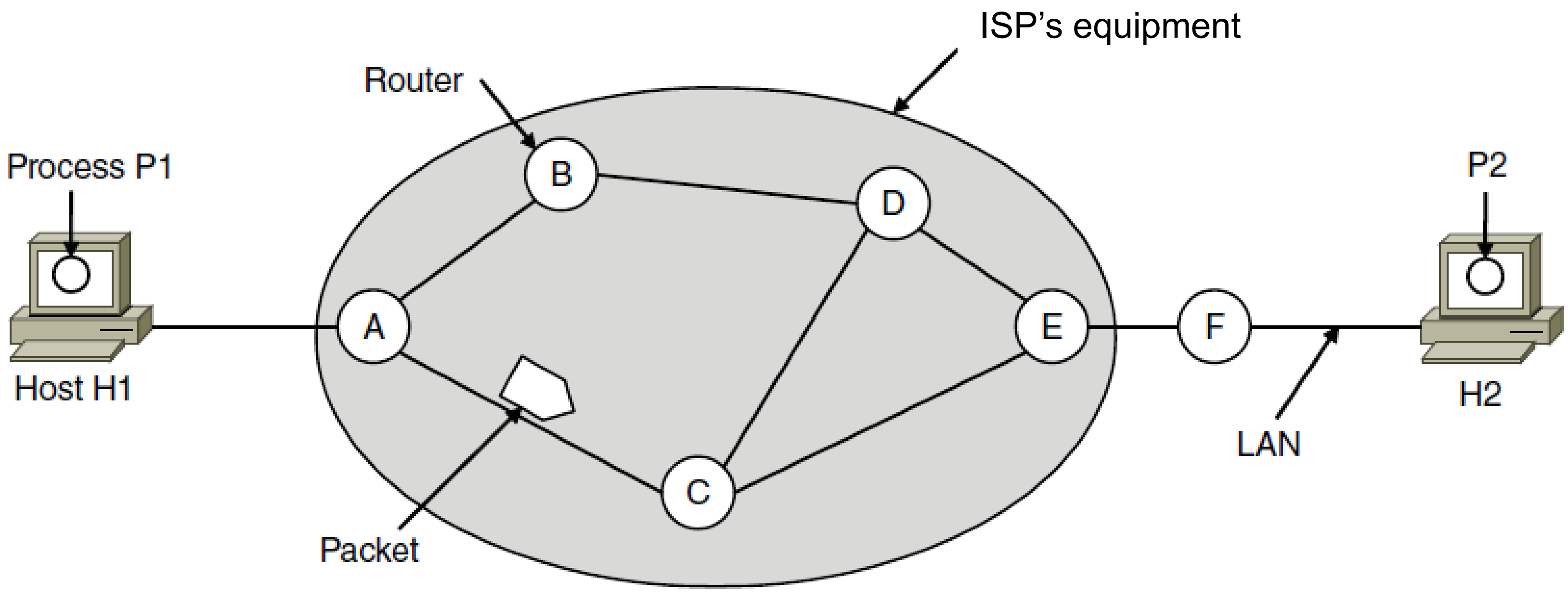
The Network Layer

Chapter 5

Network Layer Design Issues

- Store-and-forward packet switching
- Services provided to transport layer
- Implementation of connectionless service
- Implementation of connection-oriented service
- Comparison of virtual-circuit and datagram networks

Store-and-Forward Packet Switching

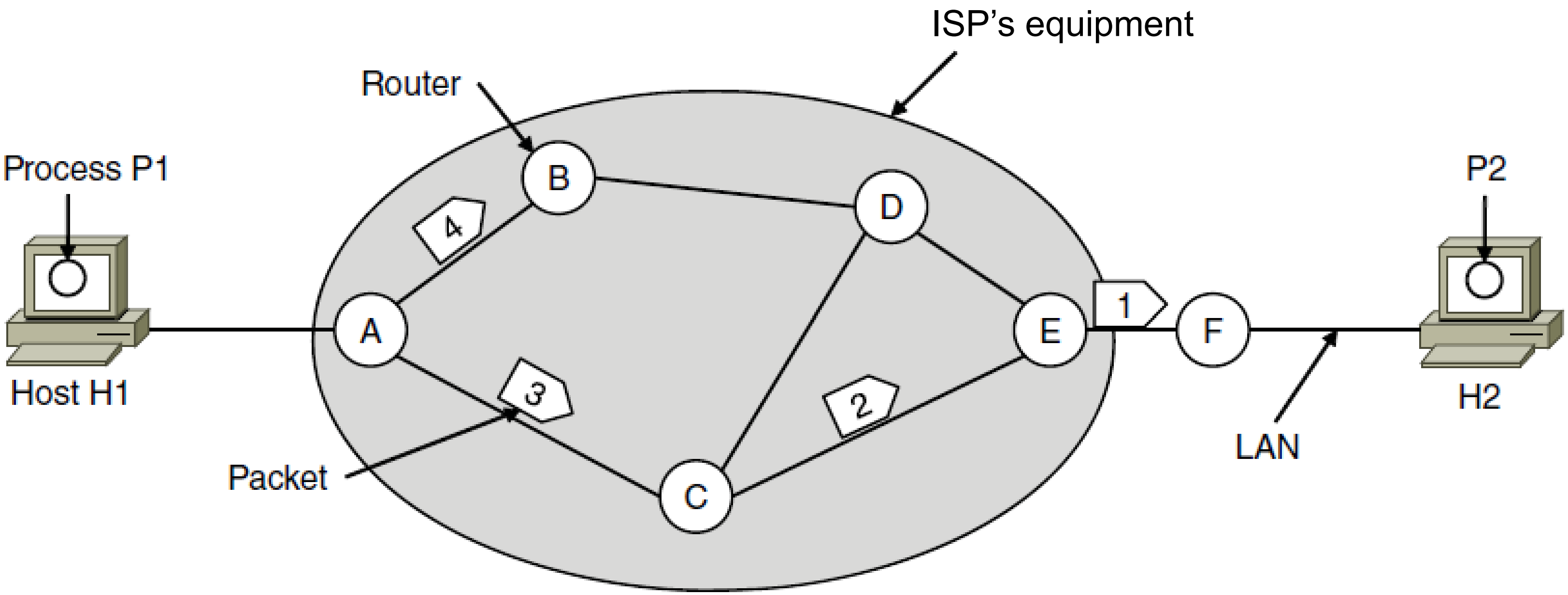


The environment of the network layer protocols.

Services Provided to the Transport Layer

- Services independent of router technology.
- Transport layer shielded from number, type, topology of routers.
- Network addresses available to transport layer use uniform numbering plan even across LANs and WANs

Implementation of Connectionless Service



A's table (initially)

Dest.	Line
A	
B	B
C	C
D	B
E	C
F	C

A's table (later)

A	
B	B
C	C
D	B
E	D
F	D

C's Table

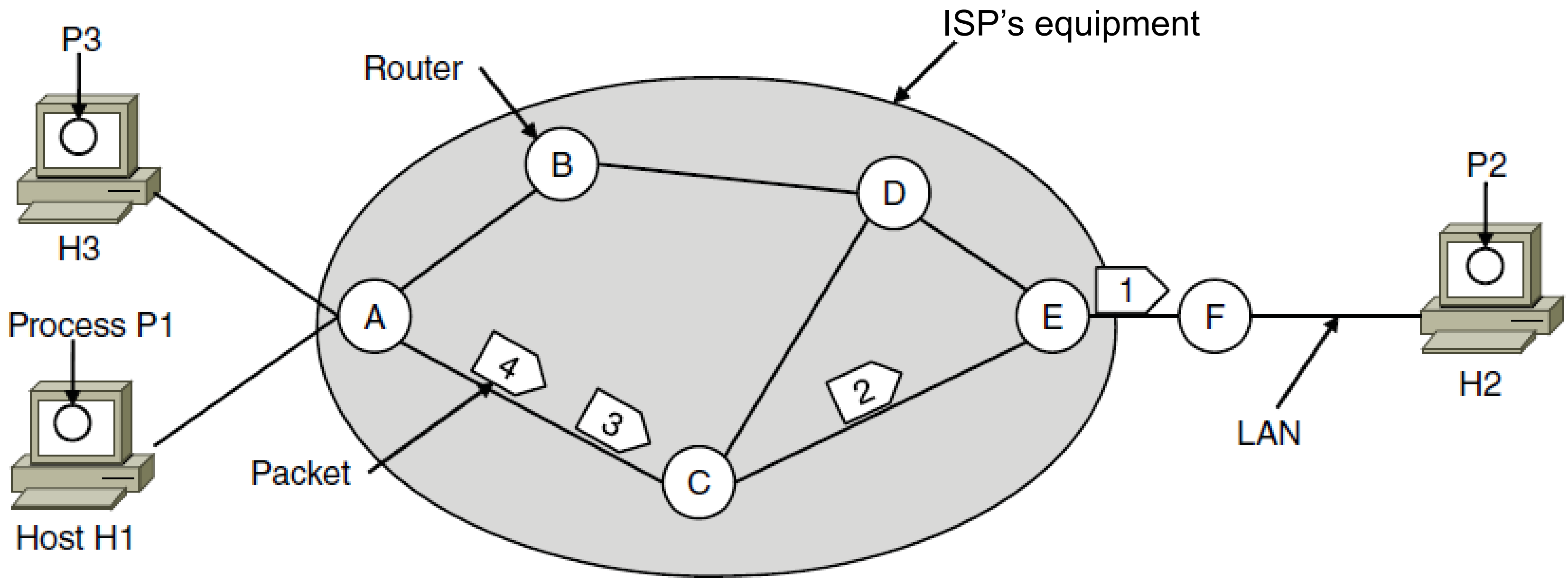
A	A
B	A
C	
D	E
E	E
F	E

E's Table

A	C
B	D
C	C
D	D
E	
F	F

Routing within a datagram network

Implementation of Connection-Oriented Service



A's table

In		Out	
H1	1	C	1
H3	1	C	2

C's Table

A	1	E	1
A	2	E	2

E's Table

C	1	F	1
C	2	F	2

Routing within a virtual-circuit network

Comparison of Virtual-Circuit and Datagram Networks

Issue	Datagram network	Virtual-circuit network
Circuit setup	Not needed	Required
Addressing	Each packet contains the full source and destination address	Each packet contains a short VC number
State information	Routers do not hold state information about connections	Each VC requires router table space per connection
Routing	Each packet is routed independently	Route chosen when VC is set up; all packets follow it
Effect of router failures	None, except for packets lost during the crash	All VCs that passed through the failed router are terminated
Quality of service	Difficult	Easy if enough resources can be allocated in advance for each VC
Congestion control	Difficult	Easy if enough resources can be allocated in advance for each VC

Comparison of datagram and virtual-circuit networks

Routing Algorithms (1)

- Optimality principle
- Shortest path algorithm
- Flooding
- Distance vector routing
- Link state routing
- Routing in ad hoc networks

Routing Algorithms (2)

- Broadcast routing
- Multicast routing
- Anycast routing
- Routing for mobile hosts
- Routing in ad hoc networks

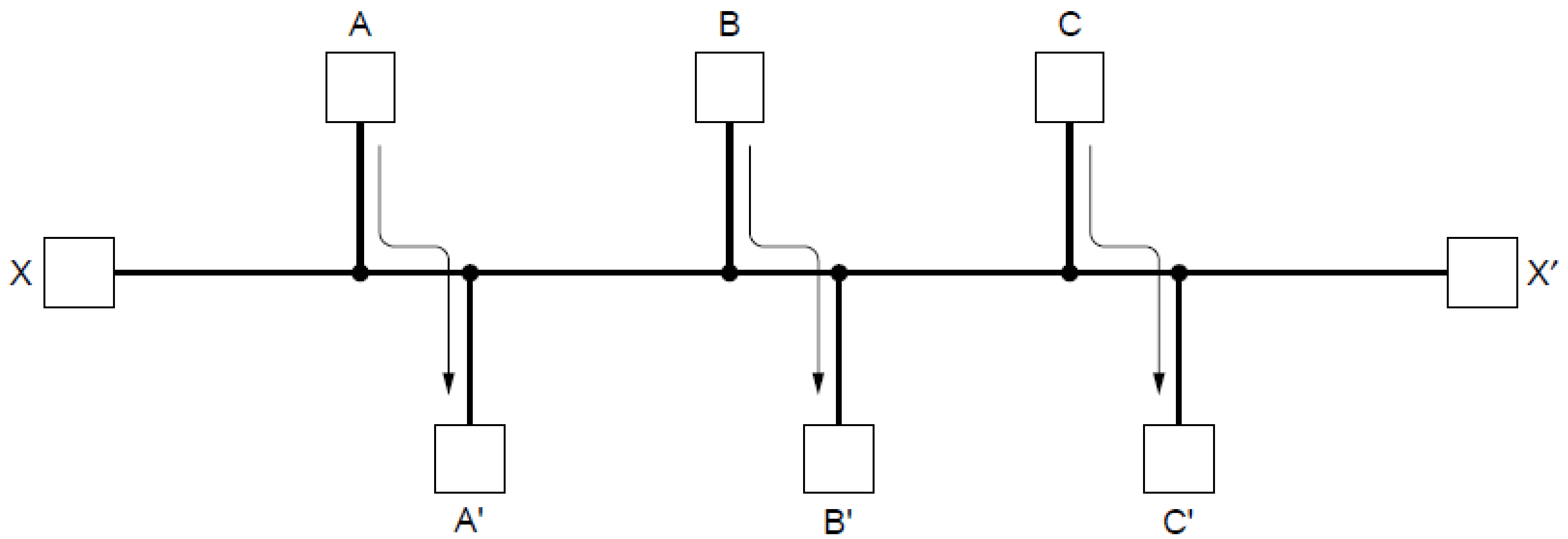
Routing Vs Forwarding

- Routing is making the decision which routes to use, and forwarding, is what happens when a packet arrives
- Router has two processes inside it. One of them handles each packet as it arrives, looking up the outgoing line to use for it in the routing tables. This process is **forwarding**. The other process is responsible for filling in and updating the routing tables.

Routing Algorithms

- Desirable properties of routing algorithm:
  - Correctness – Right path is chosen
  - Simplicity – Ease of use and implementation
  - Robustness – reliability in event of failure
  - Stability - converge to fixed set of paths
  - Fairness – Fair to all hosts
  - Efficiency – Utilization, delay

Fairness vs. Efficiency



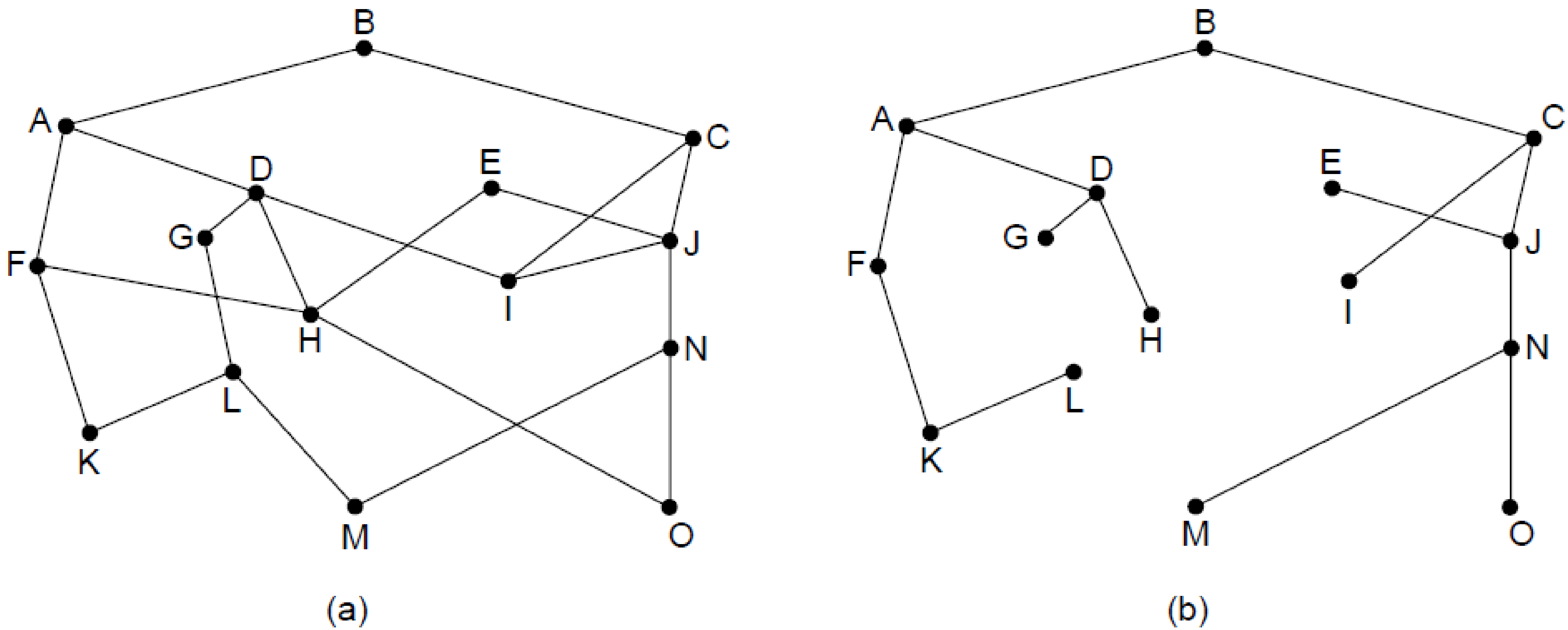
Network with a conflict between fairness and efficiency.

Routing Algorithms

- Types of routing algorithm:
  - Nonadaptive RA – do not base their routing decisions on any measurements or estimates of the current topology and traffic. Instead the routes are computed in advance, offline and downloaded to routers when network boots. Eg Static Routing
  - Adaptive RA - change their routing decisions to reflect changes in the topology, and sometimes changes in the traffic as well. They differ in where they get their information, when they change the routes, and what metric is used for optimization. Eg Distance Vector Routing, Link State Routing

The Optimality Principle

Statement about optimal routes without regard to network topology or traffic
It states that if router J is on the optimal path from router I to router K, then the optimal path from J to K also falls along the same route.



(a) A network. (b) A sink tree for router *B.*

Flooding

A simple method to send a packet to all network nodes

Each node floods a new packet received on an incoming link by sending it out all of the other links

Flooding generates vast numbers of duplicate packets, in fact, an infinite number unless some measures are taken to damp the process.

One such measure is to have a hop counter contained in the header of each packet that is decremented at each hop.

The packet being discarded when the counter reaches zero.

Ideally, the hop counter should be initialized to the length of the path from source to destination.

If the sender does not know how long the path is, it can initialize the counter to the worst case i.e. the full diameter of the network.

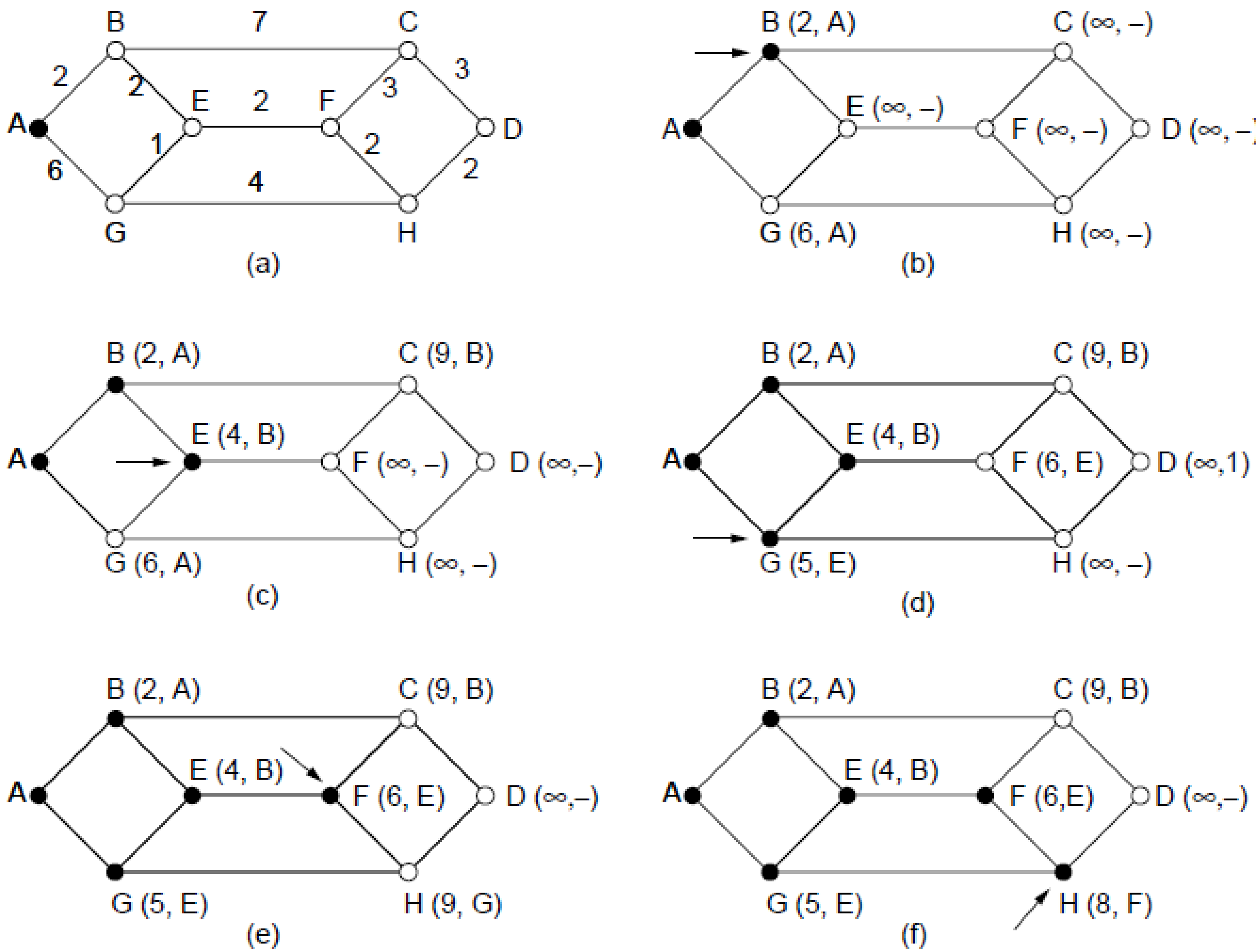
First, it ensures that a packet is delivered to every node in the network.

This may be wasteful if there is a single destination that needs the packet,

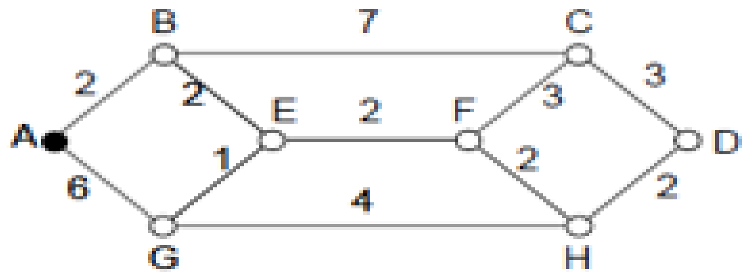
but it is effective for broadcasting information.

flooding will find a path if one exists, to get a packet to its destination(e.g. in a military network located in a war zone).

Shortest Path Algorithm (1)



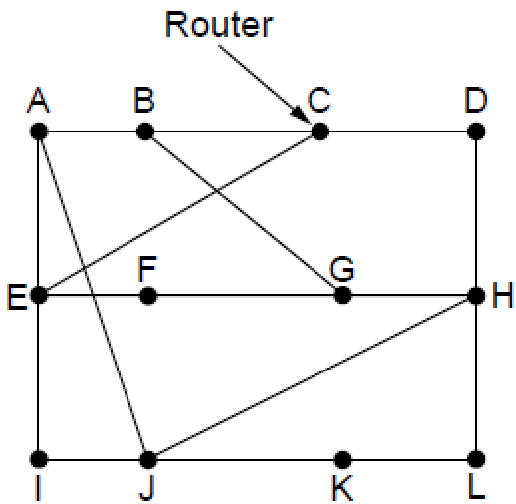
The first five steps used in computing the shortest path from *A to D.* The arrows indicate the working node



(a)

A	B	C	D	E	F	G	H
	2 A	∞	∞	∞	∞	6 A	∞
+2 B	✓	9 B	∞	4 B	∞	6 A	∞
+4 E	✓	9 B	∞	✓	6 A	5 E	∞
+5 G	✓	9 B	∞	✓	6 A	✓	9 G
+6 F	✓	9 B	∞	✓	✓	✓	8 F
+8 H	✓	9 B	10 H	✓	✓	✓	✓
+9 C	✓	✓	10 H	✓	✓	✓	✓

Distance Vector Routing



(a)

To	A	I	H	K	New estimated delay from J	Line
A	0	24	20	21	8	A
B	12	36	31	28	20	A
C	25	18	19	36	28	I
D	40	27	8	24	20	H
E	14	7	30	22	17	I
F	23	20	19	40	30	I
G	18	31	6	31	18	H
H	17	20	0	19	12	H
I	21	0	14	22	10	I
J	9	11	7	10	0	–
K	24	22	22	0	6	K
L	29	33	9	9	15	K
	JA delay is 8	JI delay is 10	JH delay is 12	JK delay is 6	New routing table for J	

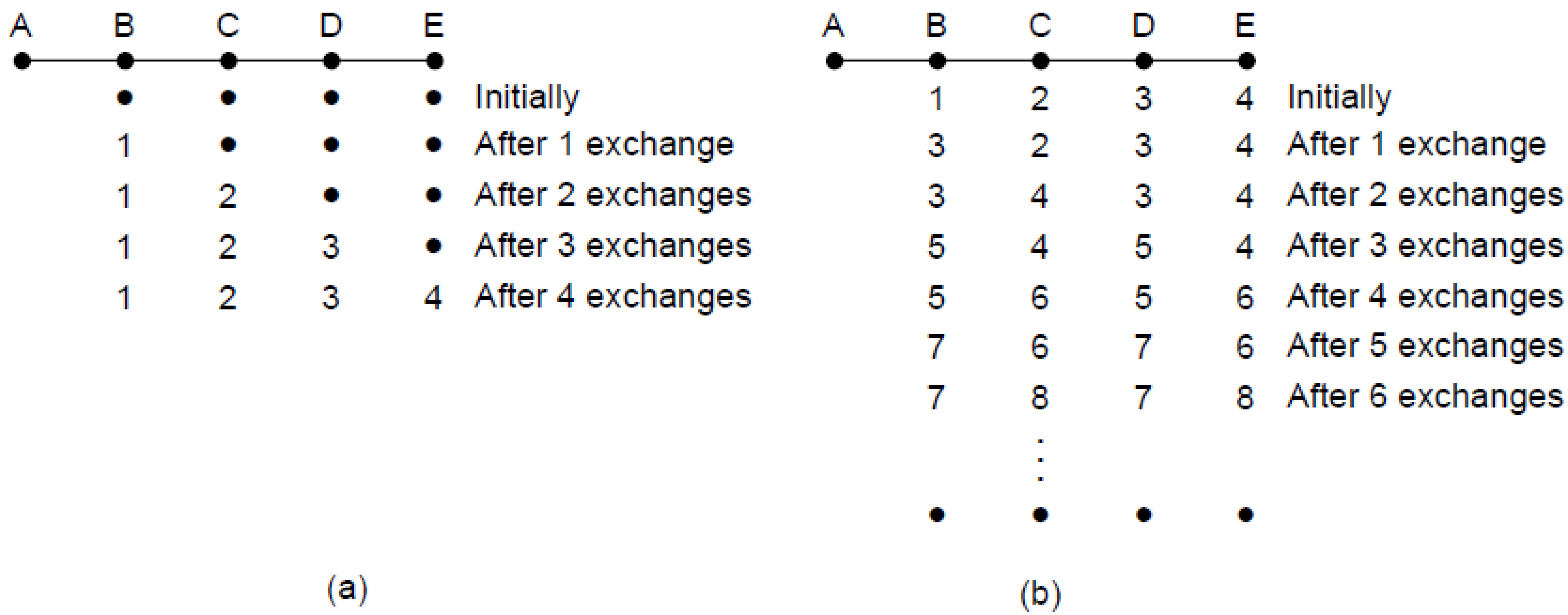
Vectors received from J's four neighbors

(b)

(a) A network.

(b) Input from *A, I, H, K, and the new routing table* for *J.*

The Count-to-Infinity Problem

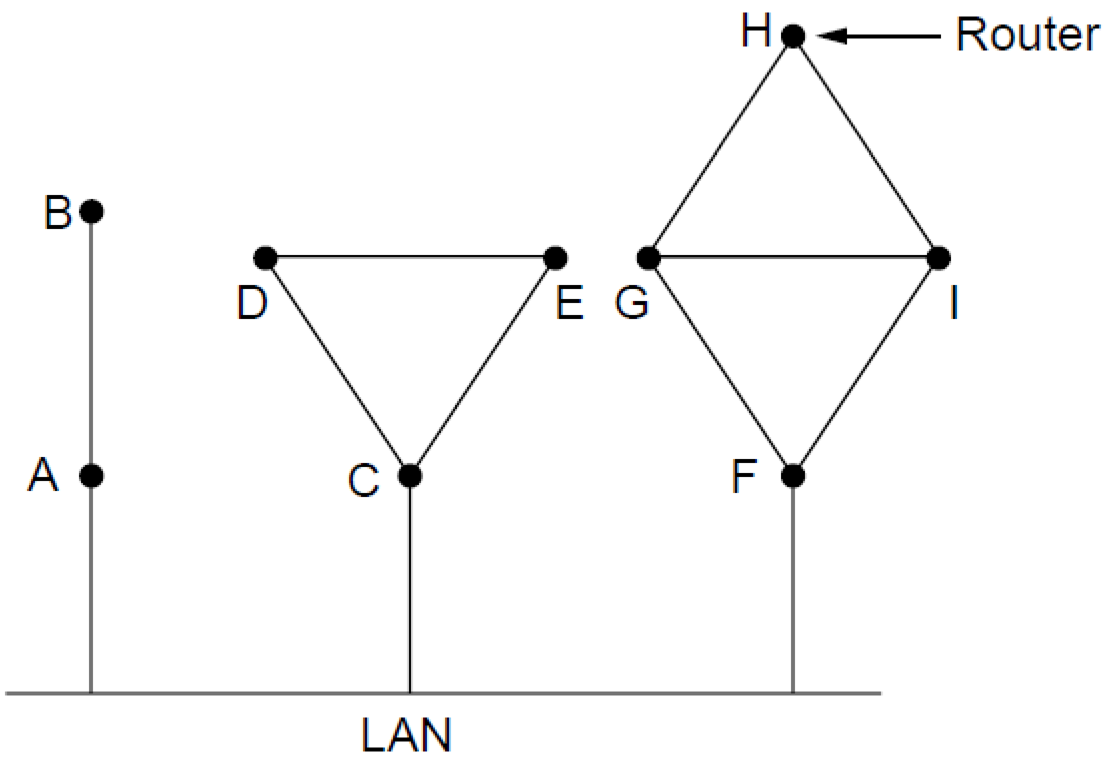


The count-to-infinity problem

Link State Routing

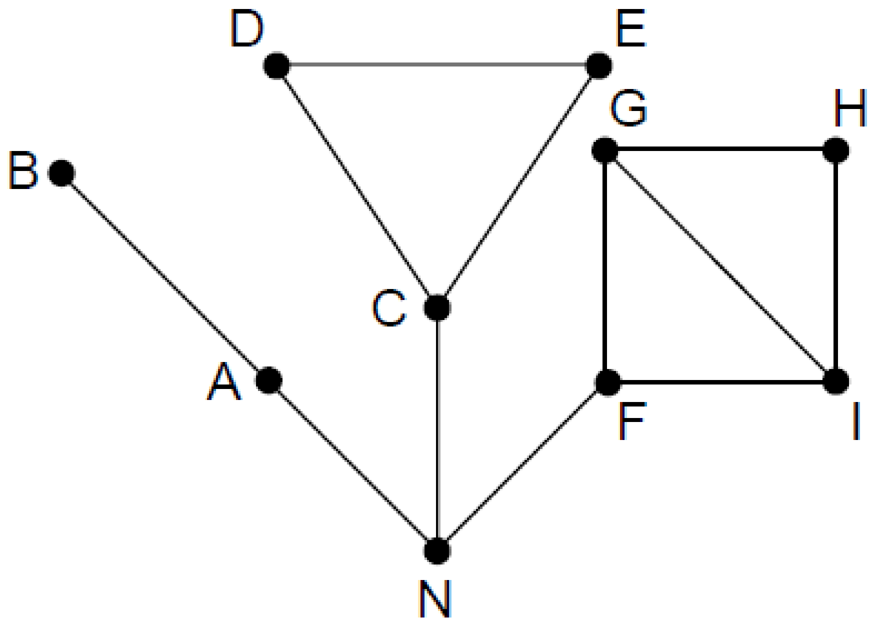
- Discover neighbors, learn network addresses.
- Set distance/cost metric to each neighbor.
- Construct packet telling all learned.
- Send packet to, receive packets from other routers.
- Compute shortest path to every other router.

