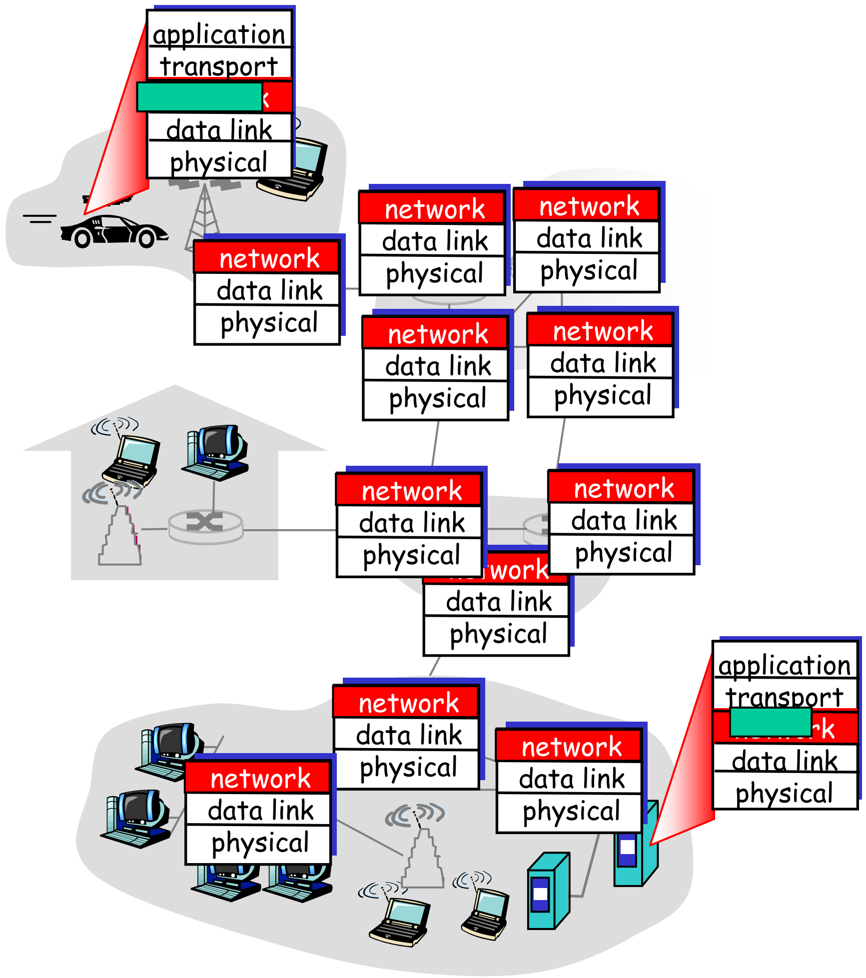
Distributed Systems

7. Network Layer

Werner Nutt

Network Layer

- Transports segments 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



Key Network-Layer Functions

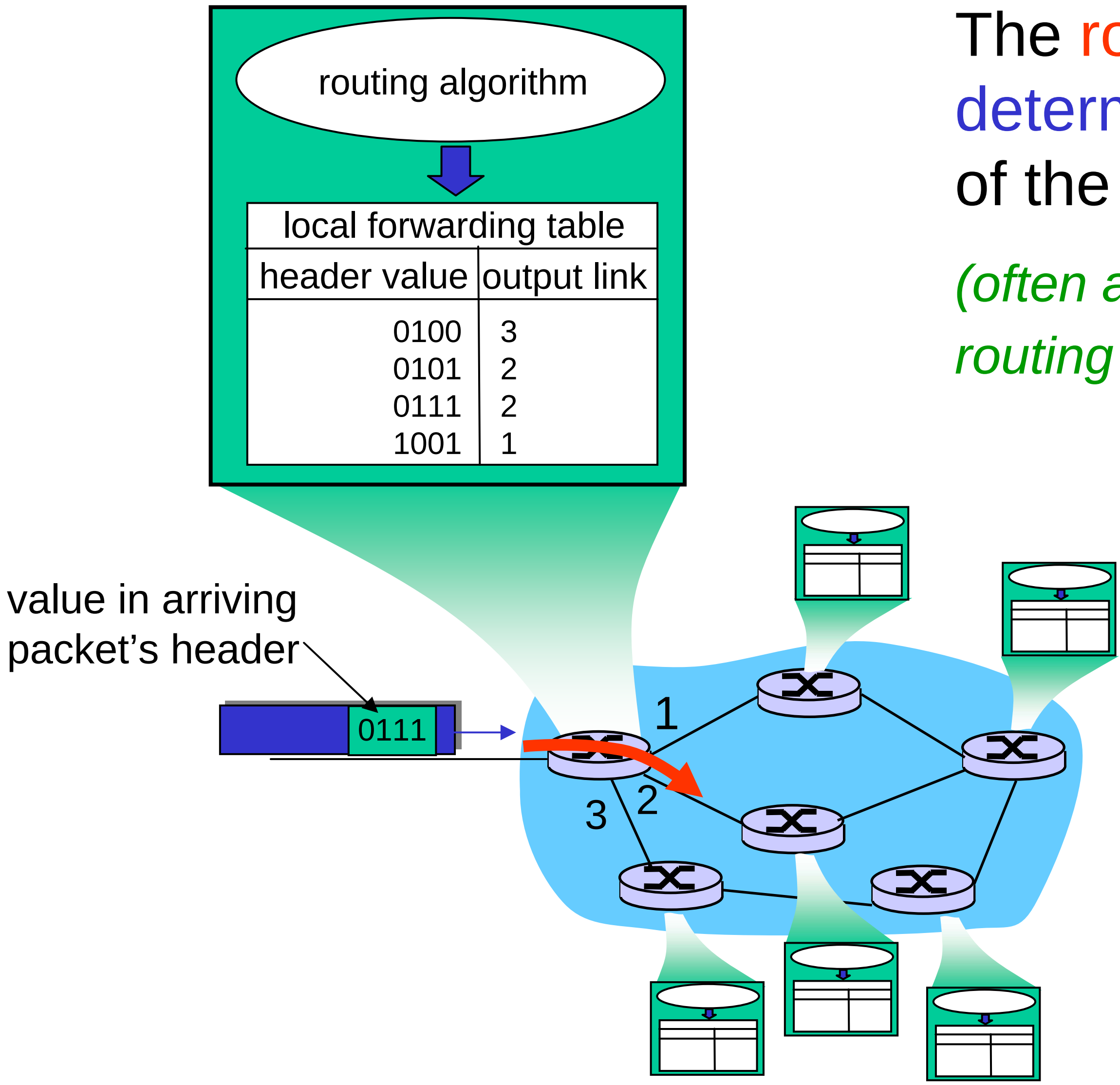
- *Forwarding:* move packets from router's input to appropriate router output
- *Routing:* determine route taken by packets from source to destination

→ *Routing Algorithms*

Analogy:

- Routing: process of planning trip from source to destination
- Forwarding: process of getting through single interchange

Routing is Implemented by Forwarding



The routing algorithm determines the content of the forwarding table

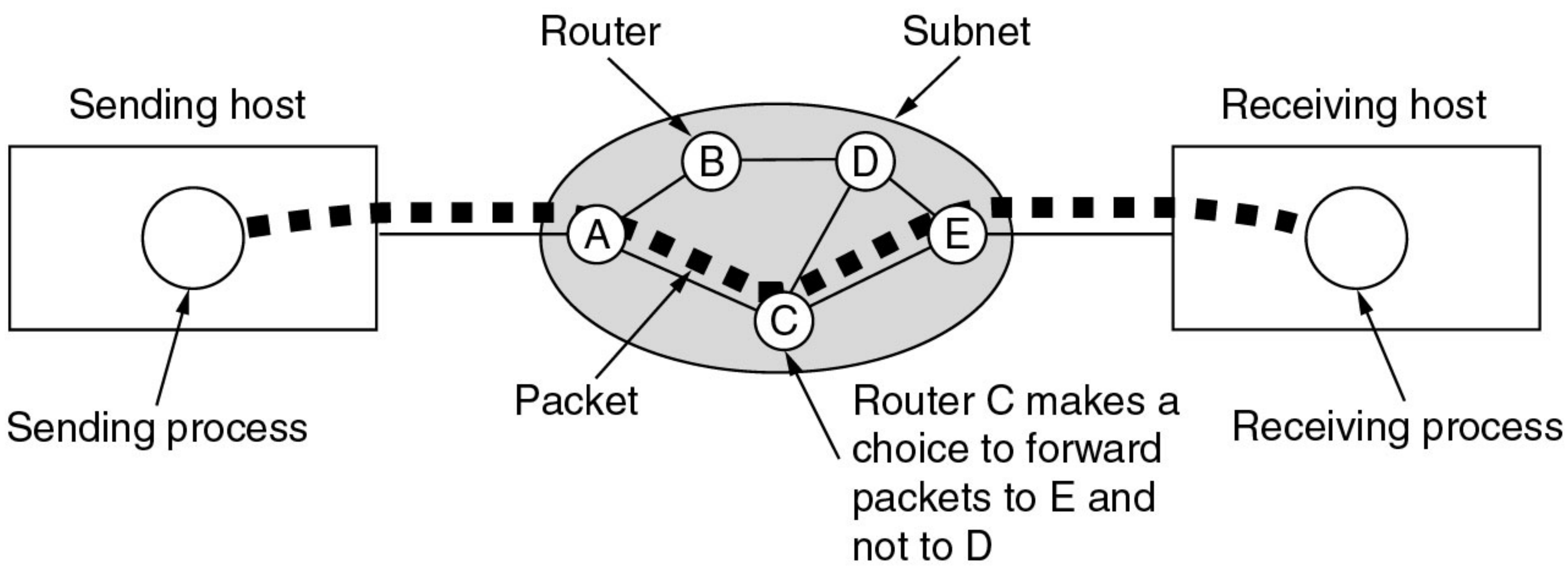
(often also called routing table)

