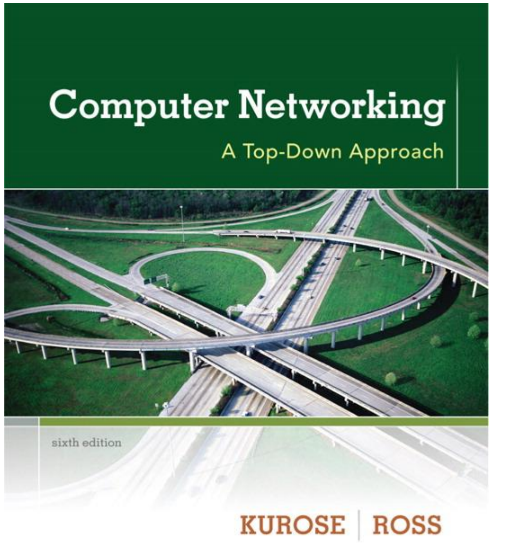
Chapter 4
Network Layer

Part 1 (of 3)



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Computer Networking: A Top Down Approach
6th edition
Jim Kurose, Keith Ross
Addison-Wesley
March 2012

Chapter 4: network layer

chapter goals:

- understand principles behind network layer services:
  - network layer service models
  - forwarding versus routing
  - how a router works
  - routing (path selection)
  - broadcast, multicast
- instantiation, implementation in the Internet

Chapter 4: outline

4.1 introduction

4.2 virtual circuit and datagram networks

4.3 what's inside a router

4.4 IP: Internet Protocol
- datagram format
- IPv4 addressing
- ICMP
- IPv6

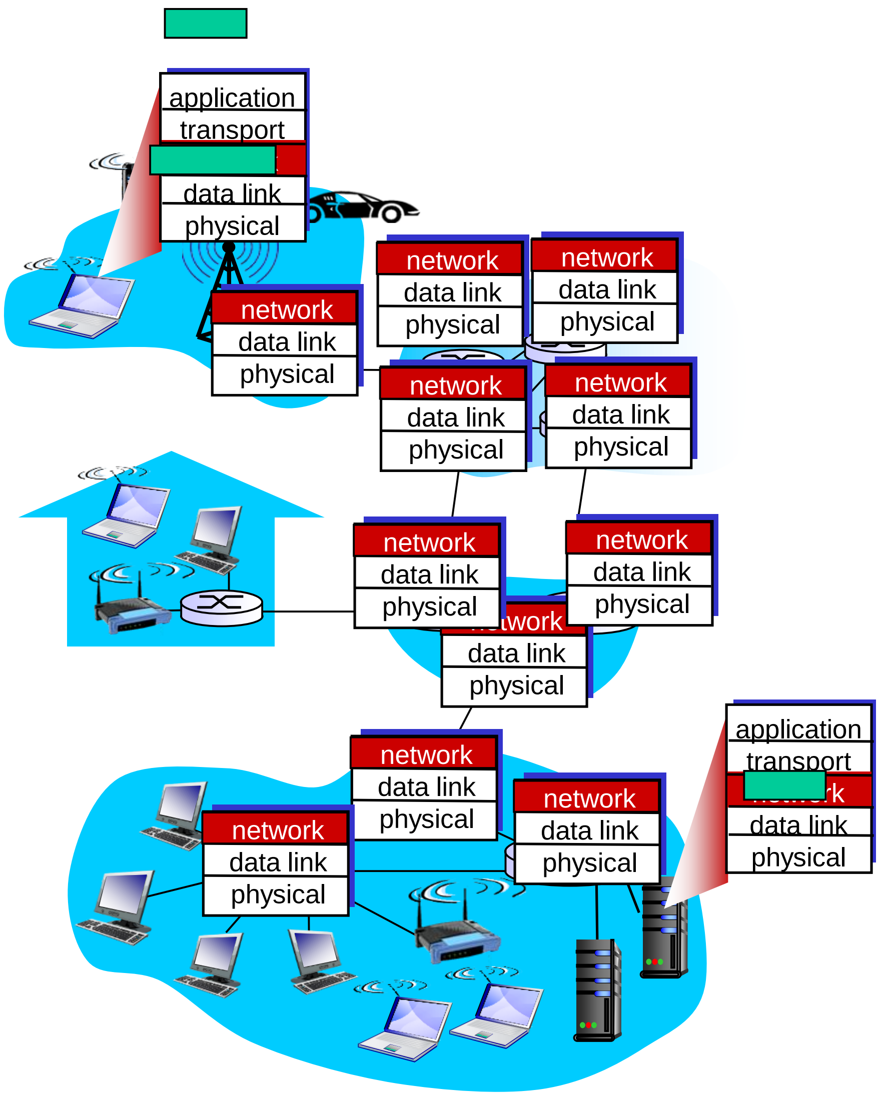
4.5 routing algorithms
- link state
- distance vector
- hierarchical routing

4.6 routing in the Internet
- RIP
- OSPF
- BGP

4.7 broadcast and multicast routing

Network layer

- transport segment from sending to receiving host
- on sending side encapsulates segments into datagrams
- on receiving side, delivers segments to transport layer
- network layer protocols in *every* host, router
- router examines header fields in all IP datagrams passing through it



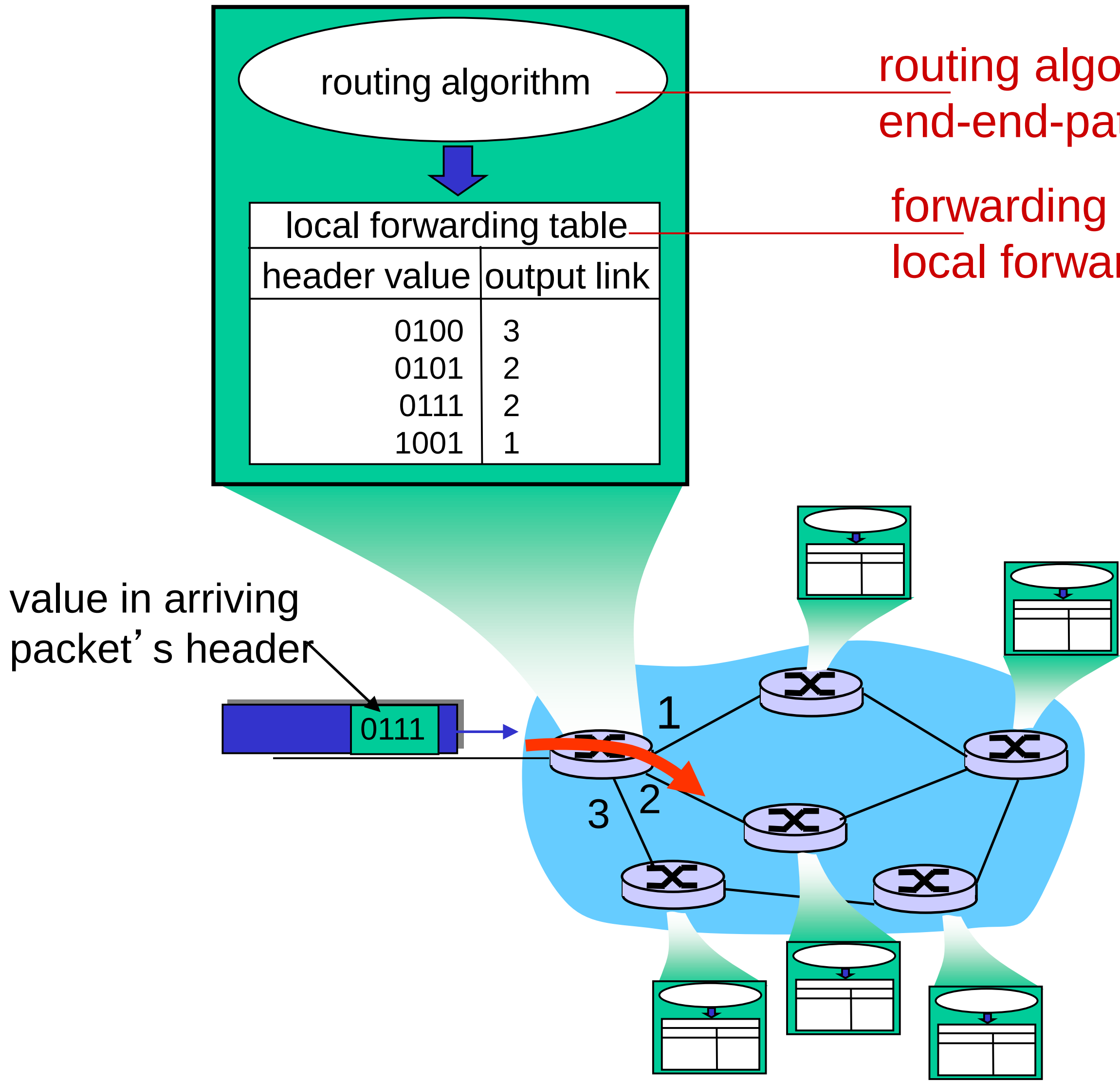
Two key network-layer functions

- *forwarding:* move packets from router's input to appropriate router output
- *routing:* determine route taken by packets from source to dest.
  - *routing algorithms*

analogy:

- *routing:* process of planning trip from source to dest
- *forwarding:* process of getting through single interchange

Interplay between routing and forwarding



routing algorithm determines end-end-path through network

forwarding table determines local forwarding at this router

Connection setup

- 3rd important function in *some* network architectures:
  - ATM, frame relay, X.25
- before datagrams flow, two end hosts *and* intervening routers establish virtual connection
  - routers get involved
- network vs transport layer connection service:
  - *network:* between two hosts (may also involve intervening routers in case of VCs)
  - *transport:* between two processes

Network service model

Q: What *service model* for "channel" transporting datagrams from sender to receiver?

example services for individual datagrams:

- guaranteed delivery
- guaranteed delivery with less than 40 msec delay

example services for a flow of datagrams:

- in-order datagram delivery
- guaranteed minimum bandwidth to flow
- restrictions on changes in inter-packet spacing

Network layer service models:

Network Architecture	Service Model	Guarantees ? Bandwidth	Loss	Order	Timing	Congestion feedback
Internet	best effort	none	no	no	no	no (inferred via loss)
ATM	CBR Constant Bit Rate	constant rate	yes	yes	yes	no congestion
ATM	VBR Variable	guaranteed rate	yes	yes	yes	no congestion
ATM	ABR Available Bit Rate	guaranteed minimum	no	yes	no	yes
ATM	UBR Unspecified Bit Rate	none	no	yes	no	no

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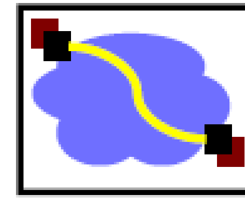
Circuit Versus Packet Switching



Circuit Switching

- Fast switches can be built relatively inexpensively
- Inefficient for bursty data
- Predictable performance (e.g. hard QoS)
- Requires circuit establishment before communication

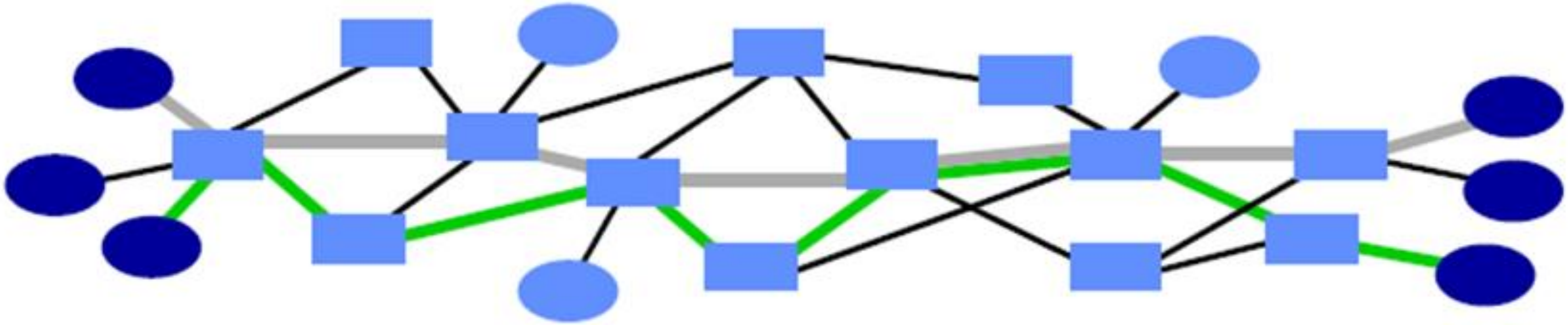
Packet Switching

- Switch design is more complex and expensive
- Allows statistical multiplexing
- Difficult to provide QoS guarantees
- Data can be sent without signaling delay and overhead

Can we get the benefits of both?

Virtual Circuits

- Each wire carries many “virtual” circuits.
- Forwarding based on virtual circuit (VC) identifier
  - IP header: src, dst, etc.
  - Virtual circuit header: just “VC”
  - A path through the network is set up when the VC is established
- Can support wide range of quality of service.
  - No guarantees: best effort service
  - Weak guarantees: delay < 300 msec, …
  - Strong guarantees: e.g. equivalent of physical circuit



Virtual Circuits Versus Packet Switching

- Many similarities:
  - Forwarding based on “address” (VCID or dest address)
  - Statistical multiplexing for efficiency
  - Must have buffers space on switches
- Virtual circuit switching:
  - Uses short circuit identifiers to forward packets
  - Switches keep (hard) state for each circuit, so they can more easily implement features such as quality of service
  - Failures result in loss of virtual circuit
- Packet switching:
  - Use full destination addresses for forwarding packets
  - Can send data right away: no need to establish a connection first
  - Switches are stateless: easier to recover from failures
  - Adding QoS is hard

Asynchronous Transfer Mode (ATM)

- Standards for carriage of a complete range of user traffic, including voice, data, and video signals
- Example: ISDN (Integrated Services Digital Network)
- FORE Systems was a leading computer network switching equipment company, producing ATM network interface cards
- **F**rancois Bitz, **O**nat Menzilcioğlu, **R**obert Sansom, and **E**ric Cooper

Connection, connection-less service

- *datagram* network provides network-layer *connectionless* service
- *virtual-circuit* network provides network-layer *connection* service
- analogous to TCP/UDP connecton-oriented / connectionless transport-layer services, but:
  - *service:* host-to-host
  - *no choice:* network provides one or the other
  - *implementation:* in network core

Virtual circuits

"source-to-dest path behaves much like telephone circuit"

- performance-wise
- network actions along source-to-dest path

- call setup, teardown for each call *before* data can flow
- each packet carries VC identifier (not destination host address)
- *every* router on source-dest path maintains "state" for each passing connection
- link, router resources (bandwidth, buffers) may be *allocated* to VC (dedicated resources = predictable service)

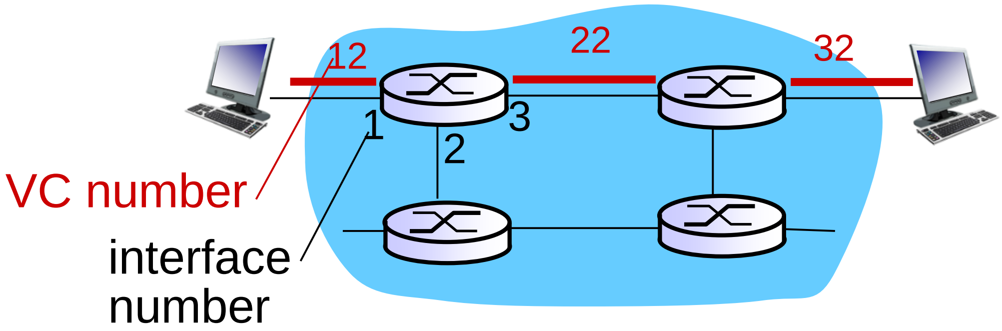
VC implementation

a VC consists of:

1. *path* from source to destination
2. *VC numbers*, one number for each link along path
3. *entries in forwarding tables* in routers along path

- packet belonging to VC carries VC number (rather than dest address)
- VC number can be changed on each link.
  - new VC number comes from forwarding table

VC forwarding table

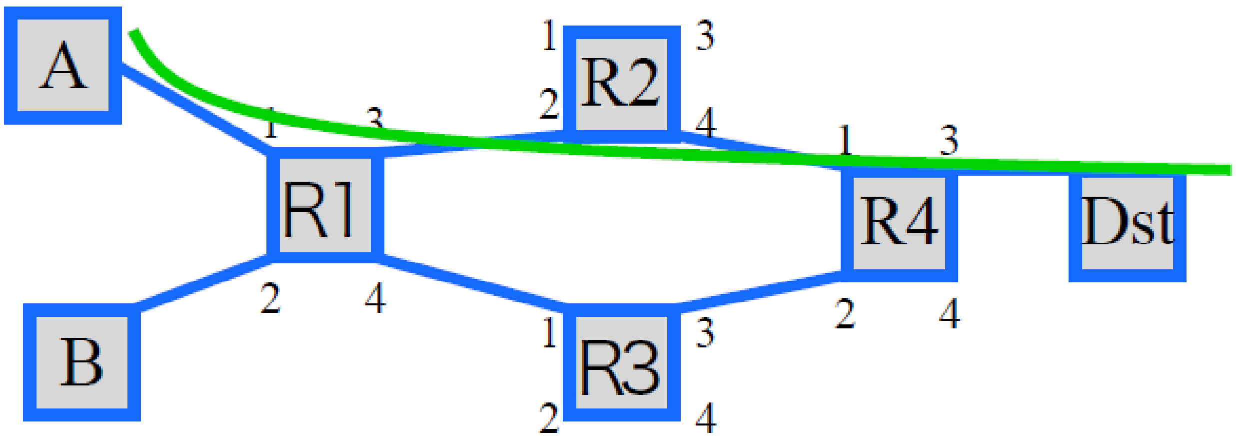


forwarding table in northwest router:

Incoming interface	Incoming VC #	Outgoing interface	Outgoing VC #
1	12	3	22
2	63	1	18
3	7	2	17
1	97	3	87
…	…	…	…

VC routers maintain connection state information!

