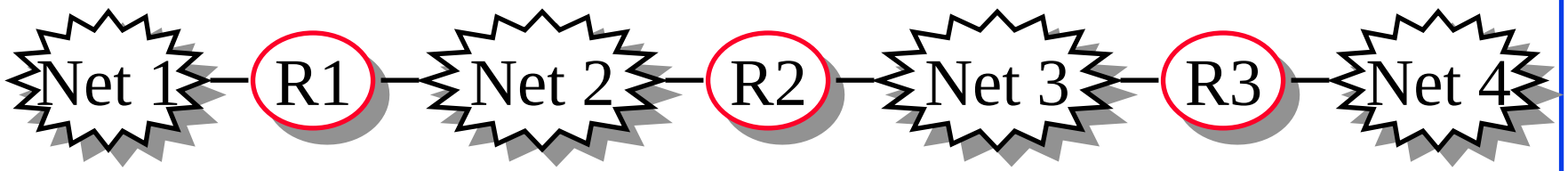
The Network Layer: Data Plane



Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@wustl.edu

Audio/Video recordings of this lecture are available online at:

http://www.cse.wustl.edu/~jain/cse4703-26/

Student Questions



Overview

1. Network Layer Basics
2. What's inside a router?
3. Forwarding Protocols: IPv4, DHCP, NAT, IPv6
4. Software Defined Networking

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

Student Questions



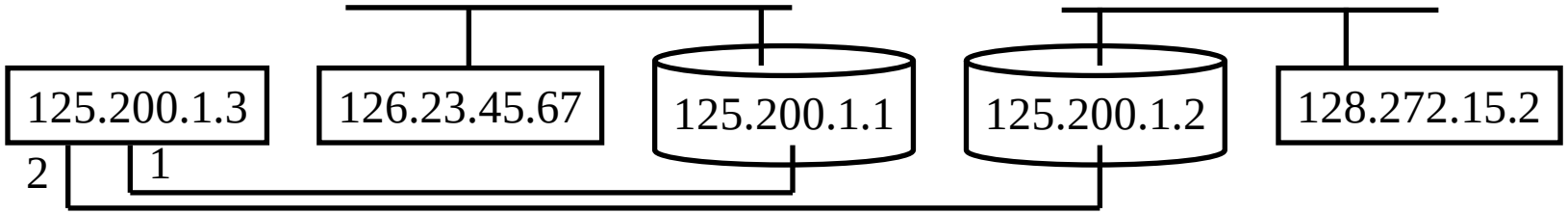
Network Layer Basics

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

Student Questions

Forwarding and Routing

- **Forwarding**: Input link to output link via Address prefix lookup in a table.
- **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

Student Questions

- I feel like I understand how generalized forwarding works, but not exactly why generalized forwarding exists. Are there any examples of why it can be important or useful to consider other values besides the address in determining the interface?

Speed of the link is one possibility. Interfaces are like multiple airports in a city.

- Why does the longest prefix match use the most specific prefix?

That is the shortest path.

Ref: Optional Homework: R3 in the textbook

©2026 Raj Jain

Network Service Models

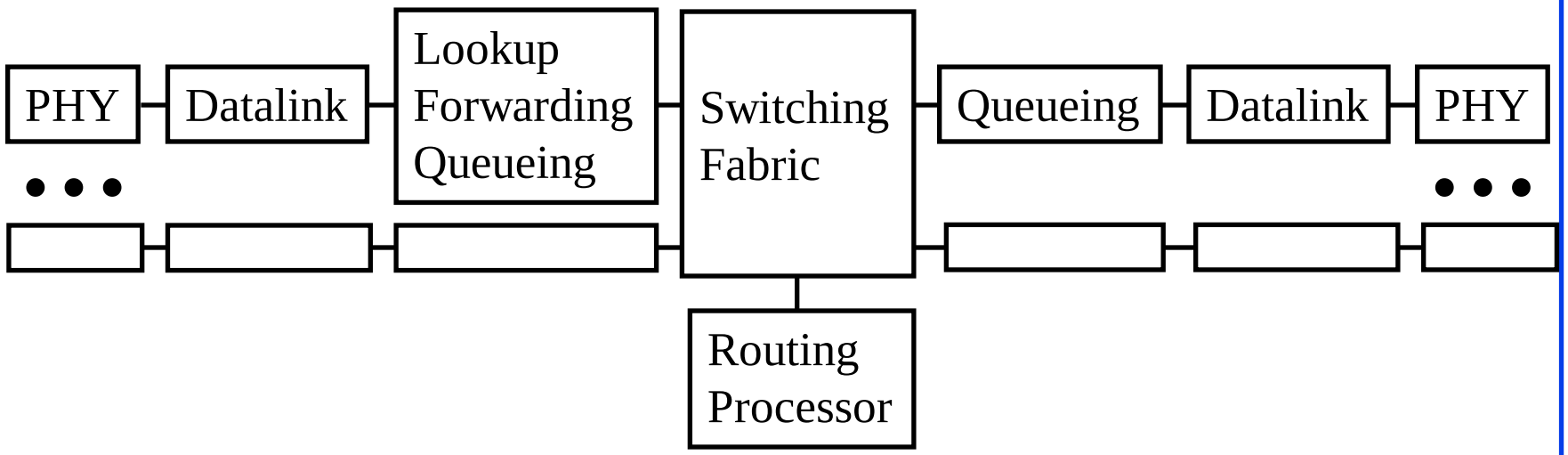
- Guaranteed Delivery: No packets lost
- Bounded delay: Maximum delay
- In-order packet delivery: Some packets may be missing
- Guaranteed minimal throughput
- Guaranteed maximum jitter: Delay variation
- Security Services (optional in most networks)
- ATM offered most of these (no longer used).
- IP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

Optional Homework: R4, R5 in the textbook

Student Questions

©2026 Raj Jain

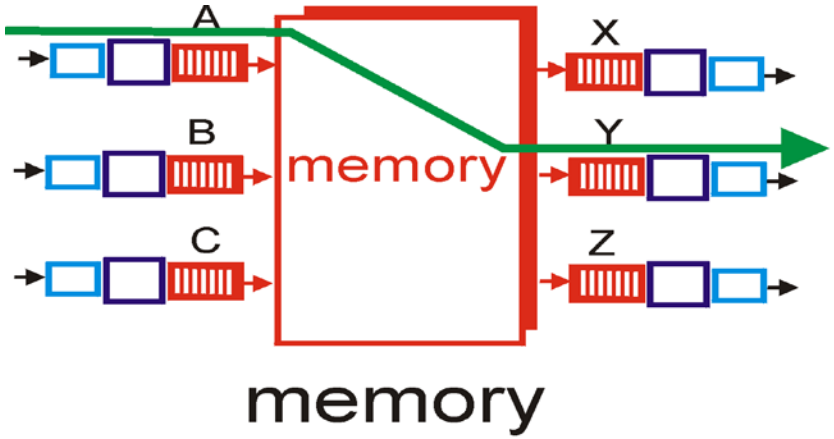
What's Inside a Router?



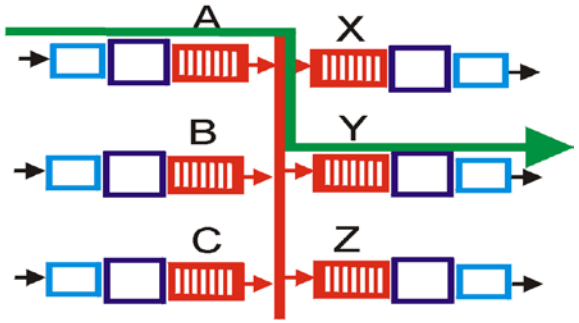
- **Input Ports**: receive packets, lookup address, queue
  Use **Content Addressable Memories** (CAMs) and caching
- **Switch Fabric**: Send from the input port to the output port
- **Output Ports**: Queuing, transmitting packets

Student Questions

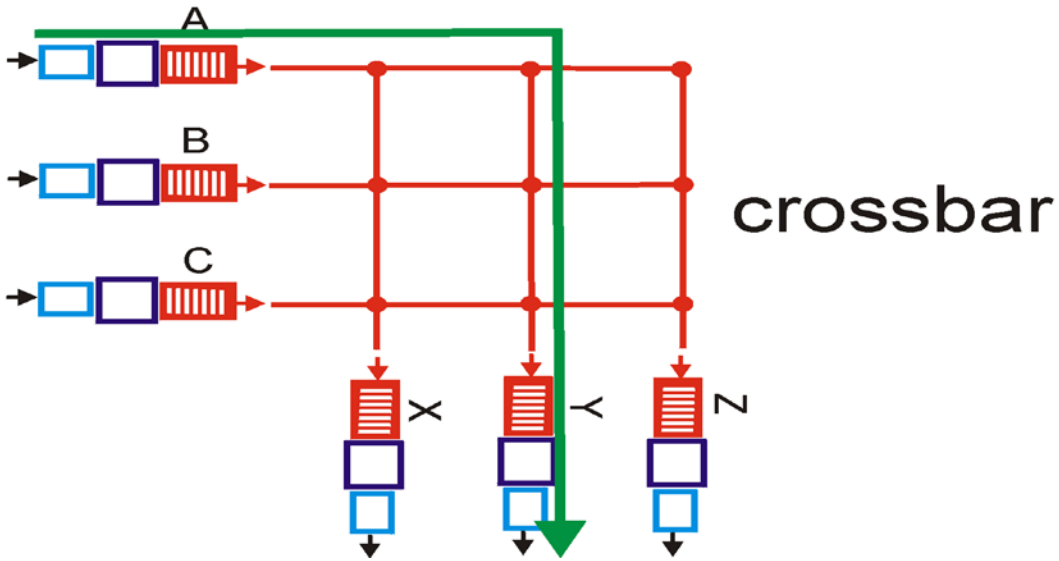
Types of Switching Fabrics



memory



bus



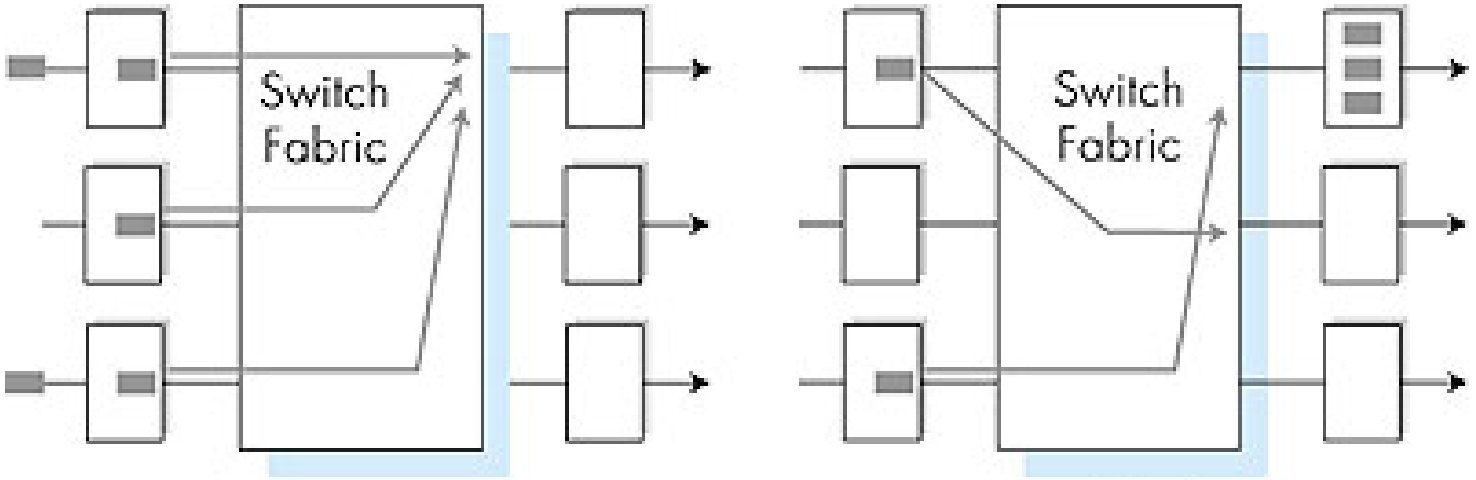
crossbar

Student Questions

©2026 Raj Jain

Where Does Queuing Occur?