Learning about the Neighbors (1)



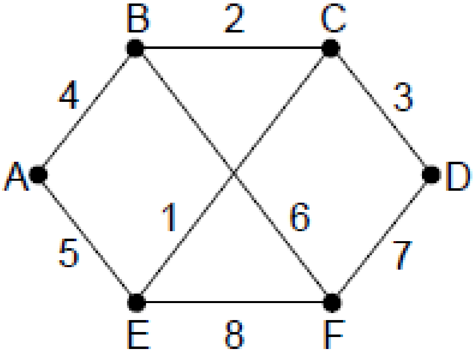
Nine routers and a broadcast LAN.

Learning about the Neighbors (2)



A graph model of previous slide.

Building Link State Packets



(a)

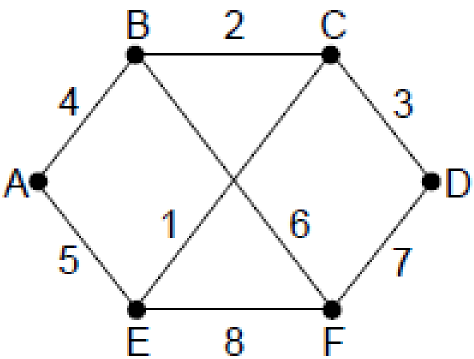
Link State Packets

A		B		C		D		E		F	
Seq.		Seq.		Seq.		Seq.		Seq.		Seq.	
Age		Age		Age		Age		Age		Age	
B	4	A	4	B	2	C	3	A	5	B	6
E	5	C	2	D	3	F	7	C	1	D	7
		F	6	E	1			F	8	E	8

(b)

(a) A network. (b) The link state packets for this network.

Distributing the Link State Packets



(a)

Link State Packets

A	
Seq.	
Age	
B	4
E	5

B	
Seq.	
Age	
A	4
C	2
F	6

C	
Seq.	
Age	
B	2
D	3
E	1

D	
Seq.	
Age	
C	3
F	7

E	
Seq.	
Age	
A	5
C	1
F	8

F	
Seq.	
Age	
B	6
D	7
E	8

(b)

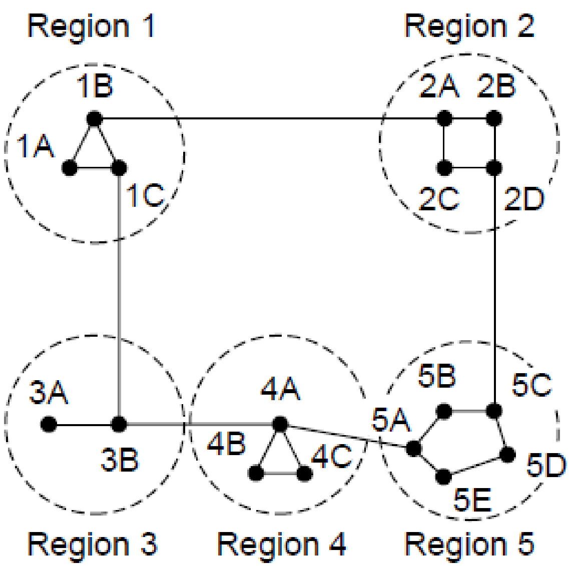
Source	Seq.	Age	A	C	F	A	C	F	Data
A	21	60	0	1	1	1	0	0	
F	21	60	1	1	0	0	0	1	
E	21	59	0	1	0	1	0	1	
C	20	60	1	0	1	0	1	0	
D	21	59	1	0	0	0	1	1	

The packet buffer for router *B* in previous slide

Hierarchical Routing

- As networks grow in size, the routing tables grow proportionally
- Not only is router memory consumed by ever-increasing tables, but more CPU time is needed to scan them and more bandwidth is needed to send status reports about them.
- The routers are divided into what we will call **regions**.
- Two levels may not be sufficient for huge networks
- It may be necessary to group the regions into clusters, the clusters into zones, the zones into groups
- How many levels should the hierarchy have?
- For example, consider a network with 720 routers. If there is no hierarchy, each router needs 720 routing table entries. If the network is partitioned into 24 regions of 30 routers each, each router needs 30 local entries plus 23 remote entries for a total of 53 entries. If a three-level hierarchy is chosen, with 8 clusters each containing 9 regions of 10 routers, each router needs 10 entries for local routers, 8 entries for routing to other regions within its own cluster, and 7 entries for distant clusters, for a total of 25 entries.

Hierarchical Routing



(a)

Full table for 1A

Dest.	Line	Hops
1A	–	–
1B	1B	1
1C	1C	1
2A	1B	2
2B	1B	3
2C	1B	3
2D	1B	4
3A	1C	3
3B	1C	2
4A	1C	3
4B	1C	4
4C	1C	4
5A	1C	4
5B	1C	5
5C	1B	5
5D	1C	6
5E	1C	5

(b)

Hierarchical table for 1A

Dest.	Line	Hops
1A	–	–
1B	1B	1
1C	1C	1
2	1B	2
3	1C	2
4	1C	3
5	1C	4

(c)

Hierarchical routing.

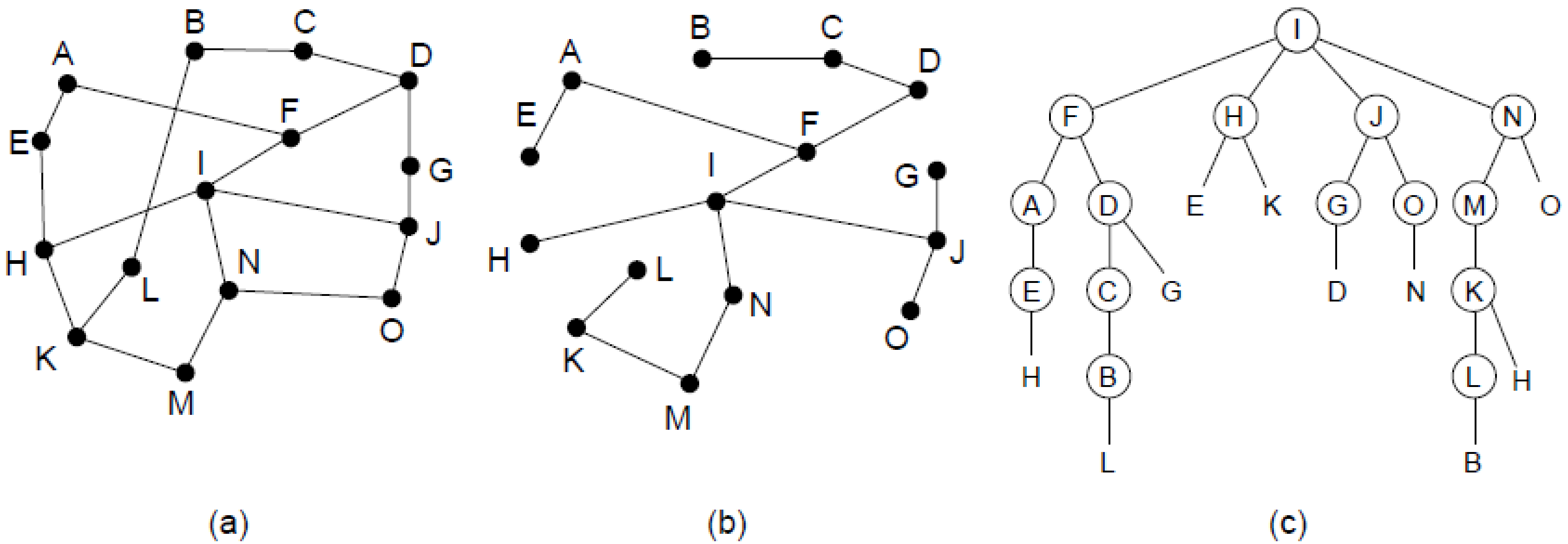
Broadcast Routing

- Sending a packet to all destinations simultaneously is called **broadcasting**
- One broadcasting method that requires no special features from the network is for the source to simply send a distinct packet to each destination.
- An improvement is **multidestination routing**, in which each packet contains either a list of destinations or a bit map indicating the desired destinations.
- When a packet arrives at a router, the router checks all the destinations to determine the set of output lines that will be needed. The router generates a new copy of the packet for each output line to be used and includes in each packet only those destinations that are to use the line
- A better broadcast routing technique is **flooding**

Broadcast Routing – Reverse Path Forwarding

- When a broadcast packet arrives at a router, the router checks to see if the packet arrived on the link that is normally used for sending packets *toward* the source of the broadcast.
- If so, there is an excellent chance that the broadcast packet itself followed the best route from the router and is therefore the first copy to arrive at the router.
- This being the case, the router forwards copies of it onto all links except the one it arrived on.
- If, however, the broadcast packet arrived on a link other than the preferred one for reaching the source, the packet is discarded as a likely duplicate.

Broadcast Routing

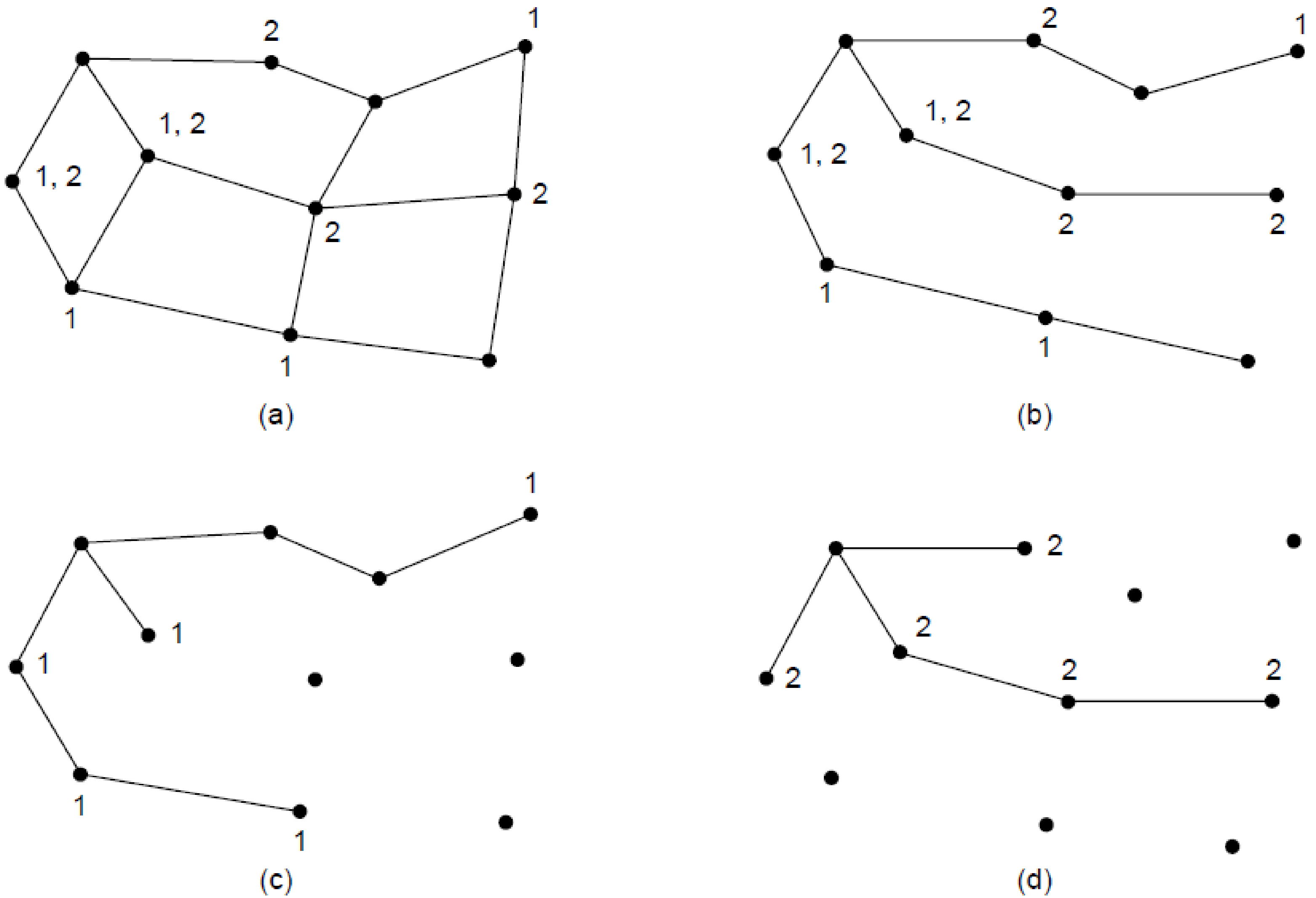


Reverse path forwarding. (a) A network. (b) A sink tree for I. (c) The tree built by reverse path forwarding.

Multicast Routing

- Multicasting is a special case of broadcasting
- All multicasting schemes require some way to create and destroy groups and to identify which routers are members of a group
- Assume that each group is identified by a multicast address and that routers know the groups to which they belong
- If the group is dense, broadcast is a good start but it reaches all routers. The solution is pruning the broadcast tree by removing links that do not lead to members
- If OSPF is used, each routers knows complete topology, they can construct its own pruned spanning tree for each sender to the group. Eg. **MOSPF** (**Multicast OSPF**)

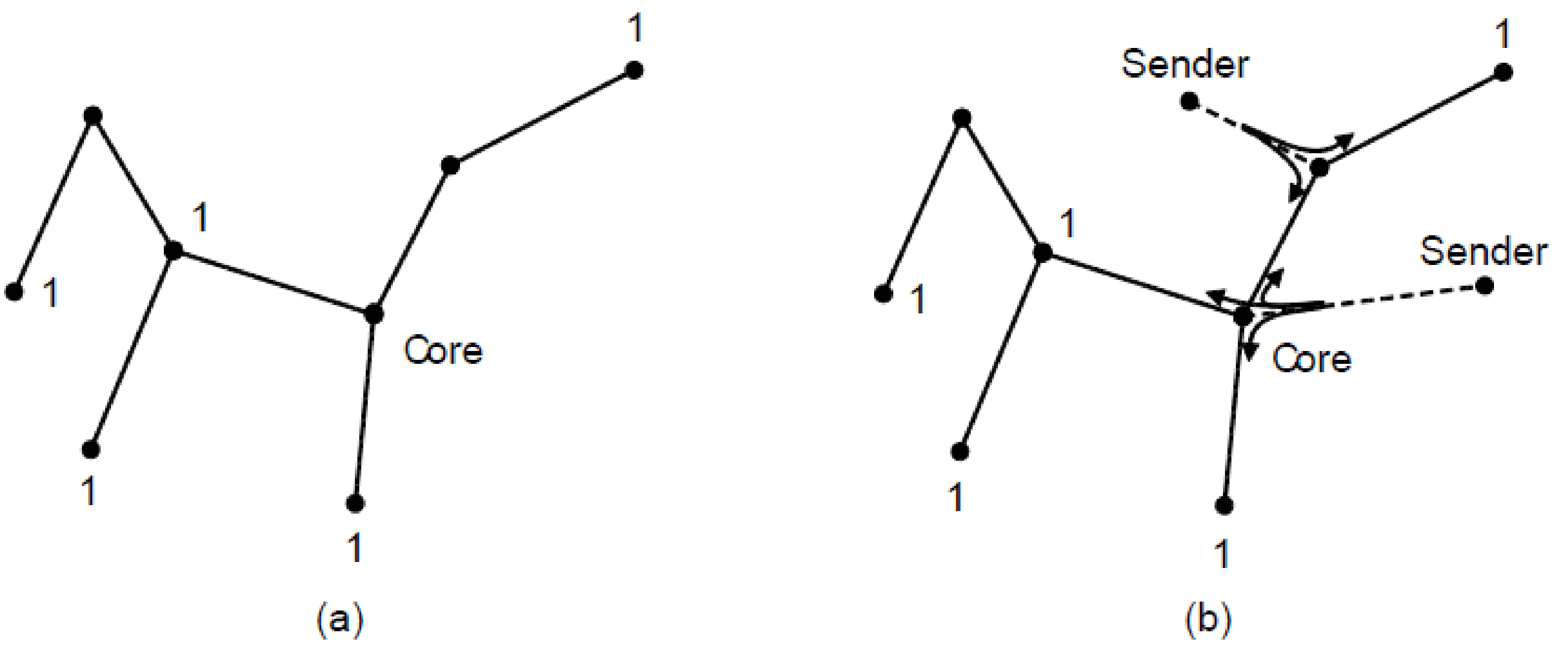
Multicast Routing (1)



(a) A network. (b) A spanning tree for the leftmost router. (c) A multicast tree for group 1. (d) A multicast tree for group 2.

Multicast Routing (2)

- All of the routers agree on a root (called the **core** or **rendezvous point**)
- Build the tree by sending a packet from each member to the root
- The tree is the union of the paths traced by these packets
- To send to this group, a sender sends a packet to the core

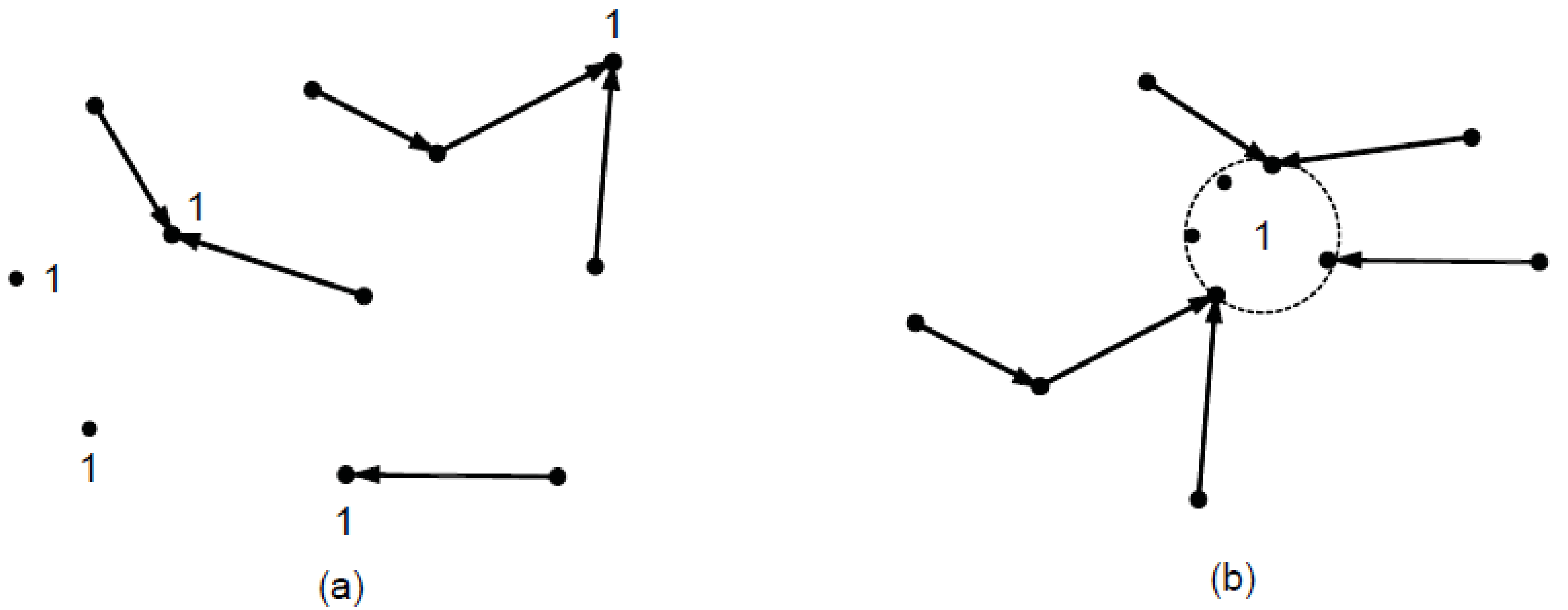


a) Core-based tree for group 1.

b) Sending to group 1.

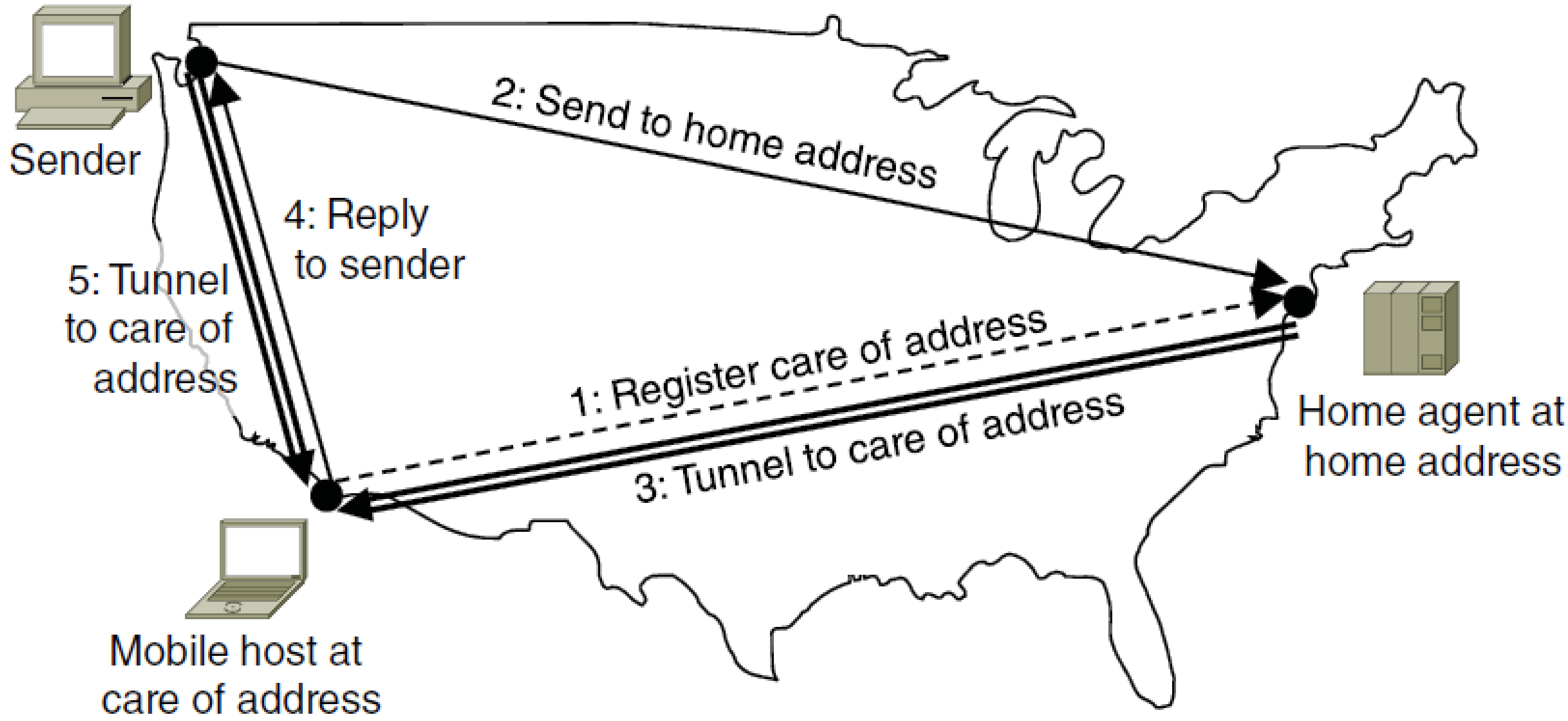
Anycast Routing

- A packet is delivered to the nearest member of a group
- Can be achieved using regular DV or LSR
- All members of the group will be given same address, say 1
- This procedure works because the routing protocol does not realize that there are multiple instances of destination 1. That is, it believes that all the instances of node 1 are the same node



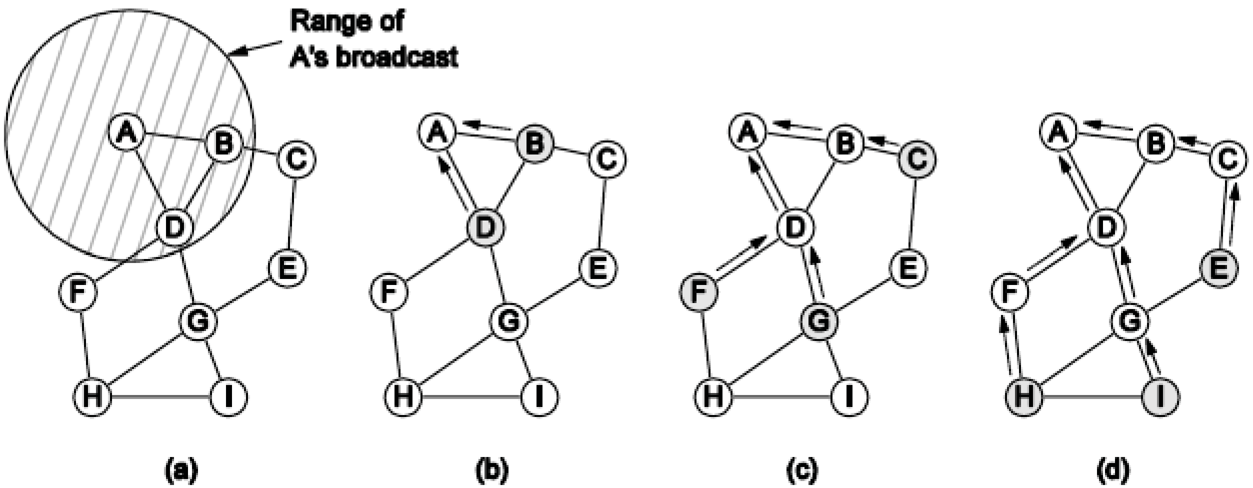
a) Anycast routes to group 1.
b) Topology seen by the routing protocol.

Routing for Mobile Hosts



Packet routing for mobile hosts

Routing in Ad Hoc Networks



a) Range of A's broadcast.
b) After B and D receive it.
c) After C, F, and G receive it.
d) After E, H, and I receive it.

The shaded nodes are new recipients. The dashed lines show possible reverse routes. The solid lines show the discovered route.

Congestion Control Algorithms (1)

- Approaches to congestion control
- Traffic-aware routing
- Admission control
- Traffic throttling
- Load shedding

Congestion Control

Too many packets present in the network causes packet delay and loss that degrades performance. This situation is called **congestion**.

The network and transport layers share the responsibility for handling congestion.

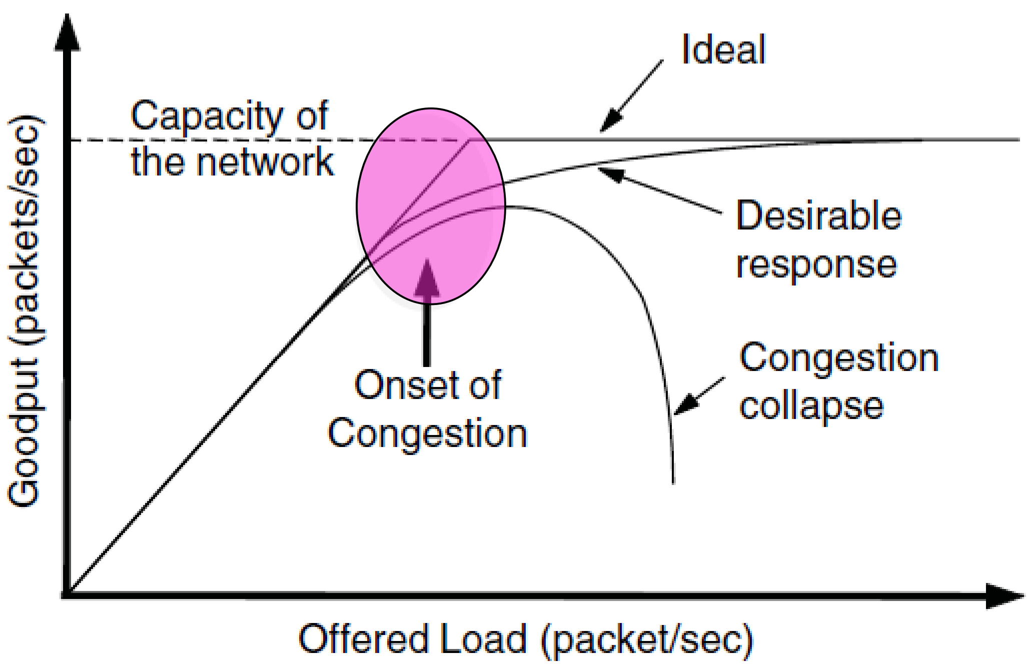
Since congestion occurs within the network, it is the network layer that directly experiences it and must ultimately determine what to do with the excess packets.

However, the most effective way to control congestion is to reduce the load that the transport layer is placing on the network. This requires the network and transport layers to work together.

Congestion Control (2)

Congestion results when too much traffic is offered; performance degrades due to loss/retransmissions

- Goodput (useful packets) trails offered load



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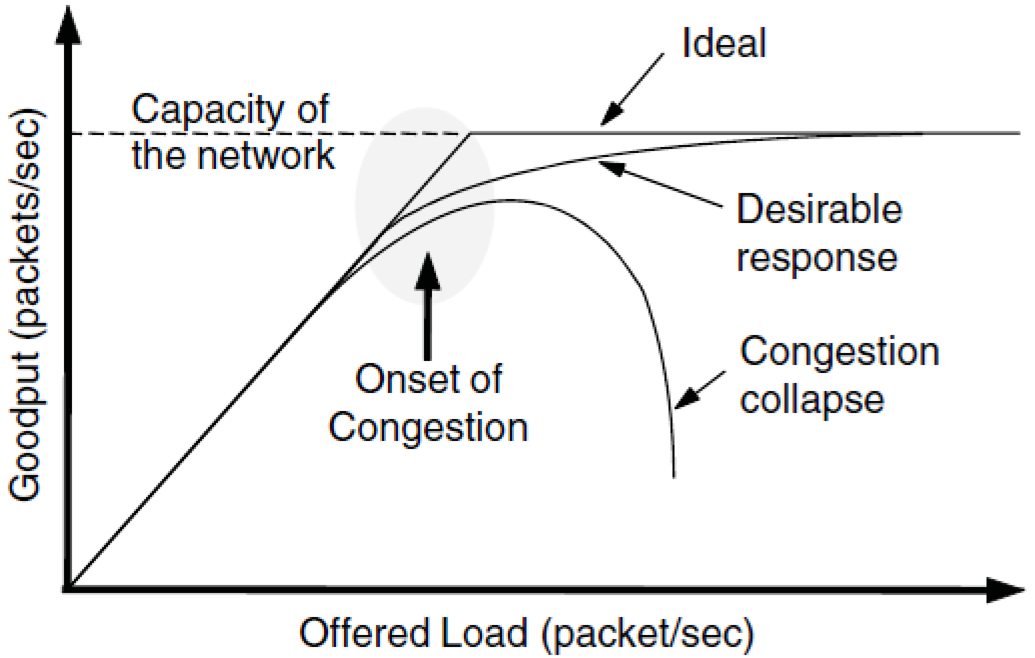
Congestion Control Algorithms (2)



When too much traffic is offered, congestion sets in and performance degrades sharply.