VC ID (label / tag) swapping



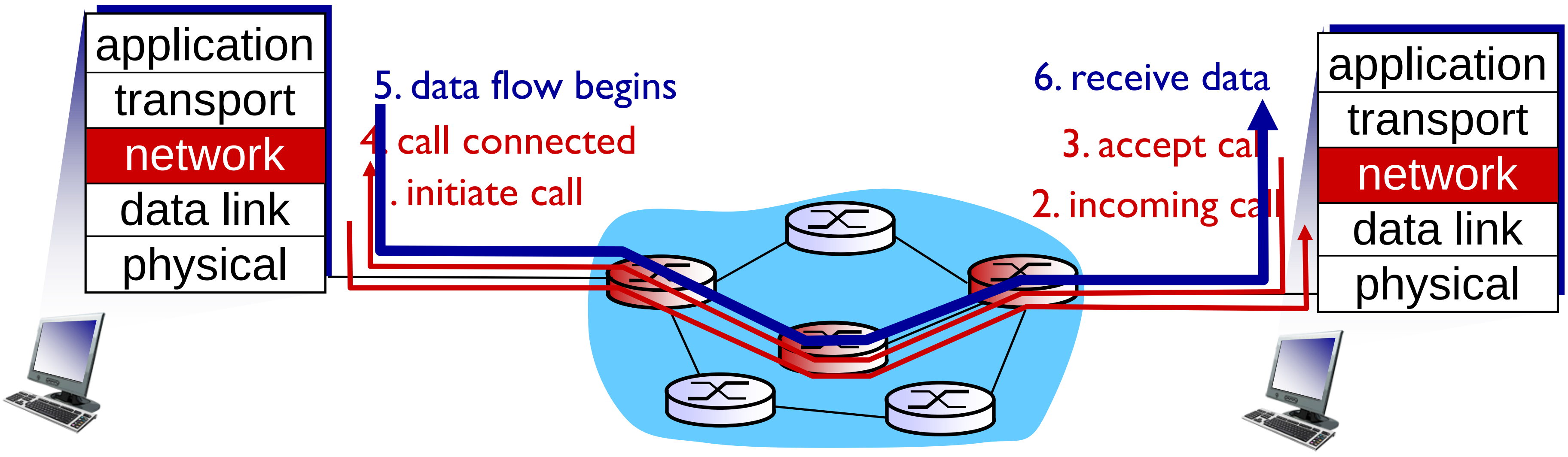
- **Global VC ID allocation -- ICK! Solution: Per-link uniqueness.** ***Change VCI each hop.***

Scalability, agreement on all routers…

	Input Port	Input VCI	Output Port	Output VCI
R1:	**1**	**5**	**3**	**9**
R2:	**2**	**9**	**4**	**2**
R4:	**1**	**2**	**3**	**5**

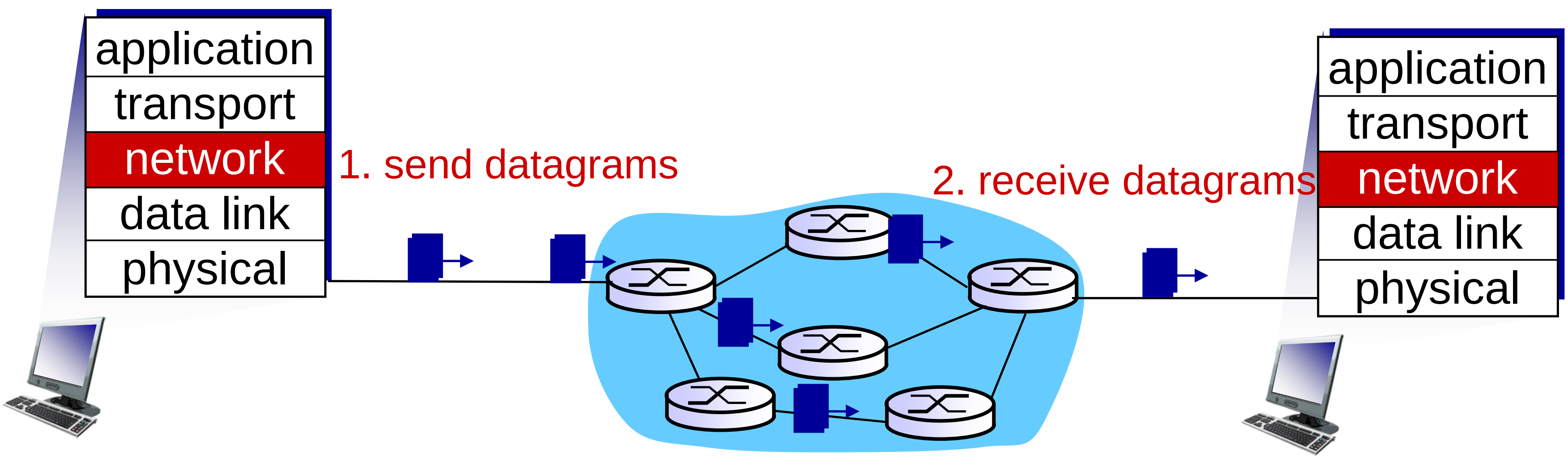
Virtual circuits: signaling protocols

- used to setup, maintain teardown VC
- used in ATM, frame-relay, X.25
- not used in today's Internet



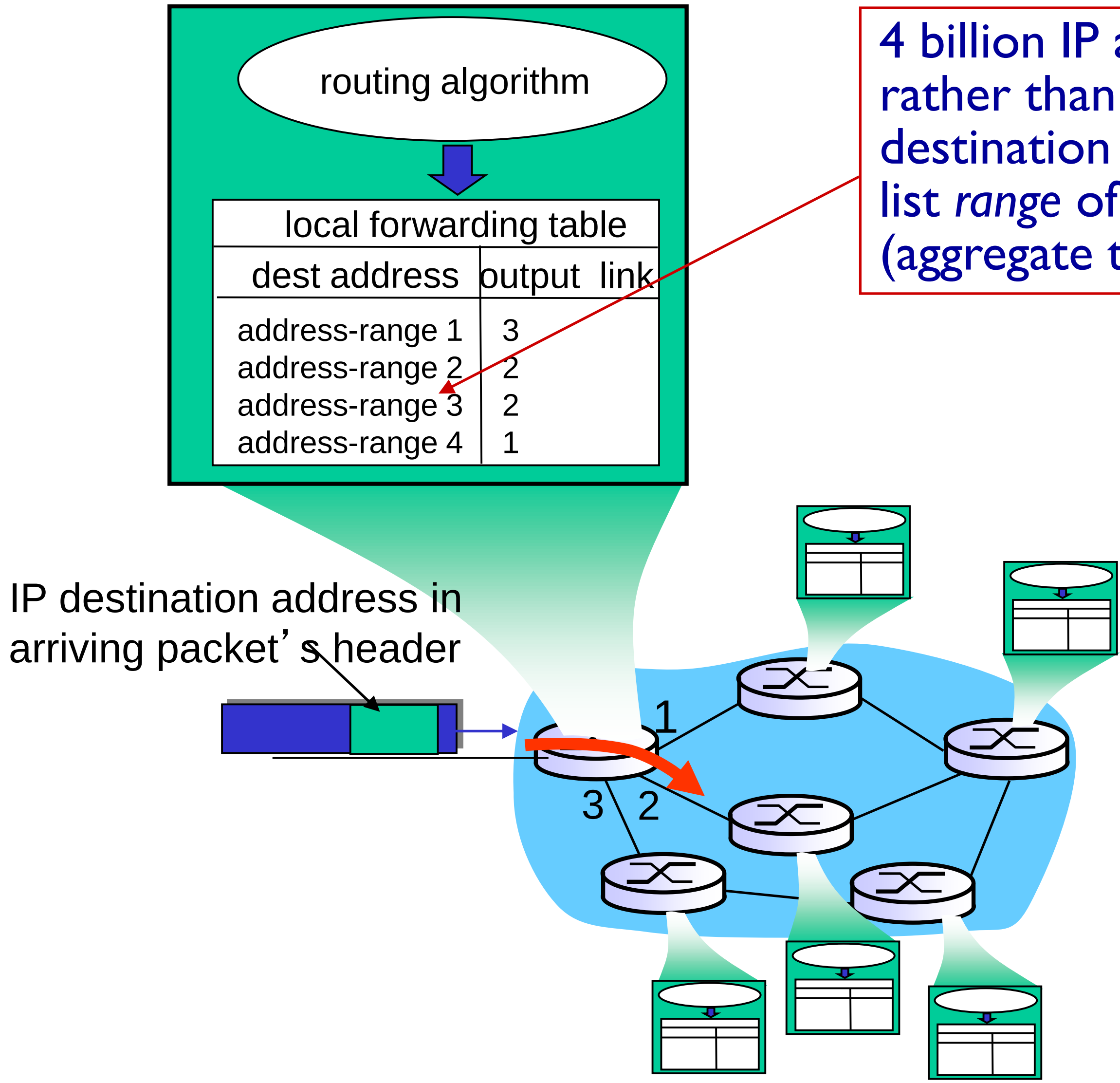
Datagram networks

- no call setup at network layer
- routers: no state about end-to-end connections
  - no network-level concept of "connection"
- packets forwarded using destination host address



Datagram forwarding table

4 billion IP addresses, so rather than list individual destination address list *range* of addresses (aggregate table entries)



Datagram forwarding table

Destination Address Range	Link Interface

`11001000 00010111 00010000 00000000`
through
`11001000 00010111 00010111 11111111`
	0

`11001000 00010111 00011000 00000000`
through
`11001000 00010111 00011000 11111111`
	1

`11001000 00010111 00011001 00000000`
through
`11001000 00010111 00011111 11111111`
	2

otherwise	3

Q: but what happens if ranges don't divide up so nicely?

Longest prefix matching

longest prefix matching

when looking for forwarding table entry for given destination address, use *longest* address prefix that matches destination address.

Destination Address Range	Link interface
11001000 00010111 00010*** *********	0
11001000 00010111 00011000 *********	1
11001000 00010111 00011*** *********	2
otherwise	3

examples:

DA: 11001000 00010111 00010110 10100001 which interface?

DA: 11001000 00010111 00011000 10101010 which interface?

Datagram or VC network: why?

Internet (datagram)

- data exchange among computers
  - "elastic" service, no strict timing req.
- many link types
  - different characteristics
  - uniform service difficult
- "smart" end systems (computers)
  - can adapt, perform control, error recovery
  - ***simple inside network, complexity at "edge"***

ATM (VC)

- evolved from telephony
- human conversation:
  - strict timing, reliability requirements
  - need for guaranteed service
- "dumb" end systems
  - telephones
  - ***complexity inside network***

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- link state
- distance vector
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4.6 routing in the Internet
- RIP
- OSPF
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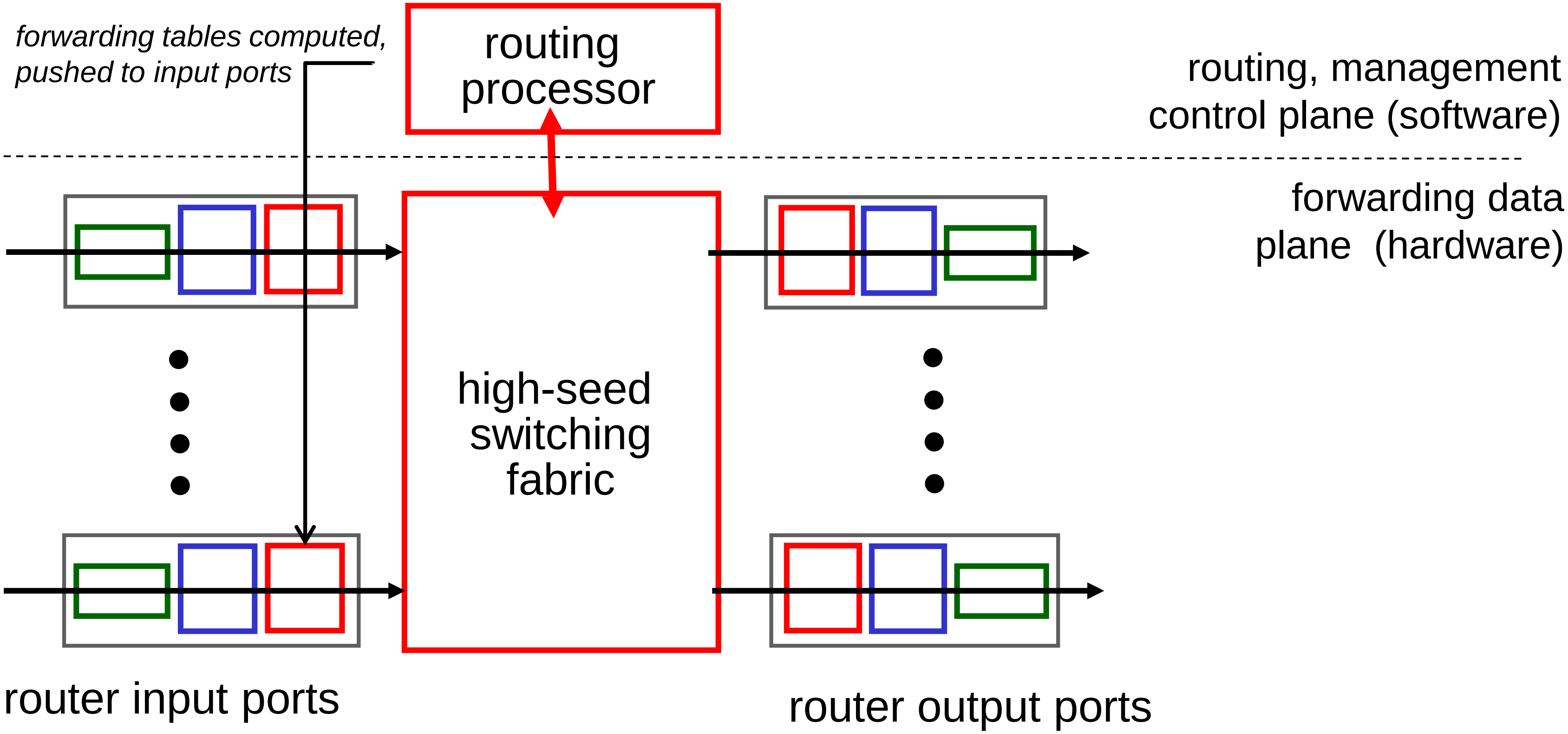
4.7 broadcast and multicast routing

Router architecture overview

two key router functions:

- run routing algorithms/protocol (RIP, OSPF, BGP)
- *forwarding* datagrams from incoming to outgoing link



How much buffering?

- RFC 3439 rule of thumb: average buffering equal to "typical" RTT (say 250 msec) times link capacity C
  - e.g., C = 10 Gpbs link: 2.5 Gbit buffer
- recent recommendation: with *N* flows, buffering equal to

$$\frac{RTT \cdot C}{\sqrt{N}}$$

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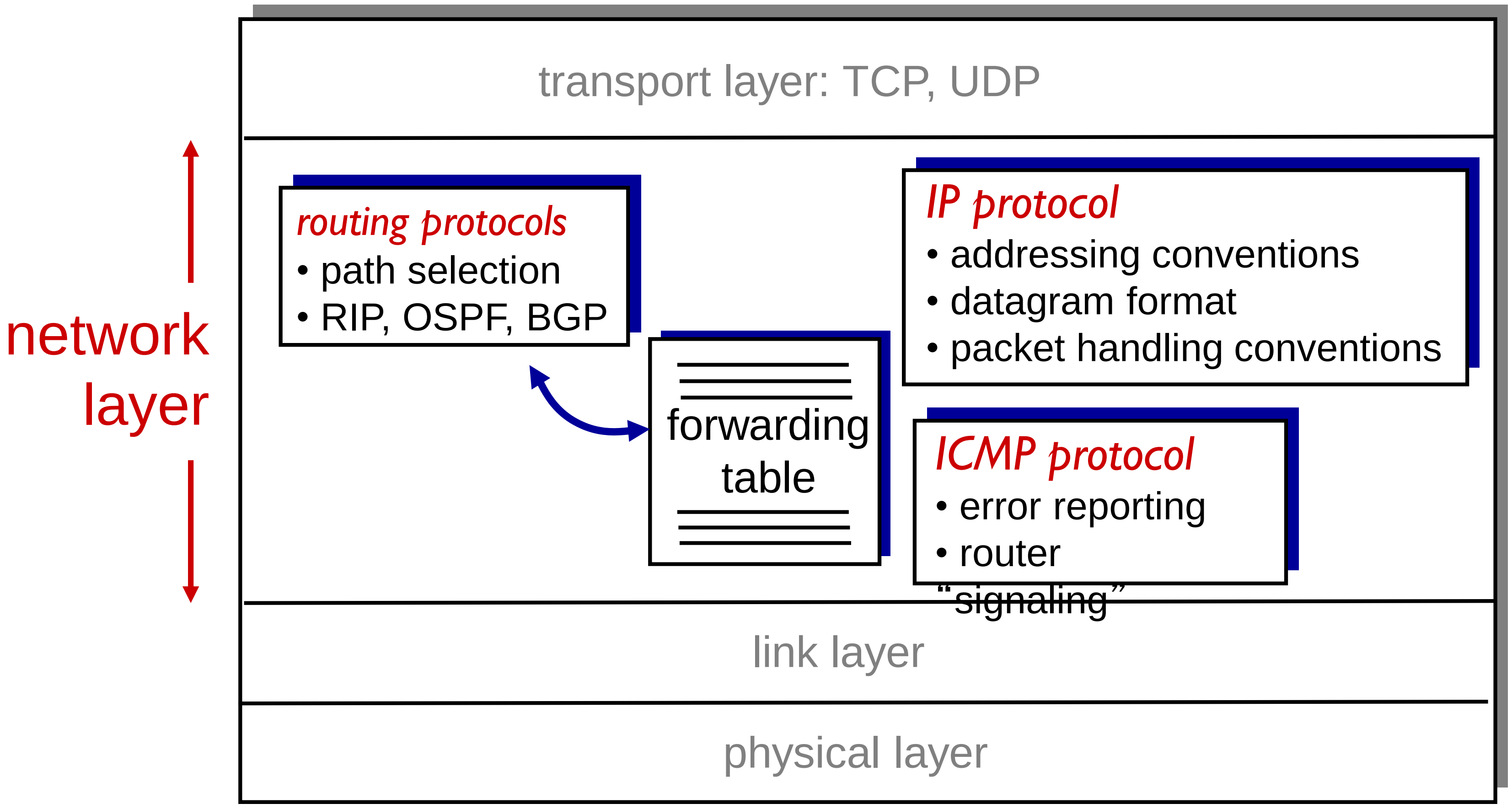
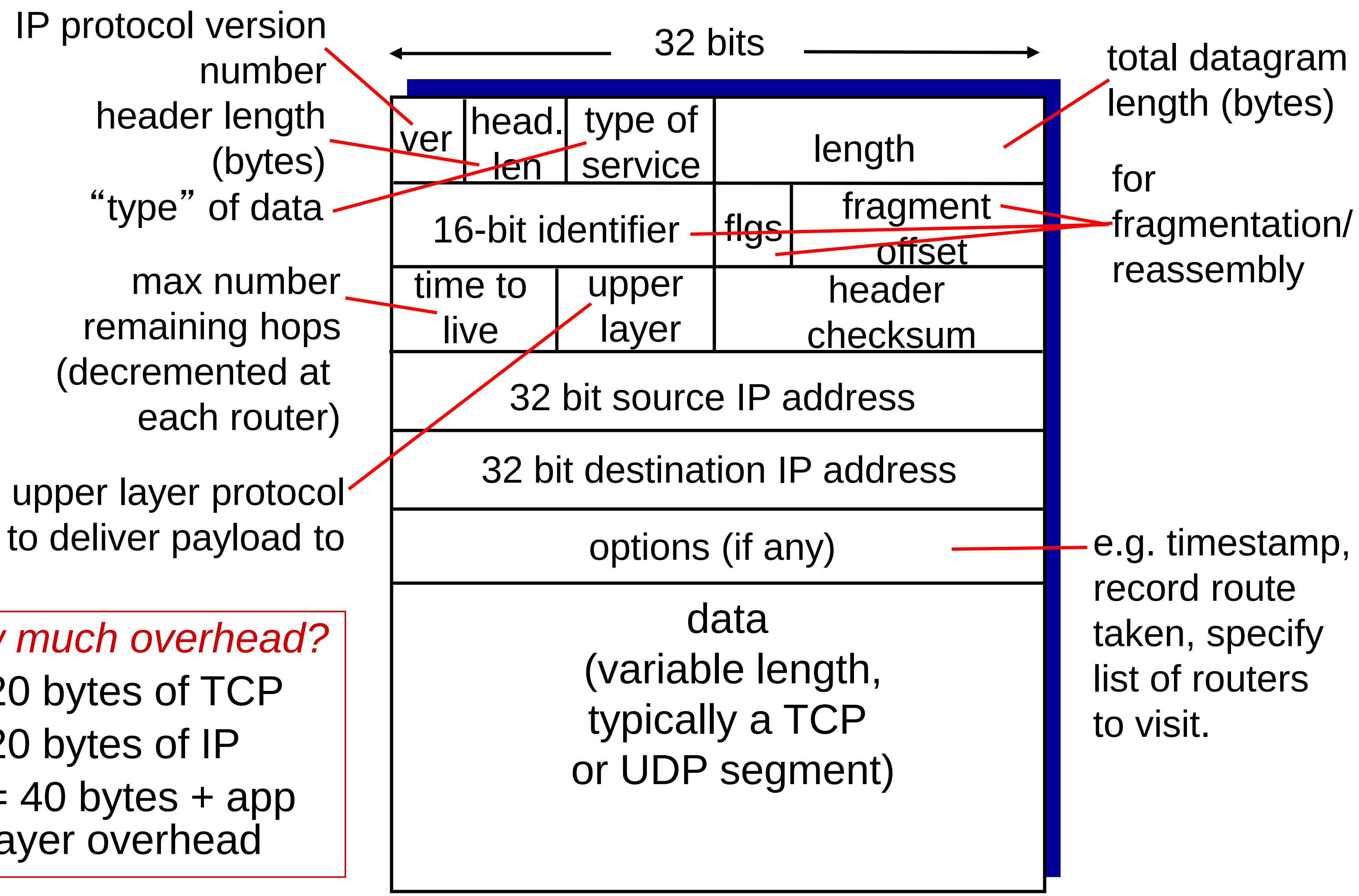
The Internet network layer

host, router network layer functions:



IP datagram format



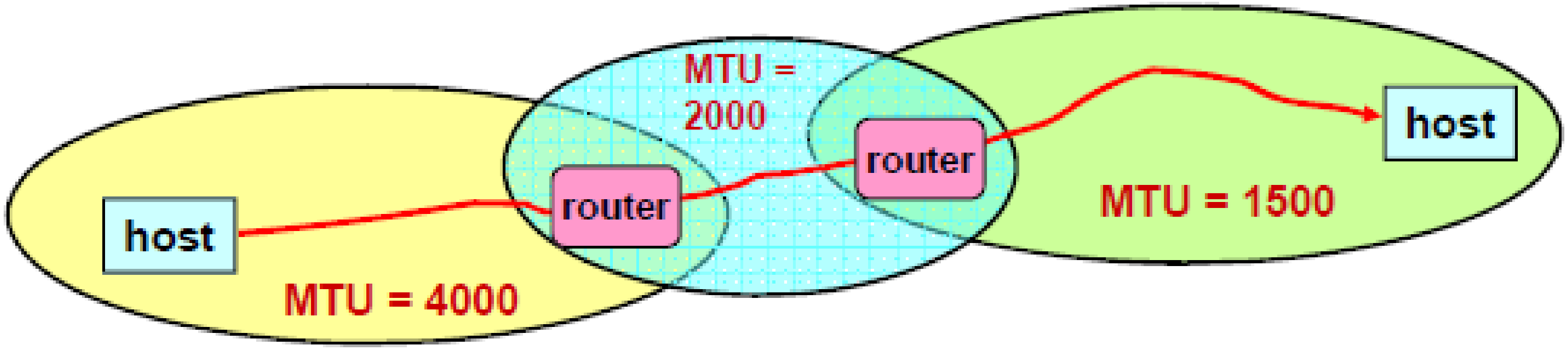
how much overhead?

