Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

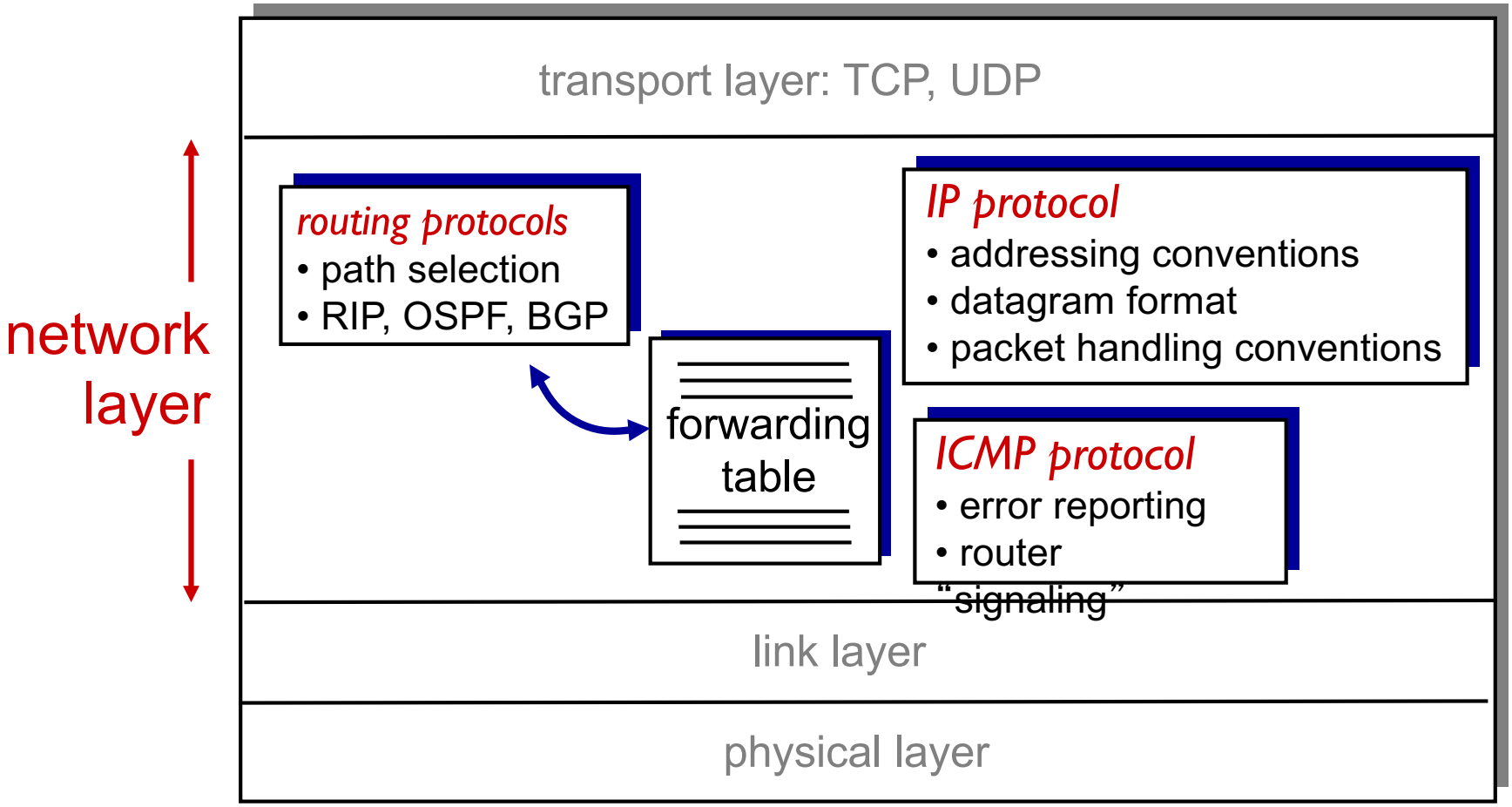
4.2 What's inside a router

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

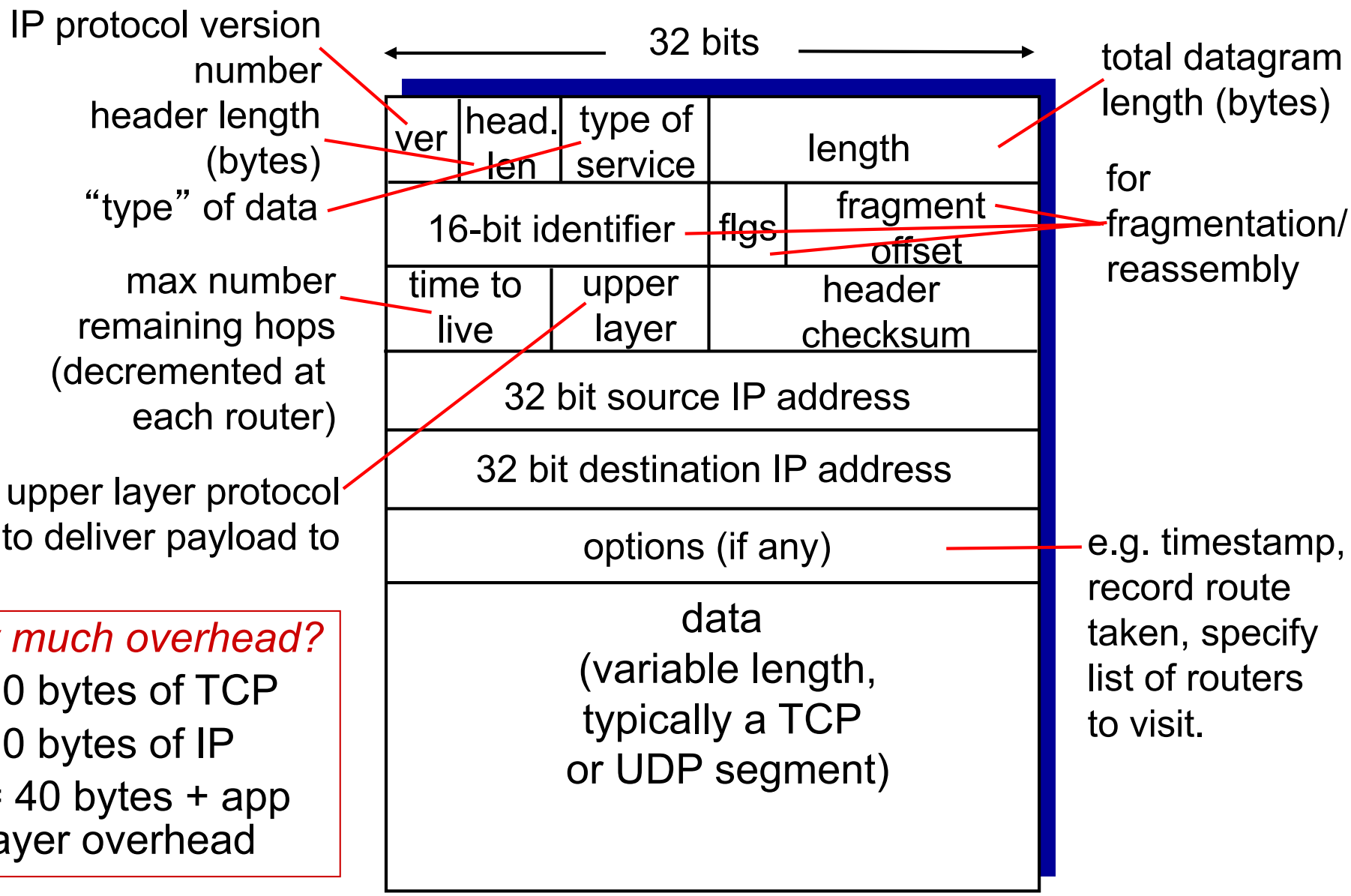
4.4 Generalized Forward and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

The Internet network layer

host, router network layer functions:



IP datagram format

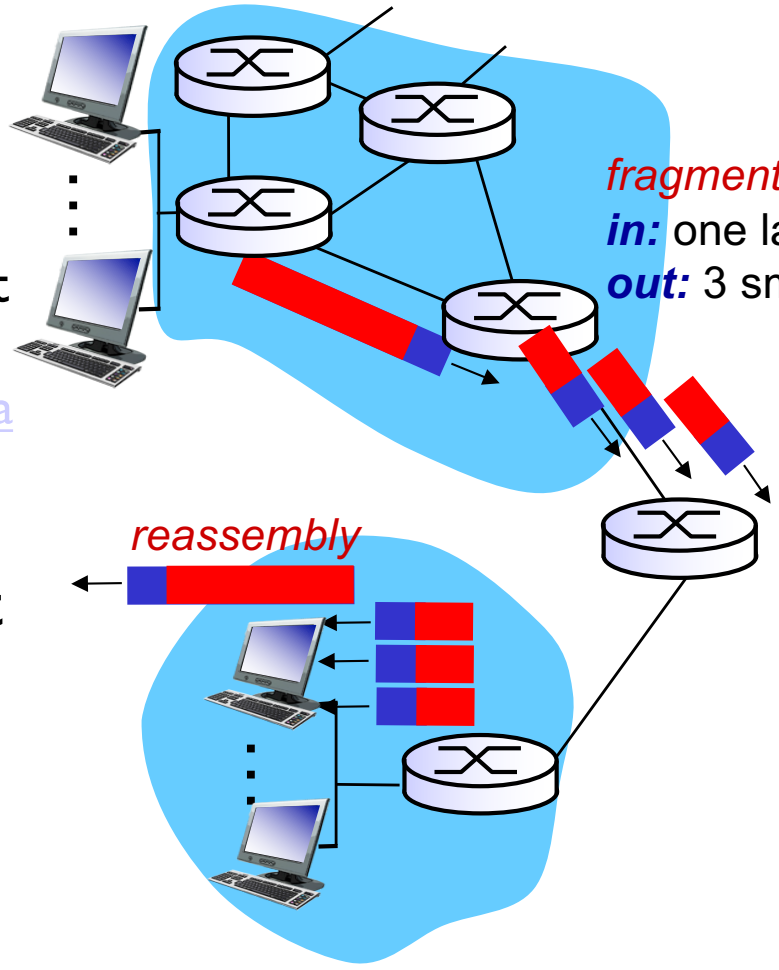


how much overhead?

