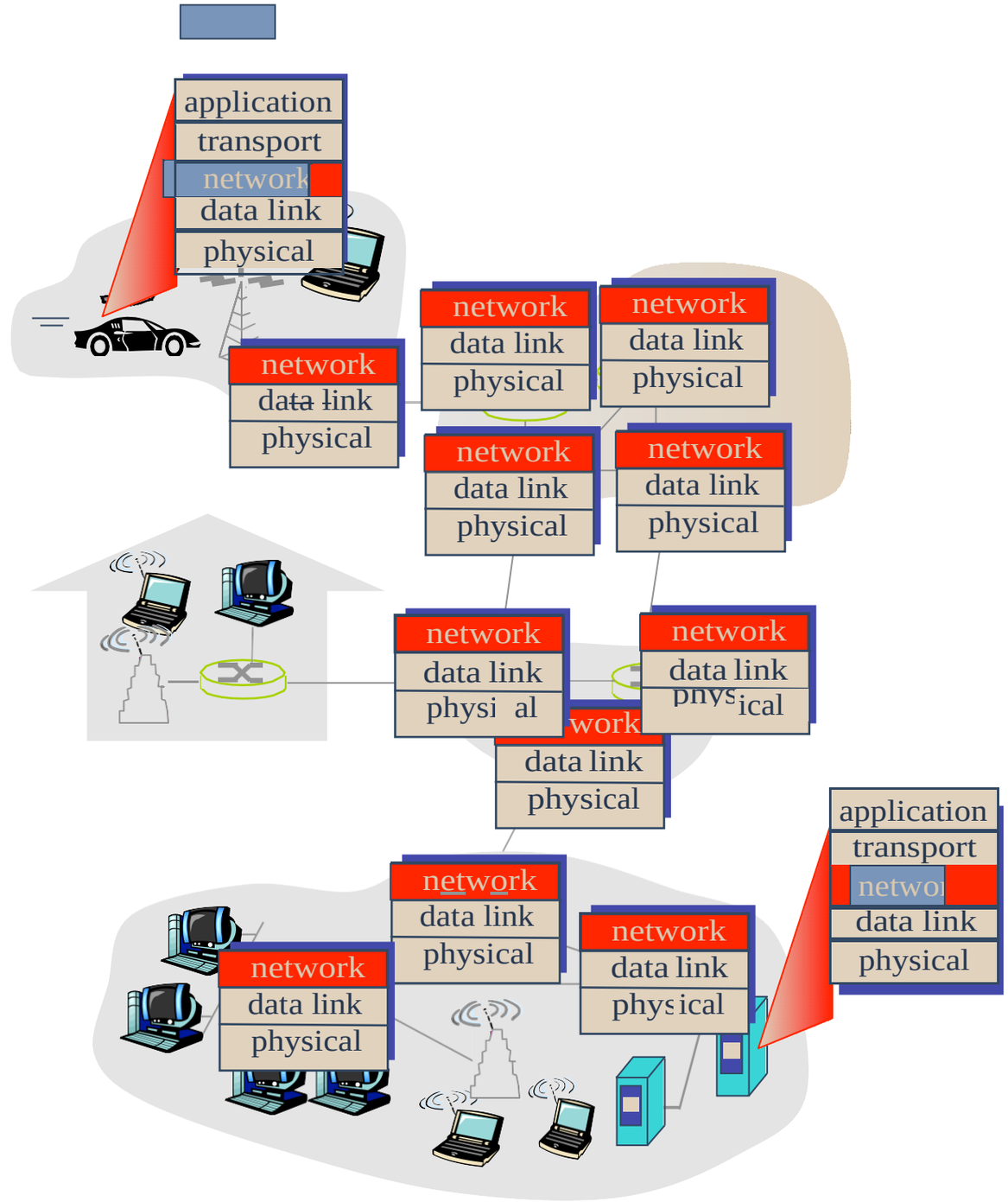
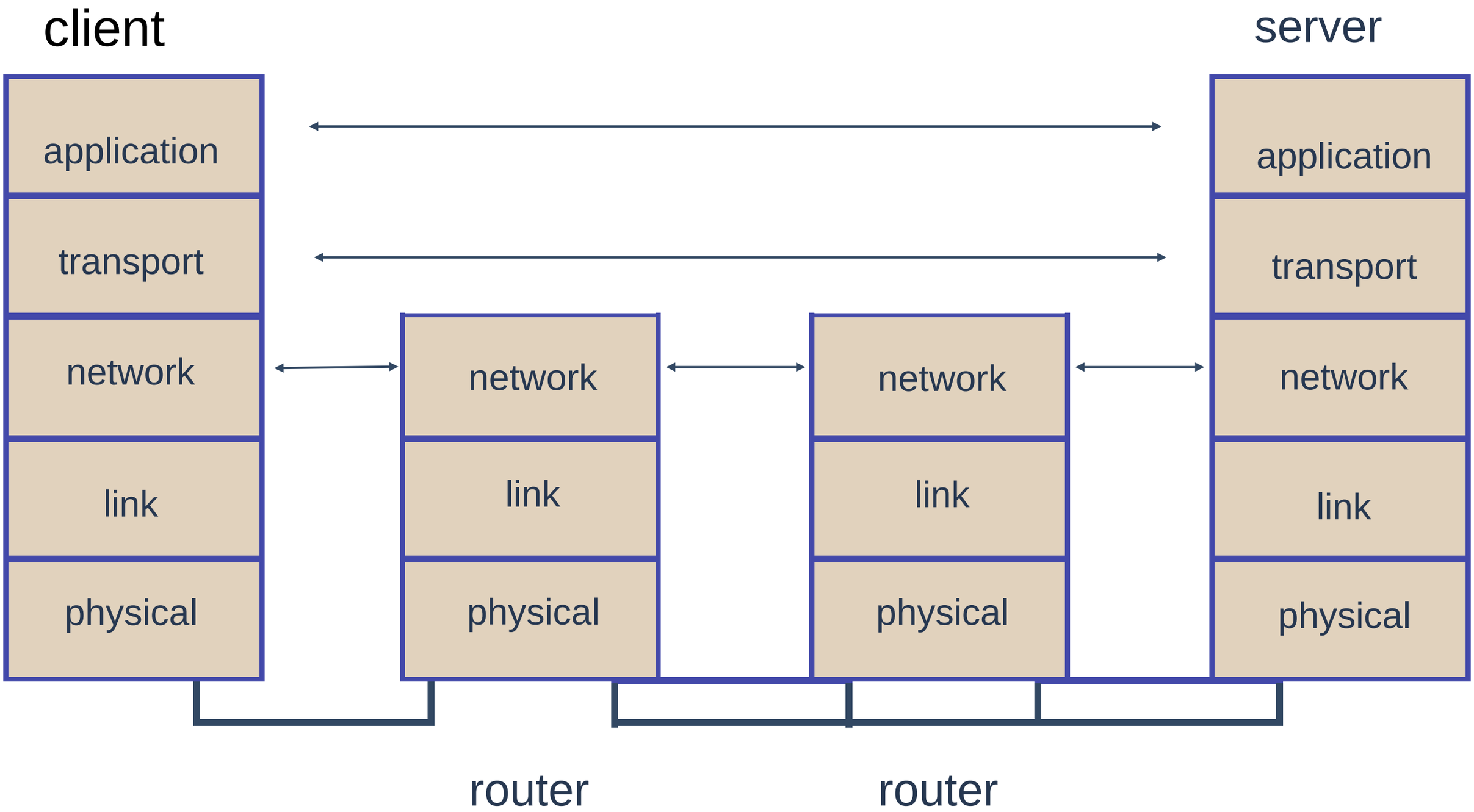
Module 3
Network Layer

