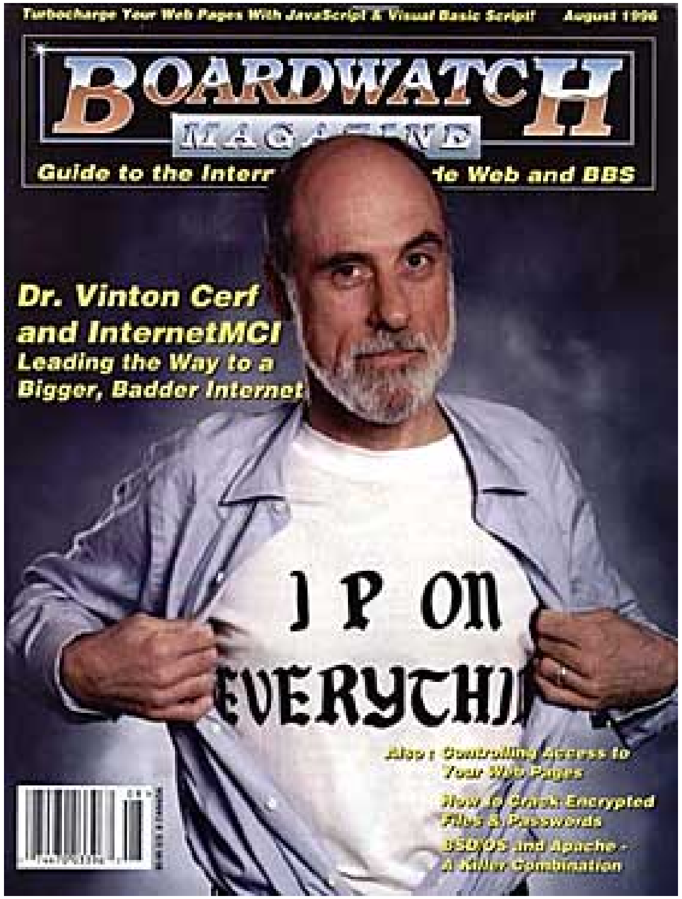
Network layer: DHCP, NAT, Tunneling & Routing

Vivek Shah

Based on slides compiled by
Marcos Vaz Salles

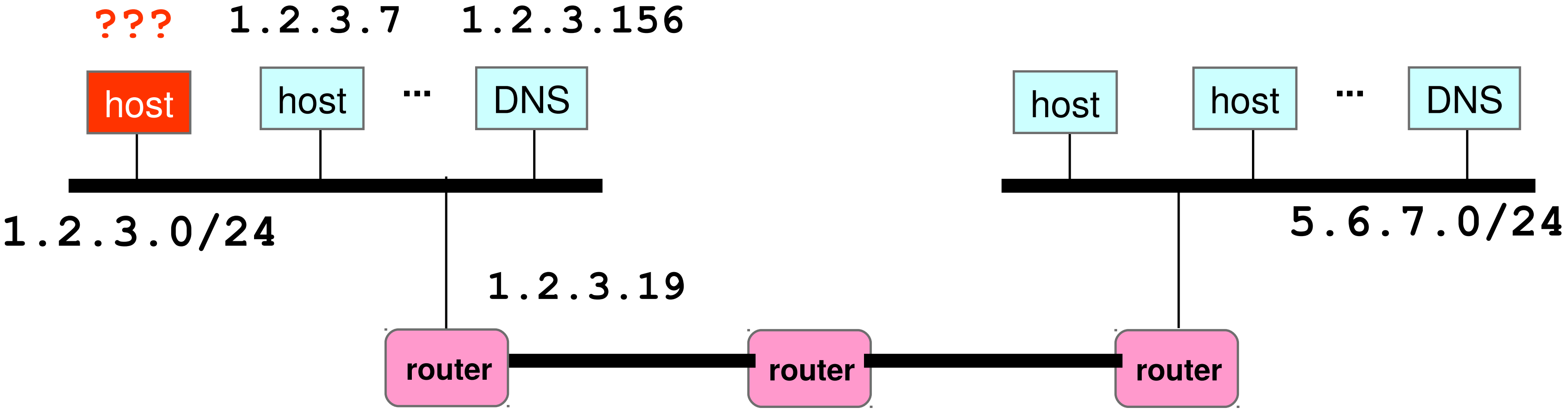


Recap: Network layer

- What is the “best effort guarantee” of network layer ?
- Why can fragmentation happen at routers ? How does IPv4 handle it ? Why does IPv6 not handle it ?
- What do forwarding tables in routers contain ? Why is longest prefix match chosen ?
- Why is an IP address hierarchical ? What is a subnet mask ?
- How are IP addresses allocated ?

How To Bootstrap an End Host?

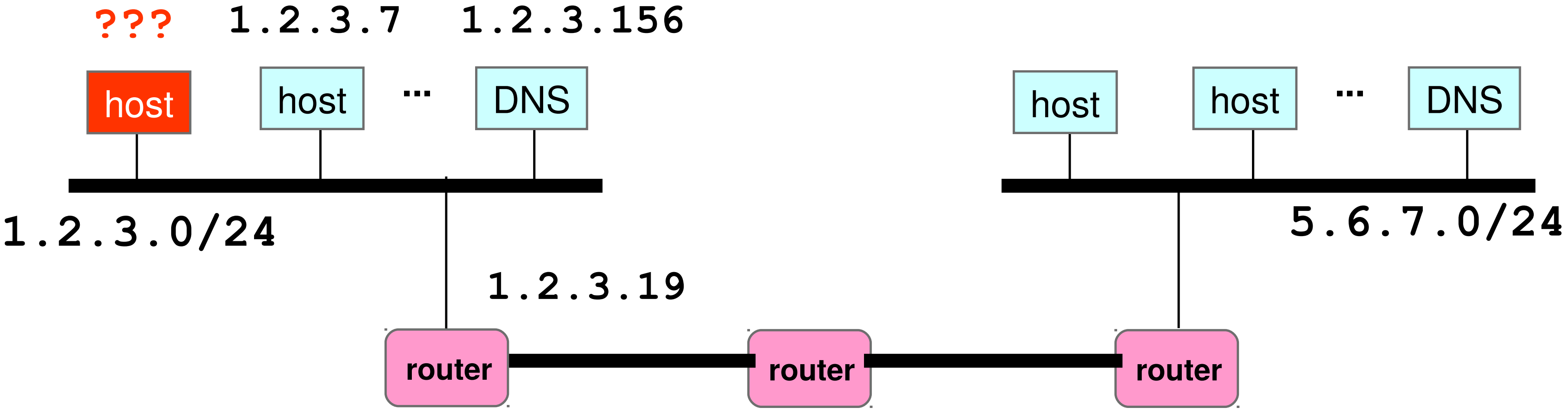
- What local Domain Name System server to use?
- What IP address the host should use?
- How to send packets to remote destinations?
- How to ensure incoming packets arrive?



Source: Freedman

Avoiding Manual Configuration

- Dynamic Host Configuration Protocol (DHCP)
  - End host learns how to send packets
  - Learn IP address, DNS servers, and gateway
- Address Resolution Protocol (ARP)
  - Others learn how to send packets to the end host
  - Learn mapping between IP address & interface address