- 20 bytes of TCP
- 20 bytes of IP
- = 40 bytes + app layer overhead

IP Delivery Model

- *Best effort service*
  - Network will do its best to get packet to destination
- Does NOT guarantee:
  - Any maximum latency or even ultimate success
  - Informing the sender if packet does not make it
  - Delivery of packets in same order as they were sent
  - Just one copy of packet will arrive
- Implications
  - Scales very well (really, it does)
  - Higher level protocols must make up for shortcomings
    - Reliably delivering ordered sequence of bytes → TCP
  - Some services not feasible (or hard)
    - Latency or bandwidth guarantees

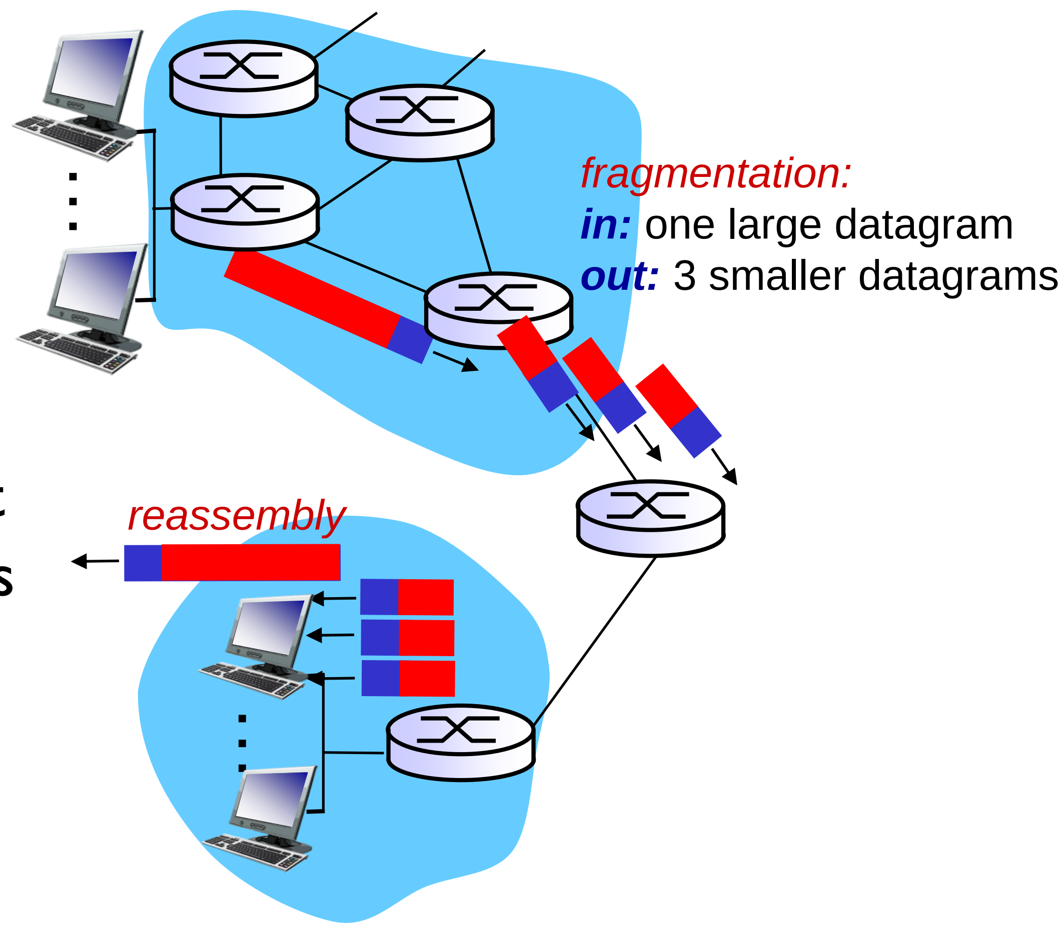
IP Fragmentation



- Every network has own Maximum Transmission Unit (MTU)
  - Largest IP datagram it can carry within its own packet frame
    - E.g., Ethernet is 1500 bytes
  - Don't know MTUs of all intermediate networks in advance
- IP Solution
  - When hit network with small MTU, router fragments packet
  - Destination host reassembles the paper – why?

IP fragmentation, reassembly

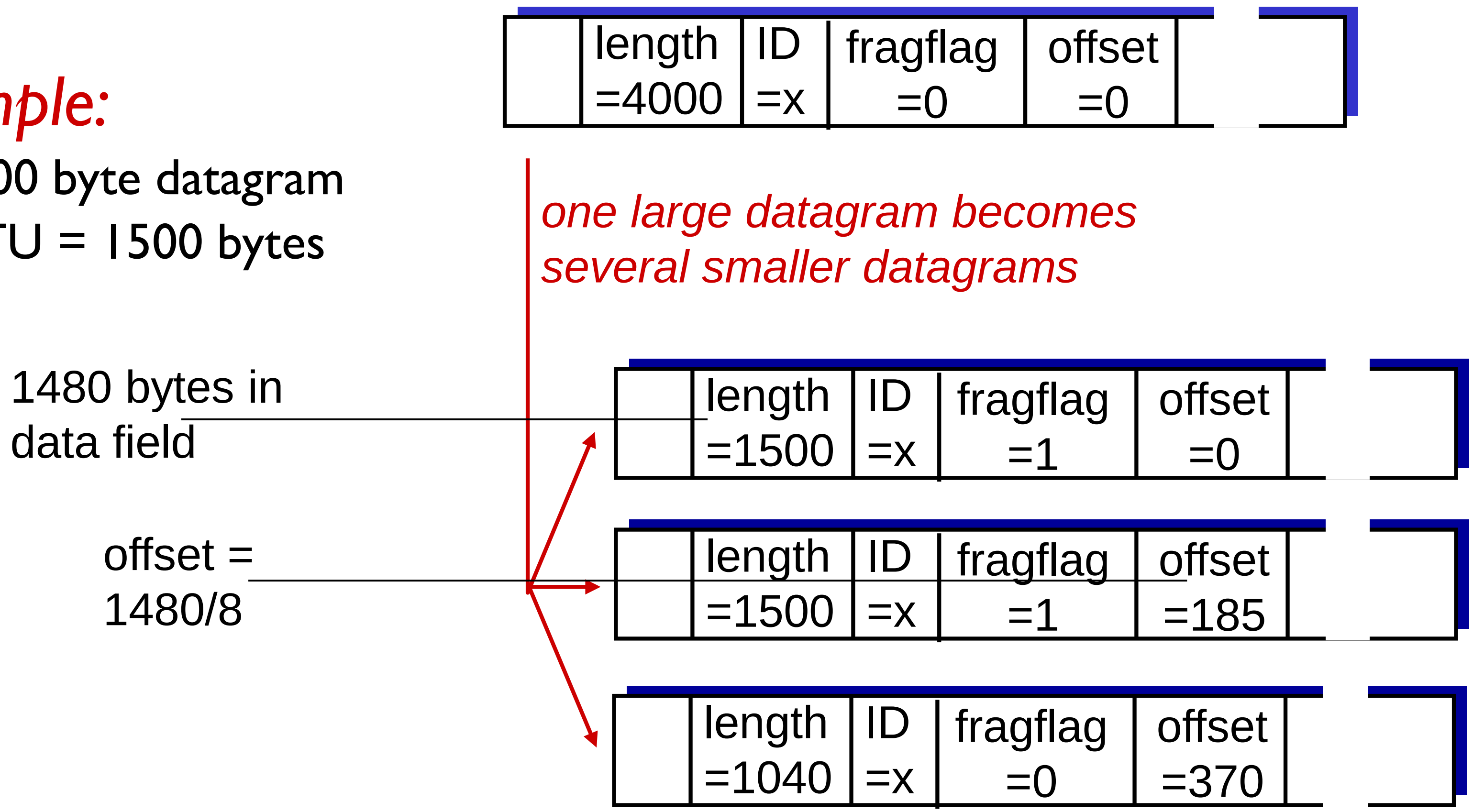
- network links have MTU (max.transfer size) - largest possible link-level frame
  - different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only at final destination
  - IP header bits used to identify, order related fragments



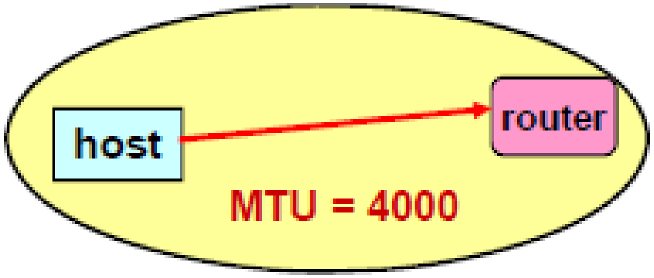
IP fragmentation, reassembly

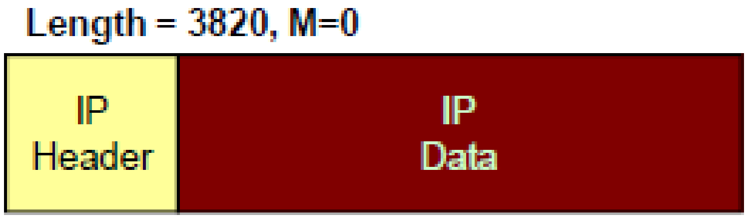
example:

- 4000 byte datagram
- MTU = 1500 bytes



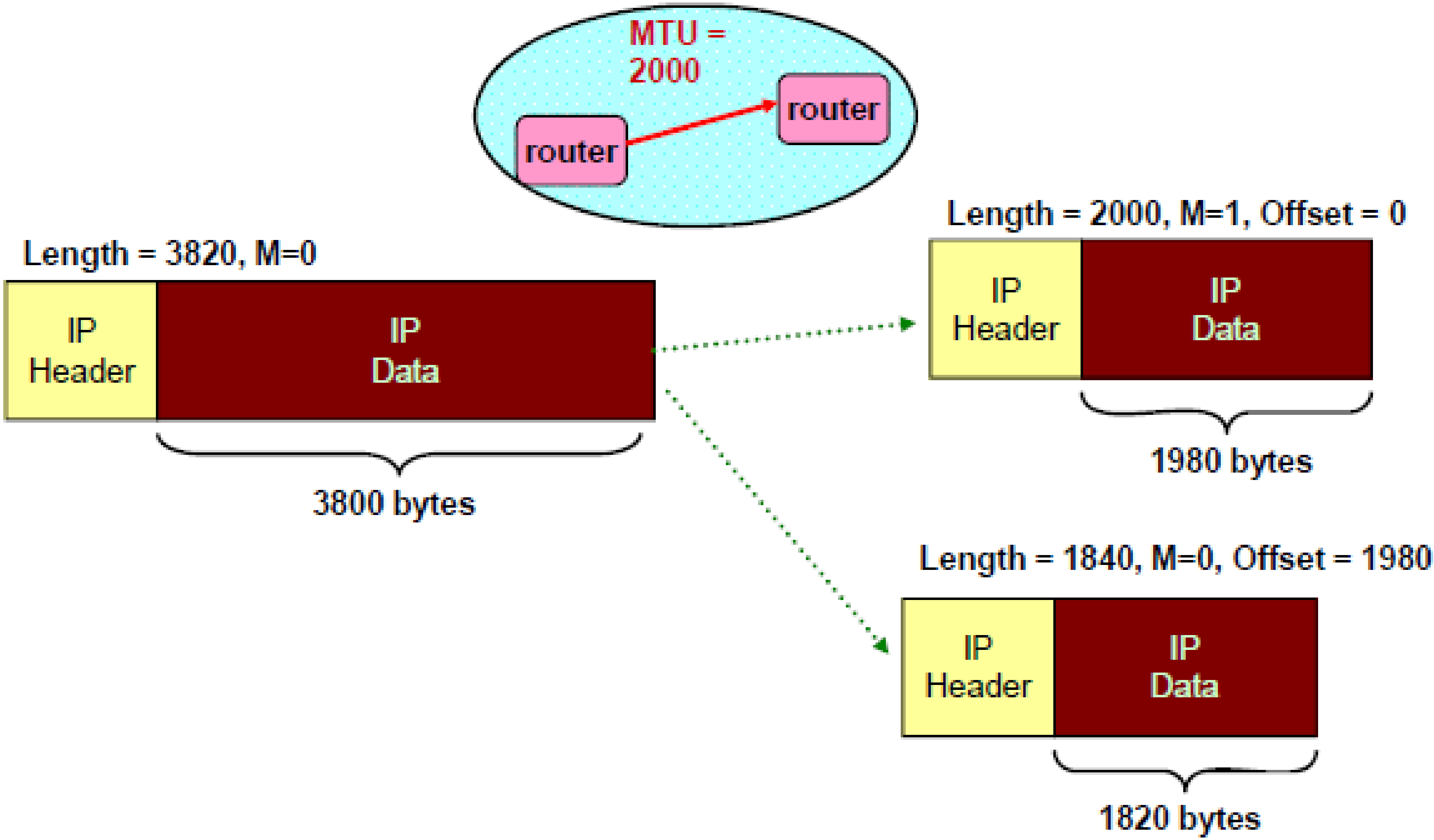
IP Fragmentation Example #1



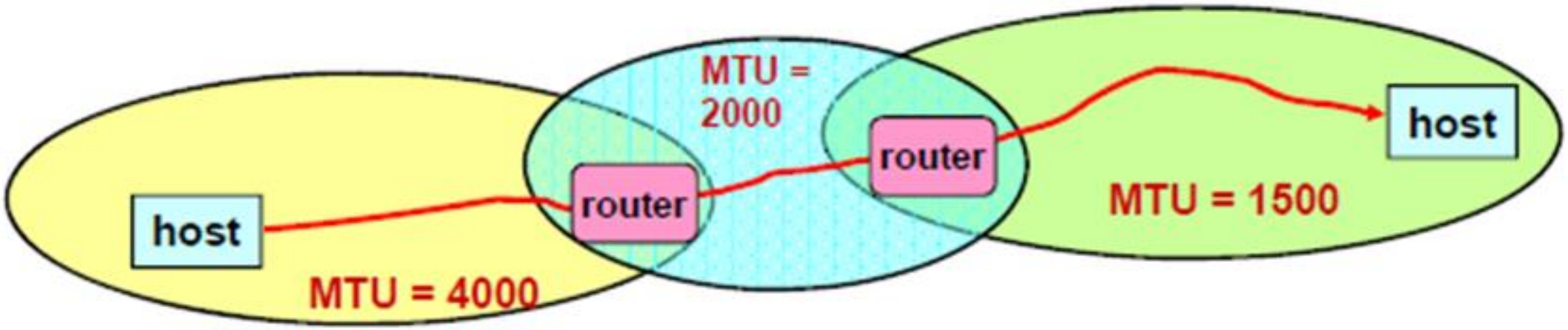


(20 bytes header)

IP Fragmentation Example #2

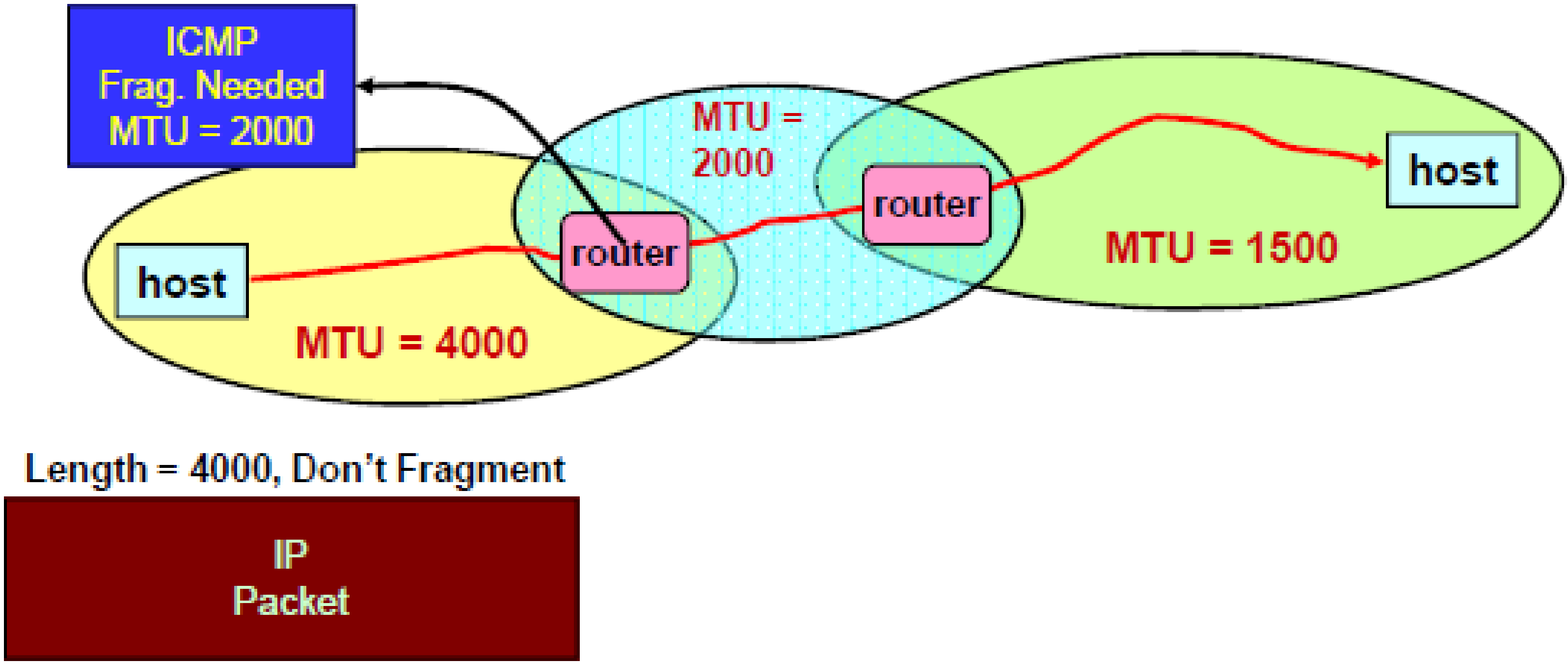


IP MTU Discovery with ICMP

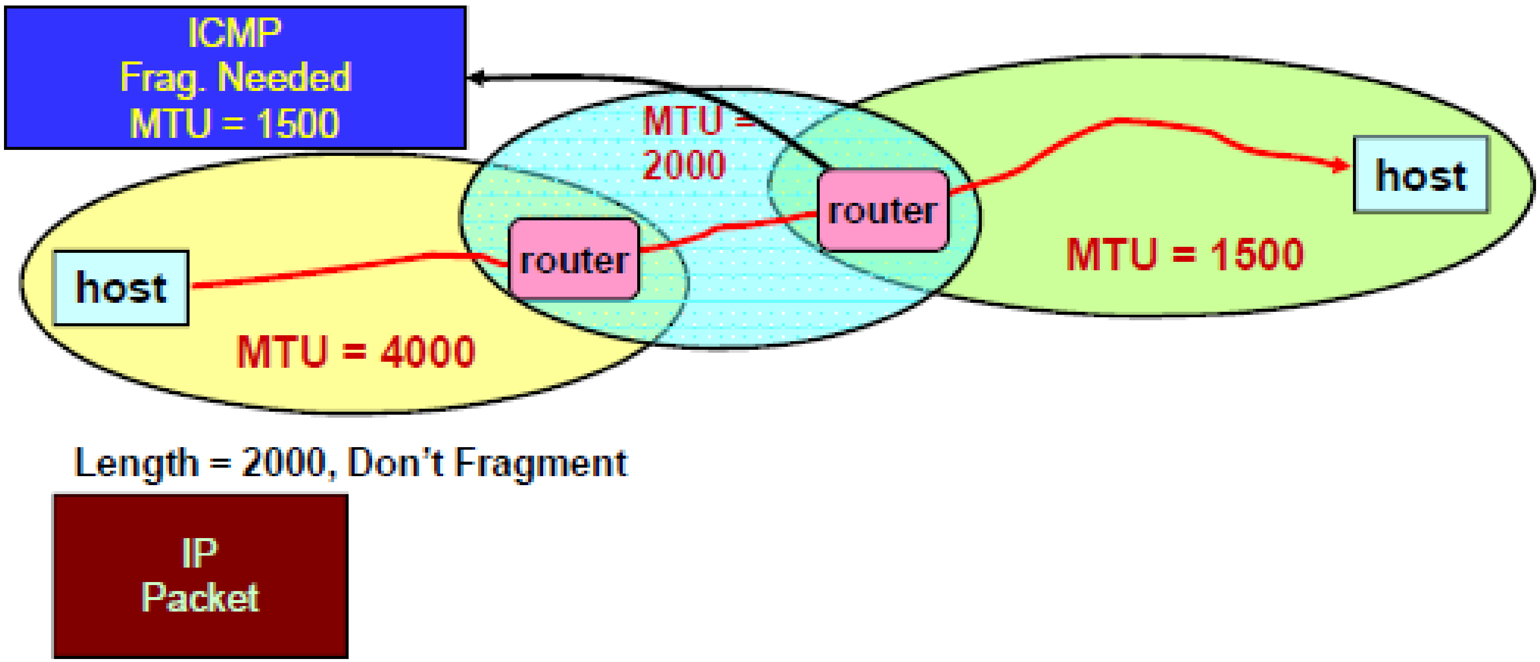


- Typically send series of packets from one host to another
- Typically, all will follow same route
  - Routes remain stable for minutes at a time
- Makes sense to determine path MTU before sending real packets
- Operation: Send max-sized packet with "do not fragment" flag set
  - If encounters problem, ICMP message will be returned
    - "Destination unreachable: Fragmentation needed"
    - Usually indicates MTU problem encountered