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

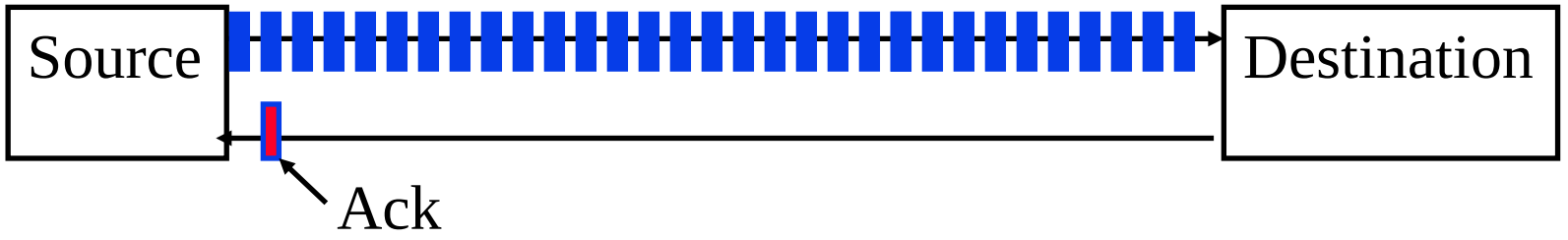


Output Port Contention at Time *t*

One Packet Time Later

Student Questions

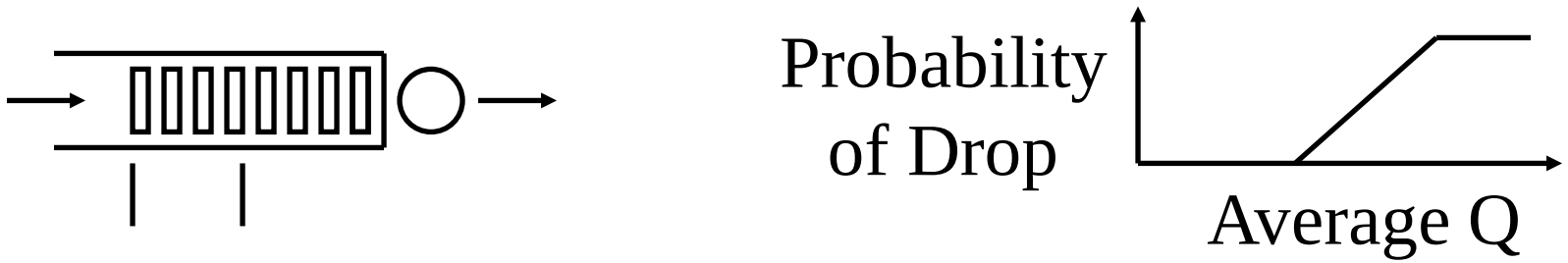
Ideal Buffering



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

Student Questions

Packet Dropping Policies



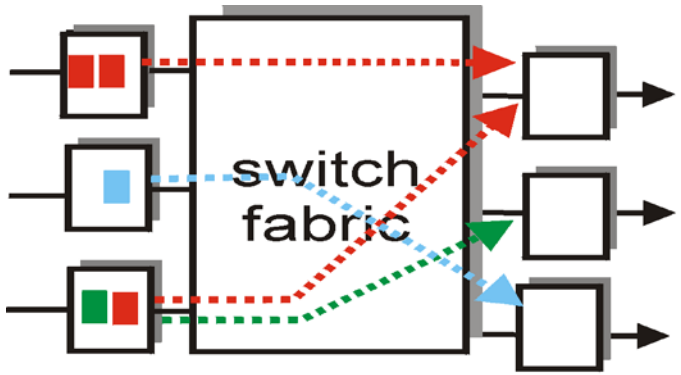
- **Drop-Tail**: Drop the arriving packet
- **Random Early Drop (RED):** Drop arriving packets even before the queue is full
  - Routers measure the average queue and drop incoming packets with a certain probability

  ⇒ **Active Queue Management** (AQM)

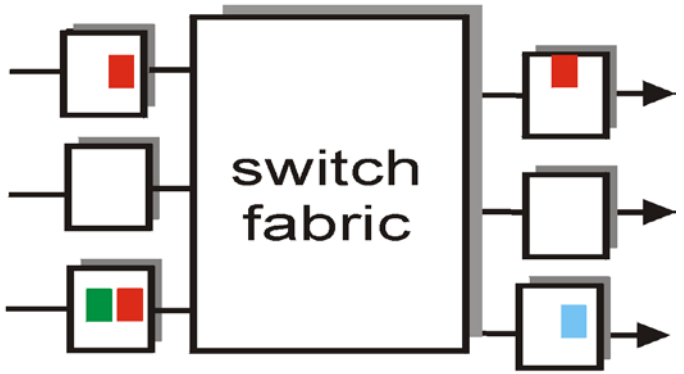
Student Questions

Head-of-Line Blocking

- The packet at the head of the queue is waiting
  ⇒ Other packets can not be forwarded even if they go to another destination.



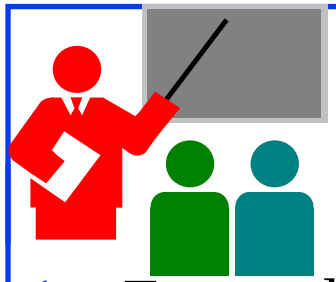
output port contention at time t - only one red packet can be transferred



green packet experiences HOL blocking

Student Questions

©2026 Raj Jain



Network Layer Basics: Review

1. Forwarding uses a routing table to find the output port for datagrams using **the longest prefix match**. Routing protocols make the table.
2. Routers include input/output ports, **switching fabric**, and processors.
3. Datagrams may be dropped even if the queues are not full (**Random early drop**).
4. Queueing at the input may result in **head-of-line blocking**.

Student Questions

Ref: Read Sections 4.1, 4.2, full, Page 303-330 of the textbook. Try R1 through R16

