The Network Layer

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Audio/Video recordings of this lecture are available on-line at:

http://www.cse.wustl.edu/~jain/cse473-09/

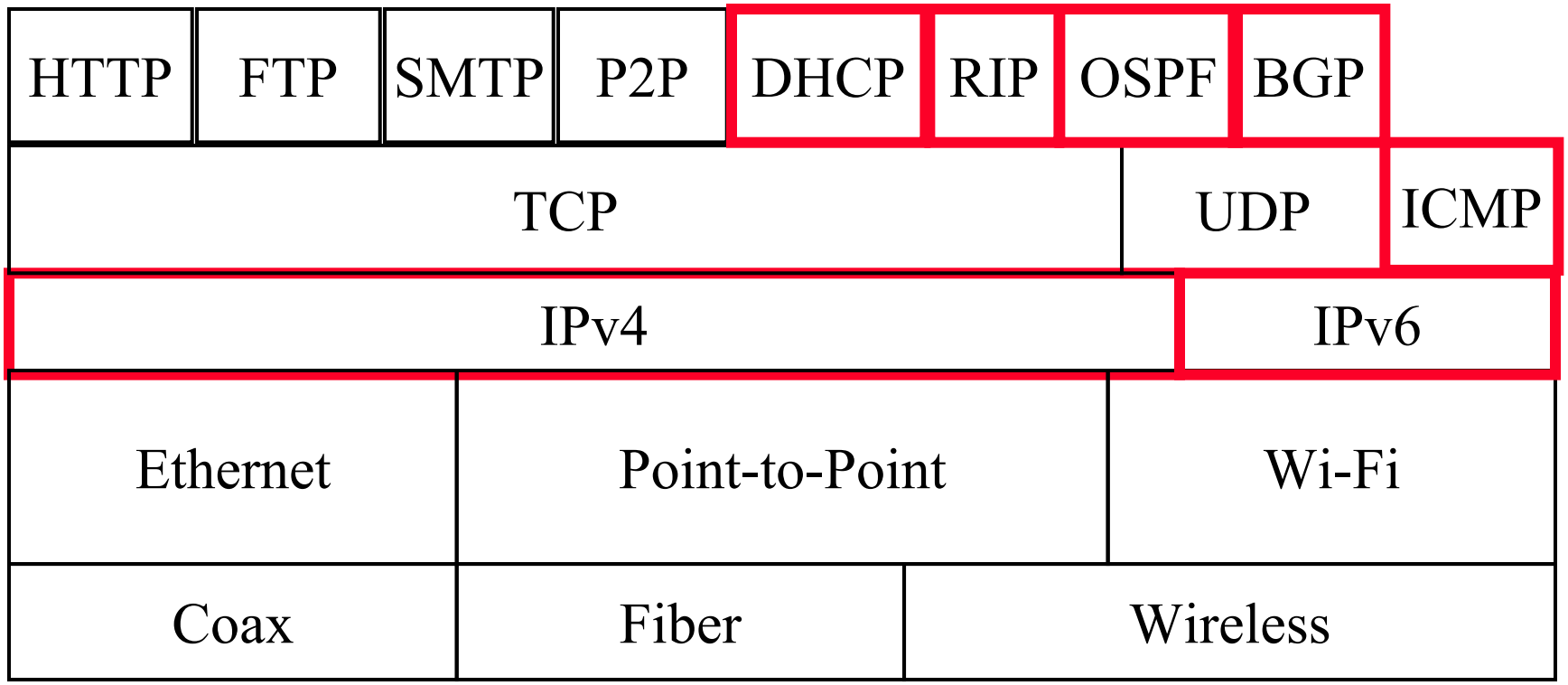
1. Network Layer Basics
2. Forwarding Protocols: IPv4, ICMP, DHCP, NAT, IPv6
3. Routing Algorithms: Link-State, Distance Vector
4. Routing Protocols: RIP, OSPF, BGP

Note: This class lecture is based on Chapter 4 of the textbook (Kurose and Ross) and the figures provided by the authors.

Network Layer Basics

1. Forwarding and Routing
2. Connection Oriented Networks: ATM Networks
3. Classes of Service
4. Router Components
5. Packet Queuing and Dropping

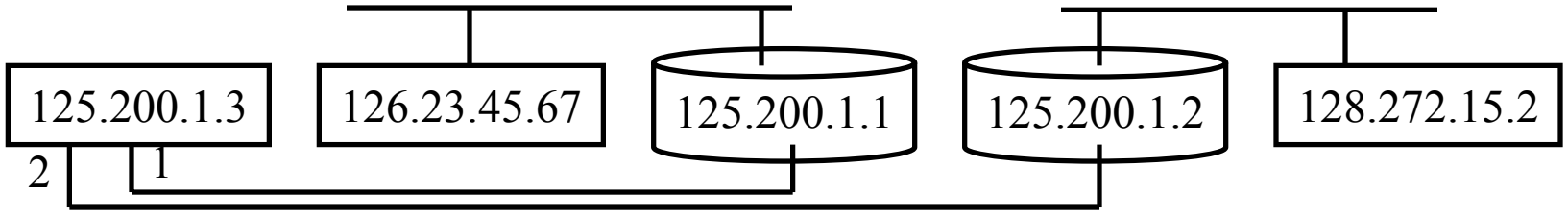
Network Layer Protocols



- Forwarding: IPv4 and IPv6
- Routing: RIP, OSPF, BGP, …
- Control and Management: ICMP, DHCP, …

Forwarding and Routing

- **Forwarding**: Input link to output link via Address prefix lookup.
- **Routing**: Making the Address lookup table
- **Longest Prefix Match**



Prefix	Next Router	Interface
126.23.45.67/32	125.200.1.1	1
128.272.15/24	125.200.1.2	2
128.272/16	125.200.1.1	1

"Route Print" Command in Windows

MAC: netstat -rn

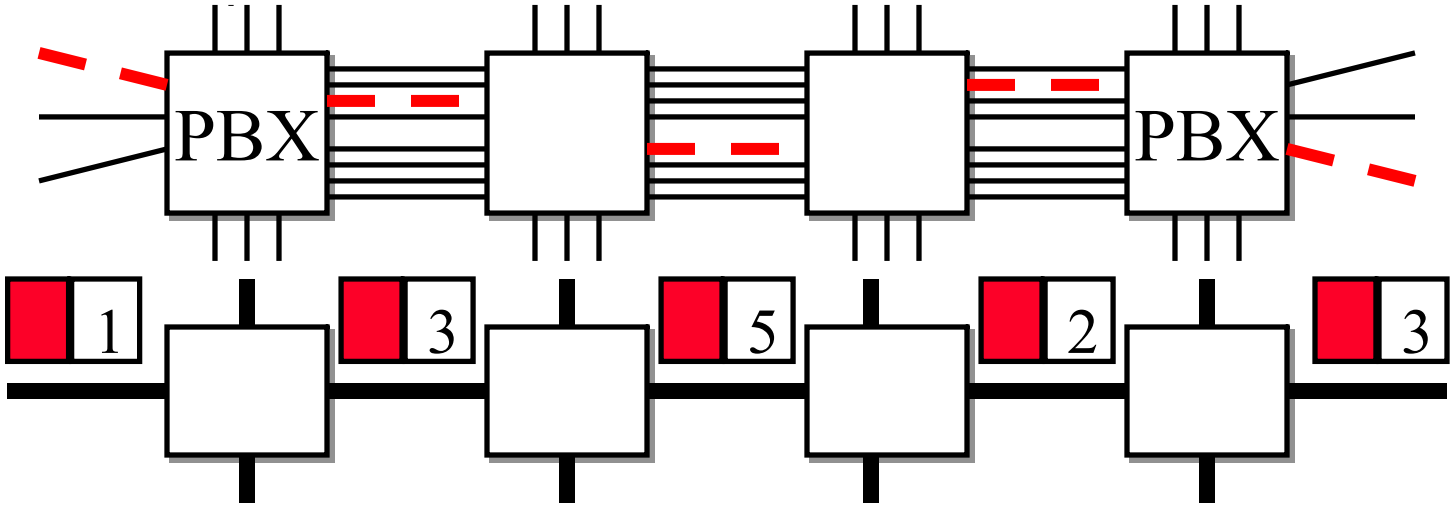
```
===========================================================================
Interface List
0x1 ........................... MS TCP Loopback interface
0x2 ...00 16 eb 05 af c0 ...... Intel(R) WiFi Link 5350 - Packet Scheduler Miniport
0x3 ...00 1f 16 15 7c 41 ...... Intel(R) 82567LM Gigabit Network Connection - Packet Scheduler Miniport
0x40005 ...00 05 9a 3c 78 00 ...... Cisco Systems VPN Adapter - Packet Scheduler Miniport
===========================================================================
===========================================================================
Active Routes:
Network Destination        Netmask          Gateway       Interface  Metric
          0.0.0.0          0.0.0.0      192.168.0.1   192.168.0.108       10
          0.0.0.0          0.0.0.0      192.168.0.1   192.168.0.106       10
        127.0.0.0        255.0.0.0        127.0.0.1       127.0.0.1        1
      169.254.0.0      255.255.0.0    192.168.0.106   192.168.0.106       20
      192.168.0.0    255.255.255.0    192.168.0.106   192.168.0.106       10
      192.168.0.0    255.255.255.0    192.168.0.108   192.168.0.108       10
    192.168.0.106  255.255.255.255        127.0.0.1       127.0.0.1       10
    192.168.0.108  255.255.255.255        127.0.0.1       127.0.0.1       10
    192.168.0.255  255.255.255.255    192.168.0.106   192.168.0.106       10
    192.168.0.255  255.255.255.255    192.168.0.108   192.168.0.108       10
        224.0.0.0        240.0.0.0    192.168.0.106   192.168.0.106       10
        224.0.0.0        240.0.0.0    192.168.0.108   192.168.0.108       10
  255.255.255.255  255.255.255.255    192.168.0.106   192.168.0.106       1
  255.255.255.255  255.255.255.255    192.168.0.106           40005       1
  255.255.255.255  255.255.255.255    192.168.0.108   192.168.0.108       1
Default Gateway:       192.168.0.1
===========================================================================
Persistent Routes:
  None
```

Note: 127.0.0.1 = Local Host, 224.x.y.z = Multicast on local LAN

Home Exercise 4A

- **Try but do not submit**
- Use "Route Help" to learn the route command
- Ping www.google.com to find its address
- Enable both wired and wireless interfaces on your computer
- Update your computers routing table so that preferred path for www.google.com is via wireless interface
- Print the new routing table
- Verify using tracert

ATM Networks



- Asynchronous transfer mode
- Uses fixed size 53-byte **cells**
- **Connection Oriented Network Layer**
  ⇒ Connection setup before data transfer
- Cells contain **Virtual Circuit Identifiers** (VCI)
- Switch forwarding tables contain:
  Input Interface + VCI → Output Interface + New VCI

Classes of Service

Standby

Guaranteed

Joy Riders

Confirmed

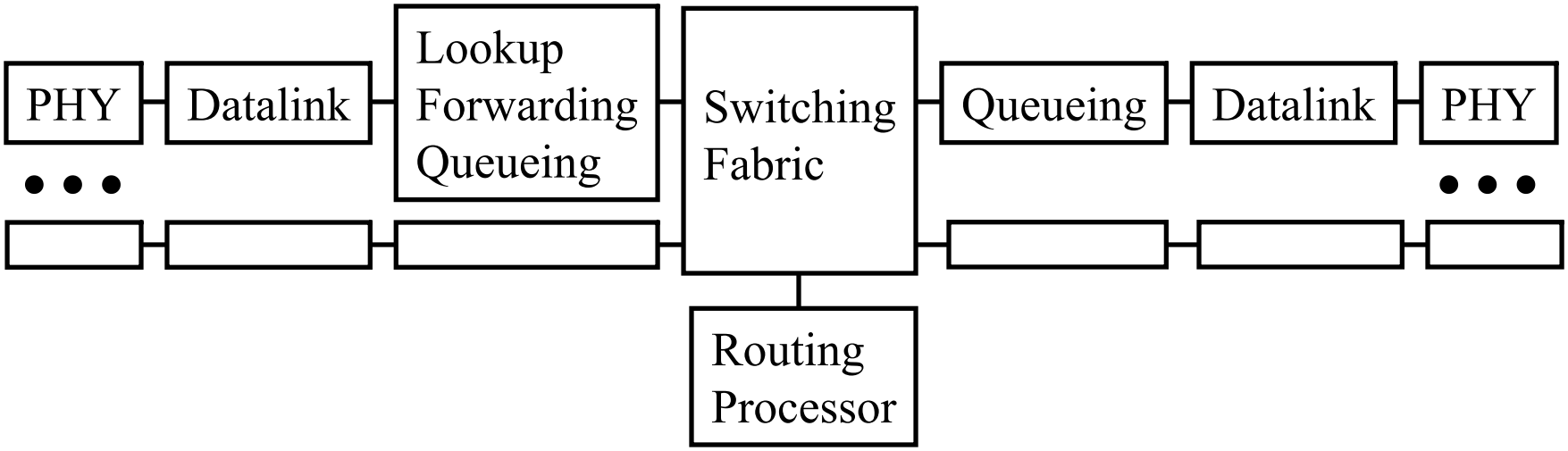
ATM Classes of Service

- ABR (Available bit rate): Source follows feedback. Max throughput with minimum loss.
- UBR (Unspecified bit rate): User sends whenever it wants. No feedback. No guarantee. Cells may be dropped during congestion.
- CBR (Constant bit rate): User declares required rate. Throughput, delay and delay variation guaranteed.
- VBR (Variable bit rate): Declare avg and max rate.
  - rt-VBR (Real-time): Conferencing. Max delay guaranteed.
  - nrt-VBR (non-real time): Stored video.
- GFR (Guaranteed Frame Rate): Min Frame Rate

Network Service Models

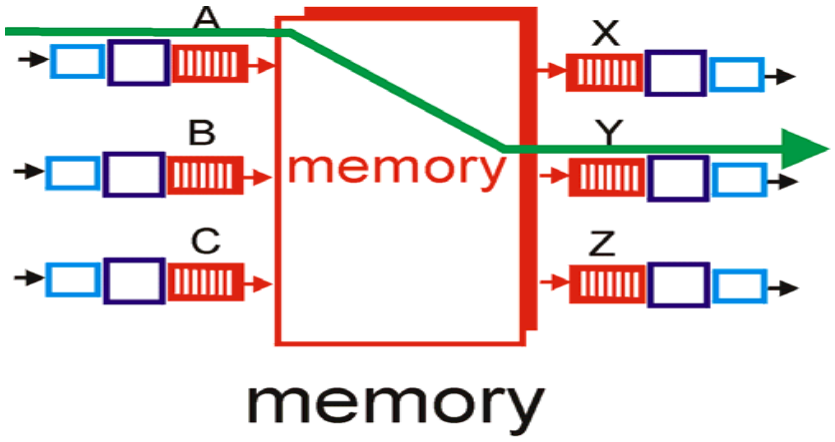
- Guaranteed Delivery: No packets lost
- Bounded delay: Maximum delay
- In-Order packet delivery: Some packets may be missing
- Guaranteed minimal throughput
- Guaranteed maximum jitter: Delay variation
- Security Services (optional in most networks)
- ATM offered most of these
- IP offers none of these $\Rightarrow$ Best effort service (Security is optional)

What's Inside a Router?