Network layer

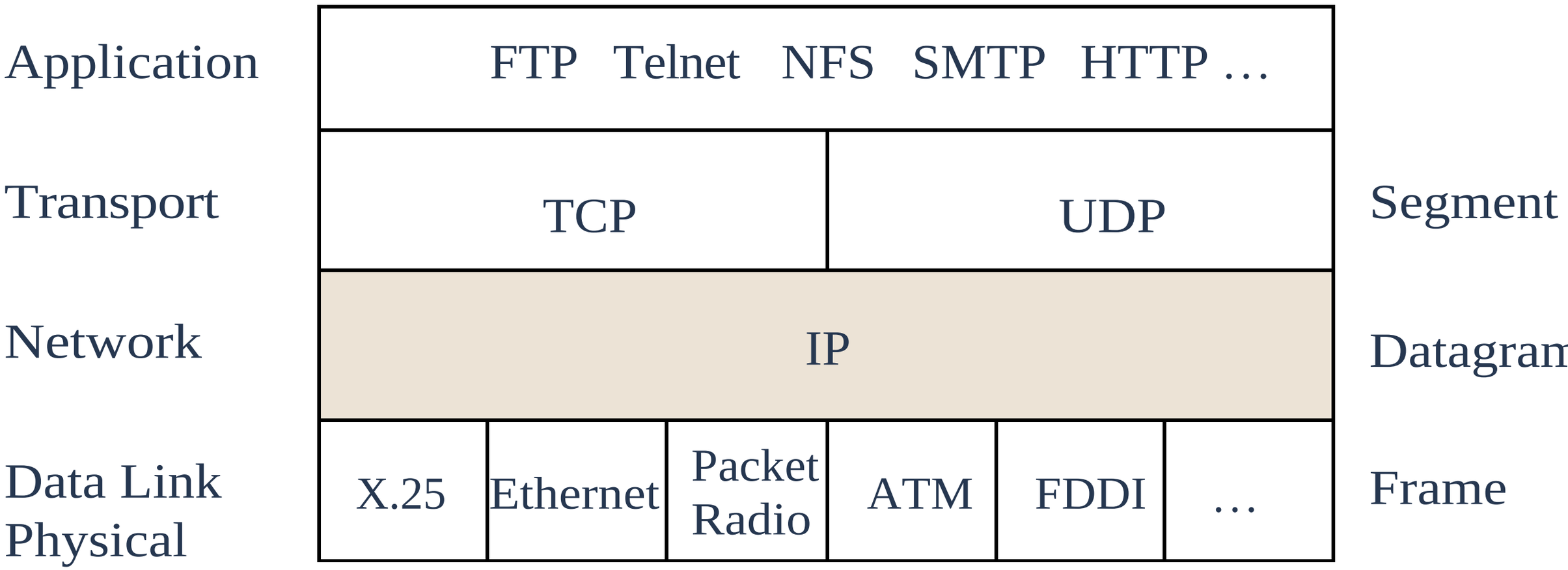
- transport segment from sending to receiving host
- on sending side encapsulates segments into datagrams
- on receiving side, delivers segments to transport layer
- network layer protocols in *every* host, router
- router examines header fields in all IP datagrams passing through it



Network Layer is Host-to-Host



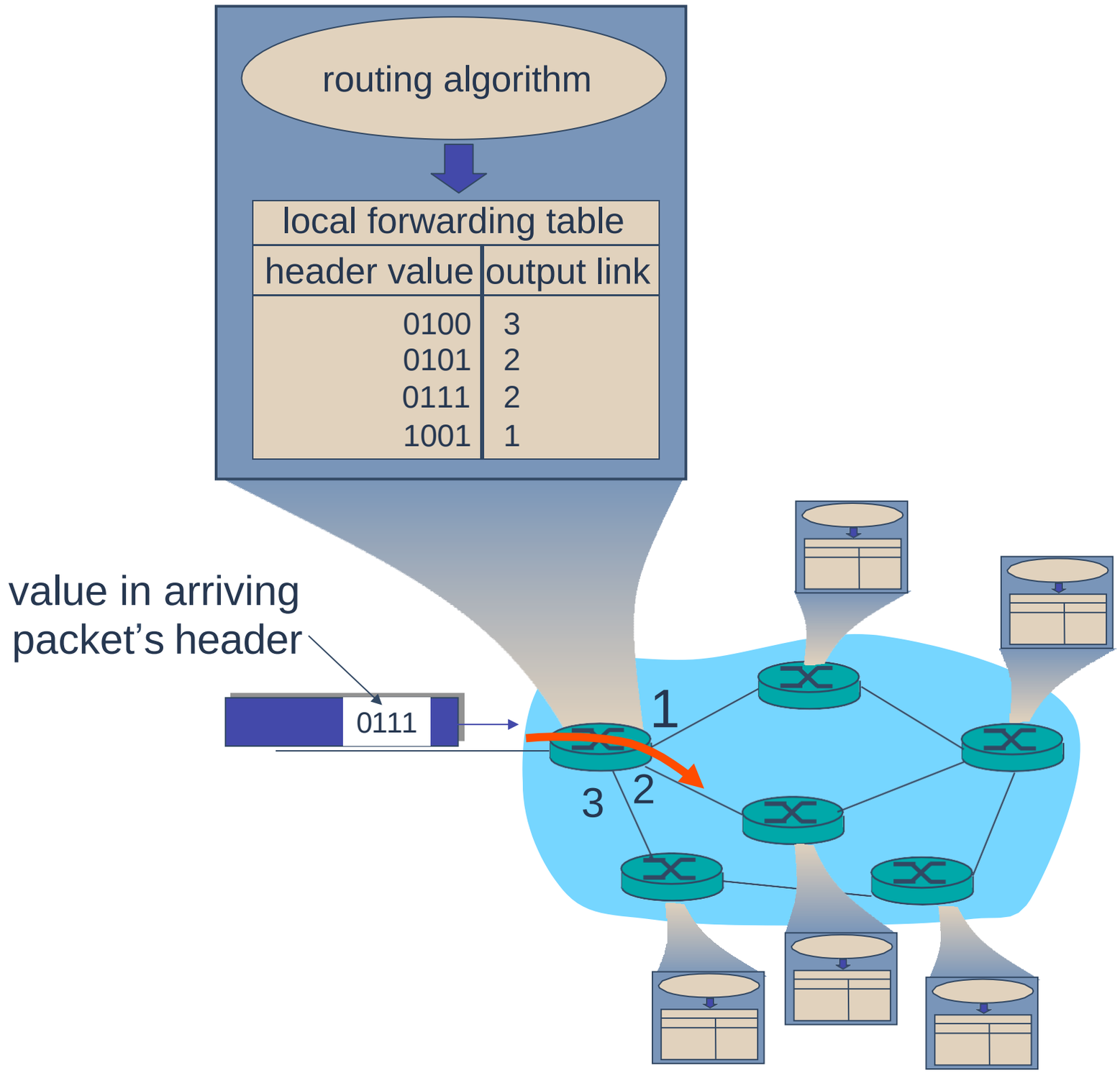
Internet Protocols



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 destination.
  - *routing algorithms*
- *Connection service:* before datagrams flow, two end hosts *and* intervening routers establish virtual connection (VC)
  - Needed in *some* network architectures: ATM, frame relay, X.25
  - Network vs transport layer connection service:
    - network: between two hosts (may also involve intervening routers in case of VCs)
    - transport: between two processes

Interplay Between Routing and Forwarding



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 ?				Congestion feedback
		Bandwidth	Loss	Order	Timing	
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

Network layer connection and connection-less service

- Datagram network provides network-layer connectionless service
- Virtual Circuit (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 network core