©2026 Raj Jain

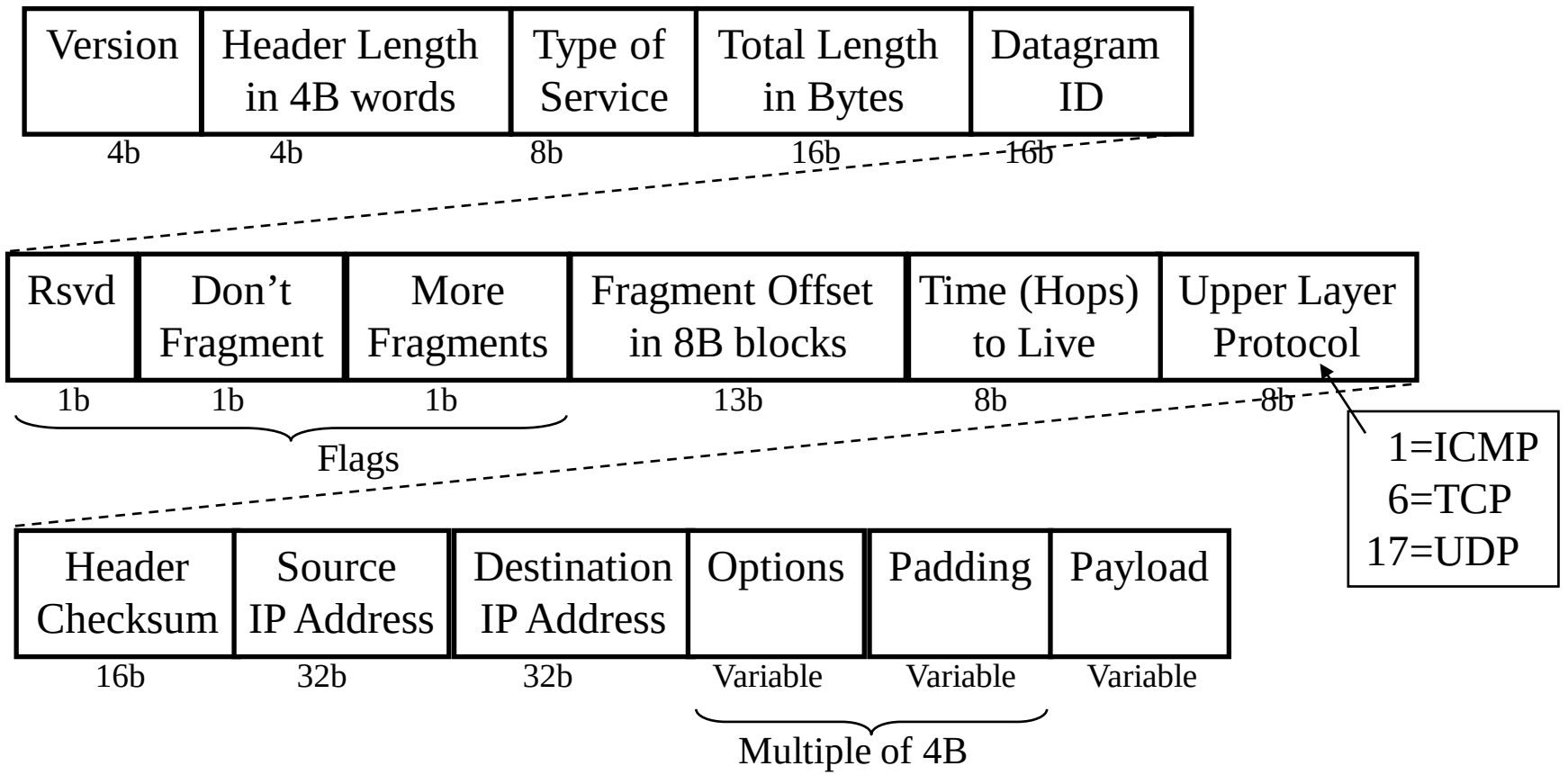


Forwarding Protocols

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. IPv6

Student Questions

IP Datagram Format



Student Questions

©2026 Raj Jain

IP Fragmentation Fields

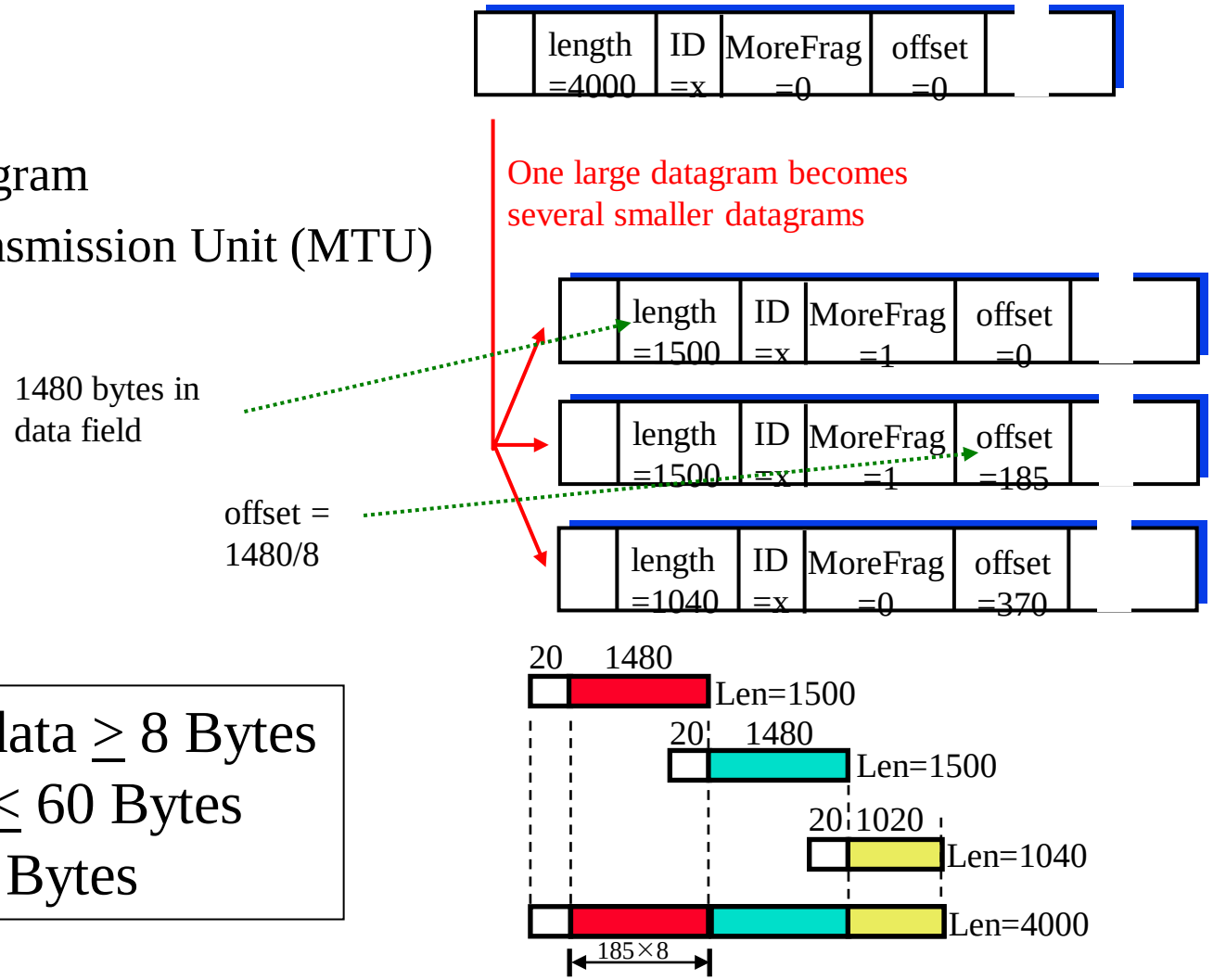
- Header length: in units of 32-bit words
- Data Unit Identifier (ID)
  - Sending host puts an identification number in each datagram
- Total length: Length of user data plus header in bytes
- Fragment Offset - Position of a fragment in the original datagram
    - In multiples of 8-byte blocks
- *More fragments* 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

Student Questions

IP Fragmentation and Reassembly

Example

- 4000 byte datagram
- Maximum Transmission Unit (MTU) = 1500 bytes



Fragment data ≥ 8 Bytes
IP Header ≤ 60 Bytes
MTU ≥ 68 Bytes

Student Questions

©2026 Raj Jain

Homework 4A: Fragmentation

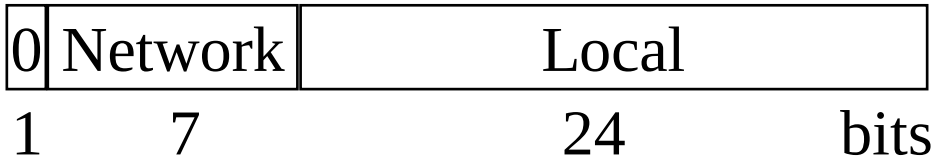
- [8 points] Consider sending a 3500-byte datagram into a link that has an MTU of 800 bytes. Suppose the original datagram is stamped with the identification number 450. How many fragments are generated? What are the values in the various fields in the IP datagram(s) generated related to fragmentation?

Student Questions

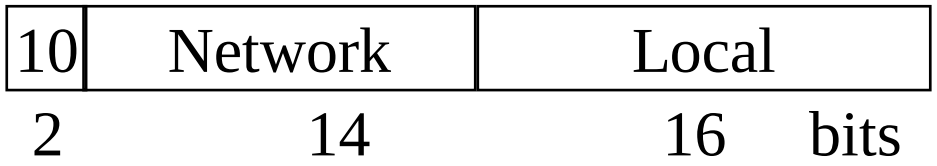
End of Part 1

IP Address Classes

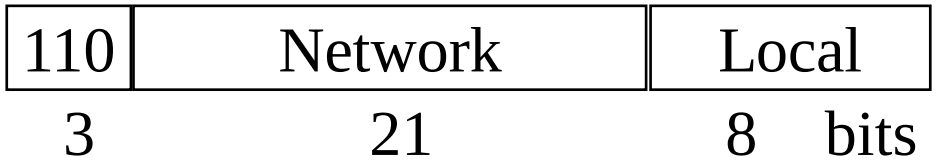
- Class A:



- Class B:



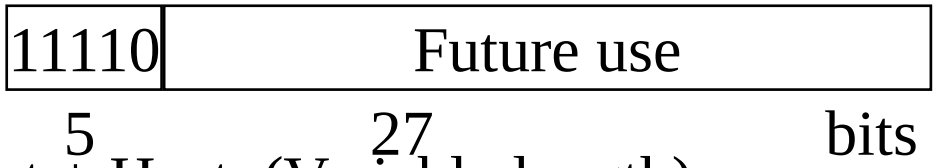
- Class C:



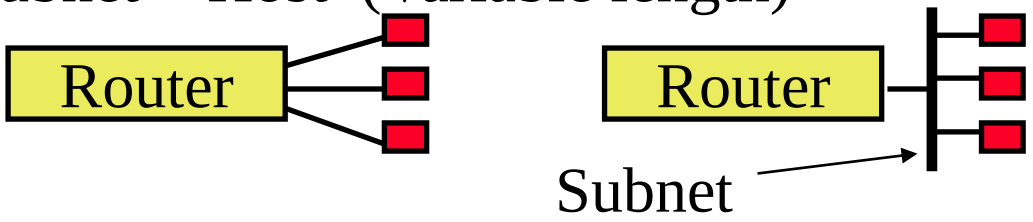
- Class D:



- Class E:



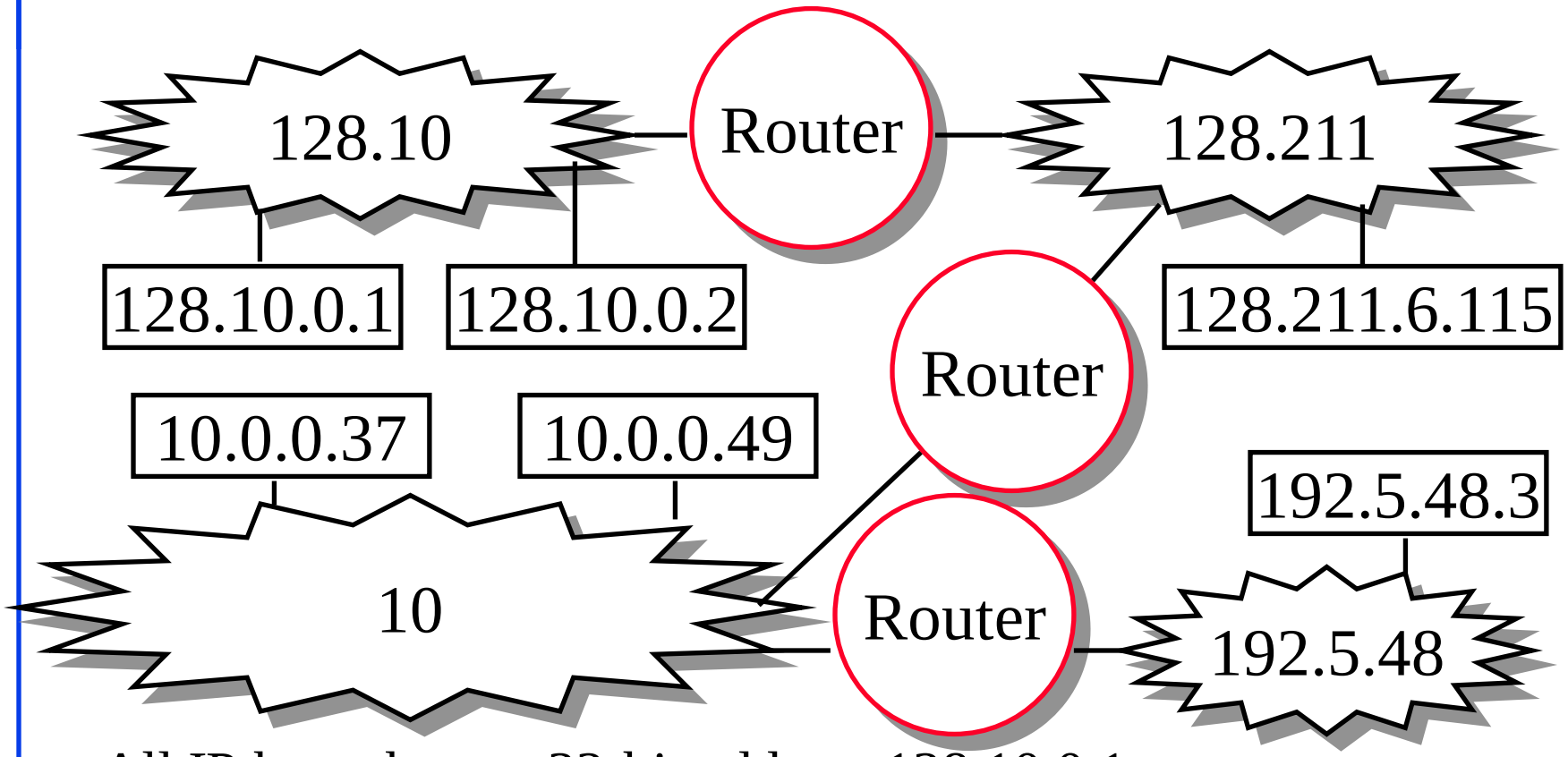
- Local = Subnet + Host (Variable length)