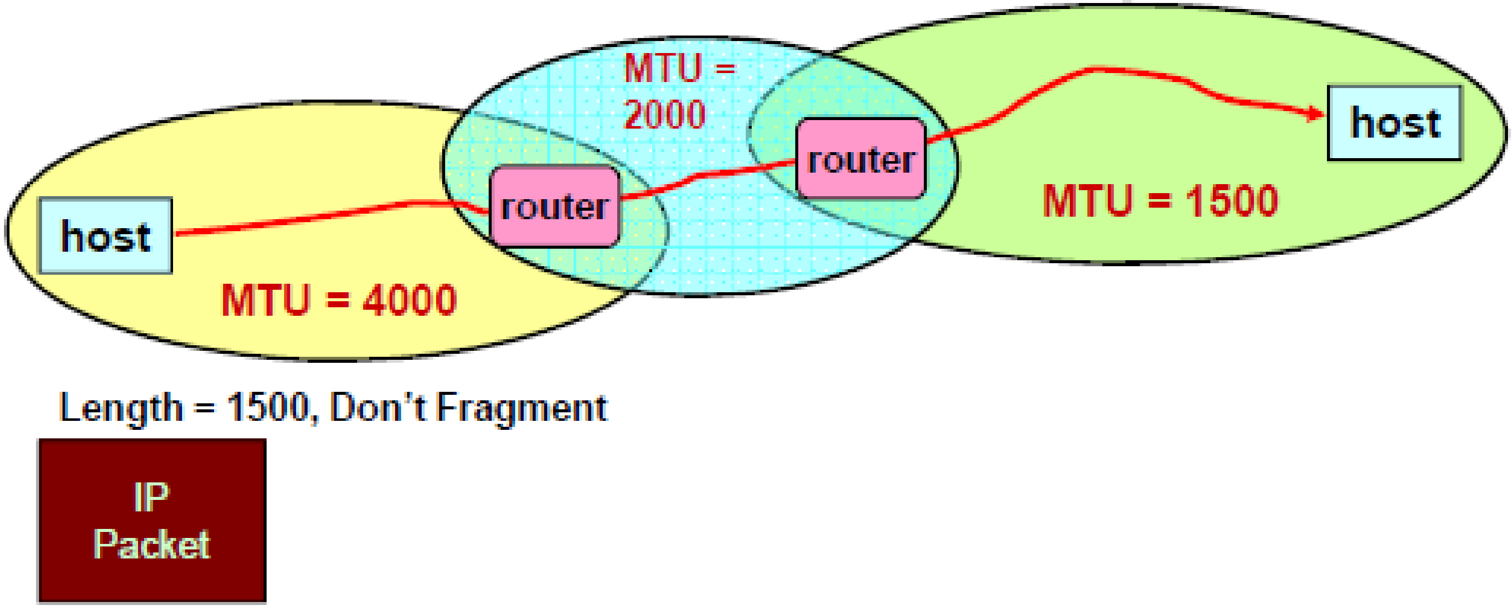
IP MTU Discovery with ICMP



IP MTU Discovery with ICMP



IP MTU Discovery with ICMP



- When successful, no reply at IP level
  - "No news is good news"
- Higher level protocol might have some form of acknowledgement

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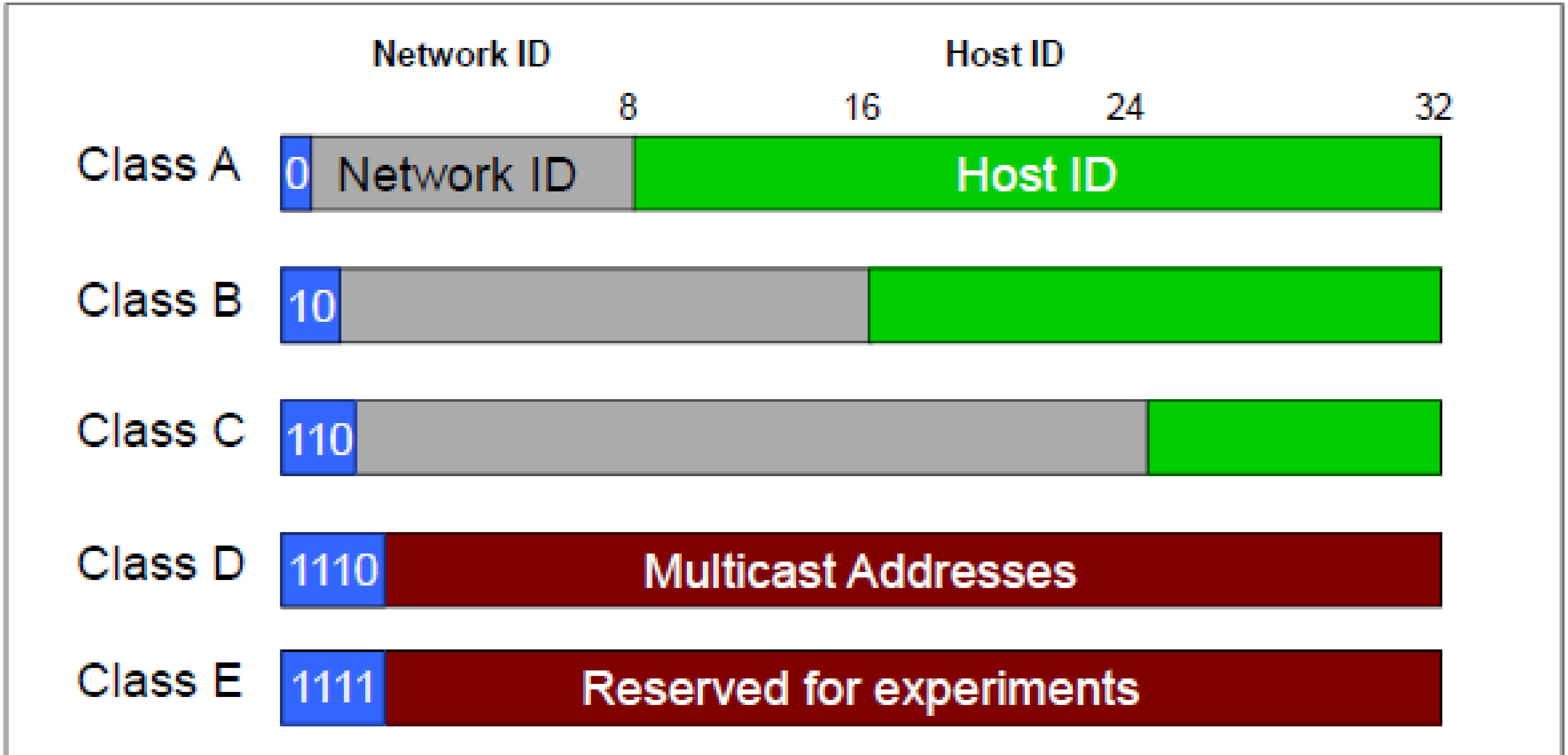
IP Address Structure

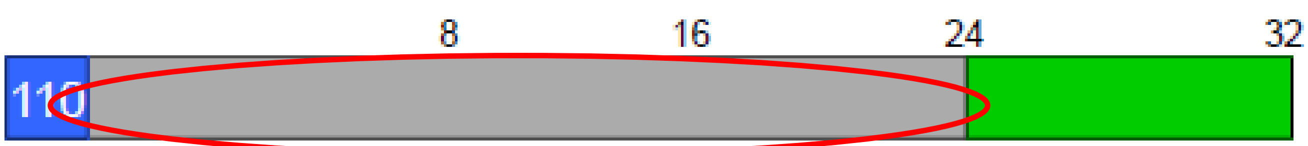
Challenge: Accommodate networks of different very sizes

Initially: classful structure (1981) (not relevant now!!!)



Original IP Route Lookup

- Address specifies prefix for forwarding table
  - Extract address type and network ID
- Forwarding table contains
  - List of class+network entries
  - A few fixed prefix lengths (8/16/24)
  - Prefix – part of address that really matters for routing
- www.cmu.edu address 128.2.11.43
  - Class B address – class + network is 128.2
  - Lookup 128.2 in forwarding table for class B
- Tables are still large!
  - 2 Million class C networks



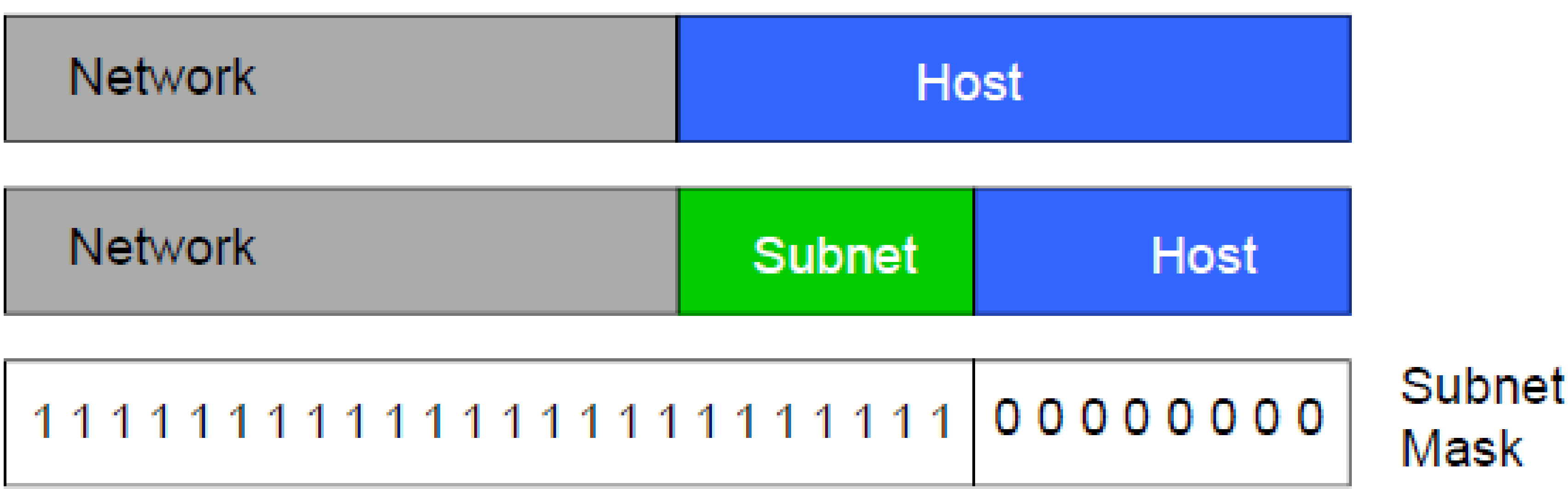
Subnet Addressing RFC917 (1984)

- Some “LANs” are very big, class A & B networks
  - Large companies, universities, …
  - Internet became popular quickly
- Cannot manage this as a single LAN
  - Hard to manage, becomes inefficient
- Need simple way to partition large networks
  - Partition into multiple IP networks that share the same prefix – called a “subnet”, part of a network

***Request for Comments**

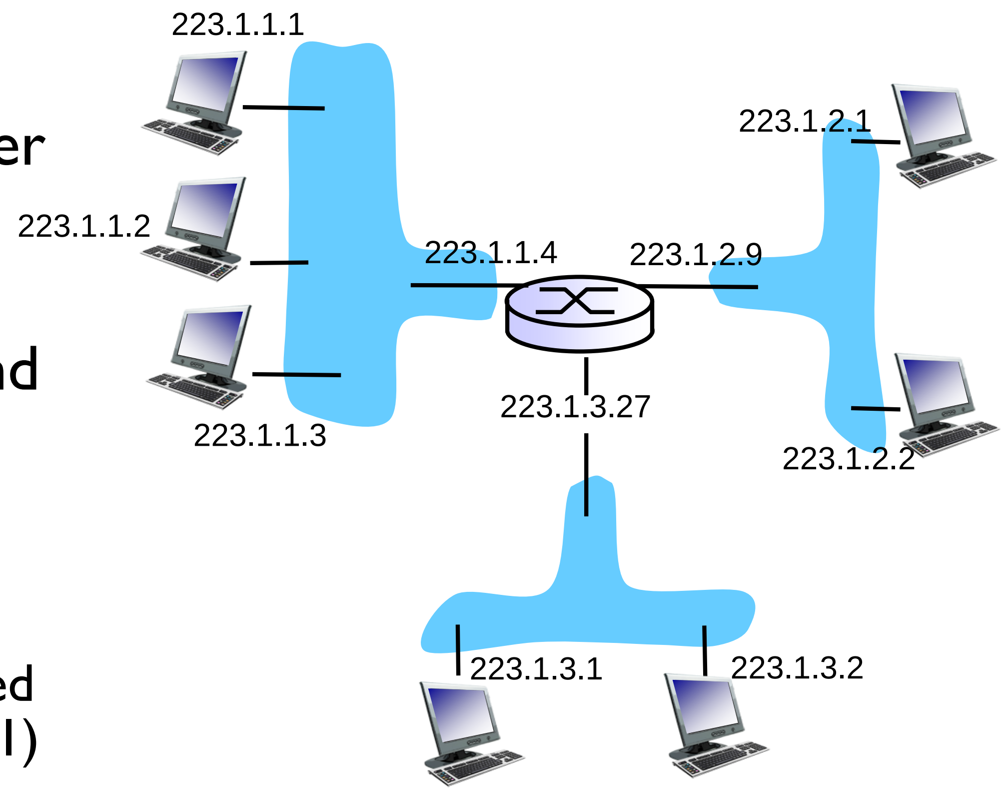
Subnetting

- Add another layer to hierarchy
- Variable length subnet masks
  - Could subnet a class B into several chunks
- Subnetting is done internally in the organization
  - It is not visible outside – important for management



IP addressing: introduction

- *IP address:* 32-bit identifier for host, router *interface*
- *interface:* connection between host/router and physical link
  - router's typically have multiple interfaces
  - host typically has one or two interfaces (e.g., wired Ethernet, wireless 802.11)
- *IP addresses associated with each interface*

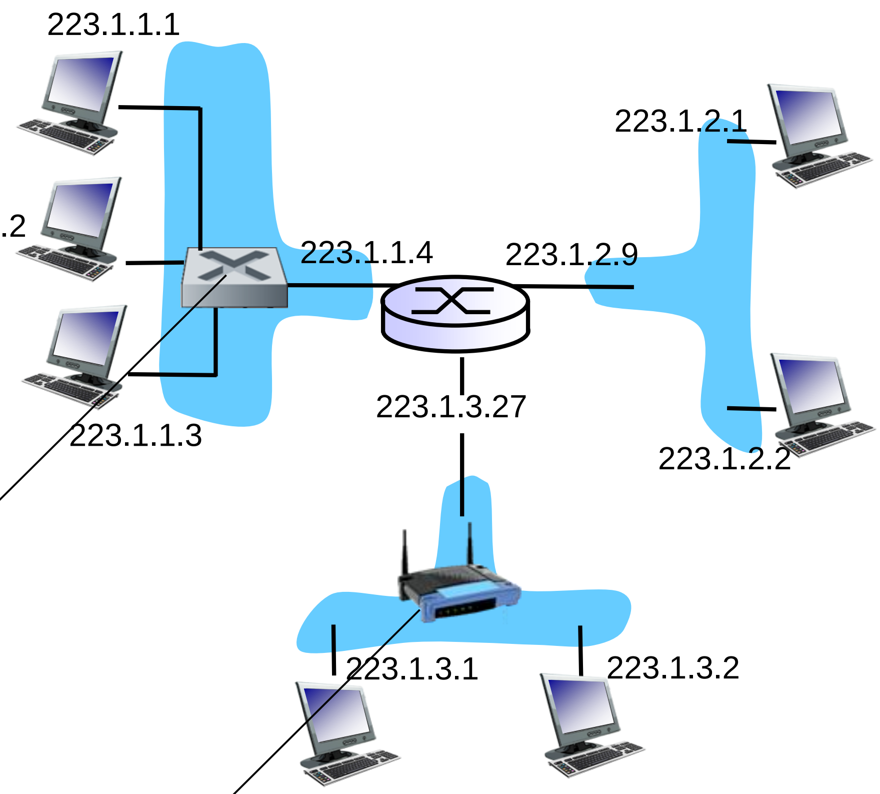


$$223.1.1.1 = \underbrace{11011111}_{223}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}\ \underbrace{00000001}_{1}$$

IP addressing: introduction

Q: how are interfaces actually connected?

A: we'll learn about that in chapter 5, 6.



