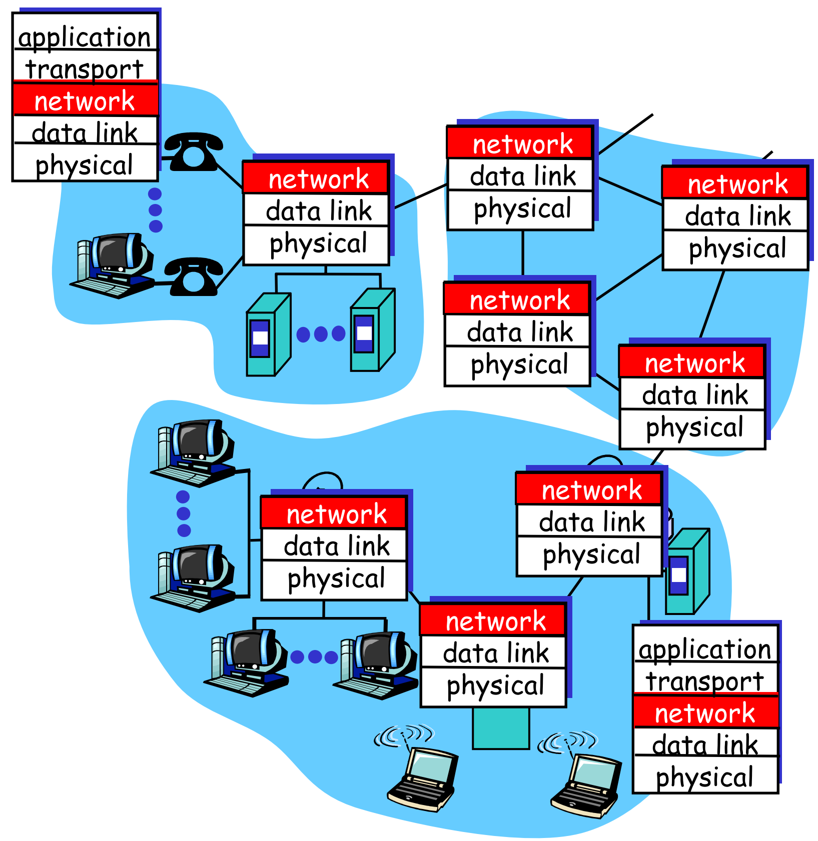
# Chapter 4: Network Layer Part I

(last revised 22/03/05)

- 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 (maybe)

# Network layer

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



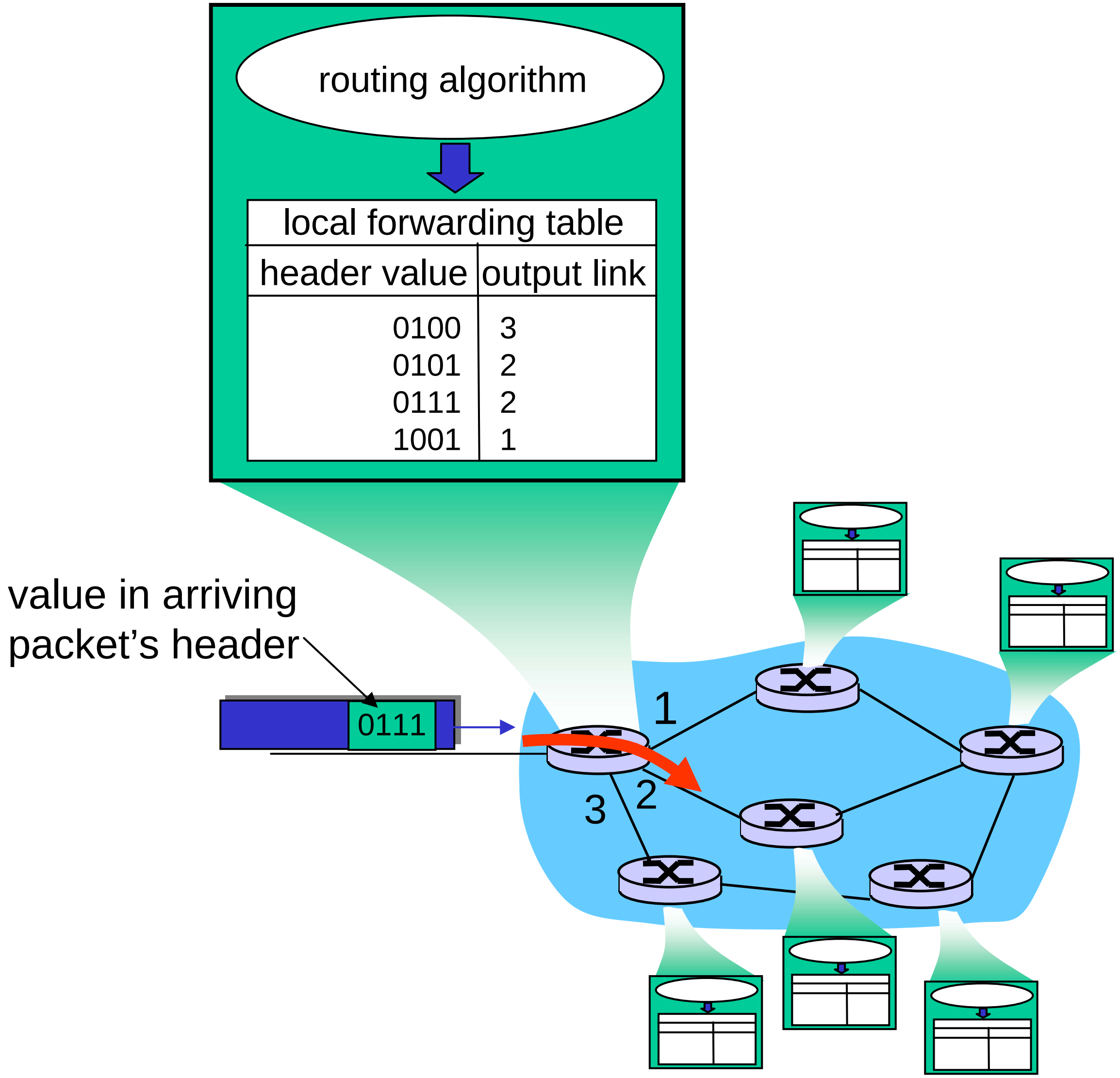
# Key Network-Layer Functions

- *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



- 3rd important function in *some* network architectures:
  - ATM, frame relay, X.25
  - Before datagrams flow, two hosts and intervening routers establish virtual connection
  - Routers get involved

- Network vs. transport layer cnctn service:
  - Network: between two hosts
  - Transport: between two processes

# Network service model

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

service abstraction

- guaranteed bandwidth?
- preservation of inter-packet timing (no jitter)?
- loss-free delivery?
- in-order delivery?
- congestion feedback to sender?

The most important abstraction provided by network layer:

virtual circuit
or
datagram?

# 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 rate | yes | yes | yes | no congestion |
| ATM | VBR | guaranteed rate | yes | yes | yes | no congestion |
| ATM | ABR | guaranteed minimum | no | yes | no | yes |
| ATM | UBR | none | no | yes | no | no |

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# Network layer connection and connection-less service

- Datagram network provides network-layer connectionless service
- VC network provides network-layer connection service
- Analogous to the transport-layer services, but:
  - Service: host-to-host
  - No choice: network provides one or the other
  - Implementation: in the 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 OD)
- *every* router on source-dest paths maintain the "state" for each passing connection
  - transport-layer connection only involved two end systems
- link, router resources (bandwidth, buffers) may be *allocated* to VC
  - to get circuit-like performance

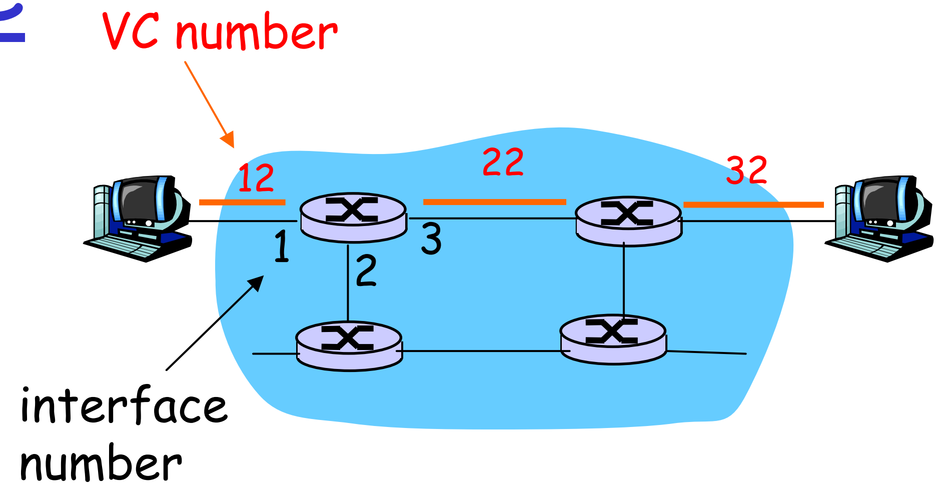
# VC implementation

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 a VC number.
- VC number must be changed on each link.
  - New VC number comes from forwarding table