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

IP fragmentation, reassembly

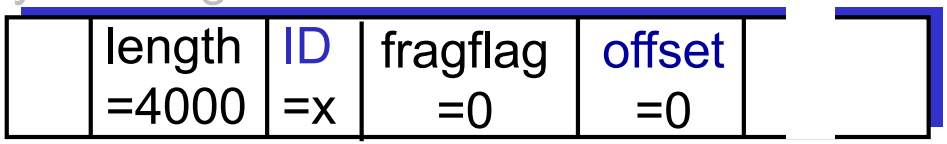
- network links have MTU (max.transfer size) - largest possible link-level frame
  - different link types, different MTUs
  - https://en.wikipedia.org/wiki/Maximum_transmission_unit
- large IP datagram divided ("fragmented") within net
  - one datagram becomes several datagrams
  - "reassembled" only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



IP fragmentation, reassembly

ID: unique per packet, incremented by sending host

offset: multiple of 8.



example:

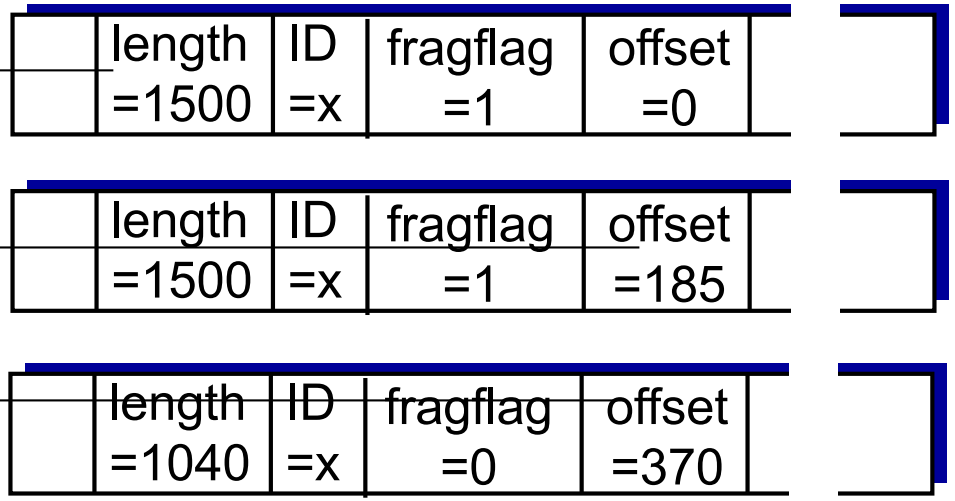
- 4000 byte datagram
- MTU = 1500 bytes

one large datagram becomes several smaller datagrams

1480 bytes in data field

offset = 1480/8

offset = 2*1480/8



Original datagram: 20+3980=4000
1st fragment: 20+1480= 1500 starts at byte 0
2nd fragment: 20+1480 = 1500 starts at byte 185*8=1480
3rd fragment: 20+1020 = 1040 starts at byte (185+185)*8=2960
Data: 1480+1480+1020=3980

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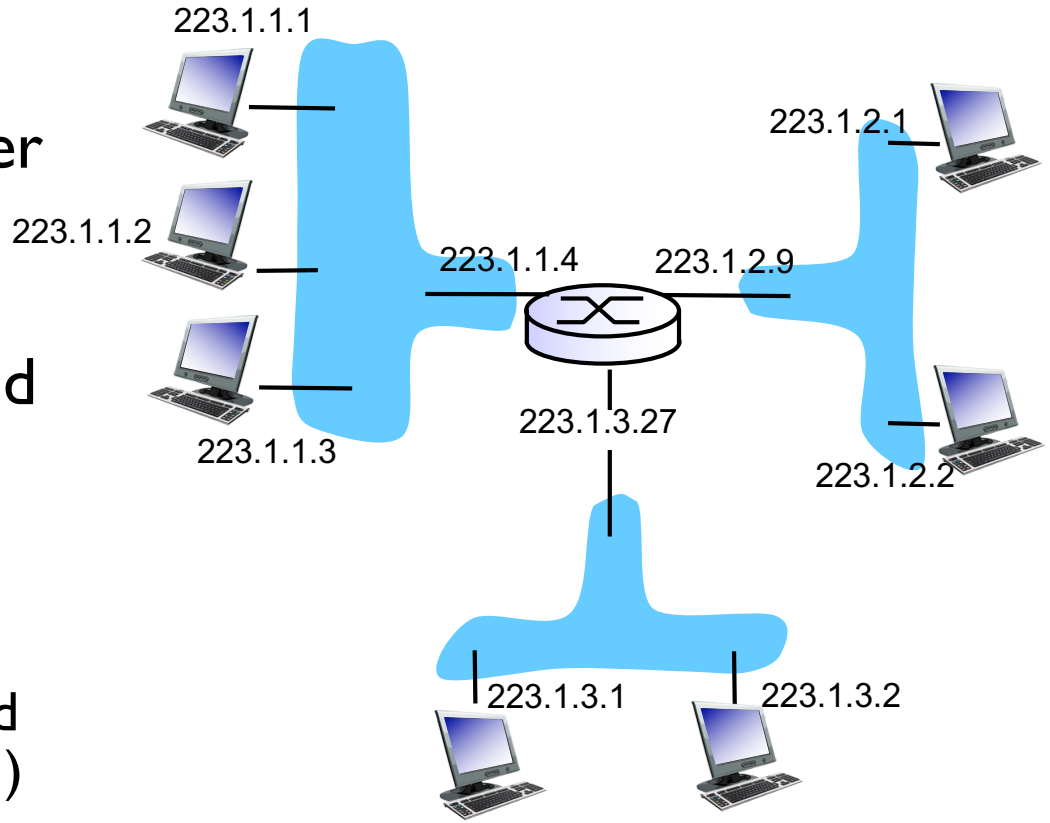
IP addressing: introduction

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



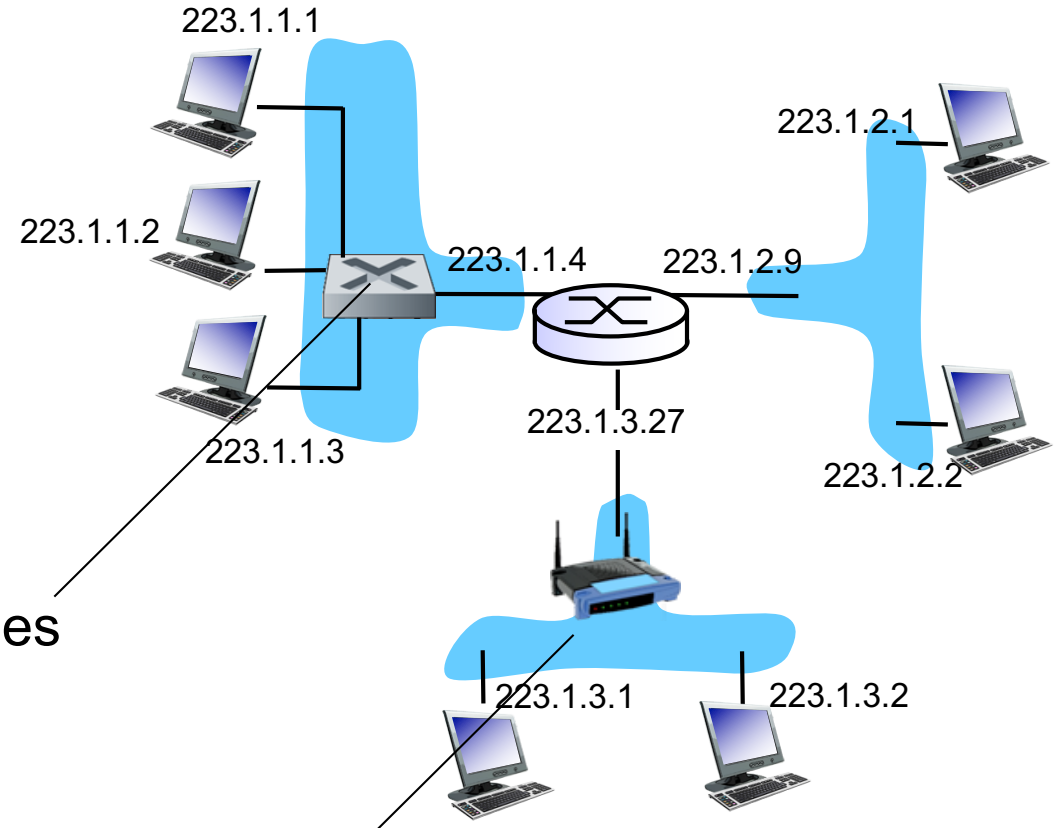
223.1.1.1 = 11011111 00000001 00000001 00000001

223 1 1 1

IP addressing: introduction

Q: how are interfaces actually connected?