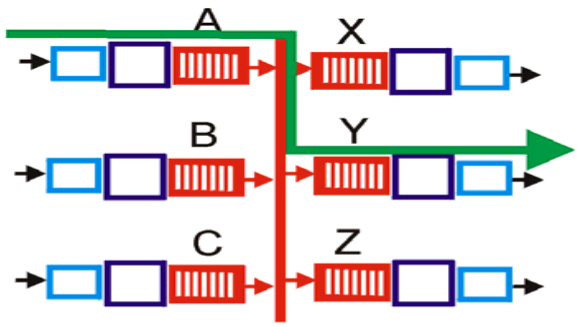


- **Input Ports**: receive packets, lookup address, queue
  Use **Content Addressable Memories** (CAMs) and caching
- **Switch Fabric**: Send from input port to output port
- **Output Ports**: Queuing, transmit packets

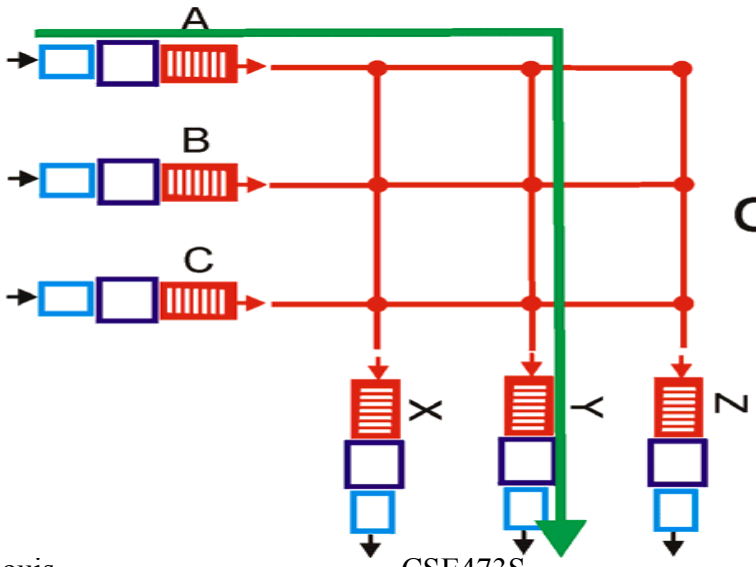
Types of Switching Fabrics



memory



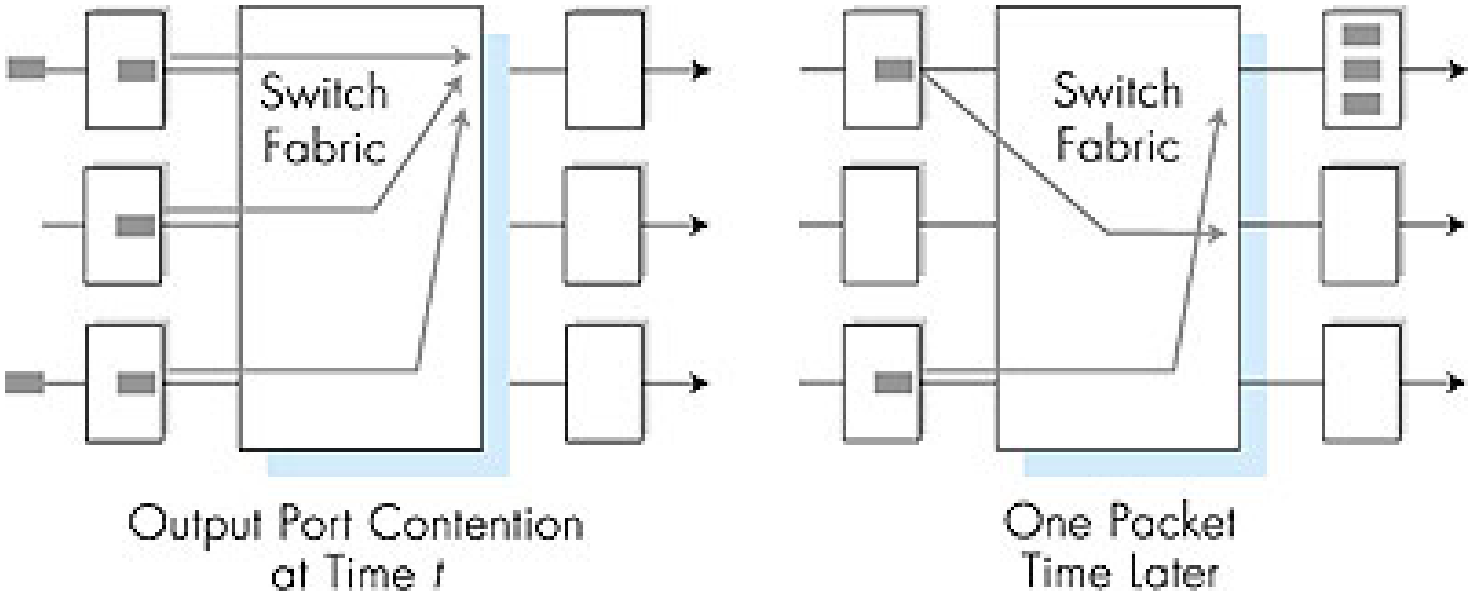
bus



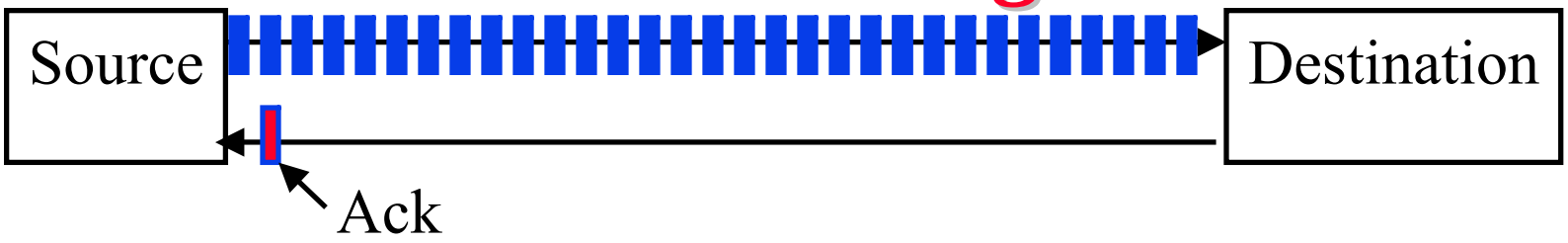
crossbar

Where Does Queuing Occur?

- If switching fabric is slow, packets wait on the input port.
- If switching fabric is fast, packets wait for output port
  ⇒ Queueing (Scheduling) and drop policies
- Queueing: First Come First Served (FCFS),
  Weighted Fair Queueing

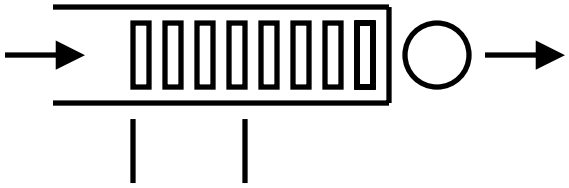


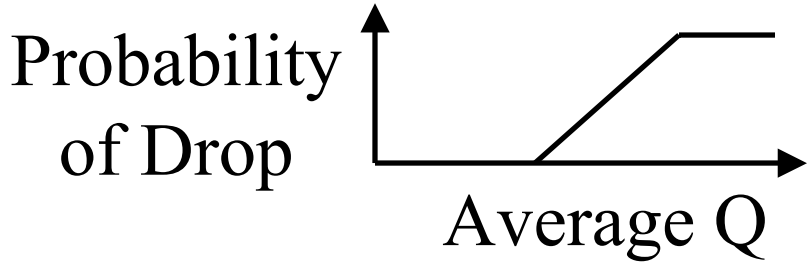
Ideal Buffering



- Flow Control Buffering = RTT*Transmission Rate
- Buffer = RTT*Transmission Rate/√(# of TCP flows)

Packet Dropping Policies



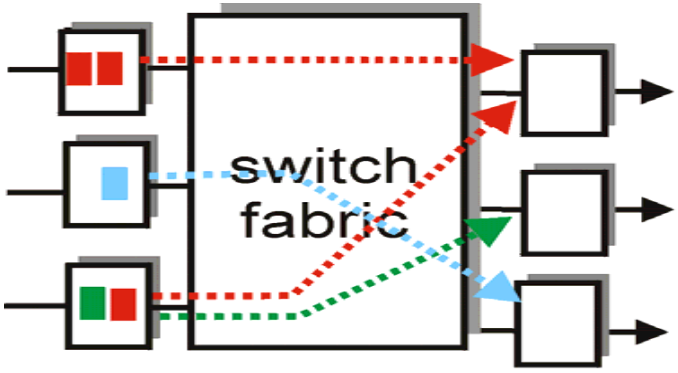


- **Drop-Tail**: Drop the arriving packet
- **Random Early Drop (RED):** Drop arriving packets even before the queue is full
  - Routers measure average queue and drop incoming packet with certain probability

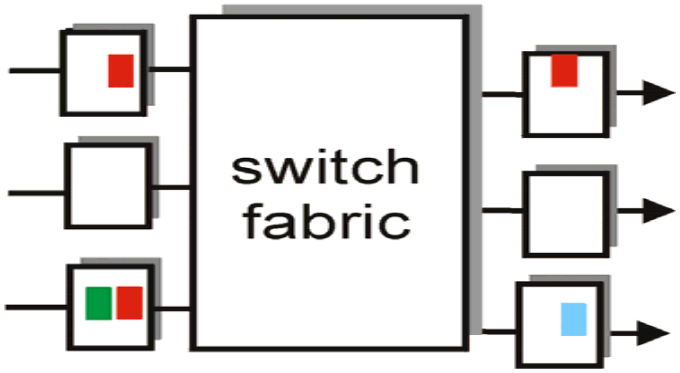
  ⇒ **Active Queue Management** (AQM)

Head-of-Line Blocking

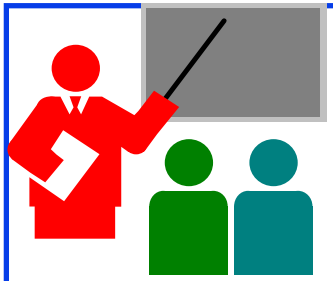
- Packet at the head of the queue is waiting
  ⇒ Other packets can not be forwarded even if they are going to other destination



output port contention at time t - only one red packet can be transferred



green packet experiences HOL blocking



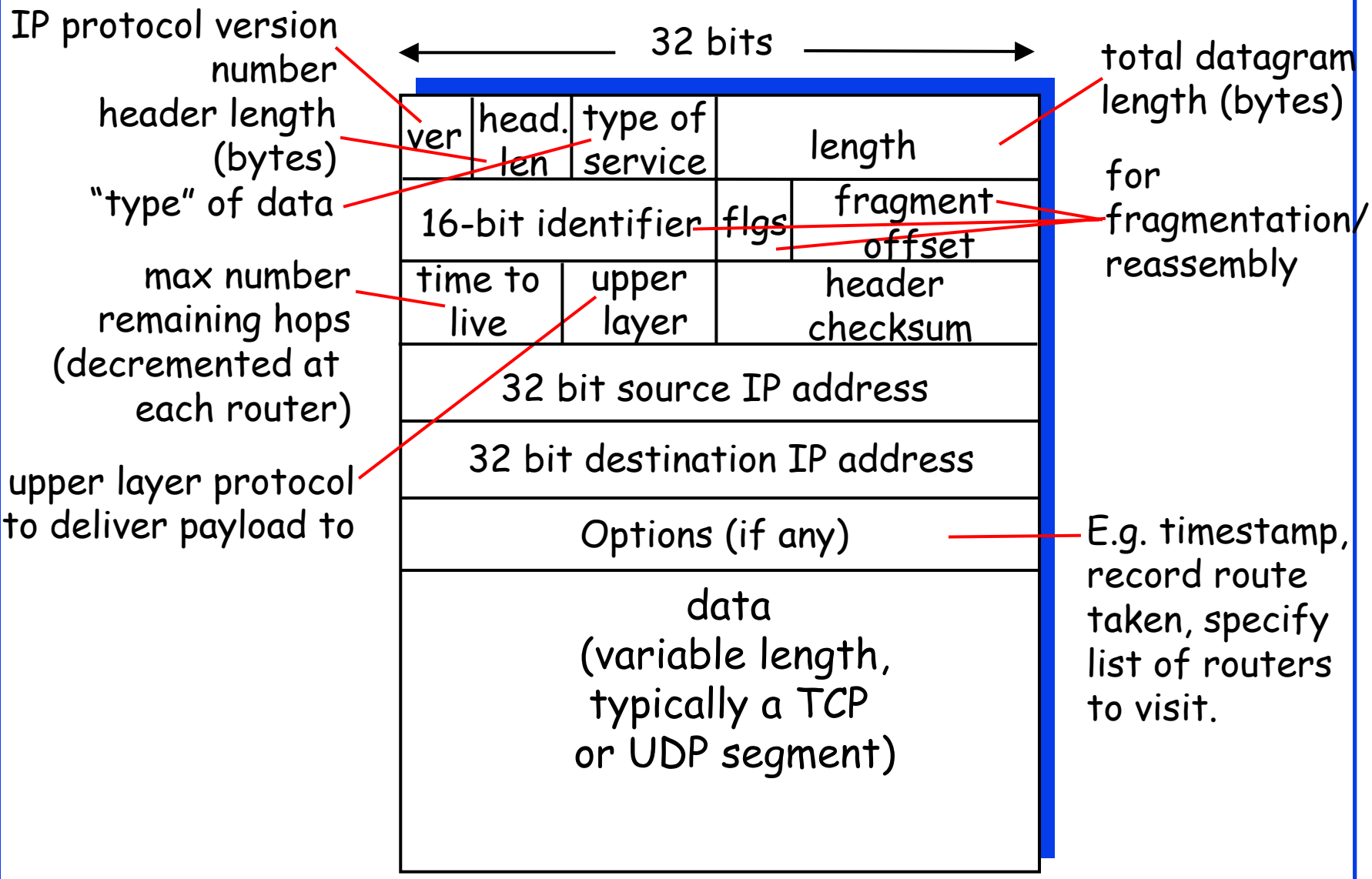
Network Layer Basics: Review

1. Forwarding uses routing table to find output port for datagrams using longest prefix match. Routing protocols make the table.
2. ATM provides a connection-oriented network layer and provides many services including throughput, delay, and jitter guarantees.
3. IP provides only best effort service (KISS).
4. Routers consist of input/output ports, switching fabric, and processors.
5. Datagrams may be dropped even if the queues are not full (Random early drop).
6. Queueing at input may result in head of line blocking.

