal addrs to dynamically allocated external addrs for traffic leaving LAN
- Full address becomes IP addr + port
  - External addr may be shared by multiple hosts over time
  - Can lead to problems if changes aren't anticipated…

IPv6

- IETF addresses many problems of IPv4 with IPv6
- 128 bit addresses (vs. 32 bit in IPv4)
  - $3.4*10^{38}$ unique host addresses (vs. $4.2*10^{9}$ in IPv4)
- Simplified 7 field header (vs. 13 fields in IPv4)
  - Faster processing in routers possible
  - More options through extension headers
  - Support for authentication, privacy, service types, mobility, …
- Compatible with IPv4 for transition
  - Some gateways and tricks to hide IPv6’s greater capabilities

Issues with IPv6

- Difficult to implement properly
- Transition from IPv4 to IPv6 hard and slow
  - Not widely deployed over backbone
    - Router/switch manufacturers not pushing it
    - ISPs and network providers not demanding it
  - Many of the benefits lost in gateways to IPv4
- Currently useful within organisation
  - But not many people to talk IPv6 with
  - Mobile phones may push adoption…

https://www.google.com/intl/en/ipv6/statistics.html