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



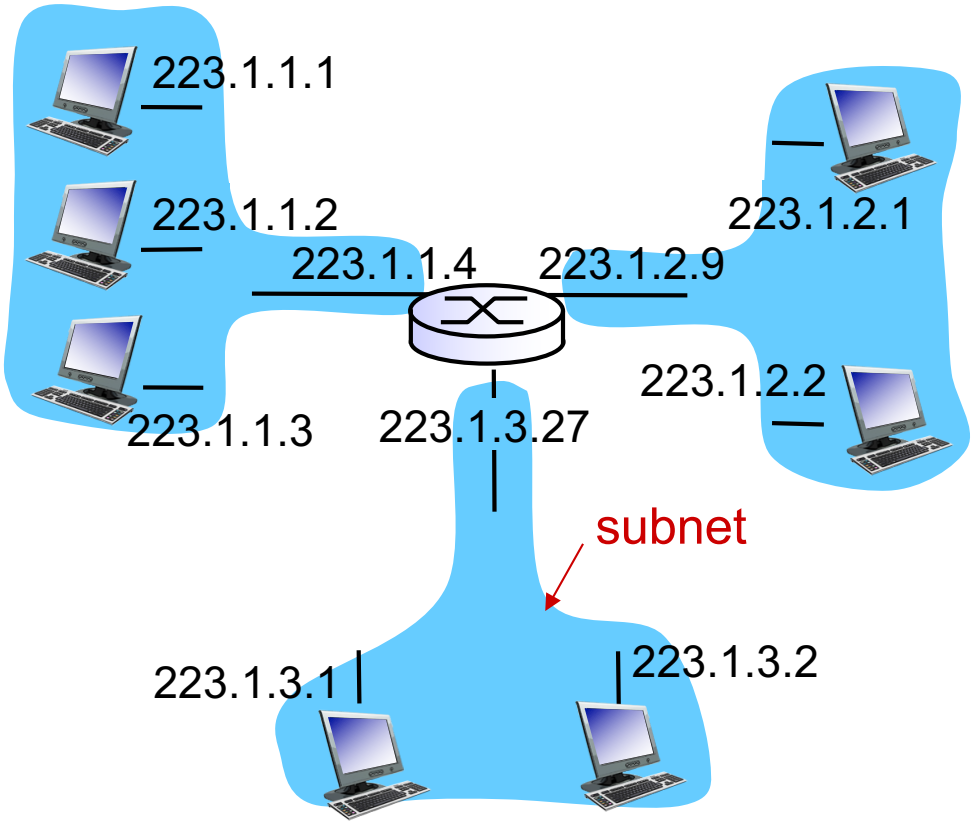
A: wired Ethernet interfaces connected by Ethernet switches

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

A: wireless WiFi interfaces connected by WiFi base station

Subnets

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

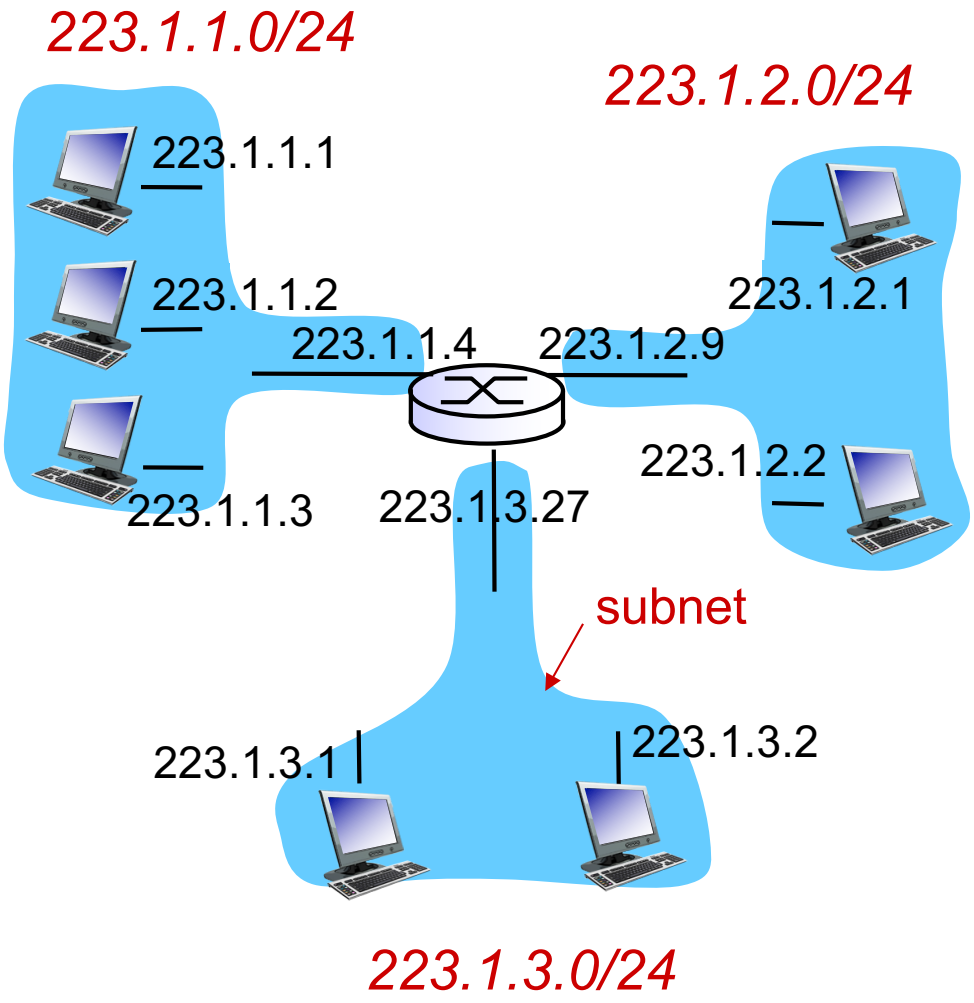


network consisting of 3 subnets

Subnets

recipe

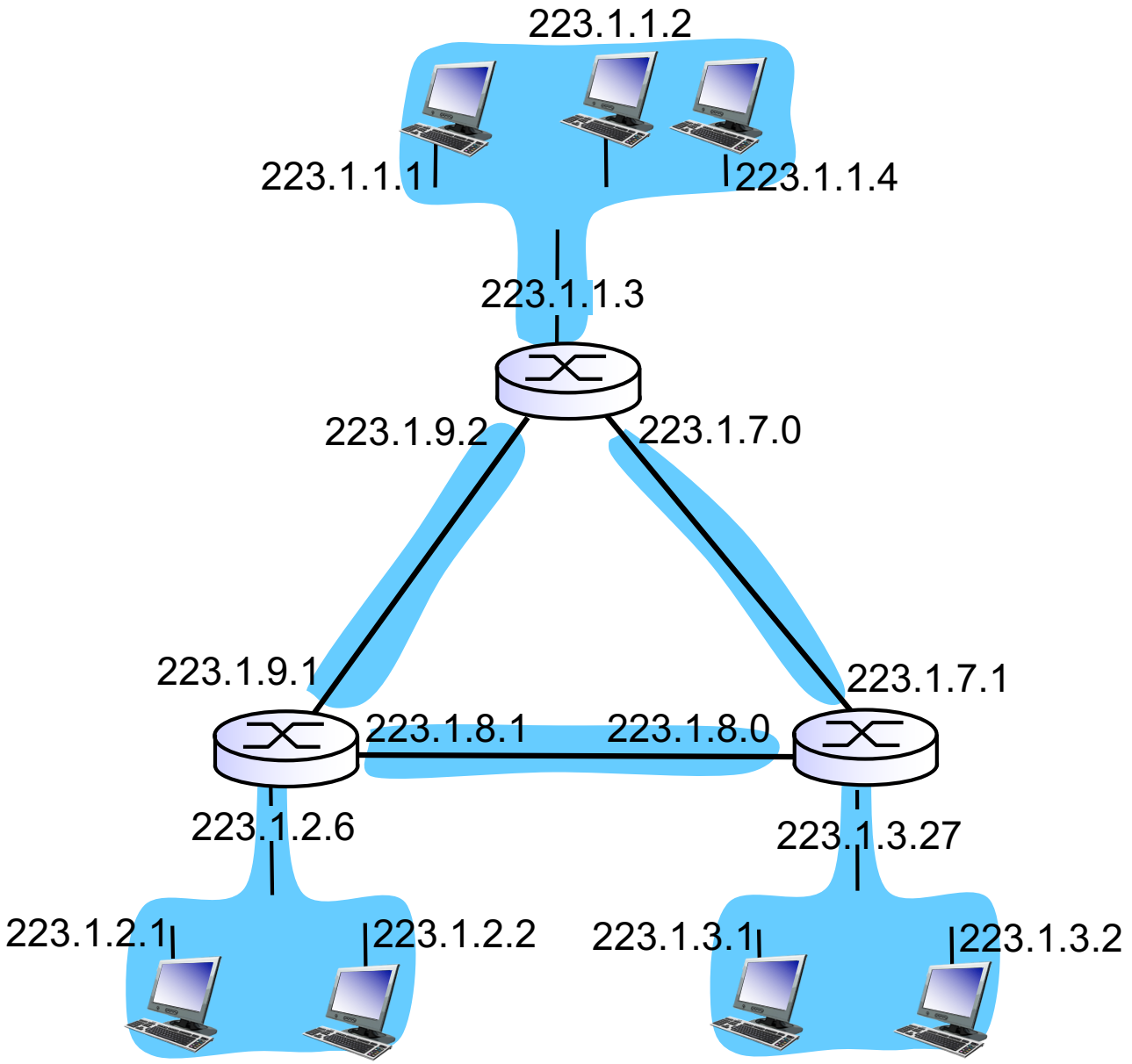
- to determine the subnets, detach each interface from its host or router, creating islands of isolated networks
- each isolated network is called a *subnet*