Virtual Circuits

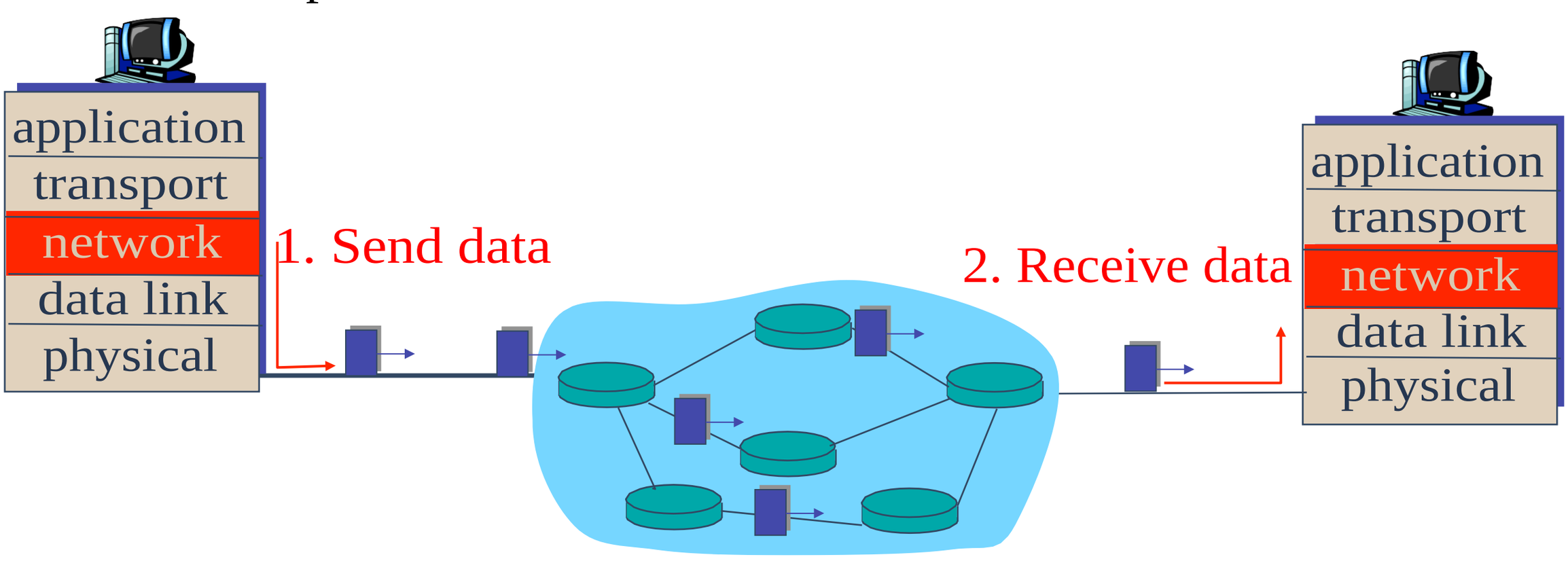
"source-to-destination path behaves much like telephone circuit"

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

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

Datagram networks

- no call setup at networklayer
- 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



Datagram Forwarding table

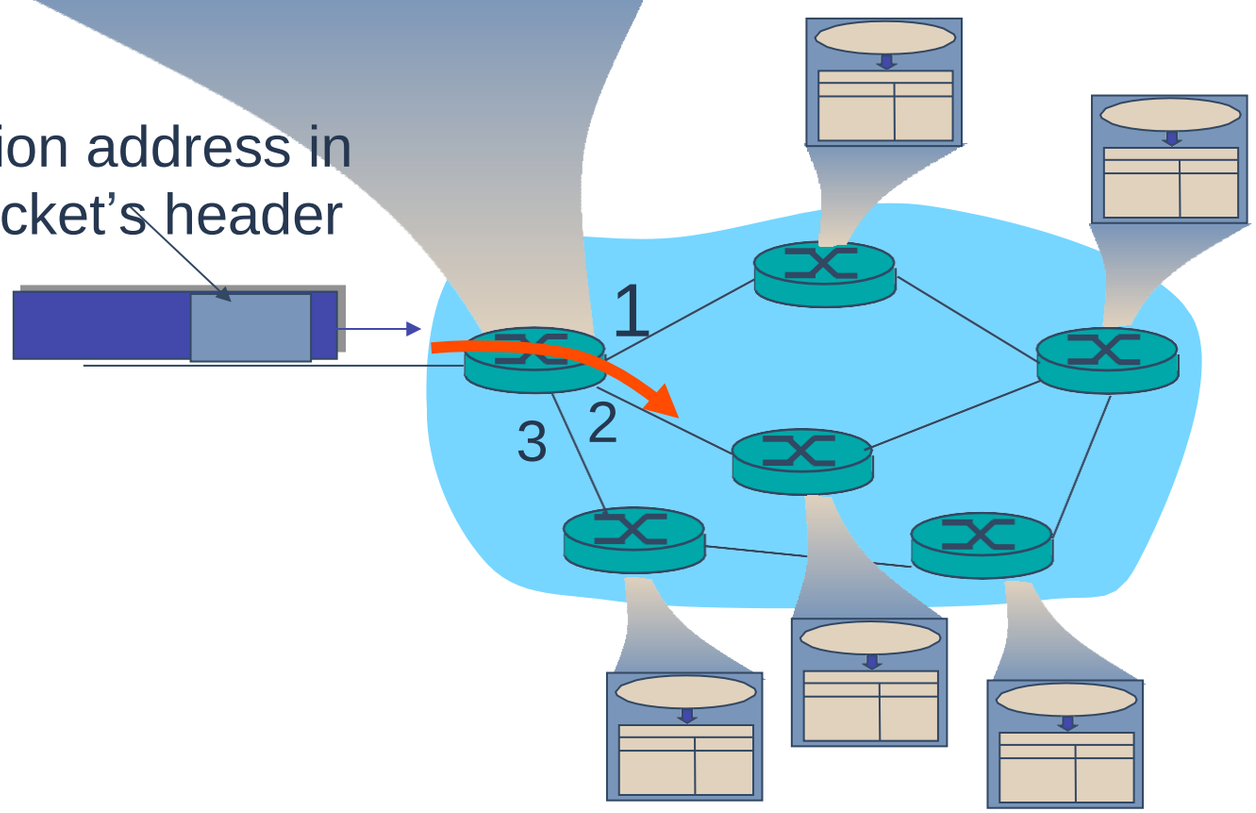
routing algorithm

local forwarding table

dest address	output link
address-range 1	3
address-range 2	2
address-range 3	2
address-range 4	1

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

IP destination address in arriving packet's header



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

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

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.
- "smart" end systems (computers)
  - → can adapt, perform control, error recovery
  - → simple inside network, complexity at "edge"
- many link types
  - → different characteristics
  - → uniform service difficult

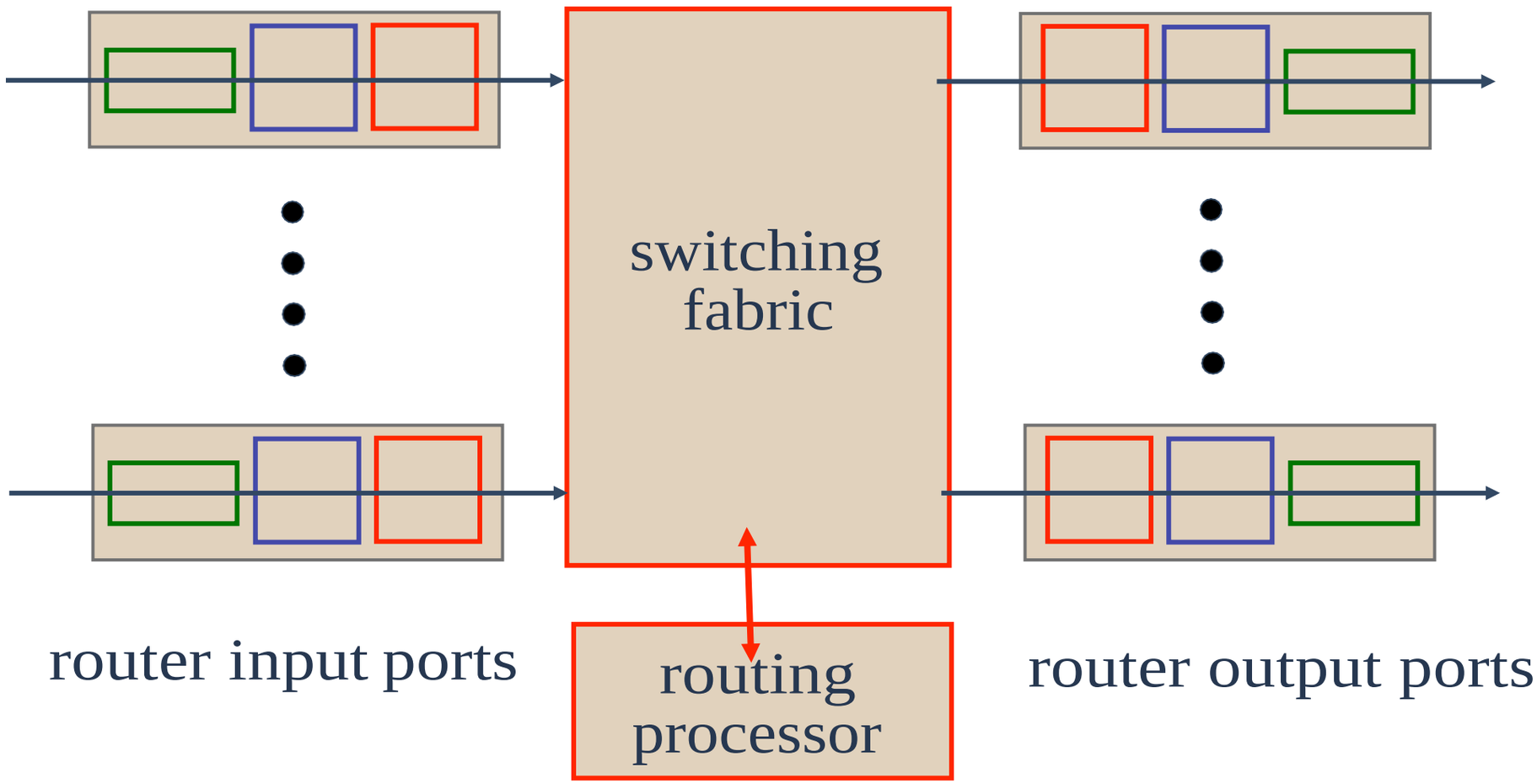
ATM (VC)