# Forwarding table



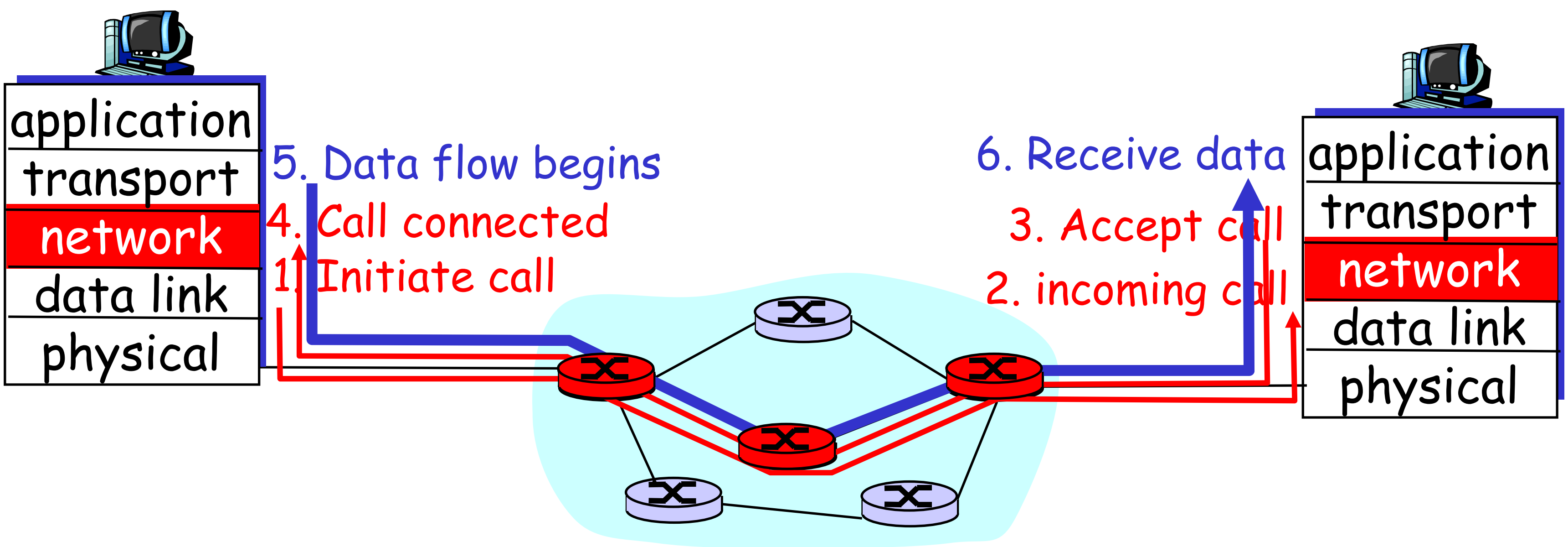

## Forwarding table in upper-left router:

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

**Routers maintain connection state information!**

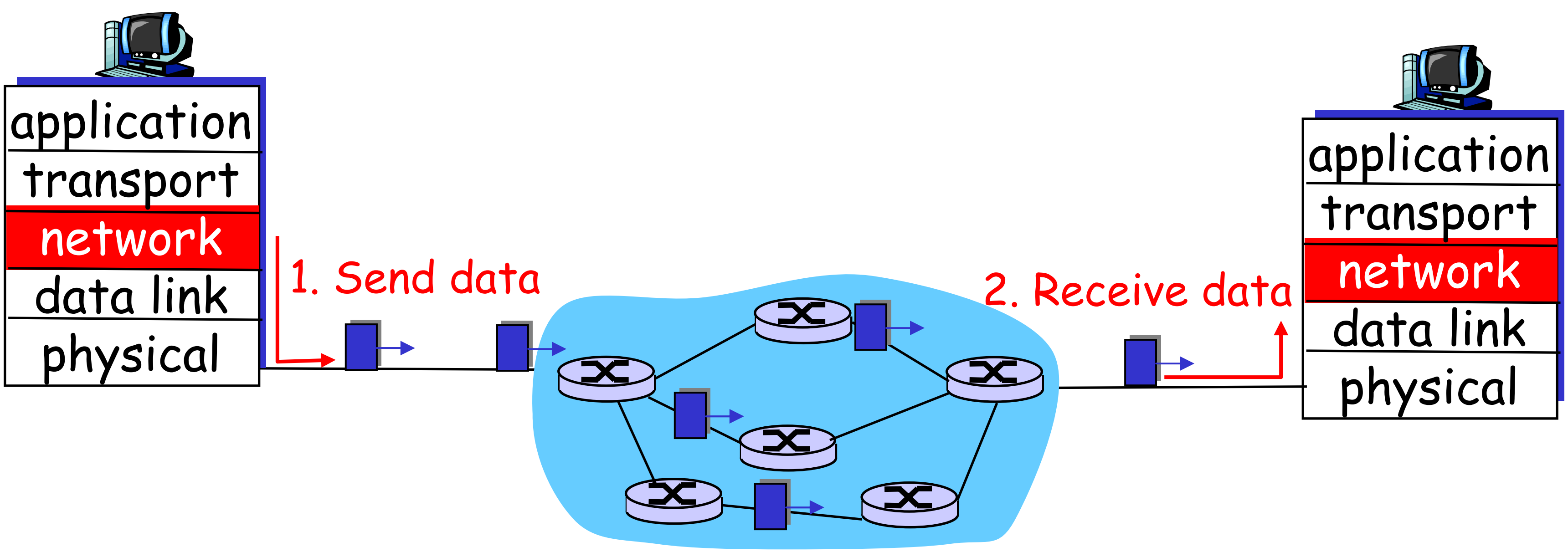
# Virtual circuits: signaling protocols

- used to setup, maintain  teardown VC
- connection setup process *still needs routing* much as in the Internet
- used in ATM, frame-relay, X.25
- not used in today's Internet



# Datagram networks

- no call setup at network layer
- routers: no state info about end-to-end connections
  - no network-level concept of "connection"
- packets forwarded using destination host address
  - packets between same source-dest pair may take different paths



# Forwarding table

4 billion possible entries

| 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 |

# Longest prefix matching

| Prefix Match | 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

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

## ATM

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

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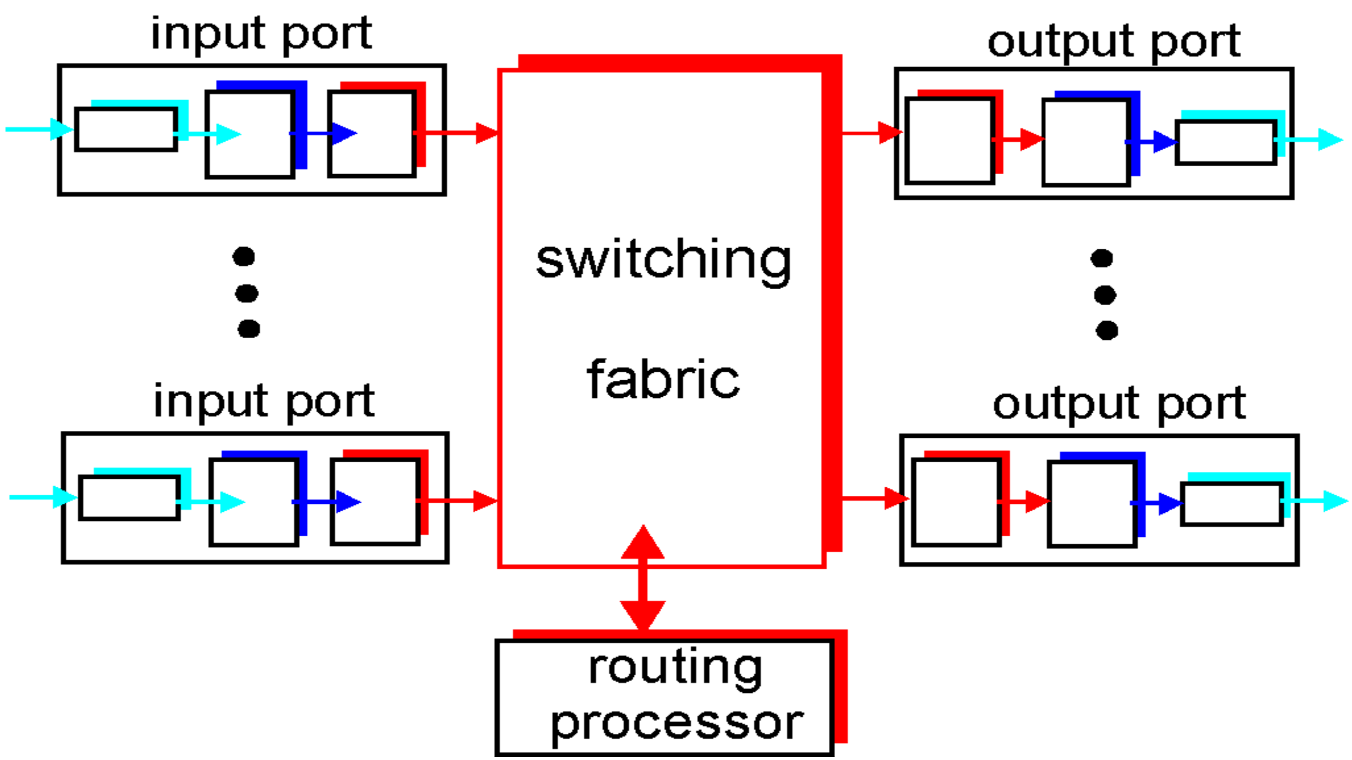
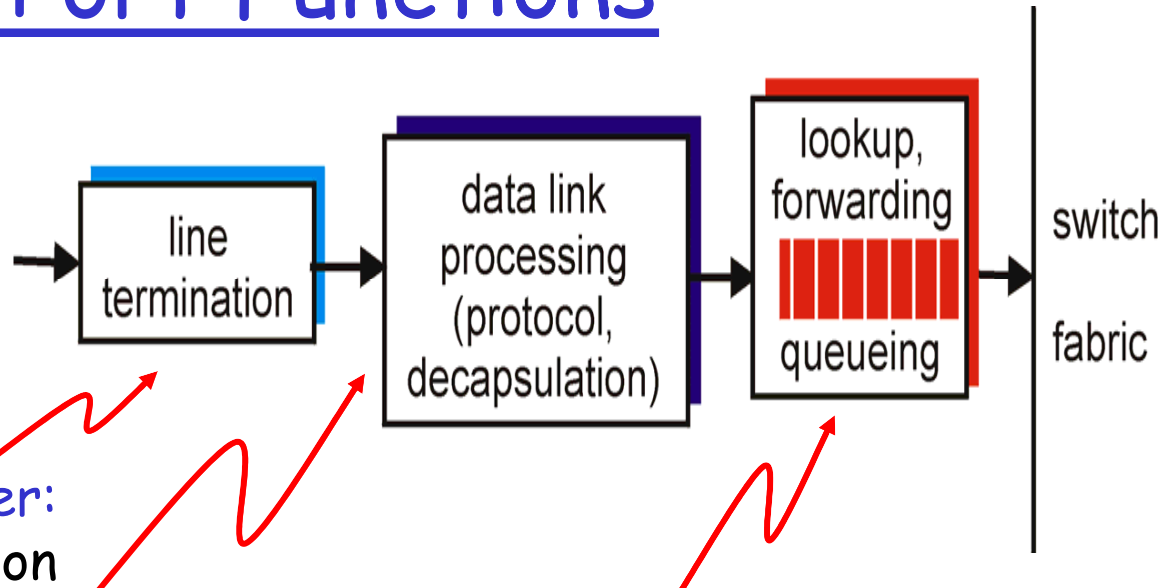
# Router Architecture Overview

Two key router functions:

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



# Input Port Functions



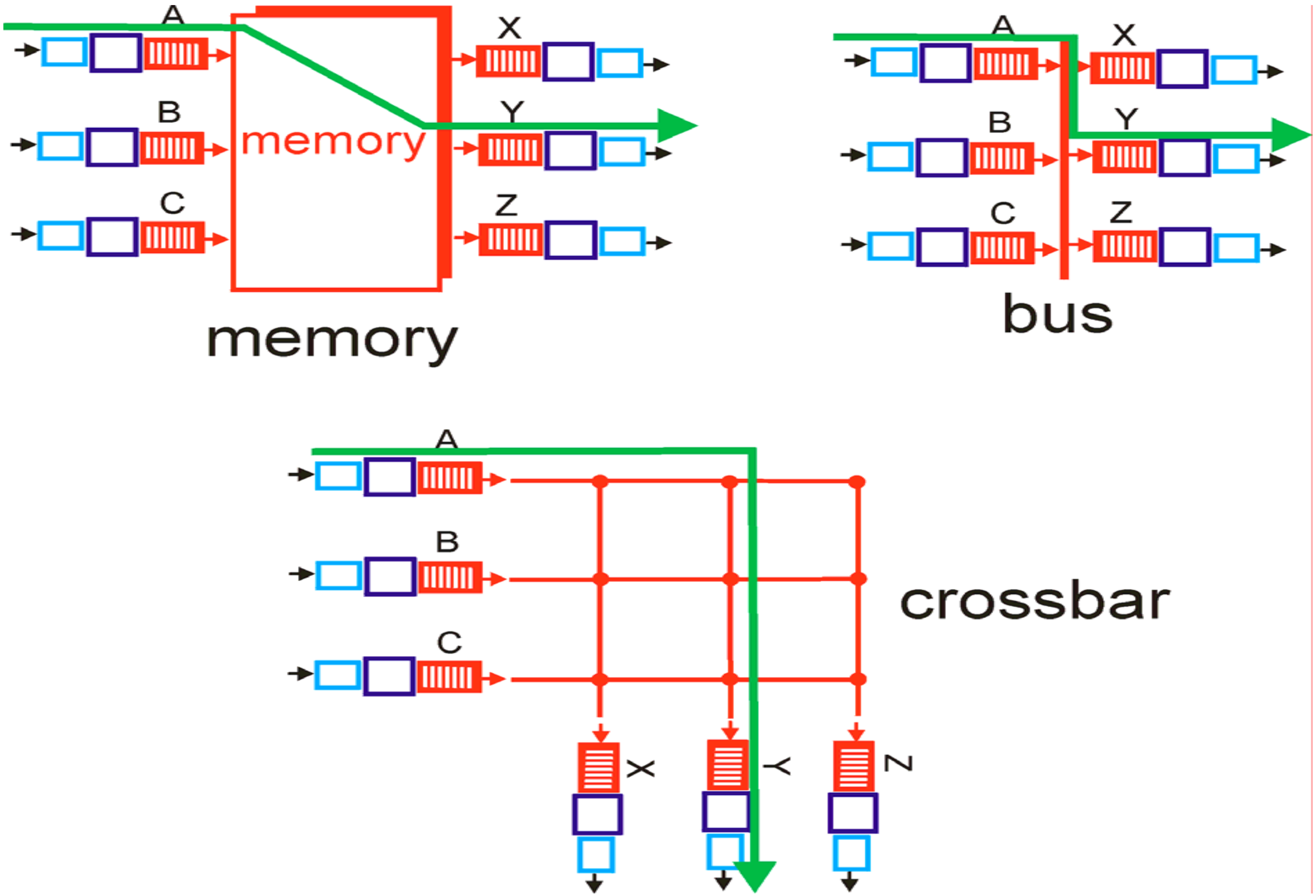

Physical layer:
bit-level reception

Data link layer:
e.g., Ethernet
see chapter 5

**Decentralized switching:**

- given datagram dest., lookup output port using forwarding table in input port memory
- goal: complete input port processing at 'line speed'
- queuing: if datagrams arrive faster than forwarding rate into switch fabric

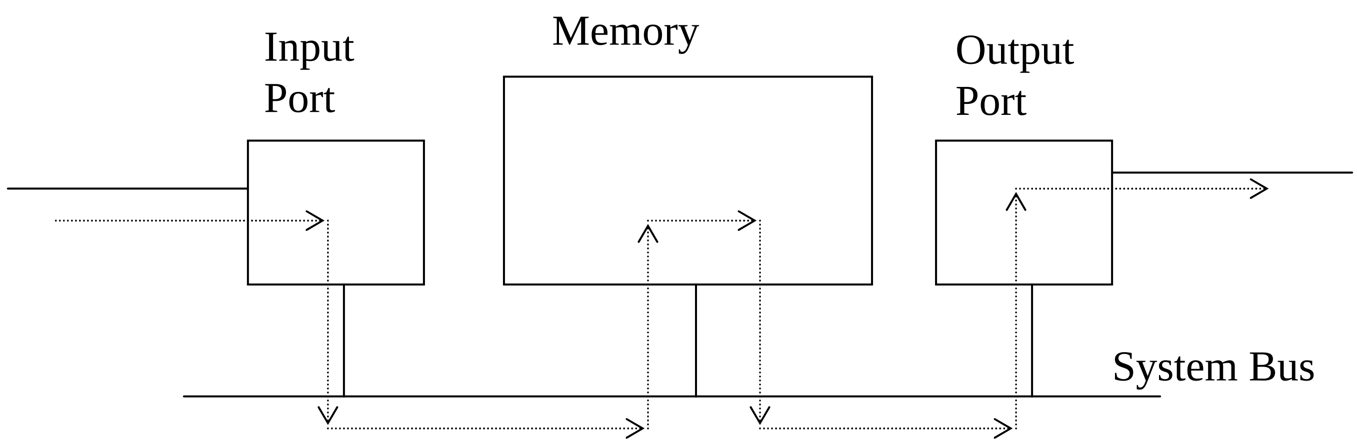
# Three types of switching fabrics



# Switching Via Memory

First generation routers:

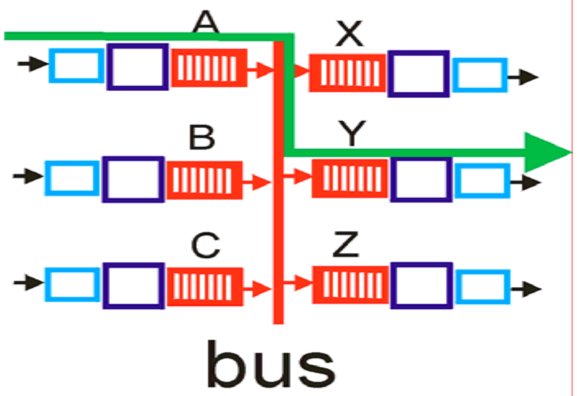
- packet copied by system's (single) CPU
- speed limited by memory bandwidth (2 bus crossings per datagram)




Modern routers:

- input port processor performs lookup, copy into memory
- Cisco Catalyst 8500

# Switching Via a Bus

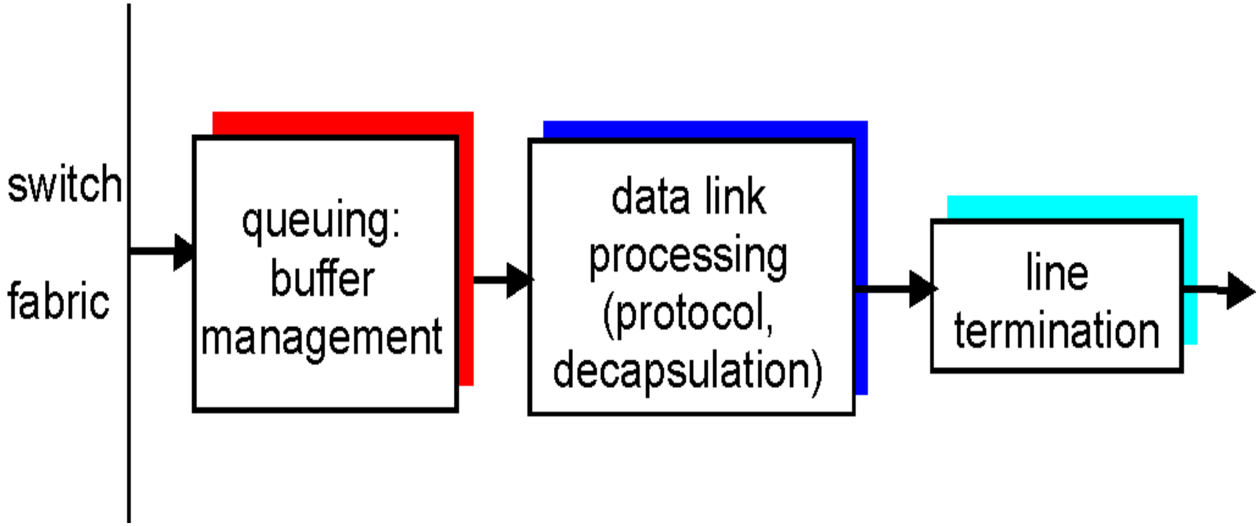



- datagram from input port memory to output port memory via a shared bus
- bus contention: switching speed limited by bus bandwidth
- 1 Gbps bus, Cisco 1900: sufficient speed for access and enterprise routers (not regional or backbone)

# Switching Via An Interconnection Network

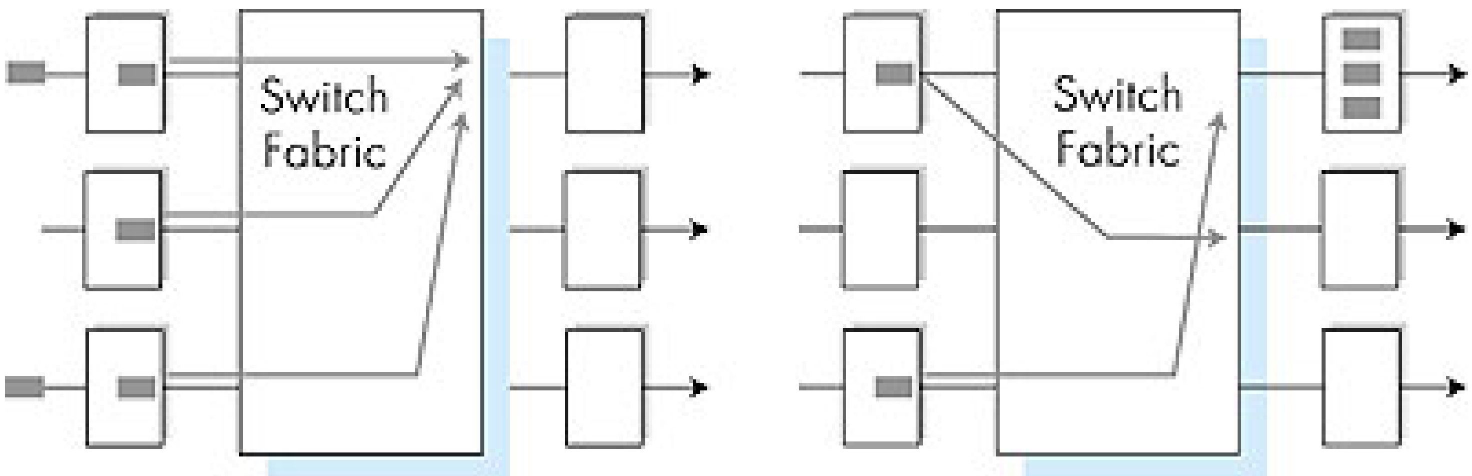
- overcome  bus bandwidth limitations
- Banyan networks, other interconnection nets initially developed to connect processors in multiprocessor
- Advanced design: fragmenting datagram into fixed length cells, switch cells through the fabric.
- Cisco 12000: switches Gbps through the interconnection network