subnet mask: /24

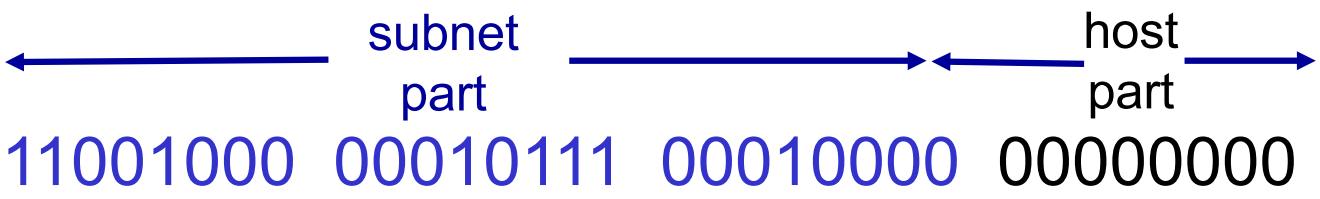
Subnets

how many?



Historic Classful Network Architecture:

Class	Starting with (bits)	Range of first byte (decimal)	Network id format	Host id format	Number of networks	Numnber of hosts
A	0	0-127	a	b.c.d	2^7 = 128	2^{24} = 16777216
B	10	128-191	a.b	c.d	2^{14} = 16384	2^{16} = 65536
C	110	192-223	a.b.c	d	2^{21} = 2097152	2^8 = 256



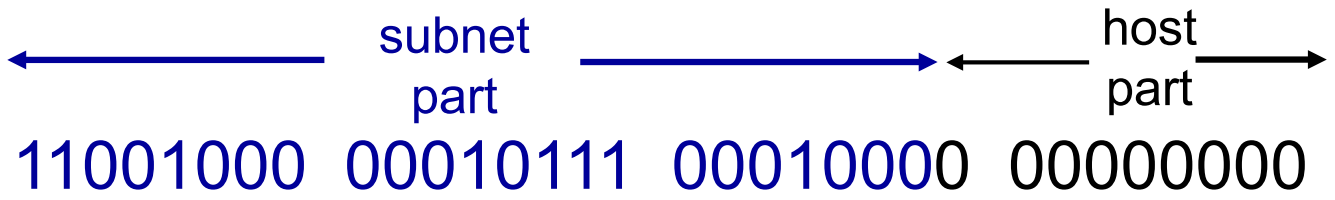
Class C network ("/24"): 200.23.16.0

Example IP in that network: 200.23.16.1

(Since 1993) 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



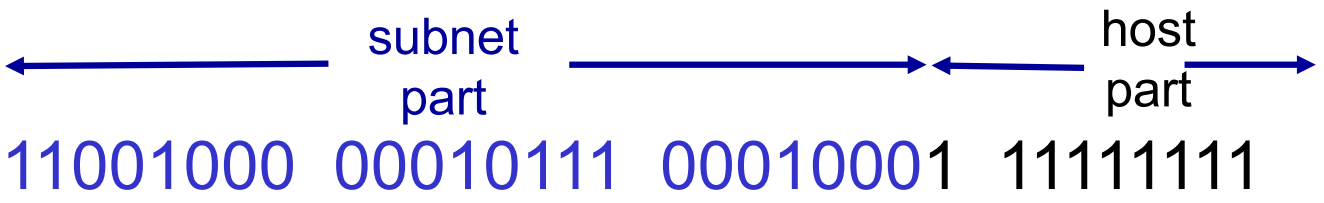
200.23.16.0/23

Q: what did we gain?

A: more efficient use of the IP address space

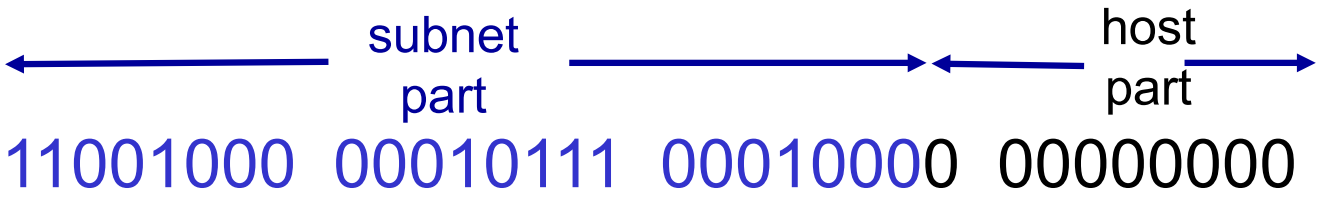
Some special IP addresses

- All 1's: means "all hosts on this subnet"



200.23.17.255/23

- All 0's: means "this subnet"



200.23.16.0/23

More IP addresses

- Reserved IP addresses for special purposes
  - 127.0.0.1: local host
  - Multicast
    - 224.0.0.0/8–239.0.0.0/8
  - Private networks:
    - not routed, typically used through NATs.
    - 24- bit block, /8 prefix, 1xA: 10.0.0.0-10.255.255.255
    - 20-bit block, /12 prefix, 16xB: 172.16.0.0- 172.31.255.255
    - 16-bit block, /16 prefix, 256xC: 192.168.0.0-192.168.255.255
  - Assigned to special institutions

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

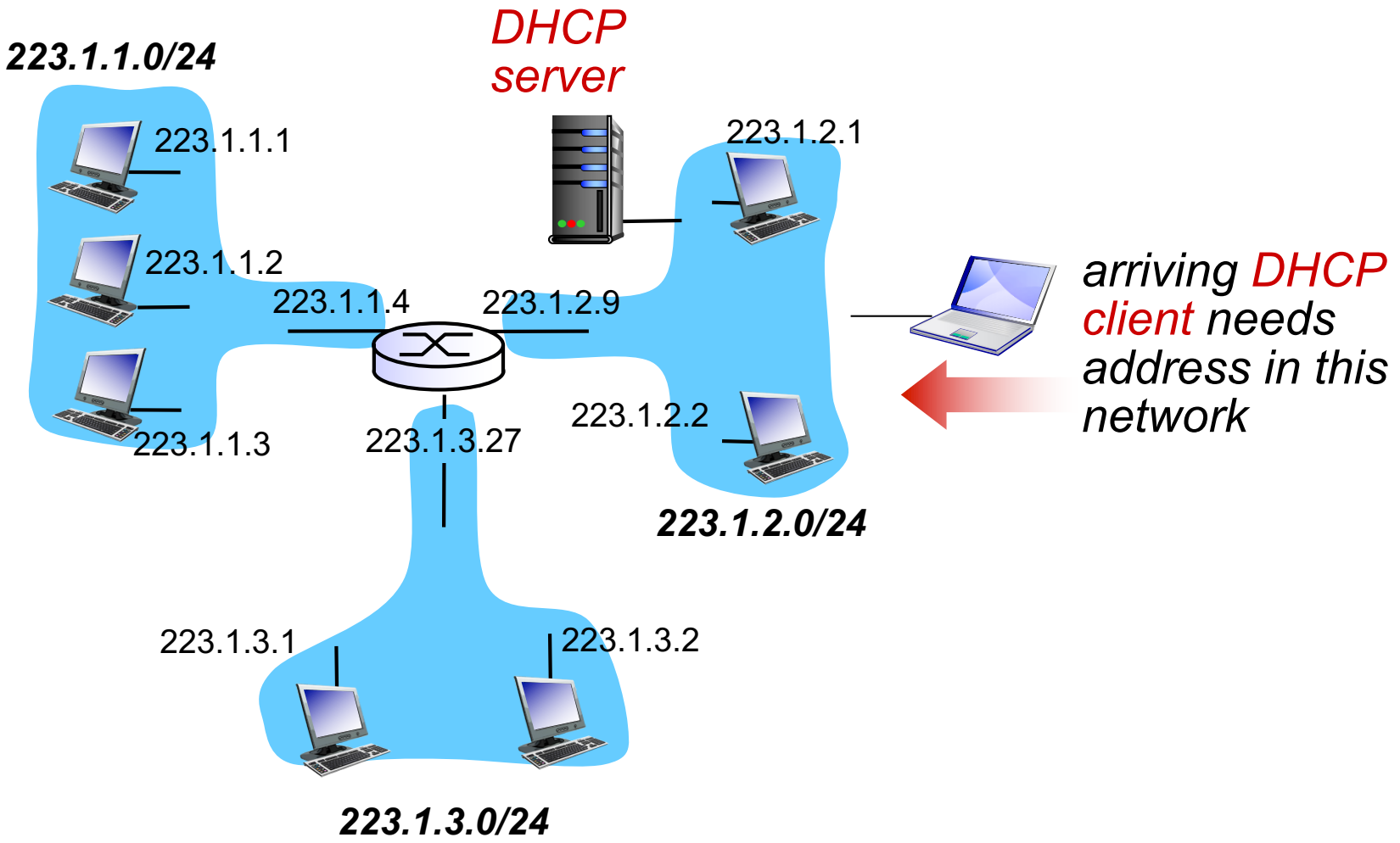
goal: allow host to *dynamically* obtain its IP address from network server when it joins network