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

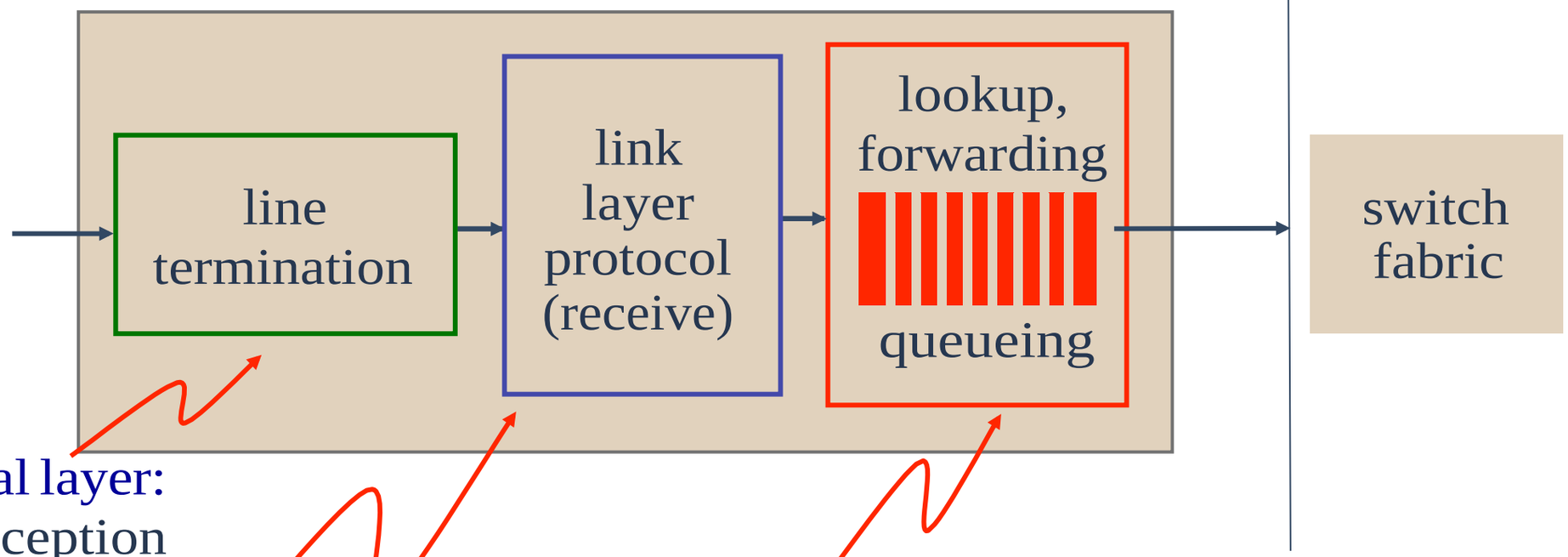
Router Architecture Overview

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

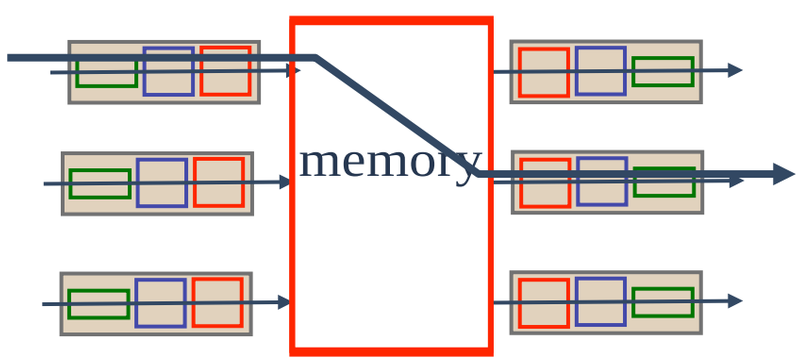
Data link layer:
e.g., Ethernet

Decentralized switching:

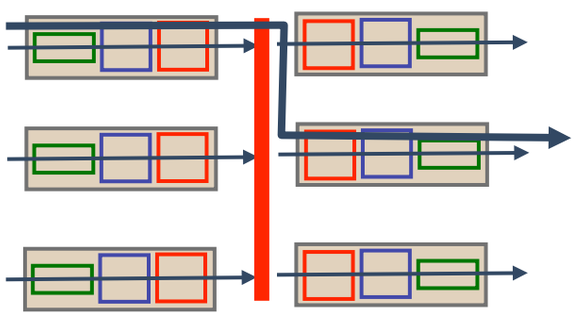
- given datagram destination, lookup output port using forwarding table in input port memory
- goal: complete input port processing at 'line speed'
- queuing: if datagrams arrive faster than forwarding rate into switch fabric

Switching fabrics

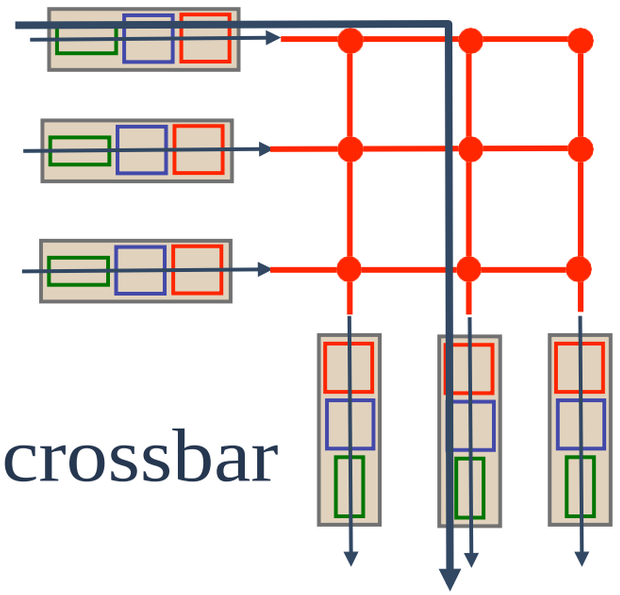
- transfer packet from input buffer to appropriate output buffer
- switching rate: rate at which packets can be transfer from inputs to outputs
  - often measured as multiple of input/output line rate
  - N inputs: switching rate N times line rate desirable
- three types of switching fabrics