Student Questions

©2026 Raj Jain

IP Addressing

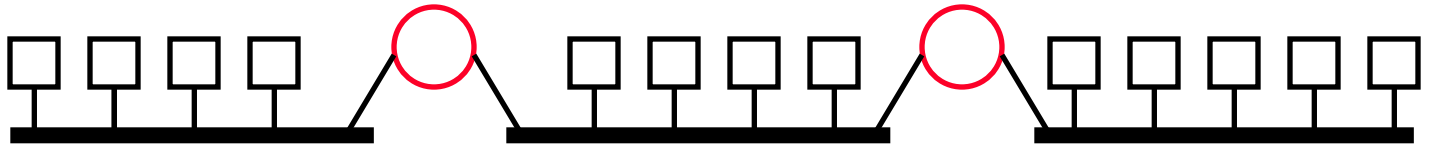


- All IP hosts have a 32-bit address.128.10.0.1 =1000 0000 0000 1010 0000 0000 0000 0001
- All hosts on a network have the same network prefix

Student Questions

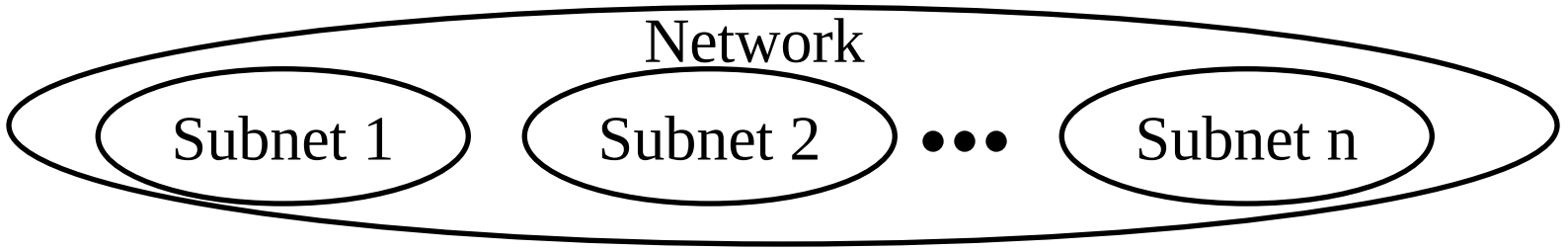
©2026 Raj Jain

Subnetting



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

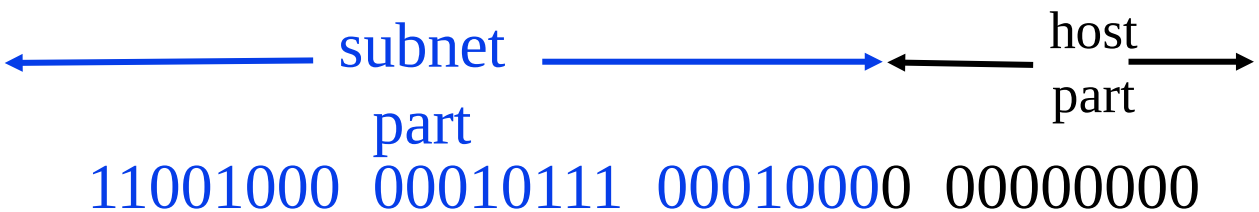
  Address: 10010100 10101000 00010000 11110001
  Mask: 11111111 11111111 11111110 00000000
  .AND. 10010100 10101000 00010000 00000000



Student Questions

IP addressing: CIDR

- CIDR: Classless Interdomain Routing
  - Subnet portion of the address of arbitrary length
  - Address format: a.b.c.d/x, where x is # bits in the subnet portion of the address
  - All 1's in the host part is used for subnet broadcast
  - All 0s in the host part were meant as "subnet address" but not used for anything. Some implementations allow it to be used as a host address. Some don't. It's better to avoid it.



200.23.16.0/23

Student Questions

Homework 4B: Subnets

- [18 points] Consider a router interconnecting three subnets: Subnet 1, Subnet 2, and Subnet 3. Suppose all of the interfaces in these three subnets must have the prefix 223.1.17/24. Also, suppose that Subnet 1 is required to support up to 60 interfaces, Subnet 2 is to support up to 80 interfaces, and Subnet 3 is to support up to 30 interfaces. Provide three network address prefixes (a.b.c.d/x) that satisfy these constraints. **Use adjacent allocations**. For each subnet, list the subnet mask to use in the hosts.

Student Questions

Forwarding an IP Datagram

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

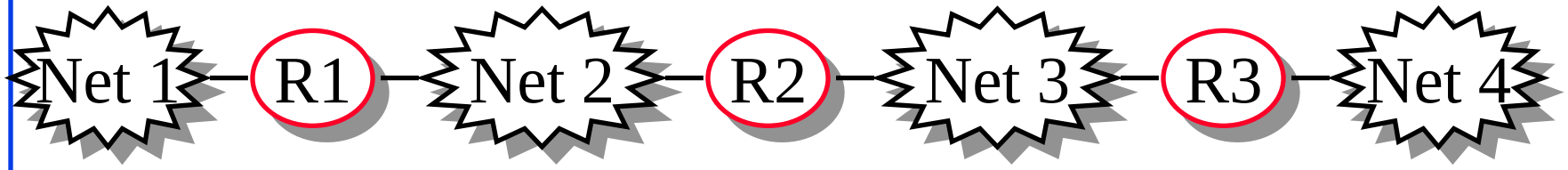


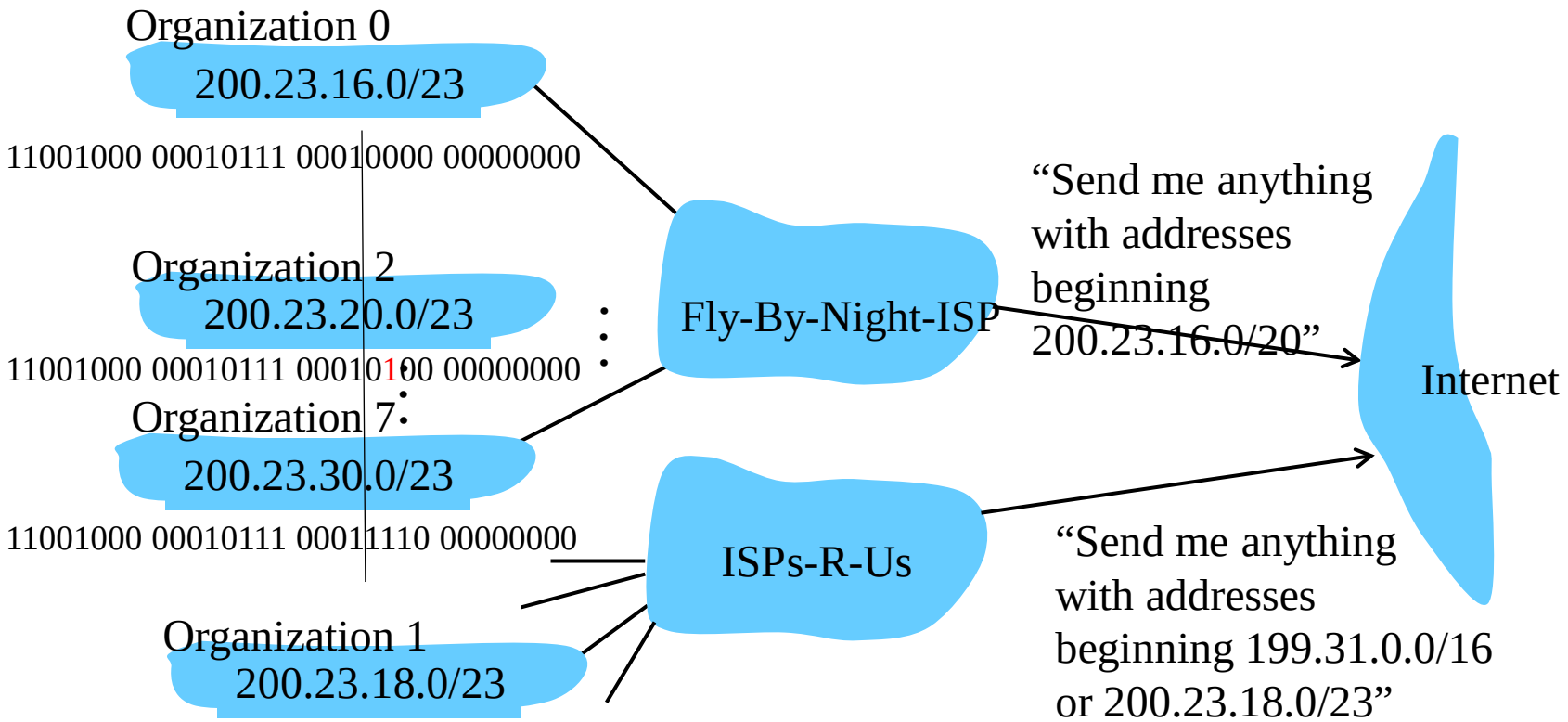
Table at R2:

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

Student Questions

Route Aggregation

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



Ref: Section 4.3.2. Try R27, R28

©2026 Raj Jain

Student Questions

"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
```

Adr & mask = Dest
⇒ Match

Longest Prefix match is used

Metric: Lower is better

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

Student Questions

©2026 Raj Jain

Lab 4A: Routing Table

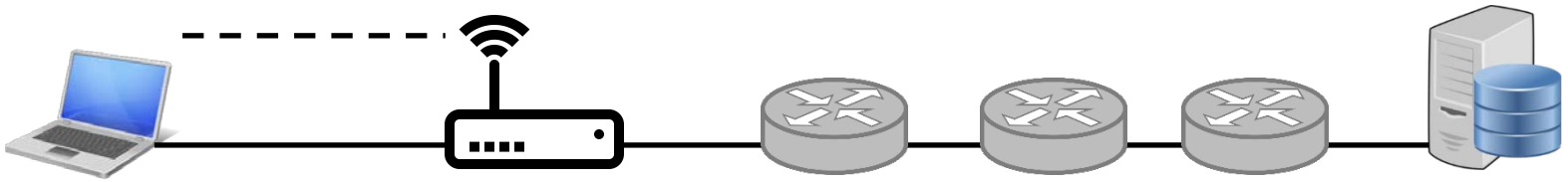
- [8 Points] Use "Route Help" in Windows (or man route in MAC) to learn the route command
- Ping www.google.com to find its address
- Ensure you have two active interfaces, preferably connected to different routers. For example, create a 2nd interface by connecting a smartphone hotspot via USB. You can also connect two smartphone with different carriers hotspots to a single computer using two USB cables.
- Print route table
- Trace route to www.google.com using tracert
- Modify the routing table so that the other interface will be used.
- Note the command you used to modify the routing table
- Print the new routing table
- Trace route to the same numeric address for www.google.com as before. Submit underlined items.

Student Questions

©2026 Raj Jain

Lab 4A Hints

- A host with two interfaces going to the same router:



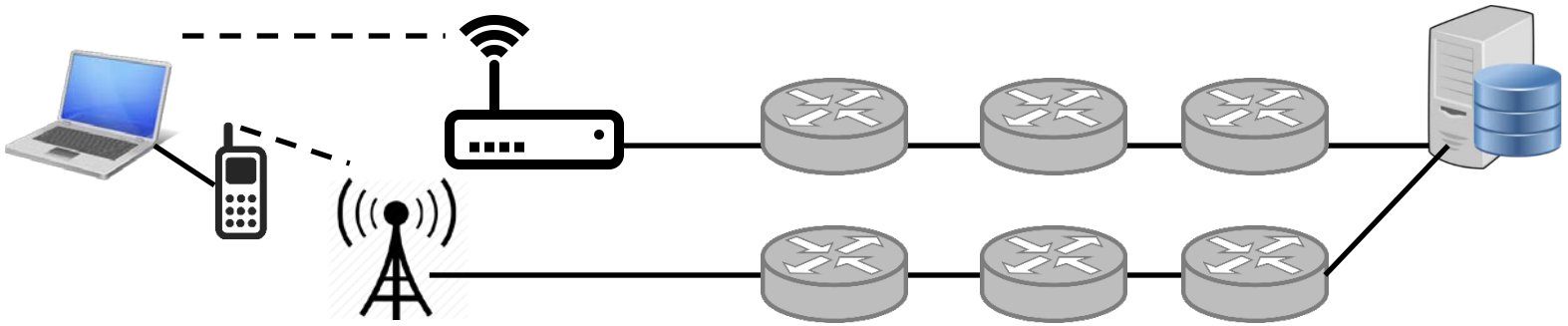
- Trace route result will not change even if you change the interface.