- 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)

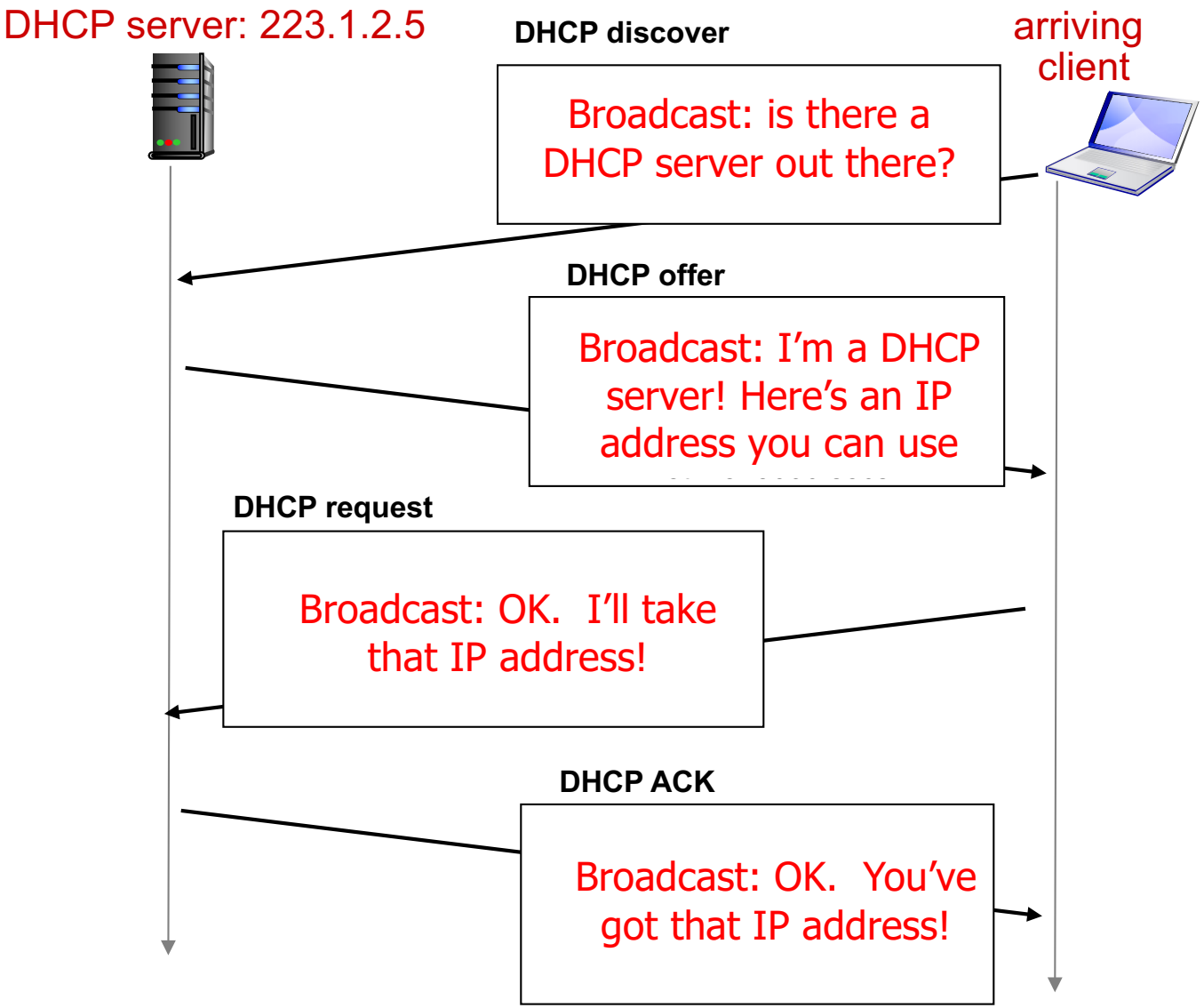
DHCP overview:

- host broadcasts "DHCP discover" msg [optional]
- DHCP server responds with "DHCP offer" msg [optional]
- host requests IP address: "DHCP request" msg
- DHCP server sends address: "DHCP ack" msg

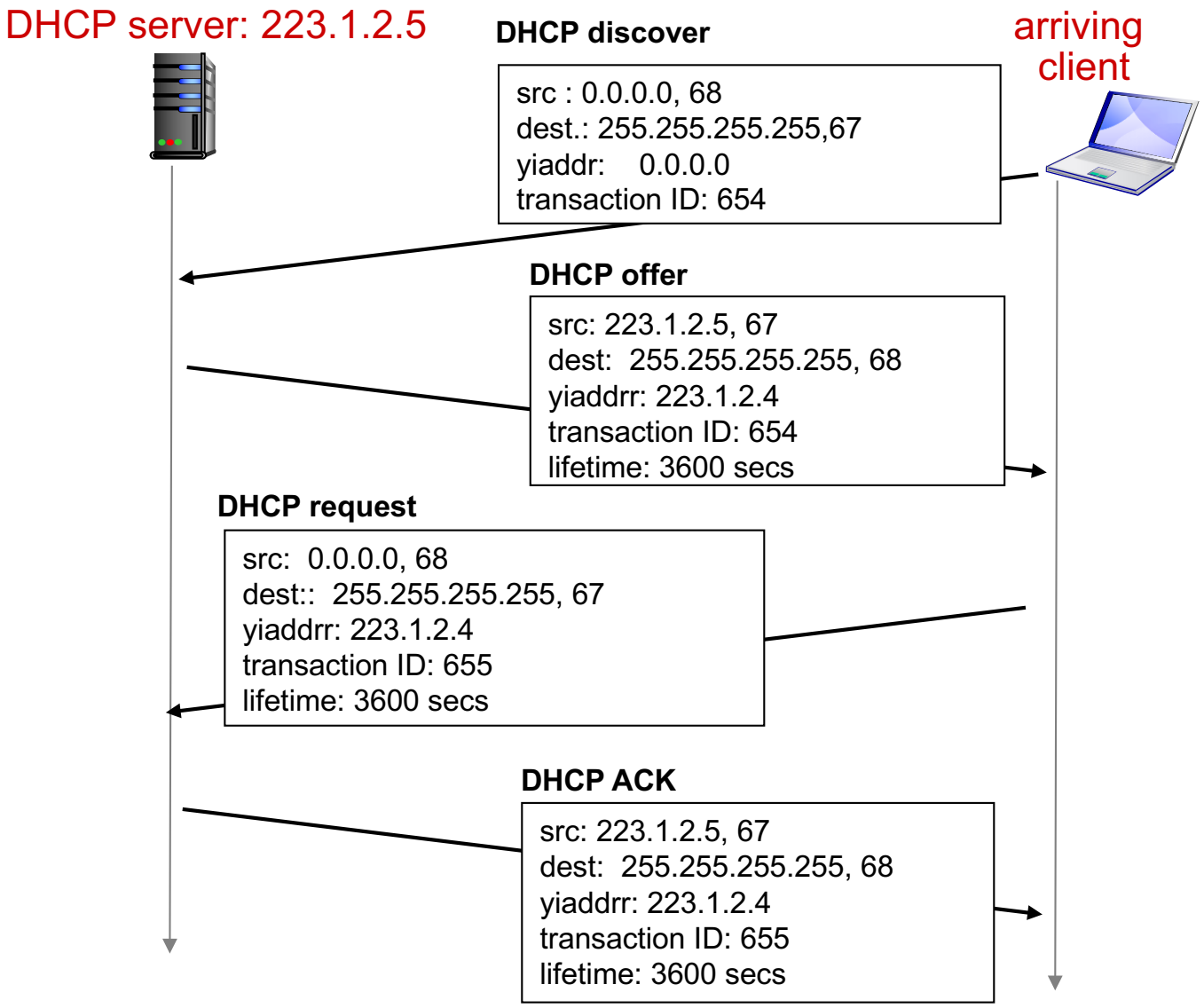
DHCP client-server scenario



DHCP client-server scenario



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?]

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  - UNIX: /etc/rc.config
- DHCP: Dynamic Host Configuration Protocol: dynamically get address from as server
  - "plug-and-play"

IP addresses: how to get one?