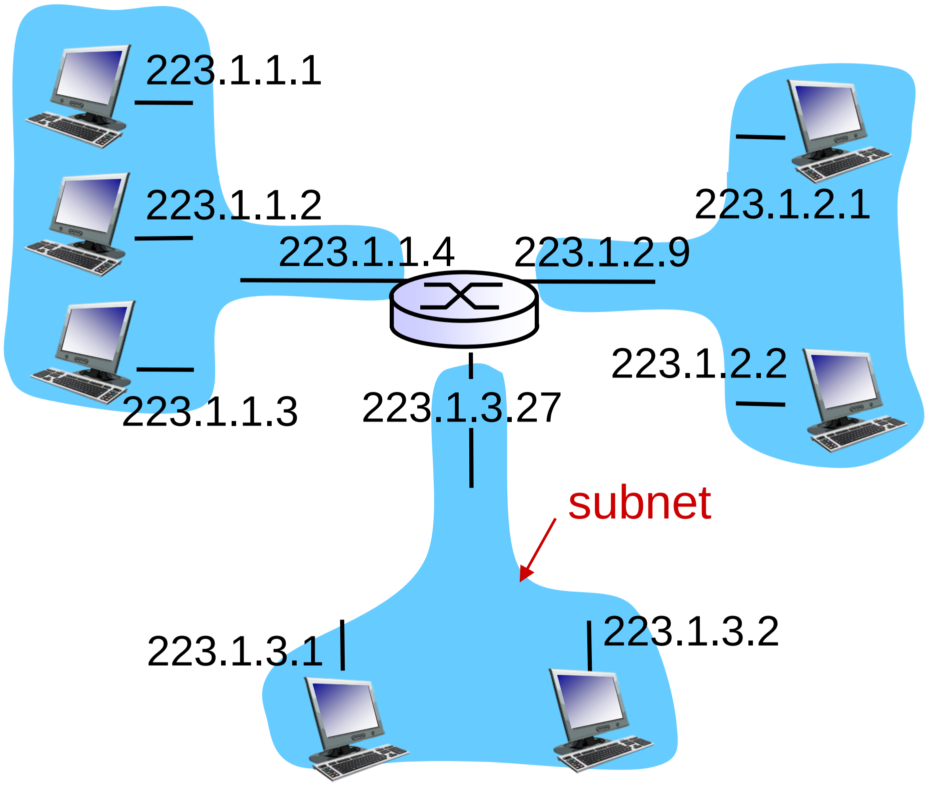
A: wired Ethernet interfaces connected by Ethernet switches

A: wireless WiFi interfaces connected by WiFi base station

For now: don't need to worry about how one interface is connected to another (with no intervening router)

Subnets

- IP address:
  - subnet part - high order bits
  - host part - low order bits
- *what's a subnet ?*
  - device interfaces with same subnet part of IP address
  - can physically reach each other *without intervening router*

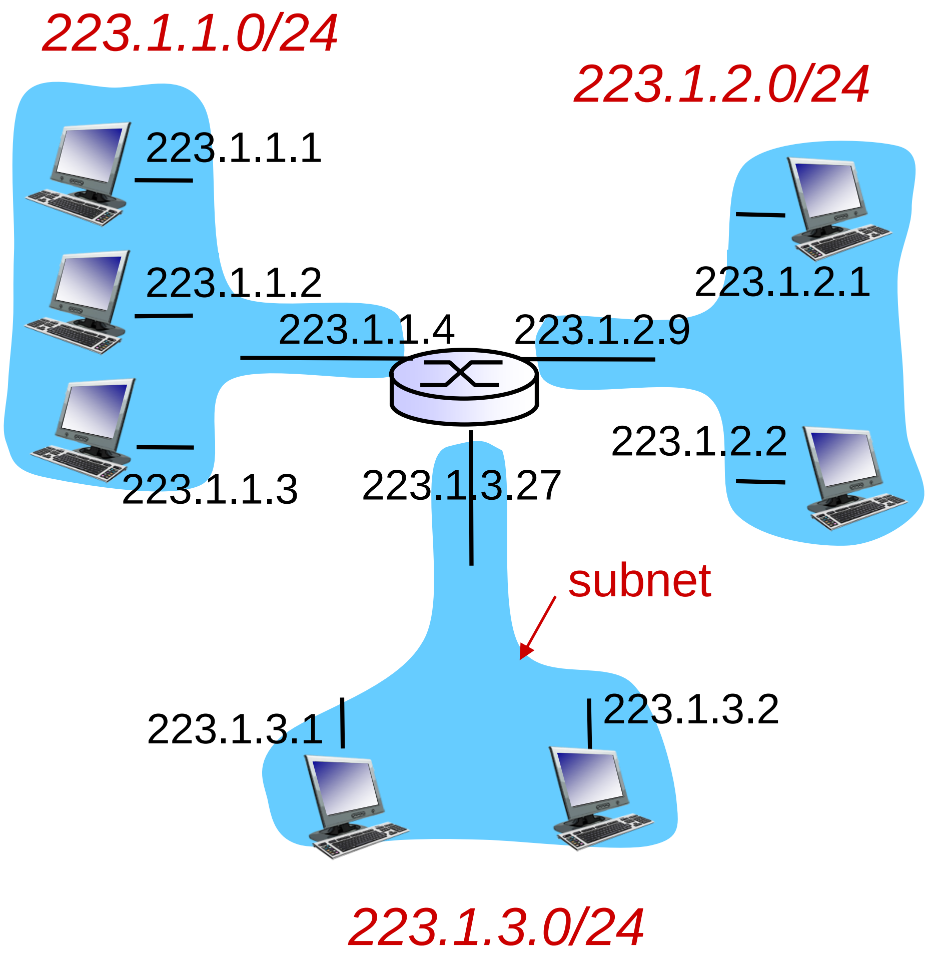


network consisting of 3 subnets

Subnets

recipe

- to determine the subnets, detach each interface from its host or router, creating islands of isolated networks
- each isolated network is called a *subnet*



subnet mask: /24

Subnetting Example

- Assume an organization was assigned address 150.100
- Assume < 100 hosts per subnet
- How many host bits do we need?
  - Seven
- What is the network mask?
  - 11111111 11111111 11111111 10000000
  - 255.255.255.128

IP addressing: CIDR

CIDR: Classless InterDomain Routing

- subnet portion of address of arbitrary length
- address format: a.b.c.d/x, where x is # bits in subnet portion of address

subnet part | host part

11001000 00010111 00010000 00000000

200.23.16.0/23

	Binary form	Dot-decimal notation
IP address	`11000000.10101000.00000101.10000010`	`192.168.5.130`
Subnet mask	`11111111.11111111.11111111.00000000`	`255.255.255.0`

- Example: 8-bit host address

	Binary form	Dot-decimal notation
IP address	11000000.10101000.00000101.10000010	192.168.5.130
Subnet mask	11111111.11111111.11111111.00000000	255.255.255.0
Network prefix	11000000.10101000.00000101.00000000	192.168.5.0

- Example: 8-bit host address

	Binary form	Dot-decimal notation
IP address	11000000.10101000.00000101.10000010	192.168.5.130
Subnet mask	11111111.11111111.11111111.00000000	255.255.255.0
Network prefix	11000000.10101000.00000101.00000000	192.168.5.0
Host part	00000000.00000000.00000000.10000010	0.0.0.130

- Example 2: **6-bit** host address

	Binary form	Dot-decimal notation
IP address	11000000.10101000.00000101.10000010	192.168.5.130
Subnet mask	11111111.11111111.11111111.**11**000000	255.255.255.192
Network prefix	11000000.10101000.00000101.10000000	192.168.5.128
Host part	00000000.00000000.00000000.00000010	0.0.0.2

IP addresses: how to get one?

Q: How does a *host* get IP address?

- hard-coded by system admin in a file
  - Windows: control-panel->network->configuration->tcp/ip->properties
  - UNIX: /etc/rc.config
- DHCP: Dynamic Host Configuration Protocol: dynamically get address from as server
  - "plug-and-play"

DHCP: Dynamic Host Configuration Protocol

goal: allow host to *dynamically* obtain its IP address from network server when it joins network

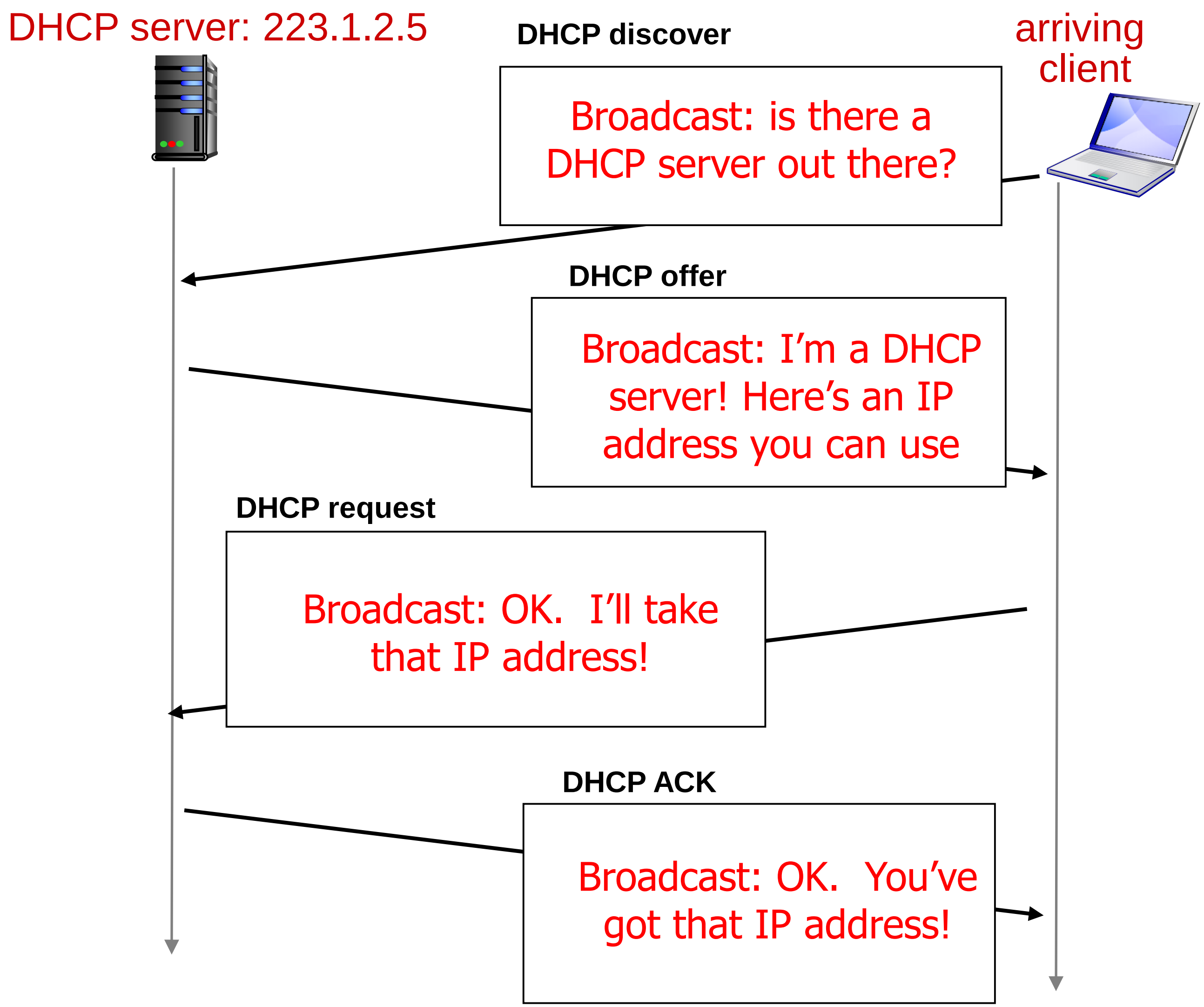
- can renew its lease on address in use
- allows reuse of addresses (only hold address while connected/"on")
- support for mobile users who want to join network (more shortly)

DHCP overview:

- host broadcasts "DHCP discover" msg [optional]
- DHCP server responds with "DHCP offer" msg [optional]
- host requests IP address: "DHCP request" msg
  - Still broadcast (not unicast): Multiple DHCP servers may exist, all servers are informed about

    the request (the agreement with particular DHCP server)
- DHCP server sends address: "DHCP ack" msg

DHCP client-server scenario



DHCP: more than IP addresses

DHCP can return more than just allocated IP address on subnet:

- address of first-hop router for client
- name and IP address of DNS server
- network mask (indicating network versus host portion of address)

IP addresses: how to get one?

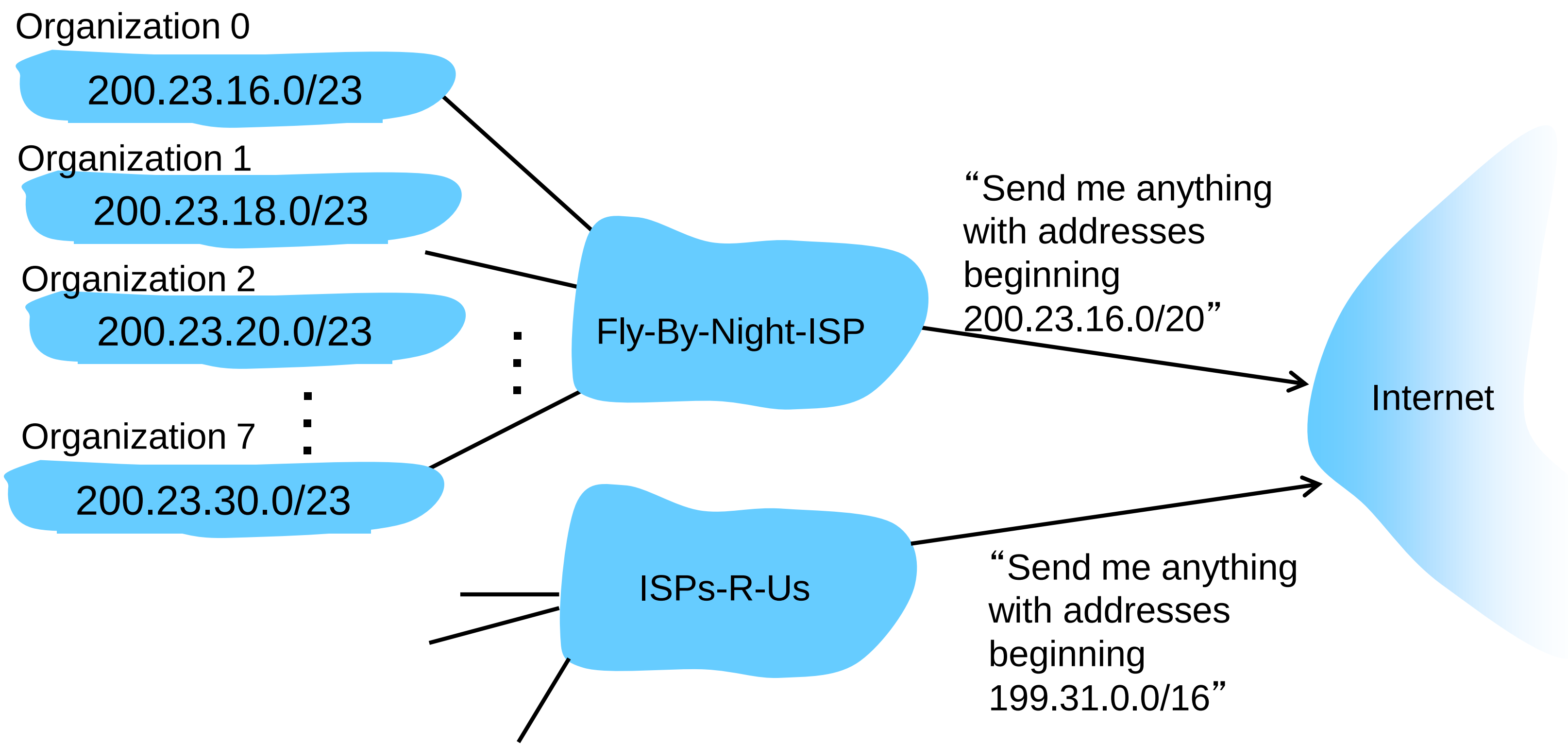
Q: how does *network* get subnet part of IP addr?

A: gets allocated portion of its provider ISP's address space

ISP's block	11001000 00010111 00010000 00000000	200.23.16.0/20
Organization 0	11001000 00010111 00010000 00000000	200.23.16.0/23
Organization 1	11001000 00010111 00010010 00000000	200.23.18.0/23
Organization 2	11001000 00010111 00010100 00000000	200.23.20.0/23
...	....	....
Organization 7	11001000 00010111 00011110 00000000	200.23.30.0/23

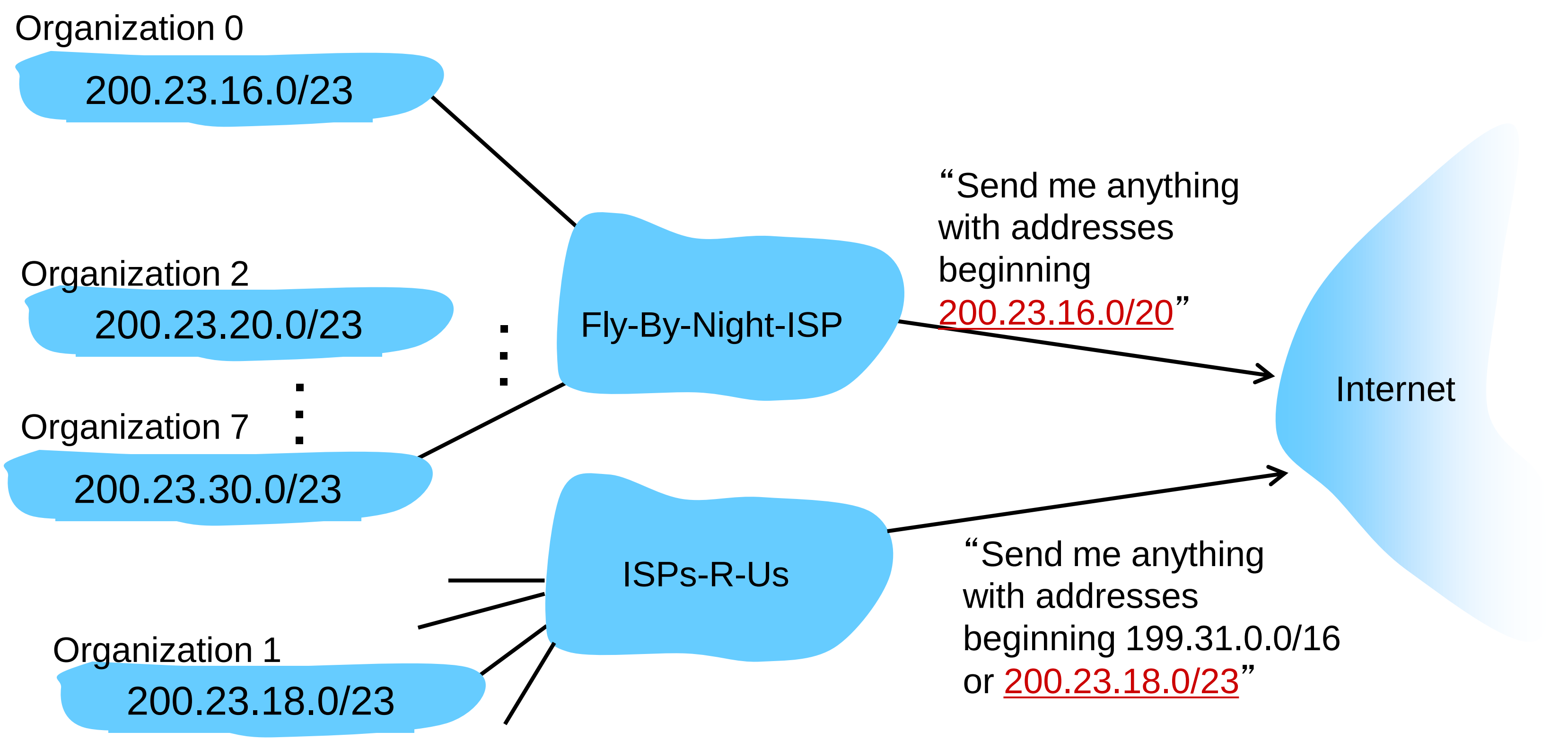
Hierarchical addressing: route aggregation

hierarchical addressing allows efficient advertisement of routing information:



Hierarchical addressing: more specific routes

ISPs-R-Us has a more specific route to Organization 1



IP addressing: the last word...

Q: how does an ISP get block of addresses?