Congestion Control (1)

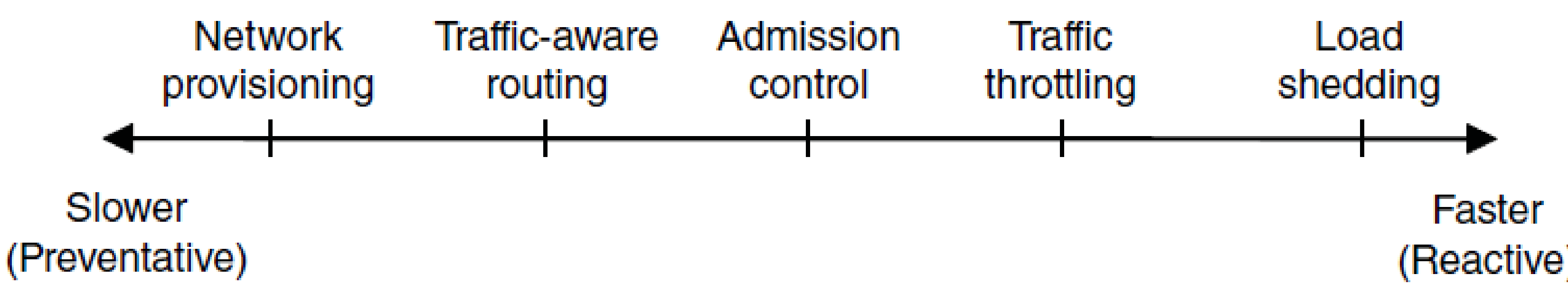
Handling congestion is the responsibility of the Network and Transport layers working together

- We look at the Network portion here
  - Network provisioning »
  - Traffic-aware routing »
  - Admission control »
  - Traffic throttling »
  - Load shedding »

Congestion Control (3) – Approaches

Network must do its best with the offered load

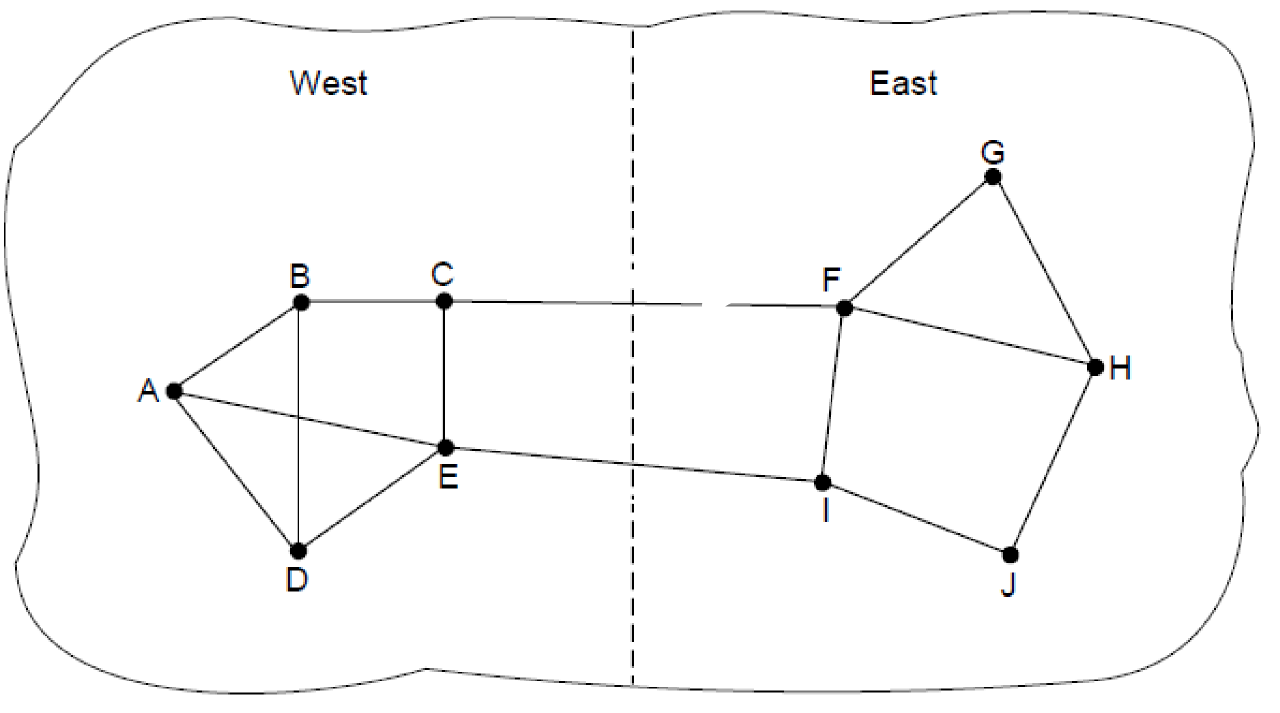
- Different approaches at different timescales
- Nodes should also reduce offered load (Transport)



Traffic-Aware Routing

Choose routes depending on traffic, not just topology

- E.g., use *EI* for West-to-East traffic if *CF* is loaded

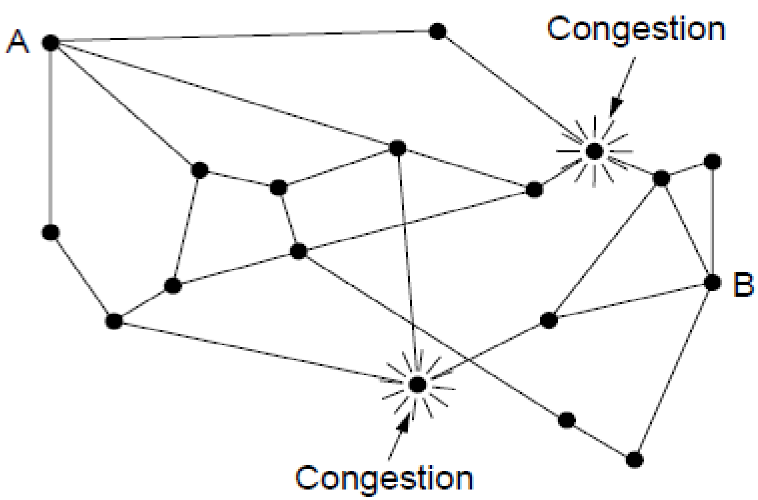


Admission Control

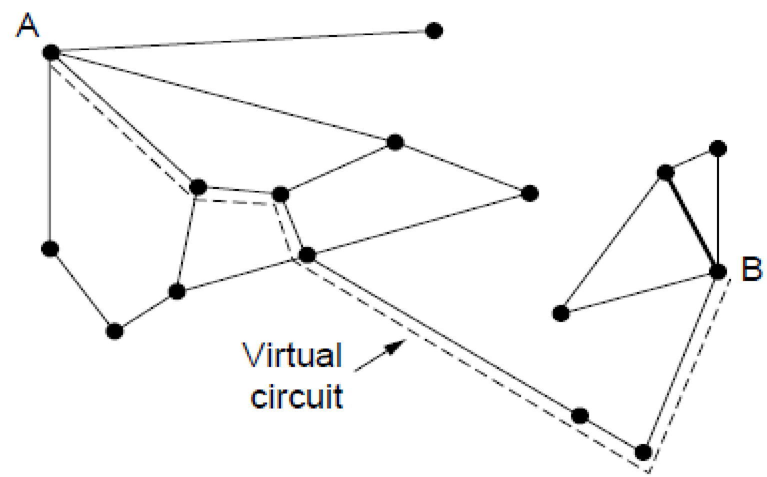
a) Admission control allows a new traffic load only if the network has sufficient capacity.

b) new connections can be refused if they would cause the network to become

c) congested.



Network with some congested nodes



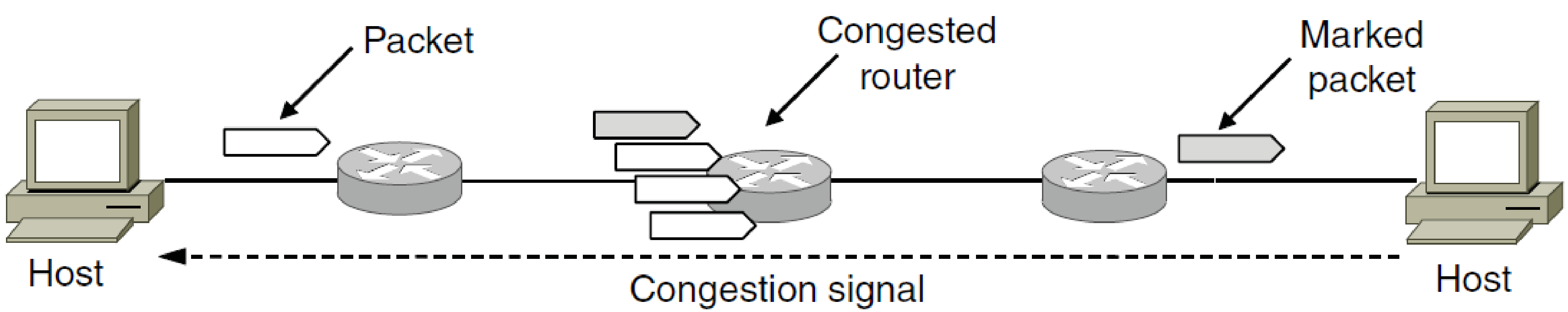
Uncongested portion and route *AB* around congestion

Traffic Throttling

When the network delivers the packet, the destination can note that there is congestion and inform the sender when it sends a reply packet.

The sender can then throttle its transmissions as before.

ECN (Explicit Congestion Notification) marks packets and receiver returns signal to sender



Choke Packet Technique

Choke packet scheme is mechanism where each link is monitored to examine how much utilization is taking place.

If the utilization goes beyond a certain threshold limit, the link goes to a warning and a special packet, called choke packet is sent to the source.

On receiving the choke packet, the source reduced the traffic in order to avoid congestion.

Choke Packet Technique

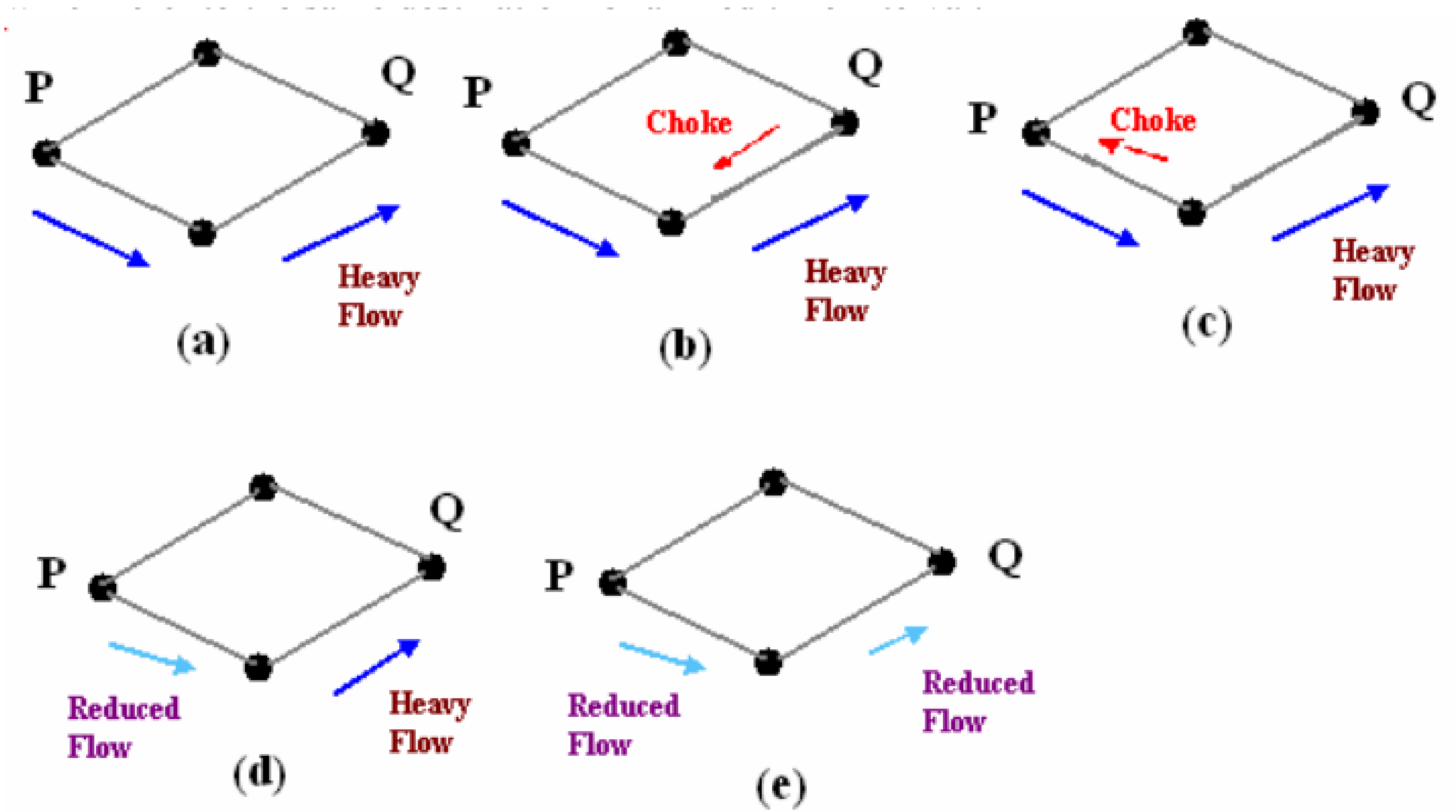


Figure 7.5.6 Depicts the functioning of choke packets, (a) Heavy traffic between nodes P and Q, (b) Node Q sends the Choke packet to P, (c) Choke packet reaches P, (d) P reduces the flow and send a reduced flow out, (e) Reduced flow reaches node Q

Hop-by Hop Choke Packets

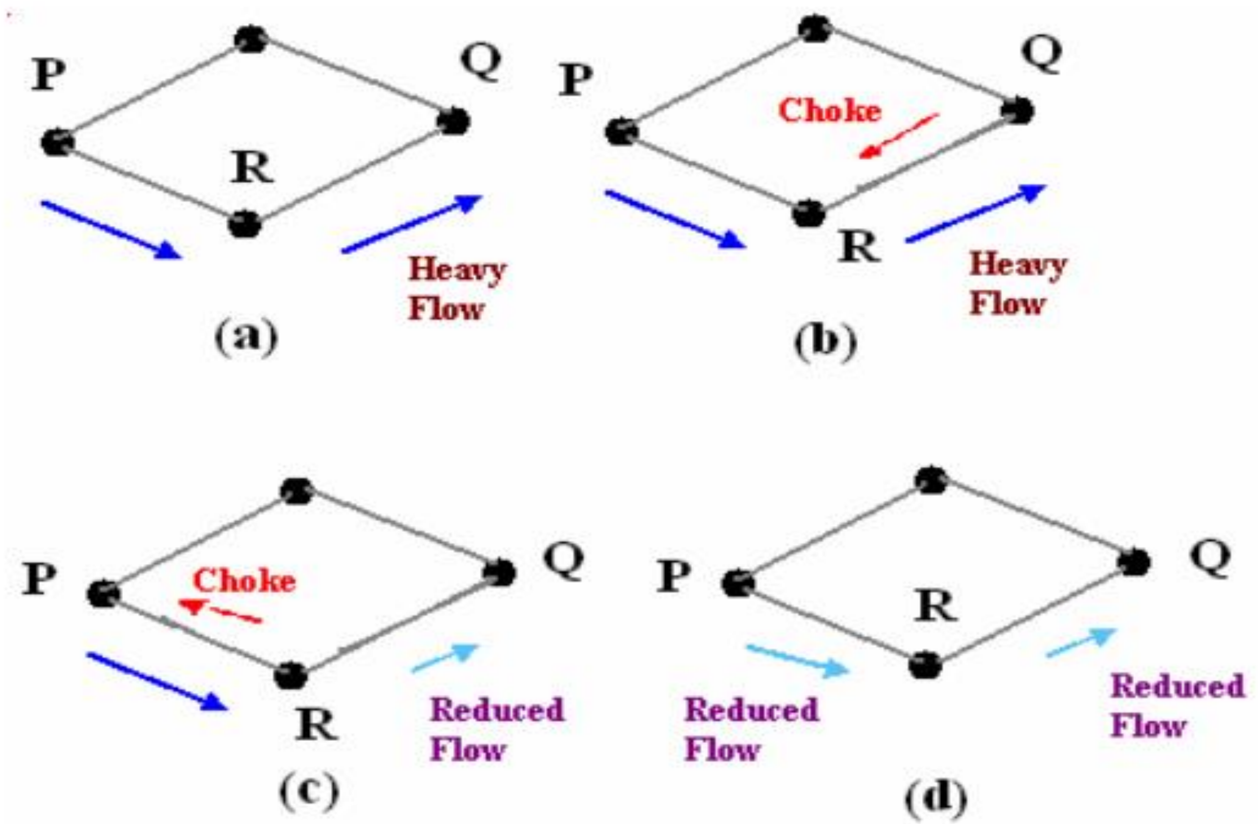


Figure 7.5.7 Depicts the functioning of Hop-by-Hop choke packets, (a) Heavy traffic between nodes P and Q, (b) Node Q sends the Choke packet to P, (c) Choke packet reaches R, and the flow between R and Q is curtail down, Choke packer reaches P, and P reduces the flow out

Quality of Service

- Application requirements
- Traffic shaping
- Packet scheduling
- Admission control
- Integrated services
- Differentiated services

Application Requirements (1)

Application	Bandwidth	Delay	Jitter	Loss
Email	Low	Low	Low	Medium
File sharing	High	Low	Low	Medium
Web access	Medium	Medium	Low	Medium
Remote login	Low	Medium	Medium	Medium
Audio on demand	Low	Low	High	Low
Video on demand	High	Low	High	Low
Telephony	Low	High	High	Low
Videoconferencing	High	High	High	Low

How stringent the quality-of-service requirements are.

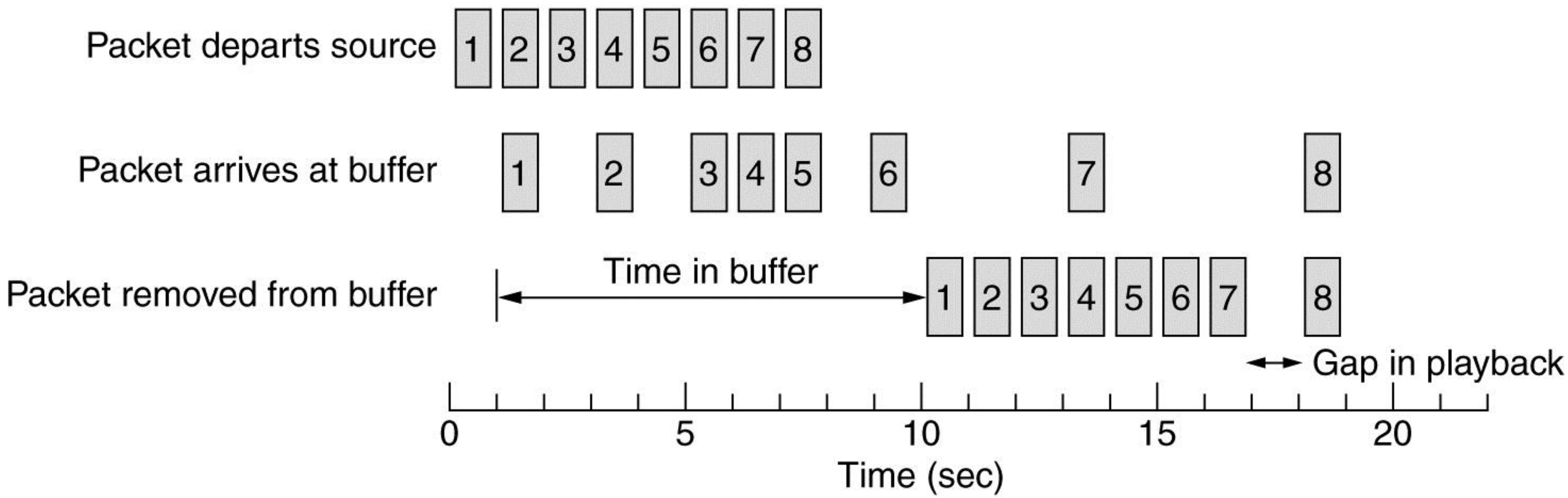
Categories of QoS and Examples

a) Constant bit rate
   - Telephony

b) Variable bit rate
   1. Real-time variable bit rate
      - Compressed videoconferencing
   2. Non-real-time variable bit rate
      - Watching a movie on demand

c) Available bit rate
   - File transfer

Buffering

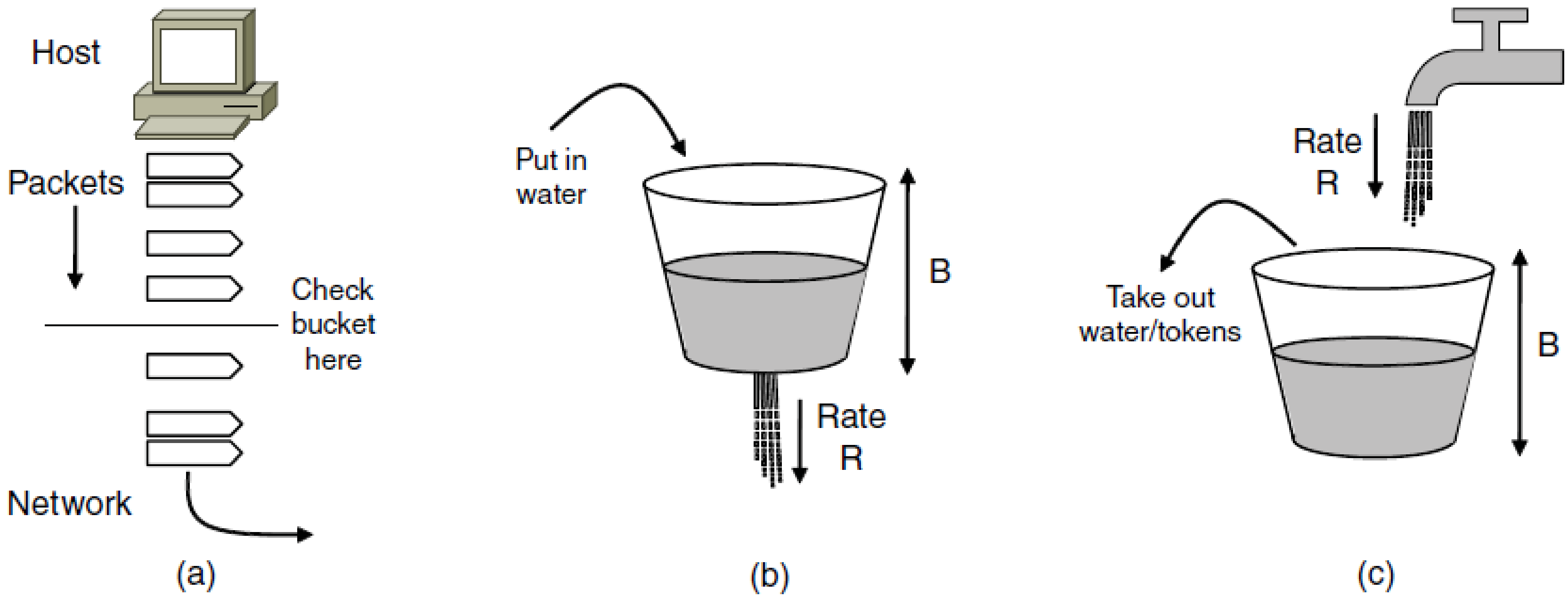


Smoothing the output stream by buffering packets.

Traffic Shaping

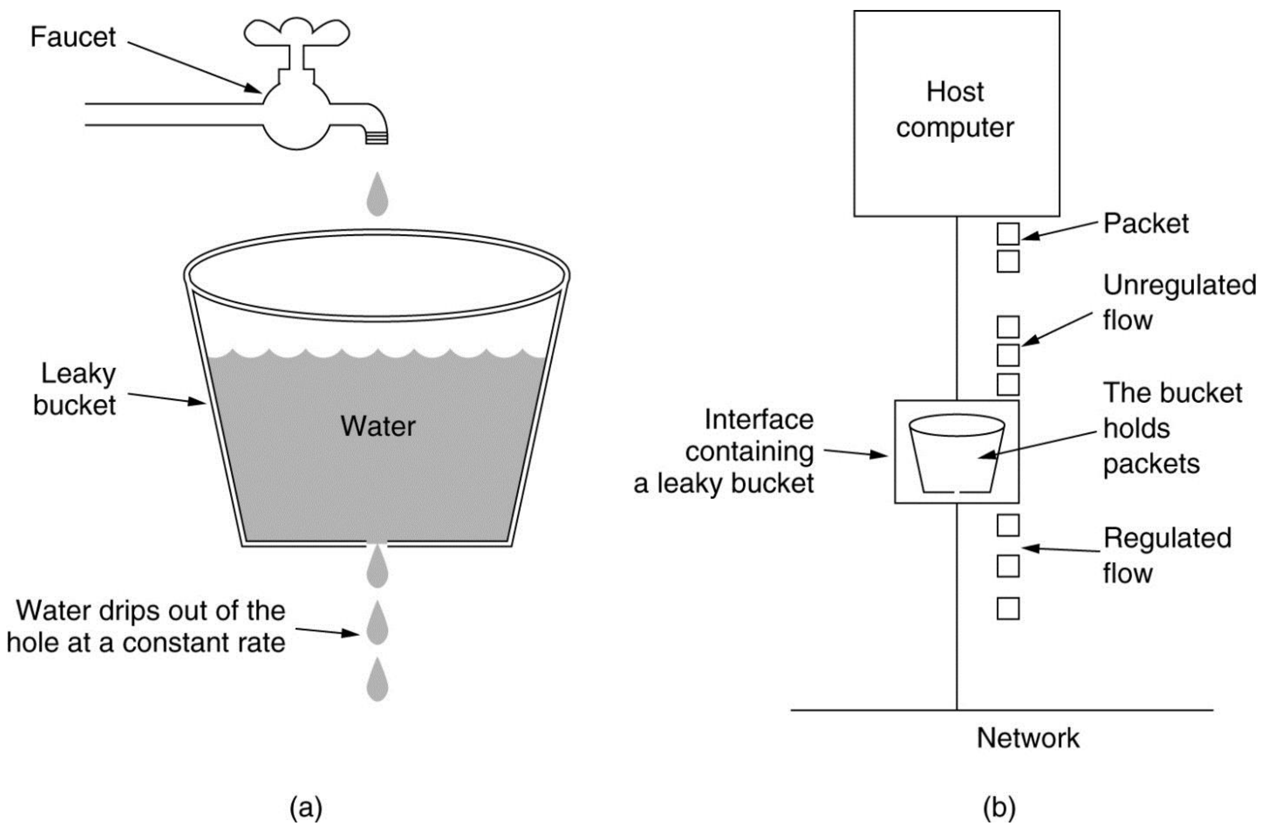
- Before the network can make QoS guarantees, it must know what traffic is being guaranteed
- In CBR, like telephone it is quite easy eg. needs 64 kbps
- **Traffic shaping** is a technique for regulating the average rate and burstiness of a flow of data that enters the network
- It allow applications to transmit a wide variety of traffic that suits their needs, including some bursts, yet have a simple and useful way to describe the possible traffic patterns to the network
- Traffic shaping reduces congestion and thus helps the network live up to its promise
- **SLA** (**Service Level Agreement**), is made over aggregate flows and long periods of time
- Monitoring a traffic flow is called **traffic policing**

Traffic Shaping (1)



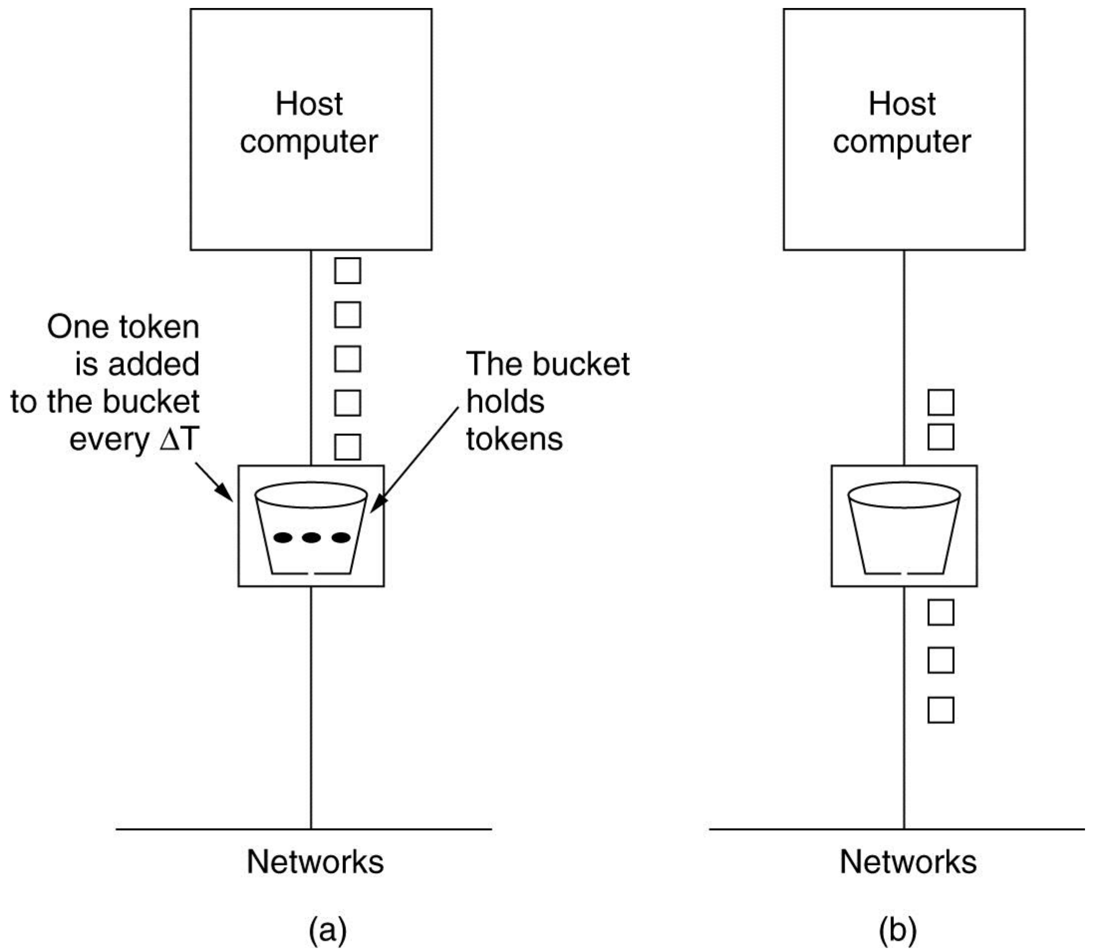
(a) Shaping packets. (b) A leaky bucket. (c) A token bucket

The Leaky Bucket Algorithm



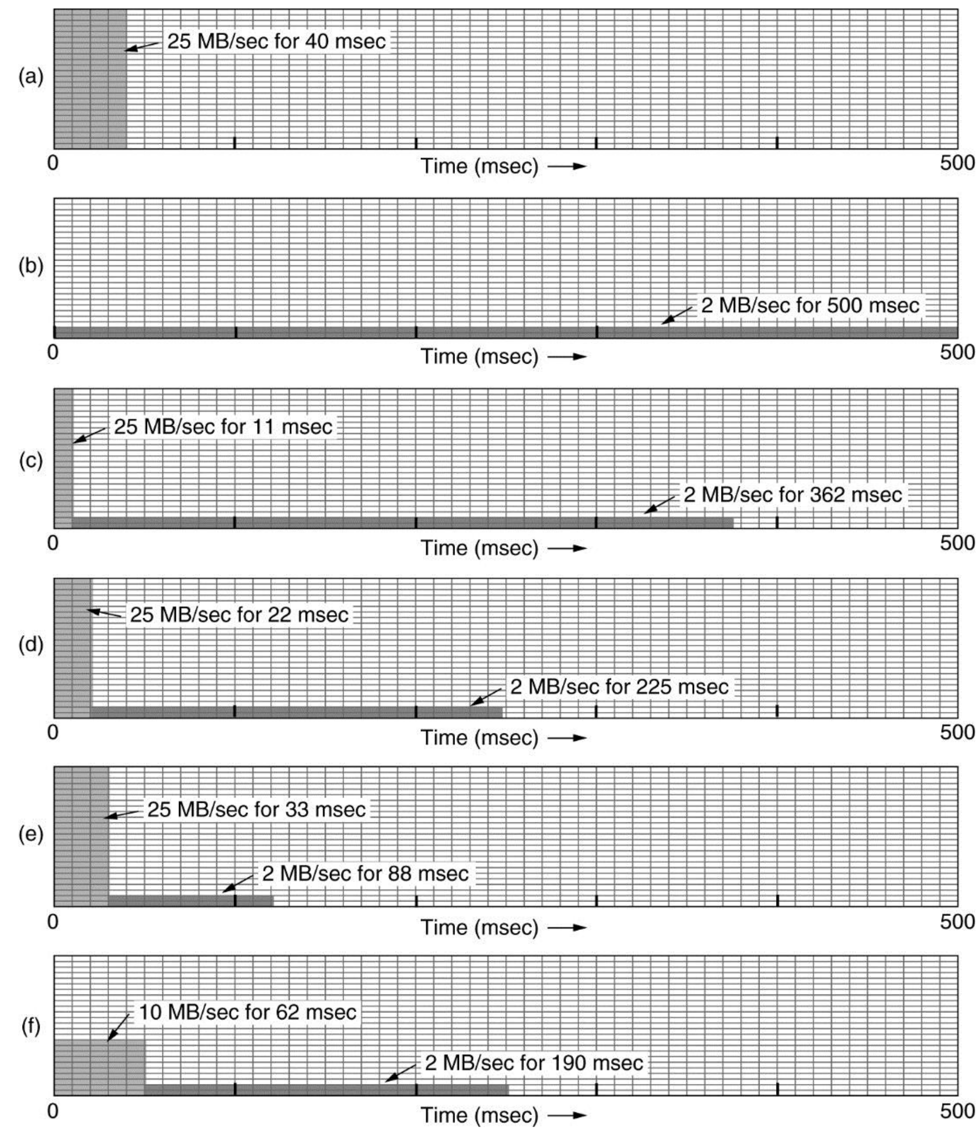
(a) A leaky bucket with water. (b) a leaky bucket with packets.