Forwarding Protocols

1. IPv4 Datagram Format
2. IP Fragmentation and Reassembly
3. IP Addressing
4. Network Address Translation (NAT)
5. Universal Plug and Play
6. Dynamic Host Control Protocol (DHCP)
7. ICMP
8. IPv6

IP Datagram Format



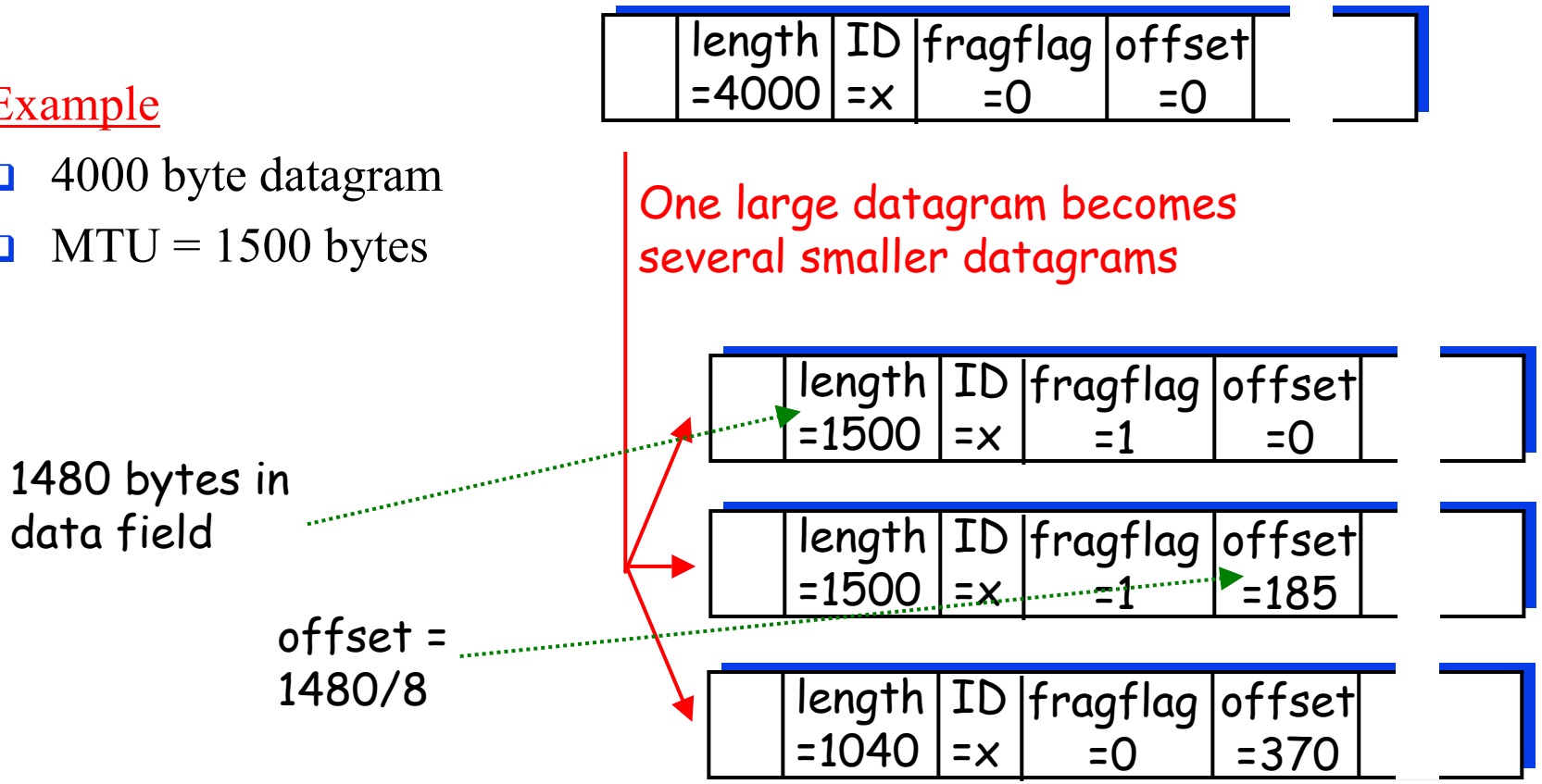
IP Fragmentation Fields

- Data Unit Identifier (ID)
  - Sending host puts an identification number in each datagram
- Total length: Length of user data plus header in octets
- Data Offset - Position of fragment in original datagram
  - In multiples of 64 bits (8 octets)
- *More* flag
  - Indicates that this is not the last fragment
- Datagrams can be fragmented/refragmented at any router
- Datagrams are reassembled only at the destination host

IP Fragmentation and Reassembly

Example

- 4000 byte datagram
- MTU = 1500 bytes



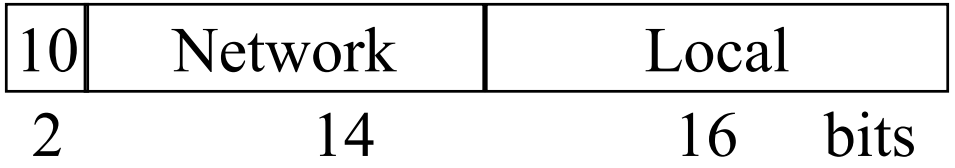
Homework 4B

- Consider sending a 2400-byte datagram into a link that has an MTU of 700 bytes. Suppose the original datagram is stamped with the identification number 422. How many fragments are generated? What are the values in the various fields in the IP datagram(s) generated related to fragmentation?

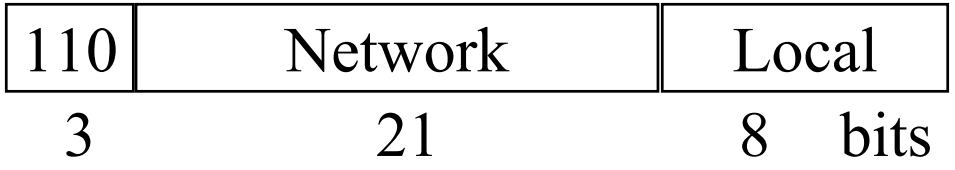
IP Address Classes

- Class A:

- Class B:

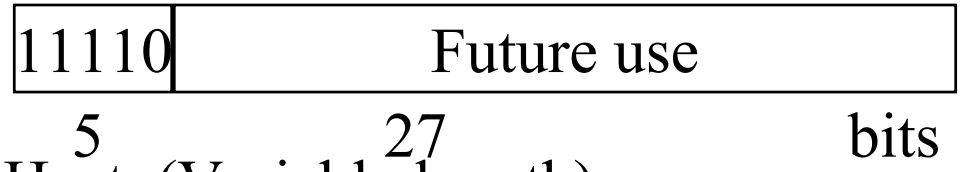


- Class C:

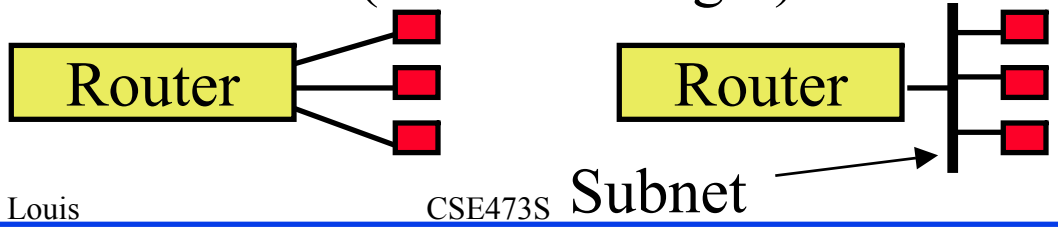


- Class D:

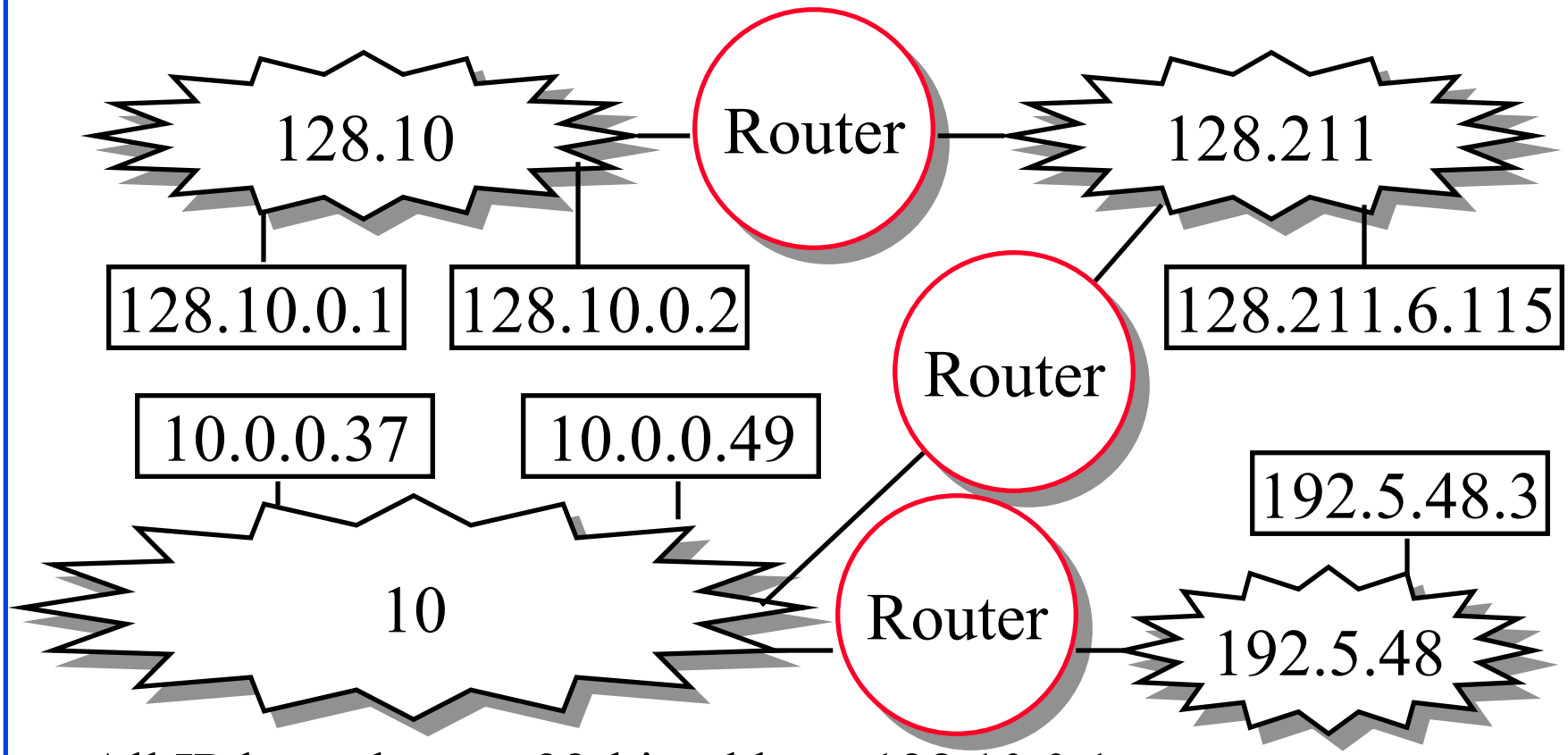
- Class E:



- Local = Subnet + Host (Variable length)

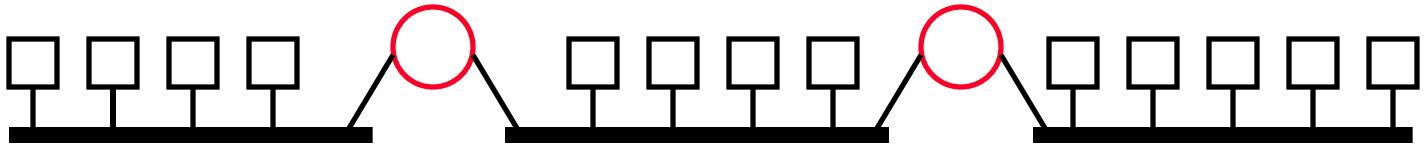


IP Addressing



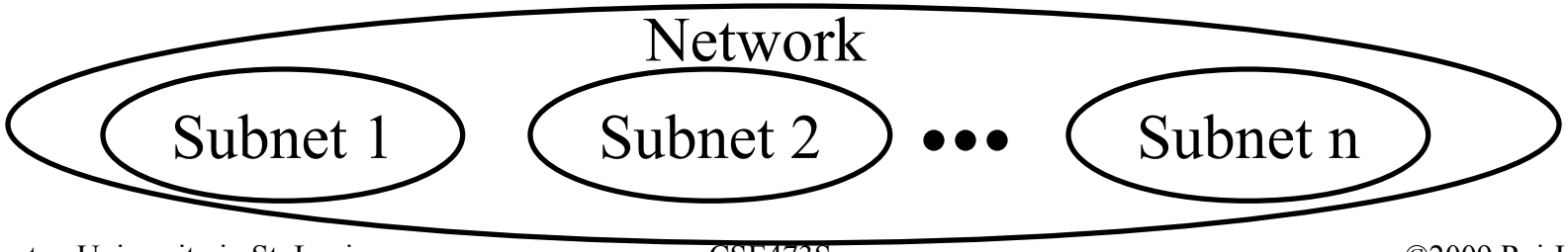
- All IP hosts have a 32-bit address.128.10.0.1 =1000 0000 0000 1010 0000 0000 0000 0001
- All hosts on a network have the same network prefix

Subnetting



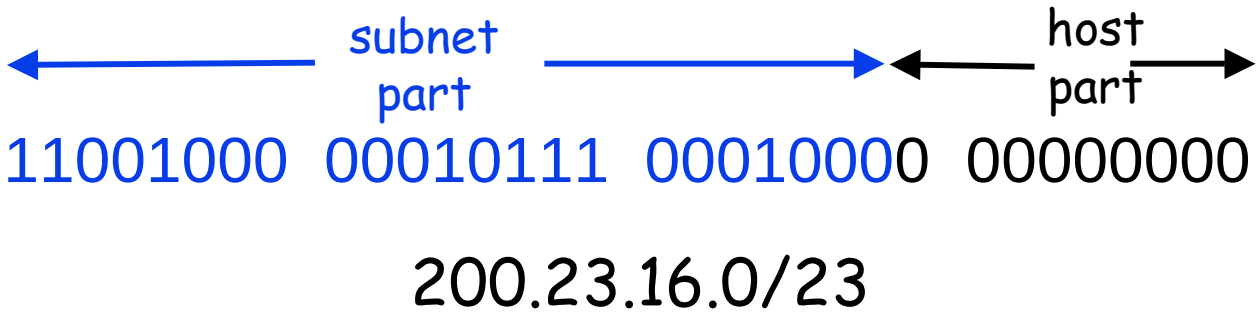
- All hosts on a subnetwork have the same prefix. Position of the prefix is indicated by a "subnet mask"
- Example: First 23 bits = subnet

  Address: 10010100 10101000 00010000 11110001
  Mask: 11111111 11111111 11111110 00000000
  .AND. 10010100 10101000 00010000 00000000



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



Home Exercise 4C

- **Try but do not submit**
- Consider a router that interconnects 3 subnets: Subnet 1, Subnet 2, and Subnet 3. Suppose all of the interfaces in each of these three subnets are required to have the prefix 223.1.17/24. Also suppose that Subnet 1 is required to support up to 63 interfaces, Subnet 2 is to support up to 95 interfaces, and Subnet 3 is to support up to 16 interfaces. Provide three network address prefixes (of the form a.b.c.d/x) that satisfy these constraints. Use adjacent allocations. For each subnet, also list the subnet mask to be used in the hosts.