memory



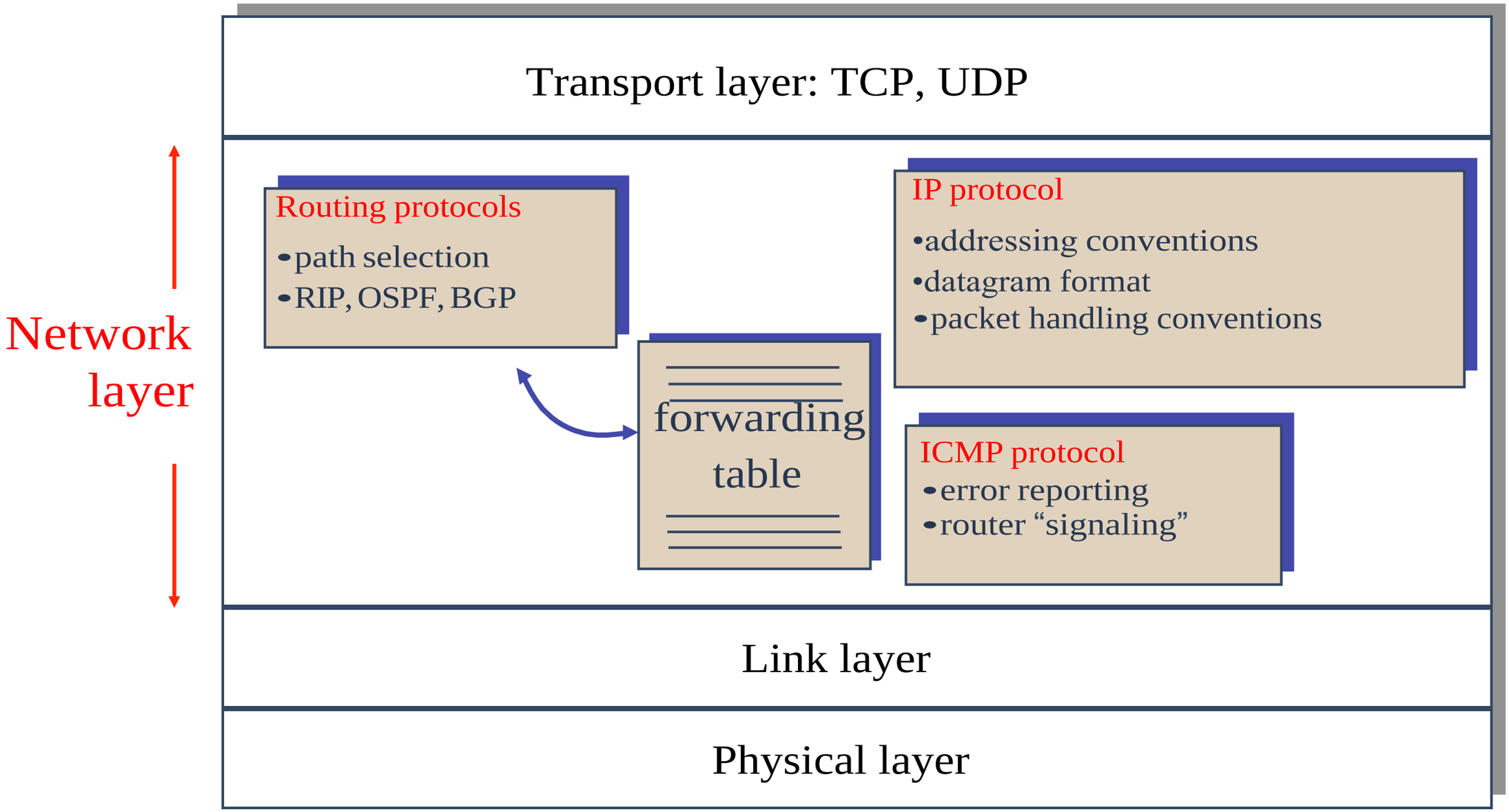
bus



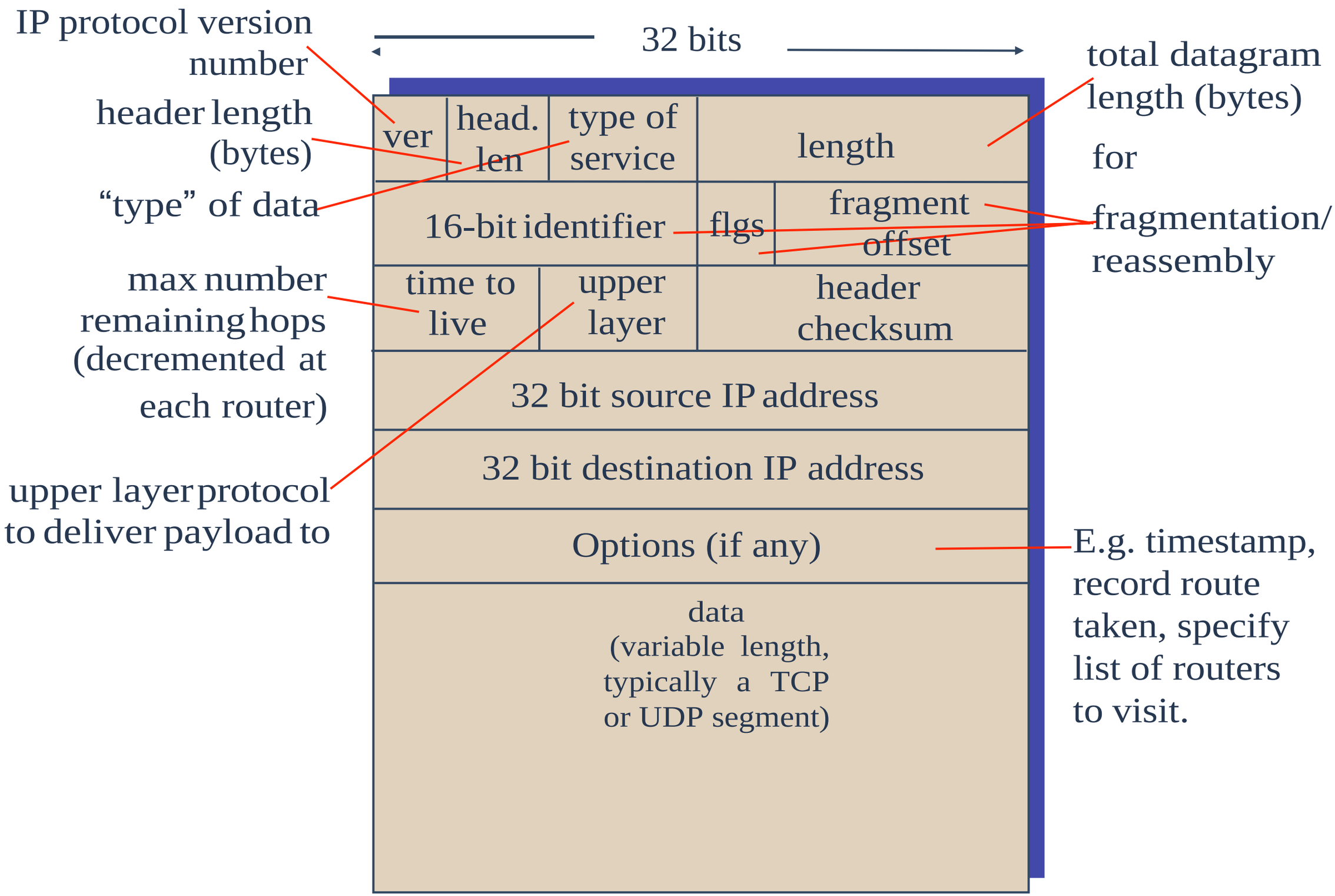
crossbar

The Internet Network layer

Host, router network layer functions:

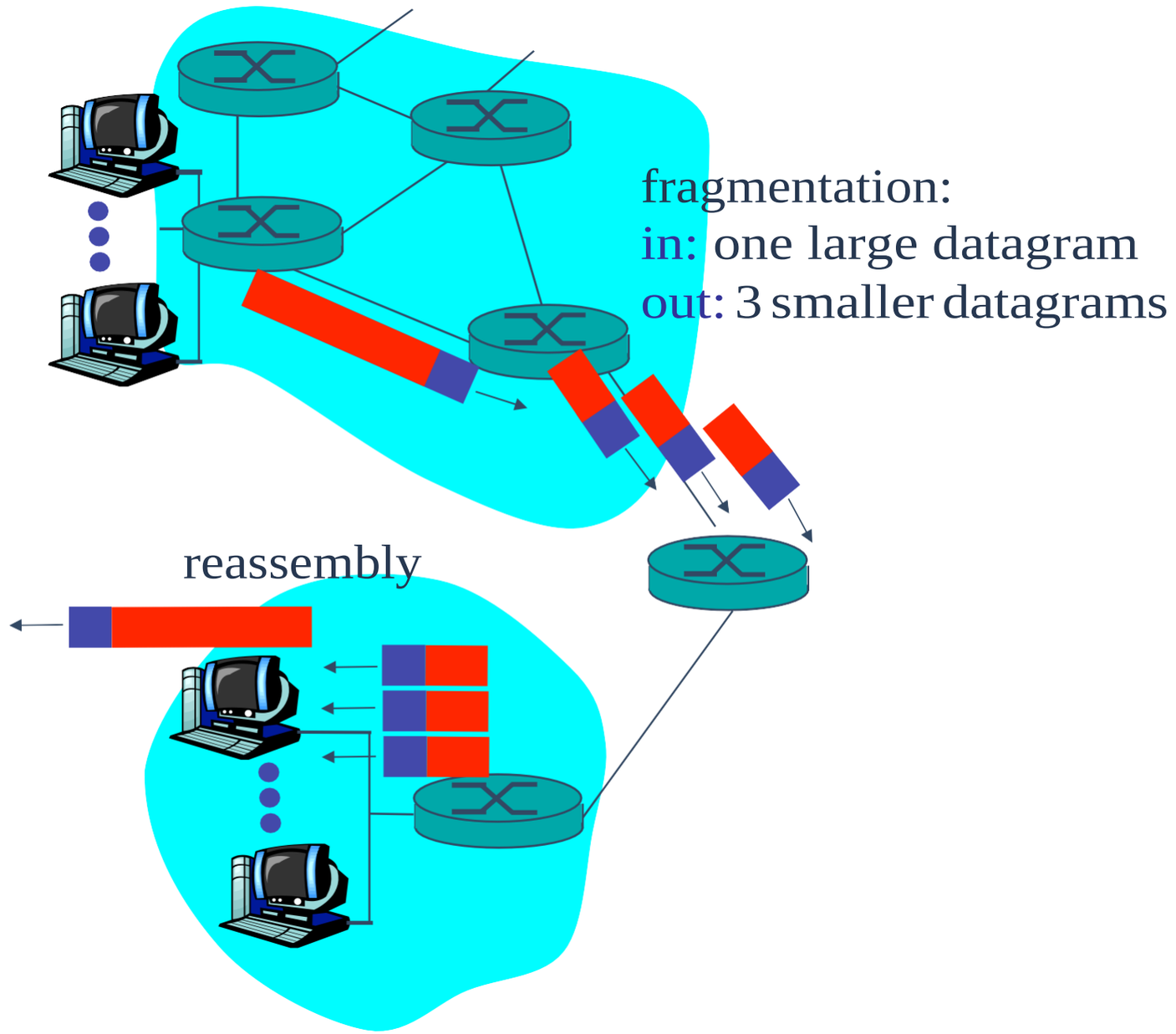


IP datagram format



IP Fragmentation & Reassembly

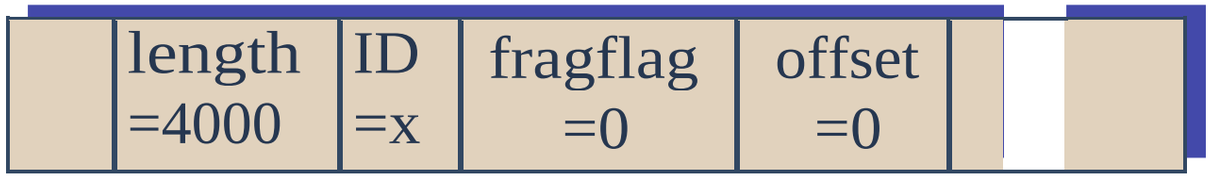
- network links have MTU (maximum transmission unit): largest possible link-level frame.
  - → different link types, different MTUs
- large IP datagram divided ("fragmented") within net
  - → one datagram becomes several datagrams
  - → "reassembled" only at final destination
  - → IP header bits used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