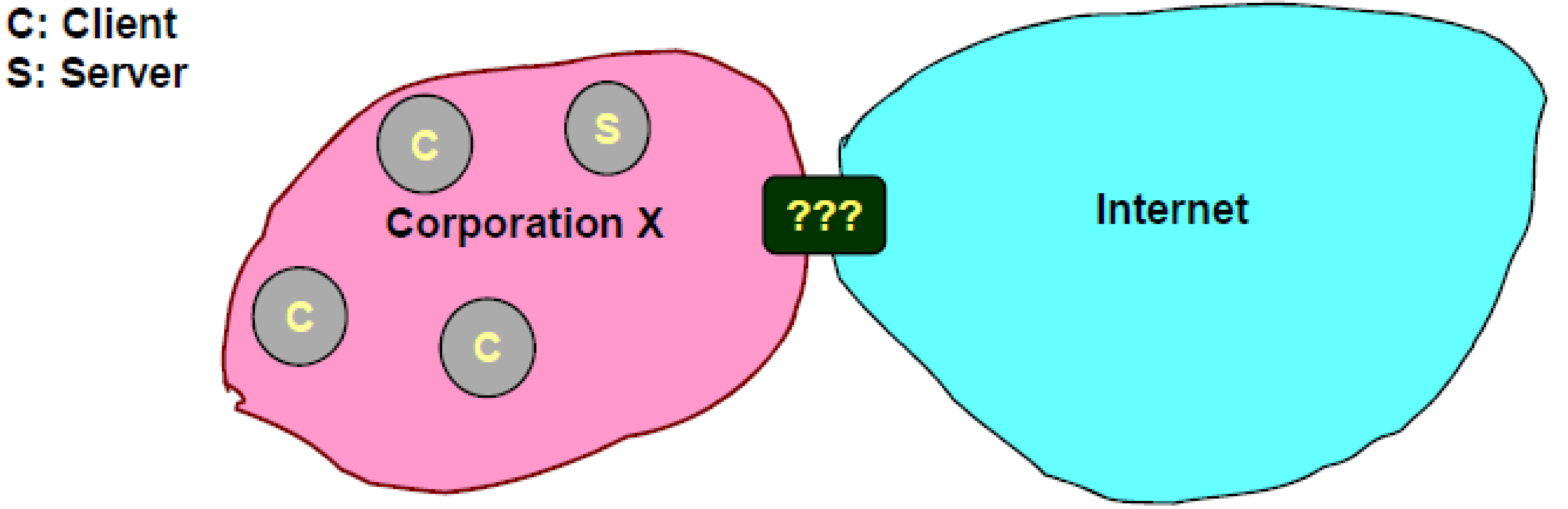
A: ICANN: Internet Corporation for Assigned Names and Numbers http://www.icann.org/

- allocates addresses
- manages DNS
- assigns domain names, resolves disputes

Altering the Addressing Model

- Original IP Model: Every host has unique IP address
- This has very attractive properties …
  - Any host can communicate with any other host
  - Any host can act as a server
    - Just need to know host ID and port number
- … but the system is open – complicates security
  - Any host can attack any other host
  - It is easy to forge packets
    - Use invalid source address
- … and it places pressure on the address space
  - Every host requires “public” IP address

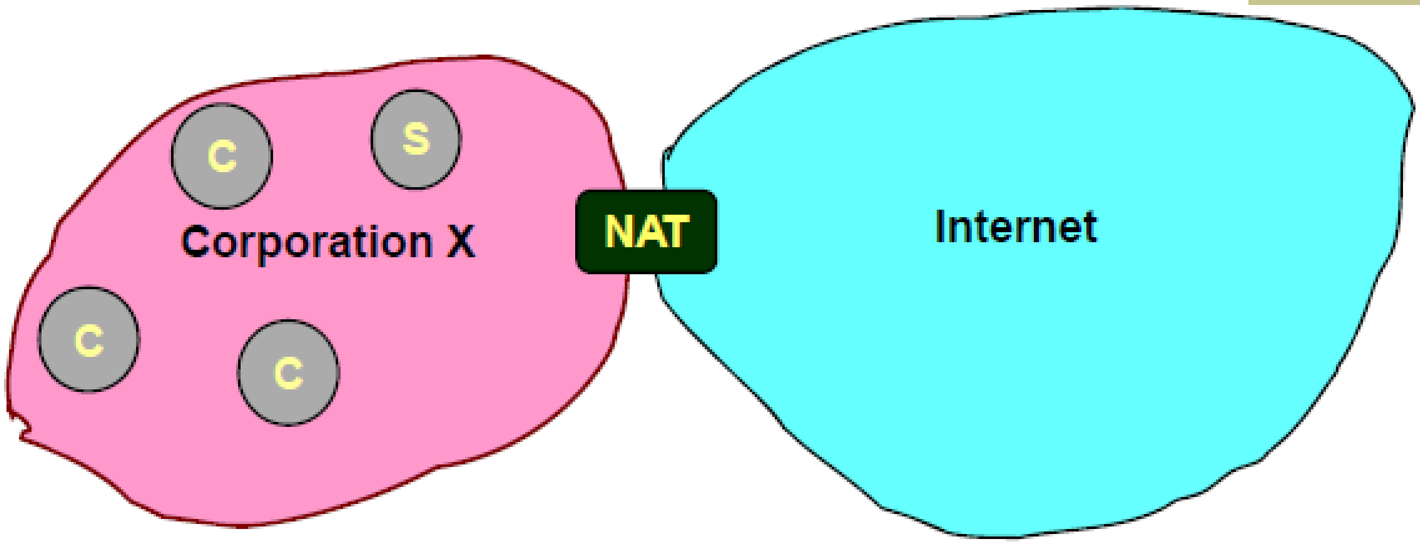
Challenges When Connecting to Public Internet



- Not enough IP addresses for every host in organization
  - Increasingly hard to get large address blocks
- Security
  - Don't want every machine in organization known to outside world
  - Want to control or monitor traffic in / out of organization

But not All Hosts are Equal!

C: Client
S: Server

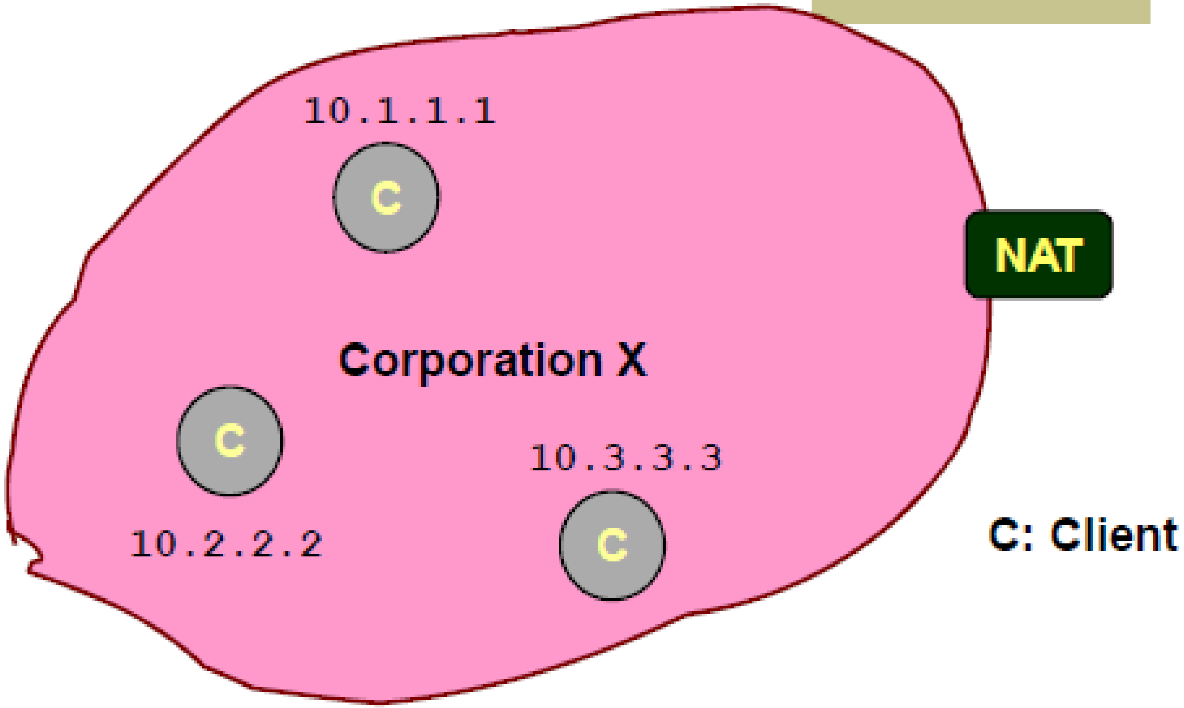


- Most machines within organization are used by individuals
  - For most applications, they act as clients
- Only a small number of machines act as servers for the entire organization
  - E.g., mail server, web, ..
  - All traffic to outside passes through firewall

(Most) machines within organization do not need public IP addresses!

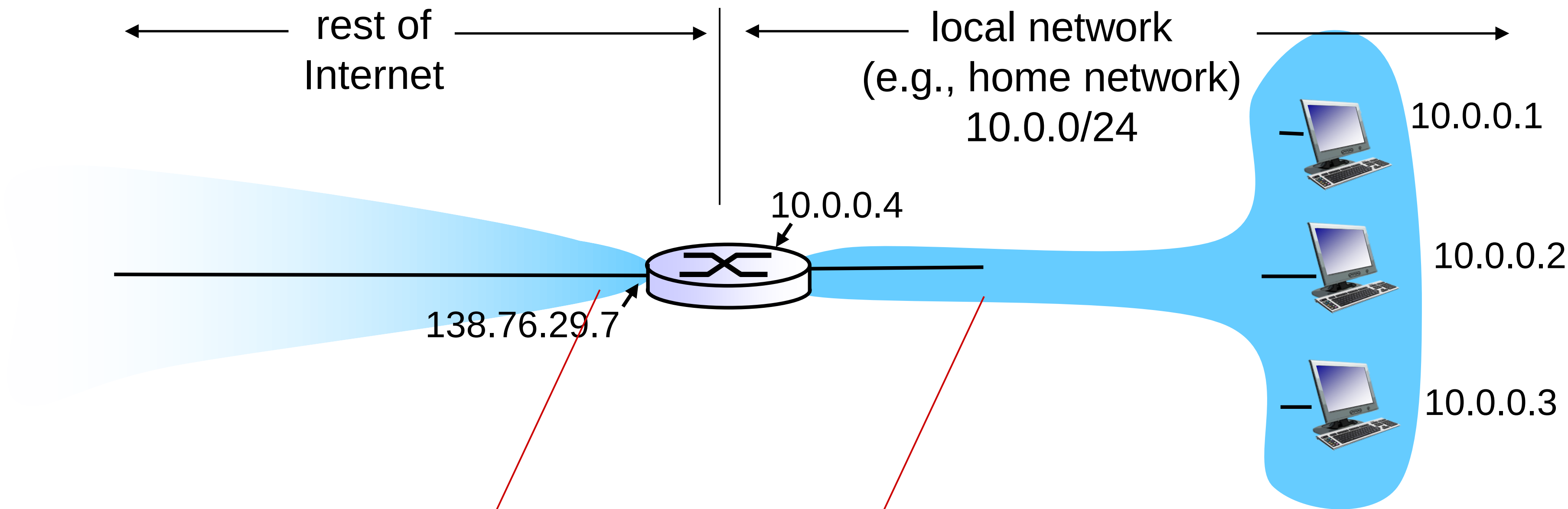
Reducing Address Use: Network Address Translation

- Within organization: assign each host a private IP address
  - IP addresses blocks 10/8 & 192.168/16 are set aside for this
  - Route within organization by IP protocol
  - Can do subnetting, ..



- The NAT translates between public and private IP addresses as packets travel to/from the public Internet
  - It does not let any packets from internal nodes “escape”
  - Outside world does not need to know about internal addresses

NAT: network address translation



all datagrams *leaving* local network have *same* single source NAT IP address: 138.76.29.7,different source port numbers

datagrams with source or destination in this network have 10.0.0/24 address for source, destination (as usual)

NAT: network address translation

motivation: local network uses just one IP address as far as outside world is concerned:

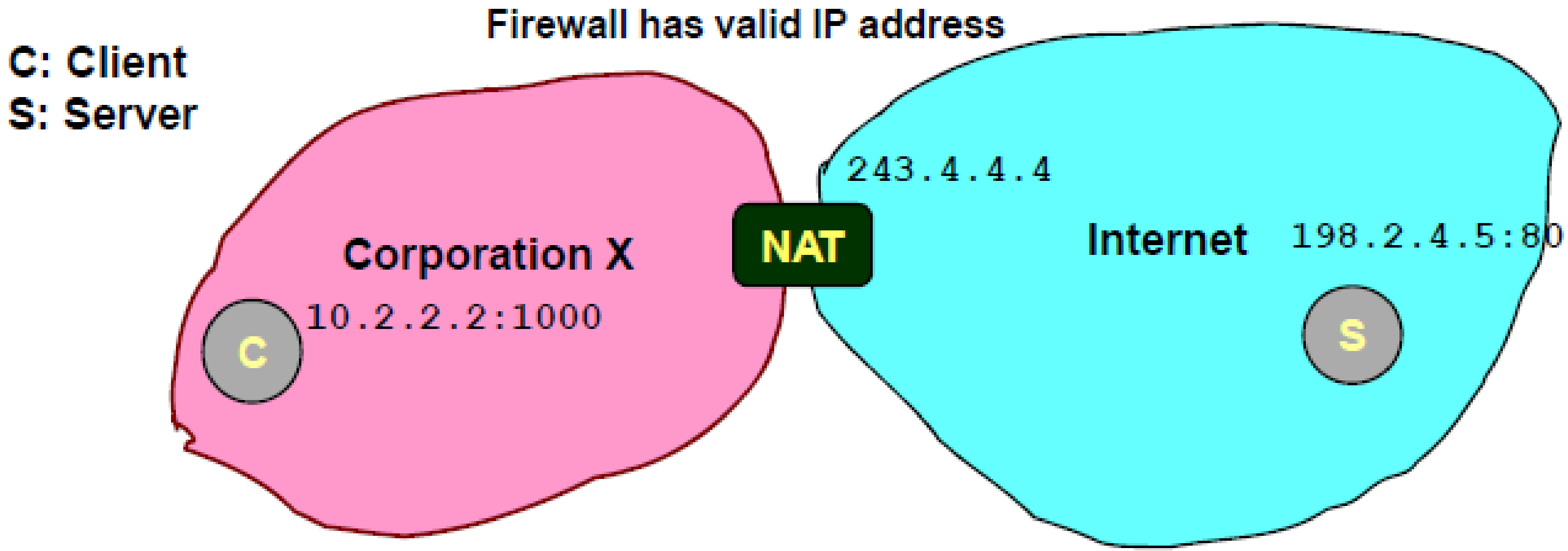
- range of addresses not needed from ISP: just one IP address for all devices
- can change addresses of devices in local network without notifying outside world
- can change ISP without changing addresses of devices in local network
- devices inside local net not explicitly addressable, visible by outside world (a security plus)

NAT: network address translation

implementation: NAT router must:

- *outgoing datagrams: replace* (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #)
  . . . remote clients/servers will respond using (NAT IP address, new port #) as destination addr
- *remember (in NAT translation table)* every (source IP address, port #) to (NAT IP address, new port #) translation pair
- *incoming datagrams: replace* (NAT IP address, new port #) in dest fields of every incoming datagram with corresponding (source IP address, port #) stored in NAT table

NAT: Opening Client Connection

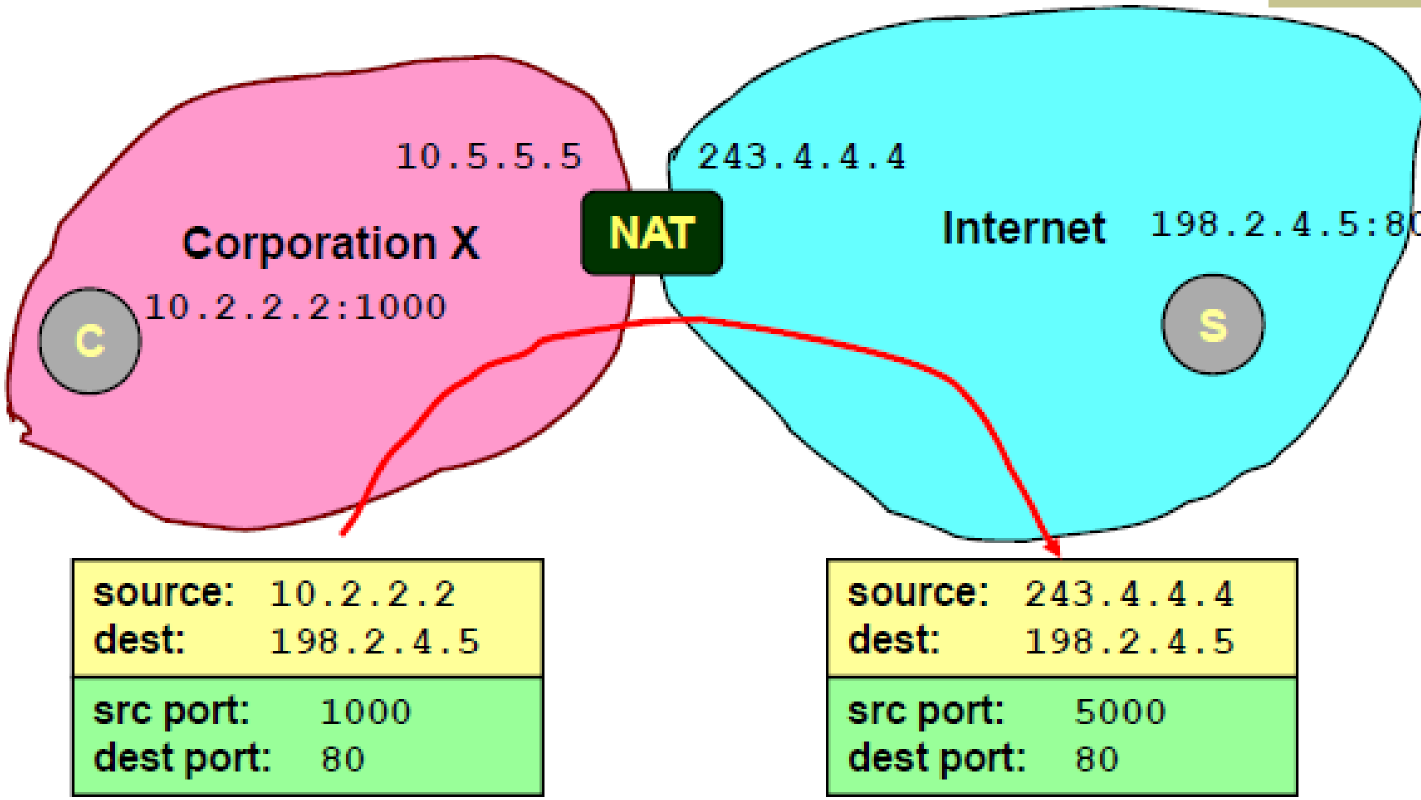


- Client 10.2.2.2 wants to connect to server 198.2.4.5:80
  - OS assigns ephemeral port (1000)
- Connection request intercepted by firewall
  - Maps client to port of firewall (5000)
  - Creates NAT table entry

Int Addr	Int Port	NAT Port
10.2.2.2	1000	5000

NAT: Client Request

C: Client
S: Server

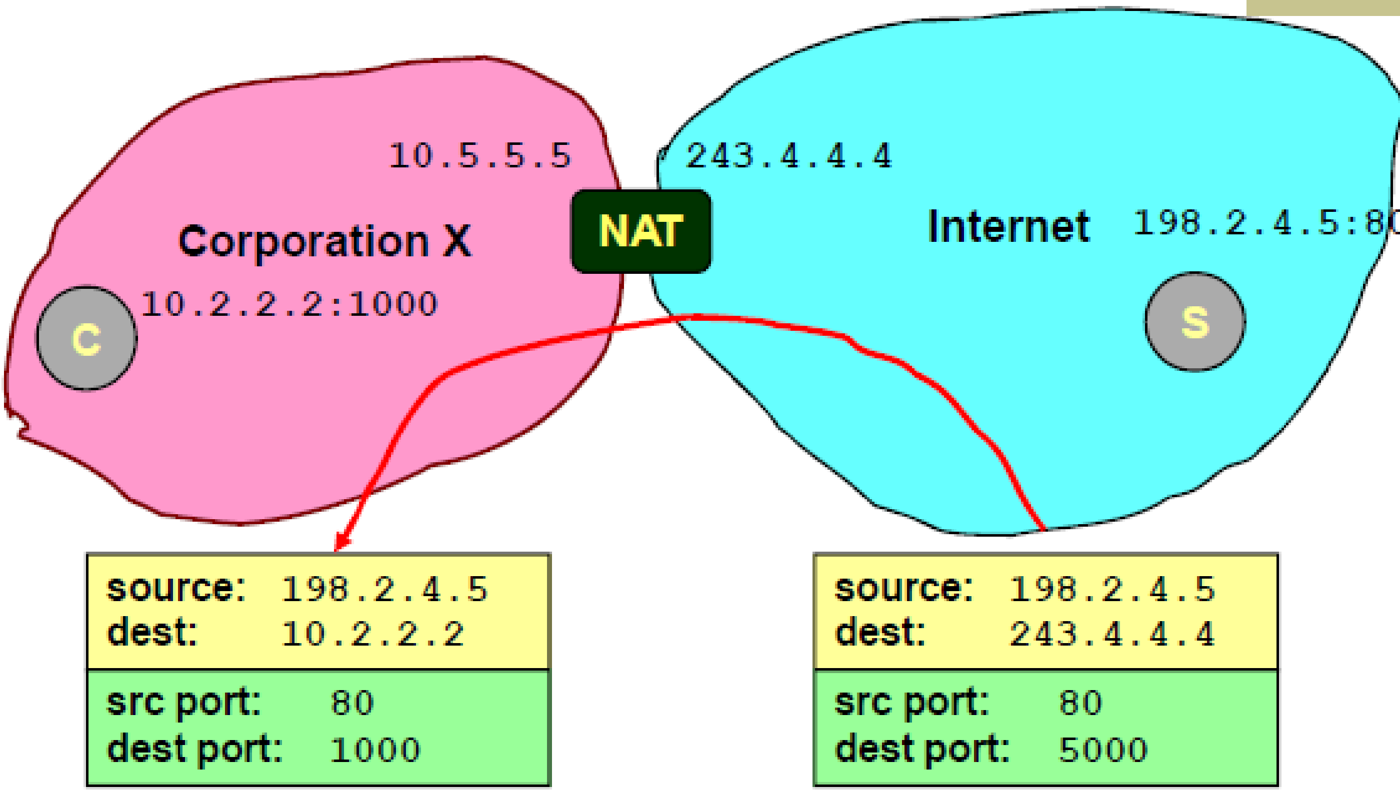


Int Addr	Int Port	NAT Port
10.2.2.2	1000	5000

- Firewall acts as proxy for client
  - Intercepts message from client and marks itself as sender