Forwarding an IP Datagram

- Delivers **datagram**s to destination network (subnet)
- Routers maintain a "routing table" of "next hops"
- Next Hop field does not appear in the datagram

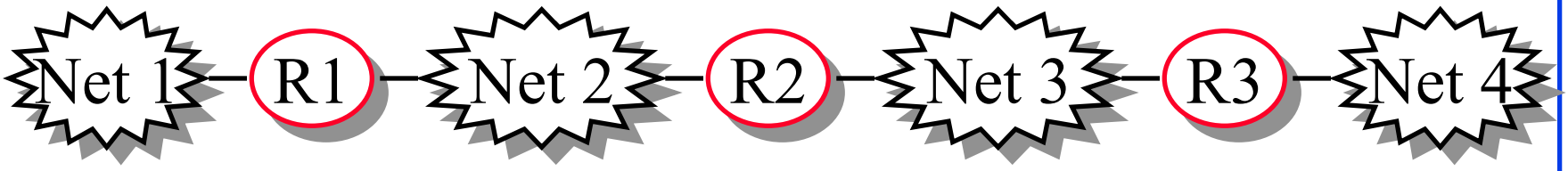
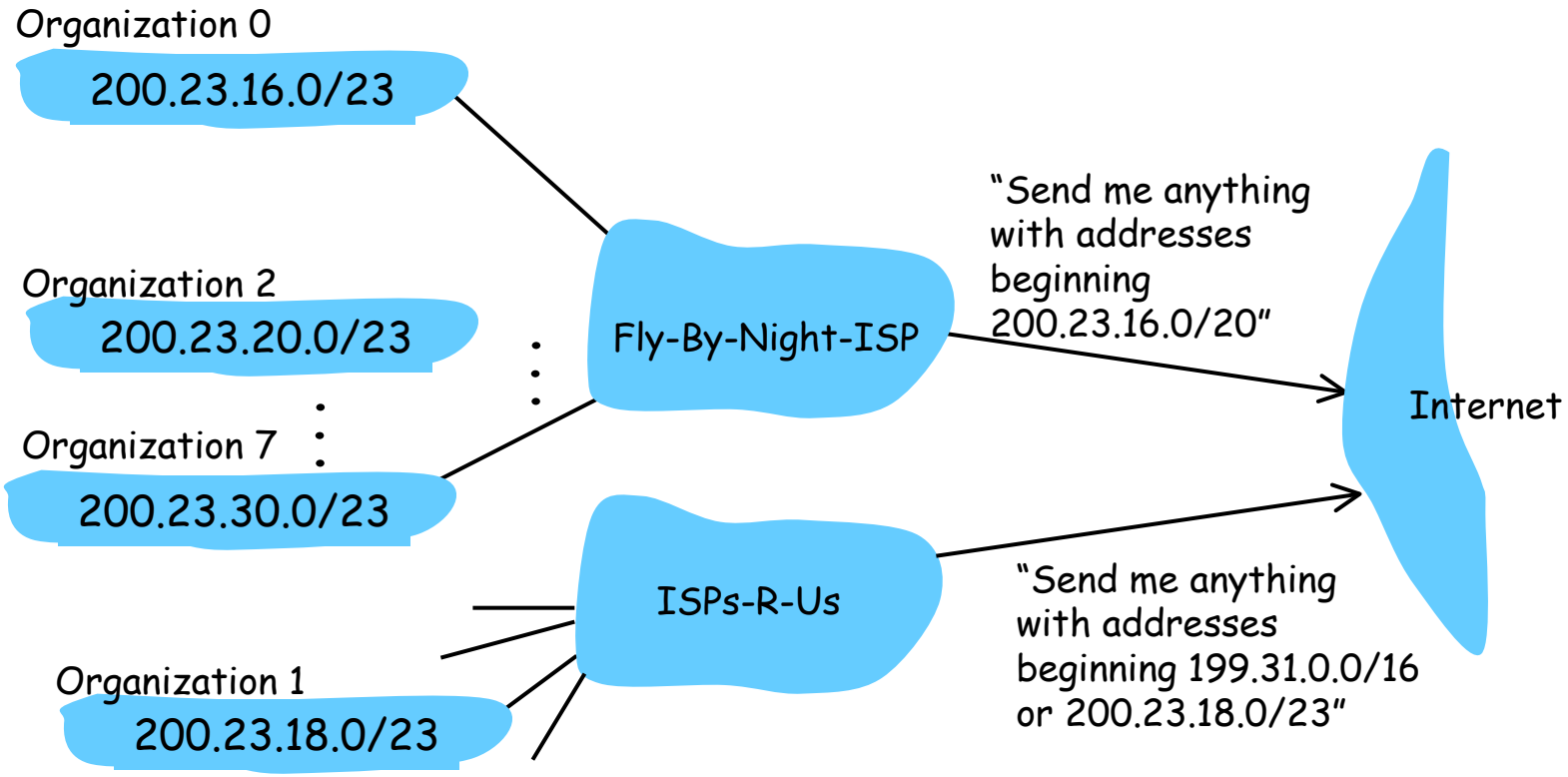


Table at R2:

Destination	Next Hop
Net 1	Forward to R1
Net 2	Deliver Direct
Net 3	Deliver Direct
Net 4	Forward to R3

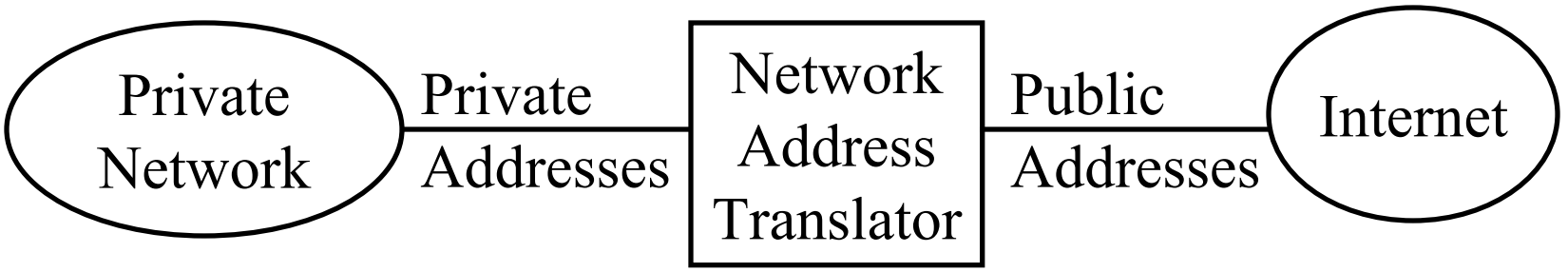
Route Aggregation

- Can combine two or more prefixes into a shorter prefix
- ISPs-R-Us has a more specific route to organization 1

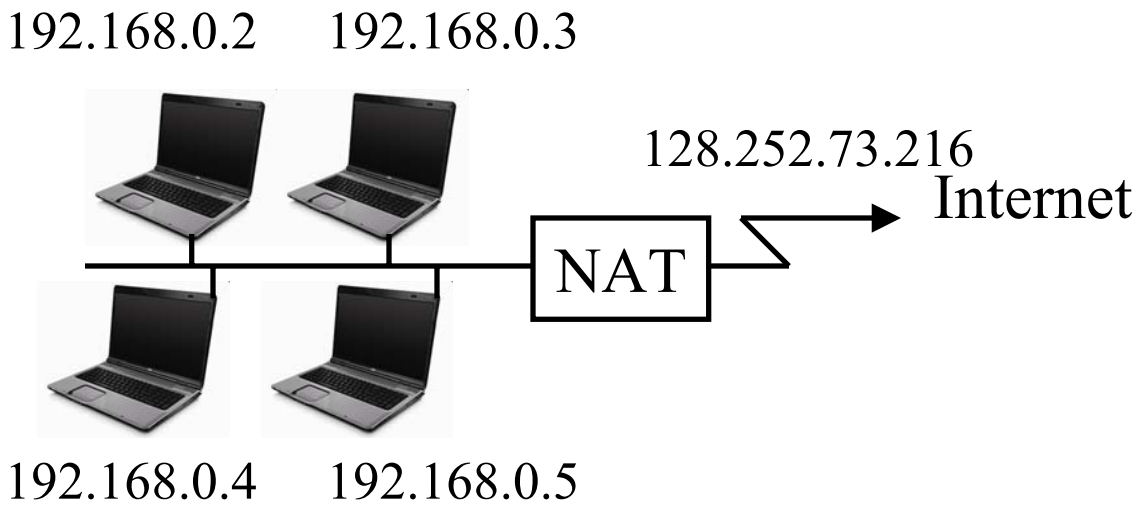


Private Addresses

- Any organization can use these inside their network Can't go on the internet. [RFC 1918]
- 10.0.0.0 - 10.255.255.255 (10/8 prefix)
- 172.16.0.0 - 172.31.255.255 (172.16/12 prefix)
- 192.168.0.0 - 192.168.255.255 (192.168/16 prefix)



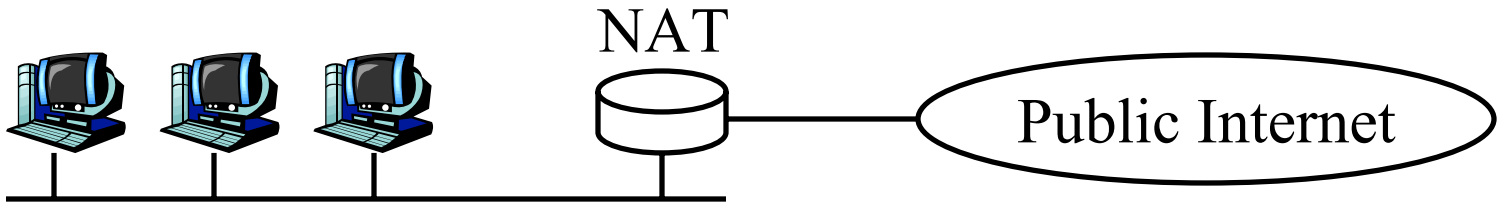
Network Address Translation (NAT)



- Private IP addresses 192.168.x.x
- Can be used by anyone inside their networks
- Cannot be used on the public Internet
- NAT overwrites source addresses on all outgoing packets and overwrites destination addresses on all incoming packets
- Only outgoing connections are possible

Universal Plug and Play

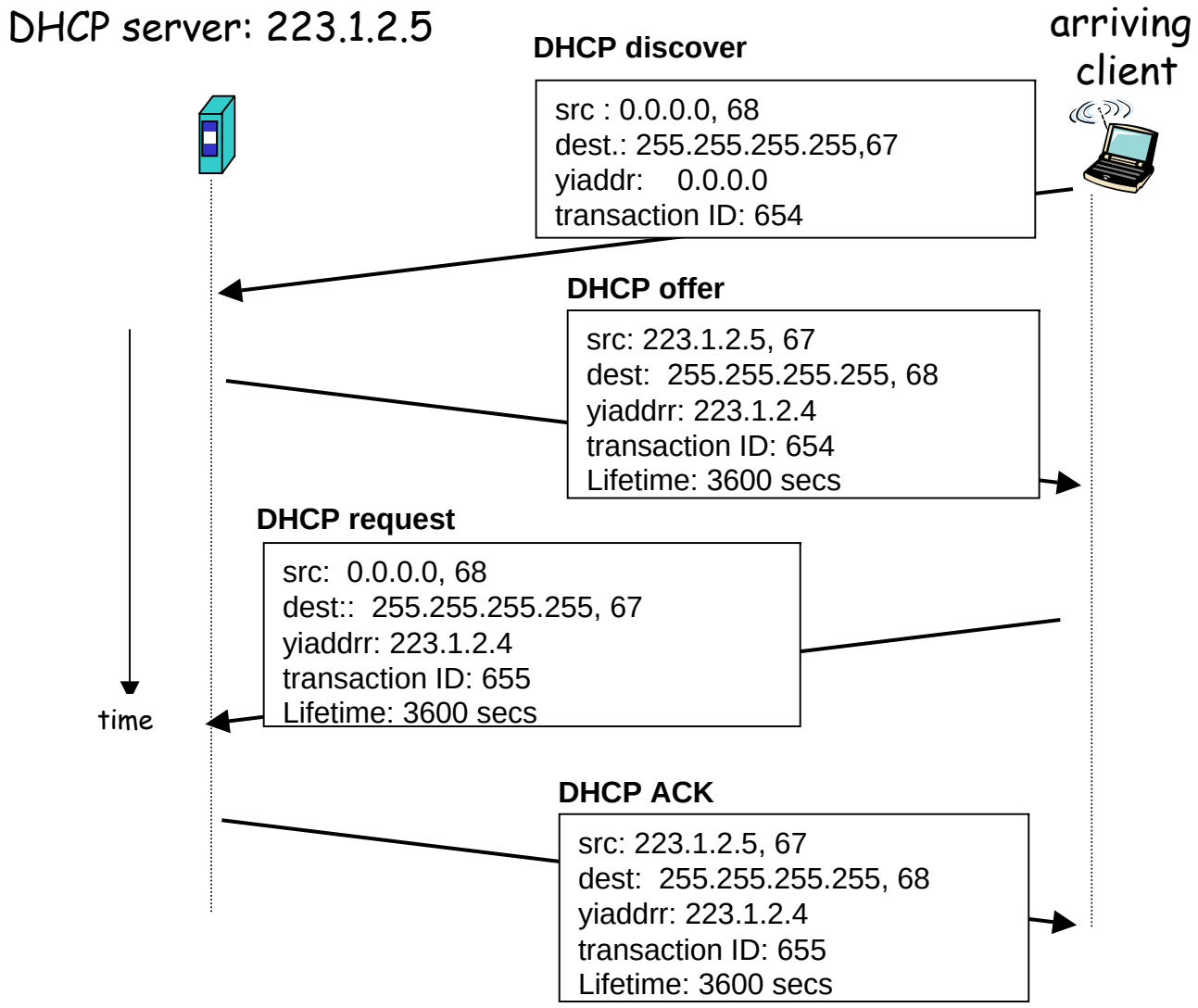
- NAT needs to be manually programmed to forward external requests
- UPnP allows hosts to request port forwarding
- Both hosts and NAT should be UPnP aware
- Host requests forwarding all port xx messages to it
- NAT returns the public address and the port #.
- Host can then announce the address and port # outside
- Outside hosts can then reach the internal host (server)