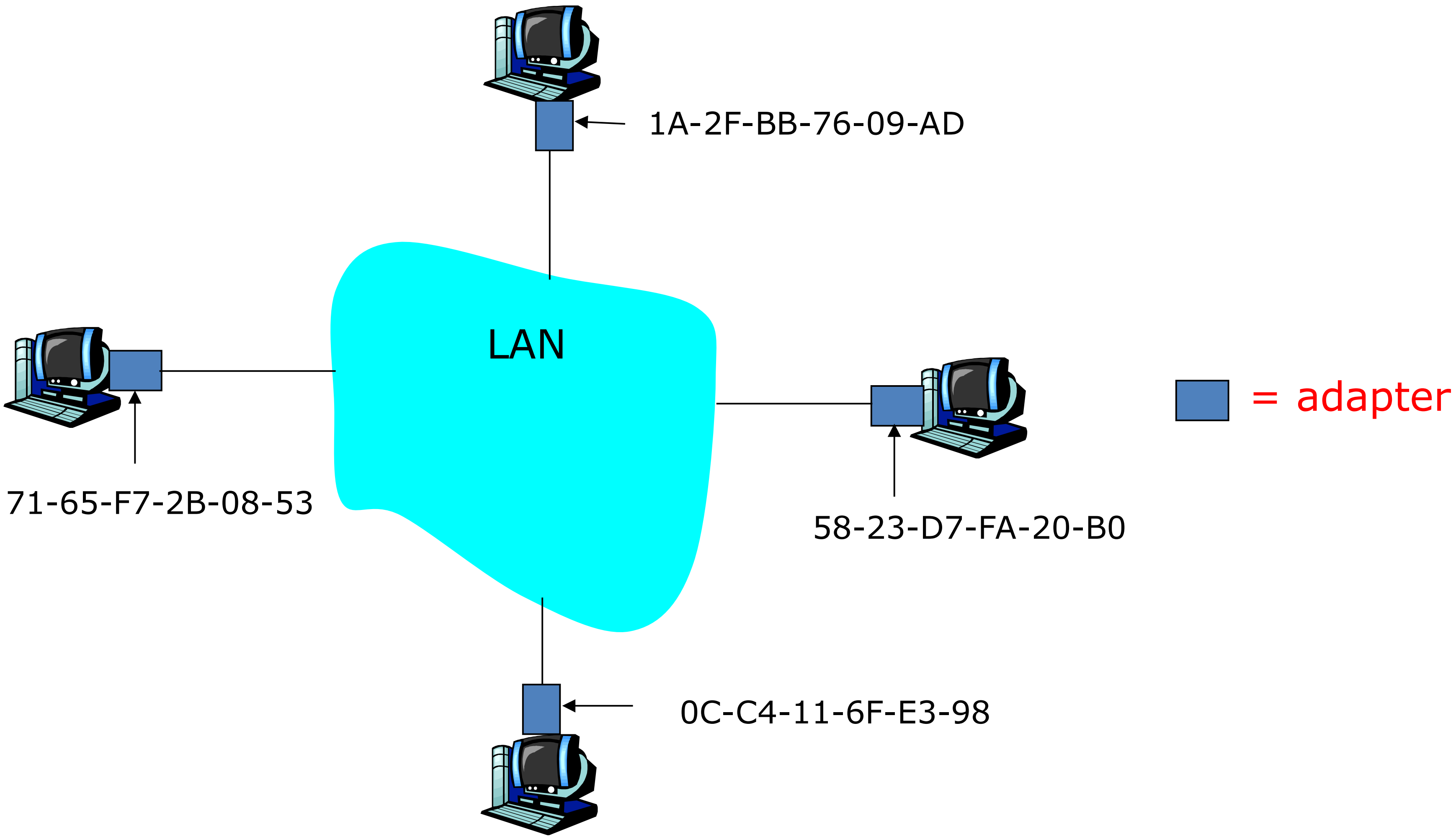
Source: Freedman

Key Ideas in Both Protocols

- **Broadcasting:** when in doubt, shout!
  - Broadcast query to all hosts in the local-area-network
  - … when you don’t know how to identify the right one
- **Caching:** remember the past for a while
  - Store the information you learn to reduce overhead
  - Remember your own address & other host’s addresses
- **Soft state:** … but eventually forget the past
  - Associate a time-to-live field with the information
  - … and either refresh or discard the information
  - Key for robustness in the face of unpredictable change

Source: Freedman

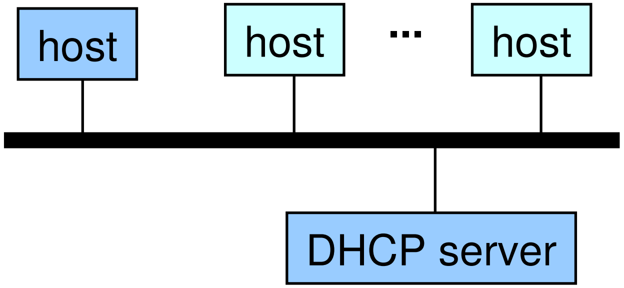
Media Access Control (MAC) Addresses



Source: Freedman

Bootstrapping Problem

- Host doesn’t have an IP address yet
  - So, host doesn’t know what source address to use
- Host doesn’t know who to ask for an IP address
  - So, host doesn’t know what destination addr to use
- Solution: shout to discover a server who can help
  - Broadcast a DHCP server-discovery message
  - Server sends a DHCP “offer” offering an address

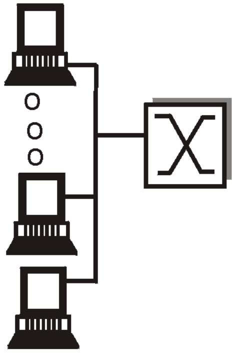


Source: Freedman

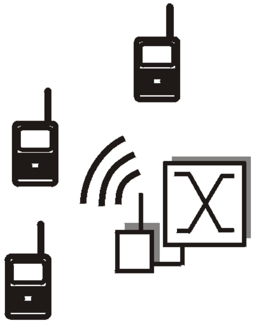
Broadcasting

- Broadcasting: sending to everyone
  - Special destination address: FF-FF-FF-FF-FF-FF
  - All adapters on the LAN receive the packet

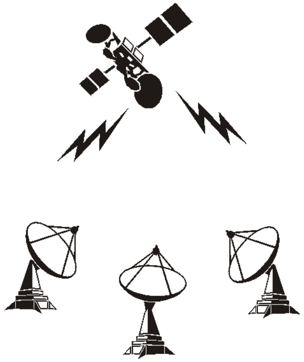
- Delivering a broadcast packet
  - Easy on a "shared media"
  - Like shouting in a room – everyone can hear you



shared wire
(e.g. Ethernet)



shared wireless
(e.g. Wavelan)



satellite

cocktail party

Source: Freedman

Response from the DHCP Server

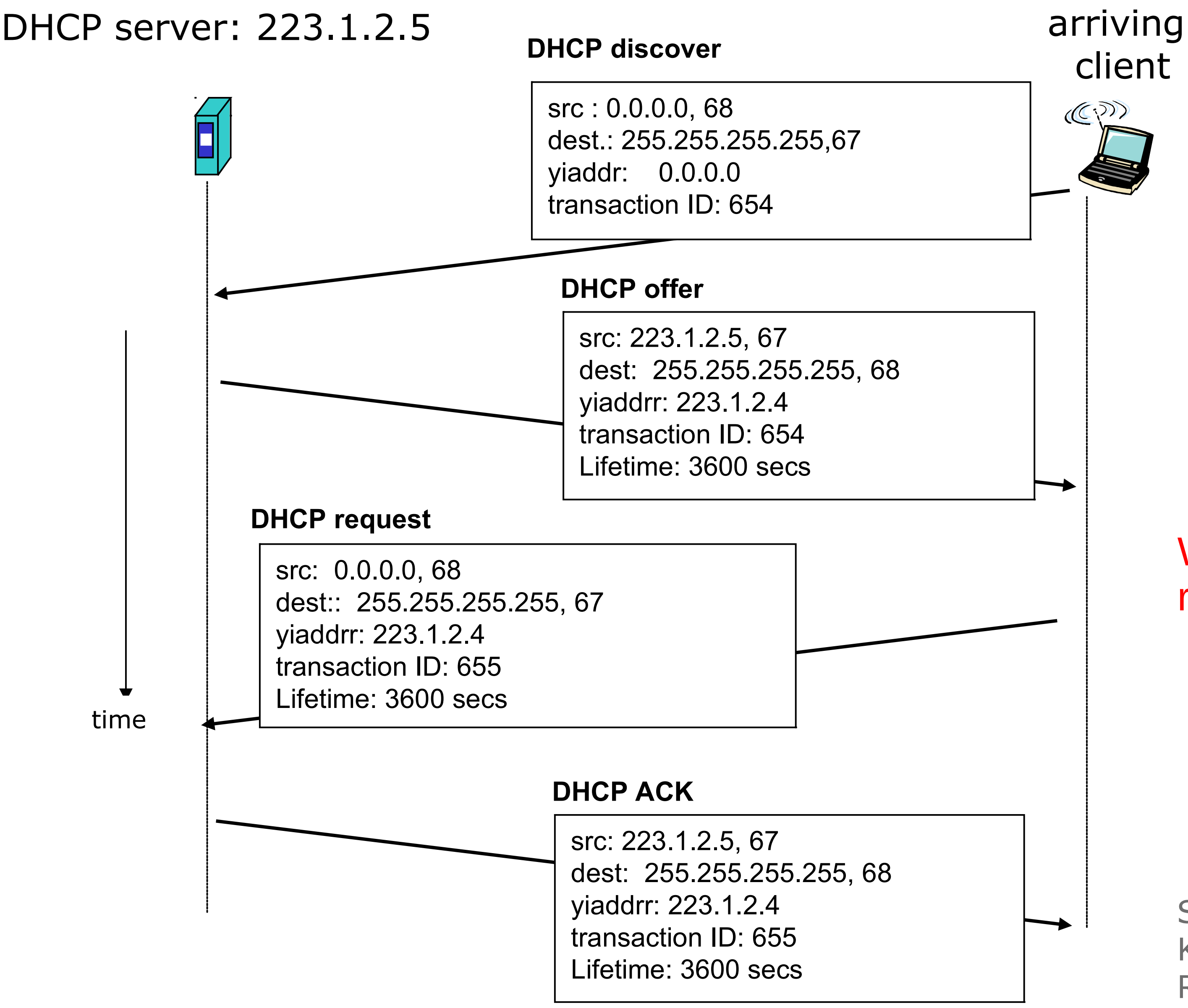
- DHCP “offer message” from the server
  - Configuration parameters (proposed IP address, mask, gateway router, DNS server, ...)
  - Lease time (the time the information remains valid)

- Multiple servers may respond
  - Multiple servers on the same broadcast media
  - Each may respond with an offer
  - The client can decide which offer to accept

- Accepting one of the offers
  - Client sends a DHCP request echoing the parameters
  - The DHCP server responds with an ACK to confirm
  - … and the other servers see they were not chosen

Source: Freedman

DHCP client-server scenario



DHCP discover

src : 0.0.0.0, 68
dest.: 255.255.255.255,67
yiaddr: 0.0.0.0
transaction ID: 654

DHCP offer

src: 223.1.2.5, 67
dest: 255.255.255.255, 68
yiaddrr: 223.1.2.4
transaction ID: 654
Lifetime: 3600 secs

DHCP request

src: 0.0.0.0, 68
dest:: 255.255.255.255, 67
yiaddrr: 223.1.2.4
transaction ID: 655
Lifetime: 3600 secs

DHCP ACK

src: 223.1.2.5, 67
dest: 255.255.255.255, 68
yiaddrr: 223.1.2.4
transaction ID: 655
Lifetime: 3600 secs

Why are DHCP request and ACK broadcast ?