```
IPv4 Route Table
===========================================================================
Active Routes:
Network Destination        Netmask          Gateway       Interface  Metric
          0.0.0.0          0.0.0.0      192.168.0.1    192.168.0.152     55
          0.0.0.0          0.0.0.0      192.168.0.1    192.168.0.151     25
```

Student Questions

Lab 4A Hints (Cont)

- If you have two routers, you can see the effect in trace route. One way to get two routers is to use your cell phone hot spot:



```
IPv4 Route Table
===========================================================================
Active Routes:
Network Destination        Netmask          Gateway       Interface  Metric
          0.0.0.0          0.0.0.0      192.168.0.1    192.168.0.151     25
          0.0.0.0          0.0.0.0      172.20.10.1     172.20.10.2     35
```

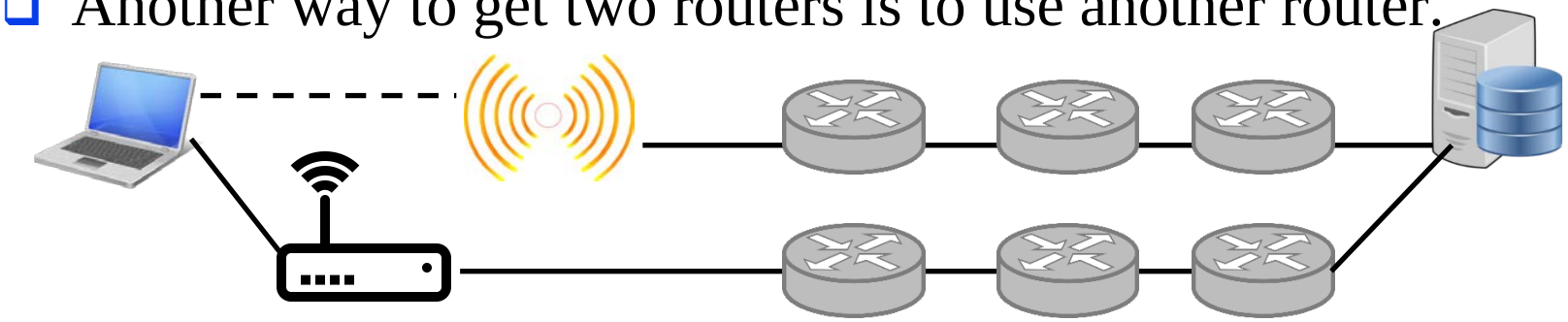
- WiFi on your phone should be disabled to ensure that it does not forward traffic to the same home router.

Student Questions

©2026 Raj Jain

Lab 4A Hints (Cont)

- One way to get two routers is to use Ethernet interface in any WUSTL lab and then use your phones hotspot. The phone's Wi-Fi should be off to ensure that it does not connect to WUSTL router.
- Another way to get two routers is to use another router.



