School of Computing Science
Simon Fraser University

CMPT 471: Networking II

Network Layer

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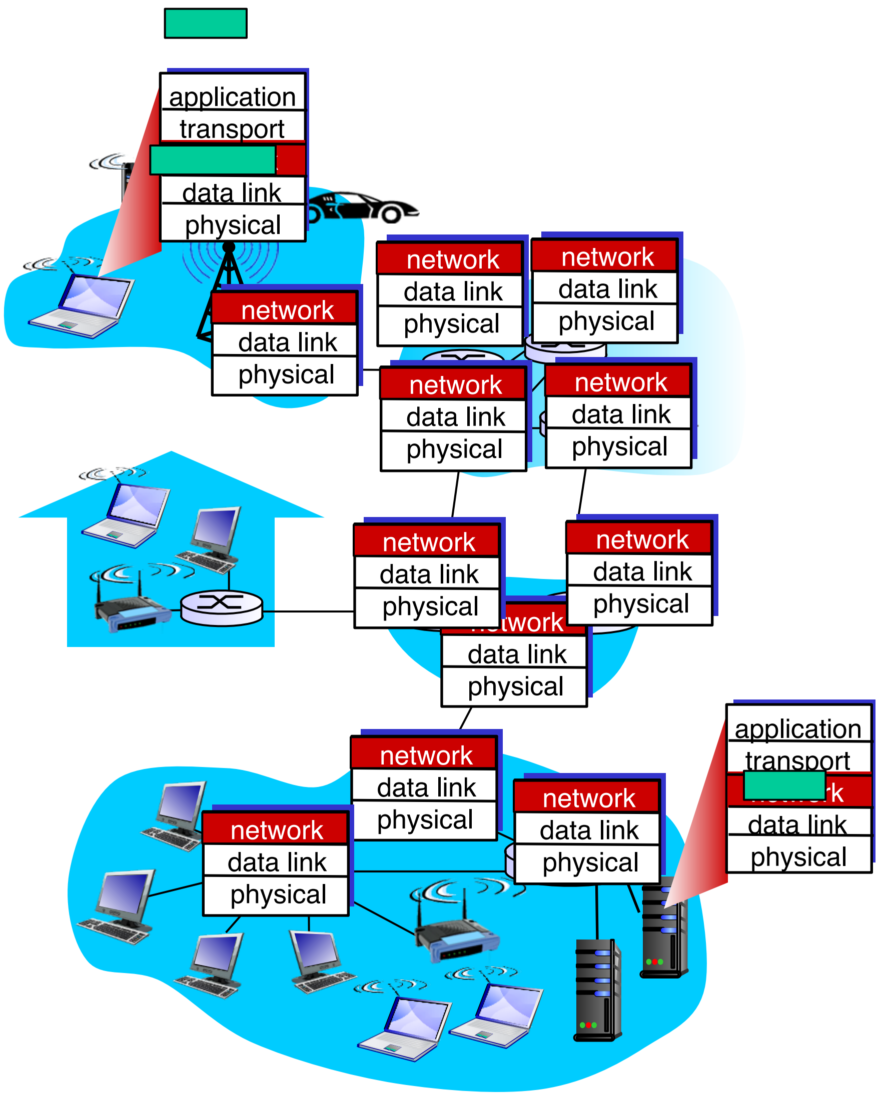
Network layer

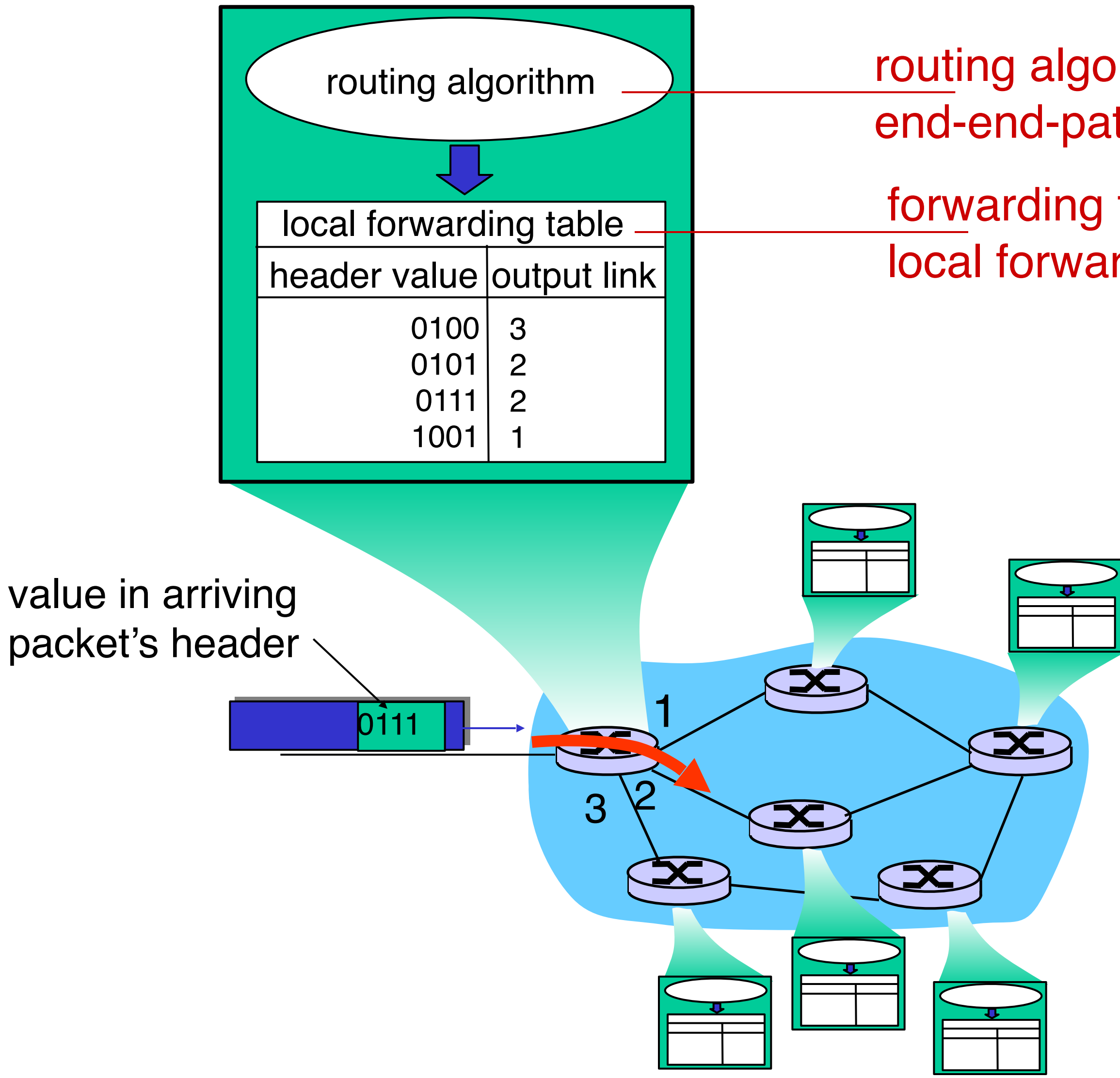
- transport segment from sending to receiving host
- on sending side encapsulates segments into datagrams
- on receiving side, delivers segments to transport layer
- network layer protocols in *every* host, router
- router examines header fields in all IP datagrams passing through it