DHCP

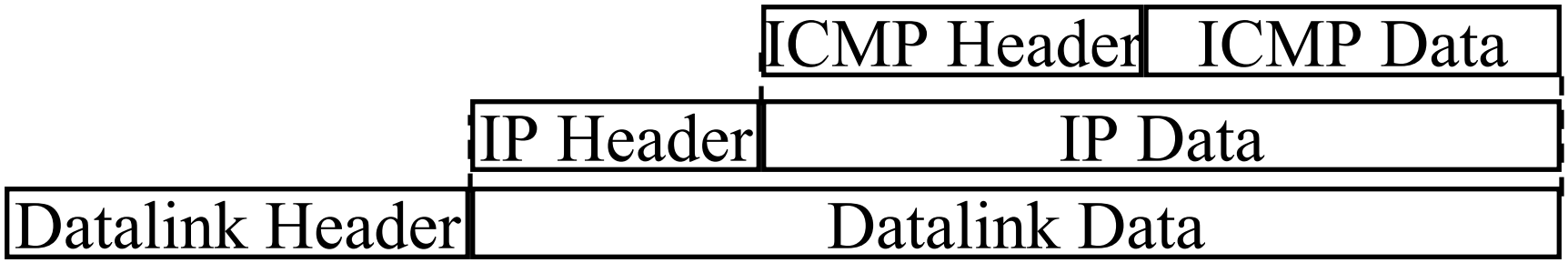
- Dynamic Host Control Protocol
- Allows hosts to get an IP address automatically from a server
- Do not need to program each host manually
- Each allocation has a limited "lease" time
- Can reuse a limited number of addresses
- Hosts broadcast "Is there a DHCP Server Here?"
- DHCP servers respond

DHCP Example

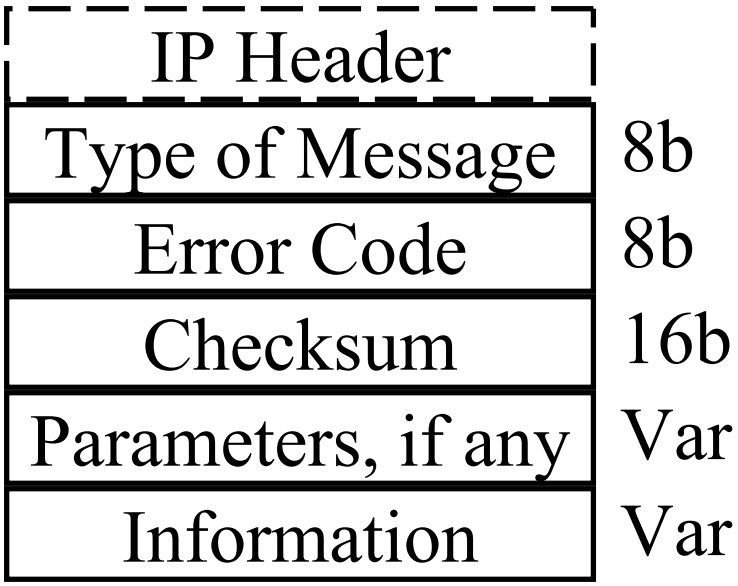


ICMP

- Internet Control Message Protocol
- Required companion to IP. Provides feedback from the network.
- ICMP: Used by IP to send error and control messages
- ICMP uses IP to send its messages (Not UDP)
- ICMP does not report errors on ICMP messages.
- ICMP reports error only on the first fragment



ICMP: Message Types



Type	Message
0	Echo reply
3	Destination unreachable
4	Source quench
5	Redirect
8	Echo request
11	Time exceeded
12	Parameter unintelligible
13	Time-stamp request
14	Time-stamp reply
15	Information request
16	Information reply
17	Address mask request
18	Address mask reply

ICMP Messages

- Source Quench: Please slow down! I just dropped one of your datagrams.
- Time Exceeded: Time to live field in one of your packets became zero." or "Reassembly timer expired at the destination.
- Fragmentation Required: Datagram was longer than MTU and "No Fragment bit" was set.
- Address Mask Request/Reply: What is the subnet mask on this net? Replied by "Address mask agent"
- PING uses ICMP echo
- Tracert uses TTL expired

Trace Route Example

```
C:\>tracert www.google.com

Tracing route to www.l.google.com [74.125.93.147]
over a maximum of 30 hops:

  1     3 ms     1 ms     1 ms  192.168.0.1
  2    12 ms    10 ms     9 ms  bras4-l0.stlsmo.sbcglobal.net [151.164.182.113]
  3    10 ms     8 ms     8 ms  dist2-vlan60.stlsmo.sbcglobal.net [151.164.14.163]
  4     9 ms     7 ms     7 ms  151.164.93.224
  5    25 ms    22 ms    22 ms  151.164.93.49
  6    25 ms    22 ms    22 ms  151.164.251.226
  7    30 ms    28 ms    28 ms  209.85.254.128
  8    61 ms    57 ms    58 ms  72.14.236.26
  9    54 ms    52 ms    51 ms  209.85.254.226
 10    79 ms   160 ms    67 ms  209.85.254.237
 11    66 ms    57 ms    68 ms  64.233.175.14
 12    60 ms    58 ms    58 ms  qw-in-f147.google.com [74.125.93.147]

Trace complete.
```

IPv6

- Shortage of IPv4 addresses ⇒ Need larger addresses
- IPv6 was designed with 128-bit addresses
- $2^{128} = 3.4\times10^{38}$ addresses
  ⇒ 665×10^{21} addresses per sq. m of earth surface
- If assigned at the rate of $10^6/\mu s$, it would take 20 years
- **Dot-Decimal**: 127.23.45.88
- **Colon-Hex:** FEDC:0000:0000:0000:3243:0000:0000:ABCD
  - Can skip leading zeros of each word
  - Can skip one sequence of zero words, e.g.,
    FEDC::3243:0000:0000:ABCD
    ::3243:0000:0000:ABCD
  - Can leave the last 32 bits in dot-decimal, e.g., ::127.23.45.88
  - Can specify a prefix by /length, e.g., 2345:BA23:0007::/50

IPv6 Header

- IPv6:

Version	Priority	Flow Label	
Payload Length		Next Header	Hop Limit
Source Address			
Destination Address			

- IPv4:

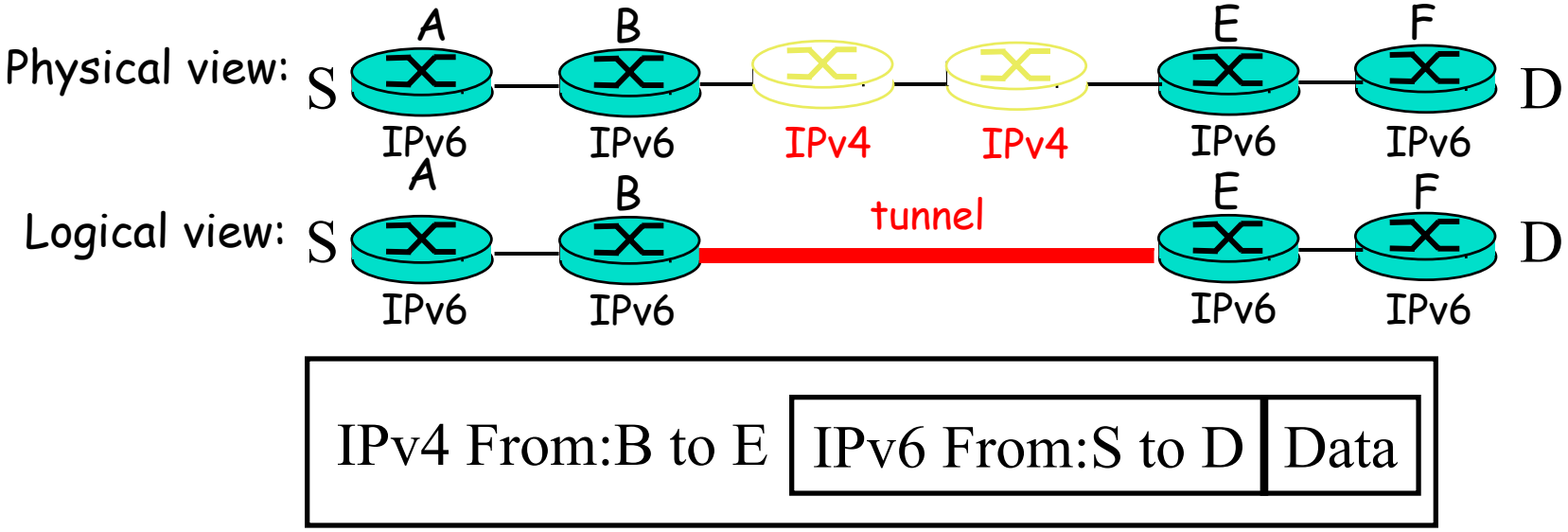
Version	IHL	Type of Service	Total Length	
Identification			Flags	Fragment Offset
Time to Live	Protocol	Header Checksum		
Source Address				
Destination Address				
Options				Padding

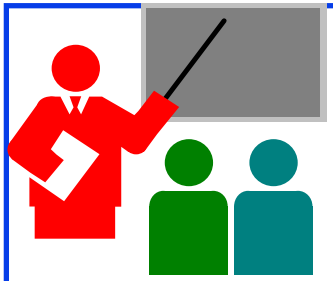
IPv6 vs. IPv4

- 1995 vs. 1975
- IPv6 only twice the size of IPv4 header
- Only version number has same position and meaning as in IPv4
- Removed: header length, type of service, identification, flags, fragment offset, header checksum ⇒ No fragmentation
- Datagram length replaced by payload length
- Protocol type replaced by next header
- Time to live replaced by hop limit
- Added: Priority and flow label
- All fixed size fields.
- No optional fields. Replaced by extension headers.
- 8-bit hop limit = 255 hops max (Limits looping)
- Next Header = 6 (TCP), 17 (UDP)

IPv4 to IPv6 Transition

- **Dual Stack**: Each IPv6 router also implements IPv4
  IPv6 is used only if source host, destination host, and all routers on the path are IPv6 aware.
- **Tunneling**:The last IPv6 router puts the entire IPv6 datagram in a new IPv4 datagram addressed to the next IPv6 router
  = **Encapsulation**





Forwarding Protocols: Review

1. IPv4 uses 32 bit addresses consisting of subnet + host
2. Private addresses can be reused
   ⇒ Helped solve the address shortage to a great extent
3. ICMP is the IP control protocol to convey IP error messages
4. DHCP is used to automatically allocate addresses to hosts
5. IPv6 uses 128 bit addresses. Requires dual stack or tunneling to coexist with IPv4.

Routing Algorithms

1. Graph abstraction
2. Distance Vector vs. Link State
3. Dijkstra's Algorithm
4. Bellman-Ford Algorithm

Rooting or Routing

- *Rooting* is what fans do at football games, what pigs do for truffles under oak trees in the Vaucluse, and what nursery workers intent on propagation do to cuttings from plants.
- *Routing* is how one creates a beveled edge on a table top or sends a corps of infantrymen into full scale, disorganized retreat

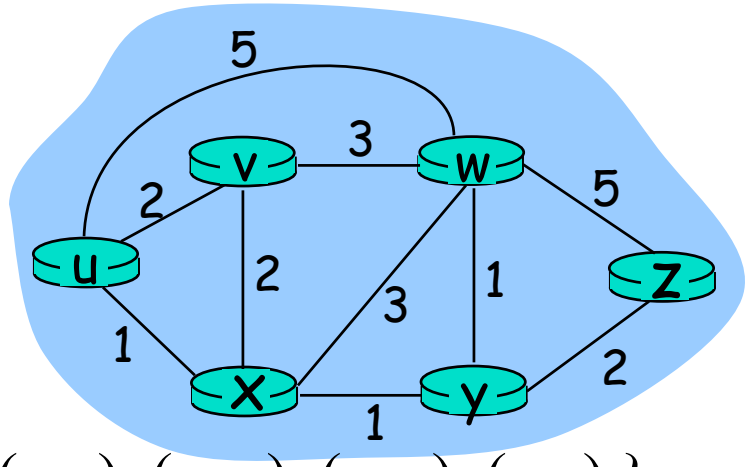
Ref: Piscitello and Chapin, p413

Routeing or Routing

- Routeing: British
- Routing: American
- Since Oxford English Dictionary is much heavier than any other dictionary of American English, British English generally prevails in the documents produced by ISO and CCITT; wherefore, most of the international standards for routing standards use the routeing spelling.

Ref: Piscitello and Chapin, p413

Graph abstraction

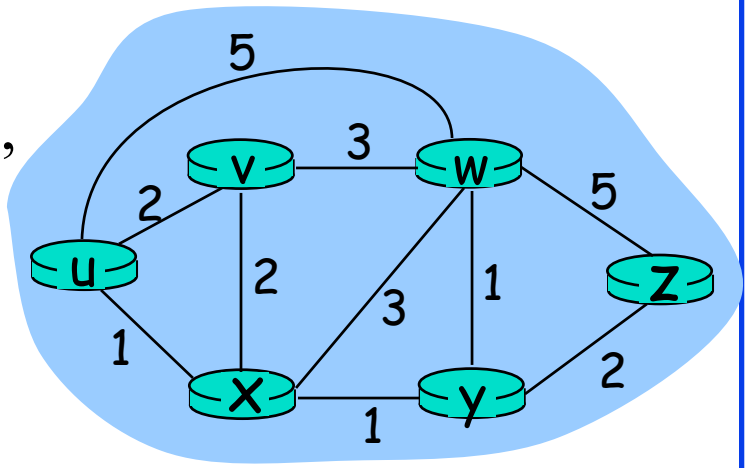


- Graph: G = (N,E)
- N = Set of routers
  = { u, v, w, x, y, z }
- E = Set of links
  ={ (u,v), (u,x), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) }
- Each link has a cost, e.g., c(w,z) = 5
- Cost of path $(x_1, x_2, \ldots, x_p) = c(x_1,x_2) + c(x_2,x_3) + \ldots + c(x_{p-1},x_p)$
- Routing Algorithms find the least cost path
- We limit to "Undirected" graphs, i.e., cost is same in both directions

Distance Vector vs Link State

Distance Vector:

- Vector of distances to all nodes, e.g., u: {u:0, v:2, w:5, x:1, y:2, z:4}
- Sent to neighbors, e.g., u will send to v, w, x
- Large vectors to small # of nodes Tell about the world to neighbors
- Older method. Used in RIP.