# Output Ports




- *Buffering* required when datagrams arrive from fabric faster than the transmission rate
- *Scheduling discipline* chooses among queued datagrams for transmission

# Output port queueing



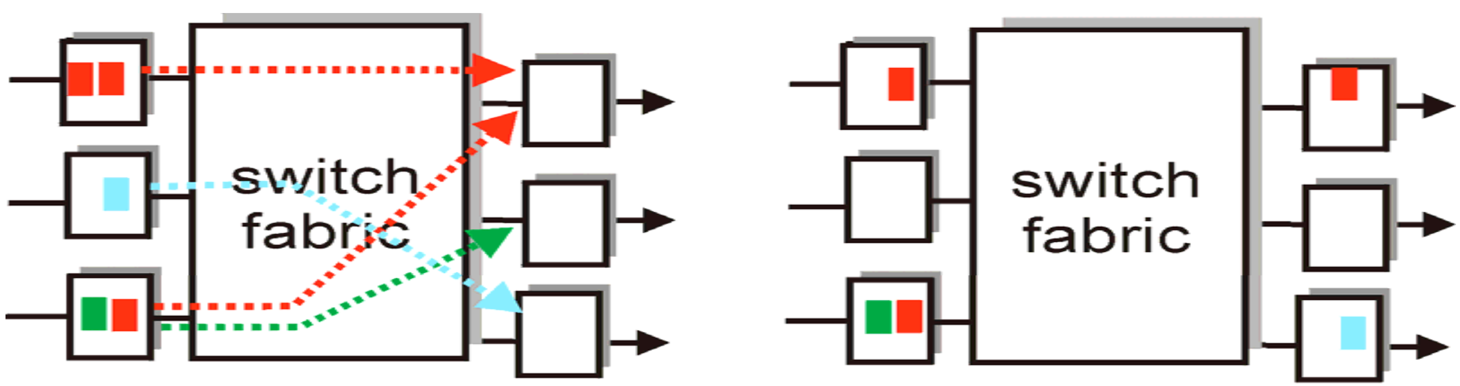

Output Port Contention at Time t

One Packet Time Later

- buffering when arrival rate via switch exceeds output line speed
- *queueing (delay) and loss due to output port buffer overflow!*

# Input Port Queuing

- Fabric slower than input ports combined -> queueing may occur at input queues
- Head-of-the-Line (HOL) blocking: queued datagram at front of queue prevents others in queue from moving forward
- *queueing delay and loss due to input buffer overflow!*




output port contention at time t - only one red packet can be transferred

green packet experiences HOL blocking

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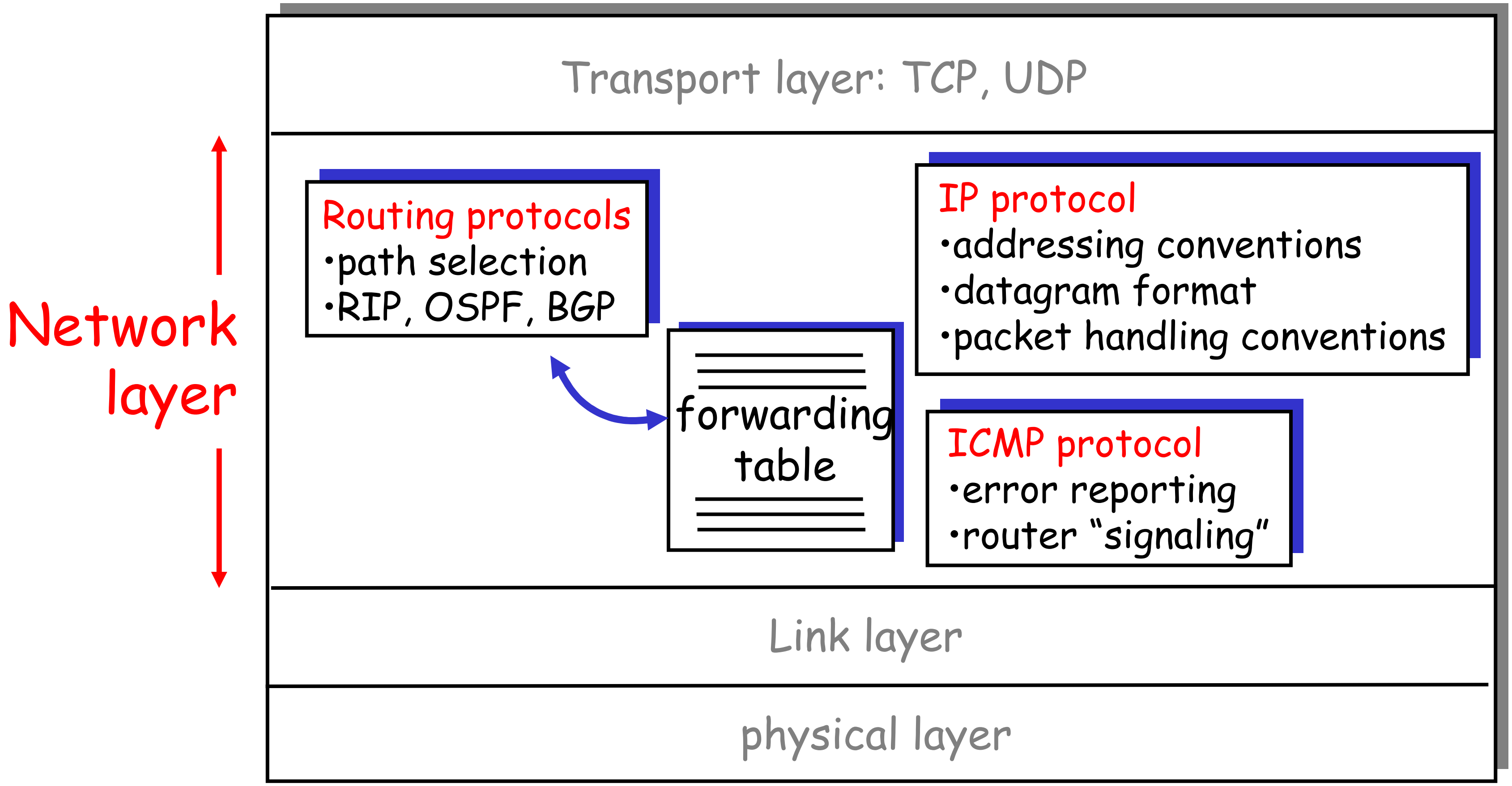
# The Internet Network layer

Host, router network layer functions:



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# IP datagram format

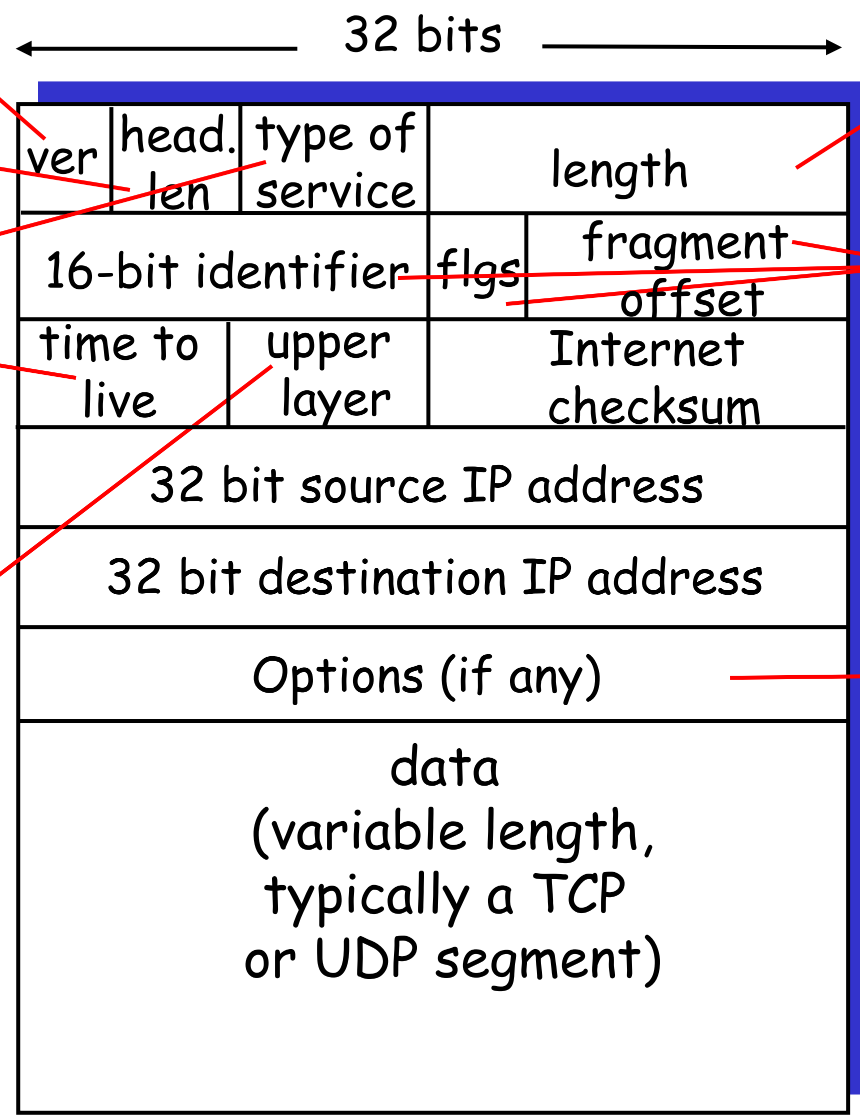
IP protocol version number

header length (bytes)