```
IPv4 Route Table
===========================================================================
Active Routes:
Network Destination        Netmask          Gateway       Interface  Metric
          0.0.0.0          0.0.0.0      192.168.0.1    192.168.0.151     25
          0.0.0.0          0.0.0.0      172.20.10.1     172.20.10.2     35
```

Student Questions

Lab 4A Hints (Cont)

- WWW.google.com may have different IP addresses on different networks, so trace the route to the same numeric address.
- WUSTL VPN rejects all traffic not going to WUSTL. So, it can not be used as the 2nd interface.
- The new metric assigned by the route command may not be what you specified. So always check using route print.
- In Windows, you may need to change the network priority of the adapter(s) to be able to see both networks. See: https://windowsloop.com/change-network-priority-in-windows/

Student Questions

Lab 4A Hints (Cont)

A. Use "route help" to learn the route command

- **Windows:** route help
- **Linux:** route help
- **MAC:**
  - man netstat
  - man route

B. Ping www.google.com to find its address

  - ping www.google.com

C. Print the new routing table

- **Windows:**
  - route print
- **Linux:**
  - route
- **MAC:**
  - netstat -nr

D. Modify routing tables

- **Windows:**
  - route add/delete/change
- **Linux:**
  - route add/del
- **MAC:**
  - sudo route –nv add

E. Verify using tracert

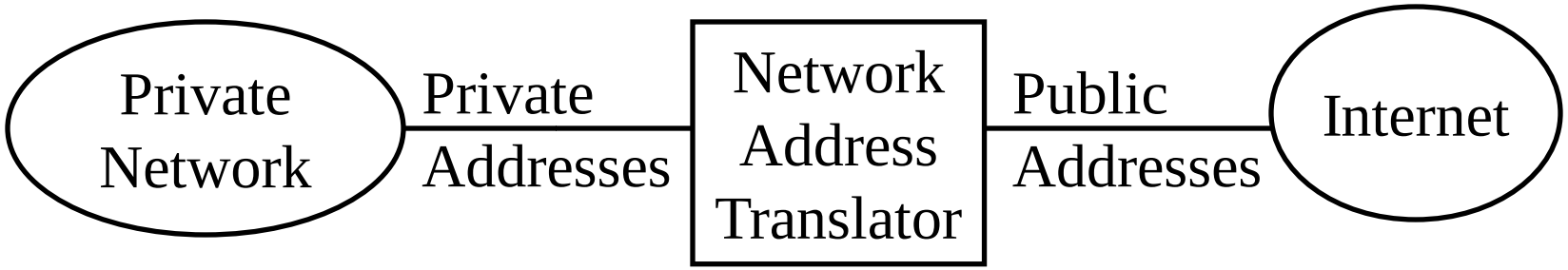
- **Windows:**
  - tracert
- **Linux:**
  - traceroute
- **MAC:**
  - traceroute

Student Questions

©2026 Raj Jain

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)

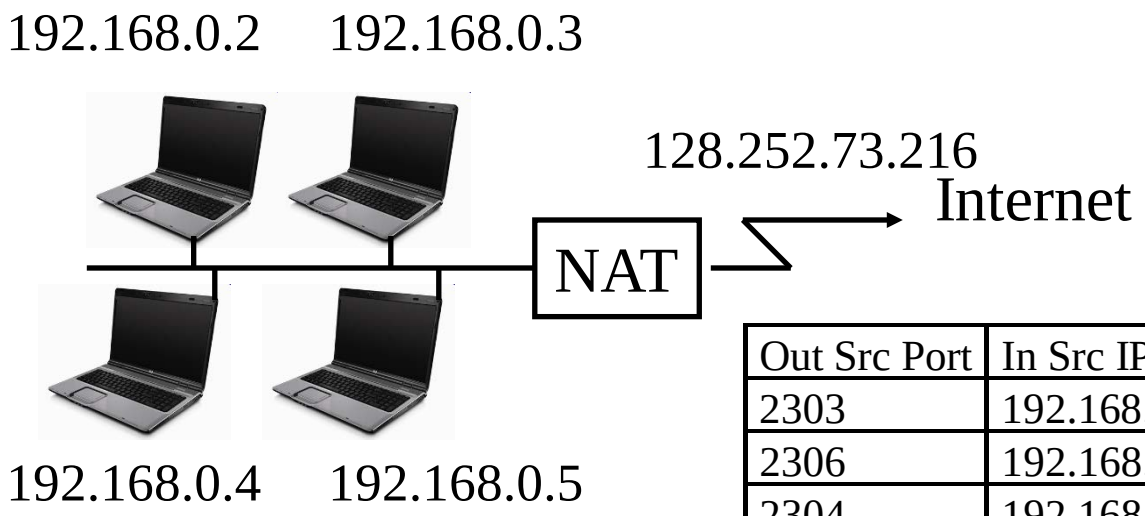


Student Questions

- What are the differences between those different classes of private addresses? What are the use cases for each one?

These are not classes. These are possibilities. The network admin can choose anyone. They will want to avoid the range used by the outer network. For example, CSE inside WUSTL.

Network Address Translation (NAT)



Out Src Port	In Src IP	In Src Port
2303	192.168.0.2	3385
2306	192.168.0.3	3385
2304	192.168.0.2	30384

- Private IP addresses 192.168.x.x: Can be used inside networks
- Cannot be used on the public Internet
- NAT overwrites the source address and source port on all outgoing packets with a unique port #. Then, it rewrites the correct destination IP and port on all incoming packets using the destination port in the packet as a key.
- Only outgoing connections are possible

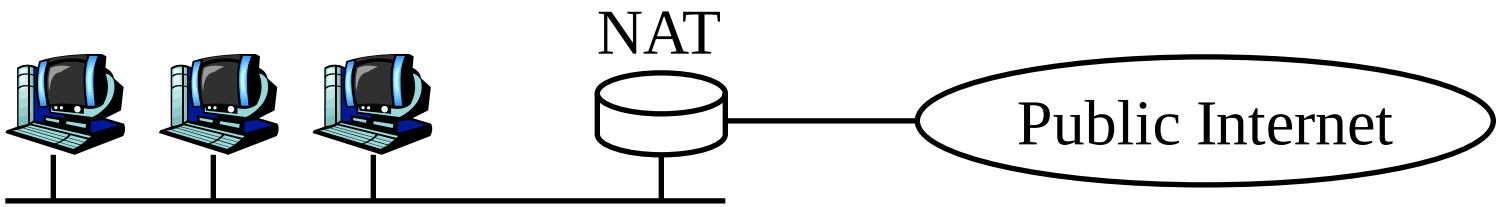
Student Questions

- How are NAT tables created?

©2026 Raj Jain

Universal Plug and Play

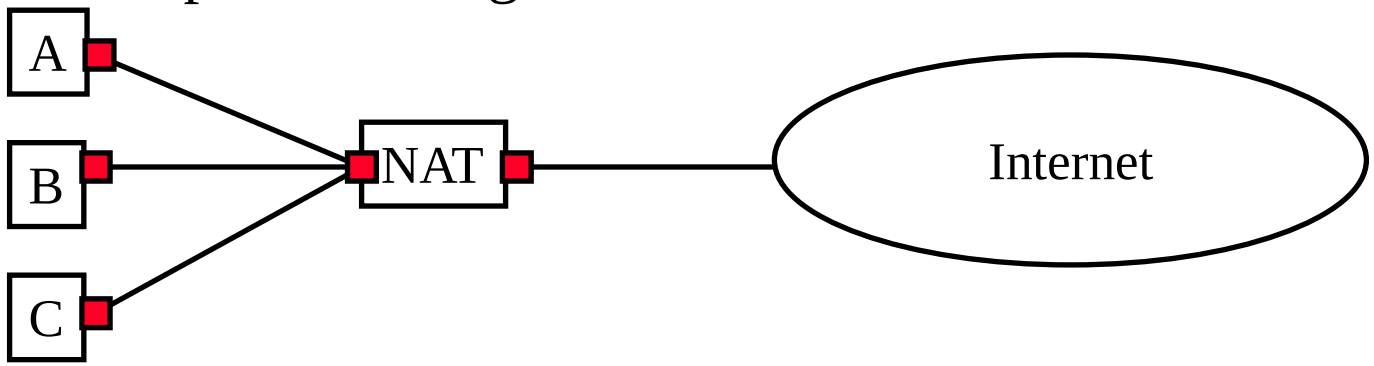
- NAT needs to be manually programmed to forward external requests
- UPnP allows hosts to request port forwarding
- Both hosts and NAT should be UPnP aware
- Host requests forwarding all port xx messages to it
- NAT returns the public address and the port #.
- The host can then announce the address and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



Student Questions

Homework 4C: NAT

- [20 points] Consider a home network of 3 computers connected to the Internet via a NAT router. Suppose the ISP assigns the router the address 24.34.112.234 and that the network address of the home network is 192.168.1.0/29.
- A. Assign addresses to all interfaces in the home network, starting with the lowest possible address.
- B. What is the subnet mask for the home computers?
- C. Suppose each host has two ongoing TCP connections, all to port 80 at host 128.119.40.86. Provide the six corresponding entries in the NAT translation table. Both NAT and computers use source ports starting at 4000.



Student Questions

©2026 Raj Jain

DHCP

- **D**ynamic **H**ost **C**ontrol **P**rotocol
- 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?"
  Sent to 255.255.255.255
- DHCP servers respond
- RFC 2132 defines DHCP options: DHCP Message type option is used to convey the type of the DHCP message. The code for this option is 53, and its length is 1. Legal values for this option are:

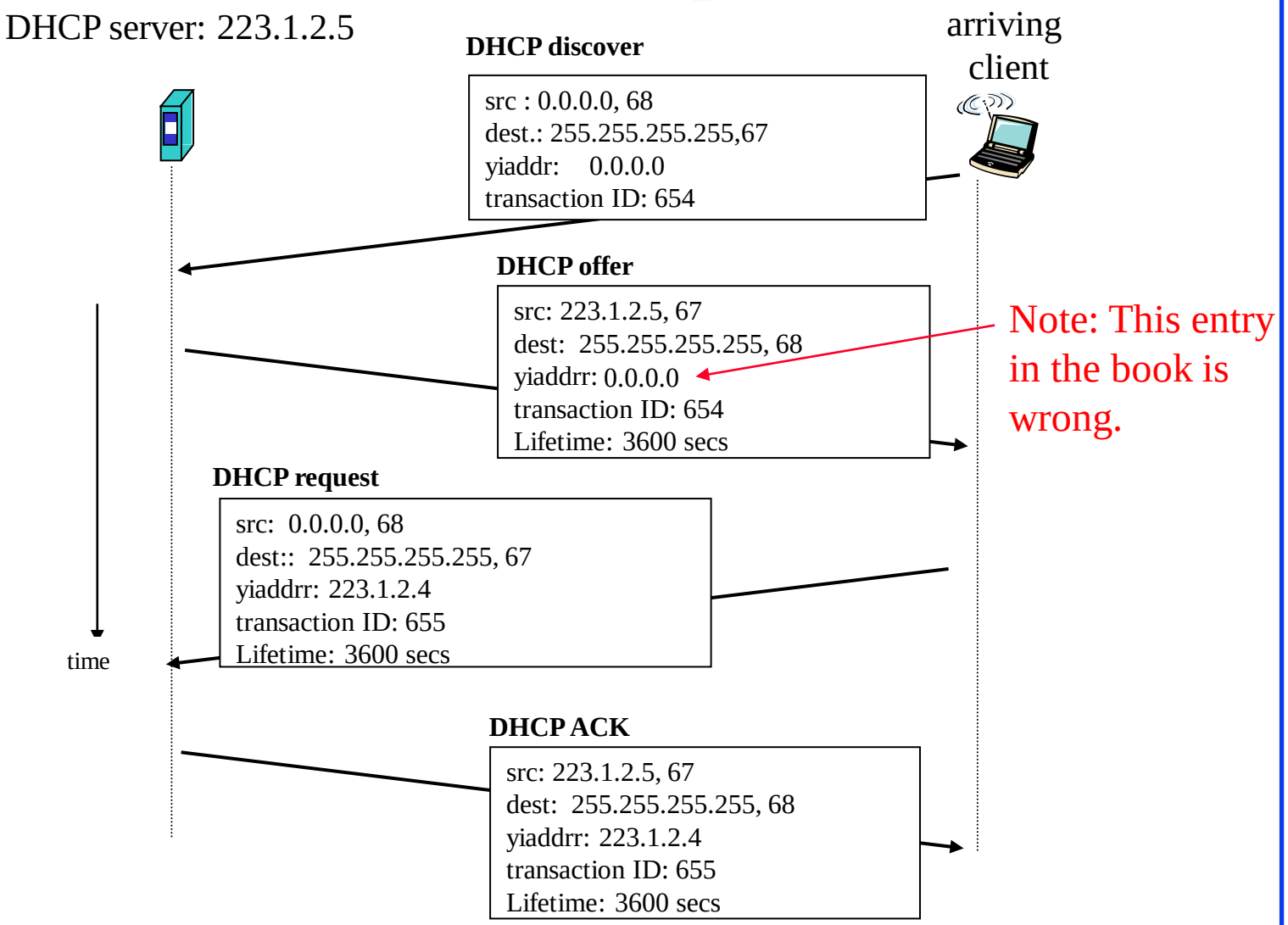
Value	Message Type	Value	Message Type
1	DHCP DISCOVER	5	DHCP ACK
2	DHCP OFFER	6	DHCP NAK
3	DHCP REQUEST	7	DHCP RELEASE
4	DHCP DECLINE	8	DHCP INFORM

Ref: https://datatracker.ietf.org/doc/html/rfc2132

Student Questions

©2026 Raj Jain

DHCP Example



Student Questions

©2026 Raj Jain

Lab 4B: DHCP

- [15 points] Download the Wireshark traces from http://gaia.cs.umass.edu/wireshark-labs/wireshark-traces.zip
- Open *dhcp-ethereal-trace-1* in Wireshark. You may need to add extension .pcap if not already present.
  Select **View → Expand All**. Answer the following questions:
  1. Examine Frame 2 marked DHCP.
     A. What transport protocol and destination port # are used by DHCP?
     B. What are the source and destination IP addresses for this frame, and why?
     C. What is the **Code-Length-Type** for the DHCP Discover option?
  2. Examine Frames 4, 5, and 6 to find Code-Length-Type for:
     A. DHCP Offer
     B. DHCP Request
     C. DHCP Ack

Student Questions

Lab 4B: DHCP (Cont)

3. Examine Frame 4:
   A. What was the IP address assigned by the DHCP server?
   B. What IP address is this frame addressed to, and why?
   C. What was other information provided by the DHCP server?
      1. Subnet Mask:
      2. Default Gateway:
      3. DNS1:
      4. DNS2:
      5. Domain Name:
      6. Lease Time:
4. Examine Frame 5 and find what preferred IP address was requested by the client?

Student Questions

End of Part 2