Switching Schemes (1)

Network = nodes connected by links

- Broadcasts *(Ethernet, wireless)*
  - send messages to all nodes
  - nodes listen for (other and own) messages ("carrier sensing")
- Circuit switching *(phone networks)*
  - establish path through network
  - physical change in the network connections
- Packet routing *(Internet Protocol)*
  - "store-and-forward"
  - unpredictable delays

Data Transport Based on Packet Routing



Switching Schemes (2)

- Virtual Circuit Switching (Frame/cell relay, e.g., *ATM)*
  - small, fixed size packets (48 byte of data for ATM),
  - padded if necessary
  - “logical” circuit switching
  - bandwidth & latency guaranteed (“virtual path”)
  - forwarding based on inspection of first few bytes
  - avoids error checking at nodes (uses reliable links)

- ATM (= Asynchronous Transfer Mode)
  - used by ISPs to realize (A)DSL

Virtual Circuit Implementation

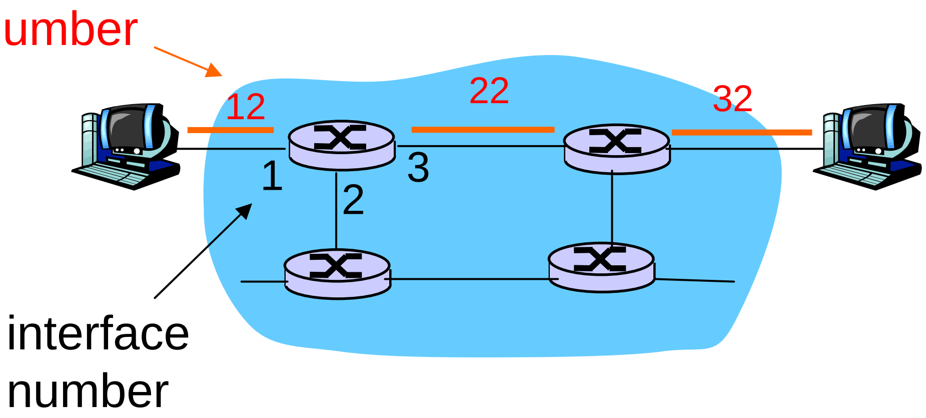
A virtual circuit (VC) consists of:

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

- A packet belonging to a VC carries VC number (rather than destination address)

- VC number can be changed on each link
  - new VC number comes from forwarding table

Virtual Circuit Forwarding Table



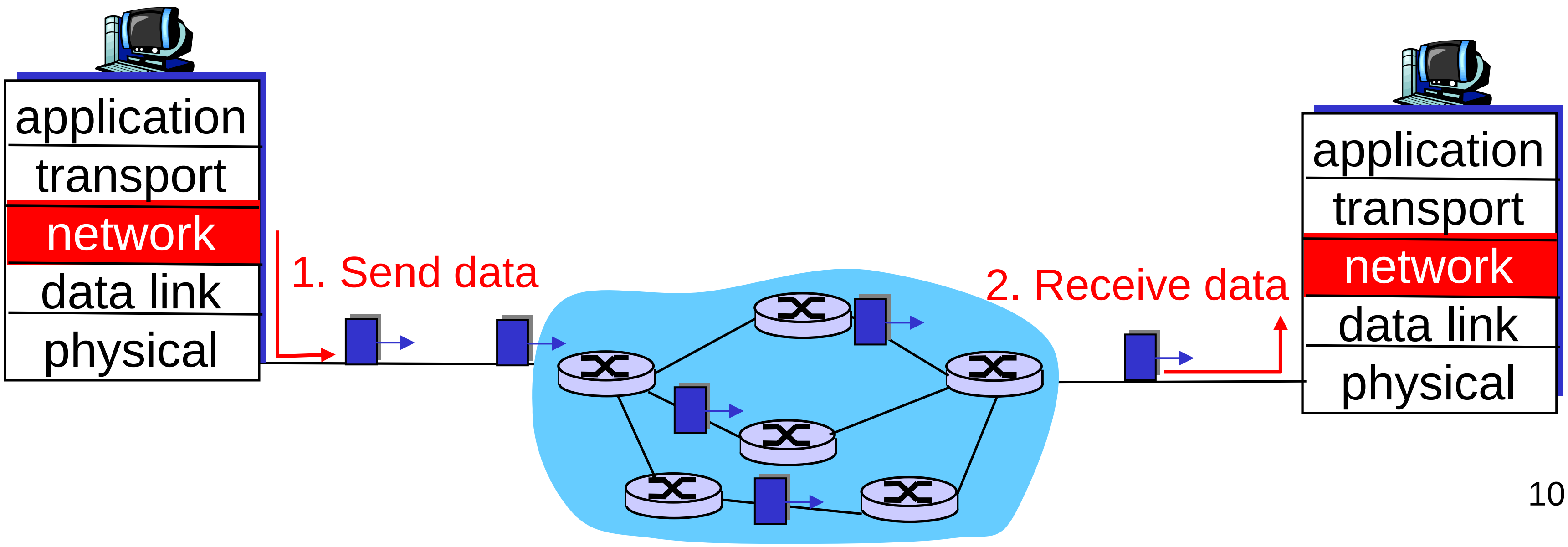
Forwarding table
in router:

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

Routers maintain connection state information!
Initially, call set-up phase according to protocol!

Datagram Networks

- No call set-up at network layer
- Routers: no state about end-to-end connections
  – no network-level concept of “connection”
- Packets forwarded using destination host address
  – packets between same source-destination 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

Network numbers

Examples

DA: 11001000 00010111 00010110 10100001 — Which interface?

DA: 11001000 00010111 00011000 10101010 — Which interface?

Datagram or VC Network: Why?

Internet (datagram)

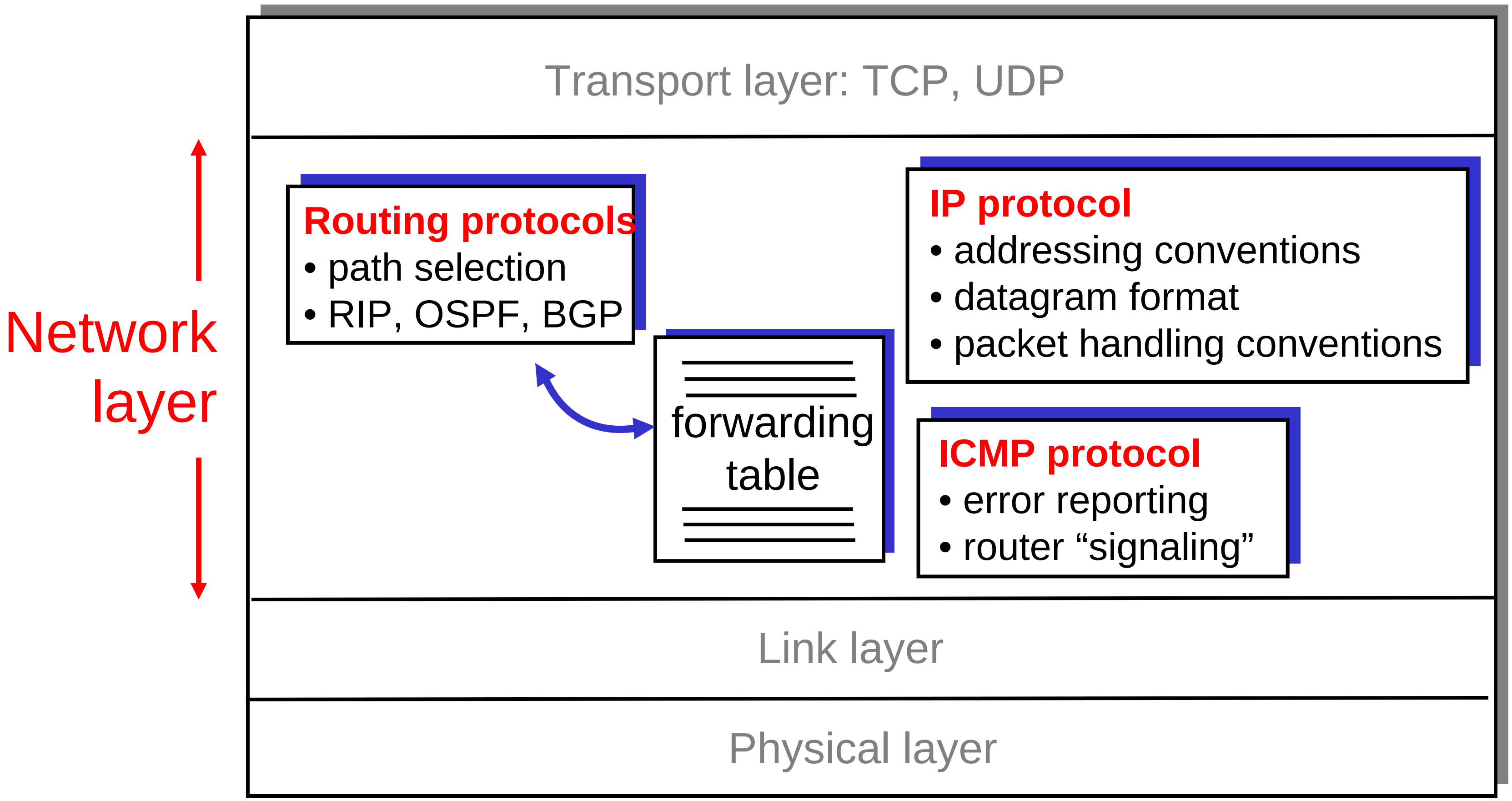
- data exchange among computers
  - "elastic" service, no strict timing requirements
- "smart" end systems (computers)
  - can adapt, perform control, error recovery
  - simple inside network, complexity at "edge"
- many link types
  - different characteristics
  - uniform service difficult