"type" of data

max number remaining hops (decremented at each router)

upper layer protocol to deliver payload to




total datagram length (bytes)

for fragmentation/ reassembly

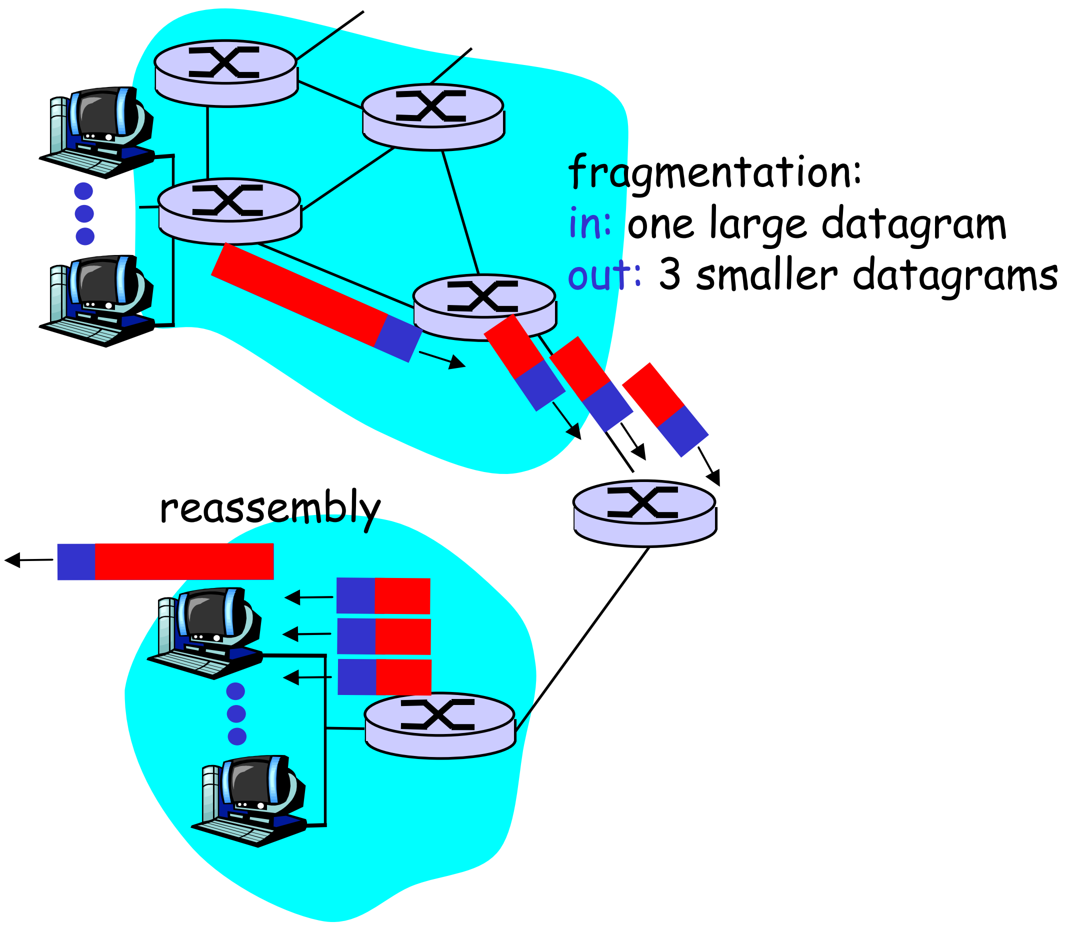
E.g. timestamp, record route taken, specify list of routers to visit.

how much overhead with TCP?

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

# IP Fragmentation & Reassembly

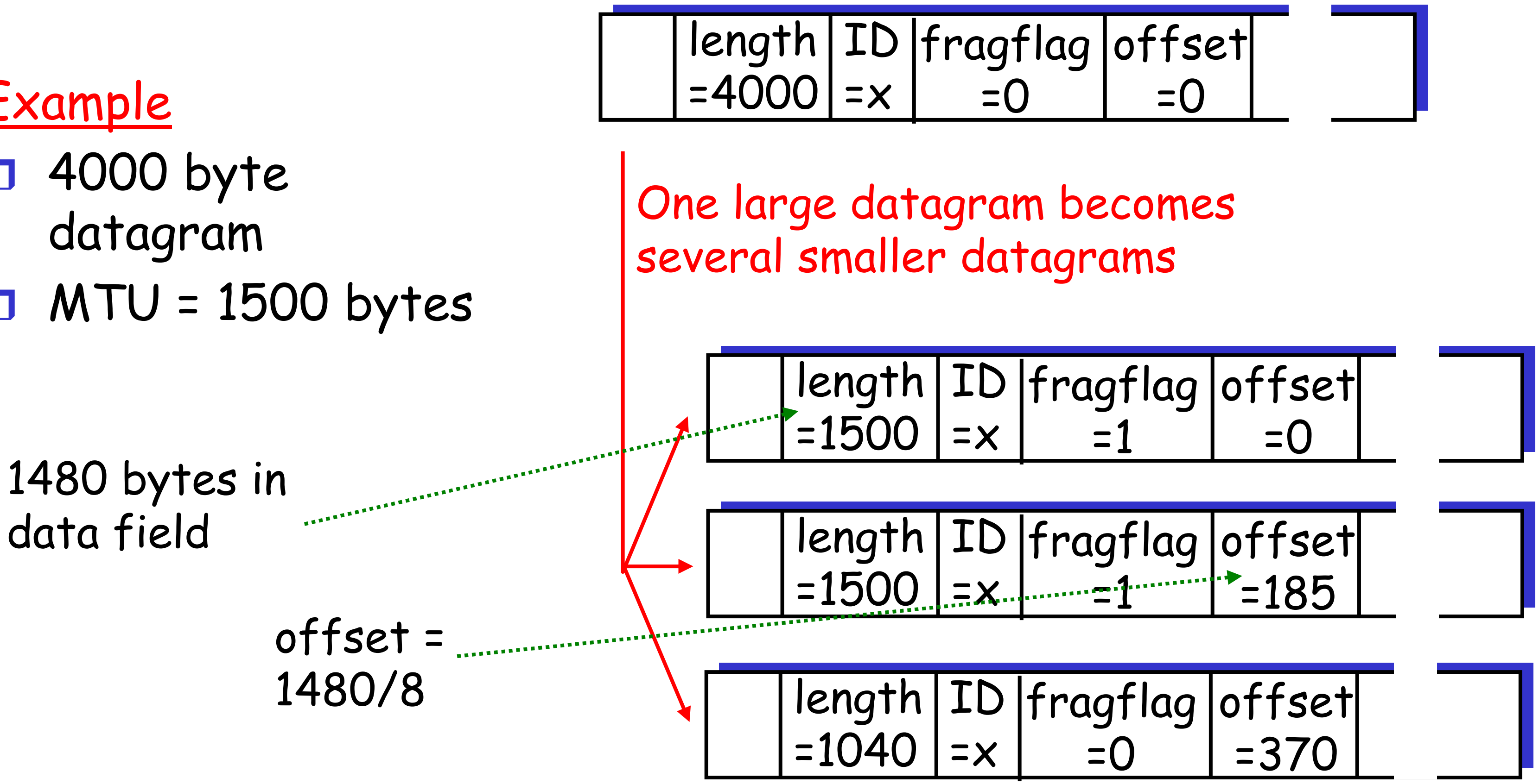
- network links have MTU (max.transfer size) - largest possible link-level frame.
  - different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only at final destination
  - IP header bits used to identify,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



# IP Fragmentation and Reassembly

Example

- 4000 byte datagram
- MTU = 1500 bytes



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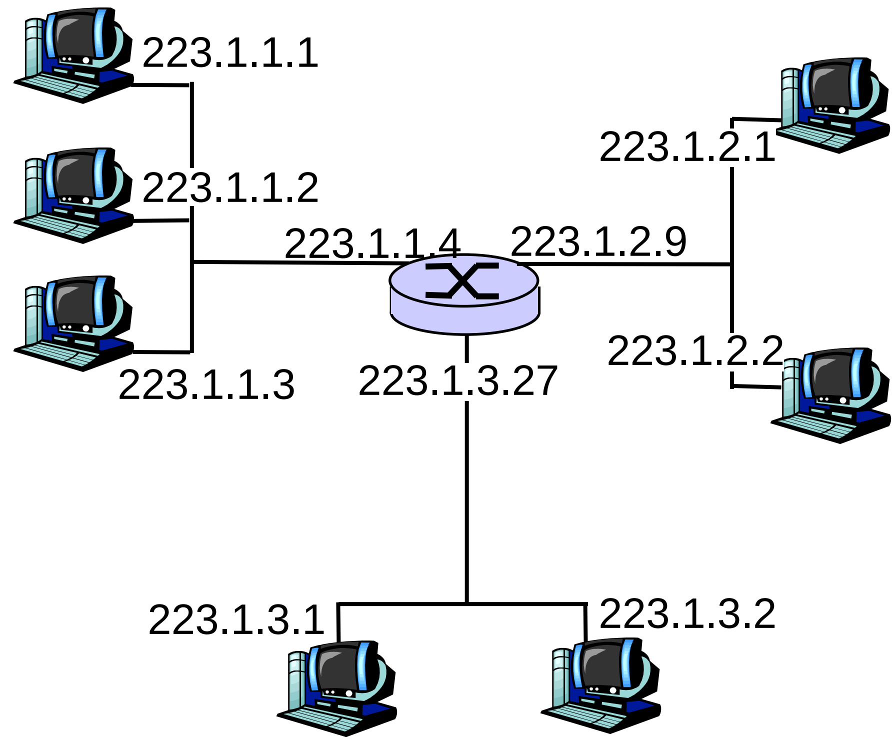
# IP Addressing: introduction

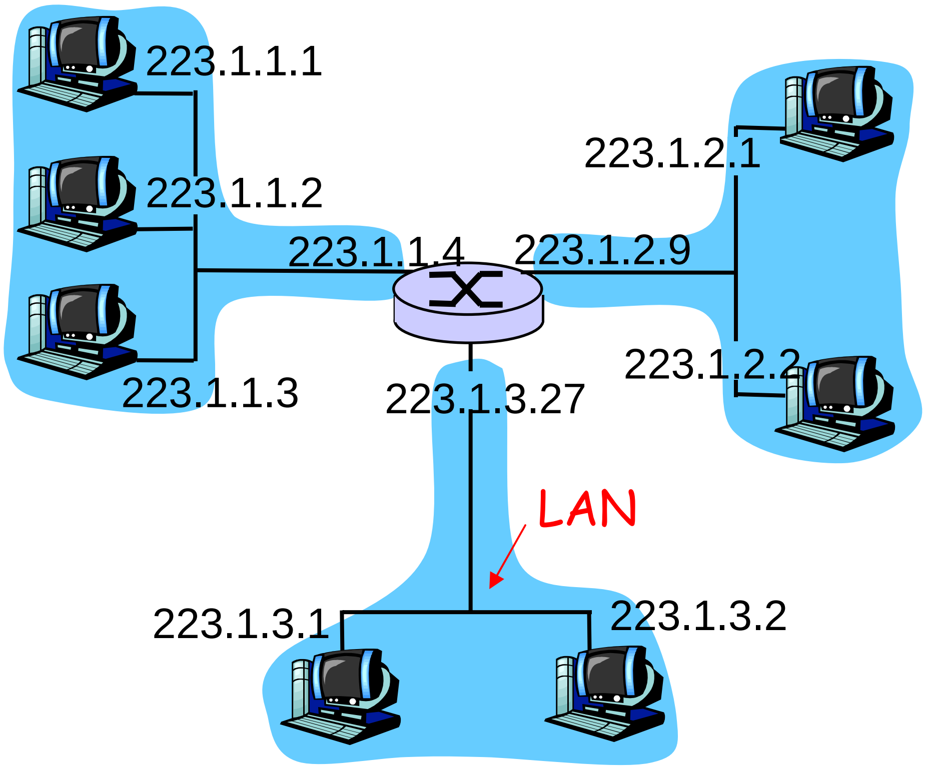
- IP address: 32-bit identifier for host, router *interface*
- *interface:* connection between host/router and physical link
  - router's typically have multiple interfaces
  - host may have multiple interfaces
  - IP addresses associated with each interface, *not with host or router*