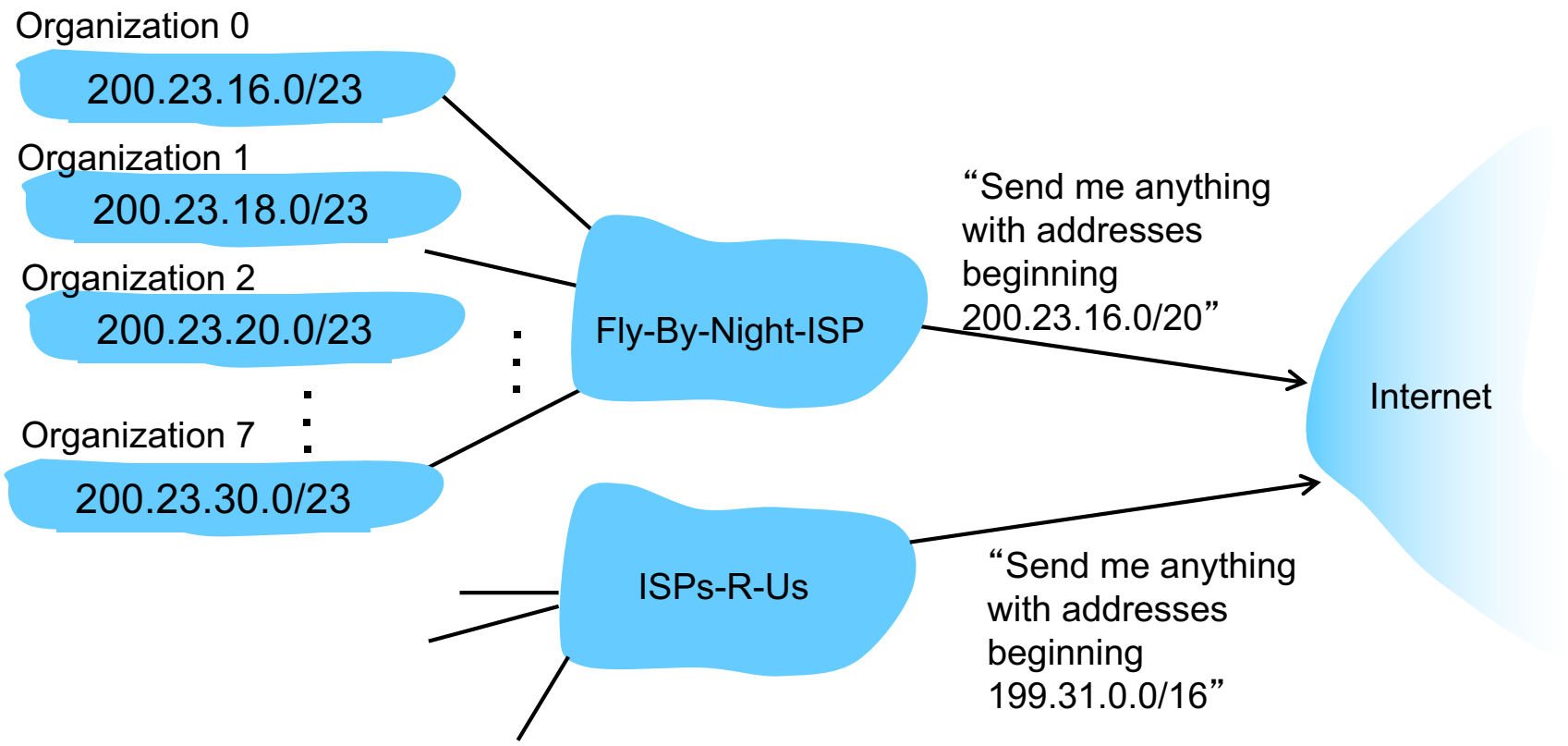
Q: how does a *network* get subnet part of IP addr?

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

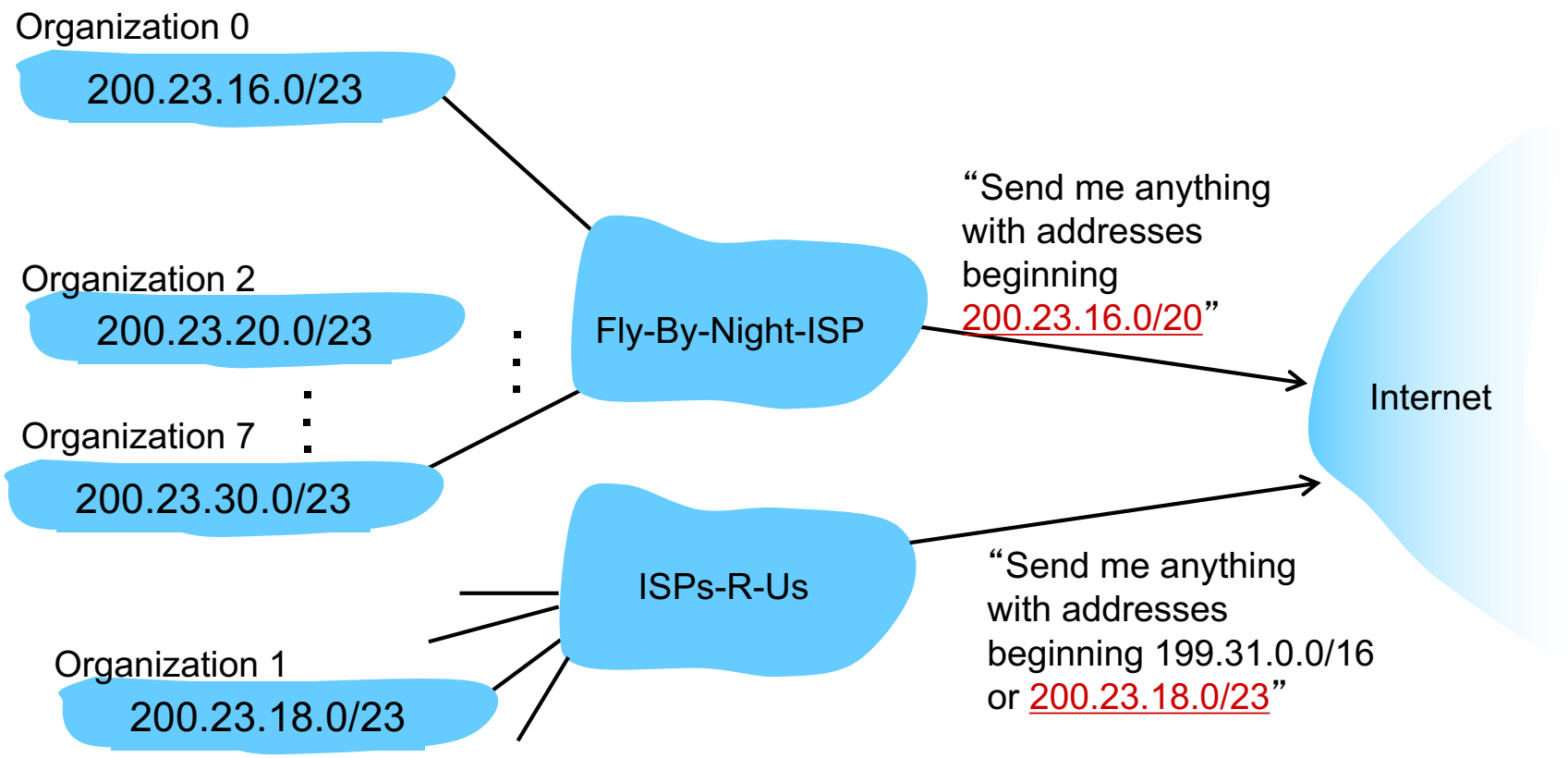
Hierarchical addressing: route aggregation

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
  - http://www.iana.org/assignments/ipv4-address-space/ipv4-address-space.xhtml
- manages DNS
- assigns domain names, resolves disputes
- delegates to regional registries (RIRs)