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's surface
- If assigned at the rate of 10^6/μs, 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
    ::3234:0000:0000: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

Student Questions

IPv6 Header

- IPv6:

Version (4b)	Traffic Class (8b)	Flow Label (20b)
Payload Length (16b)	Next Header (8b)	Hop Limit (8b)
Source Address (128b)		
Destination Address (128b)		

- IPv4:

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

Student Questions

End of Part 2

IPv6 vs. IPv4

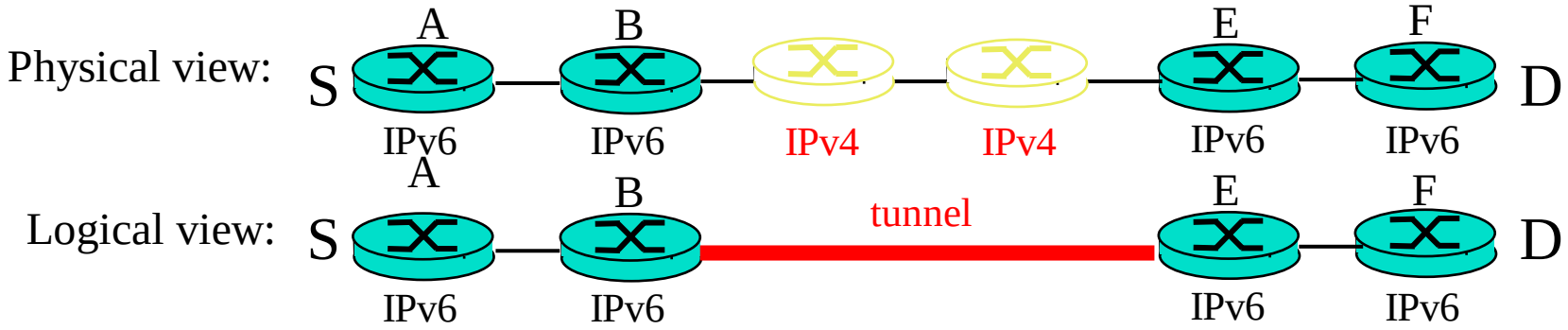
- 1995 vs. 1975
- IPv6 is only twice the size of the IPv4 header
- Only the version number has the same position and meaning as in IPv4
- Removed: header length, type of service, identification, flags, fragment offset, header checksum ⇒ No fragmentation
- Datagram length replaced by payload length
- Protocol type replaced by the "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)

Student Questions

©2026 Raj Jain

IPv4 to IPv6 Transition

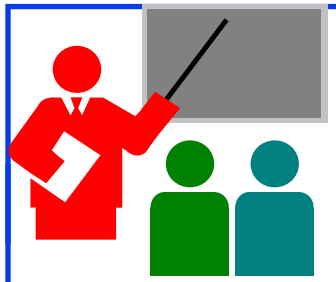
- **Dual Stack**: Each IPv6 router also implements IPv4
  IPv6 is used only if the source host, destination host, and all routers on the path are IPv6 aware.
- **Tunneling**: The last IPv6 router puts the entire IPv6 datagram in a new IPv4 datagram addressed to the next IPv6 router
  = **Encapsulation**



IPv4 From:B to E	IPv6 From:S to D	Data

Student Questions

©2026 Raj Jain



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. **DHCP** is used to allocate addresses to hosts automatically
4. IPv6 uses **128-bit addresses**. Requires dual-stack or **tunneling** to coexist with IPv4.

Student Questions

Ref: Read Section 4.3 of the textbook. Try R17 through R29.

©2026 Raj Jain

Generalized Forwarding and SDN

- Planes of Networking
- Data vs. Control Logic
- OpenFlow Protocol

Student Questions

Planes of Networking

- **Data Plane**: All activities involving as well as resulting from data packets sent by the end user, e.g.,
  - Forwarding
  - Fragmentation and reassembly
  - Replication for multicasting
- **Control Plane**: All activities that are necessary to perform data plane activities but do not involve end-user data packets
  - Making routing tables
  - Setting packet handling policies (e.g., security)
  - Base station beacons announcing the availability of services

Ref: Open Data Center Alliance Usage Model: Software Defined Networking Rev 1.0,"
http://www.opendatacenteralliance.org/docs/Software_Defined_Networking_Master_Usage_Model_Rev1.0.pdf

Student Questions

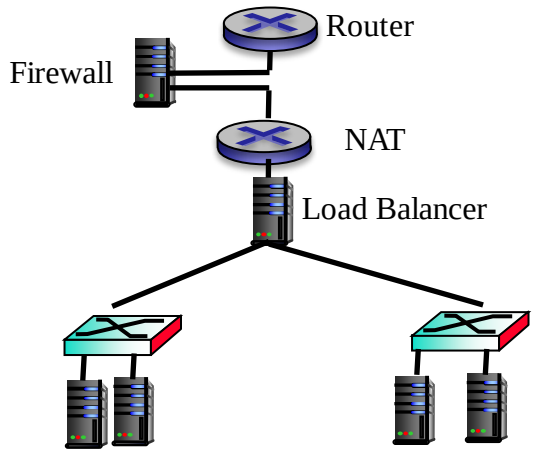
Planes of Networking (Cont)

- **Management Plane**: All activities related to provisioning and monitoring of the networks
  - Fault, Configuration, Accounting, Performance, and Security (**FCAPS**).
  - Instantiate new devices and protocols (Turn devices on/off)
  - Optional ⇒ May be handled manually for small networks.
- **Services Plane**: Middlebox services to improve performance or security, e.g.,
  - Load Balancers, Proxy Service, Intrusion Detection, Firewalls, SSL Off-loaders
  - Optional ⇒ Not required for small networks.

Student Questions

Middleboxes

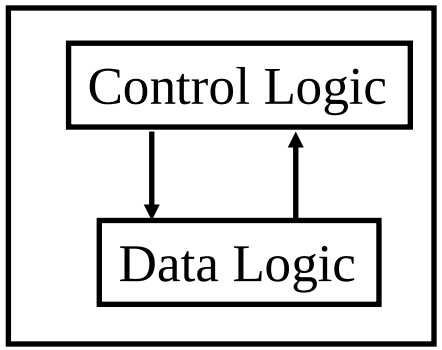
- Boxes on the data path that perform functions other than routing/forwarding.
- Addressing: NAT
- Security: Firewalls
- Performance: Load Balancers, compression



Student Questions

Data vs. Control Logic

- The Data plane runs at line rate,
  e.g., 100 Gbps for 100 Gbps Ethernet ⇒ Fast Path
  ⇒ Typically implemented using special hardware,
  e.g., Ternary Content Addressable Memories (TCAMs)
- Some exceptional data plane activities are handled by the CPU in the switch ⇒ Slow path
  e.g., Broadcast, Unknown, and Multicast (BUM) traffic
- All control activities are generally handled by the CPU



Student Questions

OpenFlow: Key Ideas

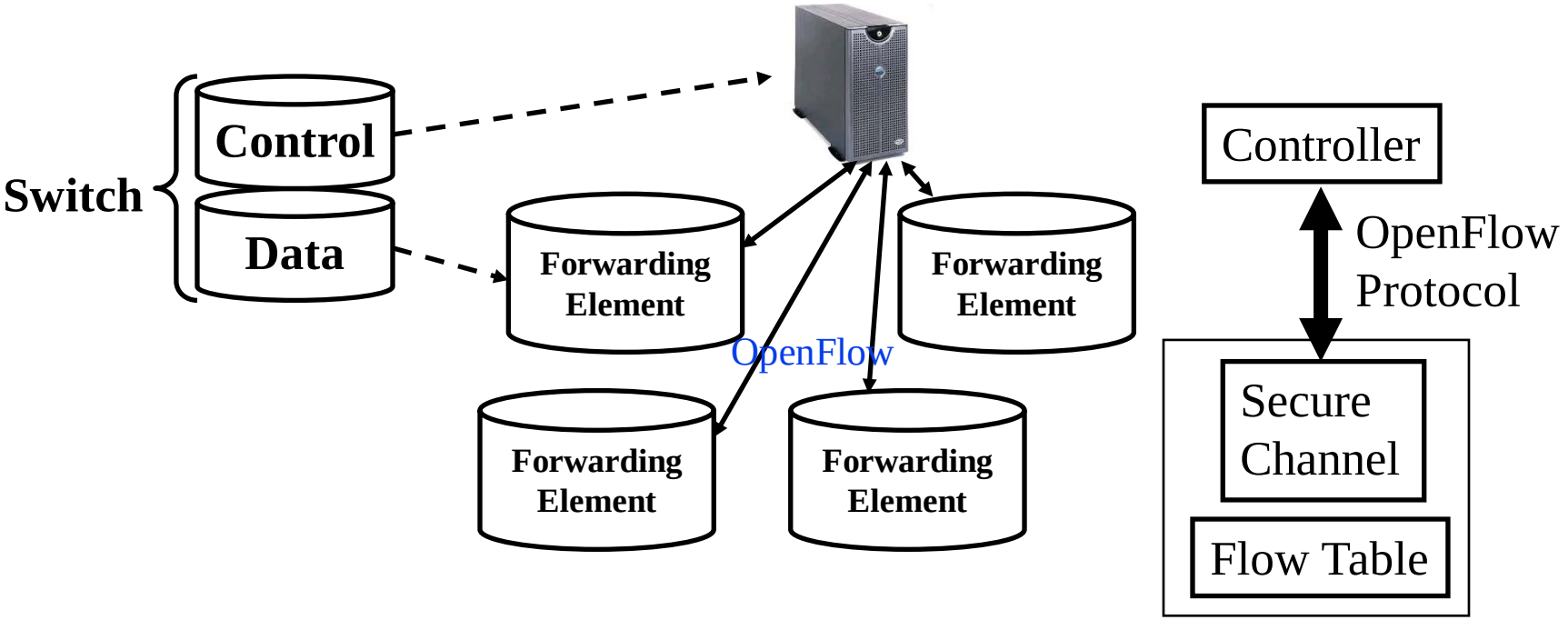
1. Separation of control and data planes
2. Centralization of control
3. Flow-based control

Student Questions

Ref: N. McKeown, et al., ``OpenFlow: Enabling Innovation in Campus Networks," ACM SIGCOMM CCR, Vol. 38, No. 2, April 2008, pp. 69-74.

©2026 Raj Jain

Separation of Control and Data Plane



- Control logic is moved to a controller
- Switches only have forwarding elements
- One expensive controller with a lot of cheap switches
- OpenFlow is the protocol to send/receive forwarding rules from the controller to switches

Student Questions

©2026 Raj Jain

OpenFlow V1.0

- On packet arrival, match the header fields with flow entries in a table, if any entry matches, perform indicated actions, and update the counters indicated in that entry.

Flow Table:

Header Fields	Actions	Counters
Header Fields	Actions	Counters
…	…	…
Header Fields	Actions	Counters

Ingress Port	Ether Source	Ether Dest	VLAN ID	VLAN Priority	IP Src	IP Dst	IP Proto	IP ToS	Src L4 Port	Dst L4 Port

Ref: http://archive.openflow.org/documents/openflow-spec-v1.0.0.pdf

©2026 Raj Jain

Student Questions

Flow Table Example

Port	Src MAC	Dst MAC	VLAN ID	Priority	EtherType	Src IP	Dst IP	IP Proto	IP ToS	Src L4 Port ICMP Type	Dst L4 Port ICMP Code	Action	Counter
*	*	0A:C8:*	*	*	*	*	*	*	*	*	*	Port 1	102
*	*	*	*	*	*	*	192.168.*.*	*	*	*	*	Port 2	202
*	*	*	*	*	*	*	*	*	*	21	21	Drop	420
*	*	*	*	*	*	*	*	0x806	*	*	*	Local	444
*	*	*	*	*	*	*	*	0x1*	*	*	*	Controller	1

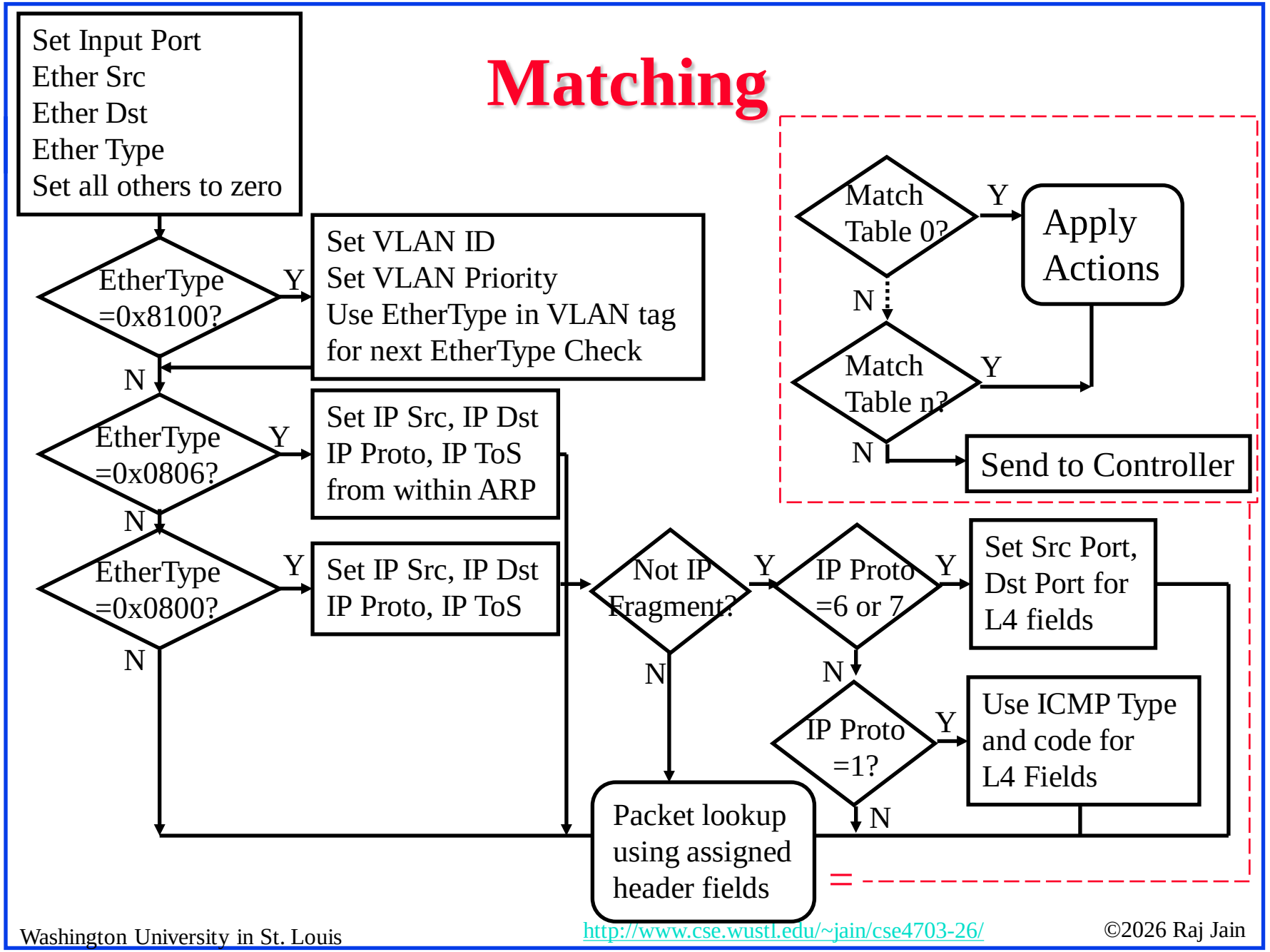
- Idle timeout: Remove entry if no packets received for this time
- Hard timeout: Remove entry after this time
- If both are set, the entry is removed if either one expires.