Source: Kurose & Ross

Deciding What IP Address to Offer

- Server as centralized configuration database
  - All parameters are statically configured in the server
  - E.g., a dedicated IP address for each MAC address
  - Avoids complexity of configuring hosts directly
  - … while still having a permanent IP address per host

- Or, dynamic assignment of IP addresses
  - Server maintains a pool of available addresses
  - … and assigns them to hosts on demand
  - Leads to less configuration complexity
  - … and more efficient use of the pool of addresses
  - Though, it is harder to track the same host over time

Source: Freedman

Soft State: Refresh or Forget

- Why is a lease time necessary?
  - Client can release the IP address (DHCP RELEASE)
    - E.g., “ipconfig /release” at the DOS prompt
    - E.g., clean shutdown of the computer
  - But, the host might not release the address
    - E.g., the host crashes (blue screen of death!)
    - E.g., buggy client software
  - And you don’t want the address to be allocated forever

- Performance trade-offs
  - Short lease time: returns inactive addresses quickly
  - Long lease time: avoids overhead of frequent renewals

Source: Freedman

Middleboxes

- Middleboxes are intermedia
  - Interposed in-between the co
  - Often without knowledge of o
- Myriad uses
  - Network address translators
  - Firewalls
  - Tunnel endpoints
  - Traffic shapers
  - Intrusion detection systems
  - Transparent Web proxy cache
  - Application accelerators

"An abomination!"

- Violation of layering
- Hard to reason about
- Responsible for subtle bugs

"A practical necessity!"

- Solve real/pressing problems
- Needs not likely to go away

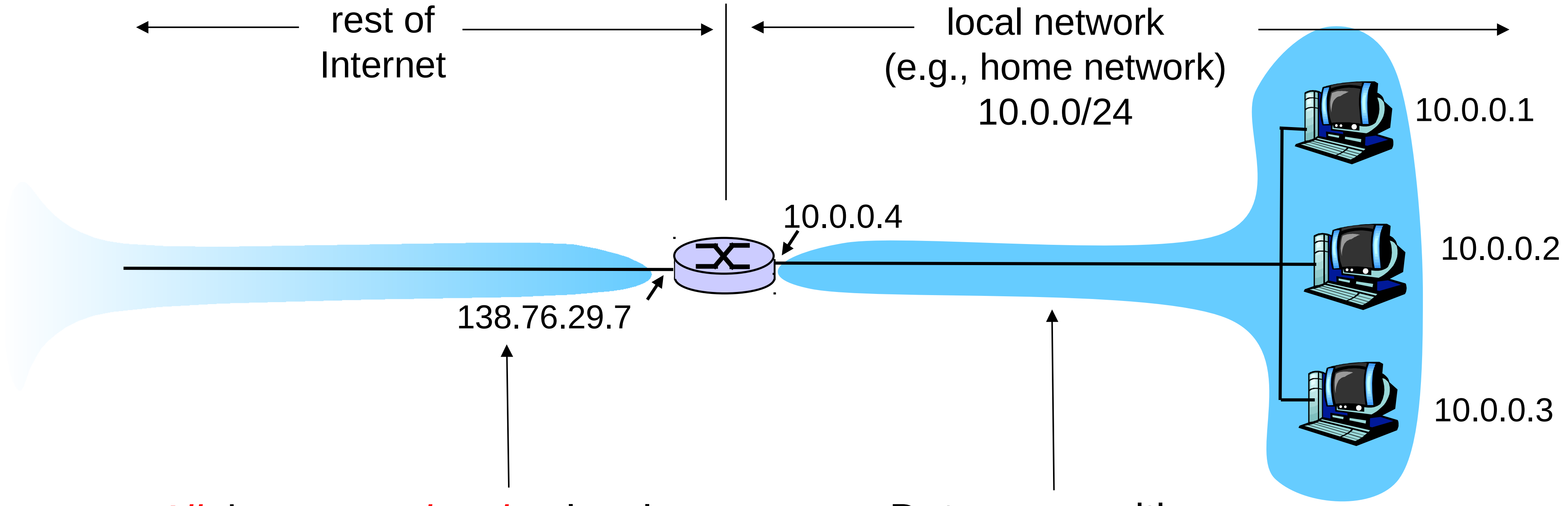
Source: Freedman

History of NATs

- IP address space depletion
  - Clear in early 90s that 2^{32} addresses not enough
  - Work began on a successor to IPv4
- In the meantime…
  - Share addresses among numerous devices
  - … without requiring changes to existing hosts
- Meant to provide short-term remedy
  - Now: NAT is widely deployed, much more than IPv6

Source: Freedman

NAT: Network Address Translation

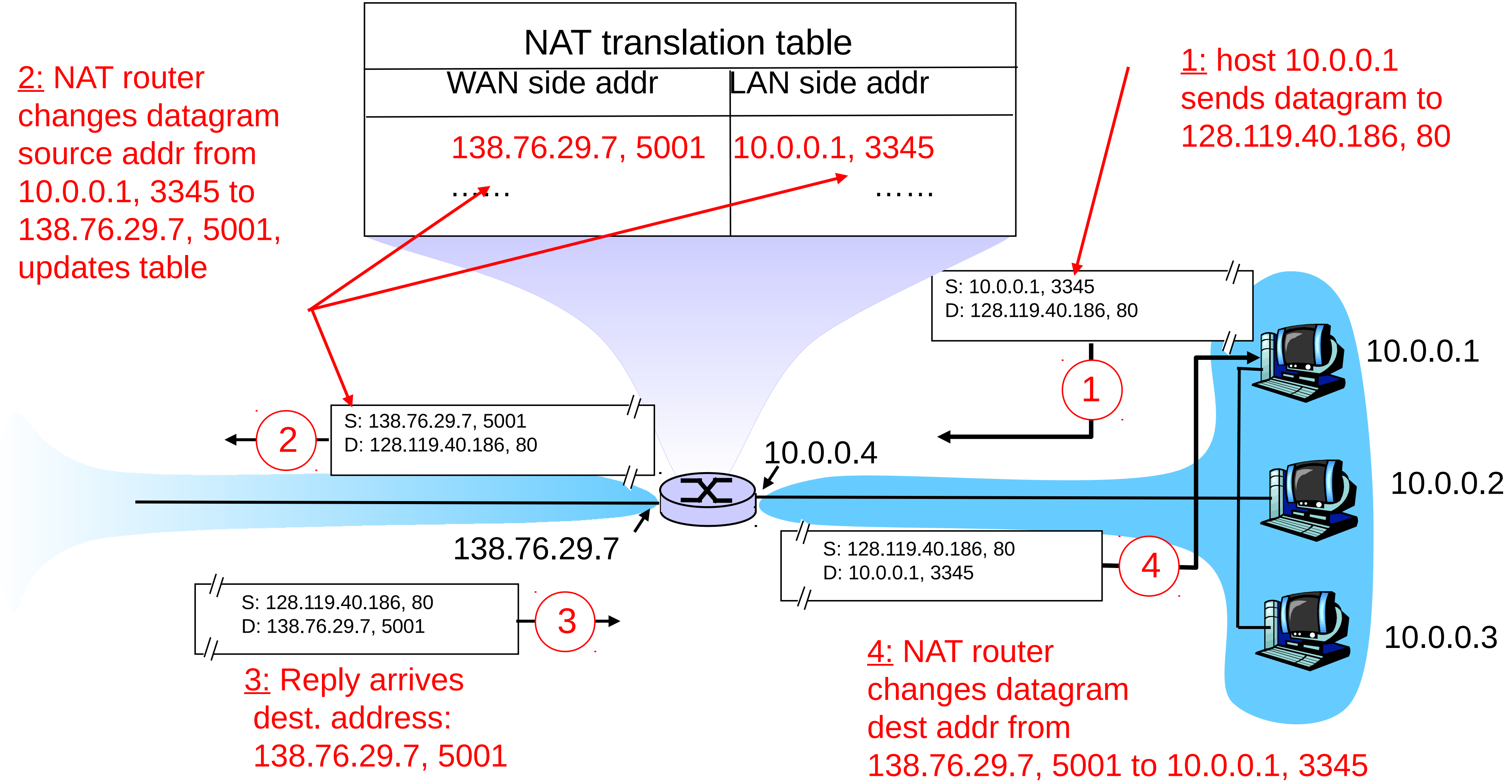


All datagrams *leaving* local network have same single source NAT IP address: 138.76.29.7, different source port numbers

Datagrams with source or destination in this network have 10.0.0/24 address for source, destination (as usual)

Source: Kurose & Ross

NAT: Network Address Translation



NAT translation table

WAN side addr	LAN side addr
138.76.29.7, 5001	10.0.0.1, 3345
……	……

1: host 10.0.0.1 sends datagram to 128.119.40.186, 80

S: 10.0.0.1, 3345
D: 128.119.40.186, 80

2: NAT router changes datagram source addr from 10.0.0.1, 3345 to 138.76.29.7, 5001, updates table

S: 138.76.29.7, 5001
D: 128.119.40.186, 80

S: 128.119.40.186, 80
D: 138.76.29.7, 5001

3: Reply arrives dest. address: 138.76.29.7, 5001

S: 128.119.40.186, 80
D: 10.0.0.1, 3345

4: NAT router changes datagram dest addr from 138.76.29.7, 5001 to 10.0.0.1, 3345