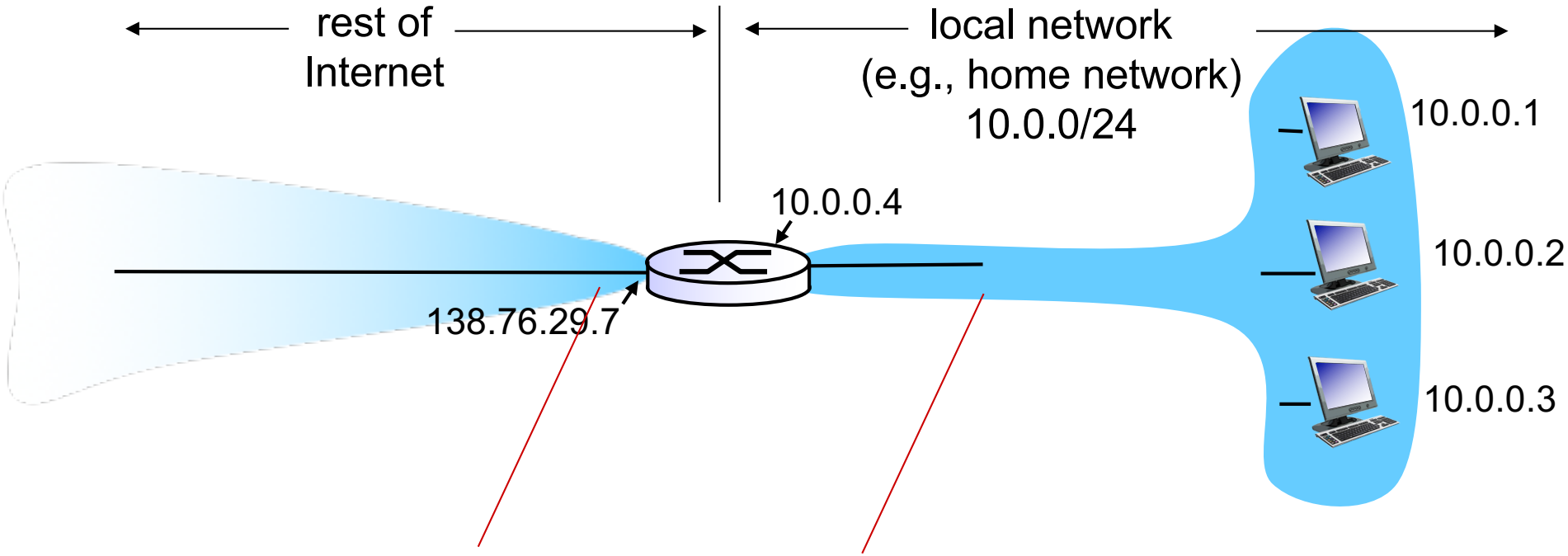
IP addresses: a scarce resource!

- More users than IP addresses
  - In the 1970's: 2^{32} was plenty of addresses
  - ~2010: 1B computers, 5B phones
- Bad utilization
  - Some prefixes are full
  - Some are reserved and unused!
- How are they allocated today?
  - http://en.wikipedia.org/wiki/List_of_assigned_/8_IPv4_address_blocks
  - ARIN: https://en.wikipedia.org/wiki/American_Registry_for_Internet_Numbers
  - http://www.caida.org/research/id-consumption/whois-map/

IP addresses: a scarce resource!

- More users than IP addresses:
  - In the 1970's: 2^{32} was plenty of addresses
  - Today: >1B computers, >7B phones
- Bad utilization of existing IP addresses
  - Some prefixes are full
  - Some are reserved and unused!
  - CAIDA's map
- Solutions:
  - DHCP: get an IP dynamically, when you use it
  - NAT: entire subnet uses one IP externally
  - IPv6: increase the IP address from 32 to 64 bits.

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:

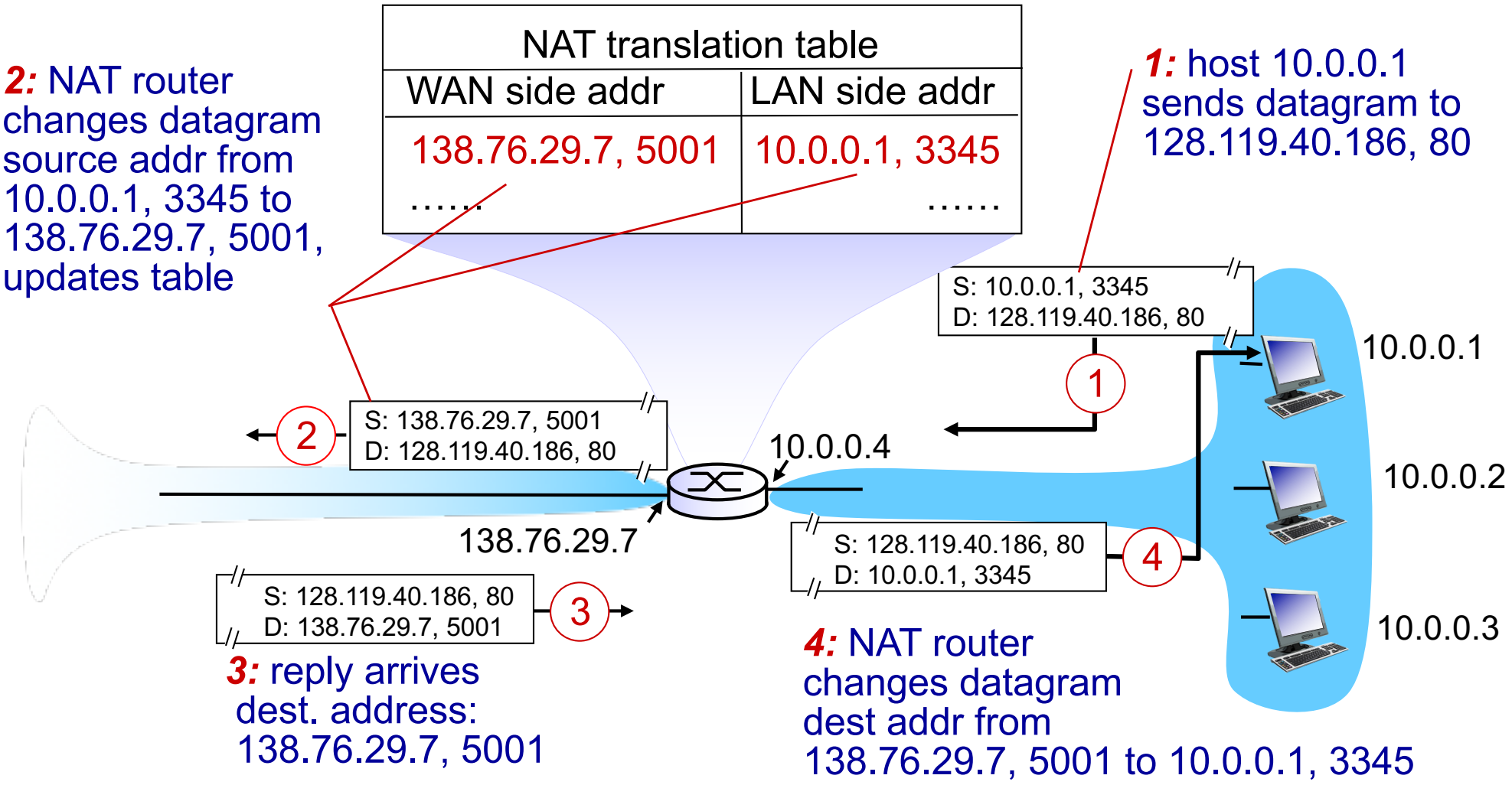
- *outgoing datagrams: replace* (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #)

  . . . 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: network address translation



* Check out the online interactive exercises for more examples: http://gaia.cs.umass.edu/kurose_ross/interactive/

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
  - address shortage should be solved by IPv6
  - violates end-to-end argument
    - NAT possibility must be taken into account by app designers, e.g., P2P applications
  - NAT traversal: what if client wants to connect to server behind NAT?

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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:

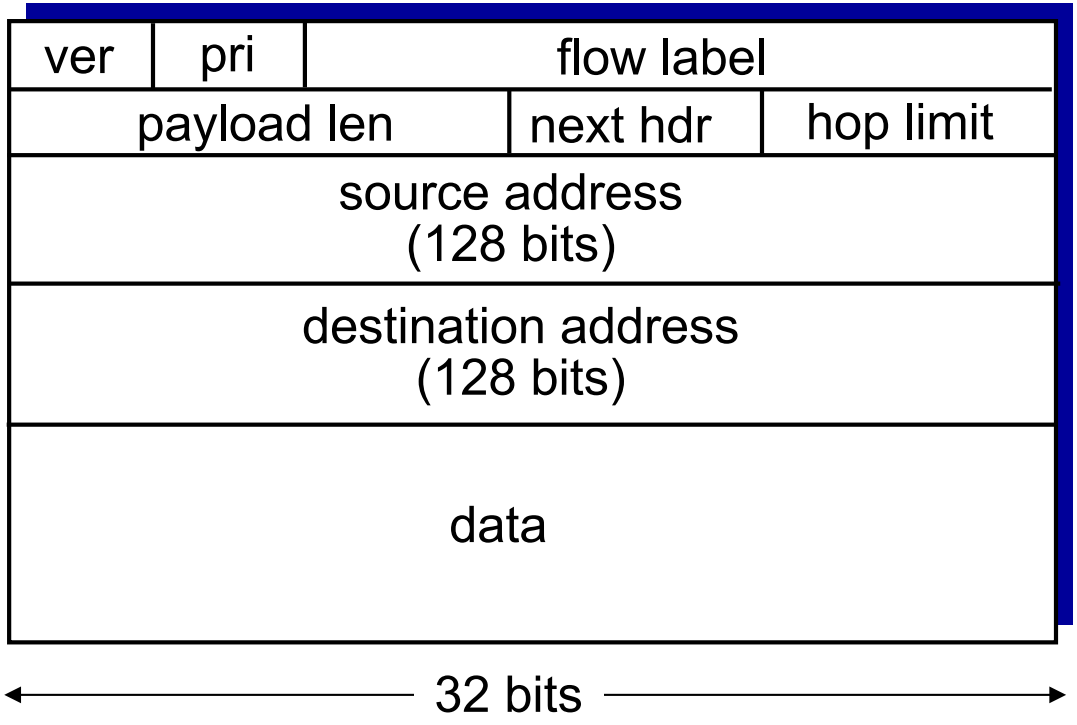
- fixed-length 40 byte header
- no fragmentation allowed