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*

Interplay between routing and forwarding

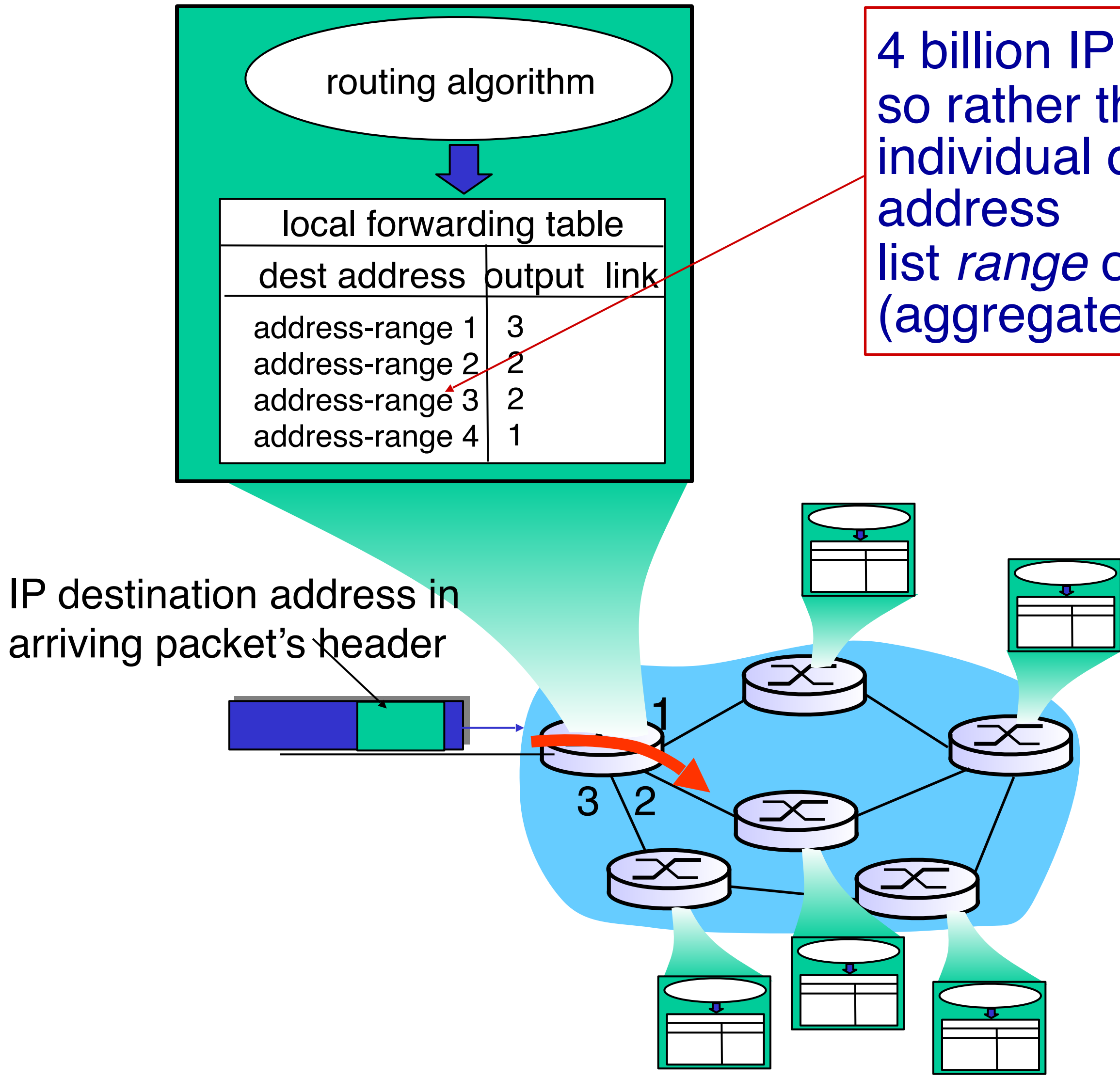


routing algorithm determines end-end-path through network

forwarding table determines local forwarding at this router

Datagram forwarding table

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



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

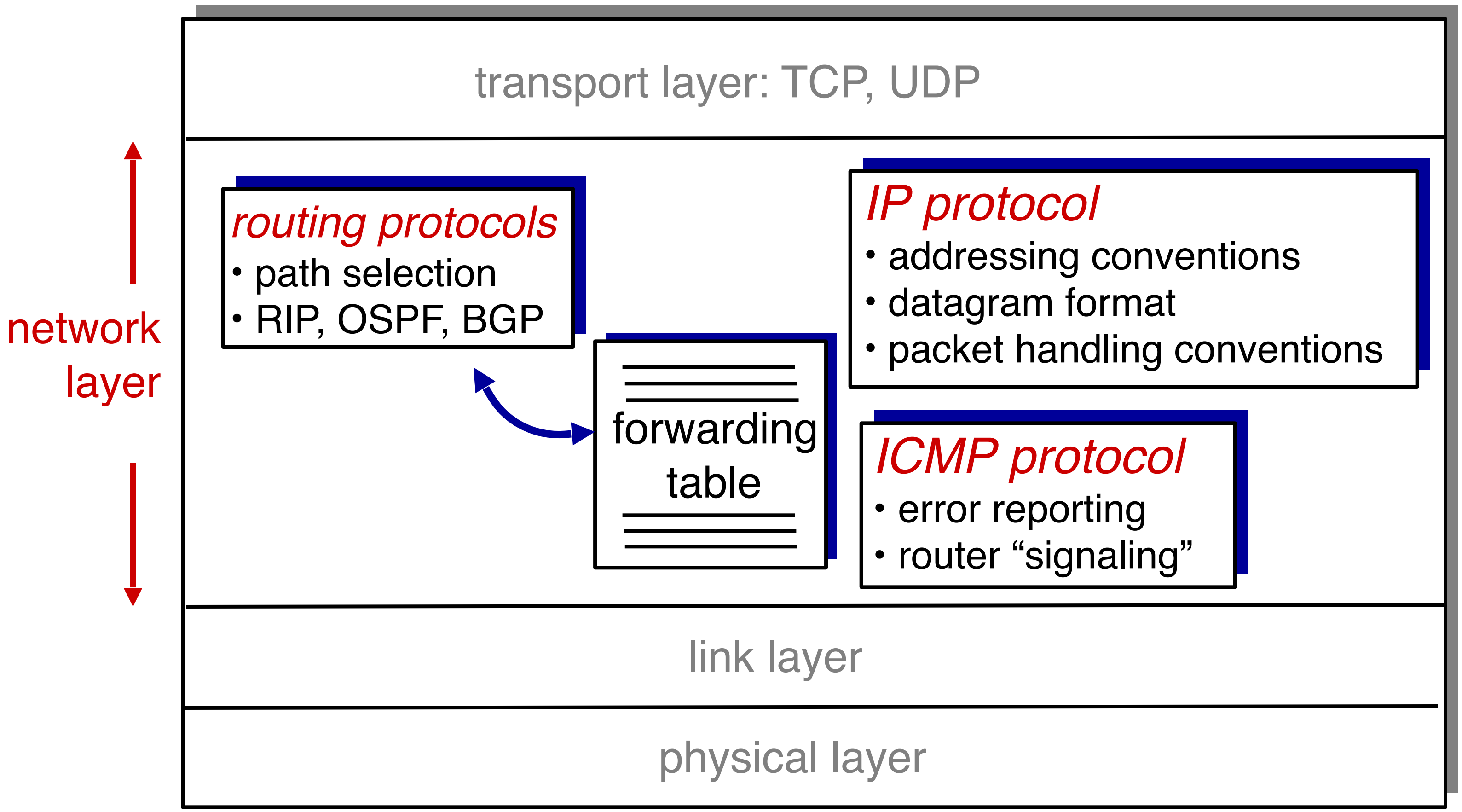
examples:

DA: 11001000 00010111 00010110 10100001 which interface?

DA: 11001000 00010111 00011000 10101010 which interface?

The Internet network layer

host, router network layer functions:



IP datagram format

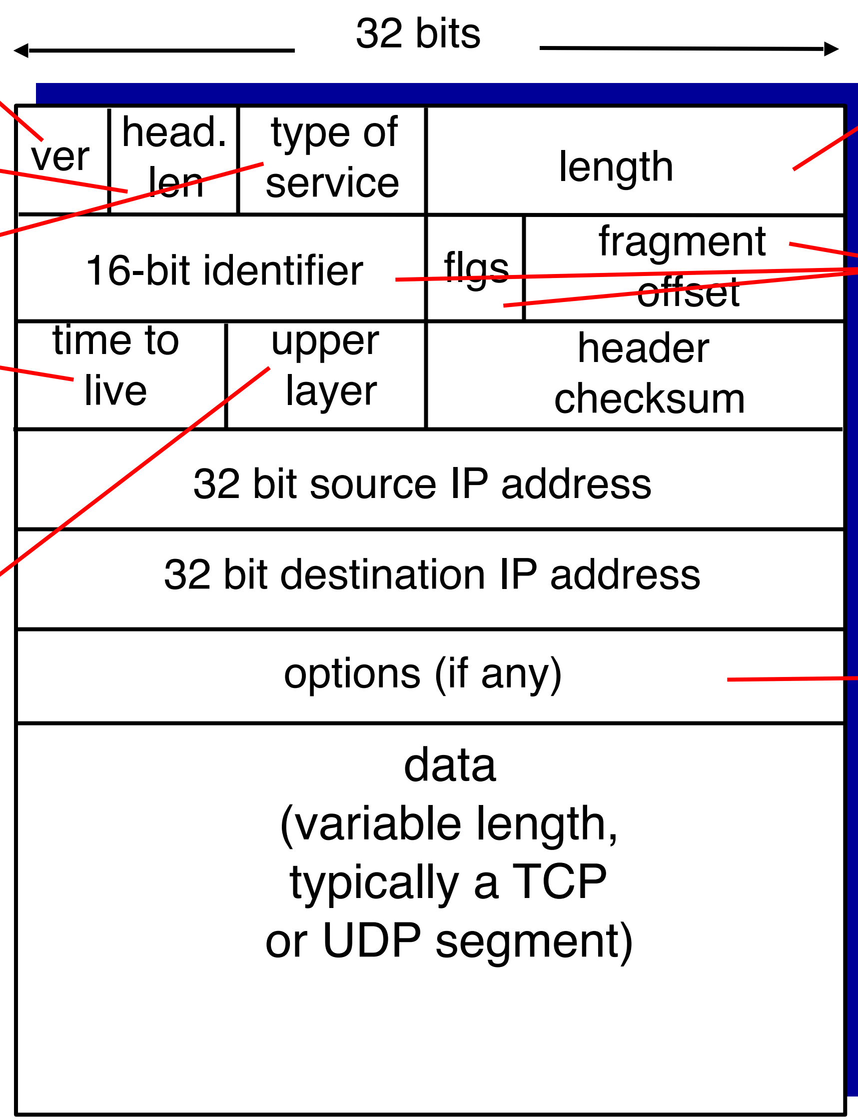
IP protocol version number

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

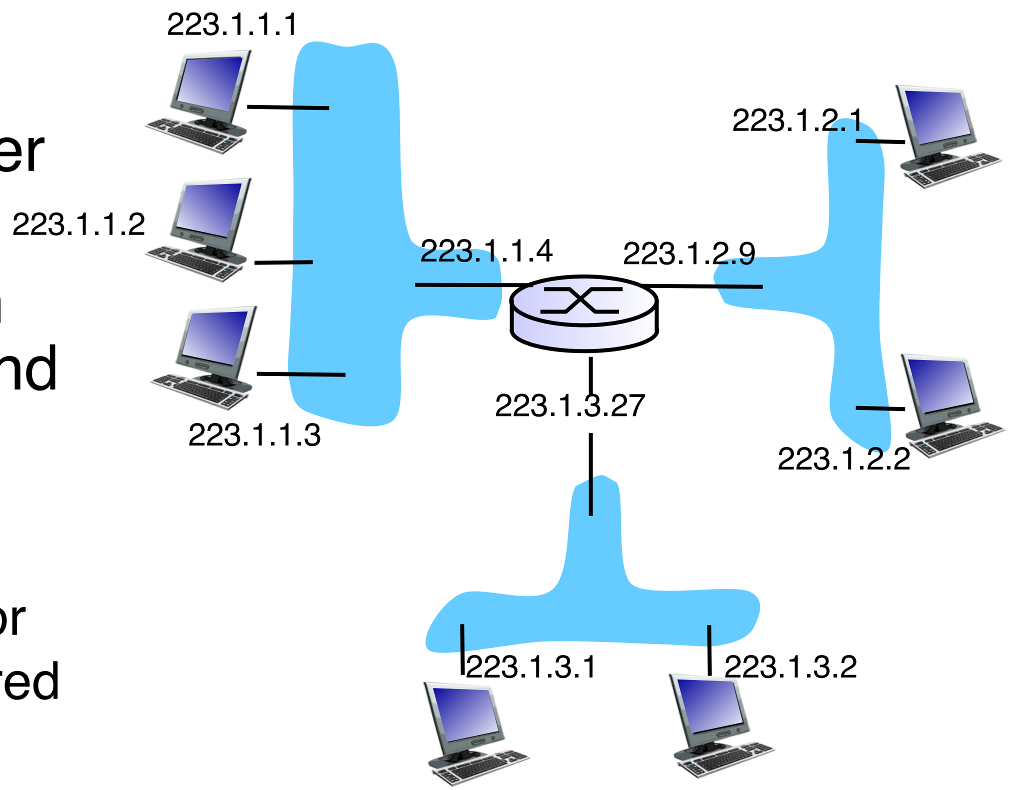
e.g. timestamp, record route taken, specify list of routers to visit.

how much overhead?

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

IP addressing: introduction

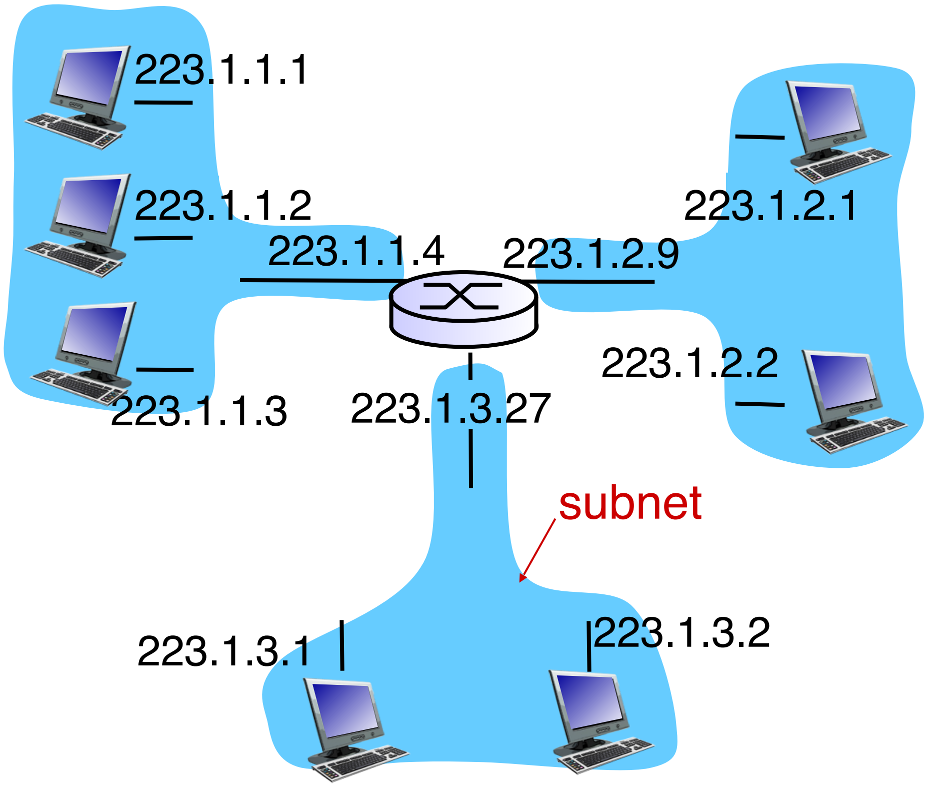
- *IP address:* 32-bit identifier for host, router *interface*
- *interface:* connection between host/router and physical link
  - router's typically have multiple interfaces
  - host typically has one or two interfaces (e.g., wired Ethernet, wireless 802.11)
- *IP addresses associated with each interface*



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

Subnets

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



network consisting of 3 subnets

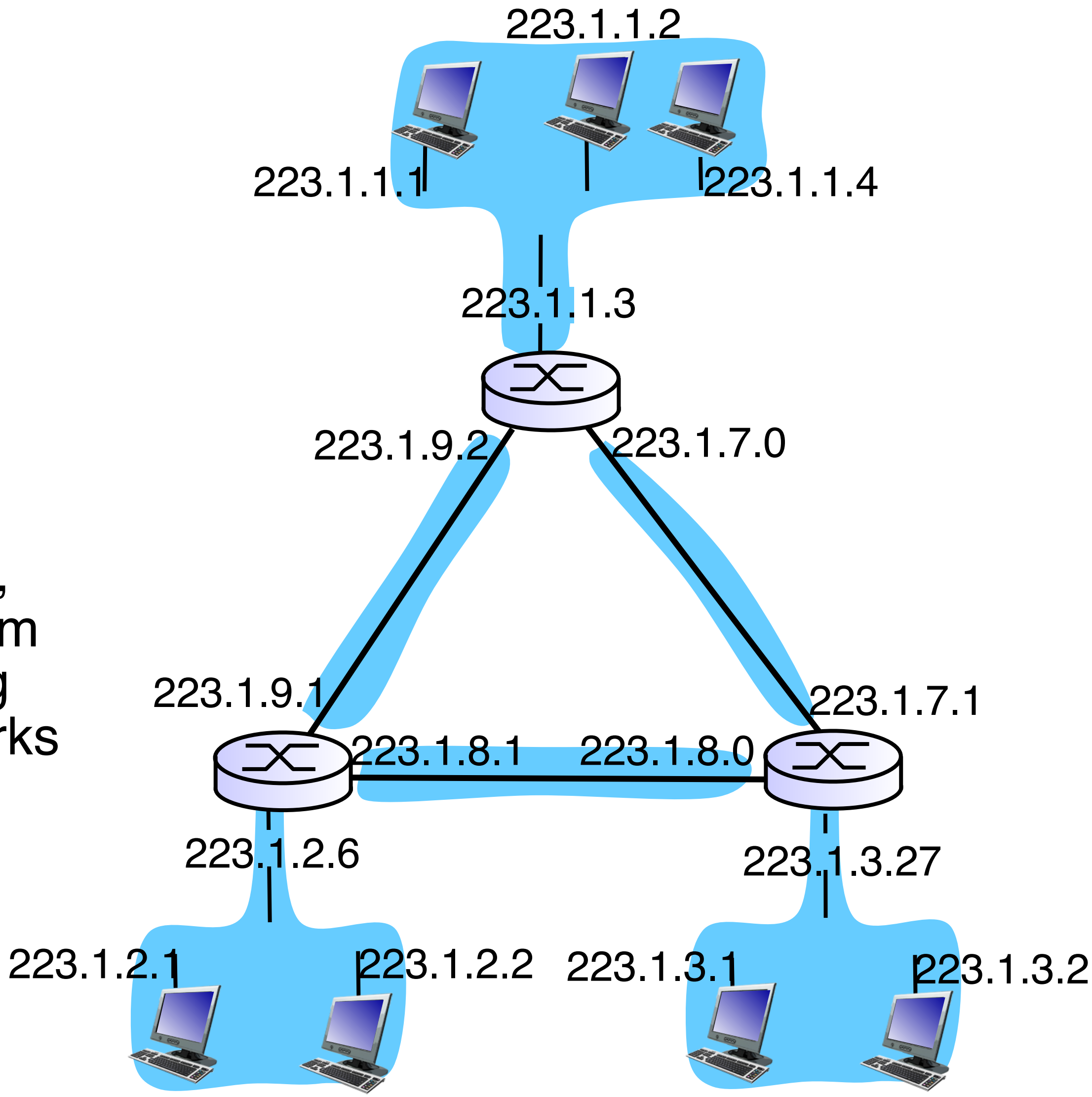
Subnets

how many?