The Token Bucket Algorithm



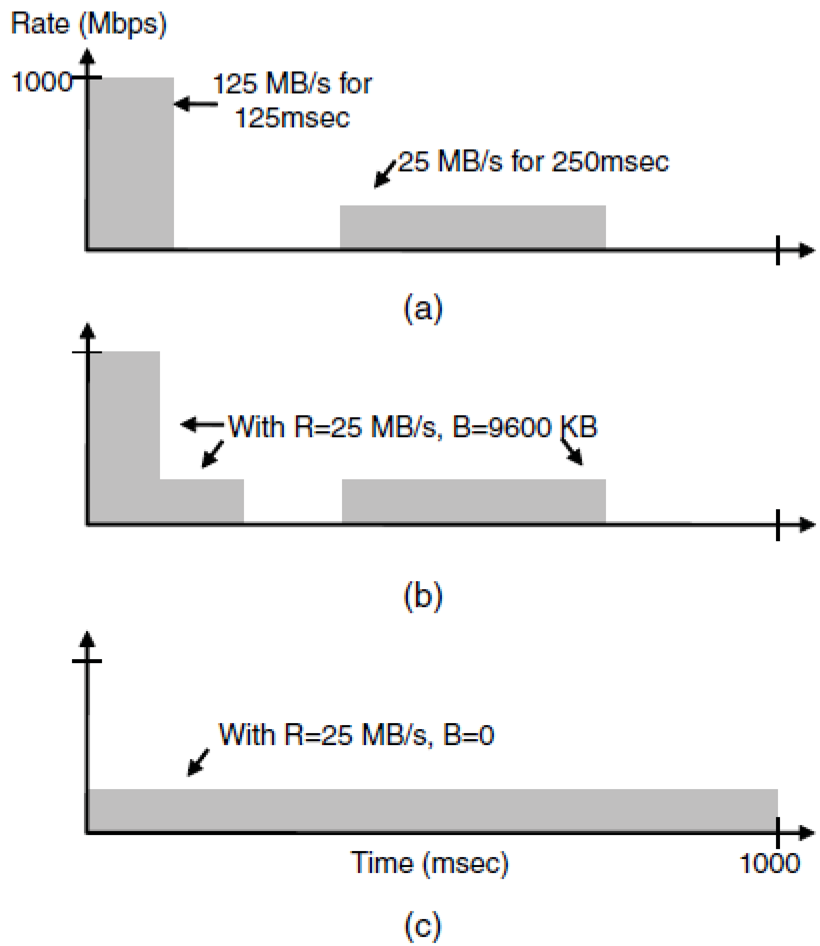
(a) Before. (b) After.

The Leaky Bucket Algorithm



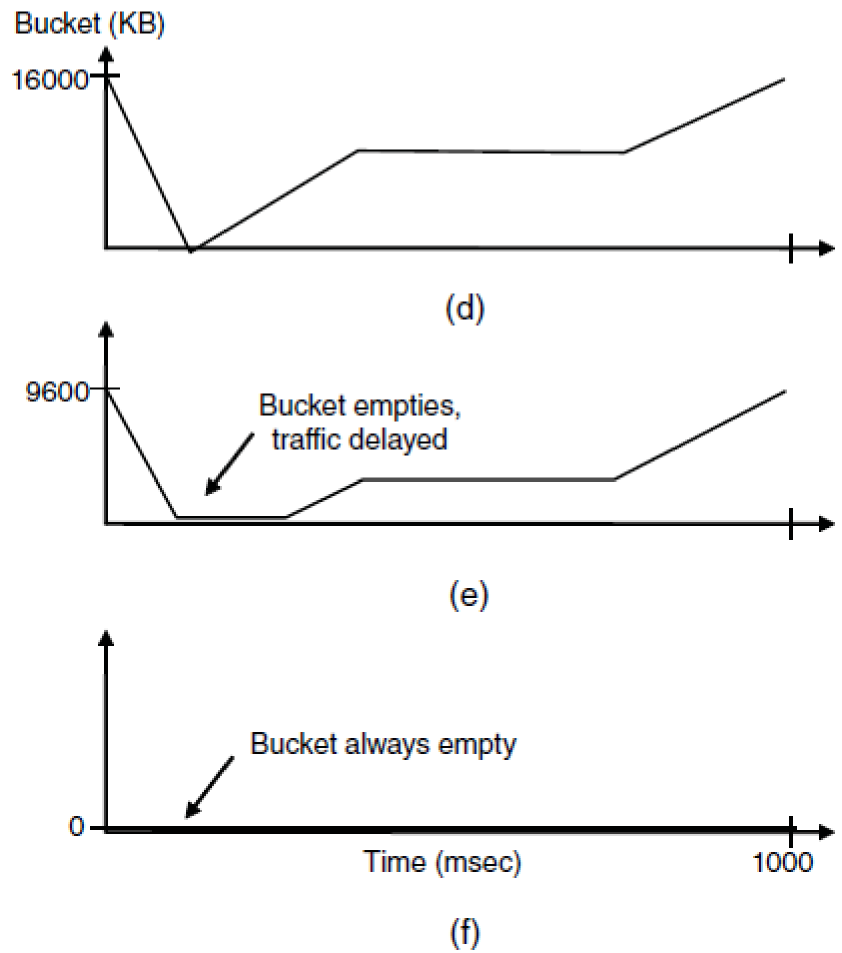
(a) Input to a leaky bucket. (b) Output from a leaky bucket. Output from a token bucket with capacities of (c) 250 KB, (d) 500 KB, (e) 750 KB, (f) Output from a 500KB token bucket feeding a 10-MB/sec leaky bucket.

Traffic Shaping (2)



(a) Traffic from a host. Output shaped by a token bucket of rate 200 Mbps and capacity (b) 9600 KB, (c) 0 KB.

Traffic Shaping (3)



Token bucket level for shaping with rate 200 Mbps and capacity (d) 16000 KB, (e) 9600 KB, and (f) 0KB..

Traffic Shaping

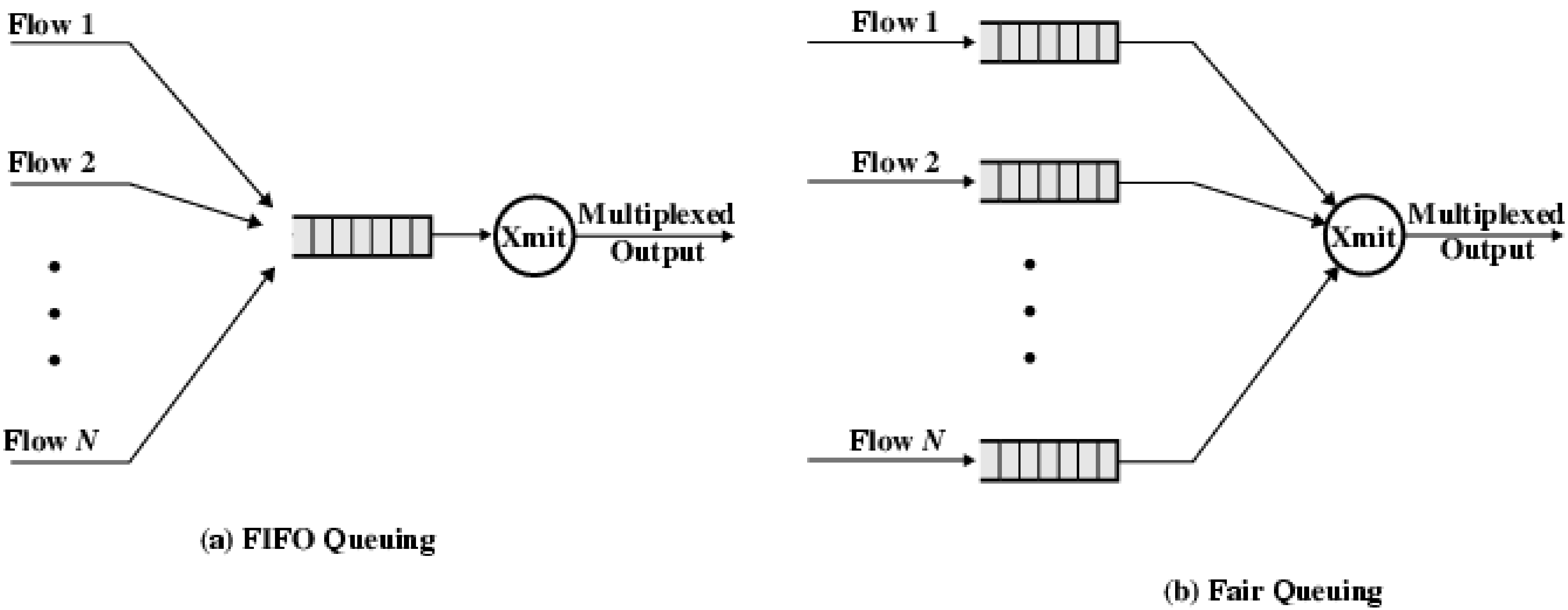
- Calculate the length of the maximum burst
- If burst length is S sec., the maximum output rate M bytes/sec, the token bucket capacity B bytes, and the token arrival rate R bytes/sec, the output burst contains a maximum of $B + RS$ bytes which gets transferred at M bytes/sec for S sec
- $B + RS = MS$ or $S = B/(M-R)$

Packet Scheduling

Kinds of resources can potentially be reserved for different flows:

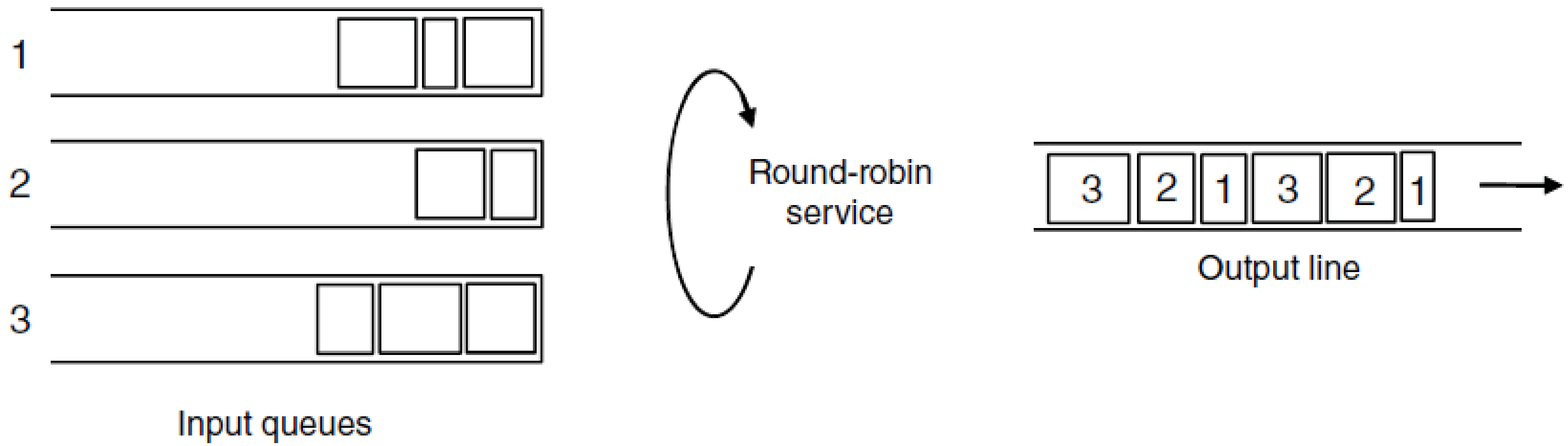
- Bandwidth.
- Buffer space.
- CPU cycles.

Packet Scheduling



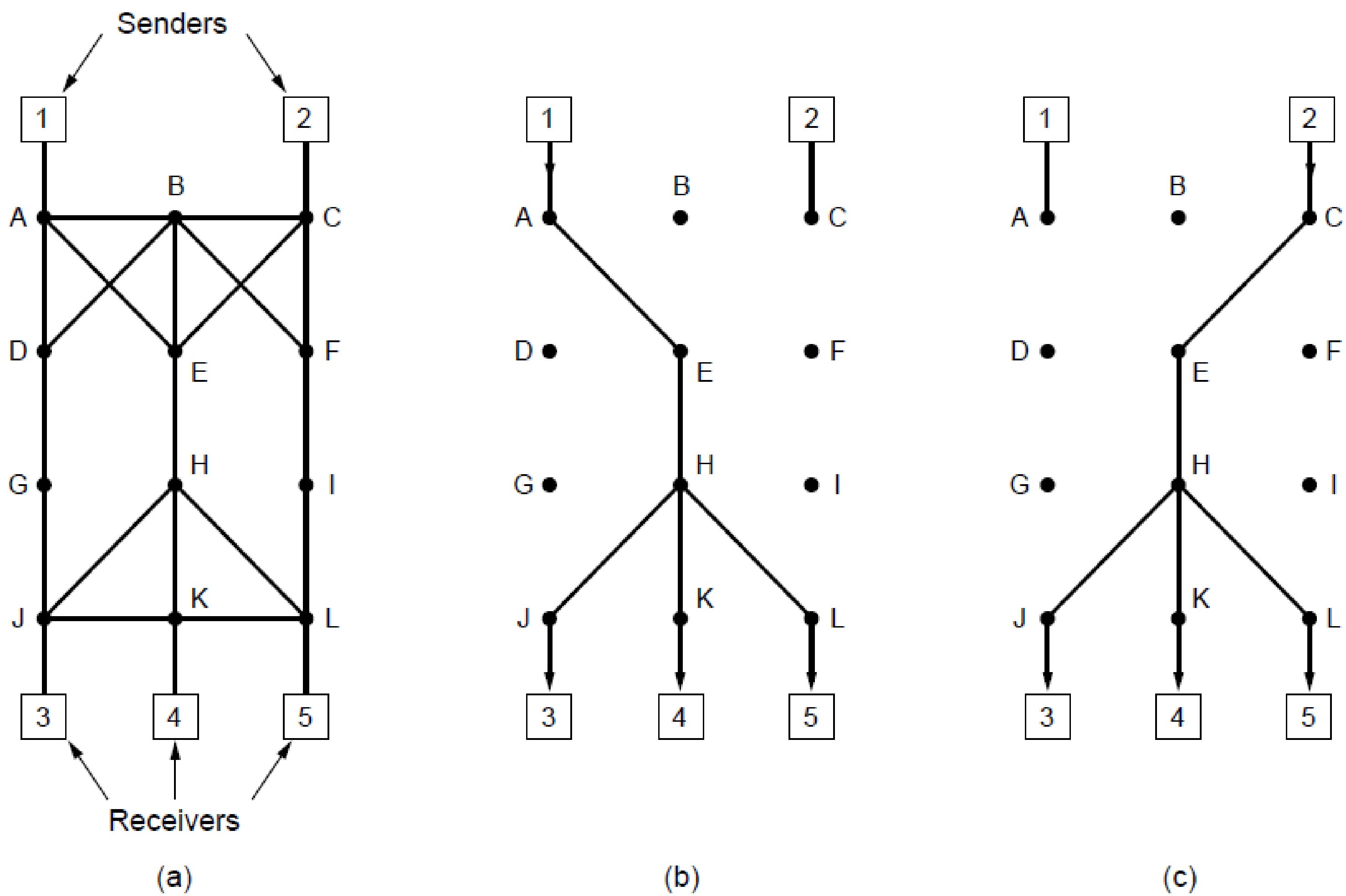
Computer Networks, Fifth Edition by Andrew Tanenbaum and David Wetherall, © Pearson Education-Prentice Hall, 2011

Packet Scheduling



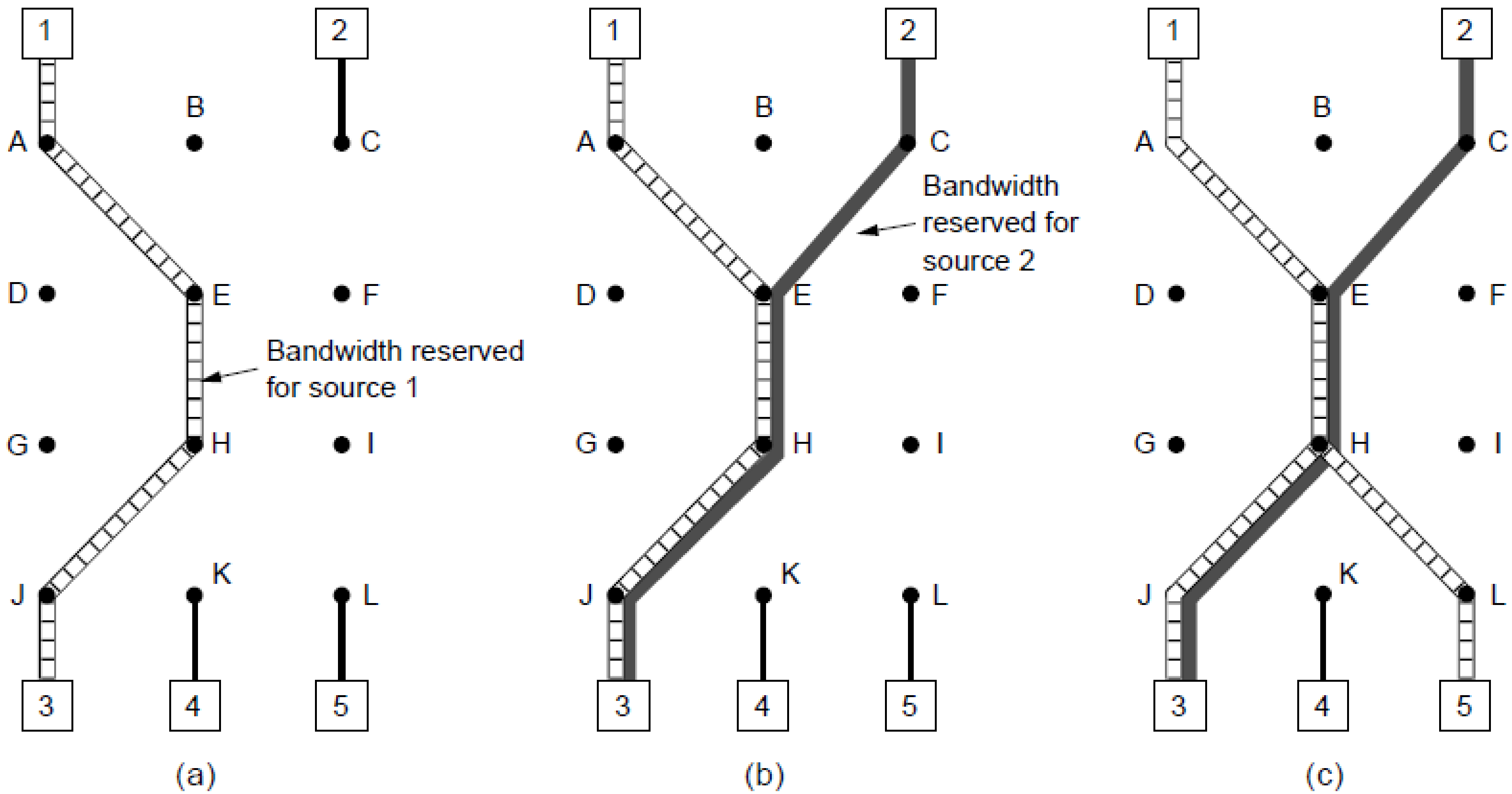
Round-robin Fair Queuing

Integrated Services (1)



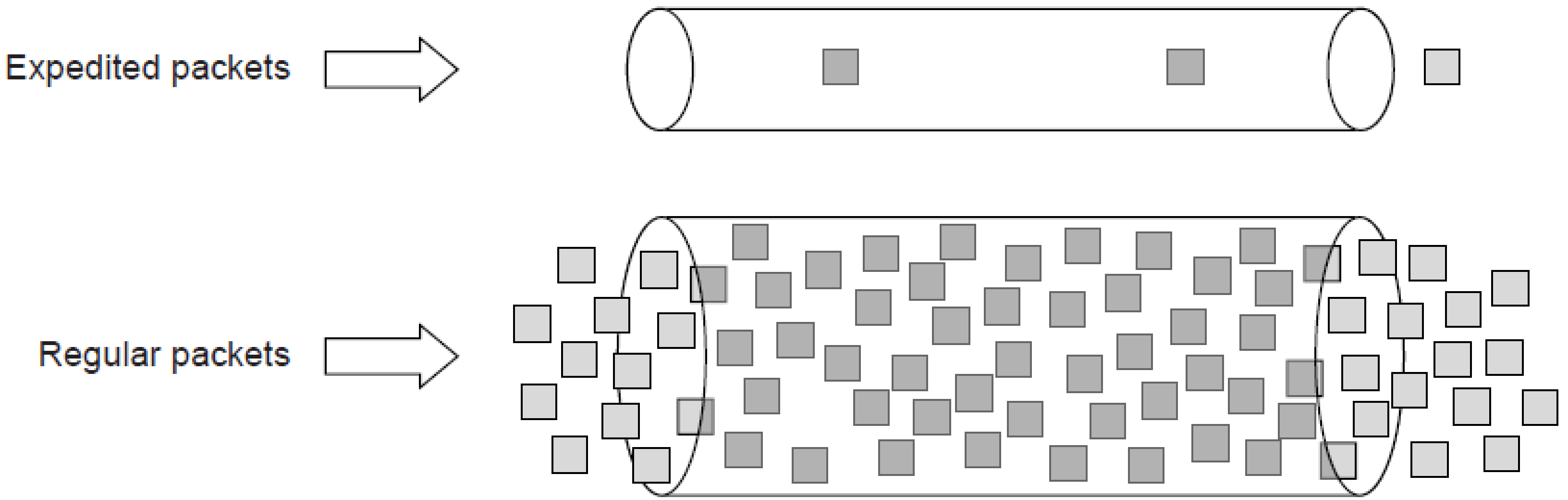
(a) A network. (b) The multicast spanning tree for host 1. (c) The multicast spanning tree for host 2.

Integrated Services (2)



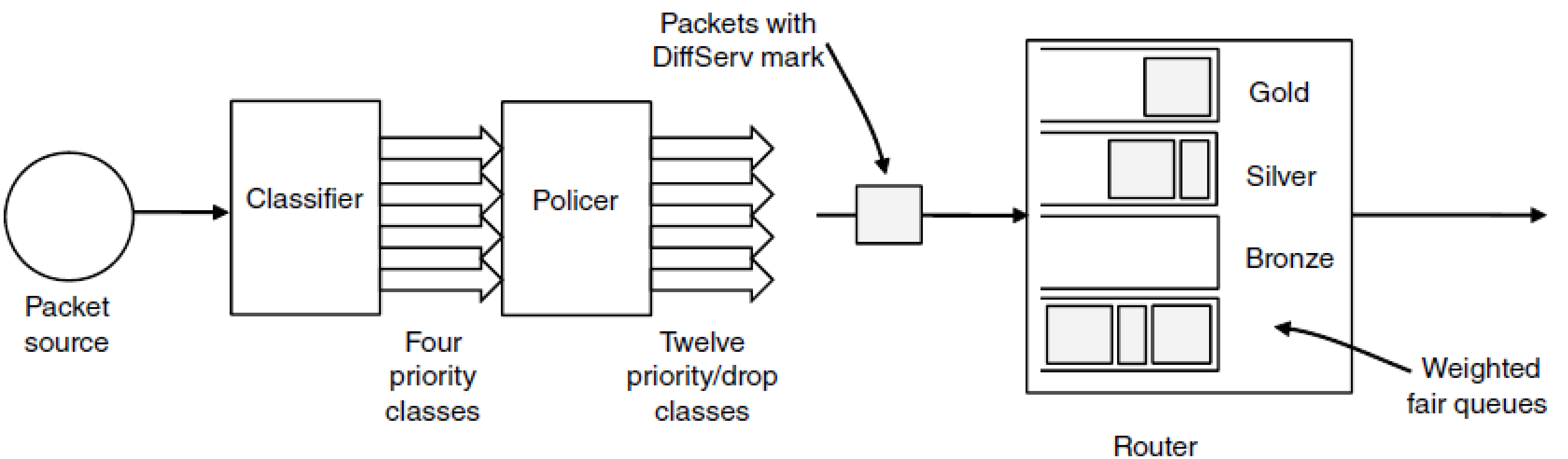
(a) Host 3 requests a channel to host 1. (b) Host 3 then requests a second channel, to host 2.
(c) Host 5 requests a channel to host 1.