ATM (VC)

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

The Internet Network Layer

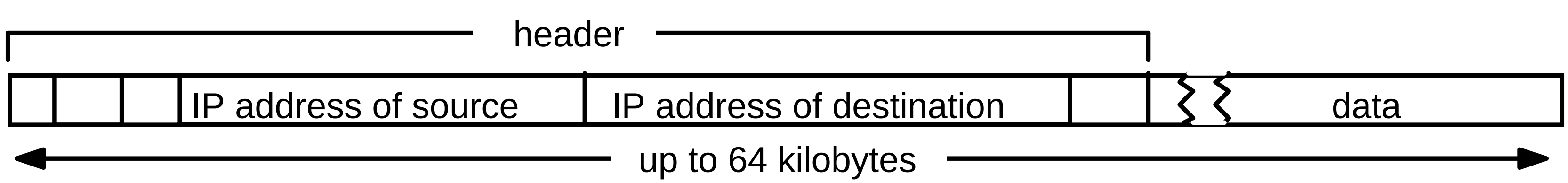
Host, router functions at the network layer:



Internet Protocol (IP)

- Enables hosts to send packets to other hosts

- Layout of an IP packet



IP Datagram Format

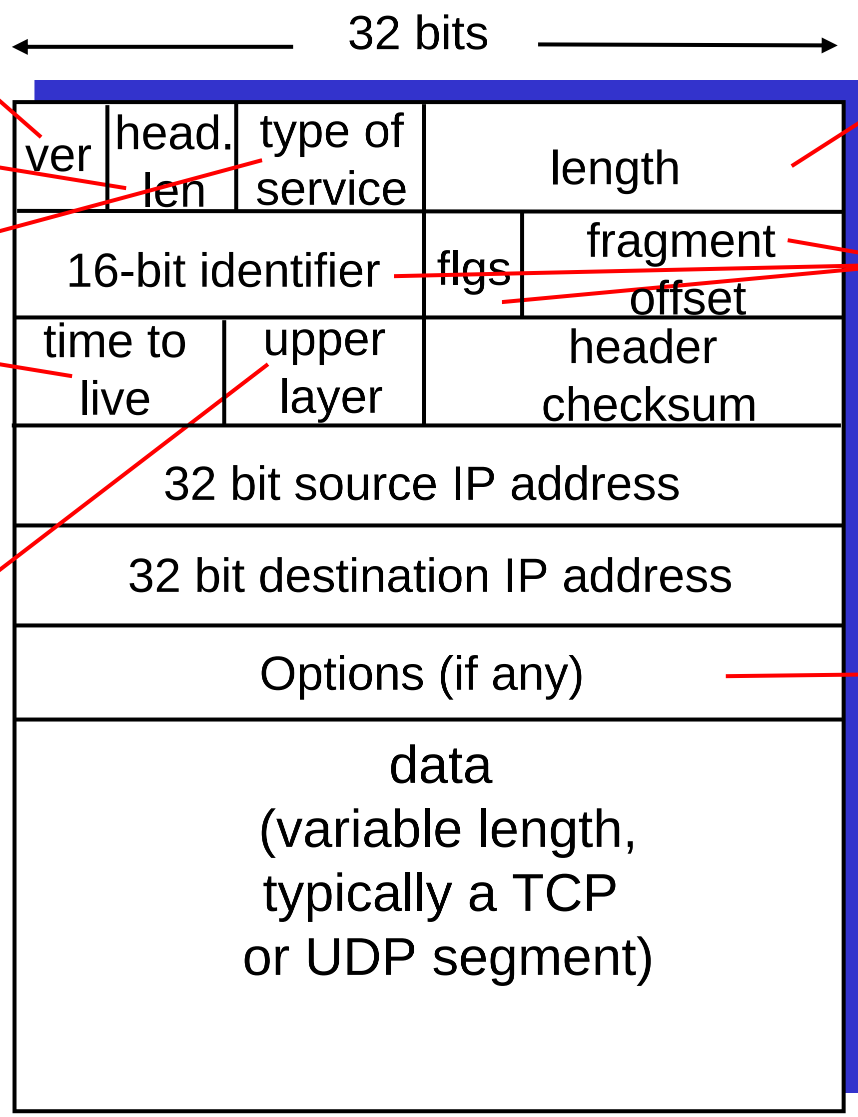
IP protocol version number

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

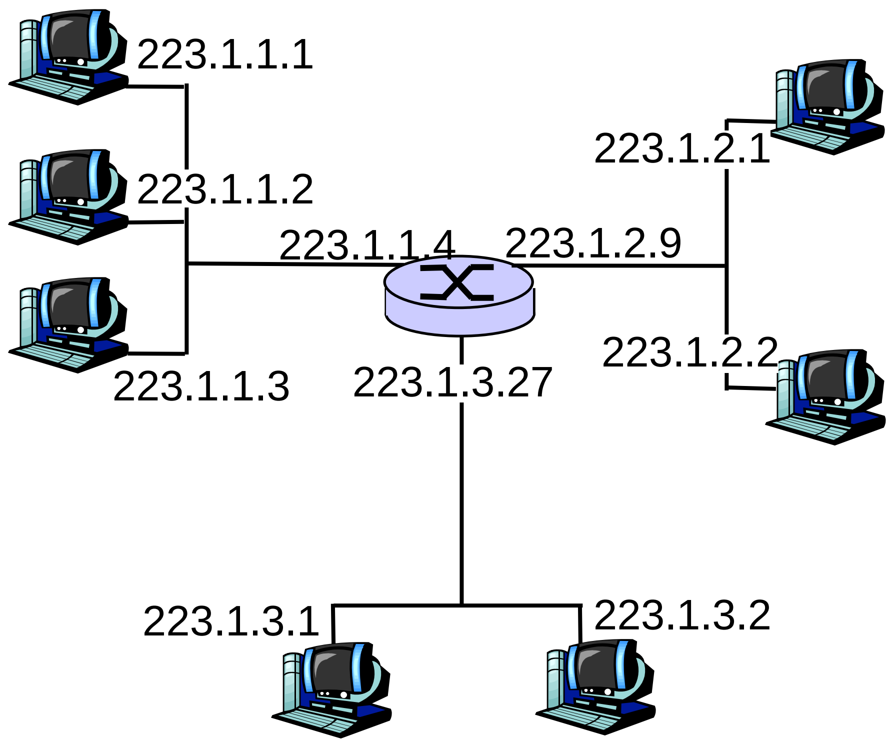
IP Addressing

Address format:

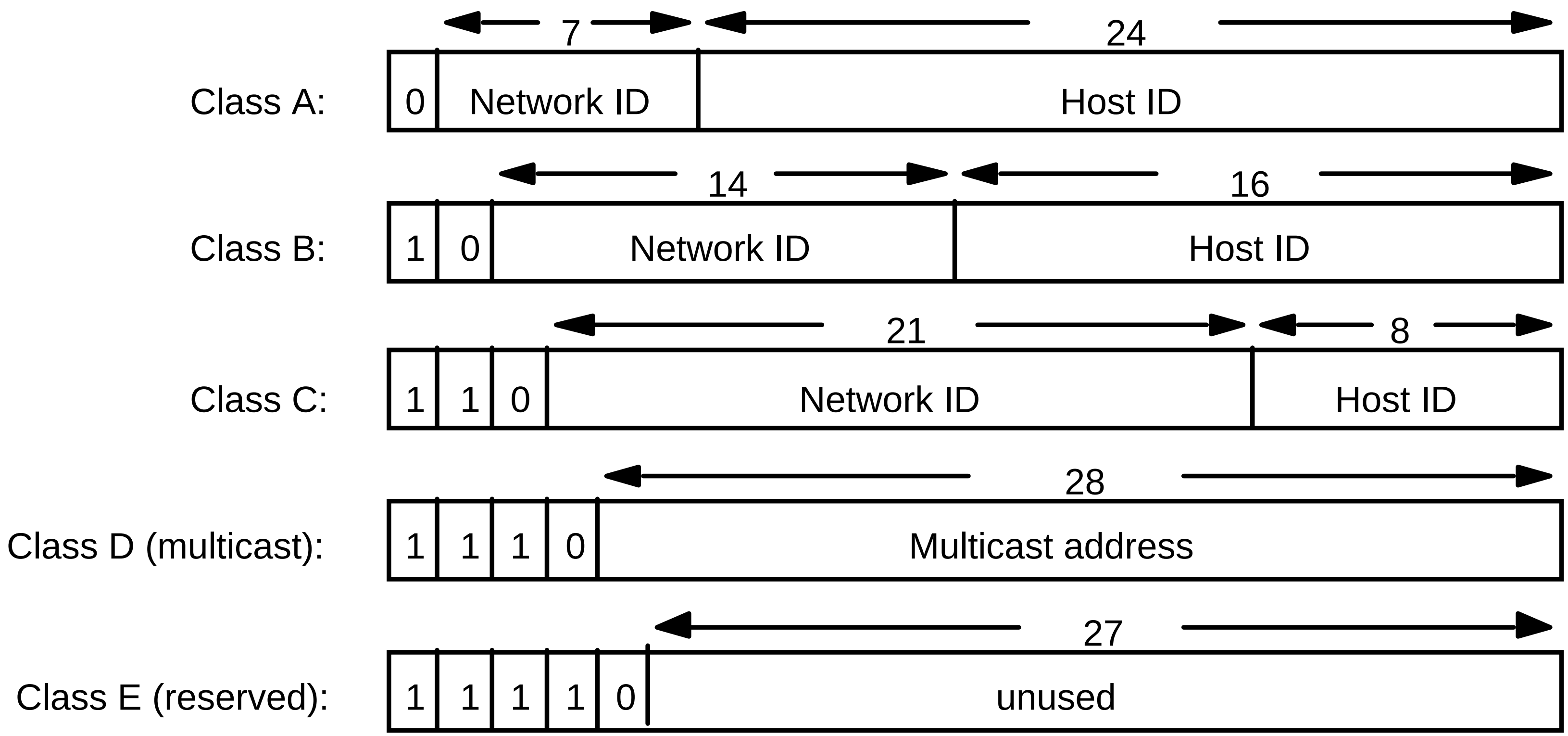
- 32 bits = 4 bytes (octets)
- Representation in “dotted decimal” notation
  193.206.186.140
- Representation in hexadecimal code
  0xc1ceba8c
- Representation in bit code
  11000001 11001110 10111010 10001100

IP Addressing (cntd)

- IP address: identifies host and router *interfaces*
- Interface: connection between host/router and physical link
  - routers typically have multiple interfaces
  - host typically has one interface
  - IP addresses associated with each interface



IP Addresses



Originally, IP addresses were divided into classes …

Hosts belong to Networks, Addresses Belong to Network Ranges

MIT Network	18.0.0.0 - 18.255.255.255
Unibz Network	193.206.186.0 - 193.206.186.255
Yahoo Network	69.147.64.0 - 69.147.127.255

- How do we describe network ranges?