- 6

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*



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 (called mask)

subnet part ← → host part

11001000 00010111 00010000 00000000

200.23.16.0/23

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

MAC addresses and ARP

- 32-bit IP address:
  - *network-layer* address for interface
  - used for layer 3 (network layer) forwarding
- MAC (or LAN or physical or Ethernet) address:
  - *used 'locally" to get frame from one interface to another physically-connected interface (same network, in IP-addressing sense)*
  - 48 bit MAC address (for most LANs) burned in NIC ROM, also sometimes software settable
  - e.g.: 1A-2F-BB-76-09-AD

hexadecimal (base 16) notation
(each "number" represents 4 bits)

ARP: address resolution protocol

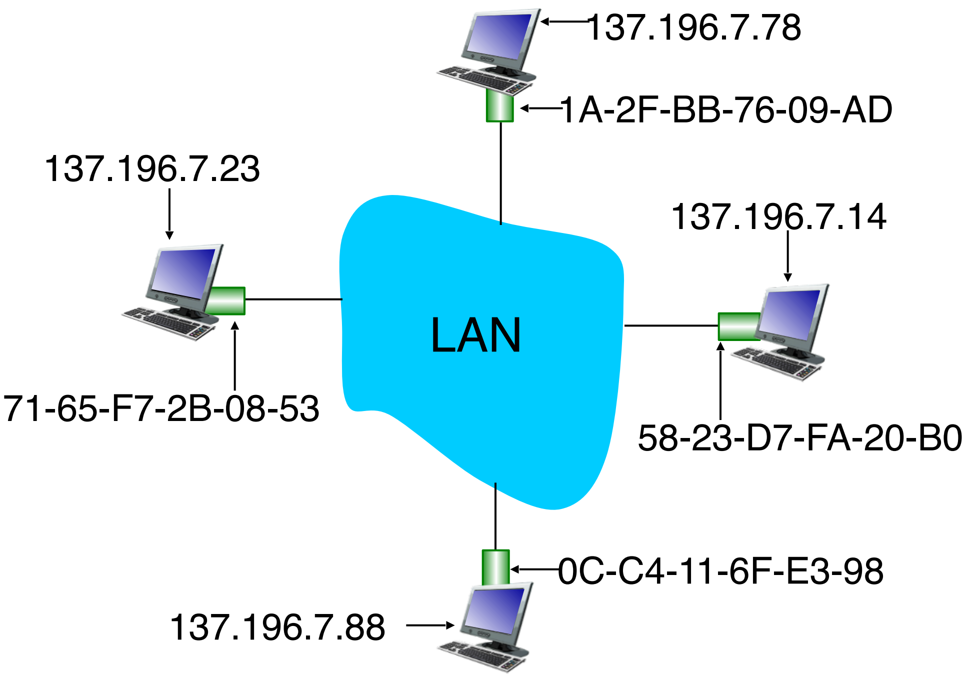
ARP: Maps IP address to MAC address

ARP table: each IP node (host, router) on LAN has table

- IP/MAC address mappings for some LAN nodes:

  < IP address; MAC address; TTL>

- TTL (Time To Live): time after which address mapping will be forgotten (typically 20 min)



ARP protocol: same LAN

- A wants to send datagram to B
  - B’s MAC address not in A’s ARP table.
- A broadcasts ARP query packet, containing B's IP address
  - dest MAC address = FF-FF-FF-FF-FF-FF
  - all nodes on LAN receive ARP query
- B receives ARP packet, replies to A with its (B's) MAC address
  - frame sent to A’s MAC address (unicast)

- A caches (saves) IP-to-MAC address pair in its ARP table until information becomes old (times out)
  - soft state: information that times out (goes away) unless refreshed
- ARP is “plug-and-play”:
  - nodes create their ARP tables ***without*** *intervention from net administrator*

IPv6: motivation

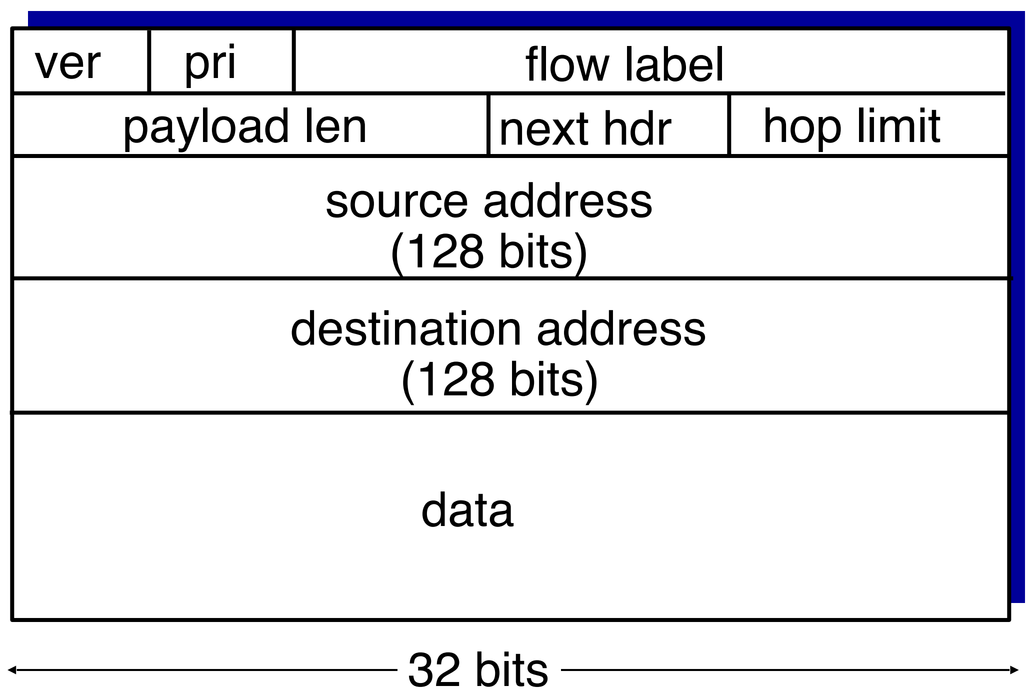
- *initial motivation:* 32-bit address space soon to be completely allocated.
- additional motivation:
  - header format helps speed processing/forwarding
  - header changes to facilitate QoS