Source: Kurose & Ross

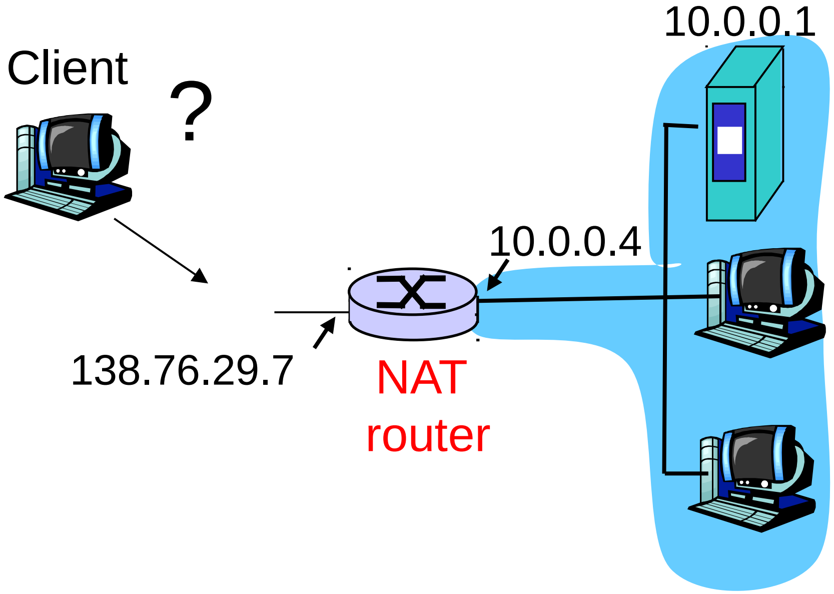
Maintaining the Mapping Table

- Create an entry upon seeing an outgoing packet
  - Packet with new (source addr, source port) pair
- Eventually, need to delete entries to free up #'s
  - When? If no packets arrive before a timeout
  - (At risk of disrupting a temporarily idle connection)
- Yet another example of "soft state"
  - I.e., removing state if not refreshed for a while

Source: Freedman

NAT Traversal Problem

- client wants to connect to server with address 10.0.0.1
  - server address 10.0.0.1 local to LAN (client can’t use it as destination addr)
  - only one externally visible NATed address: 138.76.29.7



- How can we deal with incoming connections?
- How do we map to multiple services inside the NAT’ed subnet?

Source: Kurose & Ross (partial)

Where is NAT Implemented?

- Home router (e.g., Linksys box)
  - Integrates router, DHCP server, NAT, etc.
  - Use single IP address from the service provider

- Campus or corporate network
  - NAT at the connection to the Internet
  - Share a collection of public IP addresses
  - Avoid complexity of renumbering hosts/routers when changing ISP (w/ provider-allocated IP prefix)

Source: Freedman

NAT limitations and criticism

- 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, e.g., P2P applications
    - address shortage should instead be solved by IPv6

Source: Kurose & Ross (partial)

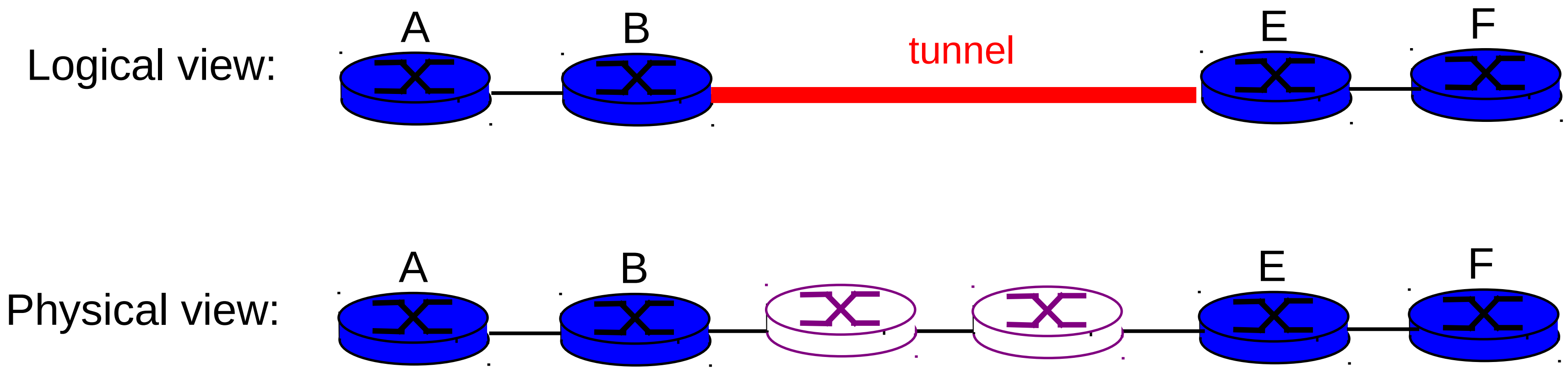
Transition From IPv4 To IPv6

- 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

Source: Kurose & Ross

IP Tunneling to Build Overlay Links

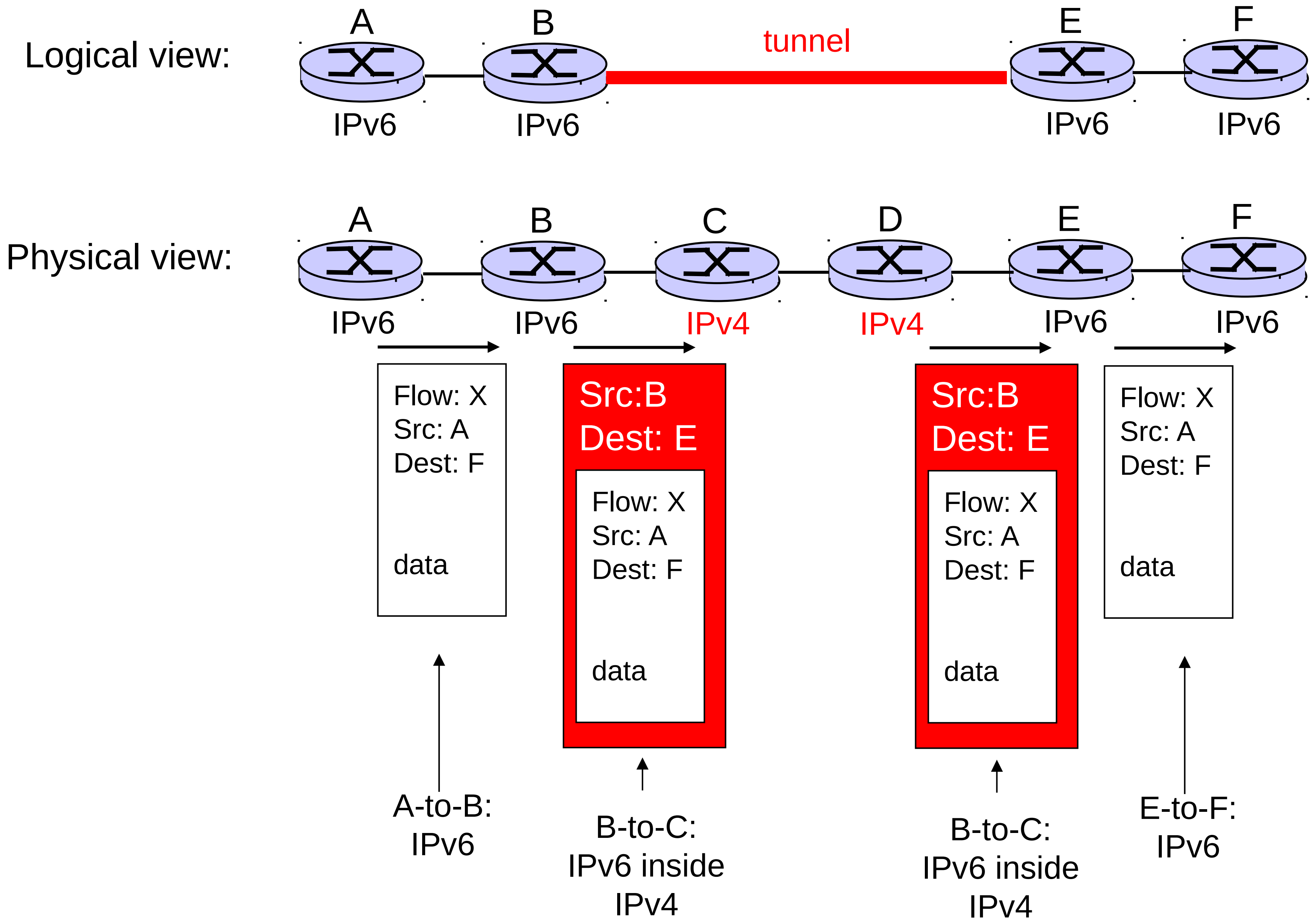
- IP tunnel is a virtual point-to-point link
  - Illusion of a direct link between two separated nodes



- Encapsulation of the packet inside an IP datagram
  - Node B sends a packet to node E
  - … containing another packet as the payload