- Note: all addresses in a range
  - agree on their first N bits (network prefix)
  - vary on the remaining 32-N bits (host address)

- CIDR Notation (CIDR = Classless Interdomain Routing)

  - MIT Network 18.0.0.0/8
  - Unibz Network 193.206.186/24
  - Yahoo Network 69.147.64.0/18

IP Addressing: CIDR

- **CIDR**: **C**lassless **I**nter**D**omain **R**outing
  - subnet portion of address of arbitrary length
  - address format: a.b.c.d/x, where x is # bits in subnet portion of address

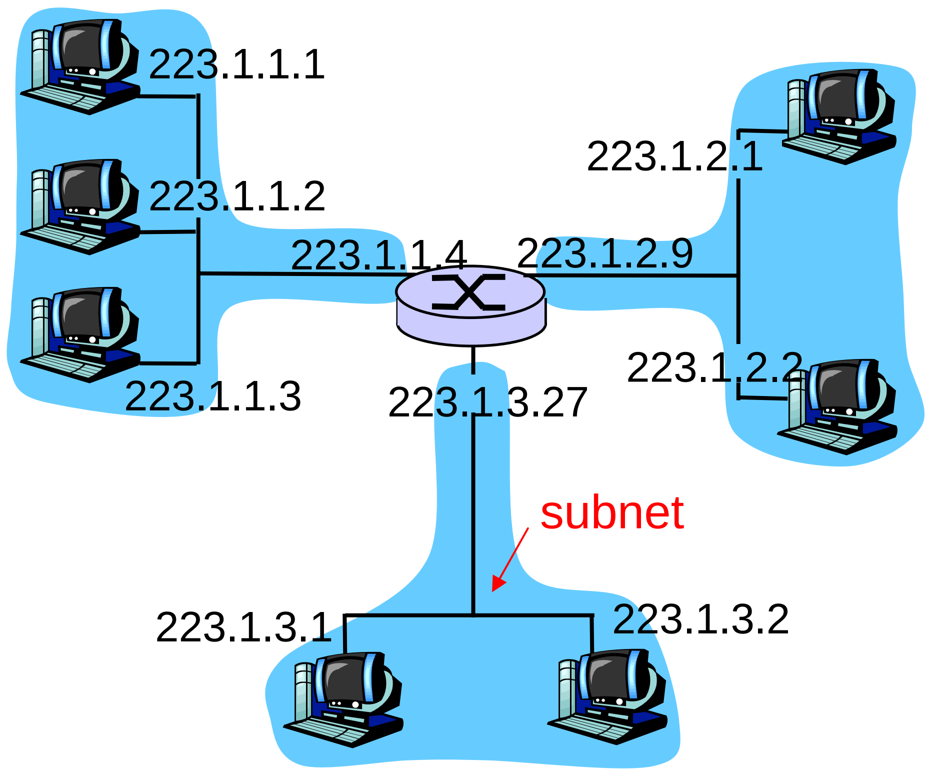
subnet part | host part

11001000 00010111 00010000 00000000

200.23.16.0/23

Subnets

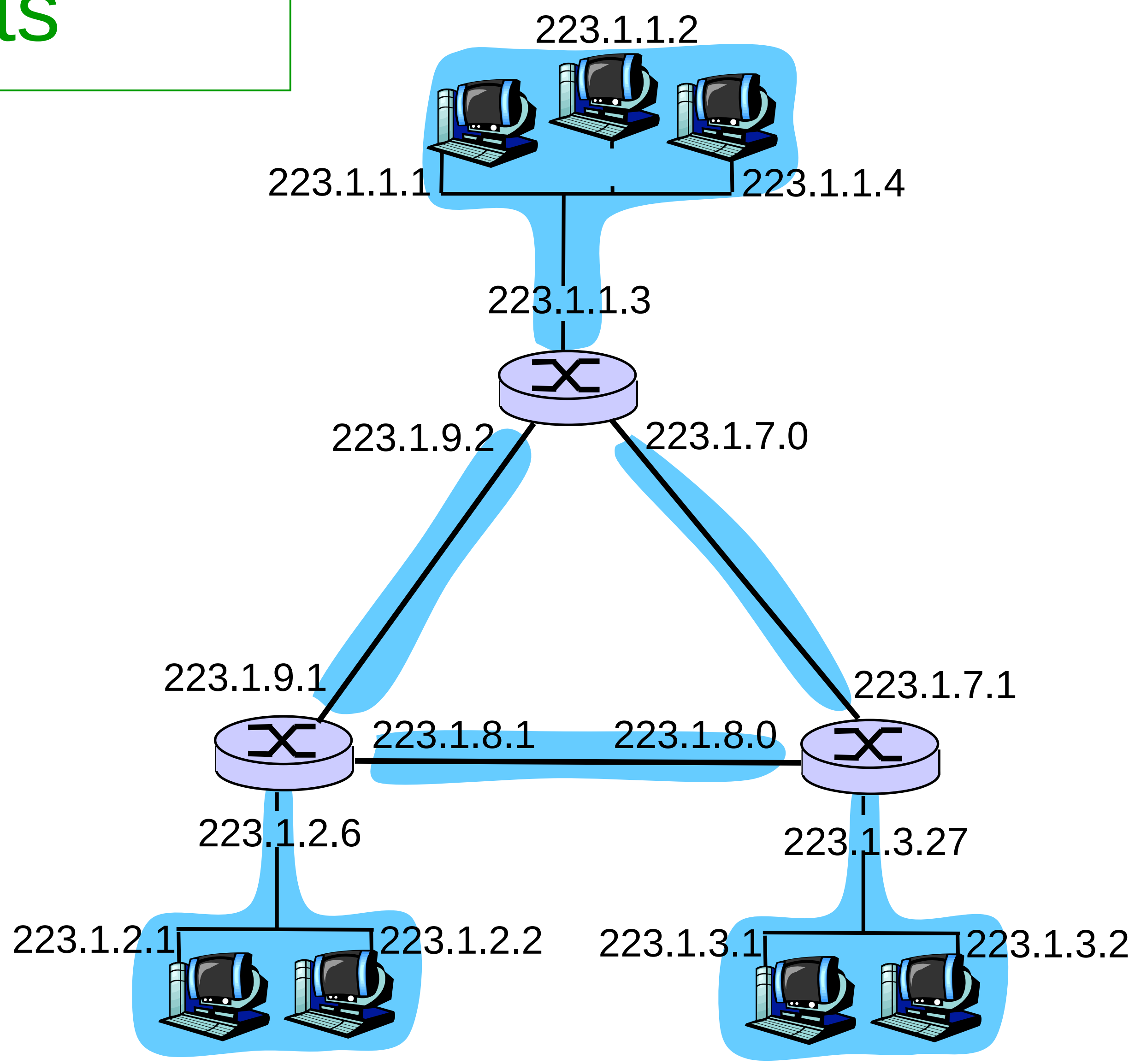
- IP address:
  - subnet part (high order bits)
  - host part (low order bits)
- *What's a subnet ?*
  - device interfaces with same subnet part of IP address
  - can physically reach each other without intervening router