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

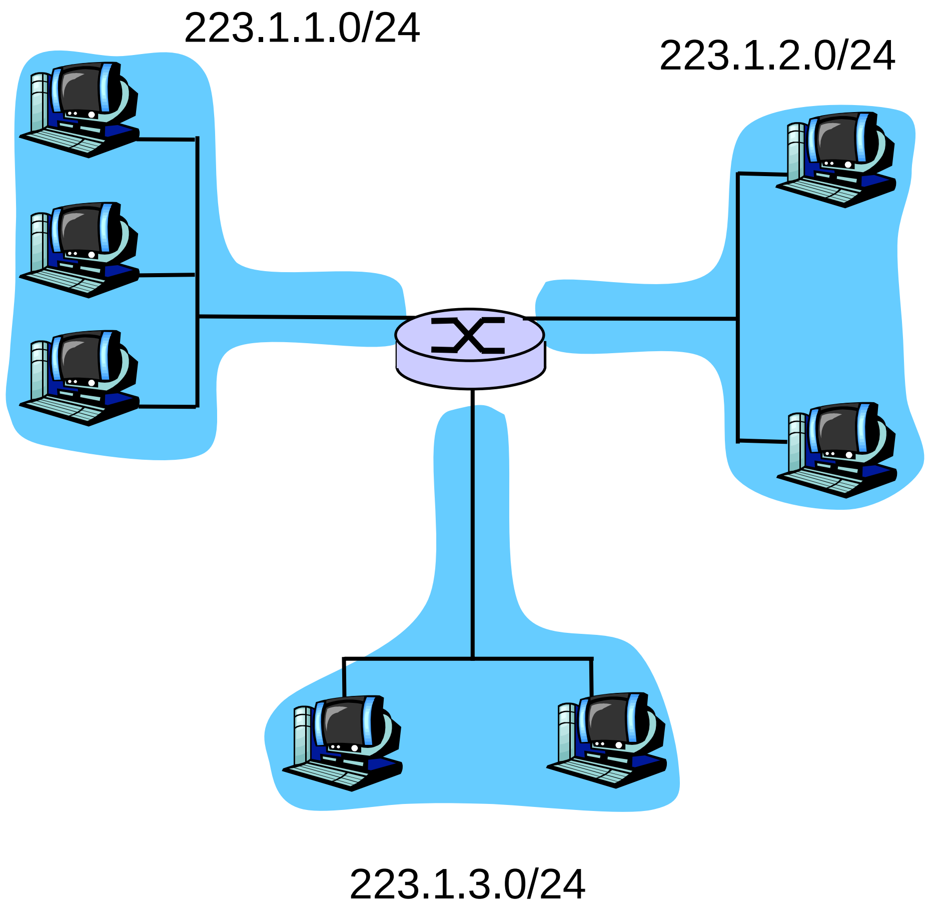
# Subnets

- 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
(for IP addresses starting with 223, first 24 bits are network address)

# Subnets



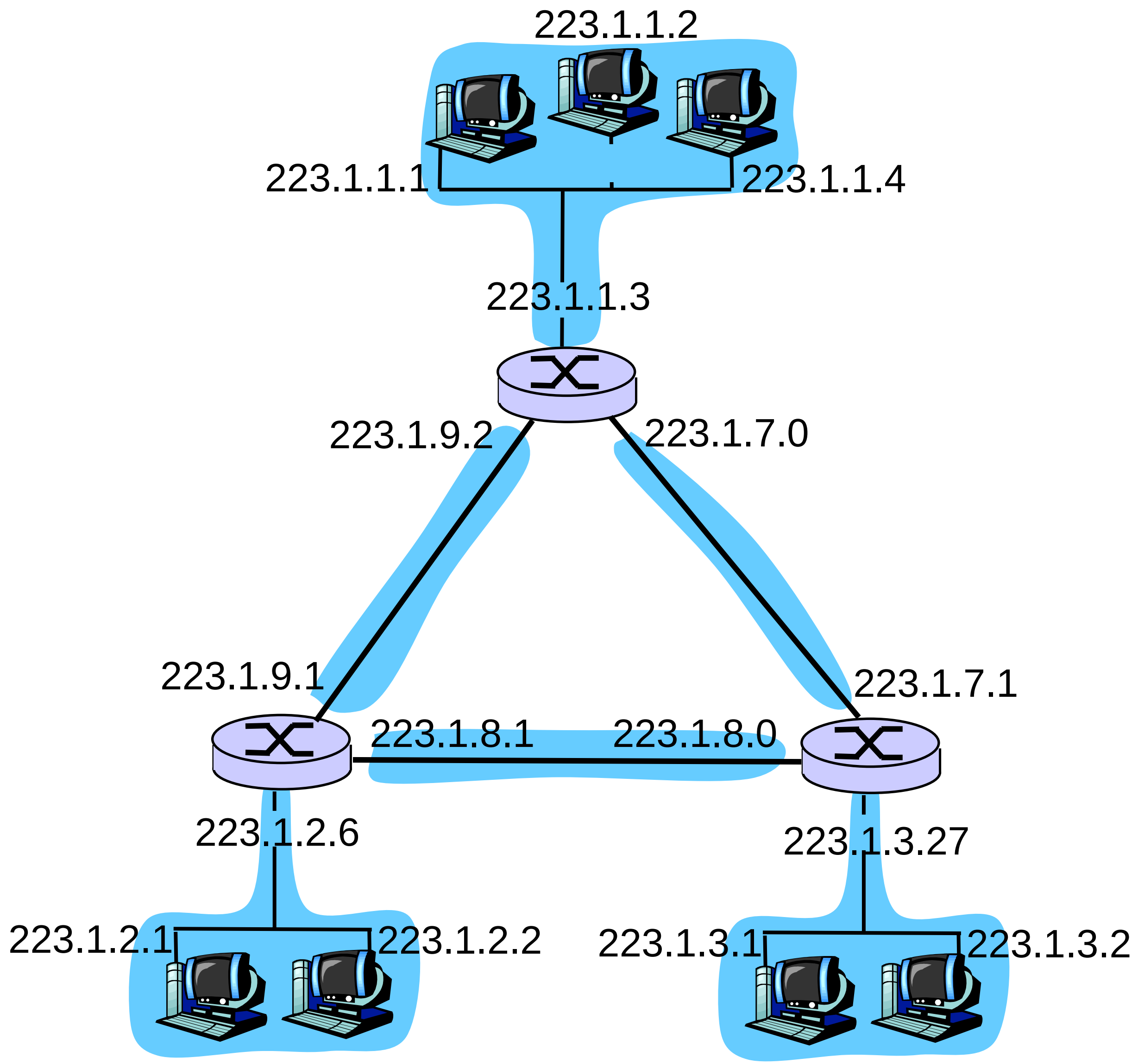

## Recipe

- 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

# Subnets

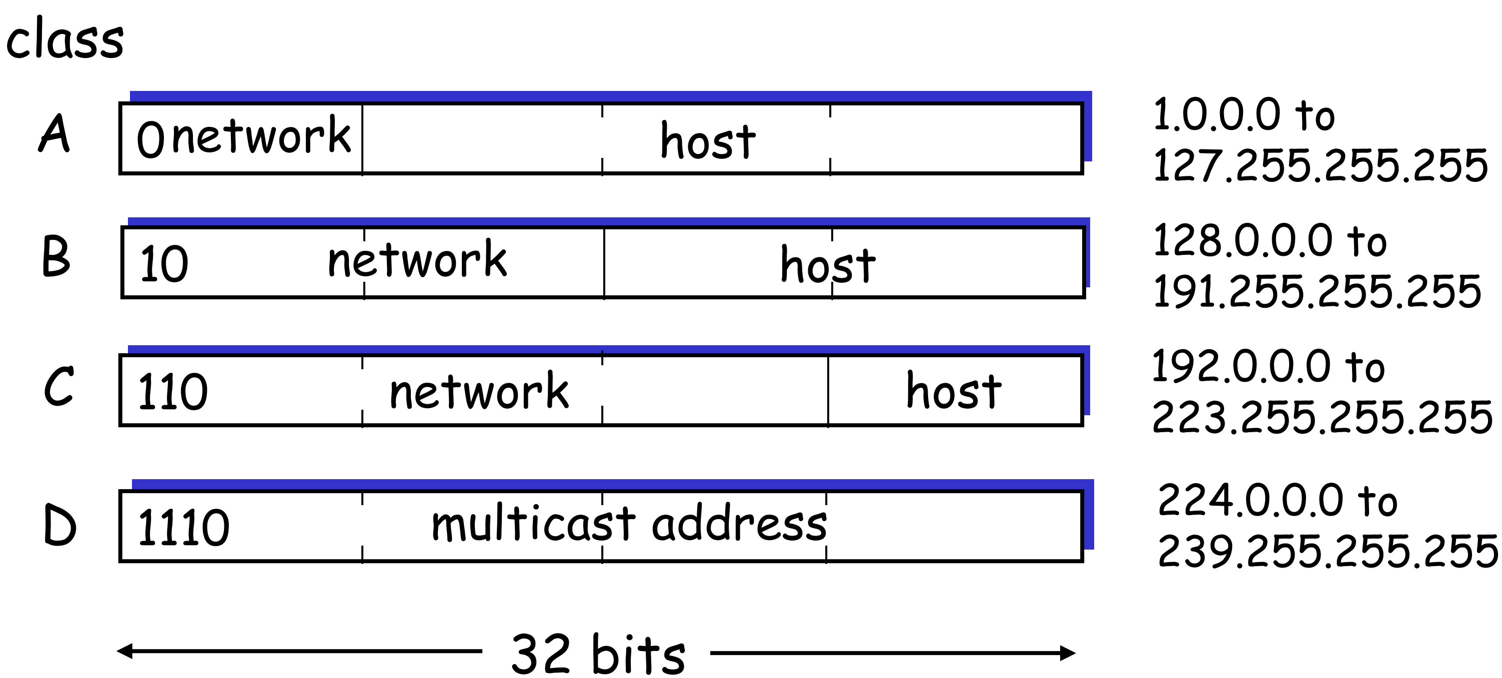
How many?



# IP Addresses

given notion of "network", let's re-examine IP addresses:

"class-full" addressing:



# IP addressing: CIDR

- classful addressing:
  - inefficient use of address space, address space exhaustion
  - e.g., class B net allocated enough addresses for 65K hosts, even if only 2K hosts in that network
- CIDR: Classless InterDomain Routing
  - network portion of address of arbitrary length
  - address format: a.b.c.d/x, where x is # bits in network portion of address

network part

host part

11001000 00010111 00010000 00000000

200.23.16.0/23

# IP addresses: how to get one?

Q: How does *host* get IP address?