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

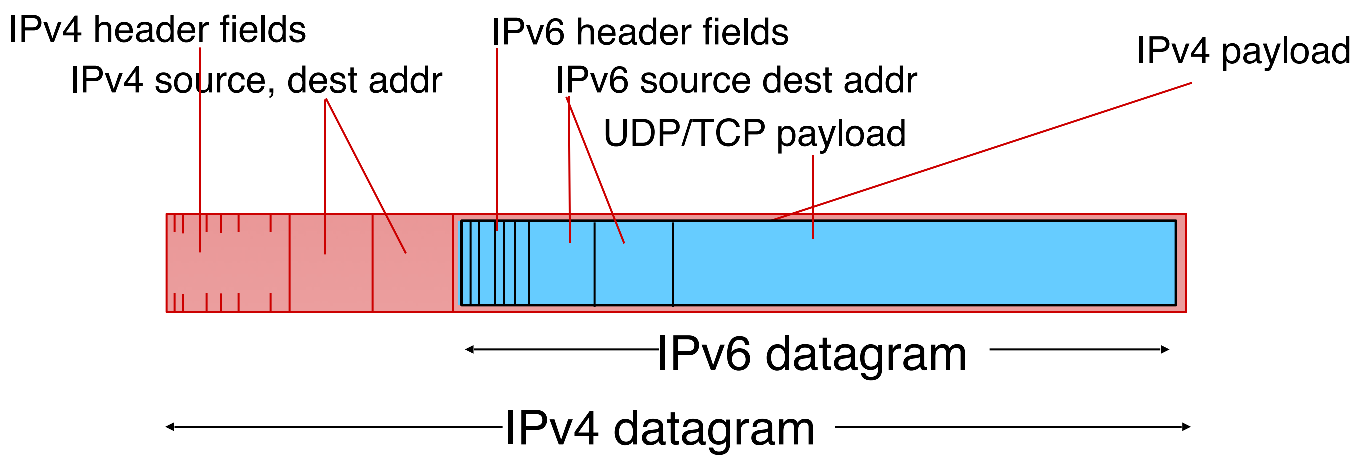


Other changes from IPv4

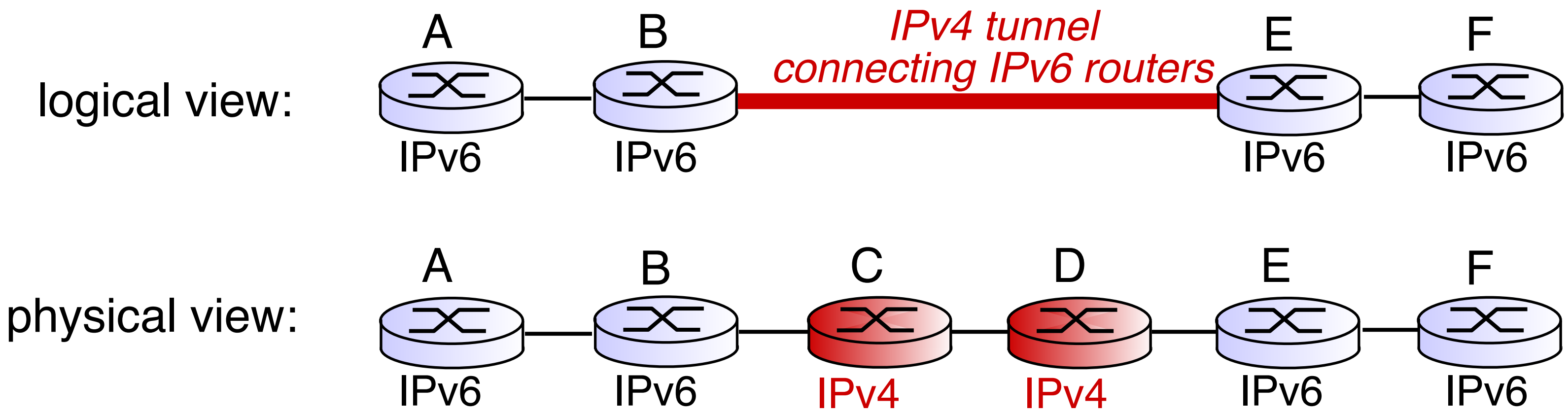
- *checksum*: removed entirely to reduce processing time at each hop
- *options:* allowed, but outside of header, indicated by “Next Header” field
- *ICMPv6:* new version of ICMP
  - additional message types, e.g. “Packet Too Big”
  - multicast group management functions

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
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IPv6
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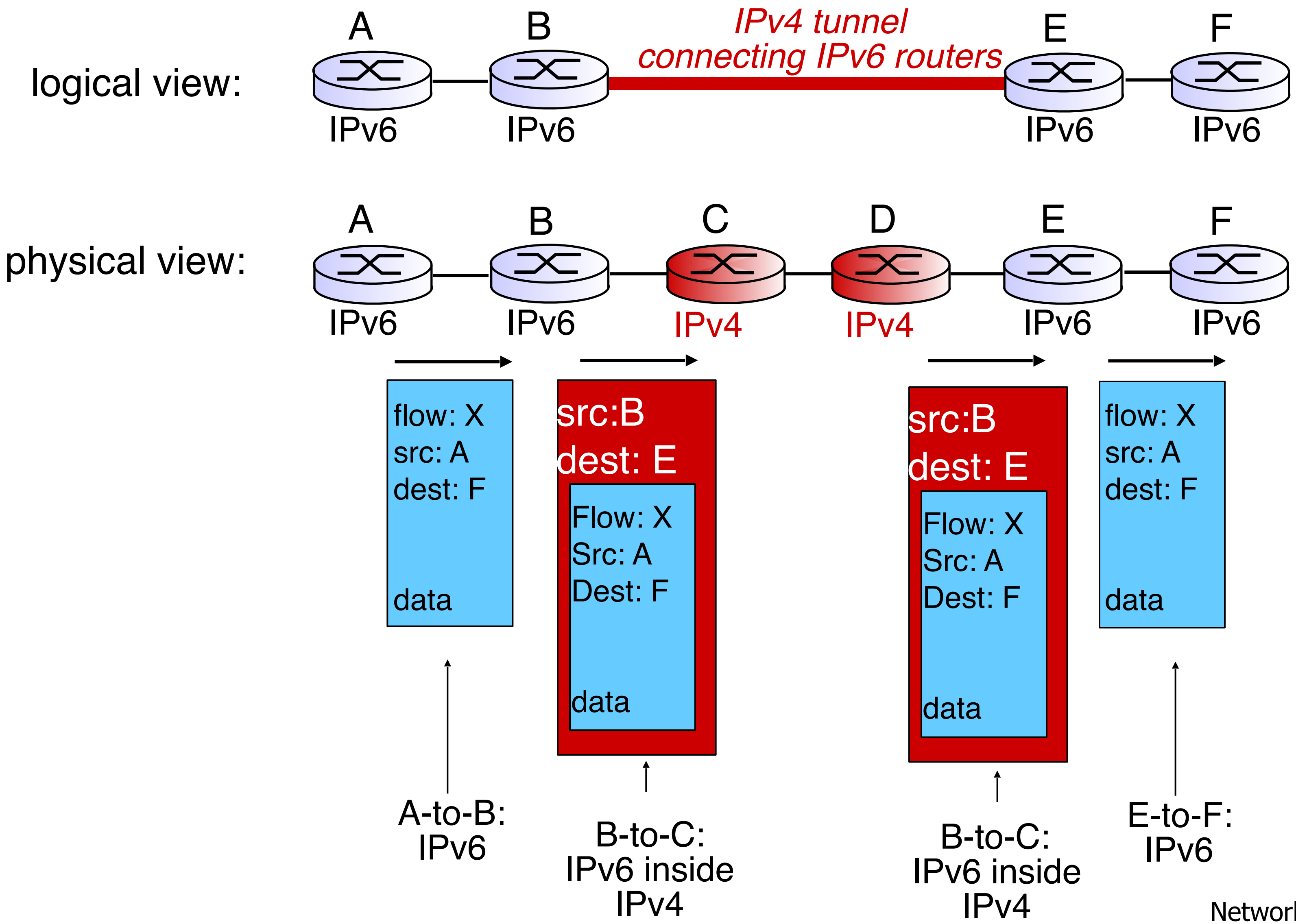
IPv6

Tunneling



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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

Routing Algorithms

- **Needed to populate forwarding tables**
- **They run in "control plane"**
  - Typically invoked in the order of 10s of seconds or whenever a change in network topology happens
  - They are much slower than forwarding algorithms that run in "control plane" at "wire speed" (micro/nano seconds)

Routing Algorithms

- **Problem solved by routing algorithms:**

Find optimal path between any two points in the network (graph)

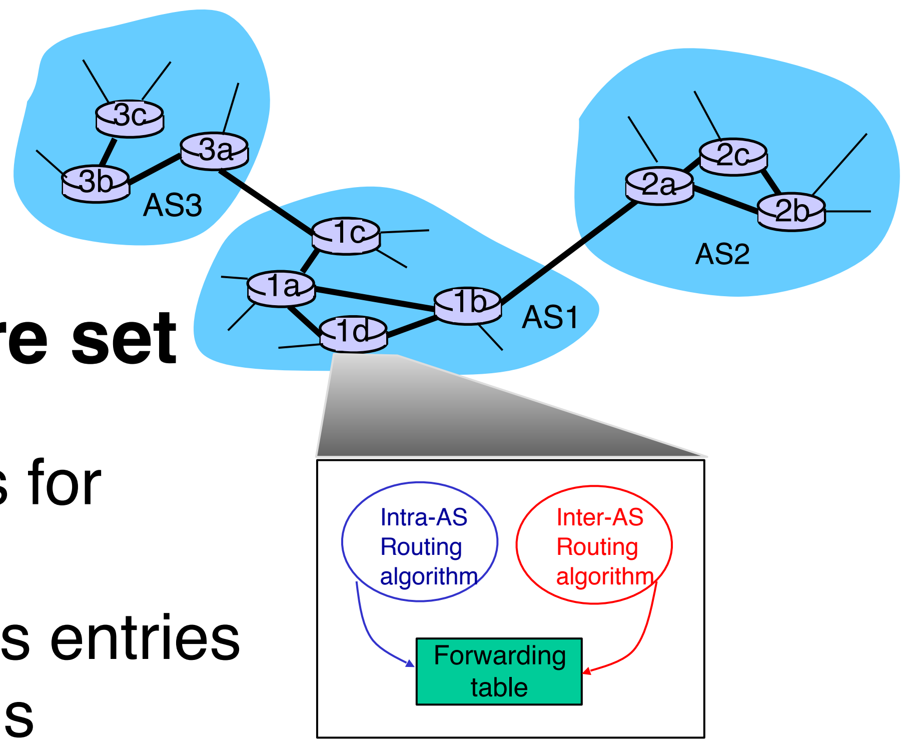
  - ➔ use graph algorithms (shortest path)

- **If Network = Internet ➔ huge graph**
  - And sub graphs (sub nets) controlled by different entities

- **How do we solve this problem?**

Hierarchical Routing

- **Solve routing problem in two levels:**
- **Intra AS (Autonomous System)**
  - **Use any algorithm, based on admin**
  - **graph algorithms**
- **Inter-ASes**
  - **Use global, standard, routing (BGP)**
- **Forwarding tables are set by both:**
  - intra-AS → sets entries for internal destinations
  - inter-AS & intra-AS sets entries for external destinations