Source: Freedman

IP Tunneling



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

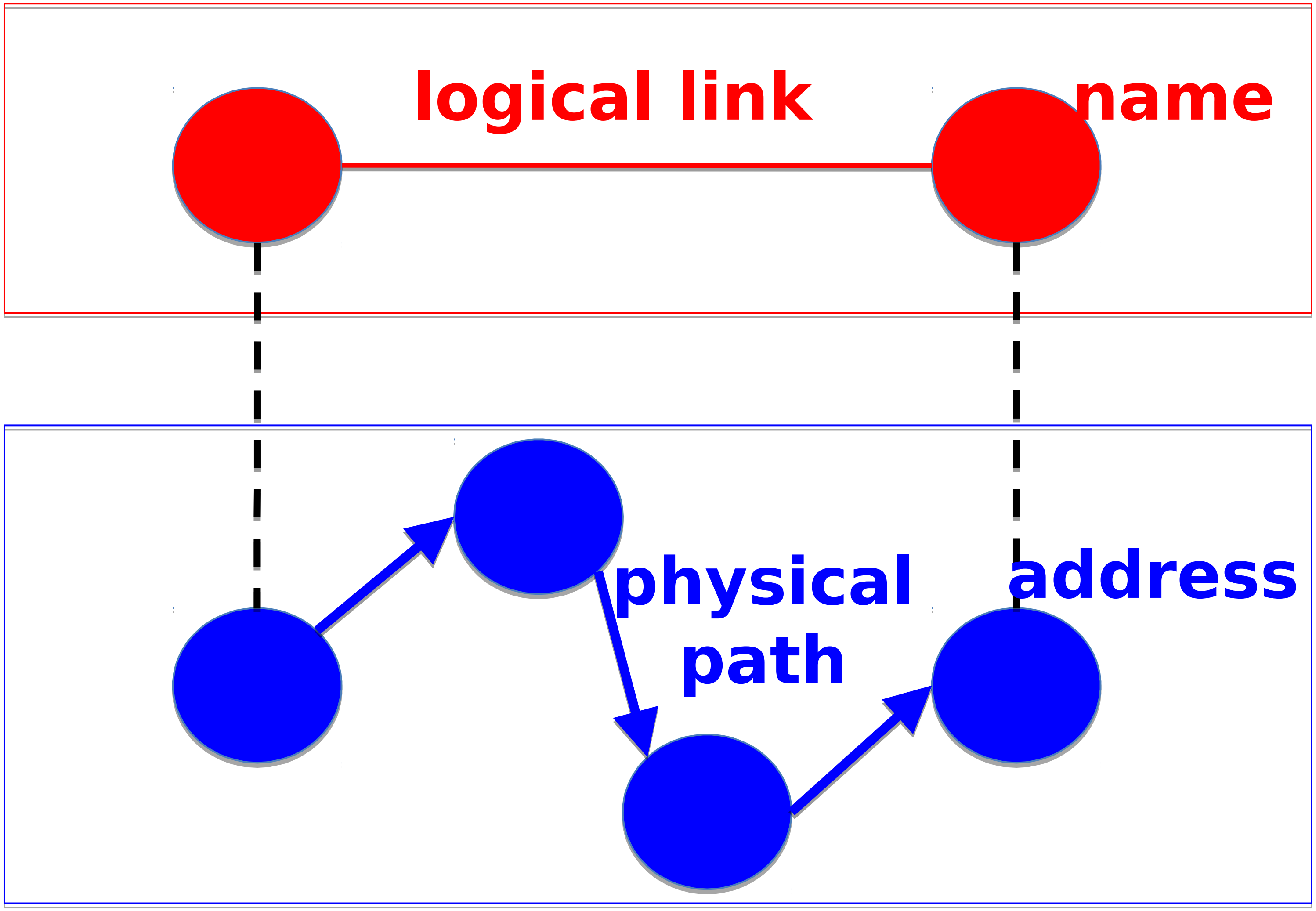
B-to-C:
IPv6 inside
IPv4

B-to-C:
IPv6 inside
IPv4

E-to-F:
IPv6

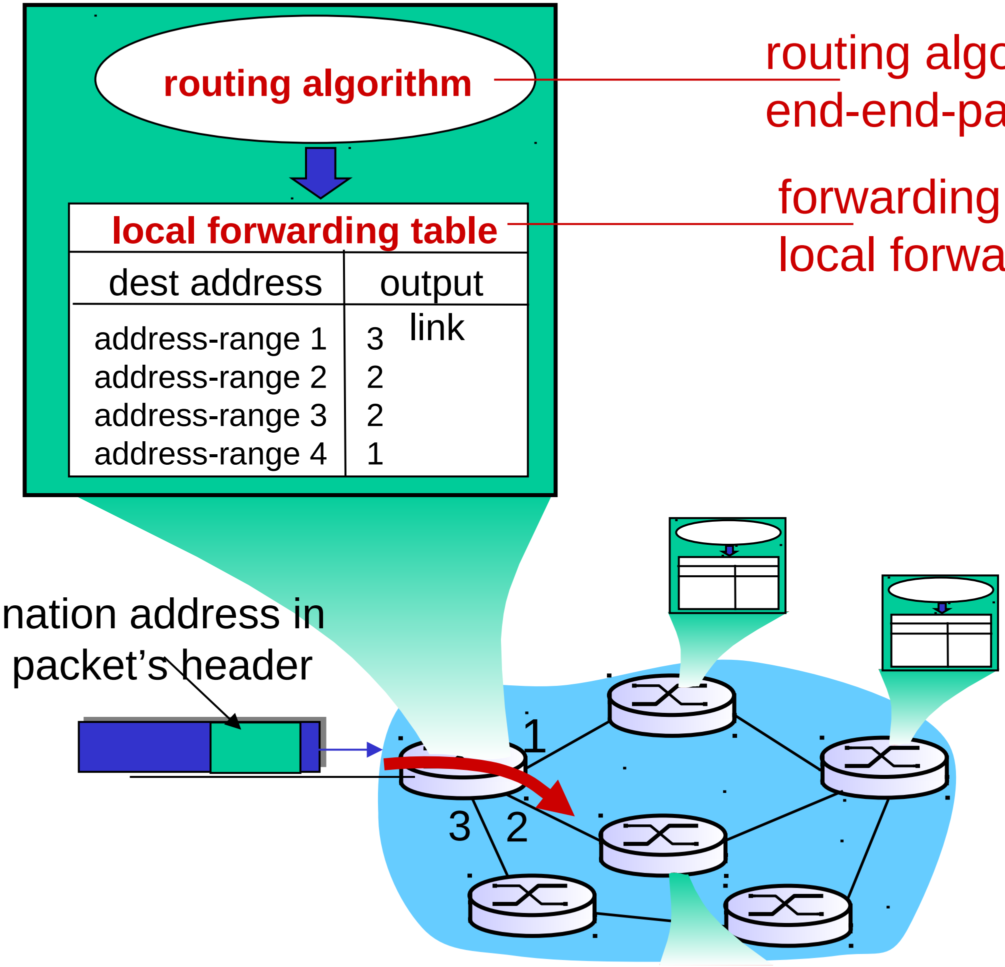
Source:
Kurose
& Ross

Routing: Mapping Link to Path



Source: Freedman

Interplay of routing and forwarding



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

routing algorithm determines end-end-path through network

forwarding table determines local forwarding at this router

IP destination address in arriving packet’s header

Source: Kurose & Ross

Three Issues to Address

- What does the protocol compute?
  - E.g., shortest paths
- What algorithm does the protocol run?
  - E.g., link-state routing
- How do routers learn end-host locations?
  - E.g., injecting into the routing protocol

Source: Freedman

Routing Algorithm Classification

Q: global or decentralized information?

global:

- all routers have complete topology, link cost info
- "link state" algorithms

decentralized:

- router knows physically-connected neighbors, link costs to neighbors
- iterative process of computation, exchange of info with neighbors
- "distance vector" algorithms

Q: static or dynamic?

static:

- routes change slowly over time

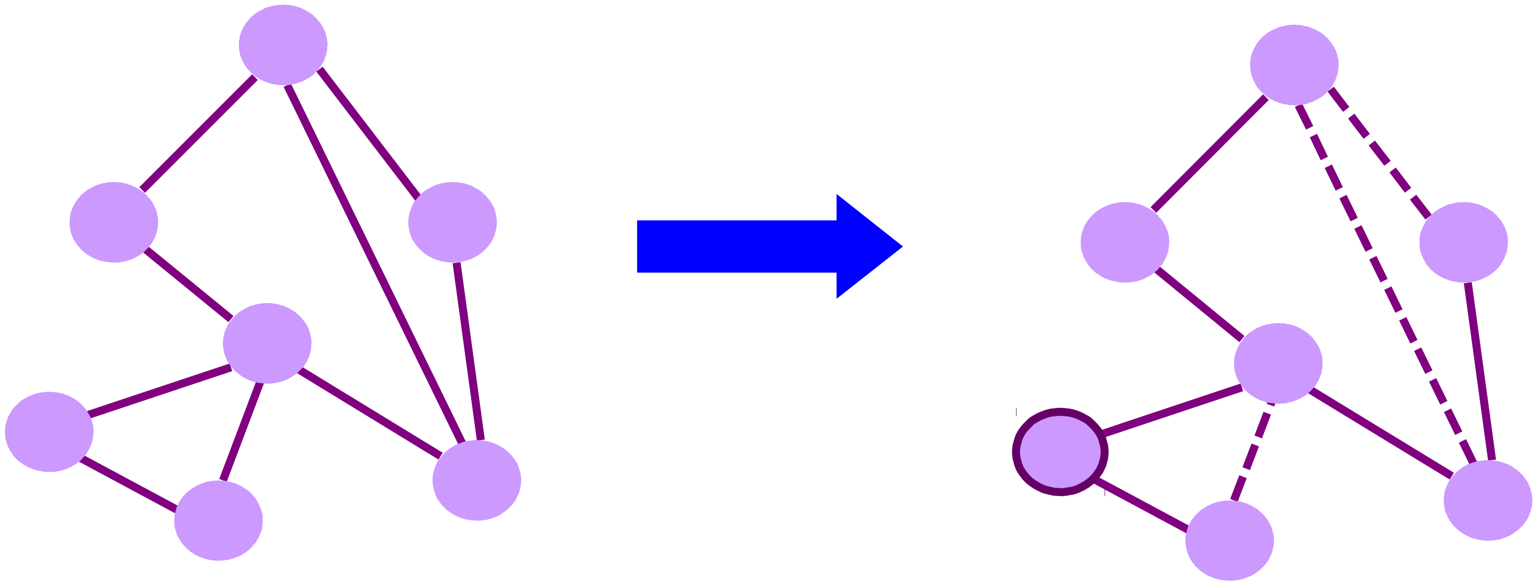
dynamic:

- routes change more quickly
  - periodic update
  - in response to link cost changes

Source: Kurose & Ross

What to Compute ?