NAT: Server Response

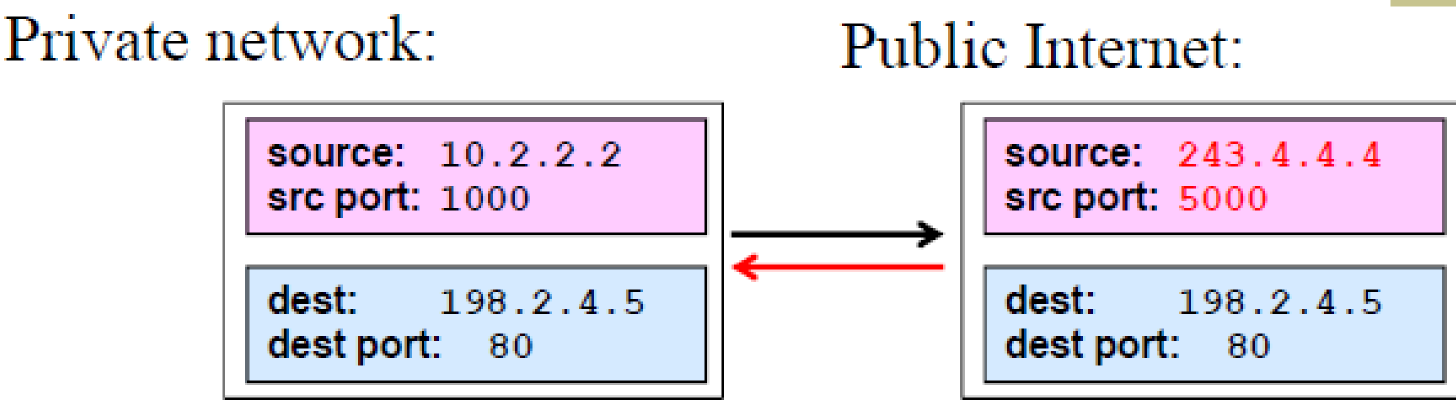
C: Client
S: Server



Int Addr	Int Port	NAT Port
10.2.2.2	1000	5000

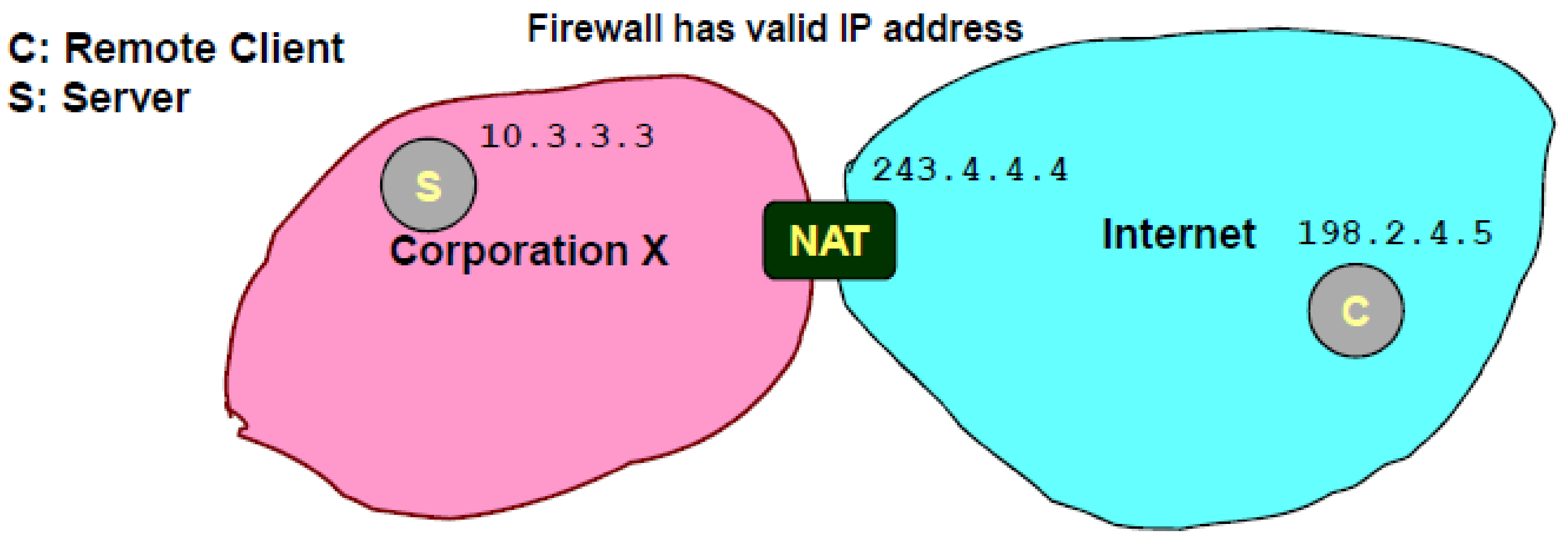
- Firewall acts as proxy for client
  - Acts as destination for server messages
  - Relabels destination to local addresses

Client Request Mapping



- NAT manages mapping between two four-tuples
- Mapping must be unique: one to one
- Must respect practical constraints
  - Cannot modify server IP address or port number
  - Client has limited number of IP addresses, often 1
  - Mapping client port numbers is important!
- Mapping must be consistent
  - The same for all packets in a communication session

NAT: Enabling Servers



- Use *port mapping* to make servers available

Int Addr	Int Port	NAT Port
10.3.3.3	80	80

  - Manually configure NAT table to include entry for well-known port
  - External users give address 243.4.4.4:80
  - Requests forwarded to server

Additional NAT Benefits

- They significantly reduce the need for public IP addresses
- NATs directly help with security
  - Hides IP addresses used in internal network
    - Easy to change ISP: only NAT box needs to have IP address
    - Fewer registered IP addresses required
  - Basic protection against remote attack
    - Does not expose internal structure to outside world
    - Can control what packets come in and out of system
    - Can reliably determine whether packet from inside or outside

- And NATs have many additional benefits
  - NAT boxes make home networking simple
  - Can be used to map between addresses from different address families, e.g, IPv4 and IPv6

NAT Challenges

- NAT has to be consistent during a session.
  - Mapping (hard state) must be maintained during the session
    - Recall Goal 1 of Internet: Continue despite loss of networks or gateways
  - Recycle the mapping after the end of the session
    - May be hard to detect
- NAT only works for certain applications.
  - Some applications (e.g. ftp) pass IP information in payload - oops
  - Need application level gateways to do a matching translation
- NATs are a problem for peer-peer applications
  - File sharing, multi-player games, …
  - Who is server?
  - Need to “punch” hole through NAT

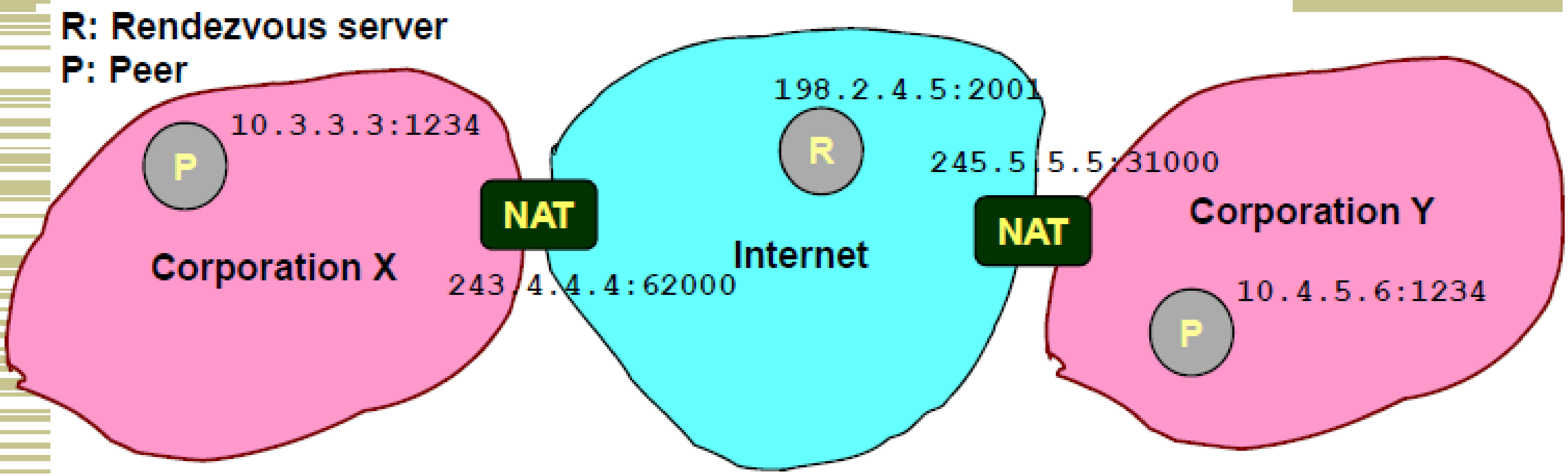
Principle: Fate Sharing

- "You can lose state information relevant to an entity's connections if and only if the entity itself is lost"
  - Example: OK to lose TCP state if either endpoint crashes
  - The TCP connection is no longer useful anyway!
- It is NOT okay to lose it if an unrelated entity goes down
  - Example: if an intermediate router reboots
- NATs violate this principle: if a NAT goes down, all communication session it supports are lost!
  - Unless you add redundancy and put state in persistent storage
- Bad news: many stateful "middleboxes" violate this rule
  - Firewalls, mobility services, … - more on this later
- Good news: today's hardware is very reliable

NAT: network address translation

- 16-bit port-number field:
  - 60,000 simultaneous connections with a single LAN-side address!
- NAT is controversial:
  - routers should only process up to layer 3
  - violates end-to-end argument
    - NAT possibility must be taken into account by app designers, e.g., P2P applications
  - address shortage should instead be solved by IPv6

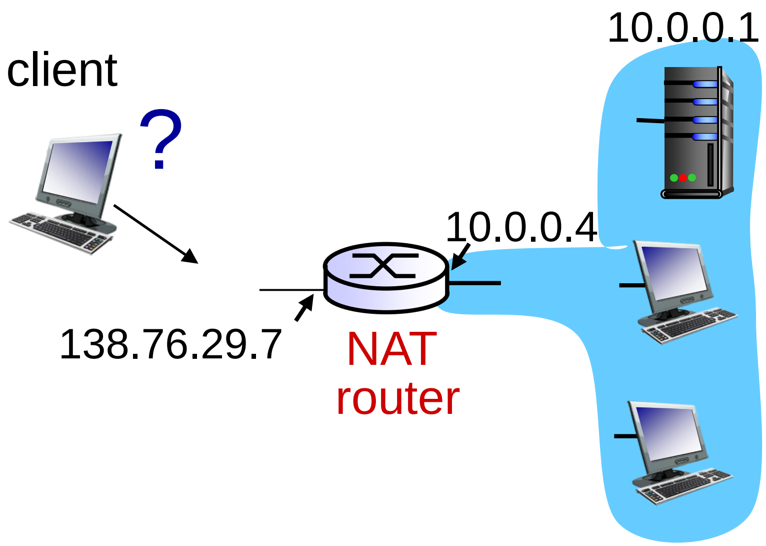
Many Options Exist for Peer-Peer



- NAT recognizes certain protocols and behaves as a application gateway
  - Used for standard protocols such as ftp
- Applications negotiate directly with NAT or firewall – need to be authorized
  - Multiple protocols dealing with different scenarios
- Punching holes in NAT: peers contact each other simultaneously using a known public (IP, port), e.g. used with rendezvous service
  - Use publicly accessible rendezvous service to exchange accessibility information
  - Assumes NATs do end-point independent mapping
- But remains painful!

NAT traversal problem

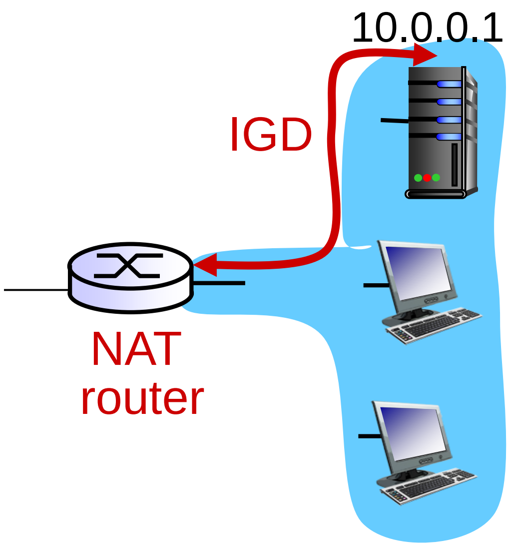
- client wants to connect to server with address 10.0.0.1
  - server address 10.0.0.1 local to LAN (client can't use it as destination addr)
  - only one externally visible NATed address: 138.76.29.7
- *solution1:* statically configure NAT to forward incoming connection requests at given port to server
  - e.g., (123.76.29.7, port 2500) always forwarded to 10.0.0.1 port 25000



NAT traversal problem

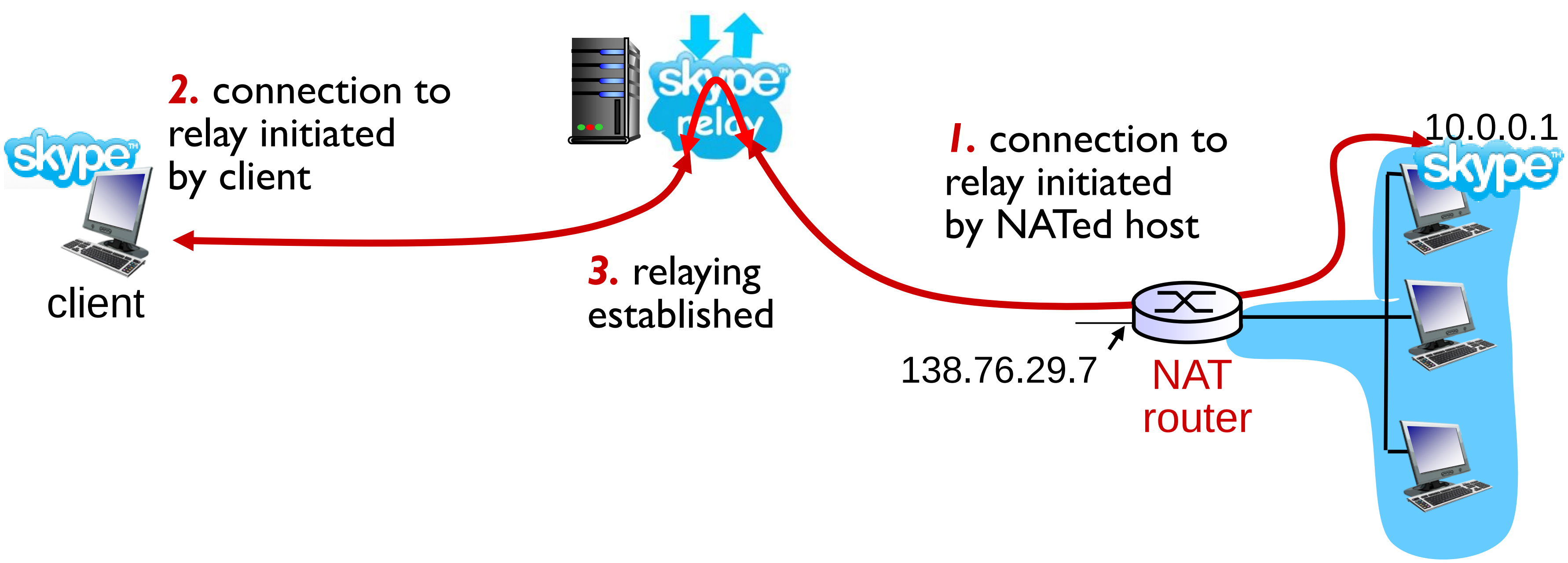
- *solution 2:* Universal Plug and Play (UPnP) Internet Gateway Device (IGD) Protocol. Allows NATed host to:
  - learn public IP address (138.76.29.7)
  - add/remove port mappings (with lease times)

  i.e., automate static NAT port map configuration



NAT traversal problem

- *solution 3:* relaying (used in Skype)
  - NATed client establishes connection to relay
  - external client connects to relay
  - relay bridges packets between to connections



Chapter 4: outline

4.1 introduction

4.2 virtual circuit and datagram networks

4.3 what's inside a router

4.4 IP: Internet Protocol

- datagram format
- IPv4 addressing
- ICMP
- IPv6

4.5 routing algorithms

- link state
- distance vector
- hierarchical routing

4.6 routing in the Internet

- RIP
- OSPF
- BGP

4.7 broadcast and multicast routing

ICMP: internet control message protocol

- used by hosts & routers to communicate network-level information
  - error reporting: unreachable host, network, port, protocol
  - echo request/reply (used by ping)
- network-layer "above" IP:
  - ICMP msgs carried in IP datagrams
- ICMP message: type, code plus first 8 bytes of IP datagram causing error

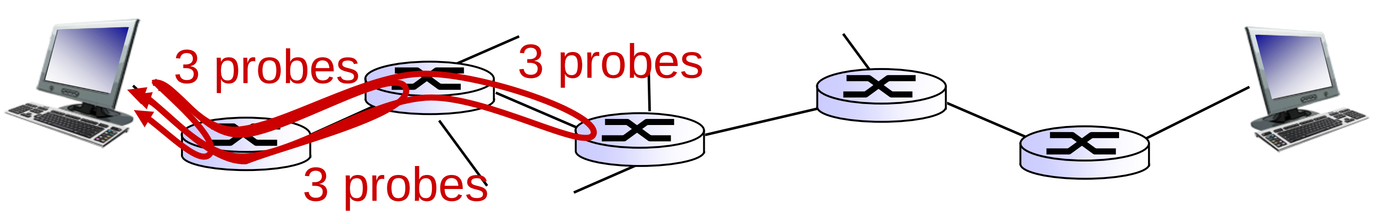
Type	Code	description
0	0	echo reply (ping)
3	0	dest. network unreachable
3	1	dest host unreachable
3	2	dest protocol unreachable
3	3	dest port unreachable
3	6	dest network unknown
3	7	dest host unknown
4	0	source quench (congestion control - not used)
8	0	echo request (ping)
9	0	route advertisement
10	0	router discovery
11	0	TTL expired
12	0	bad IP header

Traceroute and ICMP

- source sends series of UDP segments to dest
  - first set has TTL =1
  - second set has TTL=2, etc.
  - unlikely port number
- when *n*th set of datagrams arrives to nth router:
  - router discards datagrams
  - and sends source ICMP messages (type 11, code 0)
  - ICMP messages include name of router & IP address
- when ICMP messages arrives, source records RTTs

stopping criteria:

- UDP segment eventually arrives at destination host
- destination returns ICMP "port unreachable" message (type 3, code 3)
- source stops



IPv6: motivation

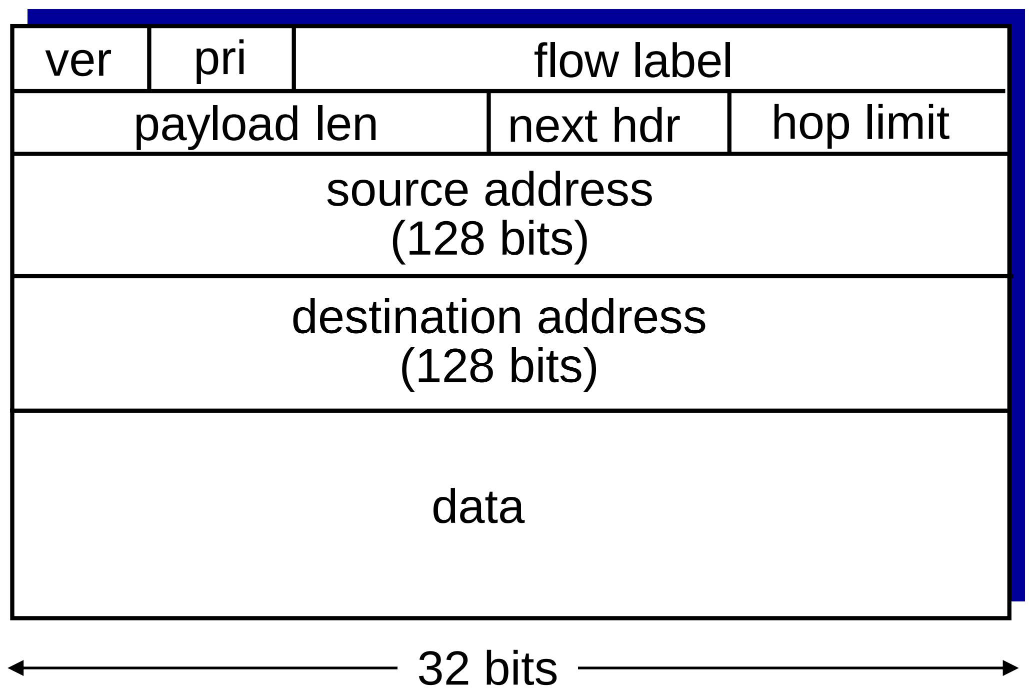
- *initial motivation:* 32-bit address space soon to be completely allocated.
- additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS

IPv6 datagram format:

- fixed-length 40 byte header
- no fragmentation allowed

IPv6 datagram format

priority: identify priority among datagrams in flow
flow Label: identify datagrams in same "flow."
(concept of "flow" not well defined).
next header: identify upper layer protocol for data

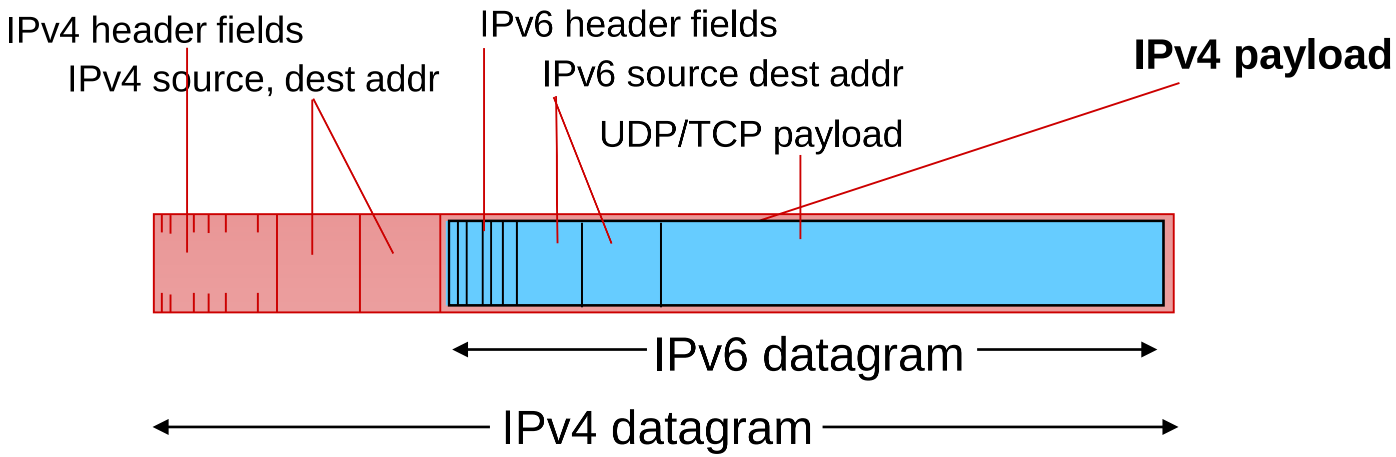


Other changes from IPv4

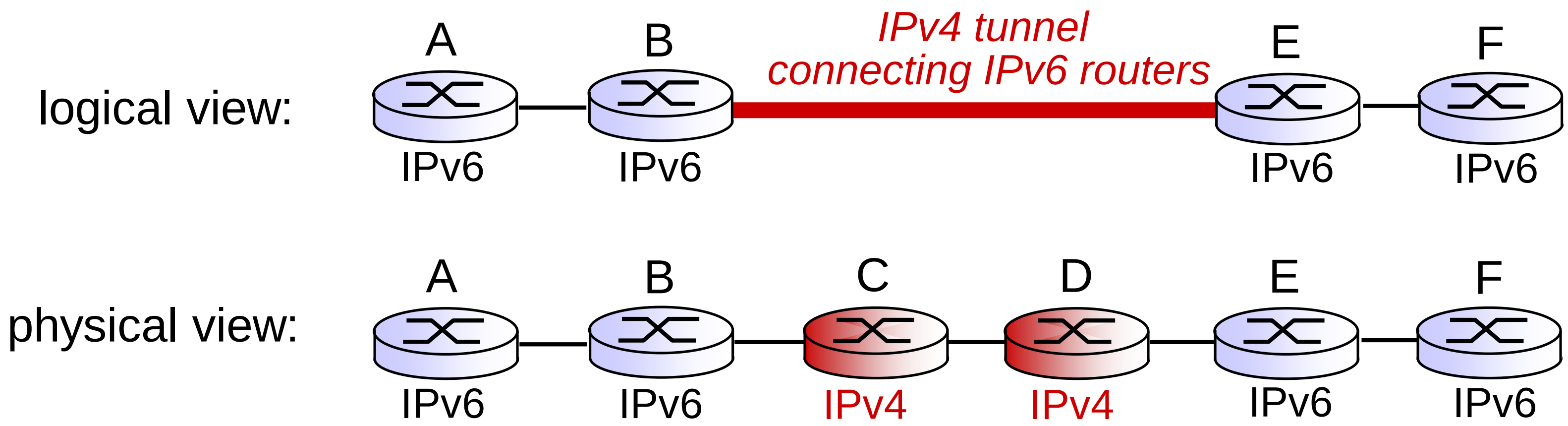
- *checksum:* removed entirely to reduce processing time at each hop
- *options:* allowed, but outside of header, indicated by "Next Header" field
- *ICMPv6:* new version of ICMP
  - additional message types, e.g. "Packet Too Big"
  - multicast group management functions

Transition from IPv4 to IPv6

- not all routers can be upgraded simultaneously
  - no "flag days"
  - how will network operate with mixed IPv4 and IPv6 routers?
- *tunneling:* IPv6 datagram carried as *payload* in IPv4 datagram among IPv4 routers



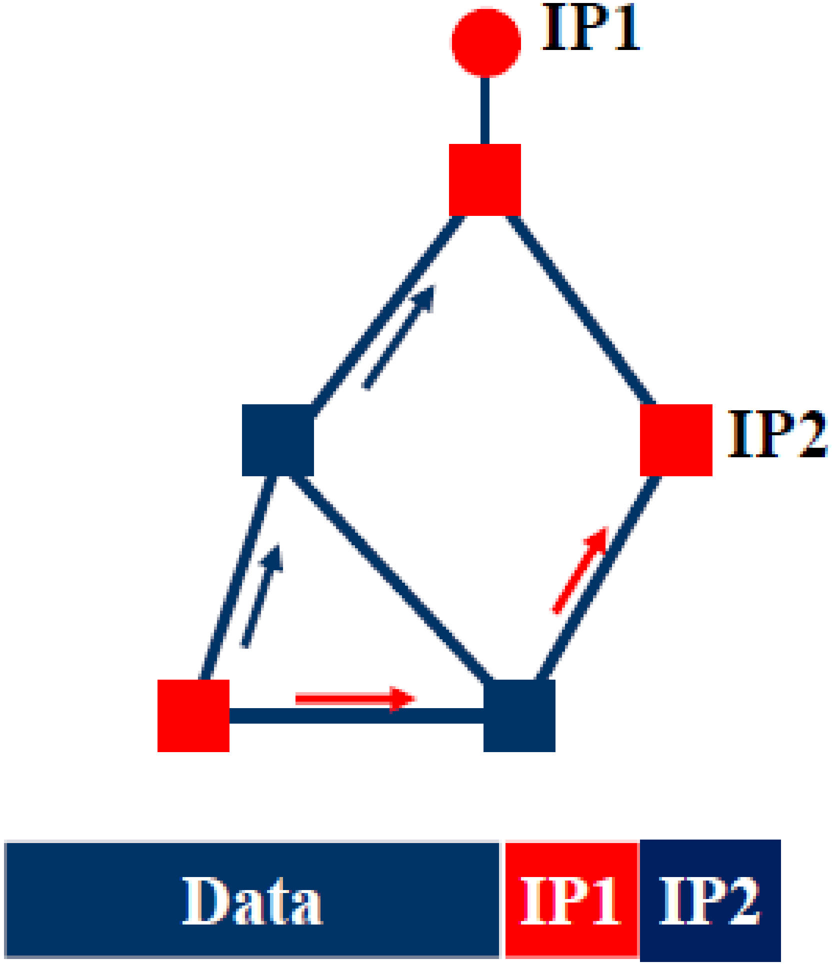
Tunneling



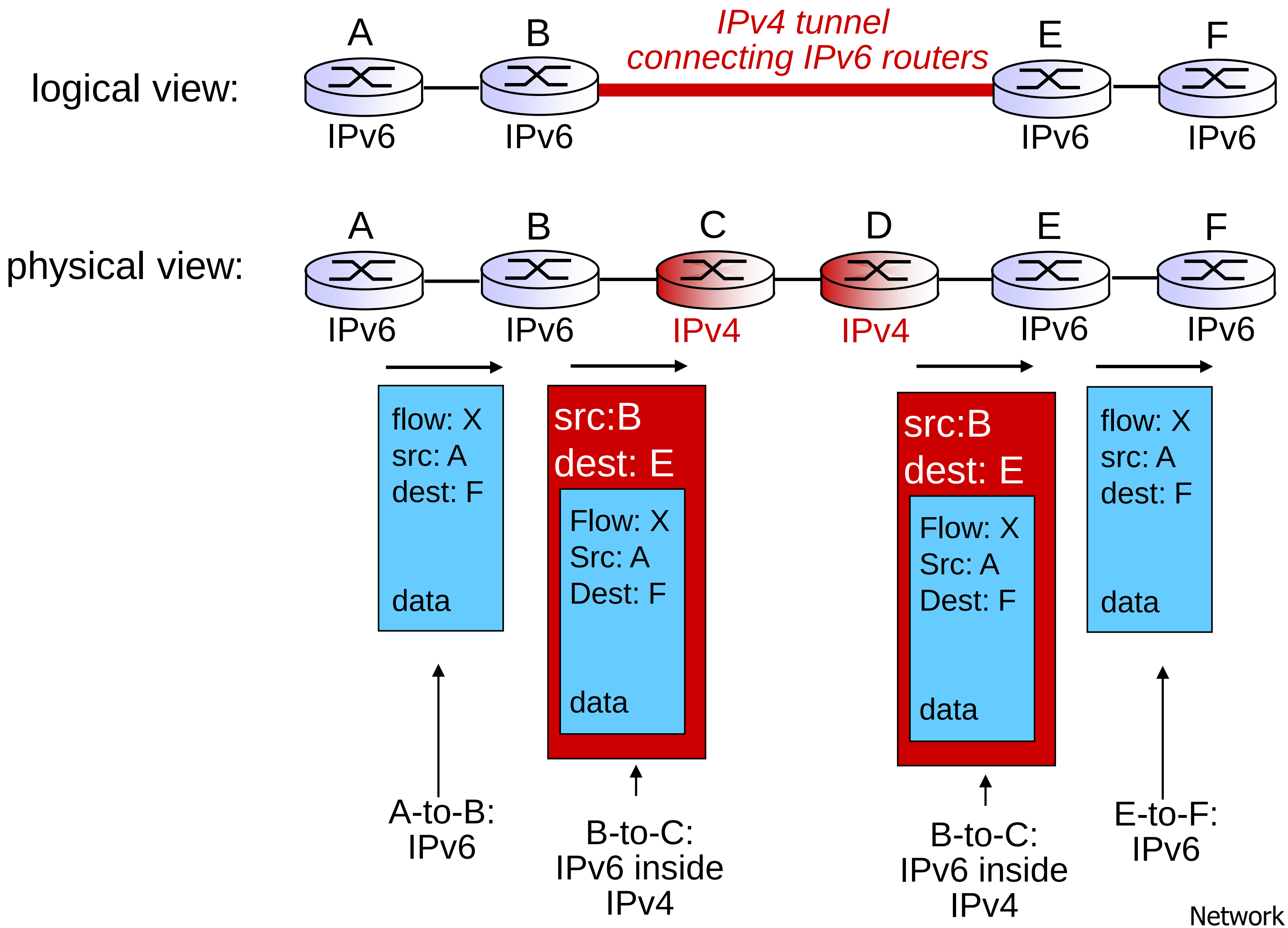
logical view:
A
B
IPv4 tunnel
connecting IPv6 routers
E
F
IPv6
IPv6
IPv6
IPv6
physical view:
A
B
C
D
E
F
IPv6
IPv6
IPv4
IPv4
IPv6
IPv6

Tunneling

- Force a packet to go to a specific point in the network
  - Cannot rely on routers on regular path, e.g., an IPv6 packet
- Achieved by adding an extra IP header to the packet with a new destination address
  - Similar to putting a letter in another envelope
- Used to deal with new IP features
  - Mobile IP,..
  - Multicast, IPv6, research, ..

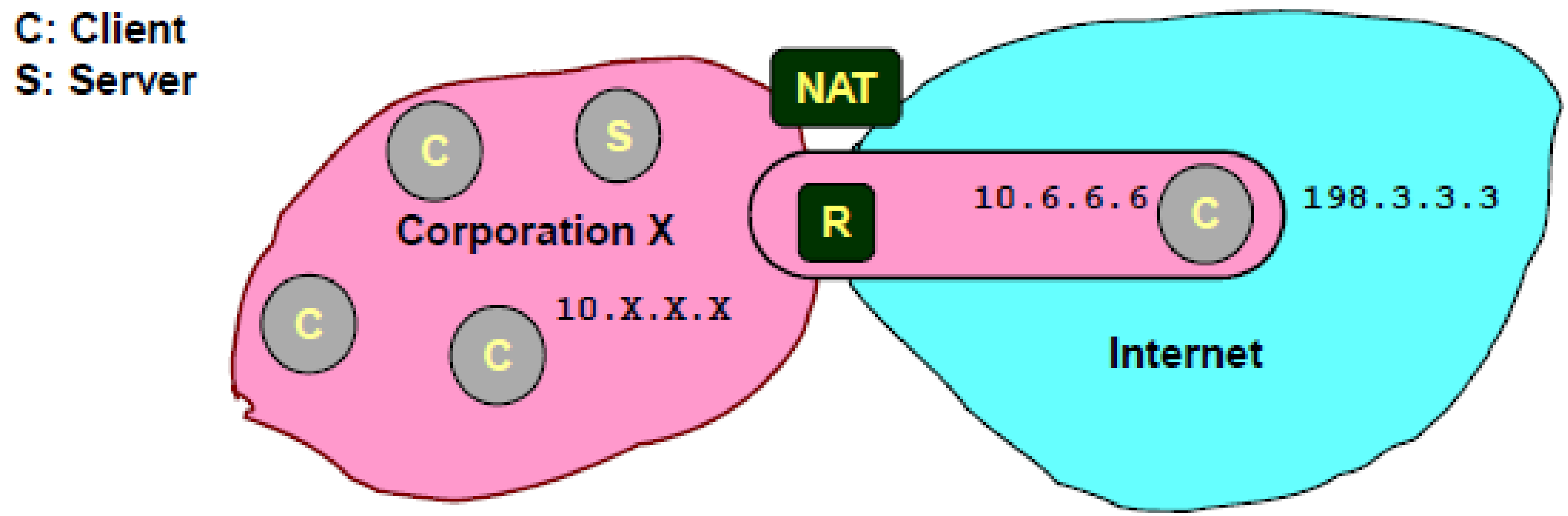


Tunneling



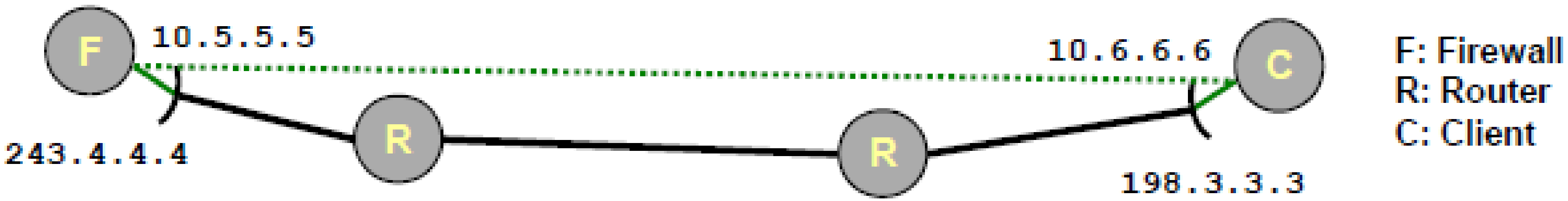
logical view:
A
B
IPv4 tunnel
connecting IPv6 routers
E
F
IPv6
IPv6
IPv6
IPv6
physical view:
A
B
C
D
E
F
IPv6
IPv6
IPv4
IPv4
IPv6
IPv6
flow: X
src: A
dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
src:B
dest: E
Flow: X
Src: A
Dest: F
data
flow: X
src: A
dest: F
data
A-to-B:
IPv6
B-to-C:
IPv6 inside
IPv4
B-to-C:
IPv6 inside
IPv4
E-to-F:
IPv6

Extending Private Network

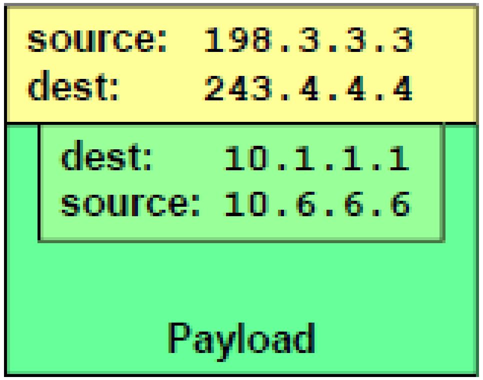


- Supporting Road Warrior
  - Employee working remotely with assigned IP address 198.3.3.3
  - Wants to appear to rest of corporation as if working internally
    - From address 10.6.6.6 – can also be a public address, e.g., 128.2.6.6
    - Gives access to internal services (e.g., ability to send mail), (library access…)
- Virtual Private Network (VPN)
  - Overlays private network on top of regular Internet

Supporting VPN by Tunneling



- Idea: client sets up tunnel to company's firewall
- Example: client wants to send packet to internal node 10.1.1.1
- Entering Tunnel
  - Add extra IP header directed to firewall (243.4.4.4)
  - Original header becomes part of payload
  - Possible to encrypt it
- Exiting Tunnel
  - Firewall receives packet
  - Strips off header
  - Sends through internal network to destination



IPv6: adoption

- US National Institutes of Standards estimate [2013]:
  - ~3% of industry IP routers
  - ~11% of US gov't routers

- *Long (long!) time for deployment, use*
  - 20 years and counting!
  - think of application-level changes in last 20 years: WWW, Facebook, …
  - *Why?*