Intra-AS Routing

- also known as *interior gateway protocols (IGP)*
- most common intra-AS routing protocols:
  - **RIP:** Routing Information Protocol
    - Distance vector, Bellman-Ford algorithm, distributed
    - Old and small networks
  - **OSPF:** Open Shortest Path First
    - Link state, Dijkstra's algorithm, centralized
    - Most current networks
  - **IGRP:** Interior Gateway Routing Protocol
    - Cisco proprietary

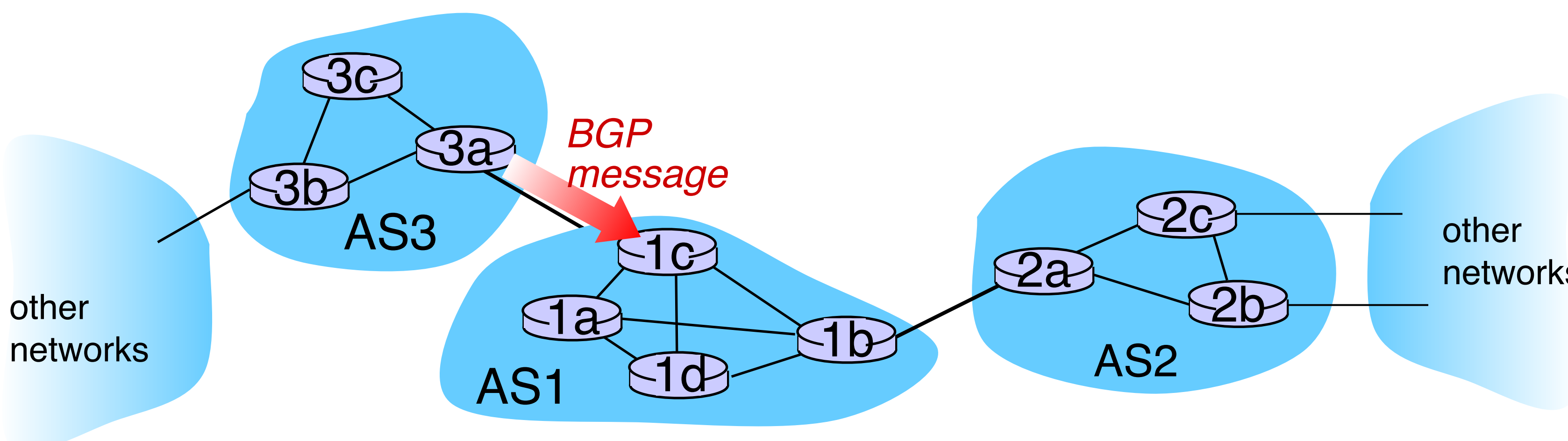
Internet inter-AS routing: BGP

- BGP (Border Gateway Protocol): *the* de facto inter-domain routing protocol
  - "glue that holds the Internet together"
- BGP provides each AS a means to:
  - eBGP: obtain subnet reachability information from neighboring ASs.
  - iBGP: propagate reachability information to all AS-internal routers.
  - determine "good" routes to other networks based on reachability information and policy.
- allows subnet to advertise its existence to rest of Internet: *"I am here"*

BGP basics

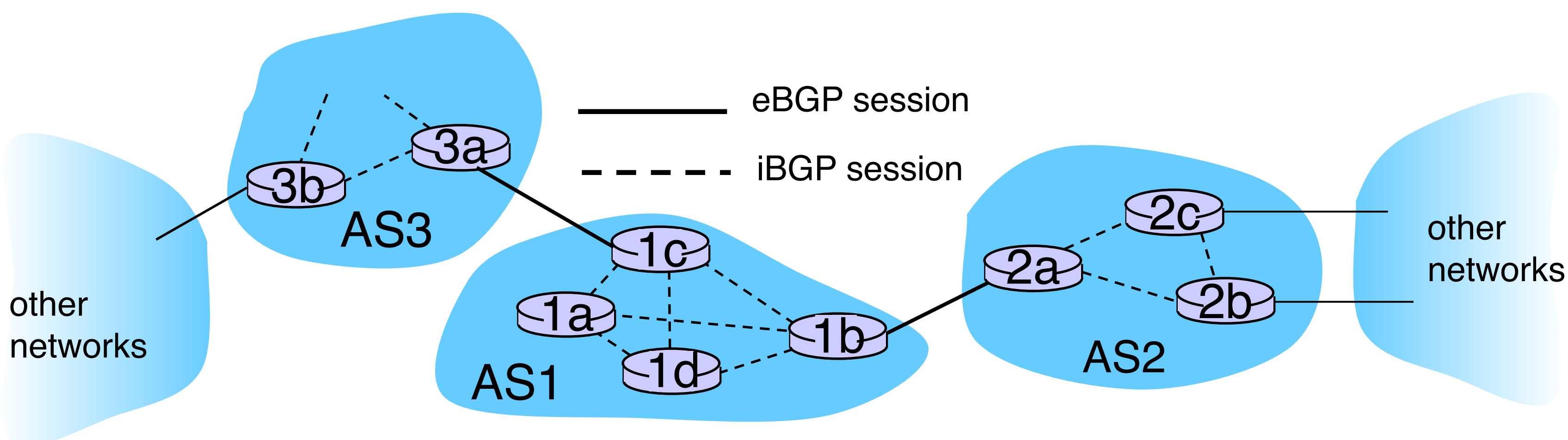
- BGP session: two BGP routers ("peers") exchange BGP messages:
  - advertising *paths* to different destination network prefixes ("path vector" protocol)
  - exchanged over semi-permanent TCP connections

- when AS3 advertises a prefix to AS1:
  - AS3 *promises* it will forward datagrams towards that prefix
  - AS3 can aggregate prefixes in its advertisement



BGP basics: distributing path information

- using eBGP session between 3a and 1c, AS3 sends prefix reachability info to AS1.
  - 1c can then use iBGP do distribute new prefix info to all routers in AS1
  - 1b can then re-advertise new reachability info to AS2 over 1b-to-2a eBGP session
- when router learns of new prefix, it creates entry for prefix in its forwarding table.



BGP route selection

- router may learn about more than 1 route to destination AS, selects route based on:
  1. local preference value attribute: policy decision
  2. shortest AS-PATH
  3. closest NEXT-HOP router: hot potato routing
  4. additional criteria

Why different Intra-, Inter-AS routing ?

policy:

- inter-AS: admin wants control over how its traffic routed, who routes through its net.
- intra-AS: single admin, so no policy decisions needed

scale:

- hierarchical routing saves table size, reduced update traffic

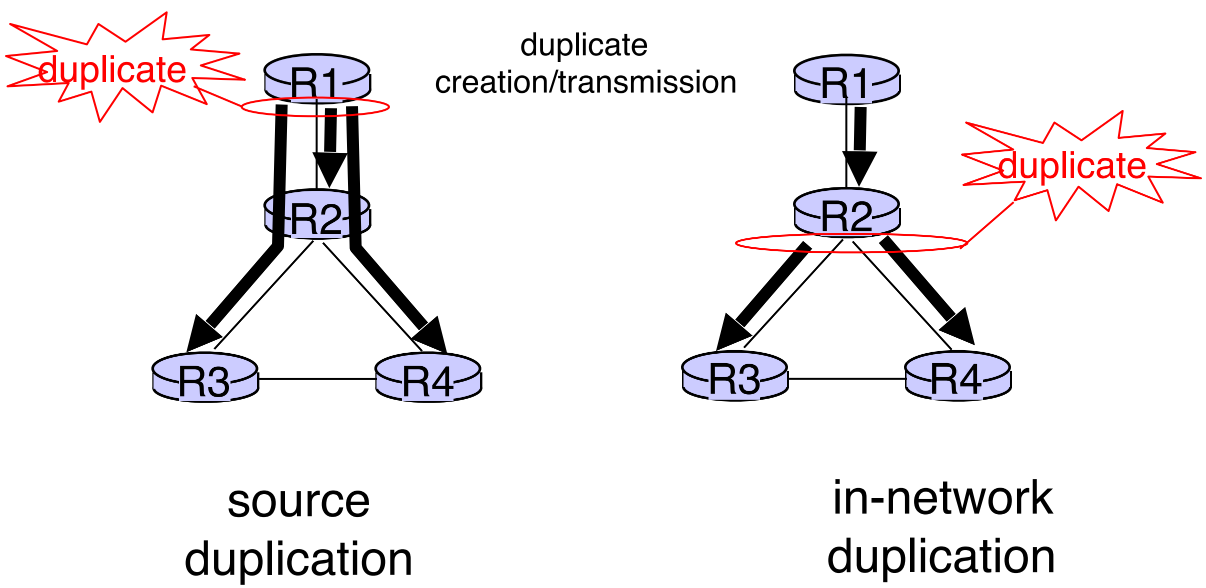
performance:

- intra-AS: can focus on performance
- inter-AS: policy may dominate over performance

Multicast/Broadcast routing

- **Broadcast: deliver packets from source to all other nodes**
- **Multicast: deliver packets to subset of nodes**