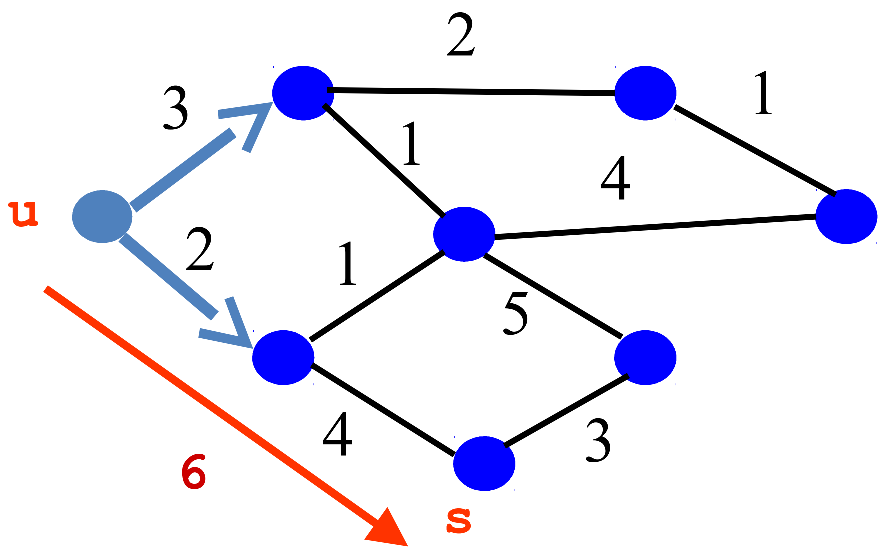
- Shortest path(s) between pairs of nodes
  - A shortest-path tree rooted at each node
  - Min hop count or min sum of edge weights



Source: Freedman

Shortest Path Problem

- Compute: *path costs* to all nodes
  - From a given source u to all other nodes
  - Cost of the path through each outgoing link
  - Next hop along the least-cost path to s



Source: Freedman

Link State : Dijkstra’s Algorithm

- Flood the topology information to all nodes
- Each node computes shortest paths to other nodes

Initialization

```
S = {u}
for all nodes v
   if (v is adjacent to u)
      D(v) = c(u,v)
   else D(v) = ∞
```

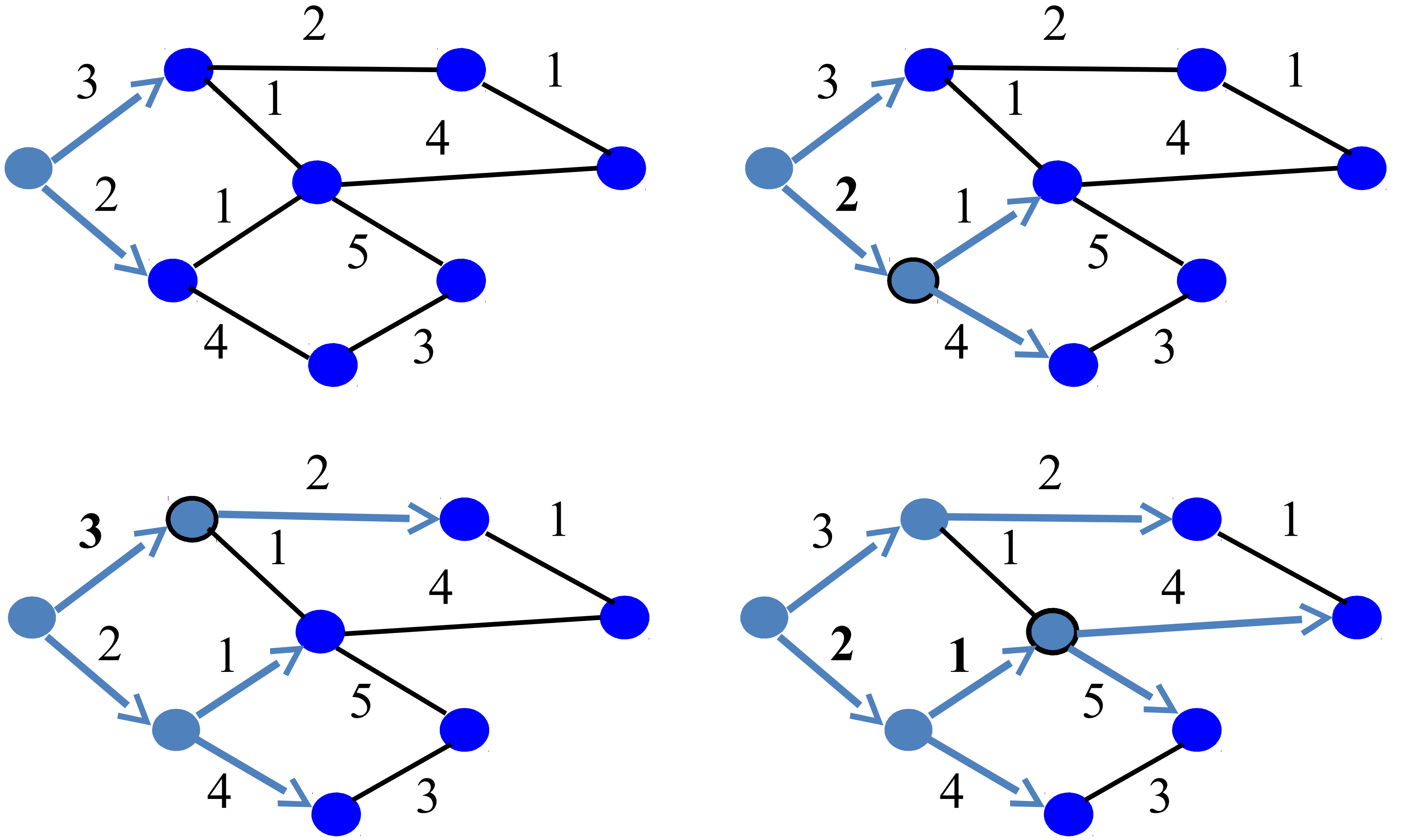
Loop

```
add w with smallest D(w) to S
update D(v) for all adjacent v:
    D(v) = min{D(v), D(w) + c(w,v)}
until all nodes are in S
```