Differentiated Services (1)



Expedited packets experience a traffic-free network

Differentiated Services (2)



A possible implementation of assured forwarding

Internetworking

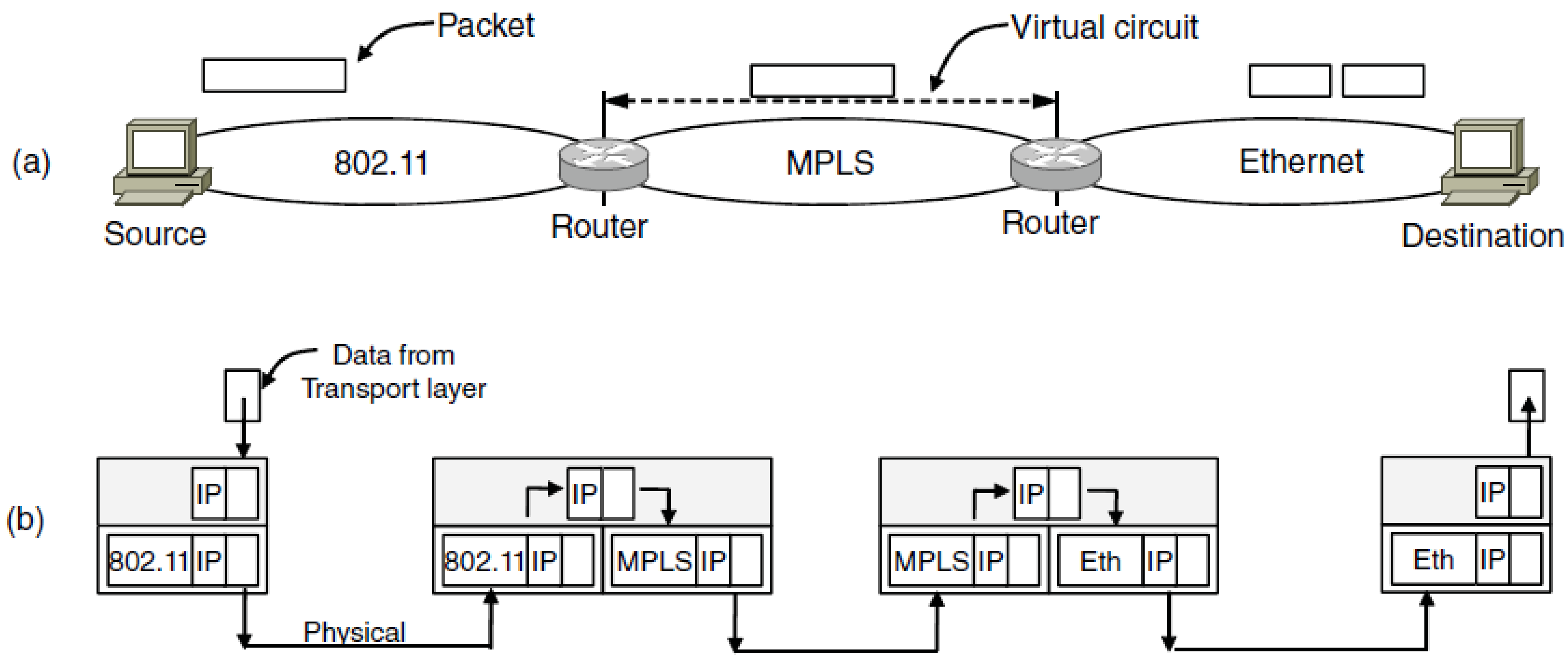
- How networks differ
- How networks can be connected
- Tunneling
- Internetwork routing
- Packet fragmentation

How Networks Differ

Item	Some Possibilities
Service offered	Connectionless versus connection oriented
Addressing	Different sizes, flat or hierarchical
Broadcasting	Present or absent (also multicast)
Packet size	Every network has its own maximum
Ordering	Ordered and unordered delivery
Quality of service	Present or absent; many different kinds
Reliability	Different levels of loss
Security	Privacy rules, encryption, etc.
Parameters	Different timeouts, flow specifications, etc.
Accounting	By connect time, packet, byte, or not at all

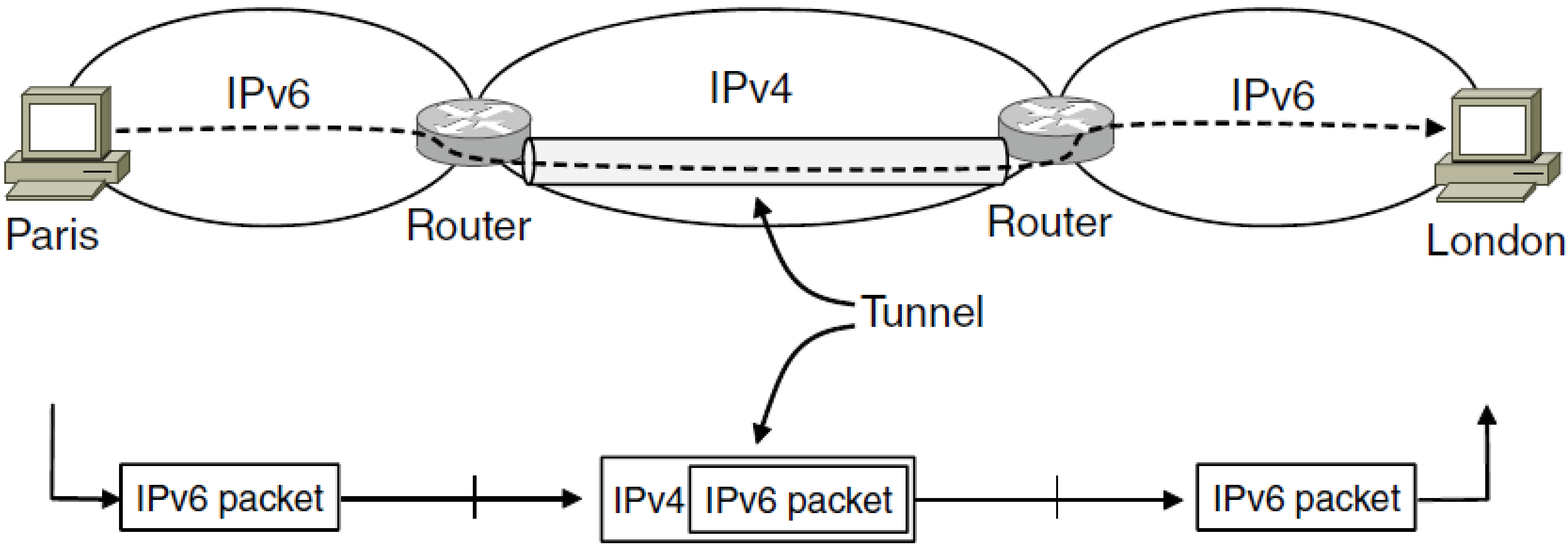
Some of the many ways networks can differ

How Networks Can Be Connected



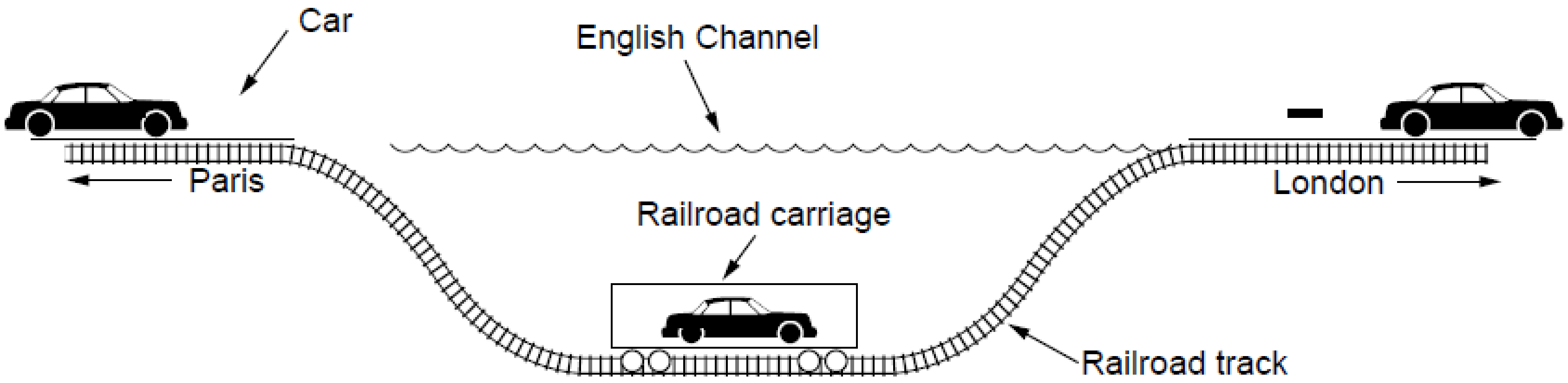
a) A packet crossing different networks.
b) Network and link layer protocol processing.

Tunneling (1)



Tunneling a packet from Paris to London.

Tunneling (2)



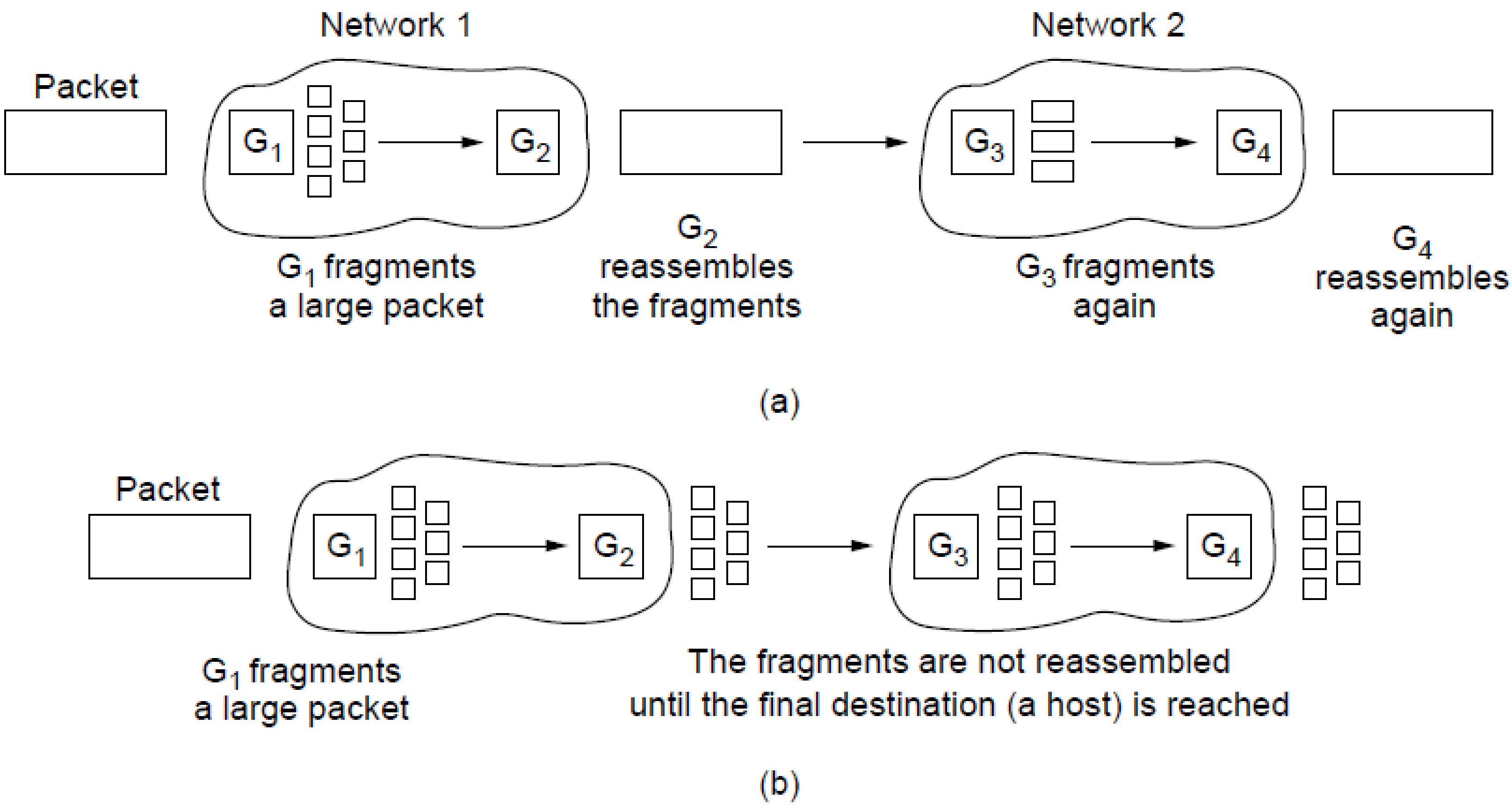
Tunneling a car from France to England

Packet Fragmentation (1)

Packet size issues:

- Hardware
- Operating system
- Protocols
- Compliance with (inter)national standard.
- Reduce error-induced retransmissions
- Prevent packet occupying channel too long.

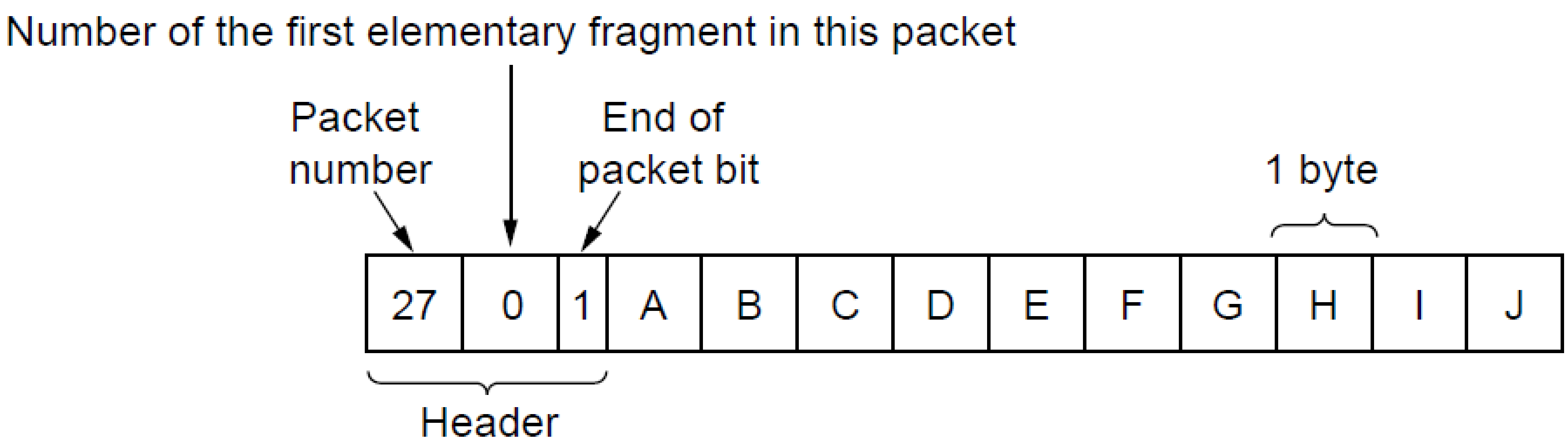
Packet Fragmentation (2)



a) Transparent fragmentation.

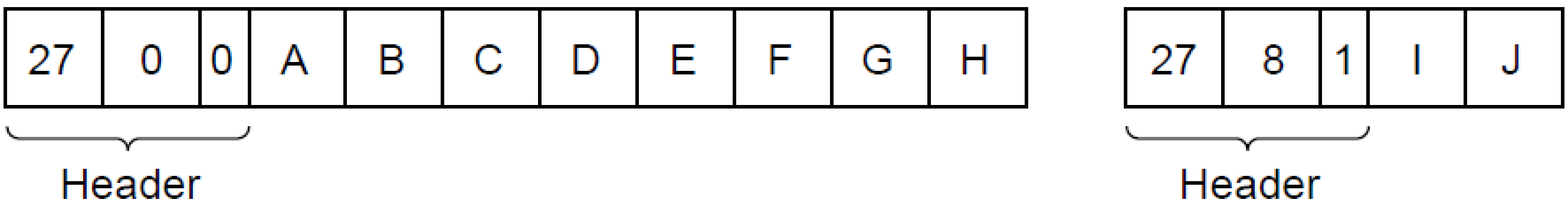
b) Nontransparent fragmentation

Packet Fragmentation (3)



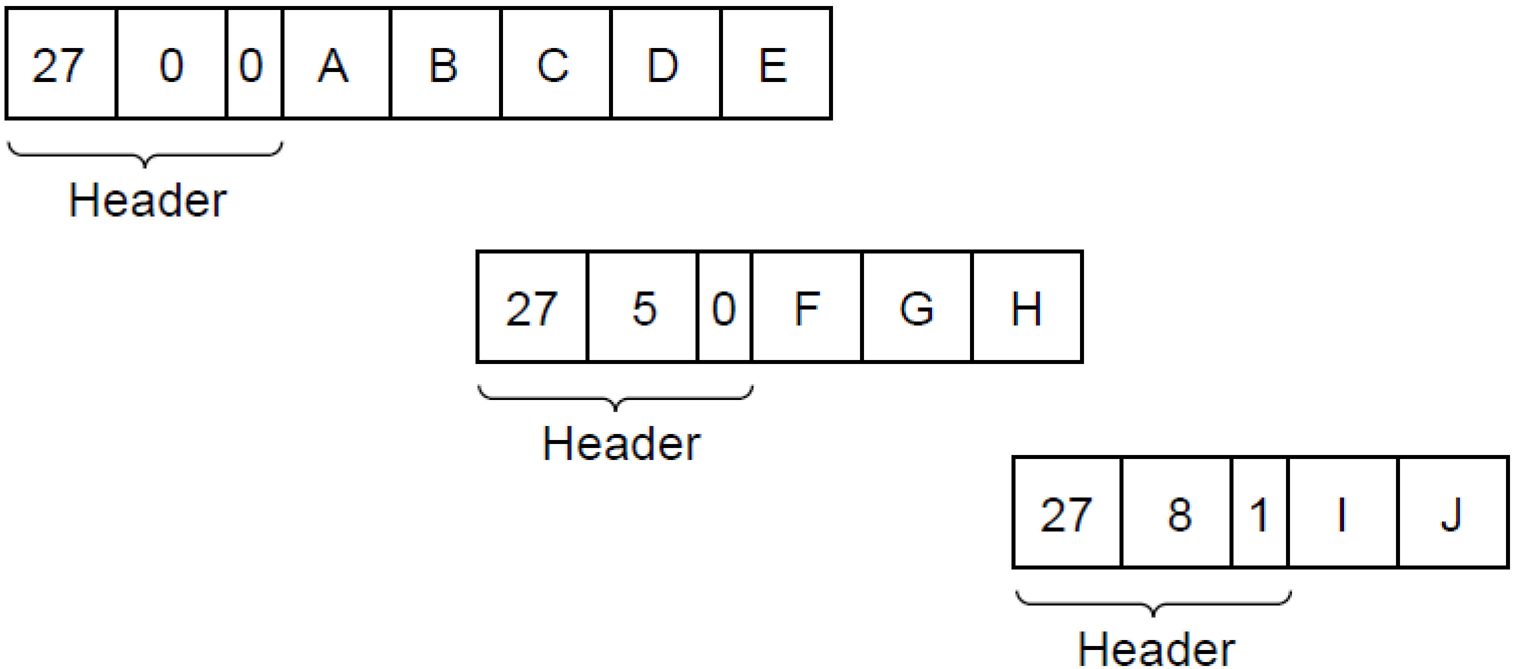
Fragmentation when the elementary data size is 1 byte.
(a) Original packet, containing 10 data bytes.

Packet Fragmentation (4)



Fragmentation when the elementary data size is 1 byte
(b) Fragments after passing through a network
with maximum packet size of 8 payload bytes plus header.

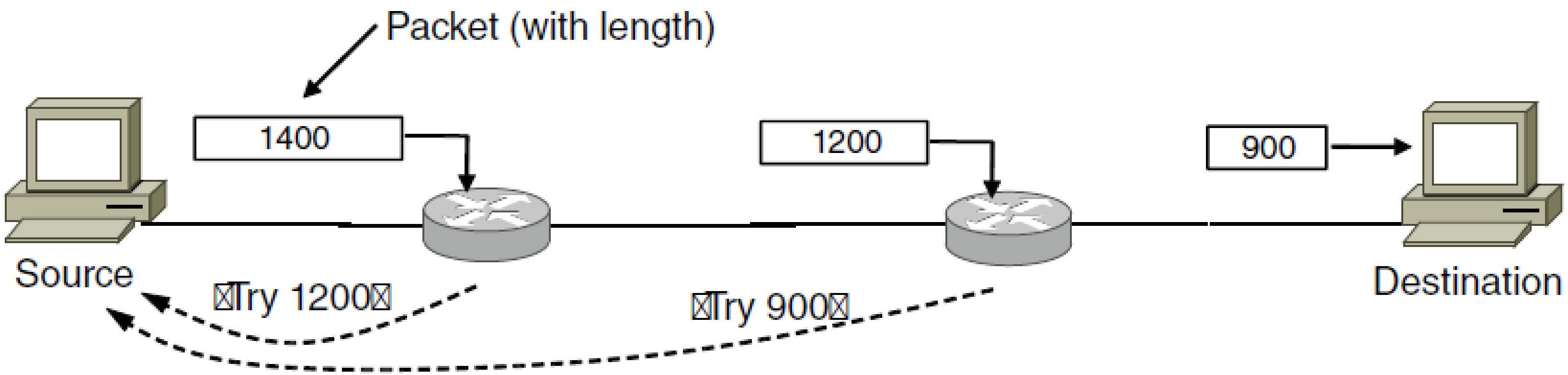
Packet Fragmentation (5)



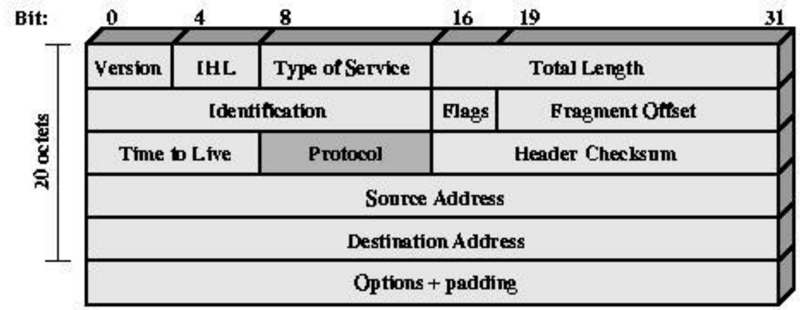
Fragmentation when the elementary data size is 1 byte

(c) Fragments after passing through a size 5 gateway.

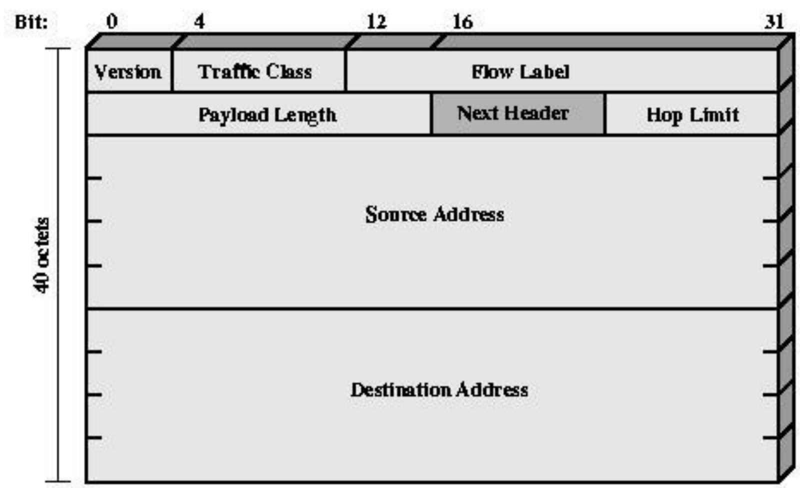
Packet Fragmentation (6)



Path MTU Discovery



(a) IPv4 Header



(b) IPv6 Header

Figure 2.2 IP Headers

Fragmentation and Reassembly

a) Networks may have different maximum packet size
b) Router may need to fragment datagrams before sending to next network
c) Fragments may need further fragmenting in later networks
d) Reassembly done only at final destination since fragments may take different routes

Fragmentation and Reassembly

a) If Reassembly permitted at intermediate routers
   - Large buffers needed to store partial datagram
   - All fragment must pass thru same gateway

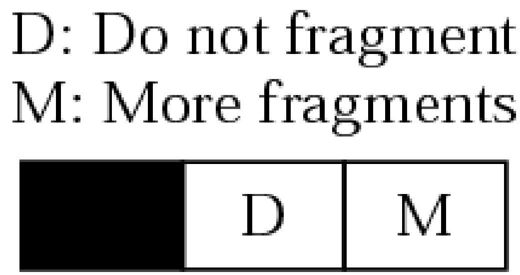
Fragmentation Example

MTUs for some networks

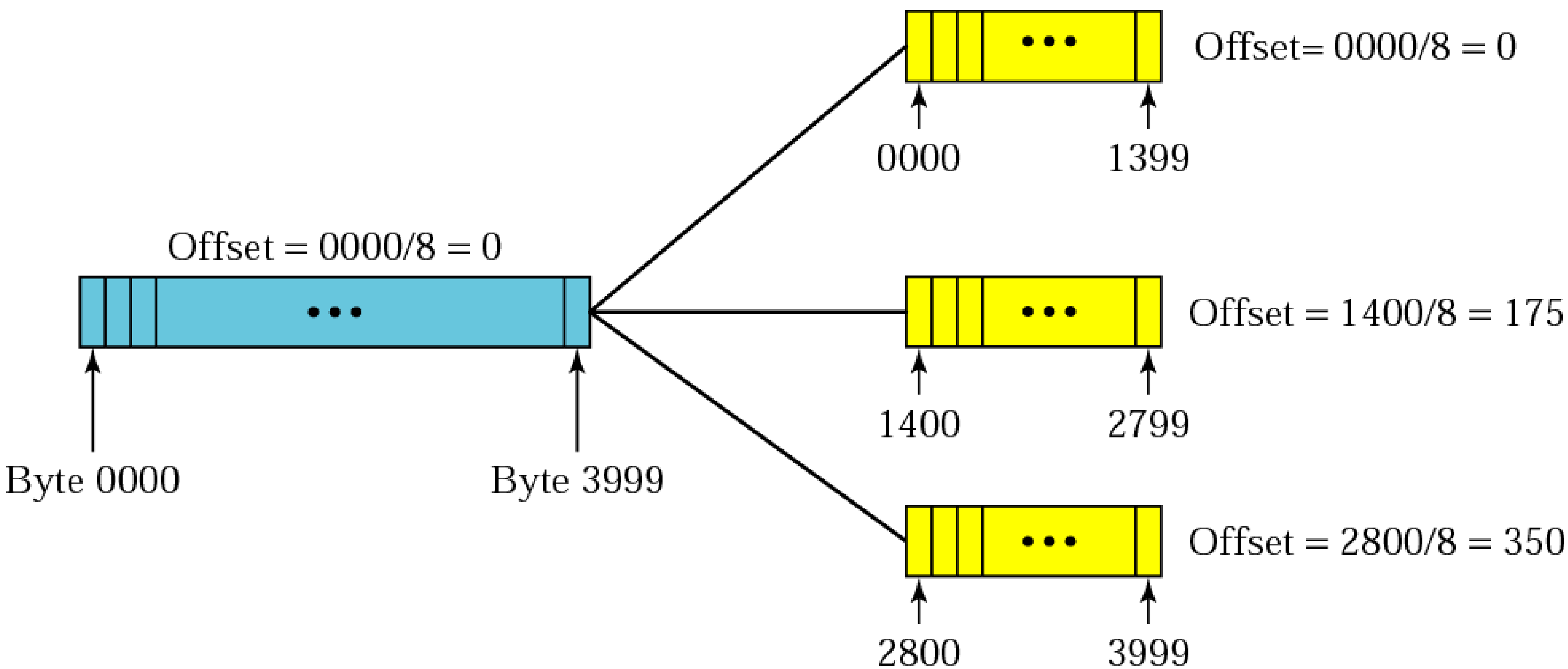
Protocol	*MTU*
Hyperchannel	65,535
Token Ring (16 Mbps)	17,914
Token Ring (4 Mbps)	4,464
FDDI	4,352
Ethernet	1,500
X.25	576
PPP	296

Fragmentation Example

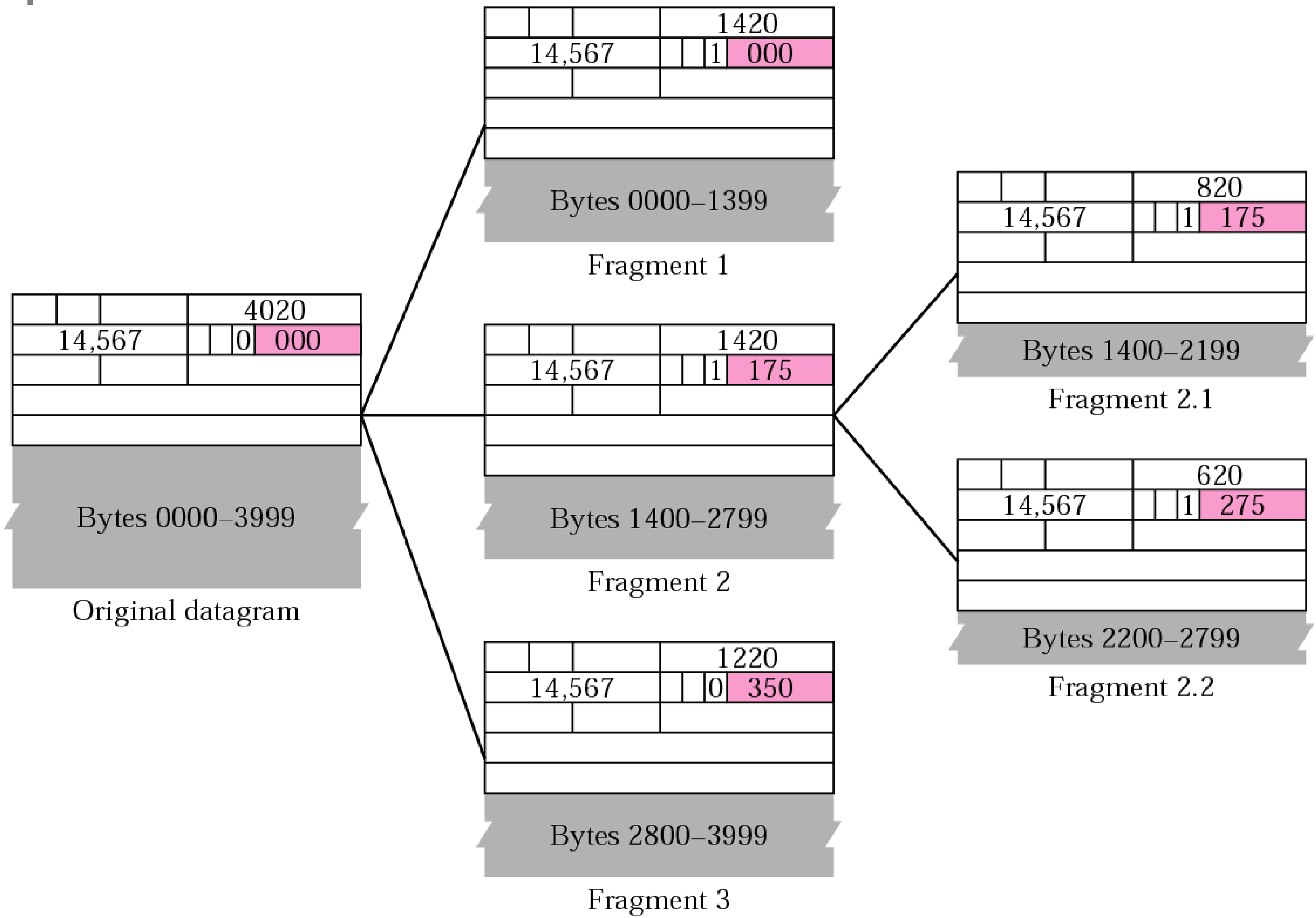
Flags field



Fragmentation Example



Fragmentation Example



The Network Layer Principles (1)

- Make sure it works
- Keep it simple
- Make clear choices
- Exploit modularity
- Expect heterogeneity

. . .

The Network Layer Principles (2)

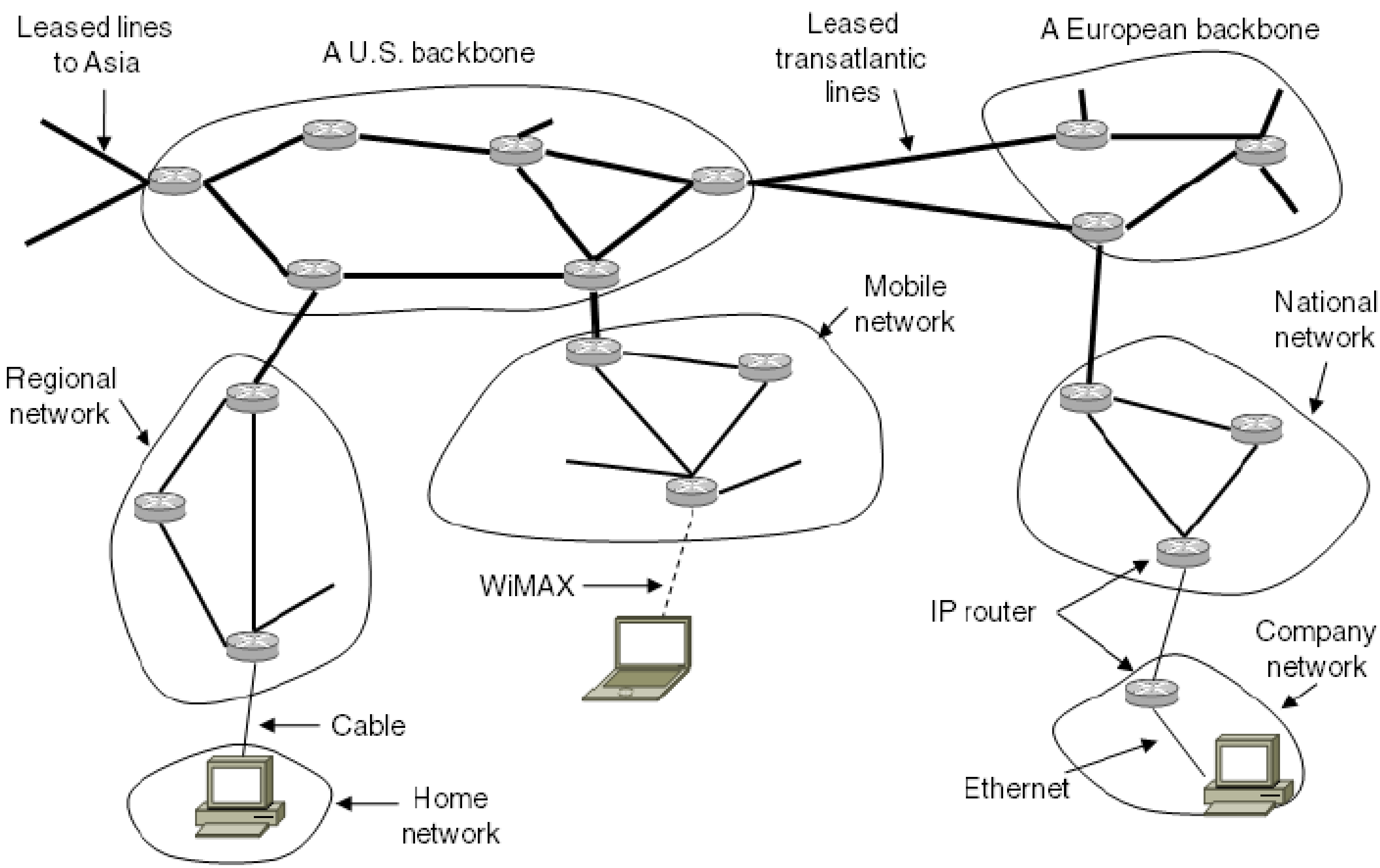
. . .