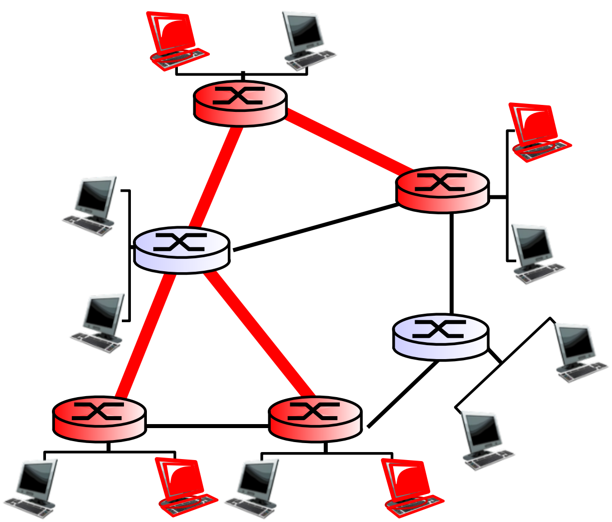
- source duplication is inefficient:



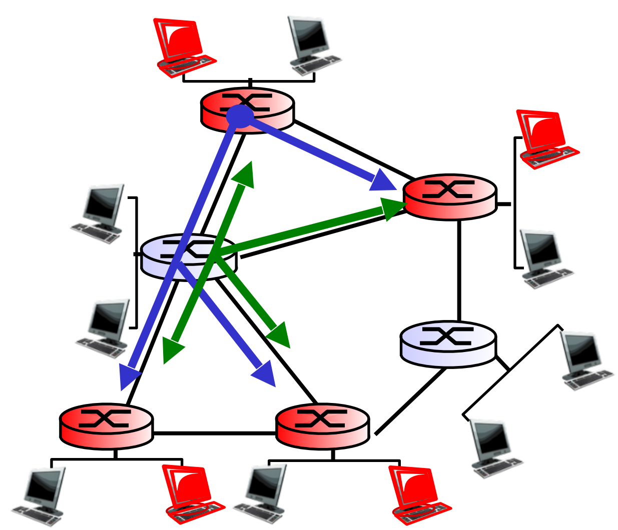
Multicast routing: problem statement

goal: find a tree (or trees) connecting routers having local mcast group members

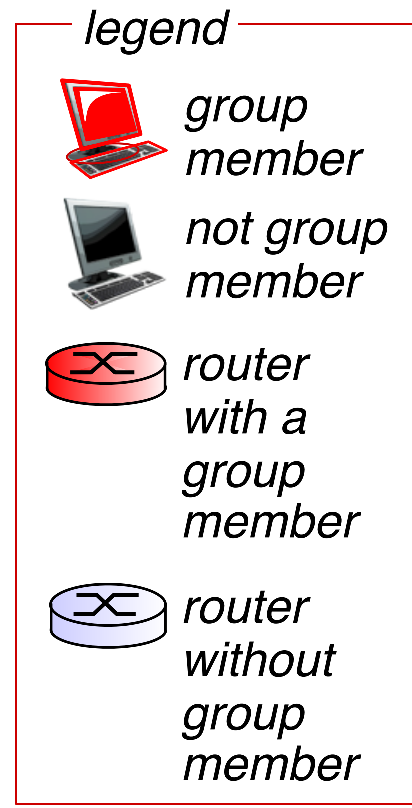
- ***Two approaches:***
- *shared-tree:* same tree used by all group members
- *source-based:* different tree from each sender to rcvrs



shared tree



source-based trees



Approaches for building mcast trees

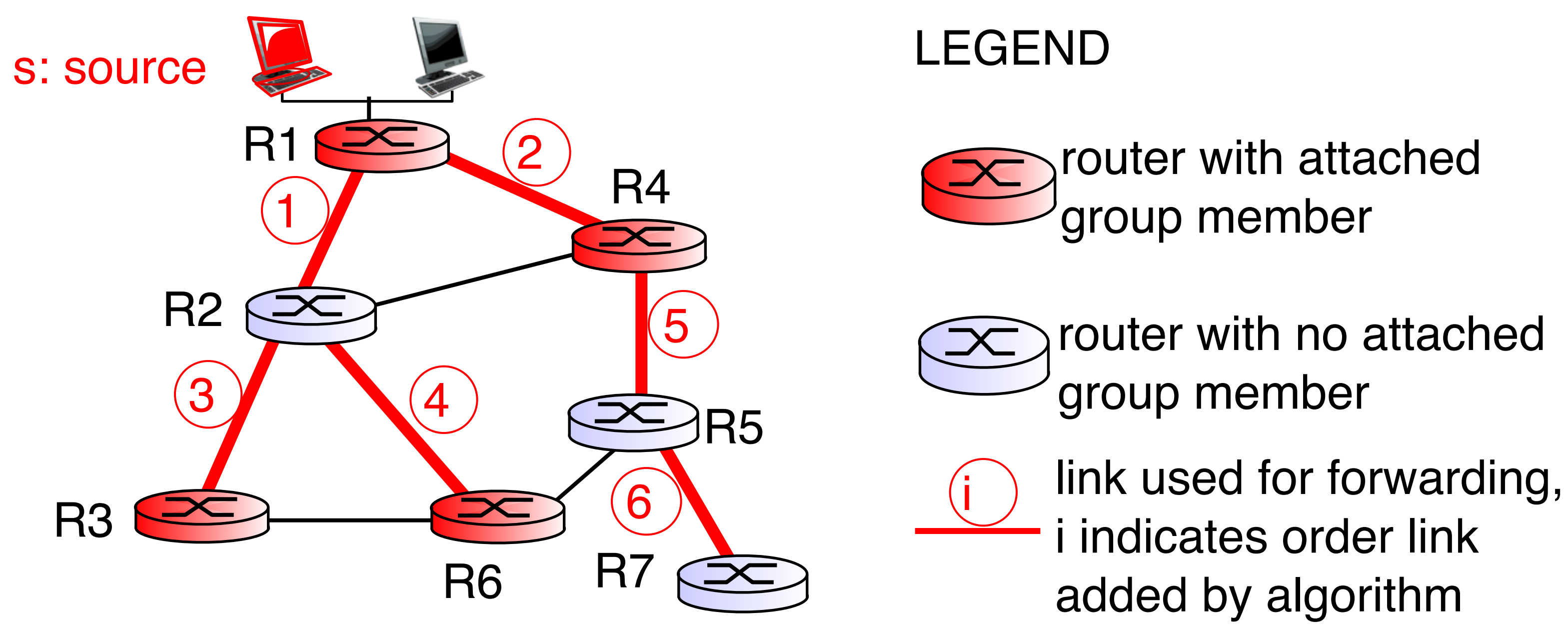
approaches:

- *source-based tree:* one tree per source
  - shortest path trees
  - reverse path forwarding
- *group-shared tree:* group uses one tree
  - minimal spanning (Steiner)
  - center-based trees

…we first look at basic approaches, then specific protocols adopting these approaches

Shortest path tree

- mcast forwarding tree: tree of shortest path routes from source to all receivers
  - Dijkstra's algorithm

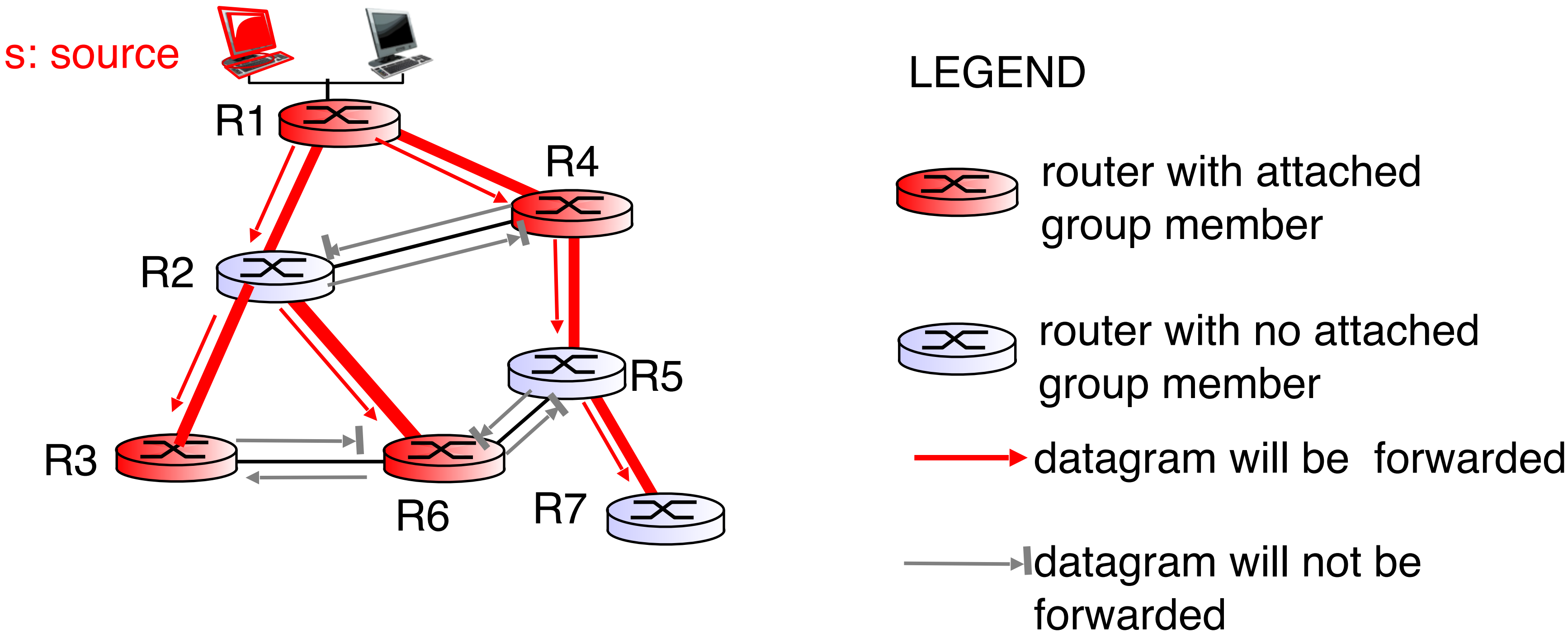


Reverse path forwarding

- rely on router's knowledge of unicast shortest path from it to sender
- each router has simple forwarding behavior:

if (mcast datagram received on incoming link on shortest path back to source)
then flood datagram onto all outgoing links
else ignore datagram