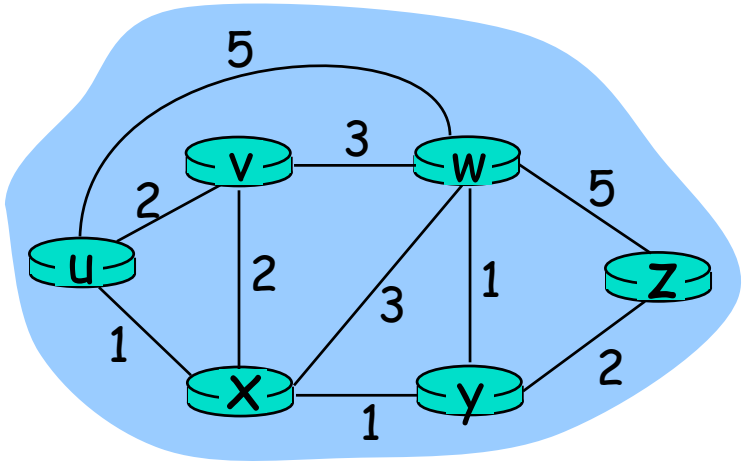
Link State:

- Vector of link cost to neighbors, e.g, u: {v:2, w:5, x:1}
- Sent to all nodes, e.g., u will send to v, w, x, y, z
- Small vectors to large # of nodes Tell about the neighbors to the world
- Newer method. Used in OSPF.

Dijkstra's Algorithm

- Goal: Find the least cost paths from a given node to all other nodes in the network
- Notation:
  c(i,j) = Link cost from i to j if i and j are connected
  D(k) = Total path cost from s to k
  N' = Set of nodes so far for which the least cost path is known
- Method:
  - Initialize: N'={u}, D(v) = c(u,v) for all neighbors of u
  - Repeat until N includes all nodes:
    - Find node $w \notin N'$, whose D(w) is minimum
    - Add w to N'
    - Update D(v) for each neighbor of w that is not in N'
      D(v) = min[D(v), D(w) + c(w,v)] for all $v \notin N'$

Dijkstra's Algorithm: Example

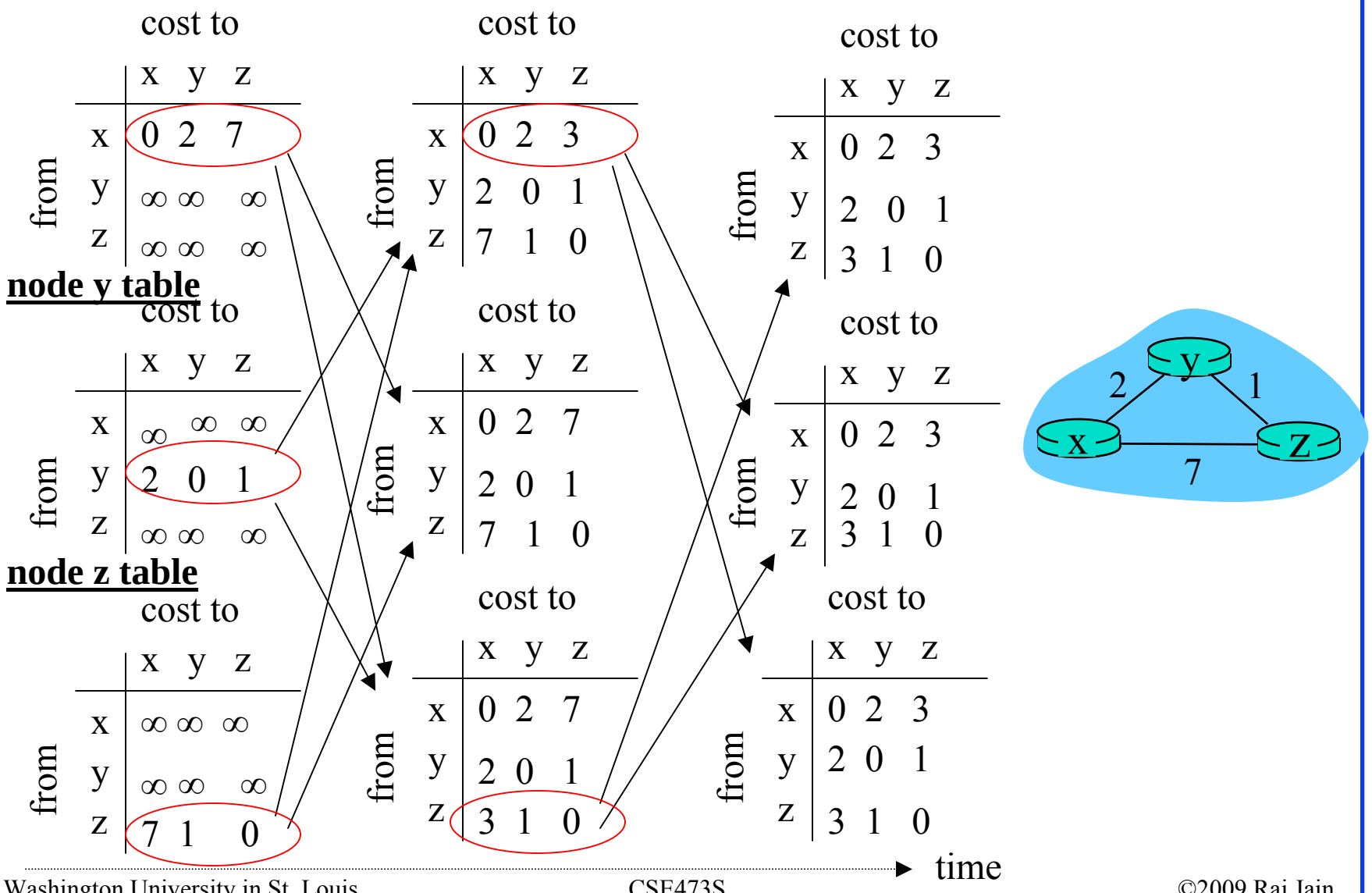


	N'	D(v)	Path	D(w)	Path	D(x)	Path	D(y)	Path	D(z)	Path
0	{u}	2	u-v	5	u-w	1	u-x	∞	-	∞	-
1	{u, x}	2	u-v	4	u-x-w			2	u-x-y	∞	-
2	{u, x, y}	2	u-v	3	u-x-y-w					4	u-x-y-z
3	{u, x, y, v}			3	u-x-y-w					4	u-x-y-z
4	{u, x, y, v, w}									4	u-x-y-z
5	{u, x, y, v, w, z}										

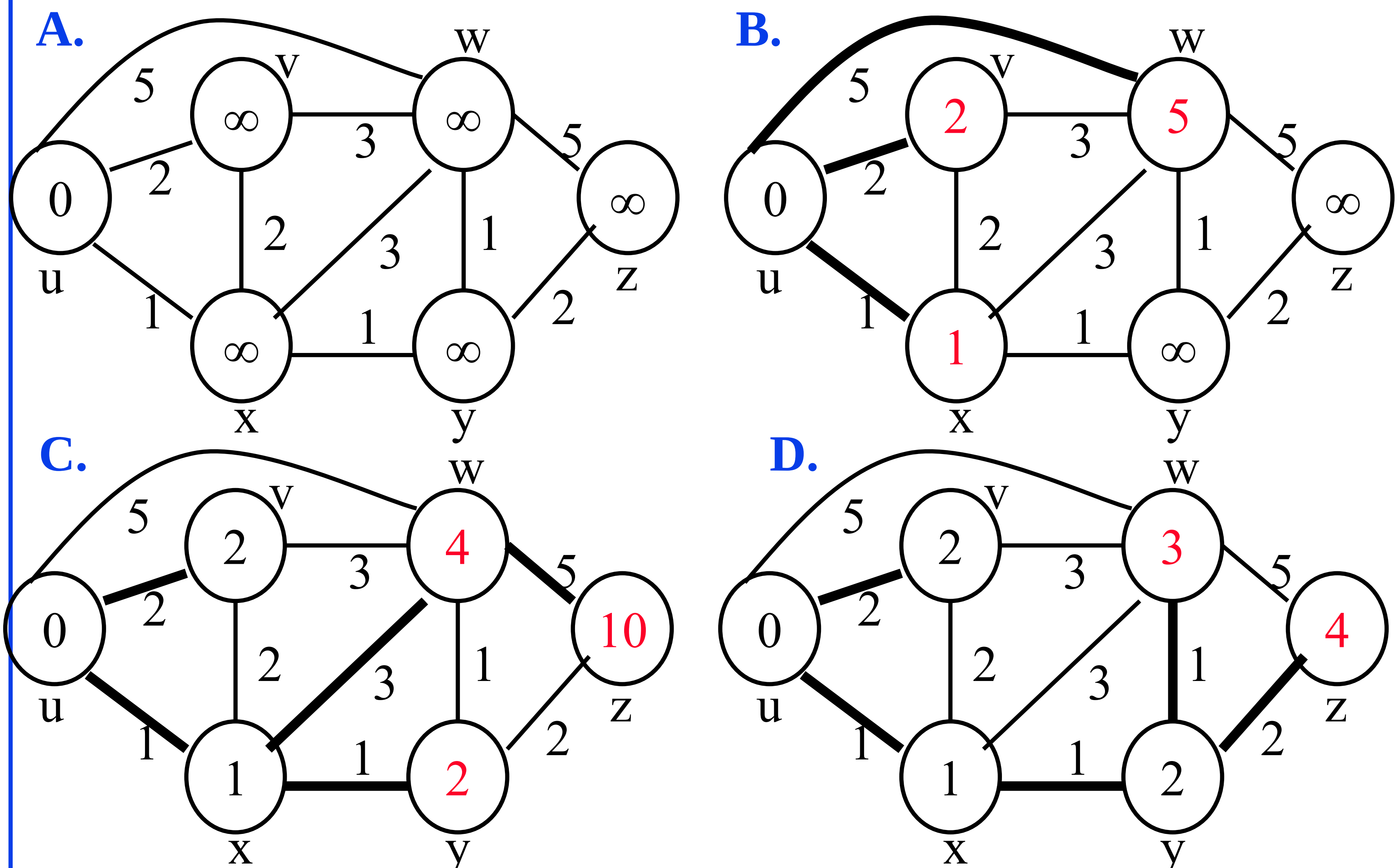
Bellman-Ford Algorithm

- Notation:
  u = Source node
  c(i,j) = link cost from i to j
  h = Number of hops being considered
  $D_u(n)$ = Cost of h-hop path from u to n
- Method:
  1. Initialize: $D_u(n) = \infty$ for all $n \neq u$; $D_u(u) = 0$
  2. For each node: $D_u(n) = \min_j [D_u(j) + c(j,n)]$
  3. If any costs change, repeat step 2

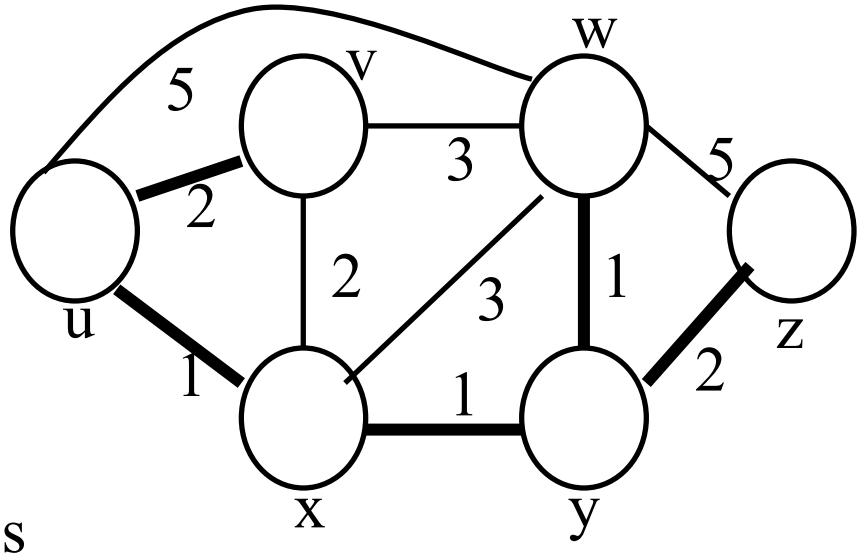
Bellman Ford Example 1



Bellman-Ford Example 2



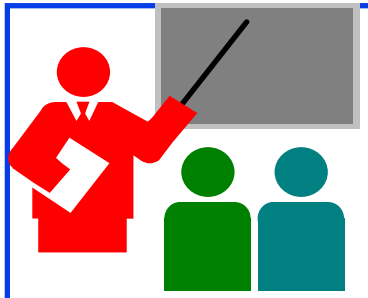
Bellman-Ford: Tabular Method



If cost changes

⇒ Recompute the costs to all neighbors

h	D(v)	Path	D(w)	Path	D(x)	Path	D(y)	Path	D(z)	Path
0	∞	-	∞	-	∞	-	∞	-	∞	-
1	2	u-v	5	u-w	1	u-x	∞	-	∞	-
2	2	u-v	4	u-x-w	1	u-x	2	u-x-y	10	u-w-z
3	2	u-v	3	u-x-y-w	1	u-x	2	u-x-y	4	u-x-y-z
4	2	u-v	3	u-x-y-w	1	u-x	2	u-x-y	4	u-x-y-z

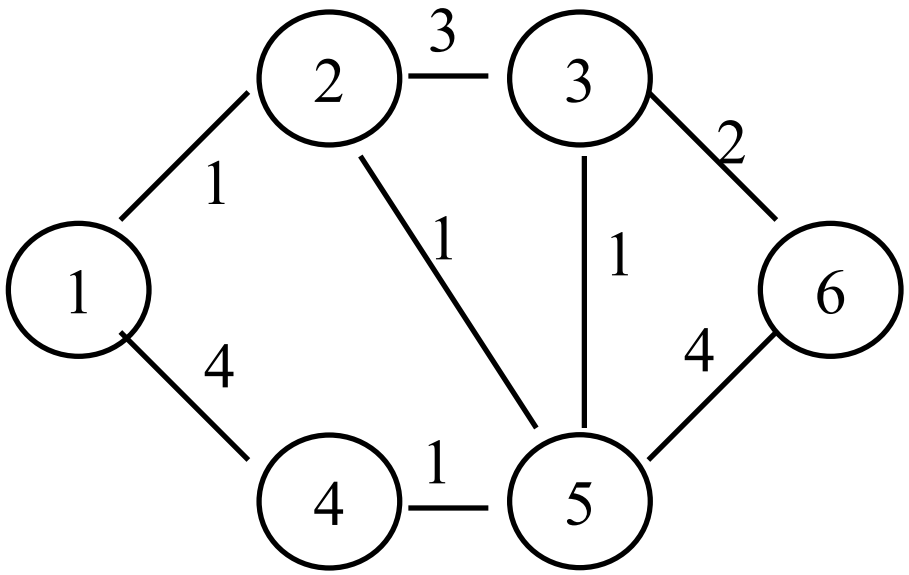


Routing Algorithms: Summary

1. Distance Vectors: Distance to all nodes in the network sent to neighbors
2. Link State: Cost of link to neighbors sent to entire network
3. Dijkstra's algorithm is used to compute shortest path using link state
4. Bellman Ford's algorithm is used to compute shortest paths using distance vectors

Homework 4E

Prepare the routing calculation ***table*** for node 1 in the following network using (a) Dijkstra's algorithm (b) Bellman Ford Algorithm.