IP Fragmentation and Reassembly

Example

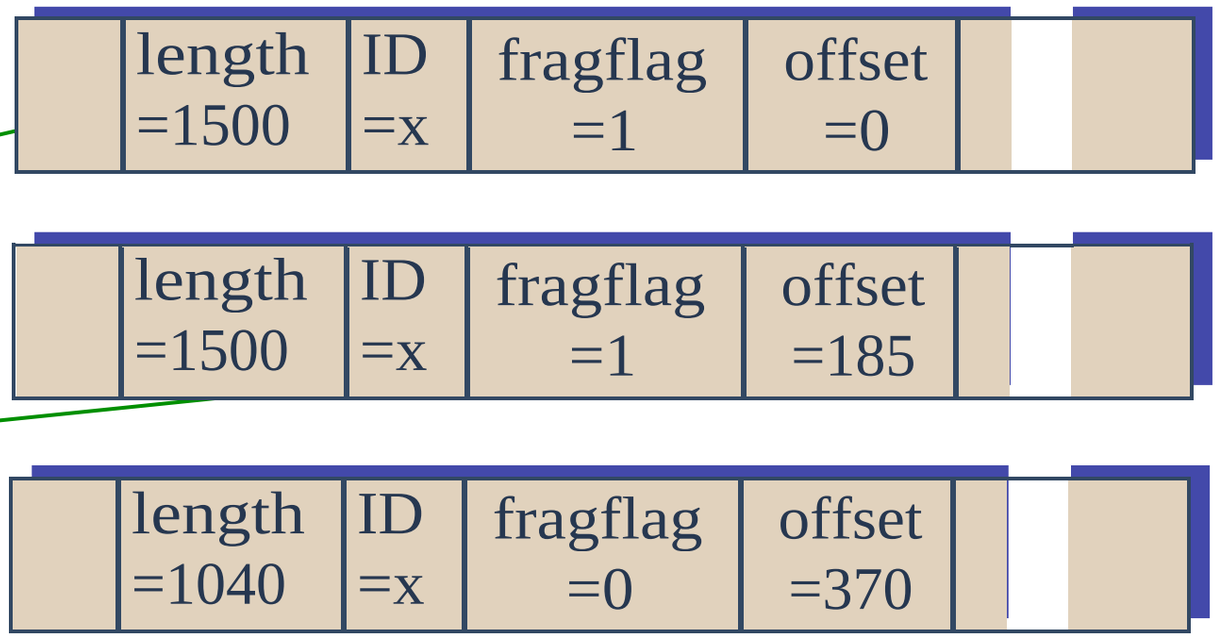
- 4000 byte datagram
- MTU = 1500 bytes



One large datagram becomes several smaller datagrams

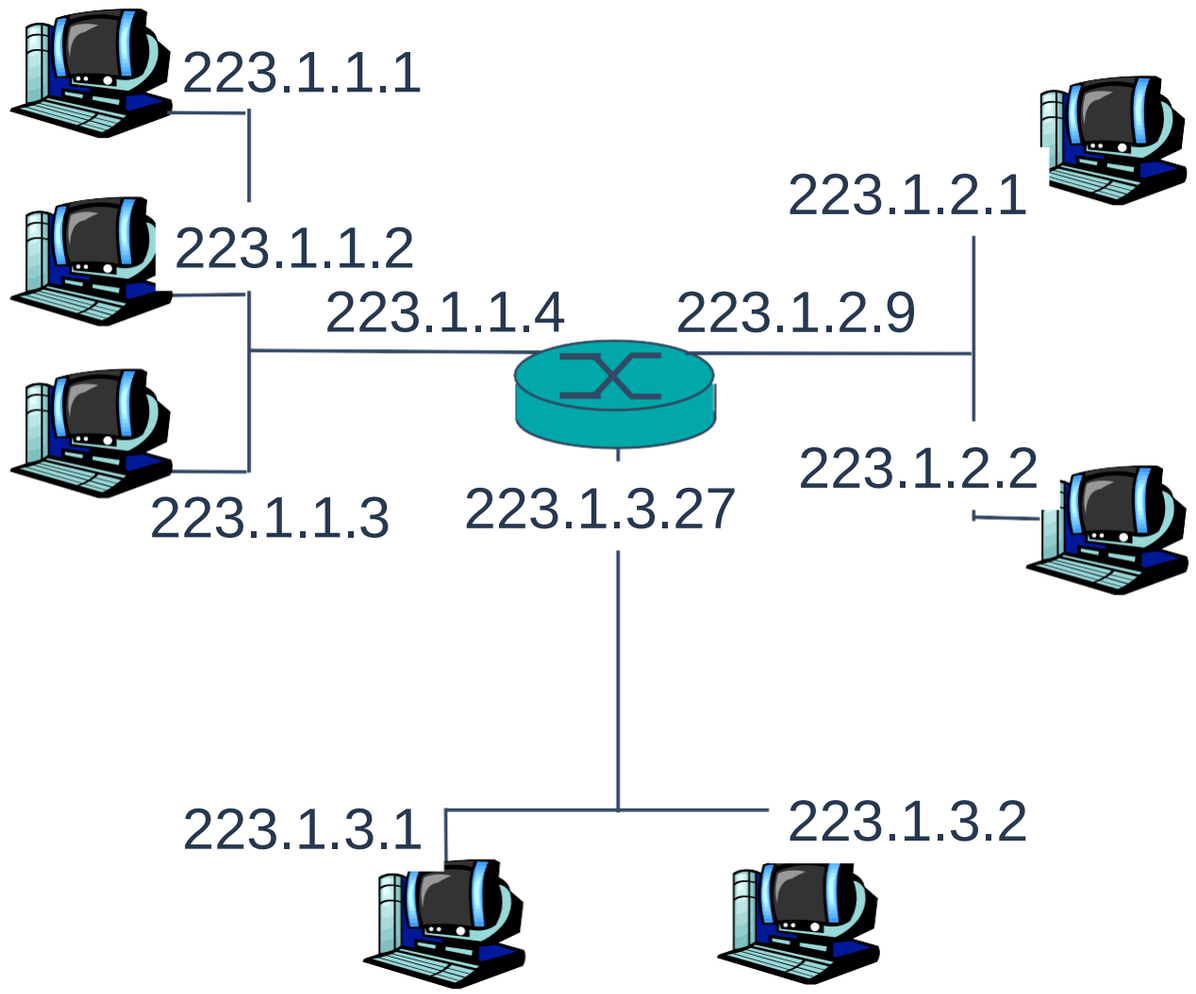
1480 bytes in data field

offset = 1480/8



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 interface
  - IP addresses associated with each interface

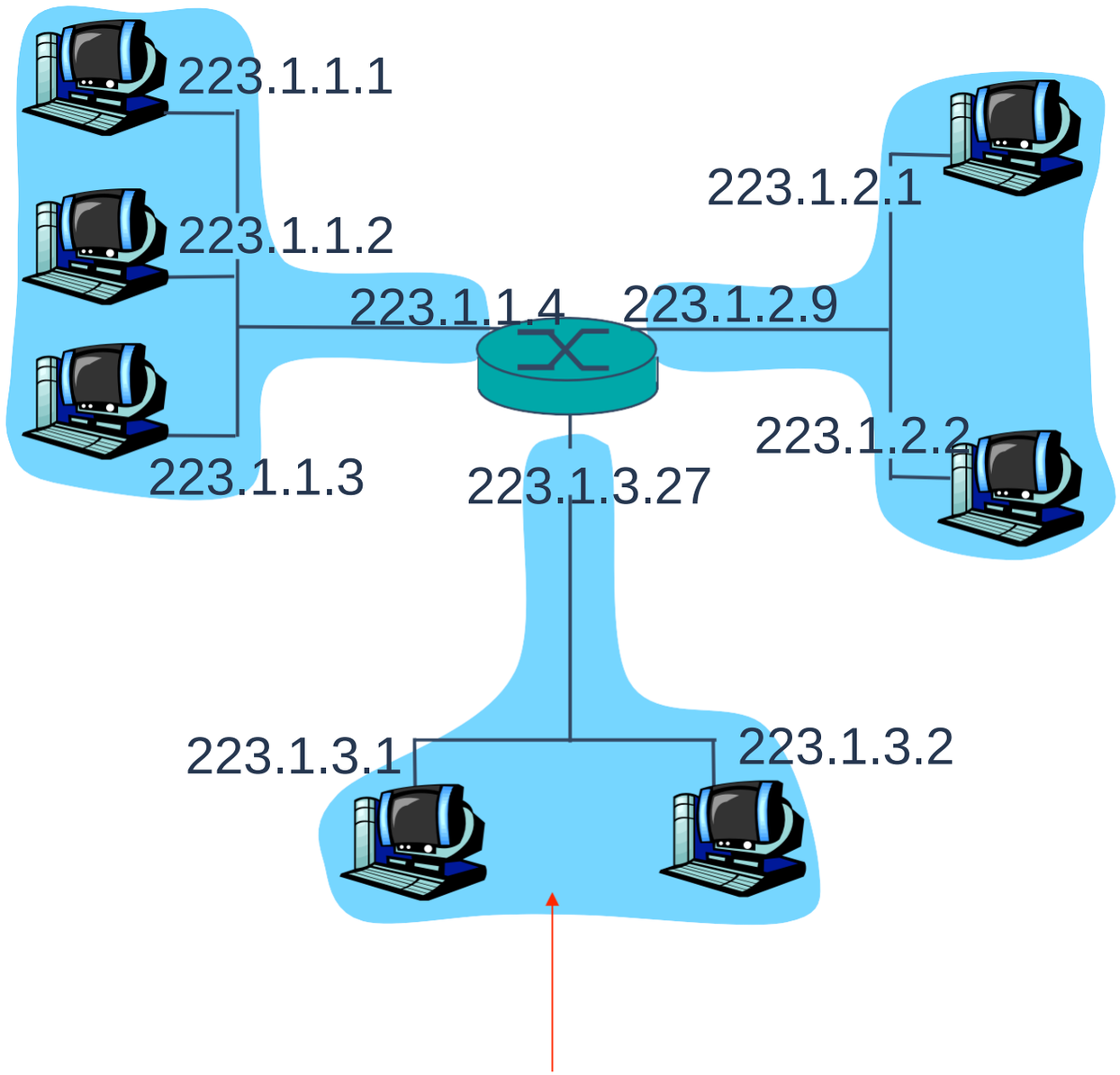


223.1.1.1 = 11011111 00000001 00000001 00000001

223 1 1 1

Subnets

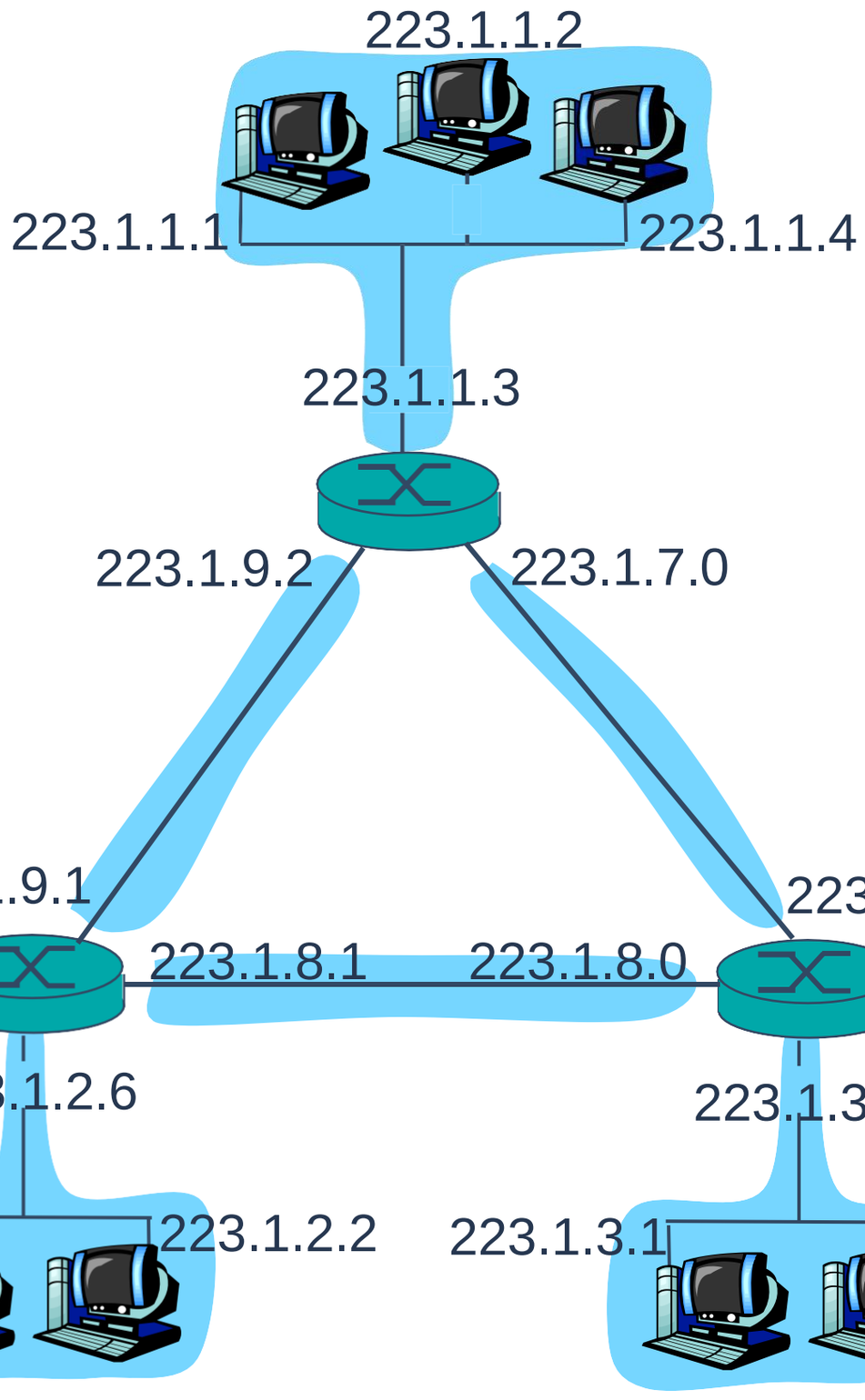
- IP address:
  - subnet part (high order bits)
  - host part (low order bits)
- *What's a subnet ?*
  - device interfaces with same subnet part of IP address
  - can physically reach each other without intervening router