Network consisting of 3 subnets

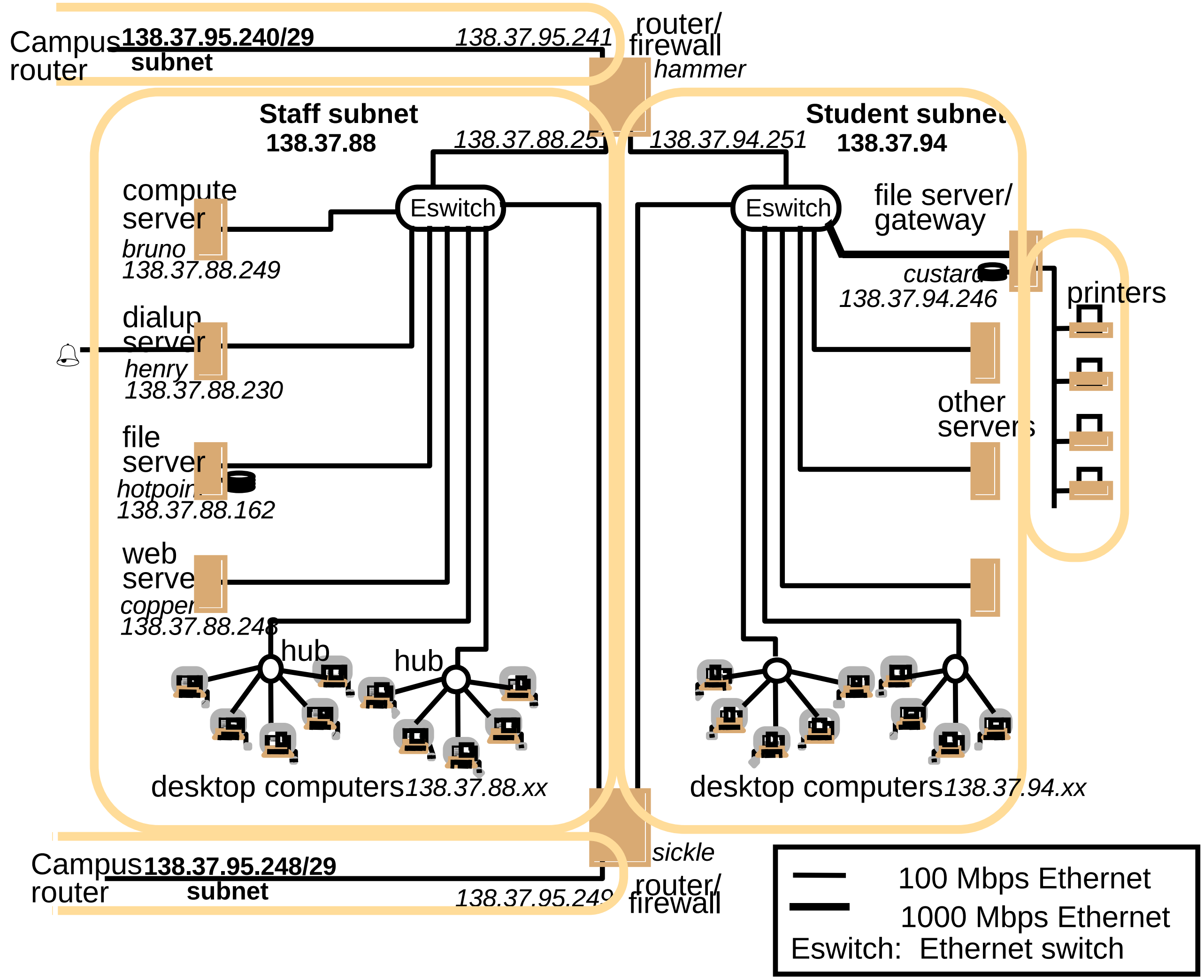
Subnets

How many?



A University LAN With Public IP Addresses

Simplified view of the Queen Mary and Westfield College Computer Science network



(Ethernet at FUB is switched)

Subnet Masks

Suppose: A packet for destination 193.206.186.140 arrives at router

How does the router know to which network the packet should go?

Routers have two pieces of information per network entry

- Network address 193.206.186.0
- 32 bit mask 255.255.255.0

  (represents number of significant bits as in CIDR notation)

Algorithm:

For each network entry

compute: (destination address) AND (subnet mask)

if result = network address, then destination in network

Special Addresses

- Address ranges for private networks
  (no routing over the Internet!?):

  10.0.0.0/8, 172.16.0.0/12, 192.168.0.0/16

- Network address: lowest number in range
- Broadcast address: highest number in range
- Gateway address: often second highest number in range
- Loopback network: 127.0.0.0/8
  virtual interface connection a host to itself
- Localhost: 127.0.0.1

IP Address Quiz

- How many possible subnet masks are there?
- What are the possible numbers that can occur in a mask position?
- What is the network mask of the Stanford Univ. network (171.64.0.0/14)?
- How many addresses are there on the Stanford network?
- Which of the following addresses could belong to a host at Stanford:
  171.74.212.31 ?
  171.68.0.31 ?
  171.67.212.44 ?
- Host **`actarus.inf.unibz.it`** has the address 10.10.20.5 and mask 255.255.252.0.

  What is the broadcast address on that host's network?
  What is (probably) the gateway address?

IP Addresses: How to Get One?

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

- Hard-coded by system administrator in a file
  - Windows: control-panel->network connections-> local area connections -> properties
  - LINUX (Debian/Ubuntu): /etc/network/interfaces

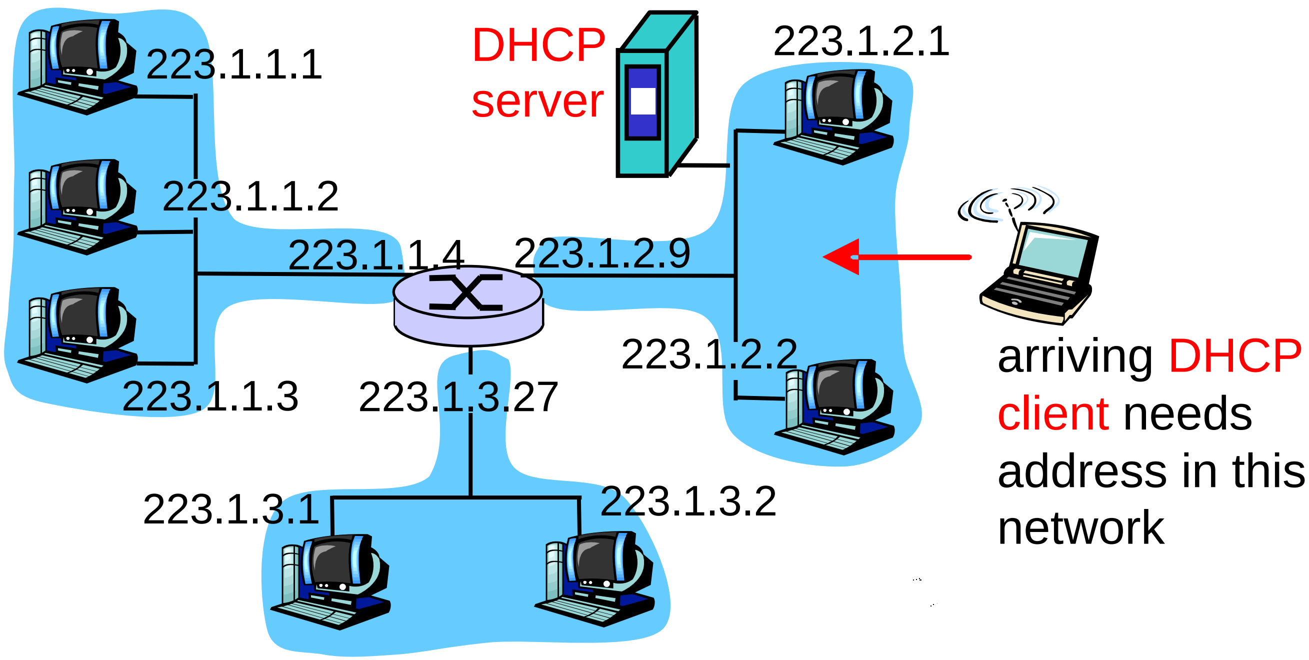
- DHCP: Dynamic Host Configuration Protocol: dynamically get address from as server
  - "plug-and-play"

DHCP: Dynamic Host Configuration Protocol

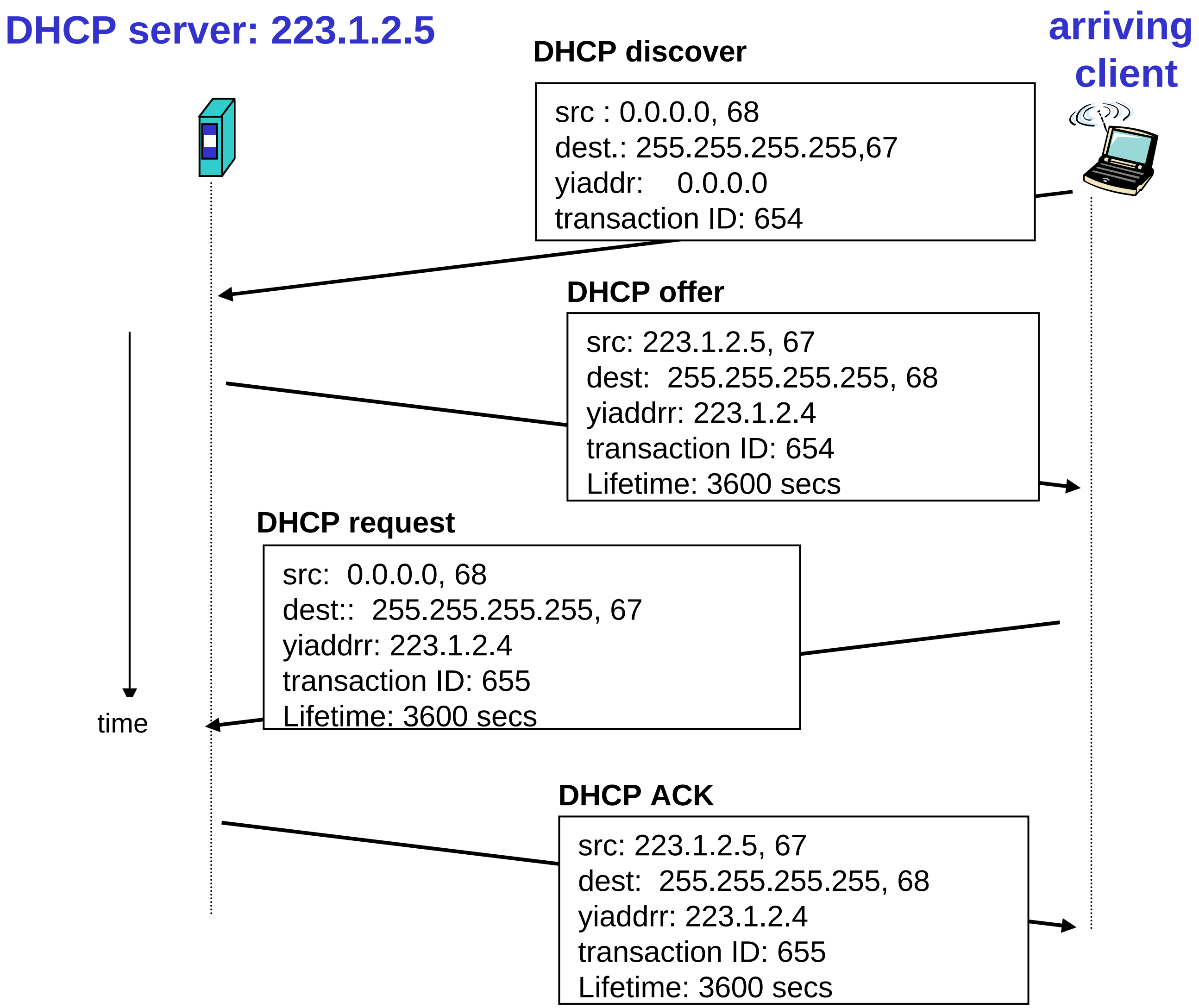
Goal: Allow a host to *dynamically* obtain its IP address from a network server when it joins network.