Reverse path forwarding: example

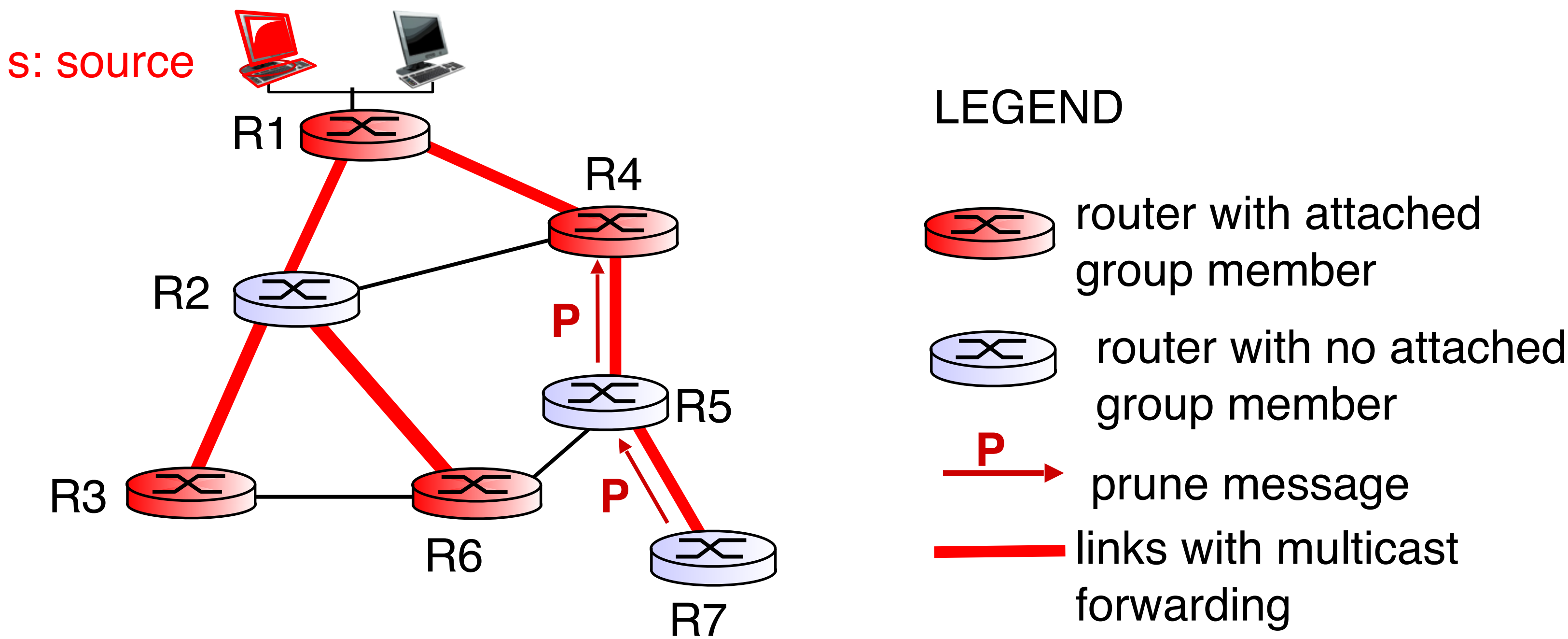


- result is a source-specific *reverse* SPT
  - may be a bad choice with asymmetric links

    (assumes shortest path R1→R2 is the same as R2→R1)

Reverse path forwarding: pruning

- forwarding tree contains subtrees with no mcast group members
  - no need to forward datagrams down subtree
  - "prune" msgs sent upstream by router with no downstream group members



Shared-tree: Steiner tree

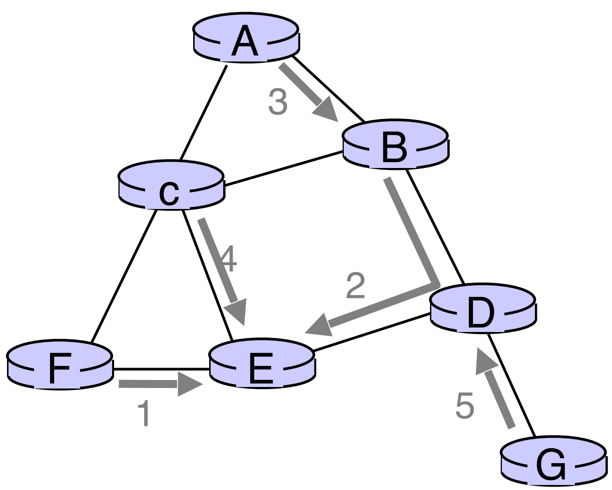
- *Steiner tree:* minimum cost tree connecting all routers with attached group members
- problem is NP-complete
- excellent heuristics exist
- not used in practice:
  - computational complexity
  - information about entire network needed
  - monolithic: rerun whenever a router needs to join/ leave

Center-based tree (Heuristic)

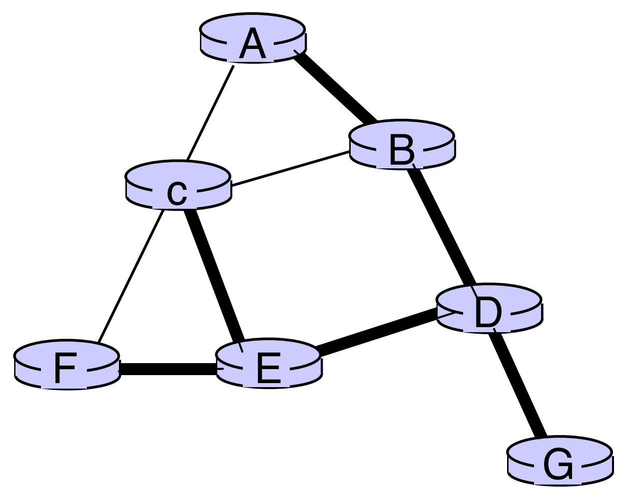
- single delivery tree shared by all
- one router identified as *"center"* of tree
- to join:
  - edge router sends unicast *join-msg* addressed to center router
  - *join-msg* "processed" by intermediate routers and forwarded towards center
  - *join-msg* either hits existing tree branch for this center, or arrives at center
  - path taken by *join-msg* becomes new branch of tree for this router

Center-based tree: example

- Chose a center node
- each node sends unicast join message to center node
  - message forwarded until it arrives at a node already belonging to spanning tree



(a) stepwise construction of spanning tree (center: E)



(b) constructed spanning tree

Internet Multicasting Routing: DVMRP

- DVMRP: distance vector multicast routing protocol, RFC1075
- *flood and prune:* reverse path forwarding, source-based tree
  - RPF tree based on DVMRP's own routing tables constructed by communicating DVMRP routers
  - no assumptions about underlying unicast
  - initial datagram to mcast group flooded everywhere via RPF
  - routers not wanting group: send upstream prune msgs

DVMRP: continued…

- *soft state:* DVMRP router periodically (1 min.) "forgets" branches:
  - mcast data again flows down unpruned branch
  - downstream router: reprune or else continue to receive data
- routers can quickly regraft to tree
  - following IGMP join at leaf
- DVMRP: commonly implemented in commercial router

PIM: Protocol Independent Multicast

- not dependent on any specific underlying unicast routing algorithm (works with all)
- two different multicast distribution scenarios :

dense:

- group members densely packed, in "close" proximity.
- bandwidth more plentiful

sparse:

- # networks with group members small wrt # interconnected networks
- group members "widely dispersed"
- bandwidth not plentiful

Consequences of sparse-dense dichotomy:

dense

- group membership by routers *assumed* until routers explicitly prune
- *data-driven* construction on mcast tree
- bandwidth and non-group-router processing *wasted*
- *Uses flood and prune RPF*

sparse:

- no membership until routers explicitly join
- *receiver- driven* construction of mcast tree
- bandwidth and non-group-router processing *conservative*
- Uses center-based tree

Summary

- **Network layer: forwarding and routing**
- **Routing: hierarchical**
  - **intra-AS: local, optimal**
  - **and Inter-AS (BGP): global, policy based**
- **Routing and protocols for Broadcast and Multicast**