- Avoid static options and parameters
- Look for good design (not perfect)
- Strict sending, tolerant receiving
- Think about scalability
- Consider performance and cost

The Network Layer in the Internet (1)

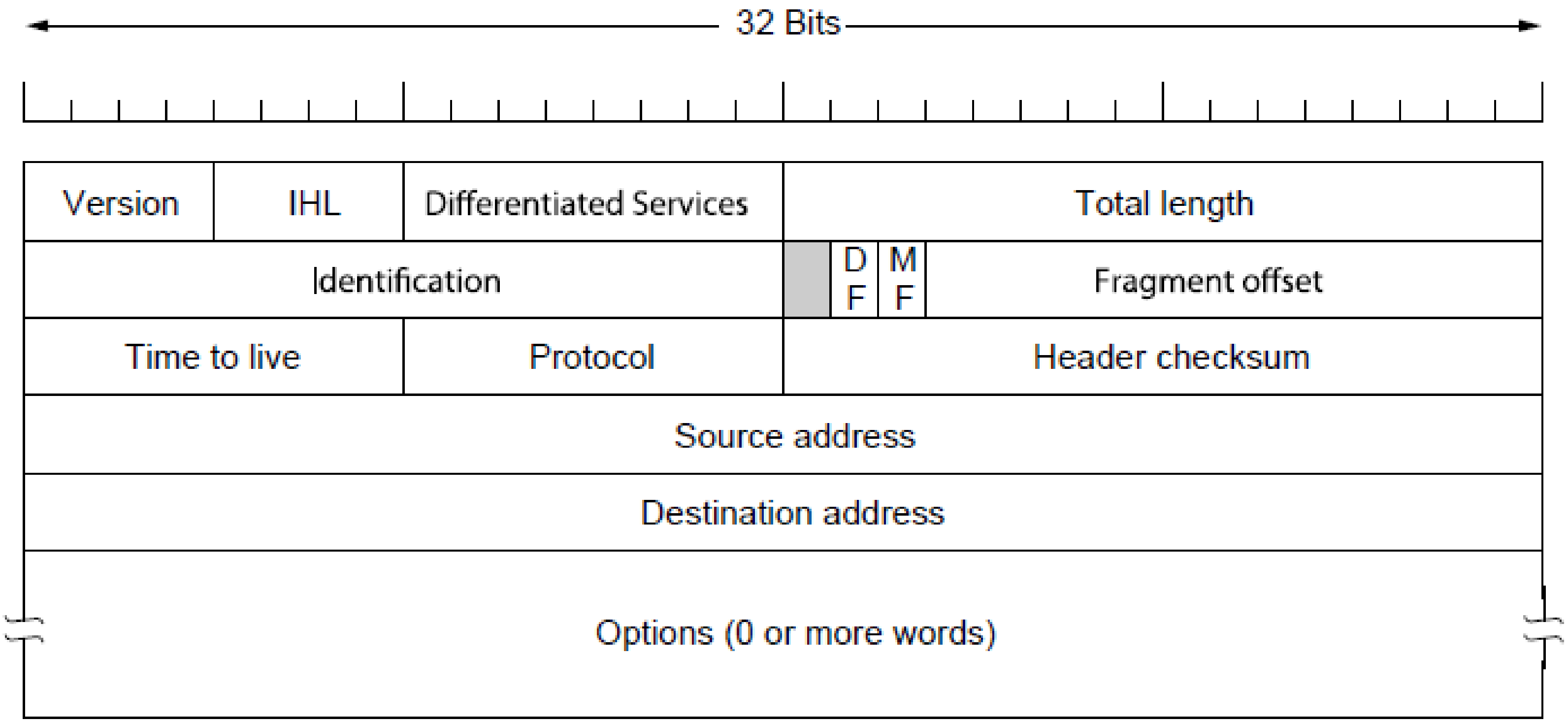
- The IP Version 4 Protocol
- IP Addresses
- IP Version 6
- Internet Control Protocols
- Label Switching and MPLS
- OSPF—An Interior Gateway Routing Protocol
- BGP—The Exterior Gateway Routing Protocol
- Internet Multicasting
- Mobile IP

The Network Layer in the Internet (2)



The Internet is an interconnected collection of many networks.

The IP Version 4 Protocol (1)



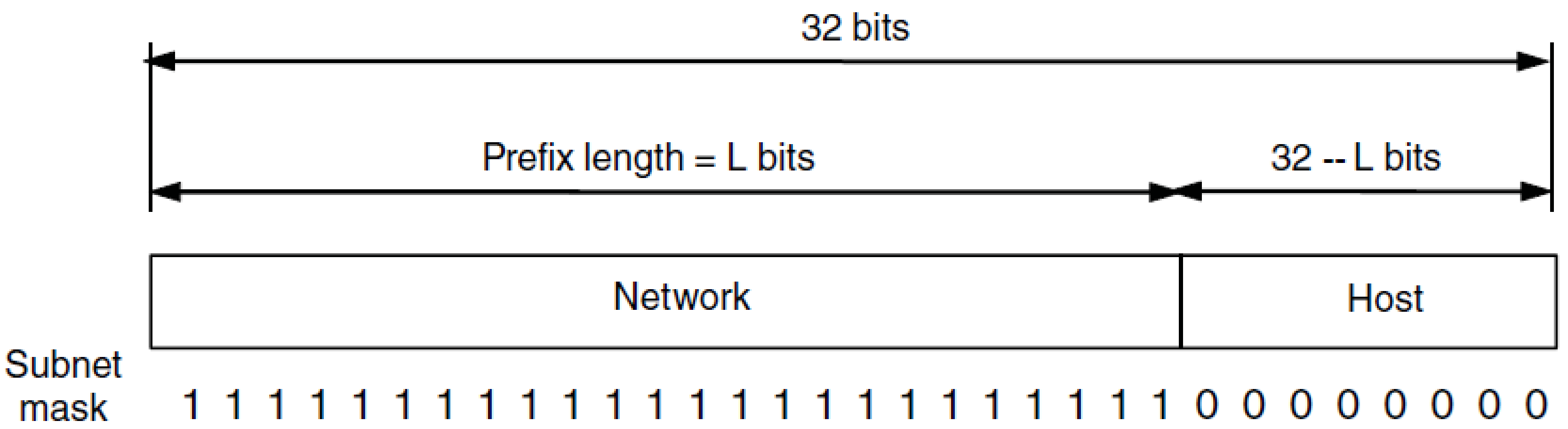
The IPv4 (Internet Protocol) header.

The IP Version 4 Protocol (2)

Option	Description
Security	Specifies how secret the datagram is
Strict source routing	Gives the complete path to be followed
Loose source routing	Gives a list of routers not to be missed
Record route	Makes each router append its IP address
Timestamp	Makes each router append its address and timestamp

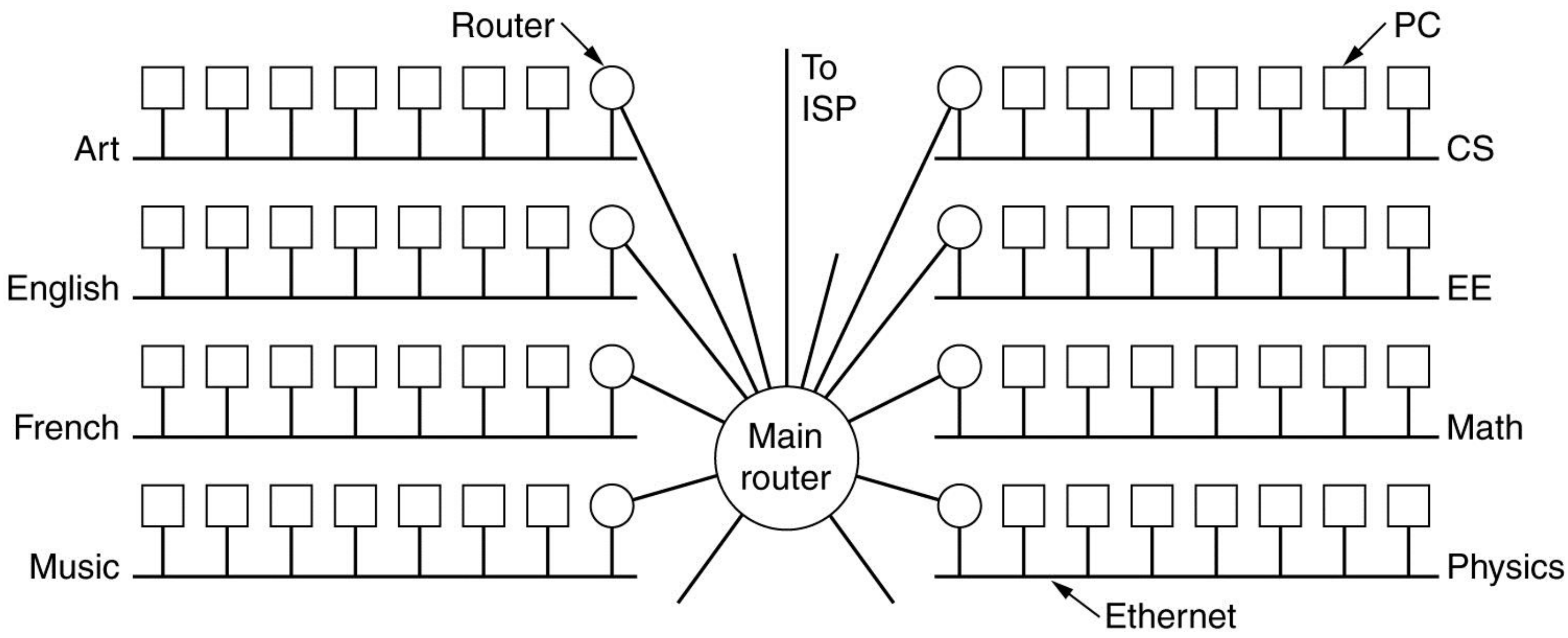
Some of the IP options.

IP Addresses (1)



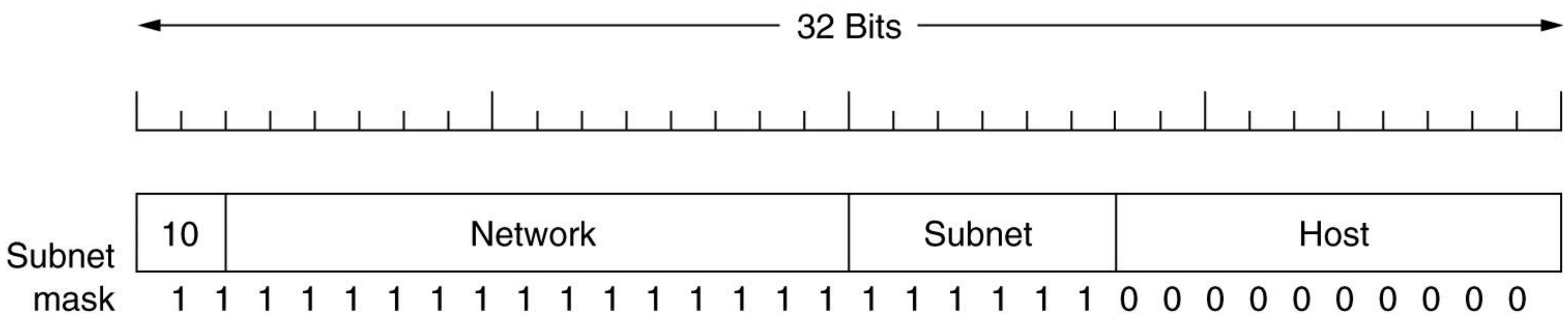
An IP prefix.

Subnets



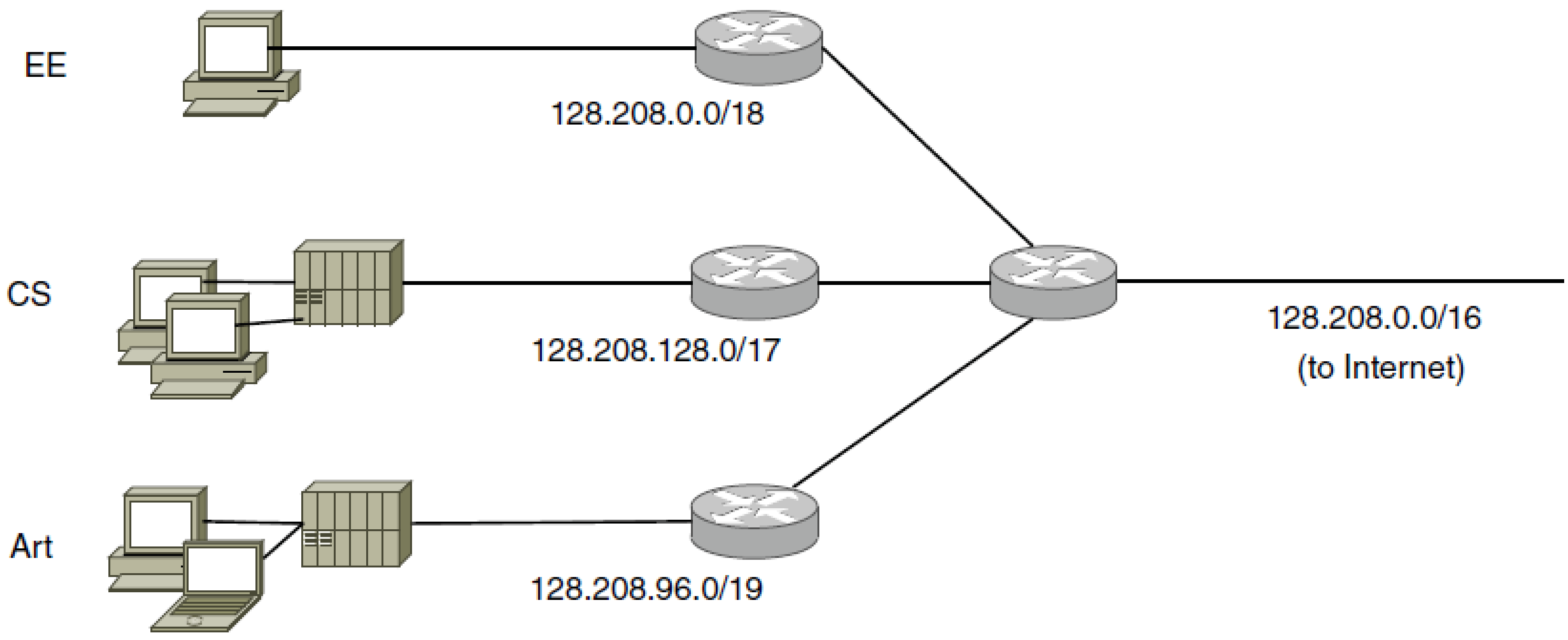
A campus network consisting of LANs for various departments.

Subnets (2)



A class B network subnetted into 64 subnets.

IP Addresses (2)



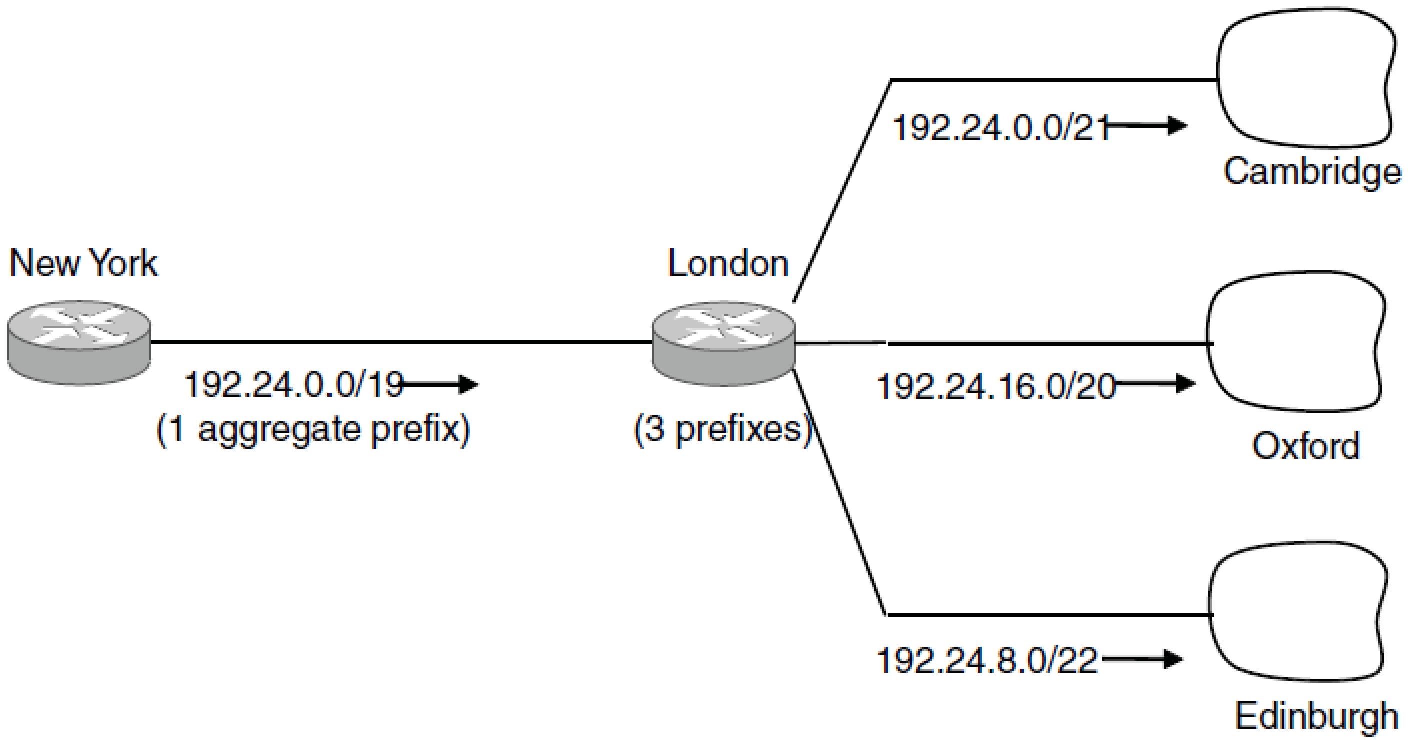
Splitting an IP prefix into separate networks with subnetting.

IP Addresses (3)

University	First address	Last address	How many	Prefix
Cambridge	194.24.0.0	194.24.7.255	2048	194.24.0.0/21
Edinburgh	194.24.8.0	194.24.11.255	1024	194.24.8.0/22
(Available)	194.24.12.0	194.24.15.255	1024	194.24.12/22
Oxford	194.24.16.0	194.24.31.255	4096	194.24.16.0/20

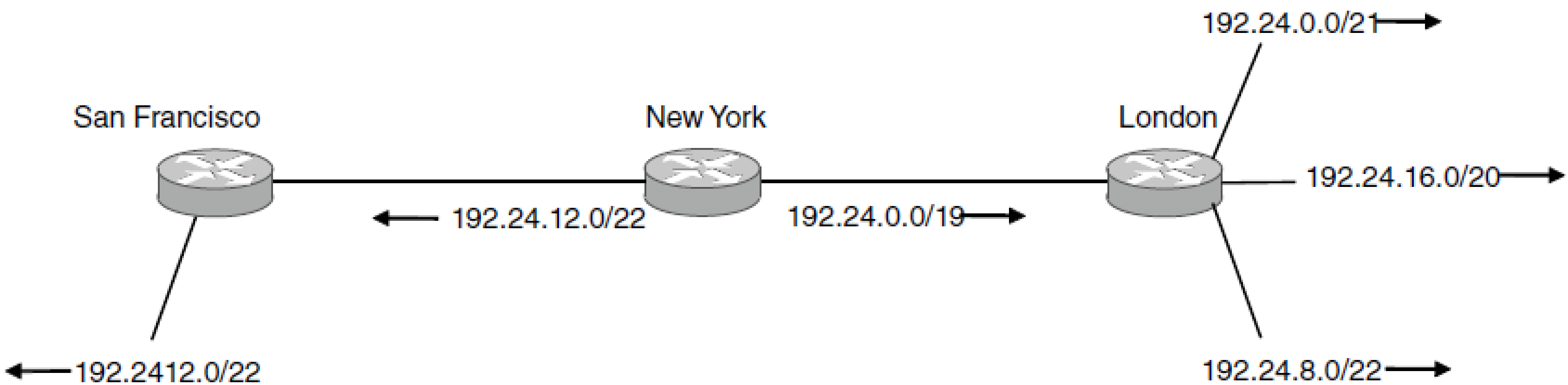
A set of IP address assignments

IP Addresses (4)



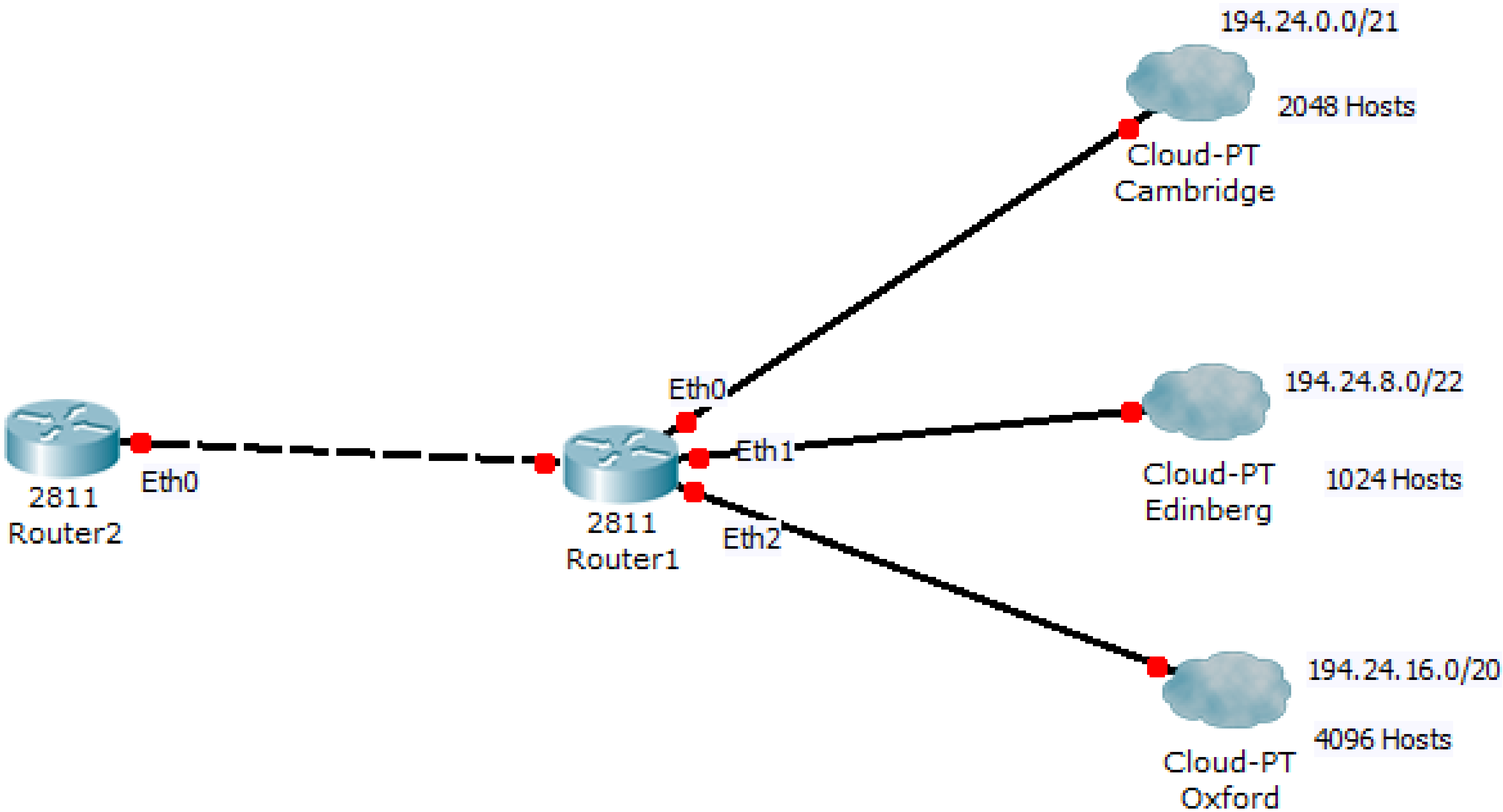
Aggregation of IP prefixes

IP Addresses (5)



Longest matching prefix routing at the New York router.

Network


194.24.0.0/21
2048 Hosts
Cloud-PT
Cambridge
Eth0
194.24.8.0/22
Eth1
Cloud-PT
Edinberg
1024 Hosts
2811
Router2
Eth0
2811
Router1
Eth2
194.24.16.0/20
4096 Hosts
Cloud-PT
Oxford

CDR – Classless InterDomain Routing

Routing Table at Router 1

	Address	Mask	Interface
Cambridge	194.24.0.0	21	Eth0
Edinberg	194.24.8.0	22	Eth1
Oxford	194.24.16.0	20	Eth2

Consider a packet with 194.24.17.4. Compare to all the entries and use longest matching entry

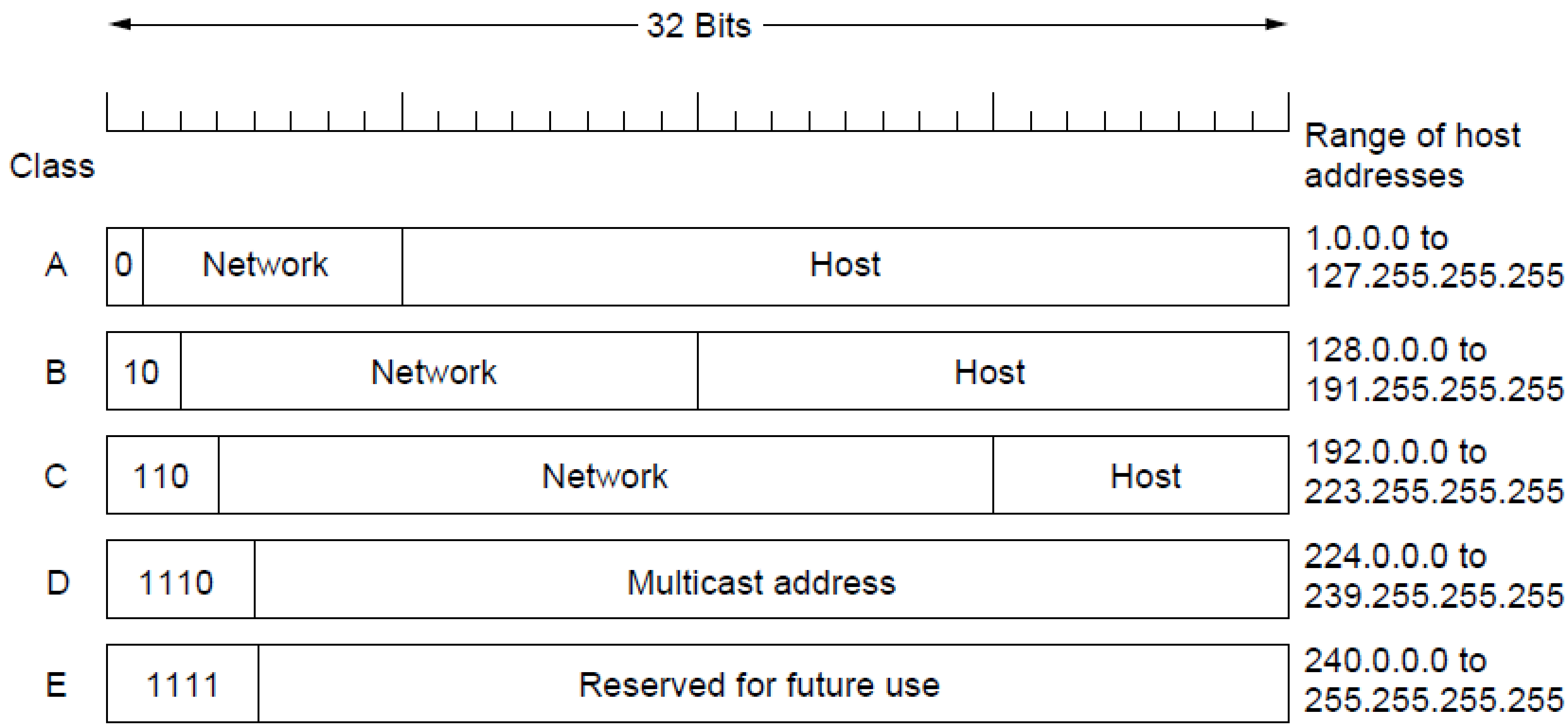
Routing Table at Router 2

	Address	Mask	Interface
Cambridge	194.24.0.0	21	Eth0
Edinberg	194.24.8.0	22	Eth0
Oxford	194.24.16.0	20	Eth0

Aggregated Routing Table at Router 2

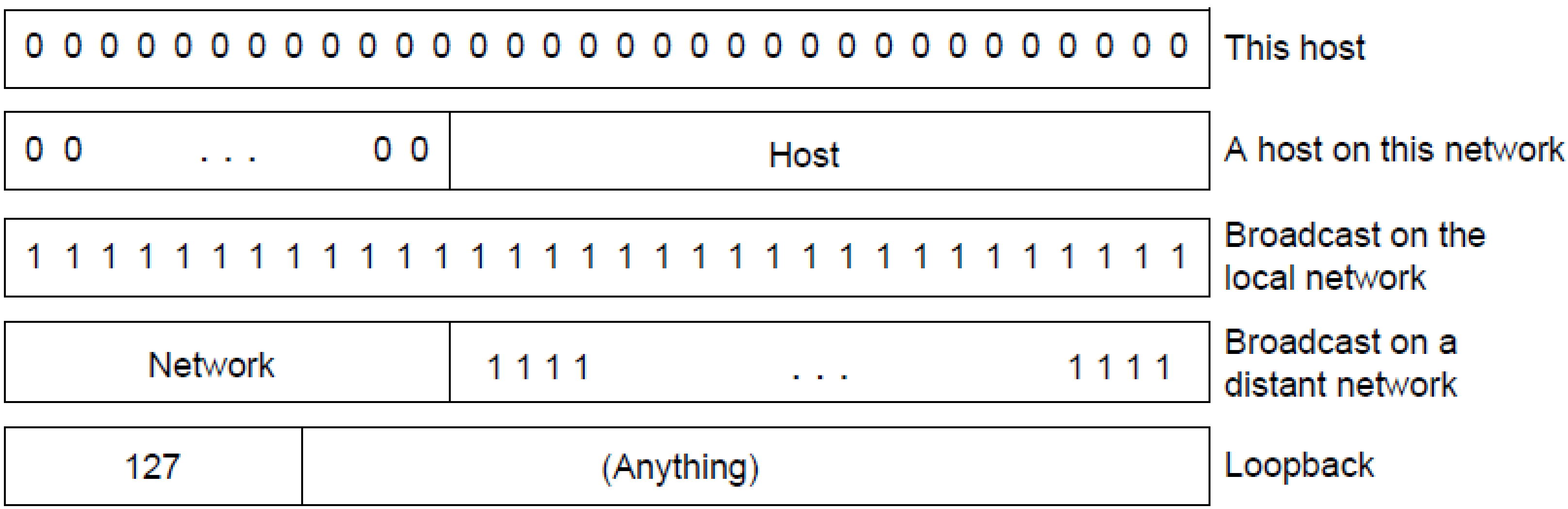
	Address	Mask	Interface
All	194.24.0.0	19	Eth0

IP Addresses (6)



IP address formats

IP Addresses (7)



Special IP addresses

The IPv4 Shortage

a) Problem: consumer ISPs typically only give one IP address per-household
   - Additional IPs cost extra
   - More IPs may not be available

b) Today's households have more networked devices than ever
   - Laptops and desktops
   - TV, bluray players, game consoles
   - Tablets, smartphones, eReaders

c) How to get all these devices online?