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

(more later)

# IP addresses: how to get one?

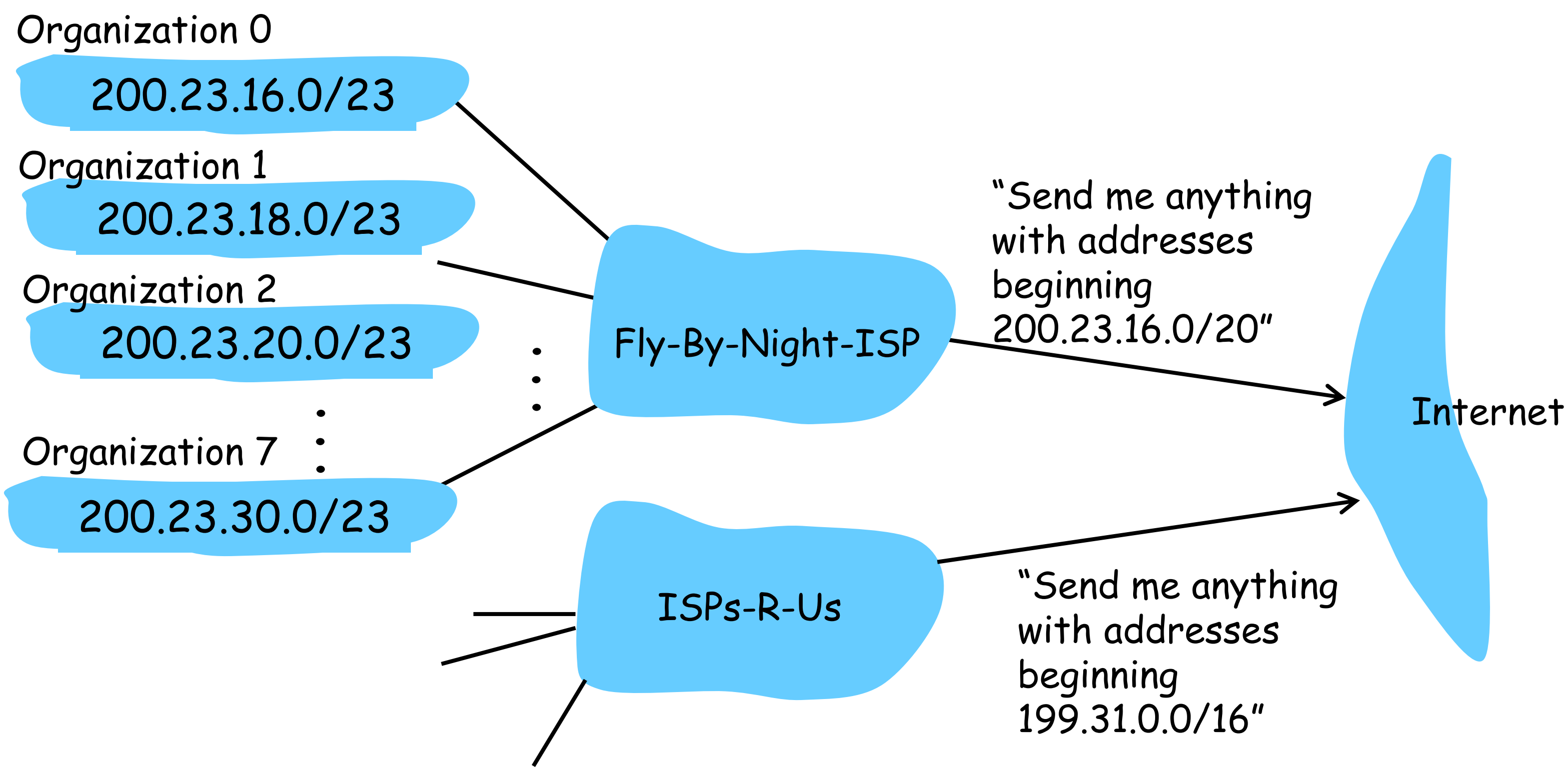
**Q:** How does *network* get subnet part of IP addr?

**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 |

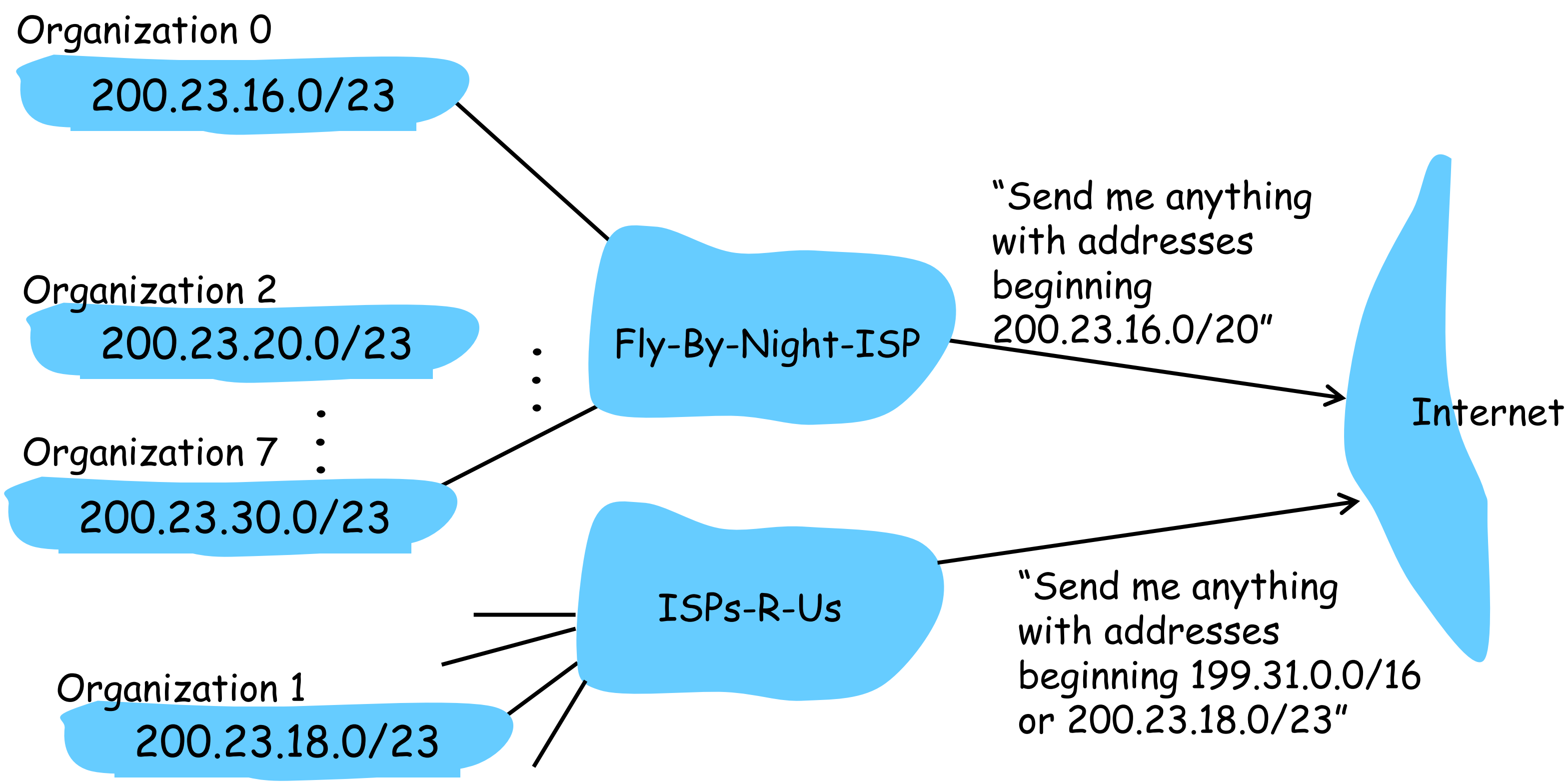
# Hierarchical addressing: route aggregation

Hierarchical addressing allows efficient advertisement of routing information:



# Hierarchical addressing: more specific routes

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



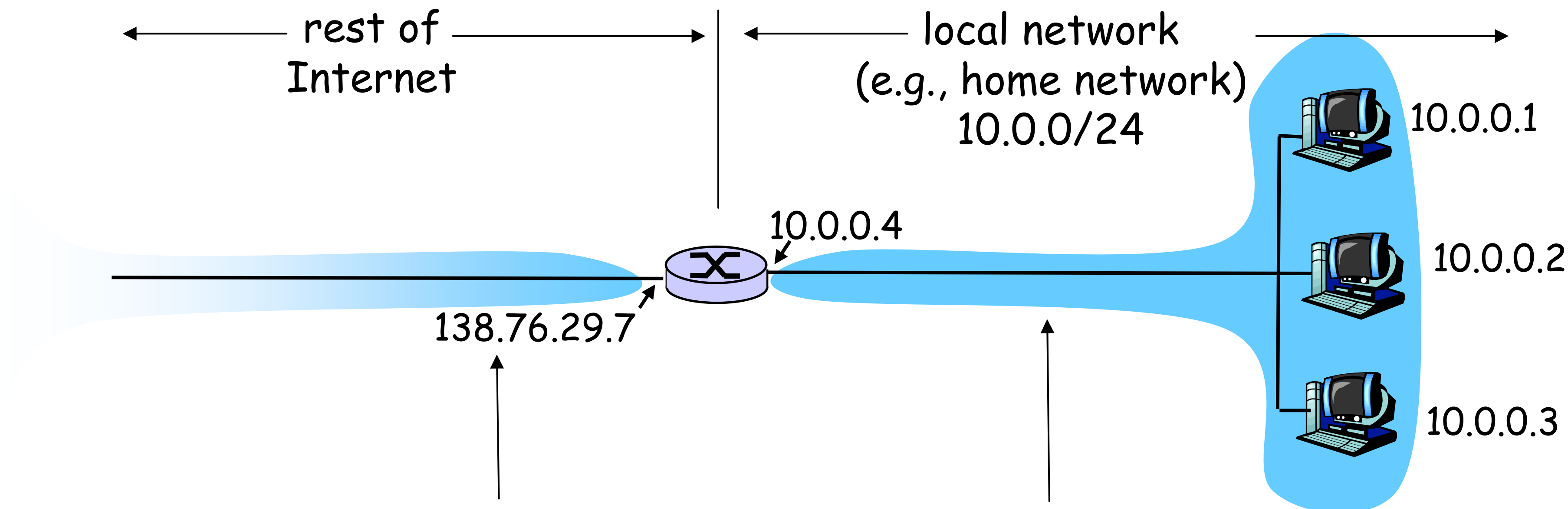
# IP addressing: the last word...

Q: How does an ISP get block of addresses?