Used in OSPF and IS-IS

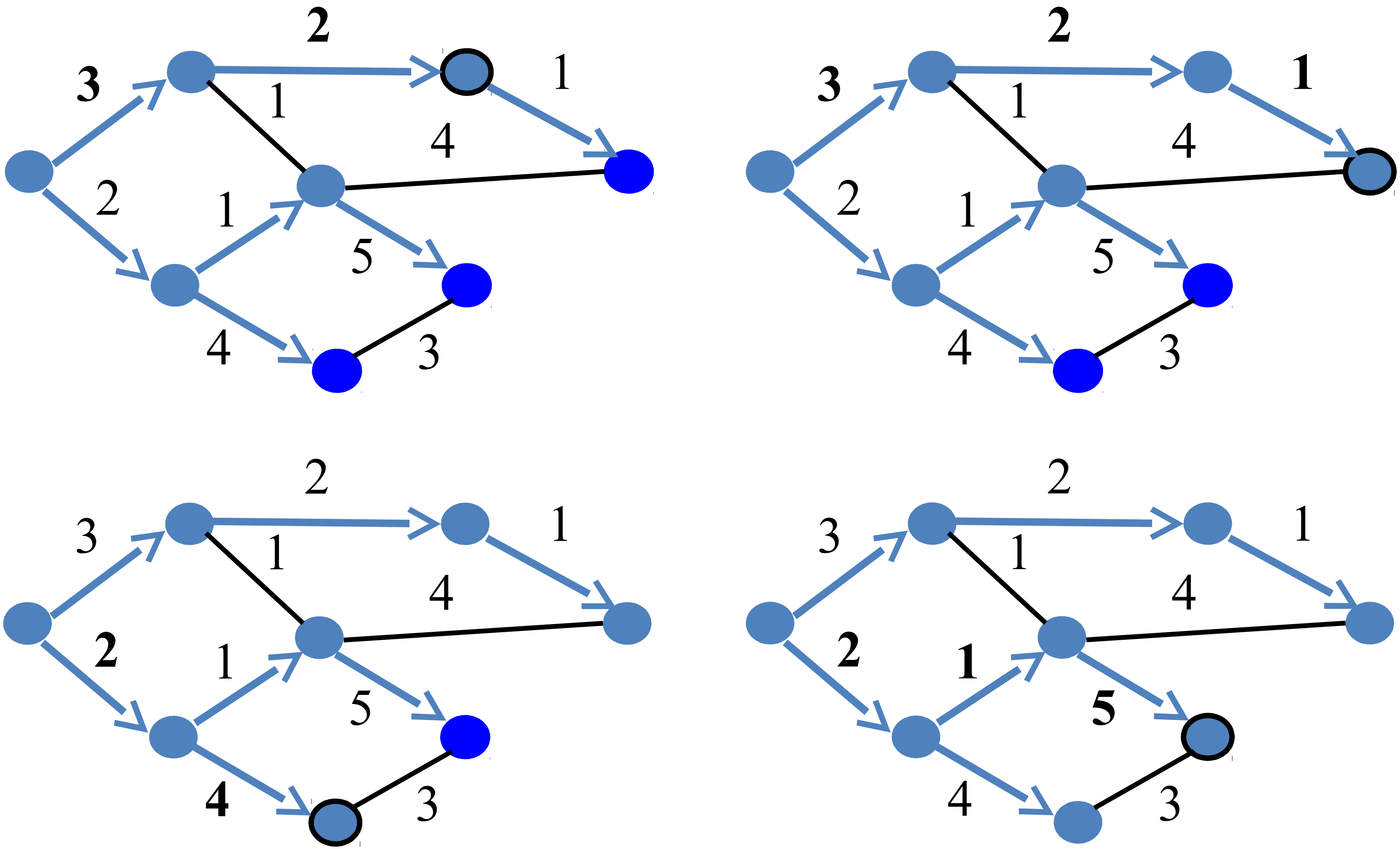
Source: Freedman

Link State : Routing Example



Source: Freedman

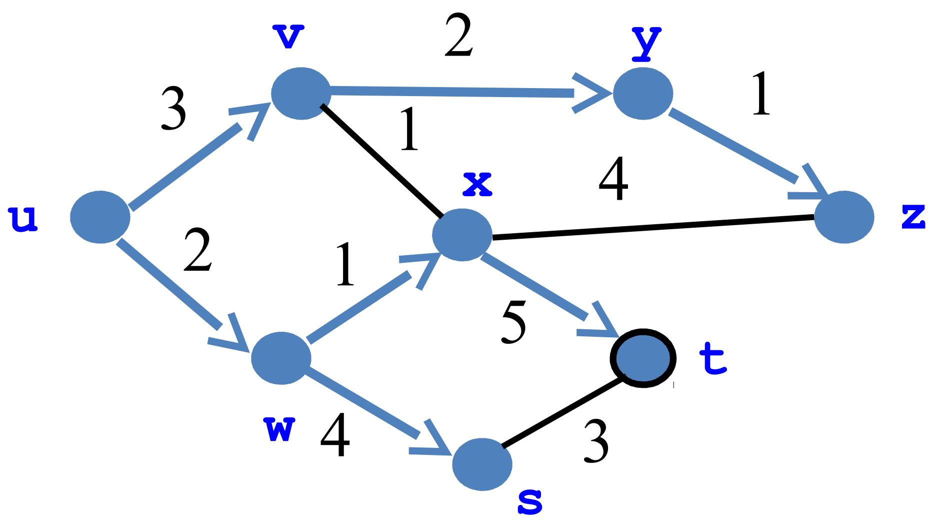
Link State : Routing Example (contd.)



Source: Freedman

Link State : Routing Example (contd.)

- Shortest-path tree from u
- Forwarding table at u



dest	link
v	(u,v)
w	(u,w)
x	(u,w)
y	(u,v)
z	(u,v)
s	(u,w)
t	(u,w)

Source: Freedman

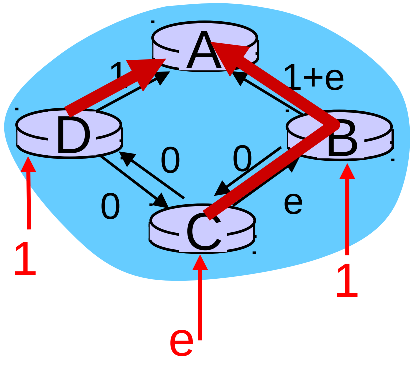
Link State Algorithm Discussion

algorithm complexity: n nodes

- each iteration: need to check all nodes, w, not in N
- n(n+1)/2 comparisons: $O(n^2)$
- more efficient implementations possible: O(nlogn)

oscillations possible:

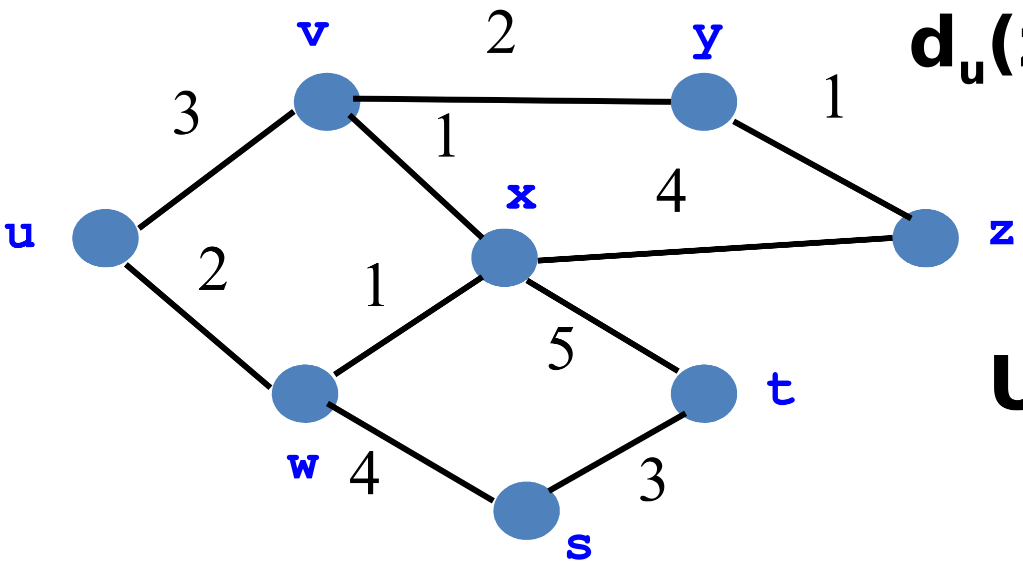
- e.g., support link cost equals amount of carried traffic:



Source: Kurose & Ross

Distance Vector : Bellman Ford Algorithm

- Define distances at each node x
  - $d_x(y)$ = cost of least-cost path from x to y
- Update distances based on neighbors
  - $d_x(y) = \min \{c(x,v) + d_v(y)\}$ over all neighbors v

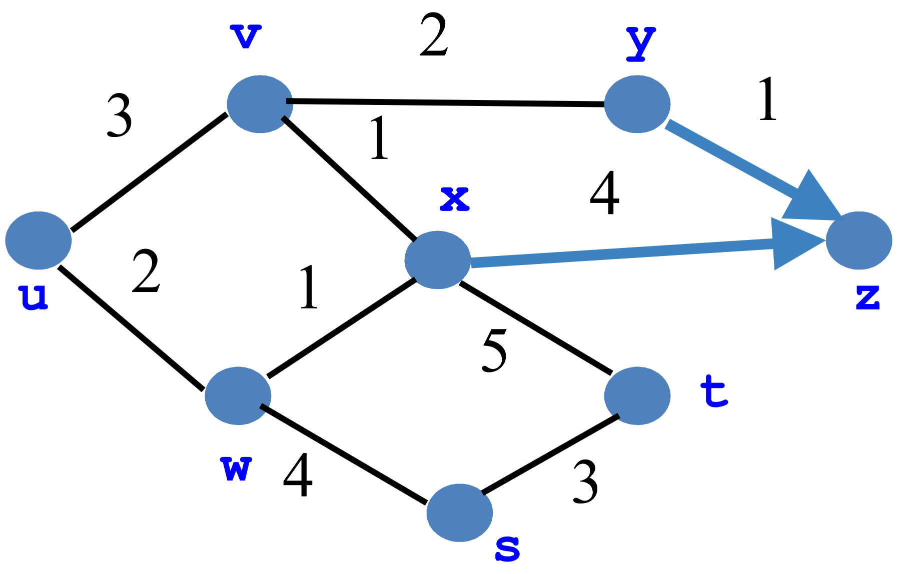


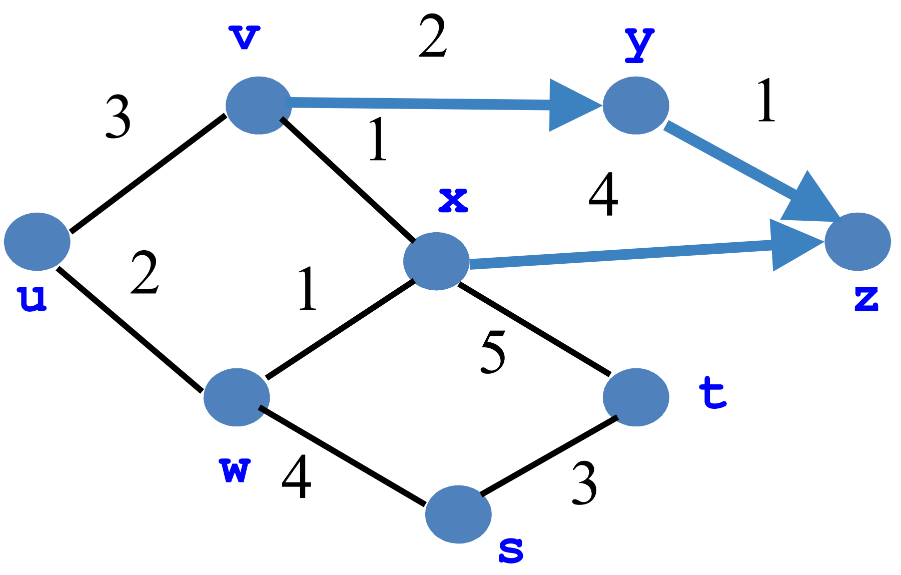
$$d_u(z) = \min\{\, c(u,v) + d_v(z),\ c(u,w) + d_w(z)\}$$