Routing Protocols

1. Autonomous Systems (AS)
2. Routing Information Protocol (RIP)
   - Counting to Infinity Problem
3. Open Shortest Path First (OSPF)
   - OSPF Areas
4. Border Gateway Protocol (BGP)

Autonomous Systems

- An internet connected by homogeneous routers under the administrative control of a single entity

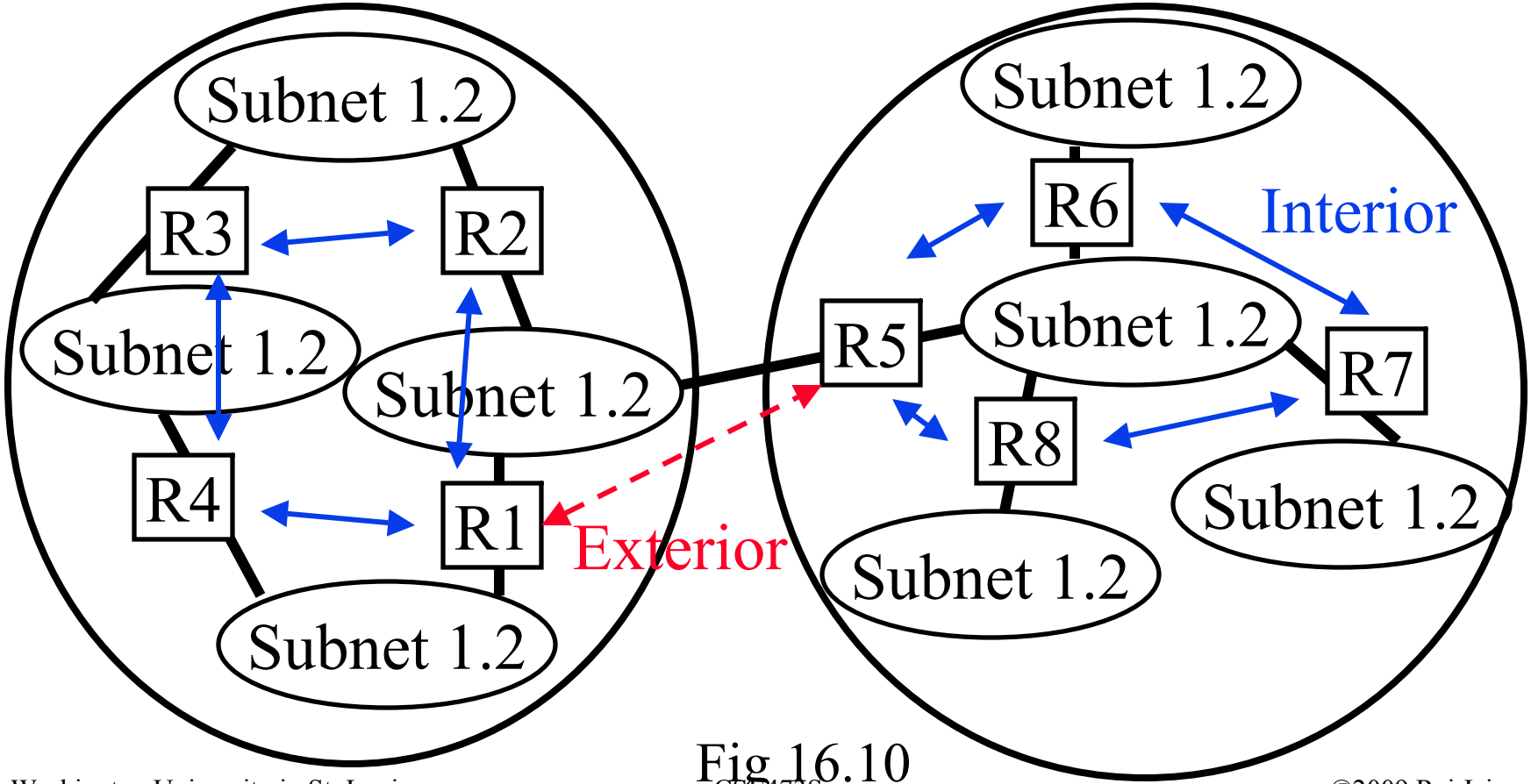


Fig 16.10

Routing Protocols

- Interior Router Protocol (IRP): Used for passing routing information among routers internal to an autonomous system. Also known as IGP.
  - Examples: RIP, OSPF
- Exterior Router Protocol (ERP): Used for passing routing information among routers between autonomous systems. Also known as EGP.
  - Examples: EGP, BGP, IDRP

    Note: EGP is a class as well as an instance in that class.

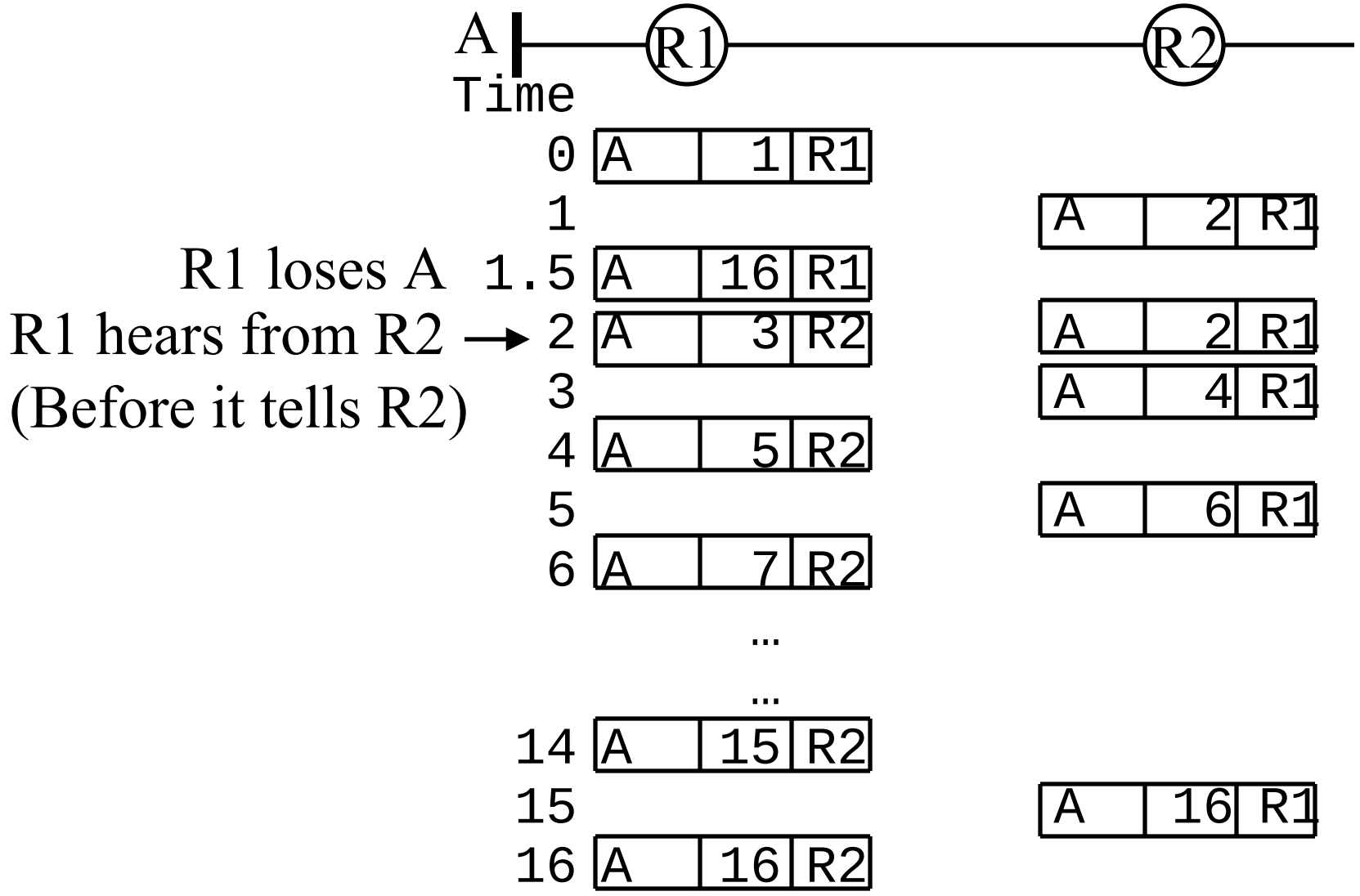
Routing Information Protocol

- RIP uses distance vector $\Rightarrow$ A vector of distances to all nodes is sent to neighbors
- Each router computes new distances:
  - Replace entries with new lower hop counts
  - Insert new entries
  - Replace entries that have the same next hop but higher cost
  - Each entry is aged.
    Remove entries that have aged out
- Send out updates every 30 seconds.

Shortcomings of RIP

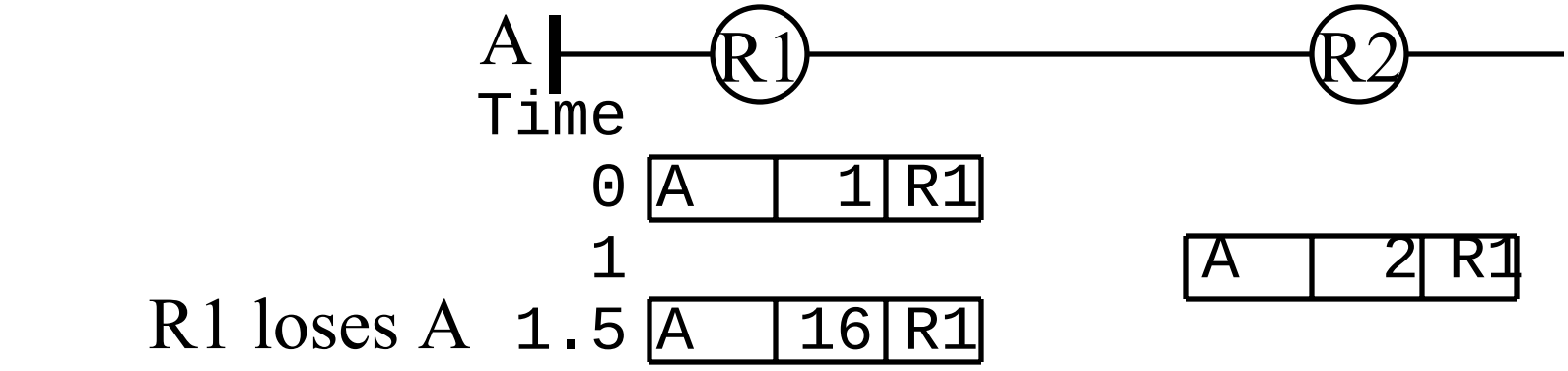
- Maximum network diameter = 15 hops
- Cost is measured in hops
  Only shortest routes. May not be the fastest route.
- Entire tables are broadcast every 30 seconds.
  Bandwidth intensive.
- Uses UDP with 576-byte datagrams.
  Need multiple datagrams.
  300-entry table needs 12 datagrams.
- An error in one routing table is propagated to all routers
- Slow convergence

Counting to Infinity Problem



Improving Convergence

- **Split Horizon**: Remember the port from which a route was learnt. Do not send the route to that port.
- **Hold-down Timer**: If a network is unreachable, ignore all updates for that network for, say, 60 s.
- **Poison Reverse and Triggered Updates**: Once a network is unreachable, it broadcasts it *immediately* to other routers and keeps the entry for some time.



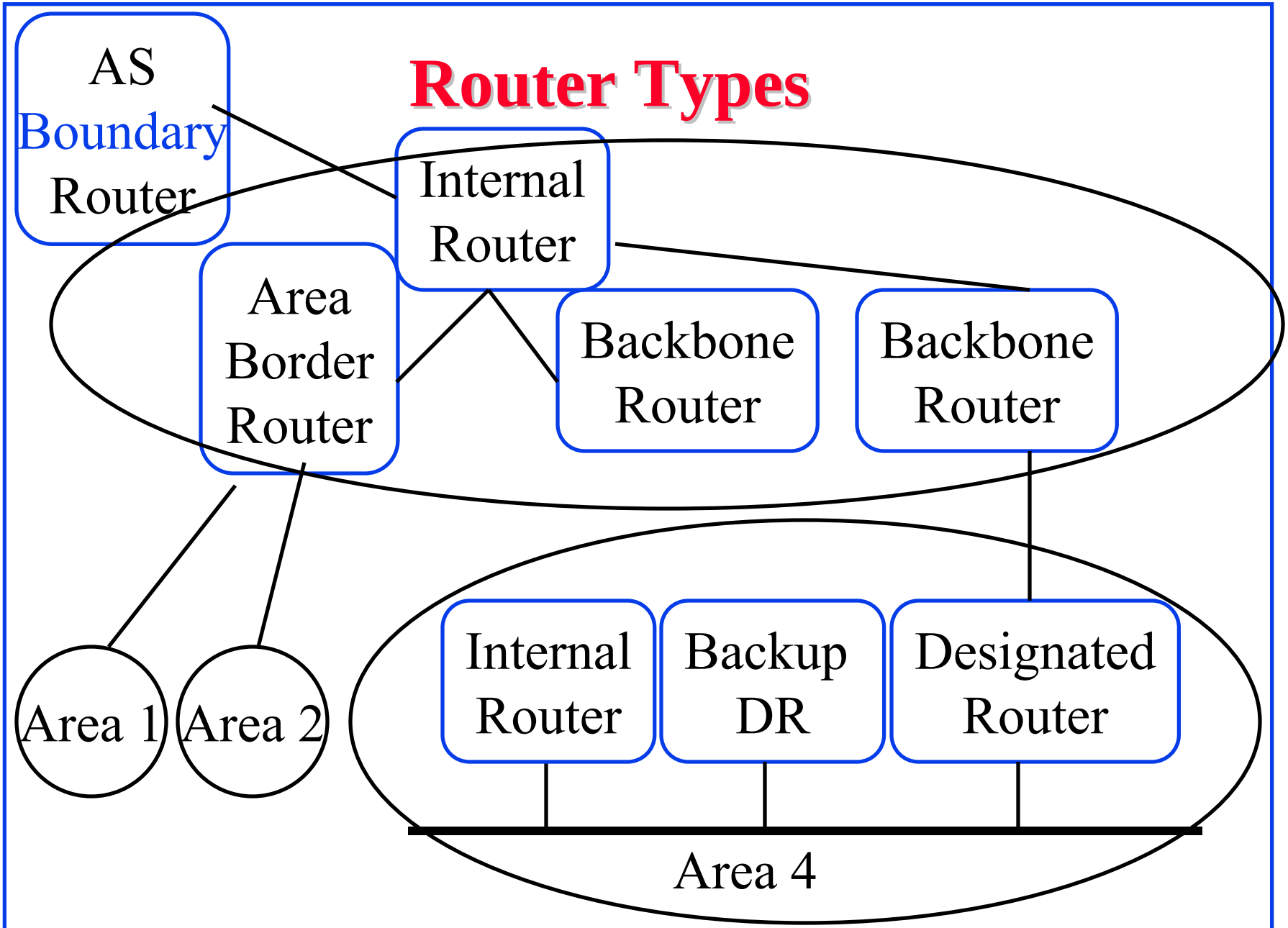
Static vs Dynamic Routing

- Static entries are put manually in the routing table. Also known as default route.
- Static entries override dynamic (learnt) entries.
- Static entry may or may not be included in the dynamic updates.
- Static entries not suitable for large highly dynamic networks.
- Static entries do not automatically change when the link goes down
- Static entries used in hub-and-spoke topologies. All branch routers are programmed to send all external packets to central office.