A: ICANN: Internet Corporation for Assigned Names and Numbers

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

# 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 word is concerned:
  - no need to be allocated range of addresses from ISP: - just one IP address is used 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:

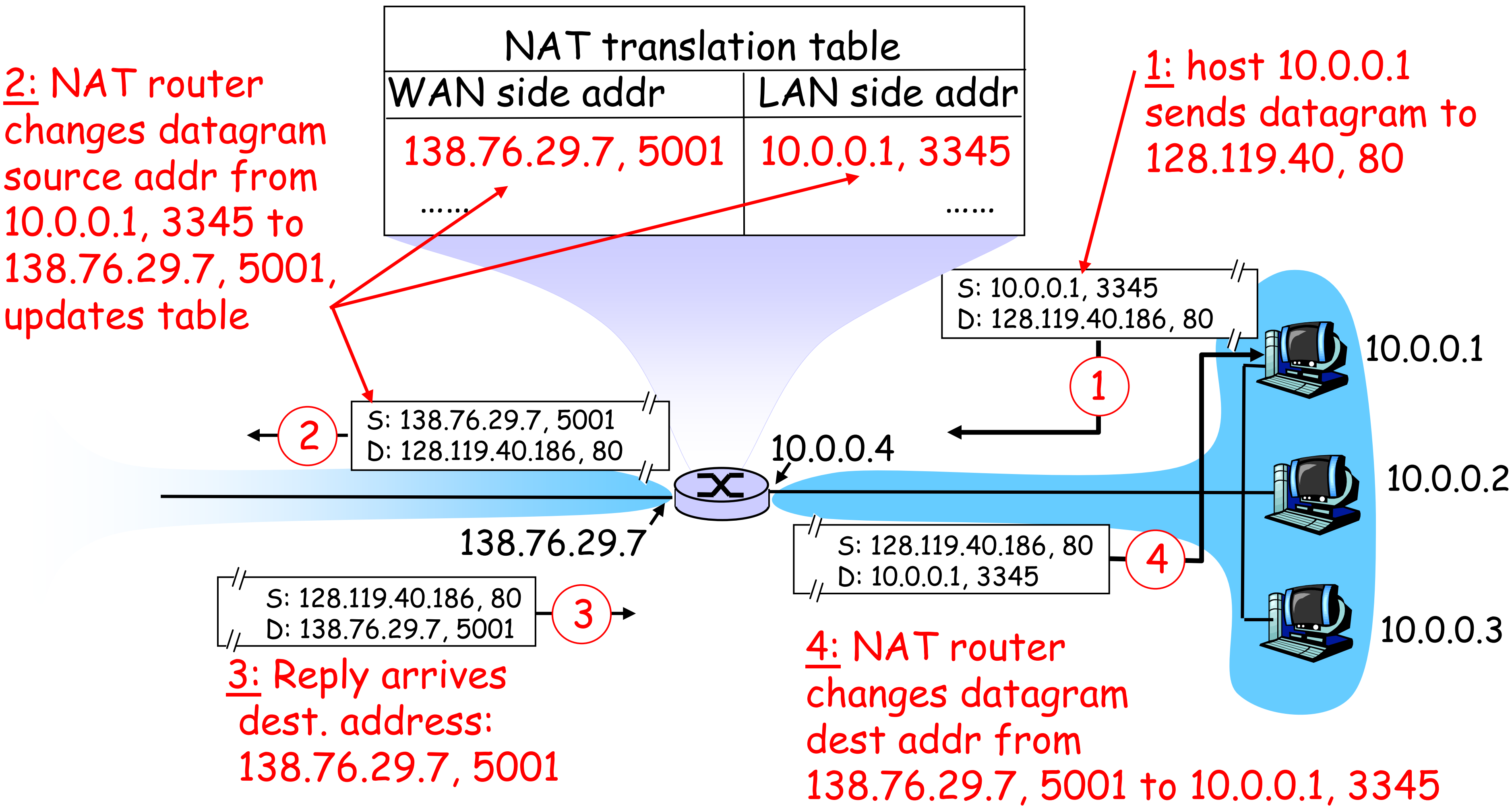
- *in outgoing datagrams: replace* (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #)

  . . . 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

- *in 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: Network Address Translation



# 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, eg, P2P applications
  - address shortage should instead be solved by IPv6

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# 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 has TTL =1
  - Second has TTL=2, etc.
  - Unlikely port number
- When nth datagram arrives to nth router:
  - Router discards datagram
  - And sends to source an ICMP message (type 11, code 0)
  - Message includes name of router& IP address

- When ICMP message arrives, source calculates RTT
- Traceroute does this 3 times

Stopping criterion

- UDP segment eventually arrives at destination host
- Destination returns ICMP "host unreachable" packet (type 3, code 3)
- When source gets this ICMP, stops.

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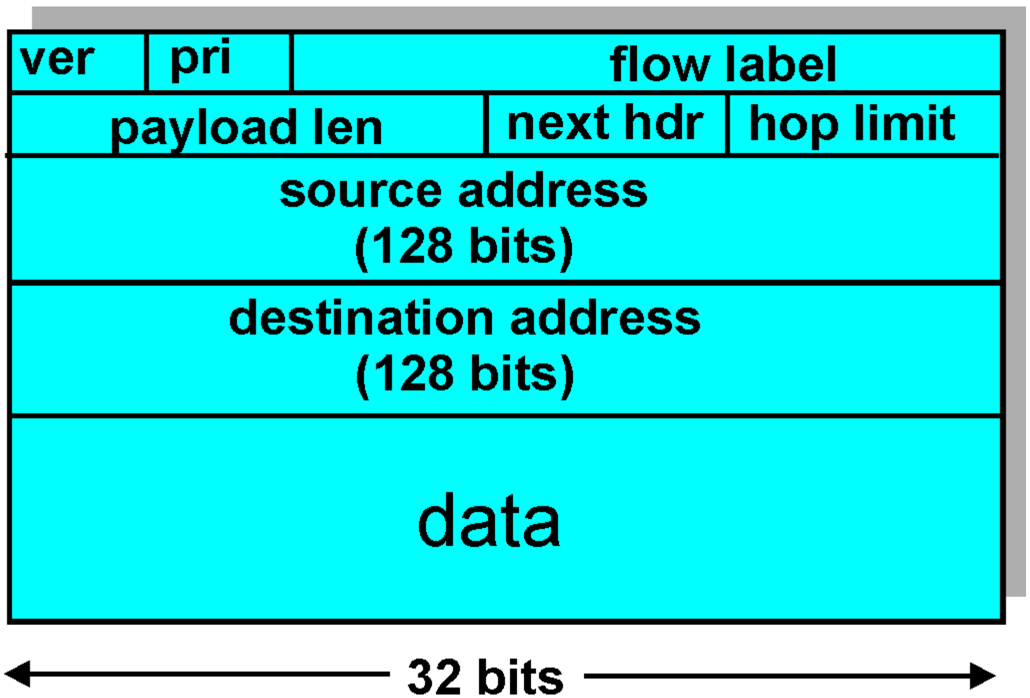
# IPv6

- 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 Header (Cont)

*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



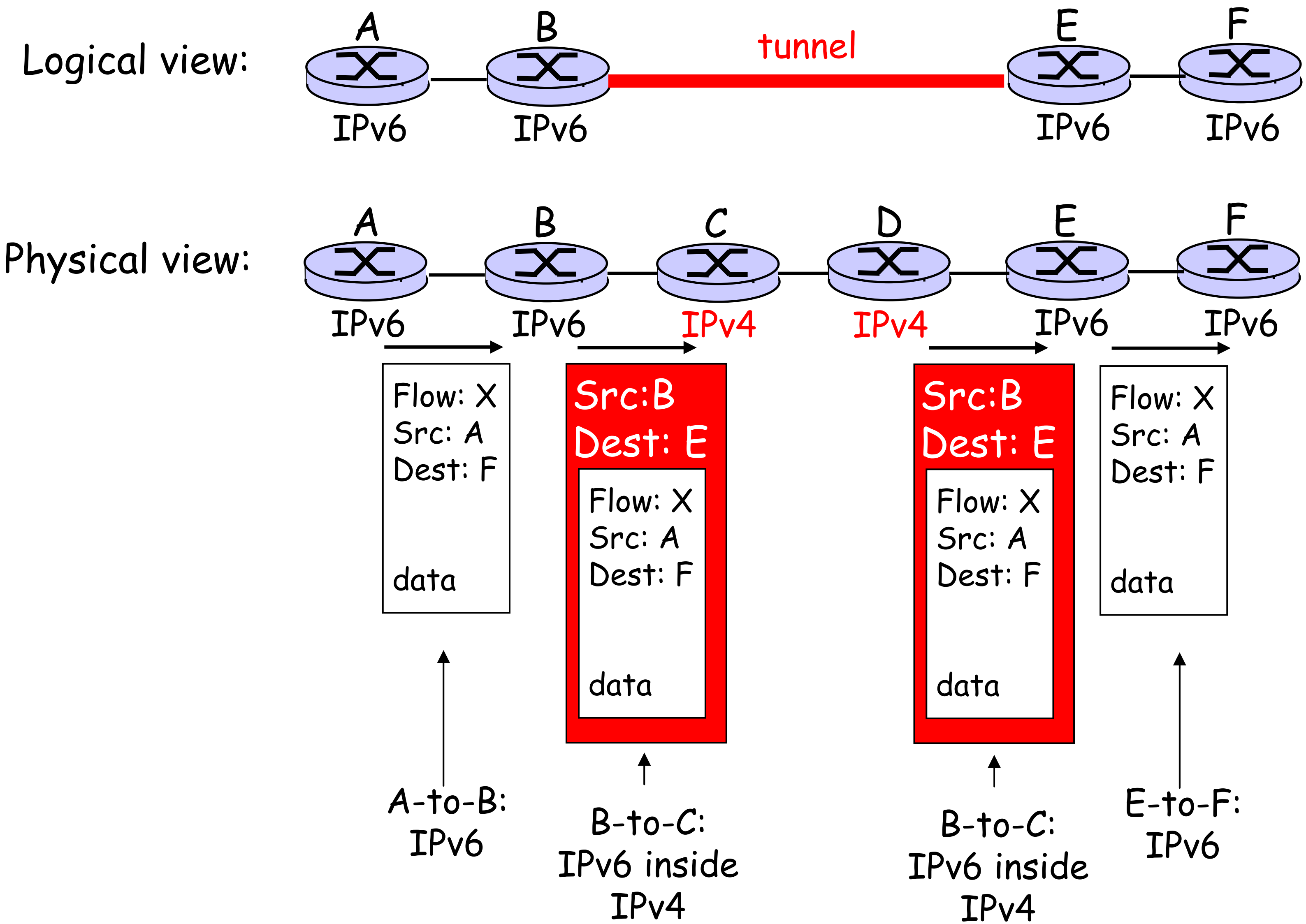
# Other Changes from IPv4

- *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 simultaneous
  - no "flag days"
  - How will the network operate with mixed IPv4 and IPv6 routers?
- Two proposed approaches:
  - *Dual Stack*: some routers with dual stack (v6, v4) can "translate" between formats
  - *Tunneling:* IPv6 carried as payload in IPv4 datagram among IPv4 routers

# Tunneling



Logical view:
A
B
E
F
tunnel
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