Used in RIP and EIGRP

Source: Freedman

Distance Vector : Routing Example





$d_y(z) = 1$

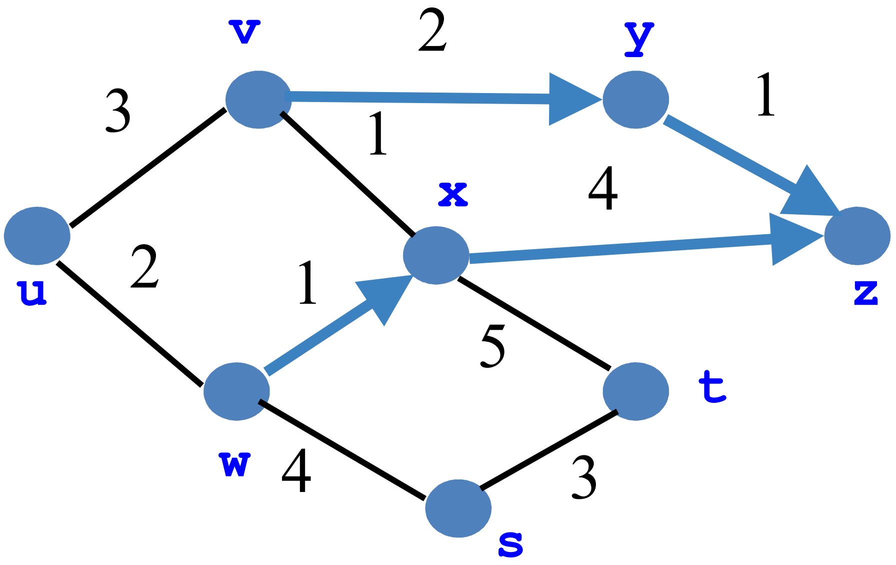
$d_x(z) = 4$

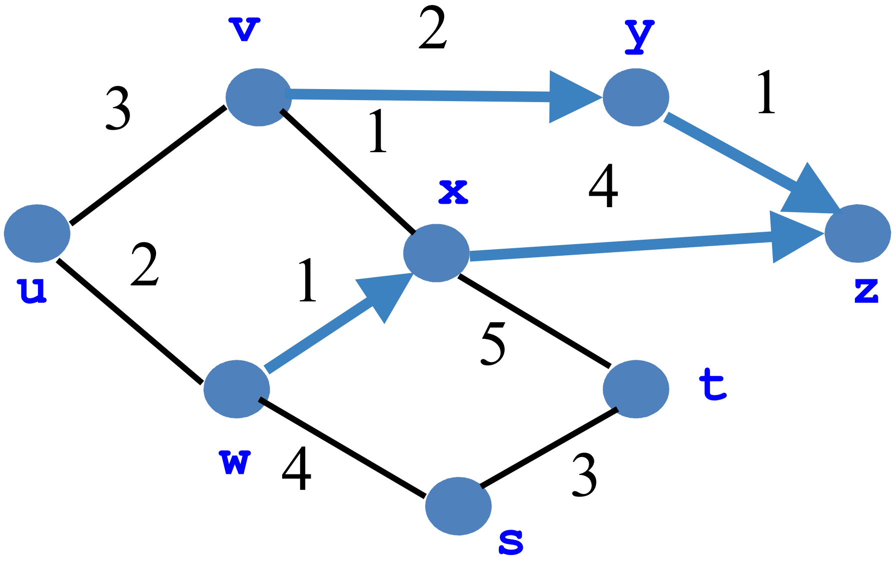
$d_v(z) = \min\{ 2+d_y(z), 1+d_x(z) \}$

$= 3$

Source: Freedman

Distance Vector : Routing Example (contd.)





$$d_w(z) = \min\{1+d_x(z),\ 4+d_s(z),\ 2+d_u(z)\}$$

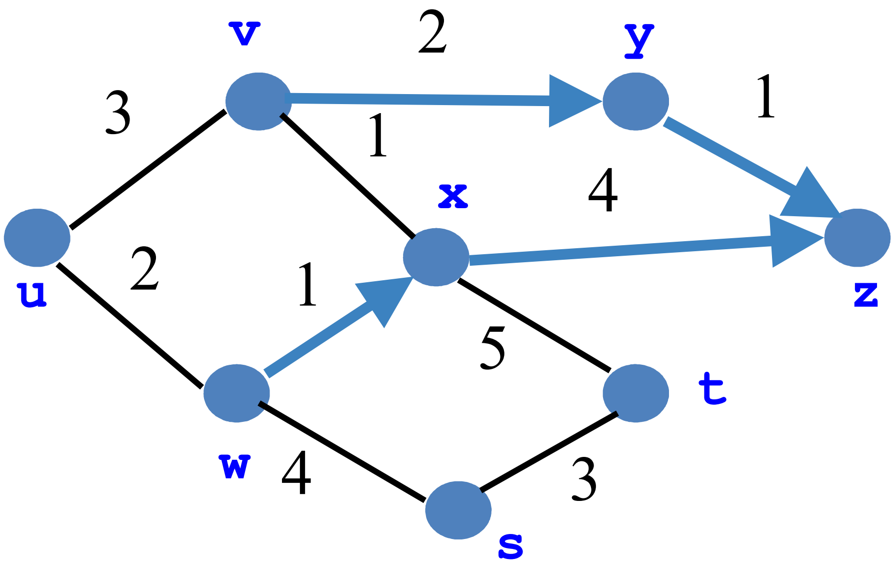
$$= 5$$

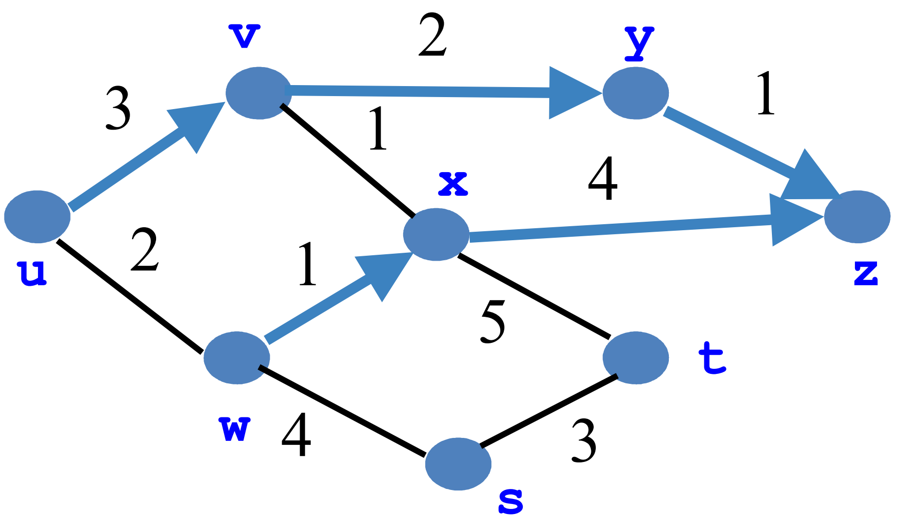
$$d_u(z) \quad = \quad ??$$

(A) 5 (B) 6 (C) 7

Source: Freedman

Distance Vector : Routing Example (contd.)





$$d_w(z) = \min\{1+d_x(z),\ 4+d_s(z),\ 2+d_u(z)\}$$

$$= 5$$

$$d_u(z) = \min\{3+d_v(z),\ 2+d_w(z)\}$$

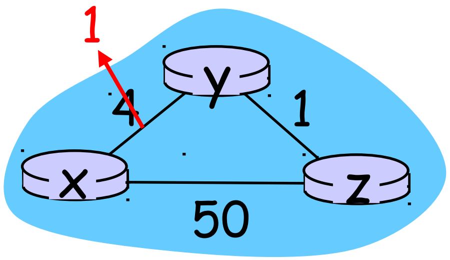
$$= 6$$

Source: Freedman

Distance Vector : Link Cost Changes

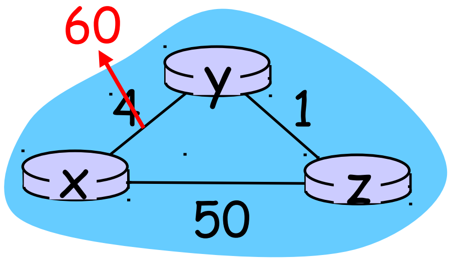
link cost changes:

- Node detects local link cost change
- Updates routing info, recalculates distance vector
- If DV changes, notify neighbors
- Good News travels fast



link cost changes:

- Node detects local link cost change
- *Bad news travels slow* - “count to infinity” problem!
- 44 iterations before algorithm stabilizes: see text
- Poisoned Reverse for faster convergence. Will this completely solve count to infinity problem?



Source: Kurose & Ross

Distance Vector : Link Cost Changes

message complexity

- ***LS:*** with n nodes, E links, O(nE) msgs sent
- ***DV:*** exchange between neighbors only
  - convergence time varies

speed of convergence

- ***LS:*** O(n2) algorithm requires O(nE) msgs
  - may have oscillations
- ***DV:*** convergence time varies
  - may be routing loops
  - count-to-infinity problem

robustness: what happens if router malfunctions?

LS:

- node can advertise incorrect *link* cost
- each node computes only its *own* table

DV:

- DV node can advertise incorrect *path* cost
- each node's table used by others
  - error propagate through network

Source: Kurose & Ross

Routing Issues

Our routing study thus far - idealization

- All routers identical
- Network “flat”

… *not* true in practice

Scale: with 600 million destinations:

- Can’t store all dest’s in routing tables!
- Routing table exchange would swamp links!

Administrative autonomy

- Internet = network of networks
- Each network admin may want to control routing in its own network

Source: Kurose & Ross

Hierarchical Routing – Standard CS trick

- Aggregate routers into regions, “autonomous systems” (AS)
- Routers in same AS run same routing protocol
  - “Intra-AS” routing protocol
  - Routers in different AS can run different intra-AS routing protocol

Gateway router:

- At “edge” of its own AS
- Has link to router in another AS

Source: Kurose & Ross

Summary

- DHCP: bootstrapping IP addresses
  - Broadcasting, caching, soft state
- NAT
  - A hack! ☺ Reading and reflection: Why?
- Many other hacks too! ☺
  - Tunneling, firewalls, mobile gateways, VPNs
- Routing Algorithms are graph based
  - Centralized → Link State
  - Distributed → Distance Vector
- Routing algorithms have different characteristics