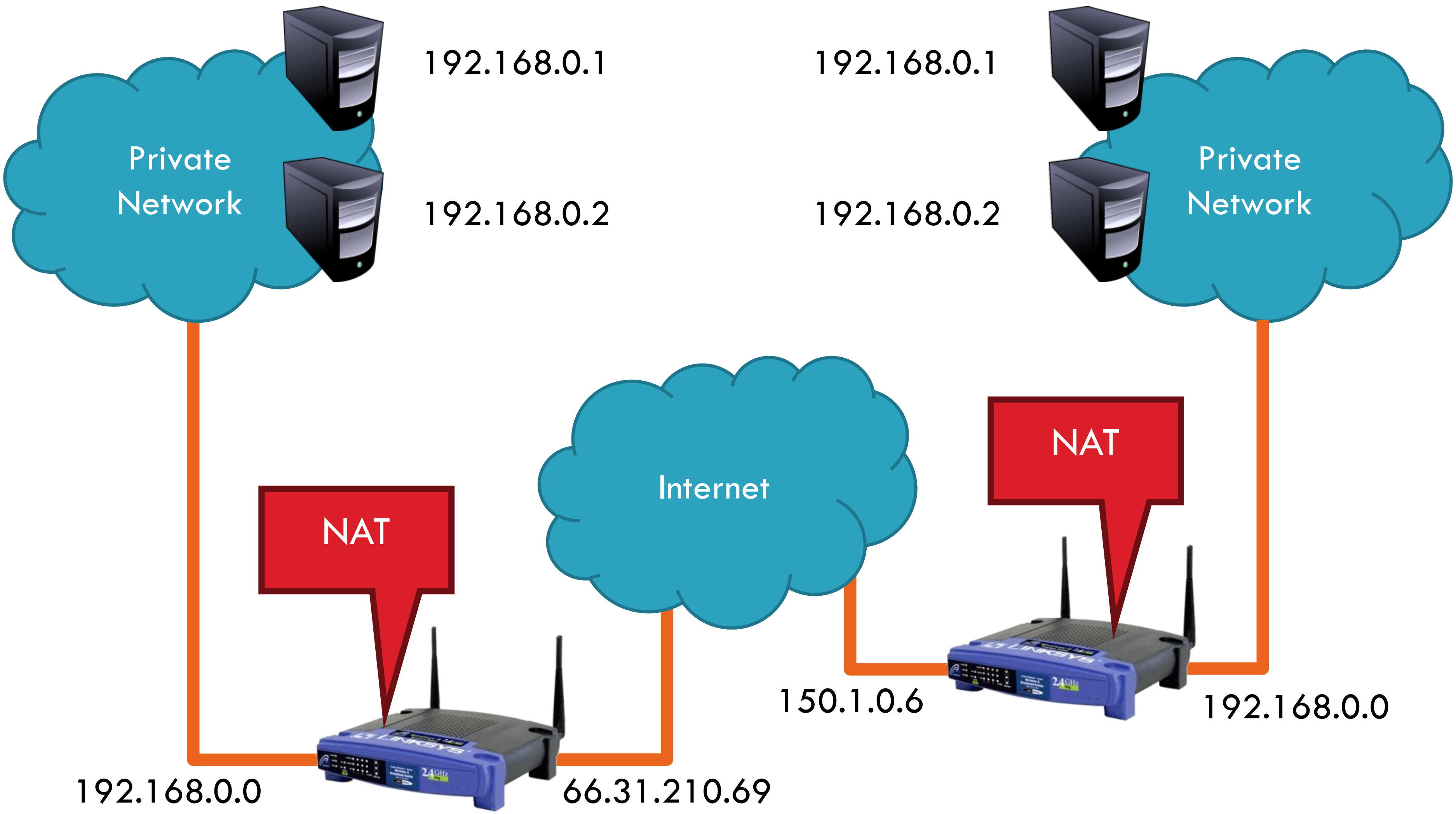
Private IP Networks

a) Idea: create a range of private IPs that are separate from the rest of the network
   - Use the private IPs for internal routing
   - Use a special router to bridge the LAN and the WAN

b) Properties of private IPs
   - Not globally unique
   - Usually taken from non-routable IP ranges (why?)

c) Typical private IP ranges
   - 10.0.0.0 – 10.255.255.255
   - 172.16.0.0 – 172.31.255.255
   - 192.168.0.0 – 192.168.255.255

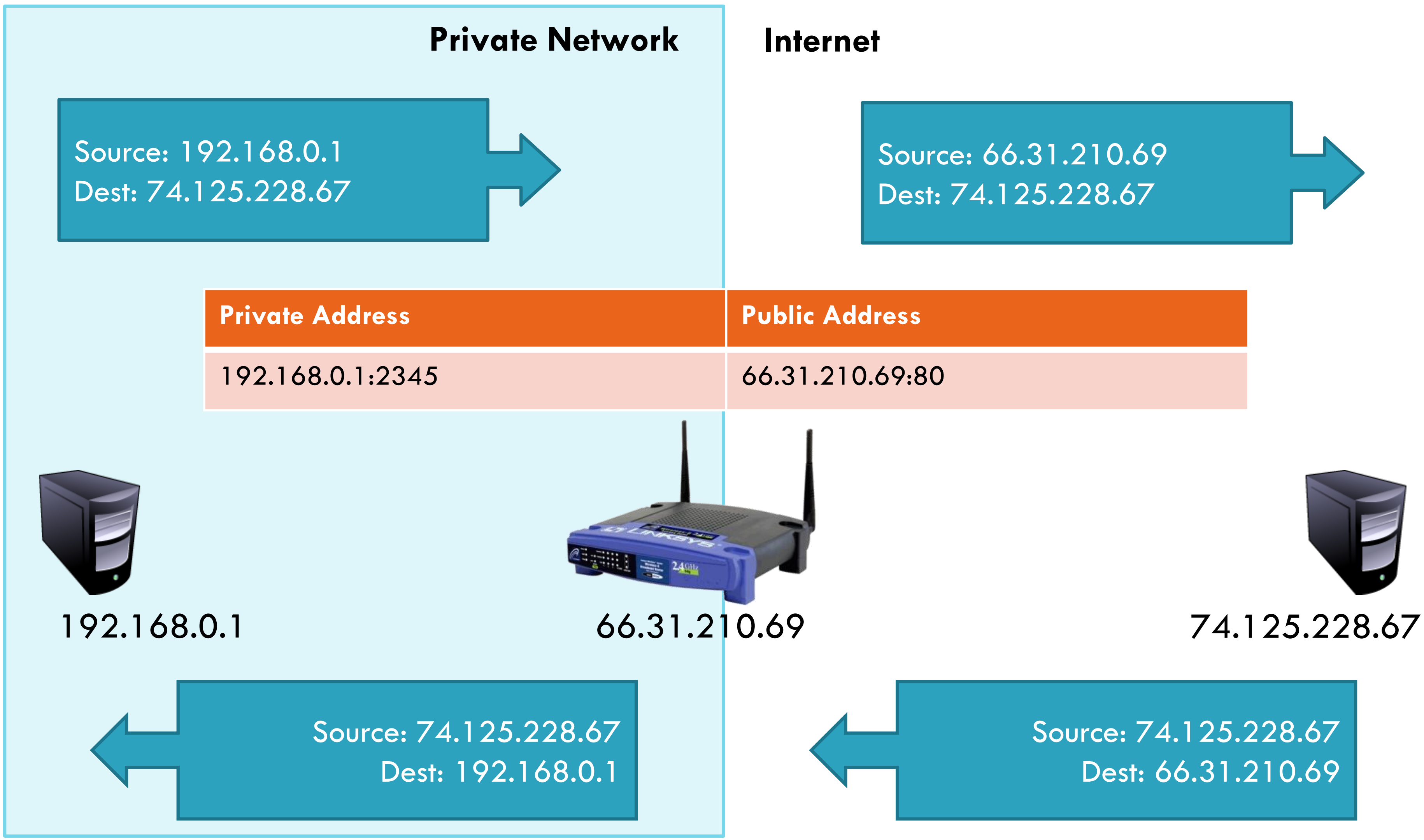
Private Networks



Network Address Translation (NAT)

a) NAT allows hosts on a private network to communicate with the Internet
   - Warning: connectivity is not seamless
b) Special router at the boundary of a private network
   - Replaces internal IPs with external IP
     - This is “Network Address Translation”
   - May also replace TCP/UDP port numbers
c) Maintains a table of active flows
   - Outgoing packets initialize a table entry
   - Incoming packets are rewritten based on the table

Basic NAT Operation



Private Address	Public Address
192.168.0.1:2345	66.31.210.69:80

Advantages of NATs

a) Allow multiple hosts to share a single public IP

b) Allow migration between ISPs
   - Even if the public IP address changes, you don't need to reconfigure the machines on the LAN

c) Load balancing
   - Forward traffic from a single public IP to multiple private hosts

Natural Firewall

Private Network | **Internet**

Private Address	Public Address

192.168.0.1

66.31.210.69

74.125.228.67

Source: 74.125.228.67
Dest: 66.31.210.69

Port Forwarding

Private Network **Internet**

Private Address	Public Address
192.168.0.1:7000	*.*.*.*

192.168.0.1

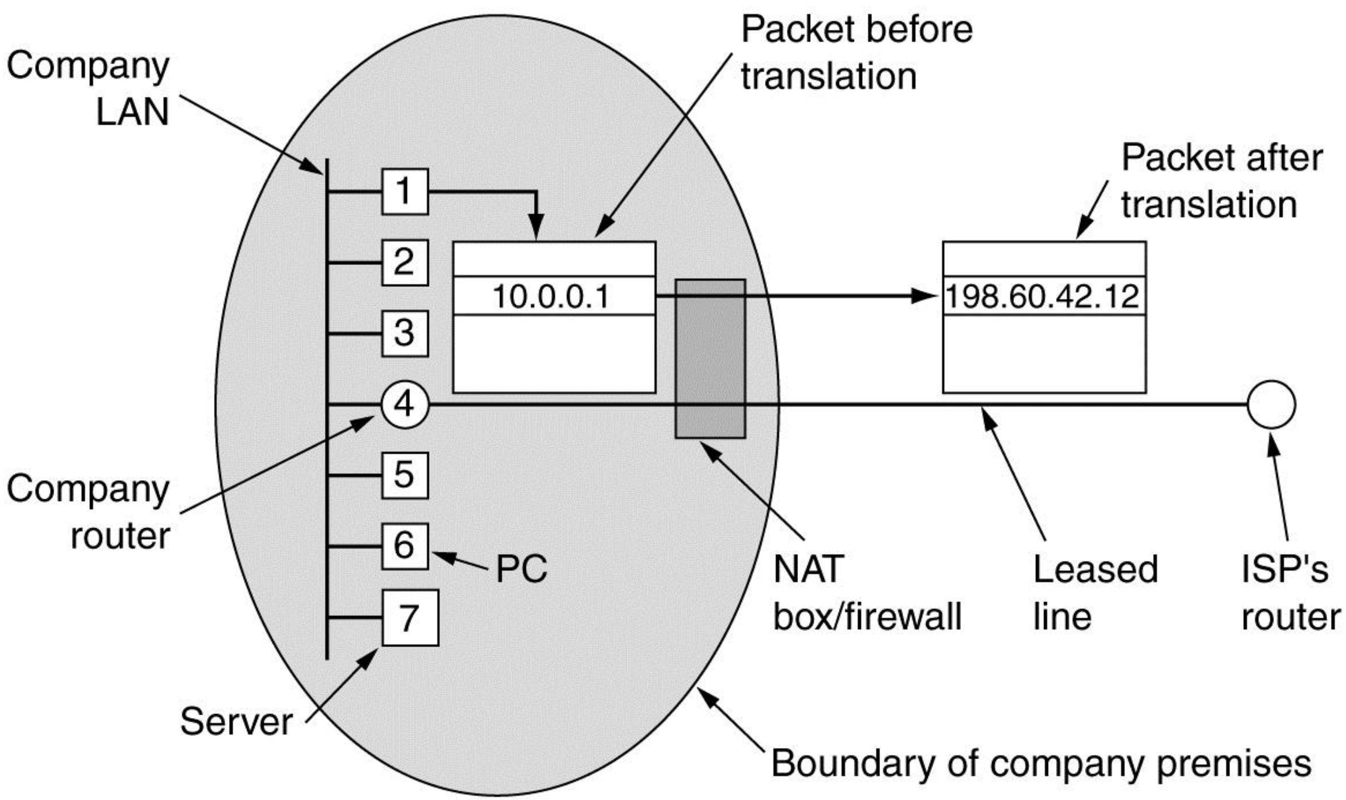
66.31.210.69

74.125.228.67

Source: 74.125.228.67:8679
Dest: 192.168.0.1:7000

Source: 74.125.228.67:8679
Dest: 66.31.210.69:7000

NAT – Network Address Translation

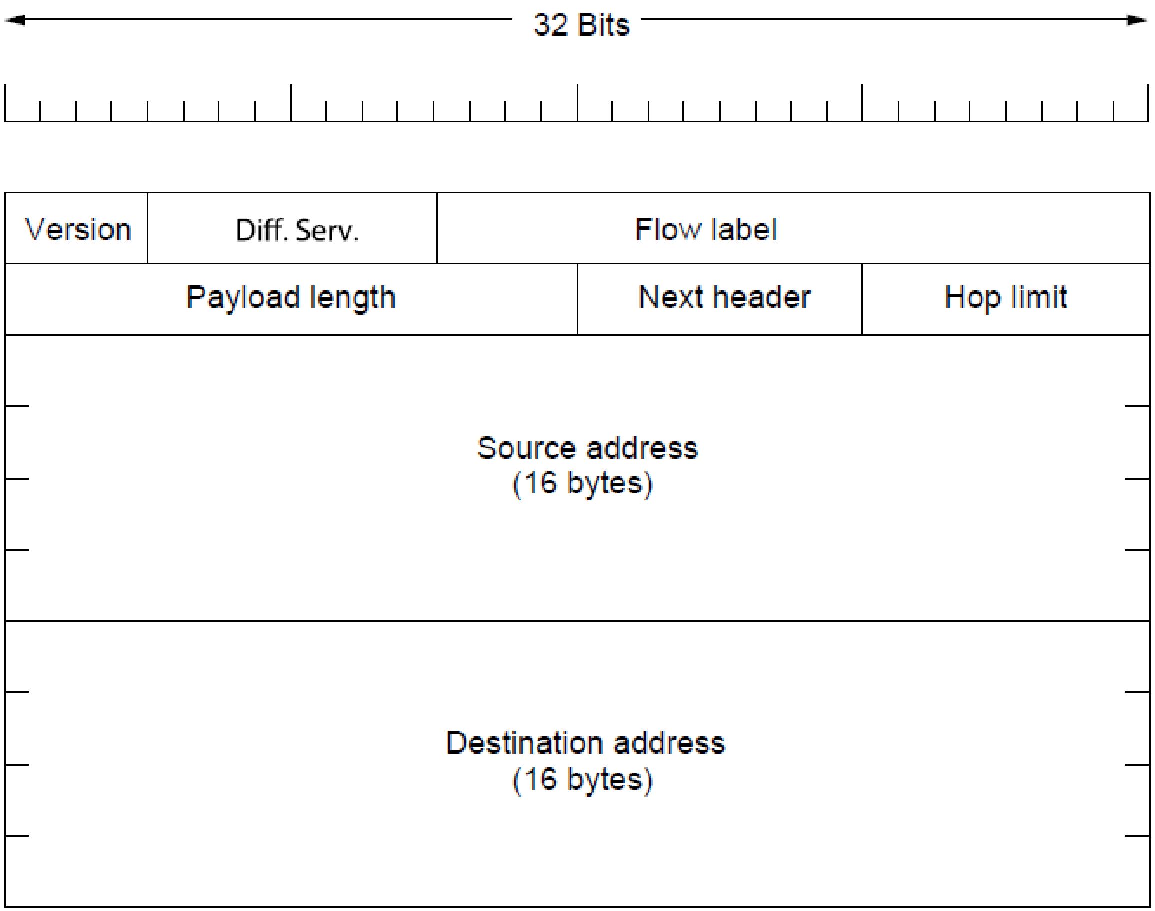


Placement and operation of a NAT box.

IP Version 6 Goals

- Support billions of hosts
- Reduce routing table size
- Simplify protocol
- Better security
- Attention to type of service
- Aid multicasting
- Roaming host without changing address
- Allow future protocol evolution
- Permit coexistence of old, new protocols. . .

IP Version 6 (1)



The IPv6 fixed header (required).

IP Version 6 (2)

Extension header	Description
Hop-by-hop options	Miscellaneous information for routers
Destination options	Additional information for the destination
Routing	Loose list of routers to visit
Fragmentation	Management of datagram fragments
Authentication	Verification of the sender's identity
Encrypted security payload	Information about the encrypted contents

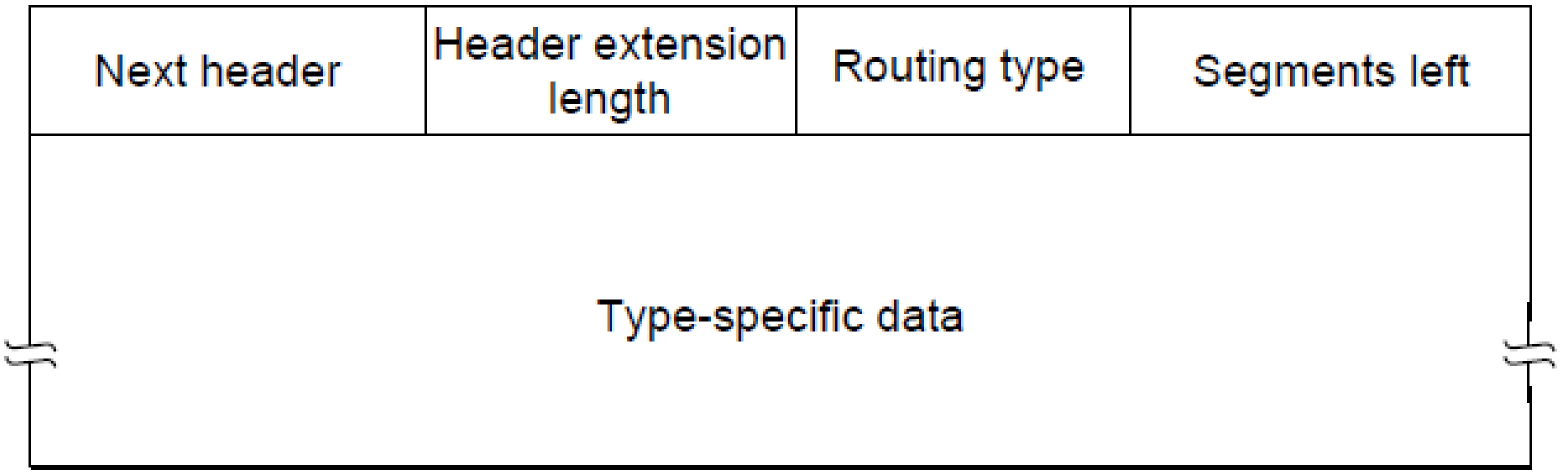
IPv6 extension headers

IP Version 6 (3)

Next header	0	194	4
Jumbo payload length			

The hop-by-hop extension header for large datagrams (jumbograms).

IP Version 6 (4)



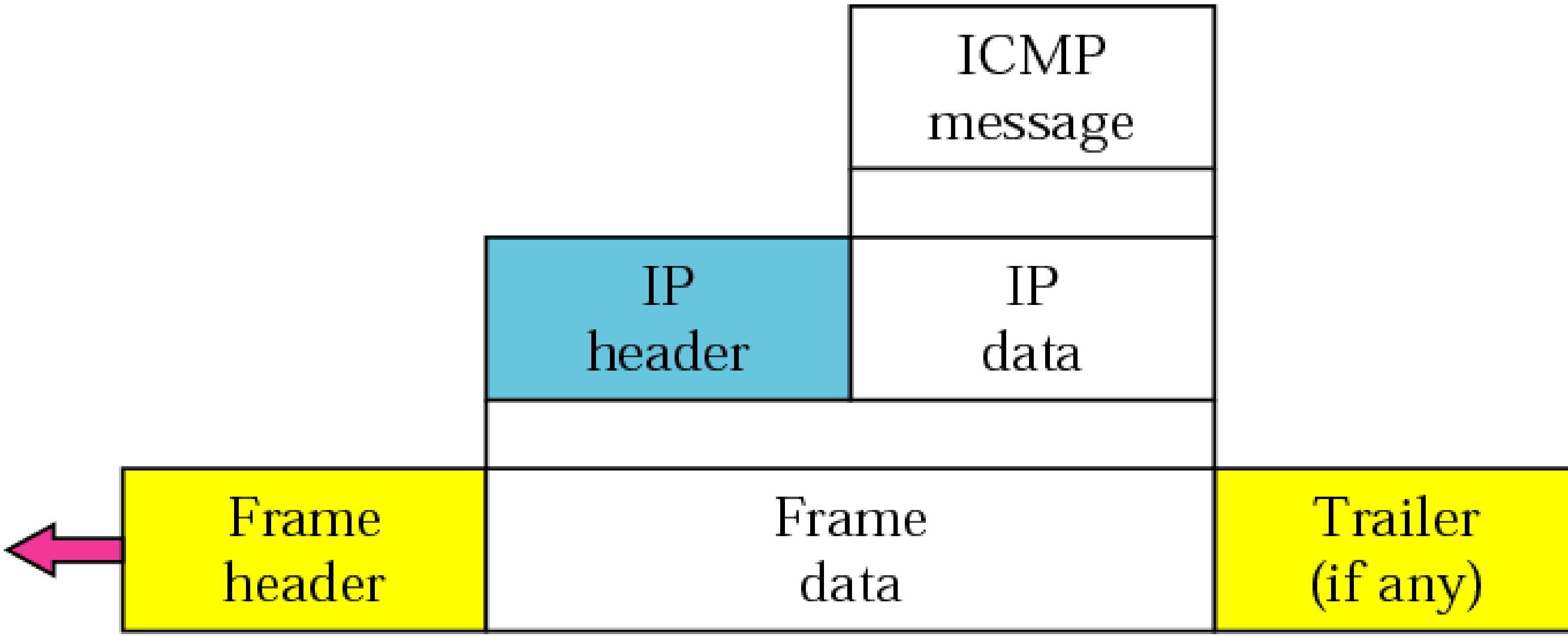
The extension header for routing.

Internet Control Protocols (1)

Message type	Description
Destination unreachable	Packet could not be delivered
Time exceeded	Time to live field hit 0
Parameter problem	Invalid header field
Source quench	Choke packet
Redirect	Teach a router about geography
Echo and Echo reply	Check if a machine is alive
Timestamp request/reply	Same as Echo, but with timestamp
Router advertisement/solicitation	Find a nearby router

The principal ICMP message types.

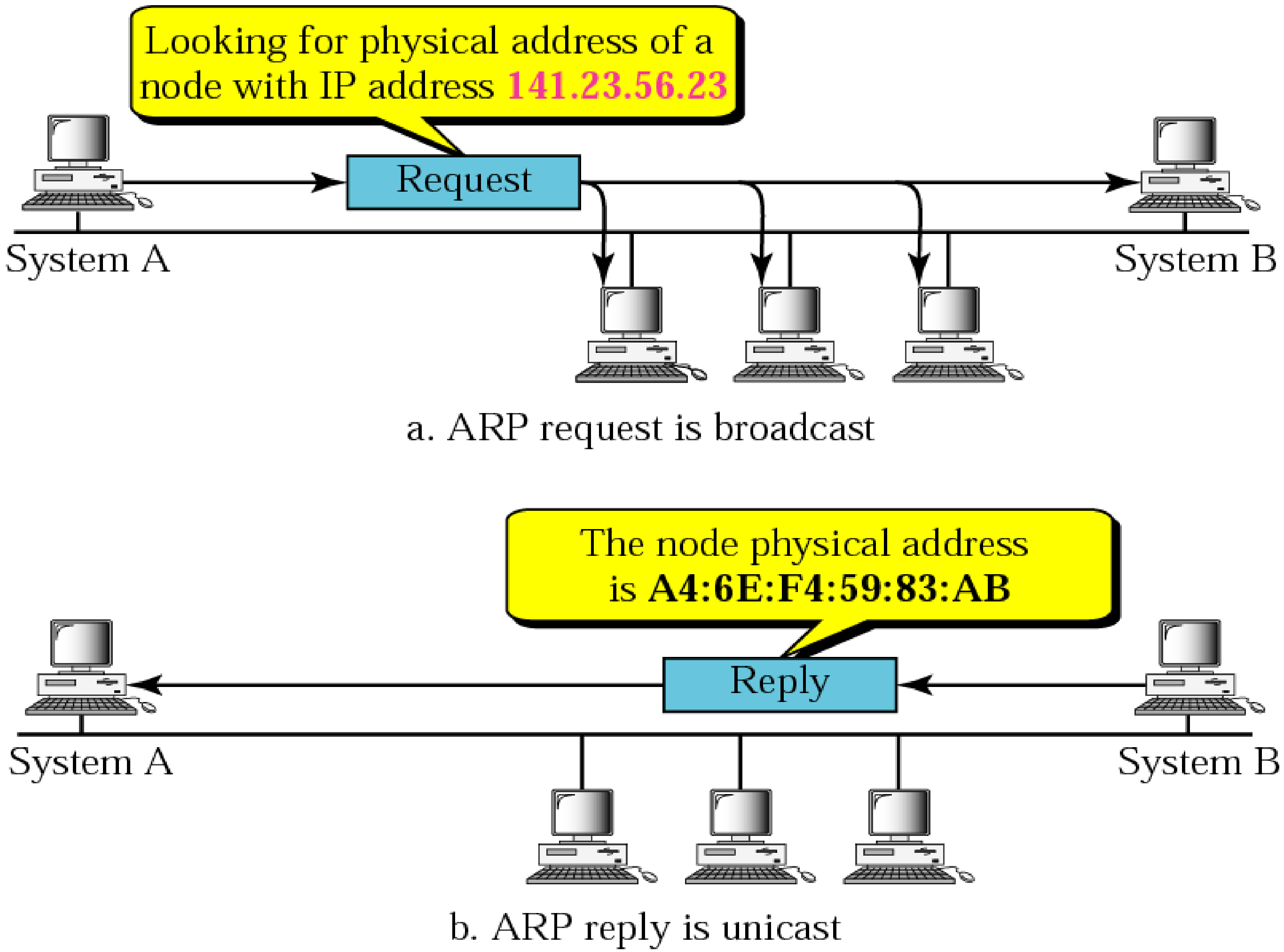
ICMP encapsulation



ICMP messages

Category	*Type*	*Message*
Error-reporting messages	3	Destination unreachable
	4	Source quench
	11	Time exceeded
	12	Parameter problem
	5	Redirection
Query messages	8 or 0	Echo request or reply
	13 or 14	Timestamp request or reply
	17 or 18	Address mask request or reply
	10 or 9	Router solicitation or advertisement

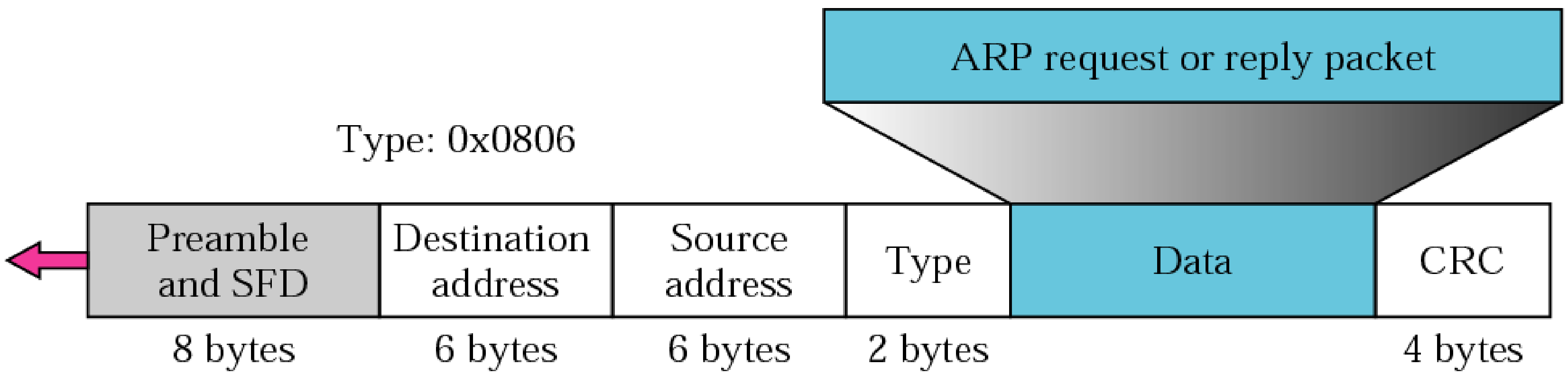
ARP– The Address Resolution Protocol



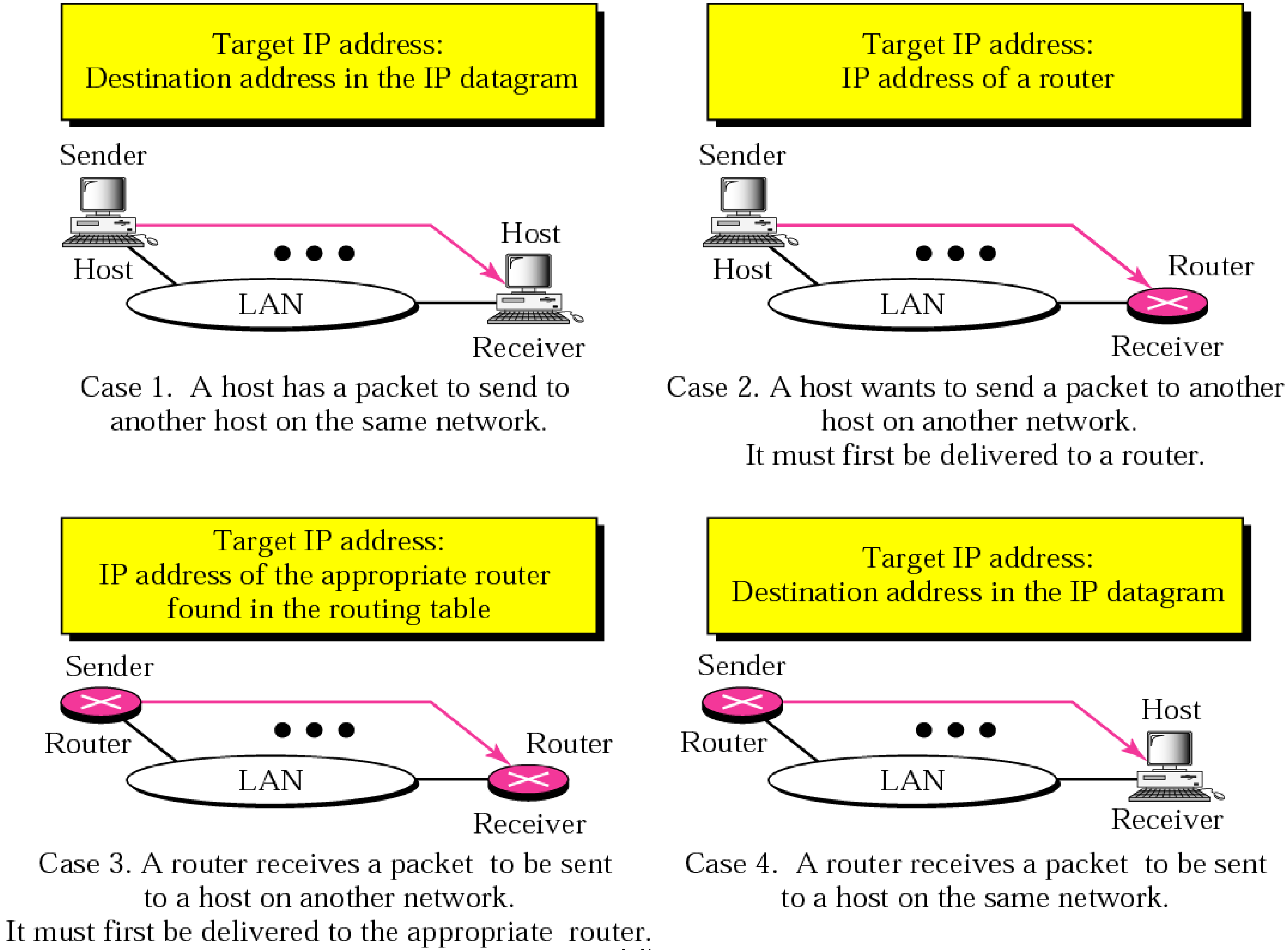
ARP packet

<table>
<tr><td colspan="2">Hardware Type</td><td>Protocol Type</td></tr>
<tr><td>Hardware length</td><td>Protocol length</td><td>Operation
Request 1, Reply 2</td></tr>
<tr><td colspan="3">Sender hardware address
(For example, 6 bytes for Ethernet)</td></tr>
<tr><td colspan="3">Sender protocol address
(For example, 4 bytes for IP)</td></tr>
<tr><td colspan="3">Target hardware address
(For example, 6 bytes for Ethernet)
(It is not filled in a request)</td></tr>
<tr><td colspan="3">Target protocol address
(For example, 4 bytes for IP)</td></tr>
</table>