Subnet (223.1.3.0/24)

Subnets

How many?



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

IP addresses: how to get one?

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

- Static allocation: hard-coded by system admin in a file
- 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)

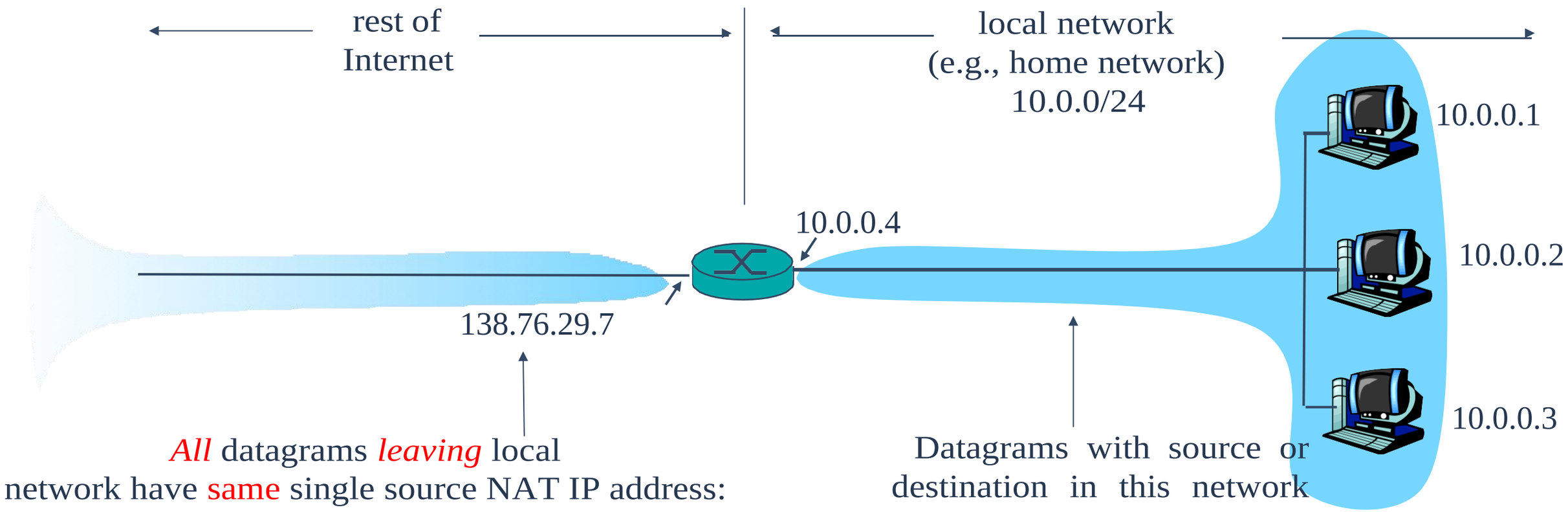
Support for mobile users who want to join network

DHCP overview:

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

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).



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 messages 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 destination
  - 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)
  - ICMP 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 “port unreachable” packet (type 3, code 3)
- when source gets this ICMP, stops.

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:

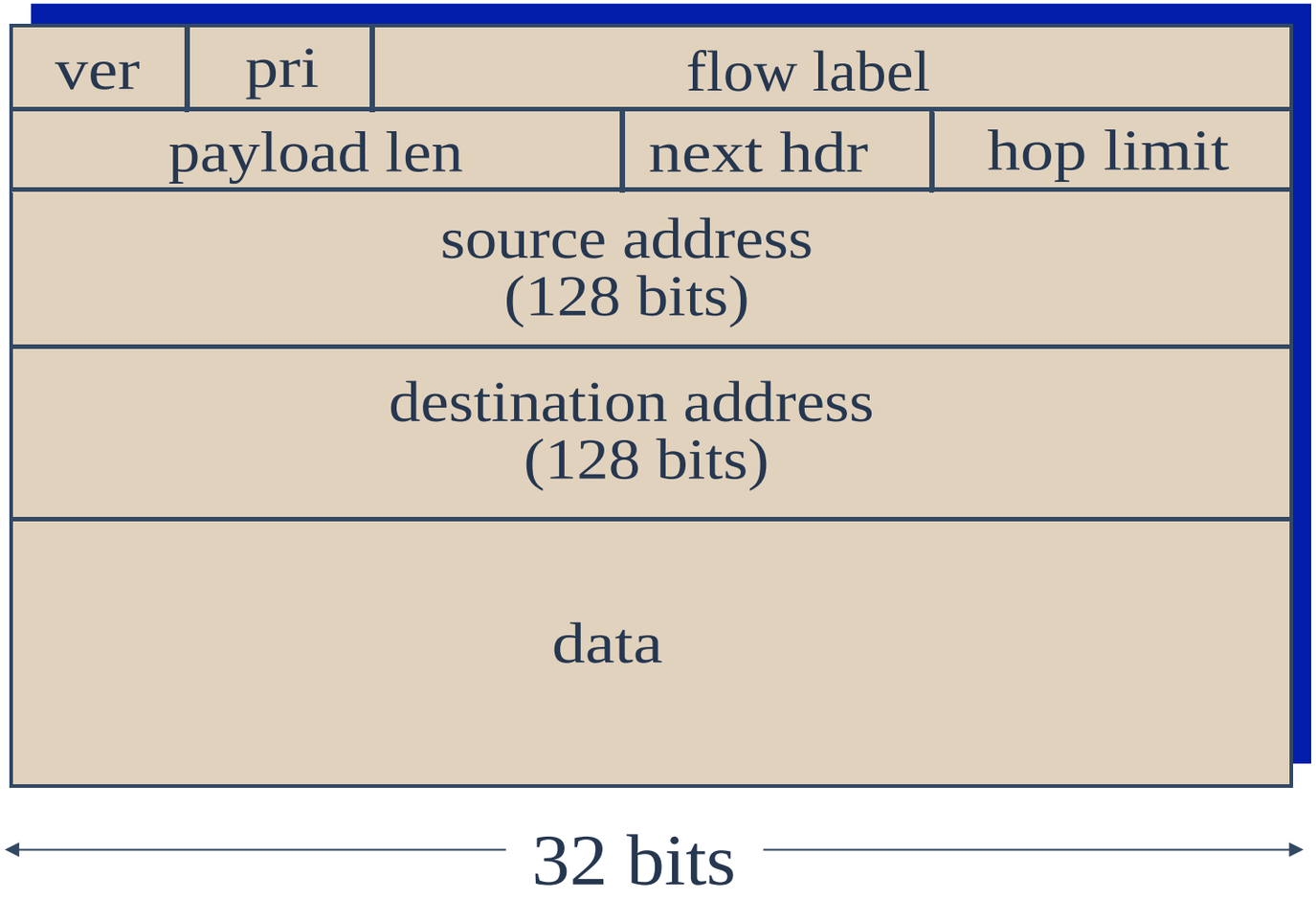
- fixed-length 40 byte header
- no fragmentation allowed

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?
- *Tunneling:* IPv6 carried as payload in IPv4 datagram among IPv4 routers