Open Shortest Path First (OSPF)

- Uses true metrics (not just hop count)
- Uses subnet masks
- Allows load balancing across equal-cost paths
- Supports type of service (ToS)
- Allows external routes (routes learnt from other autonomous systems)
- Authenticates route exchanges
- Quick convergence
- Direct support for multicast
- Link state routing ⇒ Each router broadcasts its connectivity with neighbors to entire network

Router Types



Router Types (Cont)

- **Internal Router (IR)**: All interfaces belong to the same area
- **Area Border Router (ABR):** Interfaces to multiple areas
- **Backbone Router (BR):** Interfaces to the backbone
- **Autonomous System Boundary Router (ASBR):** Exchanges routing info with other autonomous systems
- **Designated Router (DR):** Generates link-state info about the subnet
- **Backup Designated Router (BDR):** Becomes DR if DR fails.

Metrics (Cost)

- RFC 1253: Metric = 10^8/Speed

Bit Rate	Metric
9.6 kbps	10,416
19.2 kbps	5208
56 kbps	1785
64 kbps	1562
T1 (1.544 Mbps)	65
E1 (2.048 Mbps)	48
Ethernet/802.3 (10 Mbps)	10
100 Mbps or more	1

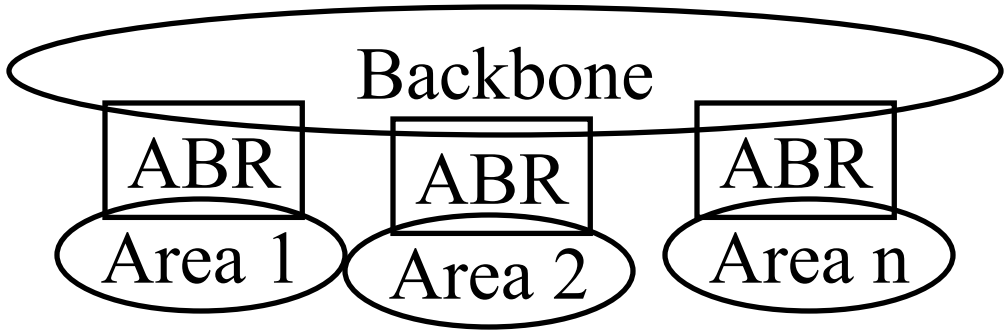
Maintaining the Database

- Databases are continually checked for synchronization by flooding LSAs
- All flooded LSAs are acked. Unacked LSAs are flooded again.
- Database information is checked. If new info, it is forwarded to other adjacencies using LSAs.
- When an entry is aged out, the info is flooded.
- Dijkstra's algorithm is run on every new info, to build new routing tables.

OSPF Areas

- Large networks are divided into areas to reduce routing traffic.
- LSAs are flooded throughout the area
- Area = domain
- Each area has a 32-bit area ID.
- Although areas are written using dot-decimal notation, they are locally assigned.
- The backbone area is area 0 or 0.0.0.0
  Other areas may be 0.0.0.1, 0.0.0.2, …
- Each router has a router ID. Typically formed from IP address of one of its interfaces.

Backbone Area

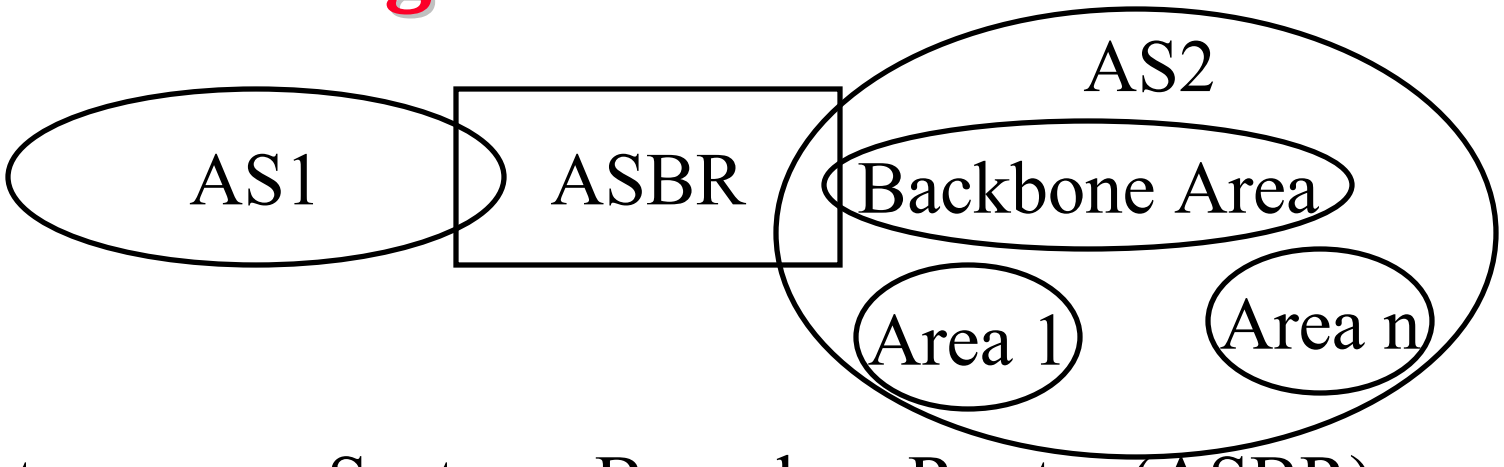


- Area border routers (ABRs) summarize the topology and transmit it to the backbone area
- Backbone routers forward it to other areas
- ABRs connect an area with the backbone area.
  ABRs contain OSPF data for two areas.
  ABRs run OSPF algorithms for the two areas.
- If there is only one area in the AS, there is no backbone area and there are no ABRs.

Inter-Area Routing

- Packets for other areas are sent to ABR
- ABR transmits the packet on the backbone
- Backbone routers send it to the destination area ABR
- Destination ABR forwards it in the destination area.

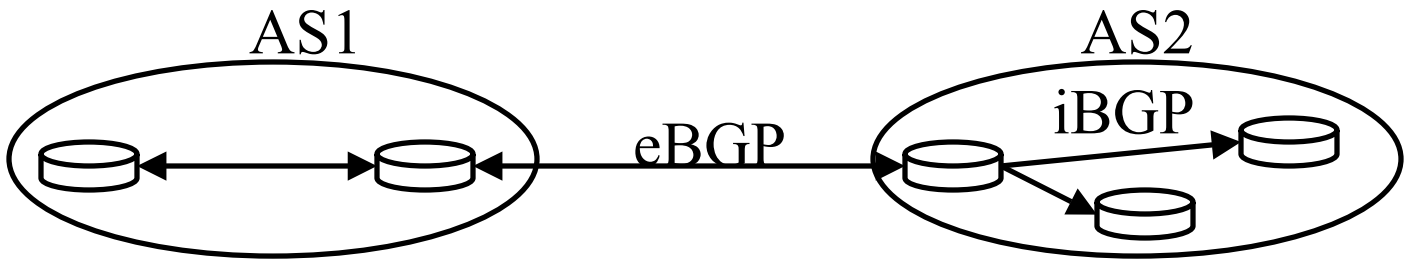
Routing Info from Other ASs



- Autonomous Systems Boundary Router (ASBR) exchanges "exterior gateway protocol (EGP)" messages with other autonomous systems
- ASBRs generate "external link advertisements." These are flooded to all areas of the AS. There is one entry for every external route.

Border Gateway Protocol

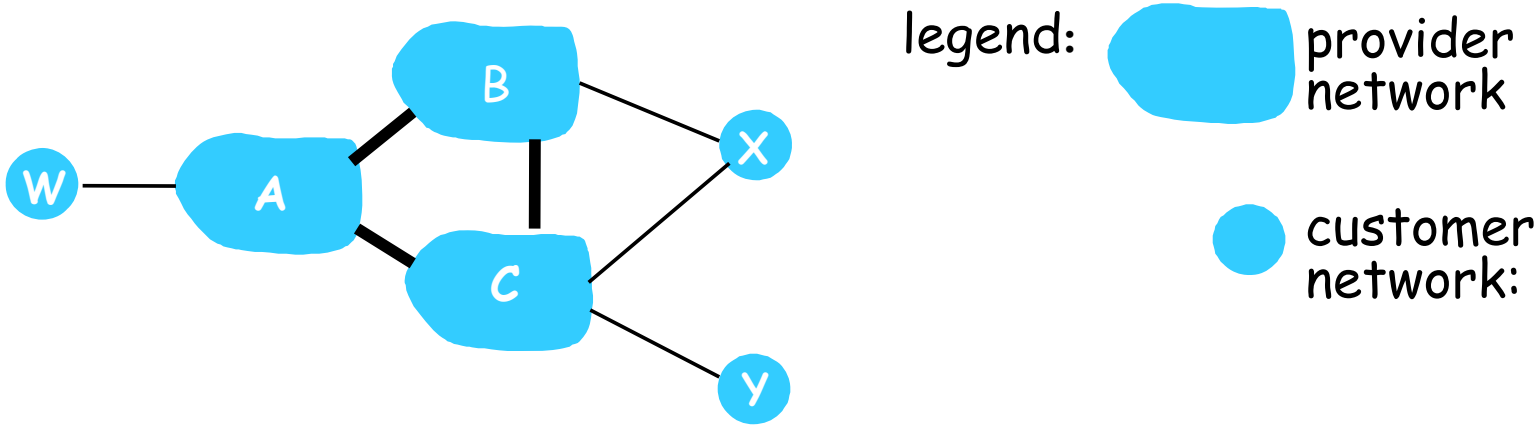
- Inter-autonomous system protocol [RFC 1267]
- Used since 1989 but not extensively until recently
- Runs on TCP (segmentation, reliable transmission)
- Advertises all transit ASs on the path to a destination address
- A router may receive multiple paths to a destination ⇒ Can choose the best path
- iBGP used to forward paths inside the AS.
  eBGP used to exchange paths between ASs.



BGP Operations

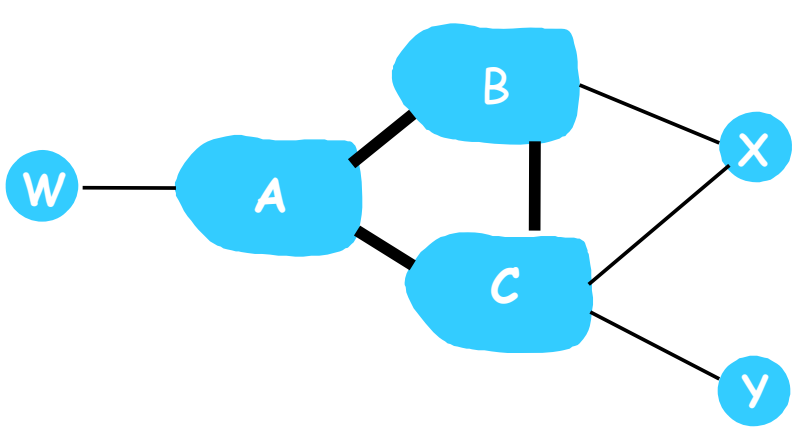
- BGP systems initially exchange entire routing tables. Afterwards, only updates are exchanged.
- BGP messages have the following information:
  - Origin of path information: RIP, OSPF, …
  - AS_Path: List of ASs on the path to reach the dest
  - Next_Hop: IP address of the border router to be used as the next hop to reach the dest
  - Unreachable: If a previously advertised route has become unreachable
- BGP speakers generate update messages to all peers when it selects a new route or some route becomes unreachable.

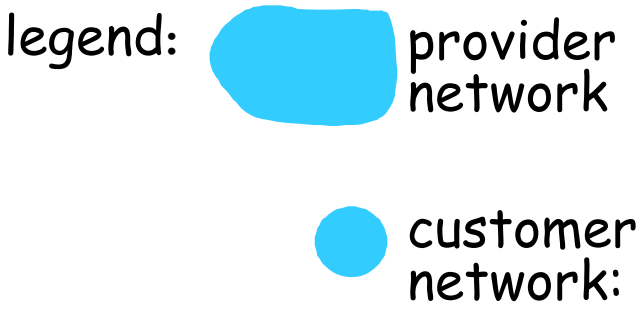
BGP Routing Policy Example



- A,B,C are provider networks
- X,W,Y are customer (of provider networks)
- X is dual-homed: attached to two networks
  - X does not want to route from B via X to C
  - .. so X will not advertise to B a route to C

BGP Routing Policy Example (Cont)

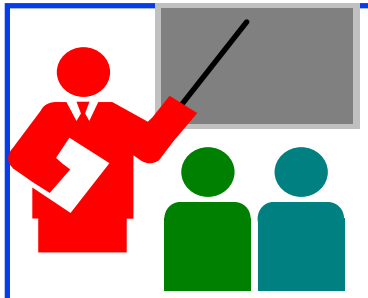




- A advertises path A-W to B
- B advertises path B-A-W to X
- Should B advertise path B-A-W to C?
  - No way! B gets no "revenue" for routing C-B-A-W since neither W nor C are B's customers
  - B wants to force C to route to w via A
  - B wants to route *only* to/from its customers!

Intra- vs. Inter-AS Routing

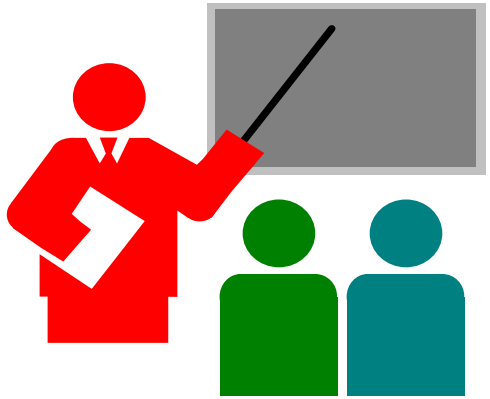
- **Policy:**
  - Inter-AS: admin wants control over how its traffic routed, who routes through its net.
  - Intra-AS: single admin, so no policy decisions needed
- **Scale**:
  - Hierarchical routing saves table size, reduced update traffic
- **Performance**:
  - Intra-AS: can focus on performance
  - Inter-AS: policy may dominate over performance



Routing Protocols: Summary

1. RIP uses distance-vector routing
2. RIP v2 fixes the slow convergence problem
3. OSPF uses link-state routing and divides the autonomous systems into multiple areas.
   Area border router, AS boundary router, designated router
4. BGP is an inter-AS protocol ⇒ Policy driven

Network Layer: Summary



1. IP is a forwarding protocol. IPv6 uses 128 bit addressing.
2. Dijkstra's algorithm allows path computation using link state
3. Bellman Ford's algorithm allows path computation using distance vectors.
4. RIP is a distance vector IGP while OSPF is a link state IGP.
5. BGP is an EGP and uses path vectors