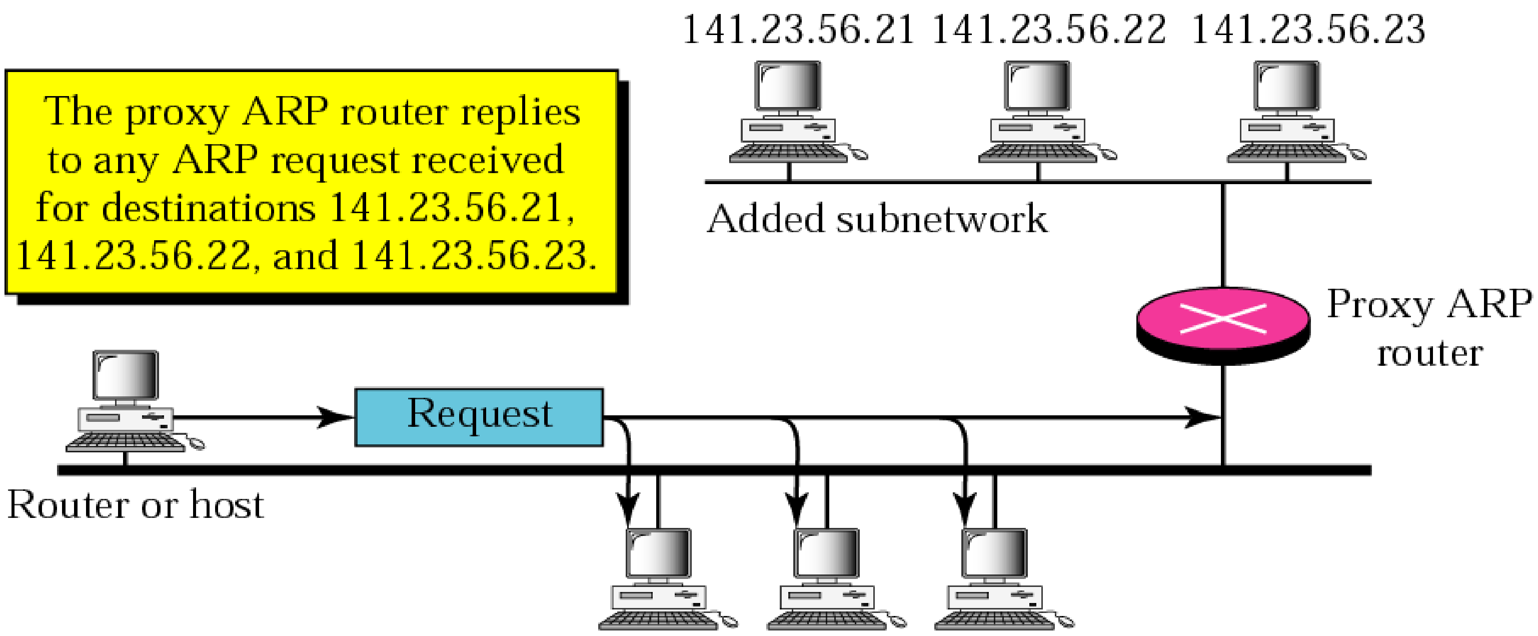
Encapsulation of ARP packet



Four cases using ARP

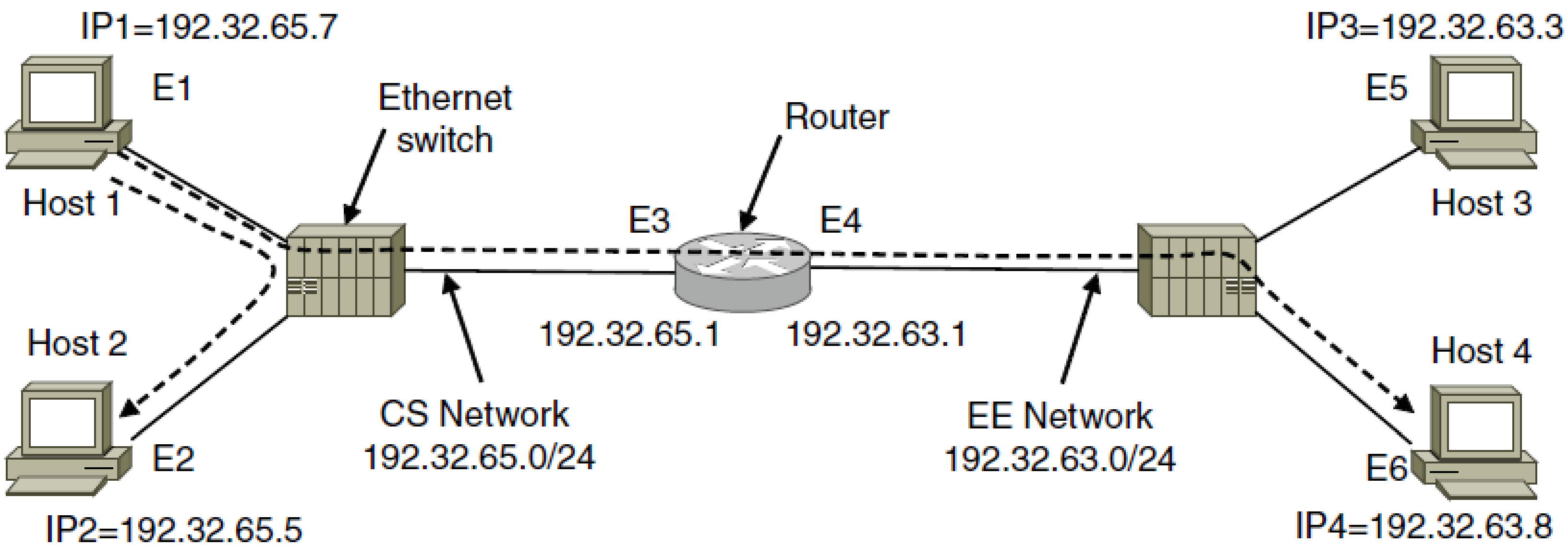


Proxy ARP



141.23.56.21
141.23.56.22
141.23.56.23
The proxy ARP router replies to any ARP request received for destinations 141.23.56.21, 141.23.56.22, and 141.23.56.23.
Added subnetwork
Proxy ARP router
Request
Router or host

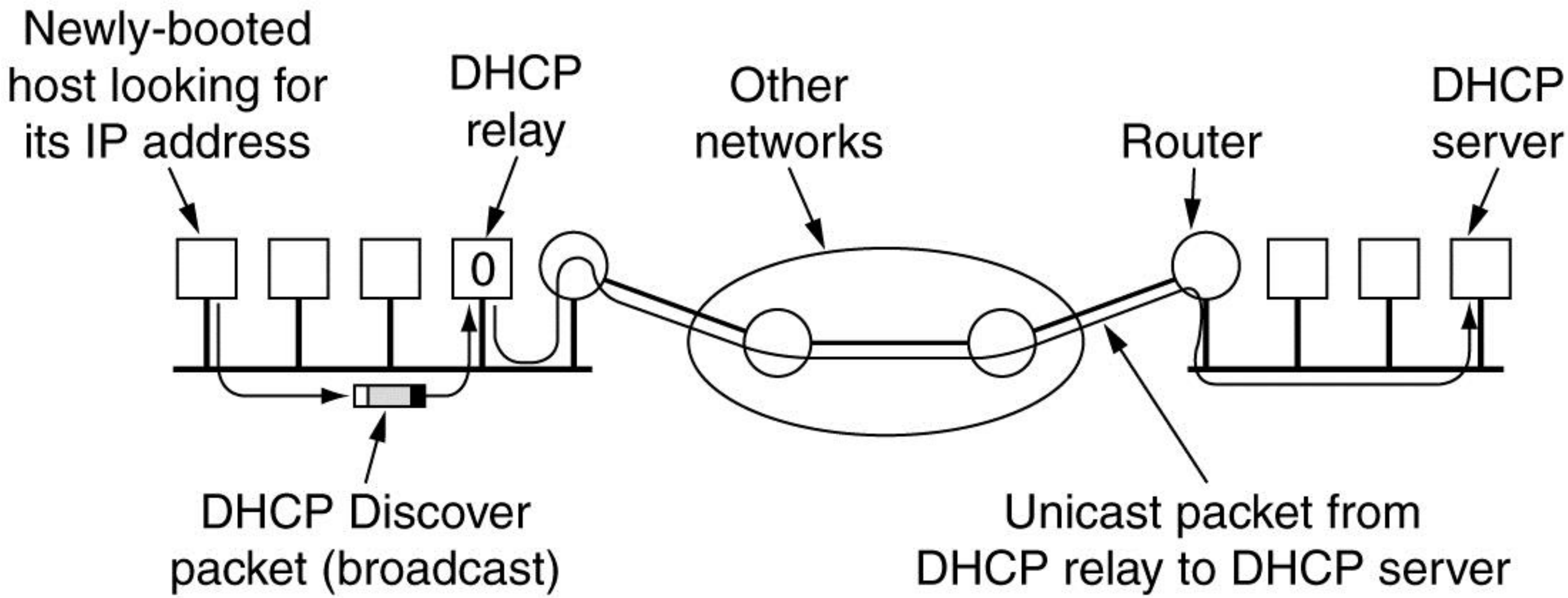
ARP



Frame	Source IP	Source Eth.	Destination IP	Destination Eth.
Host 1 to 2, on CS net	IP1	E1	IP2	E2
Host 1 to 4, on CS net	IP1	E1	IP4	E3
Host 1 to 4, on EE net	IP1	E4	IP4	E6

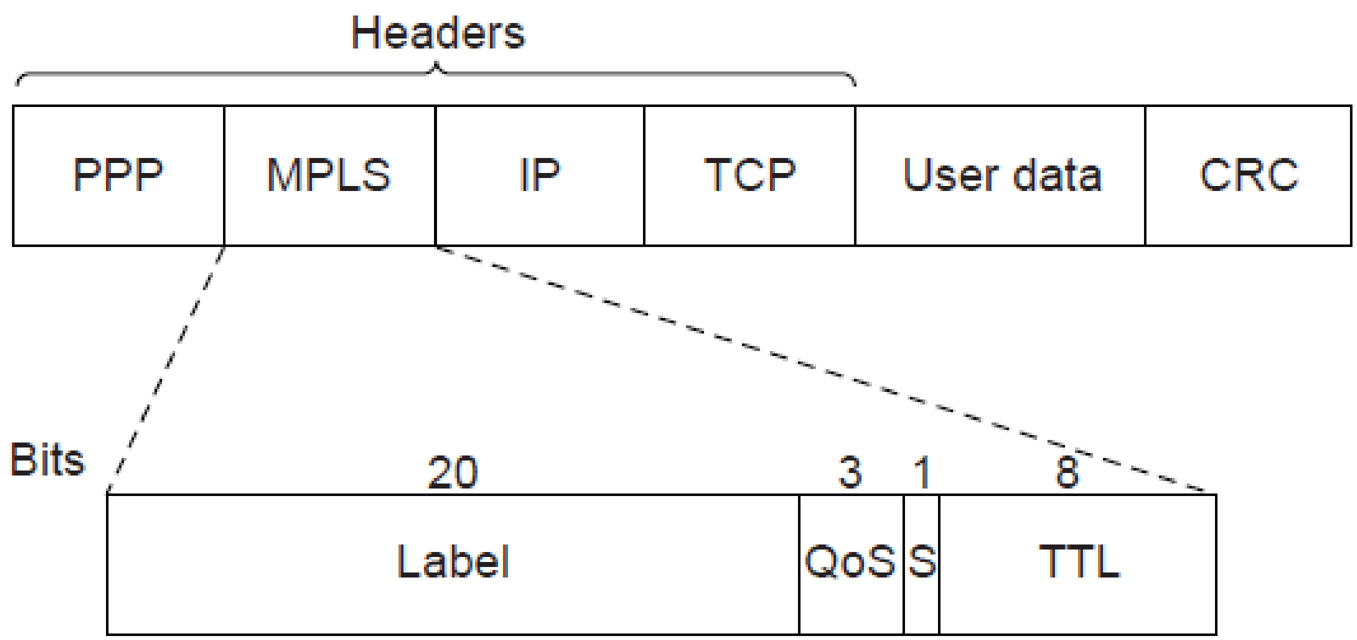
Two switched Ethernet LANs joined by a router

Dynamic Host Configuration Protocol



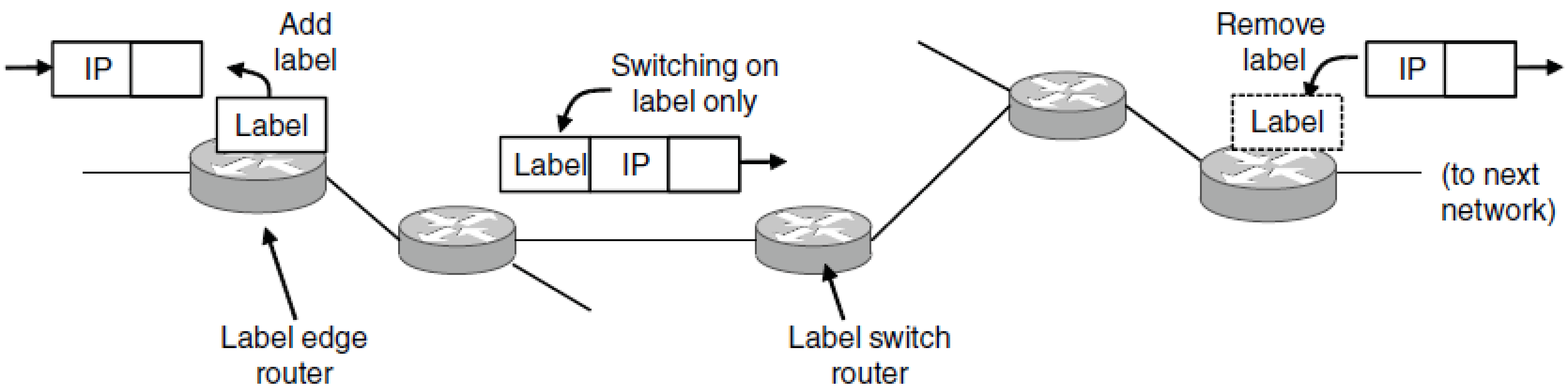
Operation of DHCP.

Label Switching and MPLS (1)



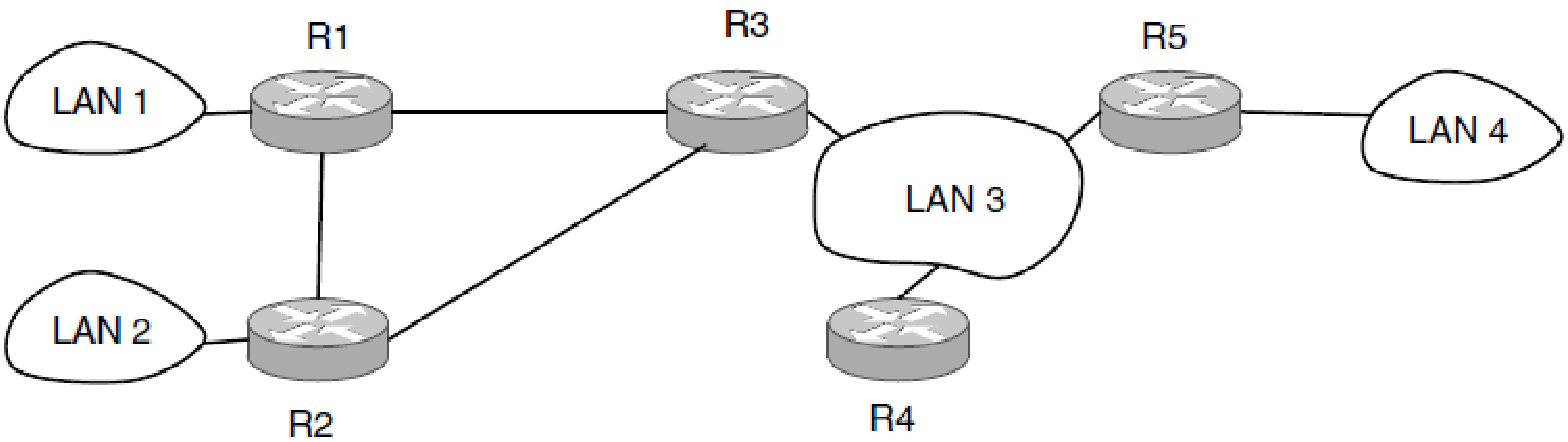
Transmitting a TCP segment using IP, MPLS, and PPP.

Label Switching and MPLS (2)



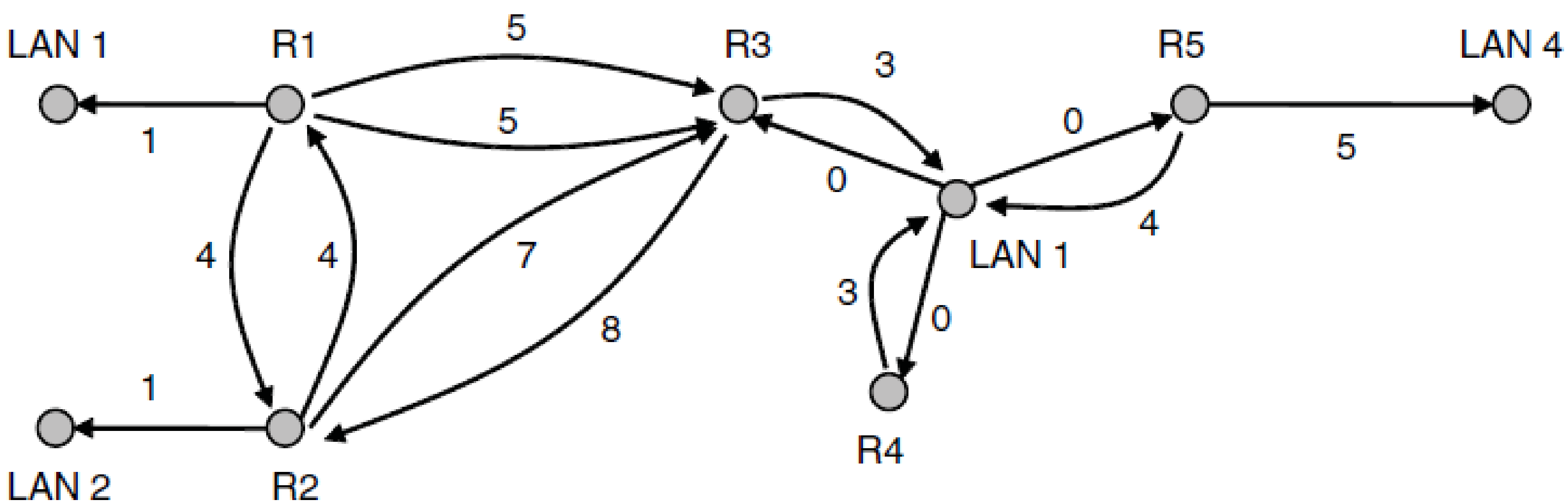
Forwarding an IP packet through an MPLS network

OSPF—An Interior Gateway Routing Protocol (1)



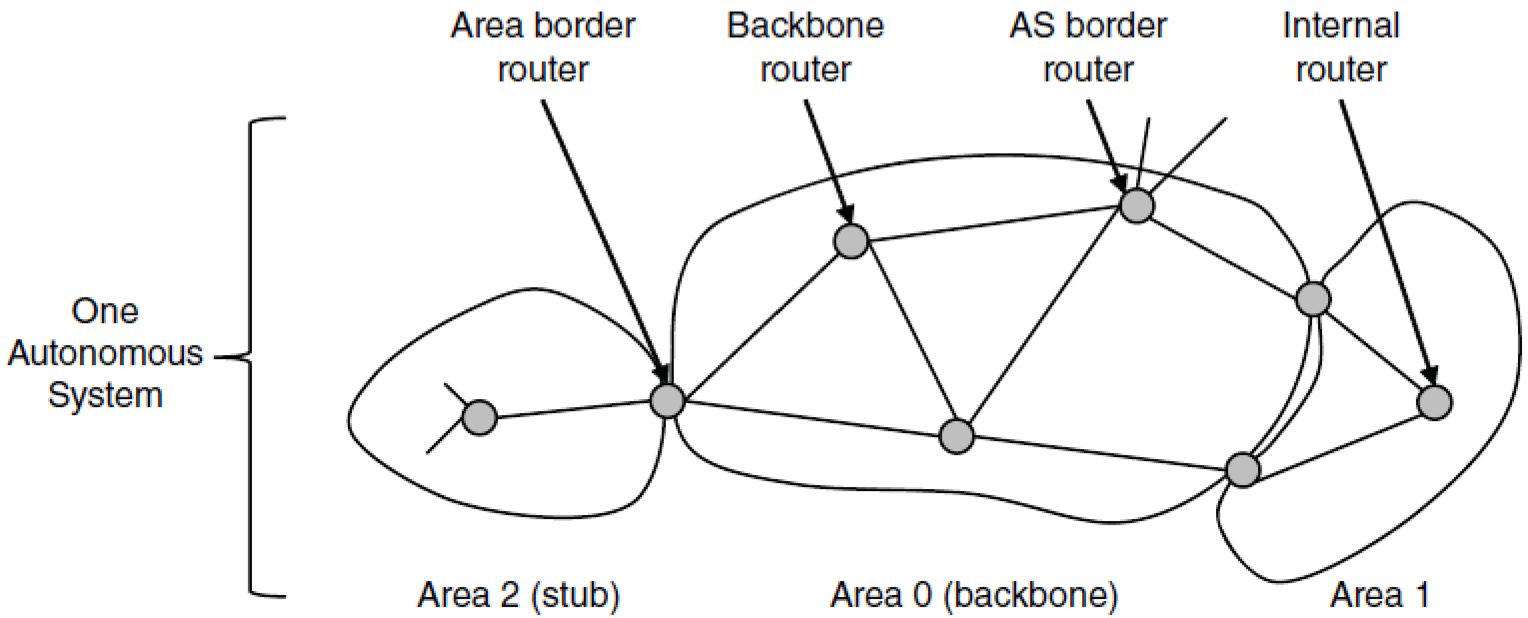
An autonomous system

OSPF—An Interior Gateway Routing Protocol (2)



A graph representation of the previous slide.

OSPF—An Interior Gateway Routing Protocol (3)



The relation between ASes, backbones, and areas in OSPF.

OSPF—An Interior Gateway Routing Protocol (4)

Message type	Description
Hello	Used to discover who the neighbors are
Link state update	Provides the sender's costs to its neighbors
Link state ack	Acknowledges link state update
Database description	Announces which updates the sender has
Link state request	Requests information from the partner

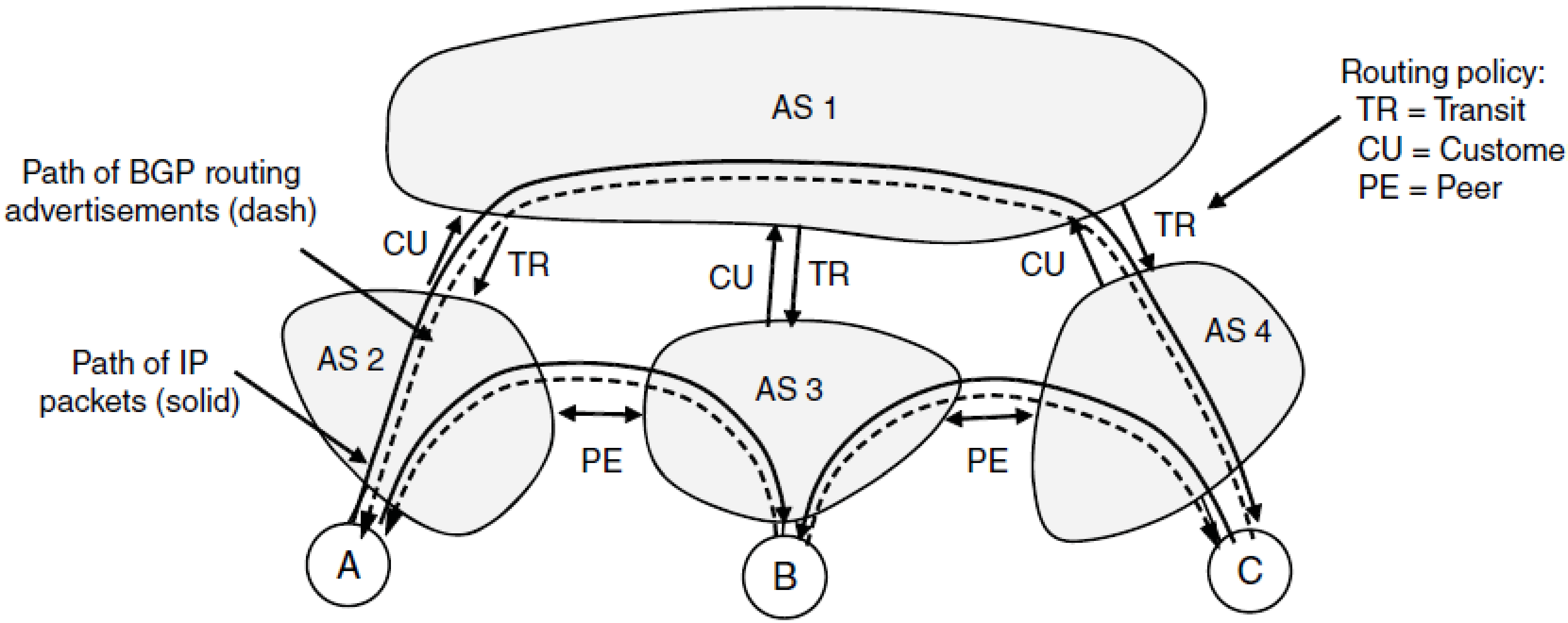
The five types of OSPF messages

BGP—The Exterior Gateway Routing Protocol (1)

Examples of routing constraints:

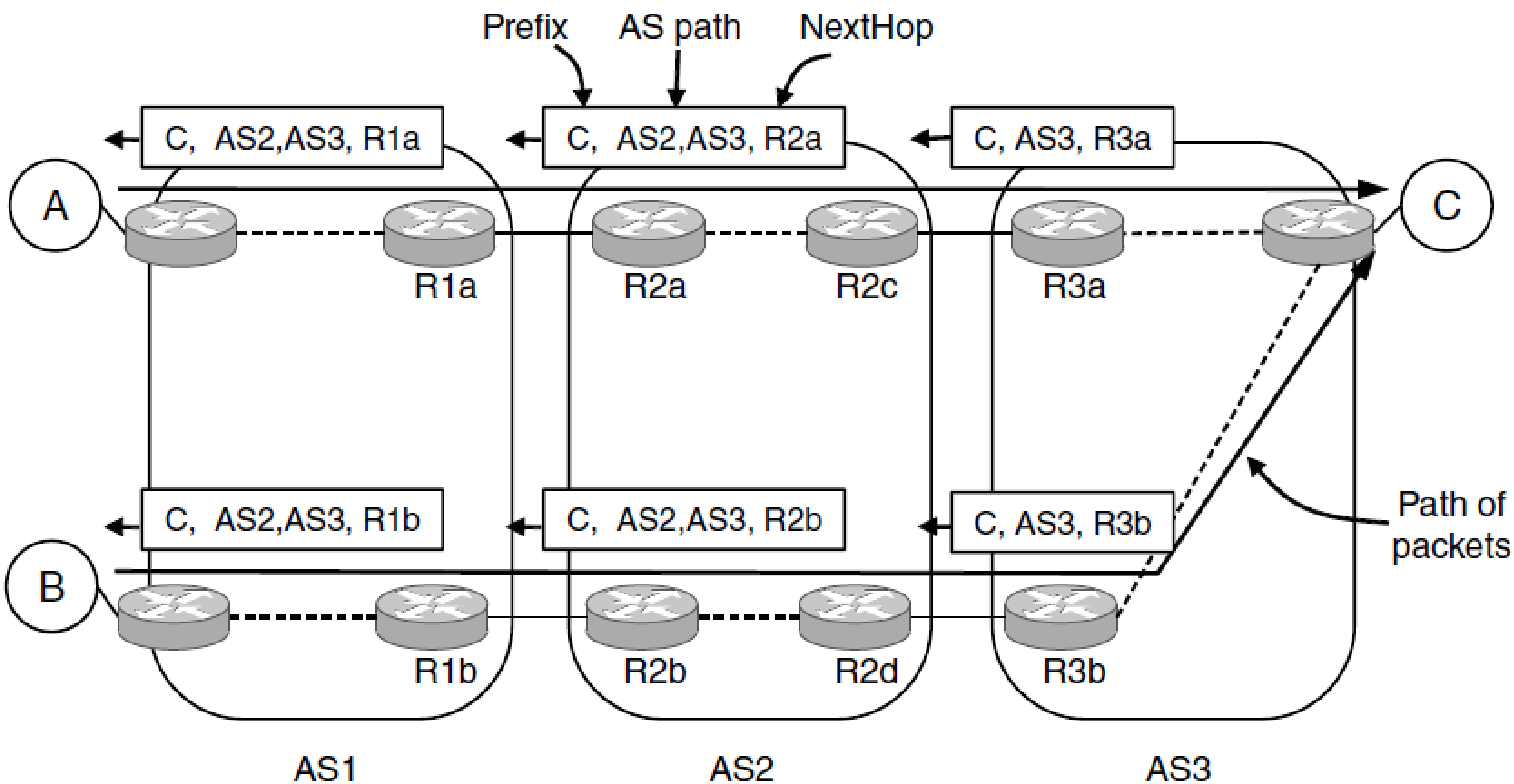
- No commercial traffic for educat. network
- Never put Iraq on route starting at Pentagon
- Choose cheaper network
- Choose better performing network
- Don’t go from Apple to Google to Apple

BGP—The Exterior Gateway Routing Protocol (2)



Routing policies between four Autonomous Systems

BGP—The Exterior Gateway Routing Protocol (3)



Propagation of BGP route advertisements

Mobile IP

Goals

- Mobile host use home IP address anywhere.
- No software changes to fixed hosts
- No changes to router software, tables
- Packets for mobile hosts – restrict detours
- No overhead for mobile host at home.

End

Chapter 5