- Can renew its lease on address in use
- Allows reuse of addresses
  (only hold address while connected and "on")
- Support for mobile users who want to join network
- DHCP overview:
  - host broadcasts "DHCP discover" message *[optional]*
  - server responds with "DHCP offer" message *[optional]*
  - host requests IP address: "DHCP request" message
  - server sends address: "DHCP ack" message

DHCP Client-Server Scenario



DHCP Client-Server Scenario



DHCP: More Than IP Address

DHCP returns more than just

the 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?

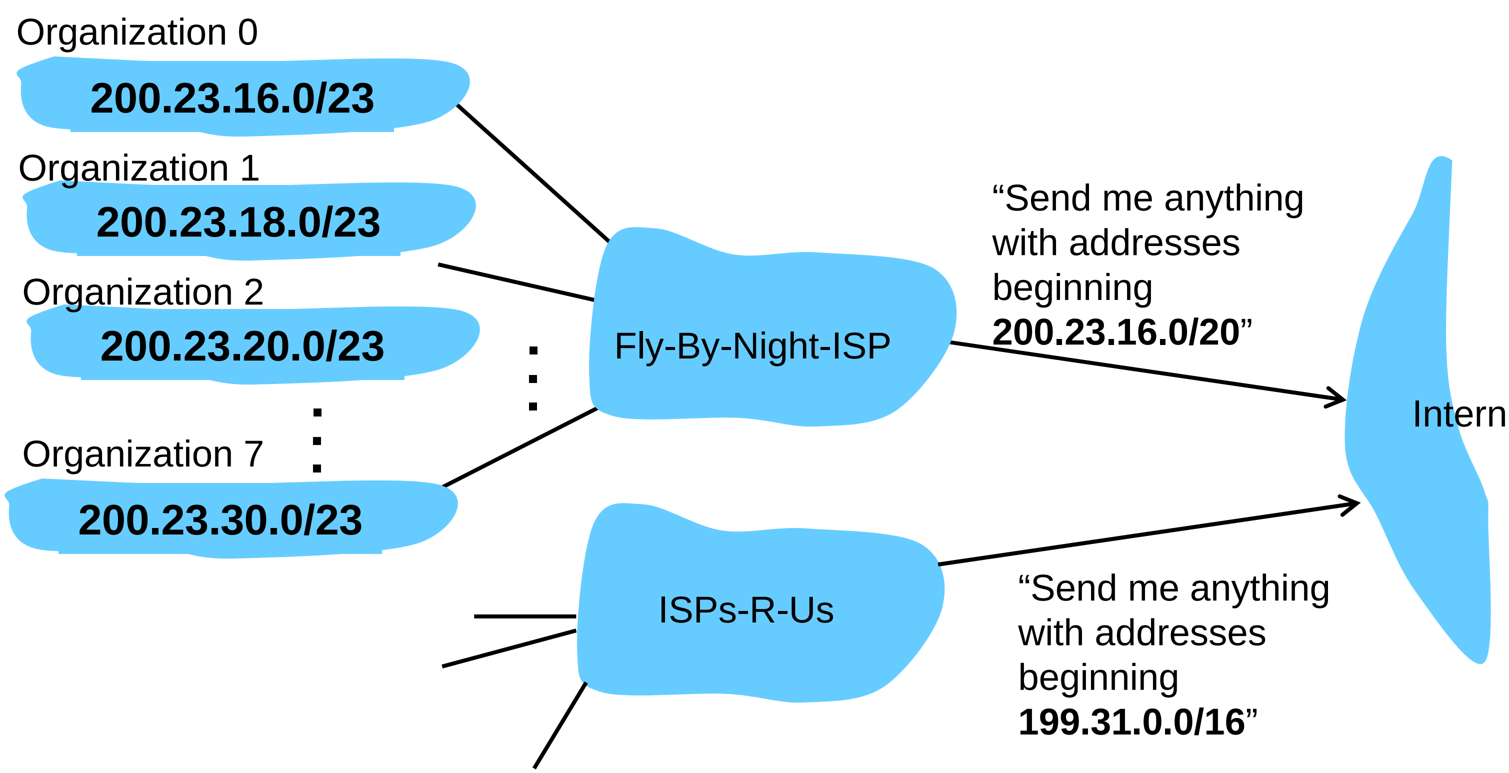
Q: How does a *network* get the subnet part of the IP addresses (i.e., its network address)?

A: From the range allocated to its 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

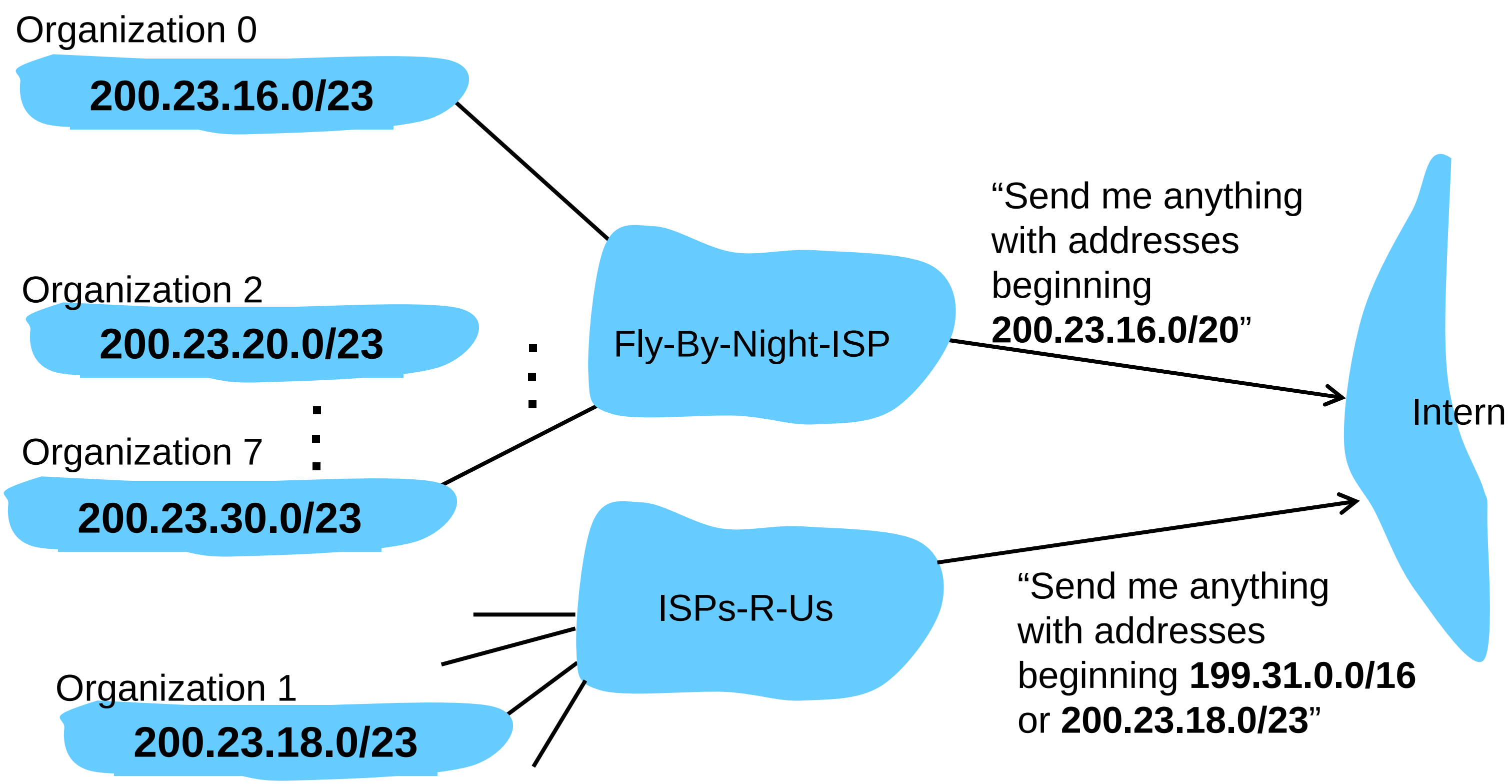
Hierarchical Addressing: Route Aggregation

Hierarchical addressing allows efficient advertisement of routing information:



Hierarchical Addressing: More Specific Routes

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



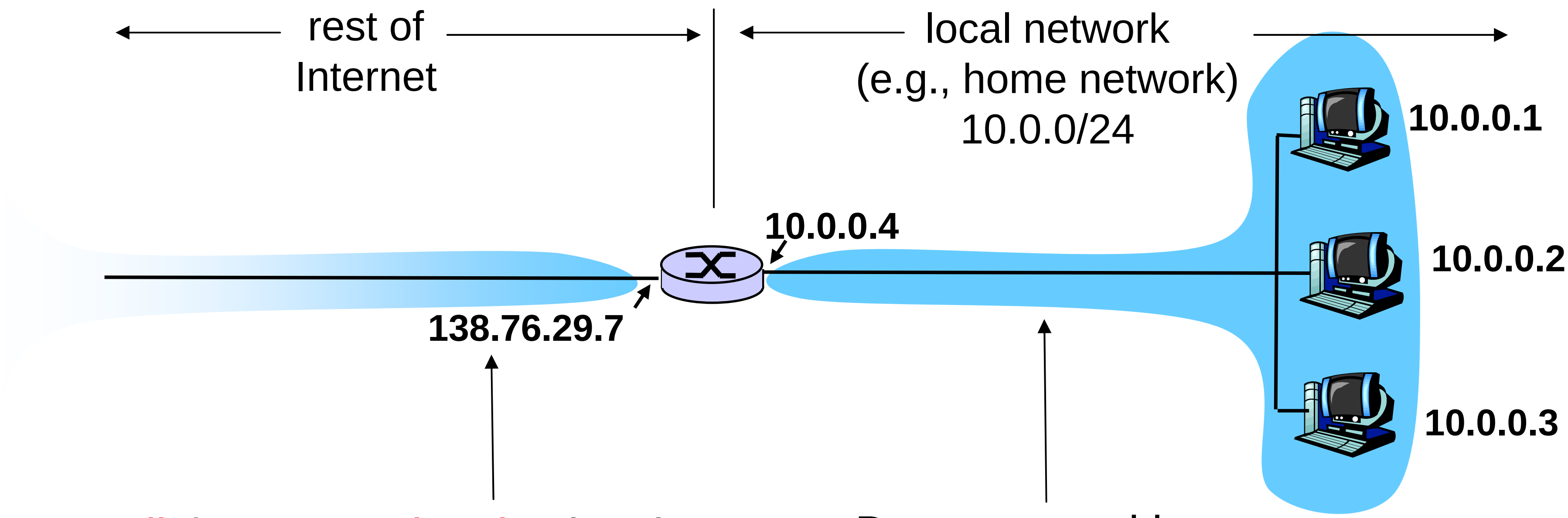
IP Addressing: The Last Word...

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 the 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 network not explicitly addressable, visible by outside world (a security plus).

NAT: Network Address Translation

Implementation: NAT router must:

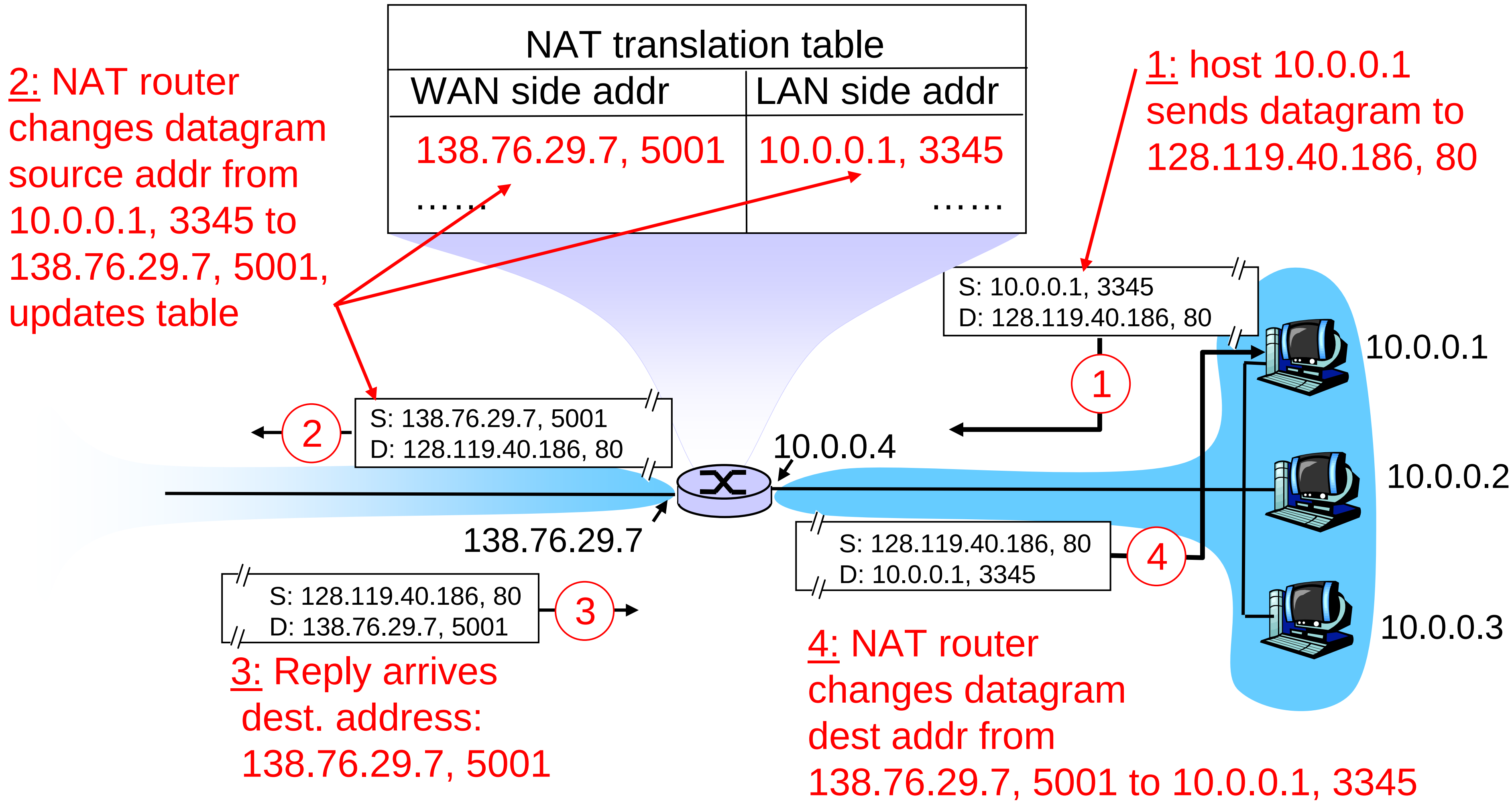
- *outgoing datagrams: replace* (source IP address, port #) of every outgoing datagram with (NAT IP address, new port #)

  . . . remote clients/servers will respond using (NAT IP address, new port #) as destination address

- *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 destination fields of every incoming datagram with corresponding (source IP address, port #) stored in NAT table

NAT: Network Address Translation



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

Routing Information on a Host

Every IP capable host needs to know about at least two classes of destinations

- locally connected computers
- everywhere else

Routing table on actarus:

```
wnutt@actarus:~$ netstat -r
Kernel IP routing table
Destination     Gateway         Genmask         Flags   MSS Window  irtt Iface
10.10.20.0      *               255.255.252.0   U         0 0          0 eth0
10.10.112.0     *               255.255.240.0   U         0 0          0 eth1
default         10.10.23.254    0.0.0.0         UG        0 0          0 eth0
```

Address Resolution

Running ARP (= Address Resolution Protocol),
a host finds out the MAC address belonging to an IP address

ARP Steps

- actarus wants to send an IP packet to 10.10.23.254
- actarus broadcasts an ARP request:
  "I have IP address 10.10.20.5 and MAC address 00:11:85:e8:ff:8f, who has IP address 10.10.23.254?"
- Gateway sends an ARP reply to actarus:
  "I have IP address 10.10.23.254 and MAC address 00:10:db:bd:ce:87"

Optimization

- Hosts keep a cache
- Hosts overhearing a request update their cache
- ARP announcements: hosts send an ARP request to themselves (why?)

IP Routing (1)

Problem: Host H1 wants to send a packet to host H2

Case 1: H2 is on the same LAN (e.g., Ethernet) as H1

Approach:

- H1 finds out the Ethernet address of H2 (MAC address)

  (physical address, unique in the world
  for every Ethernet-enabled device)

- Ethernet module of H1 sends out the packet in Ethernet format

IP Routing (2)

Case 2: H2 is on a different LAN

Approach:

- H1 sends packet to its local gateway (say, G1)
- G1 sends packet across intermediate networks to the network of H2

If a gateway receives a packet, where should it send it?

Routing Problem

- What is a good path from H1 to H2?
- What is the next step on the path?