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

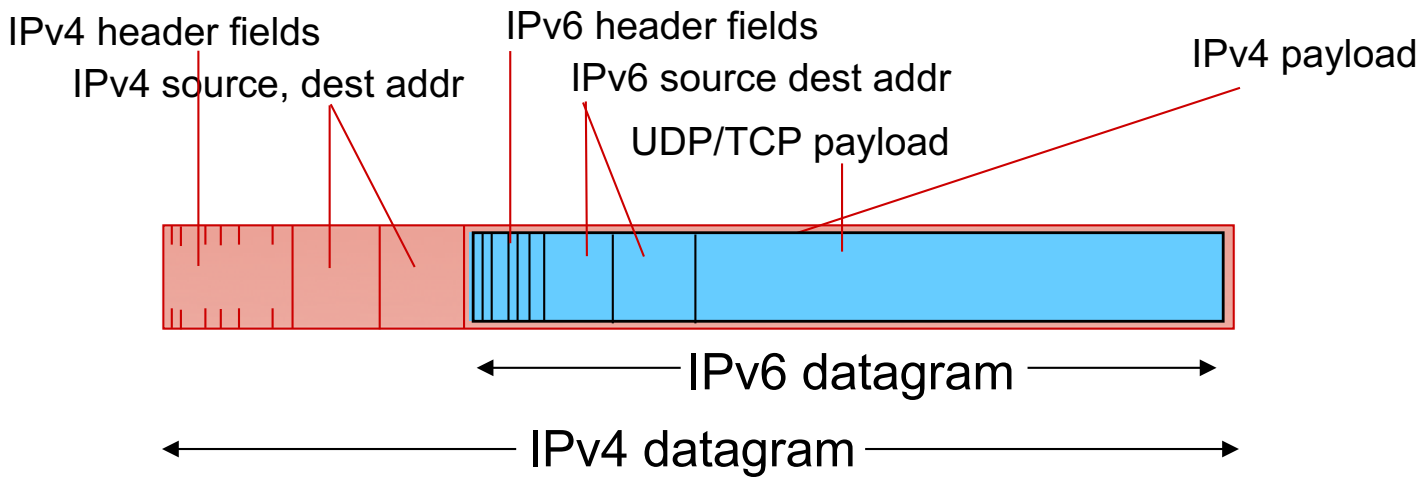


Other changes from IPv4

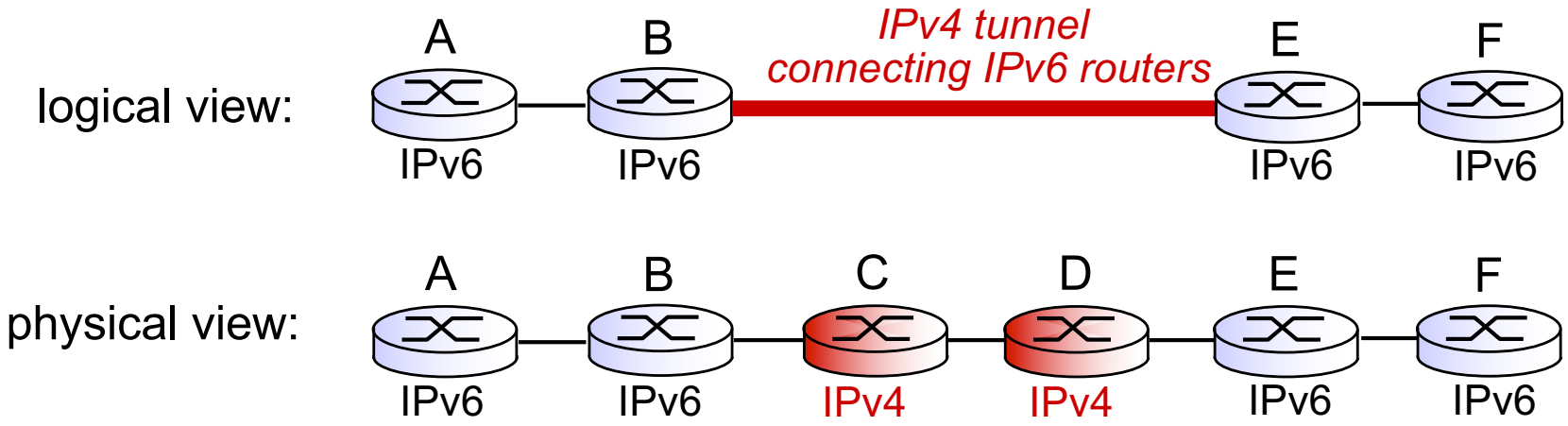
- *checksum:* removed entirely to reduce processing time at each hop
- *options:* allowed, but outside of header, indicated by "Next Header" field
- *ICMPv6:* new version of ICMP
  - additional message types, e.g. "Packet Too Big"
  - multicast group management functions

Transition from IPv4 to IPv6

- Not all routers can be upgraded simultaneously
  - no "flag days": Could we shut down the Internet on Friday on IPv4, upgrade all routers to IPv6, and restart on Monday?
- how will network operate with mixed IPv4 and IPv6 routers?
  - *'Dual stack*
  - *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
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IPv6
IPv6
IPv4
IPv4
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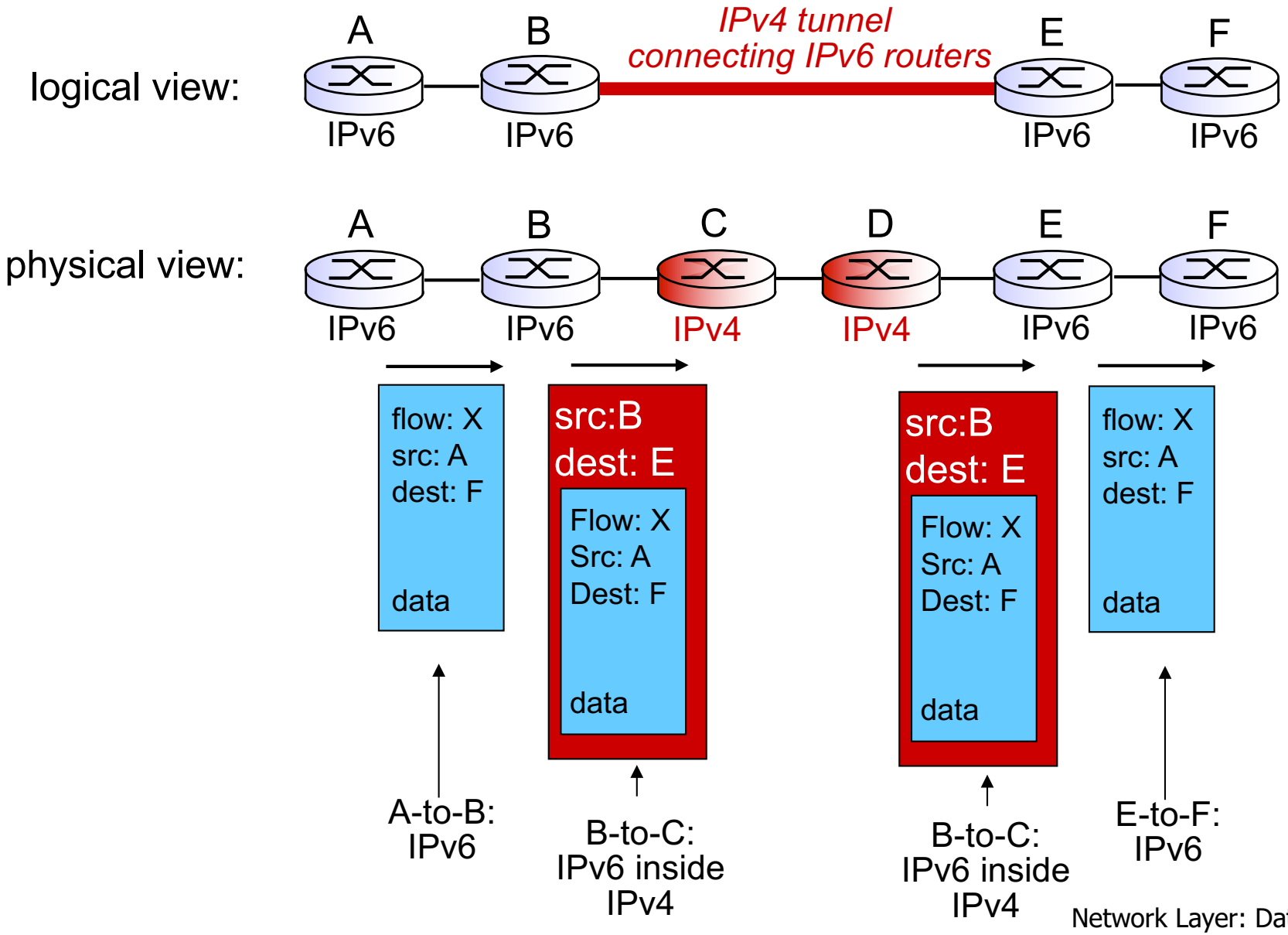
IPv6

Tunneling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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

IPv6: adoption

- Google: 8% of clients access services via IPv6
- NIST: 1/3 of all US government domains are IPv6 capable

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

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 includes 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