Ref: S. Azodolmolky, "Software Defined Networking with OpenFlow," Packt Publishing, October 2013, 152 pp., ISBN:978-1-84969-872-6 (Safari Book)

Student Questions

©2026 Raj Jain

Matching



Student Questions

©2026 Raj Jain

Counters

Per Table	Per Flow	Per Port	Per Queue
Active Entries	Received Packets	Received Packets	Transmit Packets
Packet Lookups	Received Bytes	Transmitted Packets	Transmit Bytes
Packet Matches	Duration (Secs)	Received Bytes	Transmit overrun errors
	Duration (nanosecs)	Transmitted Bytes	
		Receive Drops	
		Transmit Drops	
		Receive Errors	
		Transmit Errors	
		Receive Frame Alignment Errors	
		Receive Overrun erorrs	
		Receive CRC Errors	
		Collisions	

Student Questions

- How are counters utilized?

Actions

- Forward to Physical/**Virtual Port** *i*
- Enqueue: To a particular **queue** in the port ⇒ QoS
- Drop
- Modify Field: E.g., add/remove VLAN tags, ToS bits, Change TTL.
- Masking allows matching only selected fields, e.g., Dest. IP, Dest. MAC, etc.
- If the header matches an entry, corresponding actions are performed, and counters are updated.
- If no header matches, the packet is queued and the **header is sent to the controller**, which sends a new rule. Subsequent packets of the flow are handled by this rule.
- Secure Channel: Between the controller and the switch using TLS

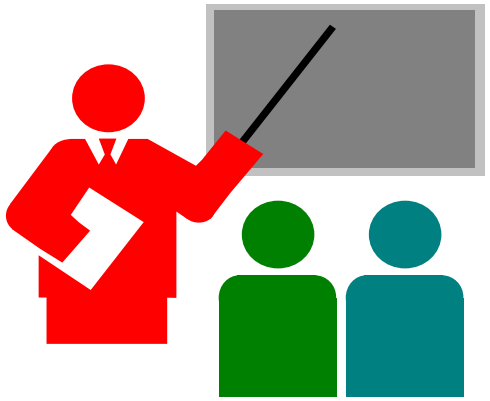
Student Questions

Actions (Cont)

- Modern switches already implement flow tables, typically using Ternary Content Addressable Memories (TCAMs)
- A controller can change the forwarding rules if a client moves.
  $\Rightarrow$ Packets for mobile clients are forwarded correctly
- A controller can send flow table entries beforehand (**Proactive**) or Send them on demand (**Reactive**). OpenFlow allows both models.

Student Questions

SDN Data Plane: Summary



1. **The Data plane** consists of packets sent by the users
2. OpenFlow separates the data plane from the **control plane** and centralizes the control plane.
3. The **controller** makes rules for forwarding and sends them to switches
4. Switches match the rules and take specified actions

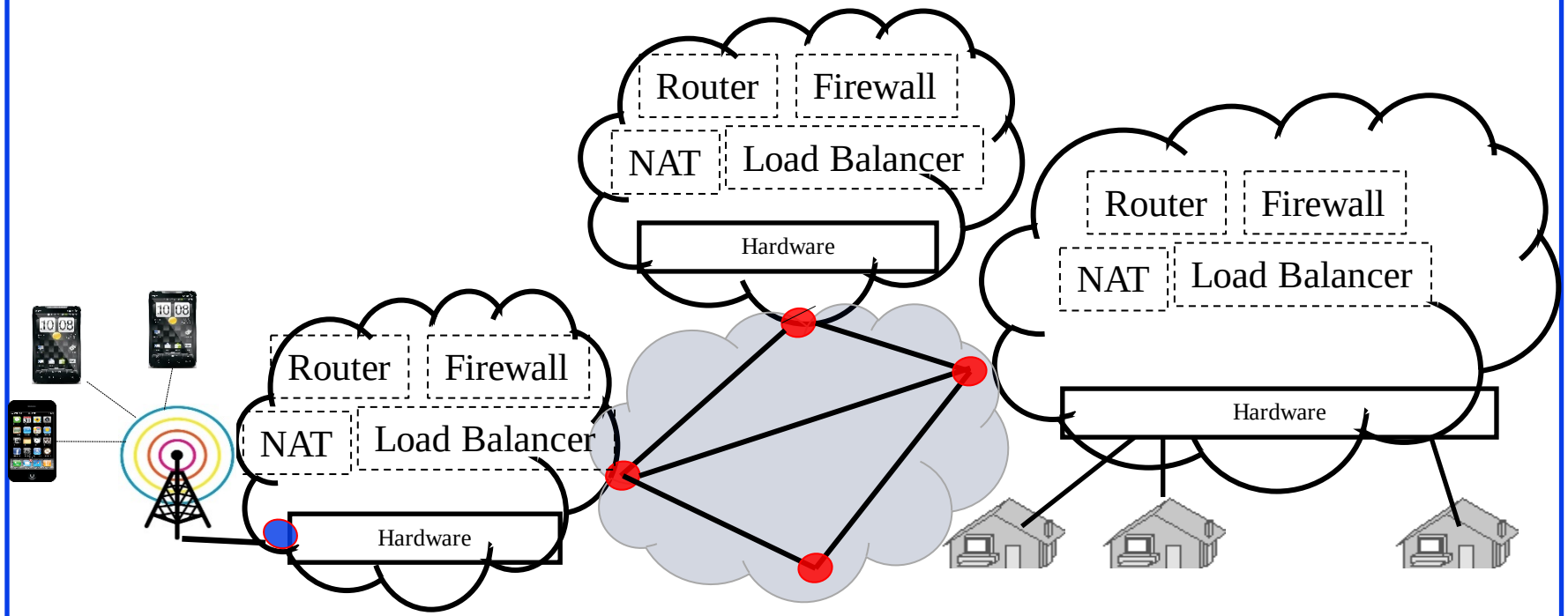
Read section 4.4 and review questions R32-R35.

Student Questions

©2026 Raj Jain

Network Function Virtualization (NFV)

- Standard hardware is fast and cheap ⇒ No specialized hardware
- Implement all functions in software
- Virtualize all functions ⇒ Cloud ⇒ Create capacity on demand

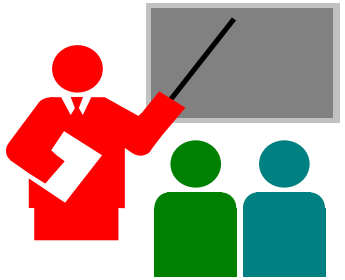


Read section 4.5

Student Questions

©2026 Raj Jain

Network Layer Data Plane: Summary



1. **Forwarding** consists of matching the destination address to a list of entries in a table. **Routing** consists of making that table.
2. IP is a forwarding protocol. IPv4 uses 32-bit addresses in **dot-decimal notation**. IPv6 uses 128-bit addresses in **Hex-Colon notation**.
3. **DHCP** is used to assign addresses dynamically.
4. **Private addresses** are used inside an enterprise network. **NAT** allows a single public address to be used by many internal hosts with private addresses.
5. **OpenFlow** separates the data plane from the control plane and centralizes the control plane.

Student Questions

©2026 Raj Jain

Acronyms

- ACK Acknowledgement
- ACM Automatic Computing Machinery
- AQM Active Queue Management
- ARP Address Resolution Protocol
- ATM Asynchronous Transfer Mode
- BGP Border Gateway Protocol
- BUM Broadcast, Unknown, and Multicast
- CAMs Content Addressable Memories
- CBR Constant bit rate
- CCR Computer Communications Review
- CIDR Classless Inter-Domain Routing
- CPU Central Processing Unit
- DHCP Dynamic Host Control Protocol
- DNS Domain Name Service
- FCAPS Fault, Configuration, Accounting, Performance and Security
- FCFS First Come First Served

Student Questions

©2026 Raj Jain

Acronyms (Cont)

FTP	File Transfer Protocol
GFR	Guaranteed Frame Rate
HTTP	Hyper-Text Transfer Protocol
ICMP	IP Control Message Protocol
ID	Identifier
IP	Inter-Network Protocol
IPv4	IP Version 4
IPv6	IP Version 6
ISP	Internet Service Provider
KISS	Keep it simple stupid
LAN	Local Area Network
MAC	Media Access Control
MS	Microsoft
MTU	Maximum Transmission Unit
NAT	Network Address Translation
PBX	Private Branch Exchange

Student Questions

©2026 Raj Jain

Acronyms (Cont)

PHY	Physical Layer
QoS	Quality of Service
RED	Random Early Drop
RFC	Request for Comment
RIP	Routing Information Protocol
RTT	Round Trip Time
SDN	Software Defined Networking
SMTP	Simple Mail Transfer Protocol
SSL	Secure Socket Layer
TCAM	Ternary Content Addressable Memory
TCP	Transmission Control Protocol
TLS	Transport Level Security
ToS	Type of Service
TTL	Time to live
UBR	Unspecified bit rate
UPnP	Universal Plug and Play

Student Questions

©2026 Raj Jain

Acronyms (Cont)

- VBR Variable bit rate
- VCI Virtual Circuit Identifiers
- VLAN Virtual Local Area Network
- VPN Virtual Private Network
- WAN Wide Area Network
- WiFi Wireless Fidelity

Student Questions

Scan This to Download These Slides



Raj Jain
http://rajjain.com

http://www.cse.wustl.edu/~jain/cse4703-26/i_4nld.htm

Student Questions

©2026 Raj Jain

Related Modules



CSE 567: The Art of Computer Systems Performance Analysis
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw





CSE 570: Recent Advances in Networking (Spring 2013)
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Spring 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u





Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

Student Questions

©2026 Raj Jain