Computers forwarding packets through a network are called routers

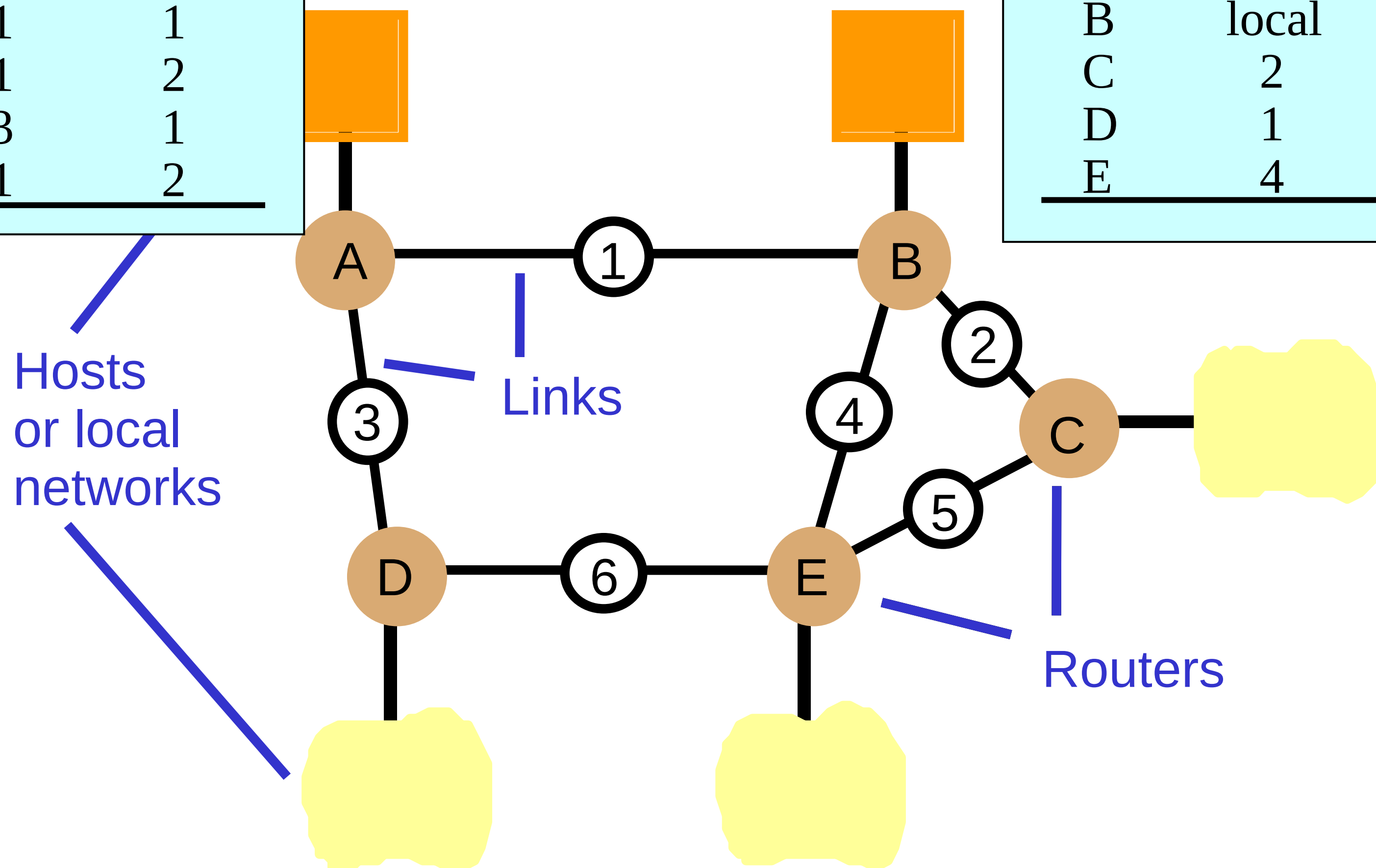
Routing: Example

Routings from A

To	*Link*	*Cost*
A	local	0
B	1	1
C	1	2
D	3	1
E	1	2

Routings from B

To	*Link*	*Cost*
A	1	1
B	local	0
C	2	1
D	1	2
E	4	1



Routing Tables

Routings from A		
To	*Link*	*Cost*
A	local	0
B	1	1
C	1	2
D	3	1
E	1	2

Routings from B		
To	*Link*	*Cost*
A	1	1
B	local	0
C	2	1
D	1	2
E	4	1

Routings from C		
To	*Link*	*Cost*
A	2	2
B	2	1
C	local	0
D	5	2
E	5	1

Routings from D		
To	*Link*	*Cost*
A	3	1
B	3	2
C	6	2
D	local	0
E	6	1

Routings from E		
To	*Link*	*Cost*
A	4	2
B	4	1
C	5	1
D	6	1
E	local	0

Sample Routes

- Send from C to A:
  - to link 2, arrive at B
  - to link 1, arrive at A

- Send from C to A if B's table is modified to:

Routings from B		
To	*Link*	*Cost*
B	local	0
C	2	1
E	4	1
default	5	-

- to link 5, arrive at E
- to link 4, arrive at B
- to link 1, arrive at A

Note the extra hop.

Approaches to Routing Algorithms

Decentralised

- a router communicates with its immediate neighbors

➔ Distance Vector algorithm (Bellman, Ford, Fulkerson)

  – realised in Router Information Protocol (RIP)

Global

- a router knows all routers in the network, their links, and the cost of sending a packet over a link

  (also called: link state protocols)

➔ Shortest Path algorithm (Dijkstra),

  – realised in Open Shortest Path First (OSPF) protocol

Distance Vector Routing: Principles

- Each router R maintains a routing table *(= distance vector)*, which records for each other router how far away it is from R *(e.g., how many hops)*
- The initial table of R has only one element: (R,local,0)
- Periodically, or when there is a change in its neighbourhood, a router sends its table to its neighbours
- When receiving a table, a router updates its local table
- When a link to a neighbour fails,
  the cost of the link is set to ∞

How does a router know that a link has failed?

Distance Vector Algorithm: Idea

Update: Every *t* seconds or when local table changes, send the full table to each accessible neighbor.

Propagation: When receiving an update from neighbor N

- if N knows a path to a new destination D, send messages for D to N
- if N knows a cheaper path to D, send messages for D to N
- if N is closer to D *(i.e., messages for D are sent to N)*, update cost for D *(Idea: N has better information about D)*

See next slide for details

Distance Vector Algorithm (Pseudo Code)

Send: Every *t* seconds or when local table *Tl* changes,
send *Tl* on each non-faulty outgoing link

Receive: Whenever a routing table *Tr* is received on link *n*:

```
for all rows Rr in Tr {// modify Rr for subsequent comparisons
    if (Rr.link ≠ n) {
        Rr.cost = Rr.cost + 1;
        Rr.link = n;
        if (Rr.destination is not in Tl) add Rr to Tl;
         // add new destination to Tl
        else for all rows Rl in Tl {
            if (Rr.destination = Rl.destination and
               (Rr.cost < Rl.cost or Rl.link = n)) Rl = Rr;
            // Rr.cost < Rl.cost : remote node has better route
            // Rl.link = n : remote node is more authoritative
        }
    }
}
```

Distance Vector Routing: Convergence

- After initialisation, all routers reach a state where all tables are correct

  (i.e., show next hop along shortest path)

- Similarly, after a new router has joined

- However, convergence is slow

Distance Vector Routing: Looping

- When links fail, tables may be updated in a way that leads to loops

  rare situation, caused by delayed messages

- Routers in a loop continuously update their tables, increasing the cost ("count to infinity")

- Solution (among others): make infinity small

  RIP: $\infty = 16$

Distance Vector Routing: Protocols

- RIP was the first Internet routing protocol
- Not scalable
- Replaced by a link state protocol

Link State Routing: Principles

- A router knows its neighbourhood, i.e.,
  - the routers it is linked to
  - the cost of the links
- Periodically, it broadcasts a map of its neighbourhood

  (the neighbourhood maps have timestamps)
- Each router
  - builds a global map, using the latest neighbourhood maps
  - computes the shortest path to each other router
- Routing table:
  - for each R, show the first hop on the shortest path to R

Dijkstra's Algorithm (1)

Input:

- graph G = (V,E)
- weight function w: E $\rightarrow$ R
- start node s $\in$ V

Output:

- function d: V $\rightarrow$ R
  - v.d is the distance from s to v (= length of shortest path)
- function pred: V \ {s} $\rightarrow$ V
  - v.pred is the predecessor of v
    on the shortest path from s to v

Dijkstra's Algorithm (2)

Input: $G = (V,E)$, $w: E \rightarrow R$, $s \in V$

Output: $d: V \rightarrow R$, $pred: V \setminus \{s\} \rightarrow V$

Ideas:

- Initial pessimistic estimates:
  - v.d = ∞ for all $v \in V$
  - v.pred = null
- Loop:
  - improve estimate of d
  - find candidate for pred
  - determine vertex v such that v.d is exact (and also v.pred)

Dijkstra's Algorithm (Pseudo Code)

```
Input: V, E, w, s

S = ∅, Q = V;        // Initialisation

For each vertex v ∈ V {
   v.d = ∞;
   v.pred = null }
s.d = 0;
While Q is not empty {     // Algorithm
   u = extractMin(Q);      // extract a vertex u for which
                           // u.d is minimal
   S = S ∪ {u};
   For each edge (u,v) outgoing from u {
      if (u.d + w(u,v) < v.d) {   // Relax v.d
         v.d = u.d + w(u,v);
         v.pred = u}
      }
   }
```

Dijkstra's Algorithm: Discussion

- If u = extractMin(Q), then the estimates for u are correct
- Shortest path from s to v:
  follow pred links
- Runtime
  – each vertex and each edge are visited only once
    ➔ total runtime = O(|E| + |V| x runtime(extractMin))
  – runtime of extractMin depends on implementation: O(log V) possible
    ➔ total runtime = O((|E| + |V|) x log(V))
- Incremental versions: needed to update routing tables

Routing: How Can All this Work?

The Internet is too large to be captured in one routing table

➔ Divide and Conquer

The Internet is divided into Autonomous Systems (ASs)
(= network with common routing protocol, e.g., RIP or OSPF)

Hierarchical Routing

- Granularity of Internet routing = ASs
- Internal traffic of an AS: finegrained routing
- Outbound traffic: send to (suitable) gateway
- At AS level: apply Boundary Gateway Protocol (BGP)
- Inbound traffic = internal traffic

Which Route Do My Packets Take?

- Unix/Linux: **`traceroute`**
- Windows: **`tracert`**

Example: **`tracert www.yahoo.com`**

How does it work?

- A packet has a time to live (TTL)
  Initially: TTL = 64 hops
- If a packet dies (TTL = 0 hops), most routers send error message back to source (ICMP “time exceeded” packet)
- Iteratively, send packets with TTL = 1, TTL = 2, …